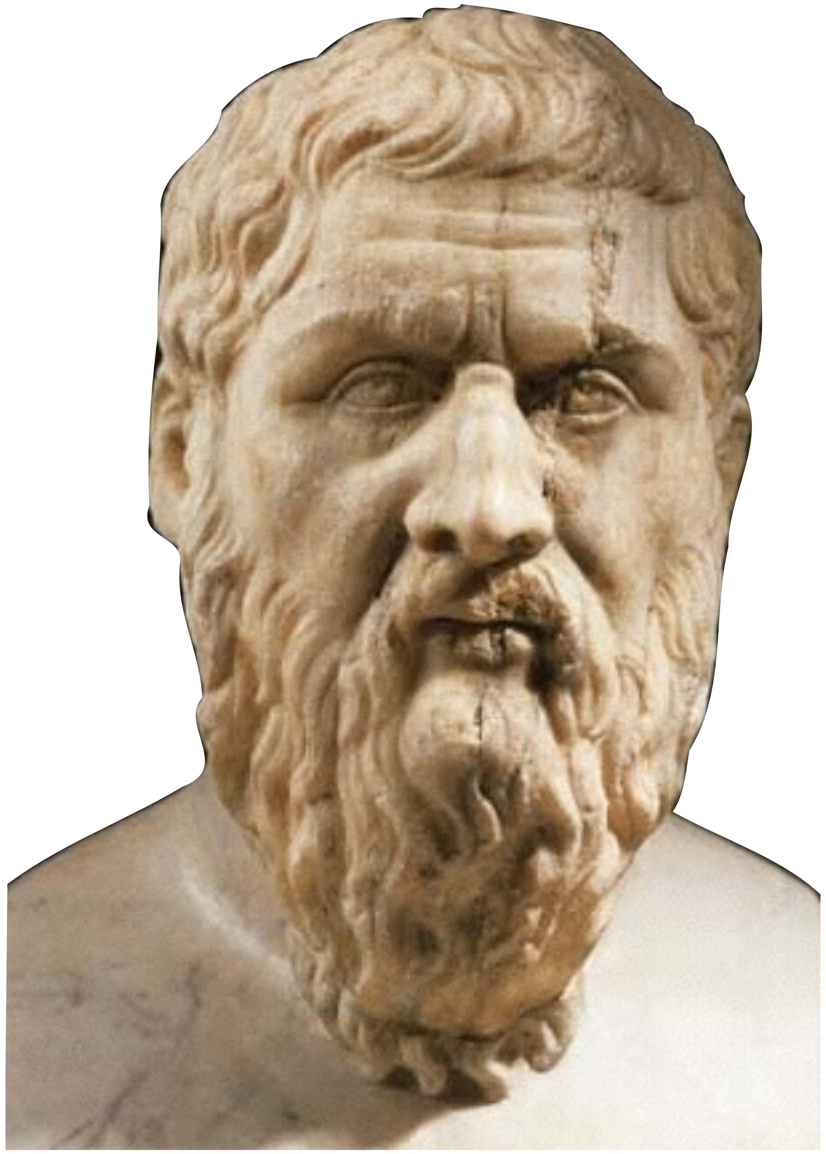
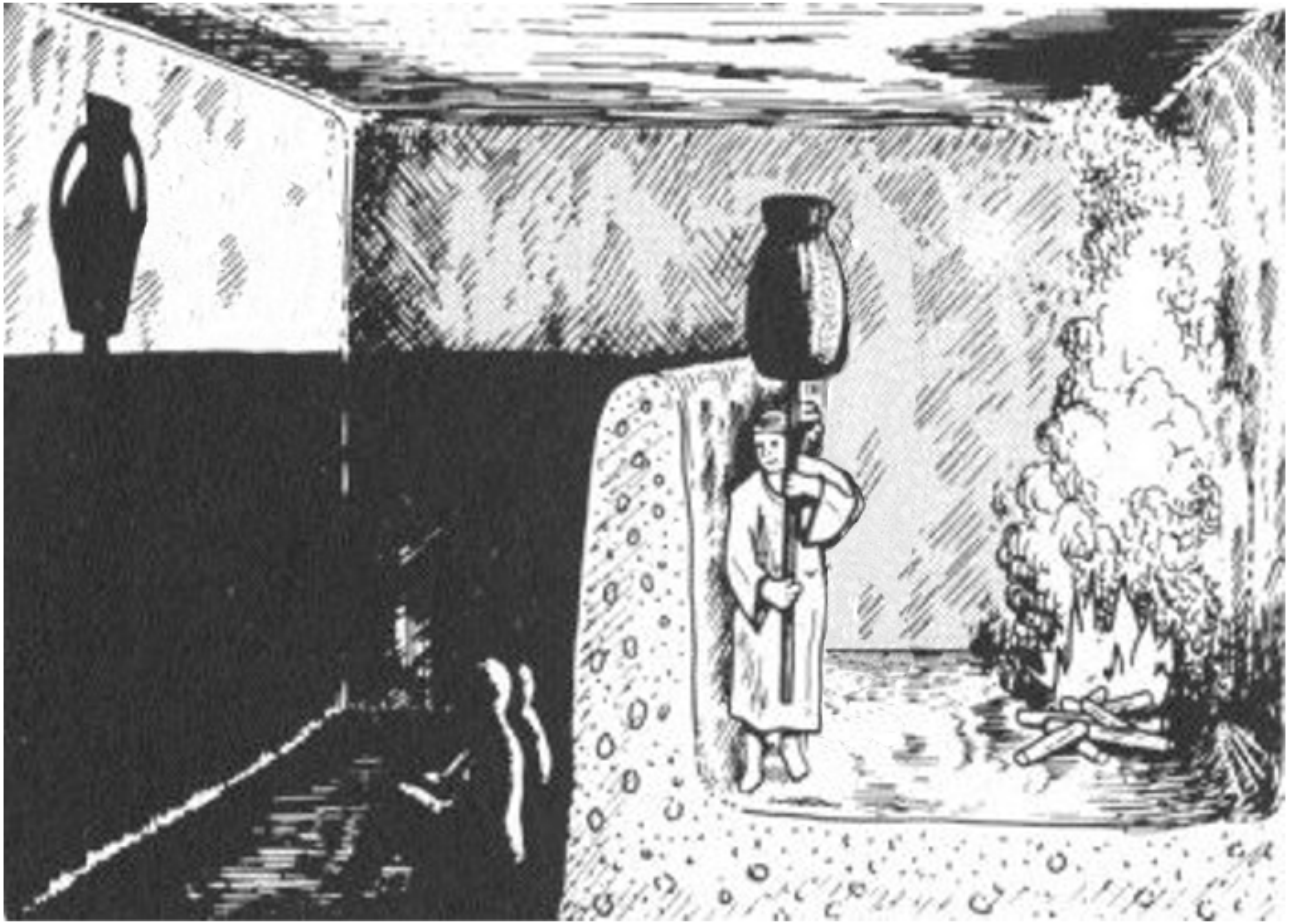


Platon

428/427–348/347 BC

Capitoline Museum, Rome.

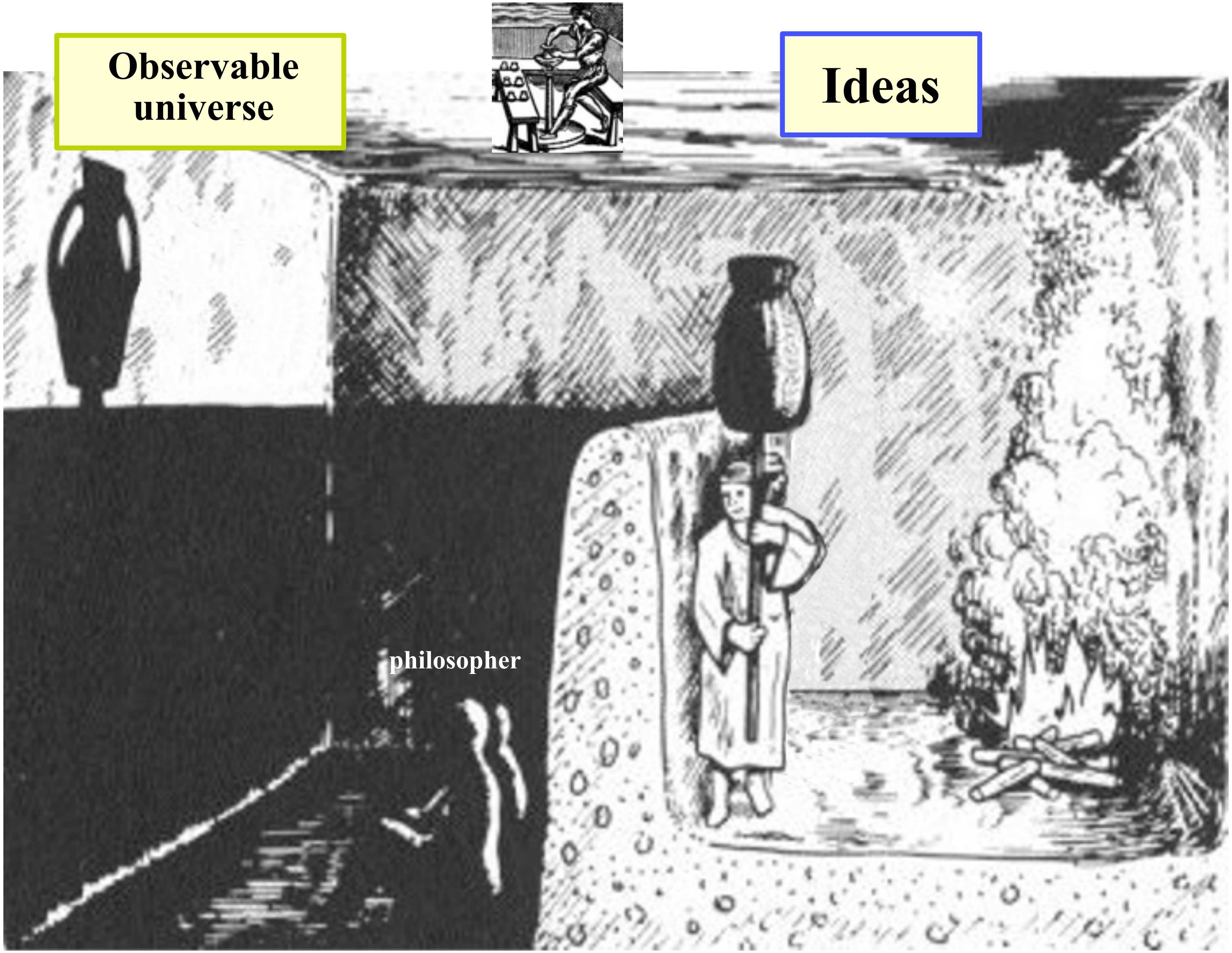
Plato's allegory of the cave*



Laszlo Szücs, image from criticalthinking-mc205.wikispaces.com

* The Republic (514a-520a)

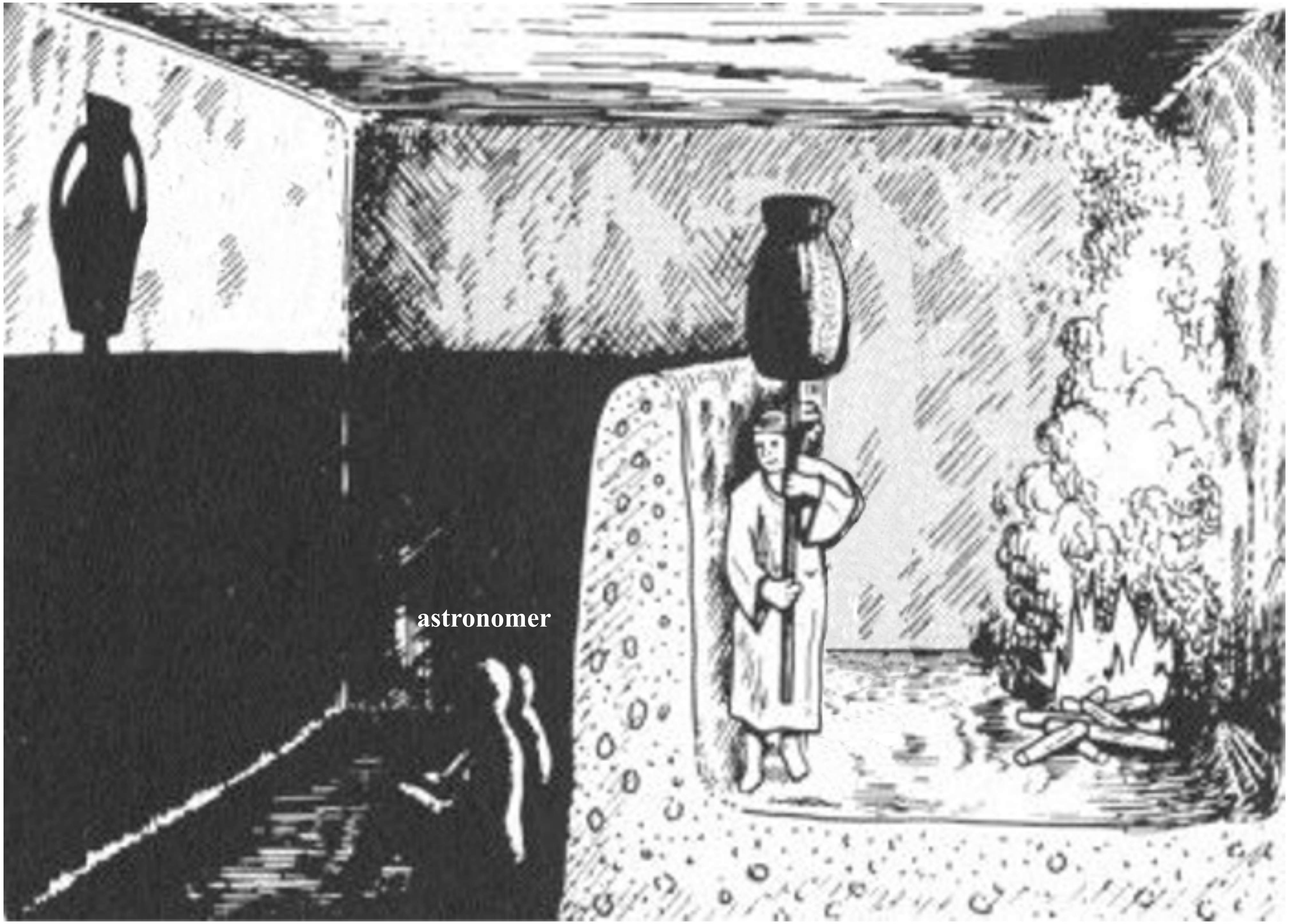
Plato's allegory of the cave*



Laszlo Szücs, image from criticalthinking-mc205.wikispaces.com

* The Republic (514a-520a)

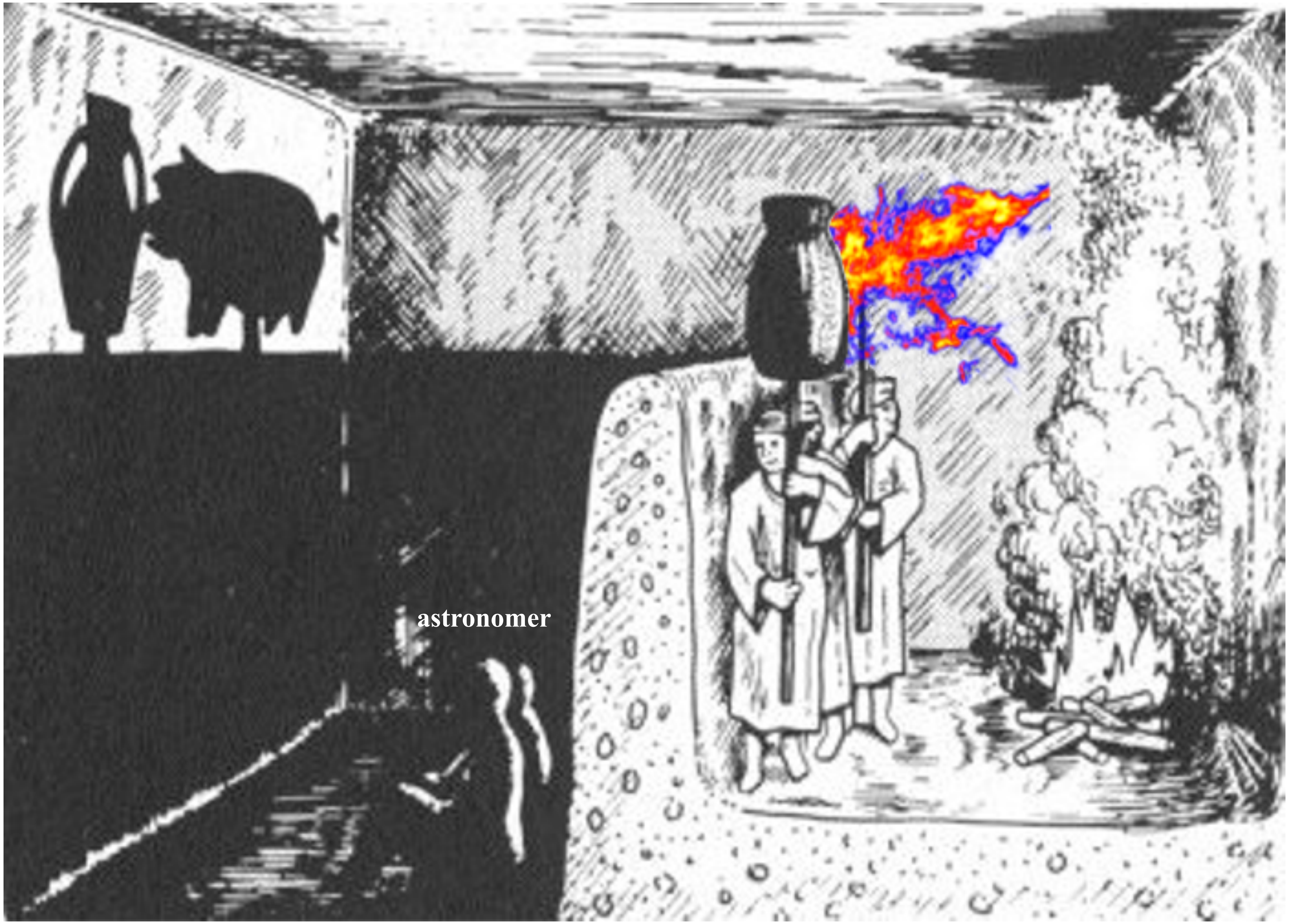
Plato's allegory of the cave* ↔ Astronomical observations



Laszlo Szücs, image from criticalthinking-mc205.wikispaces.com

* The Republic
(514a-520a)

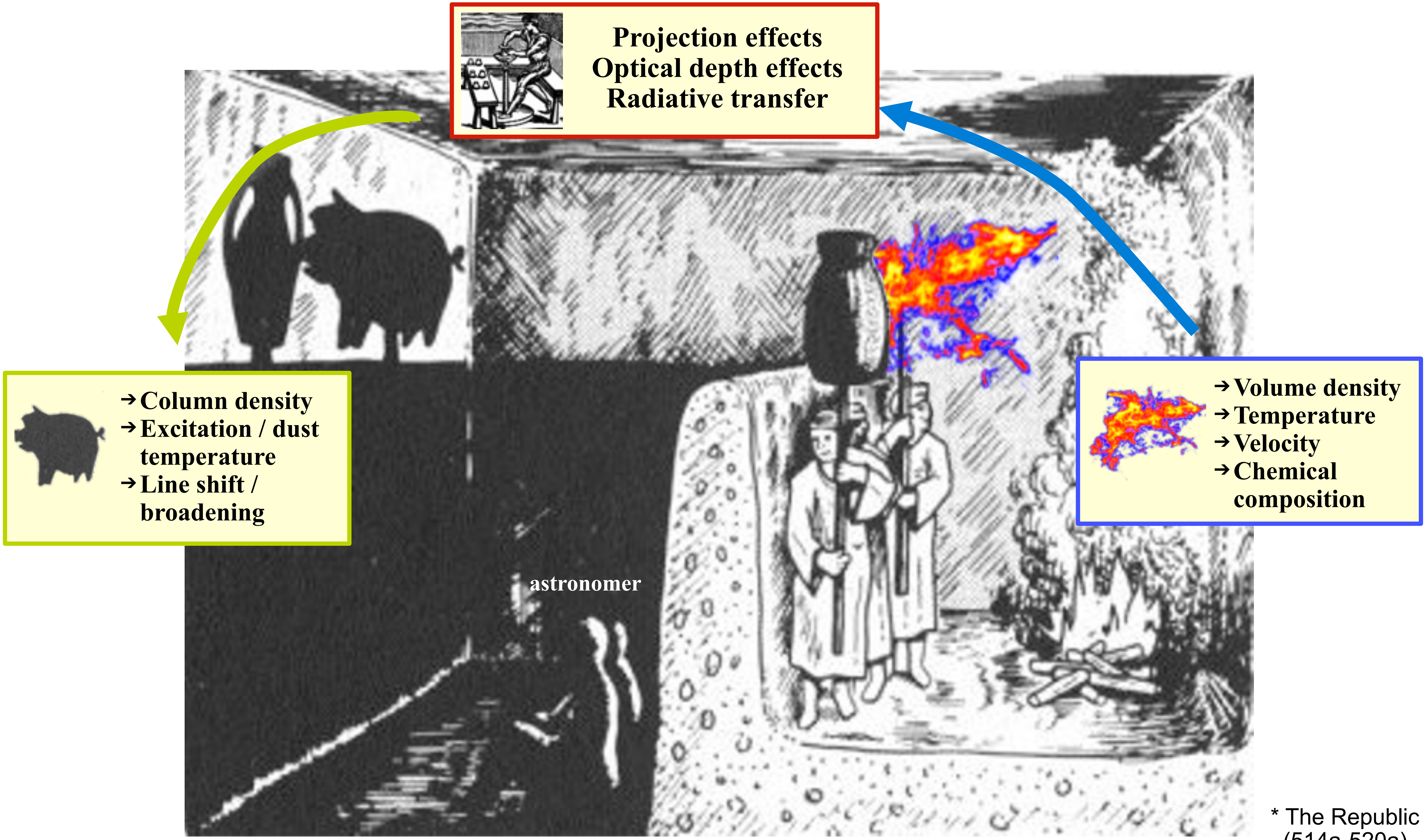
Plato's allegory of the cave* ↔ Astronomical observations



Laszlo Szücs, image from criticalthinking-mc205.wikispaces.com

* The Republic (514a-520a)

Plato's allegory of the cave* ↔ Astronomical observations



Projection effects
Optical depth effects
Radiative transfer

- → Column density
- → Excitation / dust temperature
- → Line shift / broadening

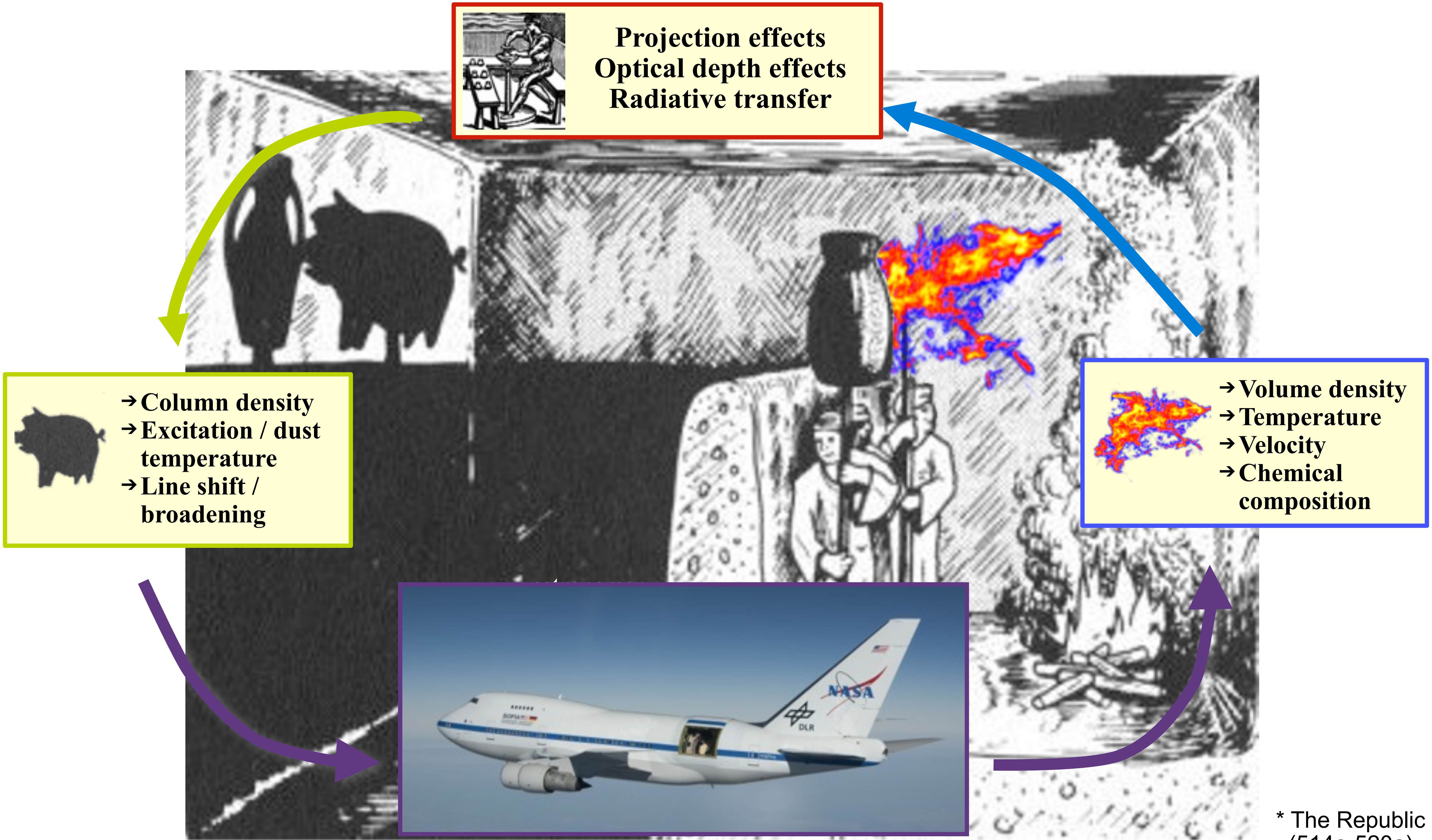
- → Volume density
- → Temperature
- → Velocity
- → Chemical composition

Laszlo Szücs, image from criticalthinking-mc205.wikispaces.com

---

* The Republic (514a-520a)

Plato's allegory of the cave* ↔ Astronomical observations



Projection effects
Optical depth effects
Radiative transfer

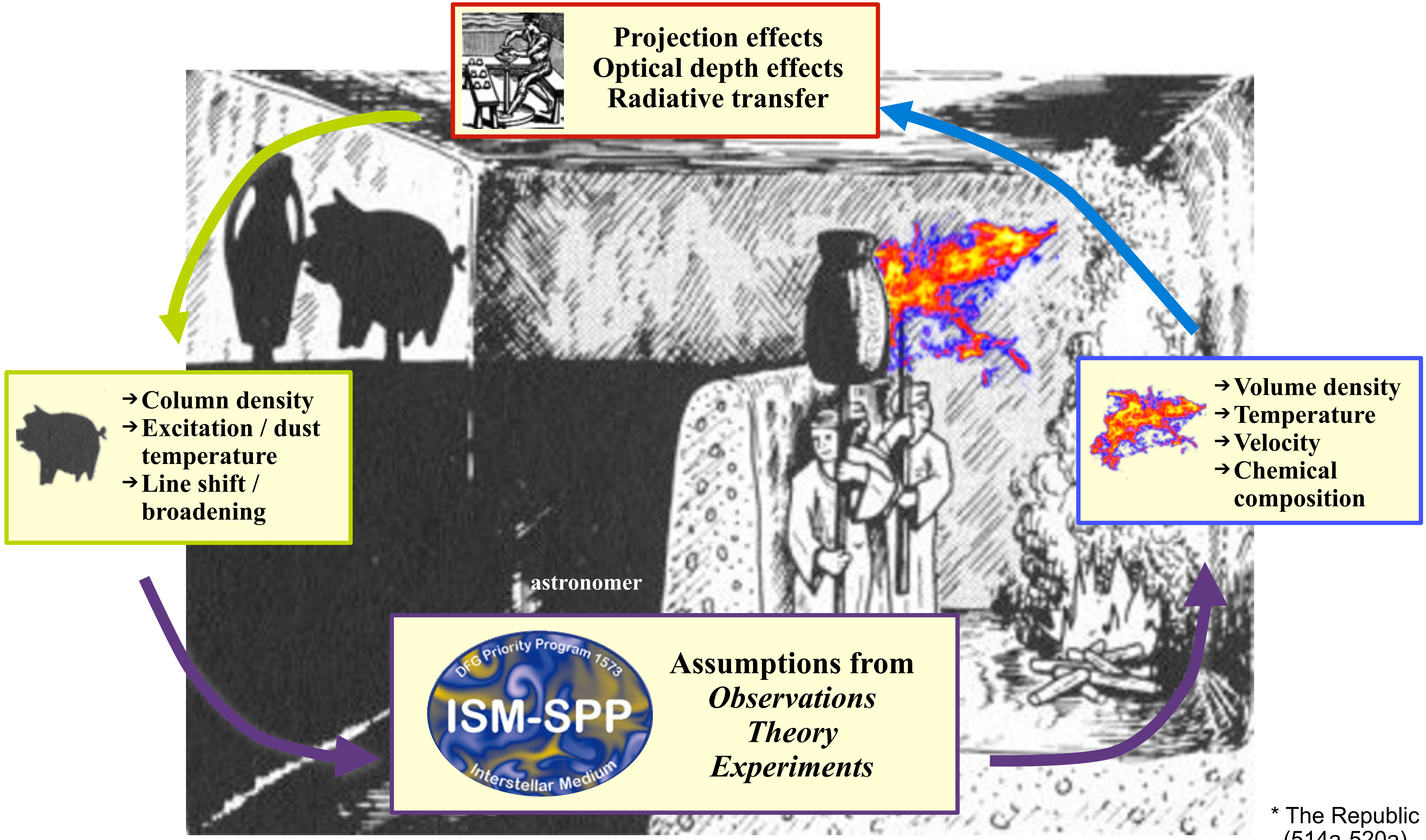
- → Column density
- → Excitation / dust temperature
- → Line shift / broadening

- → Volume density
- → Temperature
- → Velocity
- → Chemical composition

Laszlo Szücs, image from criticalthinking-mc205.wikispaces.com

* The Republic (514a-520a)

Plato's allegory of the cave* ↔ Astronomical observations



Projection effects
Optical depth effects
Radiative transfer

- → Column density
- → Excitation / dust temperature
- → Line shift / broadening

- → Volume density
- → Temperature
- → Velocity
- → Chemical composition

Assumptions from
Observations
Theory
Experiments

Laszlo Szücs, image from criticalthinking-mc205.wikispaces.com

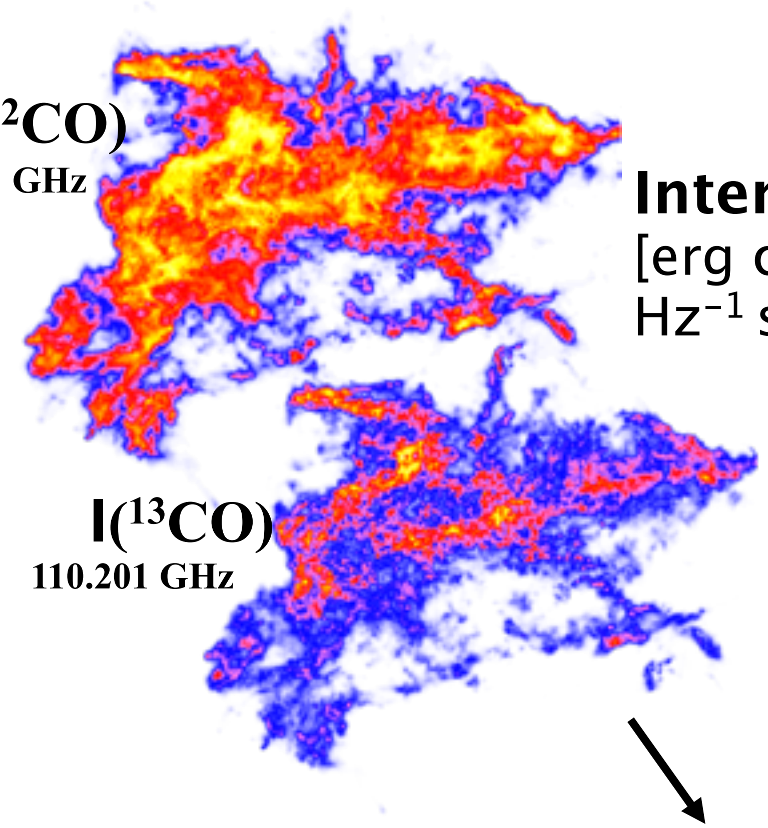
---

* The Republic (514a-520a)

Example: from CO emission to total column density

Following Wilson et al. 2009

J=1-0



Intensity
[erg cm^{-2} s^{-1} Hz^{-1} ster^{-1}]

Brightness temperature
[K]

T_B^{12}

T_B^{13}

Assumptions I.

I(^{12}CO) is optically thick

I(^{13}CO) is optically thin

Along a line of sight uniform T_{ex} and same for ^{12}CO and ^{13}CO

$$T_{\rm ex} = 5.5/\ln\left(1 + \frac{5.5}{T_B^{12} + 0.82}\right)$$

$$\tau_{13}(v) = -\ln\left[1 - \frac{T_{\rm B}^{13}}{5.3}\left\{\exp\left(\frac{5.3}{T_{\rm ex}} - 1\right)^{-1} - 0.16\right\}^{-1}\right],$$

LTE

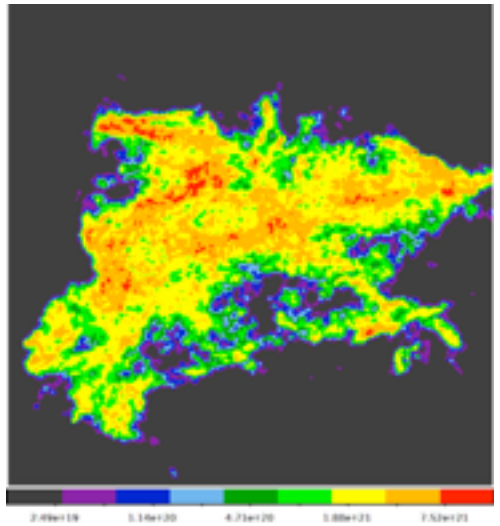
$$N(^{13}{\rm CO}) = 3.0 \times 10^{14}\frac{T_{\rm ex}\int \tau_{13}(v)dv}{1 - \exp(-5.3/T_{\rm ex})}$$

Assumptions II.

Uniform N(^{12}CO)/N(^{13}CO) ~ 60 *

N(H_2)/N(^{12}CO) ratio ~ 6.6×10^3 **

Column density
[cm^{-2}]

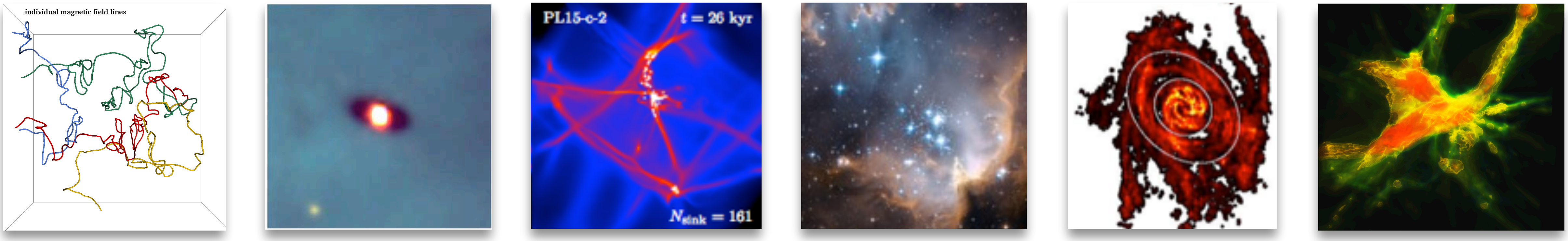


* Langer & Penzias (1990)

** Pineda et al. (2009)

Laszlo Szücs et al., in prep.

Star Formation



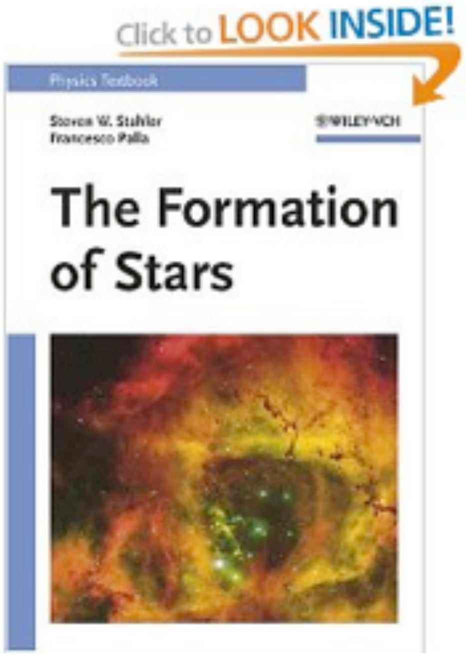
Ralf Klessen

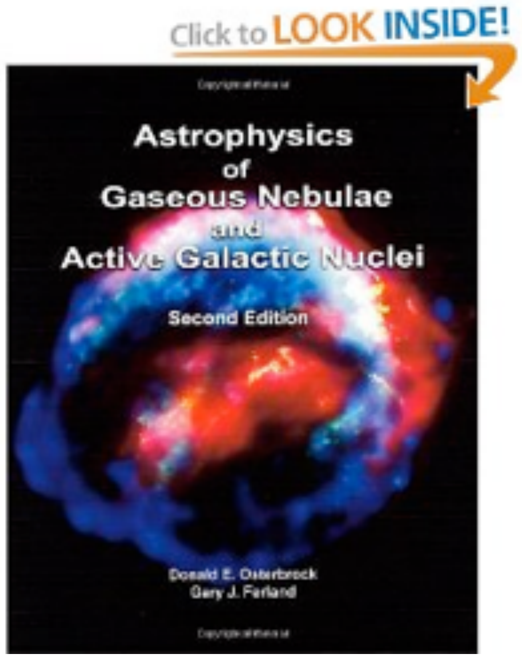
Universität Heidelberg, Zentrum für Astronomie
Institut für Theoretische Astrophysik

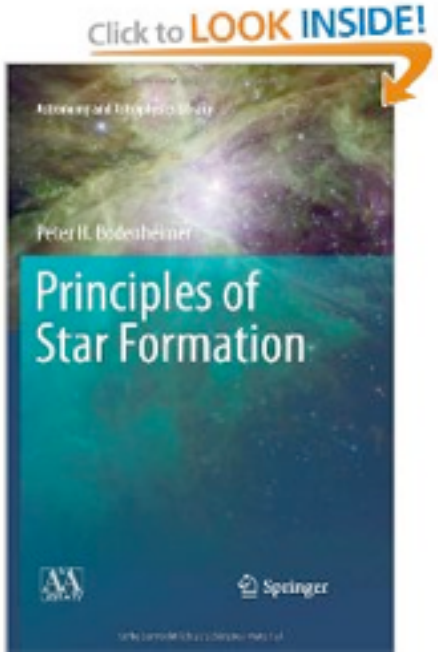
Disclaimer

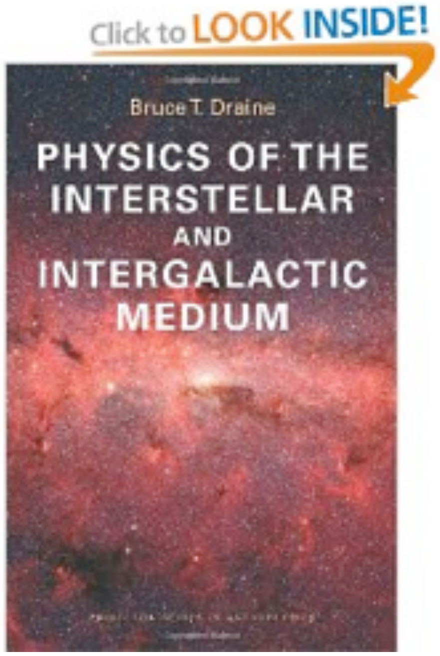
- I try to cover the field as broadly as possible, however, there will clearly be a bias towards my personal interests and many examples will be from my own work.

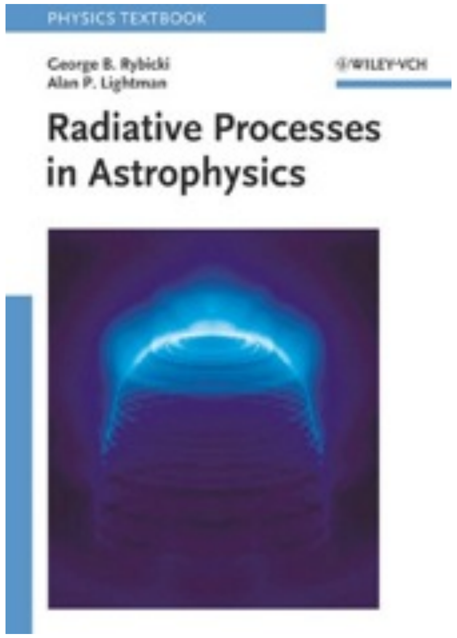
Literature

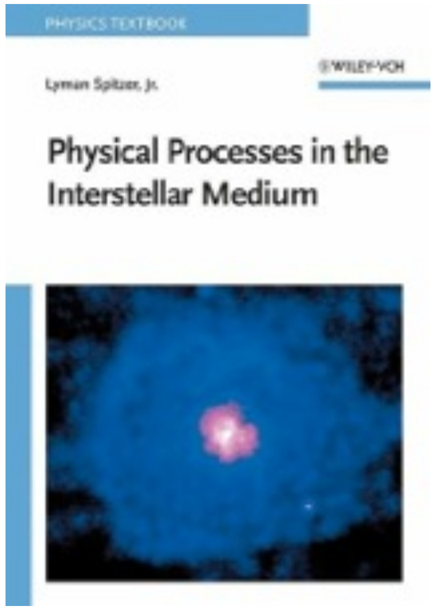

Click to LOOK INSIDE!
Physics Textbook
Steven W. Stahler
Francesco Palla
WILEY-VCH
The Formation of Stars

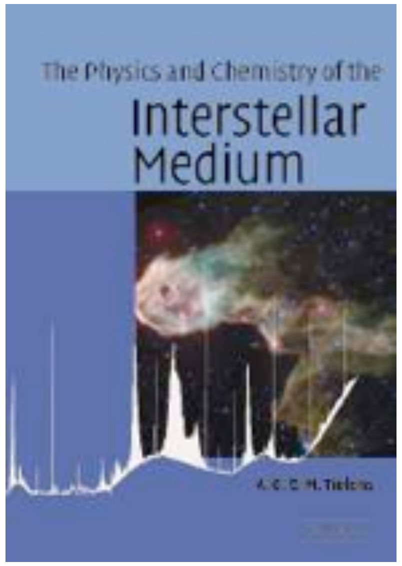

Click to LOOK INSIDE!
Astrophysics of Gaseous Nebulae and Active Galactic Nuclei
Second Edition
Donald E. Osterbrock
Gary J. Ferland

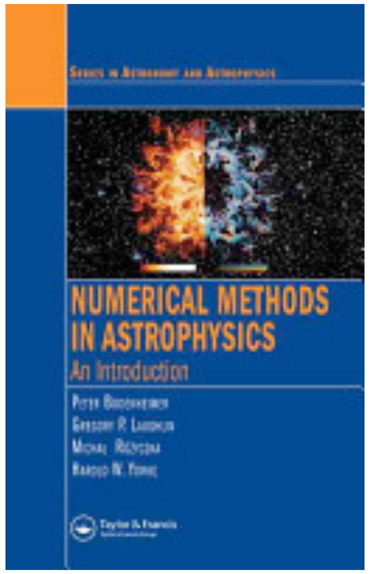

Click to LOOK INSIDE!
Peter H. Bodenheimer
Principles of Star Formation
Springer


Click to LOOK INSIDE!
Bruce T. Draine
PHYSICS OF THE INTERSTELLAR AND INTERGALACTIC MEDIUM


PHYSICS TEXTBOOK
George B. Rybicki
Alan P. Lightman
WILEY-VCH
Radiative Processes in Astrophysics


PHYSICS TEXTBOOK
Lyman Spitzer, Jr.
WILEY-VCH
Physical Processes in the Interstellar Medium


The Physics and Chemistry of the Interstellar Medium
A. G. G. M. Tielens


NUMERICAL METHODS IN ASTROPHYSICS
An Introduction
Taylor & Francis

Books

- Spitzer, L., 1978/2004, Physical Processes in the Interstellar Medium (Wiley-VCH)
- Rybicki, G.B., & Lightman, A.P., 1979/2004, Radiative Processes in Astrophysics (Wiley-VCH)
- Stahler, S., & Palla, F., 2004, "The Formation of Stars" (Weinheim: Wiley-VCH)
- Tielens, A.G.G.M., 2005, The Physics and Chemistry of the Interstellar Medium (Cambridge University Press)
- Osterbrock, D., & Ferland, G., 2006, "Astrophysics of Gaseous Nebulae & Active Galactic Nuclei, 2nd ed. (Sausalito: Univ. Science Books)
- Bodenheimer, P., et al., 2007, Numerical Methods in Astrophysics (Taylor & Francis)
- Draine, B. 2011, "Physics of the Interstellar and Intergalactic Medium" (Princeton Series in Astrophysics)
- Bodenheimer, P. 2012, "Principles of Star Formation" (Springer Verlag)

Literature

- Review Articles
  - Mac Low, M.-M., Klessen, R.S., 2004, "The control of star formation by supersonic turbulence", Rev. Mod. Phys., 76, 125
  - Elmegreen, B.G., Scalo, J., 2004, “Interstellar Turbulence 1”, ARA&A, 42, 211
  - Scalo, J., Elmegreen, B.G., 2004, “Interstellar Turbulence 2”, ARA&A, 42, 275
  - Zinnecker, H., Yorke, McKee, C.F., Ostriker, E.C., 2008, "Toward Understanding Massive Star Formation", ARA&A, 45, 481 - 563
  - McKee, C.F., Ostriker, E.C., 2008, "Theory of Star Formation", ARA&A, 45, 565
  - Kennicutt, R.C., Evans, N.J., 2012, “Star Formation in the Milky Way and Nearby Galaxies”, ARA&A, 50, 531
  - Krumholz, M., 2014, “The Big Problems in Star Formation: the Star Formation Rate, Stellar Clustering, and the Initial Mass Function”, arXiv:1402.0867

Further resources

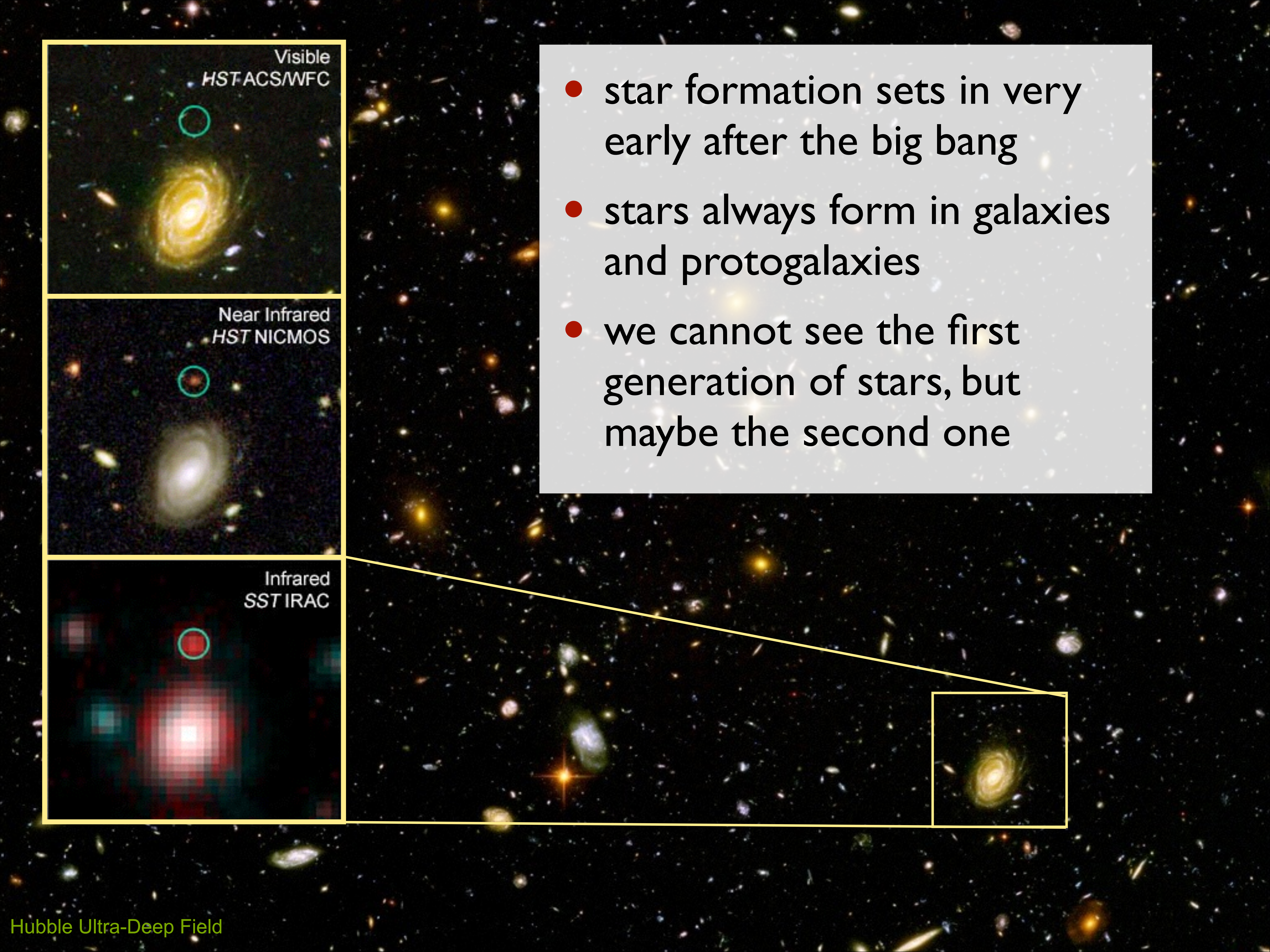
- Internet resources
  - Cornelis Dullemond: *Radiative Transfer in Astrophysics*
    http://www.ita.uni-heidelberg.de/~dullemond/lectures/radtrans_2012/index.shtml
  - Cornelis Dullemond: *RADMC-3D: A new multi-purpose radiative transfer tool*
    http://www.ita.uni-heidelberg.de/~dullemond/software/radmc-3d/index.shtml
  - List of molecules in the ISM (wikipedia):
    http://en.wikipedia.org/wiki/List_of_molecules_in_interstellar_space
  - Leiden database of molecular lines (LAMBDA)
    http://home.strw.leidenuniv.nl/~moldata/

agenda

- star formation theory
  - phenomenology
  - challenges
  - our current understanding and its limitations
- applications
  - the interstellar medium
  - the stellar mass function at birth (IMF)

NGC 3324 (Hubble, NASA/ESA)

phenomenology

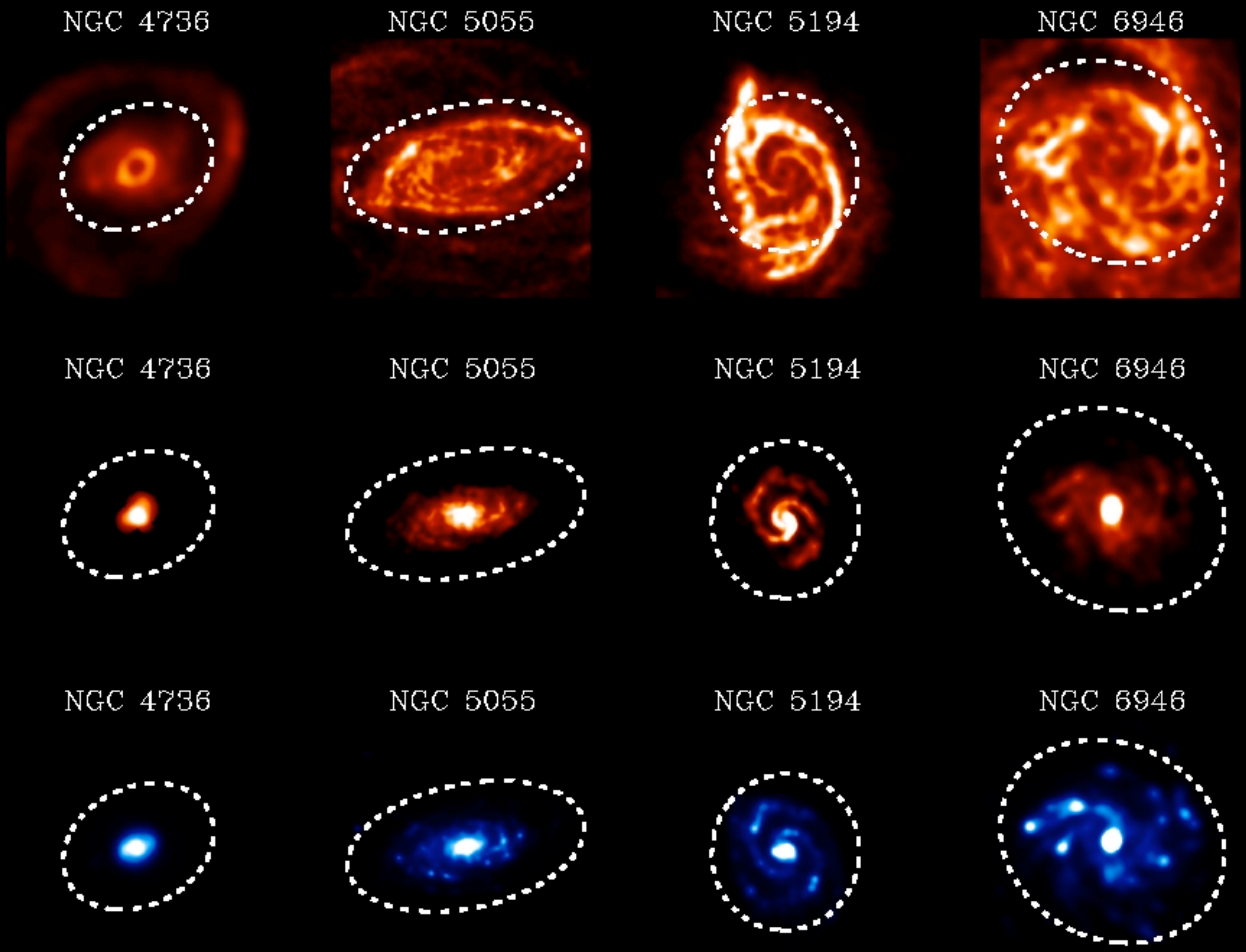


- star formation sets in very early after the big bang
- stars always form in galaxies and protogalaxies
- we cannot see the first generation of stars, but maybe the second one

Hubble Ultra-Deep Field

M51 with Hubble (additional processing R. Gendler)

- correlation between stellar birth and large-scale dynamics
- spiral arms
- tidal perturbation from neighboring galaxy



