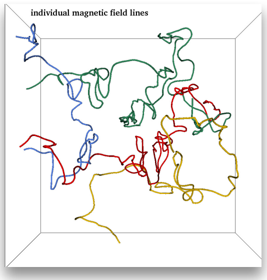
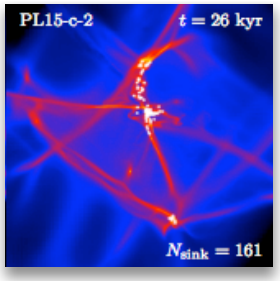
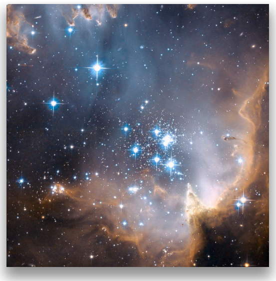
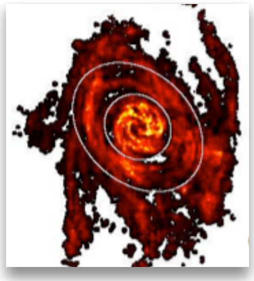
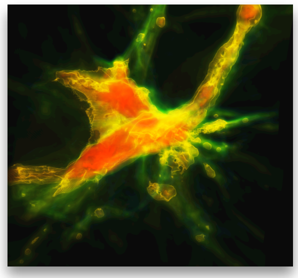
Modern Developments in Star Formation Theory











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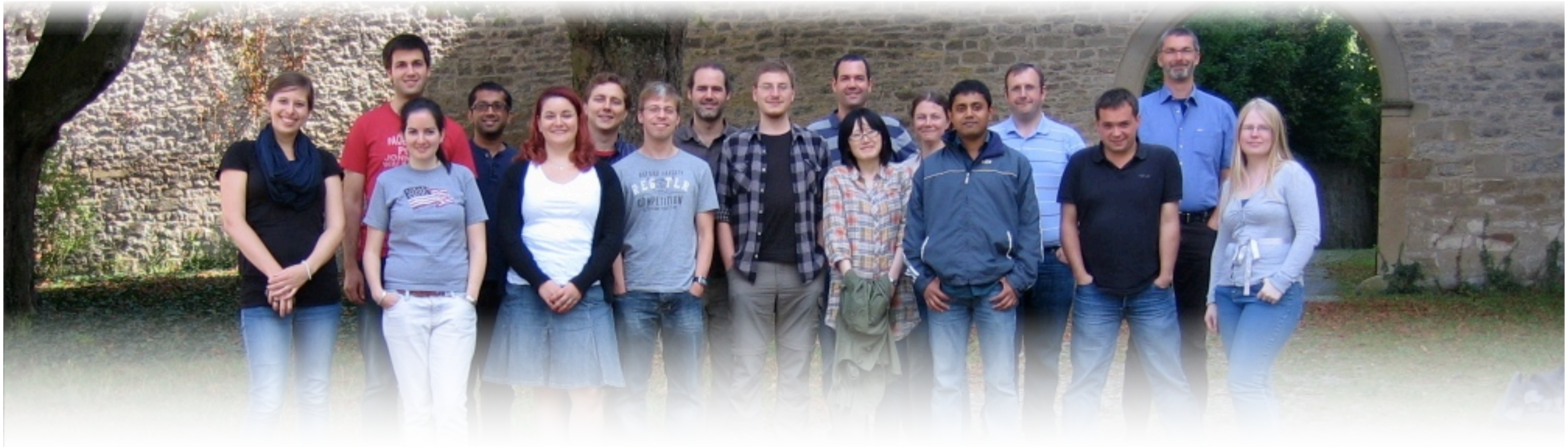
Institut für Theoretische Astrophysik

thanks to ...



... people in the group in Heidelberg:

Christian Baczynski, Clio Bertelli Motta, Erik Bertram, Frank Bigiel, Roxana Chira, Paul Clark, Gustavo Dopcke, Jayanta Dutta, Volker Gaibler, Simon Glover, Tilman Hartwig, Lukas Konstandin, Faviola Molina, Mei Sasaki, Jennifer Schober, Rahul Shetty, Rowan Smith, László Szűcs, Svitlana Zhukovska

... former group members:

Robi Banerjee, Ingo Berentzen, Christoph Federrath, Philipp Girichidis, Thomas Greif, Milica Micic, Thomas Peters, Dominik Schleicher, Stefan Schmeja, Sharanya Sur

... many collaborators abroad!

