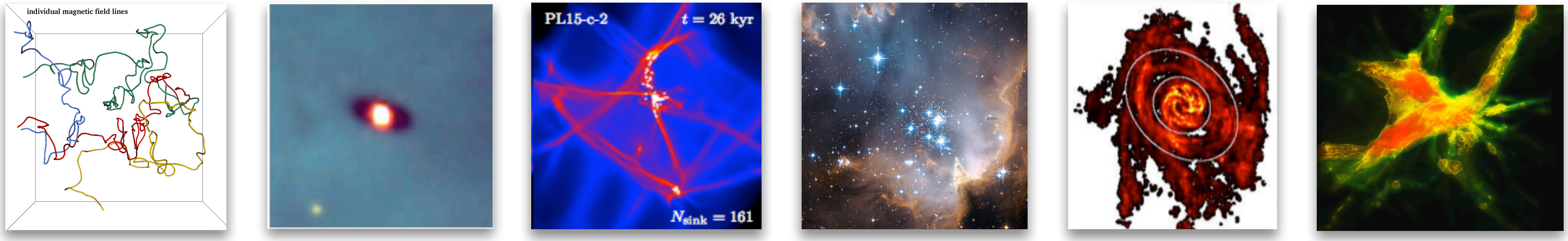
Star Formation



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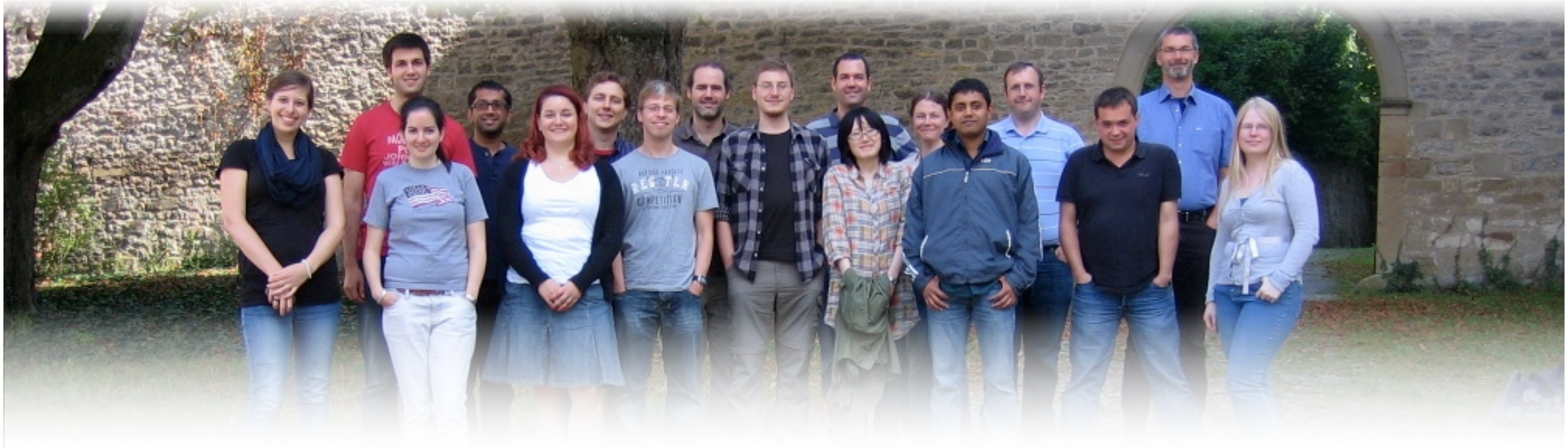
thanks to ...



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... many collaborators abroad!

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HGSFP

IMPRS

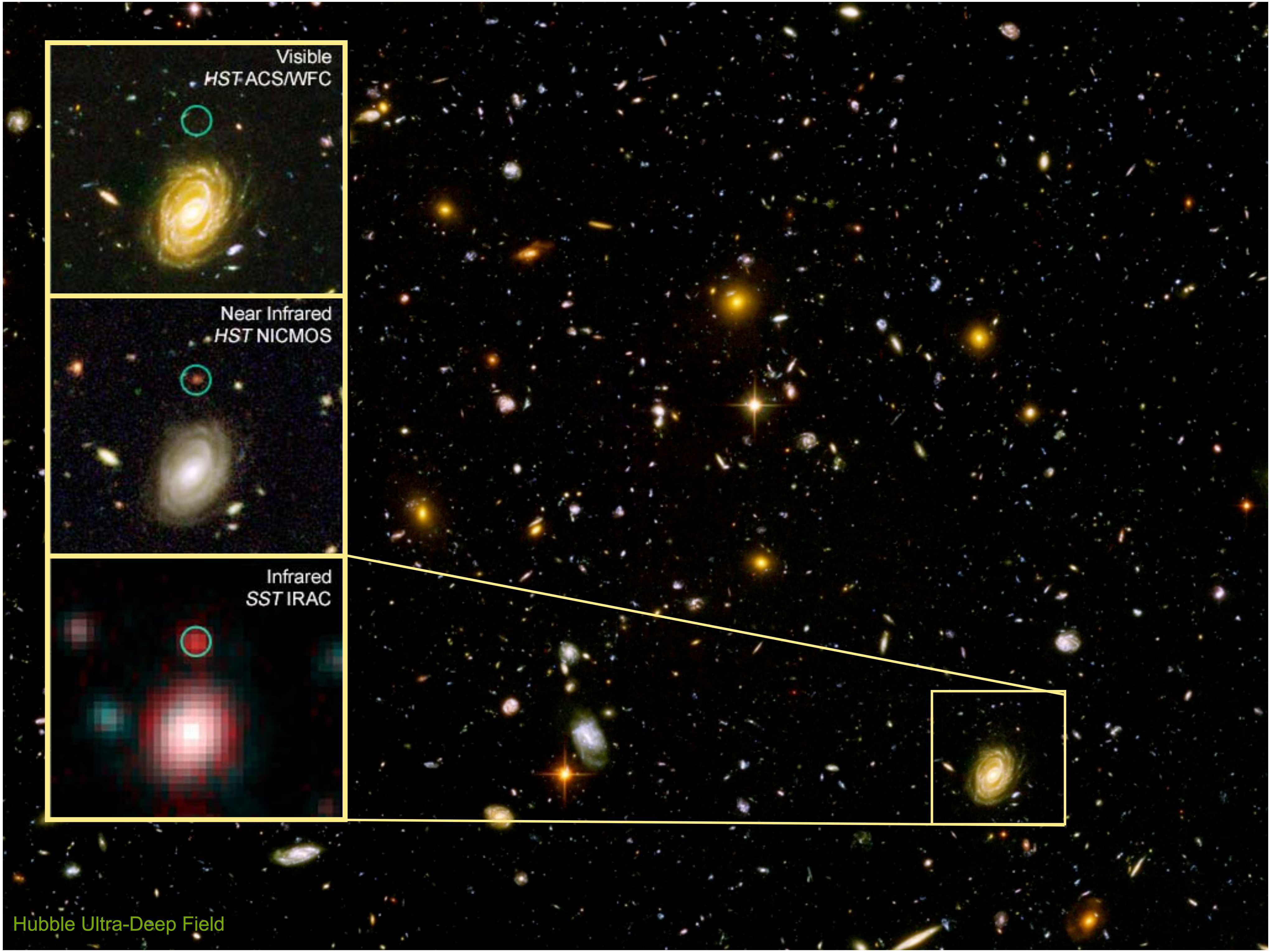
agenda

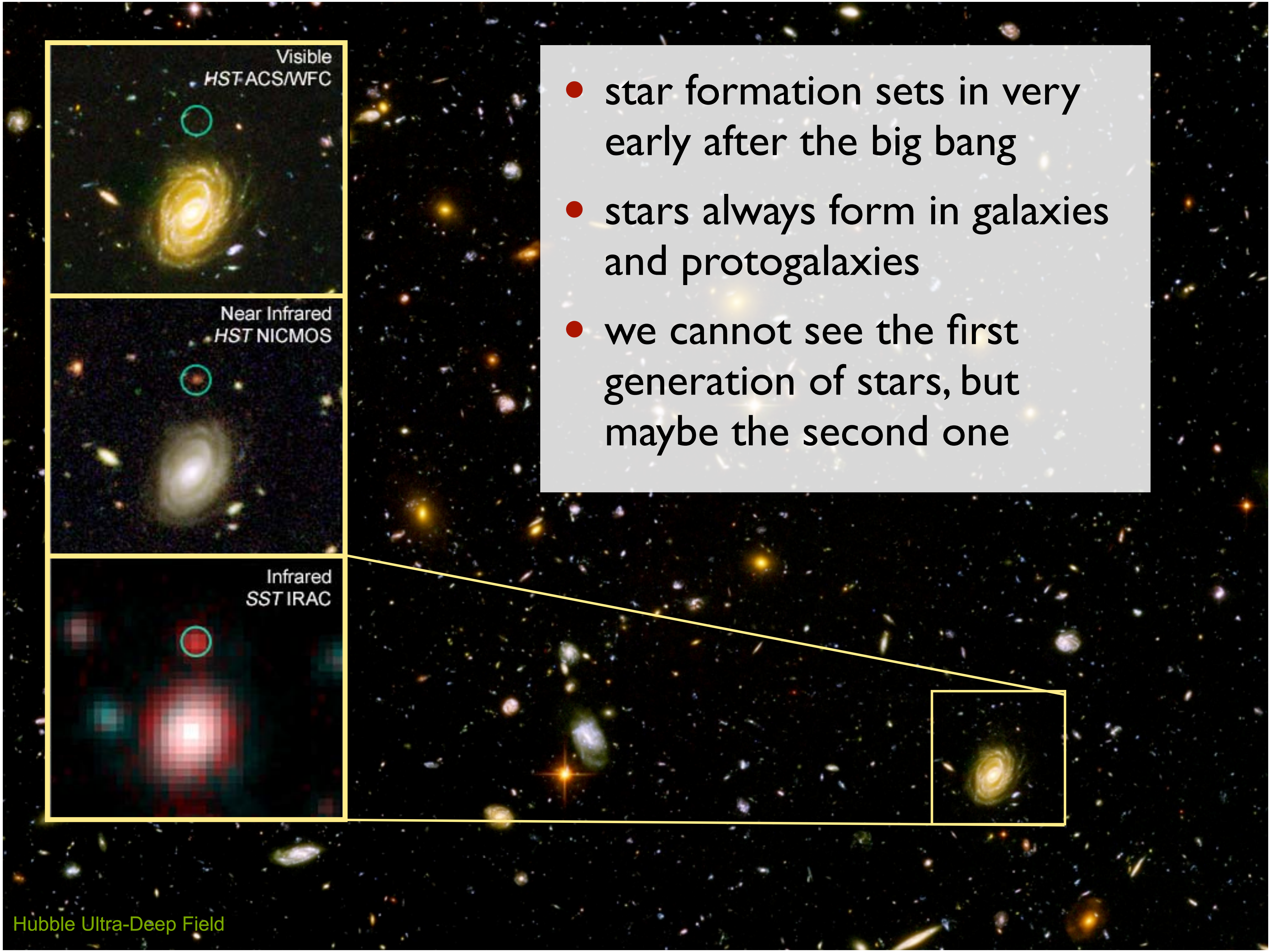
- star formation theory
  - phenomenology
  - historic remarks
  - our current understanding and its limitations
- application
  - the stellar mass function at birth (IMF)

NGC 3324 (Hubble, NASA/ESA)

phenomenology

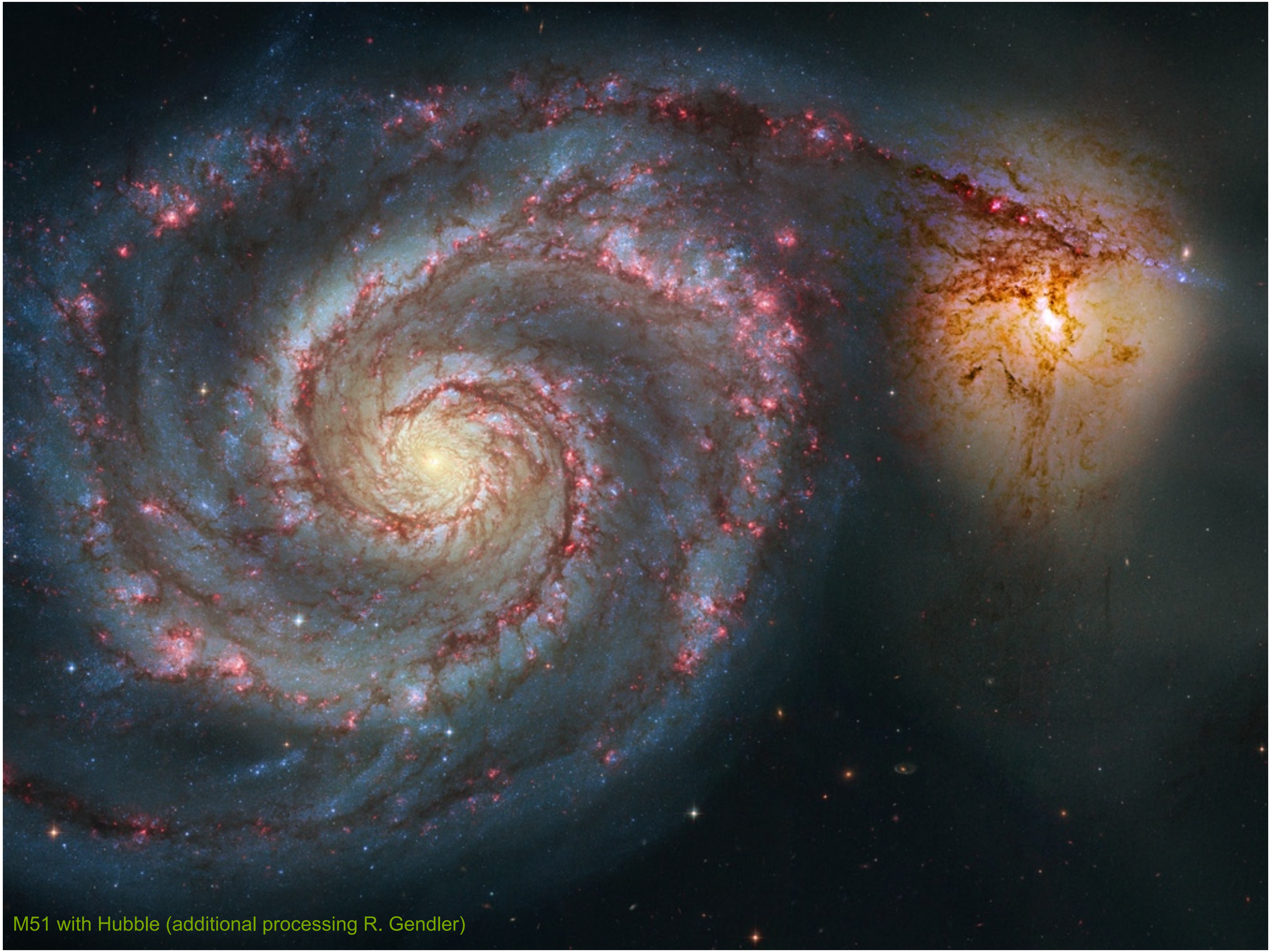
Hubble Ultra-Deep Field


Visible
HST ACS/WFC
Near Infrared
HST NICMOS
Infrared
SST IRAC
Hubble Ultra-Deep Field

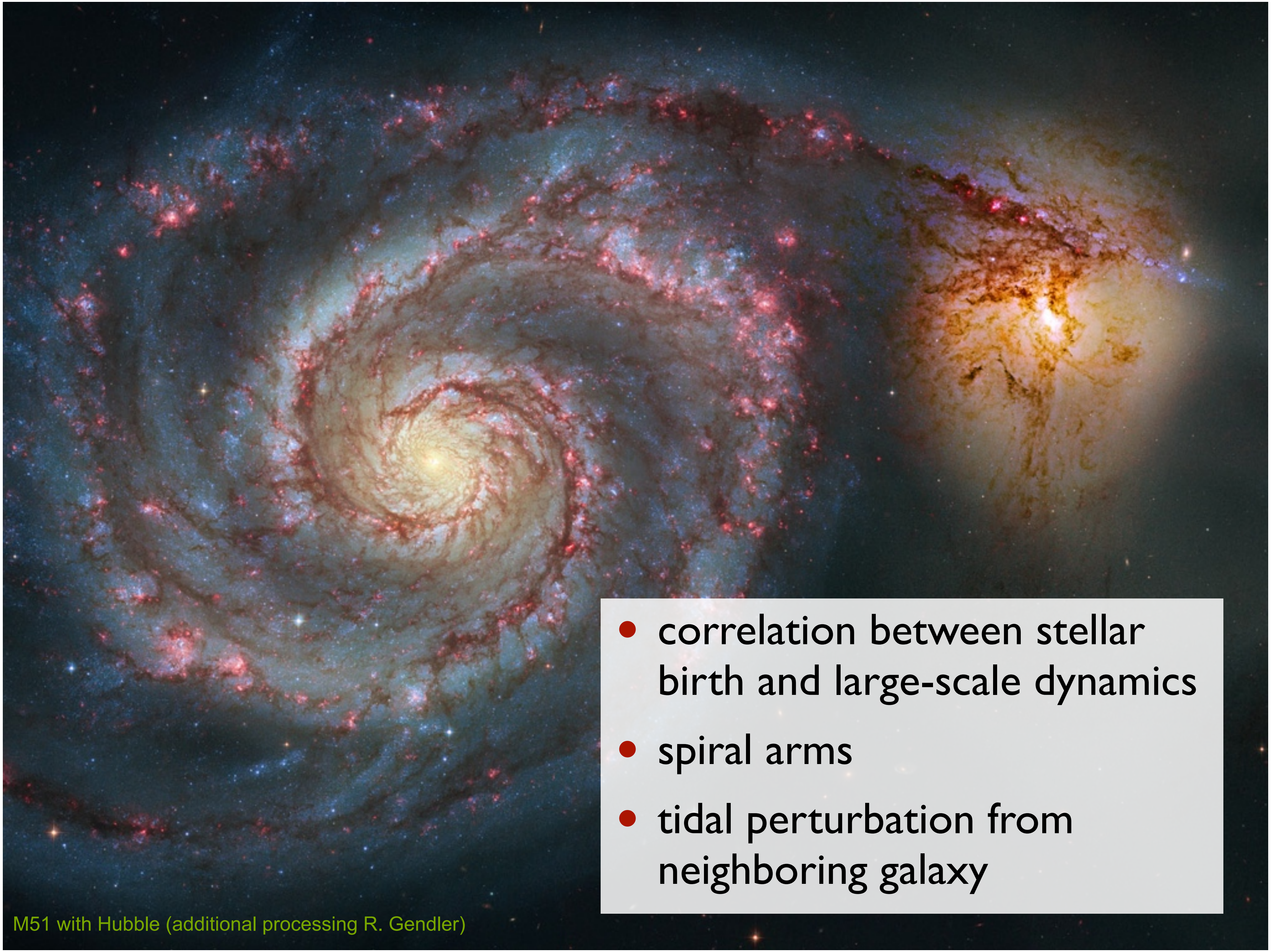


Hubble Ultra-Deep Field

- 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

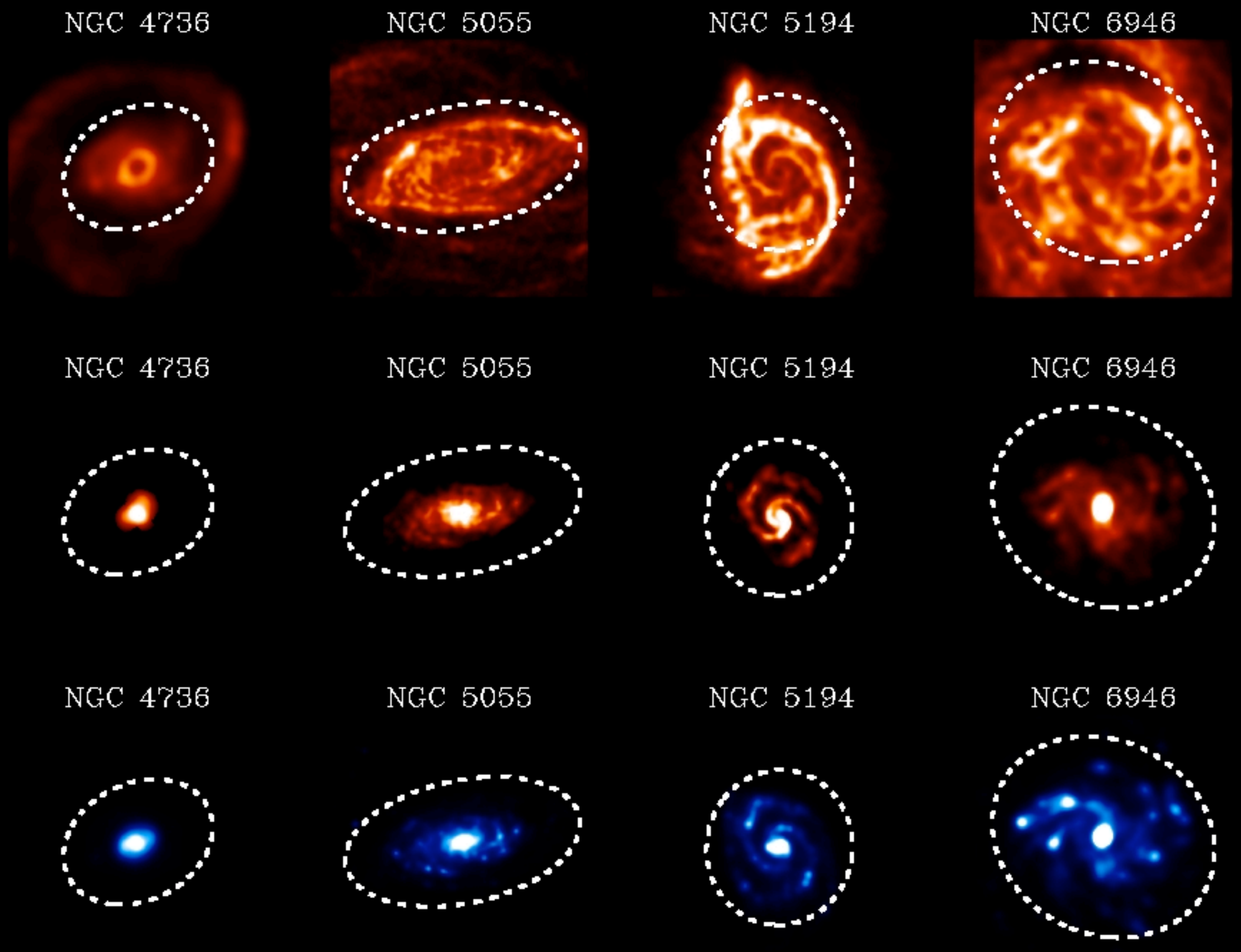


M51 with Hubble (additional processing R. Gendler)



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

M51 with Hubble (additional processing R. Gendler)

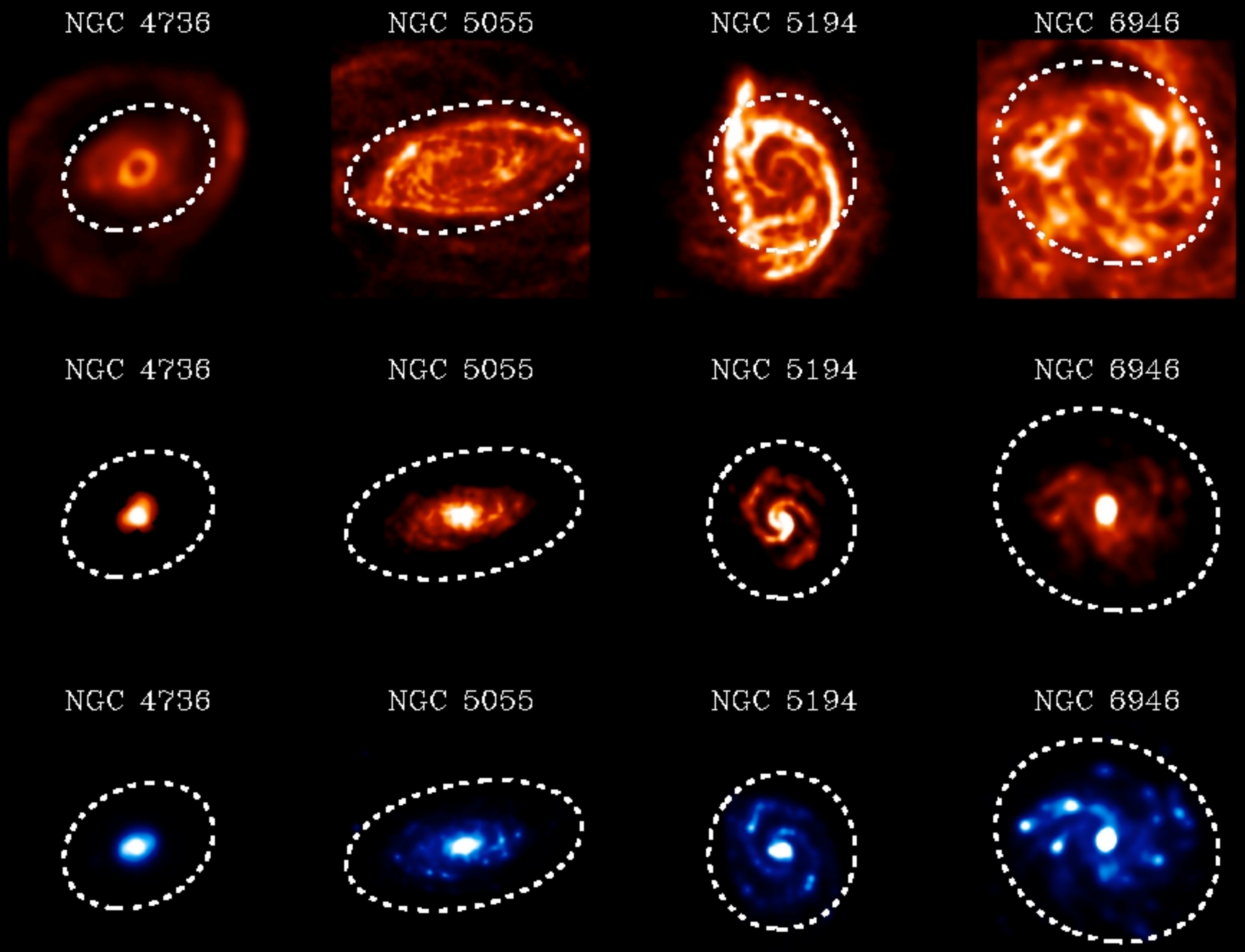


atomic hydrogen

molecular hydrogen

star formation

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



atomic hydrogen

molecular hydrogen

star formation

- HI gas more extended
- H2 and SF well correlated

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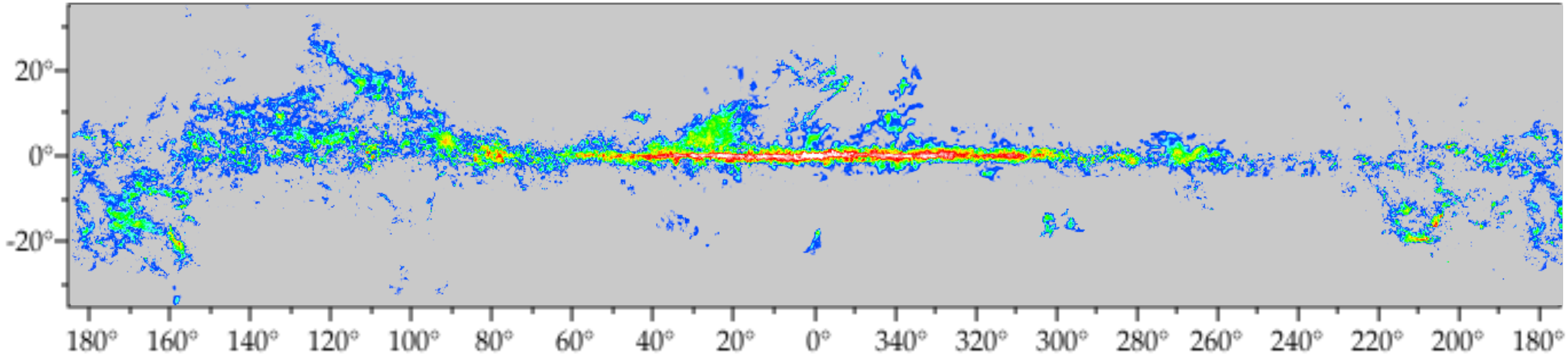
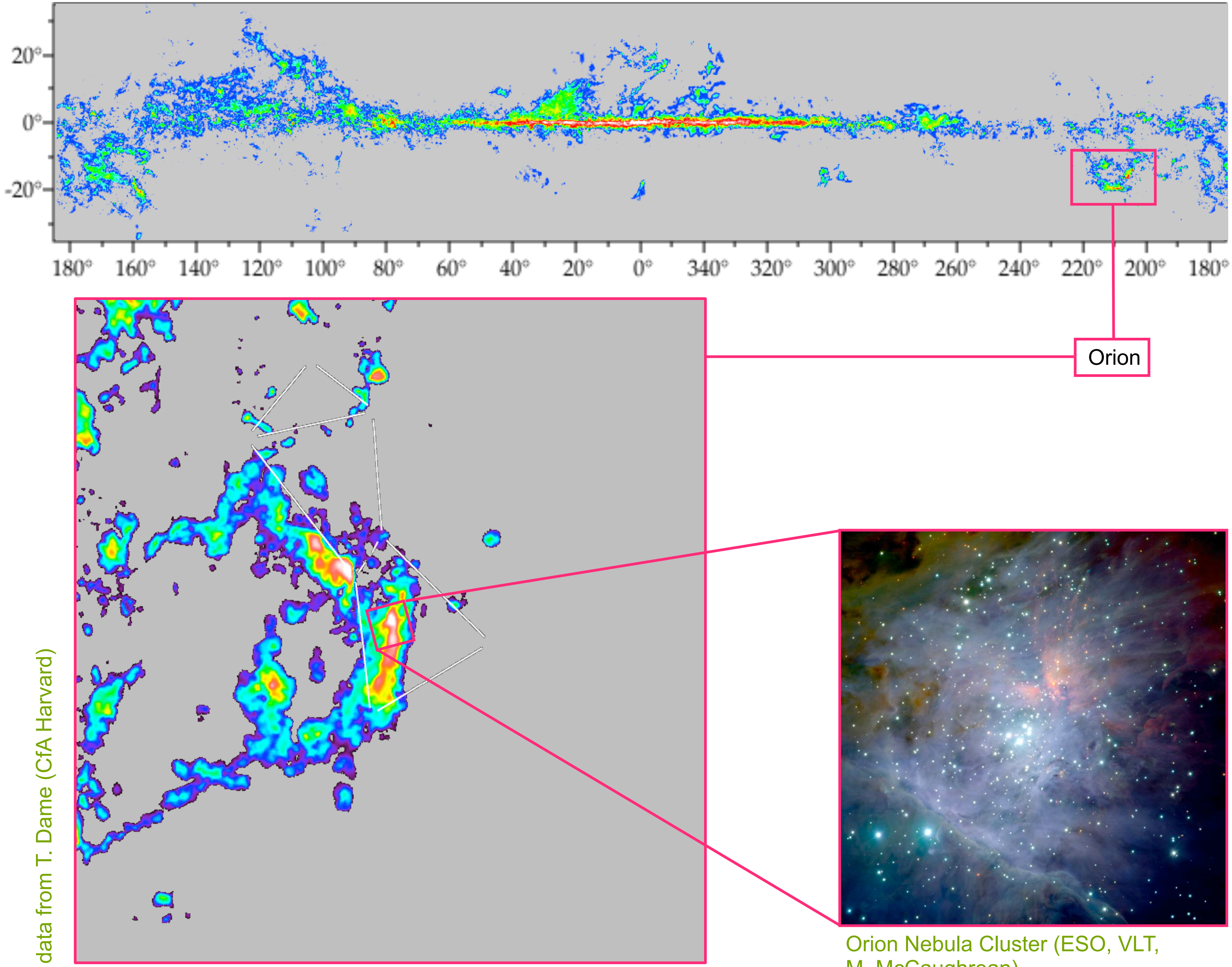


distribution of molecular
gas in the Milky Way as
traced by CO emission

data from T. Dame (CfA Harvard)



data from T. Dame (CfA Harvard)

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

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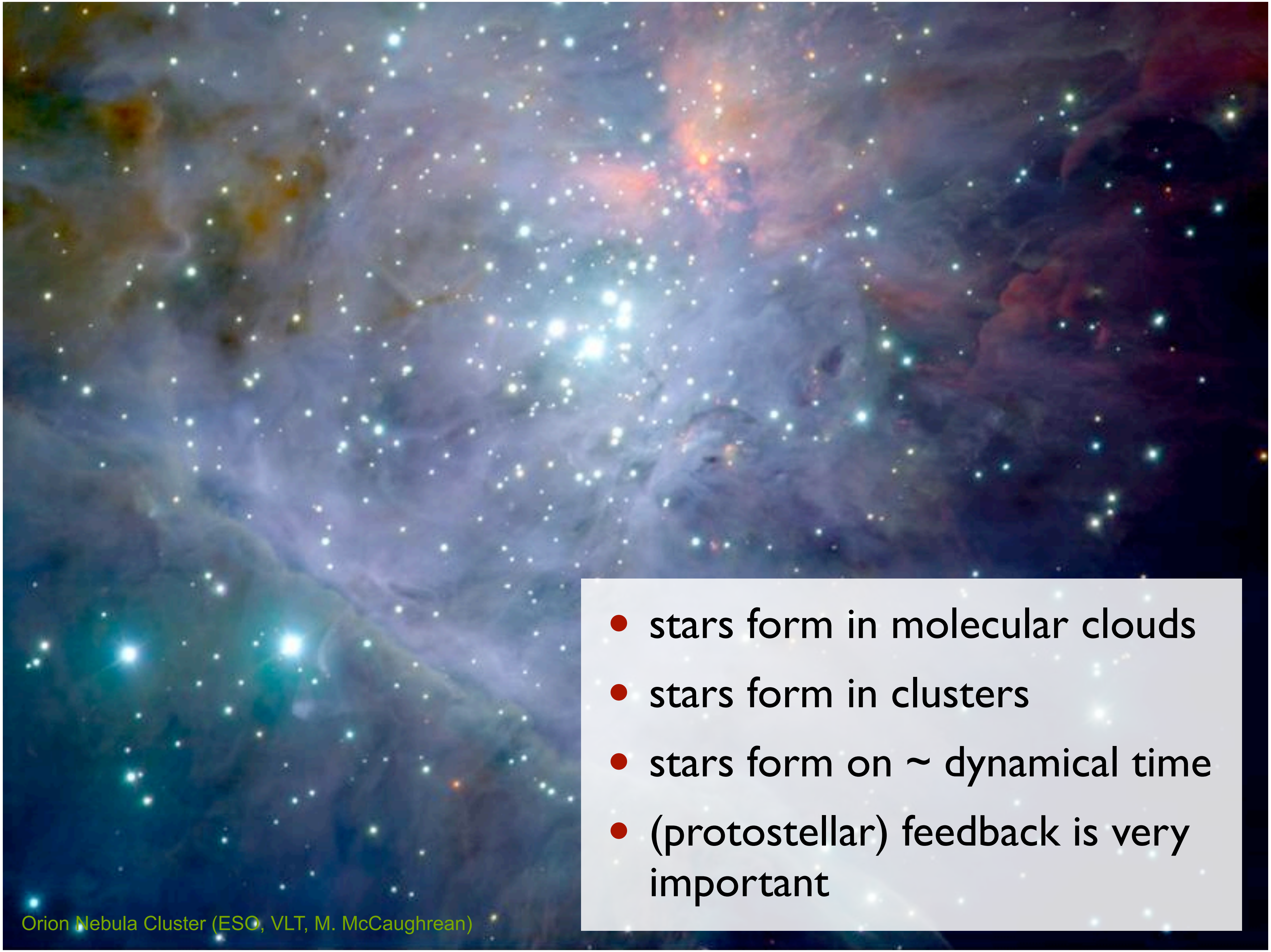
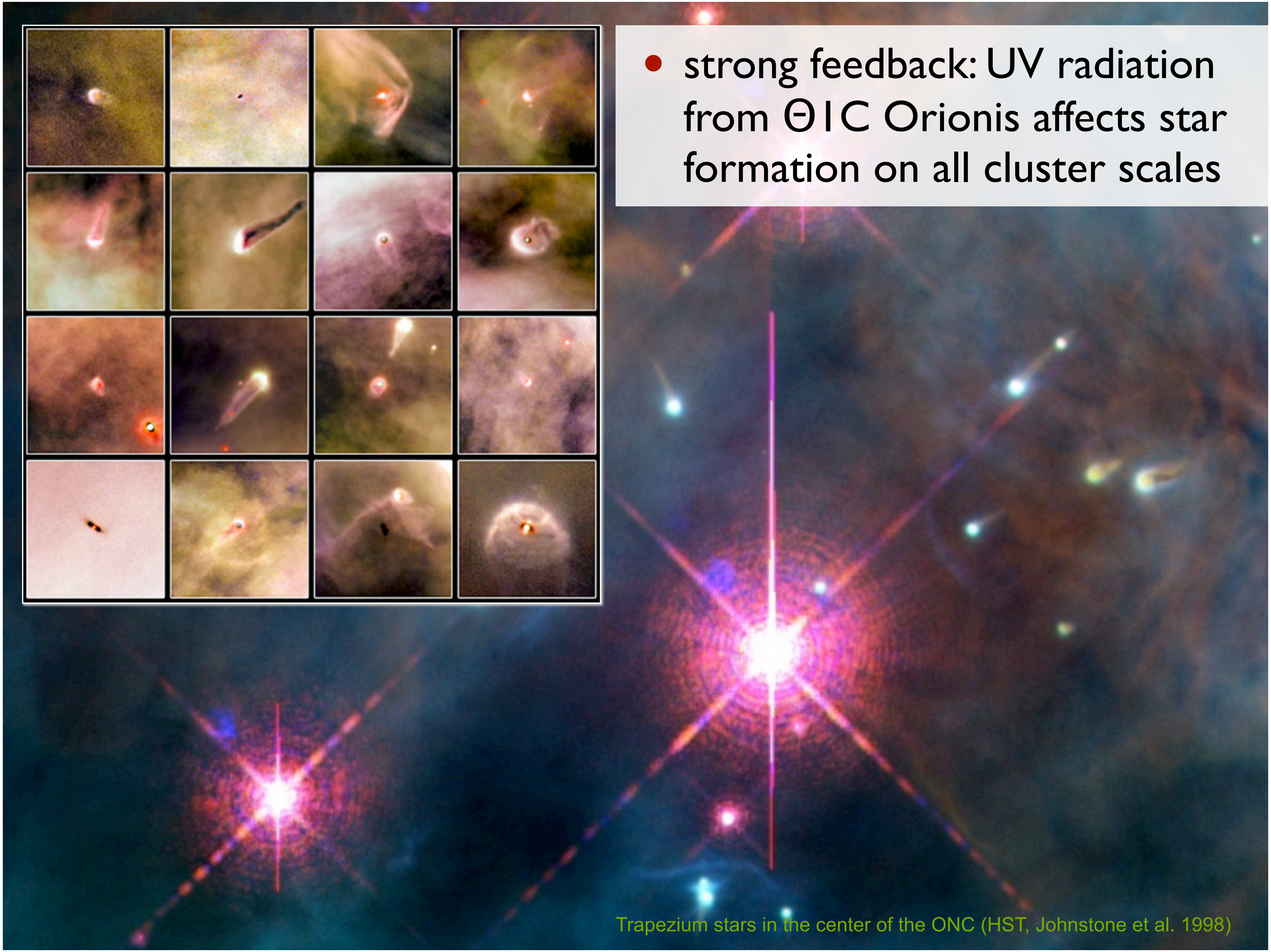