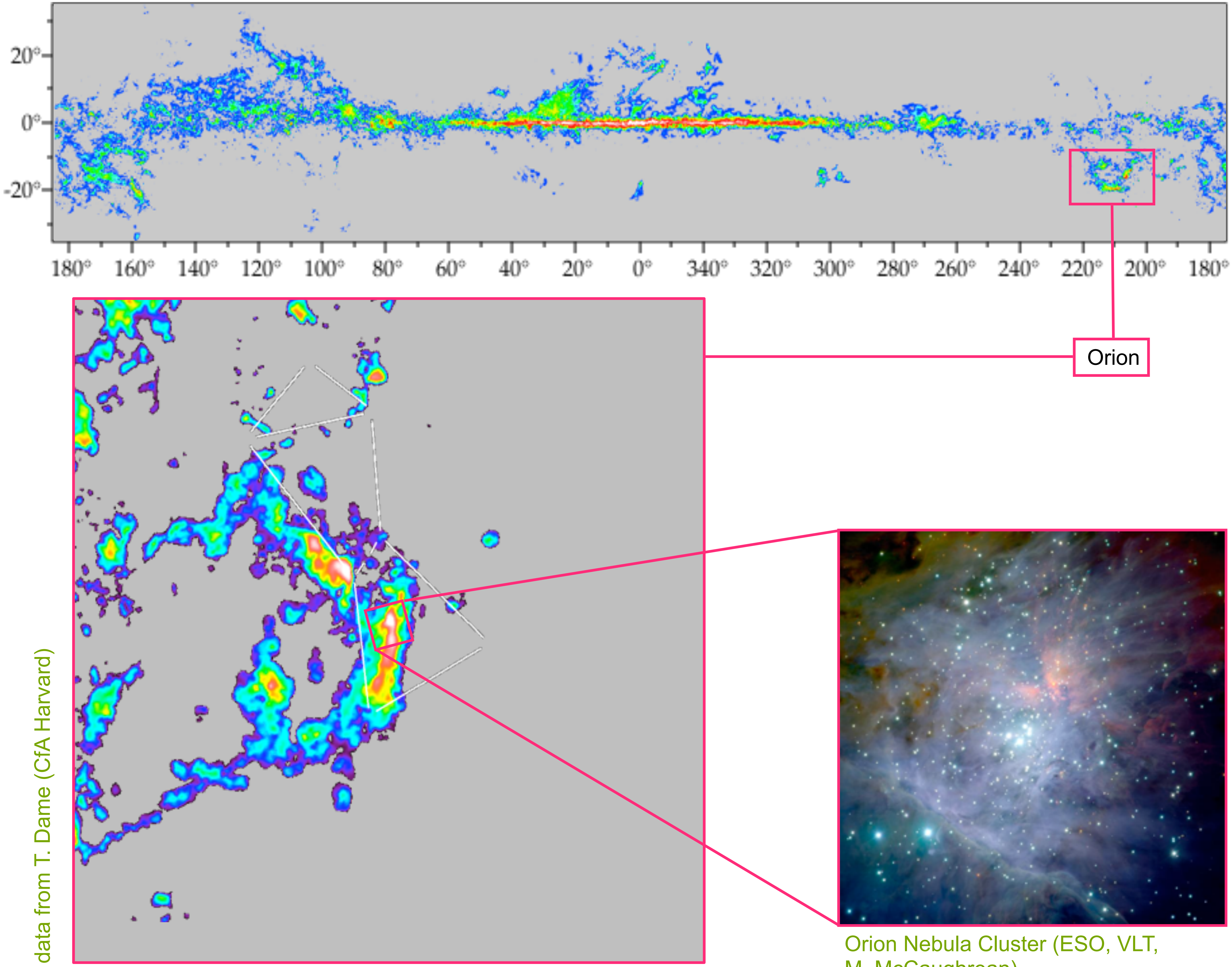
atomic hydrogen

molecular hydrogen

star formation

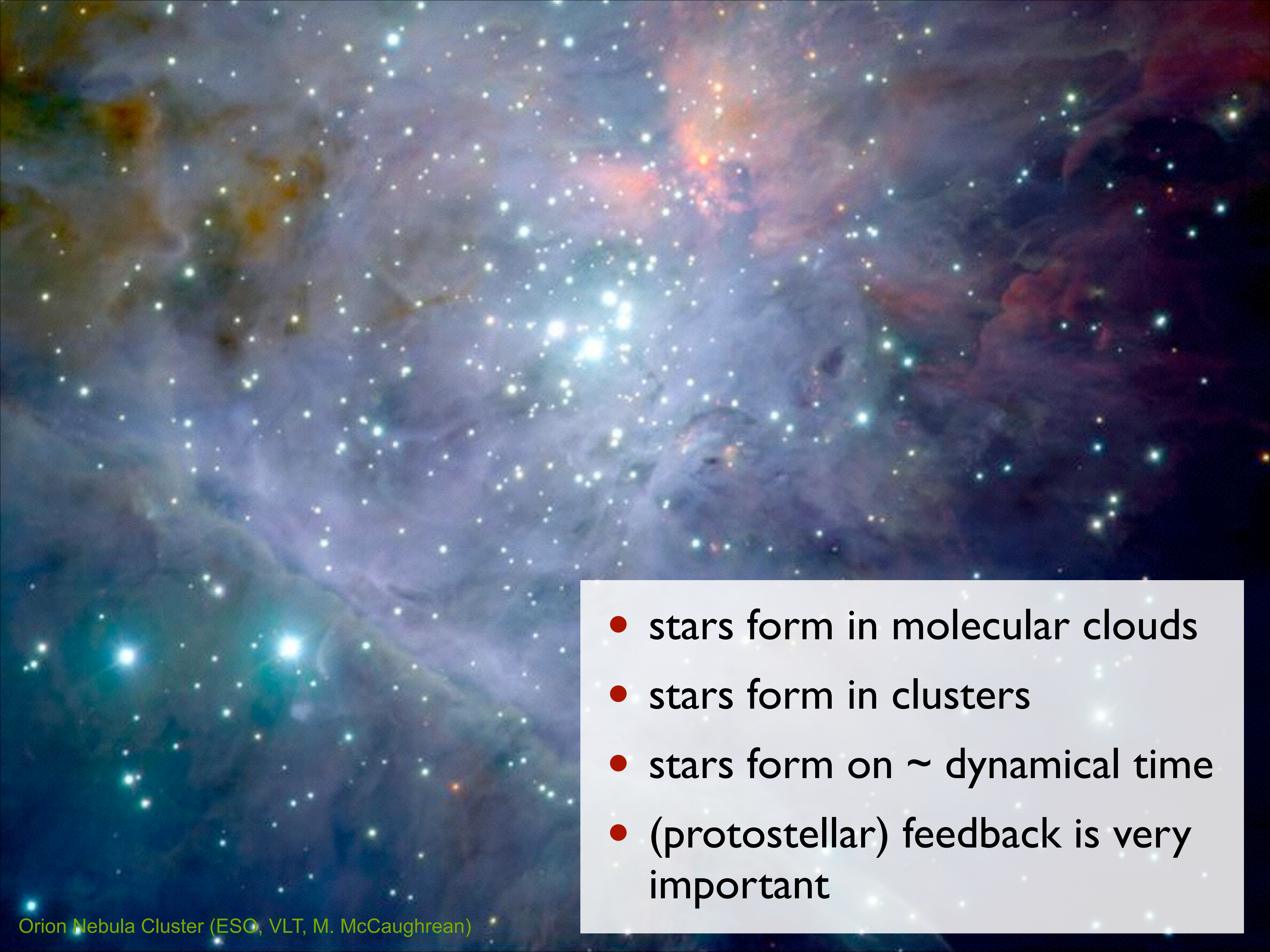
- HI gas more extended
- H2 and SF well correlated

galaxies from THINGS and HERACLES survey
(images from Frank Bigiel, ZAH/ITA)



data from T. Dame (CfA Harvard)

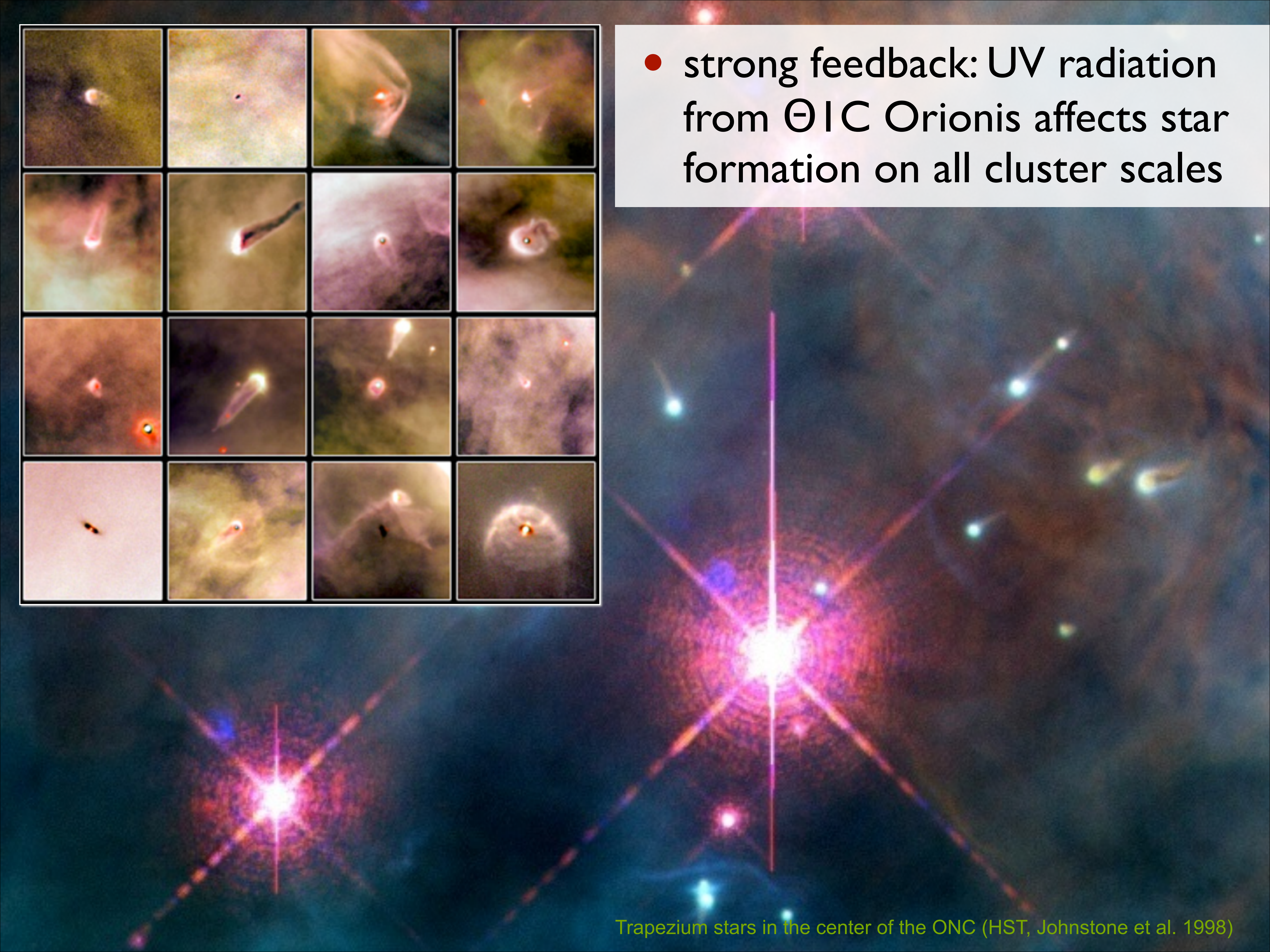
Orion Nebula Cluster (ESO, VLT, M. McCaughrean)



Orion Nebula Cluster (ESO, VLT, M. McCaughrean)

- stars form in molecular clouds
- stars form in clusters
- stars form on ~ dynamical time
- (protostellar) feedback is very important

- strong feedback: UV radiation from Θ1C Orionis affects star formation on all cluster scales



Trapezium stars in the center of the ONC (HST, Johnstone et al. 1998)

Pleiades (DSS, Palomar Observatory Sky Survey)

eventually, clusters like the ONC (1 Myr) will evolve into clusters like the Pleiades (100 Myr)

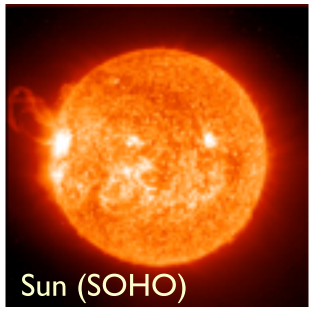
theoretical
approach

decrease in spatial scale / increase in density


Andromeda (R. Gendler)


NGC 602 in LMC (Hubble)


Proplyd in Orion (Hubble)


Sun (SOHO)


Earth

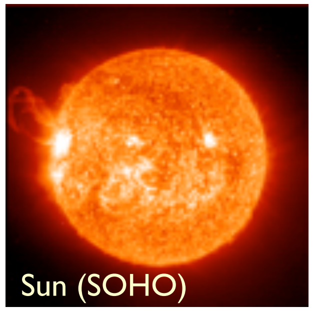
- density
  - density of ISM: few particles per cm^3
  - density of molecular cloud: few 100 particles per cm^3
  - density of Sun: 1.4 g/cm^3
- spatial scale
  - size of molecular cloud: few 10s of pc
  - size of young cluster: ~ 1 pc
  - size of Sun: 1.4×10^{10} cm

decrease in spatial scale / increase in density


Andromeda (R. Gendler)


NGC 602 in LMC (Hubble)


Proplyd in Orion (Hubble)


Sun (SOHO)


Earth

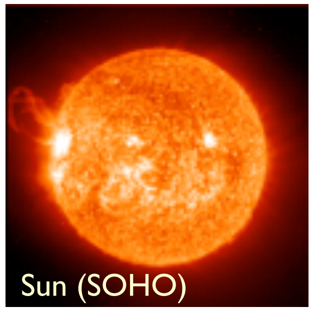
- contracting force
  - only force that can do this compression is ***GRAVITY***
- opposing forces
  - there are several processes that can oppose gravity
  - ***GAS PRESSURE***
  - ***TURBULENCE***
  - ***MAGNETIC FIELDS***
  - ***RADIATION PRESSURE***

decrease in spatial scale / increase in density


Andromeda (R. Gendler)


NGC 602 in LMC (Hubble)


Proplyd in Orion (Hubble)


Sun (SOHO)


Earth

- contracting force
  - only force that can do this compression is ***GRAVITY***
- opposing forces
  - there are several processes that can oppose gravity
  - ***GAS PRESSURE***
  - ***TURBULENCE***
  - ***MAGNETIC FIELDS***
  - ***RADIATION PRESSURE***

Modern star formation theory is based on the complex interplay between *all* these processes.

Modern star formation theory is based on the complex interplay between *all* these processes.

Carina with HST

Modern star formation theory is based on the complex interplay between *all* these processes.

HH 901/902 in Carina with HST

early theoretical models

- *Jeans (1902):* Interplay between self-gravity and thermal pressure
  - stability of homogeneous spherical density enhancements against gravitational collapse
  - dispersion relation:

$$\boxed{\omega^2 = c_s^2 k^2 - 4\pi G\rho_0}$$

  - instability when $\omega^2 < 0$
  - minimal mass: $\boxed{M_J = \tfrac{1}{6}\pi^{-5/2} G^{-3/2} \rho_0^{-1/2} c_s^3 \propto \rho_0^{-1/2} T^{+3/2}}$

Sir James Jeans, 1877 - 1946

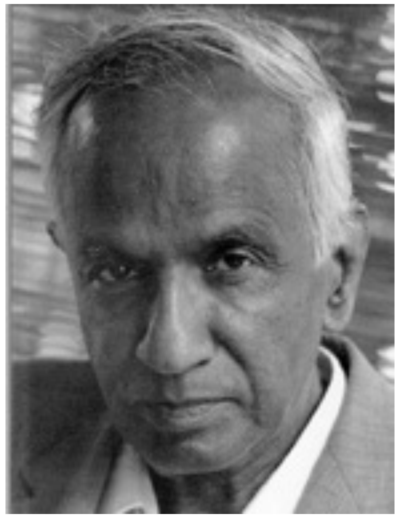
first approach to turbulence

- *von Weizsäcker (1943, 1951)* and *Chandrasekhar (1951):* concept of ***MICROTURBULENCE***
  - BASIC ASSUMPTION: separation of scales between dynamics and turbulence

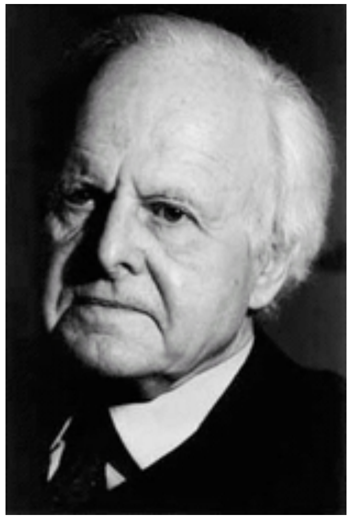
    $\ell_{\mathrm{turb}} \ll \ell_{\mathrm{dyn}}$
  - then turbulent velocity dispersion contributes to effective soundspeed:

    $$\boxed{c_c^2 \mapsto c_c^2 + \sigma_{rms}^2}$$
  - → Larger effective Jeans masses → more stability
  - BUT: *(1) turbulence depends on k:* $\sigma_{rms}^2(k)$

    (2) supersonic turbulence → $\sigma_{rms}^2(k) >> c_s^2$ *usually*



S. Chandrasekhar, 1910 - 1995



C.F. von Weiszäcker, 1912 - 2007

problems of early dynamical theory

- molecular clouds are *highly Jeans-unstable,*
  yet, they do *NOT* form stars at high rate
  and with high efficiency (Zuckerman & Evans 1974 conundrum)
  (the observed global SFE in molecular clouds is *~5%*)
  → *something prevents large-scale collapse.*
- all throughout the early 1990's, molecular clouds had been thought to be long-lived quasi-equilibrium entities.
- molecular clouds are *magnetized*

magnetic star formation

- *Mestel & Spitzer (1956):* Magnetic fields can prevent collapse*!!!*
  - Critical mass for gravitational collapse in presence of B-field
  - Critical mass-to-flux ratio (Mouschovias & Spitzer 1976)

$$\left[\frac{M}{\Phi}\right]_{cr} = \frac{\zeta}{3\pi}\left[\frac{5}{G}\right]^{1/2}$$

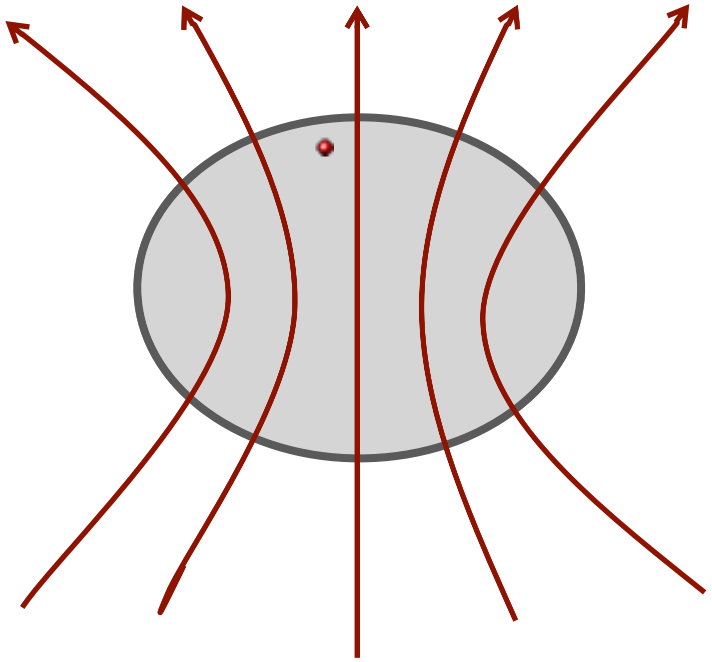
  - Ambipolar diffusion can initiate collapse

Lyman Spitzer, Jr., 1914 - 1997

“standard theory” of star formation

- BASIC ASSUMPTION: Stars form from magnetically highly subcritical cores
- Ambipolar diffusion slowly increases (M/Φ): $\tau_{AD} \approx 10\tau_{ff}$
- Once $(M/\Phi) > (M/\Phi)_{crit}$: dynamical collapse of SIS
  - Shu (1977) collapse solution
  - $dM/dt = 0.975\ c_s^3/G = \text{const.}$
- Was (in principle) only intended for isolated, low-mass stars

Frank Shu, 1943 -



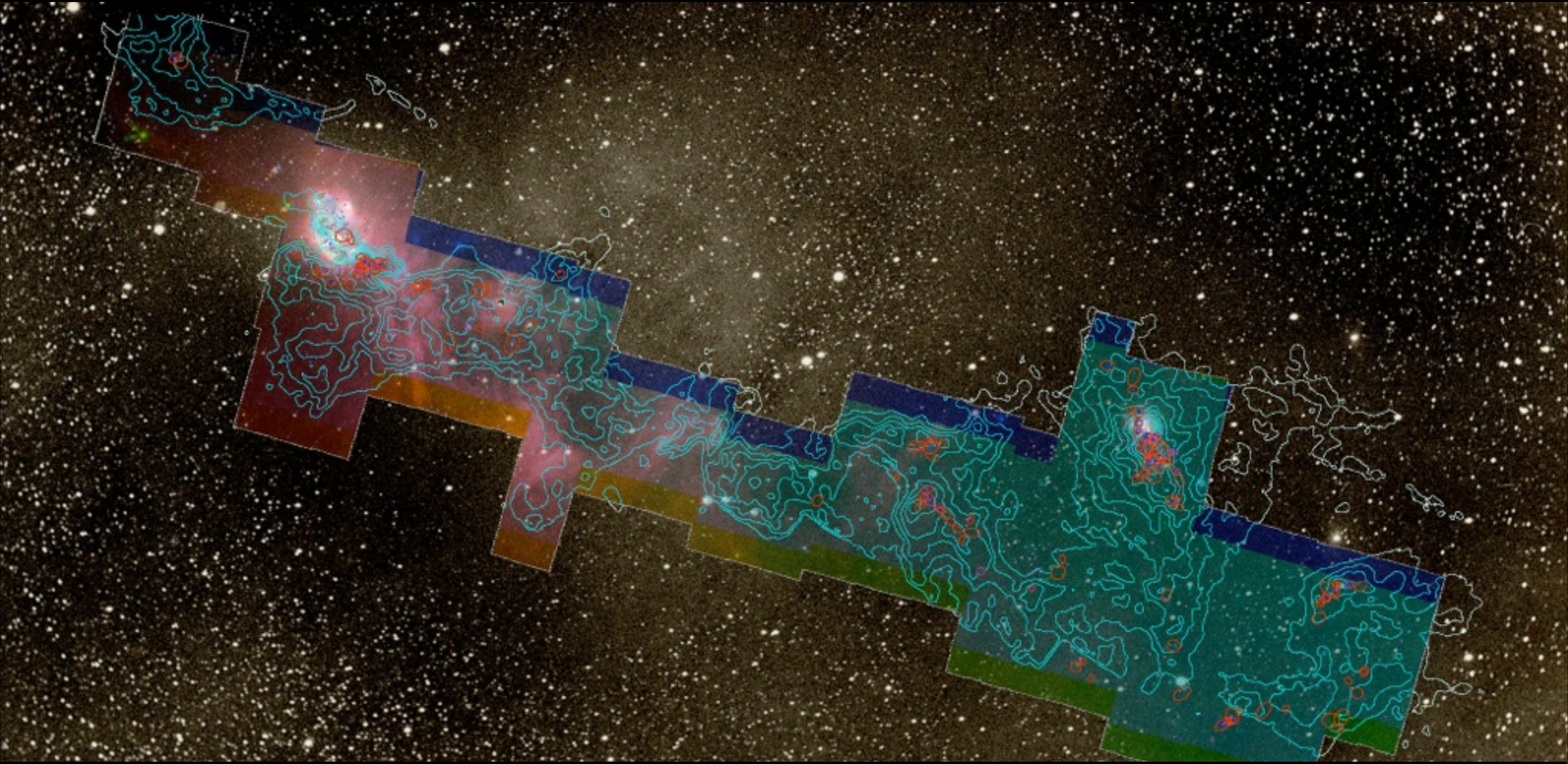
magnetic field

problems of “standard theory”

- Observed B-fields are weak, at most marginally critical (Crutcher 1999, Bourke et al. 2001)
- Magnetic fields cannot prevent decay of turbulence
  (Mac Low et al. 1998, Stone et al. 1998, Padoan & Nordlund 1999)
- Structure of prestellar cores
  (e.g. Bacman et al. 2000, Alves et al. 2001)
- Strongly time varying dM/dt
  (e.g. Hendriksen et al. 1997, André et al. 2000)
- More extended infall motions than predicted by the standard model
  (Williams & Myers 2000, Myers et al. 2000)
- Most stars form as binaries
  (e.g. Lada 2006)
- As many prestellar cores as protostellar cores in SF regions (e.g. André et al 2002)
- Molecular cloud clumps are chemically young
  (Bergin & Langer 1997, Pratap et al 1997, Aikawa et al 2001)
- Stellar age distribution small ($\tau_{ff} << \tau_{AD}$)
  (Ballesteros-Paredes et al. 1999, Elmegreen 2000, Hartmann 2001)
- Strong theoretical criticism of the SIS as starting condition for gravitational collapse
  (e.g. Whitworth et al 1996, Nakano 1998, as summarized in Klessen & Mac Low 2004)
- Standard AD-dominated theory is incompatible with observations
  (Crutcher et al. 2009, 2010ab, Bertram et al. 2011)

(see e.g. Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194)

COMPLETE = **CO**ordinated **M**olecular **P**robe **L**ine **E**xtinction **T**hermal **E**mission Survey of Star-Forming Regions



COMPLETE Collaborators,
Summer 2008:

Alyssa A. Goodman (CfA/IIC)

João Alves (Calar Alto, Spain)

Héctor Arce (Yale)

Michelle Borkin (IIC)

Paola Caselli (Leeds, UK)

James DiFrancesco (HIA, Canada)

Jonathan Foster (CfA, PhD Student)

Katherine Guenthner (CfA/Leipzig)

Mark Heyer (UMASS/FCRAO)

Doug Johnstone (HIA, Canada)

Jens Kauffmann (CfA/IIC)

Helen Kirk (HIA, Canada)

Di Li (JPL)

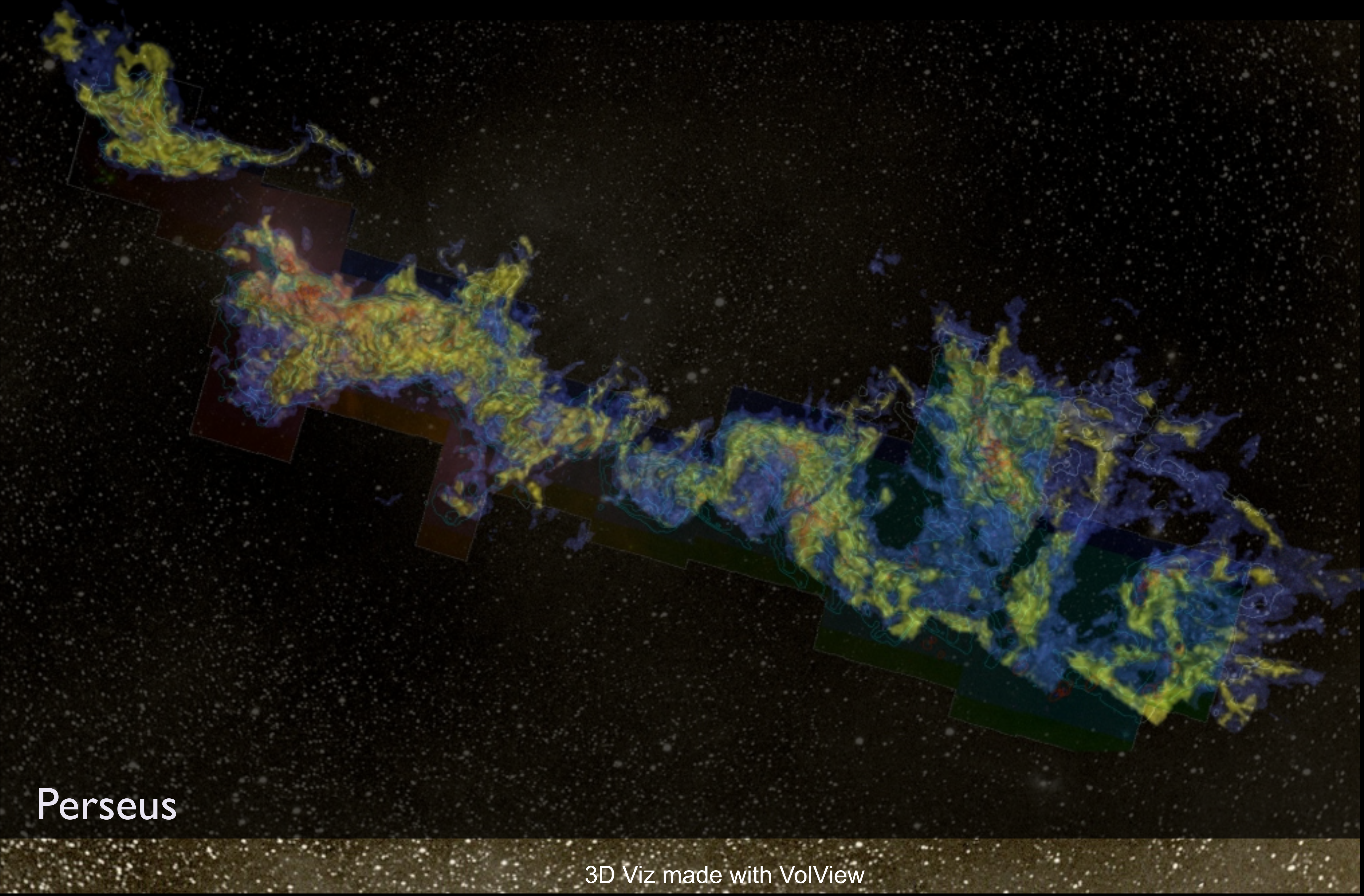
Jaime Pineda (CfA, PhD Student)

Erik Rosolowsky (UBC Okanagan)

Rahul Shetty (CfA)

Scott Schnee (Caltech)

Mario Tafalla (OAN, Spain)

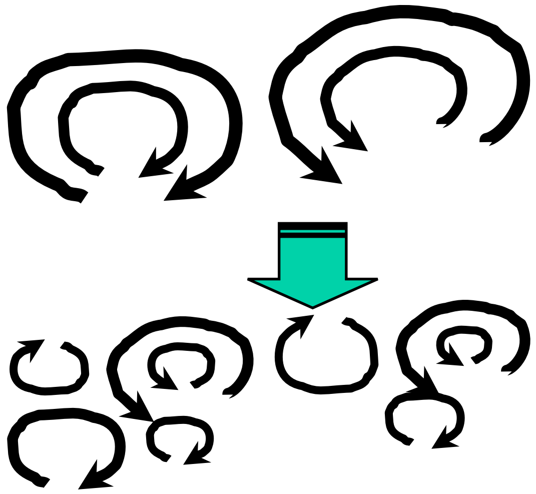


3D Viz made with VolView

properties of turbulence

- laminar flows turn *turbulent* at *high* *Reynolds* numbers

$$Re = \frac{\text{advection}}{\text{dissipation}} = \frac{VL}{\nu}$$



V= typical velocity on scale L, $\nu = \eta/\rho$ = kinematic viscosity,
turbulence for Re > 1000 → typical values in ISM 10^8-10^{10}

- Navier-Stokes equation (transport of momentum)

$$\rho\frac{d\vec{v}}{dt} = \rho\left(\frac{\partial\vec{v}}{\partial t} + (\vec{v}\cdot\vec{\nabla})\vec{v}\right) = -\vec{\nabla}P + \eta\,\vec{\nabla}^2\vec{v} + \left(\frac{\eta}{3} + \zeta\right)\vec{\nabla}(\vec{\nabla}\cdot\vec{v})$$

shear viscosity

bulk viscosity

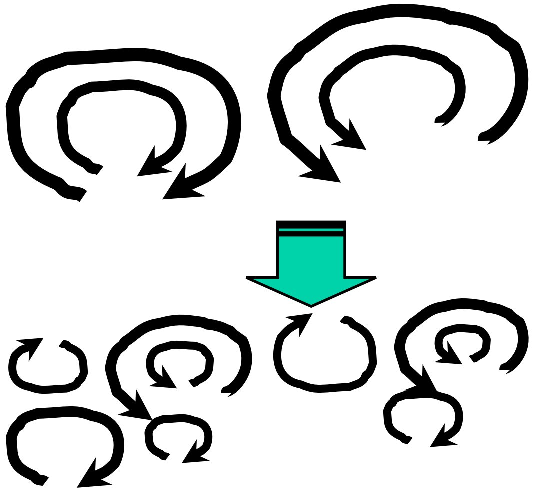
$$\sigma_{ij} \equiv \eta\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial v_k}{\partial x_k}\right) + \zeta\delta_{ij}\frac{\partial v_k}{\partial x_k}$$

viscous stress tensor

properties of turbulence

- laminar flows turn *turbulent* at *high* *Reynolds* numbers

$$Re = \frac{\text{advection}}{\text{dissipation}} = \frac{VL}{\nu}$$

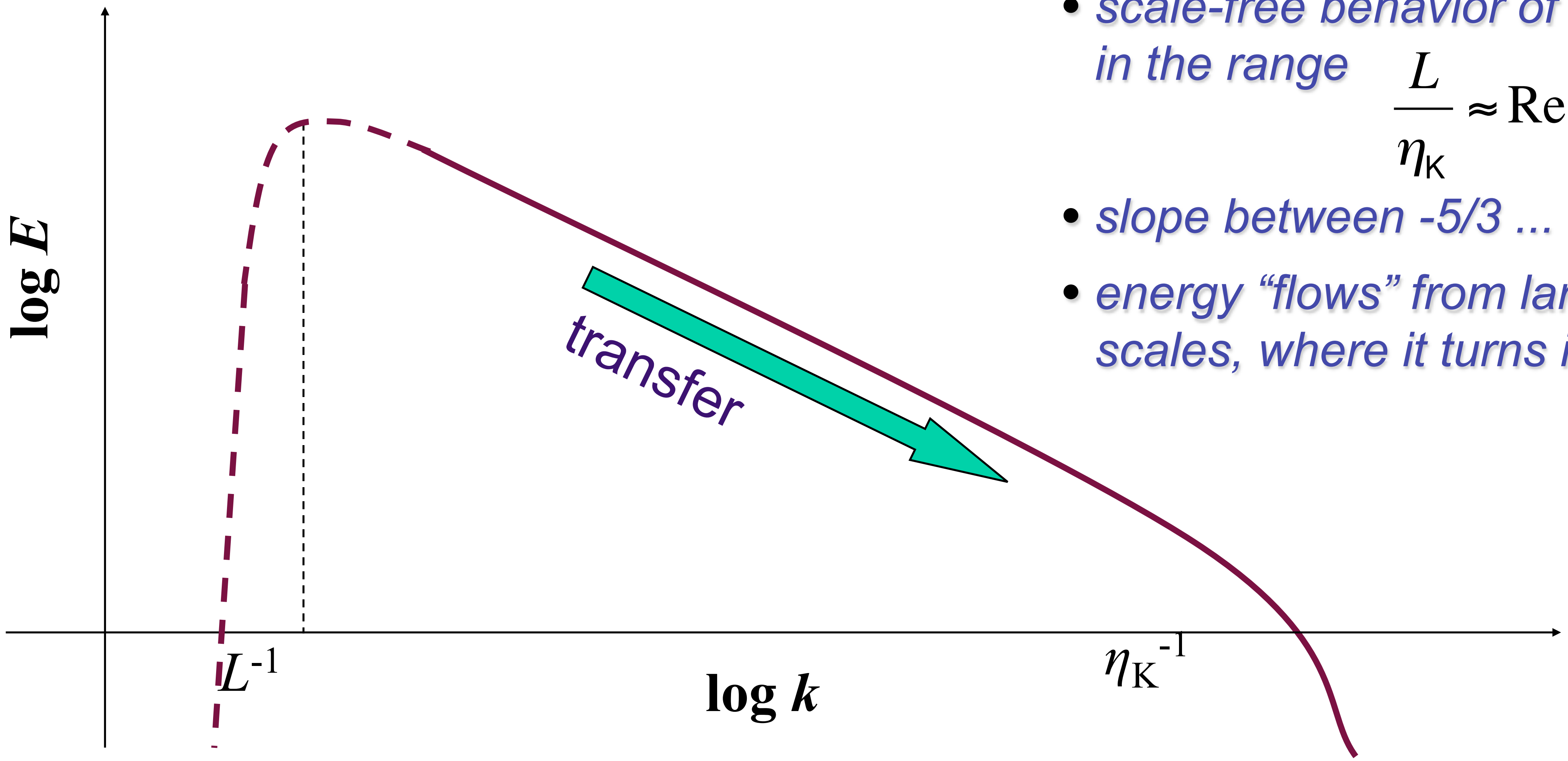


V= typical velocity on scale L, $\nu = \eta/\rho$ = kinematic viscosity,
turbulence for Re > 1000 → typical values in ISM 10^8-10^{10}

- vortex streching --> turbulence is intrinsically anisotropic
  (only on large scales you may get
  homogeneity & isotropy in a statistical sense;
  see Landau & Lifschitz, Chandrasekhar, Taylor, etc.)

(ISM turbulence: shocks & B-field
cause additional inhomogeneity)

turbulent cascade in ISM

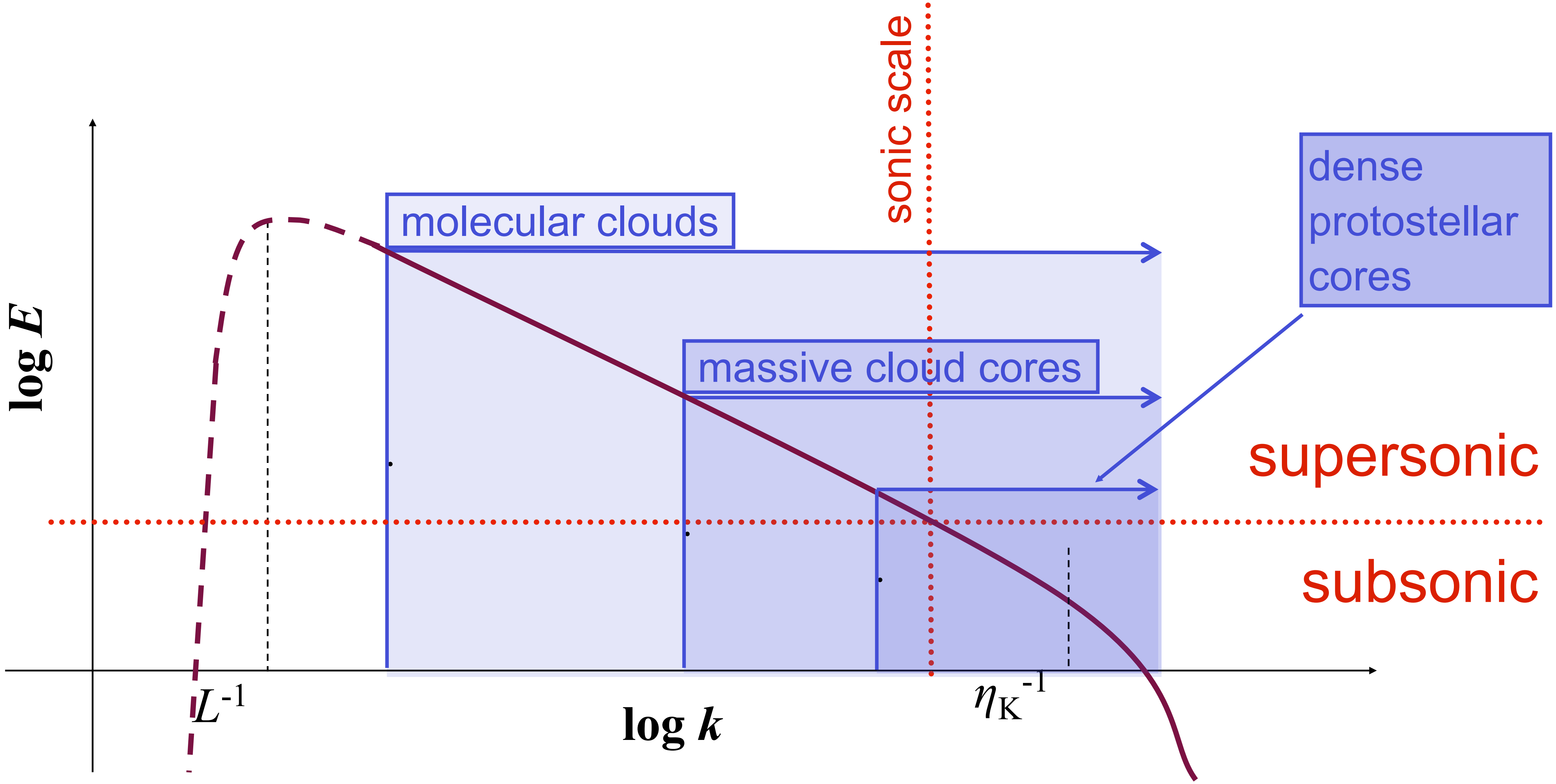


- *scale-free behavior of turbulence in the range* $\frac{L}{\eta_K} \approx \mathrm{Re}^{3/4}$
- *slope between -5/3 ... -2*
- *energy "flows" from large to small scales, where it turns into heat*

energy source & scale
NOT known
(supernovae, winds,
spiral density waves?)

dissipation scale not known
(ambipolar diffusion,
molecular diffusion?)

turbulent cascade in ISM



energy source & scale
NOT known
(supernovae, winds,
spiral density waves?)

$\sigma_{rms} << 1$ km/s
$M_{rms} \leq 1$
$L \approx 0.1$ pc

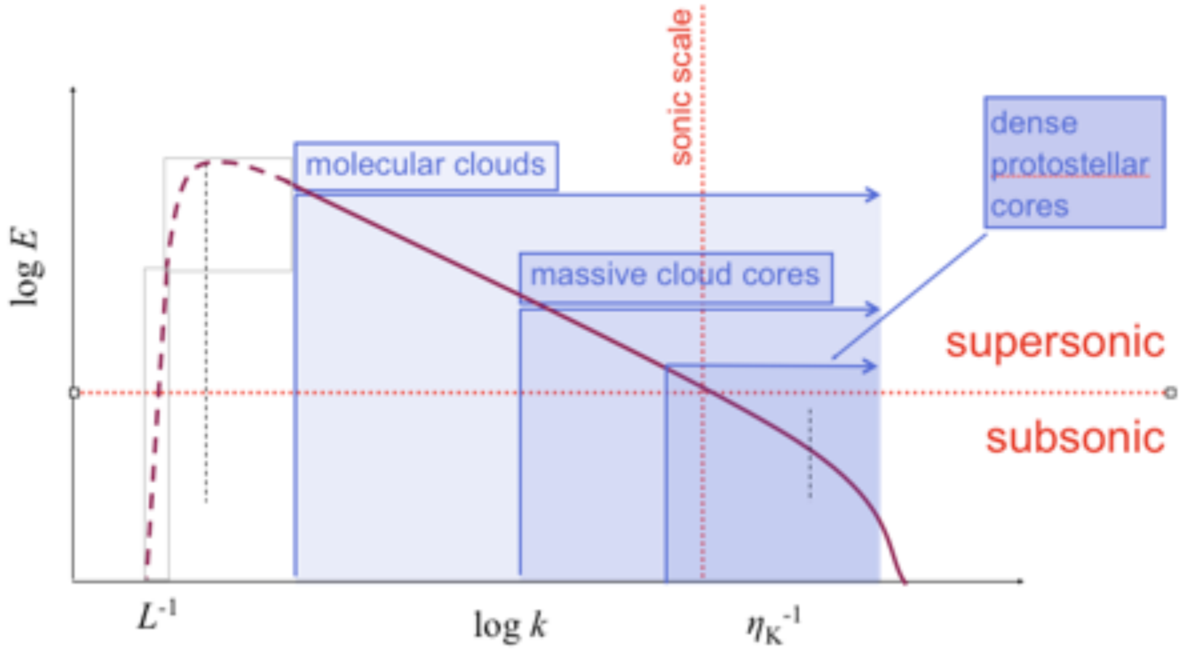
dissipation scale not known
(ambipolar diffusion,
molecular diffusion?)

gravoturbulent star formation

- BASIC ASSUMPTION:

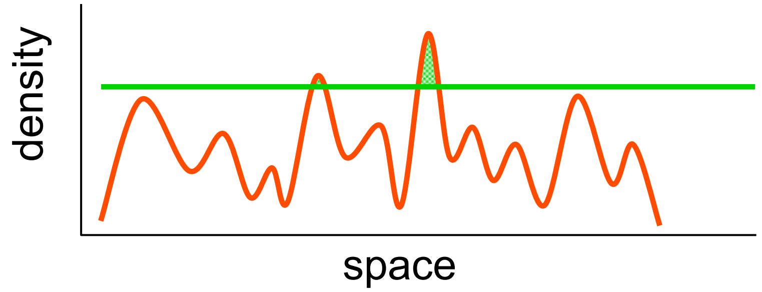
  star formation is controlled by interplay between supersonic turbulence and self-gravity

- turbulence plays a *dual role*:
  - on *large scales* it *provides support*
  - on *small scales* it can *trigger collapse*
- some predictions:
  - dynamical star formation timescale τ_{ff}
  - high binary fraction
  - complex spatial structure of embedded star clusters
  - and many more . . .



Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194
McKee & Ostriker, 2007, ARAA, 45, 565

dynamical SF in a nutshell



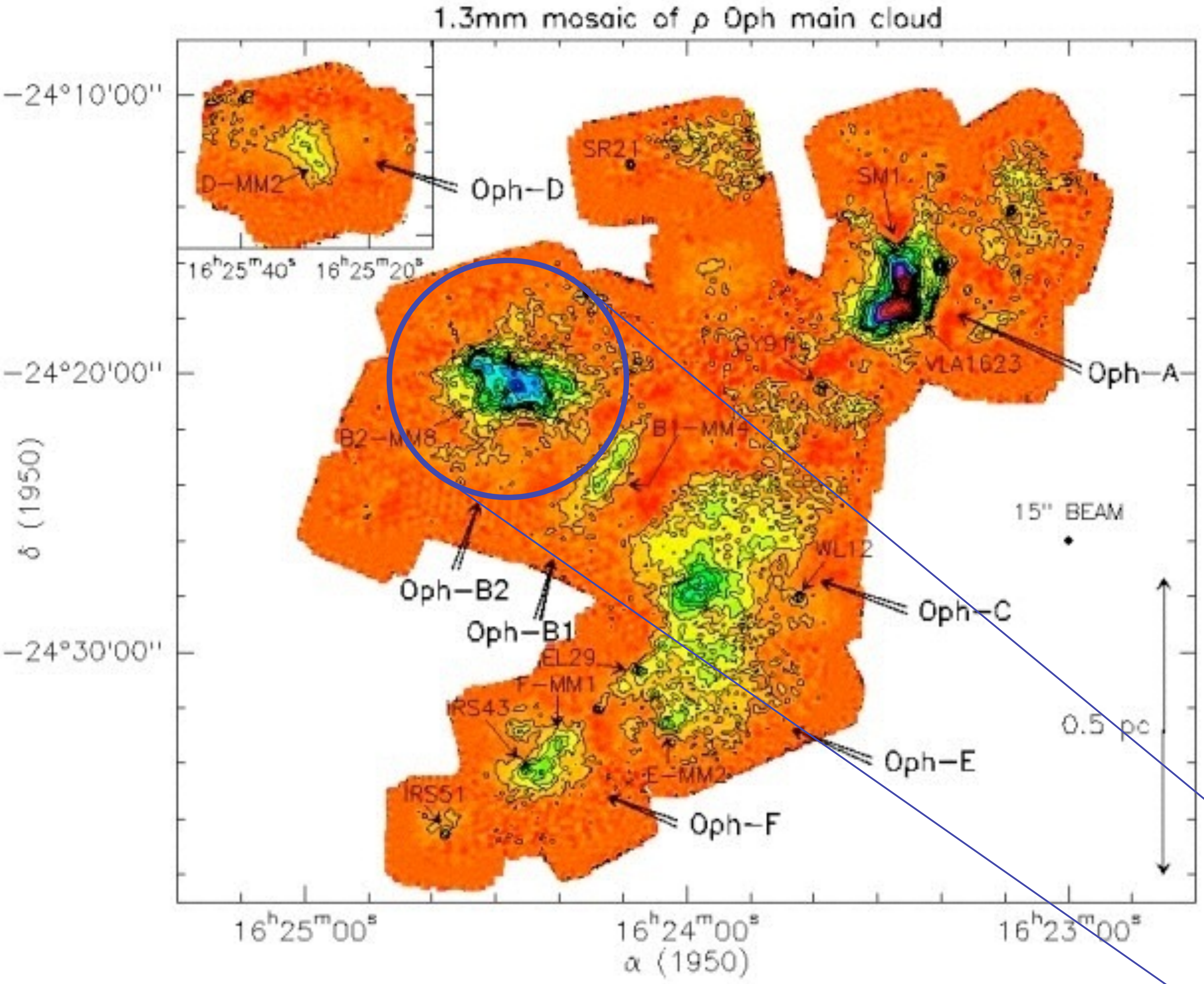
- interstellar gas is highly *inhomogeneous*
  - *gravitational instability*
  - *thermal instability*
  - *turbulent compression* (in shocks $\delta\rho/\rho \propto \mathcal{M}^2$; in atomic gas: $\mathcal{M} \approx 1...3$)
- cold *molecular clouds* can form rapidly in high-density regions at *stagnation points* of *convergent large-scale flows*
  - chemical *phase transition*: atomic → molecular
  - process is *modulated* by large-scale *dynamics* in the galaxy
- inside *cold clouds:* turbulence is highly supersonic ($\mathcal{M} \approx 1...20$)
  → *turbulence* creates large density contrast,
  gravity selects for collapse

→ ***GRAVOTUBULENT FRAGMENTATION***

- *turbulent cascade:* local compression *within* a cloud provokes collapse → formation of individual *stars* and *star clusters*

(e.g. Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194)

Density structure of MC's



(Motte, André, & Neri 1998)

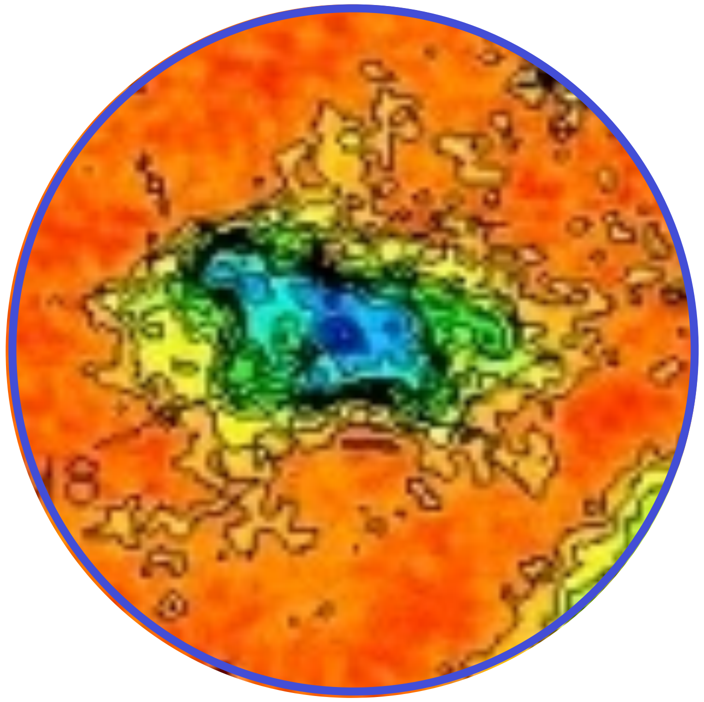
molecular clouds are highly inhomogeneous

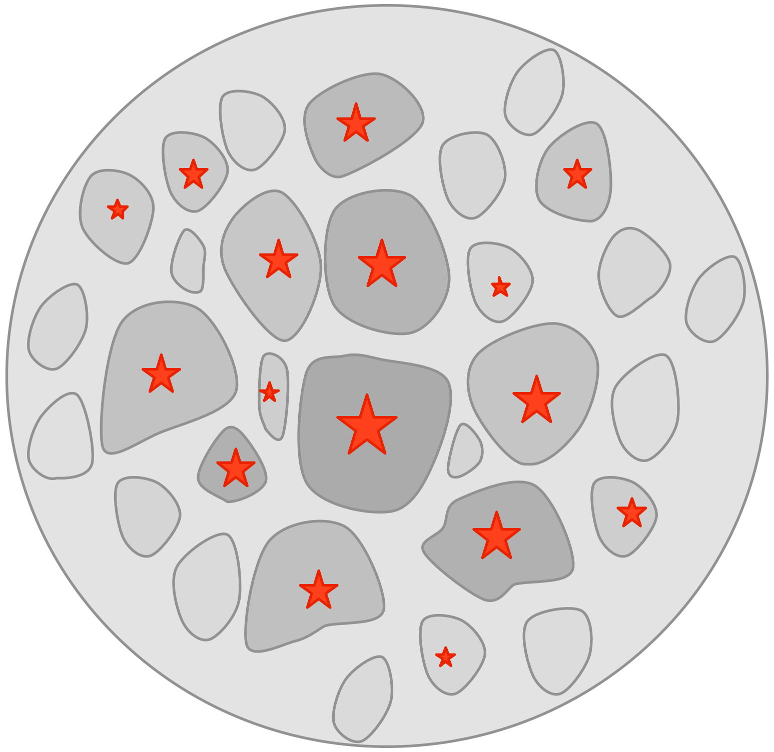
stars form in the densest and coldest parts of the cloud

ρ-Ophiuchus cloud seen in dust emission

let's focus on a cloud core like this one

Evolution of cloud cores

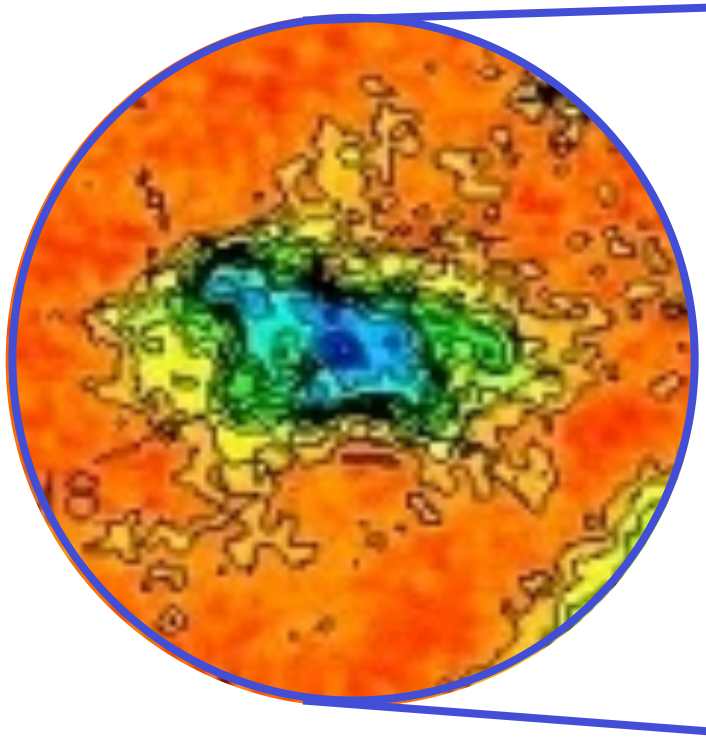


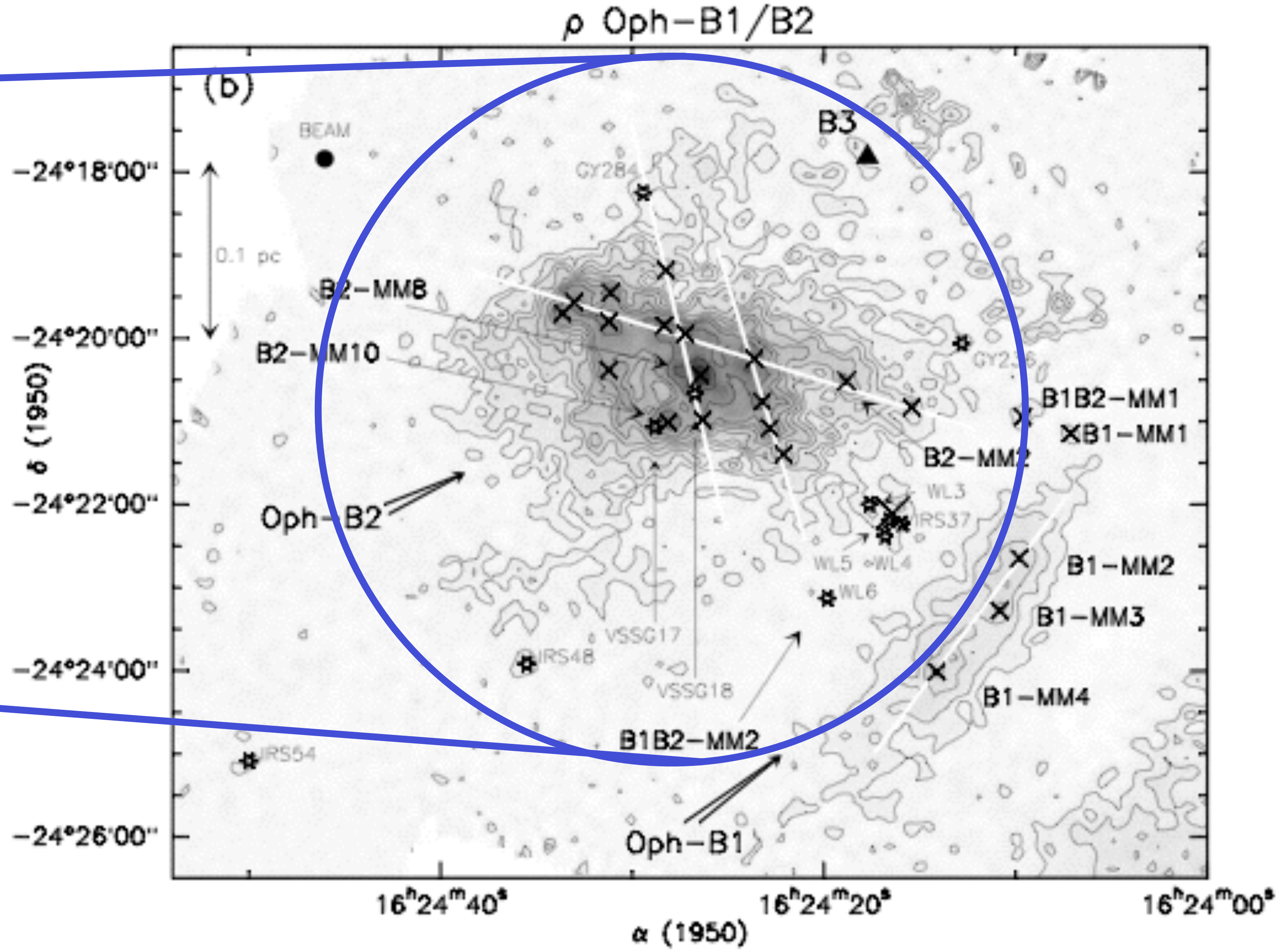


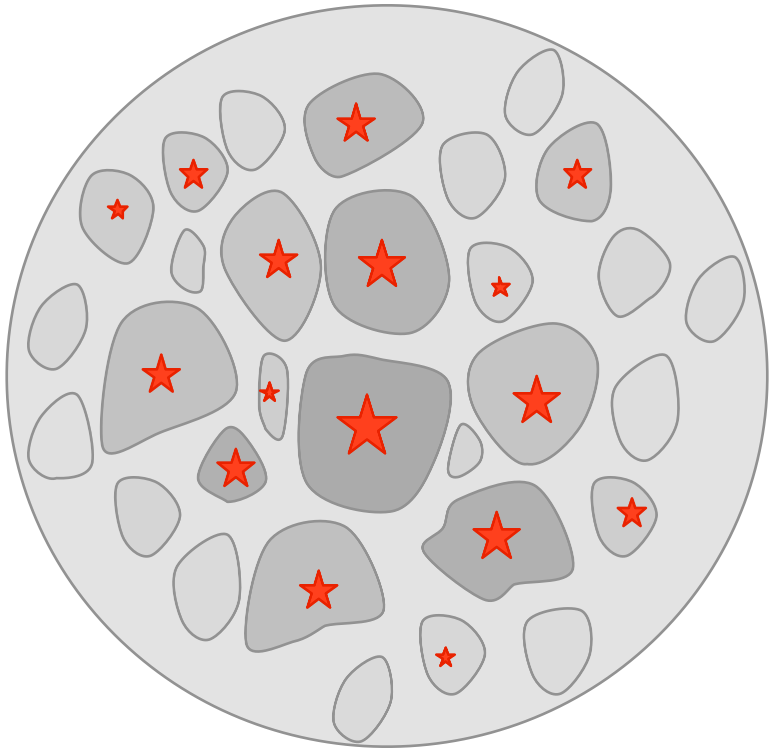
- How does this core evolve?
  Does it form one single massive star or cluster with mass distribution?