Deutsche Forschungsgemeinschaft DFG

BADEN-WÜRTTEMBERG STIFTUNG Wir stiften Zukunft

HGSFP

IMPRS

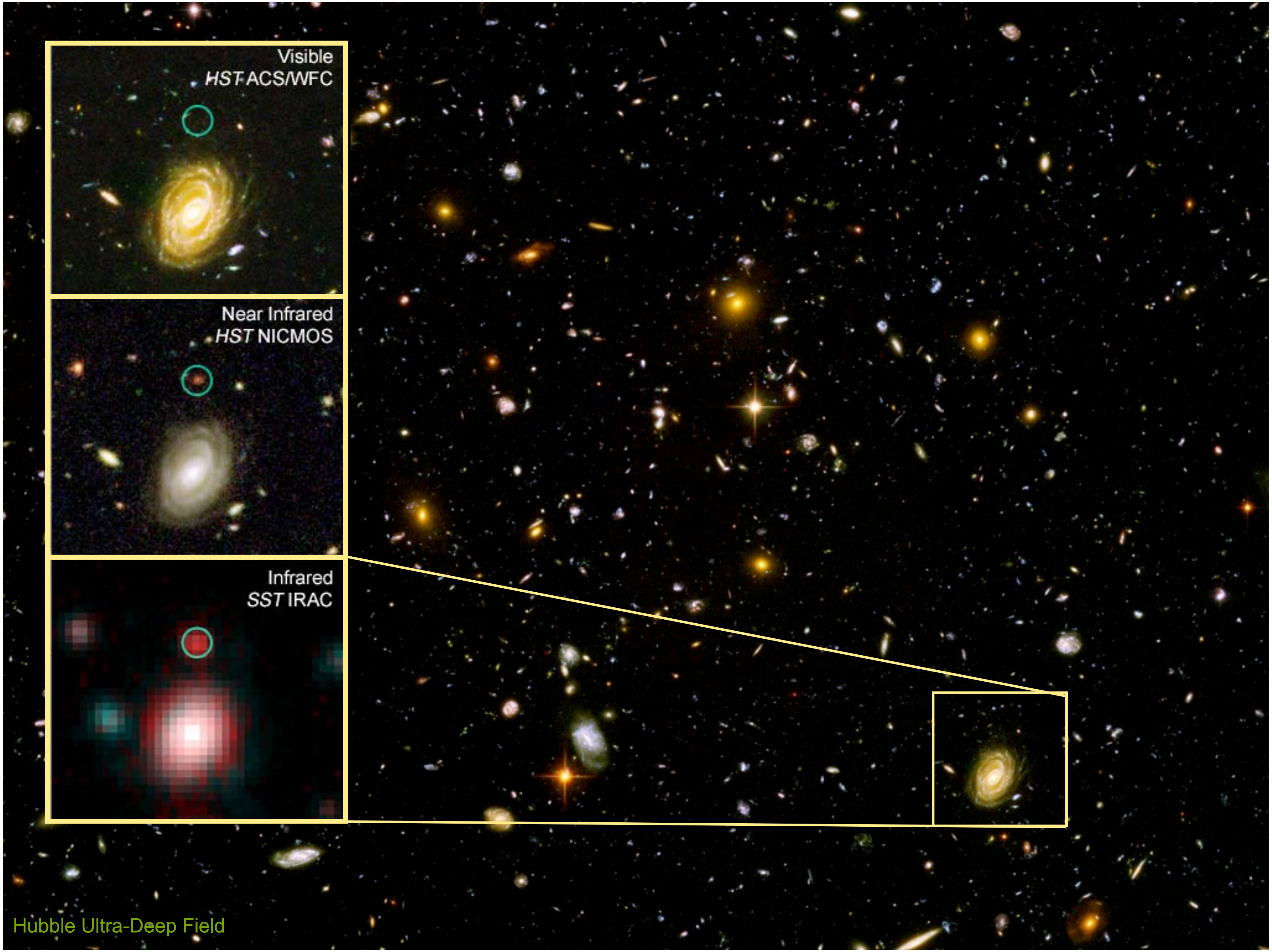
agenda

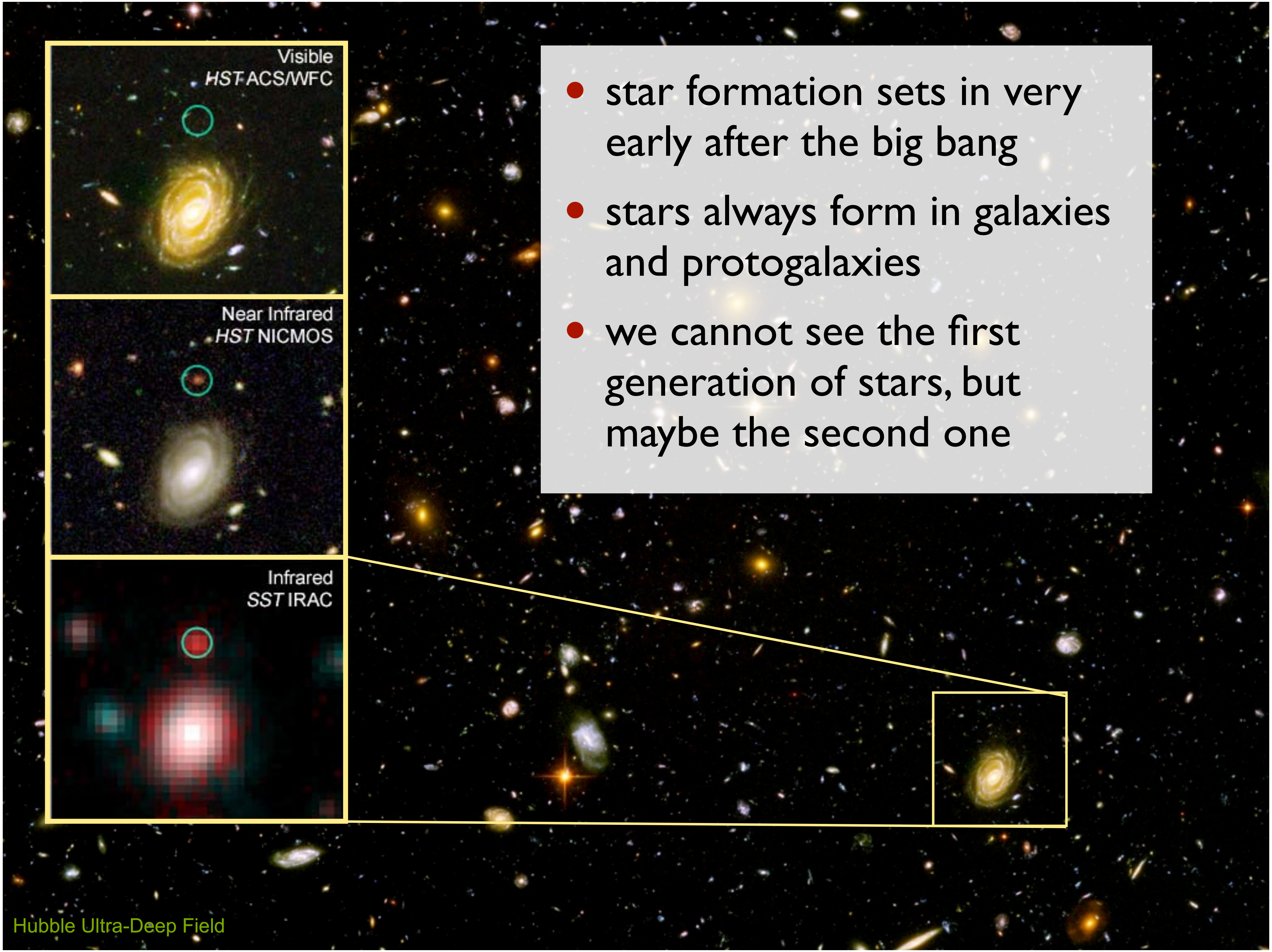
- star formation theory
  - phenomenology
  - historic remarks
  - our current understanding and its limitations
- application
  - the stellar mass function at birth (IMF)


NGC 3324 (Hubble, NASA/ESA)