Orion Nebula Cluster (ESO, VLT, M. McCaughrean)

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

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

- 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)

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

Pleiades (DSS, Palomar Observatory Sky Survey)

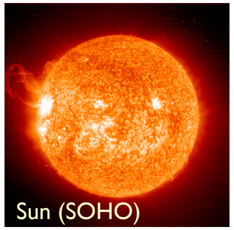
theoretical approach

decrease in spatial scale / increase in density


Andromeda (R. Gendler)


NGC 602 in LMC (Hubble)


Proplyd in Orion (Hubble)


Sun (SOHO)


Earth

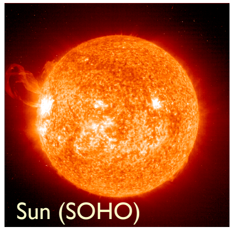
- density
  - density of ISM: few particles per cm^3
  - density of molecular cloud: few 100 particles per cm^3
  - density of Sun: 1.4 g/cm^3
- spatial scale
  - size of molecular cloud: few 10s of pc
  - size of young cluster: ~ 1 pc
  - size of Sun: 1.4×10^{10} cm

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***

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

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

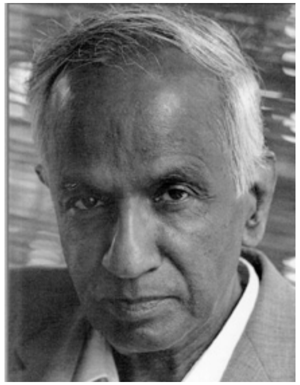
first approach to turbulence

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

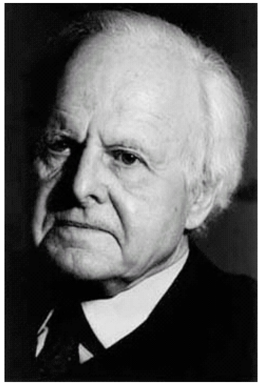
    $\ell_{\mathrm{turb}} \ll \ell_{\mathrm{dyn}}$
  - then turbulent velocity dispersion contributes to effective soundspeed:

    $$\boxed{c_c^2 \mapsto c_c^2 + \sigma_{rms}^2}$$
  - → 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

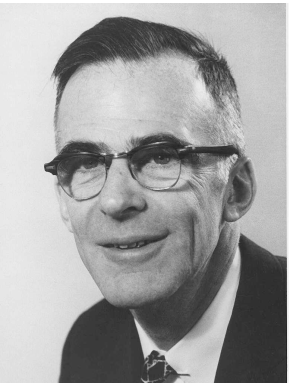
- *Mestel & Spitzer (1956):* Magnetic fields can prevent collapse*!!!*
  - Critical mass for gravitational collapse in presence of B-field

$$M_{cr} = \frac{5^{3/2}}{48\pi^2}\frac{B^3}{G^{3/2}\rho^2}$$

  - 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

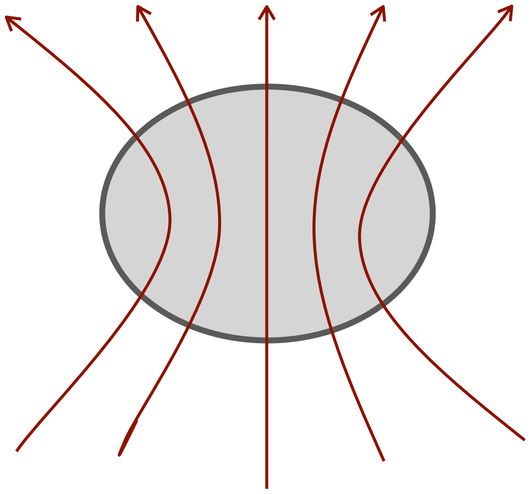


Lyman Spitzer, Jr., 1914 - 1997

“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
  - $dM/dt = 0.975\ c_s^3/G = \mathrm{const.}$
- 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)

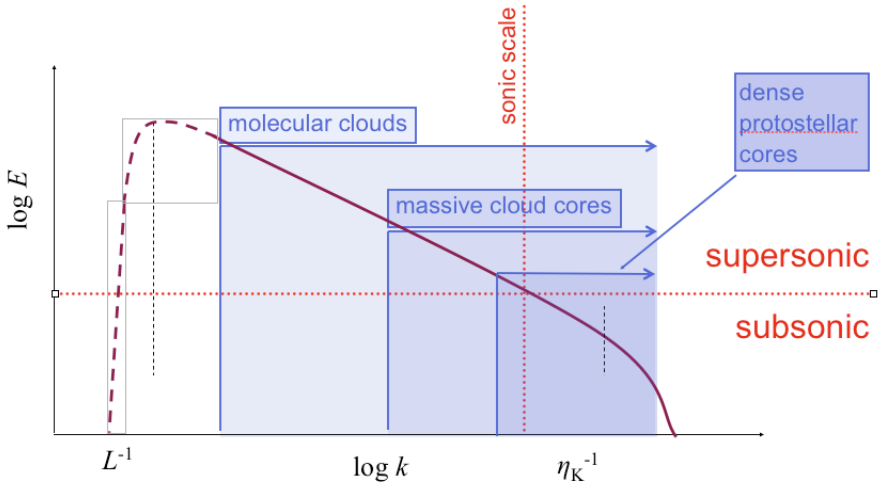
(see e.g. Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194)

gravoturbulent star formation

- BASIC ASSUMPTION:

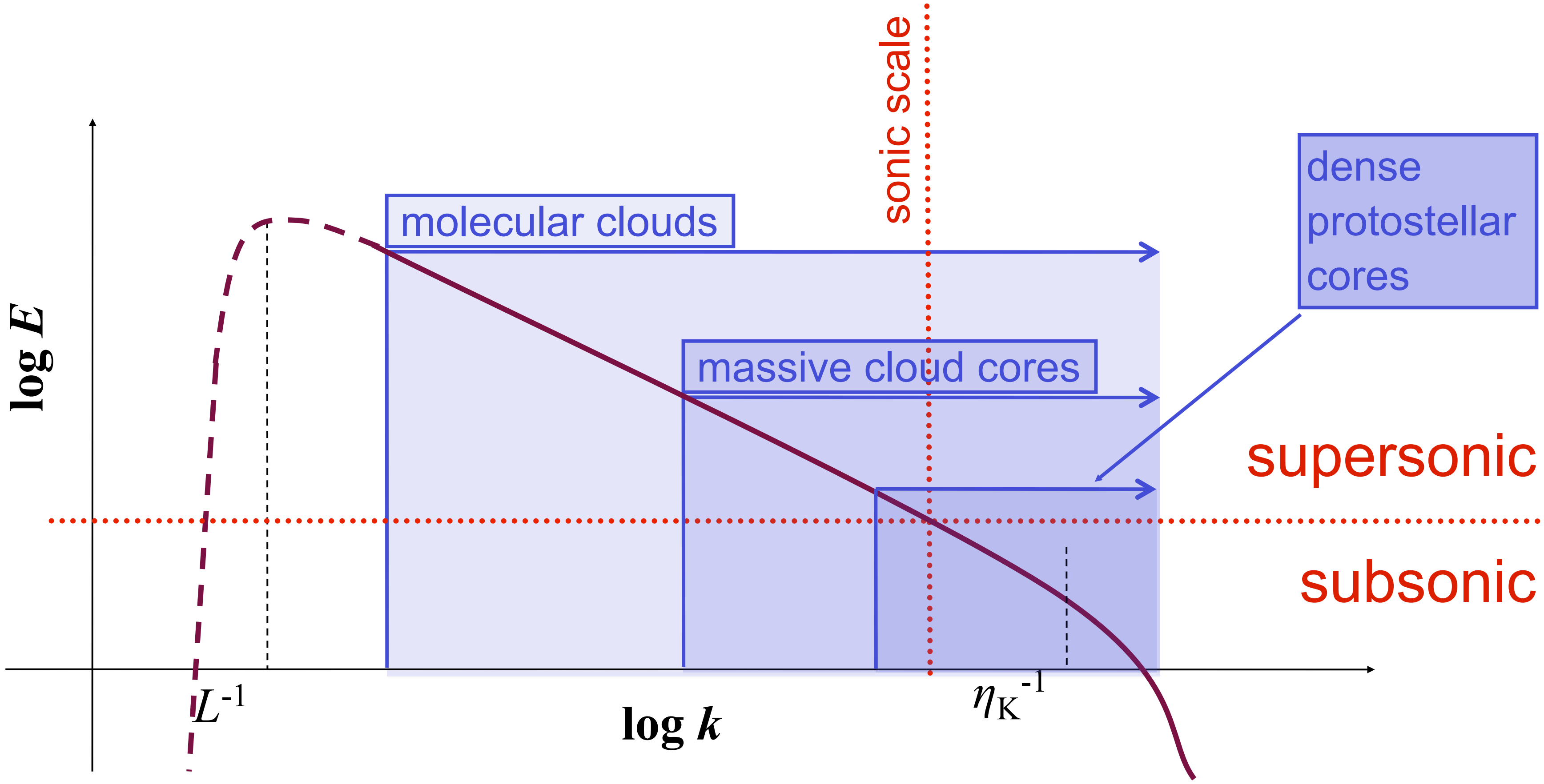
star formation is controlled by interplay between supersonic turbulence and self-gravity

- 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

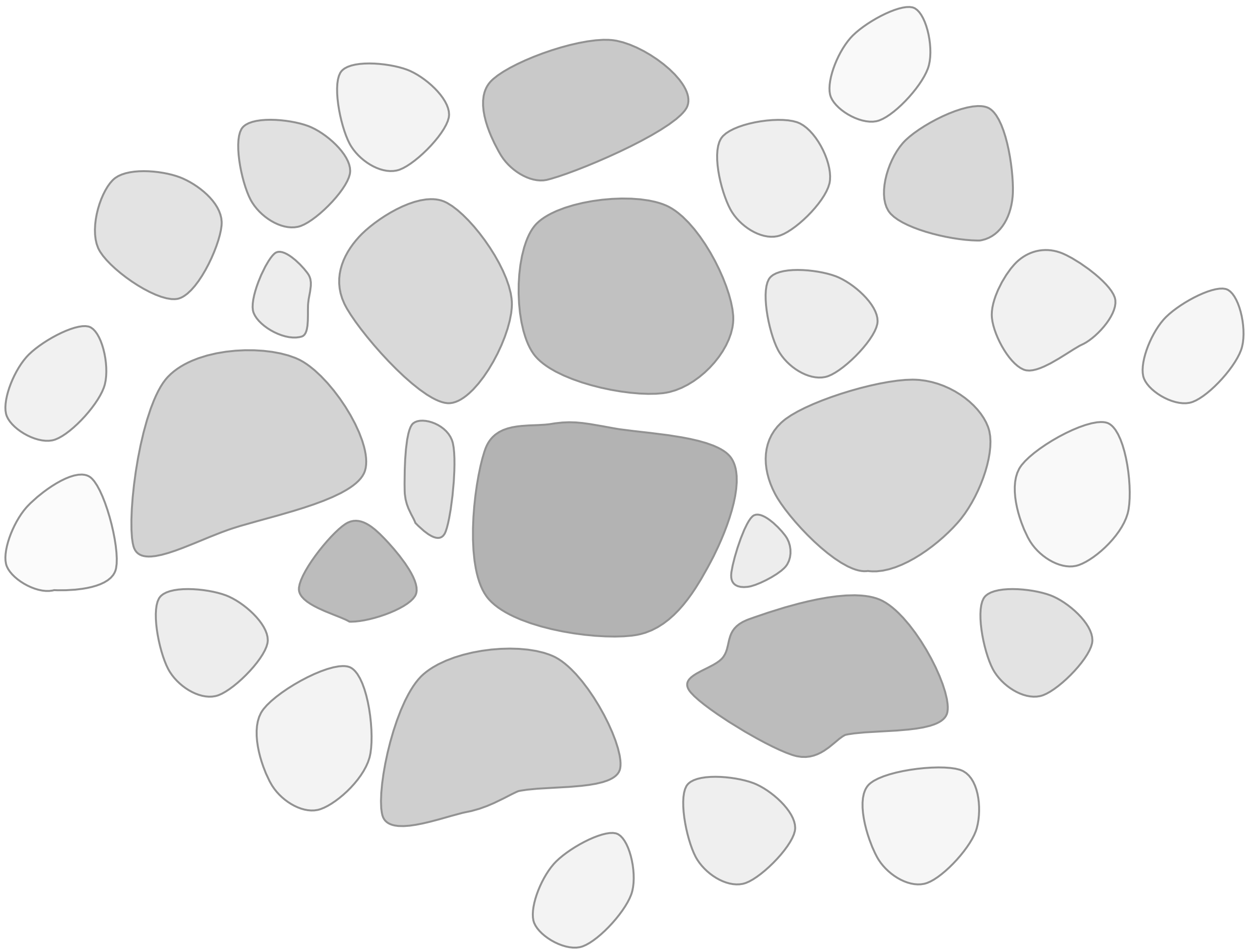
turbulent cascade in the ISM



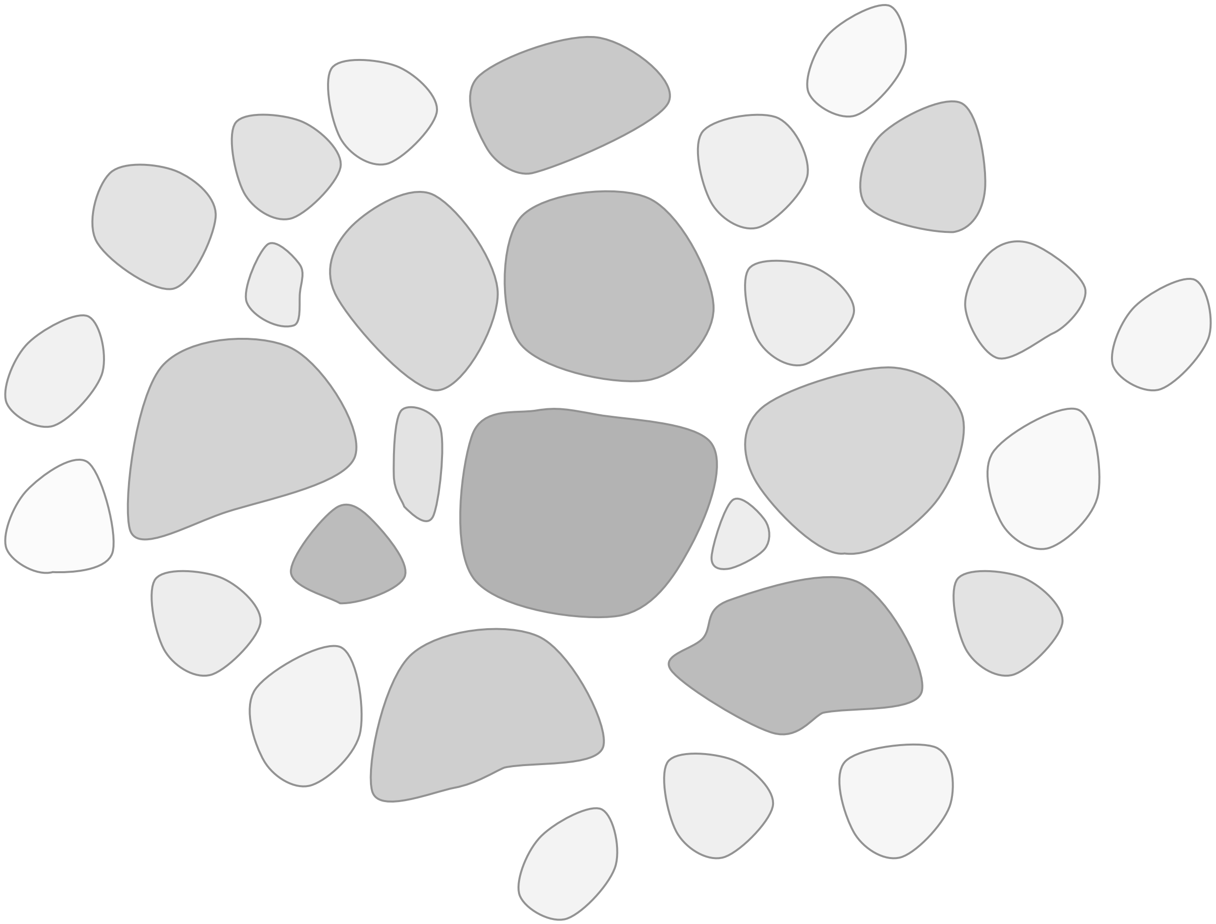
energy source & scale
NOT known
(supernovae, winds,
spiral density waves?)

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

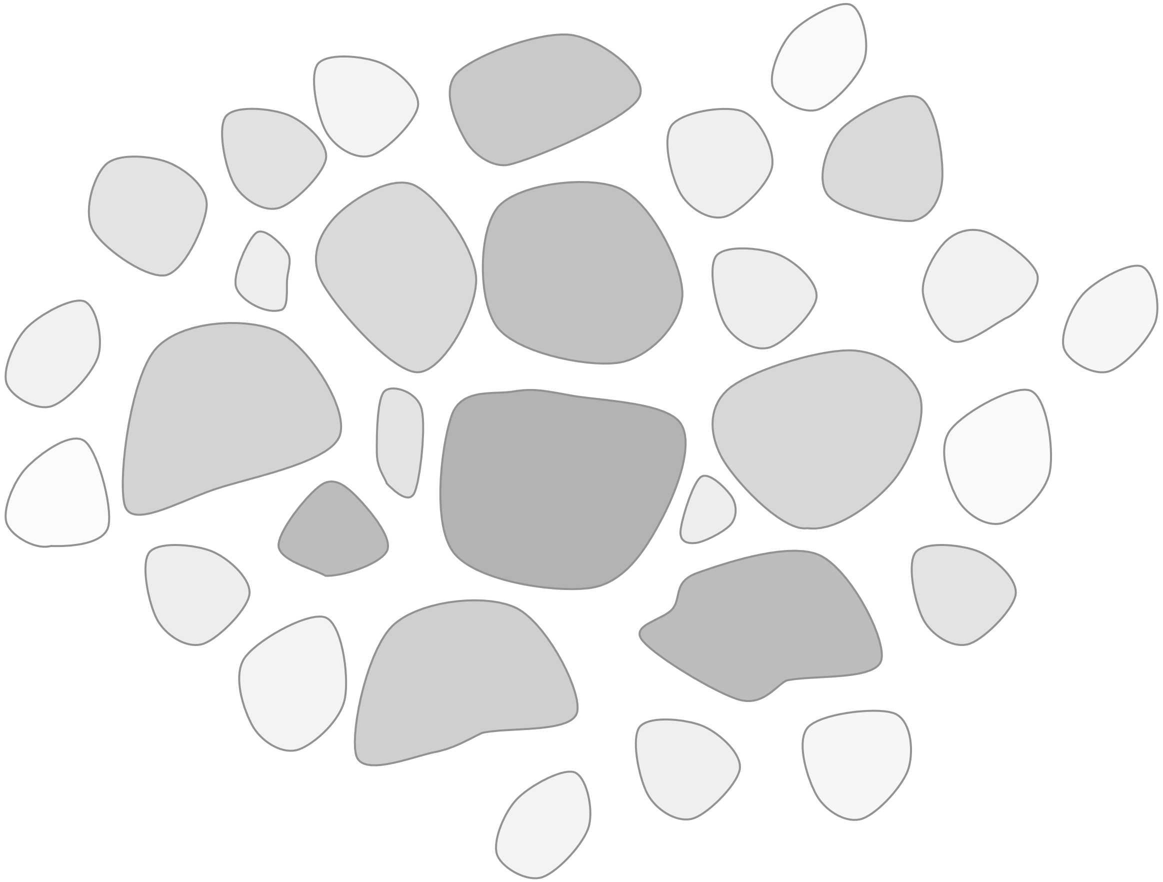
dissipation scale not known
(ambipolar diffusion,
molecular diffusion?)



turbulence creates a hierarchy of clumps



as turbulence decays locally, contraction sets in



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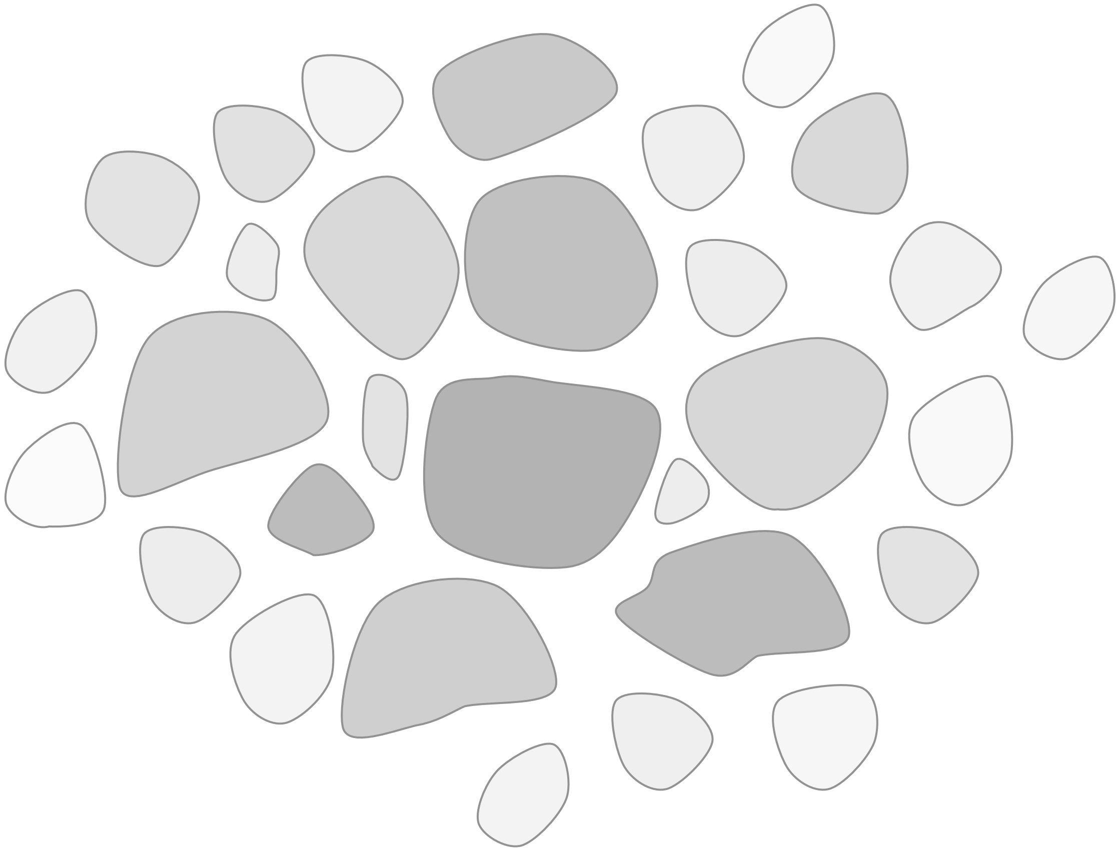
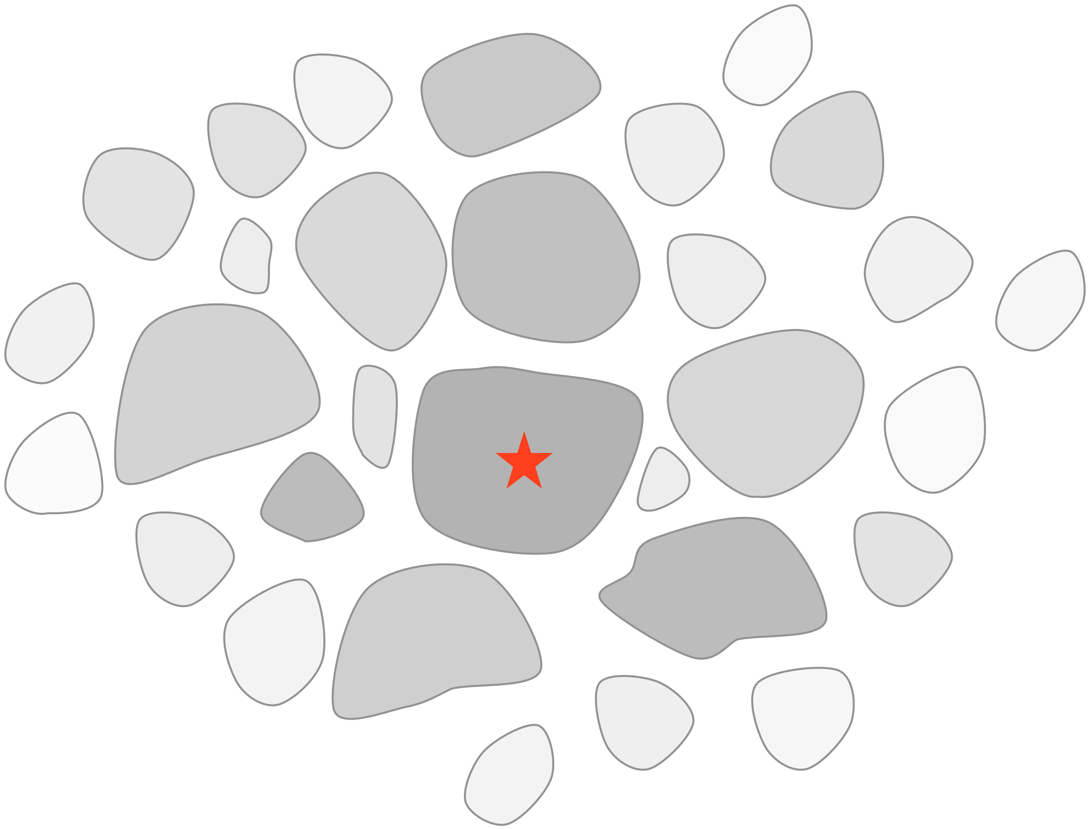


while region contracts, individual clumps collapse to form stars



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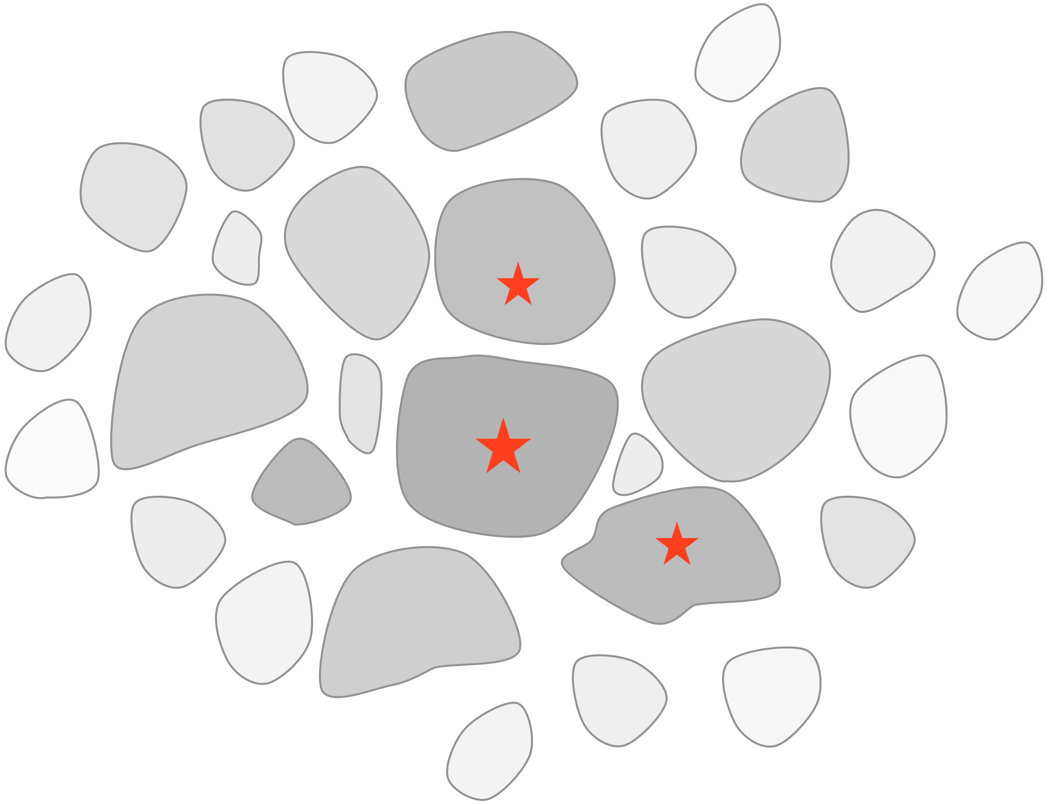

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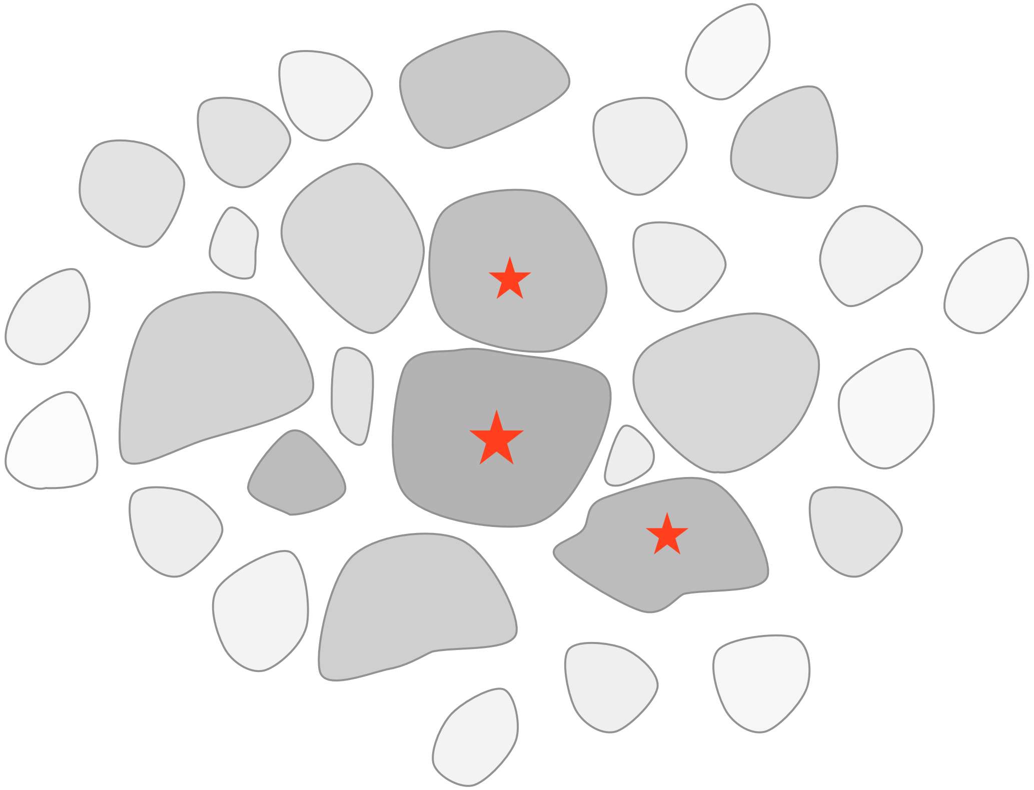
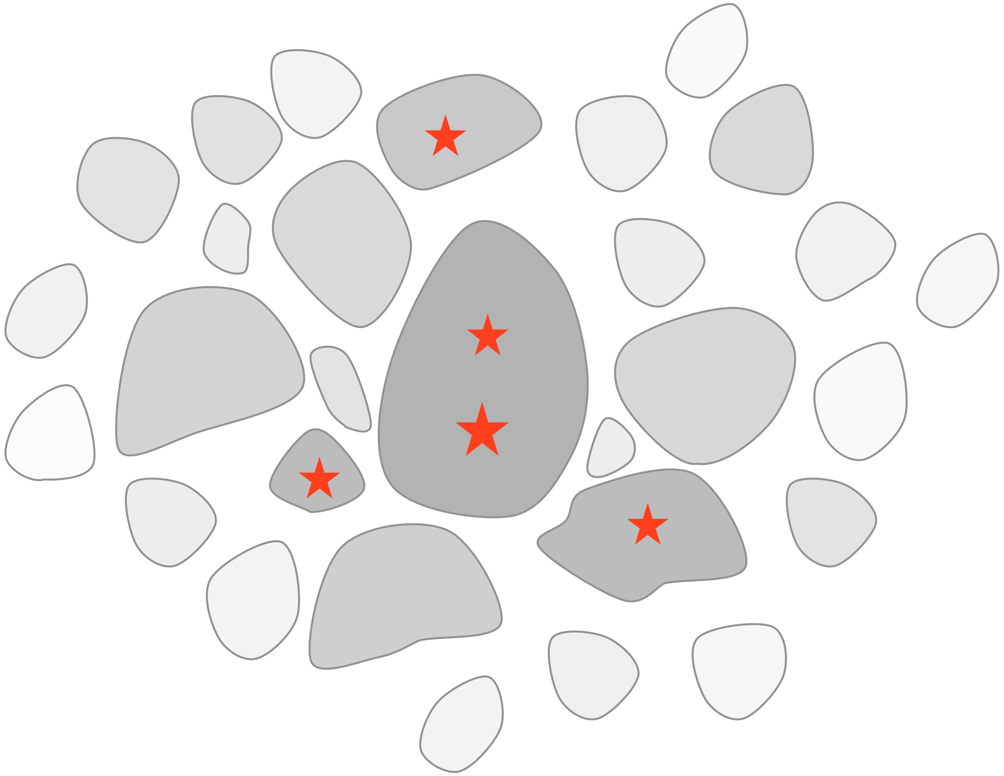
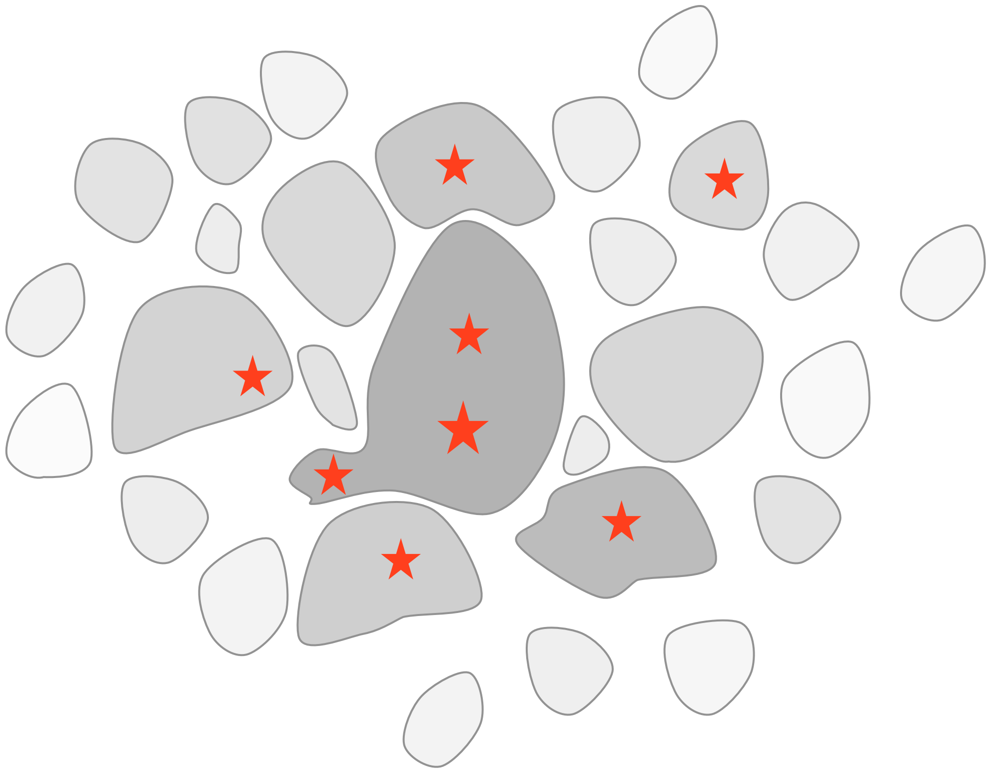


individual clumps collapse to form stars



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

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



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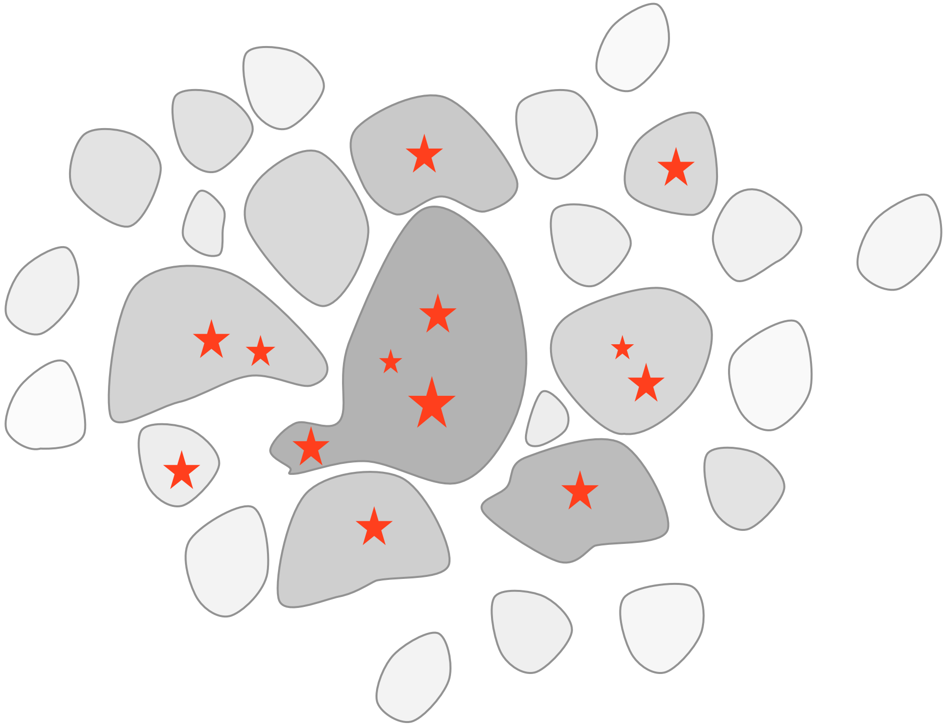