- Turbulent cascade „goes through“ cloud core
  --> NO *scale separation* possible
  --> NO *effective sound speed*
- Turbulence is supersonic!
  --> produces strong density contrasts:
  $\delta\rho/\rho \approx M^2$
  --> with typical $M \approx 10$ --> $\delta\rho/\rho \approx 100$!
- many of the shock-generated fluctuations are Jeans unstable and go into collapse
- --> expectation: *core breaks up and forms a cluster of stars*

Evolution of cloud cores





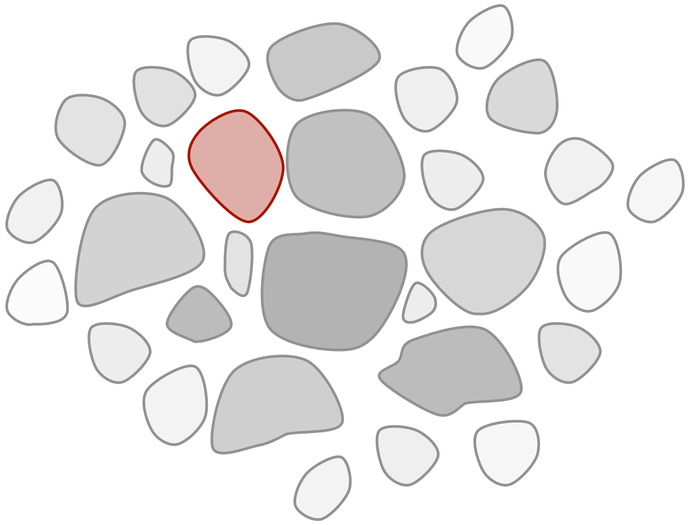


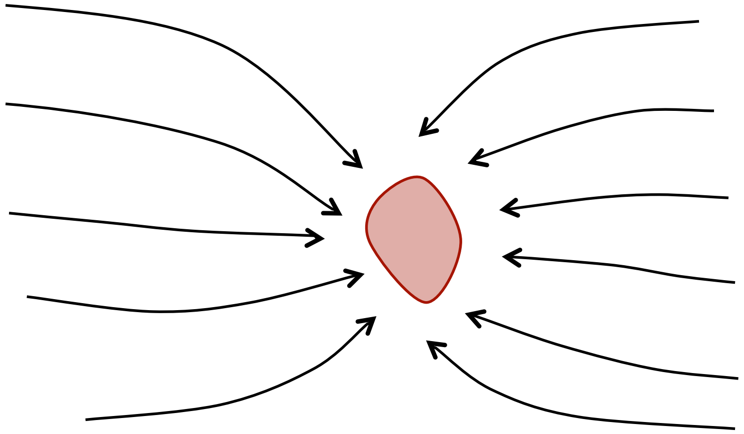
indeed ρ-Oph B1/2 contains several cores (“starless” cores are denoted by ×, cores with embedded protostars by ☆)

(Motte, André, & Neri 1998)

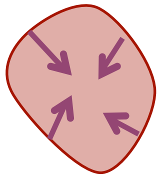
Formation and evolution of cores

- protostellar cloud cores form at *stagnation point* in *convergent turbulent flows*

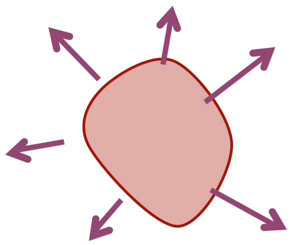




- if $M > M_{crit} \propto \rho^{-1/2}\, T^{3/2}$: collapse & star formation



- pf $M < M_{crit} \propto \rho^{-1/2}\, T^{3/2}$: reexpansion after end of external compression

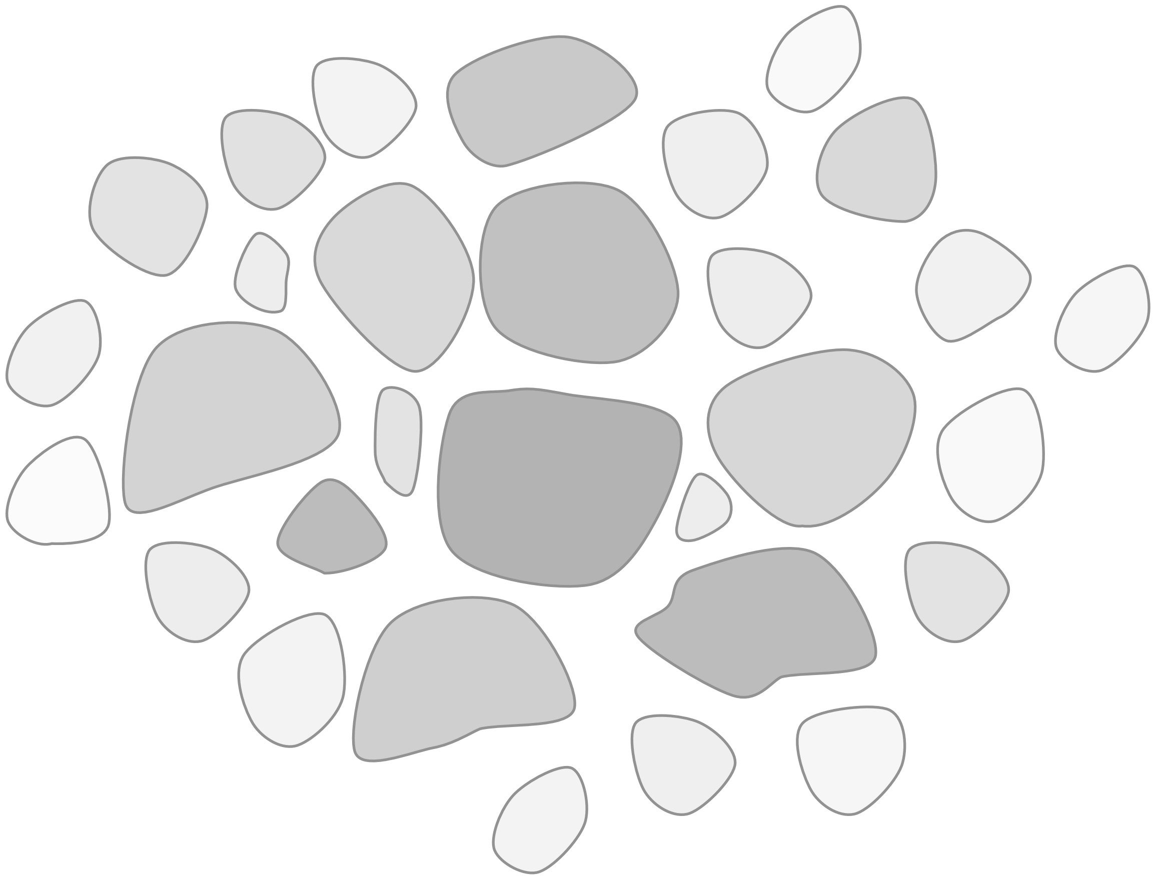


(e.g. Vazquez-Semadeni et al 2005)

- typical timescale: $t \approx 10^4 \ldots 10^5$ yr

Formation and evolution of cores

What happens to distribution of cloud cores?



Two exteme cases:

(1) turbulence dominates energy budget:

$\alpha = E_{kin}/|E_{pot}| > 1$

--> individual cores do *not* interact

--> *collapse* of *individual* cores dominates *stellar mass growth*

--> *loose cluster of low-mass stars*

(2) turbulence decays, i.e. gravity dominates:

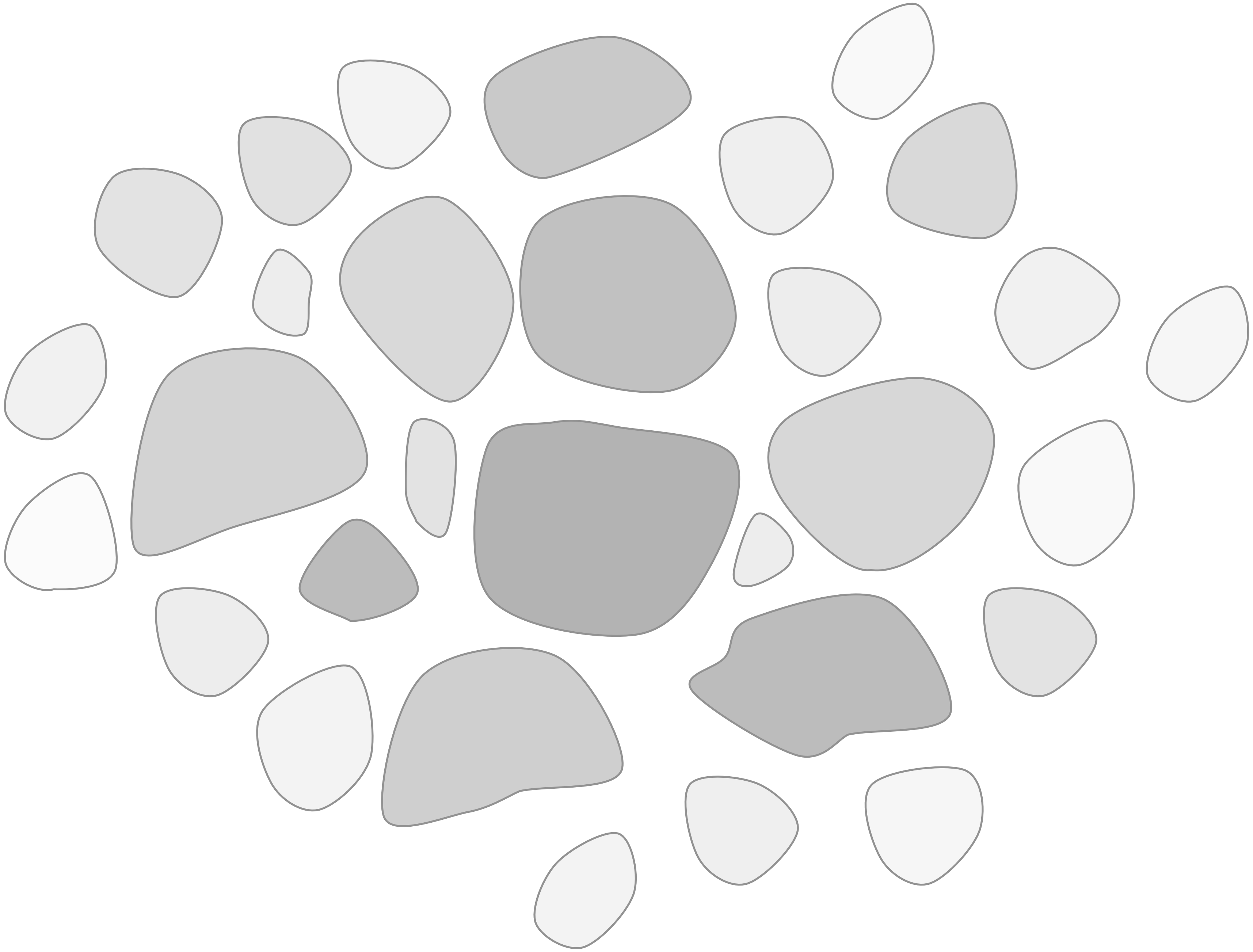
$\alpha = E_{kin}/|E_{pot}| < 1$

--> *global contraction*

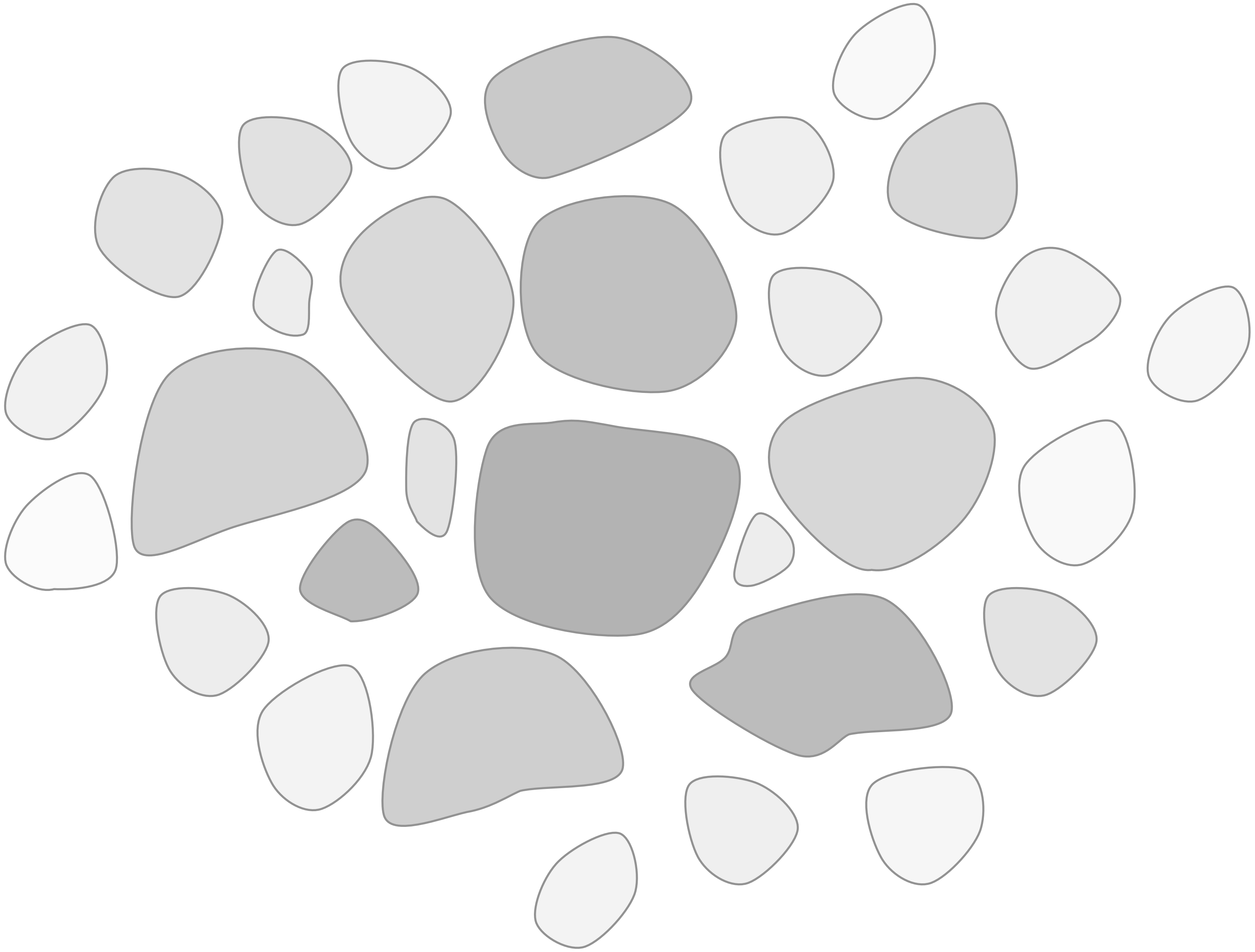
--> core do *interact* while collapsing

--> *competition* influences *mass growth*

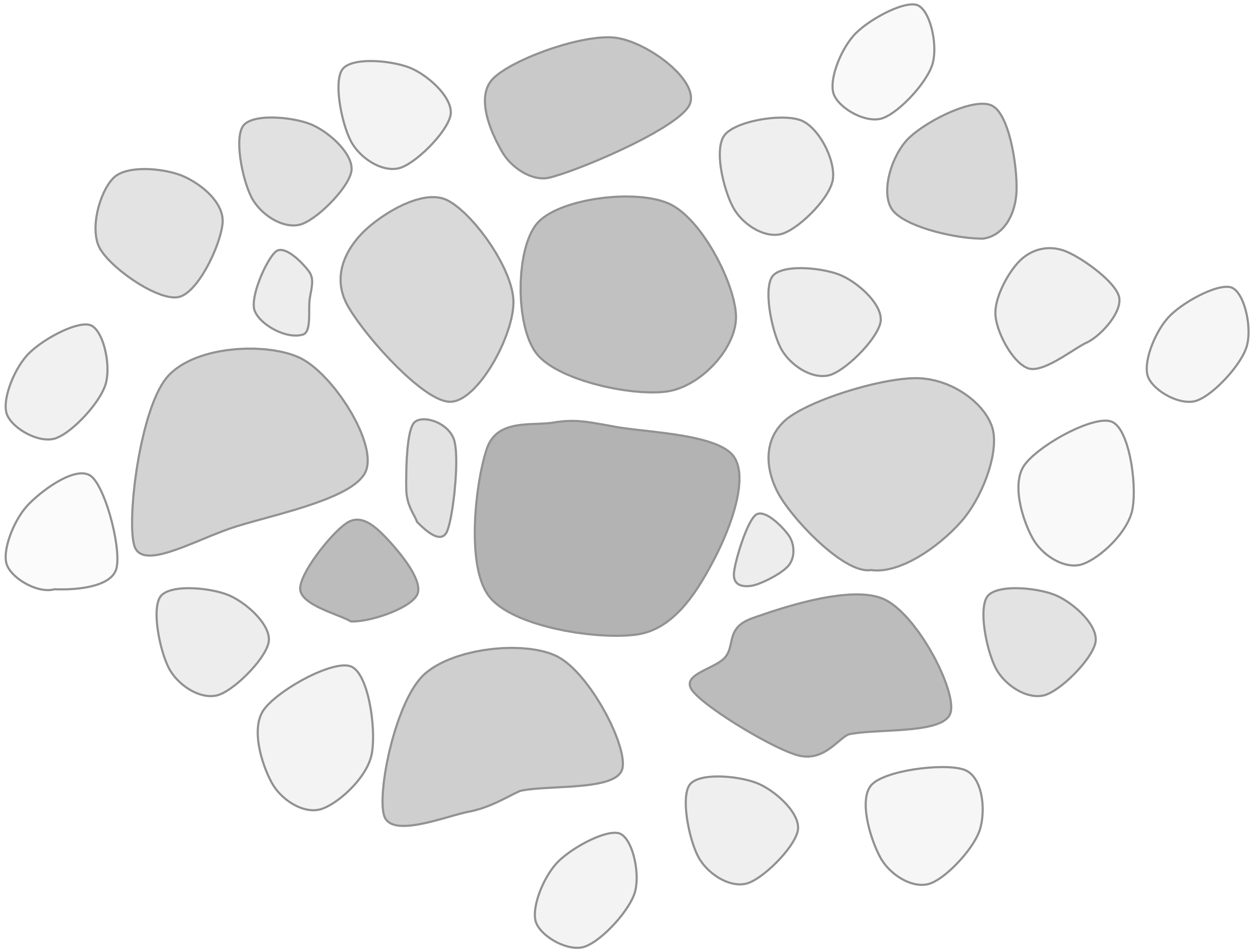
--> *dense cluster with high-mass stars*



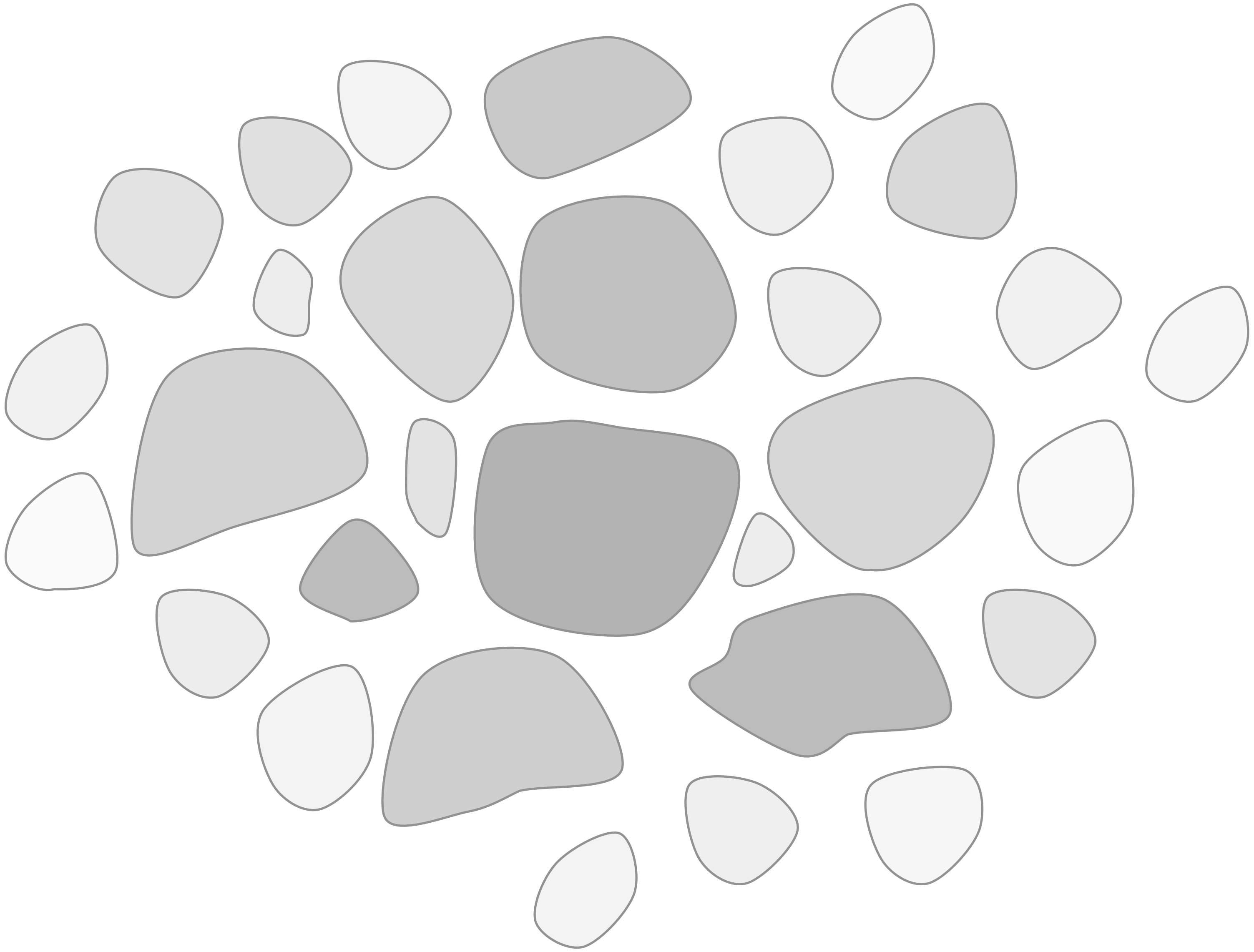
turbulence creates a hierarchy of clumps



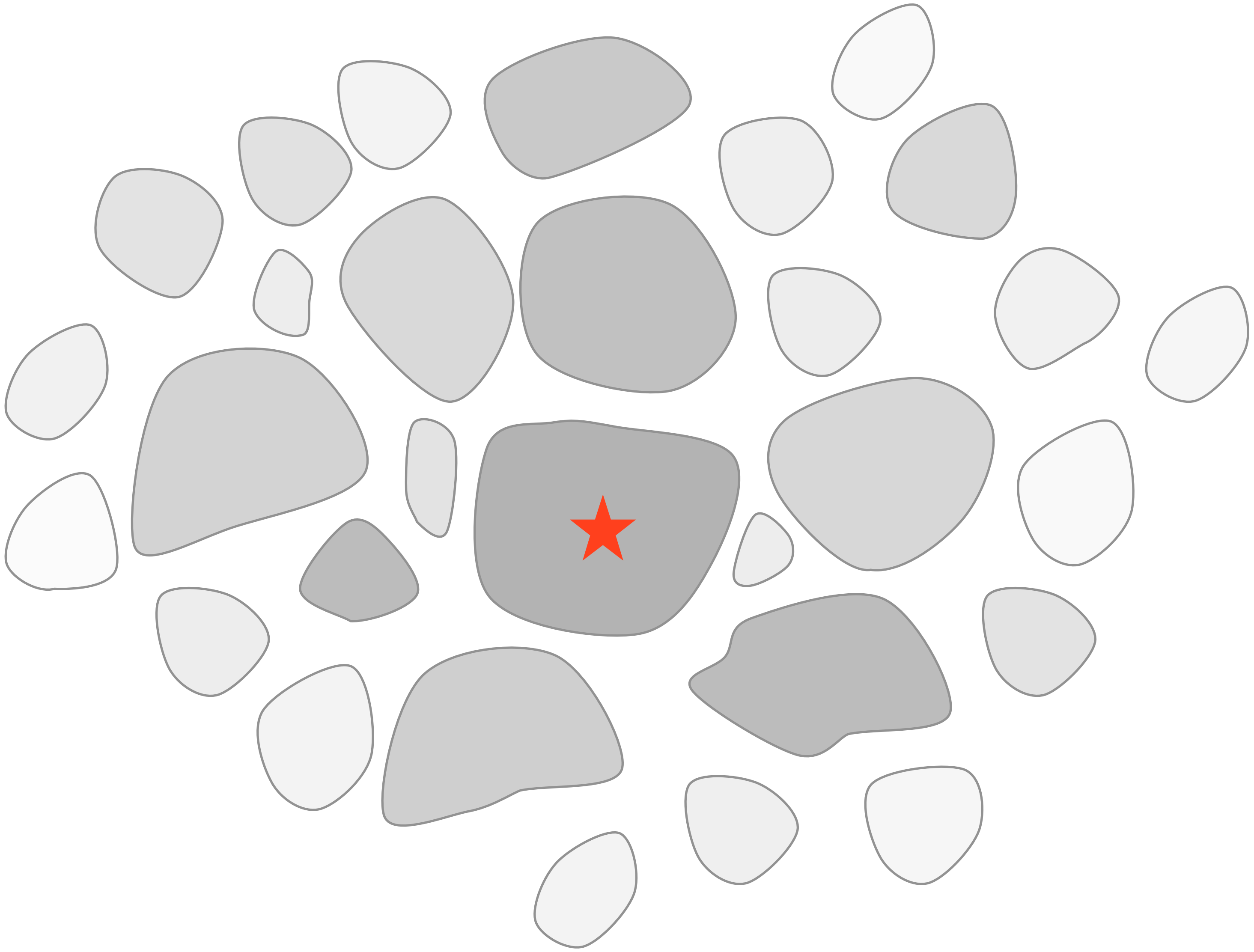
as turbulence decays locally, contraction sets in



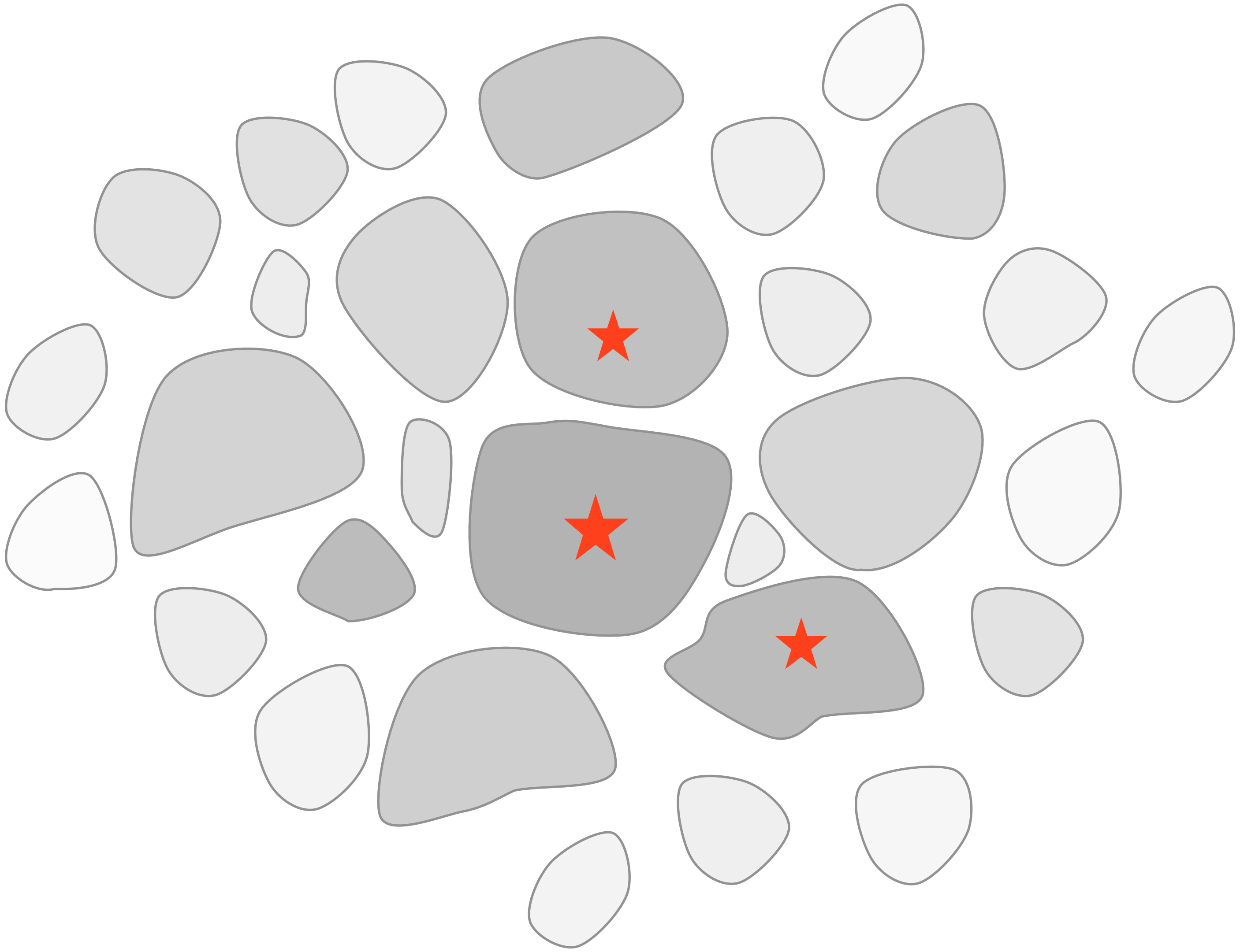
as turbulence decays locally, contraction sets in



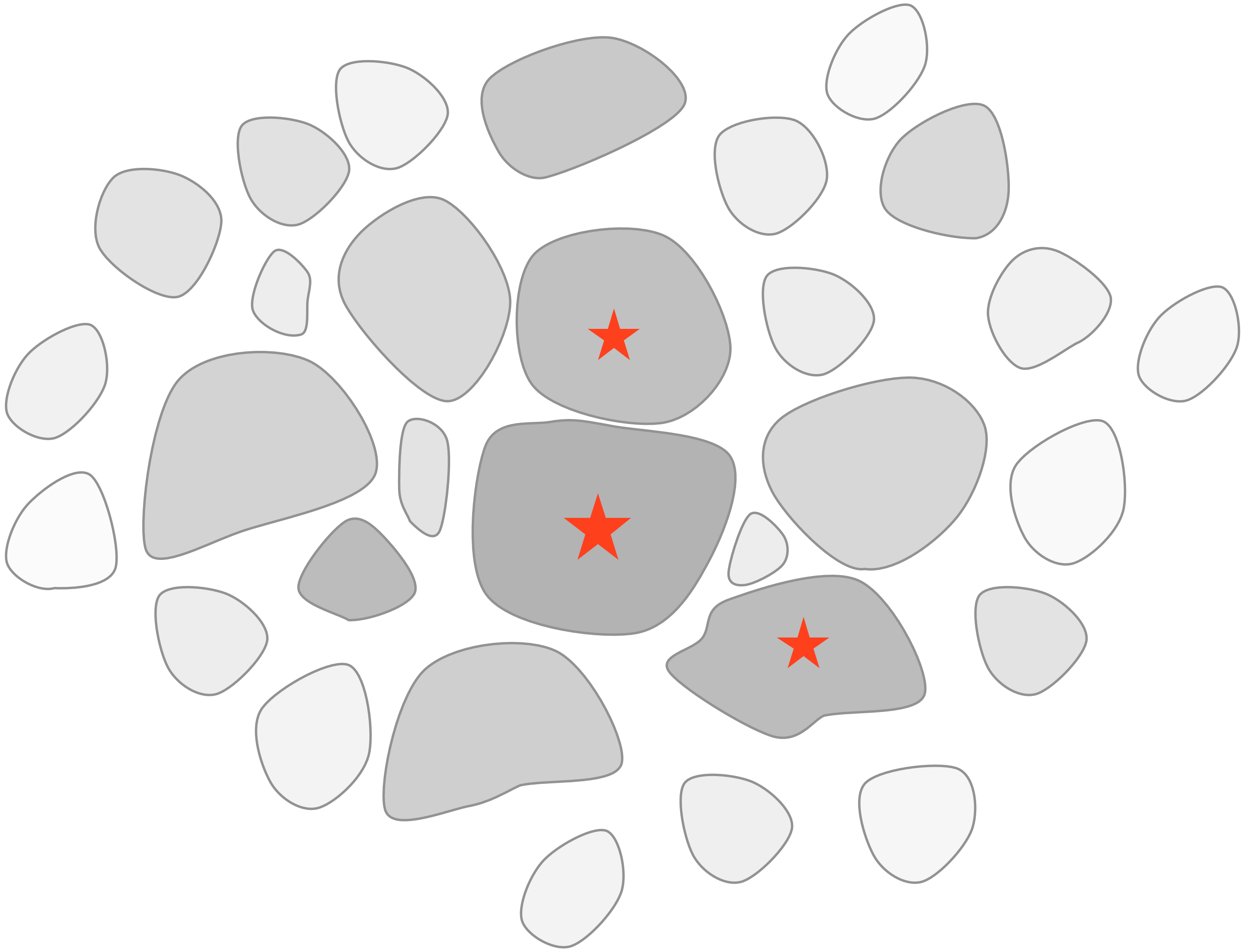
while region contracts, individual clumps collapse to form stars



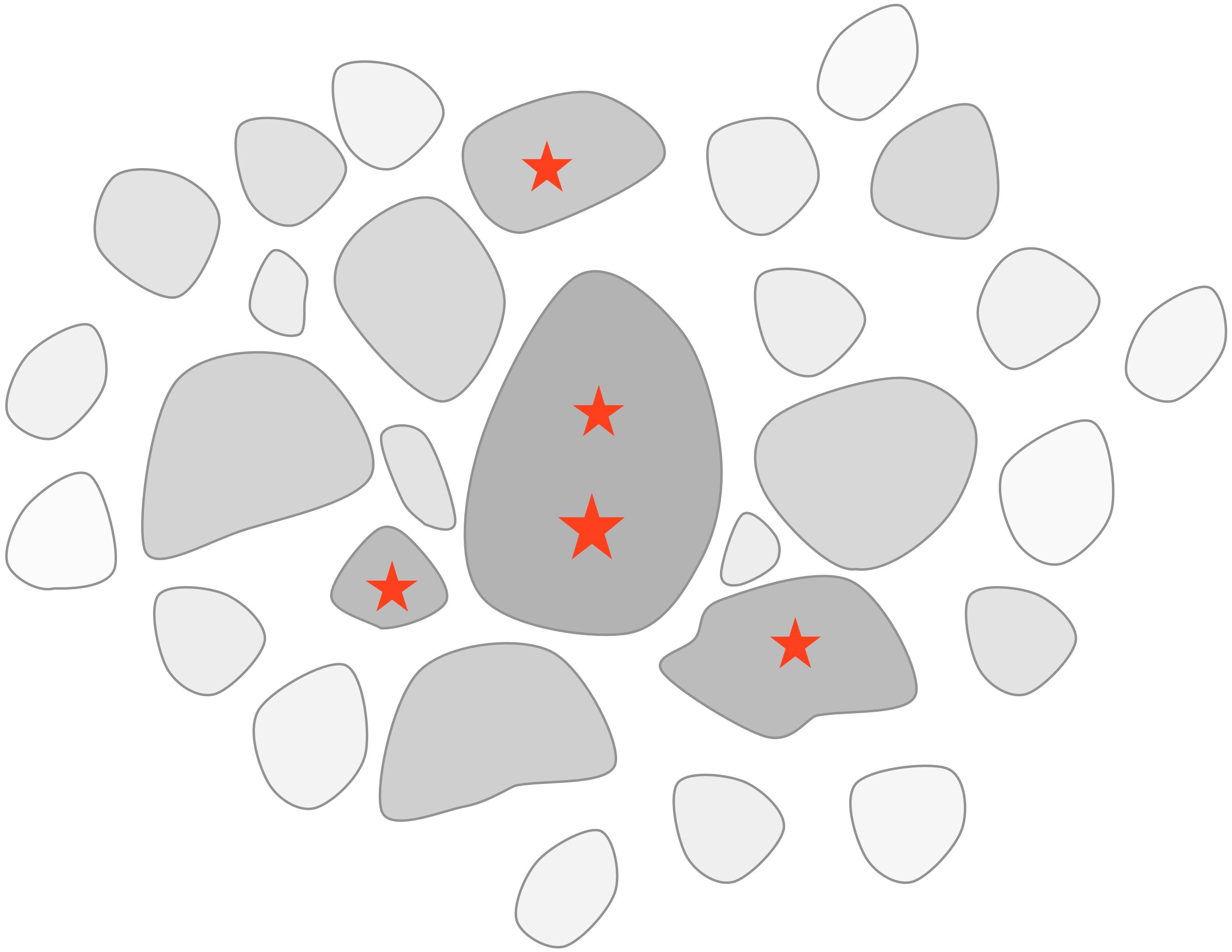
while region contracts, individual clumps collapse to form stars



individual clumps collapse to form stars

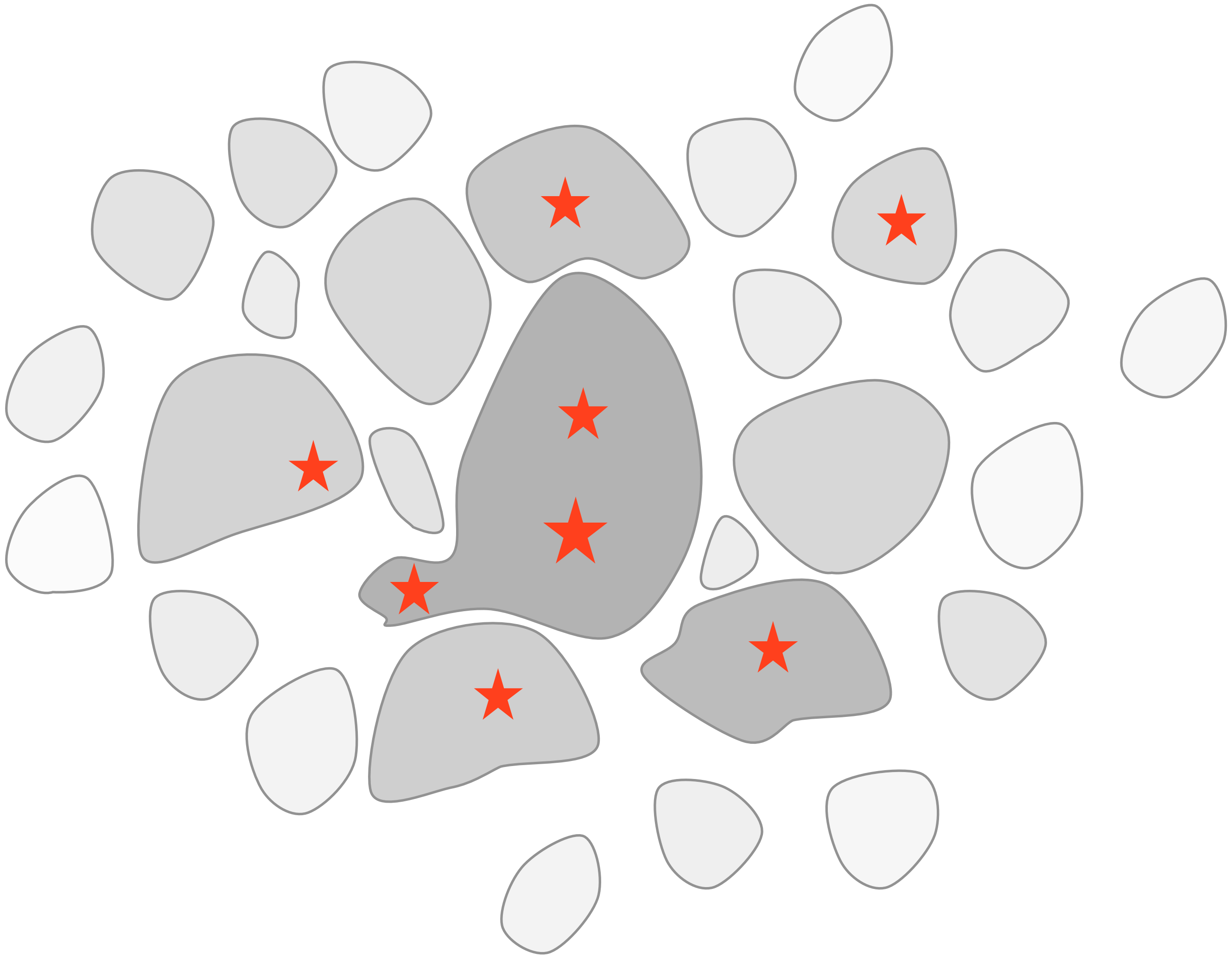


individual clumps collapse to form stars

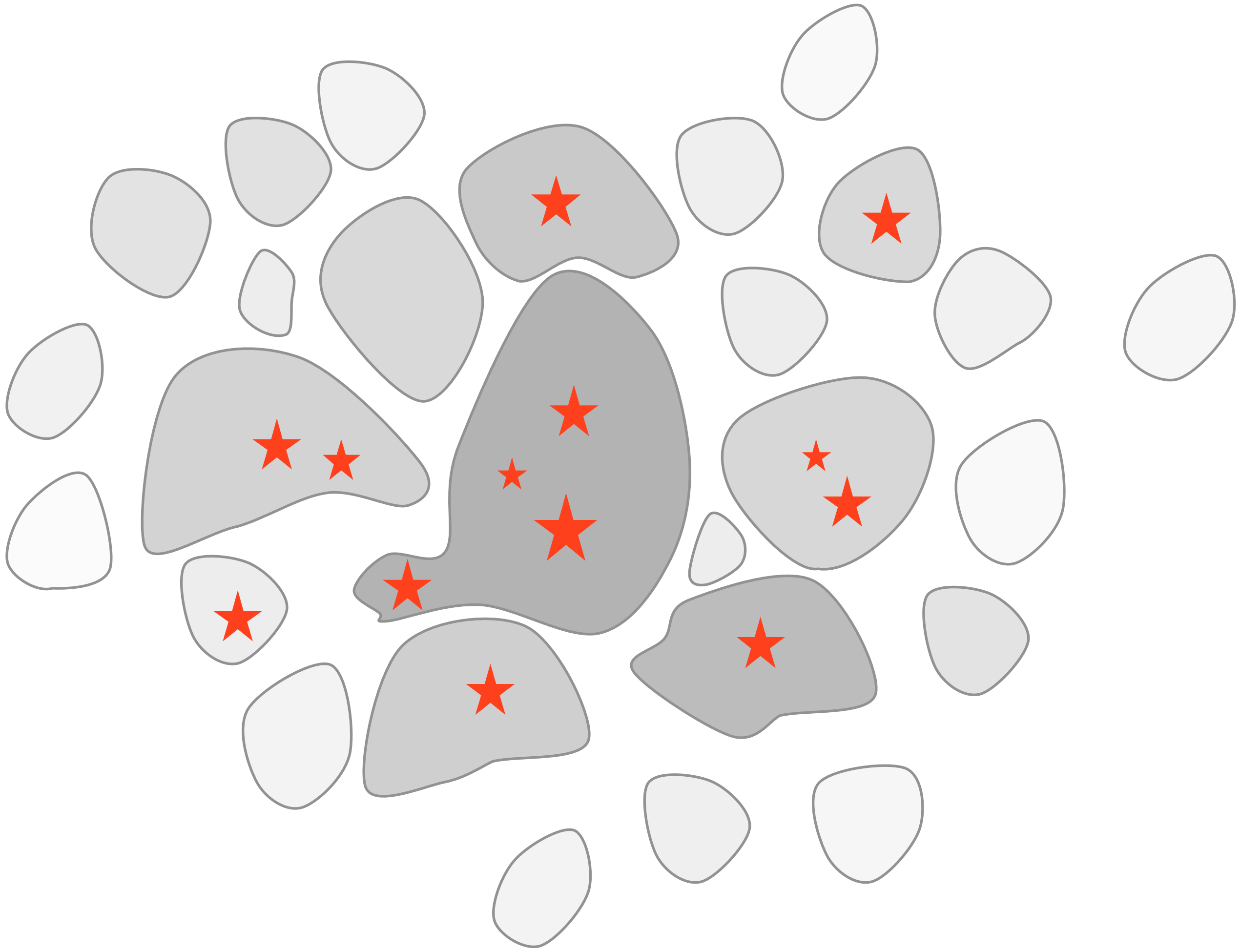


$\alpha = E_{kin}/|E_{pot}| < 1$

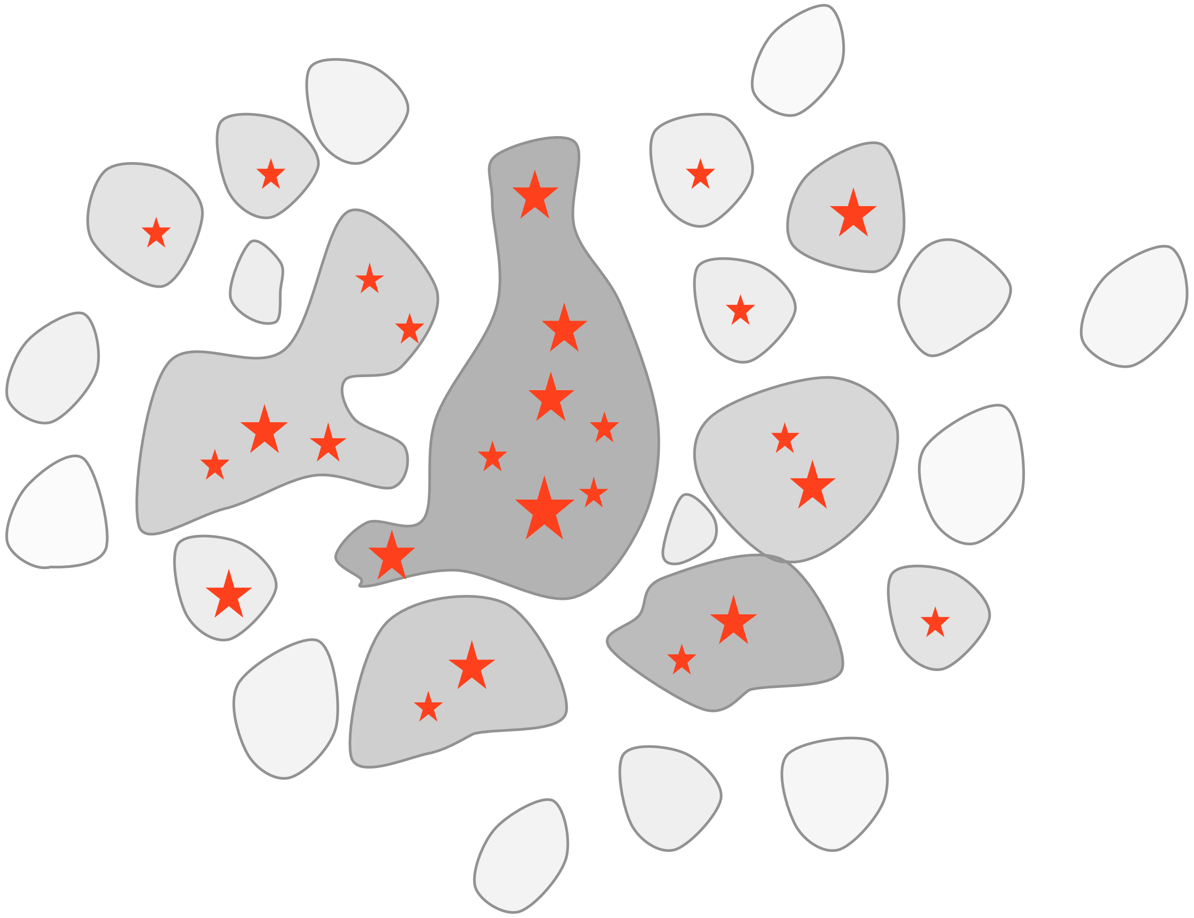
in *dense clusters*, clumps may merge while collapsing
--> then contain multiple protostars



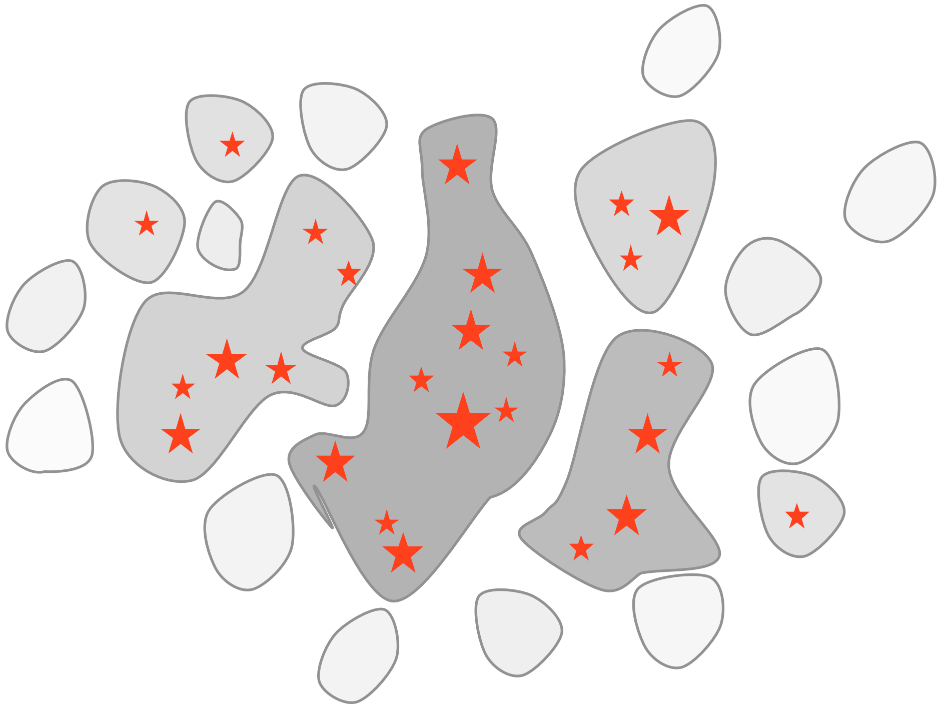
in *dense clusters*, clumps may merge while collapsing
--> then contain multiple protostars



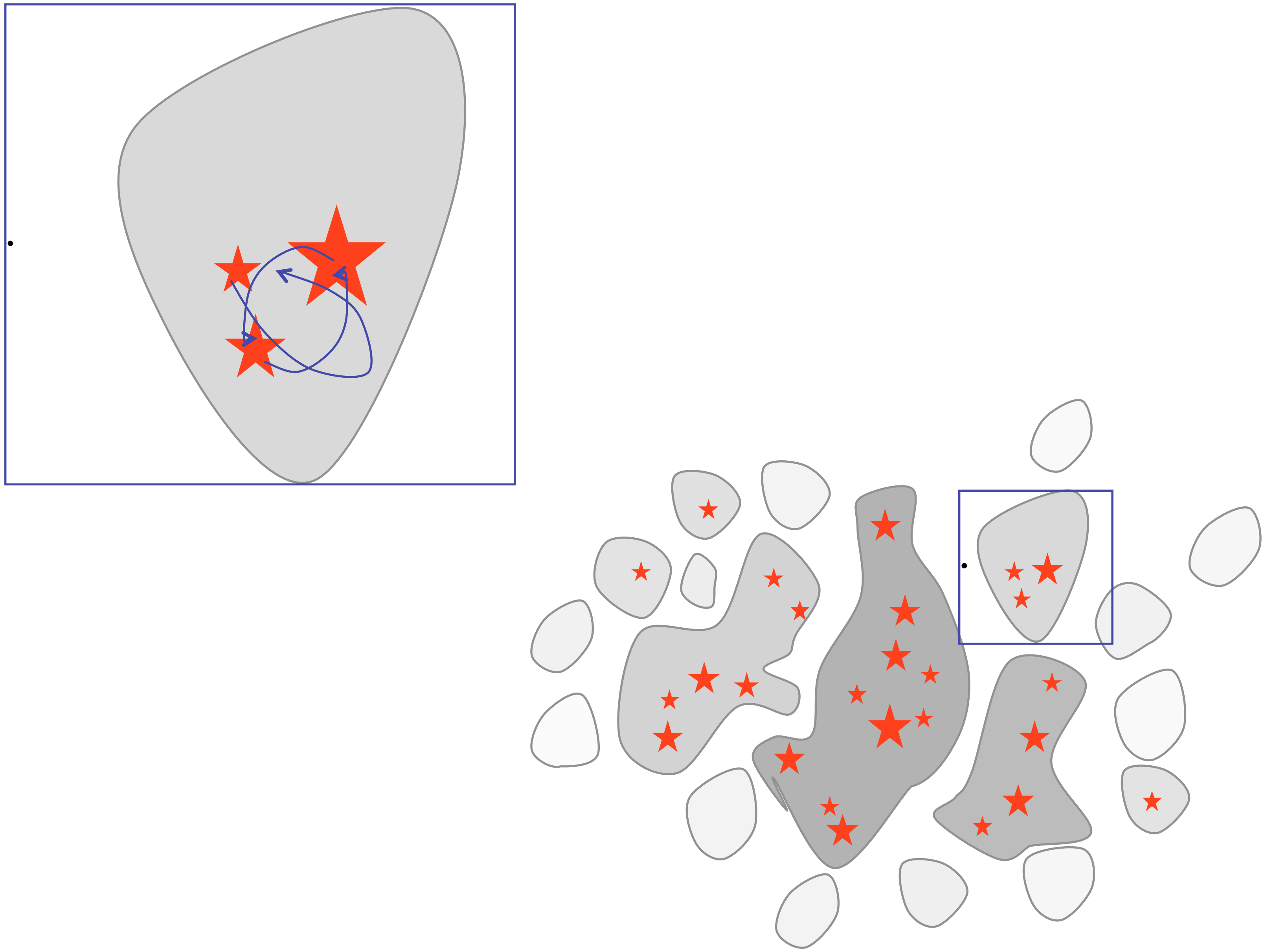
in *dense clusters*, clumps may merge while collapsing
--> then contain multiple protostars