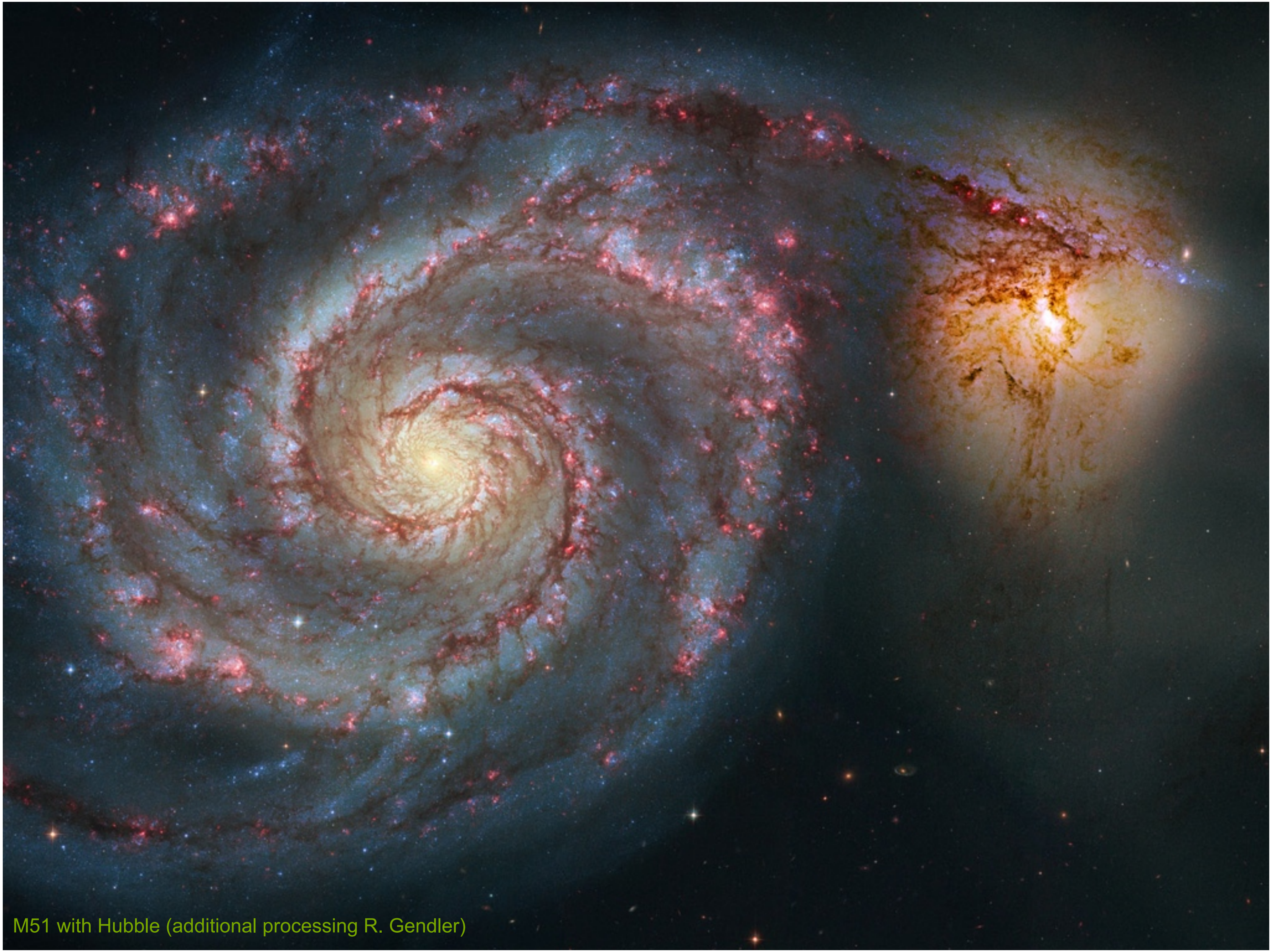
phenomenology


Hubble Ultra-Deep Field

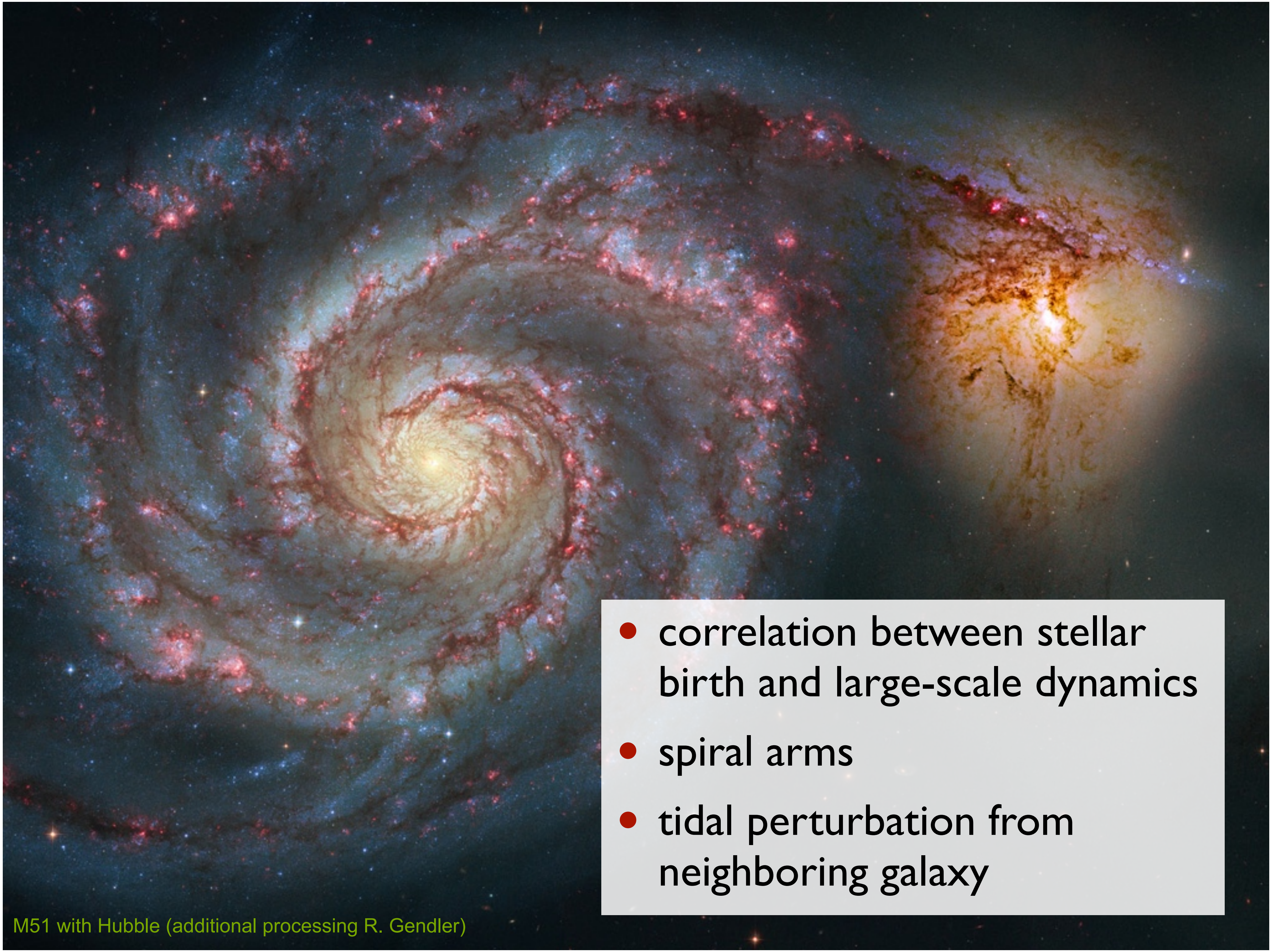

Visible
HST ACS/WFC
Near Infrared
HST NICMOS
Infrared
SST IRAC
Hubble Ultra-Deep Field



- 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

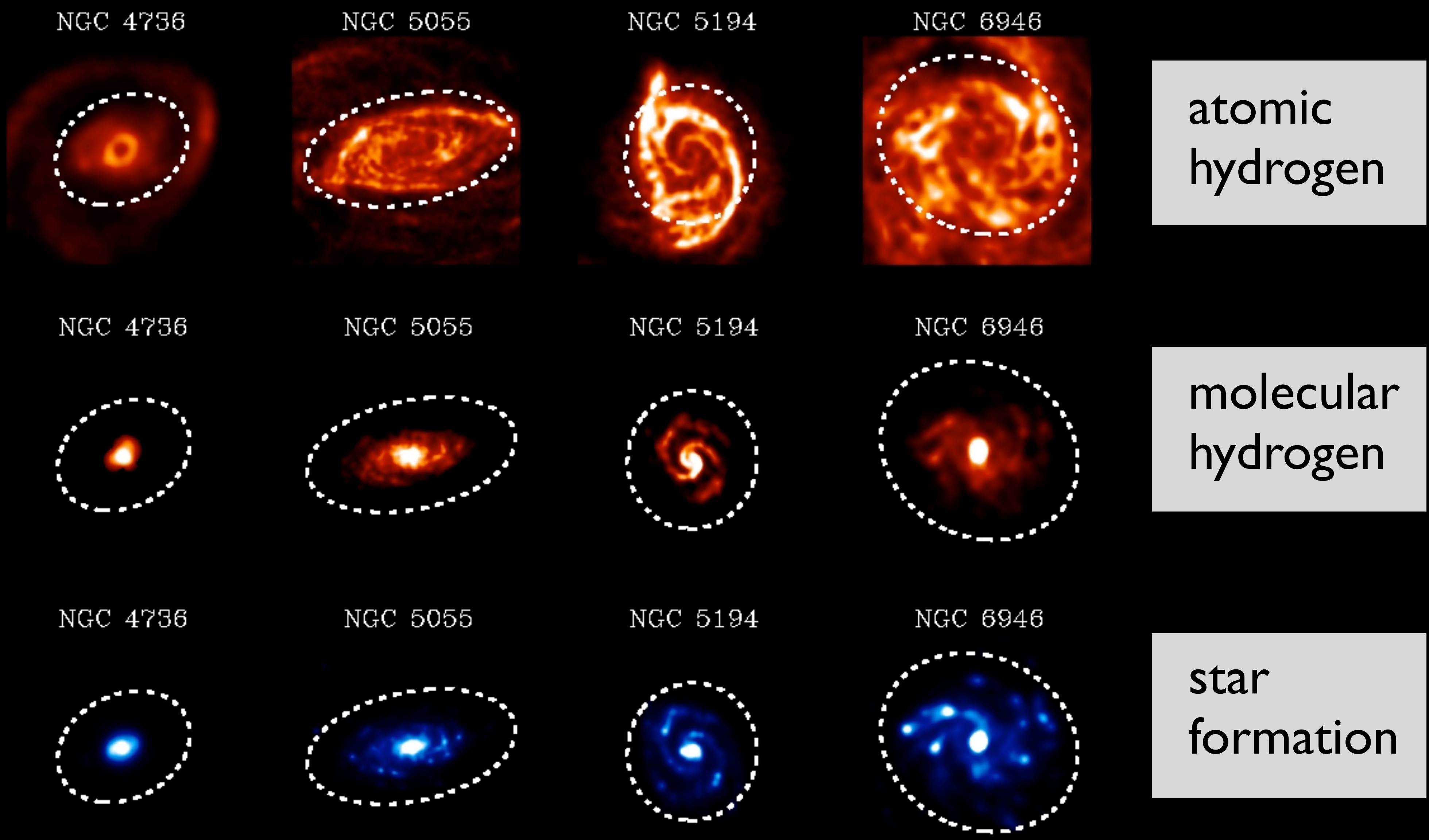


M51 with Hubble (additional processing R. Gendler)

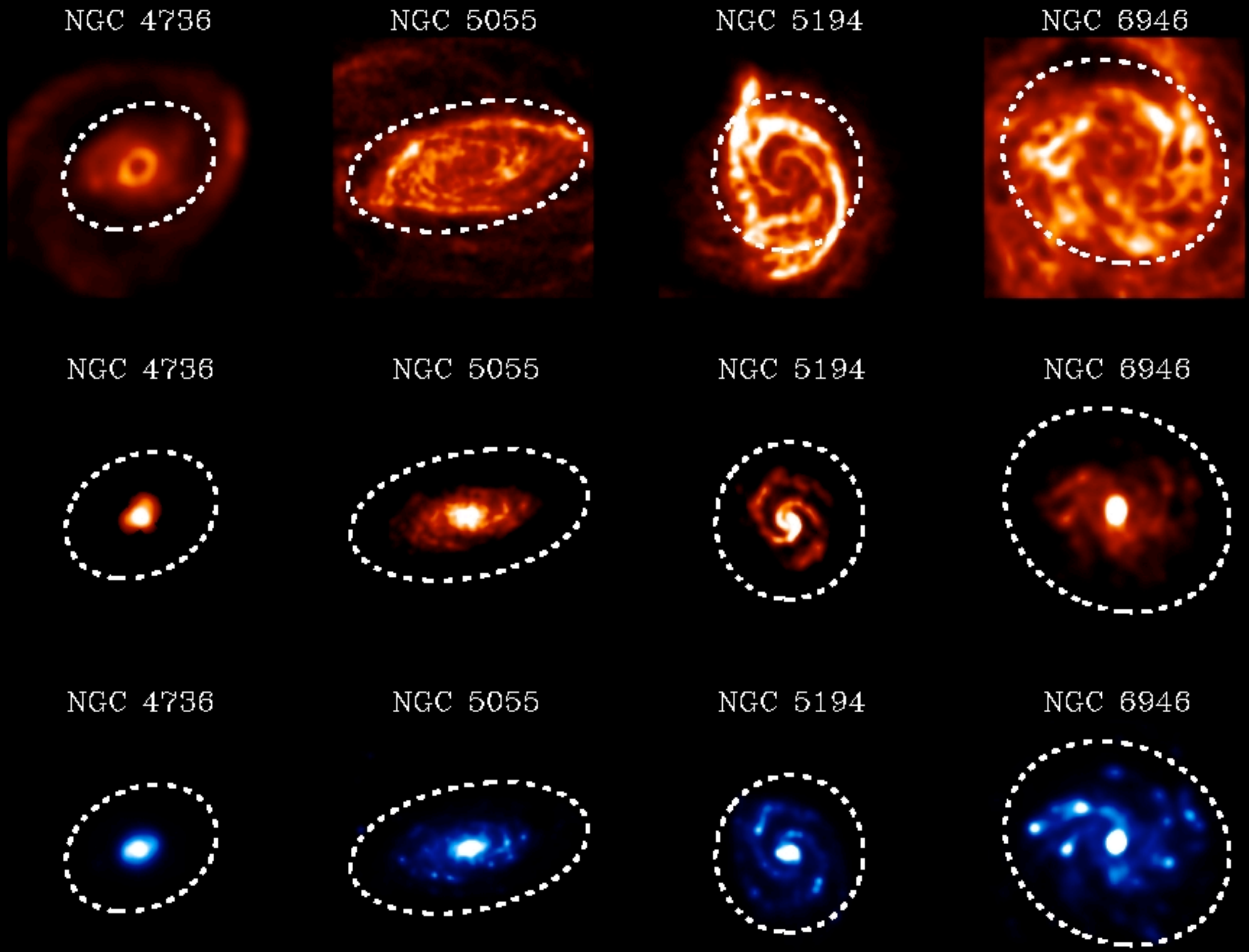


- correlation between stellar birth and large-scale dynamics
- spiral arms
- tidal perturbation from neighboring galaxy

M51 with Hubble (additional processing R. Gendler)