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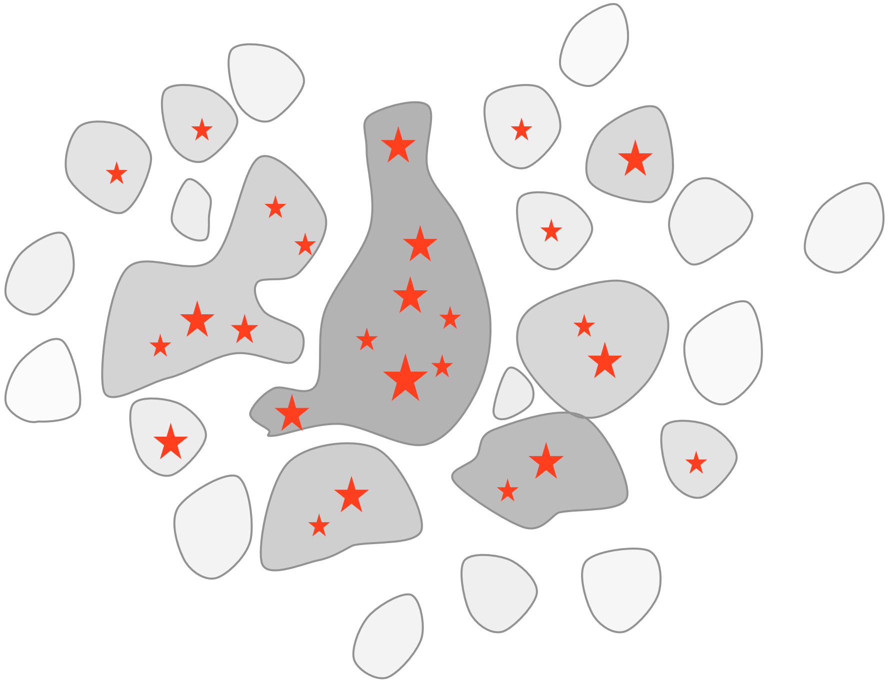
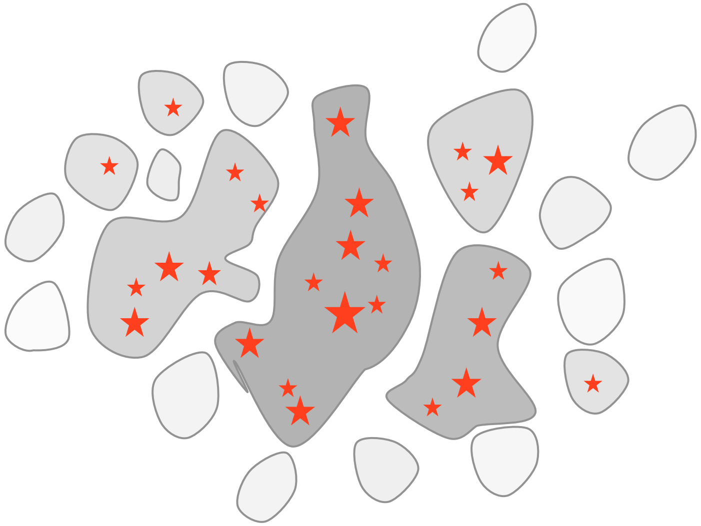


in *dense clusters*, competitive mass growth becomes important



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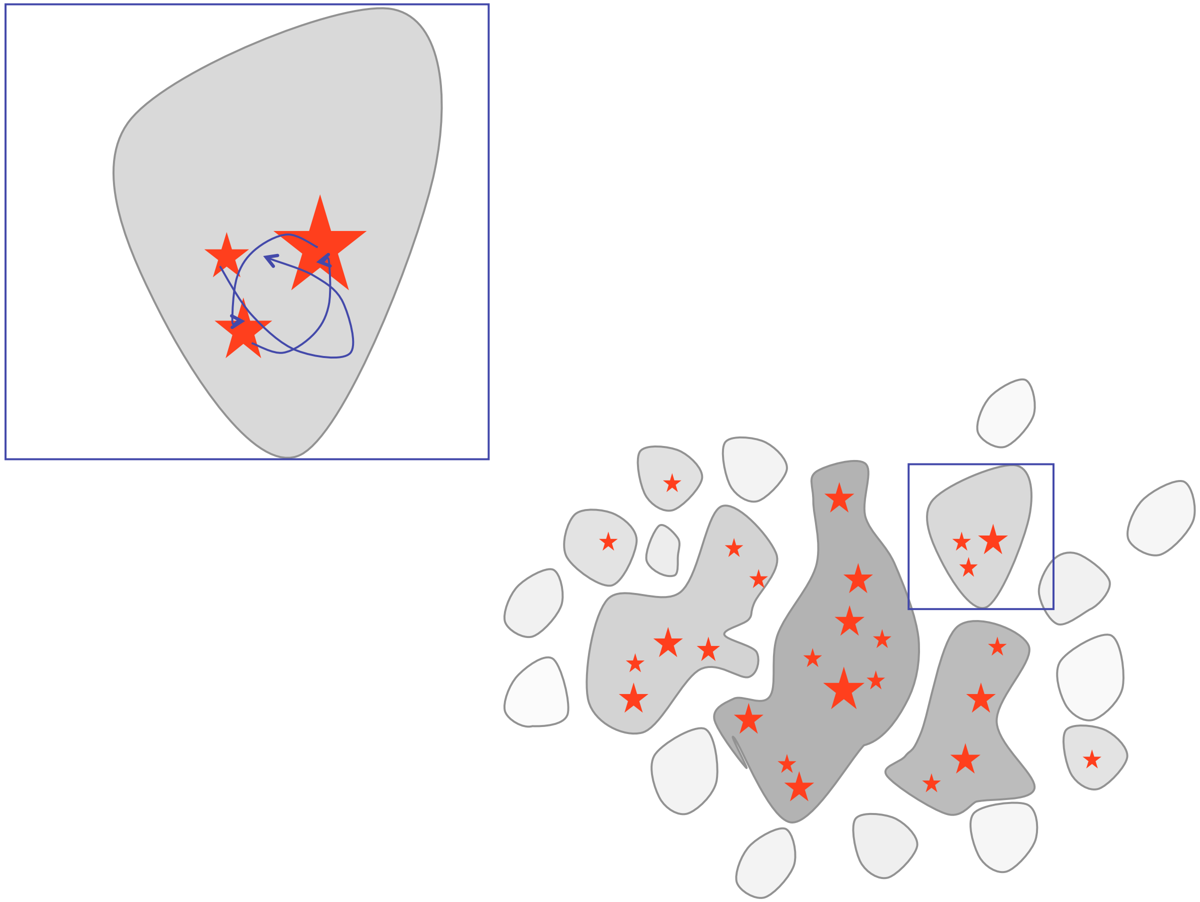
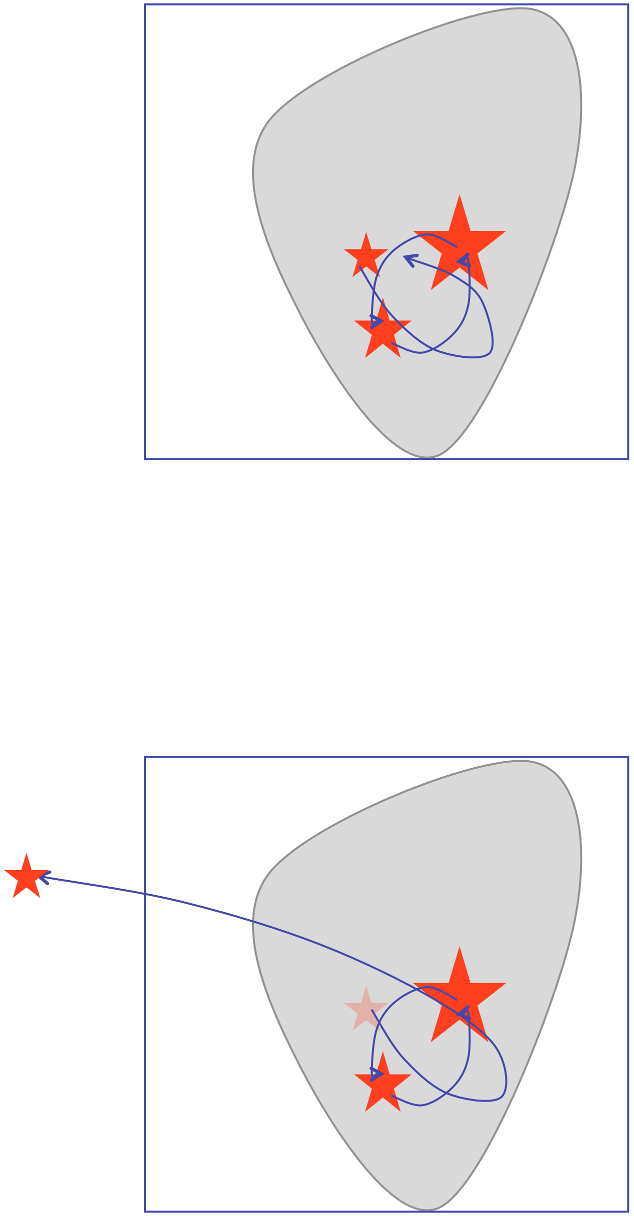
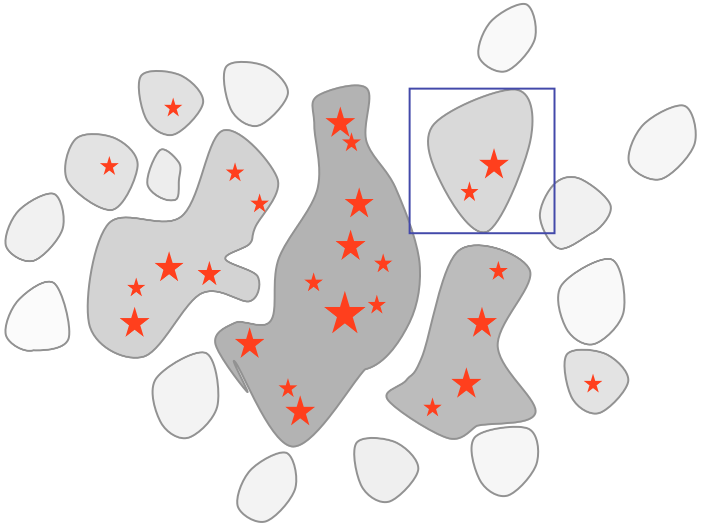
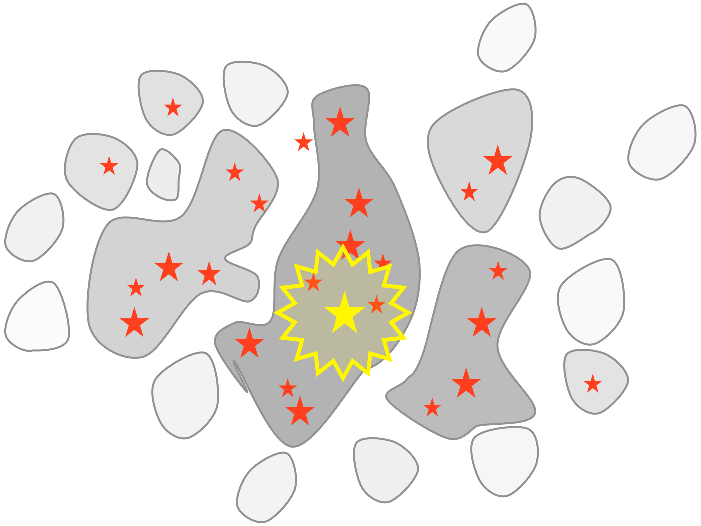


in *dense clusters*, *N*-body effects influence mass growth

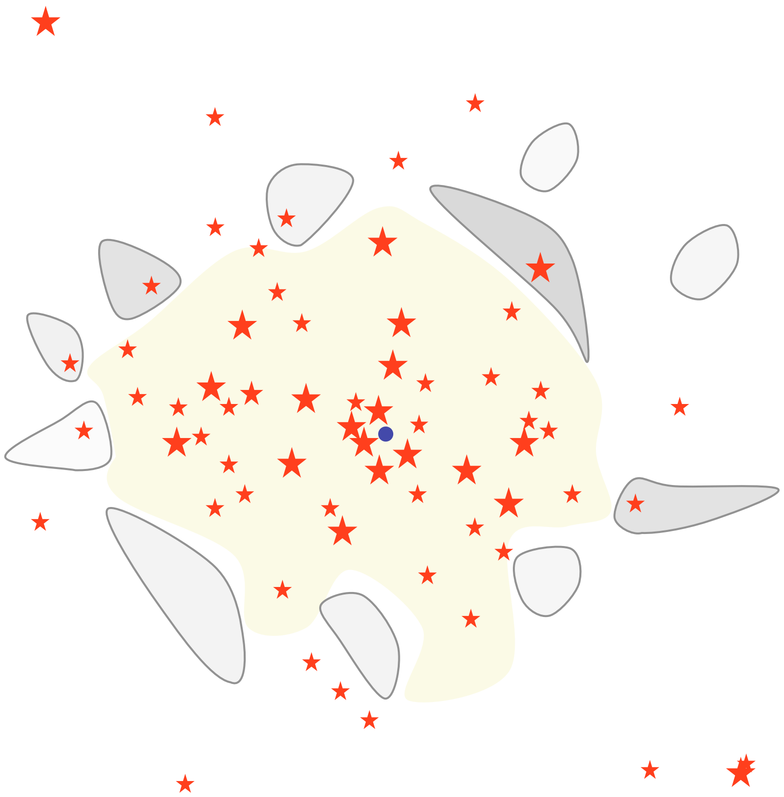




low-mass objects may
become ejected --> accretion stops



feedback terminates star formation



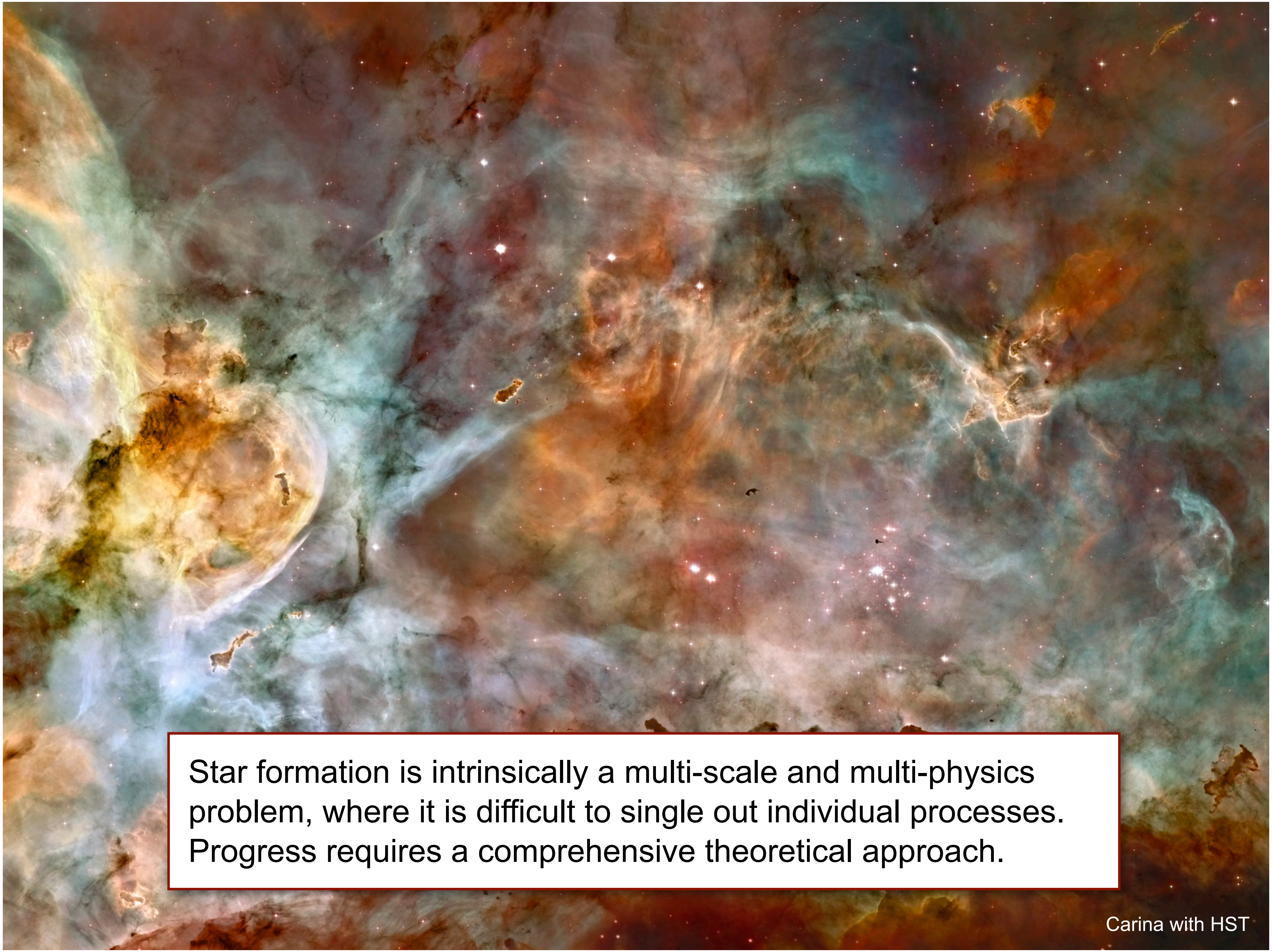
result: *star cluster*, possibly with HII region

NGC 602 in the LMC: Hubble Heritage Image

current status

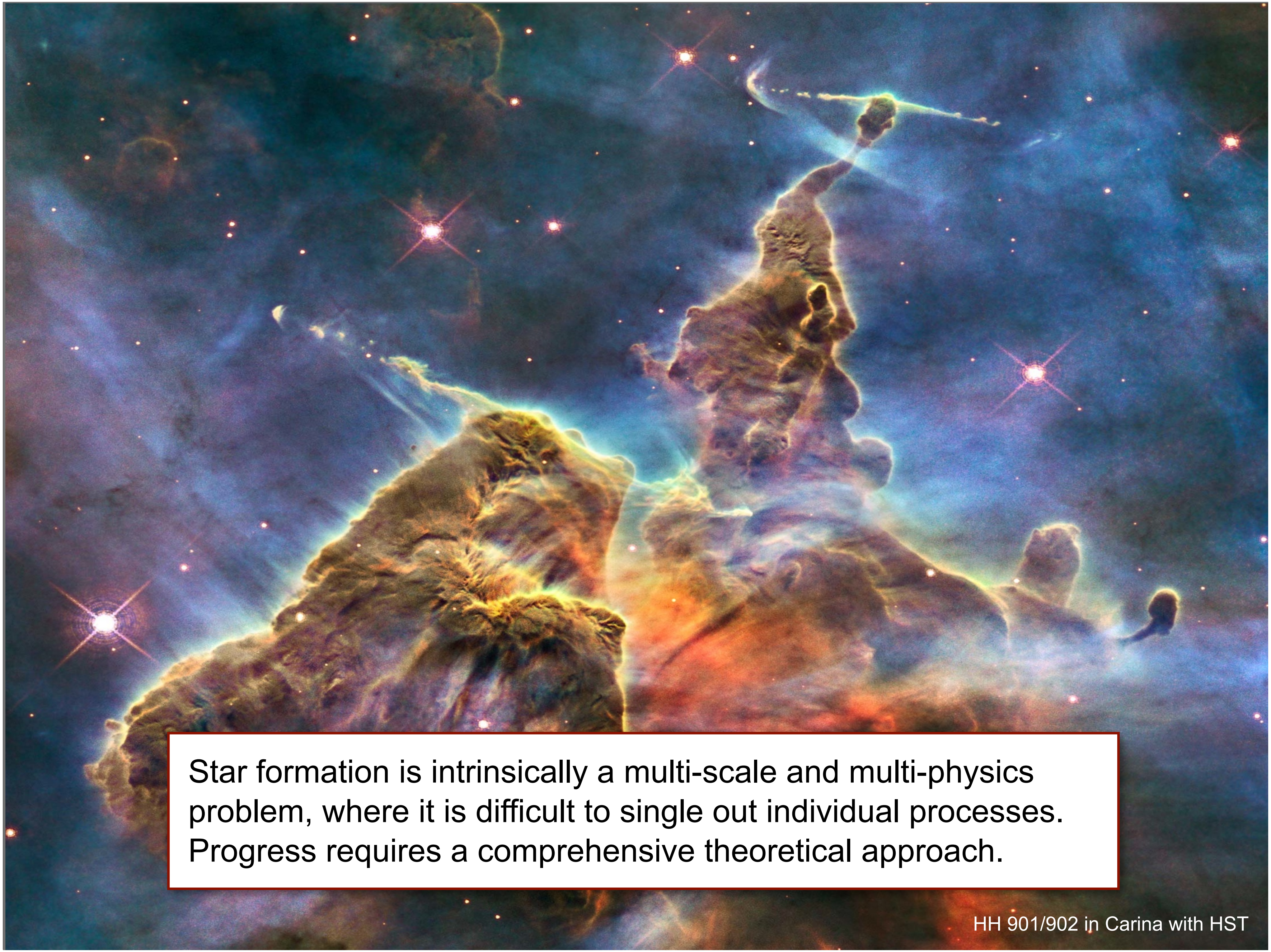
- *stars form from the complex interplay of self-gravity and a large number of competing processes (such as turbulence, B-field, feedback, thermal pressure)*
- *the relative importance of these processes depends on the environment*
  - prestellar cores --> thermal pressure is important
    molecular 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 theoretical approach.

Carina with HST

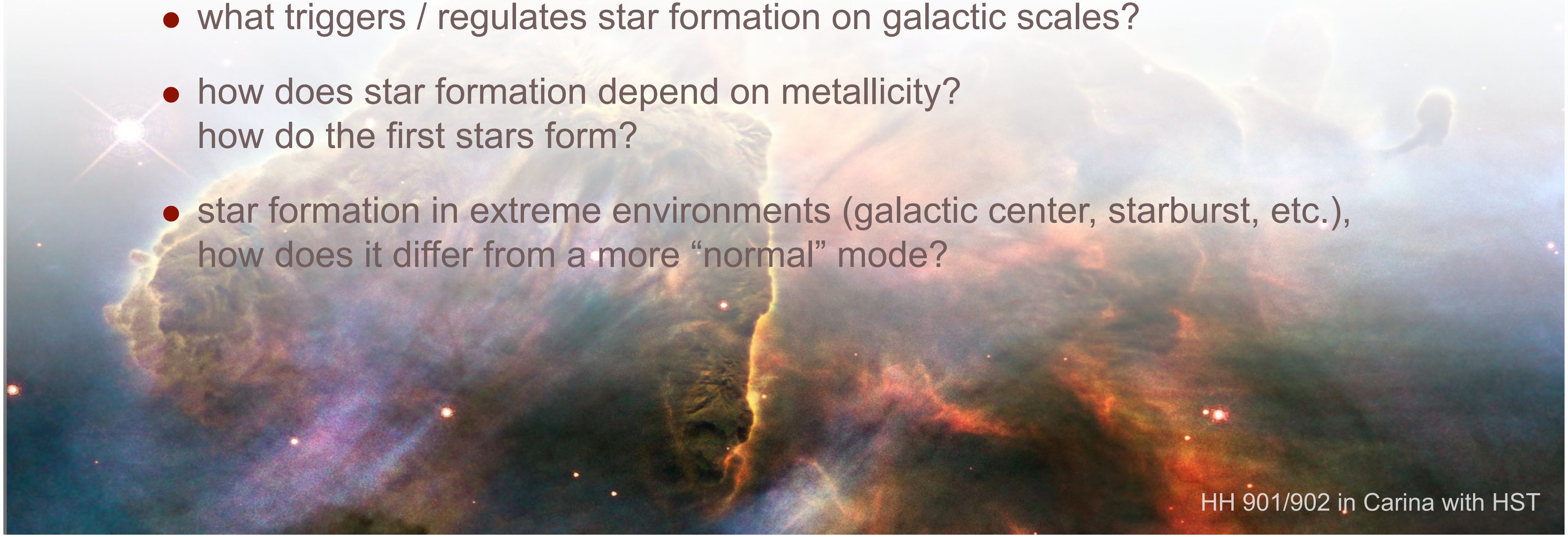


Star formation is intrinsically a multi-scale and multi-physics problem, where it is difficult to single out individual processes. Progress requires a comprehensive theoretical approach.

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?

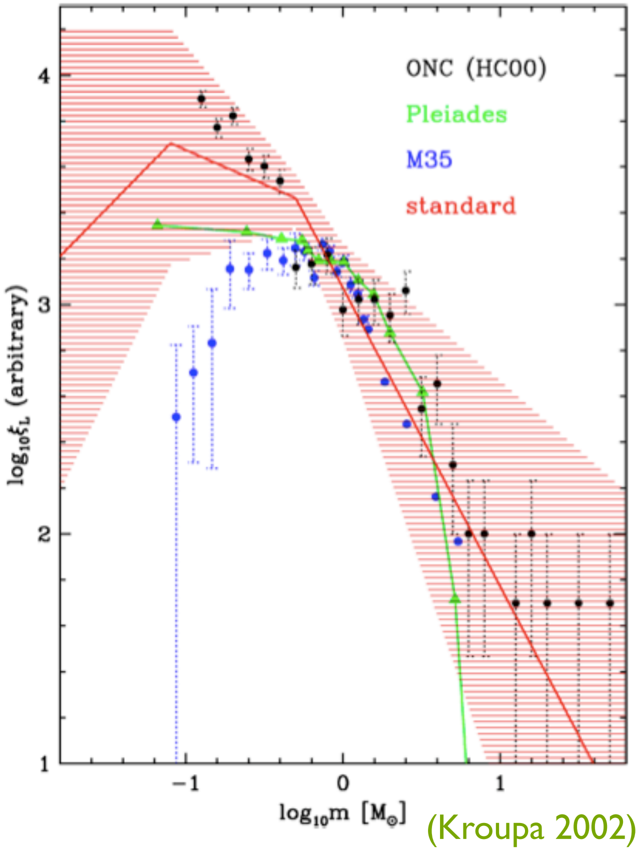


HH 901/902 in Carina with HST

Stellar mass function

stellar mass fuction

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



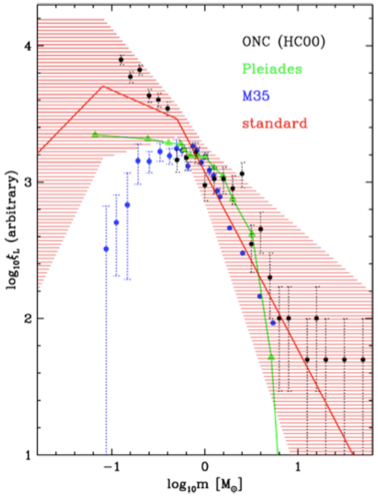
(Kroupa 2002)

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

stellar masses

- distribution of stellar masses depends on
  - turbulent initial conditions
    --> mass spectrum of prestellar cloud cores
  - collapse and interaction of prestellar cores
    --> 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

(Kroupa 2002)



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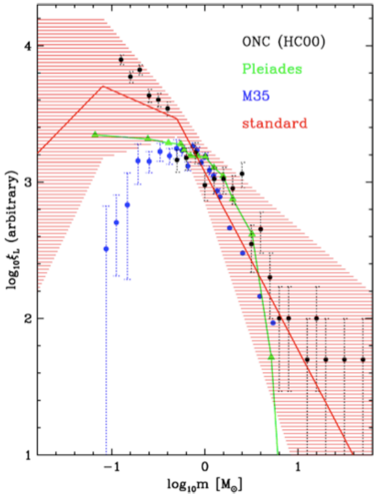


(Kroupa 2002)

example: model of Orion cloud

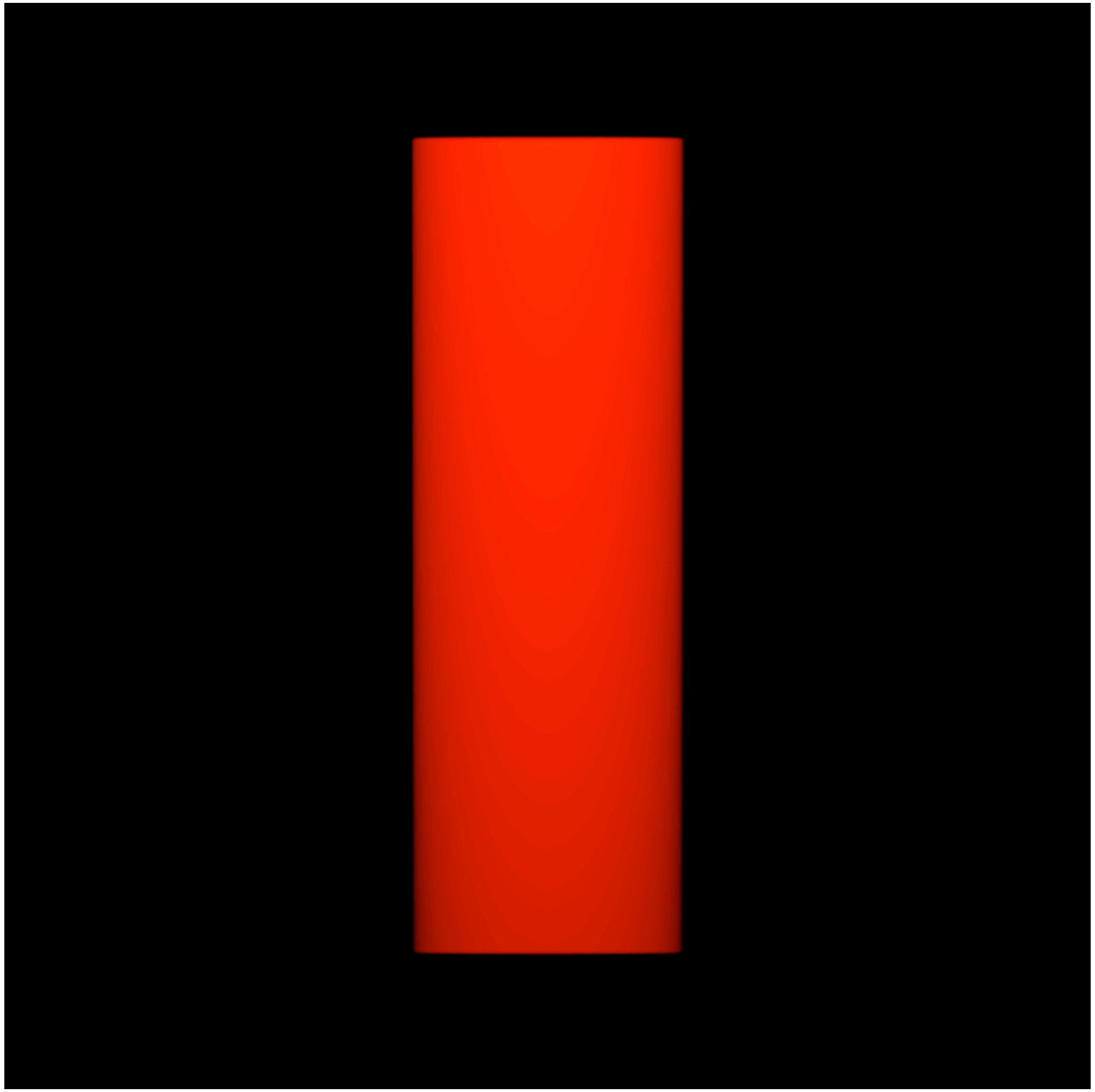
„model“ of Orion cloud:
15.000.000 SPH particles,
10^4 M_{sun} in 10 pc, mass resolution
0,02 M_{sun}, forms ~2.500
„stars“ (sink particles)

isothermal EOS, top bound, bottom unbound

has clustered as well as distributed „star“ formation

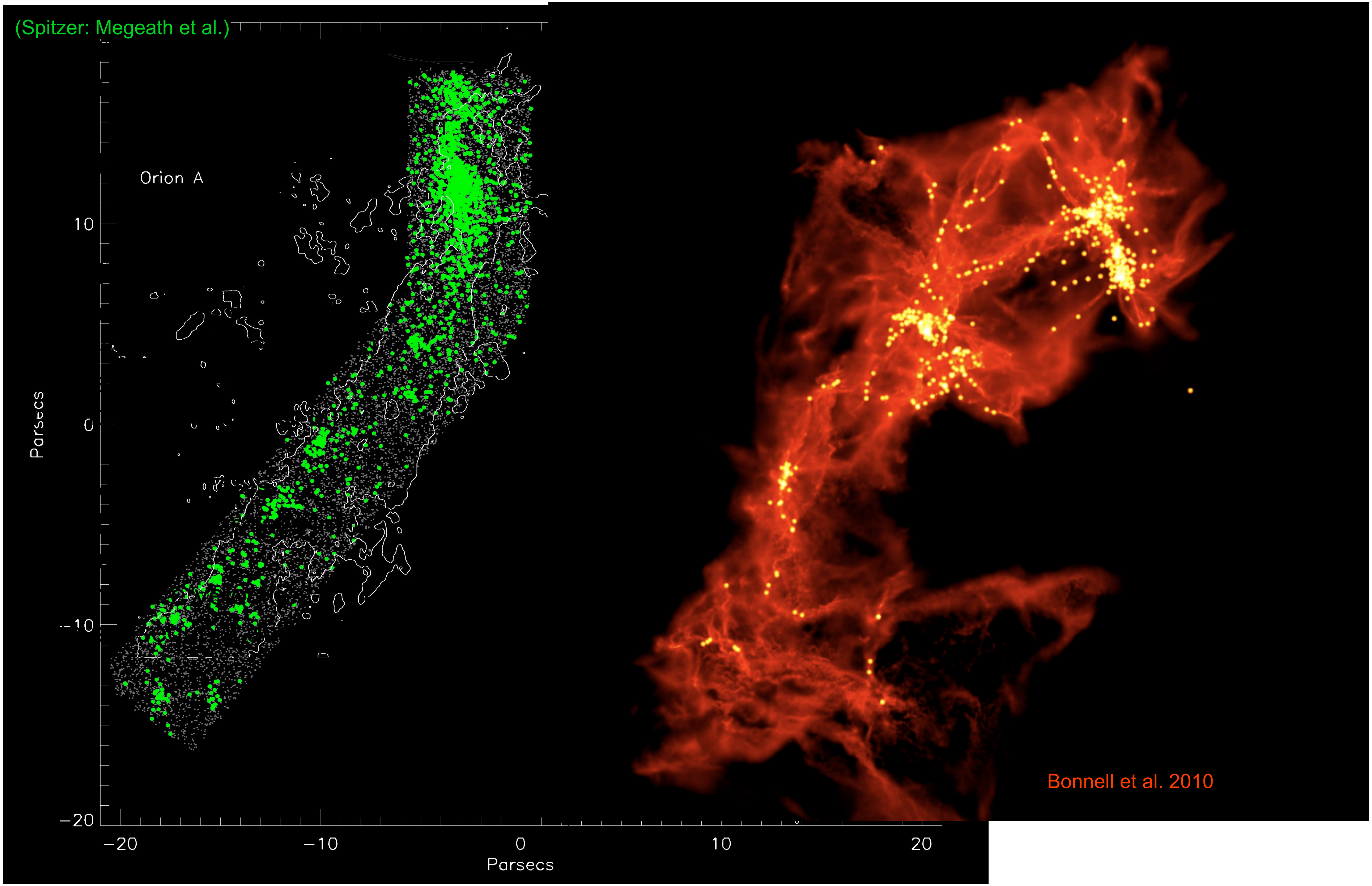
efficiency varies from 1% to 20%

develops full IMF
(distribution of sink particle masses)



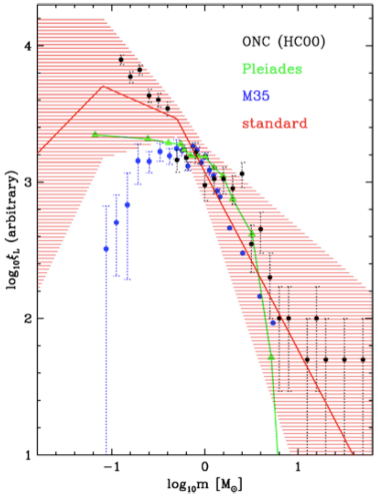
(Bonnell, Smith, Clark, & Bate 2010, MNRAS, 410, 2339)

example: model of Orion cloud


(Spitzer: Megeath et al.)