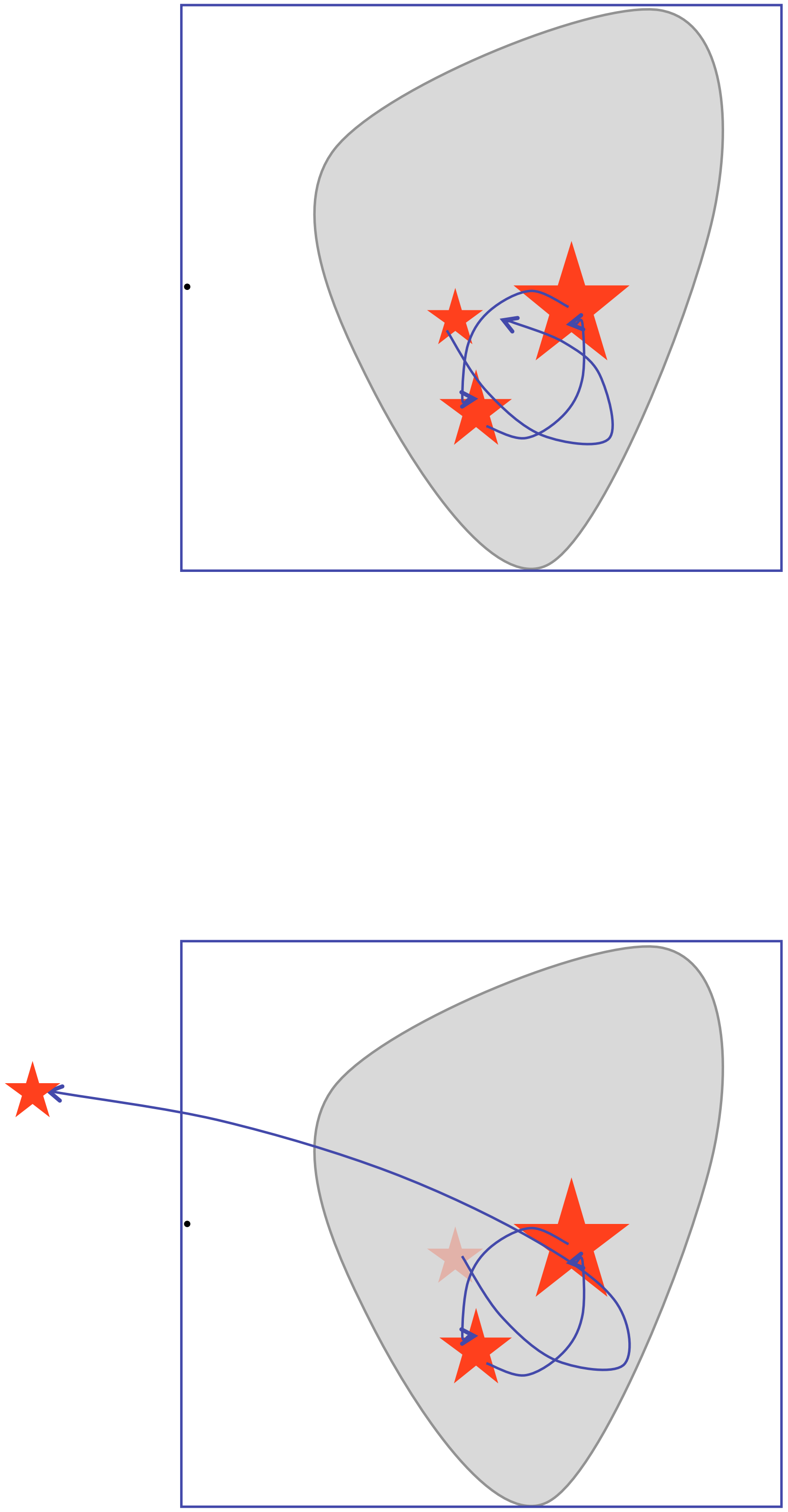
in *dense clusters*, competitive mass growth becomes important

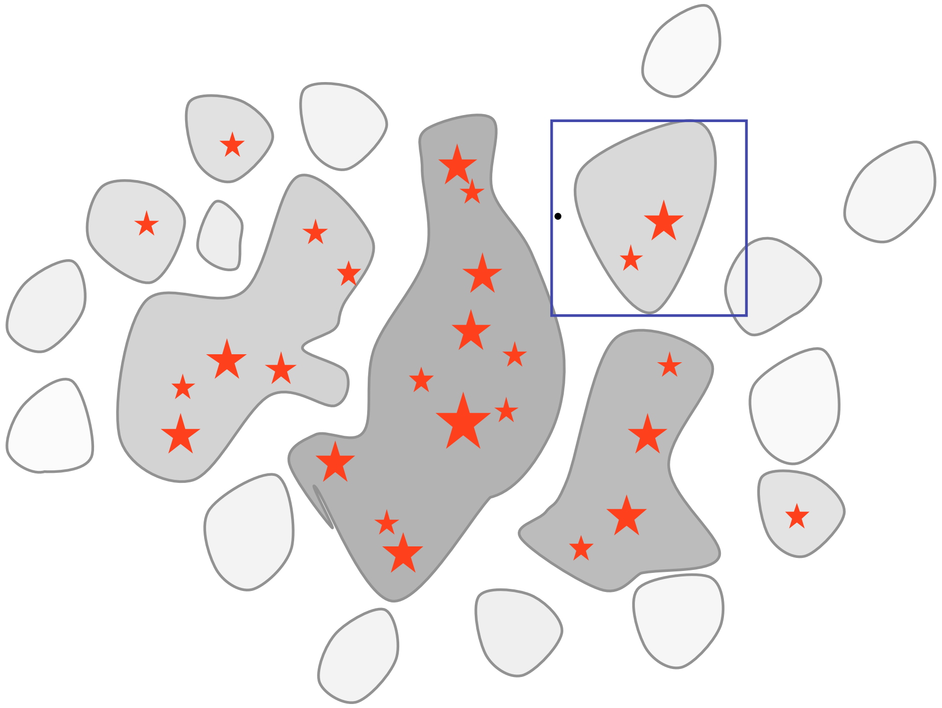


in *dense clusters*, competitive mass growth becomes important

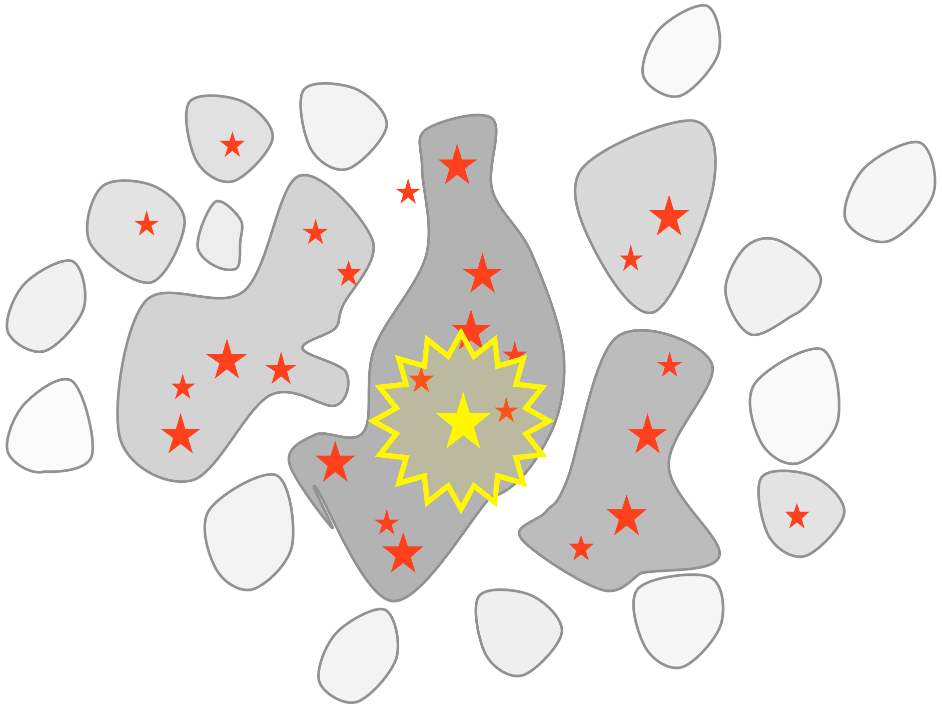


in *dense clusters*, *N*-body effects influence mass growth

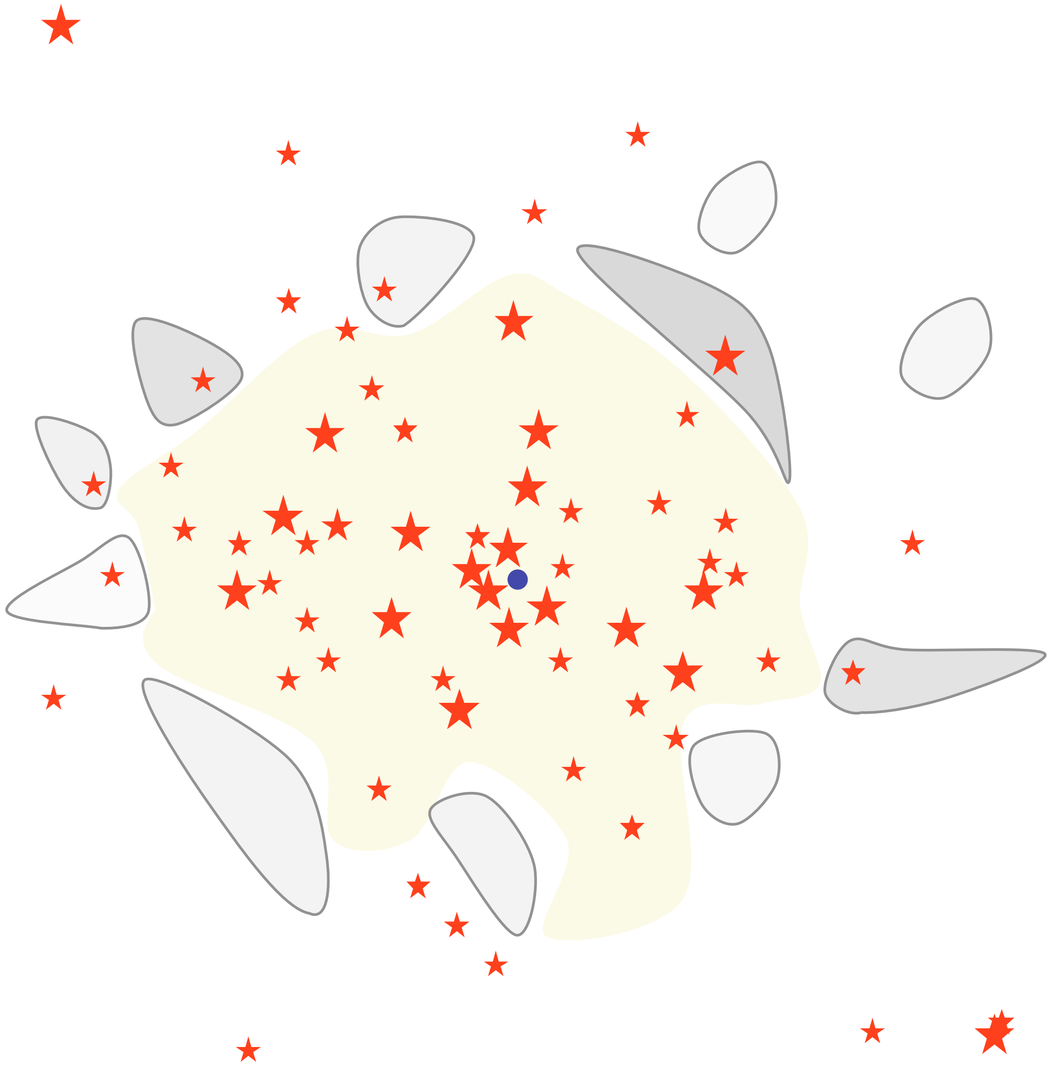




low-mass objects may
become ejected --> accretion stops



feedback terminates star formation



result: *star cluster*, possibly with HII region

NGC 602 in the LMC: Hubble Heritage Image

some concerns of simple model

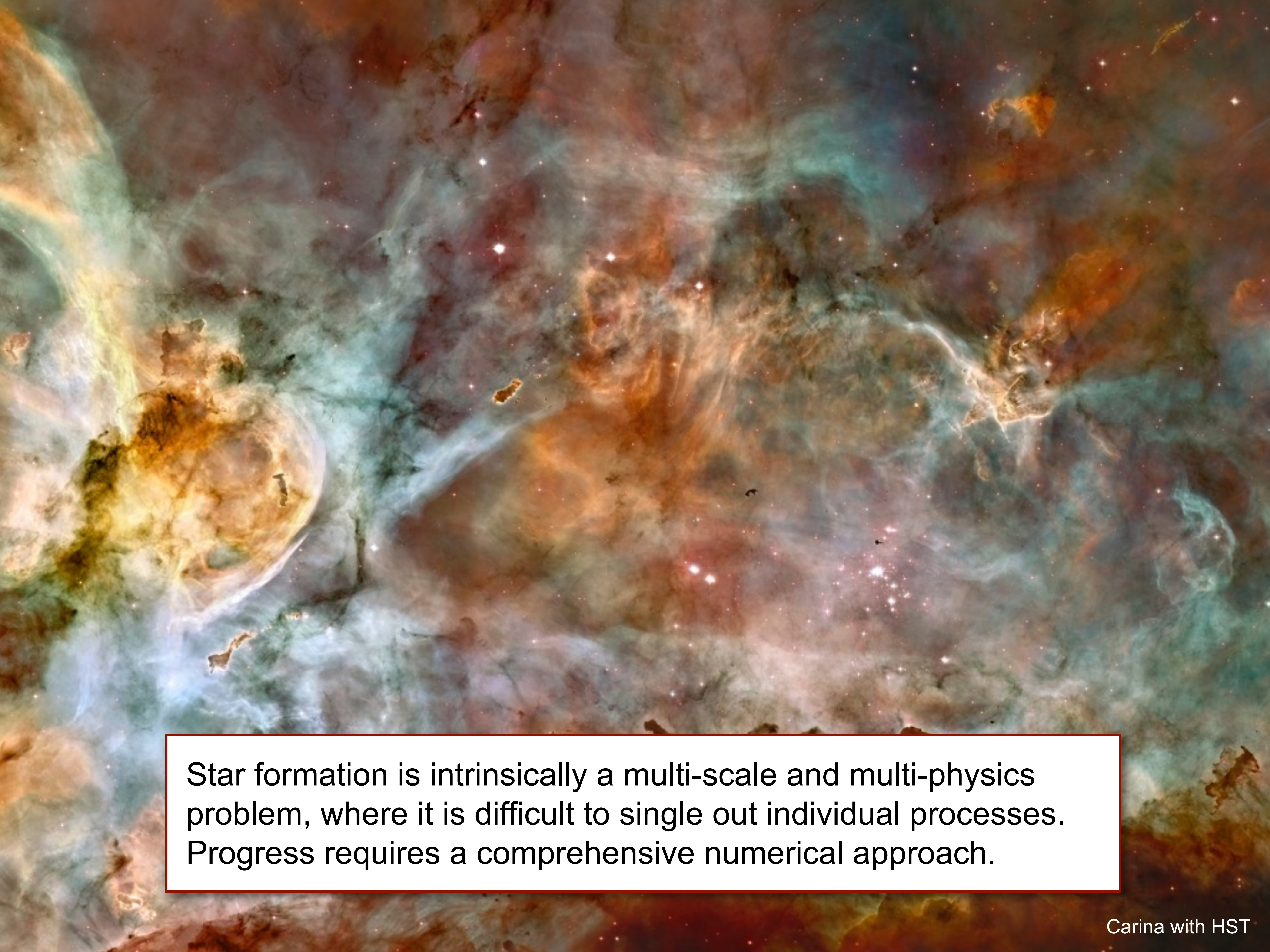
- *energy balance*
  - in molecular clouds:

    kinetic energy ~ potential energy ~ magnetic energy > thermal energy
  - models based on HD turbulence misses important physics
  - in certain environments (Galactic Center, star bursts), energy density in *cosmic rays* and *radiation* is important as well
- *time scales*
  - star clusters form fast, but more slowly than predicted by HD only (feedback and magnetic fields do help)
  - initial conditions do matter
    (turbulence does not erase memory of past dynamics)
- *star formation efficiency (SFE)*
  - SFE in gravoturbulent models is too high (again more physics needed)

current status

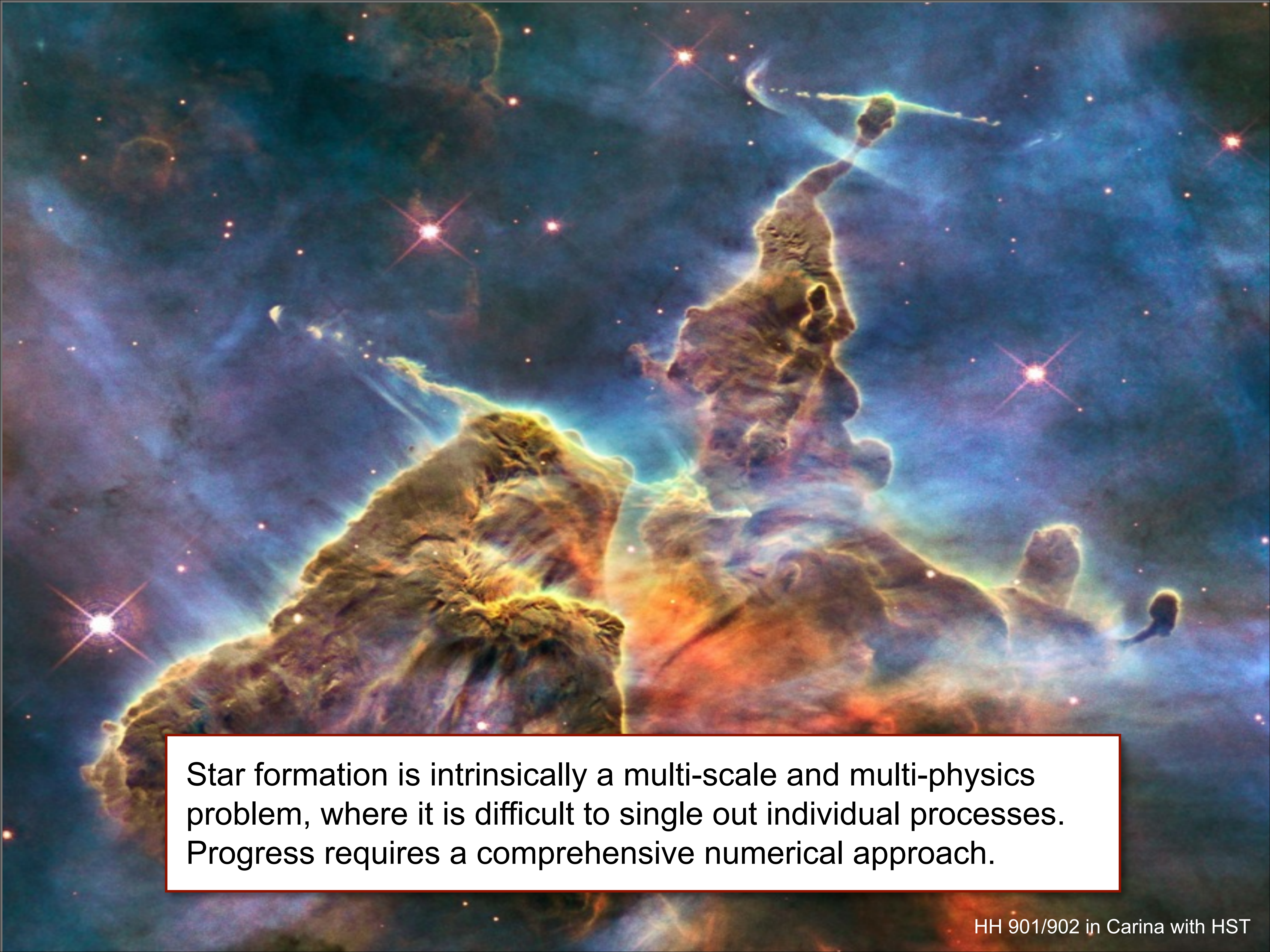
- *stars form from the complex interplay of self-gravity and a large number of competing processes (such as turbulence, B-field, feedback, thermal pressure)*
- *the relative importance of these processes depends on the environment*
  - prestellar cores --> thermal pressure is important
molecular clouds --> turbulence dominates } (Larson's relation: $\sigma \propto L^{1/2}$)
  - massive star forming regions (NGC602): radiative feedback is important
small clusters (Taurus): evolution maybe dominated by external turbulence
- *star formation is regulated by various feedback processes*
- *star formation is closely linked to global galactic dynamics (KS relation)*

Star formation is intrinsically a multi-scale and multi-physics problem, where it is difficult to single out individual processes. Simple theoretical approaches usually fail.



Star formation is intrinsically a multi-scale and multi-physics problem, where it is difficult to single out individual processes. Progress requires a comprehensive numerical approach.

Carina with HST

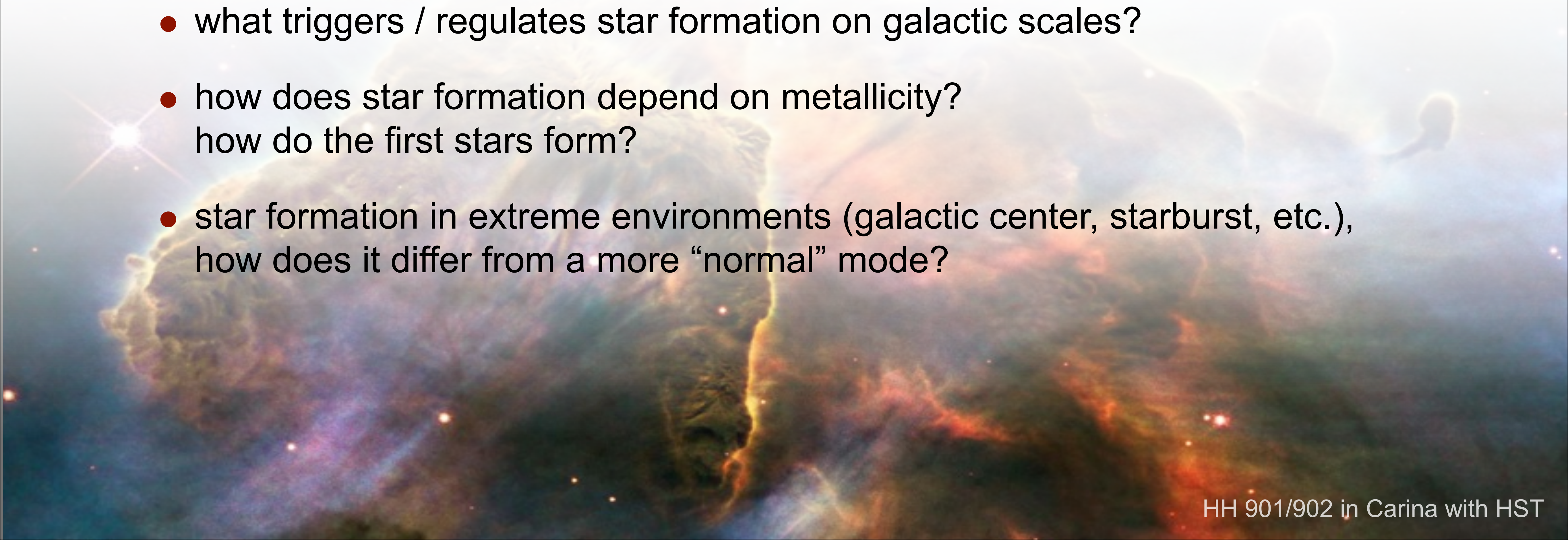


Star formation is intrinsically a multi-scale and multi-physics problem, where it is difficult to single out individual processes. Progress requires a comprehensive numerical approach.

HH 901/902 in Carina with HST

selected open questions

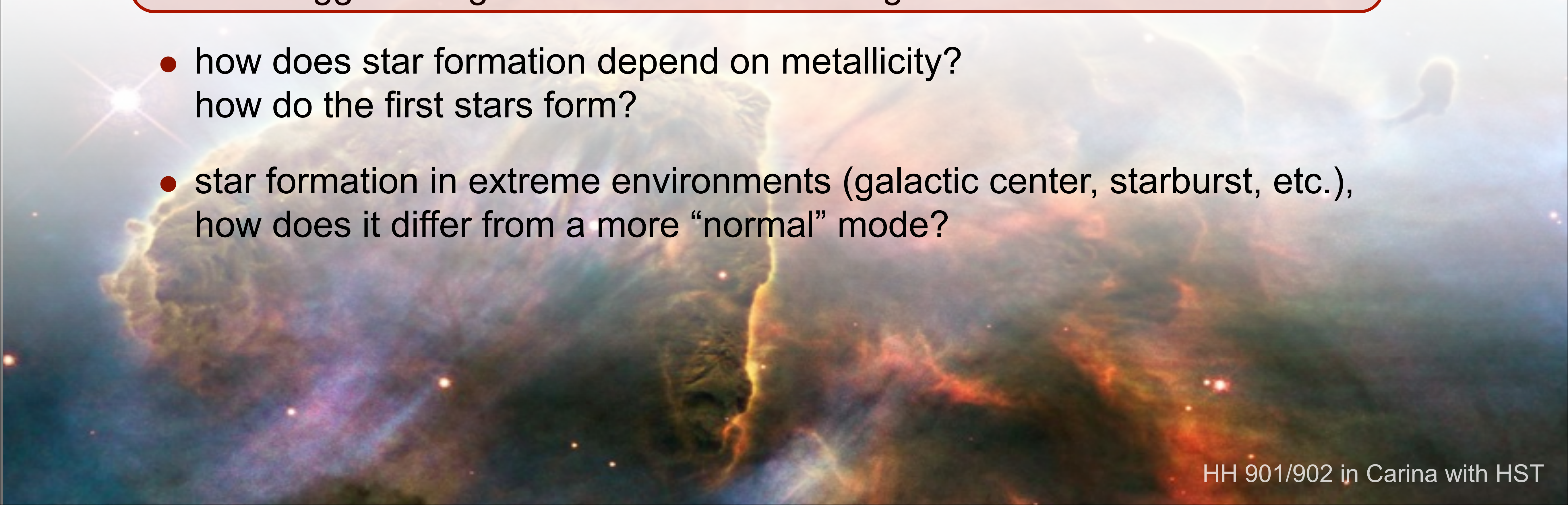
- what processes determine the initial mass function (IMF) of stars?
- what are the initial conditions for star cluster formation?
  how does cloud structure translate into cluster structure?
- how do molecular clouds form and evolve?
- what drives turbulence?
- what triggers / regulates star formation on galactic scales?
- how does star formation depend on metallicity?
  how do the first stars form?
- star formation in extreme environments (galactic center, starburst, etc.),
  how does it differ from a more “normal” mode?



HH 901/902 in Carina with HST

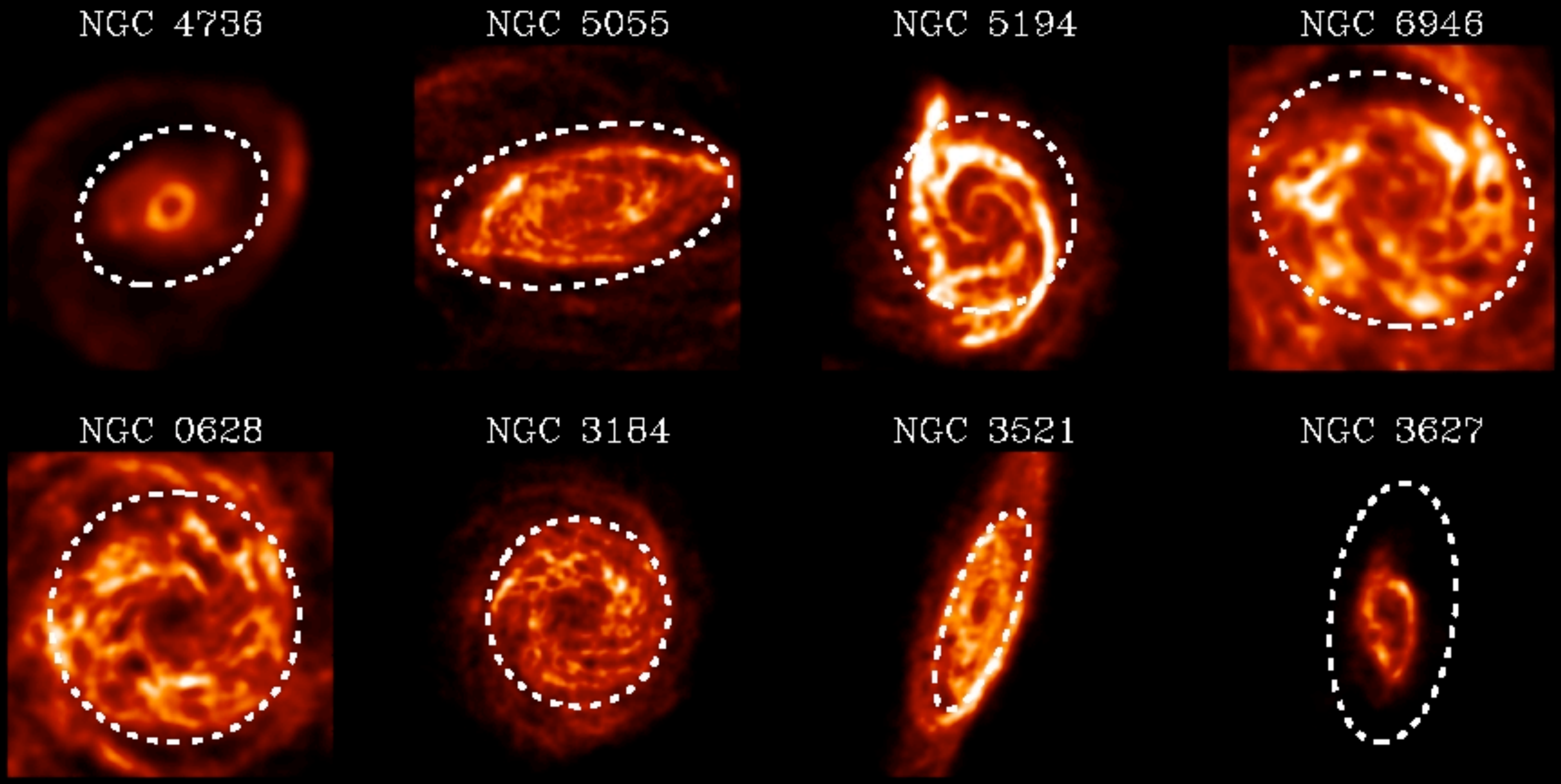
selected open questions

- what processes determine the initial mass function (IMF) of stars?
- what are the initial conditions for star cluster formation?
  how does cloud structure translate into cluster structure?
- how do molecular clouds form and evolve?
- what drives turbulence?
- what triggers / regulates star formation on galactic scales?
- how does star formation depend on metallicity?
  how do the first stars form?
- star formation in extreme environments (galactic center, starburst, etc.),
  how does it differ from a more “normal” mode?



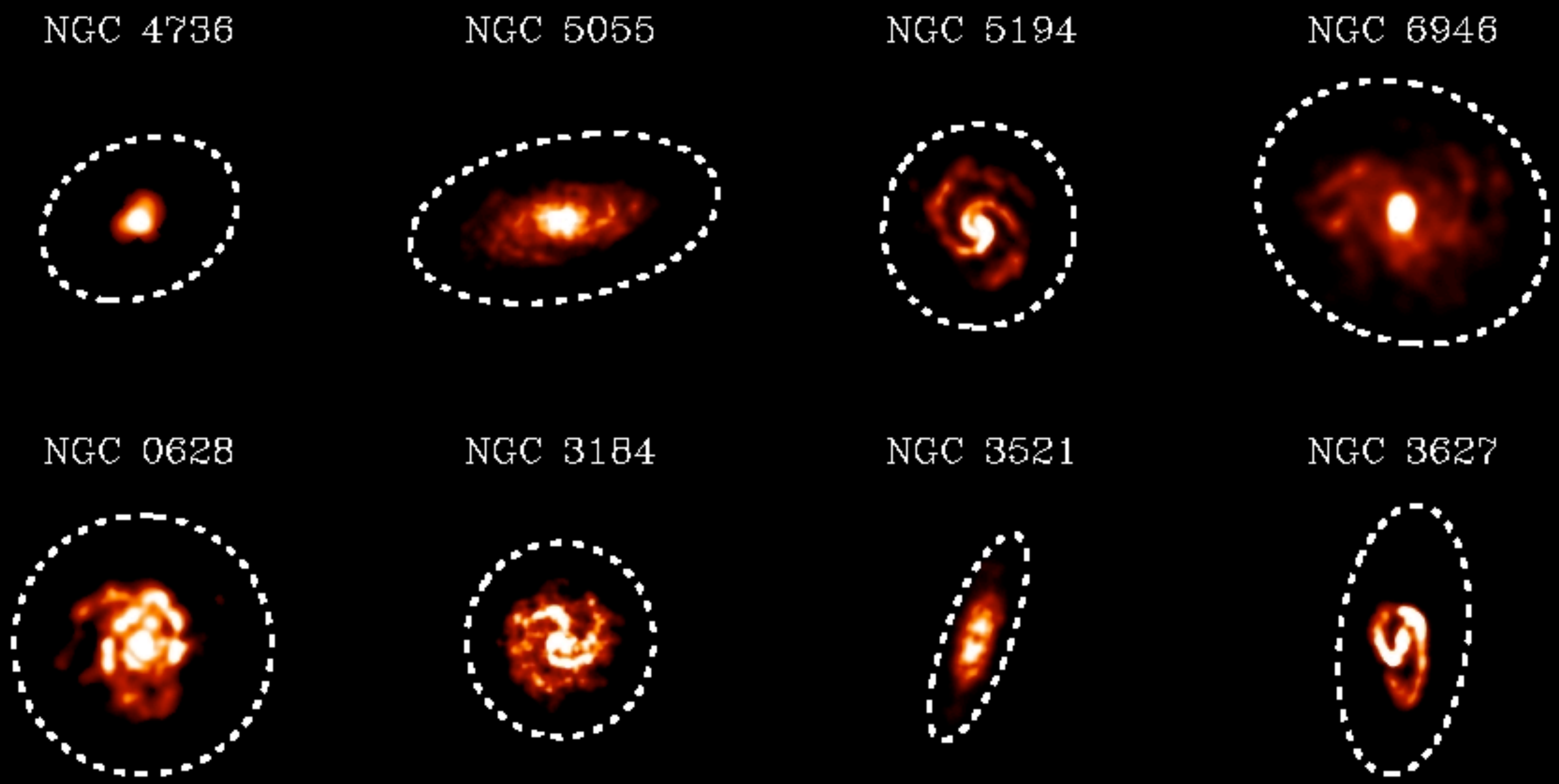
HH 901/902 in Carina with HST

HI Maps

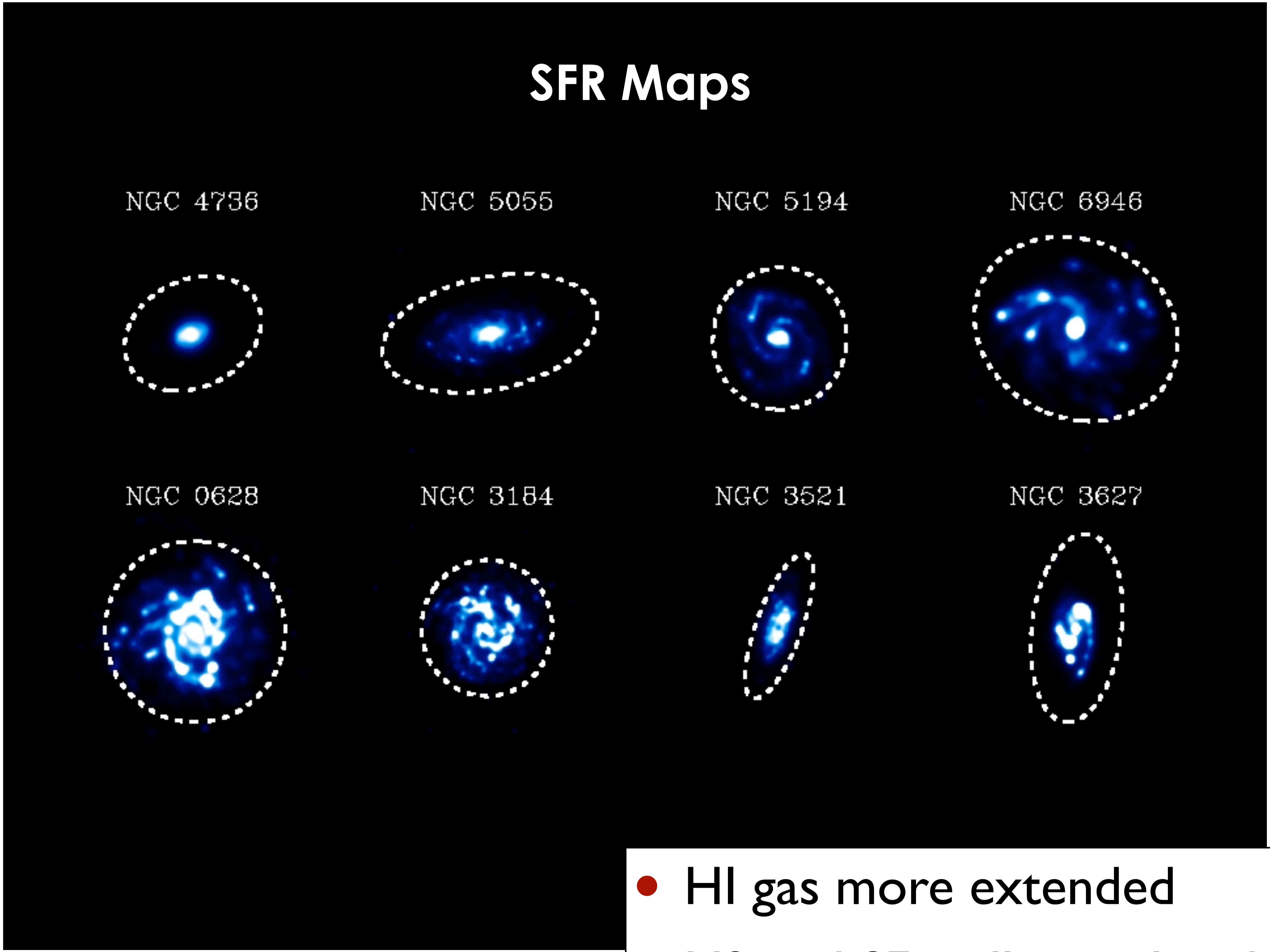


galaxies from THINGS and HERACLES survey
(images from Frank Bigiel, ZAH/ITA)

H_2 Maps



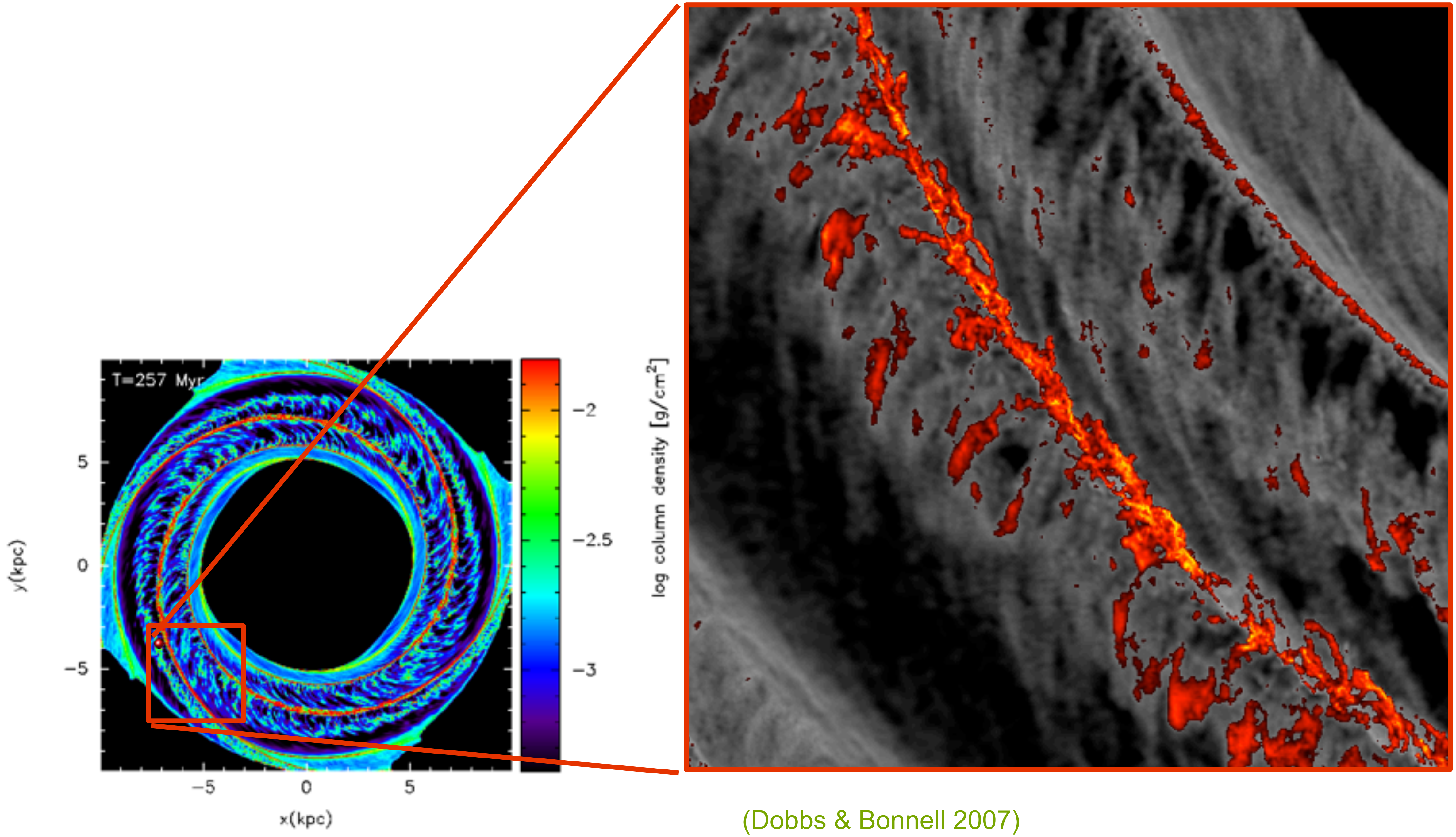
galaxies from THINGS and HERACLES survey
(images from Frank Bigiel, ZAH/ITA)



- HI gas more extended
- H2 and SF well correlated

galaxies from THINGS and HERACLES survey
(images from Frank Bigiel, ZAH/ITA)

example: full galaxy model

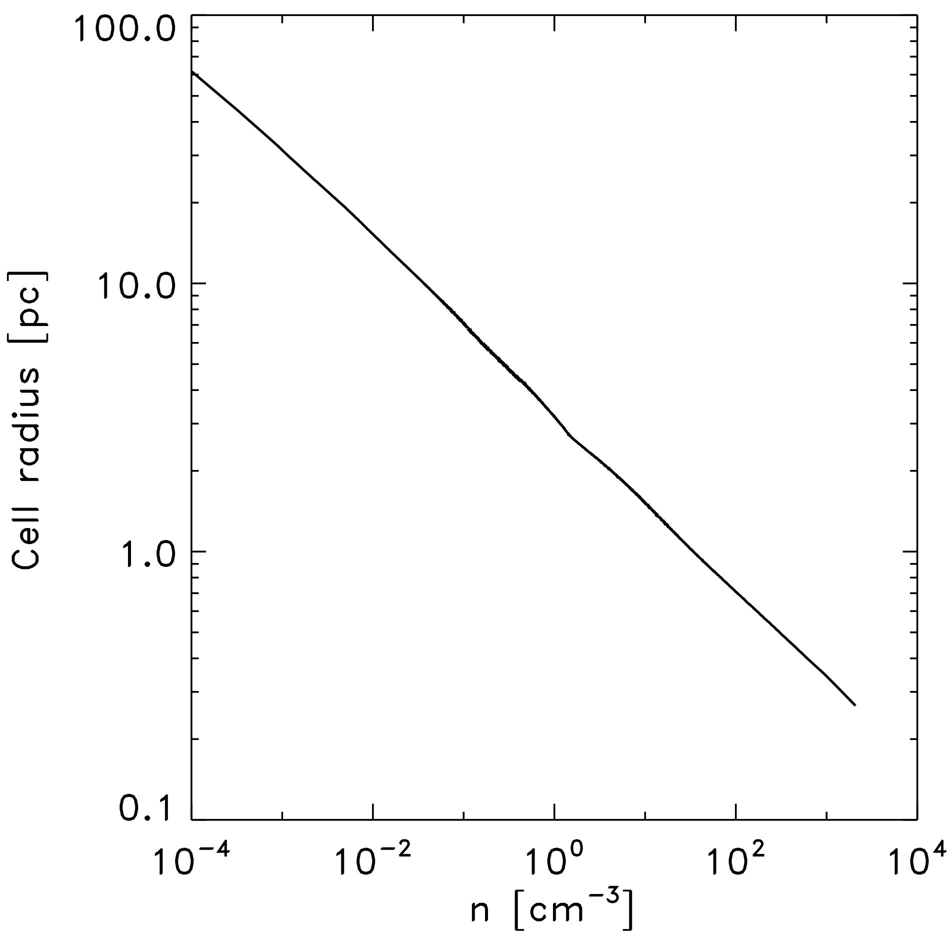


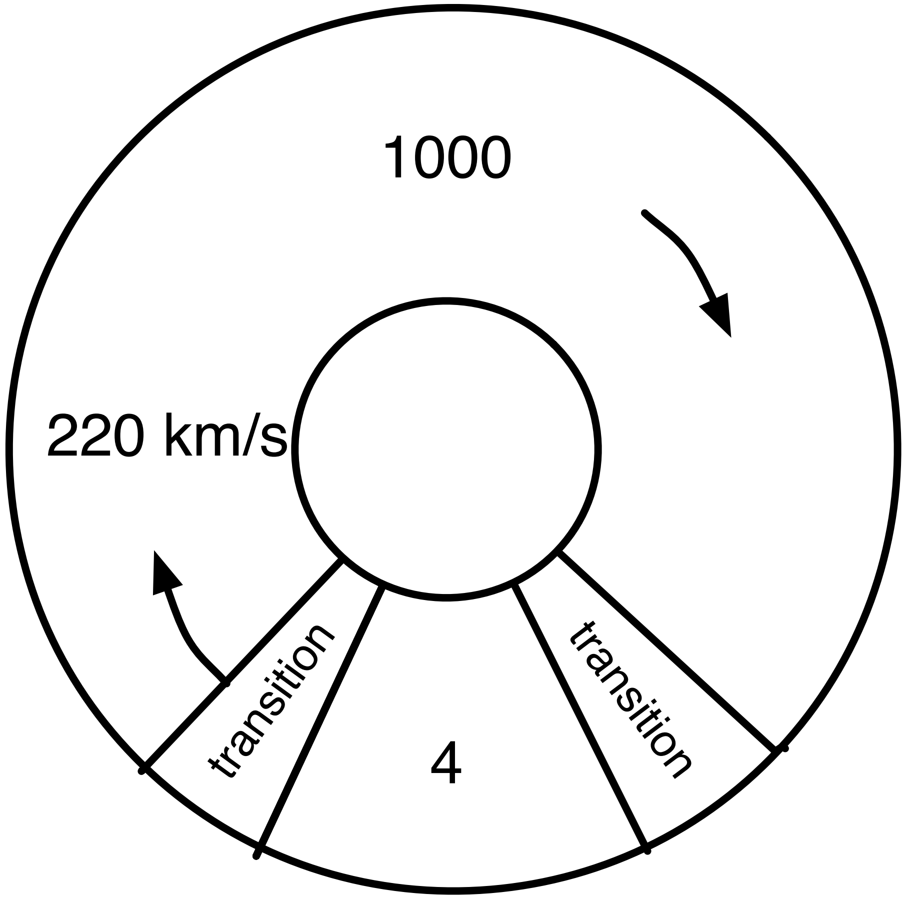
(Dobbs & Bonnell 2007)

example: full galaxy model

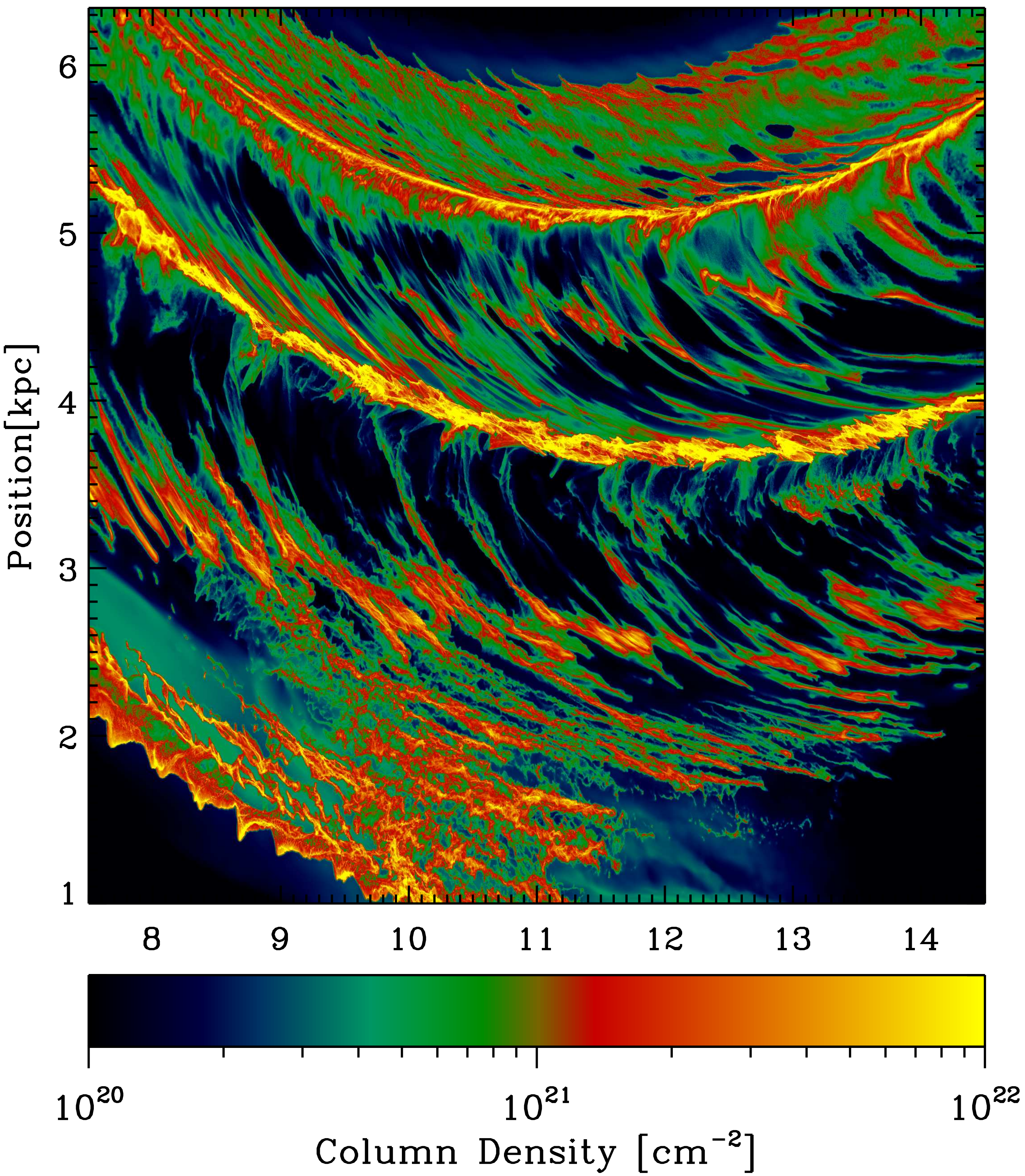
Table 1. The simulation parameters

Simulation	Surface Density $M_\odot$ pc^{-2}	Radiation Field G_0
Milky Way	10	1
Low Density	4	1
Strong Field	10	10
Low & Weak	4	0.1



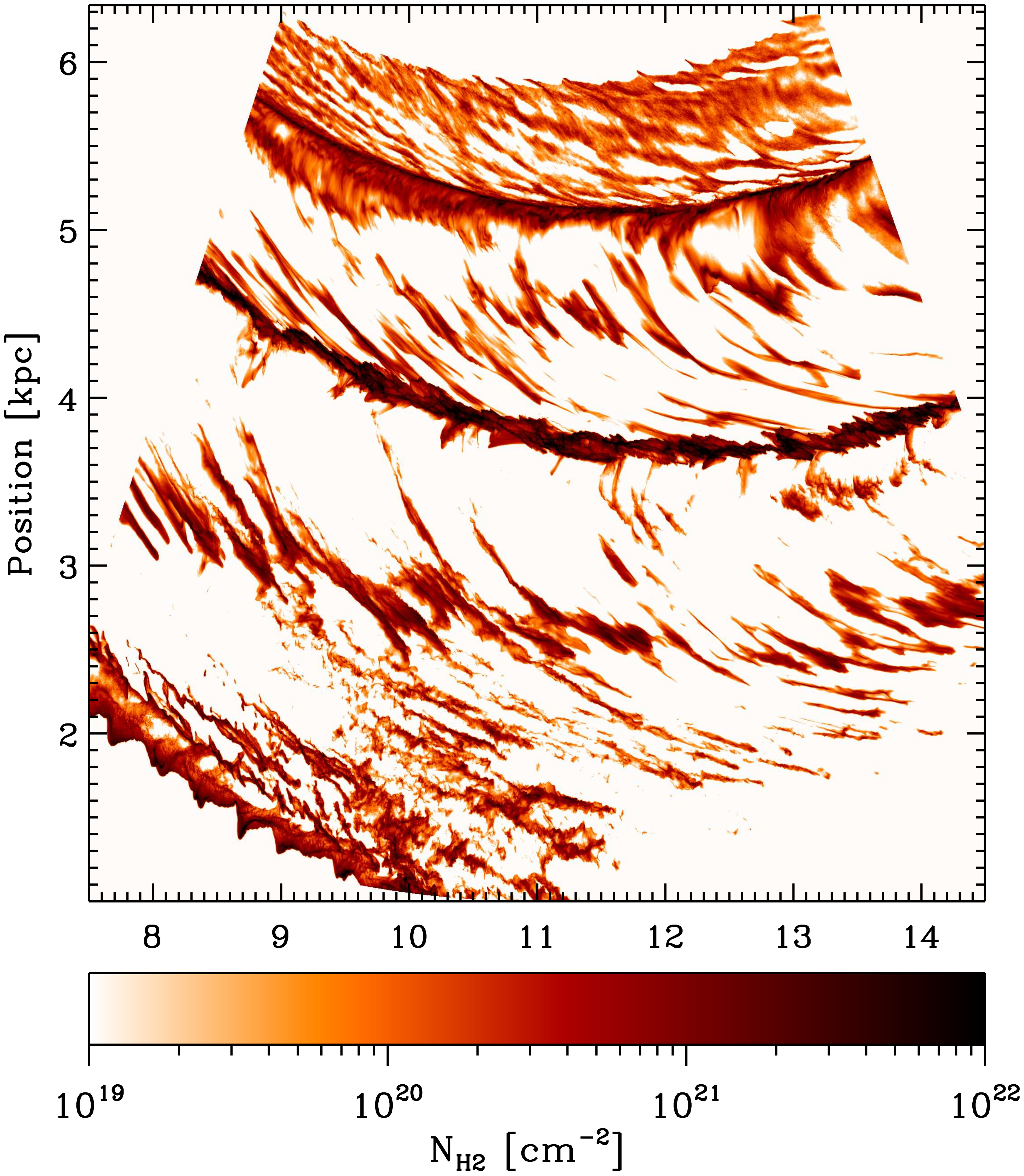


Rowan Smith et al. (2014, in prep.)