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

galaxies from THINGS and HERACLES survey
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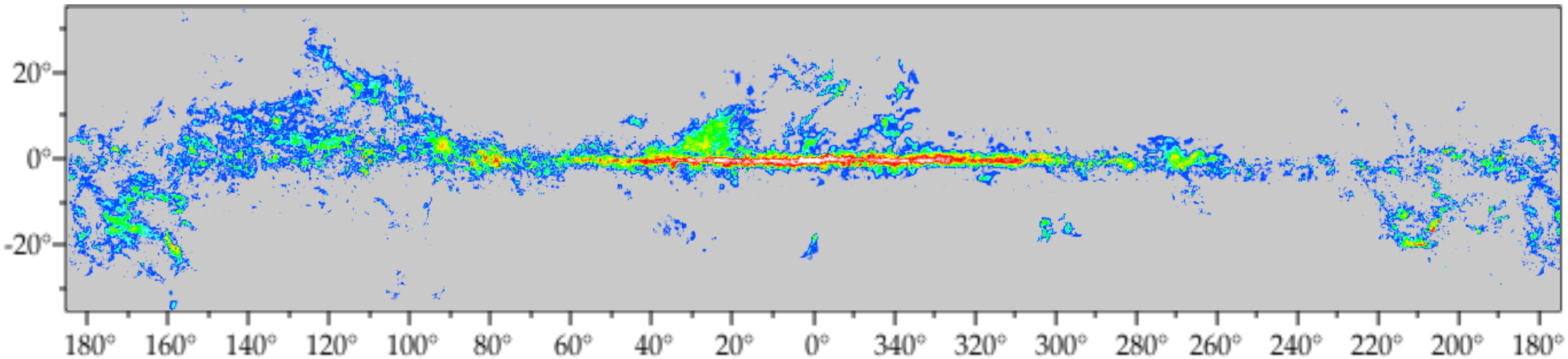
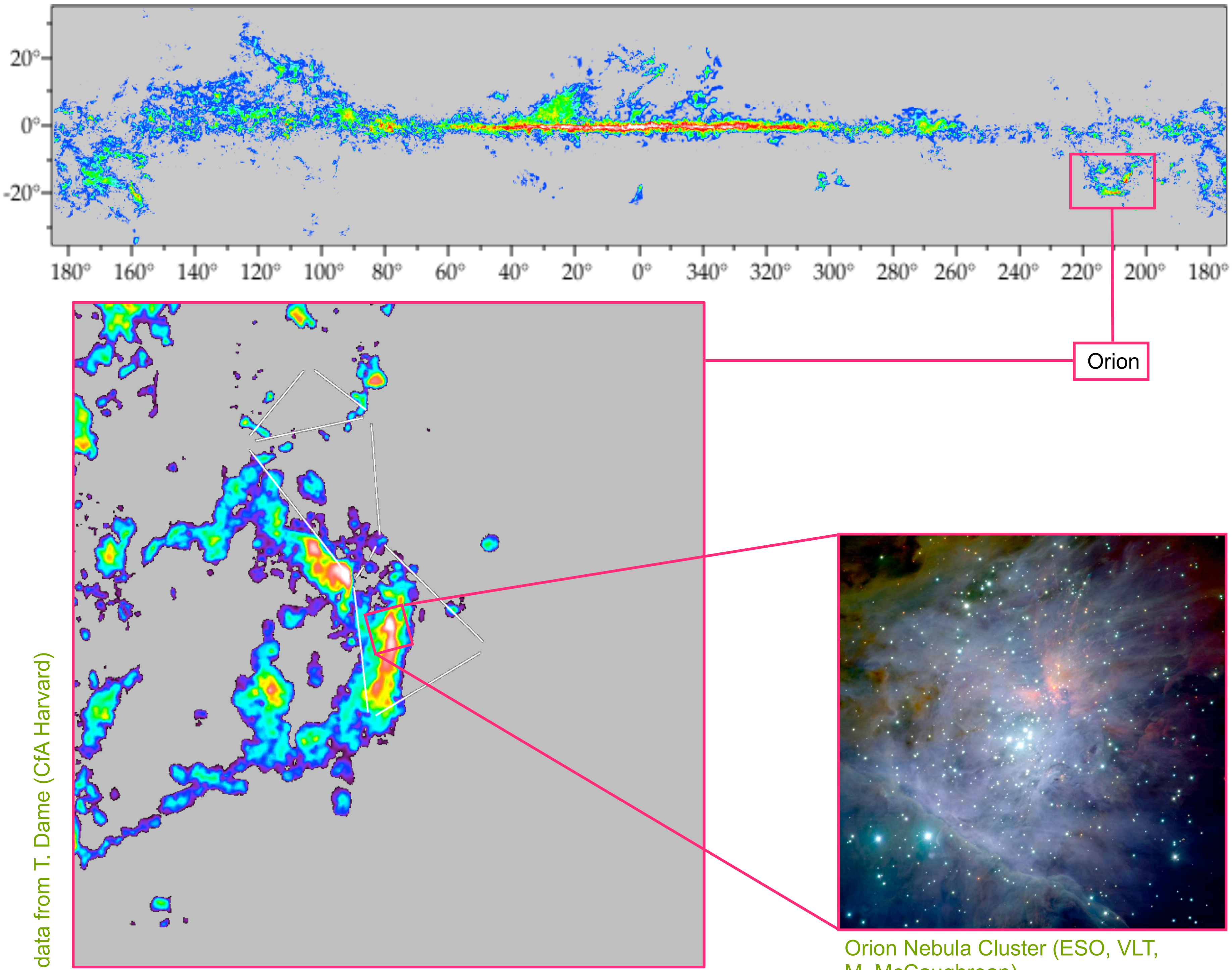


distribution of molecular gas in the Milky Way as traced by CO emission

data from T. Dame (CfA Harvard)



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

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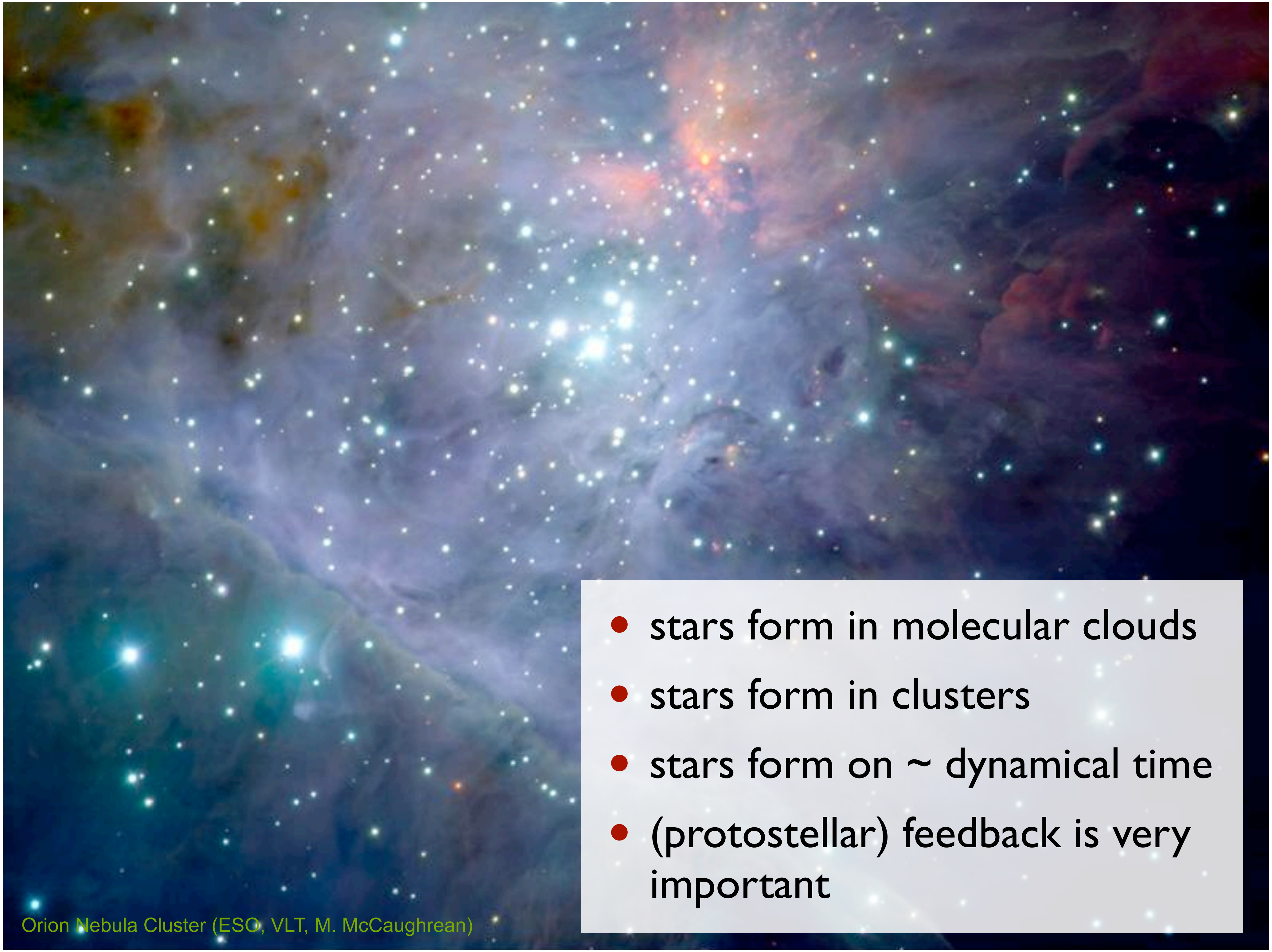