Bonnell et al. 2010

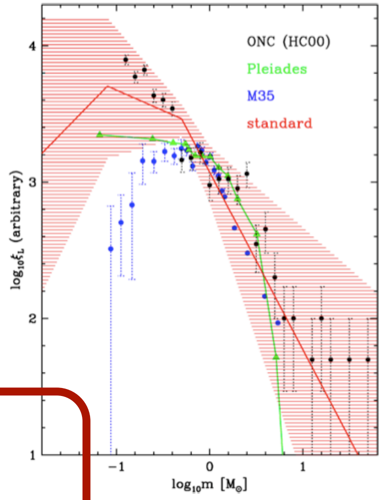
stellar mass fuction



(Kroupa 2002)

- distribution of stellar masses depends on
  - turbulent initial conditions
    --> mass spectrum of prestellar cloud cores
  - collapse and interaction of prestellar cores
    --> 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, etc.

stellar mass fuction



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application to early star formation

thermodynamics & fragmentation

degree of fragmentation depends on *EOS!*

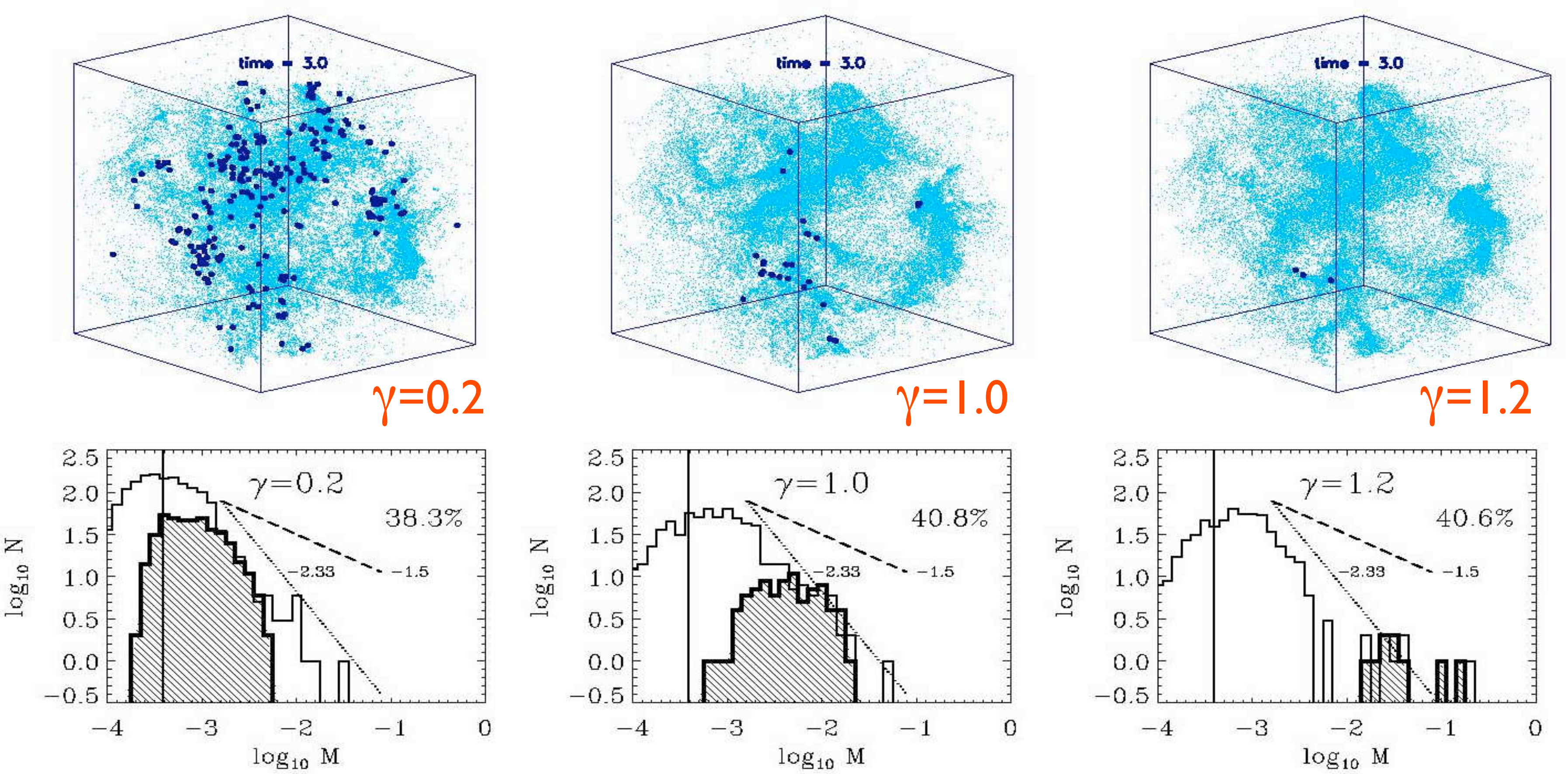
polytropic EOS: $\mathbf{p} \propto \rho^{\gamma}$

$\gamma < 1$: dense cluster of low-mass stars

$\gamma > 1$: isolated high-mass stars

(see Li et al. 2003; also Kawachi & Hanawa 1998, Larson 2003)

dependency on EOS



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

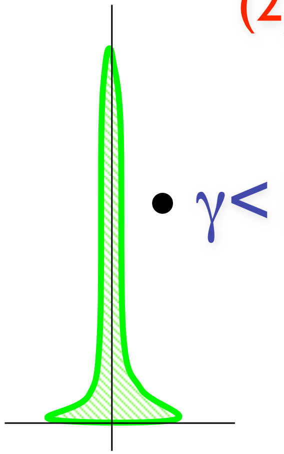
for $\gamma>1$ it is suppressed → *isolated massive stars*

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

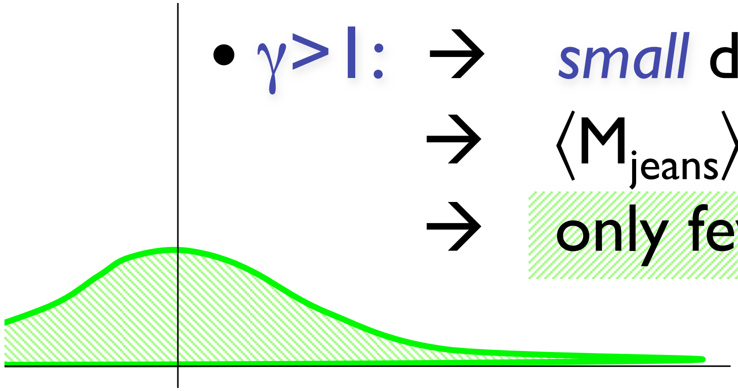
how does that work?

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

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

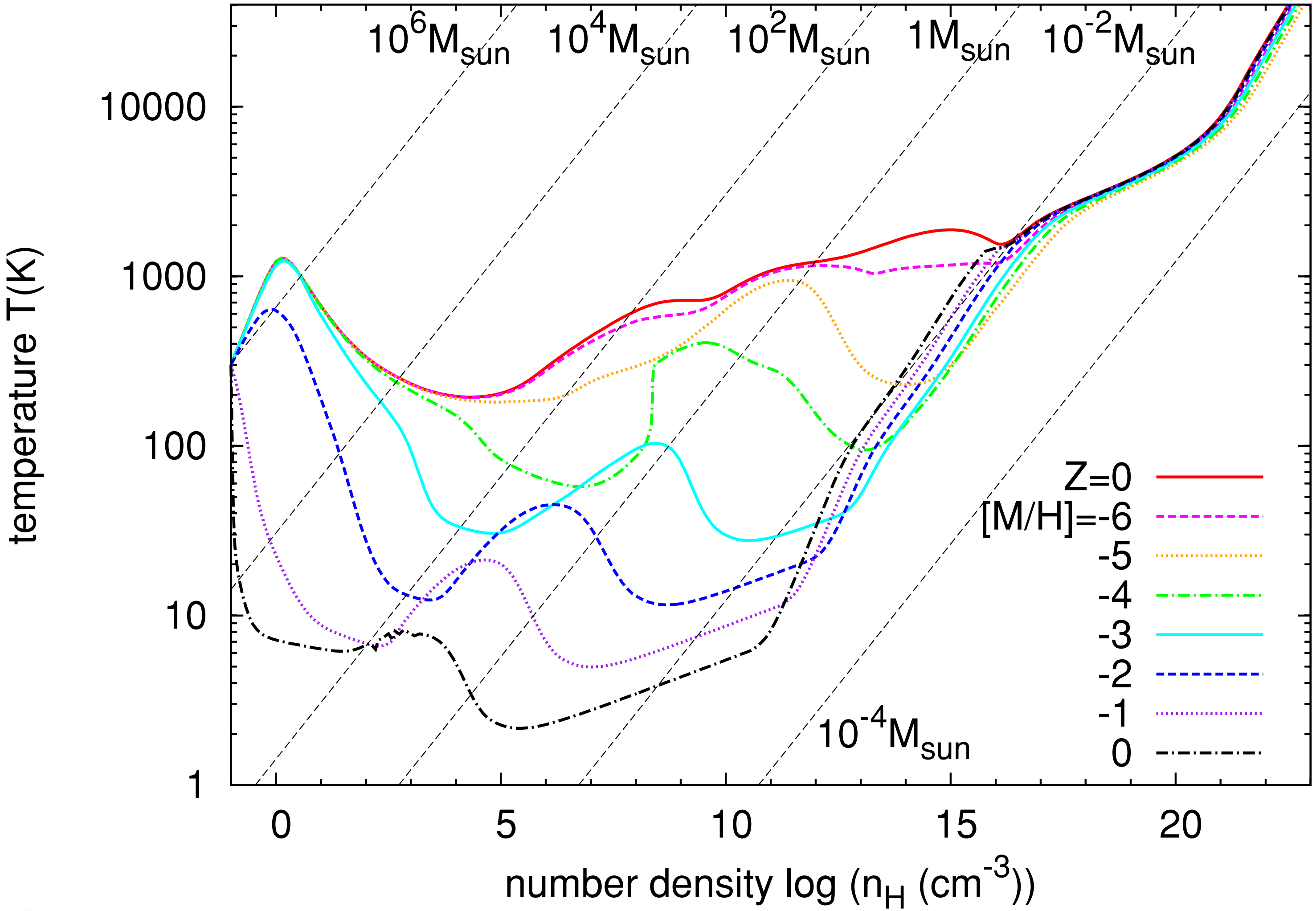


- $\gamma<1$: → *large* density excursion for given pressure
  → $\langle M_{\text{jeans}} \rangle$ becomes small
  → number of fluctuations with $M > M_{\text{jeans}}$ is large



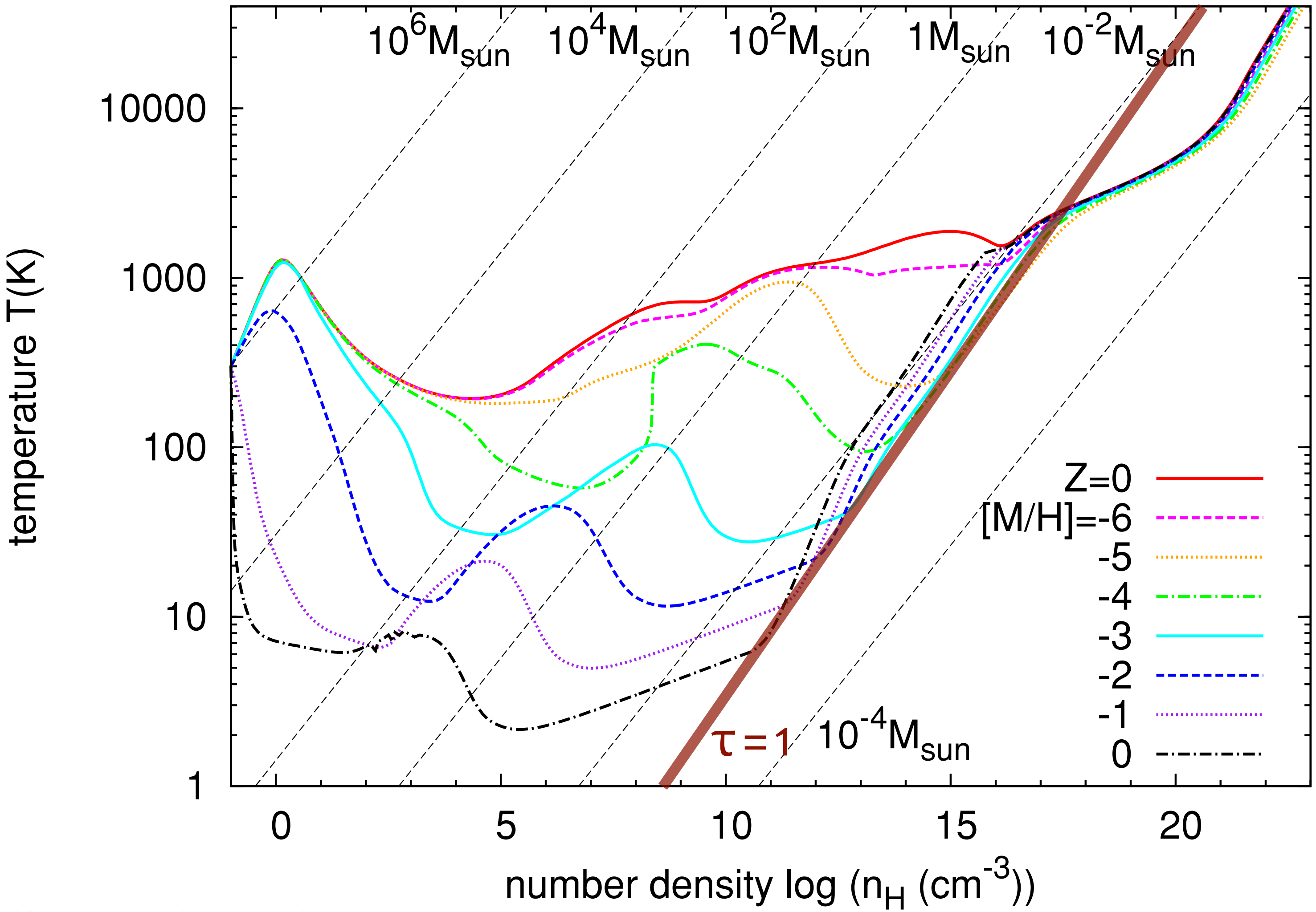
- $\gamma>1$: → *small* density excursion for given pressure
  → $\langle M_{\text{jeans}} \rangle$ is large
  → only few and massive clumps exceed M_{jeans}

EOS as function of metallicity



(Omukai et al. 2005, 2010)

EOS as function of metallicity



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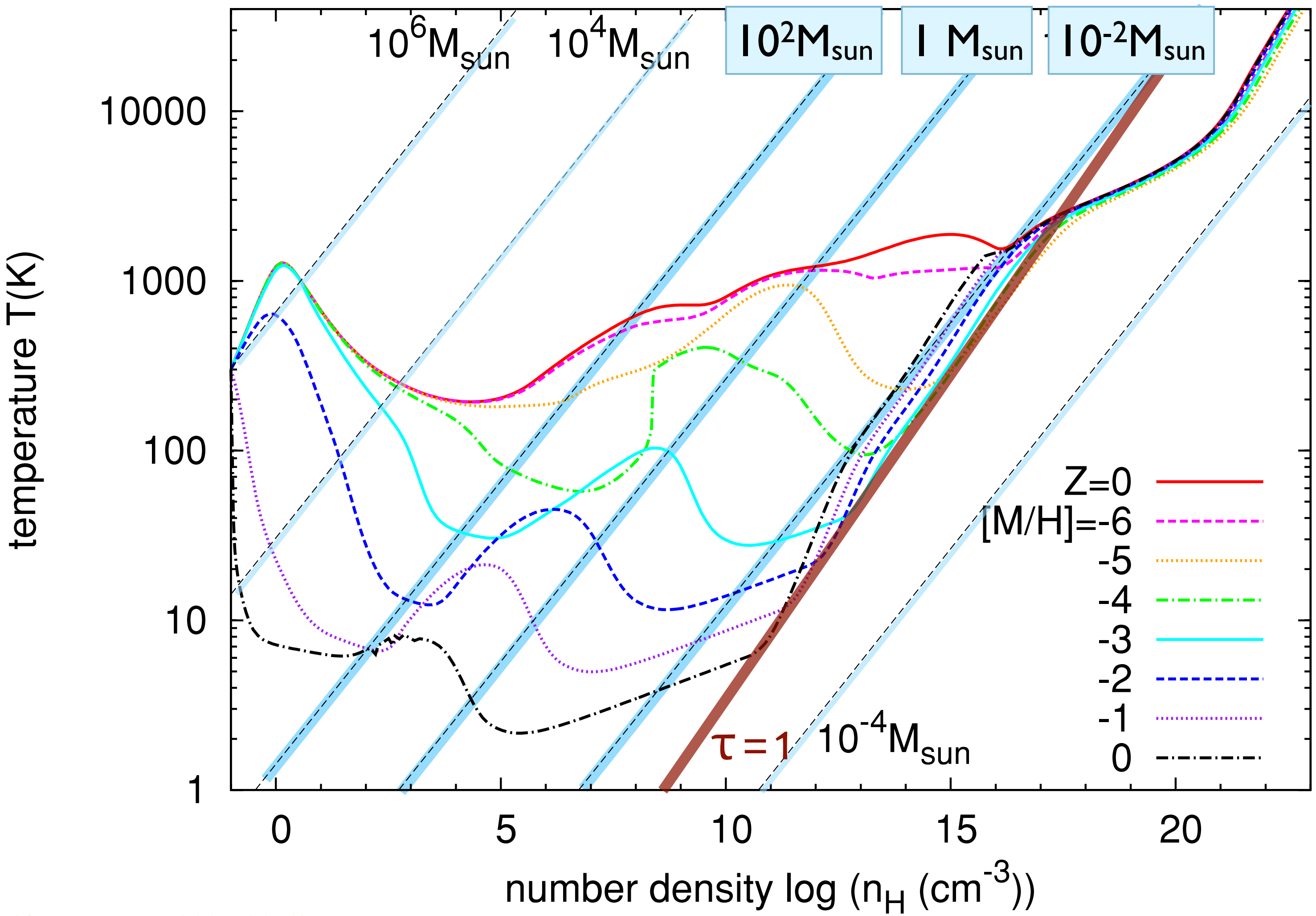

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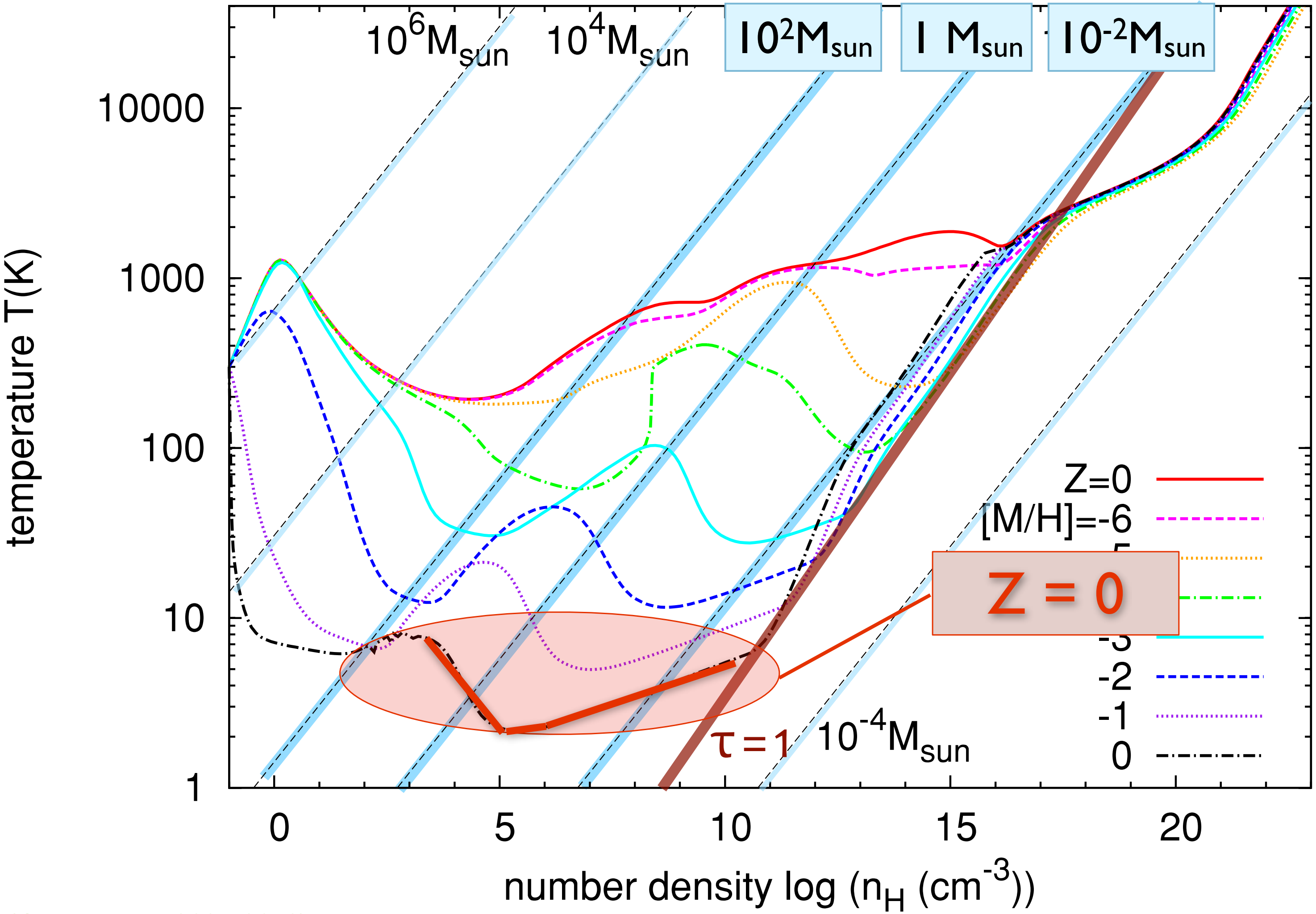
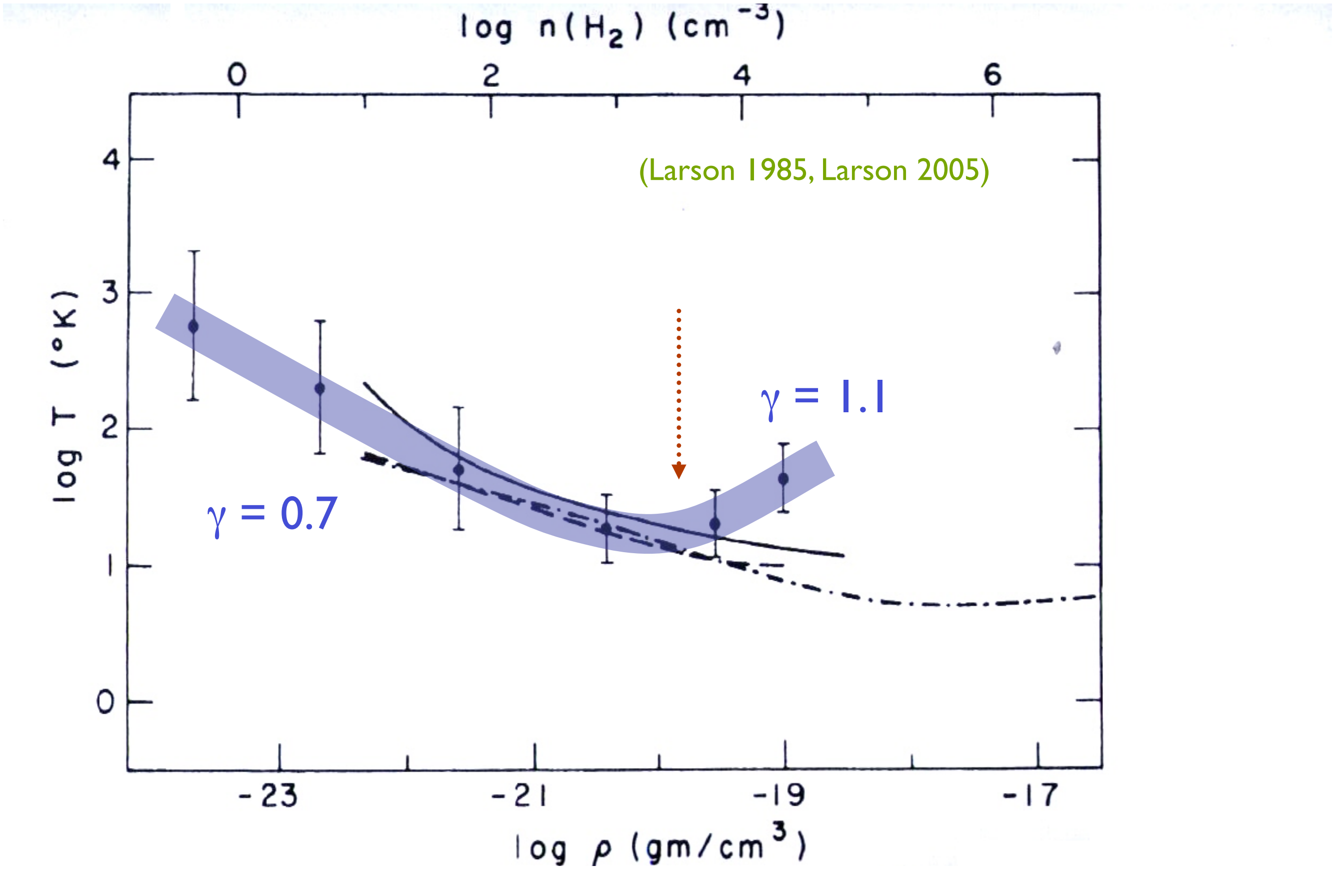
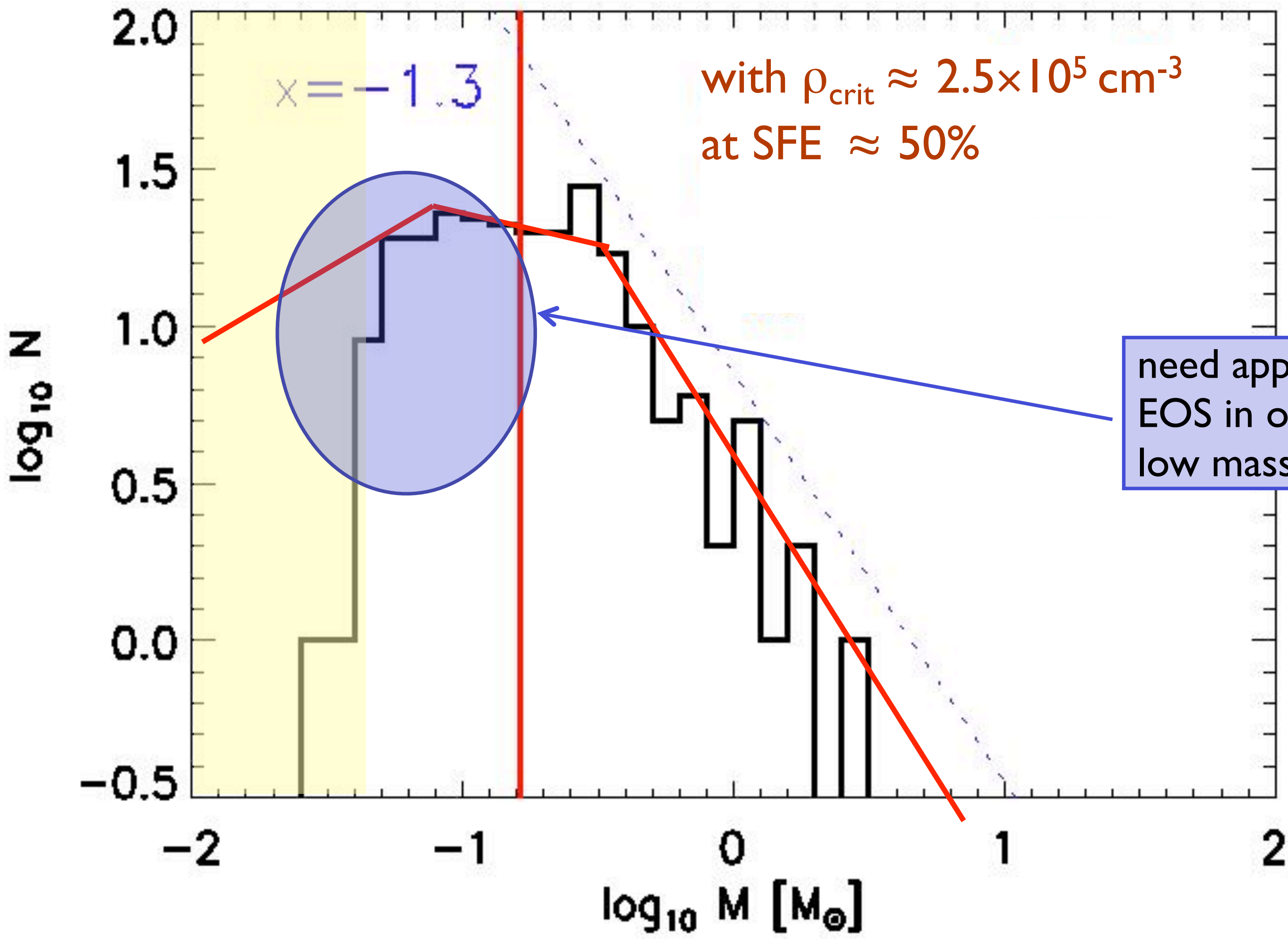


(Omukai et al. 2005, 2010)

present-day star formation



IMF in nearby molecular clouds



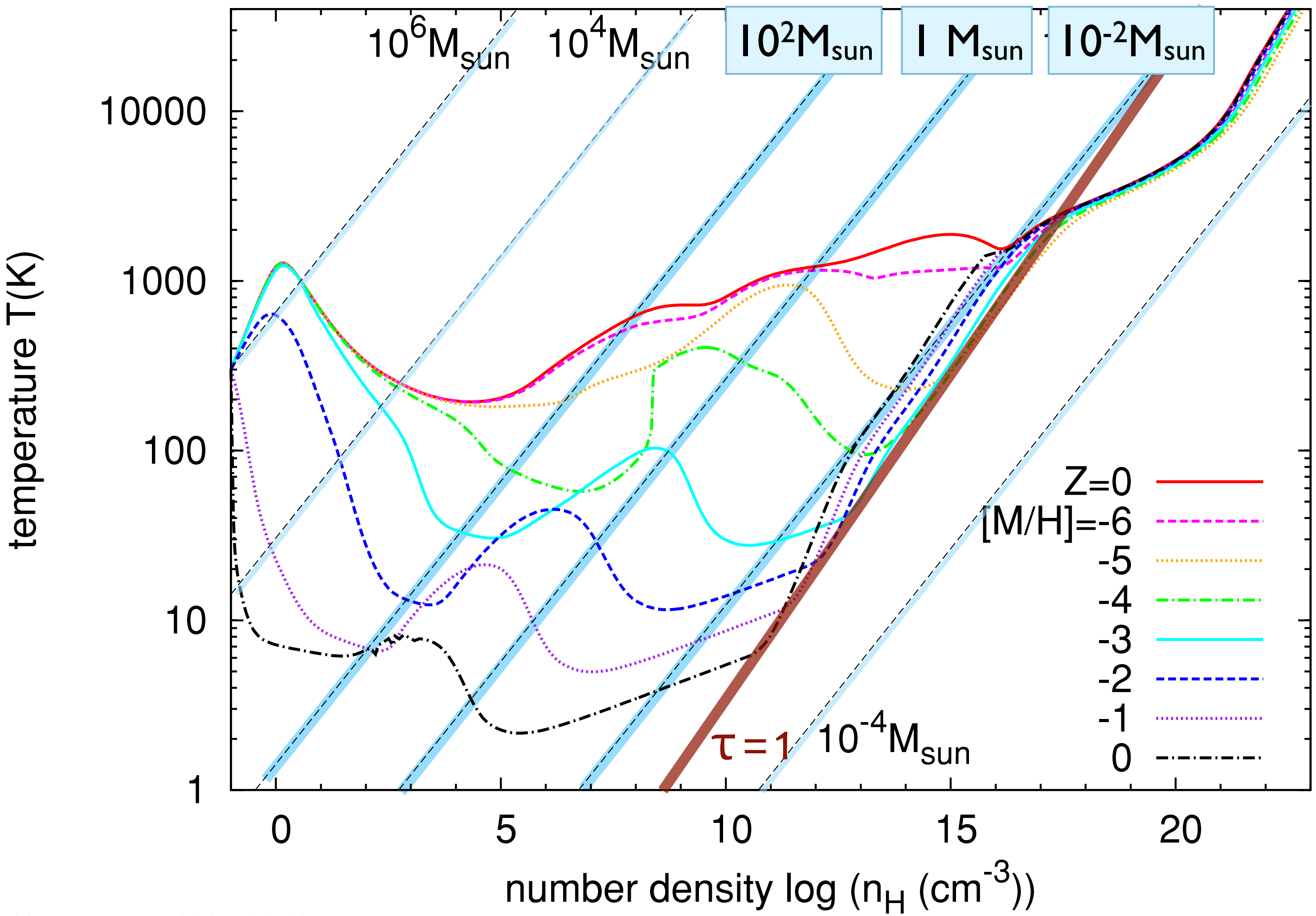
with $\rho_{crit} \approx 2.5\times10^5\ \mathrm{cm}^{-3}$

at SFE ≈ 50%

need appropriate EOS in order to get low mass IMF right

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

EOS as function of metallicity



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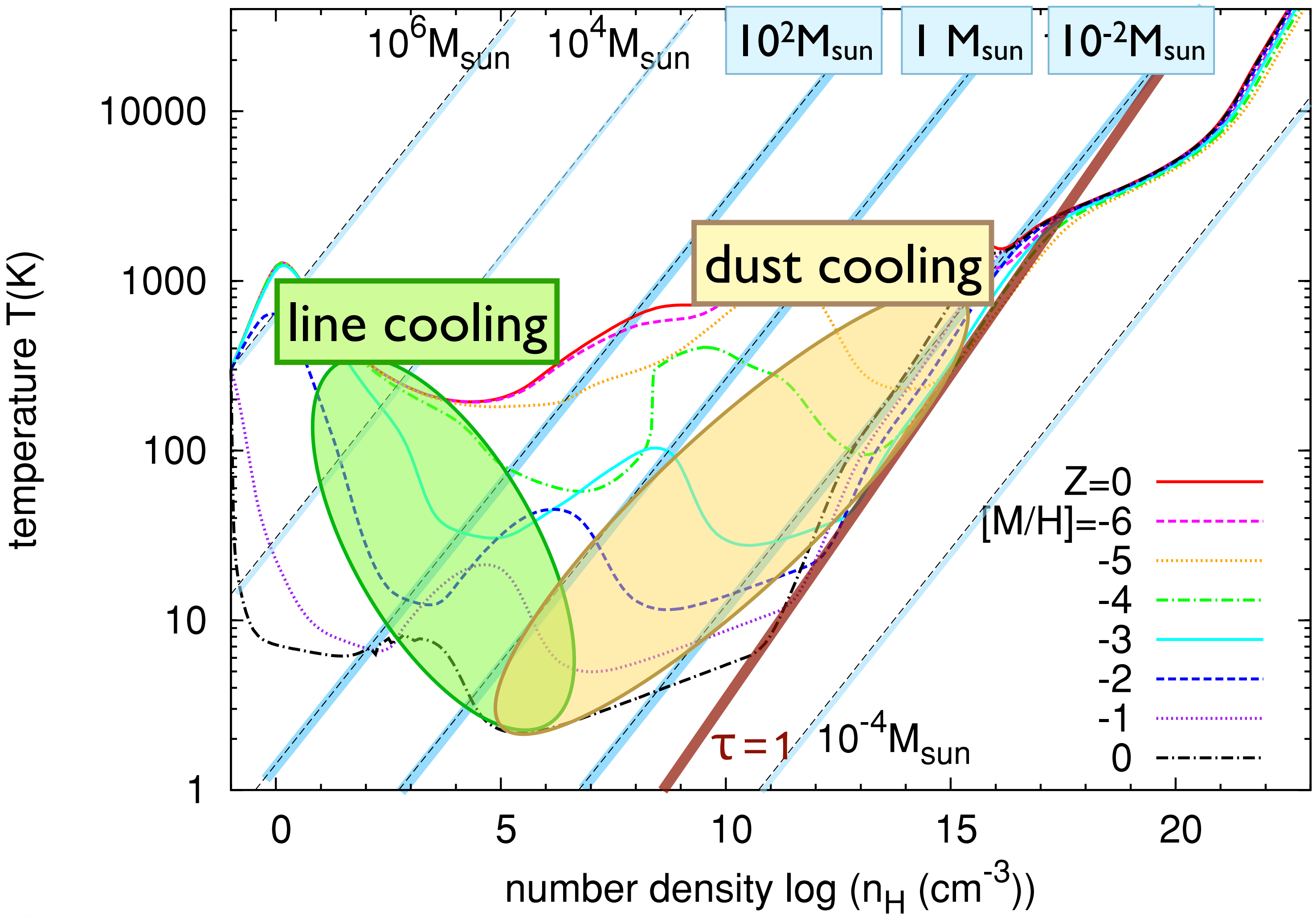
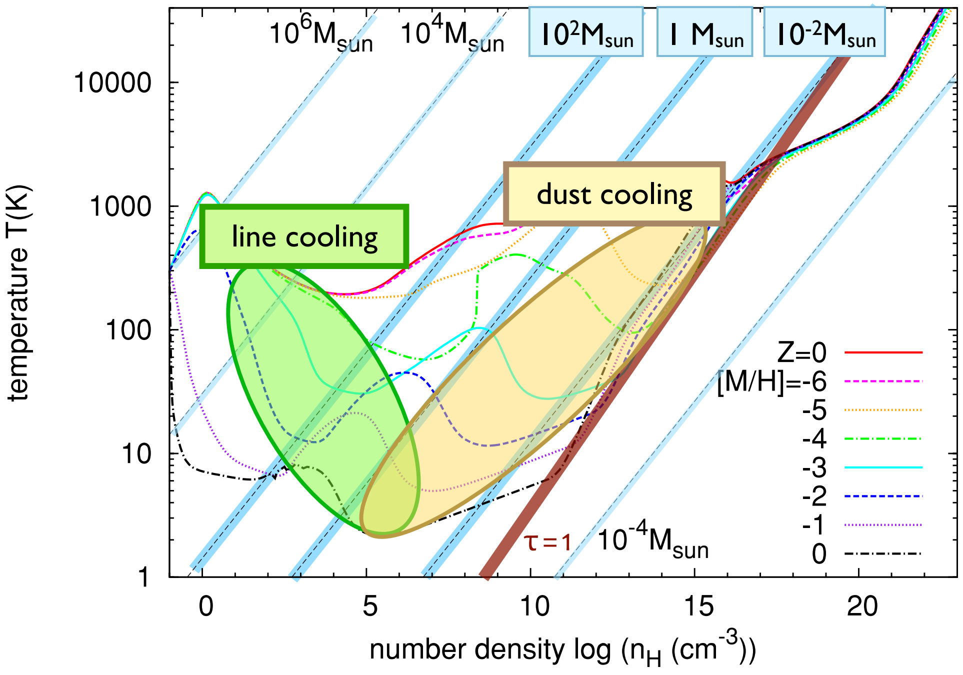