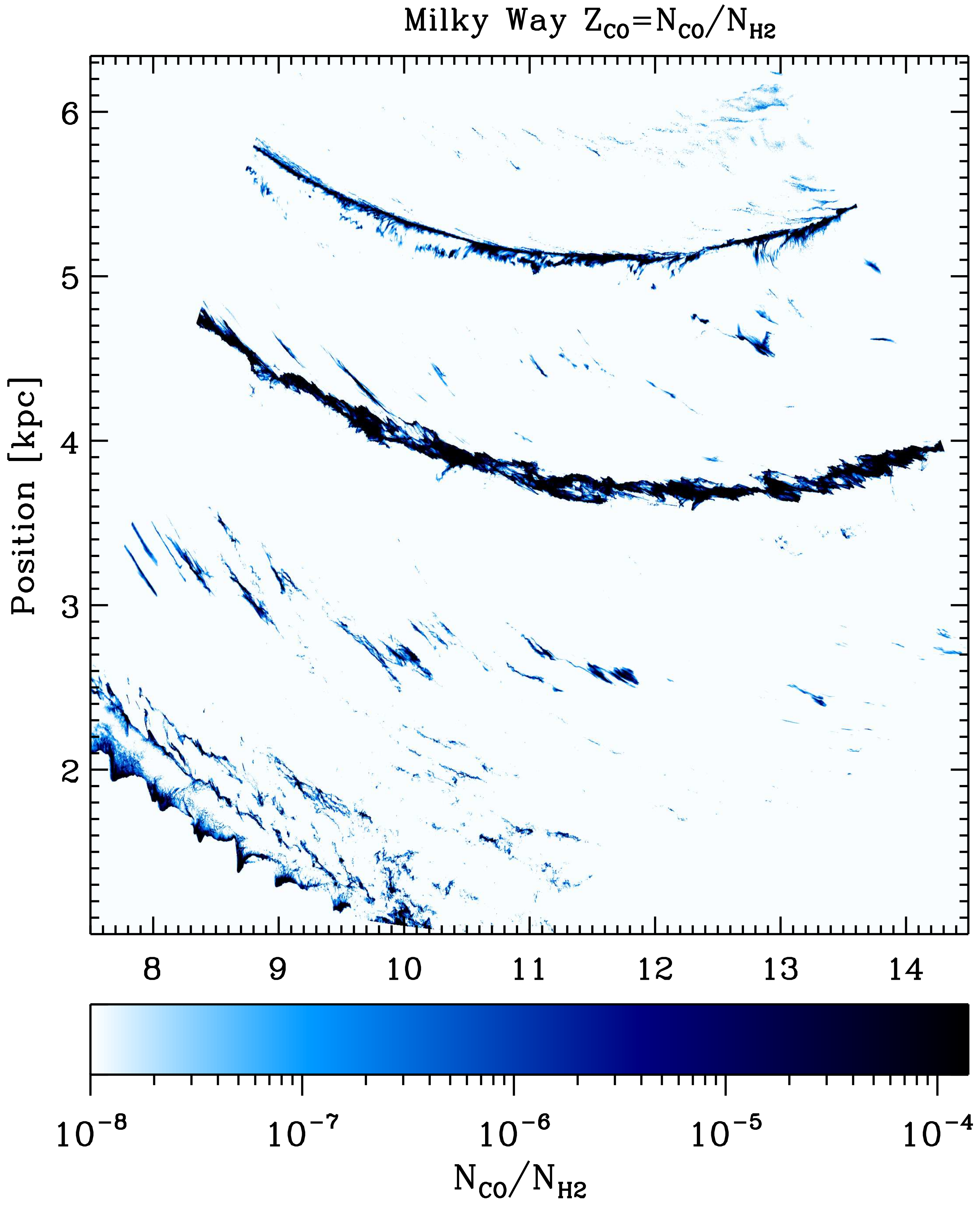


Rowan Smith et al. (2014, in prep.)

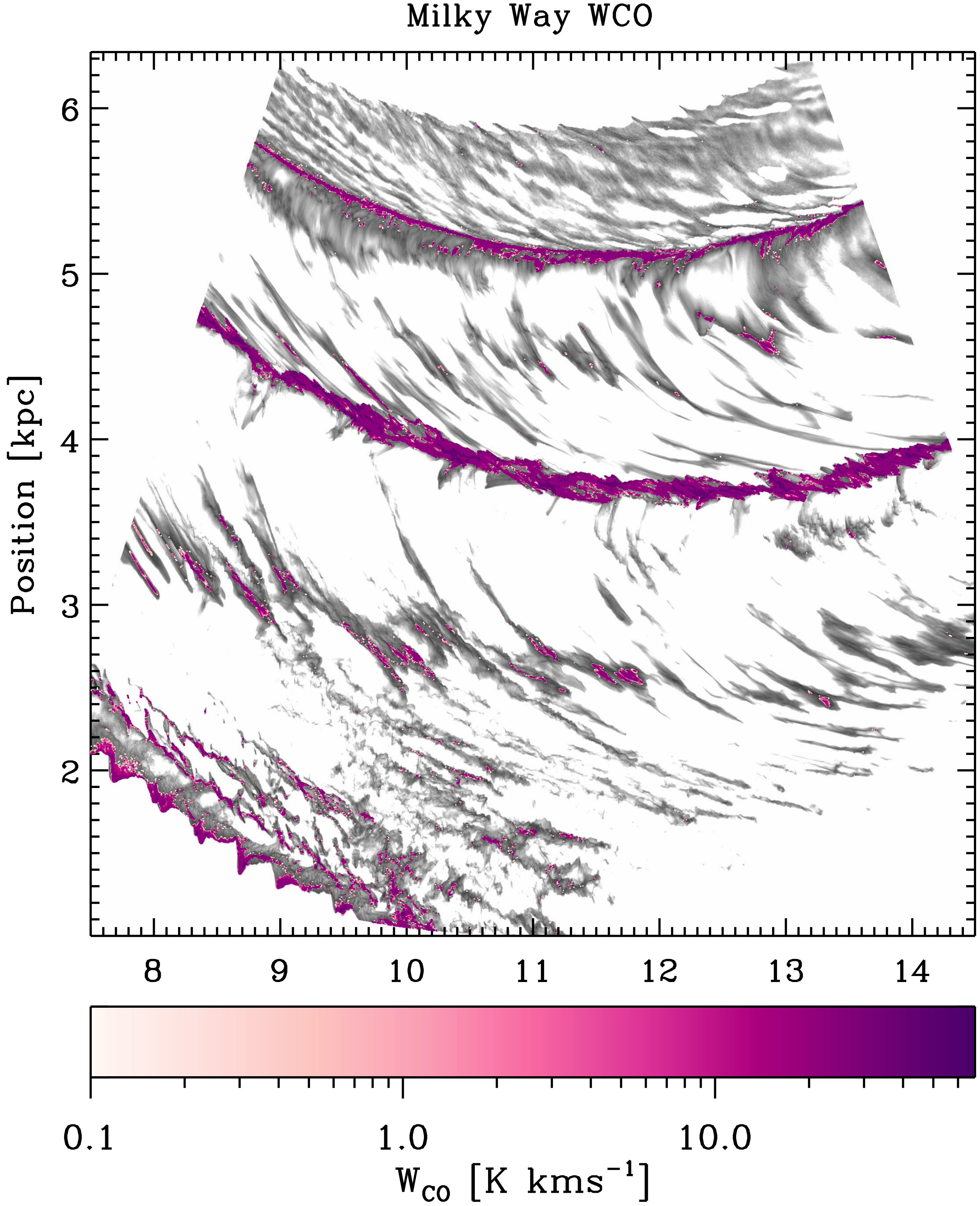
Milky Way N_{H2}



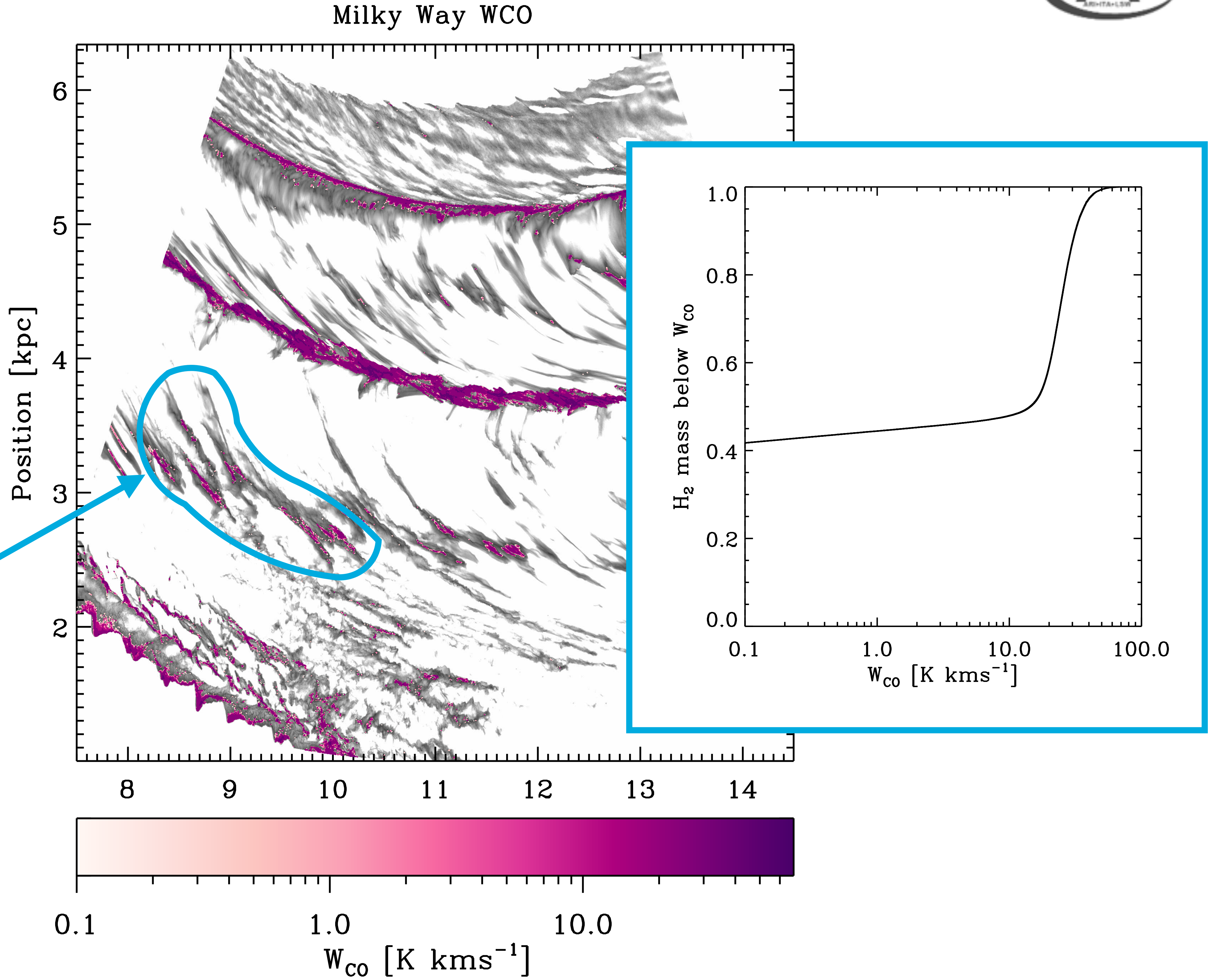
Rowan Smith et al. (2014, in prep.)



Rowan Smith et al. (2014, in prep.)



Rowan Smith et al. (2014, in prep.)

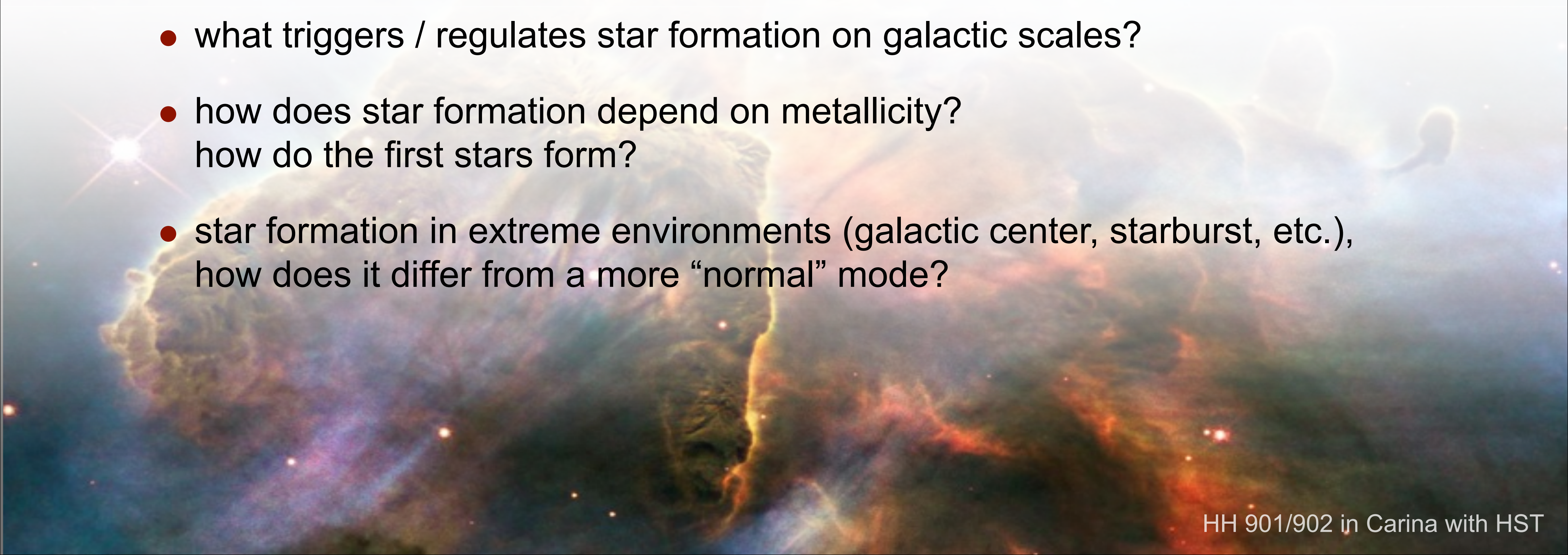


There is lots of H_2 gas that is NOT traced by CO

Rowan Smith et al. (2014, in prep.)

selected open questions

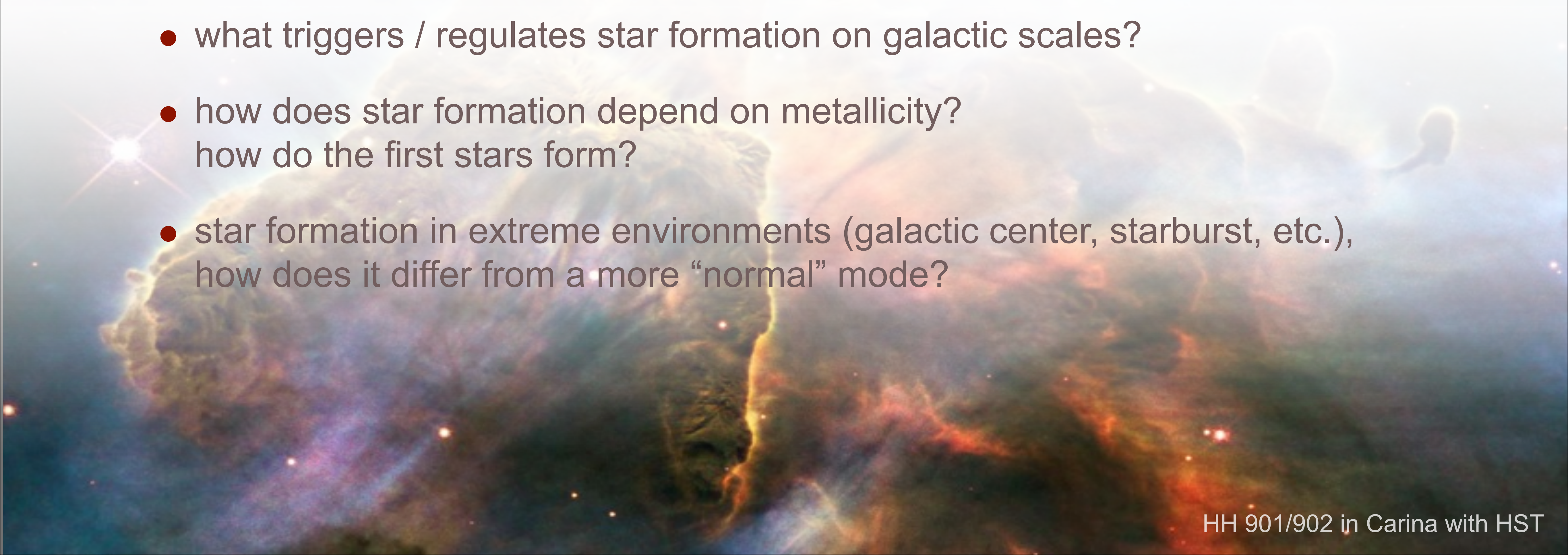
- what processes determine the initial mass function (IMF) of stars?
- what are the initial conditions for star cluster formation?
  how does cloud structure translate into cluster structure?
- how do molecular clouds form and evolve?
- what drives turbulence?
- what triggers / regulates star formation on galactic scales?
- how does star formation depend on metallicity?
  how do the first stars form?
- star formation in extreme environments (galactic center, starburst, etc.),
  how does it differ from a more “normal” mode?



HH 901/902 in Carina with HST

selected open questions

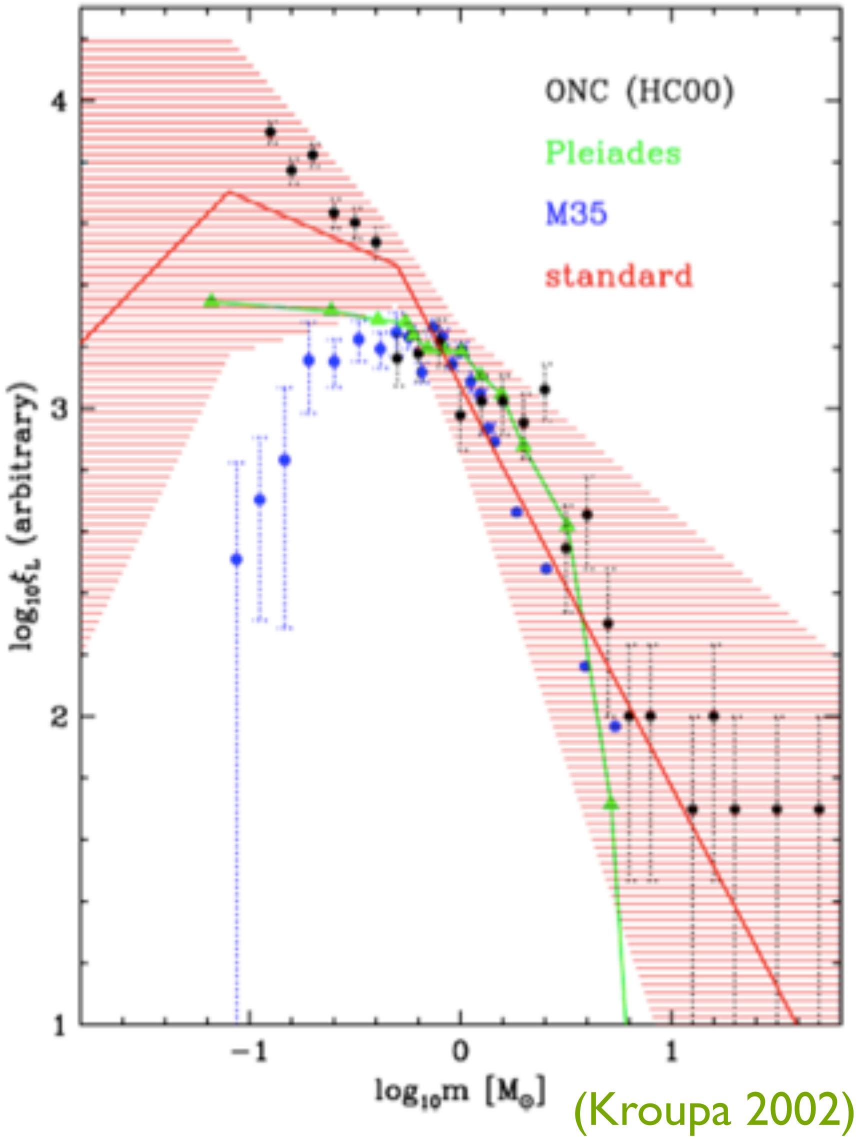
- what processes determine the initial mass function (IMF) of stars?
- what are the initial conditions for star cluster formation?
  how does cloud structure translate into cluster structure?
- how do molecular clouds form and evolve?
- what drives turbulence?
- what triggers / regulates star formation on galactic scales?
- how does star formation depend on metallicity?
  how do the first stars form?
- star formation in extreme environments (galactic center, starburst, etc.),
  how does it differ from a more “normal” mode?



HH 901/902 in Carina with HST

stellar mass fuction

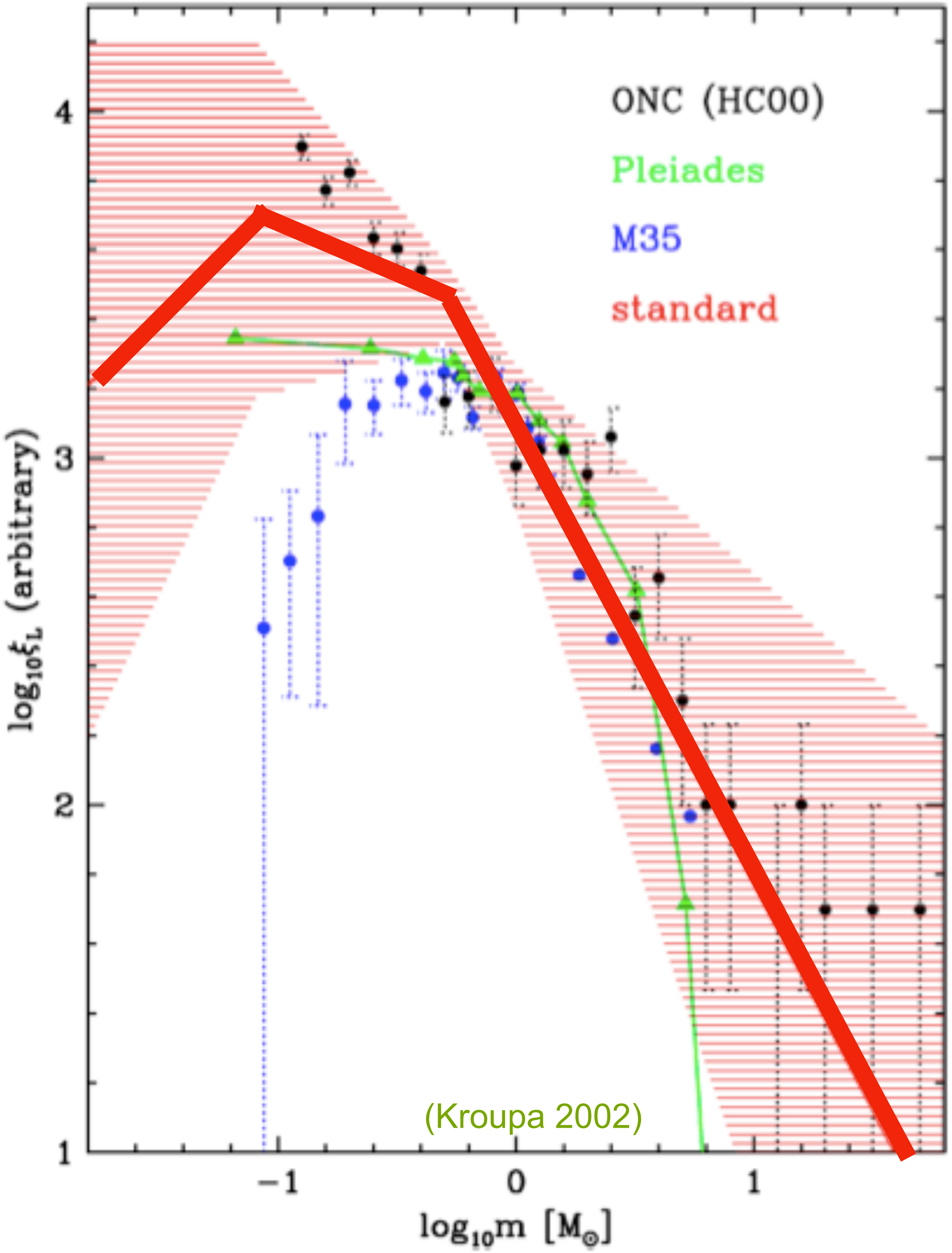
stars seem to follow a universal mass function at birth --> IMF



(Kroupa 2002)

Orion, NGC 3603, 30 Doradus
(Zinnecker & Yorke 2007)

IMF: observations 1



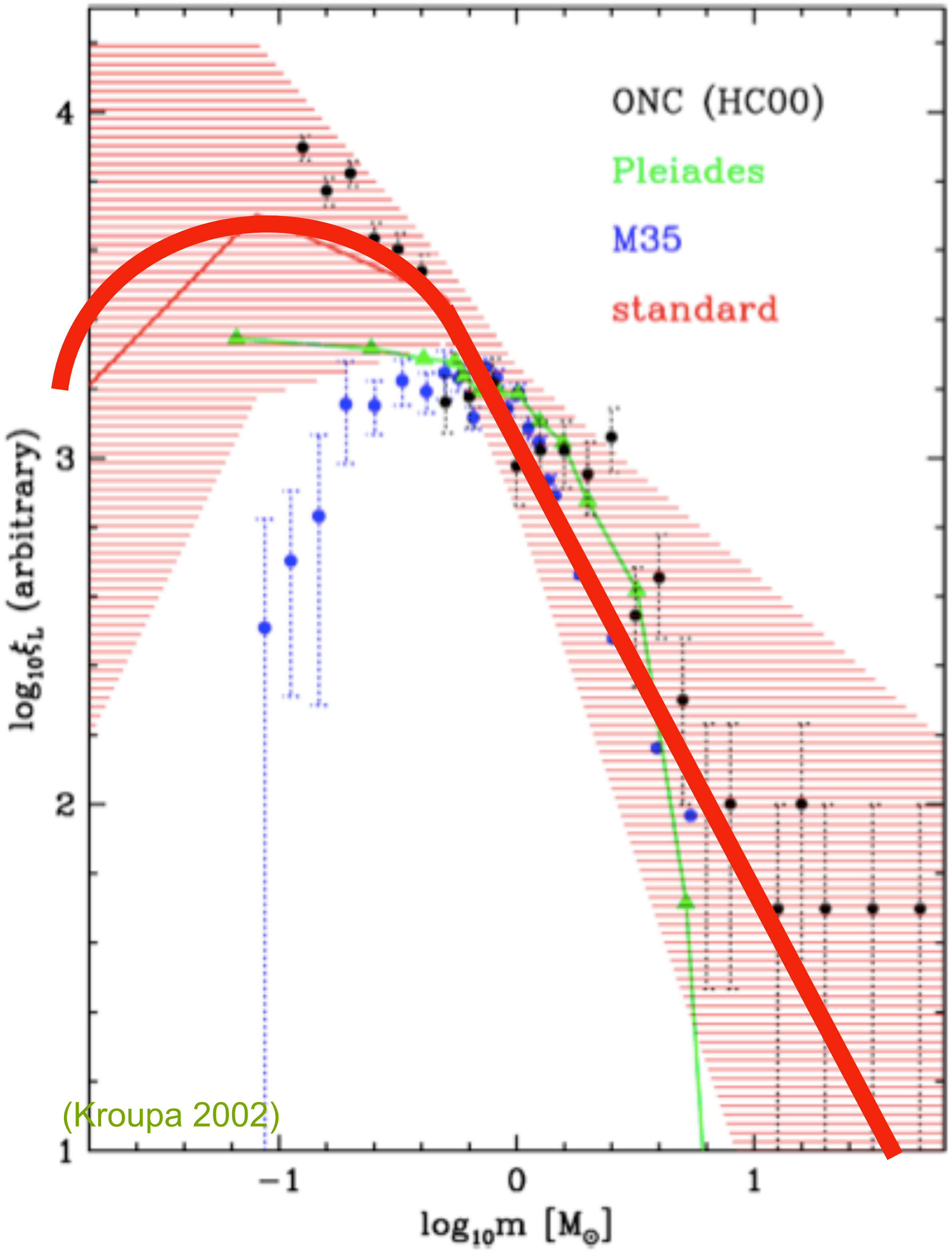
(Kroupa 2002)

power-law approximation to the IMF (Kroupa, Tout, Gillmore 1993, Kroupa 2002)

$$\xi(m)\,dm \propto m^{-\alpha}\,dm,$$

$$\xi(m) = \begin{cases} 0.26\ m^{-0.3} & \text{for}\ \ 0.01 \leqslant m < 0.08 \\ 0.035\ m^{-1.3} & \text{for}\ \ 0.08 \leqslant m < 0.5 \\ 0.019\ m^{-2.3} & \text{for}\ \ 0.5 \leqslant m < \infty. \end{cases}$$

IMF: observations 2



(Kroupa 2002)

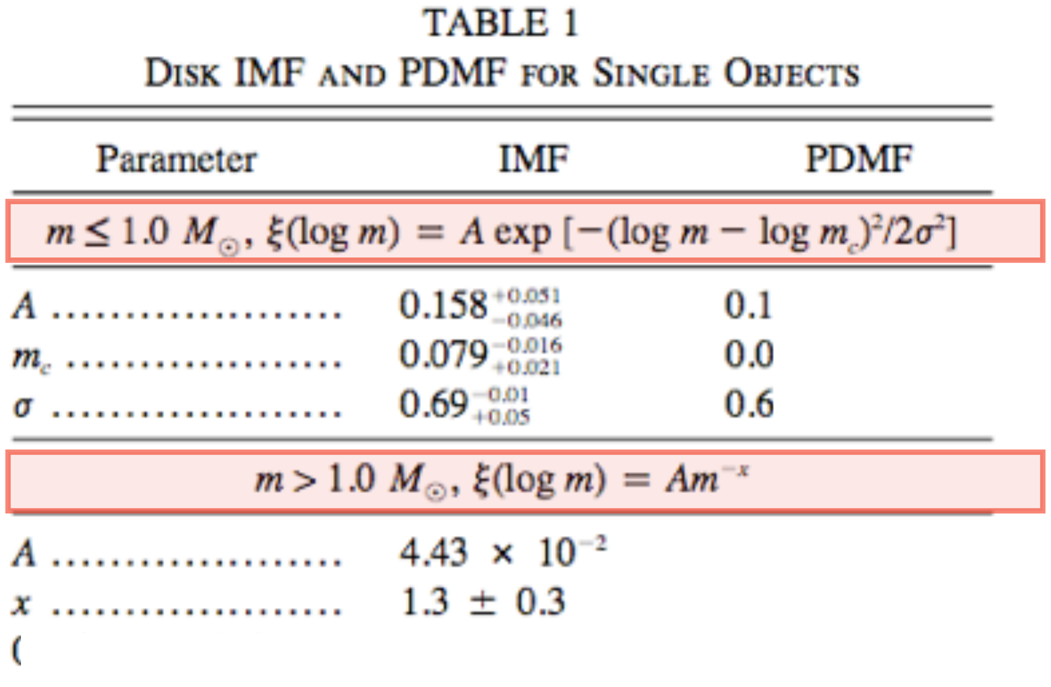
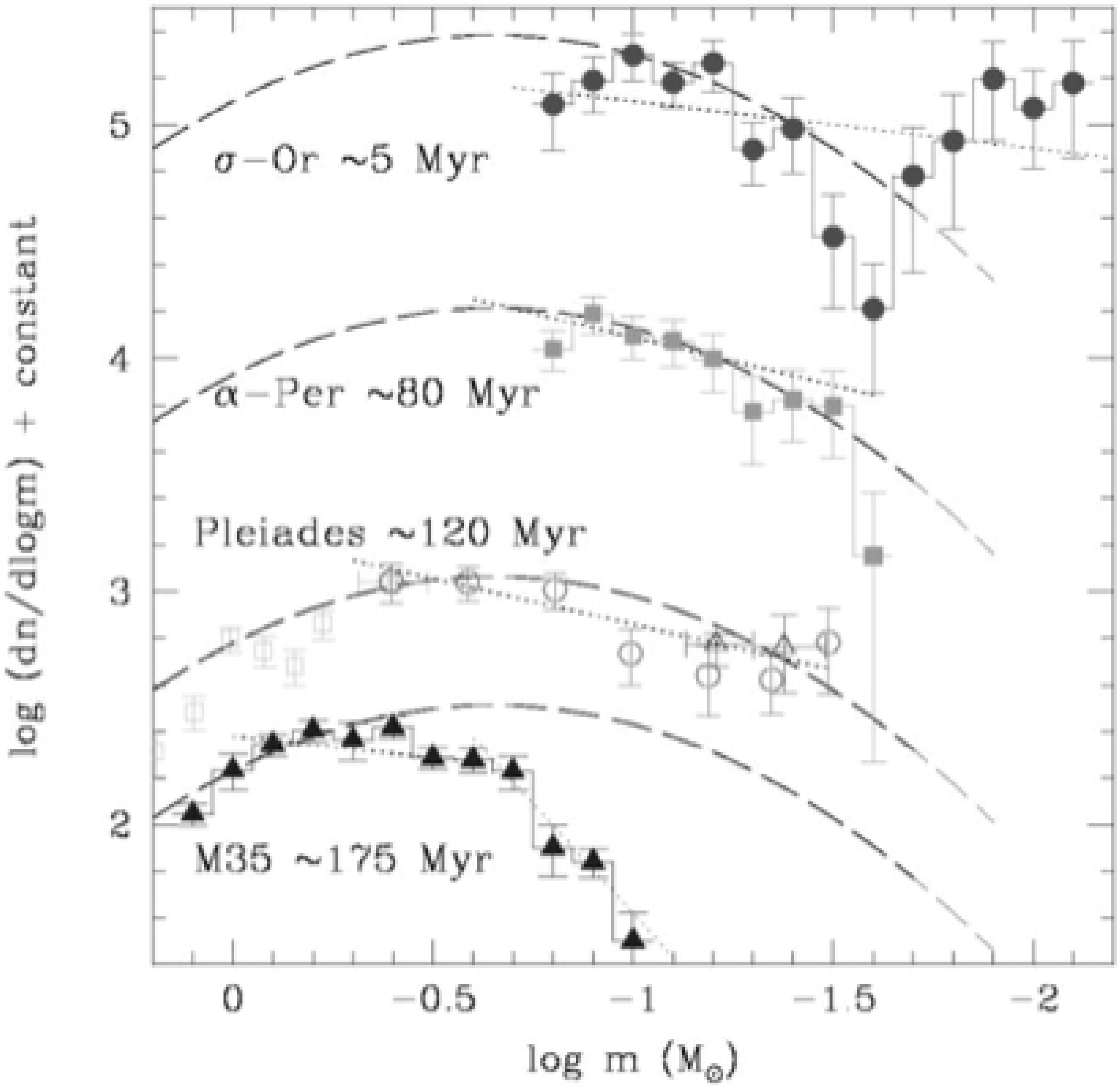


TABLE 1
Disk IMF and PDMF for Single Objects

Parameter	IMF	PDMF
$m \leq 1.0\ M_\odot$, $\xi(\log m) = A \exp\left[-(\log m - \log m_c)^2/2\sigma^2\right]$		
A	$0.158^{+0.051}_{-0.046}$	0.1
m_c	$0.079^{-0.016}_{+0.021}$	0.0
σ	$0.69^{-0.01}_{+0.05}$	0.6
$m > 1.0\ M_\odot$, $\xi(\log m) = Am^{-x}$		
A	4.43×10^{-2}	
x	1.3 ± 0.3	

(Chabrier 2003)

IMF: observations 3



comparison at low-mass end

(Chabrier 2003)

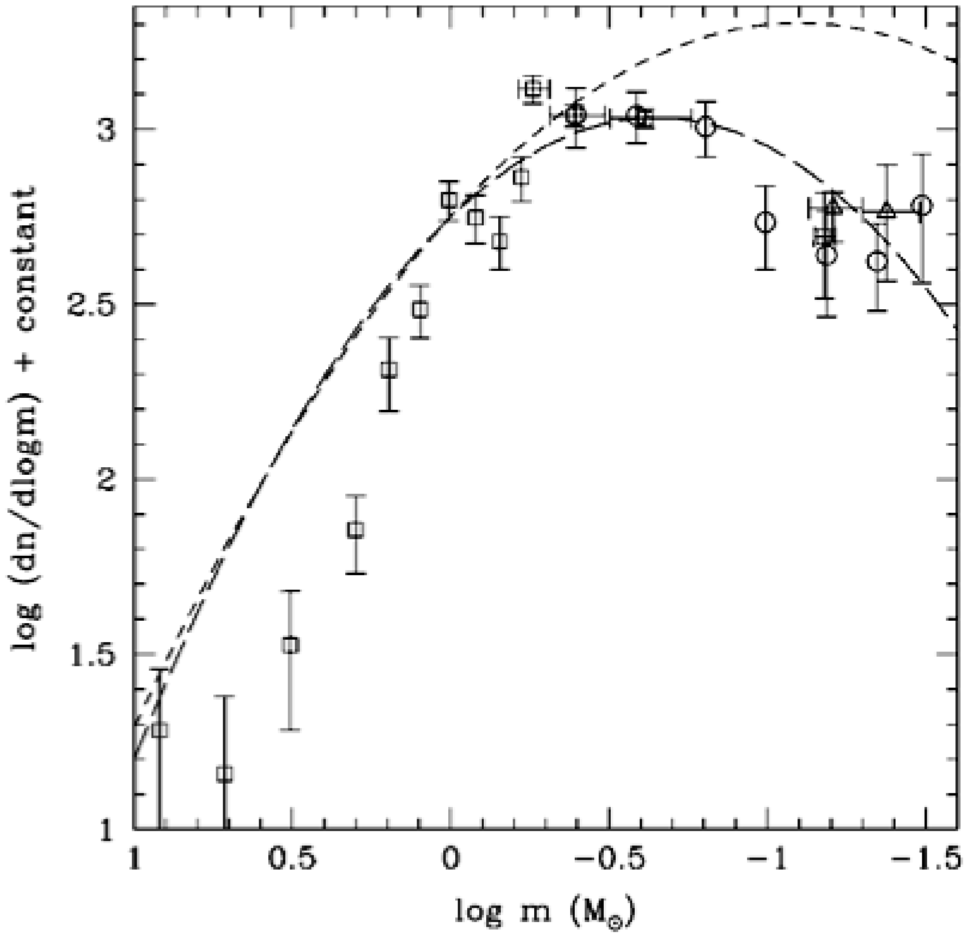


FIG. 4.—Pleiades mass function calculated with the BCAH98 and Chabrier et al. (2000a) MMRs from various observations. *Squares:* Hambly et al. (1999); *triangles:* Dobbie et al. (2002b); *circles:* Moraux et al. (2003). The short-dashed and long-dashed lines display the single (eq. [17]) and system (eq. [18]) field MFs, respectively, arbitrarily normalized to the present data.

system vs. single-star IMF

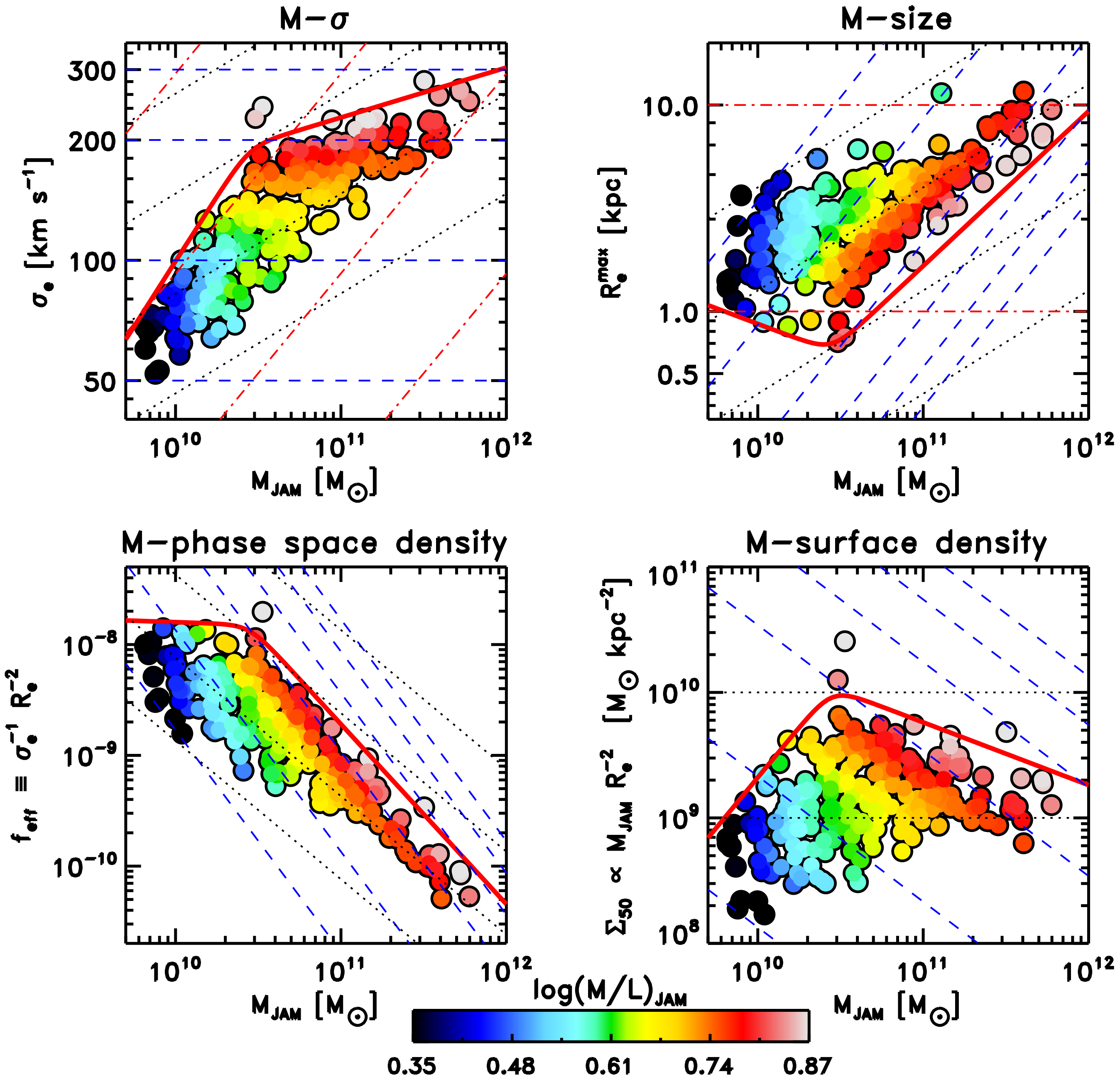
IMF: observations 4

BUT: maybe variations with galaxy type

(bottom heavy in the centers of large ellipticals)

from JAM (Jeans anisotropic multi Gaussian expansion) modeling

inferred excess of low-mass stars compared to Kroupa IMF



(Cappellari et al. 2012, Nature, 484, 485, Cappellari et al. 2012ab, MNRAS, submitted, also van Dokkum & Conroy 2010, Nature, 468, 940, Wegner et al. 2012, AJ, 144, 78, and others)

IMF: theoretical approach

- distribution of stellar masses depends on
  - turbulent initial conditions
    --> mass spectrum of prestellar cloud cores
  - collapse and interaction of prestellar cores
    --> competitive accretion and *N*-body effects
  - thermodynamic properties of gas
    --> balance between heating and cooling
    --> EOS (determines which cores go into collapse)
  - (proto) stellar feedback terminates star formation
    ionizing radiation, bipolar outflows, winds, SN

(e.g. Larson 2003, Prog. Rep. Phys.; Mac Low & Klessen, 2004, Rev. Mod. Phys, 76, 125 - 194)

IMF: theoretical approach

- distribution of stellar masses depends on
  - *turbulent initial conditions*
    --> mass spectrum of prestellar cloud cores ???
  - collapse and interaction of prestellar cores
    --> competitive accretion and *N*-body effects
  - thermodynamic properties of gas
    --> balance between heating and cooling
    --> EOS (determines which cores go into collapse)
  - (proto) stellar feedback terminates star formation
    ionizing radiation, bipolar outflows, winds, SN

(e.g. Larson 2003, Prog. Rep. Phys.; Mac Low & Klessen, 2004, Rev. Mod. Phys, 76, 125 - 194)

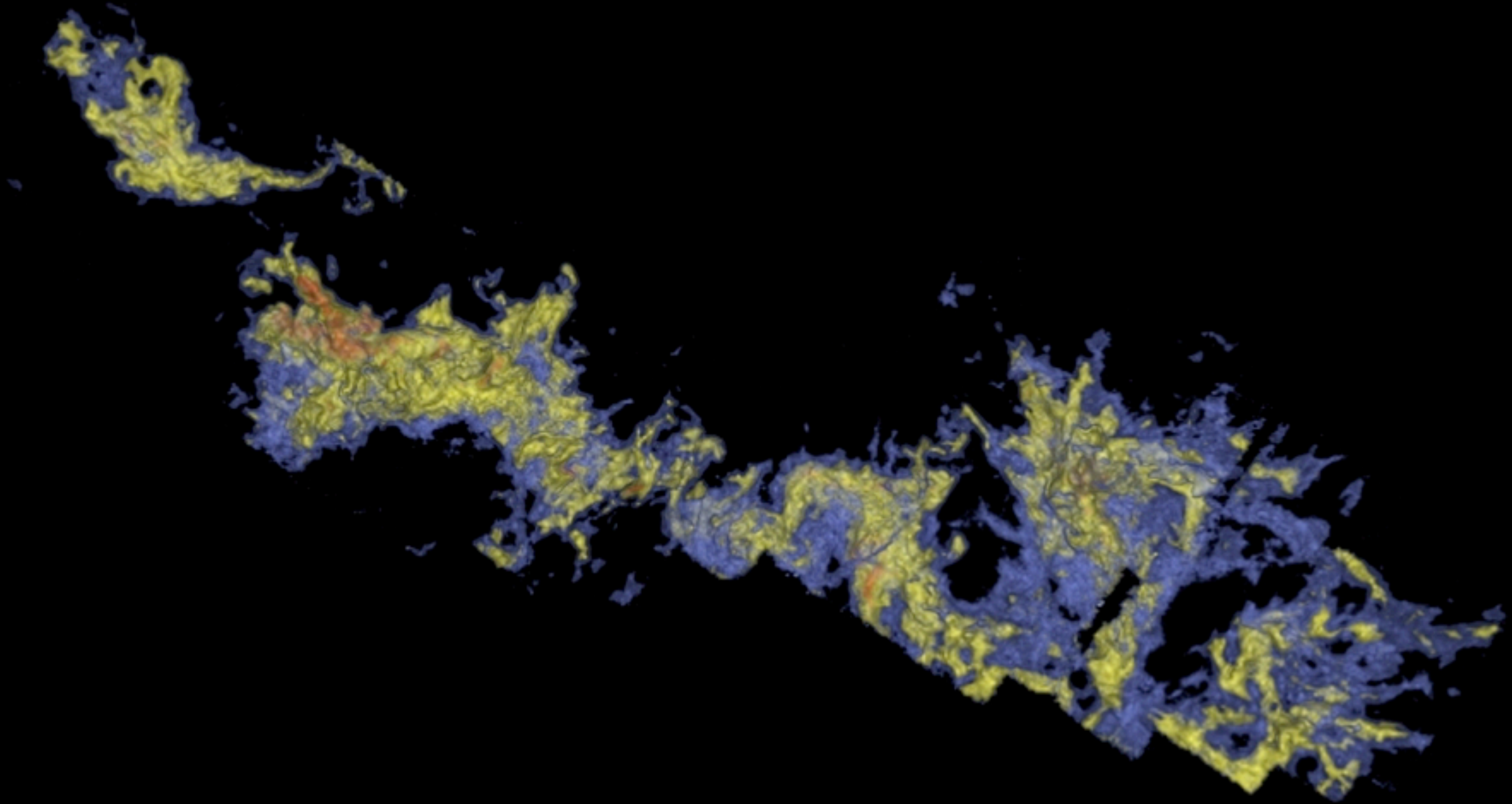
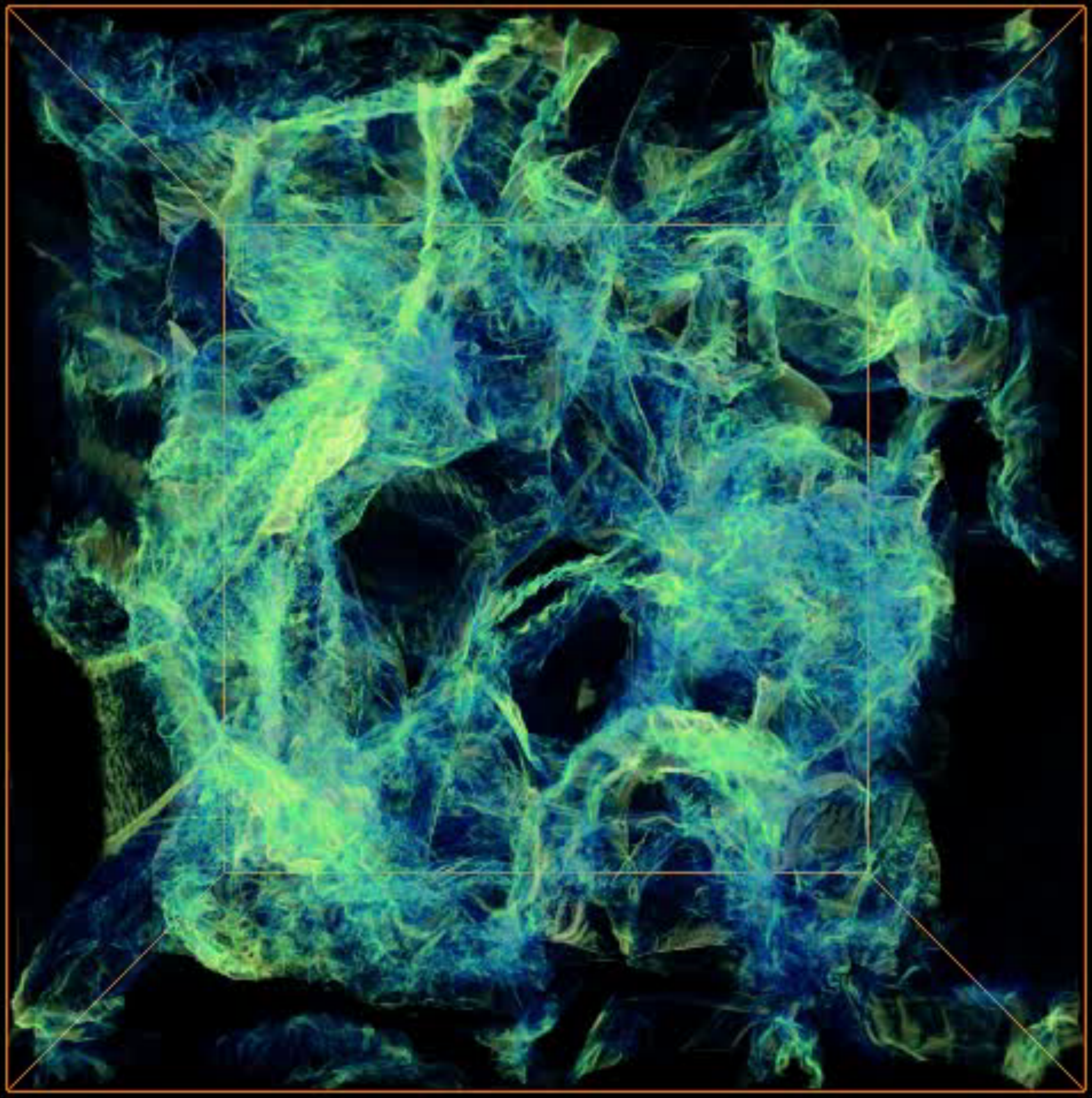
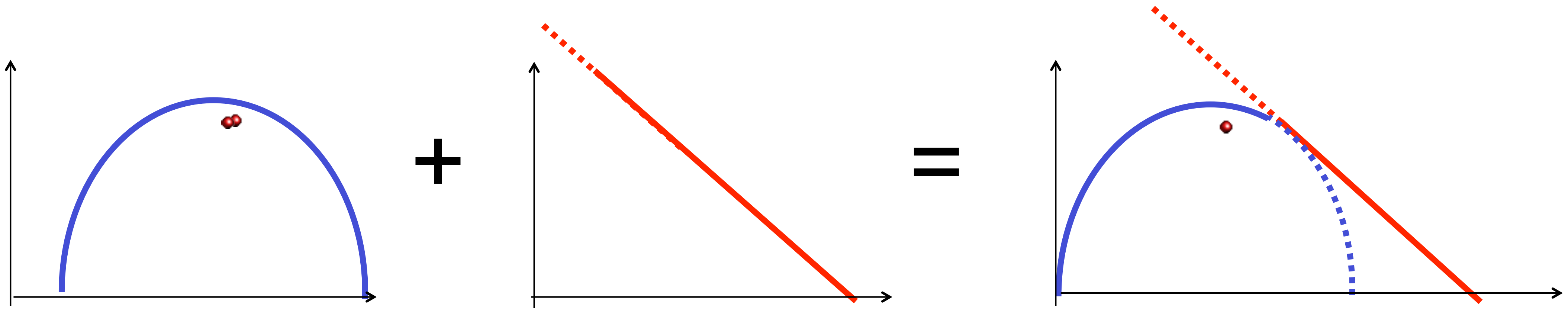


image from Alyssa Goodman: COMPLETE survey



Schmidt et al. (2009, A&A, 494, 127)

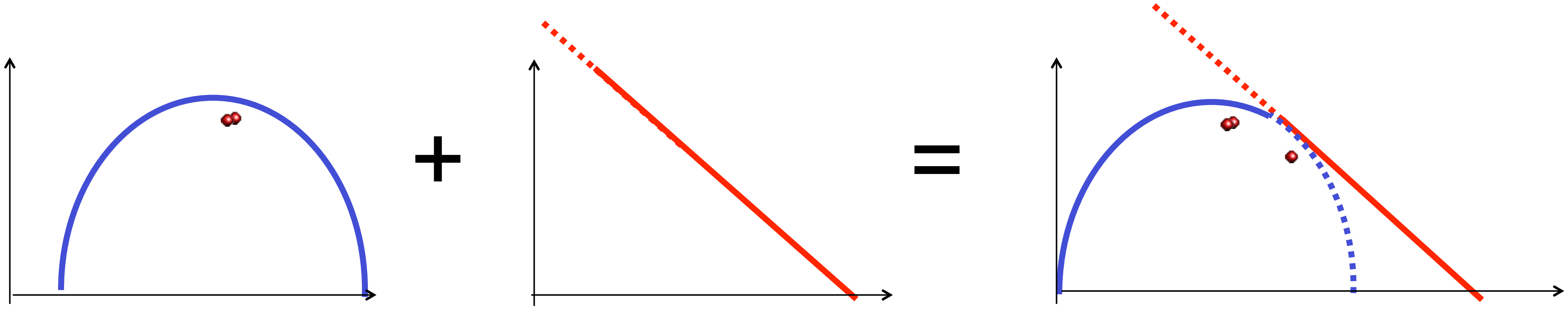
caveat: everybody gets the IMF!



- combine scale free process → *POWER LAW BEHAVIOR*
  - turbulence (Padoan & Nordlund 2002, Hennebelle & Chabrier 2008)
  - gravity in dense clusters (Bonnell & Bate 2006, Klessen 2001)
  - universality: dust-induced EOS kink insensitive to radiation field (Elmegreen et al. 2008)

- with highly stochastic processes → central limit theorem
  → *GAUSSIAN DISTRIBUTION*
  - basically mean thermal Jeans length (or feedback)
  - universality: insensitive to metallicity (Clark et al. 2009, submitted)

caveat: everybody gets the IMF!