Orion Nebula Cluster (ESO, VLT, M. McCaughrean)

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

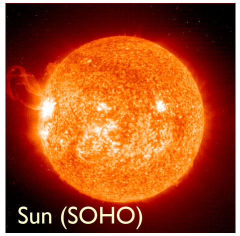
Pleiades (DSS, Palomar Observatory Sky Survey) theoretical approach

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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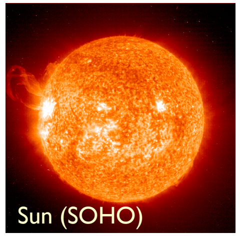
Sun (SOHO)


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)


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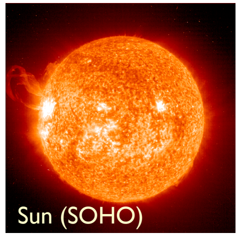
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  - ***RADIATION PRESSURE***

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:

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

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

Sir James Jeans, 1877 - 1946

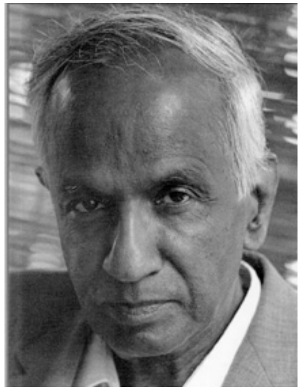
first approach to turbulence

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

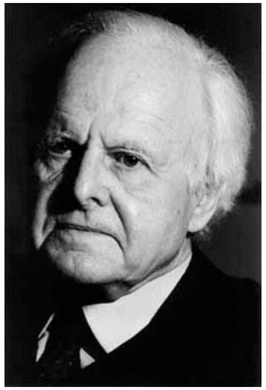
    $\ell_{turb} \ll \ell_{dyn}$
  - then turbulent velocity dispersion contributes to effective soundspeed:

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

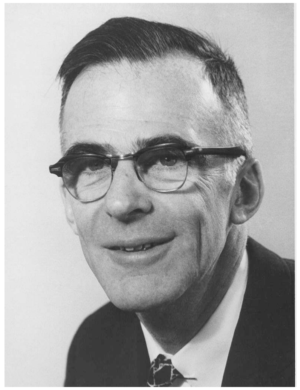
- *Mestel & Spitzer (1956):* Magnetic fields can prevent collapse*!!!*
  - Critical mass for gravitational collapse in presence of B-field

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

  - 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

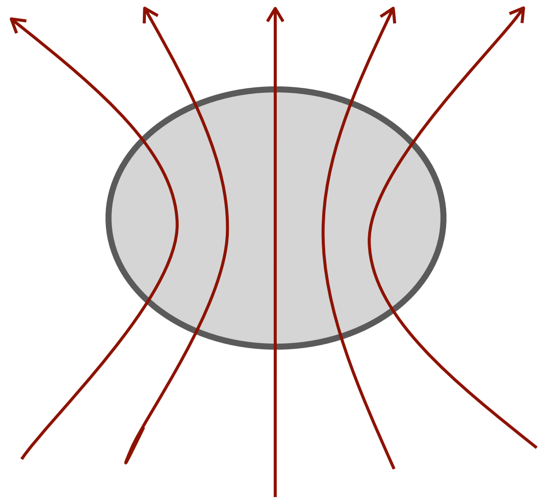


Lyman Spitzer, Jr., 1914 - 1997

“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
  - $dM/dt = 0.975\ c_s^3/G$ = const.
- Was (in principle) only intended for isolated, low-mass stars

Frank Shu, 1943 -



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)

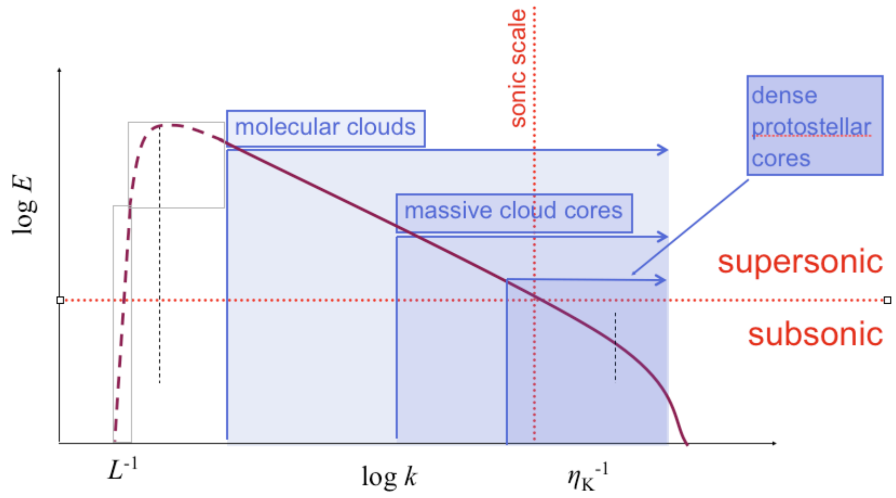
(see e.g. Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194)

gravoturbulent star formation

- BASIC ASSUMPTION:

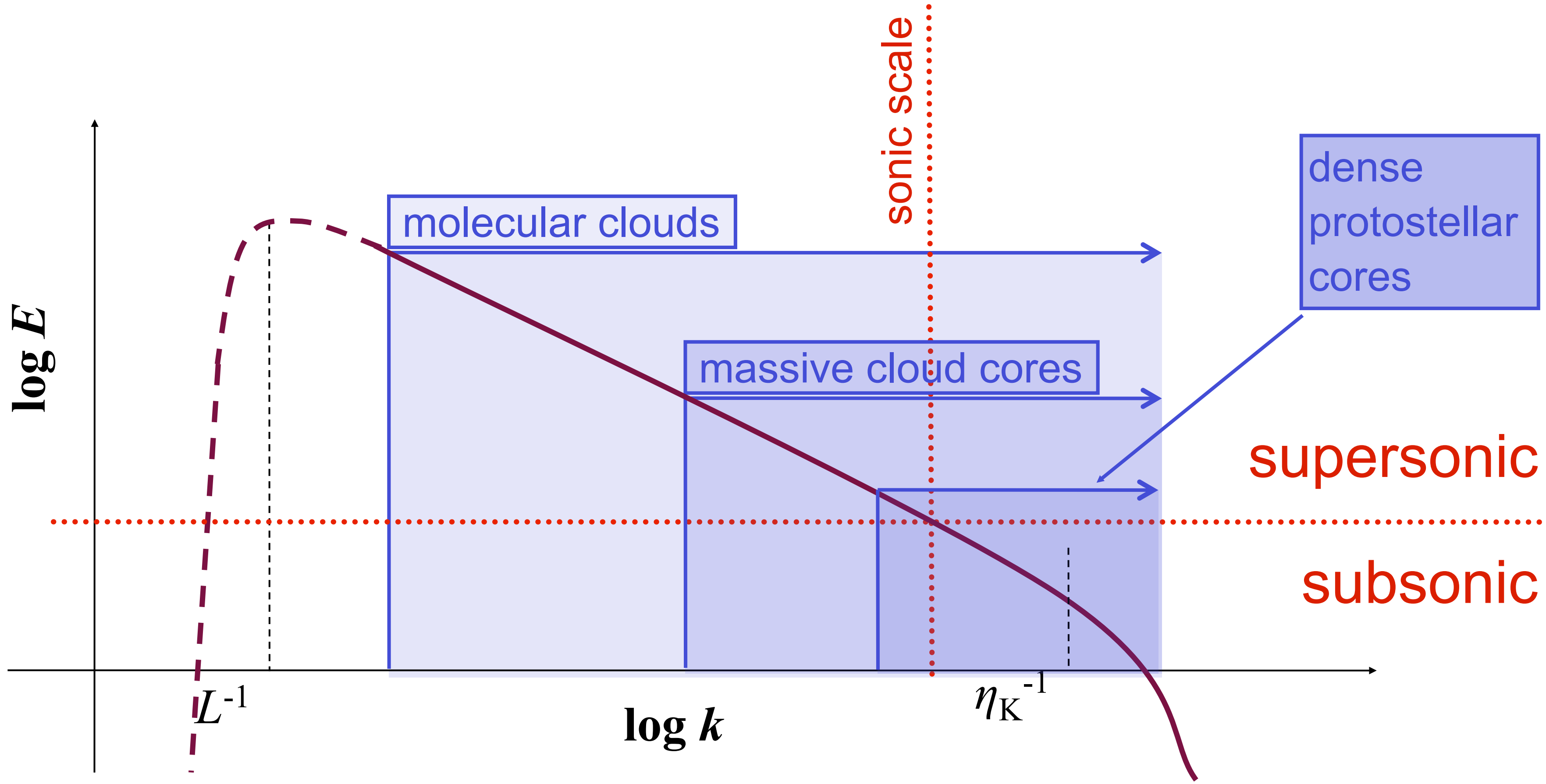
> star formation is controlled by interplay between supersonic turbulence and self-gravity