(Omukai et al. 2005, 2010)

transition: Pop III to Pop II.5



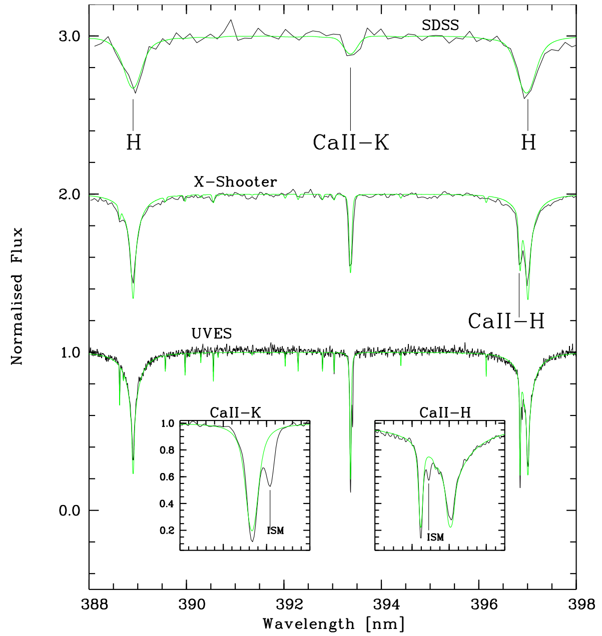
(Omukai et al. 2005, 2010)

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

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]

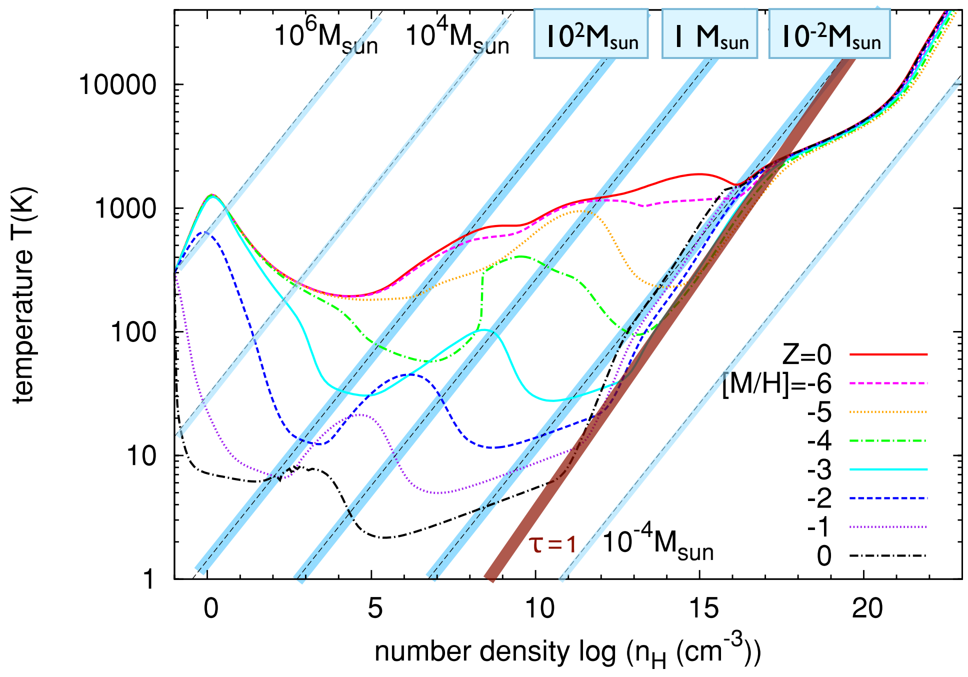
Element			$[X/H]_{1D}$		N lines	S_H	$A(X)_\odot$
		+3Dcor.	+NLTE cor.	+ 3D cor + NLTE cor			
C	≤ −3.8	≤ −4.5			G-band		8.50
N	≤ −4.1	≤ −5.0			NH-band		7.86
Mg I	−4.71 ± 0.11	−4.68 ± 0.11	−4.52 ± 0.11	−4.49 ± 0.12	5	0.1	7.54
Si I	−4.27	−4.30	−3.93	−3.96	1	0.1	7.52
Ca I	−4.72	−4.82	−4.44	−4.54	1	0.1	6.33
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

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

(Caffau et al. 2011, 2012)

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

transition: Pop III to Pop II.5

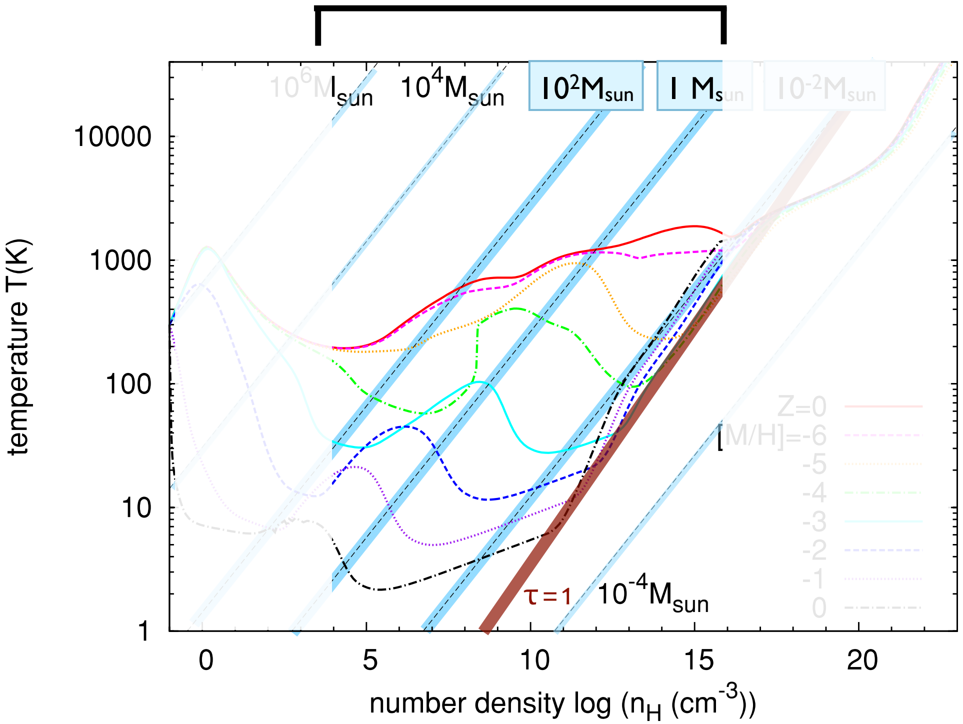


(Omukai et al. 2005, 2010)

approach problem with high-resolution hydrodynamic calculations of central parts of high-redshift halos

- SPH (40 million particles)
- time-dependent chemistry (with dust)
- sink particles to model star formation
- external dark-matter potential

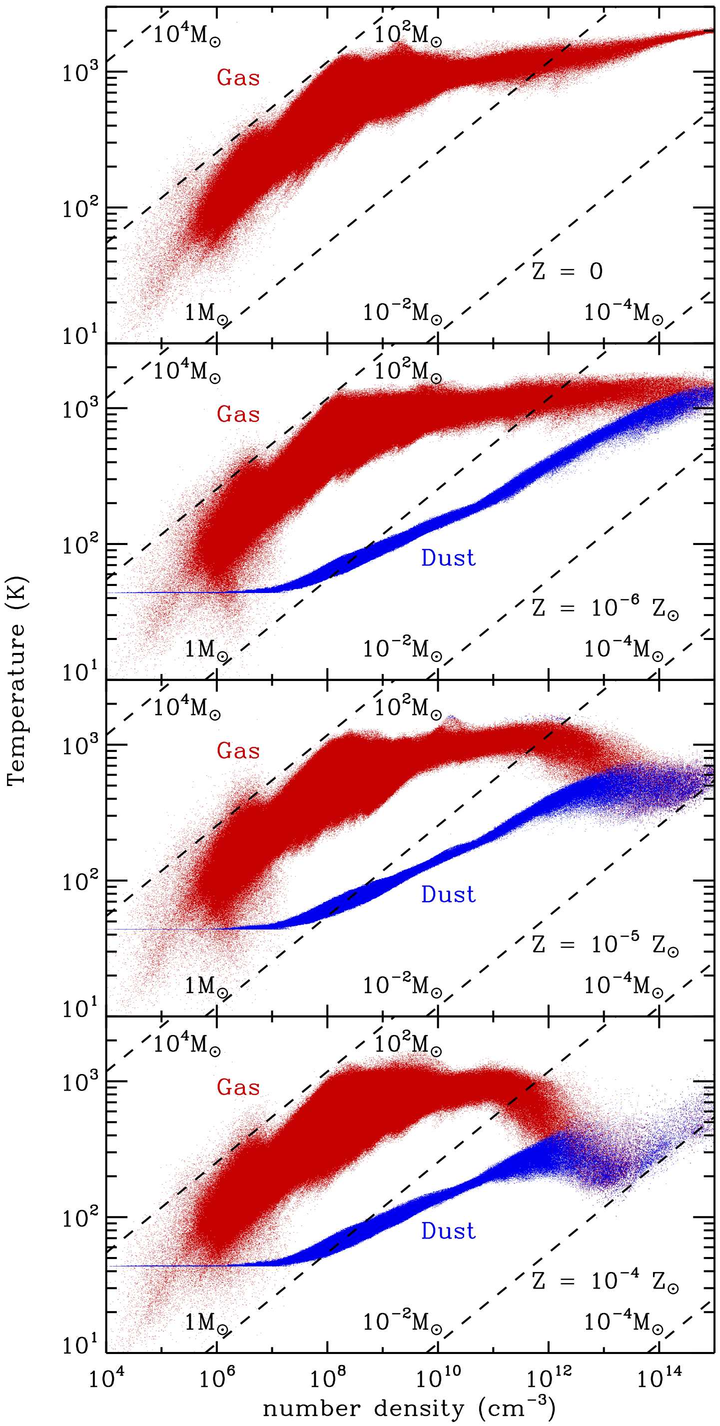
transition: Pop III to Pop II.5



approach problem with high-resolution hydrodynamic calculations of central parts of high-redshift halos

- SPH (40 million particles)
- time-dependent chemistry (with dust)
- sink particles to model star formation
- external dark-matter potential
- focus on relevant density regime
  (i.e. include dust dip and optically thick regime)

(Omukai et al. 2005, 2010)



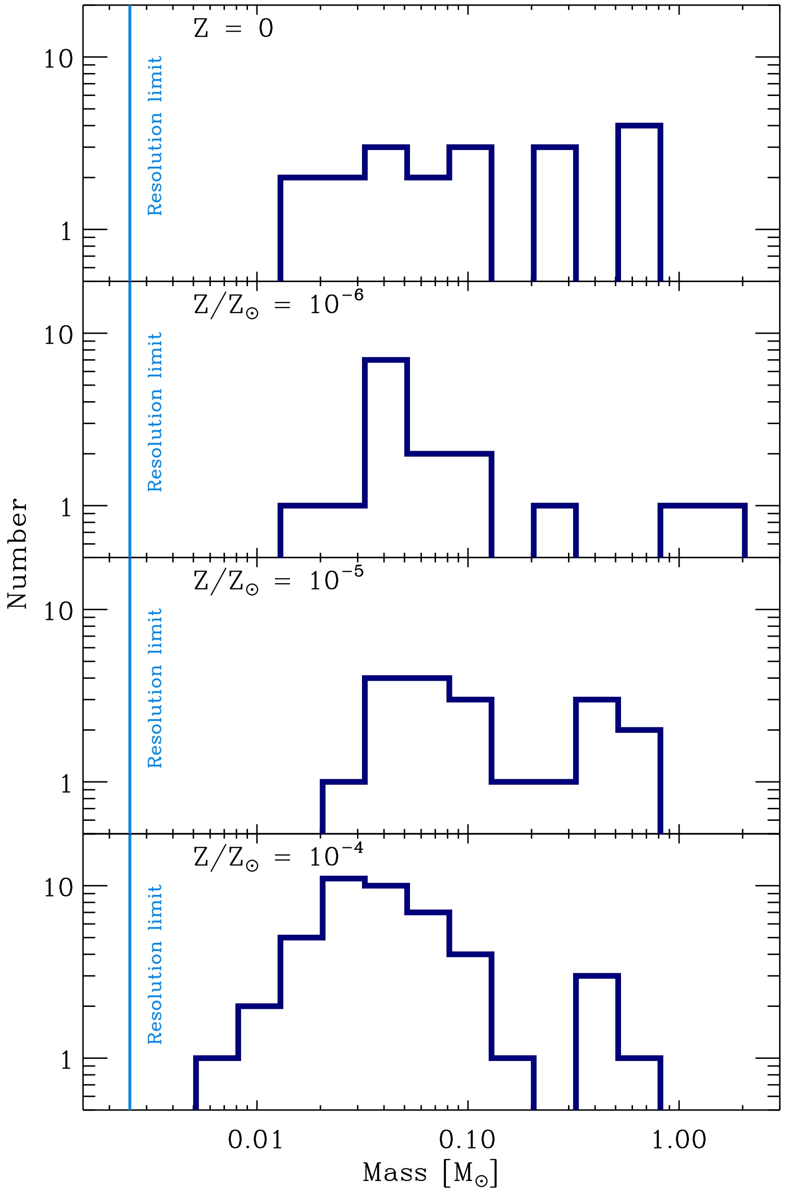
[M/H] = -ininity

[M/H] = -6

[M/H] = -5

[M/H] = -4

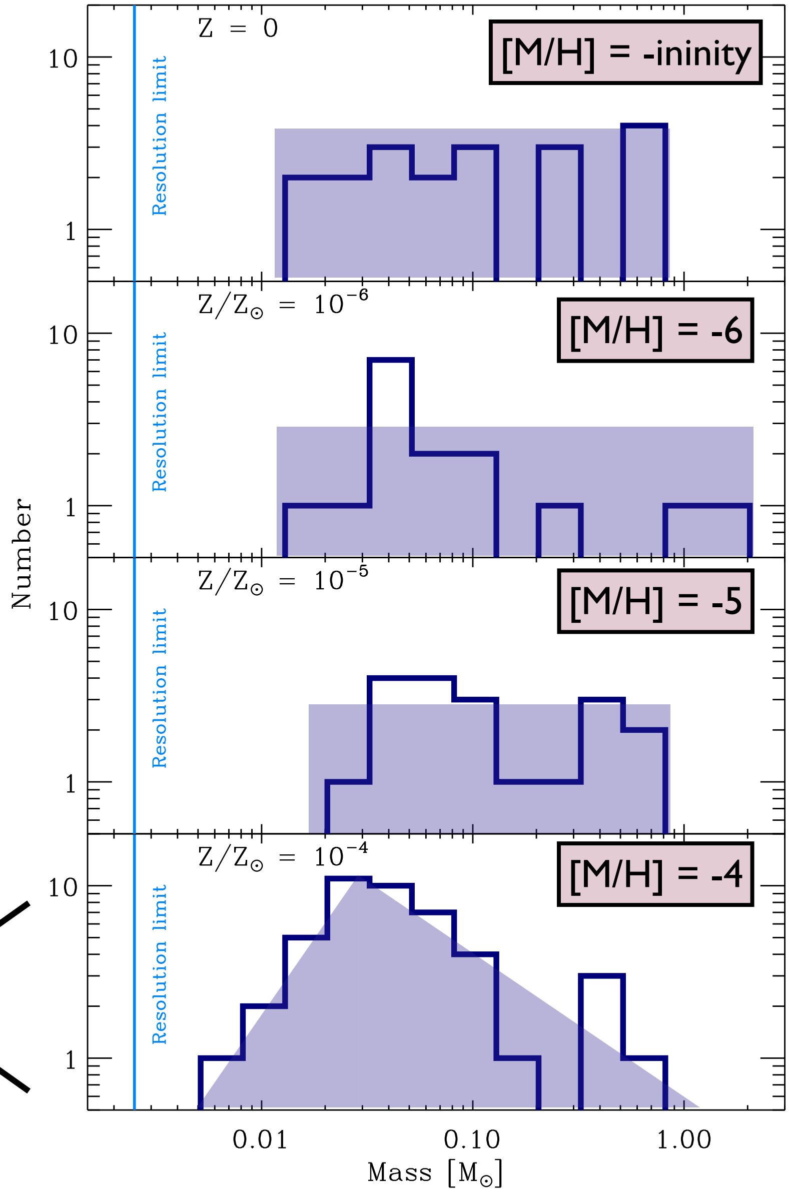
red : gas
blue: dust



Dopcke et al., 2012, submitted to ApJ, arXiv:1203.6842) hints for differences in mass spectrum

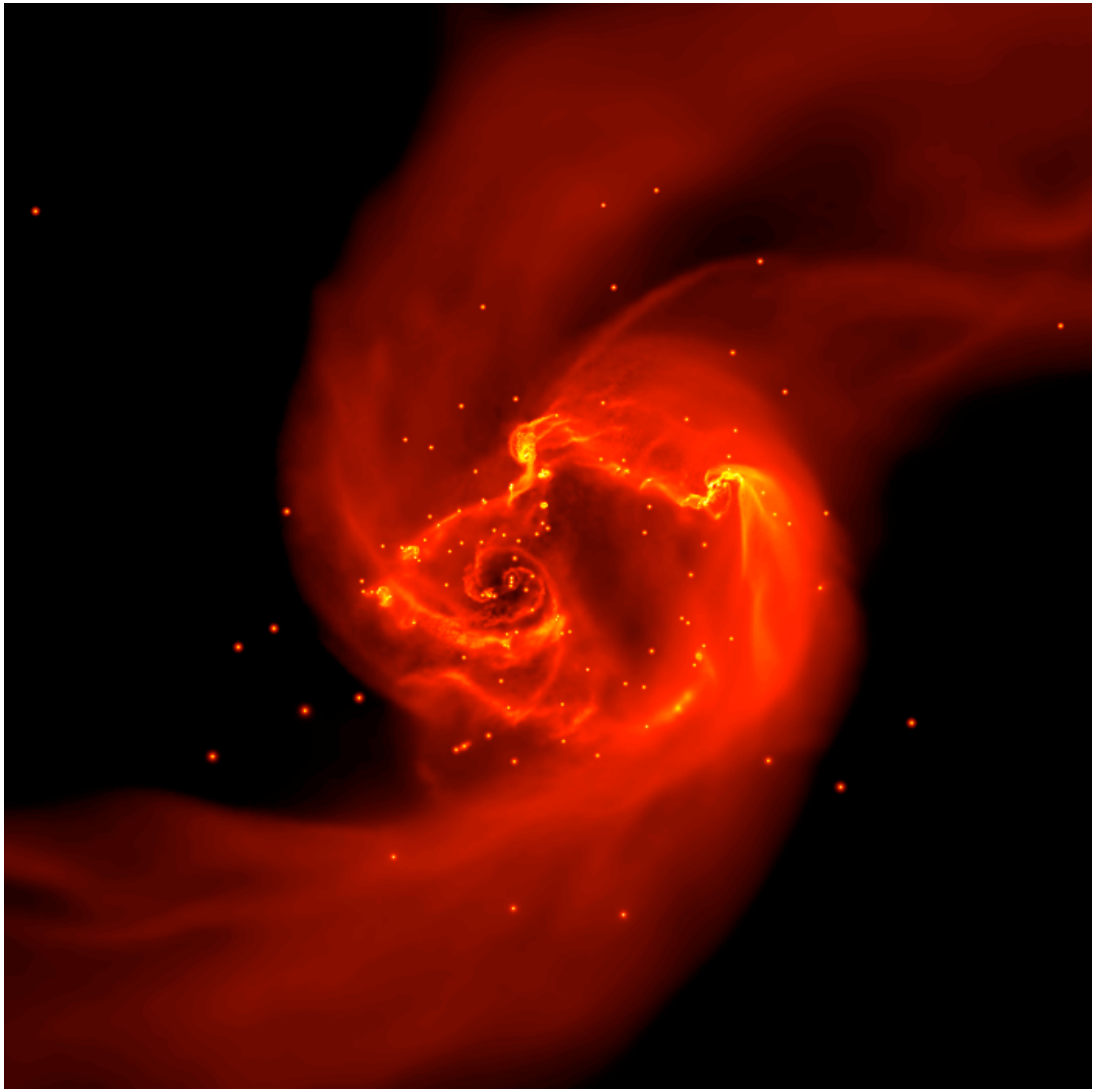
disk fragmentation mode

gravoturbulent fragmentation mode



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

dust induced fragmentation at $Z=10^{-5}$



dense cluster of low-mass protostars builds up:

- mass spectrum peaks *below* $1\ M_{sun}$
- cluster VERY dense $n_{stars} = 2.5 \times 10^9\ pc^{-3}$
- fragmentation at density $n_{gas} = 10^{12} - 10^{13}\ cm^{-3}$

(Clark et al. 2008, ApJ 672, 757)

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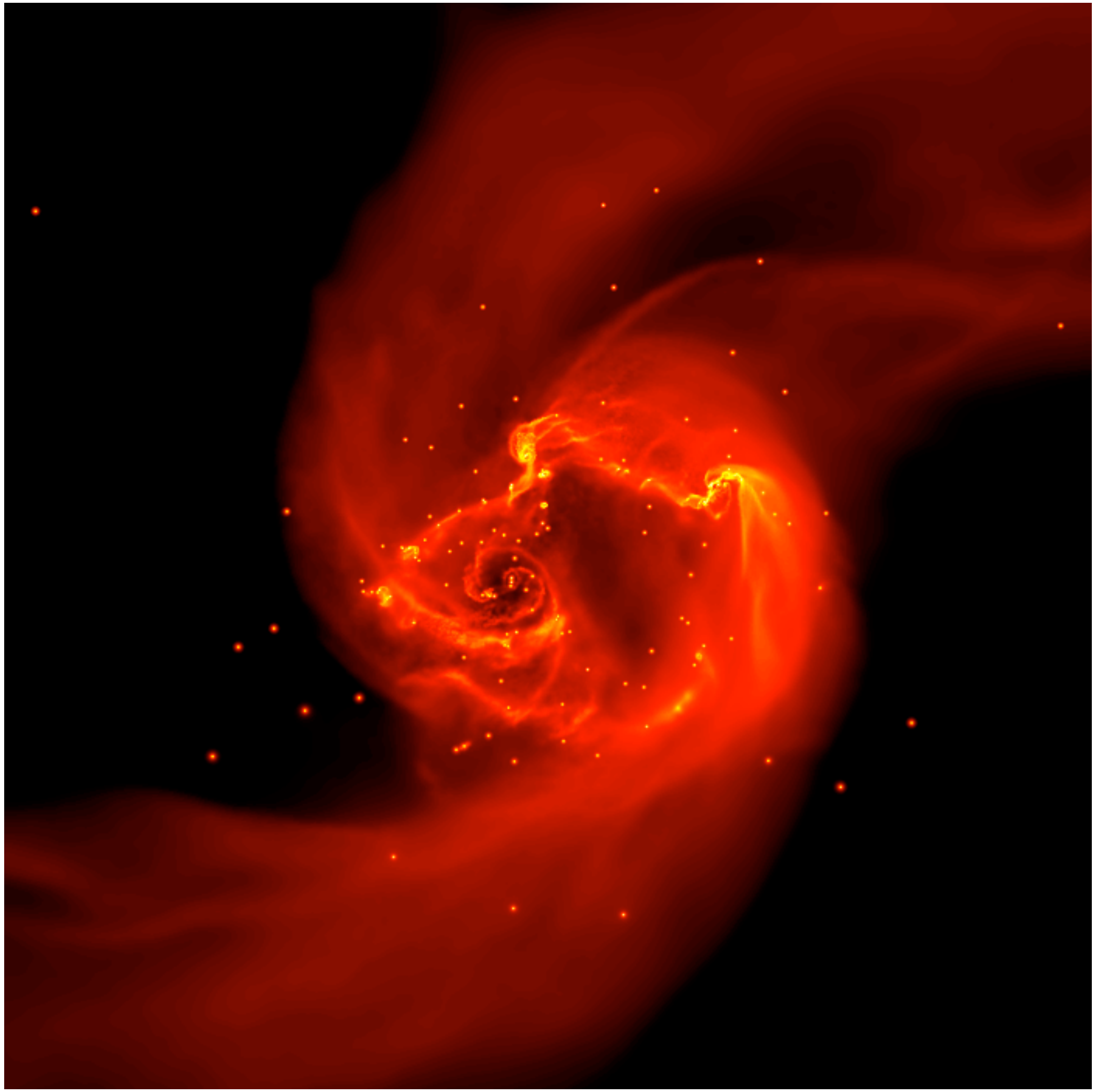

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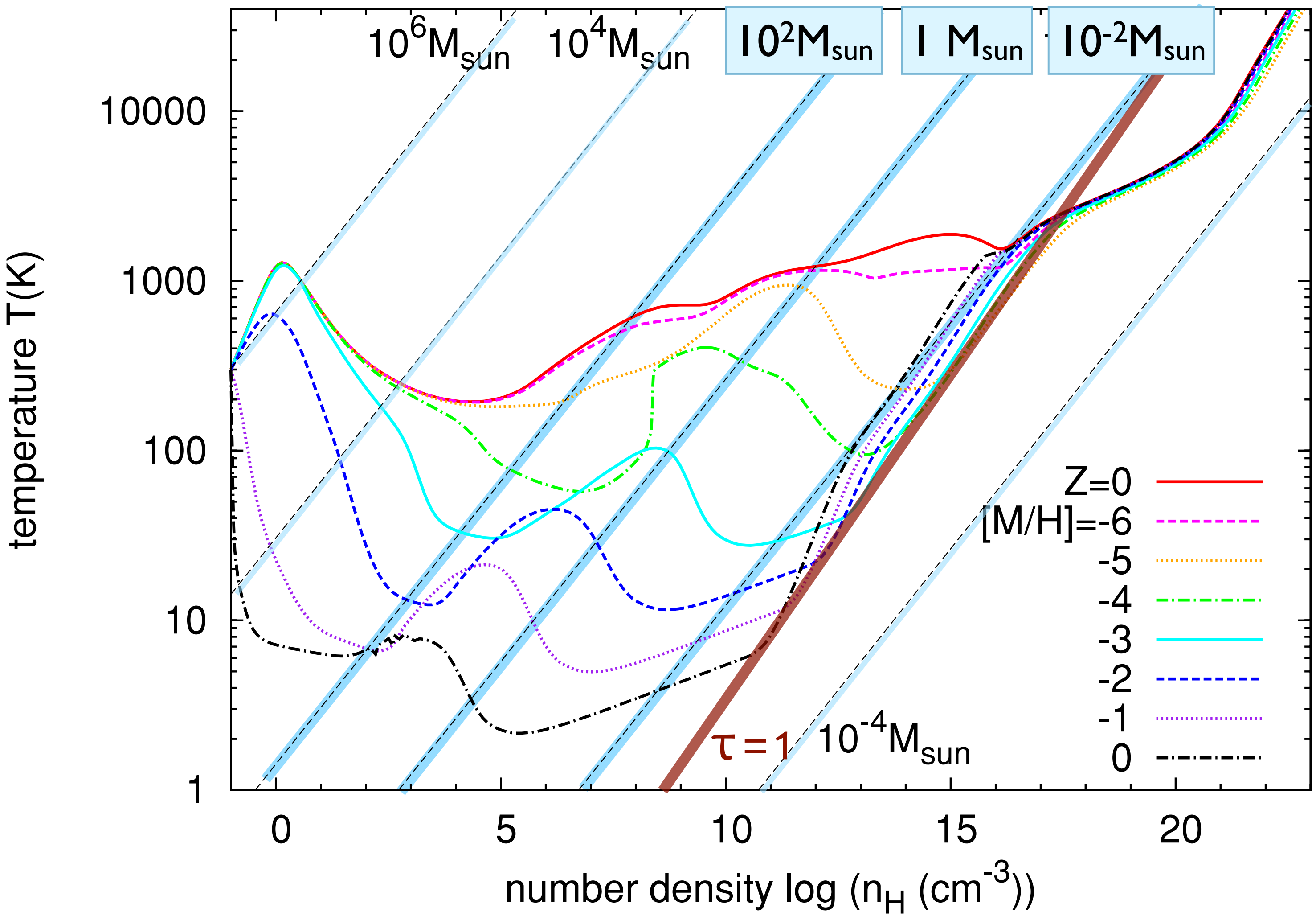
- cluster VERY dense $n_{stars} = 2.5 \times 10^{9}\ pc^{-3}$
- fragmentation at density $n_{gas} = 10^{12} - 10^{13}\ cm^{-3}$

- *predictions:*
  * low-mass stars with [Fe/H] ~ 10^{-5}
  * high binary fraction

(Clark et al. 2008, ApJ 672, 757)

EOS as function of metallicity



(Omukai et al. 2005, 2010)

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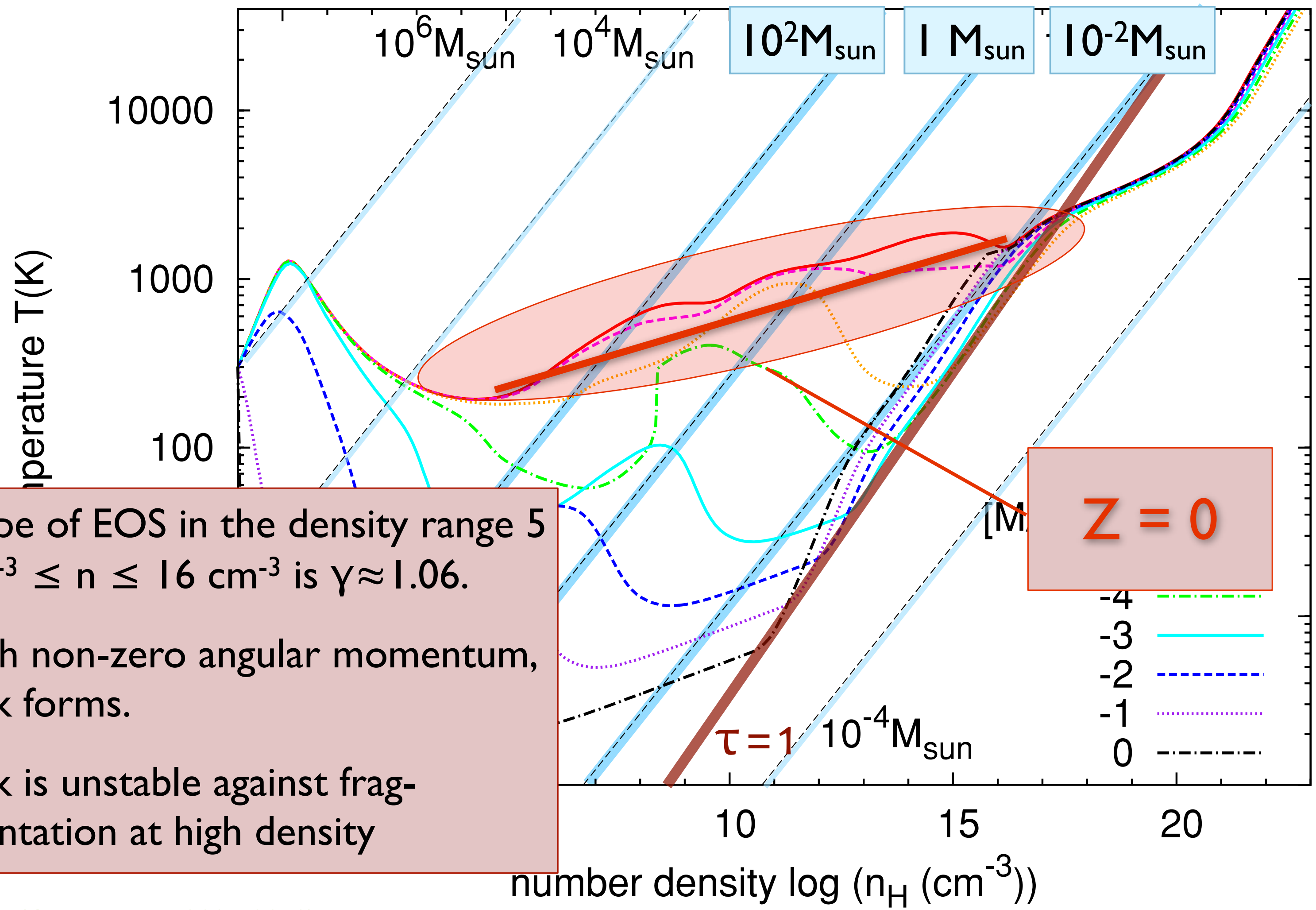


Z = 0

- 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)

metal-free star formation

- 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)