“everyone” gets the right IMF
→ better look for secondary indicators

- *stellar multiplicity*
- protostellar *spin* (including disk)
- *spatial distribution* + *kinematics* in young clusters
- *magnetic field strength* and *orientation*

IMF

- distribution of stellar masses depends on
  - turbulent initial conditions
    --> mass spectrum of prestellar cloud cores
  - collapse and interaction of prestellar cores
    --> competitive mass growth and *N*-body effects
  - thermodynamic properties of gas
    --> balance between heating and cooling
    --> EOS (determines which cores go into collapse)
  - (proto) stellar feedback terminates star formation
    ionizing radiation, bipolar outflows, winds, SN

(e.g. Larson 2003, Prog. Rep. Phys.; Mac Low & Klessen, 2004, Rev. Mod. Phys, 76, 125 - 194)

example: model of Orion cloud

„model“ of Orion cloud:
15.000.000 SPH particles,
10^4 M_{sun} in 10 pc, mass resolution 0,02 M_{sun}, forms ~2.500 „stars“ (sink particles)

isothermal EOS, top bound, bottom unbound

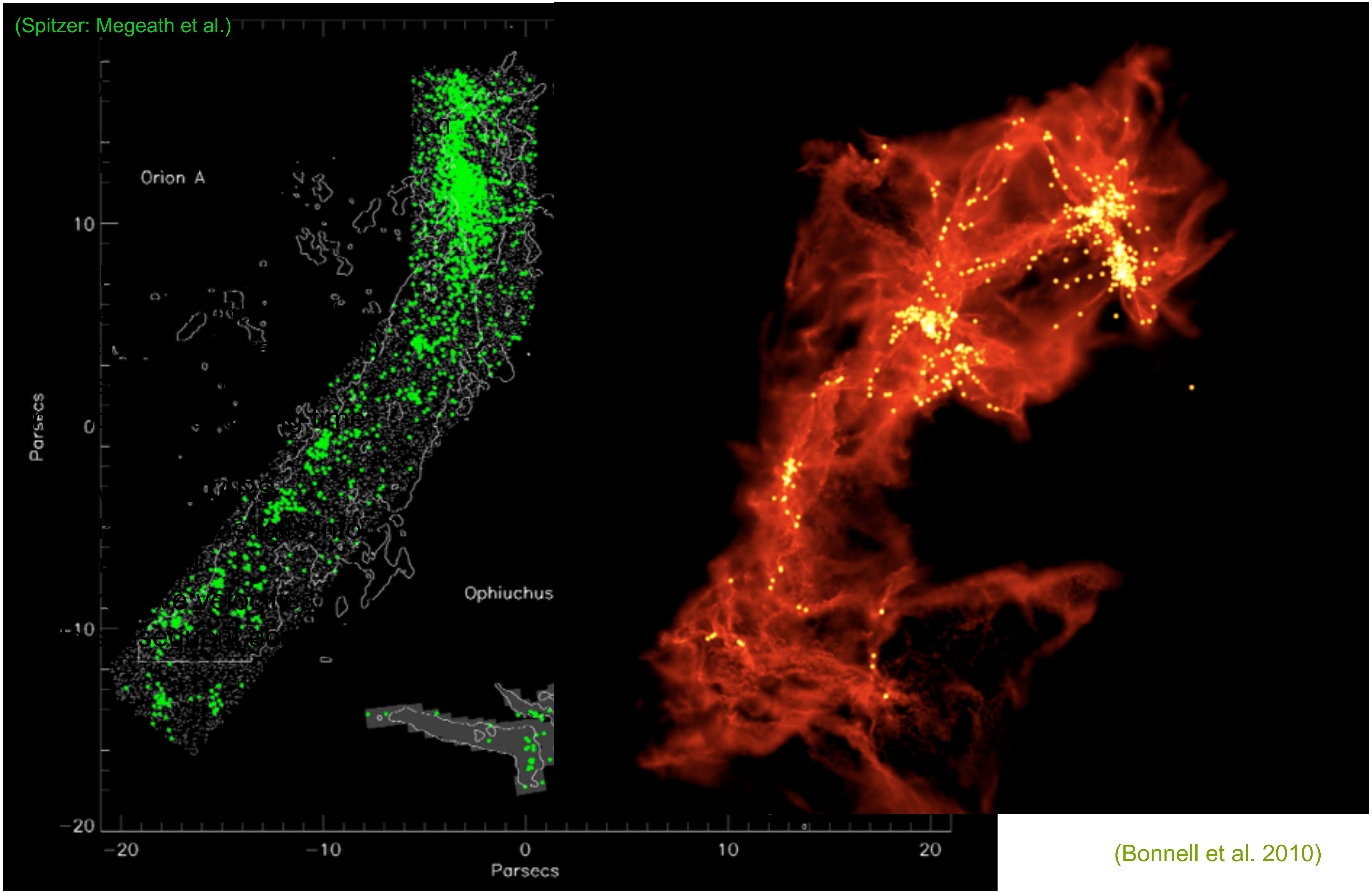
has clustered as well as distributed „star“ formation

efficiency varies from 1% to 20%

develops full IMF
(distribution of sink particle masses)

(Bonnell, Smith, Clark, & Bate 2010, MNRAS, 410, 2339)

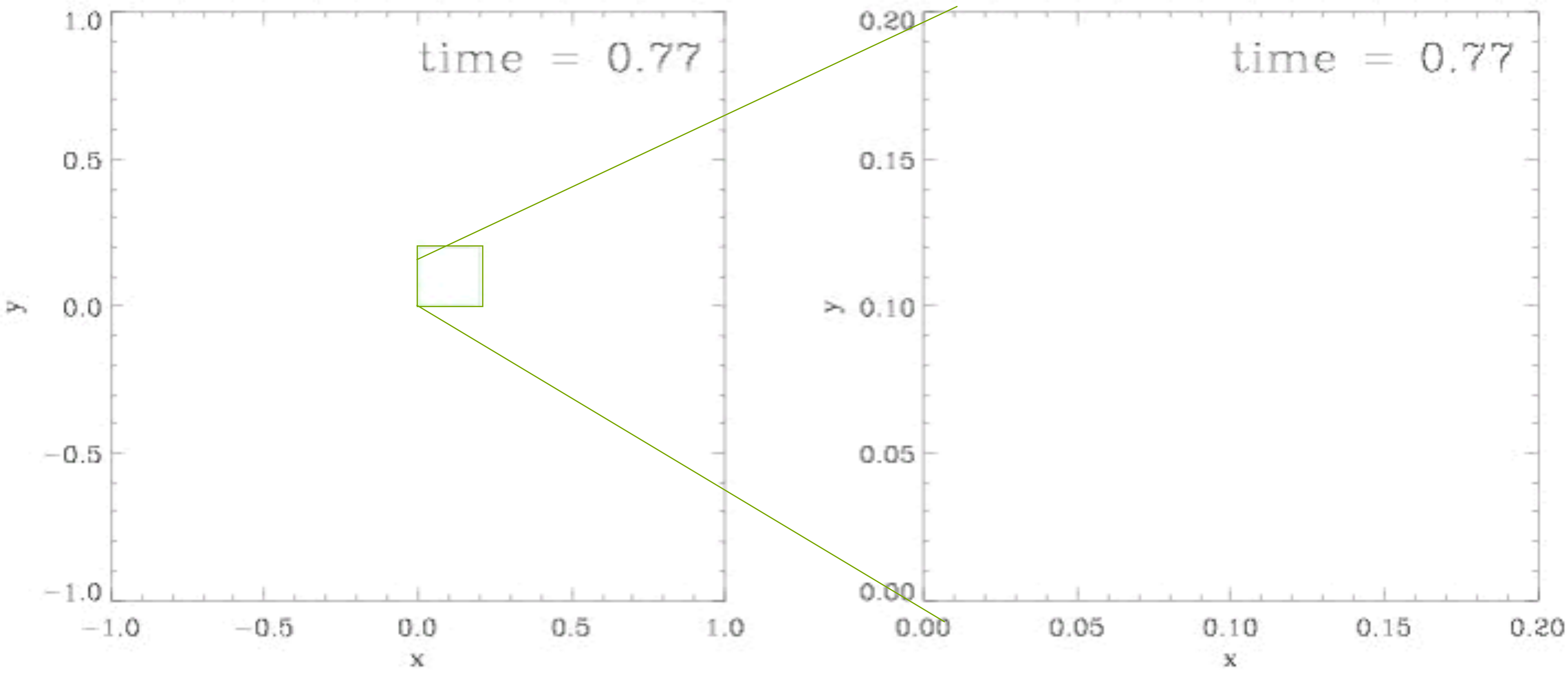
example: model of Orion cloud



(Bonnell et al. 2010)

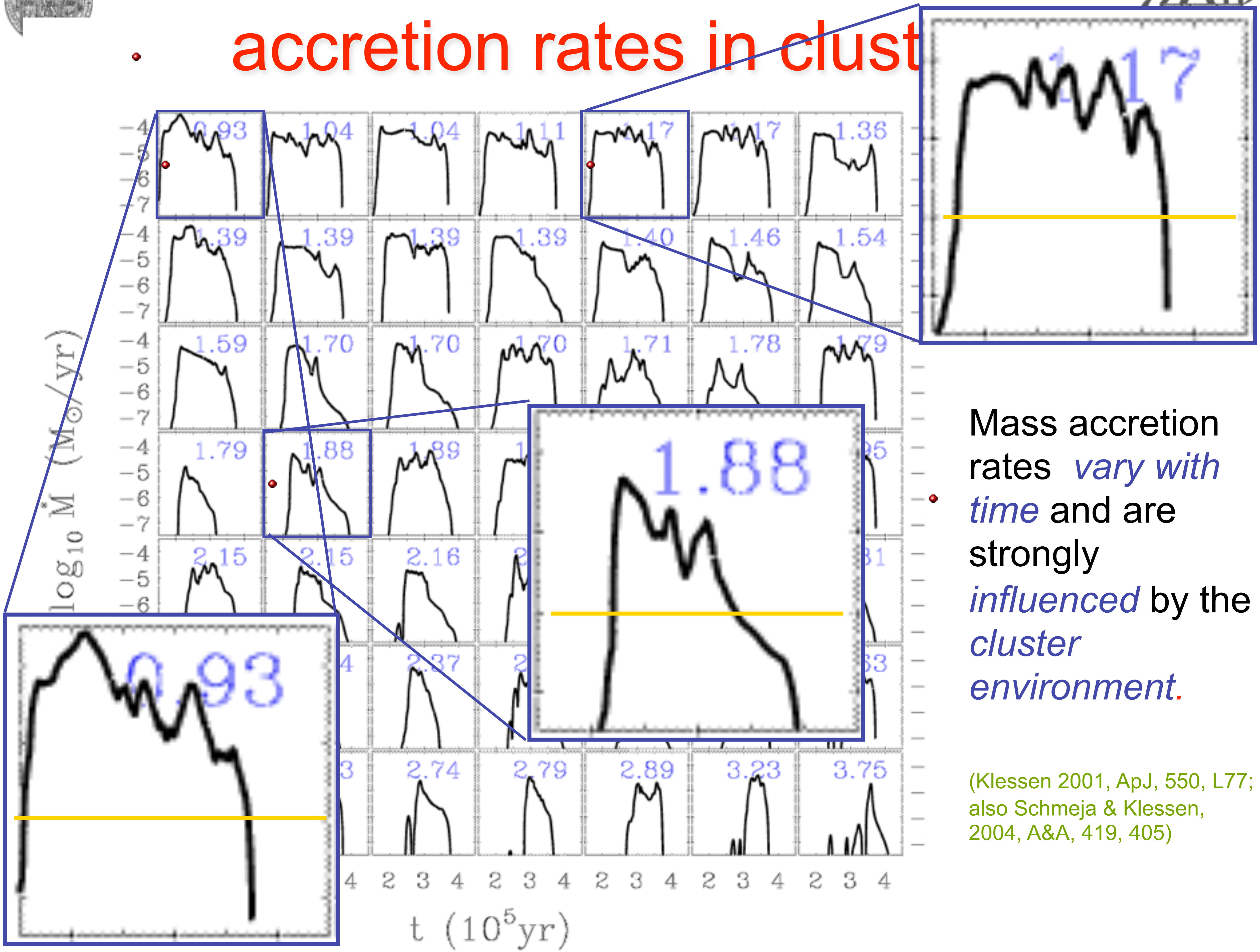
dynamics of nascent star cluster

in dense clusters protostellar interaction may be come important!



Trajectories of protostars in a nascent dense cluster created by gravoturbulent fragmentation
(from Klessen & Burkert 2000, ApJS, 128, 287)

accretion rates in clust



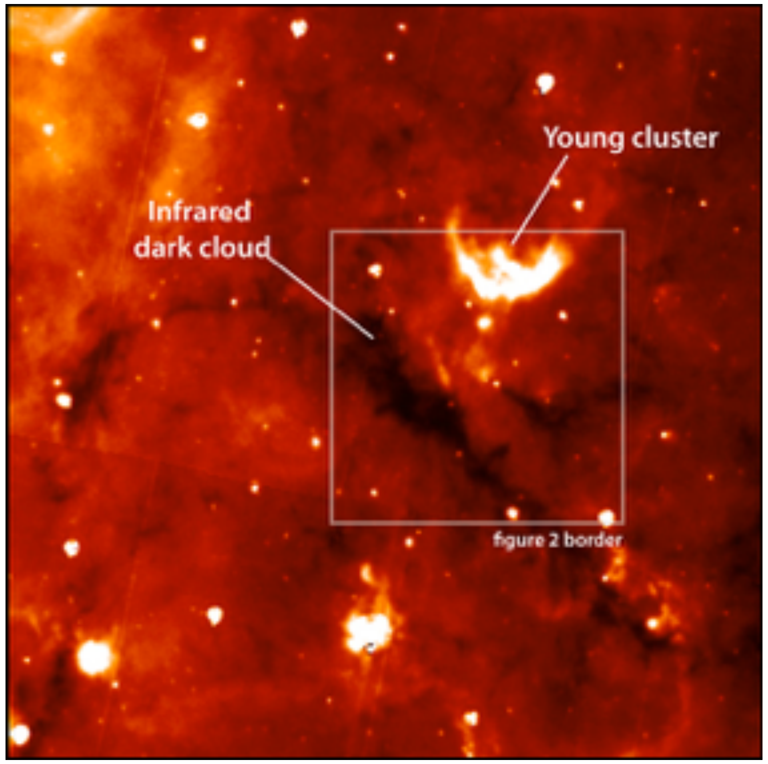
- Mass accretion rates *vary with time* and are strongly *influenced* by the *cluster environment*.

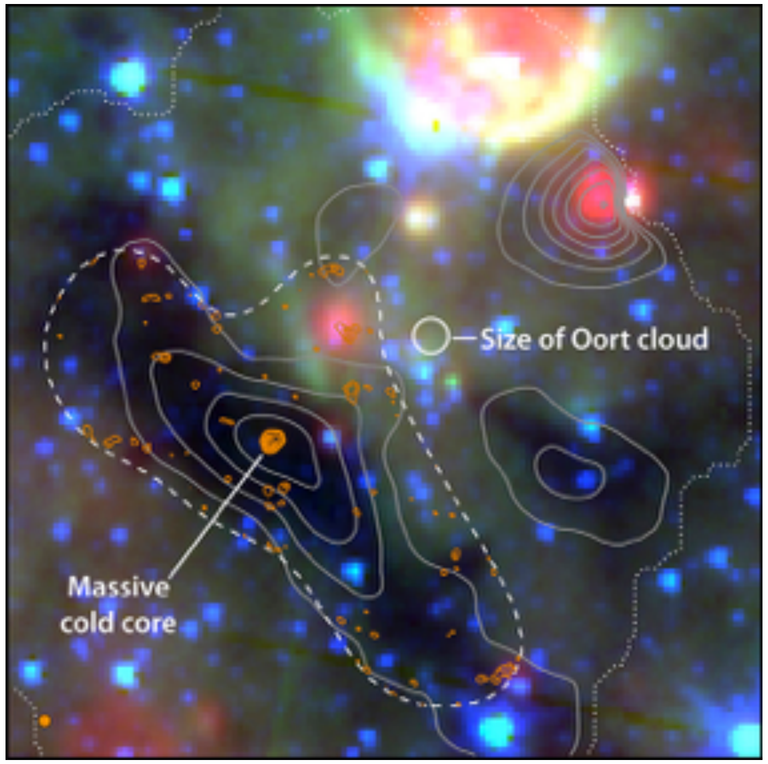
(Klessen 2001, ApJ, 550, L77; also Schmeja & Klessen, 2004, A&A, 419, 405)

initial conditions for cluster formation

ICs of star cluster formation

- key question:
  - what is the initial density profile of cluster forming cores? how does it compare low-mass cores?
- observers answer:
  - very difficult to determine!
    - most high-mass cores have some SF inside
    - infra-red dark clouds (IRDCs) are difficult to study
  - but, new results with Herschel

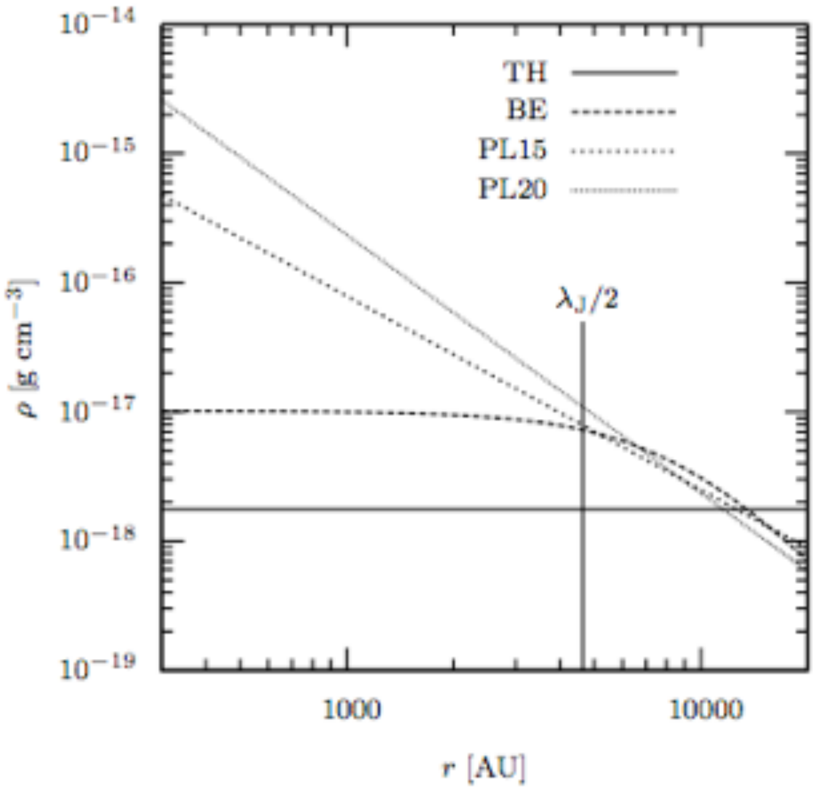




IRDC near Aquila rift, studied with the SMA: J. Swift & E. Churchwell

ICs of star cluster formation

- key question:
  - what is the initial density profile of cluster forming cores? how does it compare low-mass cores?
- theorists answer:
  - top hat (Larson Penston)
  - Bonnor Ebert (like low-mass cores)
  - power law $\rho \propto r^{-1}$ (logotrop)
  - power law $\rho \propto r^{-3/2}$ (Krumholz, McKee, et
  - power law $\rho \propto r^{-2}$ (Shu)
  - and many more



different density profiles

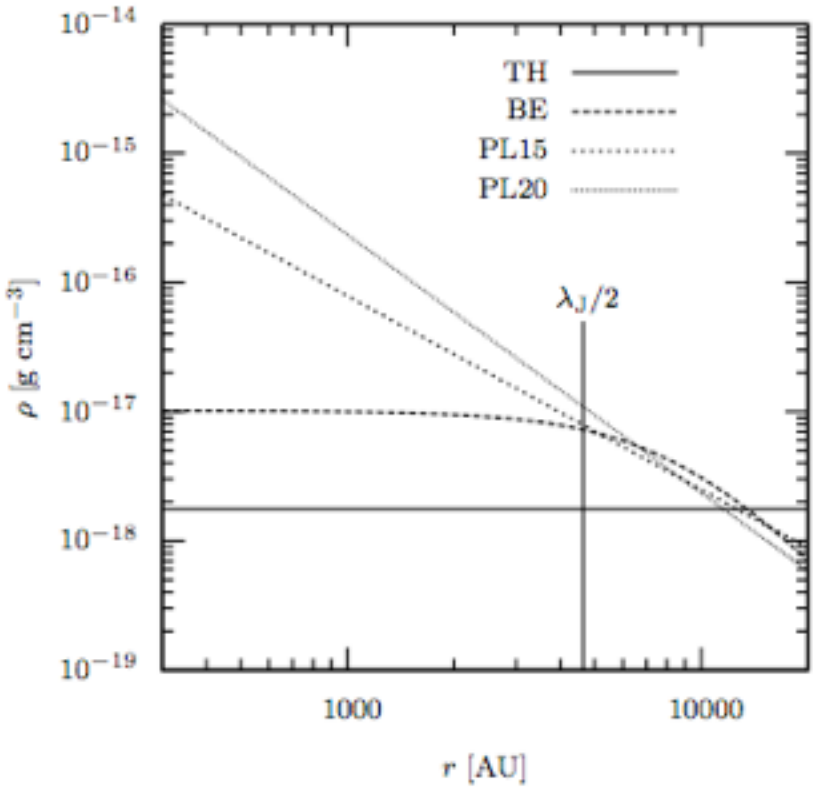
- does the density profile matter?

  .

  .

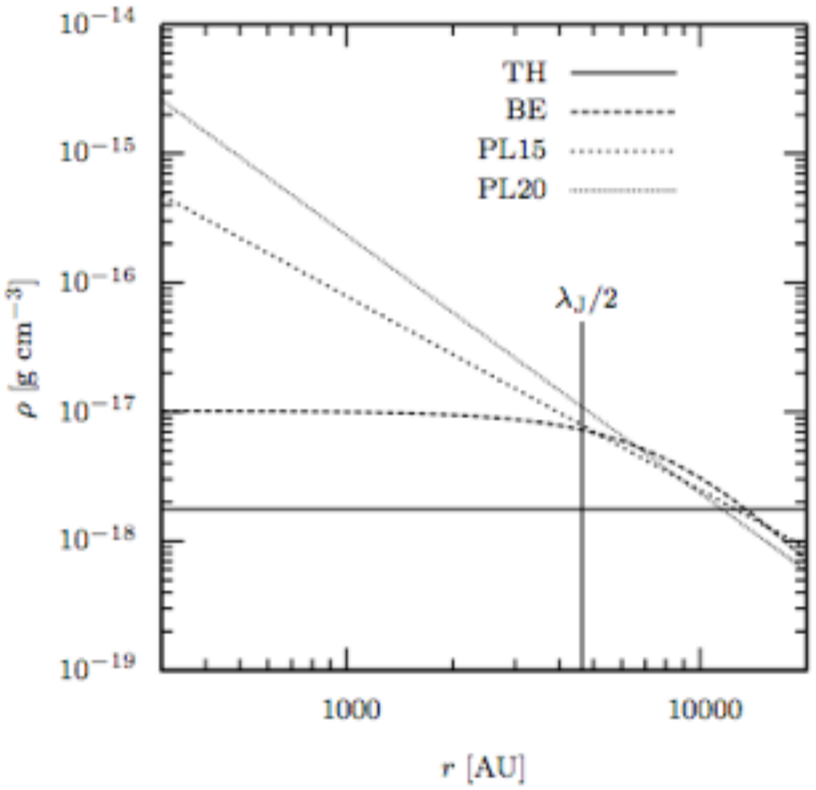
  .

- in comparison to
  - turbulence ...
  - radiative feedback ...
  - magnetic fields ...
  - thermodynamics ...

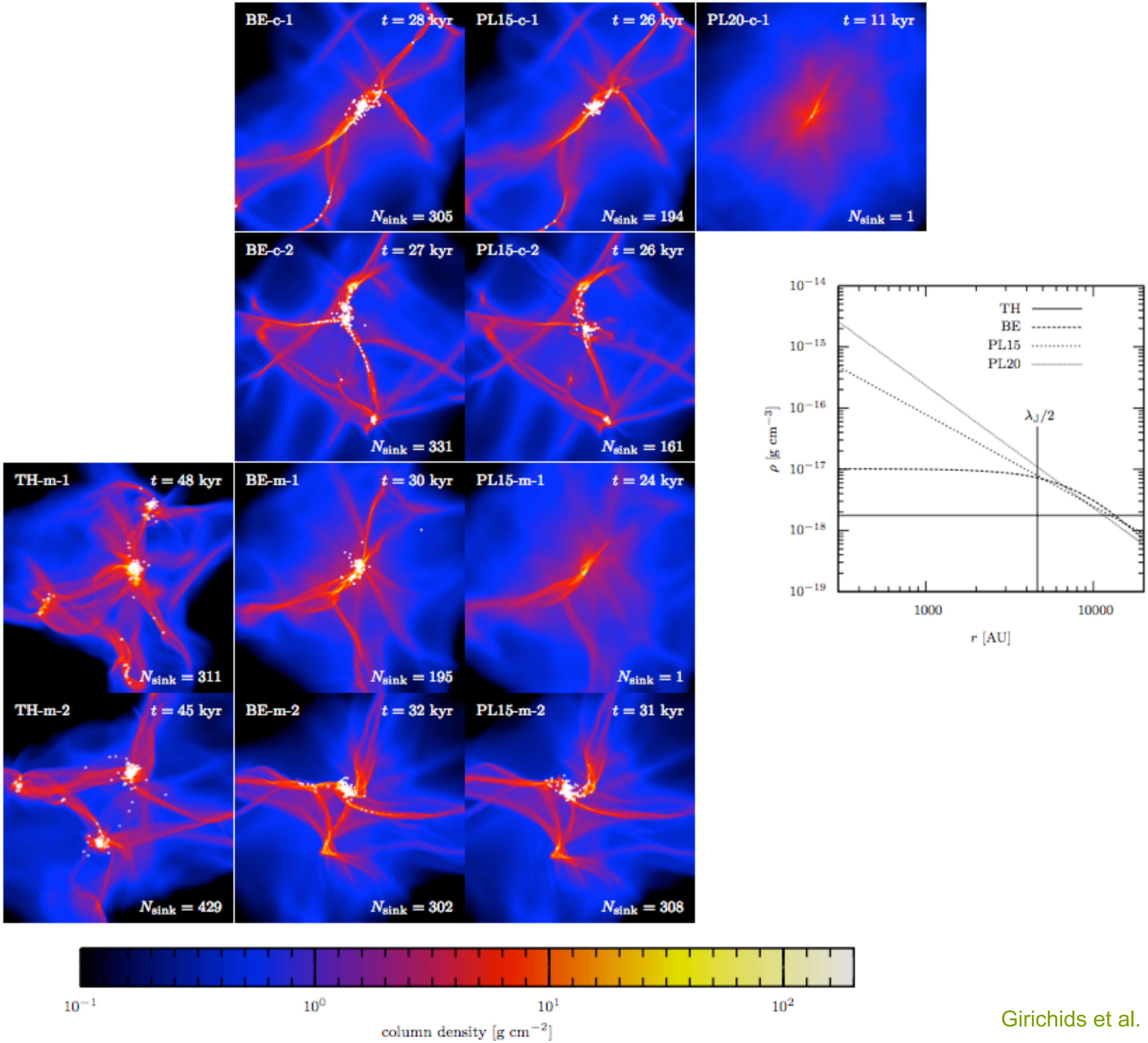


different density profiles

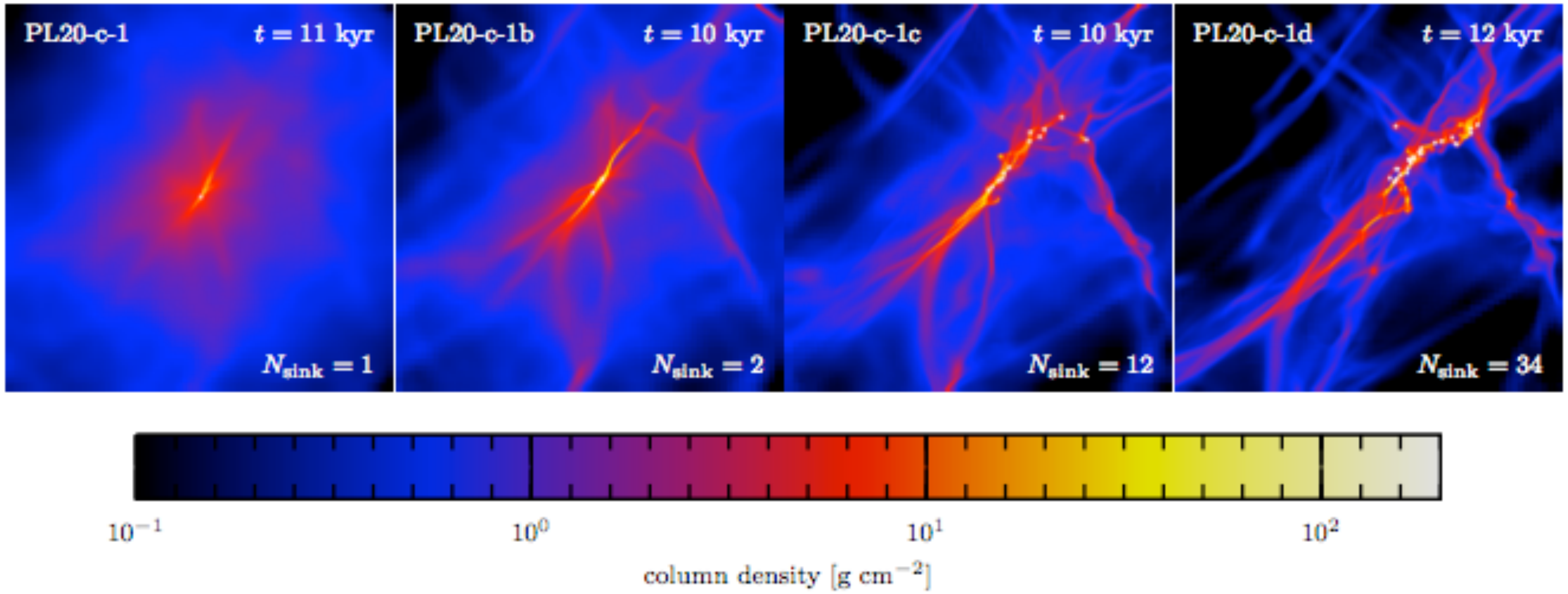
- address question in simple numerical experiment
- perform extensive parameter study
  - different profiles (top hat, BE, $r^{-3/2}$, r^{-3})
  - different turbulence fields
    - different realizations
    - different Mach numbers
    - solenoidal turbulence
dilatational turbulence
both modes
  - no net rotation, no B-fields (at the moment)



Girichids, Federrath, Banerjee, Klessen (2011abc)



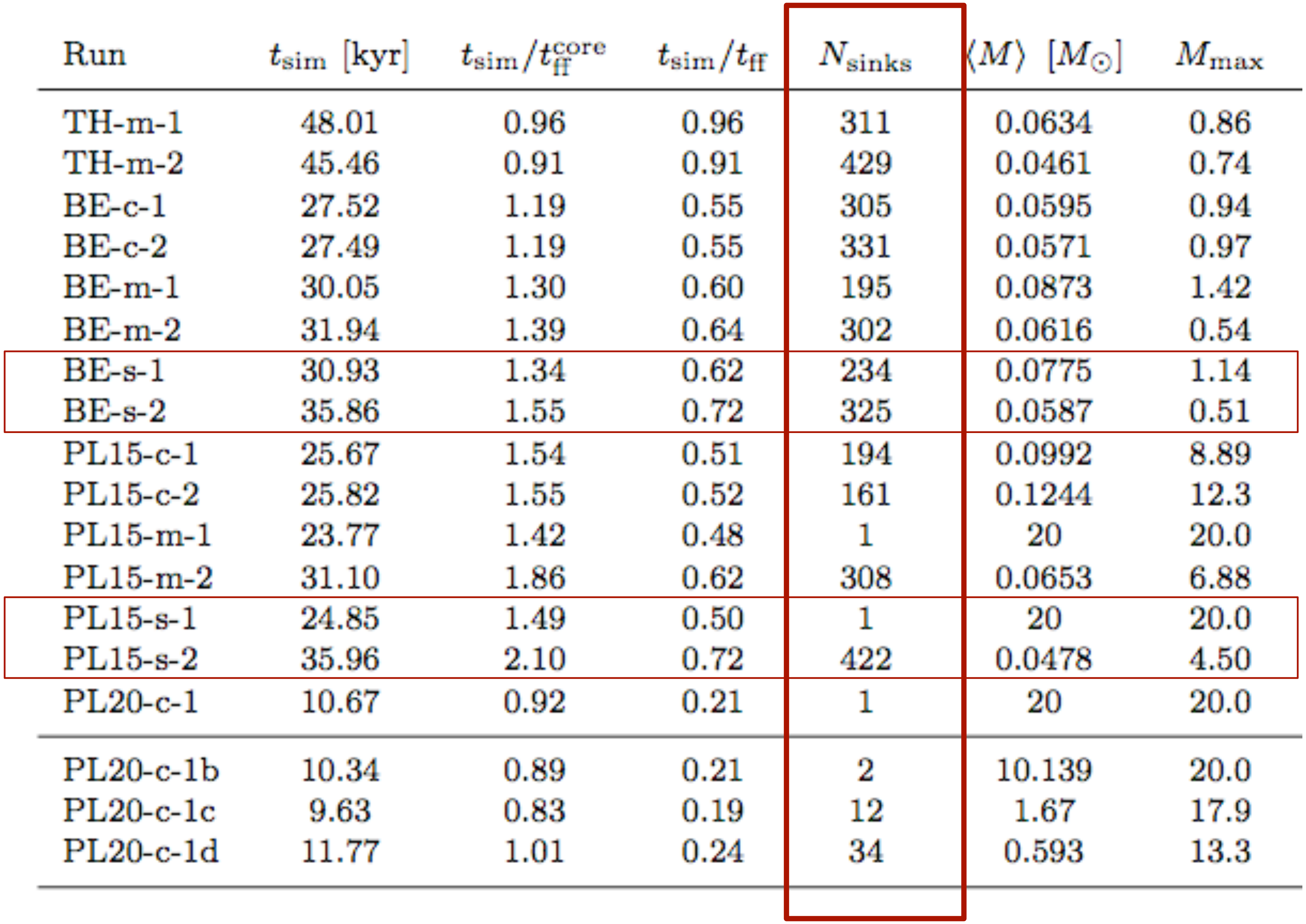
Girichids et al. (2011abc)



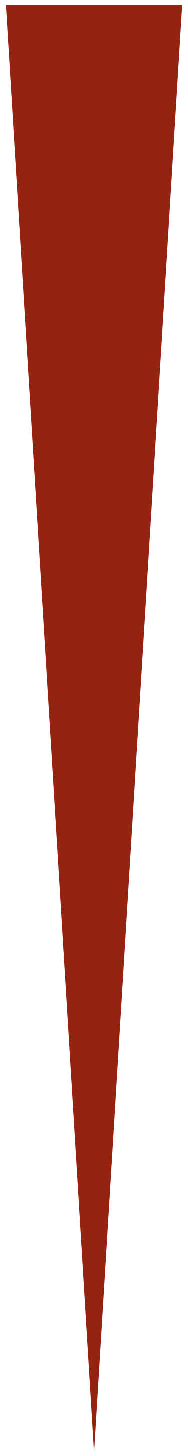
M=3 M=6 M=12 M=18

for the r^{-2} profile you need to crank up turbulence a lot to get some fragmentation!

Girichids et al. (2011abc)



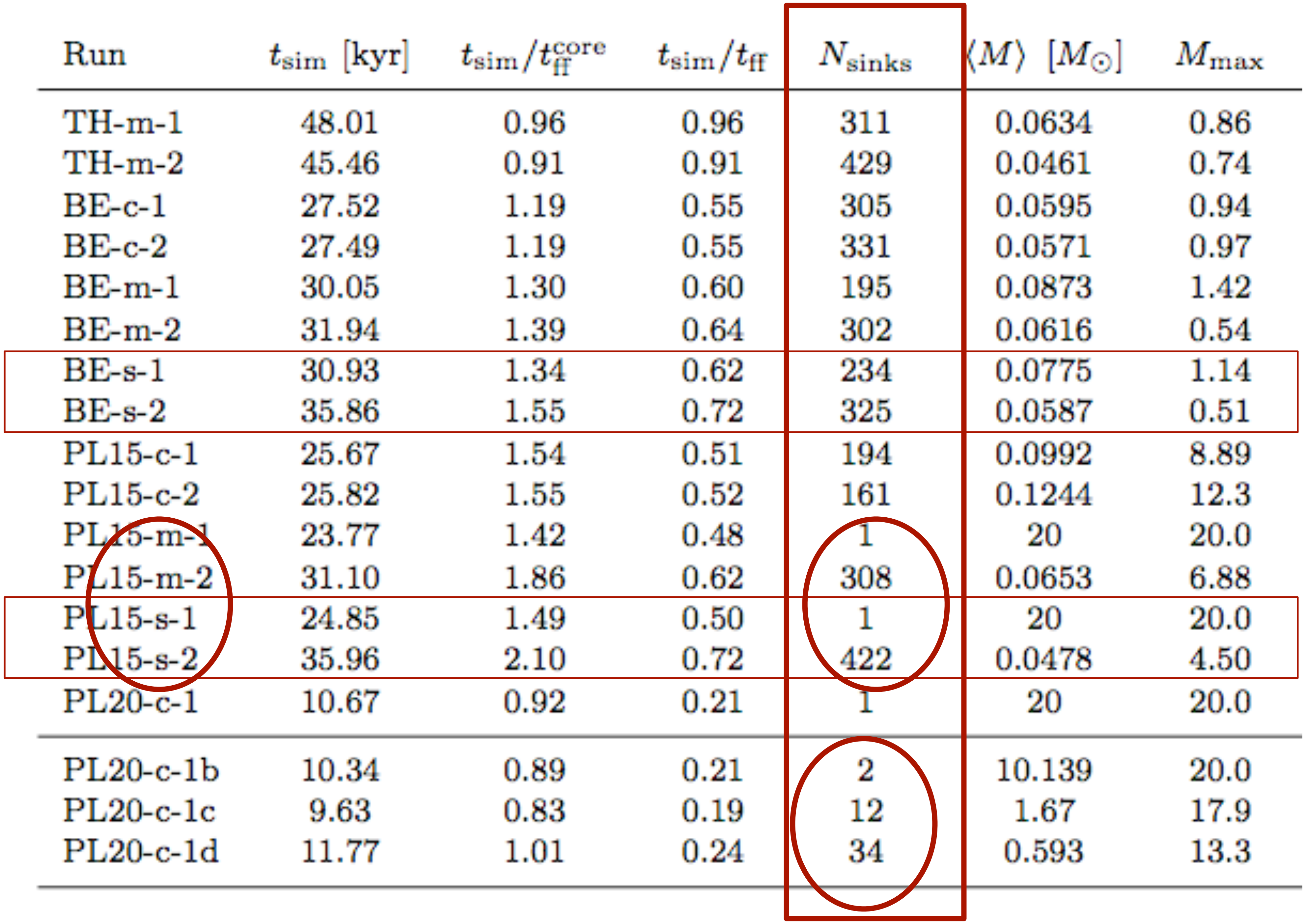
Run	t_{sim} [kyr]	$t_{\mathrm{sim}}/t_{\mathrm{ff}}^{\mathrm{core}}$	$t_{\mathrm{sim}}/t_{\mathrm{ff}}$	N_{sinks}	$\langle M \rangle$ [$M_\odot$]	M_{max}
TH-m-1	48.01	0.96	0.96	311	0.0634	0.86
TH-m-2	45.46	0.91	0.91	429	0.0461	0.74
BE-c-1	27.52	1.19	0.55	305	0.0595	0.94
BE-c-2	27.49	1.19	0.55	331	0.0571	0.97
BE-m-1	30.05	1.30	0.60	195	0.0873	1.42
BE-m-2	31.94	1.39	0.64	302	0.0616	0.54
BE-s-1	30.93	1.34	0.62	234	0.0775	1.14
BE-s-2	35.86	1.55	0.72	325	0.0587	0.51
PL15-c-1	25.67	1.54	0.51	194	0.0992	8.89
PL15-c-2	25.82	1.55	0.52	161	0.1244	12.3
PL15-m-1	23.77	1.42	0.48	1	20	20.0
PL15-m-2	31.10	1.86	0.62	308	0.0653	6.88
PL15-s-1	24.85	1.49	0.50	1	20	20.0
PL15-s-2	35.96	2.10	0.72	422	0.0478	4.50
PL20-c-1	10.67	0.92	0.21	1	20	20.0
PL20-c-1b	10.34	0.89	0.21	2	10.139	20.0
PL20-c-1c	9.63	0.83	0.19	12	1.67	17.9
PL20-c-1d	11.77	1.01	0.24	34	0.593	13.3



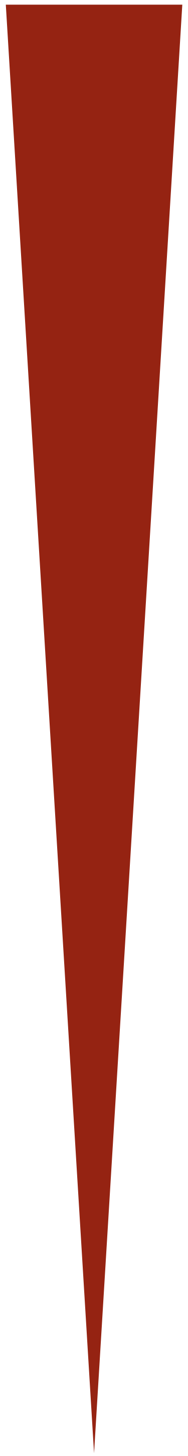
number of protostars

ICs with flat inner density profile form more fragments

Girichids et al. (2011abc)



Run	$t_{\rm sim}$ [kyr]	$t_{\rm sim}/t_{\rm ff}^{\rm core}$	$t_{\rm sim}/t_{\rm ff}$	$N_{\rm sinks}$	$\langle M \rangle$ [$M_\odot$]	$M_{\rm max}$
TH-m-1	48.01	0.96	0.96	311	0.0634	0.86
TH-m-2	45.46	0.91	0.91	429	0.0461	0.74
BE-c-1	27.52	1.19	0.55	305	0.0595	0.94
BE-c-2	27.49	1.19	0.55	331	0.0571	0.97
BE-m-1	30.05	1.30	0.60	195	0.0873	1.42
BE-m-2	31.94	1.39	0.64	302	0.0616	0.54
BE-s-1	30.93	1.34	0.62	234	0.0775	1.14
BE-s-2	35.86	1.55	0.72	325	0.0587	0.51
PL15-c-1	25.67	1.54	0.51	194	0.0992	8.89
PL15-c-2	25.82	1.55	0.52	161	0.1244	12.3
PL15-m-1	23.77	1.42	0.48	1	20	20.0
PL15-m-2	31.10	1.86	0.62	308	0.0653	6.88
PL15-s-1	24.85	1.49	0.50	1	20	20.0
PL15-s-2	35.96	2.10	0.72	422	0.0478	4.50
PL20-c-1	10.67	0.92	0.21	1	20	20.0
PL20-c-1b	10.34	0.89	0.21	2	10.139	20.0
PL20-c-1c	9.63	0.83	0.19	12	1.67	17.9
PL20-c-1d	11.77	1.01	0.24	34	0.593	13.3



number of protostars

however, the real situation is very complex: details of the initial turbulent field matter

very high Mach numbers are needed to make SIS fragment

Girichids et al. (2011abc)

different density profiles

- different density profiles lead to very different fragmentation behavior
- fragmentation is strongly suppressed for very peaked, power-law profiles

- this is *good*, because it may explain some of the theoretical controversy, we have in the field
- this is *bad*, because all current calculations are “wrong” in the sense that the formation process of the star-forming core is neglected.

Girichids et al. (2011abc)

IMF

- distribution of stellar masses depends on
  - turbulent initial conditions
    --> mass spectrum of prestellar cloud cores
  - collapse and interaction of prestellar cores
    --> competitive accretion and *N*-body effects
  - *thermodynamic properties of gas*
    --> balance between heating and cooling
    --> EOS (determines which cores go into collapse)
  - (proto) stellar feedback terminates star formation
    ionizing radiation, bipolar outflows, winds, SN

(e.g. Larson 2003, Prog. Rep. Phys.; Mac Low & Klessen, 2004, Rev. Mod. Phys, 76, 125 - 194)

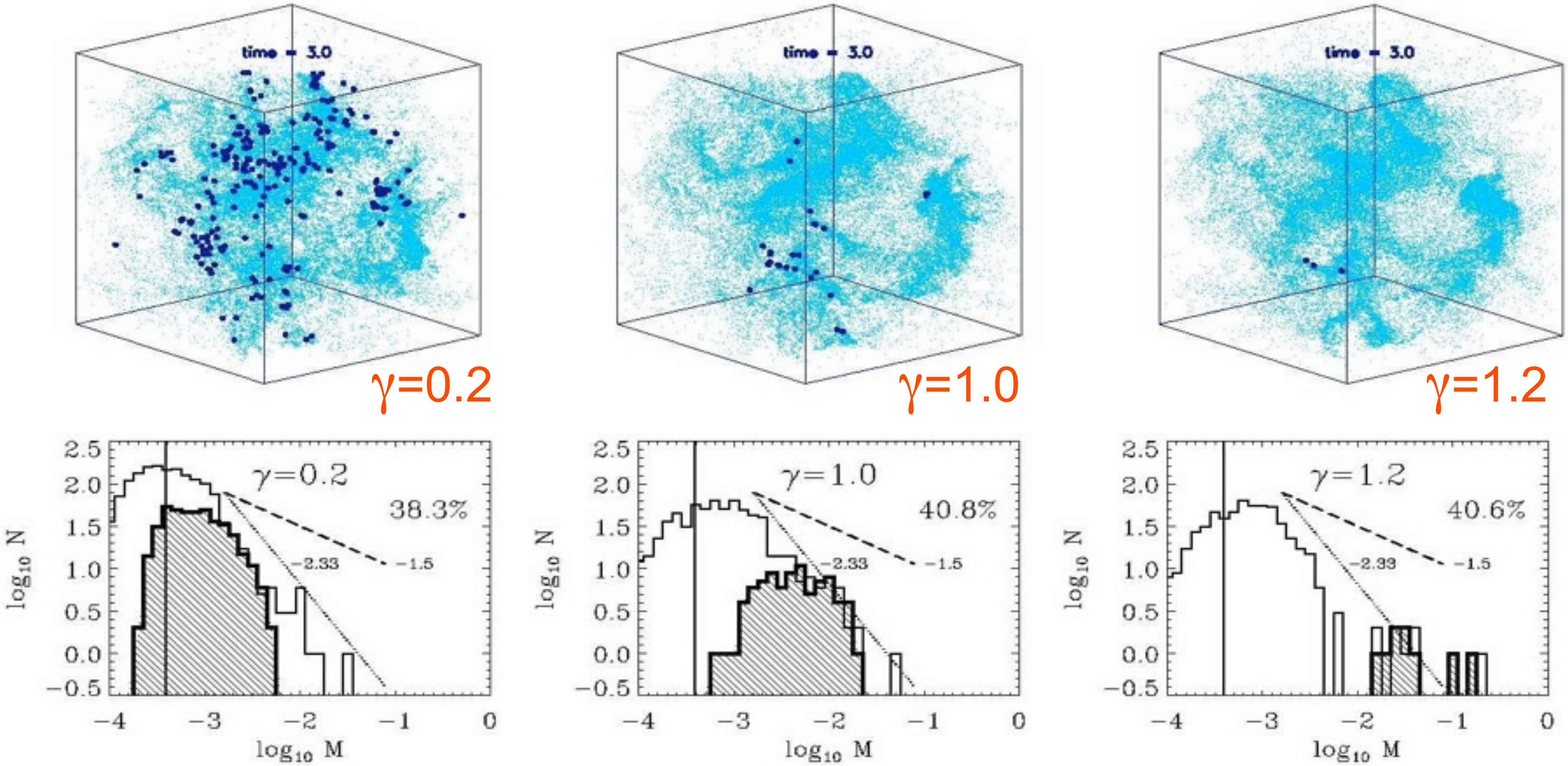
NOT IN ACTUAL TALK

dependency on EOS

- degree of fragmentation depends on *EOS!*
- polytropic EOS: $\mathbf{p} \propto \rho^{\gamma}$
- $\gamma<1$: dense cluster of low-mass stars
- $\gamma>1$: isolated high-mass stars
- (see Li, Klessen, & Mac Low 2003, ApJ, 592, 975; also Kawachi & Hanawa 1998, Larson 2003)

NOT IN ACTUAL TALK

dependency on EOS



for $\gamma<1$ fragmentation is enhanced → *cluster of low-mass stars*

for $\gamma>1$ it is suppressed → formation of *isolated massive stars*

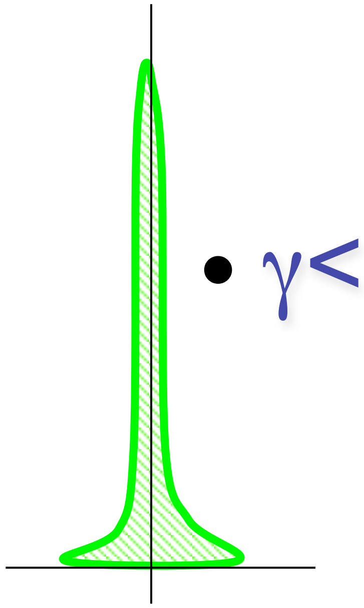
(from Li, Klessen, & Mac Low 2003, ApJ, 592, 975)

NOT IN ACTUAL TALK

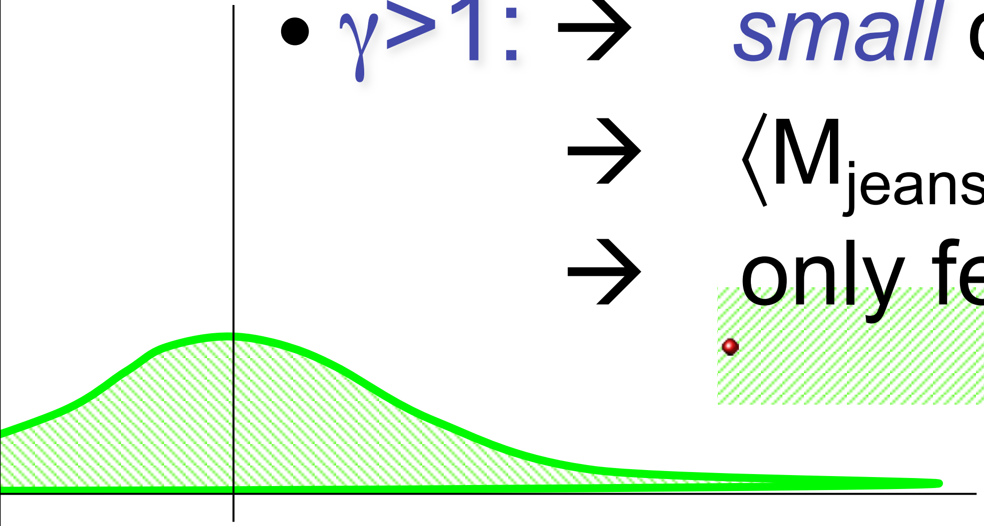
how does that work?