- 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

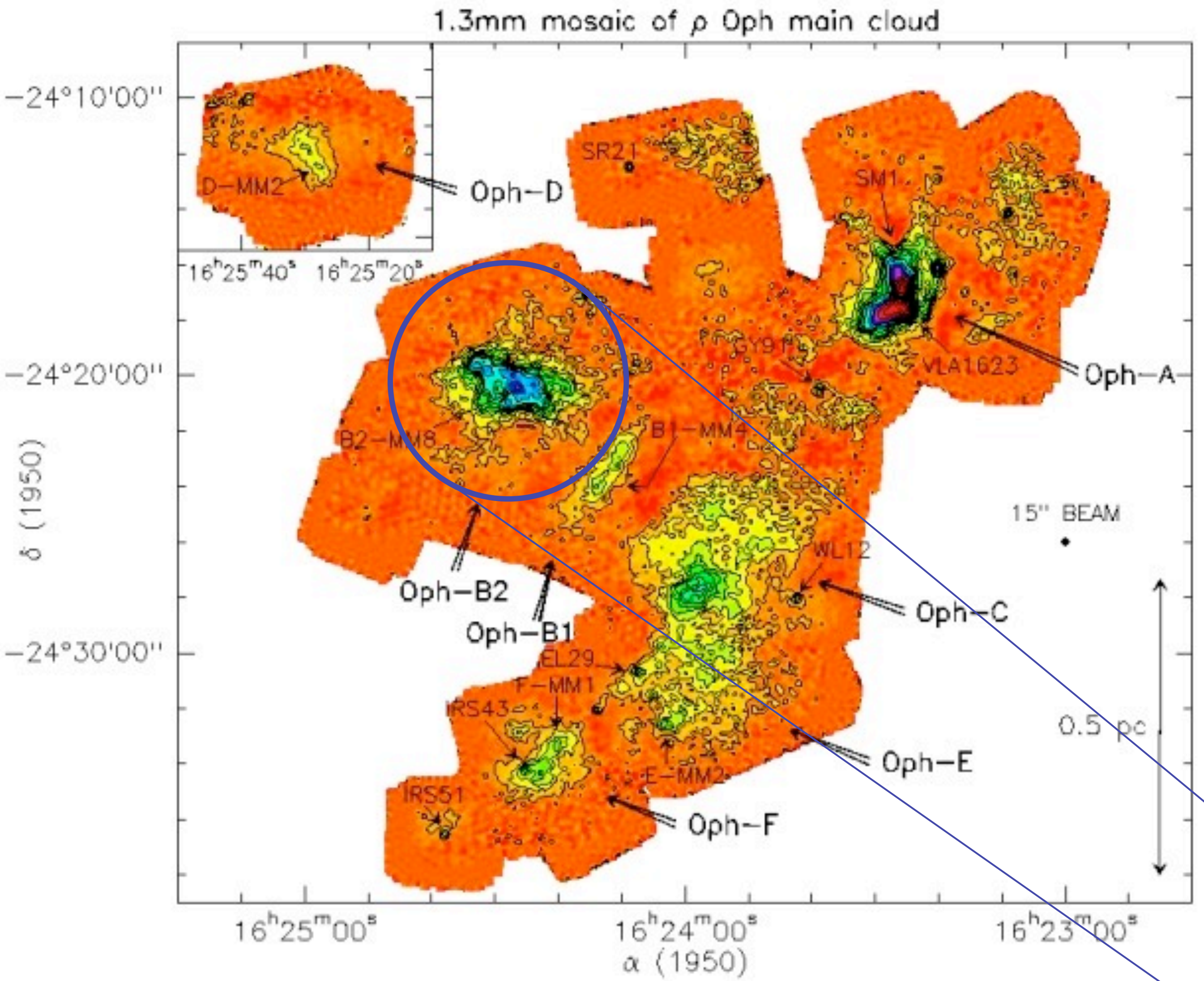


energy source & scale
NOT known
(supernovae, winds,
spiral density waves?)

σ_{rms} << 1 km/s
$M_{rms} \leq 1$
L ≈ 0.1 pc

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

Density structure of MC's



(Motte, André, & Neri 1998)

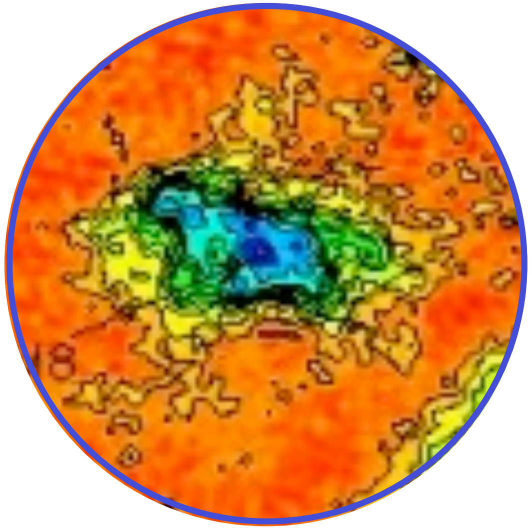
molecular clouds are highly inhomogeneous

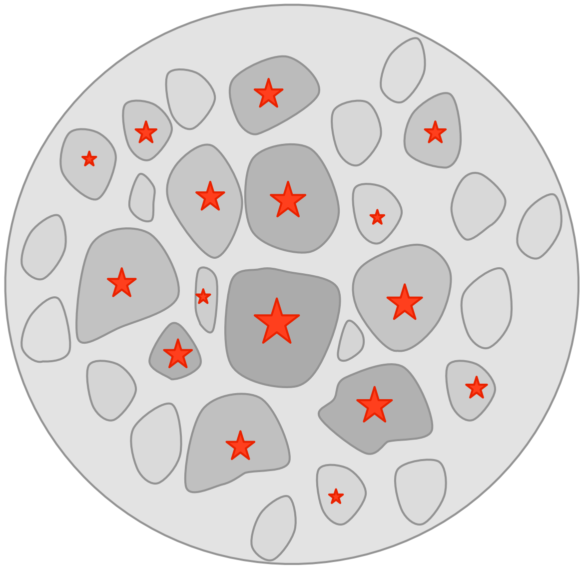
stars form in the densest and coldest parts of the cloud

ρ-Ophiuchus cloud seen in dust emission

let's focus on a cloud core like this one

Evolution of cloud cores

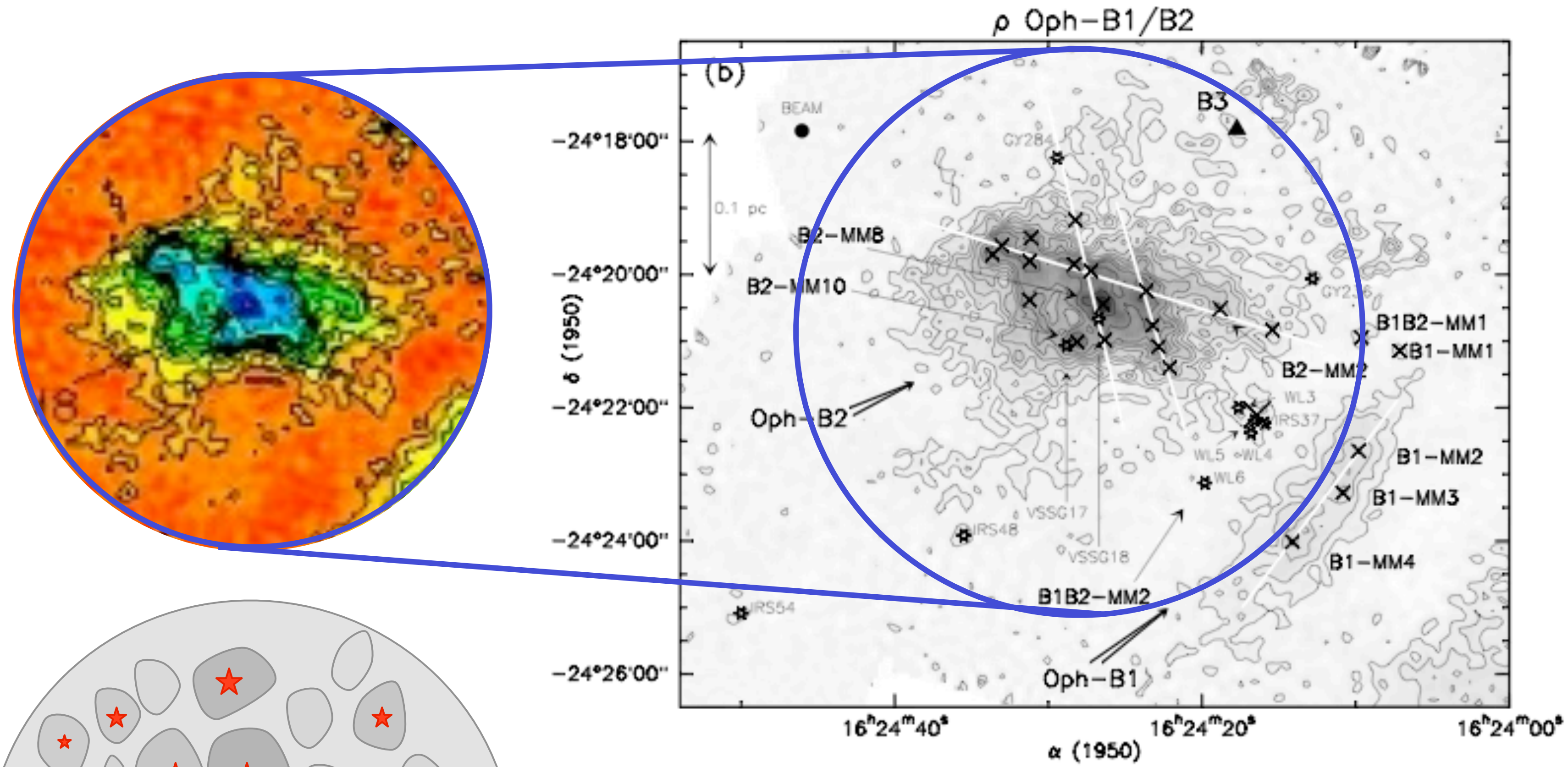


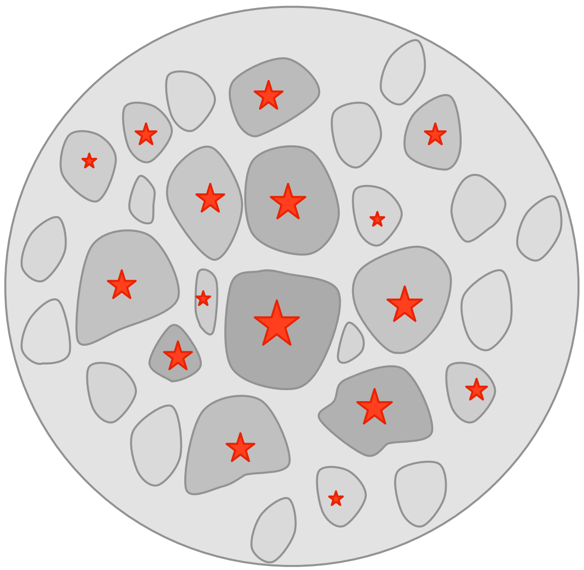


- How does this core evolve?
  Does it form one single massive star or cluster with mass distribution?