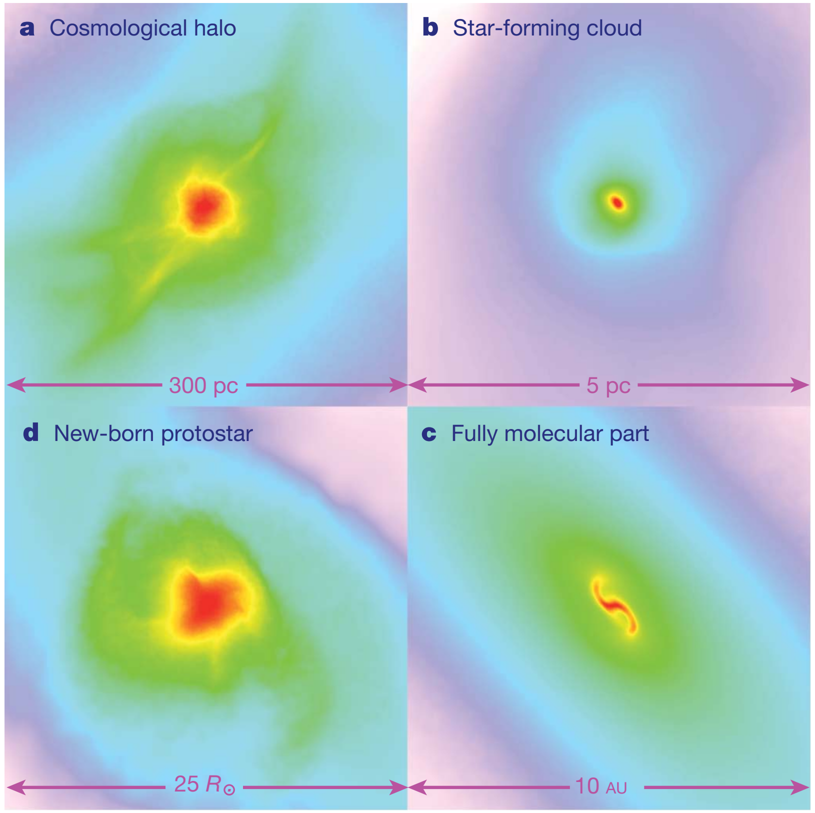


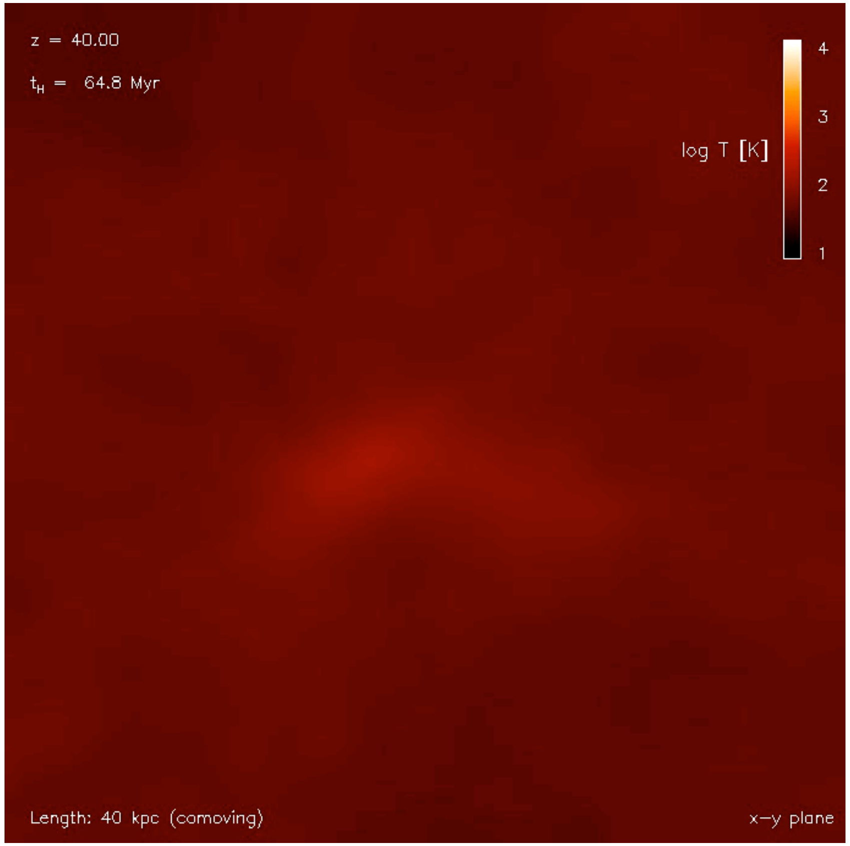
Figure 1 | Projected gas distribution around a primordial protostar. Shown is the gas density (colour-coded so that red denotes highest density) of a single object on different spatial scales. **a**, The large-scale gas distribution around the cosmological minihalo; **b**, a self-gravitating, star-forming 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)

turbulence in Pop III halos

- star formation will depend on *degree of turbulence* in protogalactic halo
- expectation: *wide range of stellar masses*, just like in present-day star formation

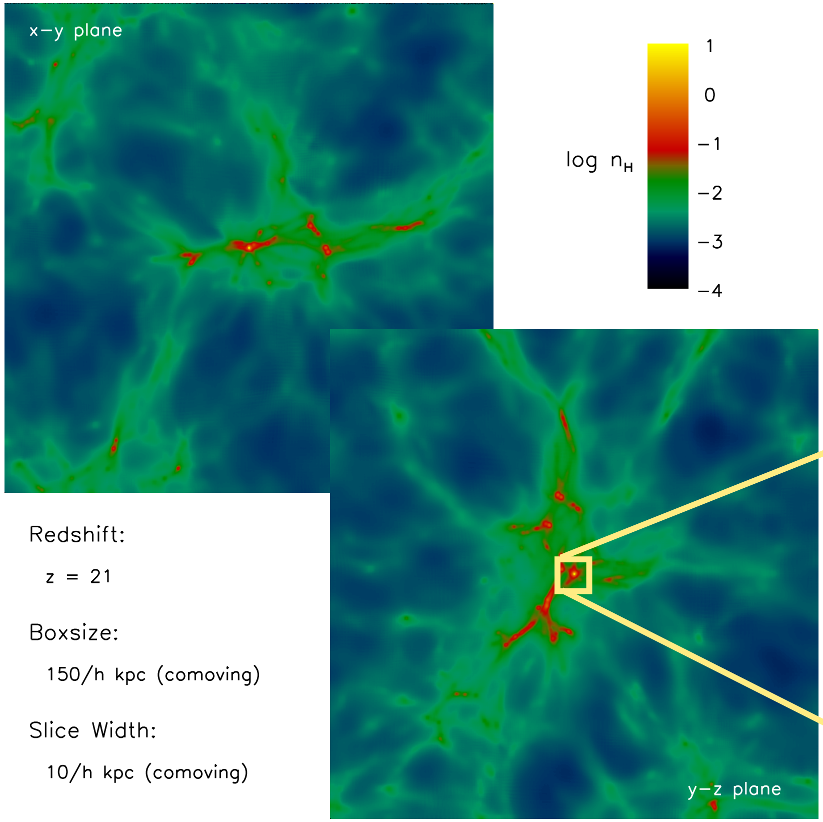
turbulence developing in an atomic cooling halo



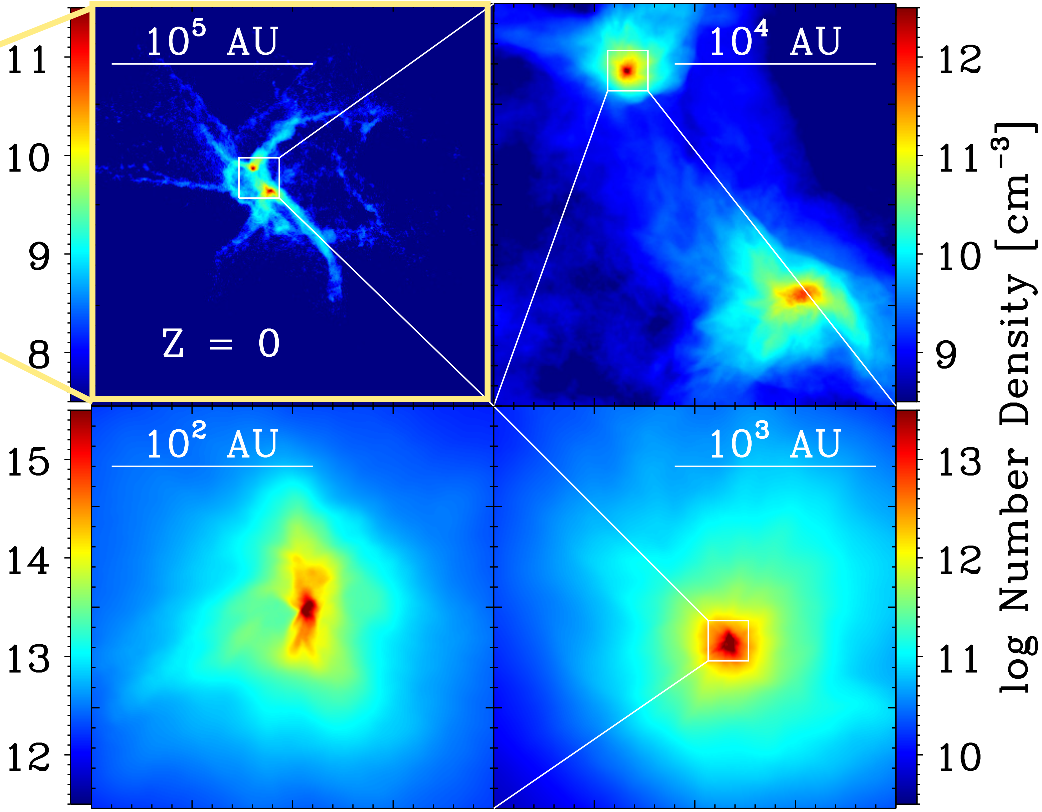
(Greif et al. 2008)

detailed look at accretion disk around first star

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



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



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

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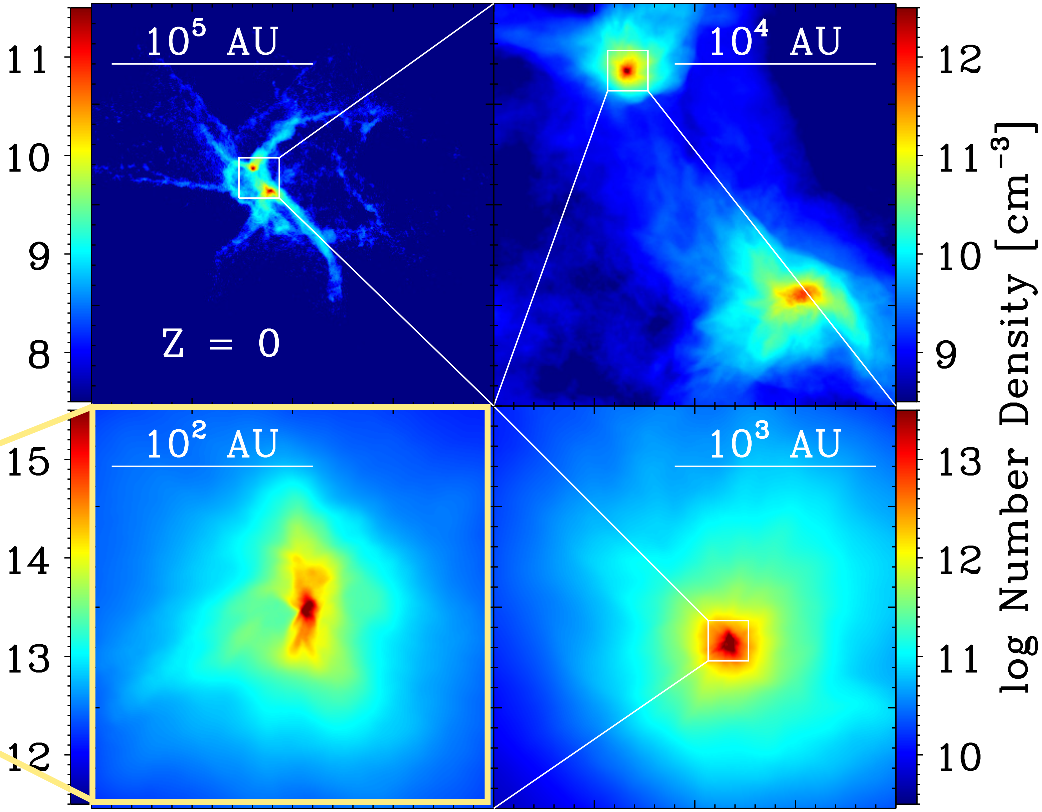


what is the time evolution of accretion disk around first star to form?

(Greif et al. 2011, ApJ, 737, 75, Greif et al. 2012, MNRAS, 424, 399, Dopcke et al. 2012, ApJ submitted, arXiv1203.6842) detailed look at accretion disk

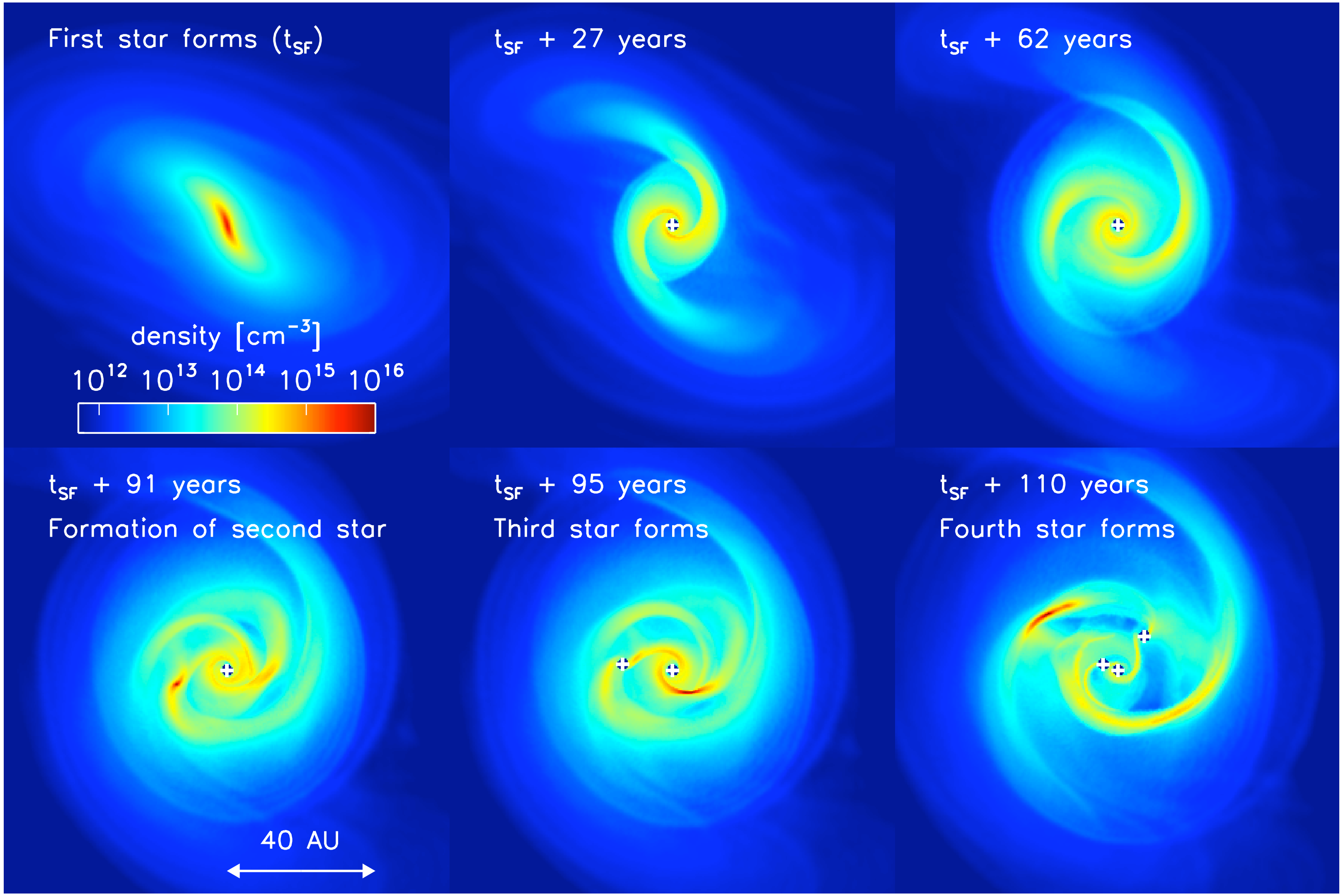
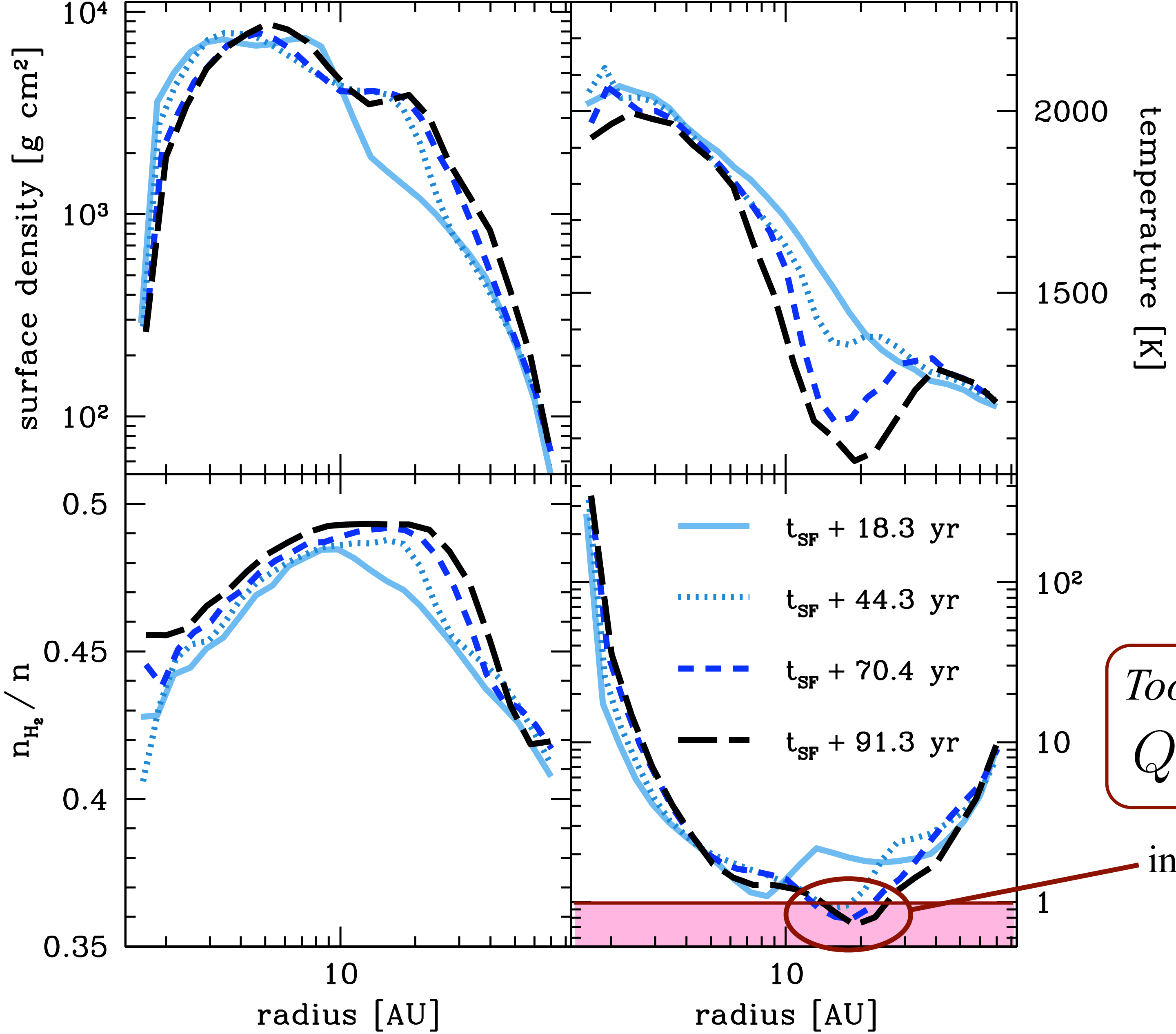


Figure 1: Density evolution in a 120 AU region around the first protostar, showing the build-up of the protostellar disk and its eventual fragmentation. We also see ‘wakes’ in the low-density regions, produced by the previous passage of the spiral arms.

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

important disk parameters



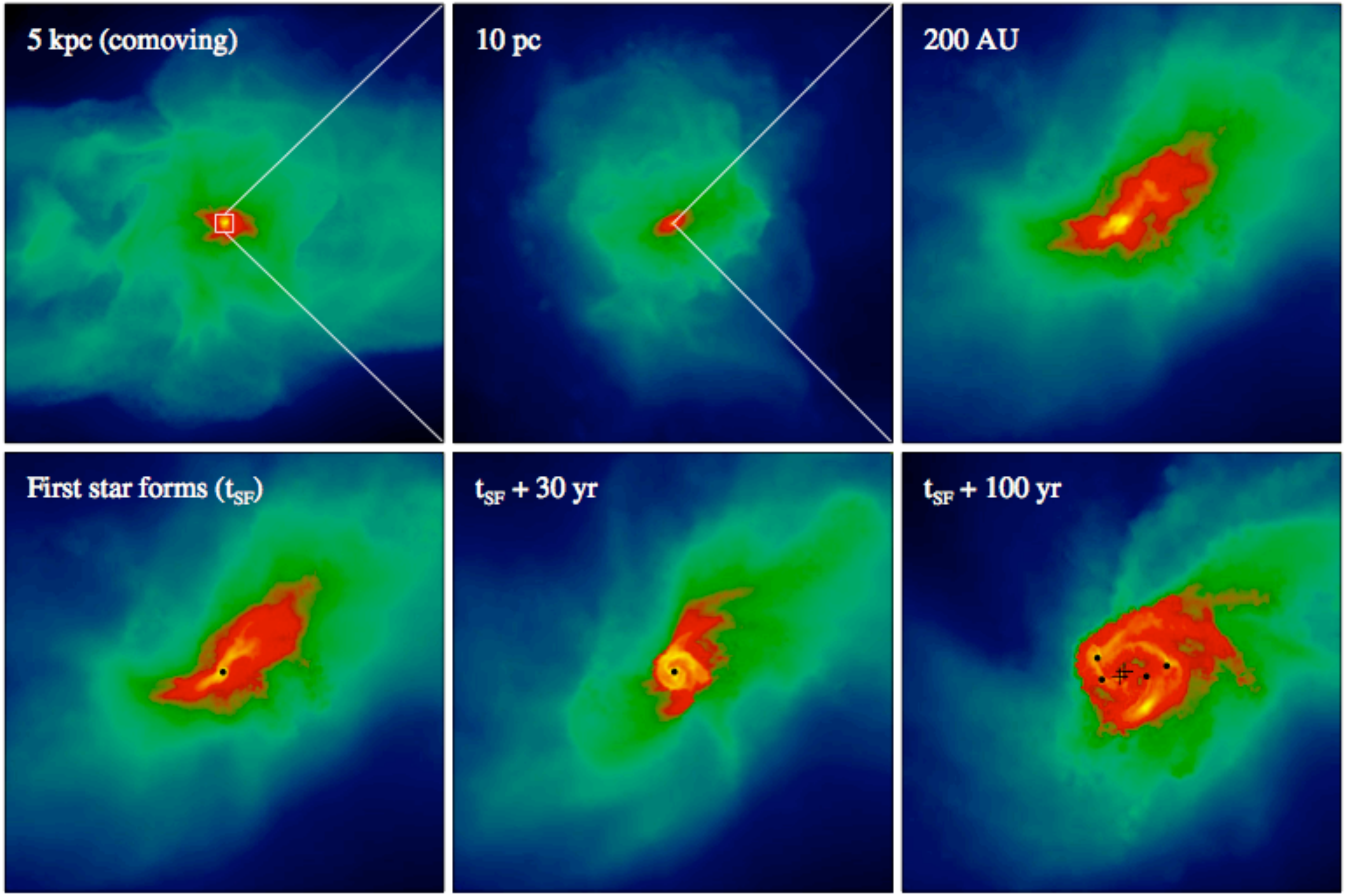
Toomre Q:

$$Q = c_{\rm s}\kappa/\pi G\Sigma$$

instability for *Q*<*1*

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

similar study with very different numerical method (AREPO)

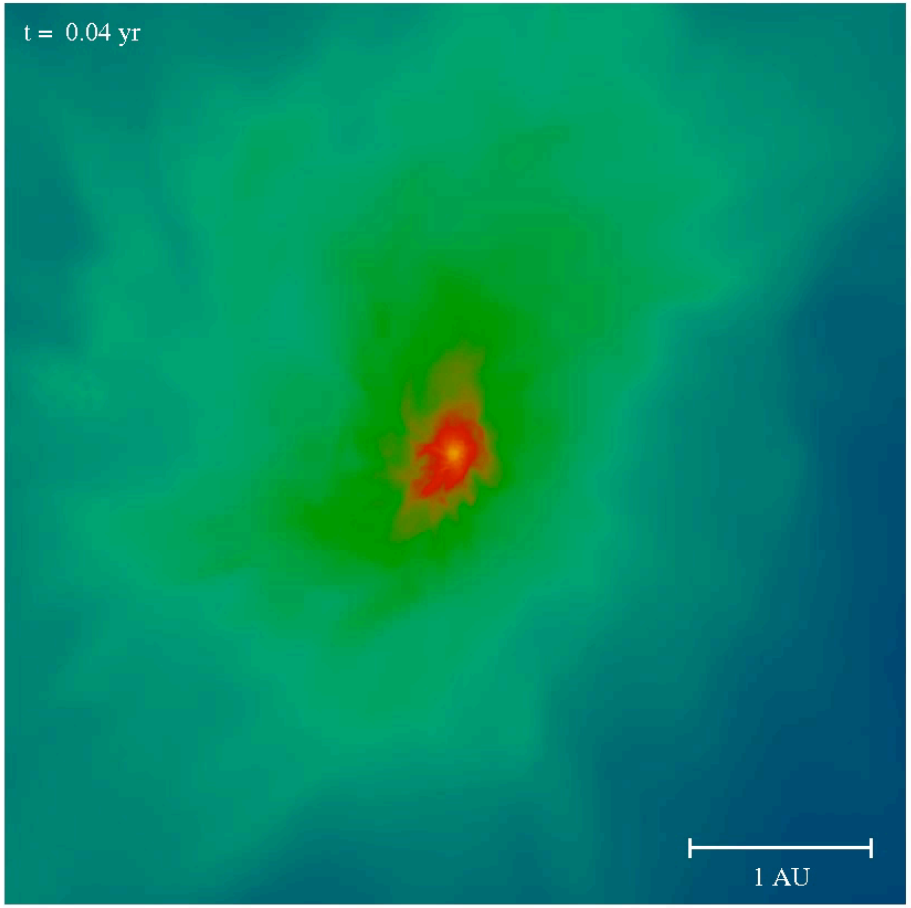


one out of five halos

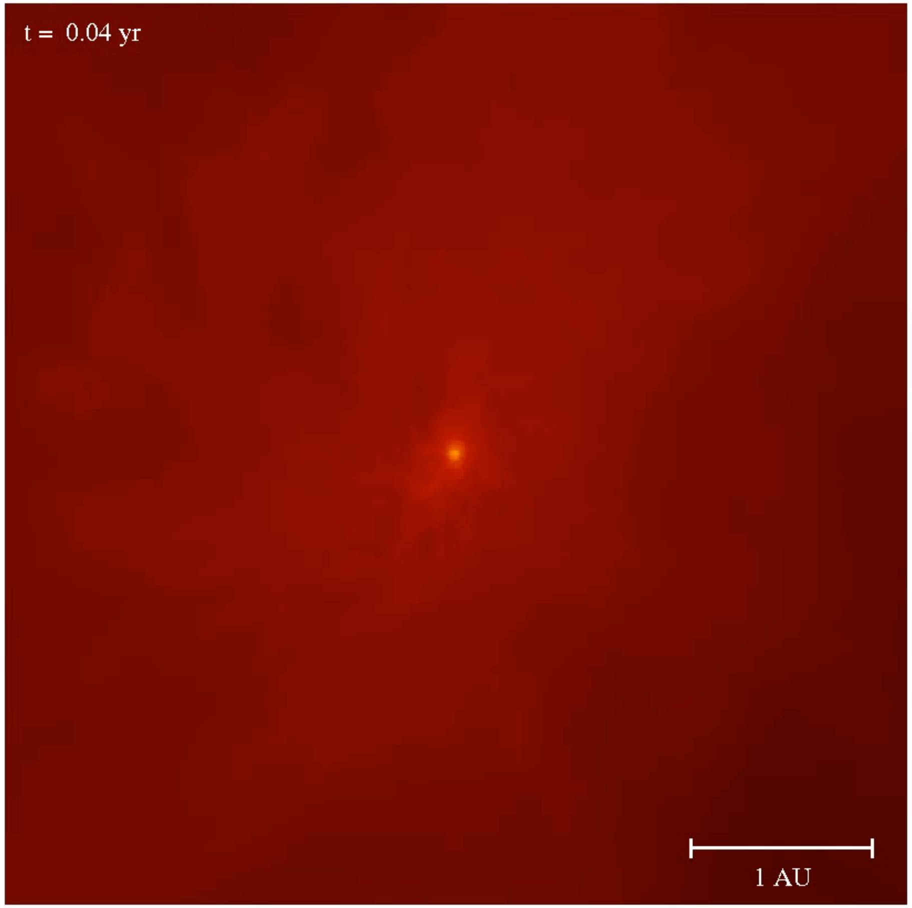
(Greif et al. 2011a, ApJ)

Most recent calculations:

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



density

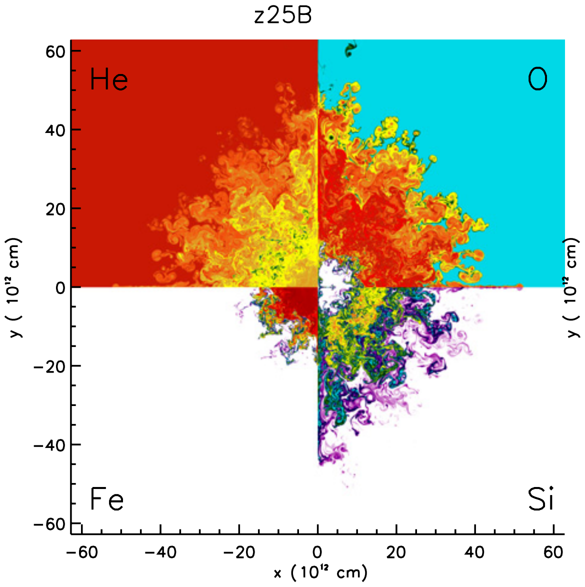


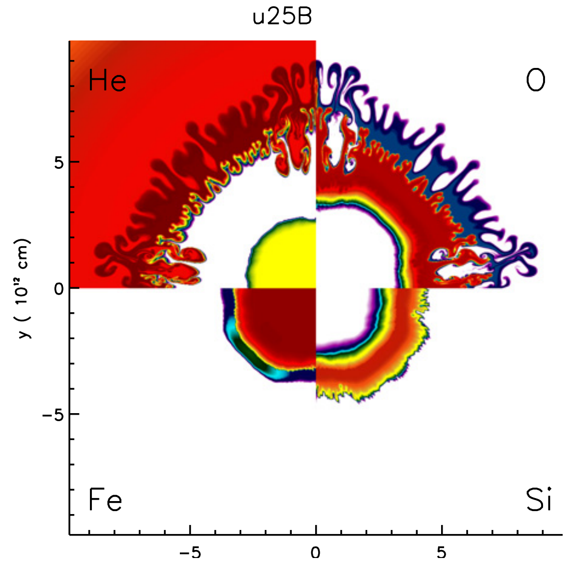
temperature

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

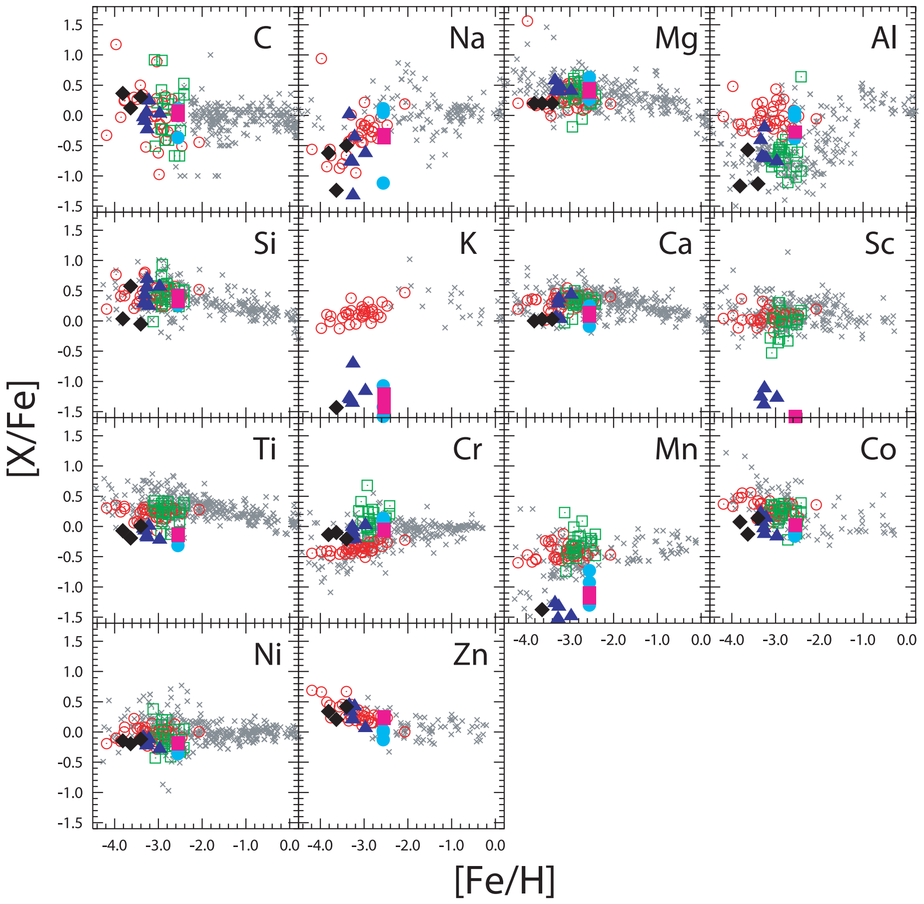
expected mass spectrum

- *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





(Joggerst et al. 2009, 2010)



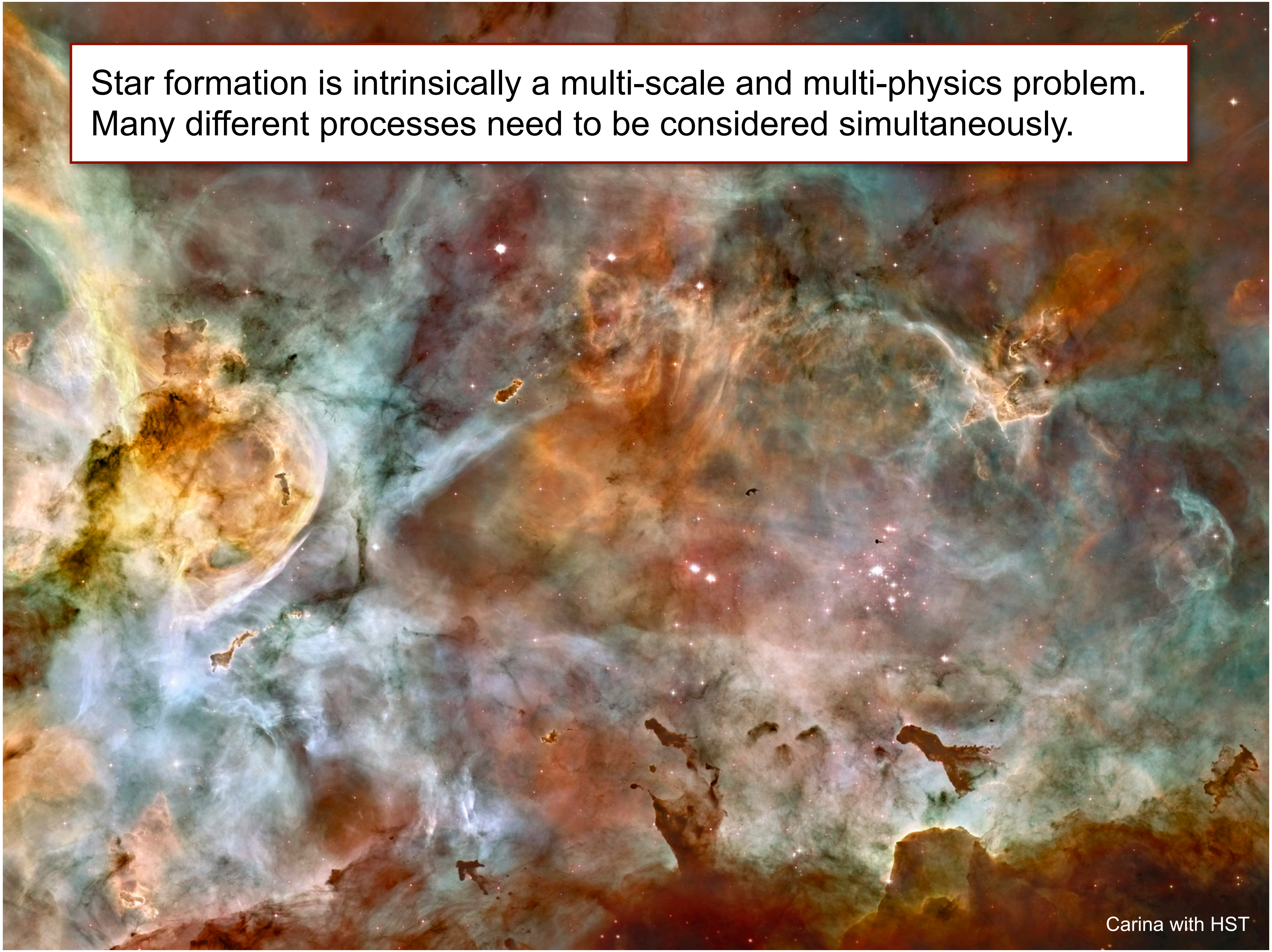
(Tominaga et al. 2007)