(1) $\mathbf{p} \propto \rho^{\gamma}$ → $\rho \propto \mathbf{p}^{1/\gamma}$

(2) $\mathbf{M}_{\mathbf{jeans}} \propto \gamma^{3/2} \rho^{(3\gamma-4)/2}$



- $\gamma<1$: → *large* density excursion for given pressure
  → $\langle M_{\mathrm{jeans}} \rangle$ becomes small
  → number of fluctuations with $M > M_{\mathrm{jeans}}$ is large



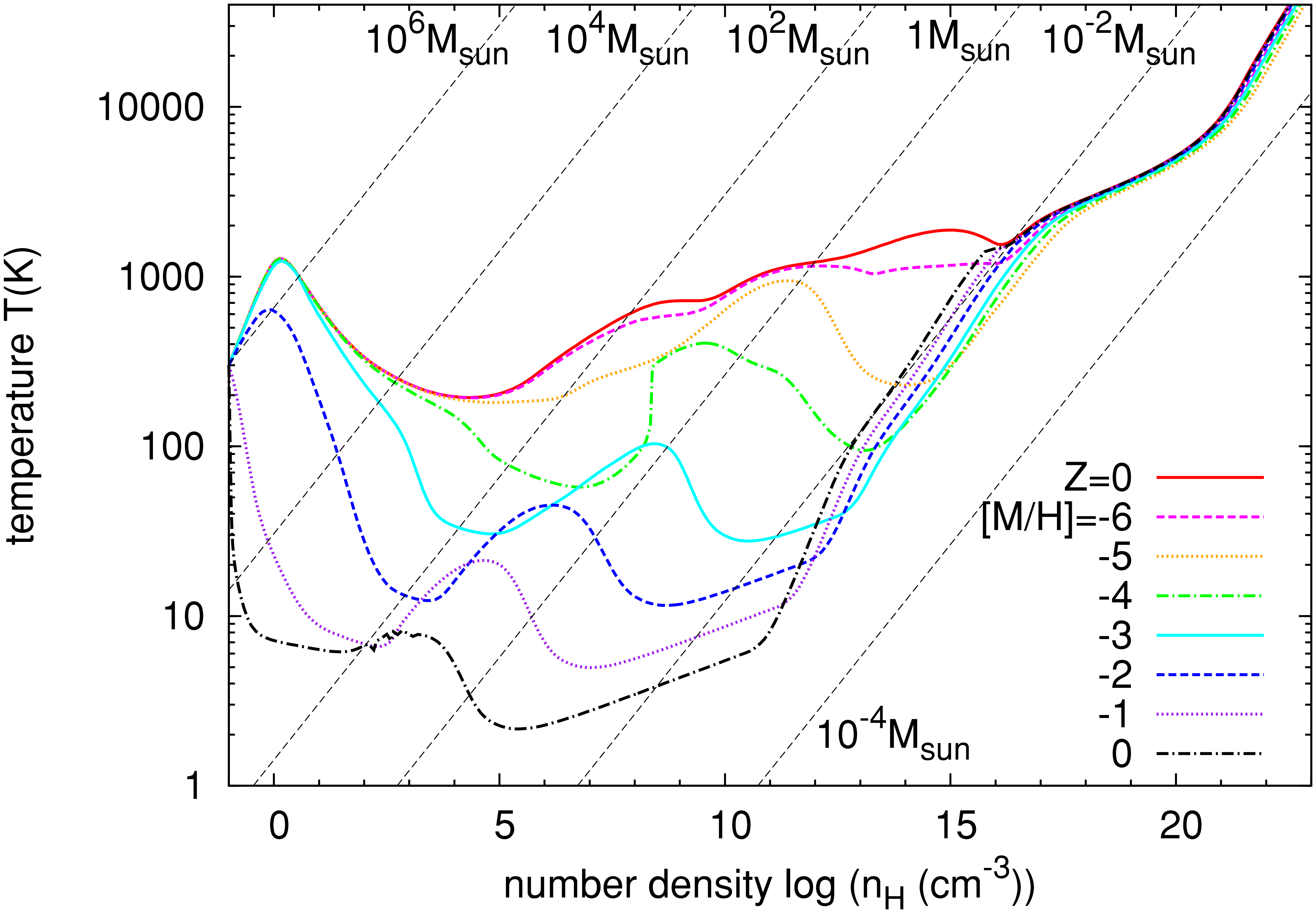
- $\gamma>1$: → *small* density excursion for given pressure
  → $\langle M_{\mathrm{jeans}} \rangle$ is large
  → only few and massive clumps exceed M_{jeans}

NOT ACTUAL TALK

EOS in different environments

NOT IN ACTUAL TALK

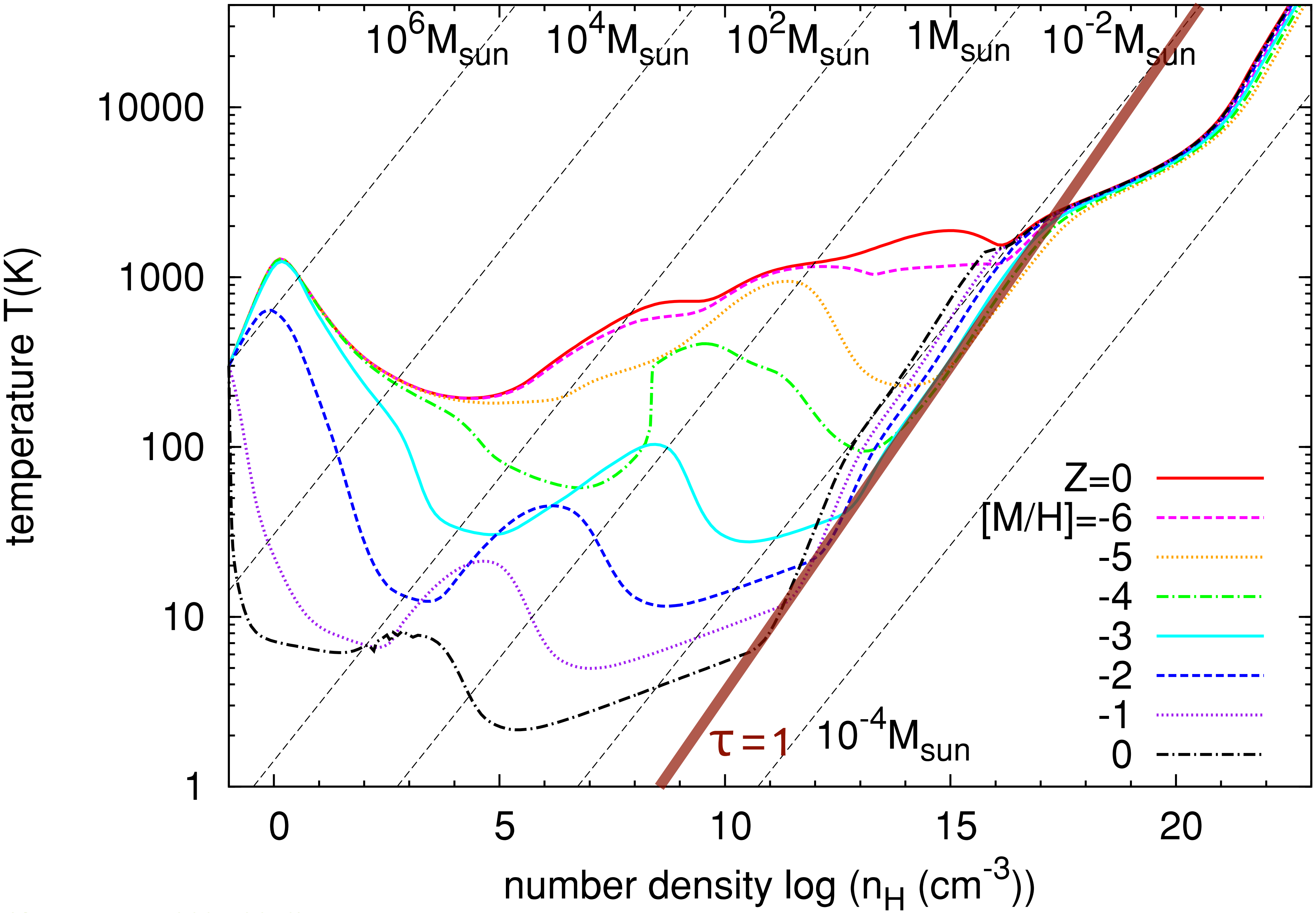
EOS as function of metallicity



(Omukai et al. 2005, 2010)

NOT IN ACTUAL TALK

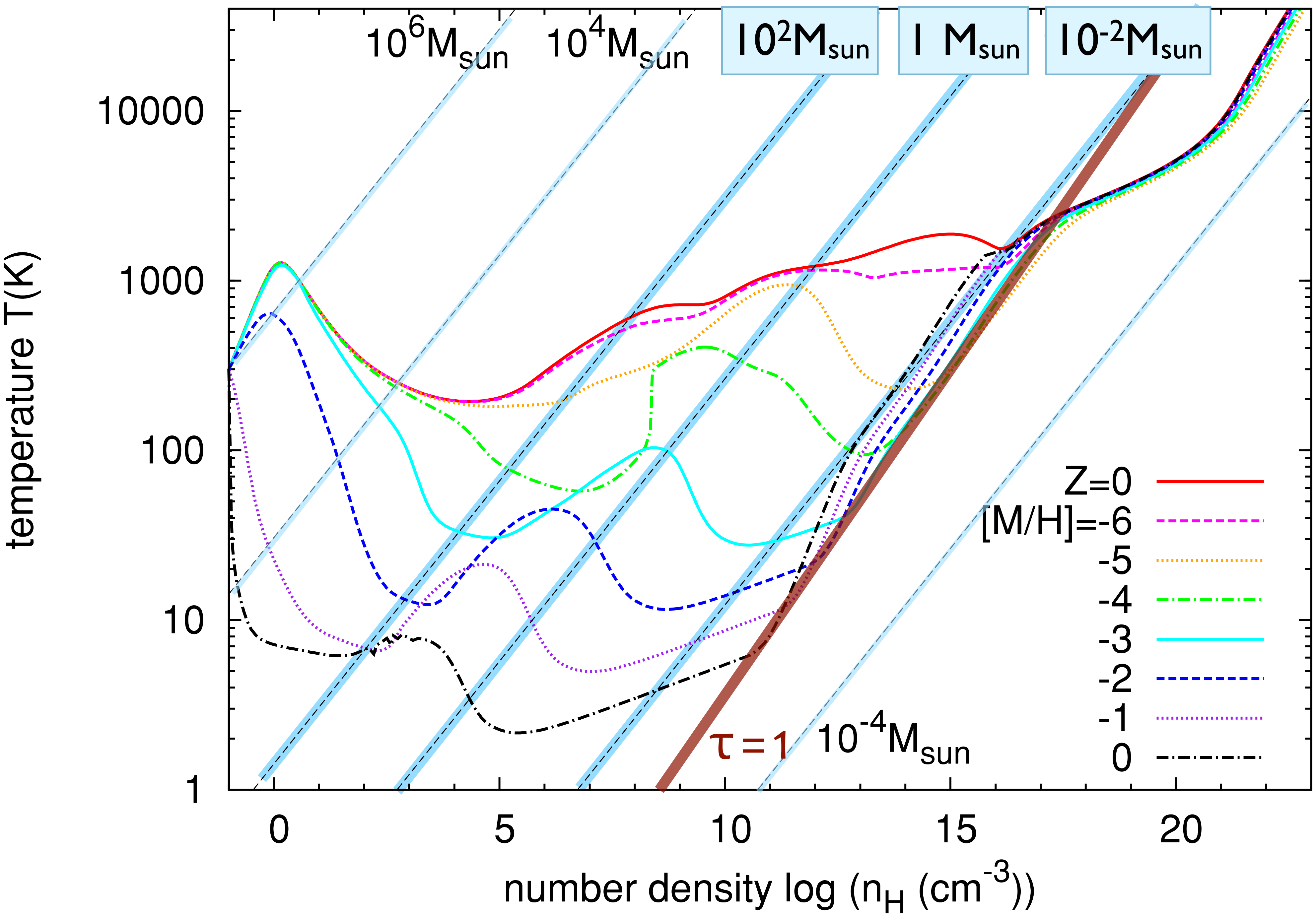
EOS as function of metallicity



(Omukai et al. 2005, 2010)

NOT IN ACTUAL TALK

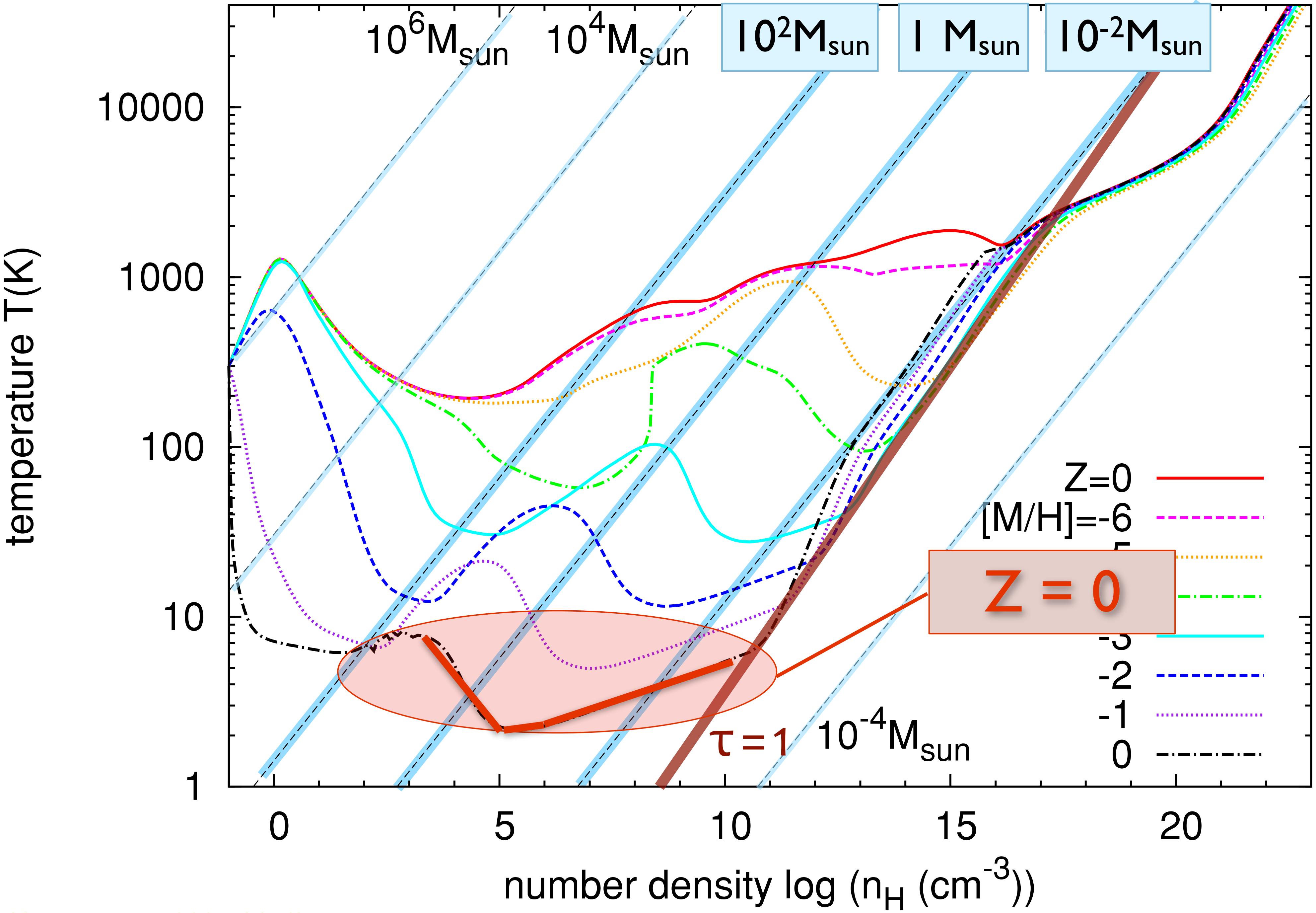
EOS as function of metallicity



(Omukai et al. 2005, 2010)

NOT IN ACTUAL TALK

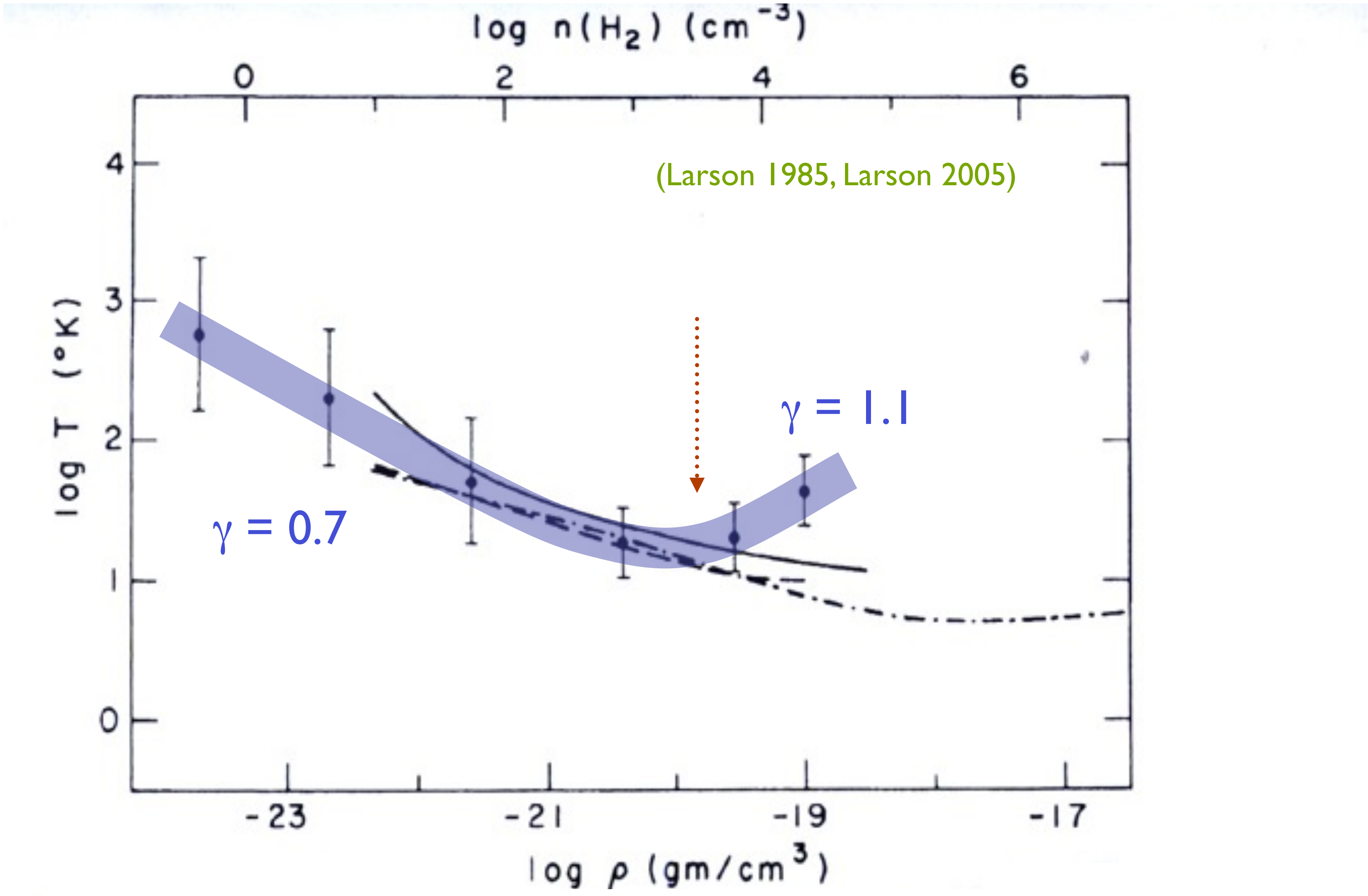
EOS as function of metallicity



(Omukai et al. 2005, 2010)

NOT IN ACTUAL TALK

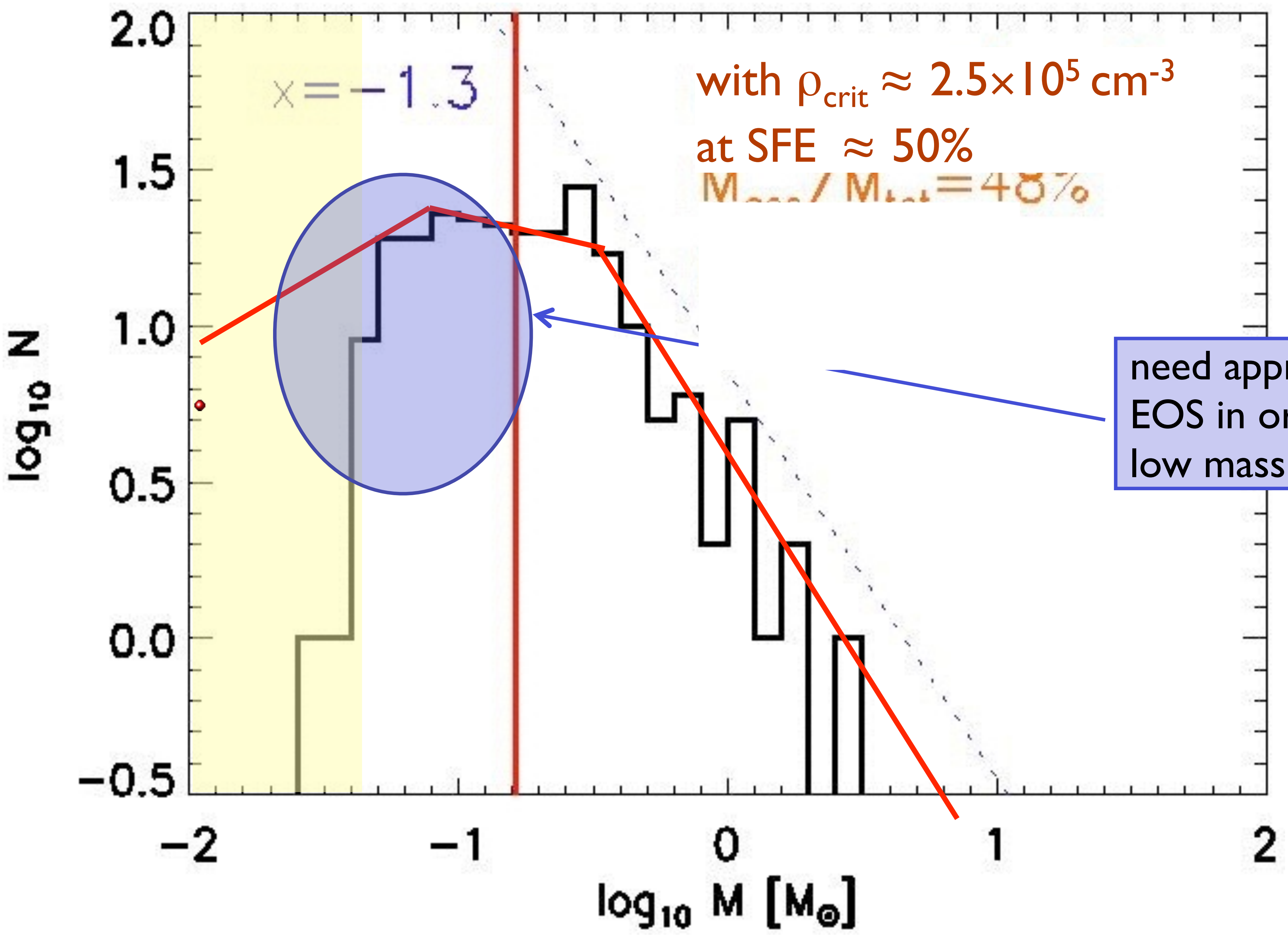
present-day star formation



(Larson 1985, Larson 2005)

NOT IN ACTUAL TALK

IMF in nearby molecular clouds



with $\rho_{crit} \approx 2.5\times10^5$ cm^{-3}

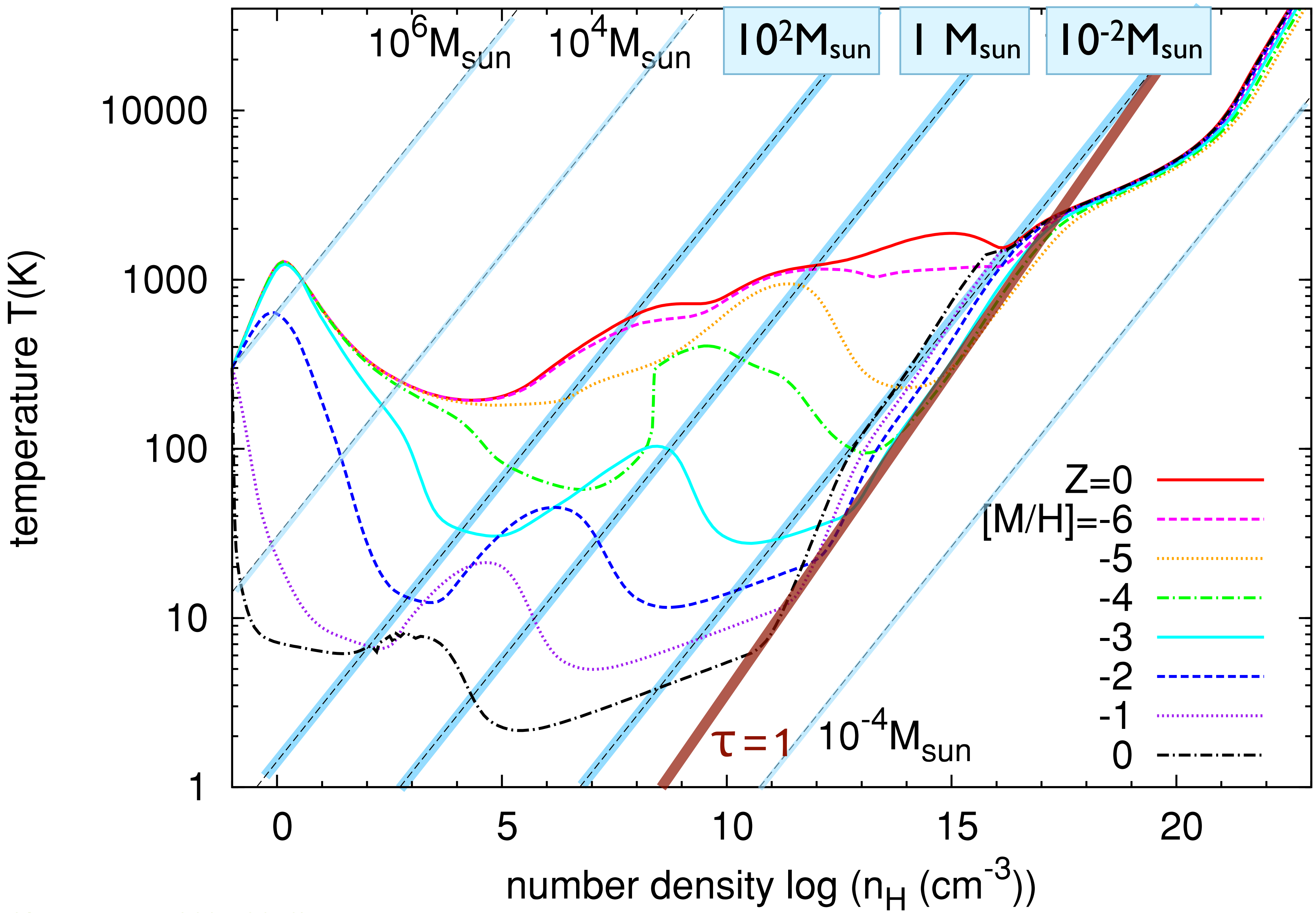
at SFE $\approx$ 50%

need appropriate EOS in order to get low mass IMF right

(Jappsen et al. 2005, A&A, 435, 611)

NOT IN ACTUAL TALK

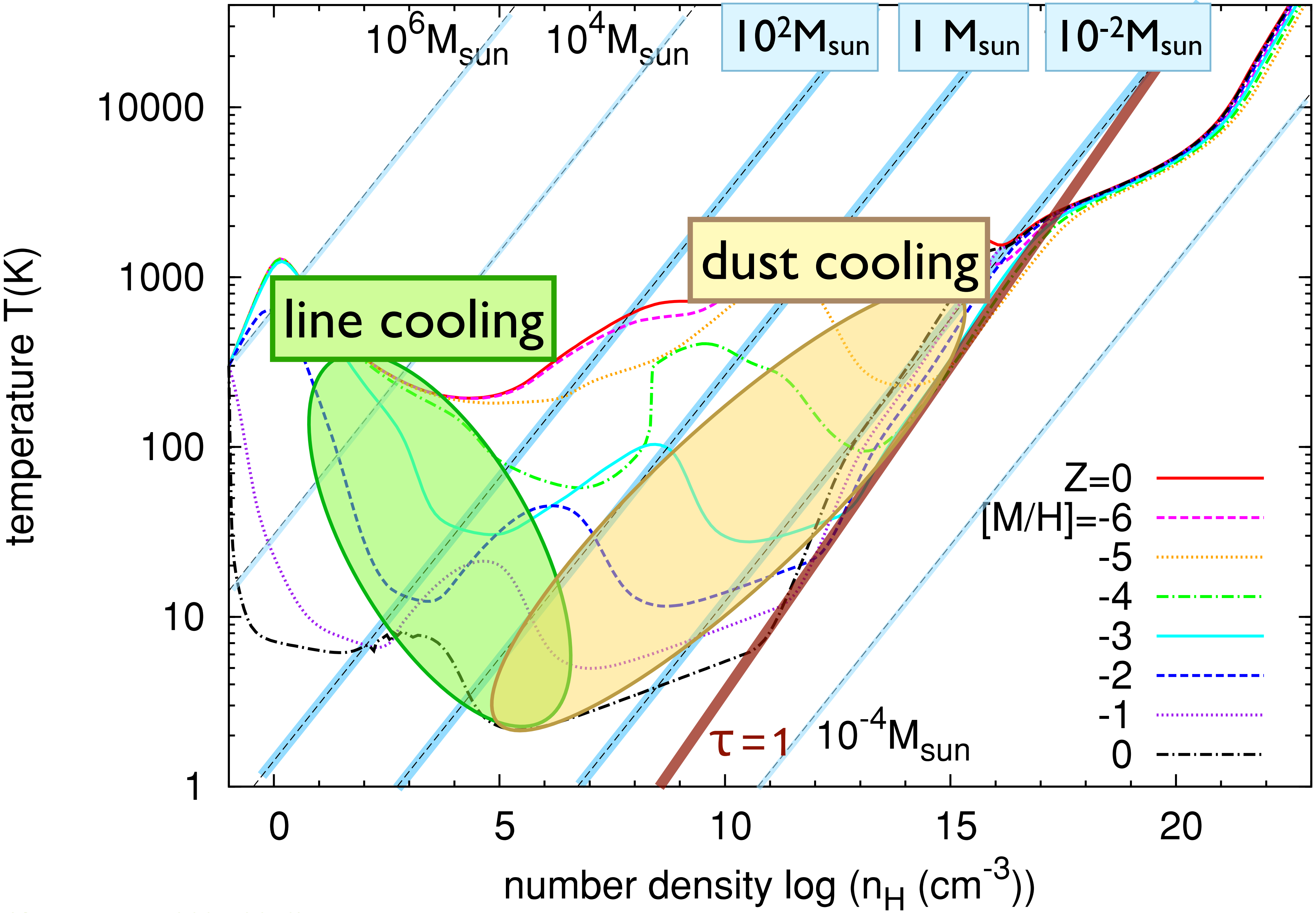
EOS as function of metallicity



(Omukai et al. 2005, 2010)

NOT IN ACTUAL TALK

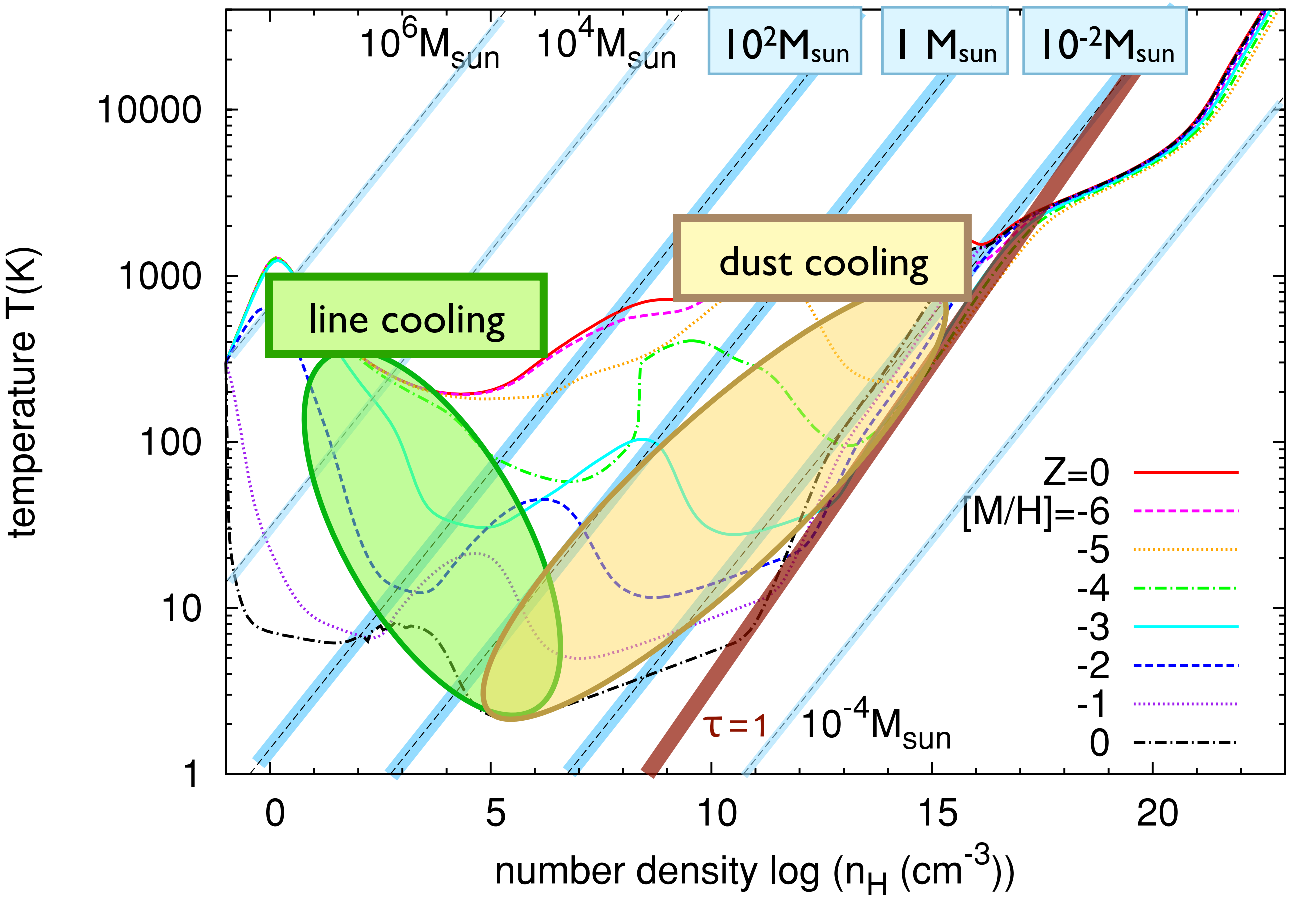
EOS as function of metallicity



(Omukai et al. 2005, 2010)

NOT IN ACTUAL TALK

transition: Pop III to Pop II.5



(Omukai et al. 2005, 2010)

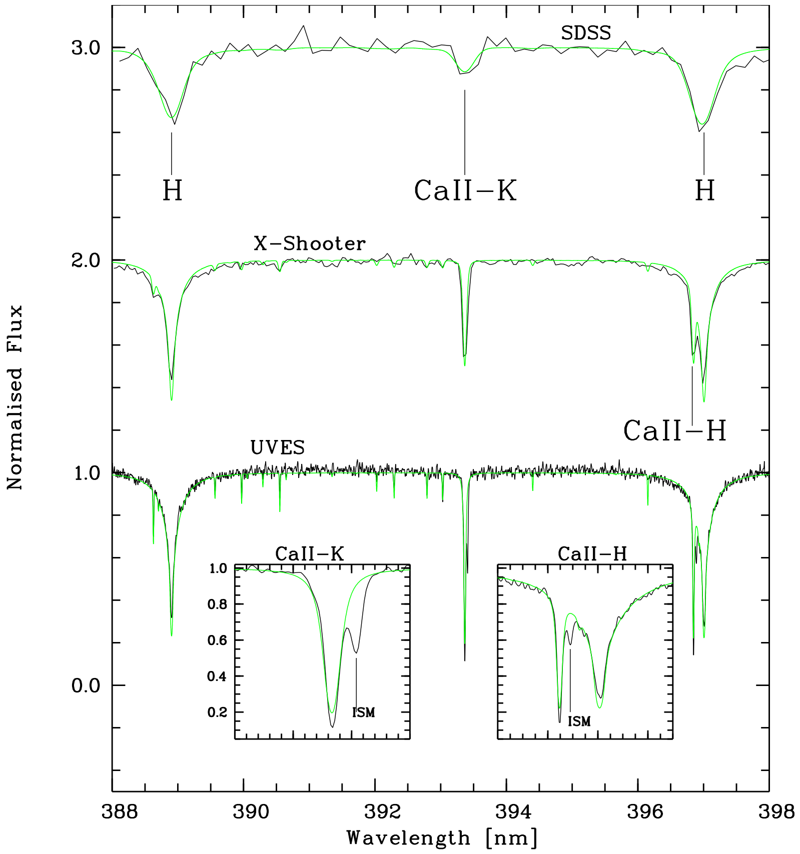
two competing models:

- cooling due to atomic fine-structure lines ($Z > 10^{-3.5}\ Z_{sun}$)
- cooling due to coupling between gas and dust ($Z > 10^{-5...-6}\ Z_{sun}$)

- which one is explains origin of extremely metal-poor stars *NB:* lines would only make very massive stars, with $M >$ few x10 M_{sun}.

NOT IN ACTUAL TALK

transition: Pop III to Pop II.5



SDSS J1029151+172927

- is first ultra metal-poor star with Z ~ $10^{-4.5}$ Z_{sun} for all metals seen (Fe, C, N, etc.)
  [see Caffau et al. 2011]
- this is in regime, where metal-lines cannot provide cooling
  [e.g. Schneider et al. 2011, 2012, Klessen et al. 2012]

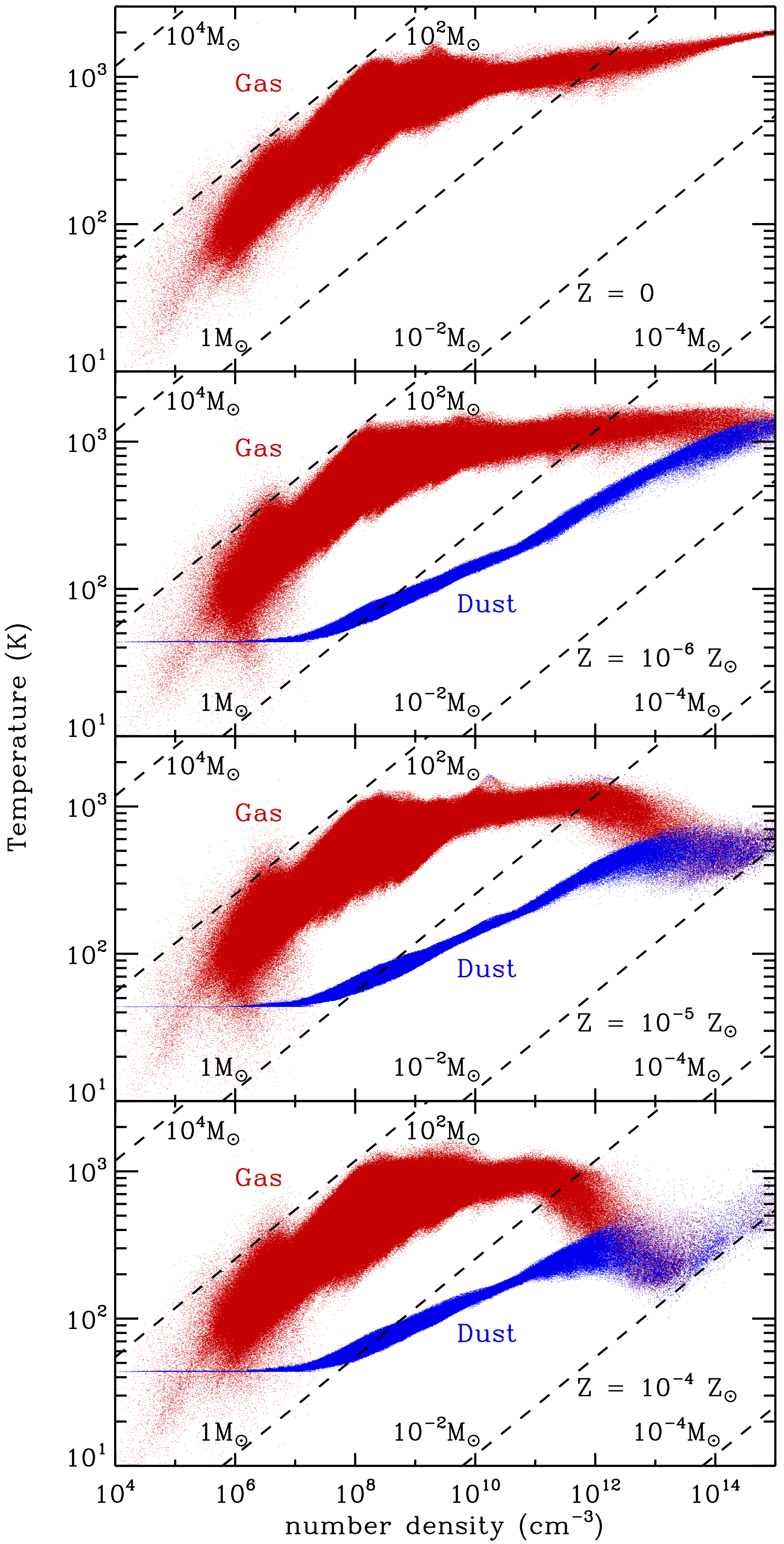
- new ESO large program to find more of these stars (120h x-shooter, 30h UVES)
  [PI E. Caffau]

NOT IN ACTUAL TALK

Element	$[X/H]_{1D}$				N lines	S_H	$A(X)_\odot$
		+3Dcor.	+NLTE cor.	+ 3D cor + NLTE cor			
C	≤ −3.8	≤ −4.5			G-band		8.50
N	≤ −4.1	≤ −5.0			NH-band		7.86
Mg I	−4.71 ± 0.11	−4.68 ± 0.11	−4.52 ± 0.11	−4.49 ± 0.12	5	0.1	7.54
Si I	−4.27	−4.30	−3.93	−3.96	1	0.1	7.52
Ca I	−4.72	−4.82	−4.44	−4.54	1	0.1	6.33
Ca II	−4.81 ± 0.11	−4.93 ± 0.03	−5.02 ± 0.02	−5.15 ± 0.09	3	0.1	6.33
Ti II	−4.75 ± 0.18	−4.83 ± 0.16	−4.76 ± 0.18	−4.84 ± 0.16	6	1.0	4.90
Fe I	−4.73 ± 0.13	−5.02 ± 0.10	−4.60 ± 0.13	−4.89 ± 0.10	43	1.0	7.52
Ni I	−4.55 ± 0.14	−4.90 ± 0.11			10		6.23
Sr II	≤ −5.10	≤ −5.25	≤ −4.94	≤ −5.09	1	0.01	2.92

(Caffau et al. 2011, 2012)

(Schneider et al. 2011,2012, Klessen et al. 2012)



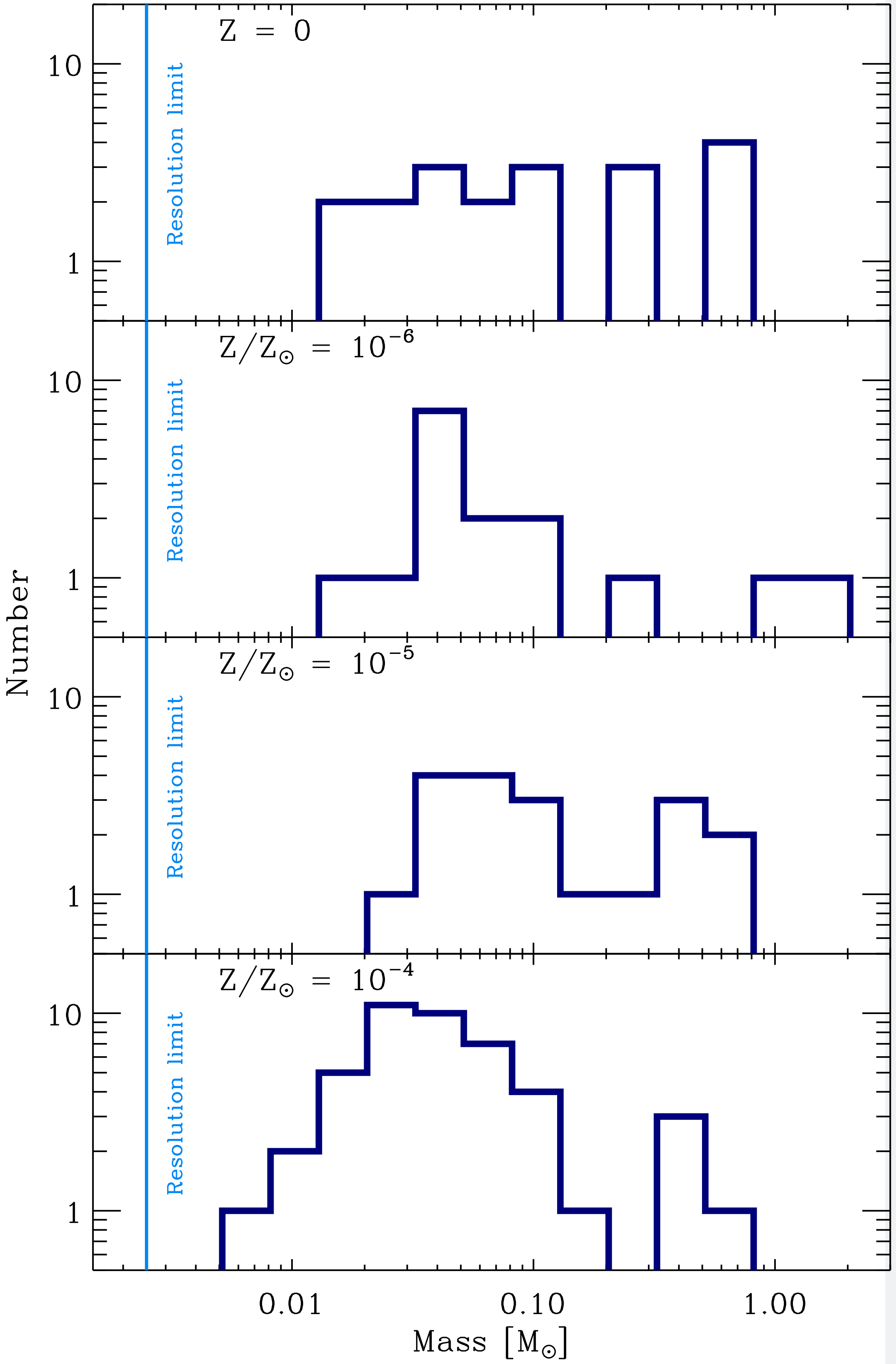
[M/H] = -ininity

[M/H] = -6

[M/H] = -5

[M/H] = -4

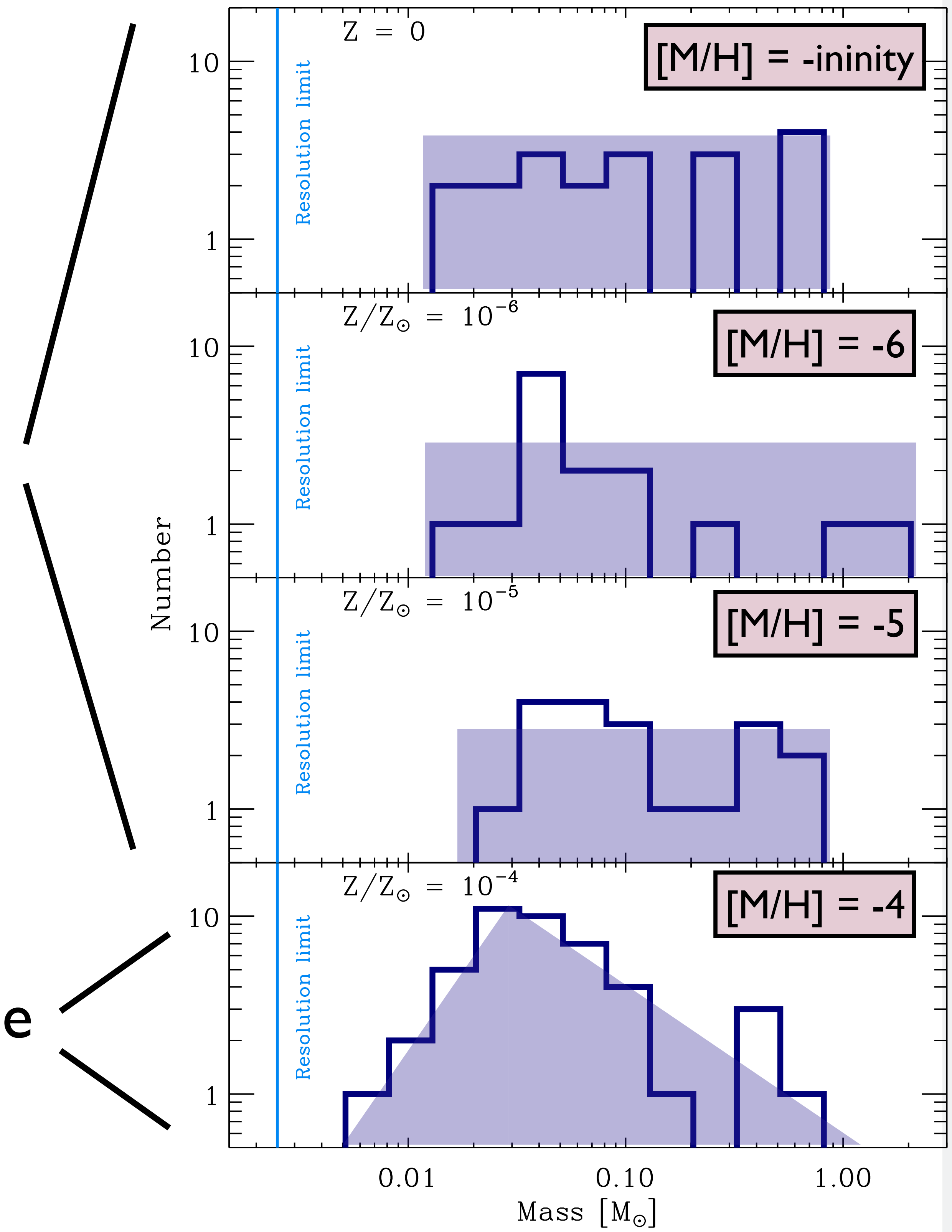
red : gas
blue: dust



Dopcke et al., 2012, submitted to ApJ, arXiv:1203.6842)

NOT IN ACTUAL TALK

hints for differences in mass spectrum



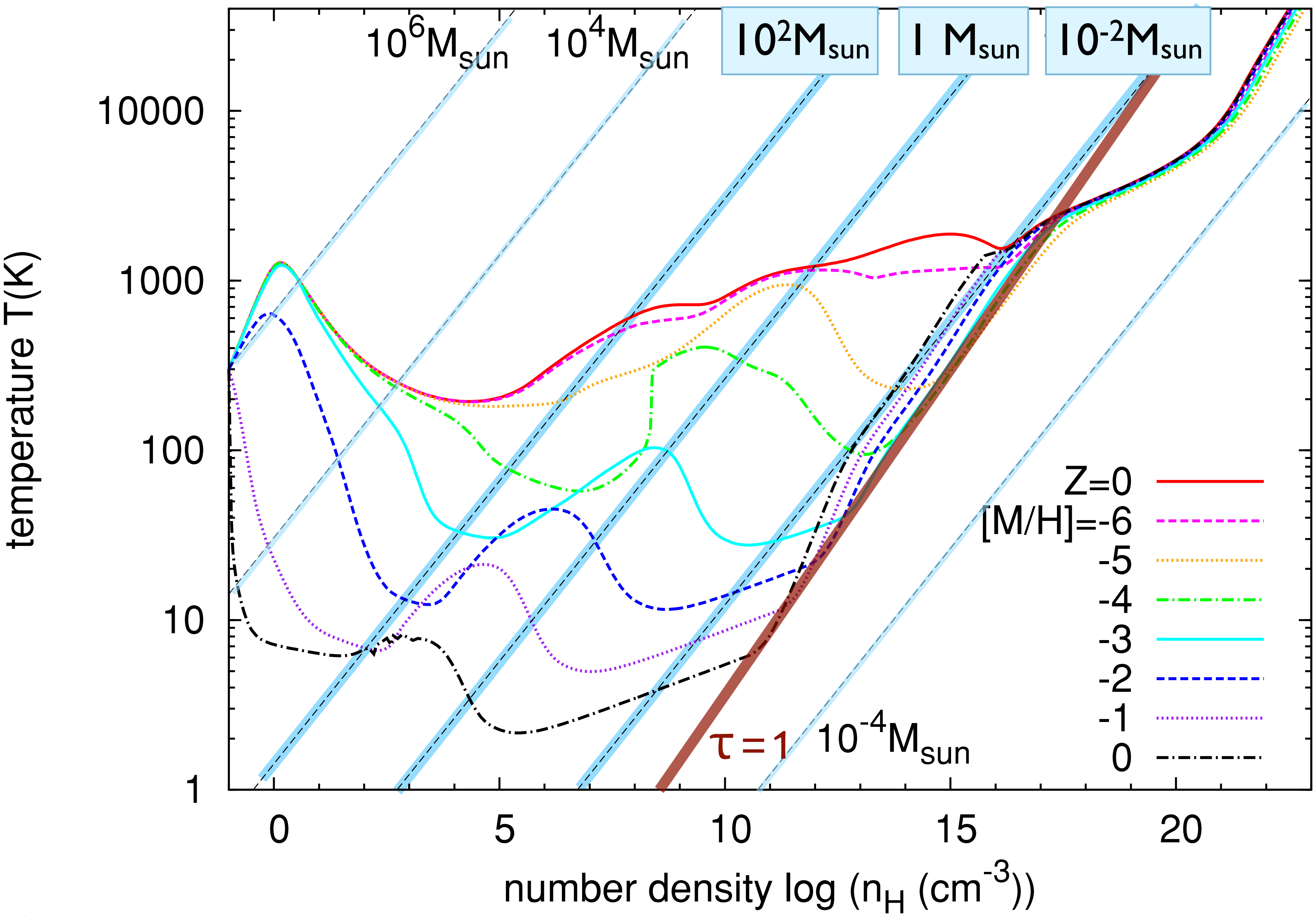
disk fragmentation mode

gravoturbulent fragmentation mode

NOT IN ACTUAL TALK

Dopcke et al., 2012, submitted to ApJ, arXiv:1203.6842)

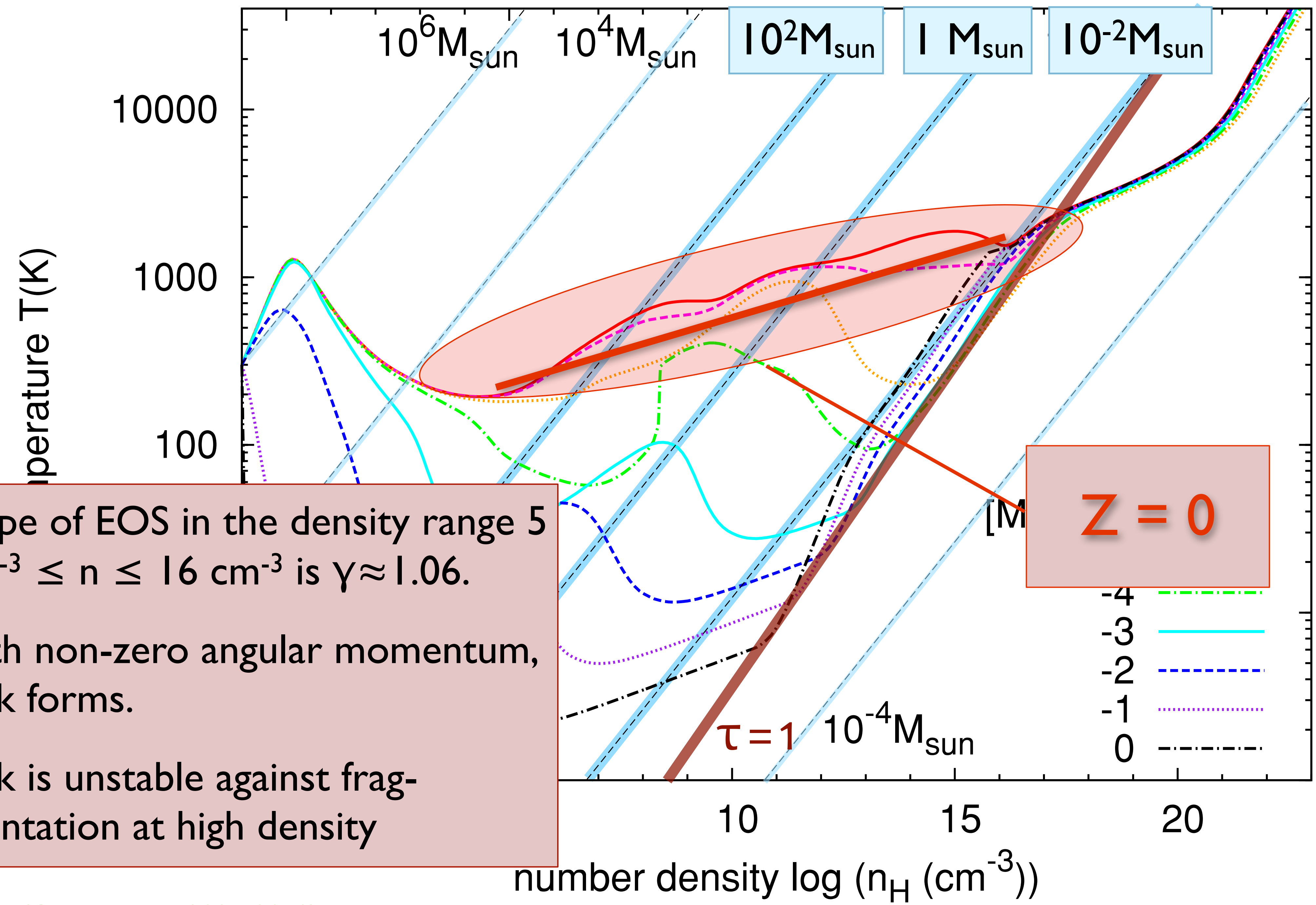
EOS as function of metallicity



(Omukai et al. 2005, 2010)

NOT IN ACTUAL TALK

EOS as function of metallicity



- slope of EOS in the density range 5 cm^{-3} ≤ n ≤ 16 cm^{-3} is $\gamma \approx 1.06$.
- with non-zero angular momentum, disk forms.
- disk is unstable against fragmentation at high density

(Omukai et al. 2005, 2010)

NOT IN ACTUAL TALK

“classical” picture

NOT IN ACTUAL TALK

- most current numerical simulations of Pop III star formation predict very massive objects

  (e.g. Abel et al. 2002, Yoshida et al. 2008, Bromm et al. 2009)

- similar for theoretical models (e.g. Tan & McKee 2004)

- there are some first hints of fragmentation, however

  (Turk et al. 2009, Stacy et al. 2010)

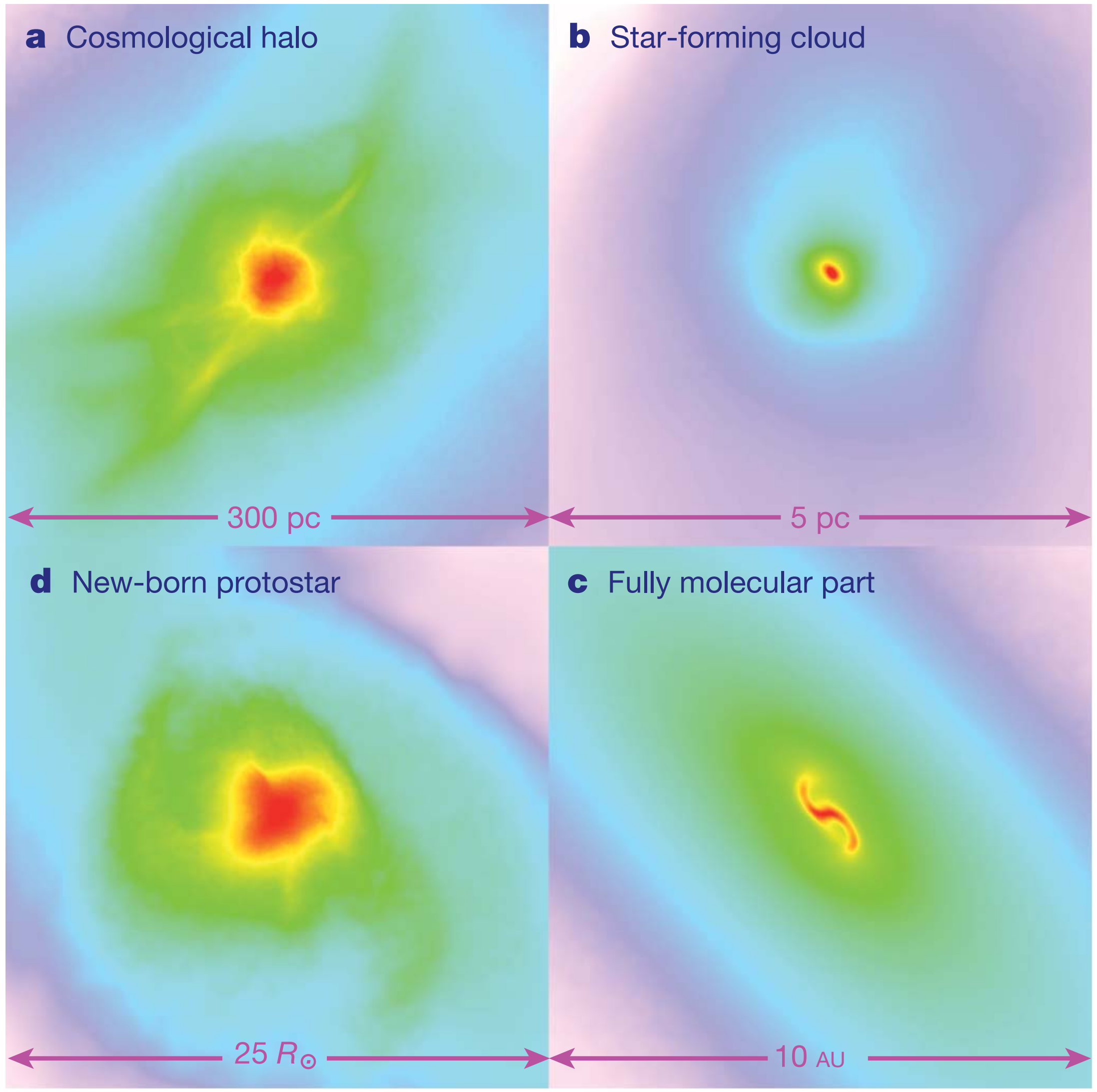
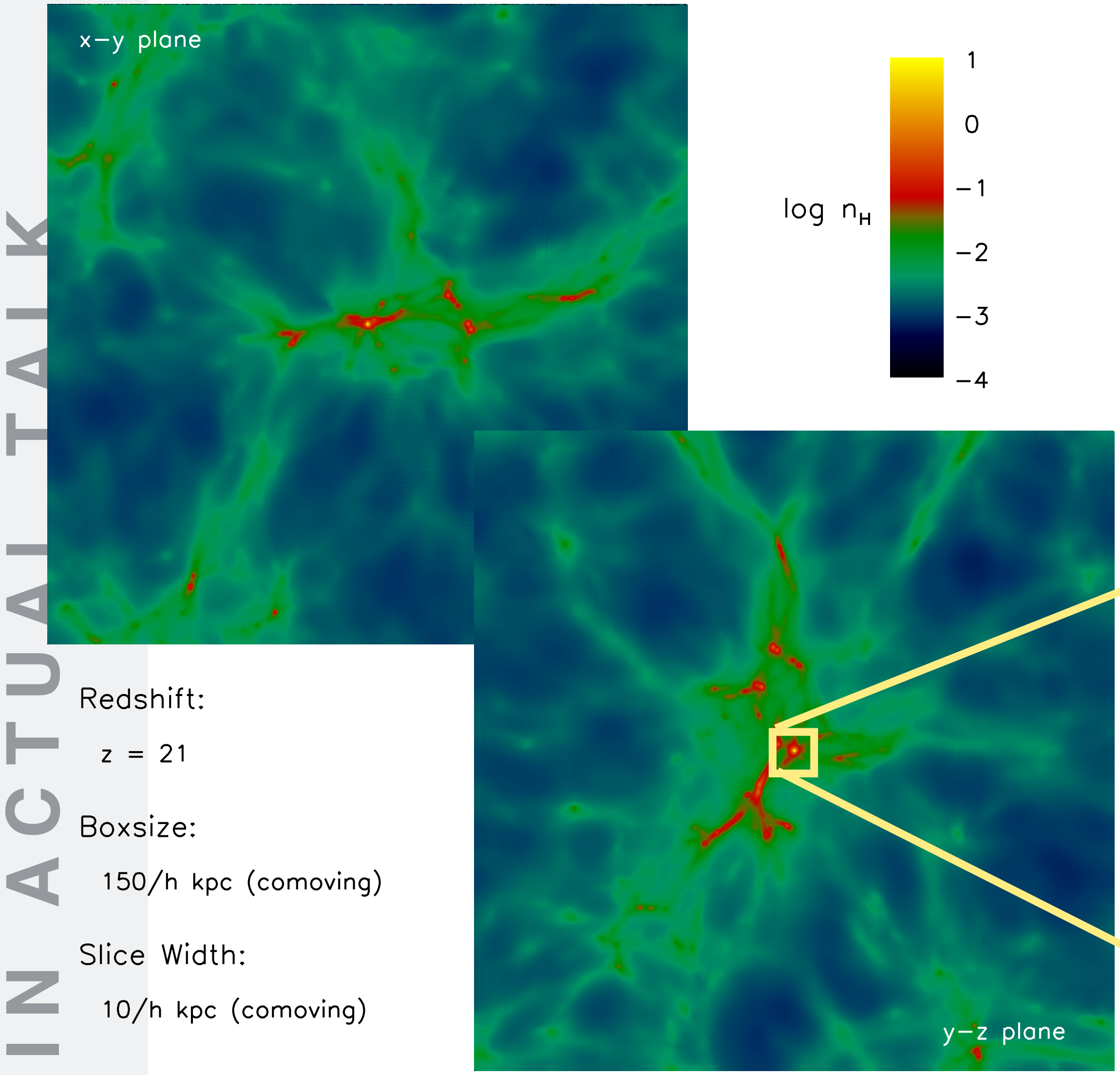


Figure 1 | Projected gas distribution around a primordial protostar. Shown is the gas density (colour-coded so that red denotes highest density) of a single object on different spatial scales. **a**, The large-scale gas distribution around the cosmological minihalo; **b**, a self-gravitating, star-forming cloud; **c**, the central part of the fully molecular core; and **d**, the final protostar. Reproduced by permission of the AAAS (from ref. 20).