- 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*

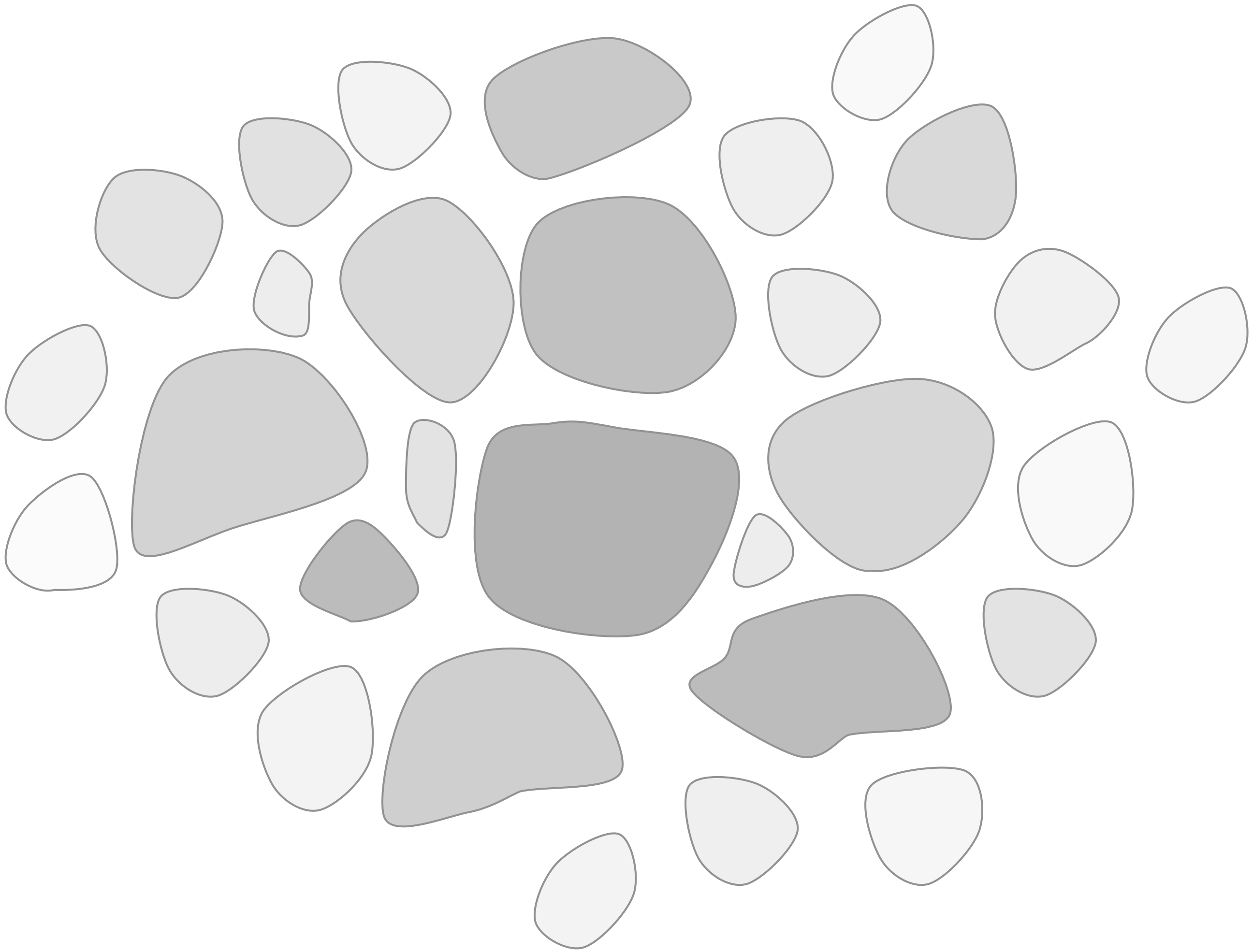
Evolution of cloud cores



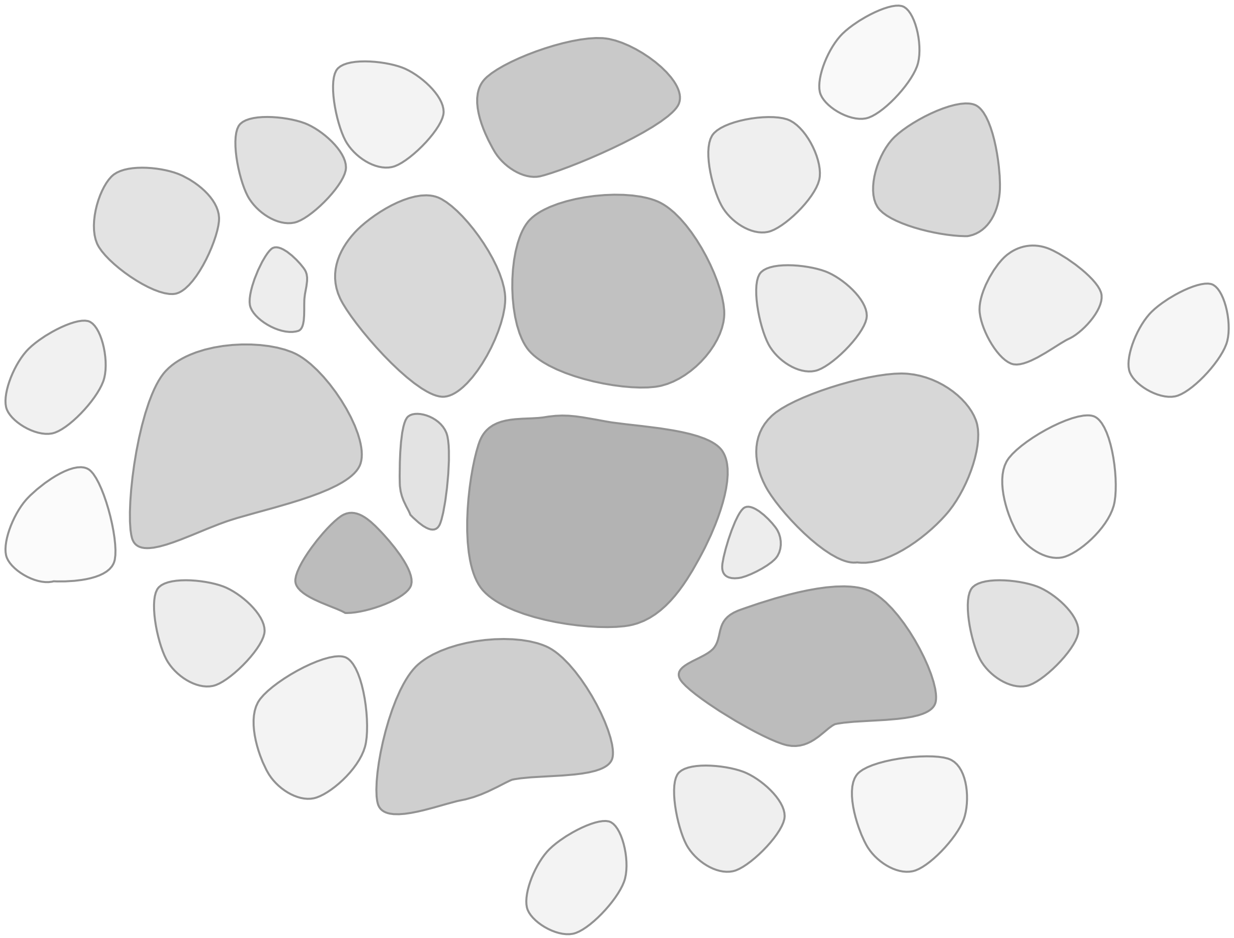


indeed ρ-Oph B1/2 contains several cores ("starless" cores are denoted by ×, cores with embedded protostars by ☆)