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 $M_\odot$

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

Carina with HST

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



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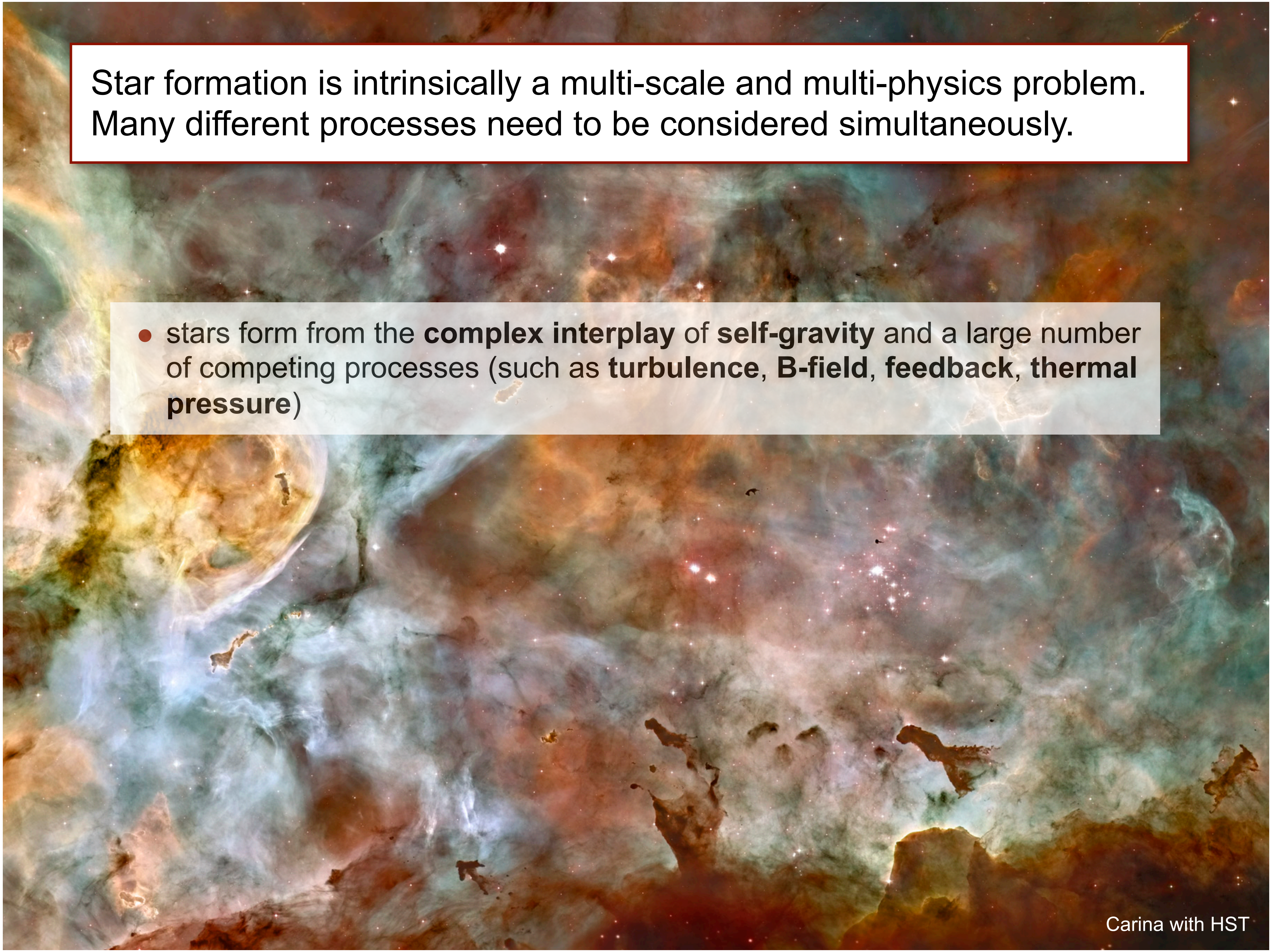

- stars form from the **complex interplay** of **self-gravity** and a large number of competing processes (such as **turbulence**, **B-field**, **feedback**, **thermal pressure**)

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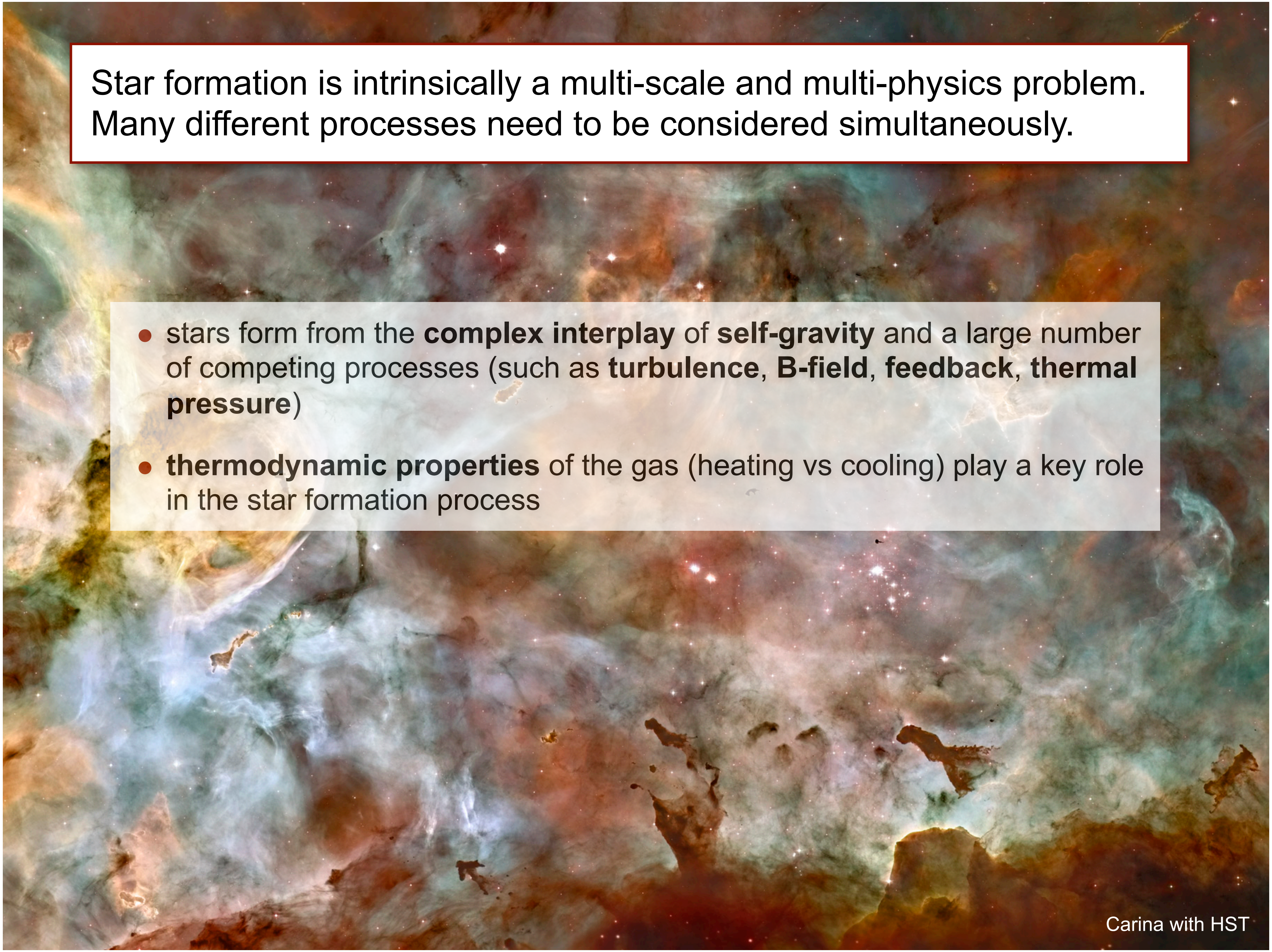
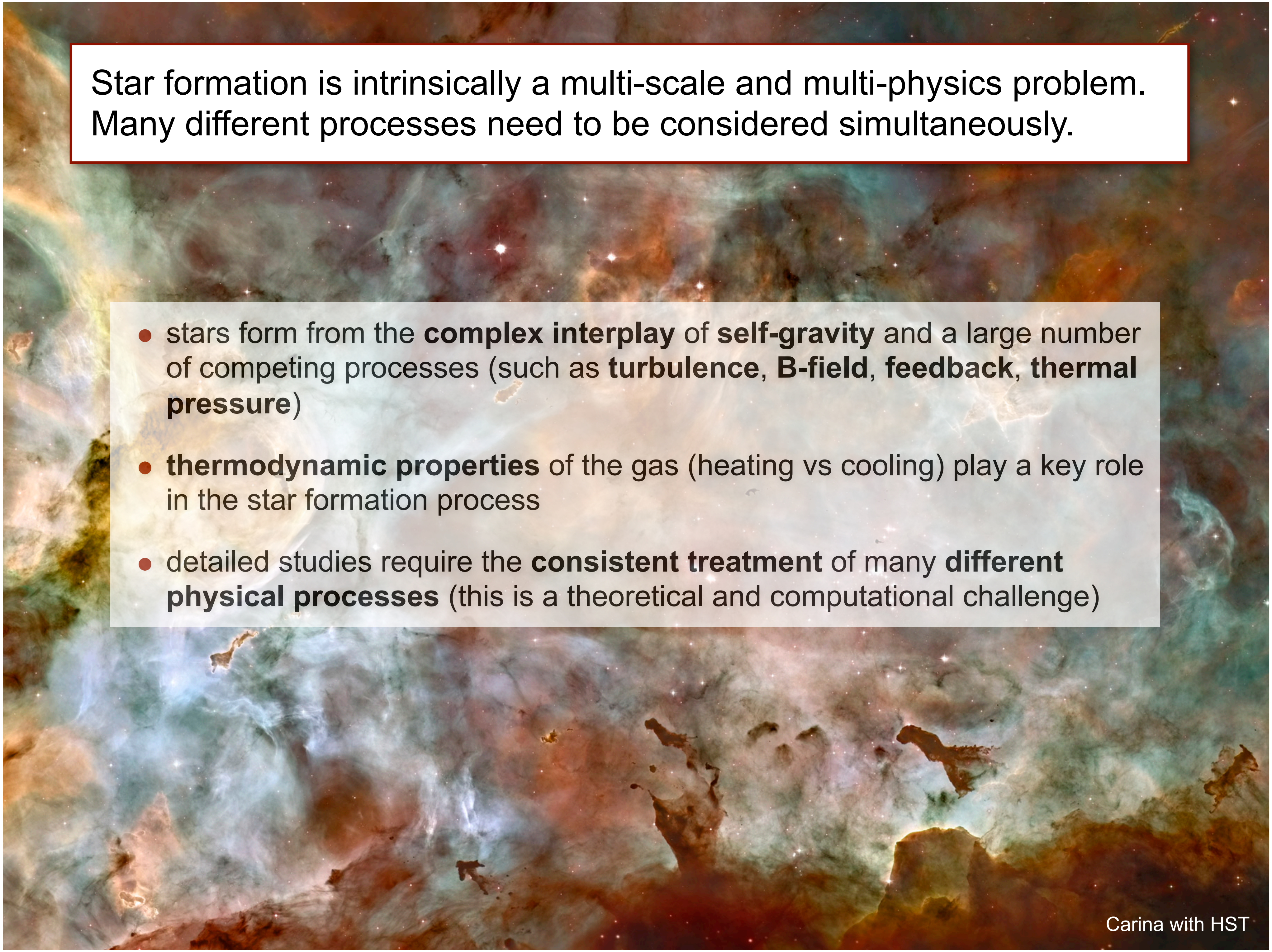
- stars form from the **complex interplay** of **self-gravity** and a large number of competing processes (such as **turbulence**, **B-field**, **feedback**, **thermal pressure**)
- **thermodynamic properties** of the gas (heating vs cooling) play a key role in the star formation process



Carina with HST



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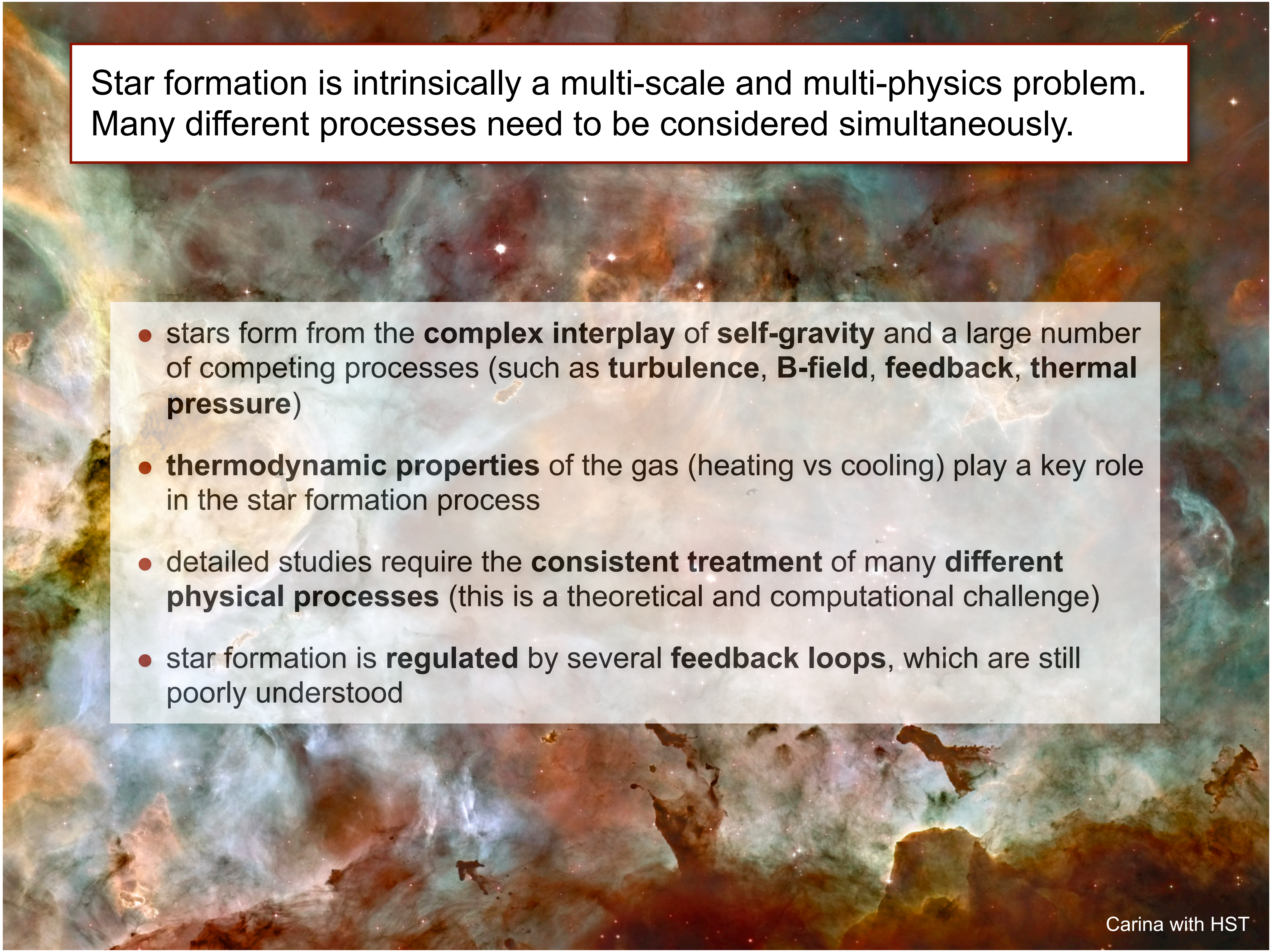
- detailed studies require the **consistent treatment** of many **different physical processes** (this is a theoretical and computational challenge)

Carina with HST



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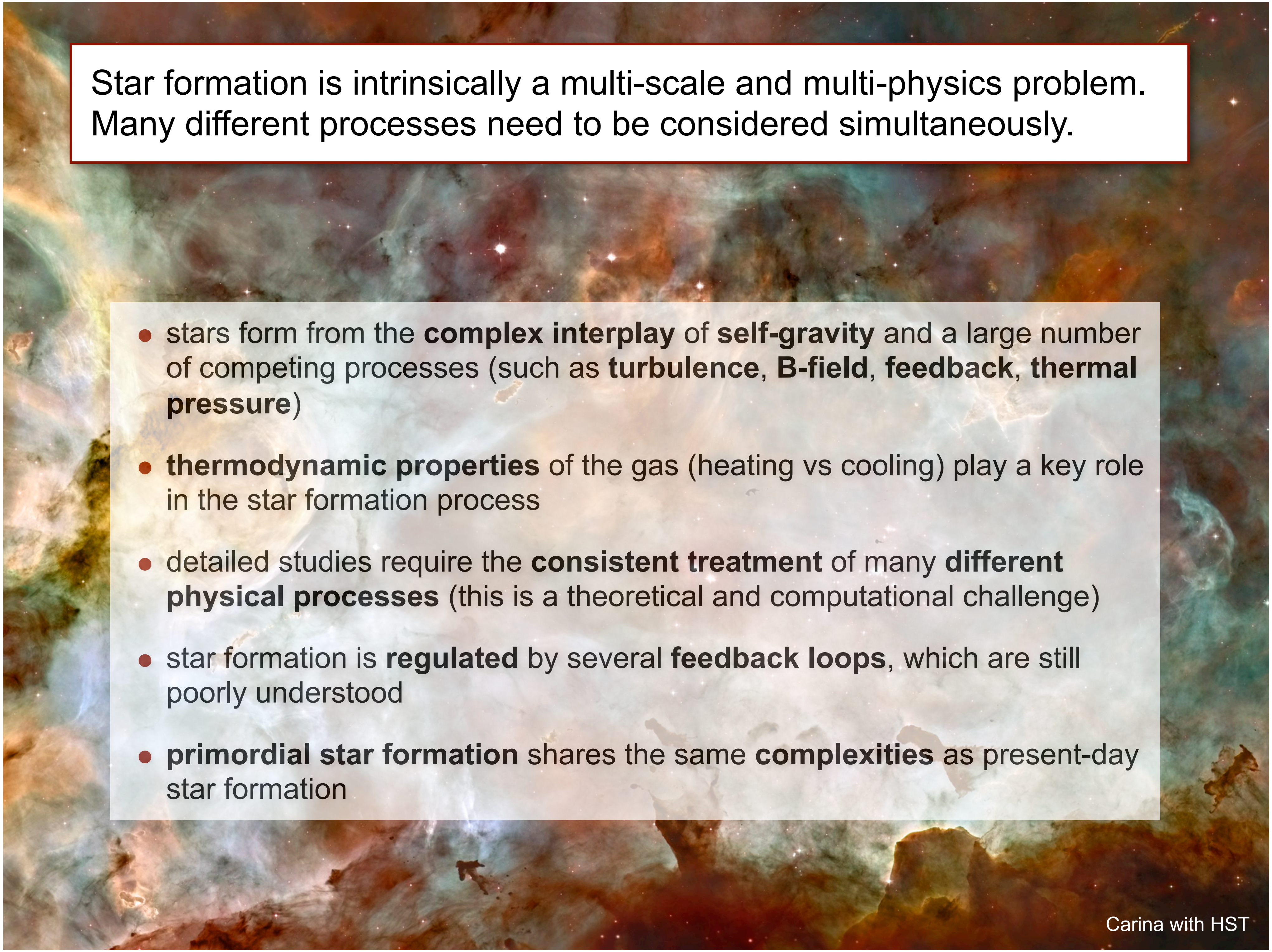
- star formation is **regulated** by several **feedback loops**, which are still poorly understood
- **primordial star formation** shares the same **complexities** as present-day star formation



Carina with HST

thanks

Protostars and Planets VI
in July 15 - 20, 2013

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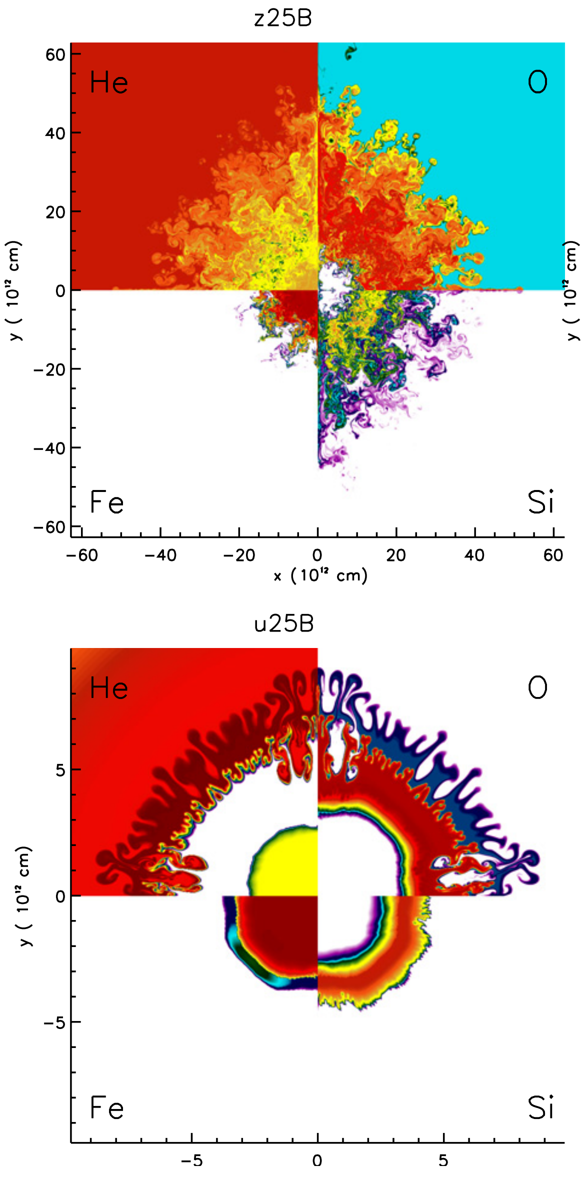
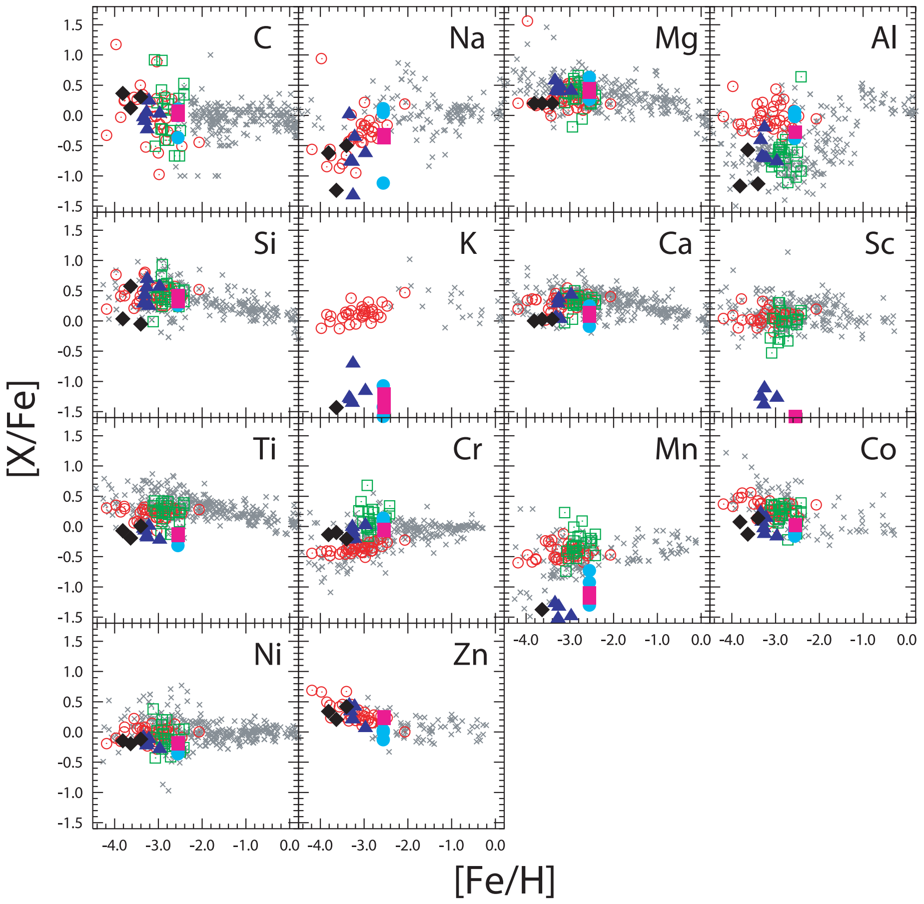
... hope to see you there!!!
(www.ppvi.org)



(Joggerst et al. 2009, 2010)

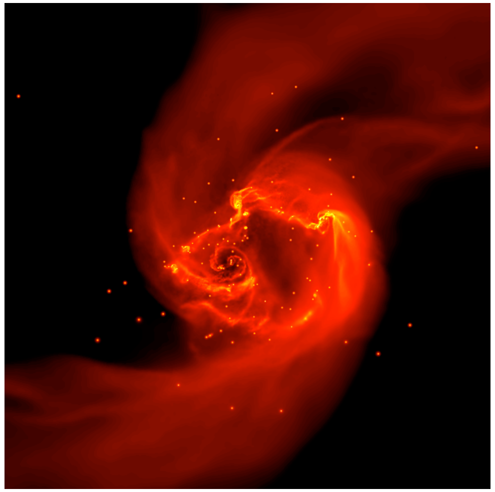


(Tominaga et al. 2007)

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 $M_\odot$

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

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*, but we expect a *wide mass range* with *typical masses of several 10s of* $M_\odot$
- disks unstable: first stars in *binaries* or *part of small clusters*
- current frontier: include *feedback* and *magnetic fields* and possibly *dark matter annihilation*?

reducing fragmentation

- from present-day star formation theory we know, that
  - magnetic fields (e.g. Peters et al.2011, Seifried et al. 2012, Hennebelle et al. 2011)
  - accretion heating (e.g. Peters et al. 2010abc, Krumholz et al. 2009, Kuipers et al. 2011)

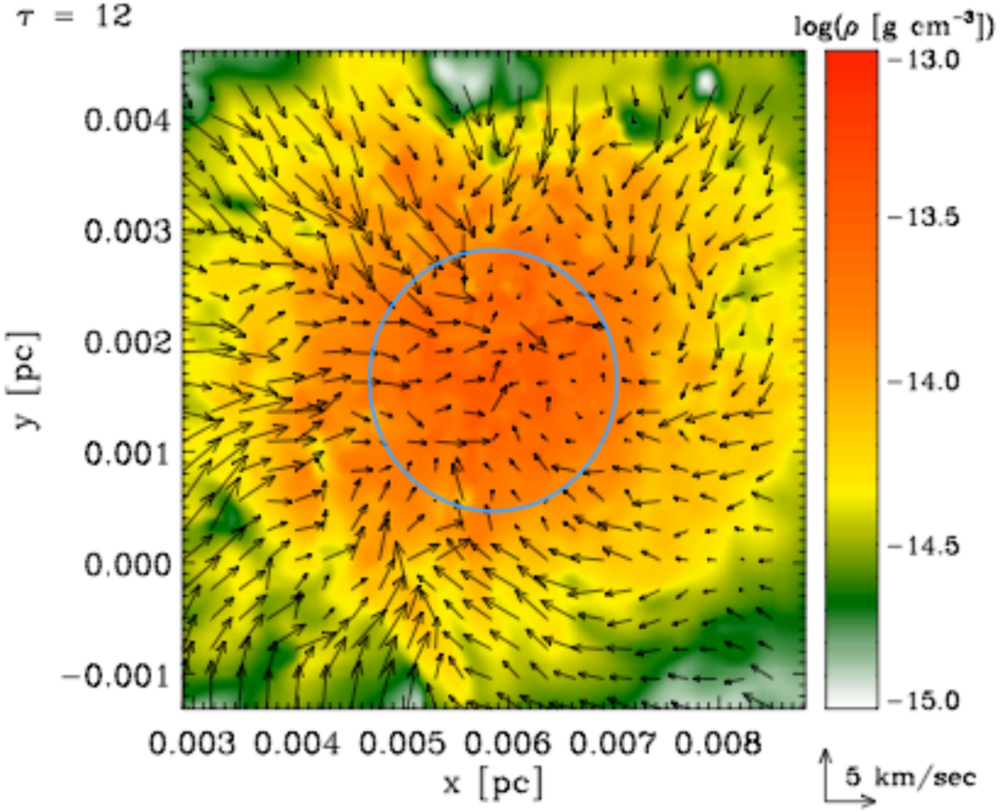
  can influence the fragmentation behavior.
- in the context of Pop III
  - radiation: talks by Hajime Susa, Athena Stacy ,Takashi Hosokawa
  - magnetic fields: talks by Jeff Oishi and Matt Turk
- all these will reduce degree of fragmentation (but not by much, see also Smith et al. 2011, 2012)
- DM annihililation might become important for disk dynamics and fragmentation (see talk by Fabio Iocco, and poster by Rowan Smith)

B fields in the early universe?

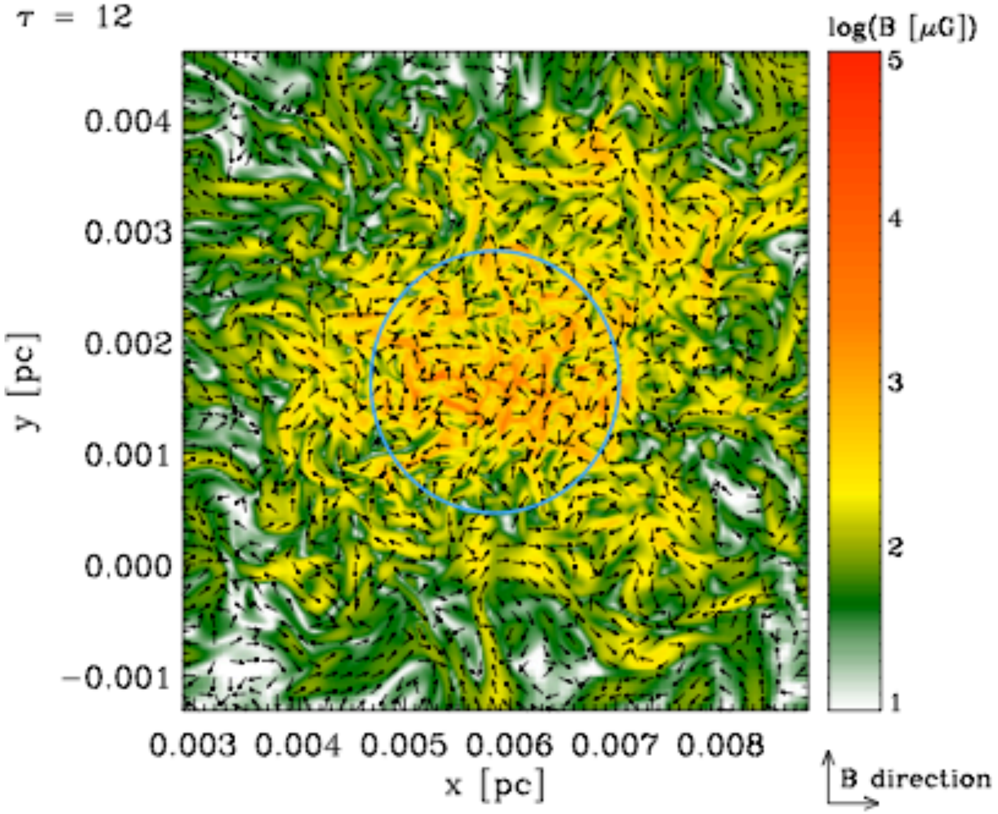
- we know the universe is magnetized (now)
- knowledge about B-fields in the high-redshift universe is extremely uncertain
  - inflation / QCD phase transition / Biermann battery / Weibel instability
- they are thought to be extremely small
- however, *THIS MAY BE WRONG*!

small-scale turbulent dynamo

- *idea:* the small-scale turbulent dynamo can generate strong magnetic fields from very small seed fields
- *approach:* model collapse of primordial gas ---> formation of the first stars in low-mass halo
- *method:* solve ideal MHD with very high resolution
  - grid-based AMR code FLASH
  - polytropic EOS with $\gamma = 1.1$
  - resolution up to 128^3 cells per Jeans volume (effective resolution 65536^3 cells)
  - see: Schleicher et al. 2010, A&A, 522, A115, Sur et al. 2010, ApJ, 721, L734, Federrath et al., 2011, ApJ, 731, 62, Schober 2012, PRE, 85, 026303, Schober et al. 2012, ApJ, 754, 99

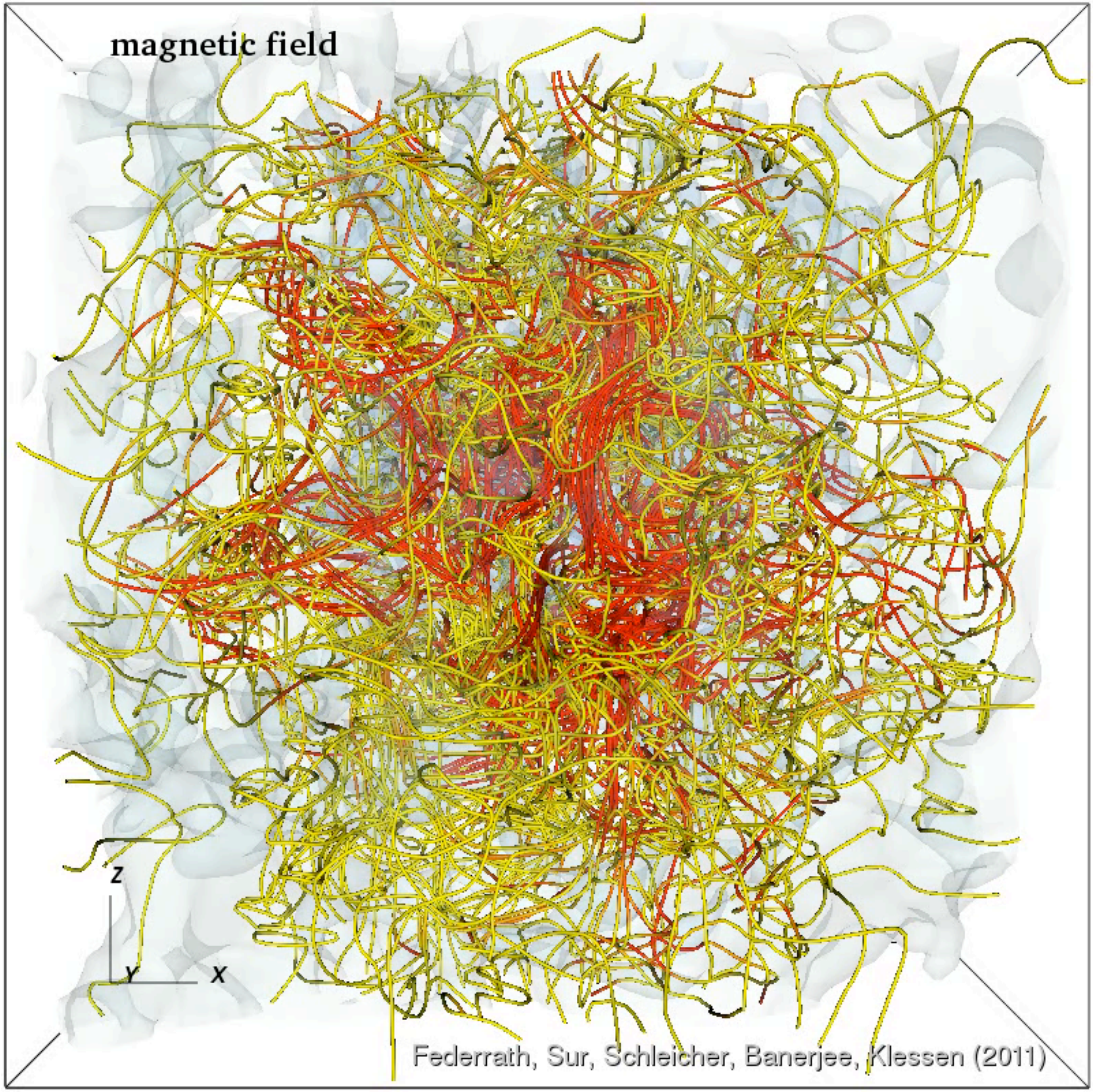


magnetic field structure

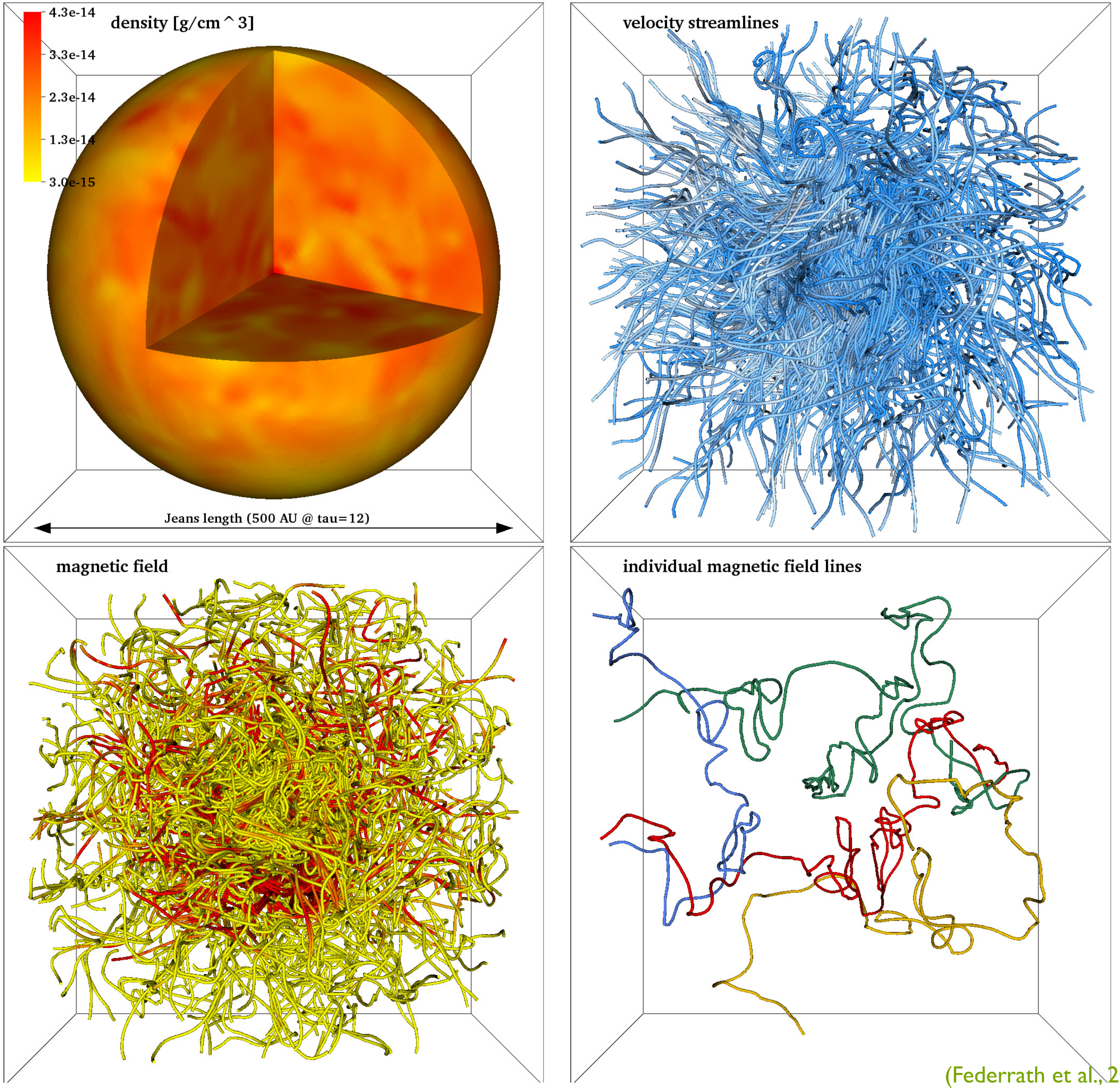


density structure

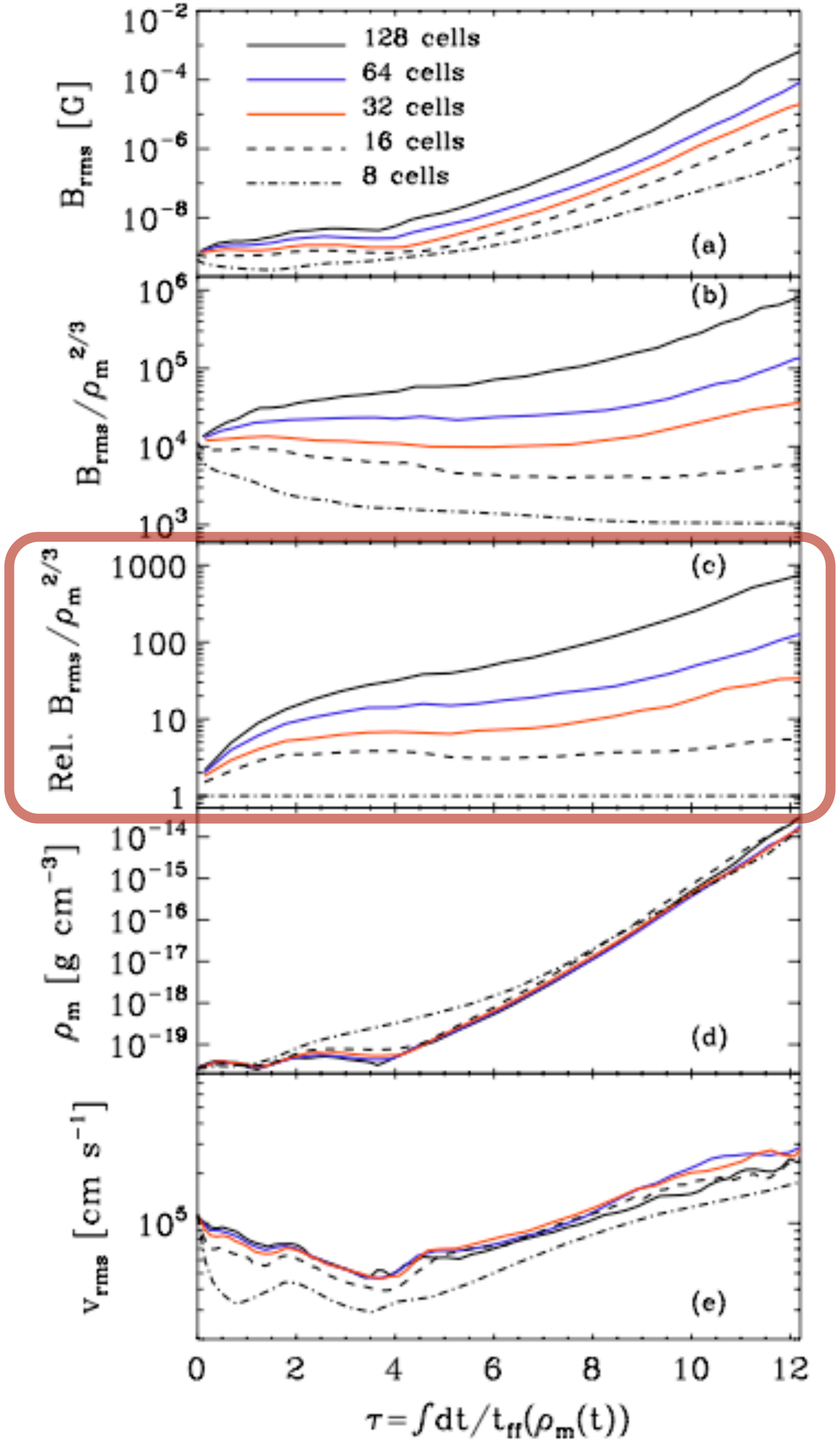
(Sur et al. 2010, ApJ, 721, L734)