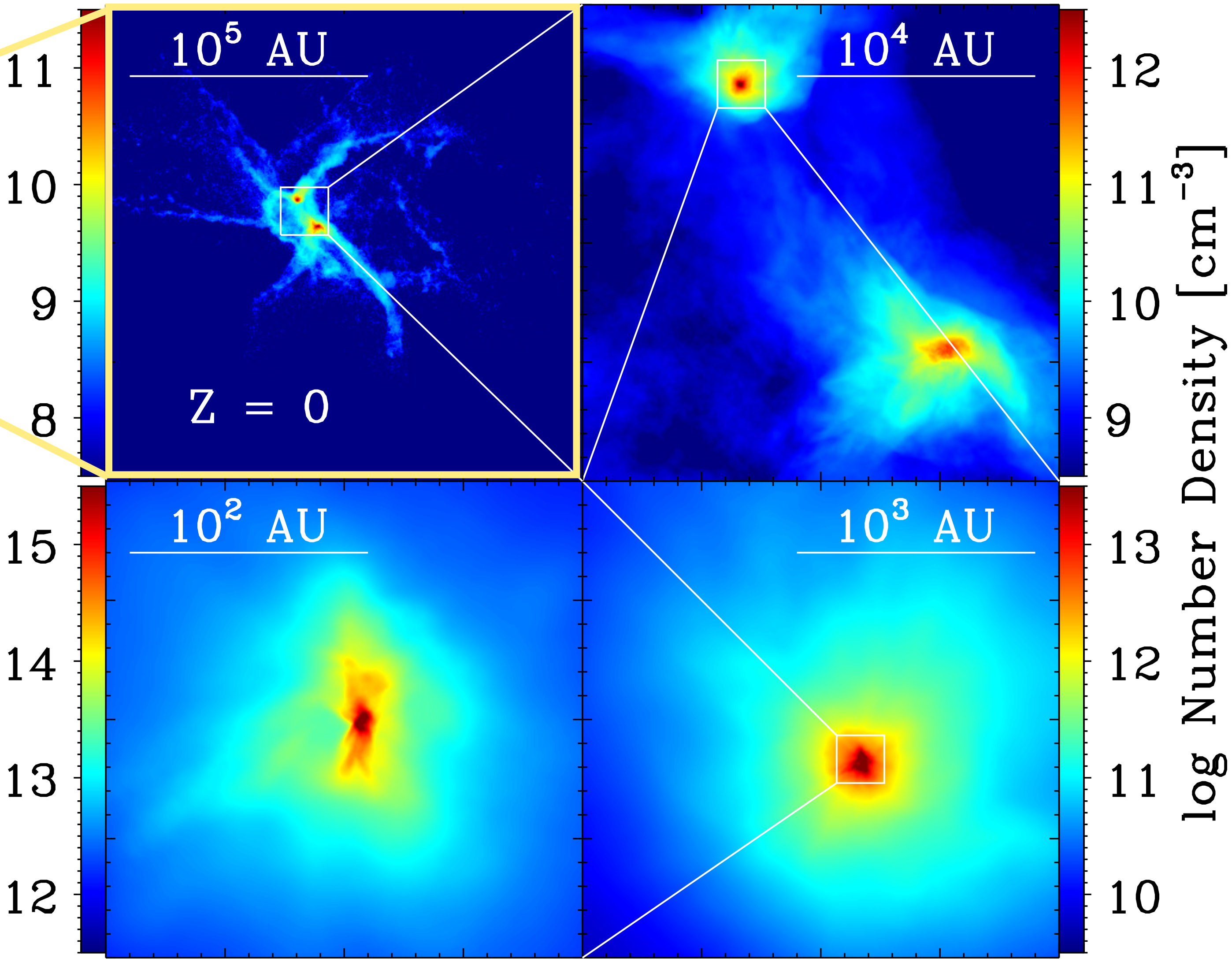
(Yoshida et al. 2008, Science, 321, 669)

detailed look at accretion disk around first star



(Greif et al., 2007, ApJ, 670, 1)

successive zoom-in calculation from cosmological initial conditions (using SPH and new grid-code AREPO)

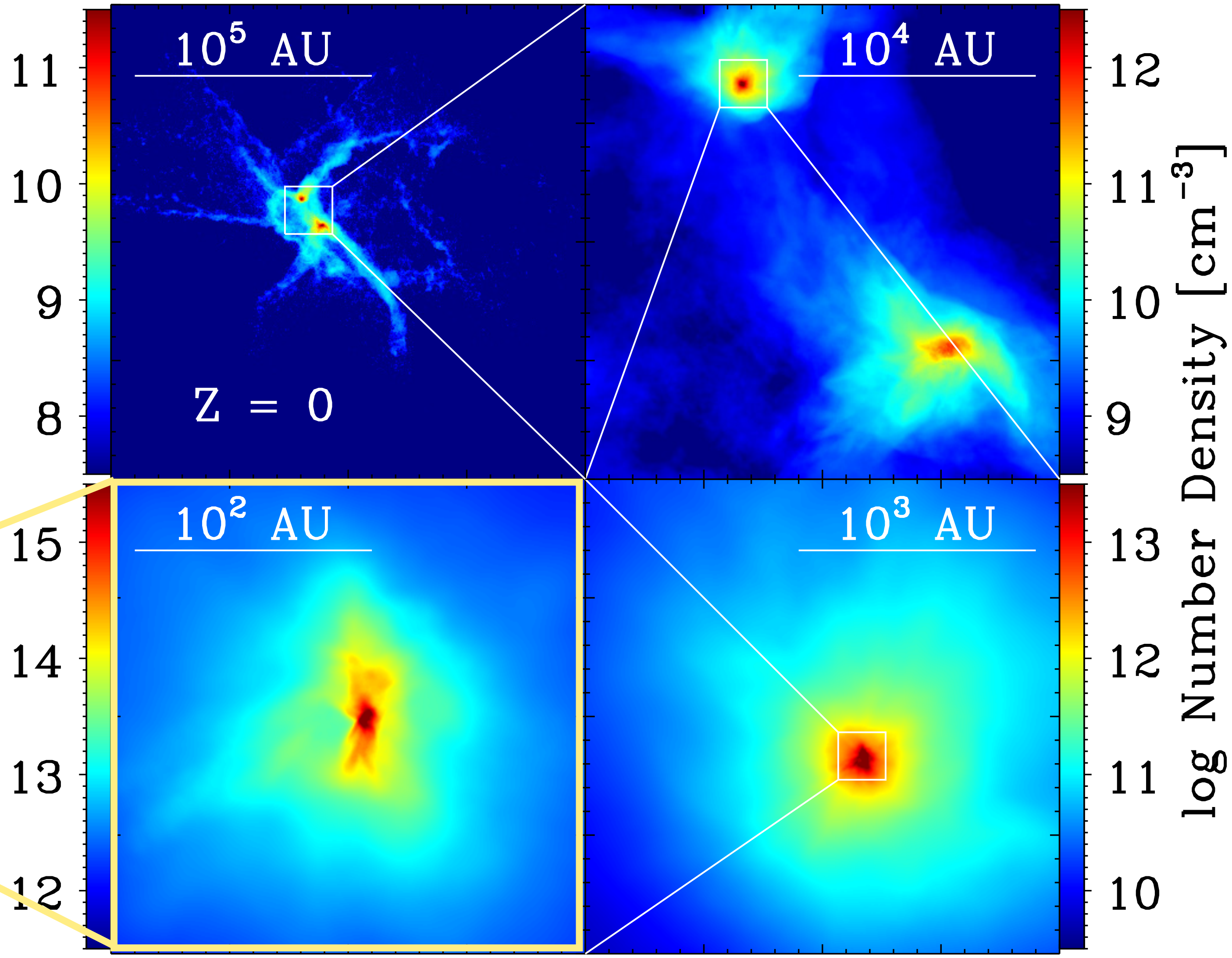


(Greif et al. 2011, ApJ, 737, 75, Greif et al. 2012, MNRAS, 424, 399, Dopcke et al. 2012, ApJ submitted, arXiv1203.6842)

NOT IN ACTUAL TALK

detailed look at accretion disk around first star

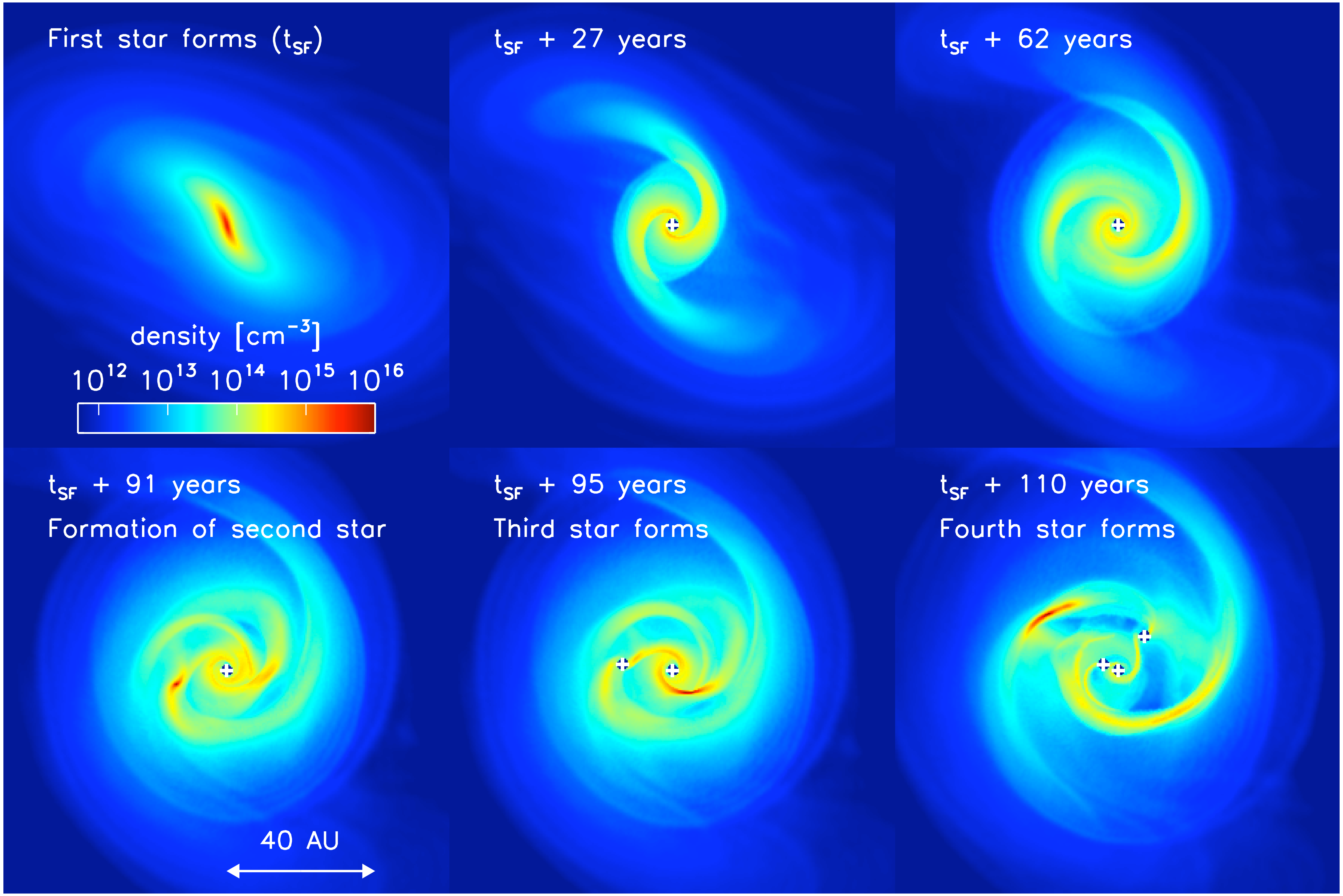
successive zoom-in calculation from cosmological initial conditions (using SPH and new grid-code AREPO)



what is the time evolution of accretion disk around first star to form?

(Greif et al. 2011, ApJ, 737, 75, Greif et al. 2012, MNRAS, 424, 399, Dopcke et al. 2012, ApJ submitted, arXiv1203.6842)

NOT IN ACTUAL TALK

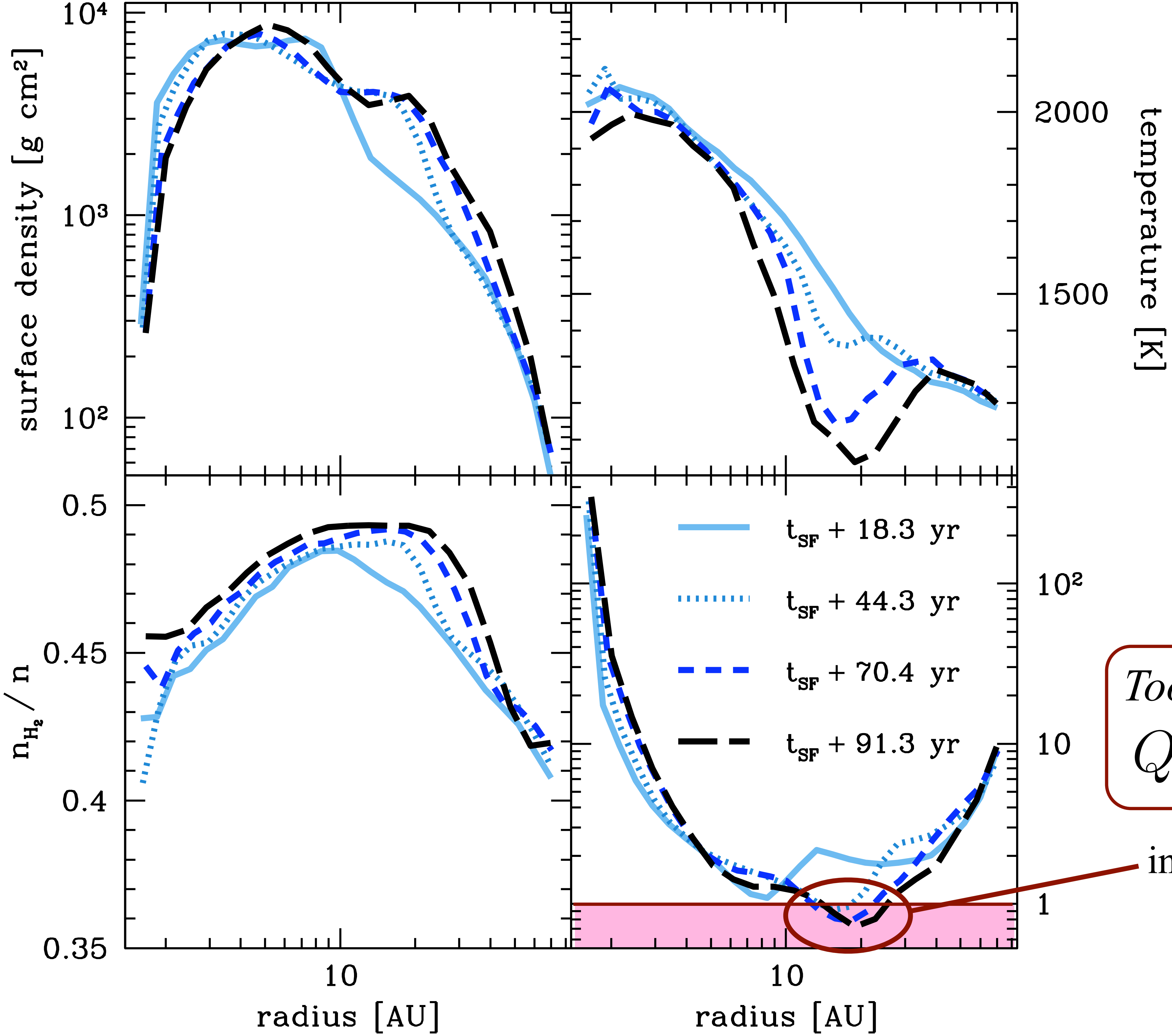


detailed look at accretion disk

Figure 1: Density evolution in a 120 AU region around the first protostar, showing the build-up of the protostellar disk and its eventual fragmentation. We also see ‘wakes’ in the low-density regions, produced by the previous passage of the spiral arms.

(Clark et al. 2011b, Science, 331, 1040)

important disk parameters



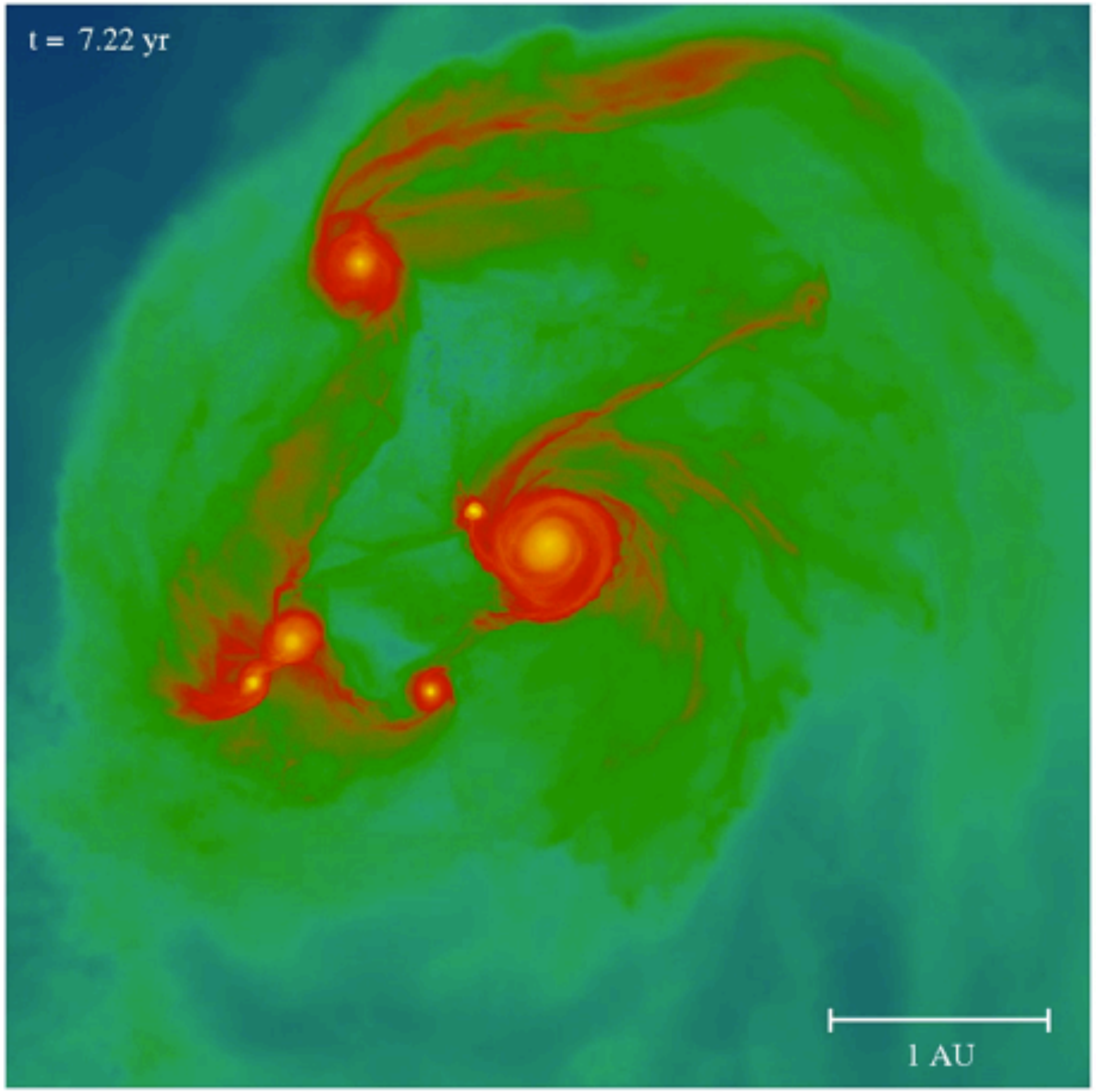
instability for *Q*<*1*

Toomre Q:

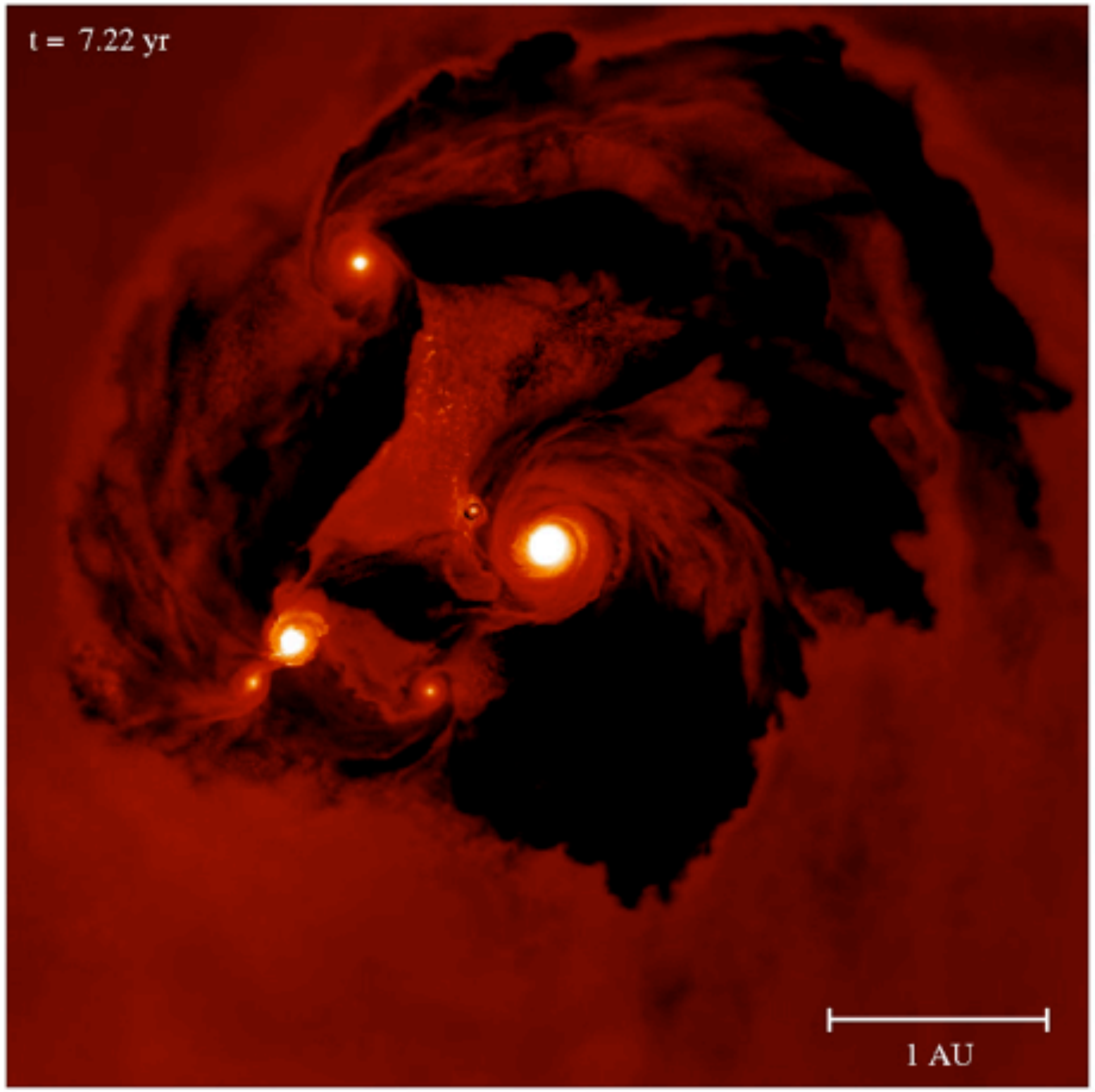
$$Q = c_s \kappa / \pi G \Sigma$$

(Clark et al. 2011b, Science, 331, 1040)

Most recent calculations:
fully sink-less simulations, following the disk build-up over ~10 years
(resolving the protostars - first cores - down to 10^5 *km ~ 0.01* $R_\odot$*)*



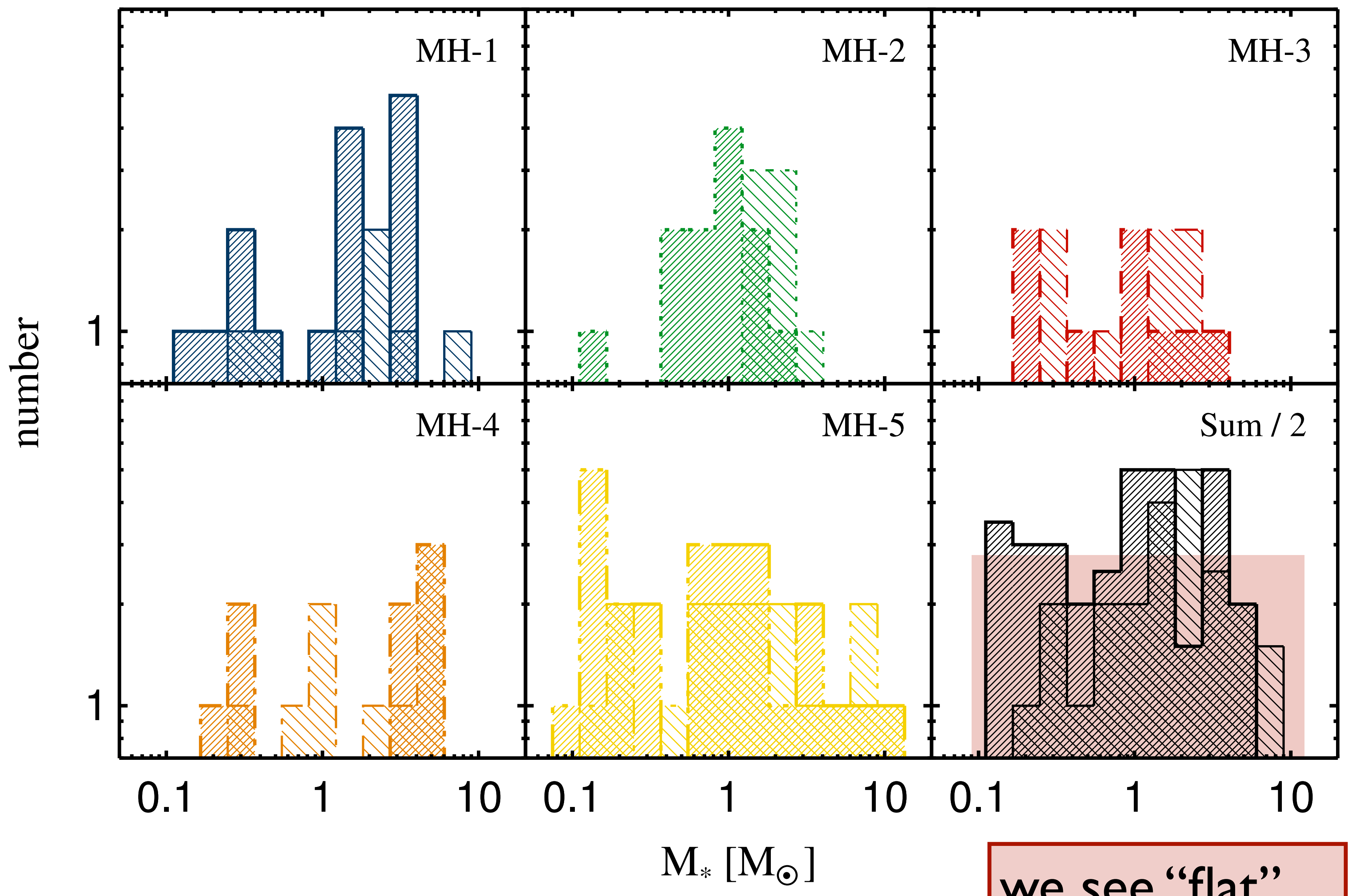
density



temperature

(Greif et al. 2012, MNRAS, 424, 399)

expected mass spectrum



we see “flat” mass spectrum

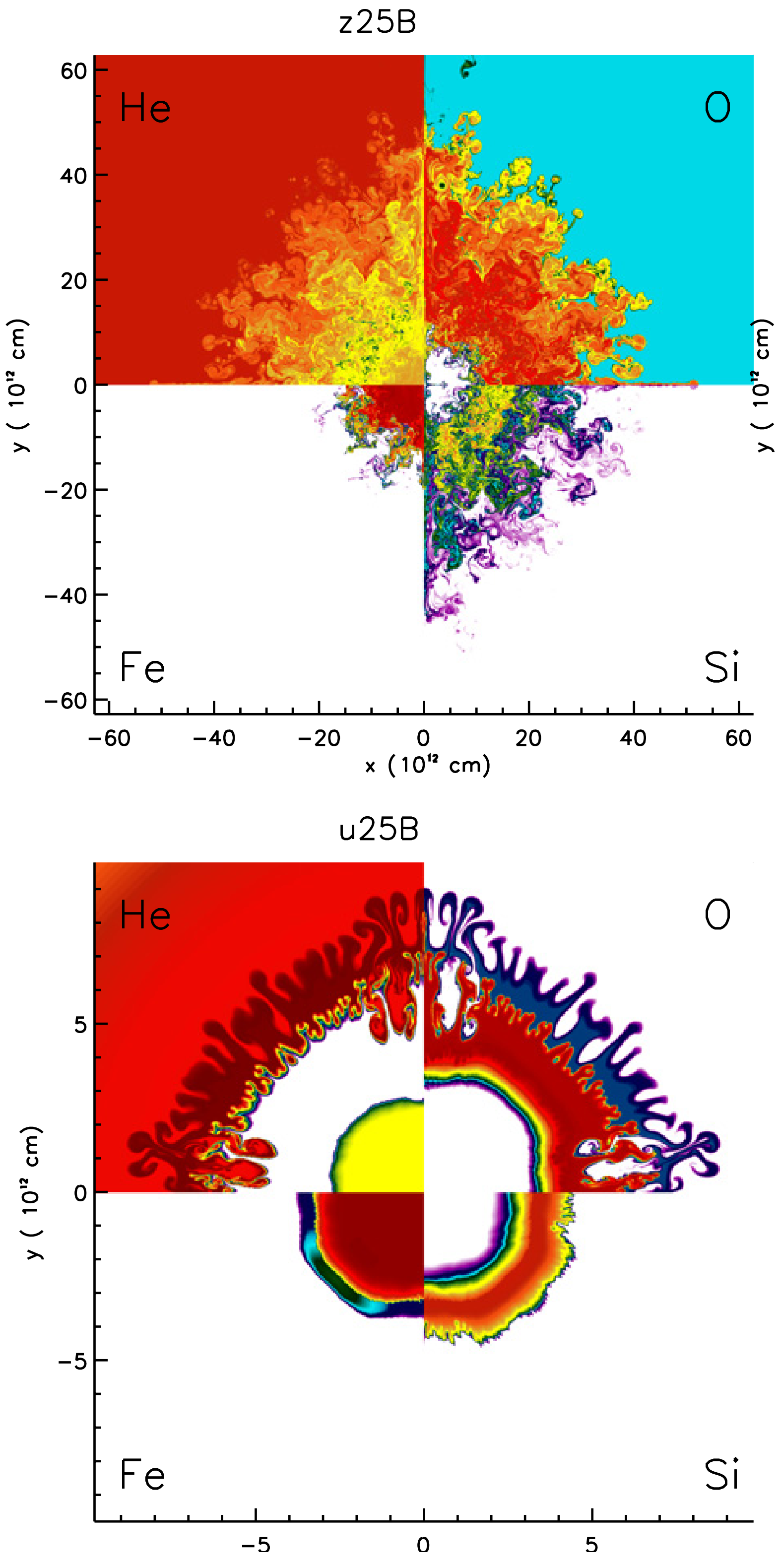
(Greif et al. 2011, ApJ, 737, 75, also Dopcke et al. 2012 ApJ submitted, arXiv1203.6842)

NOT IN ACTUAL TALK

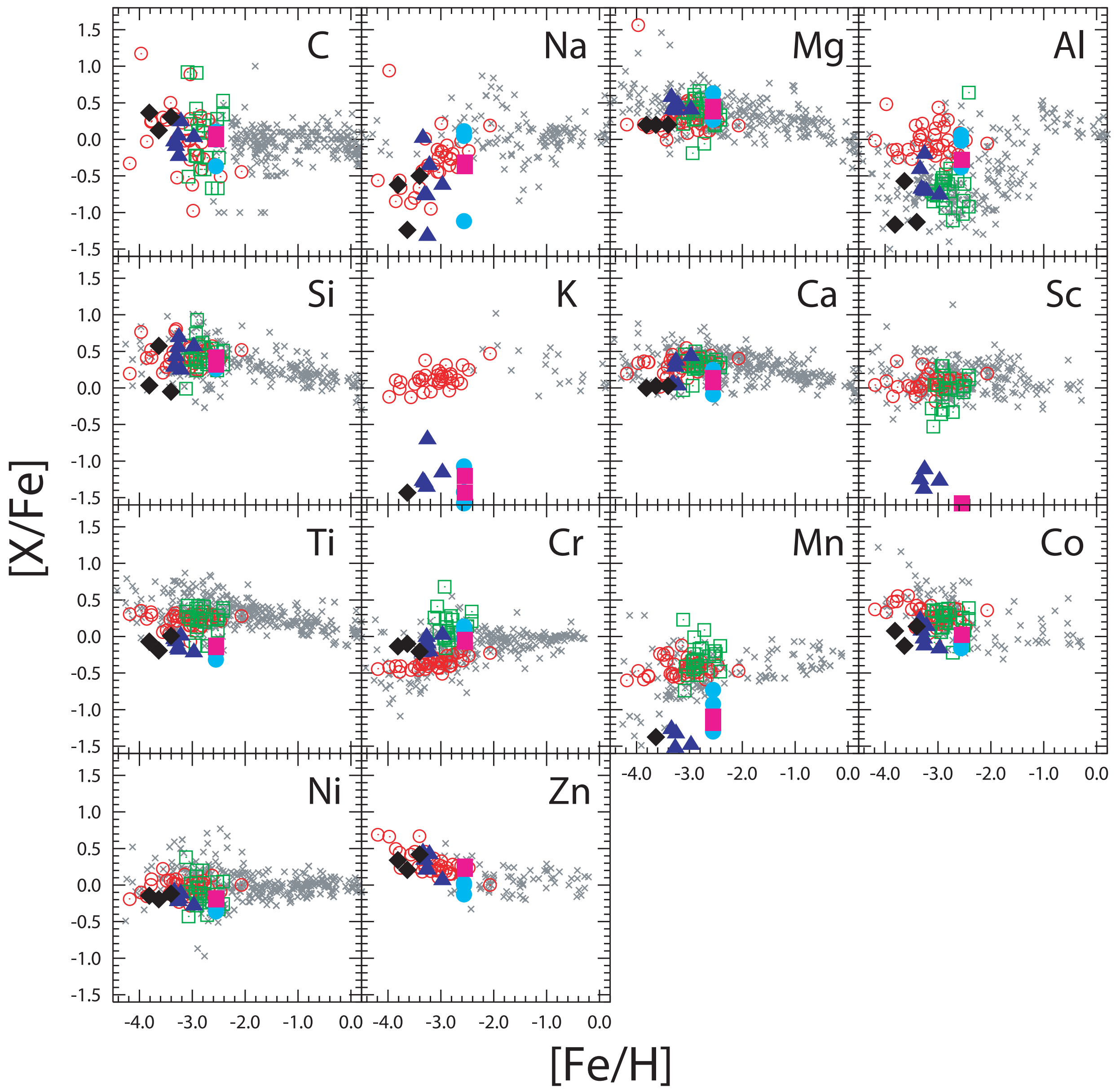
expected mass spectrum

- *expected IMF is flat* and covers a wide range of masses
- implications
  - because slope > -2, most *mass is in massive objects* as predicted by most previous calculations
  - most high-mass Pop III stars should be in *binary systems* --> source of *high-redshift gamma-ray bursts*
  - because of ejection, some *low-mass objects* (< 0.8 $M_\odot$) might have *survived* until today and could potentially be found in the Milky Way
- consistent with abundance patterns found in second generation stars

NOT IN ACTUAL TALK



(Joggerst et al. 2009, 2010)



(Tominaga et al. 2007)

The metallicities of extremely metal-poor stars in the halo are consistent with the yields of core-collapse supernovae, i.e. progenitor stars with 20 - 40 M⊙

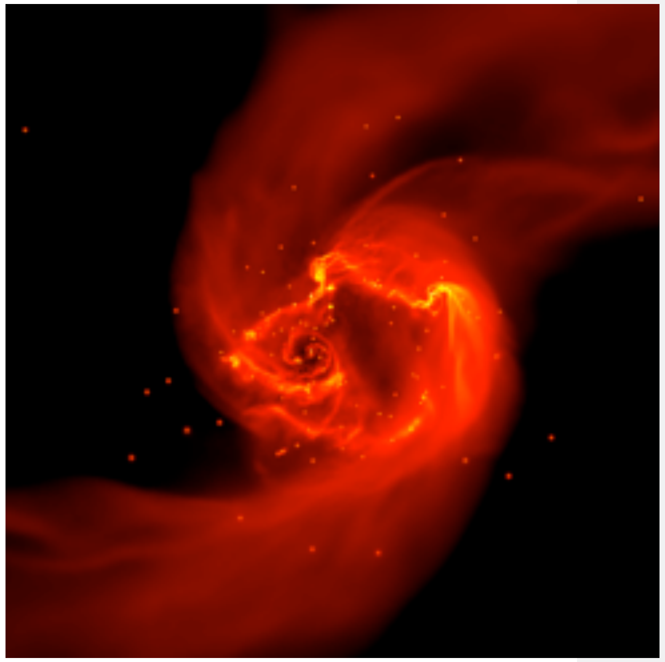
(e.g. Tominaga et al. 2007, Izutani et al. 2009, Joggerst et al. 2009, 2010)

NOT IN ACTUAL TALK

primordial star formation

- just like in present-day SF, we expect
  - *turbulence*
  - *thermodynamics*
  - *feedback*
  - *magnetic fields*

  to influence first star formation.



- masses of first stars still *uncertain* (surprises from new generation of high-resolution calculations that go beyond first collapse)
- disks unstable: first stars should be *binaries* or *part of small clusters*
- effects of feedback less important than in present-day SF

NOT IN ACTUAL TALK

questions

- is claim of Pop III stars with M ~ 0.5 $M_\odot$ really justified?
  - stellar collisions
  - magnetic fields
  - radiative feedback
- how would we find them?
  - spectral features
- where should we look?
- what about magnetic fields?

NOT IN ACTUAL TALK

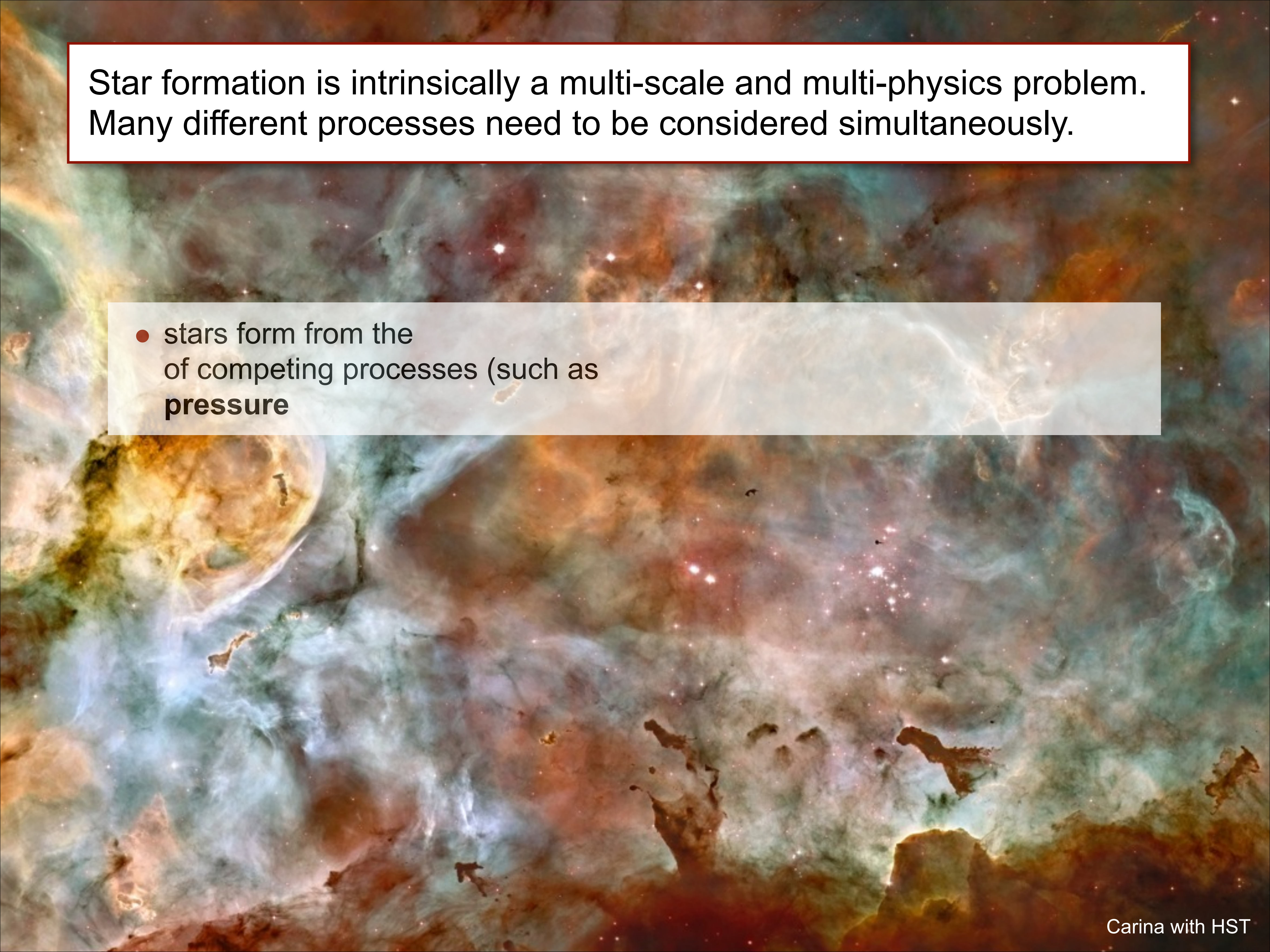
Carina with HST

Star formation is intrinsically a multi-scale and multi-physics problem. Many different processes need to be considered simultaneously.

Carina with HST

Star formation is intrinsically a multi-scale and multi-physics problem. Many different processes need to be considered simultaneously.

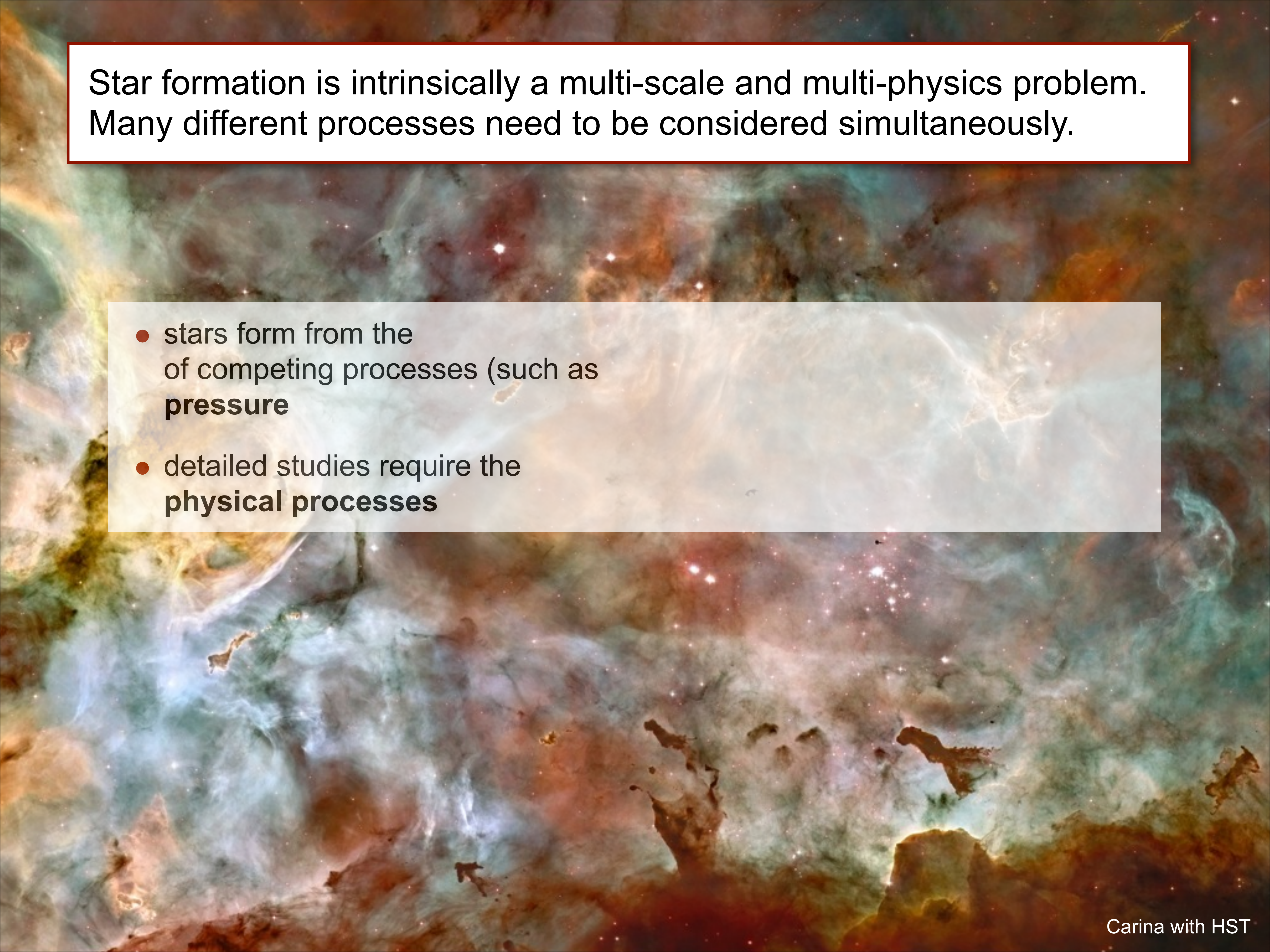
- stars form from the
  of competing processes (such as
  pressure



Carina with HST

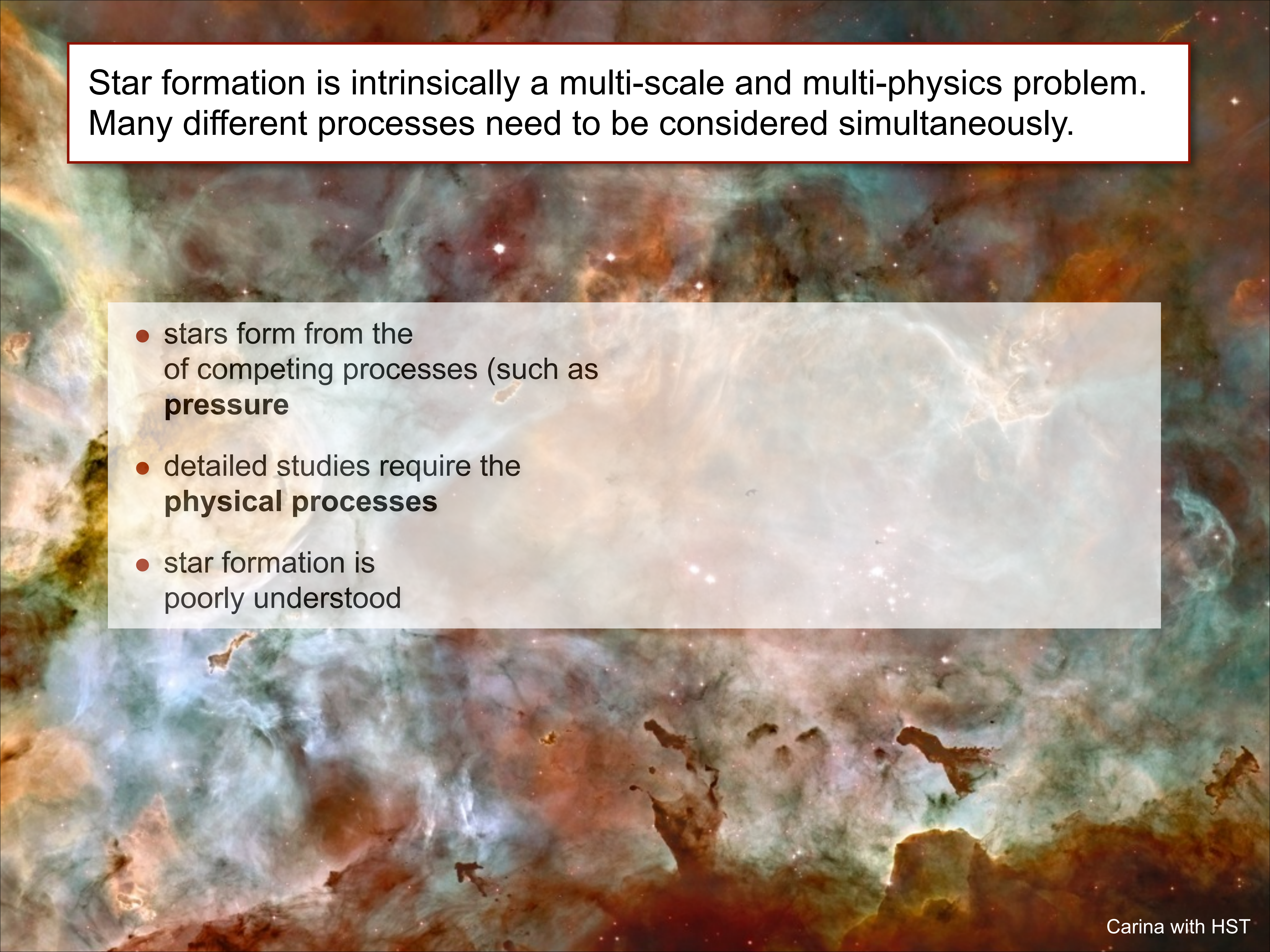
Star formation is intrinsically a multi-scale and multi-physics problem. Many different processes need to be considered simultaneously.

- stars form from the of competing processes (such as **pressure**
- detailed studies require the **physical processes**



Carina with HST

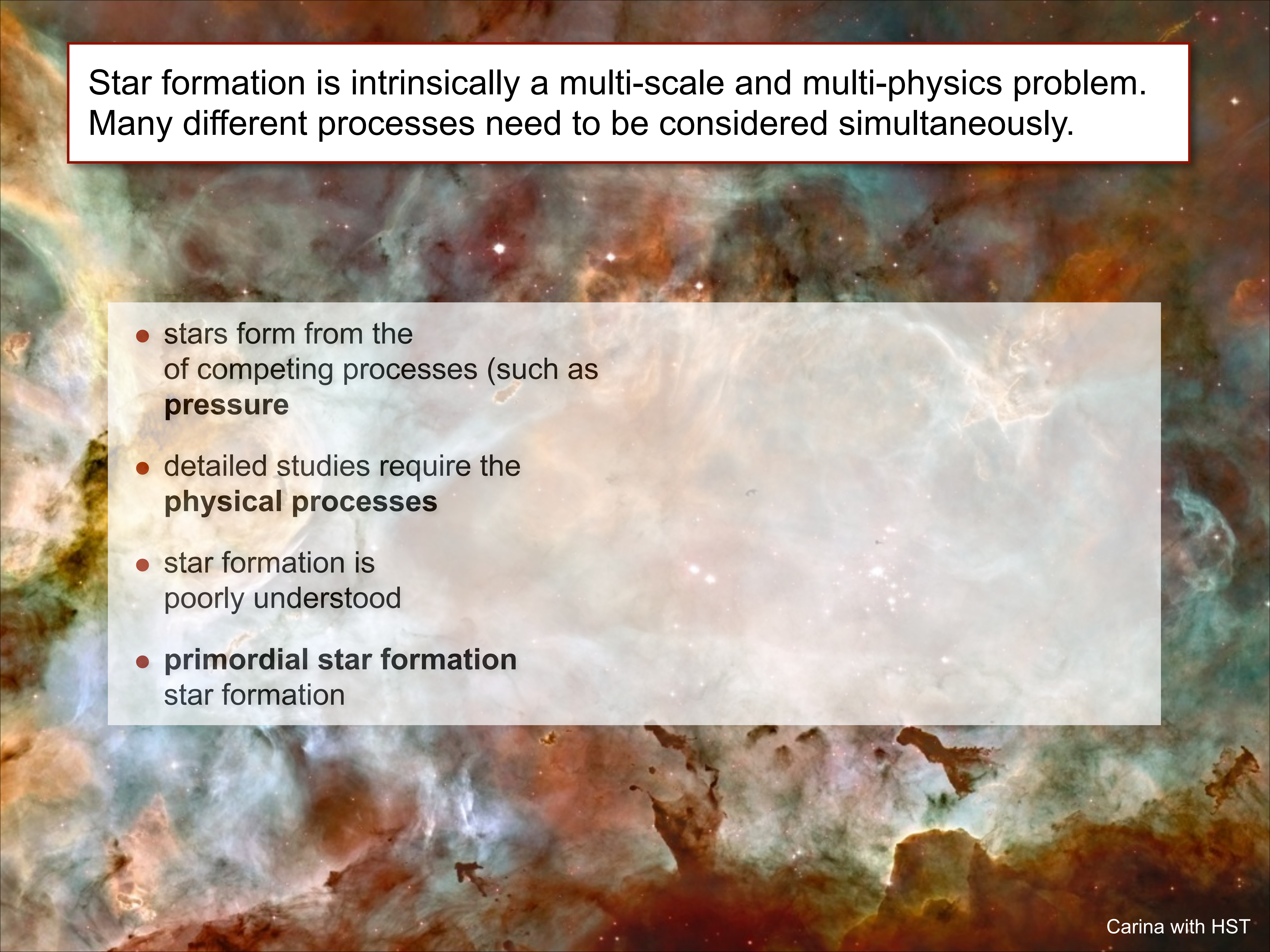
Star formation is intrinsically a multi-scale and multi-physics problem. Many different processes need to be considered simultaneously.


Carina with HST

- stars form from the of competing processes (such as **pressure**
- detailed studies require the **physical processes**
- star formation is poorly understood

Star formation is intrinsically a multi-scale and multi-physics problem. Many different processes need to be considered simultaneously.

- stars form from the
  of competing processes (such as
  pressure
- detailed studies require the
  physical processes
- star formation is
  poorly understood
- **primordial star formation**
  star formation



Carina with HST

thanks

Photo: Andre M. Hünseler