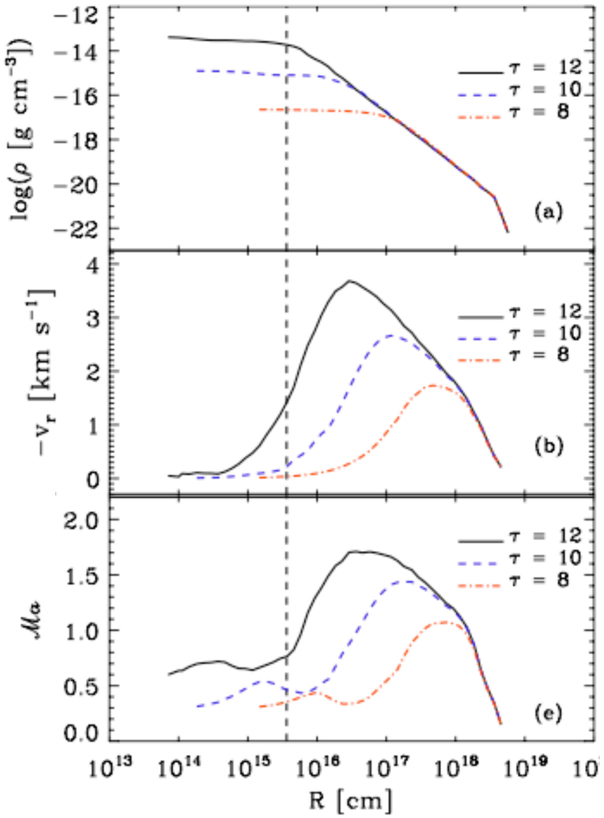


(Schleicher et al. 2010, A&A, 522, A115,   Sur et al. 2010, ApJ, 721, L734,   Federrath et al., 2011, ApJ, 731, 62)



(Federrath et al., 2011, ApJ, 731, 62)





radial density profile

radial velocity profile

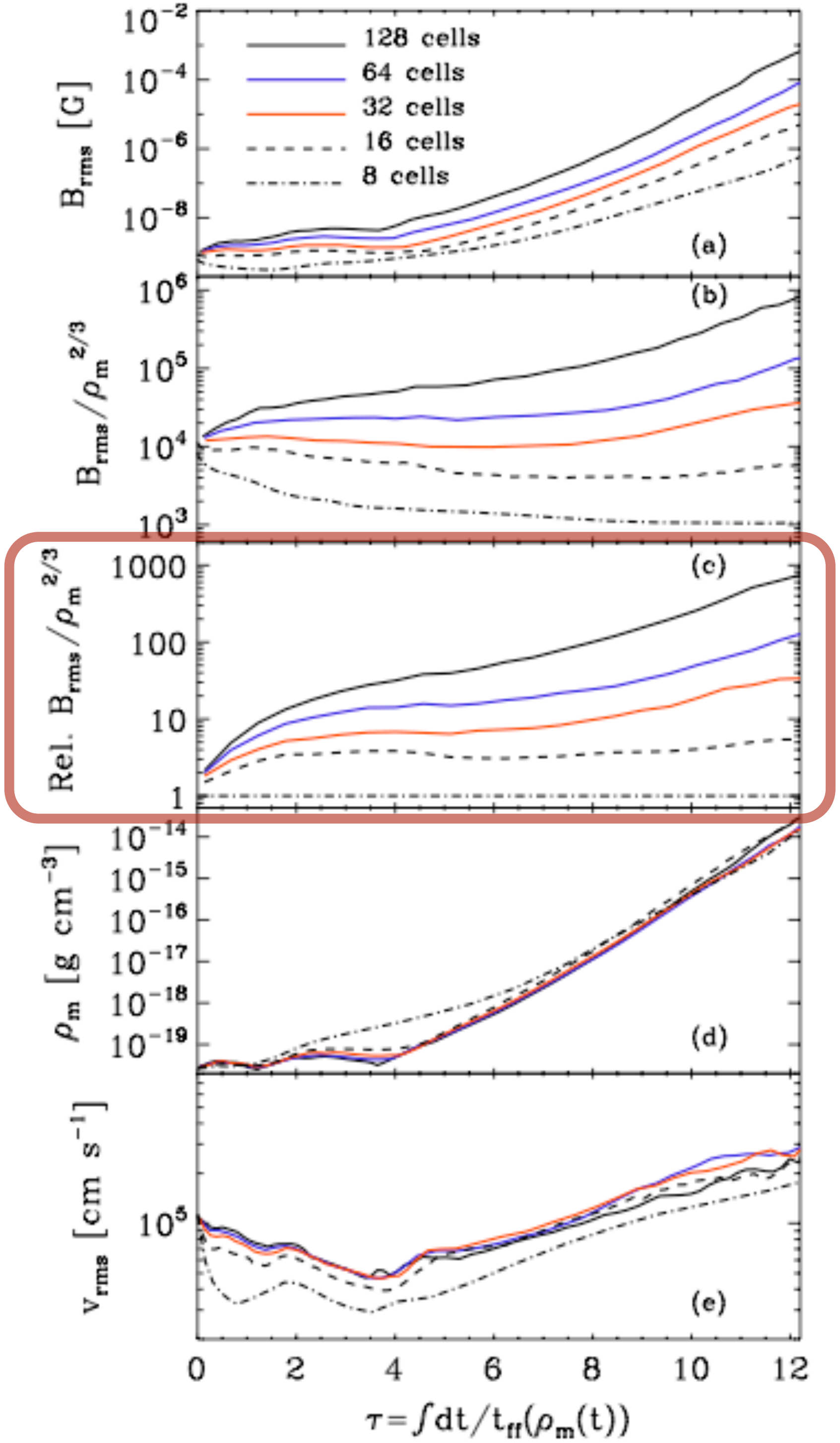
Mach number profile

Field amplification during first collapse seems unavoidable.

QUESTIONS:

- Is it really the small scale dynamo?
- What is the saturation value?
  Can the field reach dynamically important strength?

(Sur et al. 2010, ApJ, 721, L734)



Field amplification during first collapse seems unavoidable.

QUESTIONS:

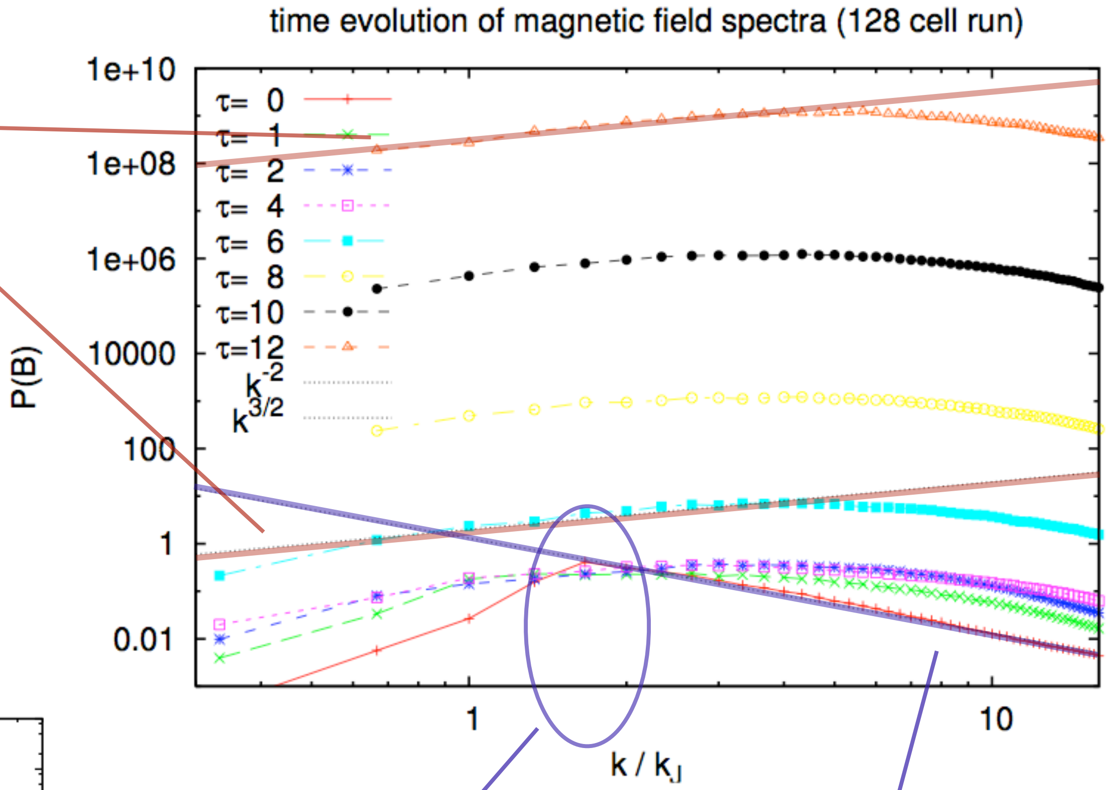
- Is it really the small scale dynamo?
- What is the saturation value?
  Can the field reach dynamically important strength?
- How does it depend on the thermodynamics of the gas (i.e. on the EOS)?

(Sur et al. 2010, ApJ, 721, L734)

Kazantsev behavior

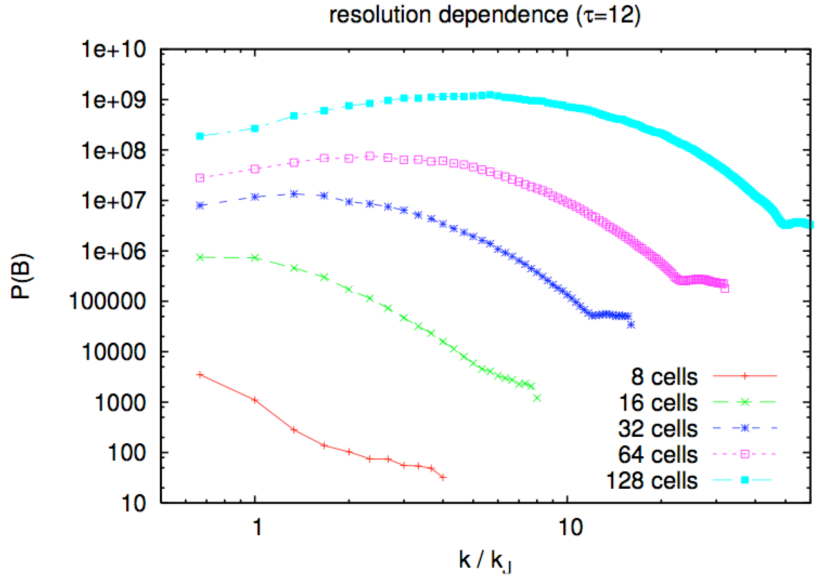
Slope +3/2 of Kazantsev theory

(e.g. Brandenburg & Subramanian, 2005, Phys. Rep., 417, 1)



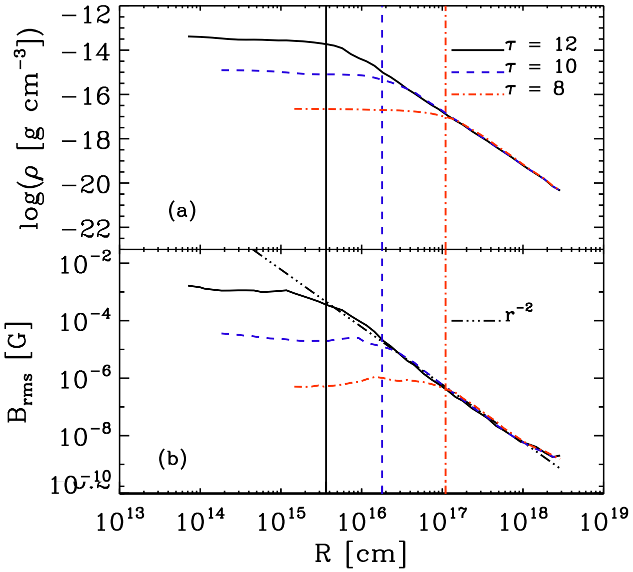
initial peak of B fluctuation spectrum

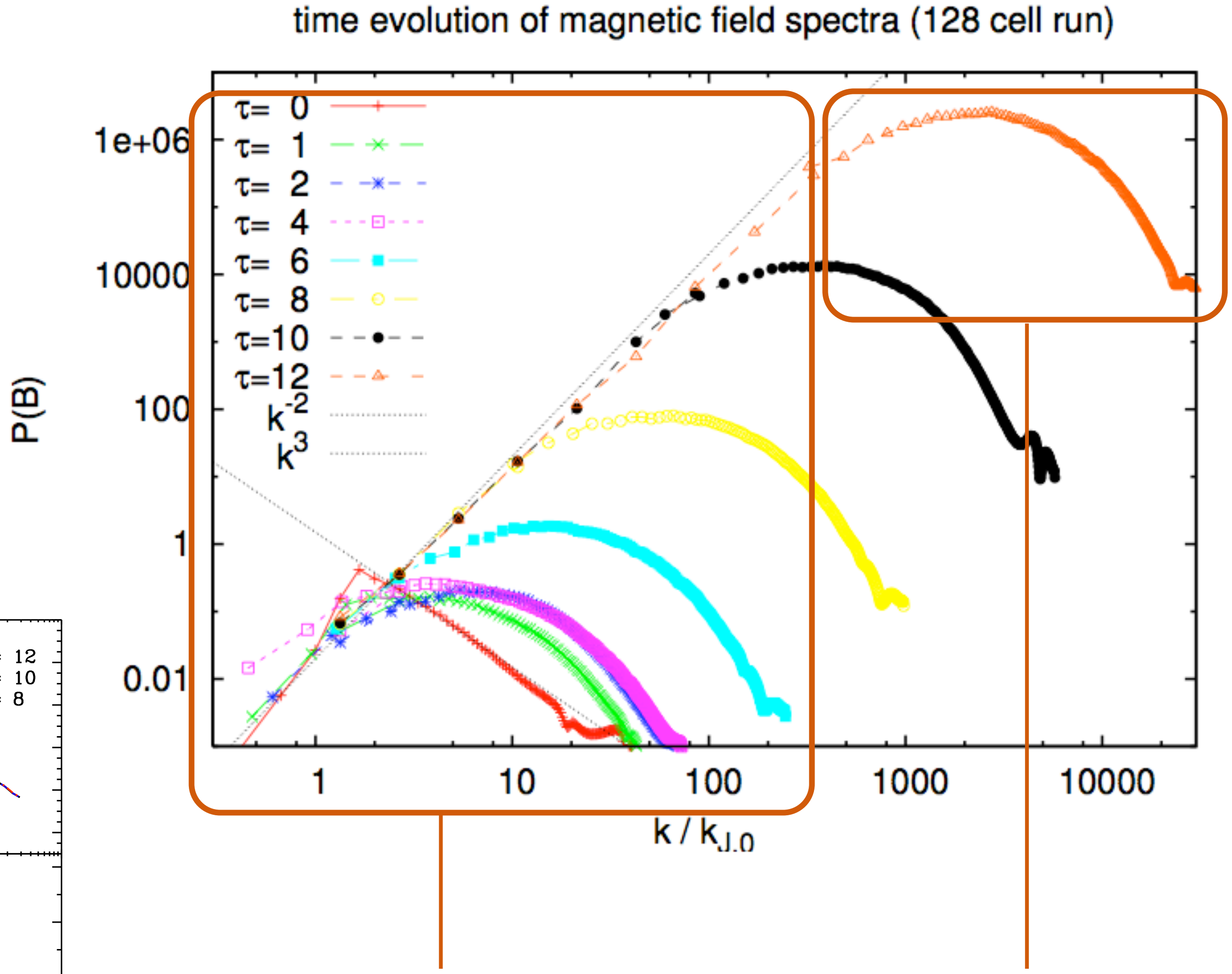
initial slope of B fluctuations



(Federrath et al., 2011, ApJ, 731, 62)

analysis of magnetic field spectra





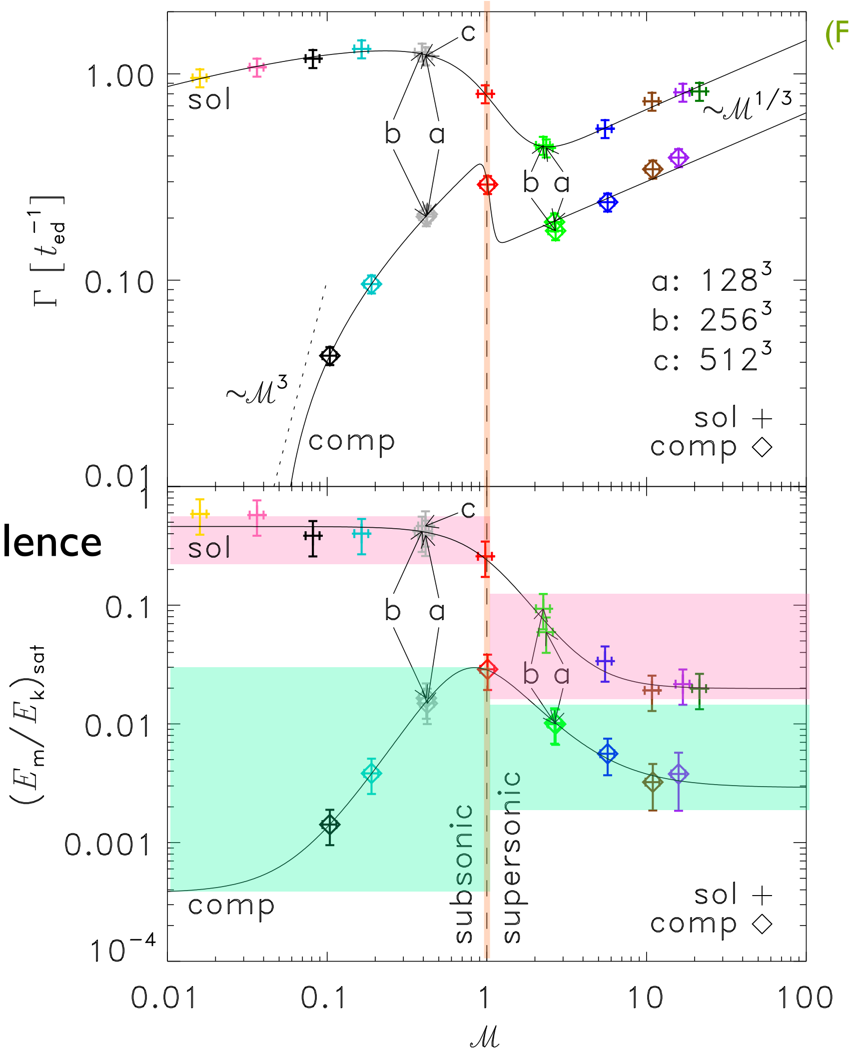
B fluctuation spectrum
in $1/r^2$ fall-off

B fluctuation spectrum
in flat inner core

(Federrath et al., 2011, ApJ, 731, 62)

Saturation level

(Federrath et al., 2011, PRL, 107, 114505)



subsonic, solenoidal turbulence

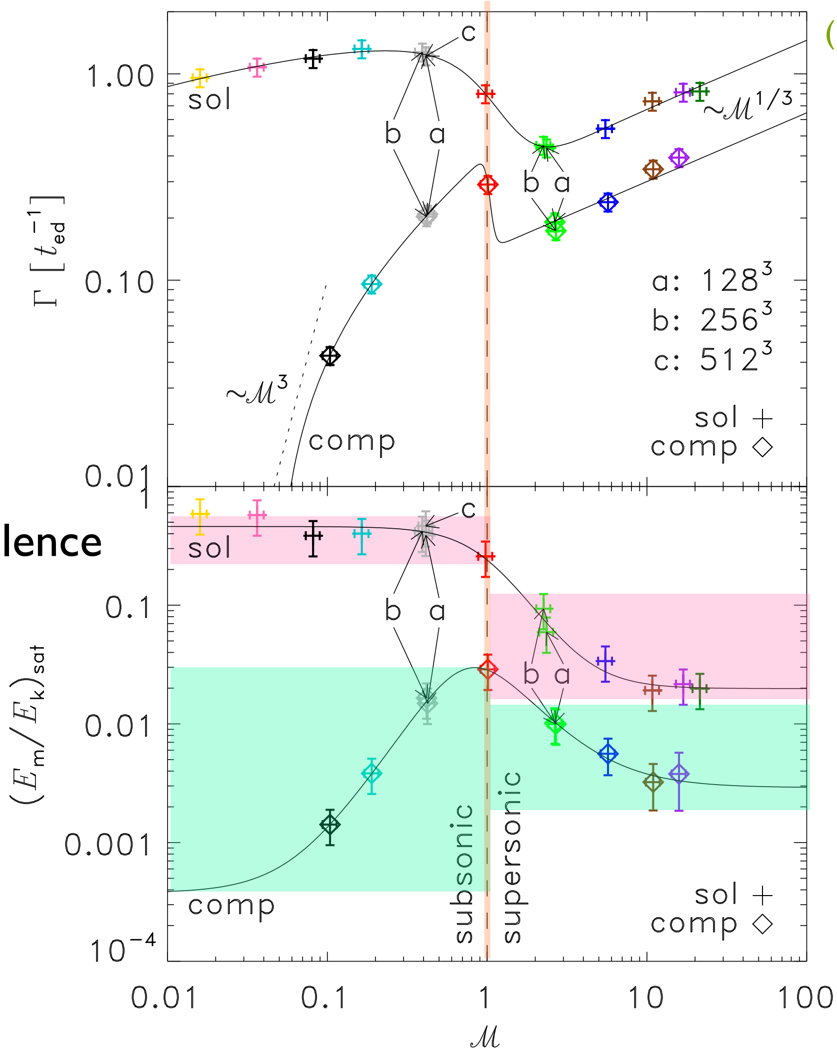
subsonic,
compressive turbulence

saturation level for supersonic, solenoidal turbulence

saturation level for supersonic, compressive turbulence

Saturation level

(Federrath et al., 2011, PRL, 107, 114505)



subsonic, solenoidal turbulence

subsonic,
compressive turbulence

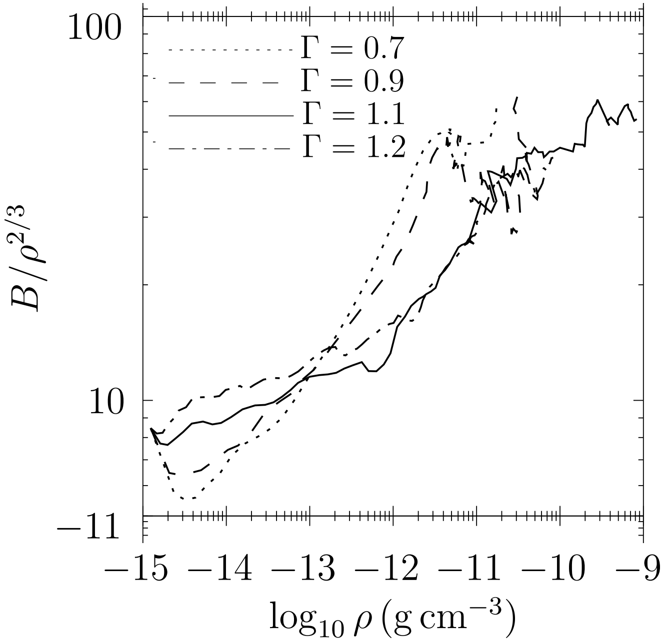
saturation level for supersonic,
solenoidal turbulence

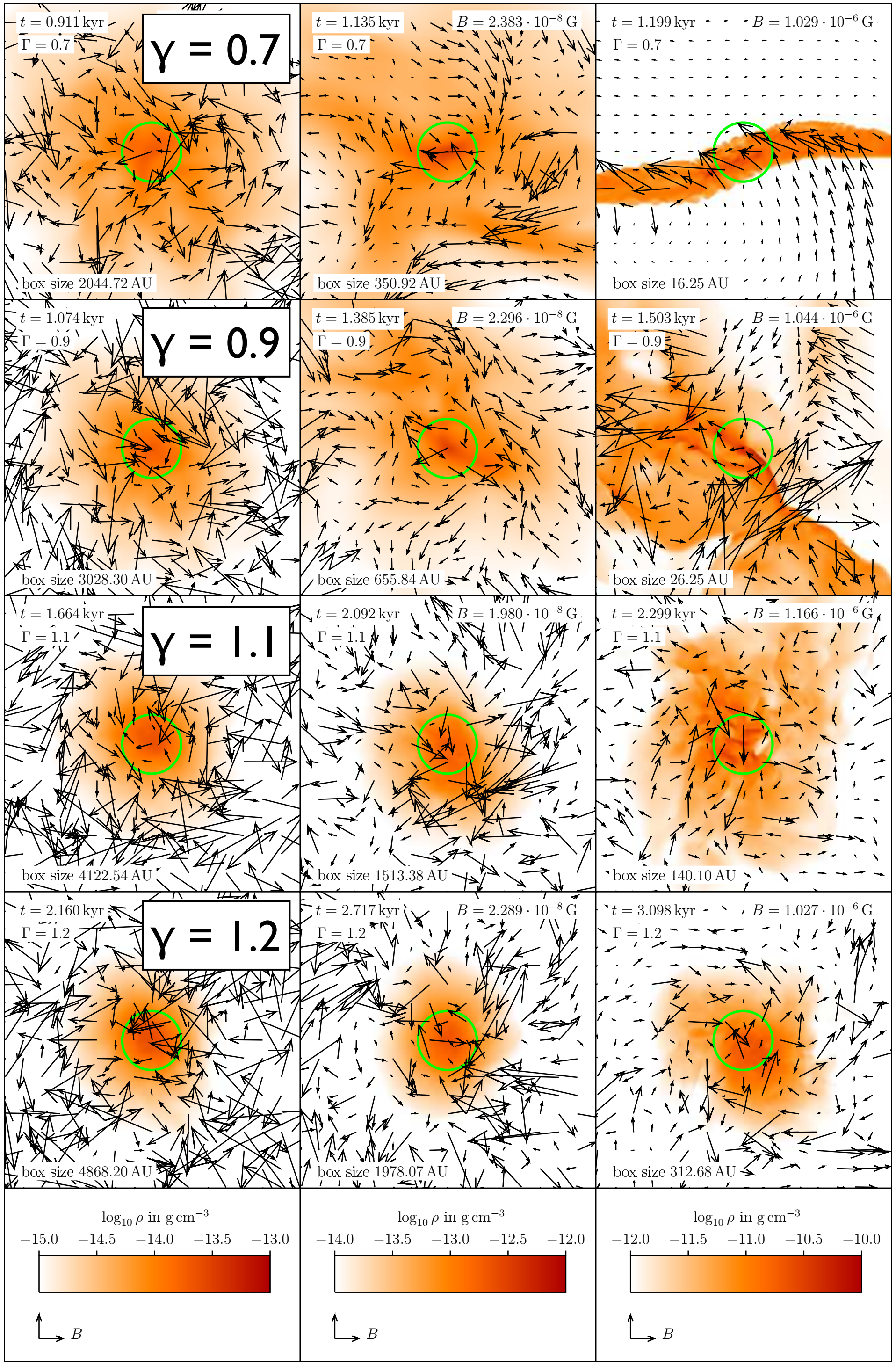
saturation level for supersonic,
compressive turbulence

This behavior is reproduced *analytically* using the *Kazantsev* formalism for very large and very small Prandtl numbers, and for the range from Kolmogorov to Burgers turbulence.

(Schober et al., 2012, PRE, 85, 026303, Schober et al. 2012, ApJ, 754, 99, Schober et al. 2012, PRE, submitted, Bovino et al., PRL, submitted)

Dependence on EOS



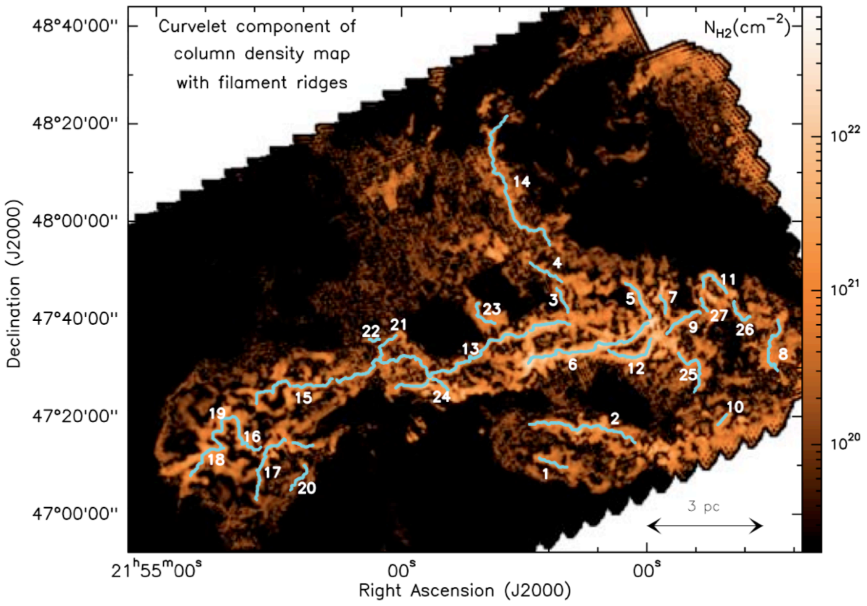


zooming in on collapsing core

- magnetic field amplification for all gamma.
- *BUT*: very different morphology:
  - *filaments for* γ *<1* and
  - *roundish structures for* γ *>1*
- implications for present-day molecular clouds?

Peters et al. (2012, ApJ, in press -- arXiv:1209.5861)

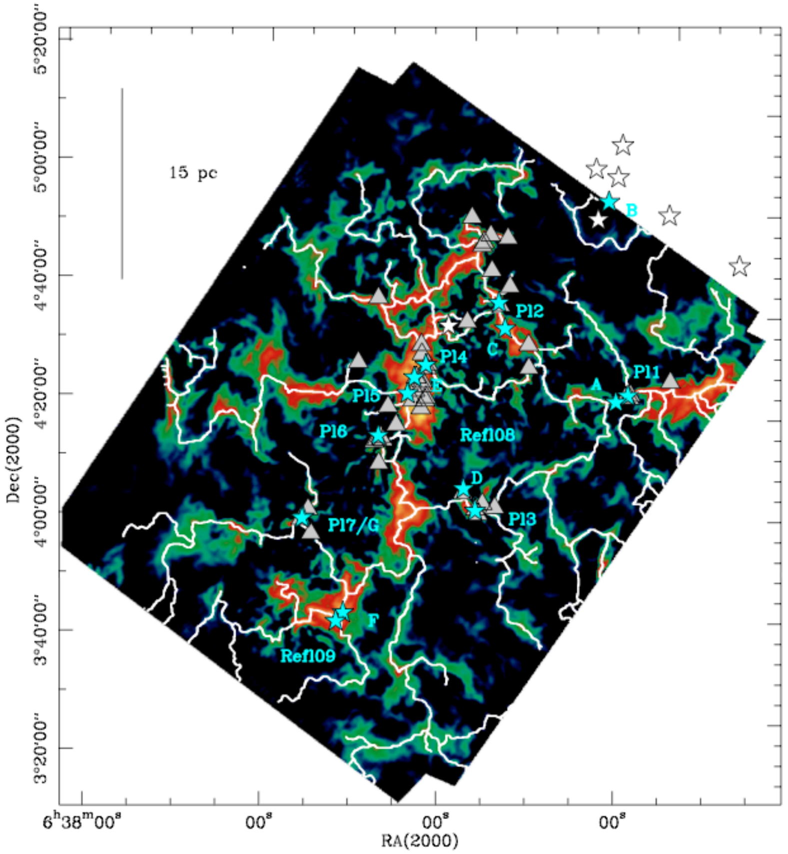
Filaments in nearby molecular clouds



IC 5146 as seen by Herschel

Arzoumanian et al. (2011, 529, L6)

- *QUESTION:* to what degree are the filaments seen in nearby molecular clouds caused by EOS effects.
- molecular clouds form in thermally unstable gas with γ ~ 0.7 (i.e. they are in a cooling regime)



Rosette as seen by Herschel

Schneider et al. (2012, A&A, 540, L11)