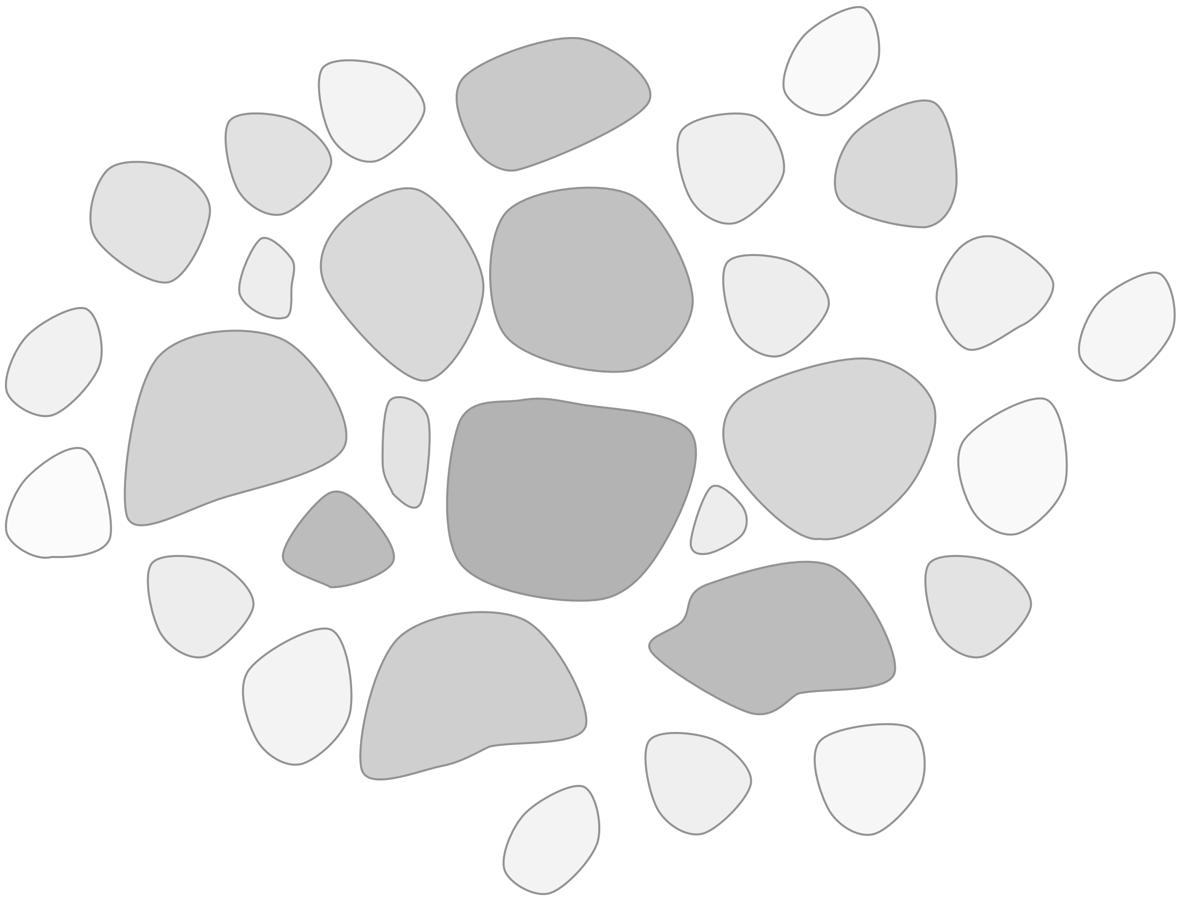
(Motte, André, & Neri 1998)



turbulence creates a hierarchy of clumps



as turbulence decays locally, contraction sets in



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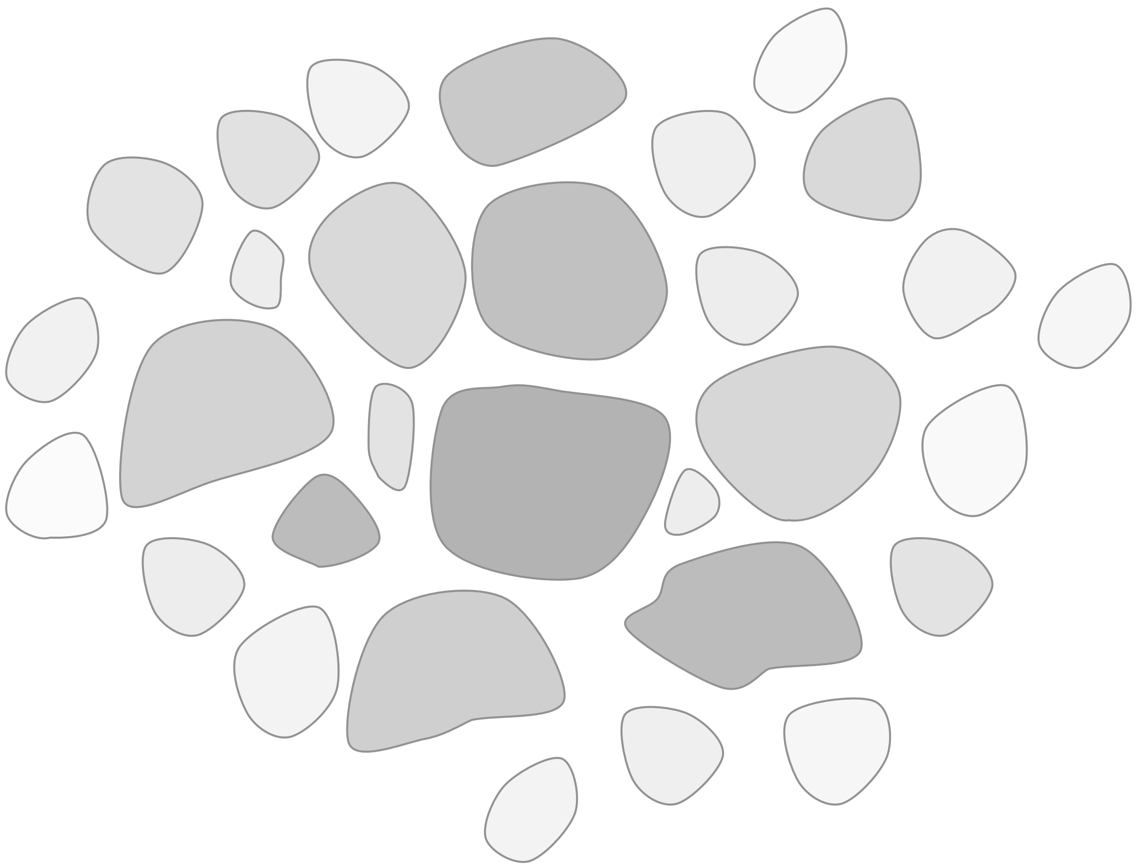
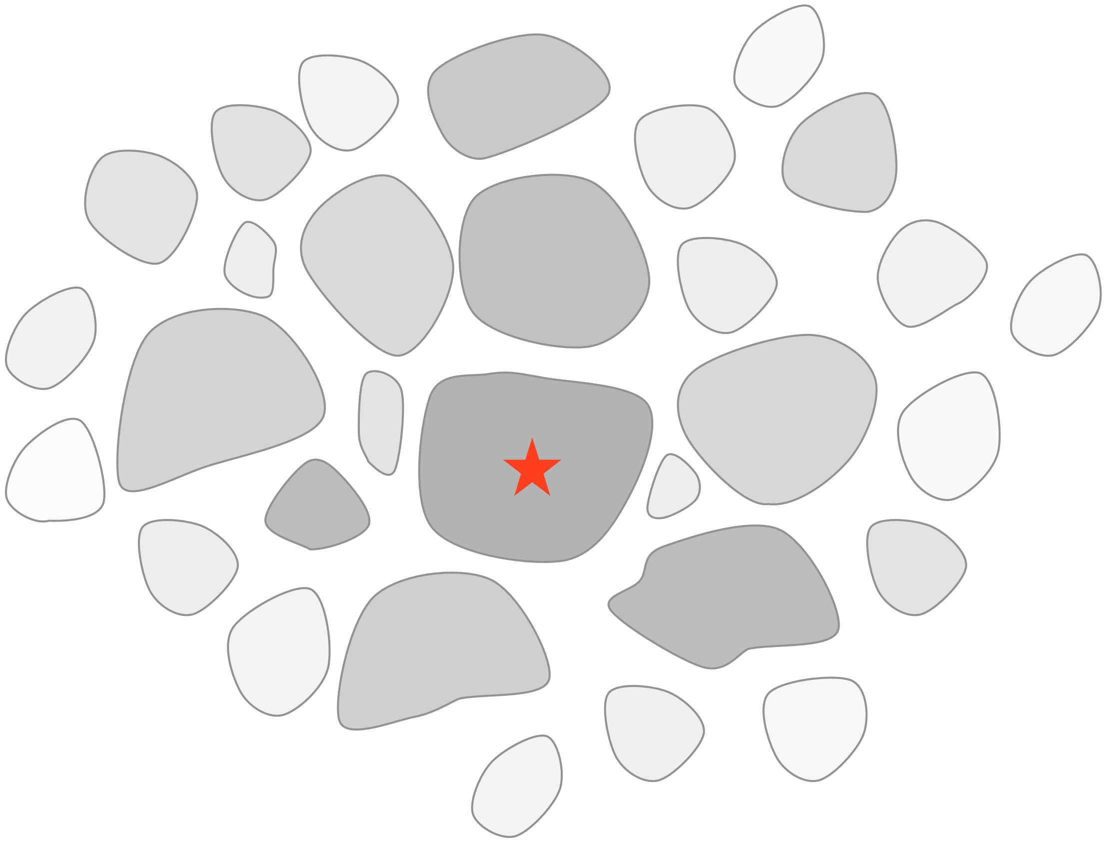


while region contracts, individual clumps collapse to form stars



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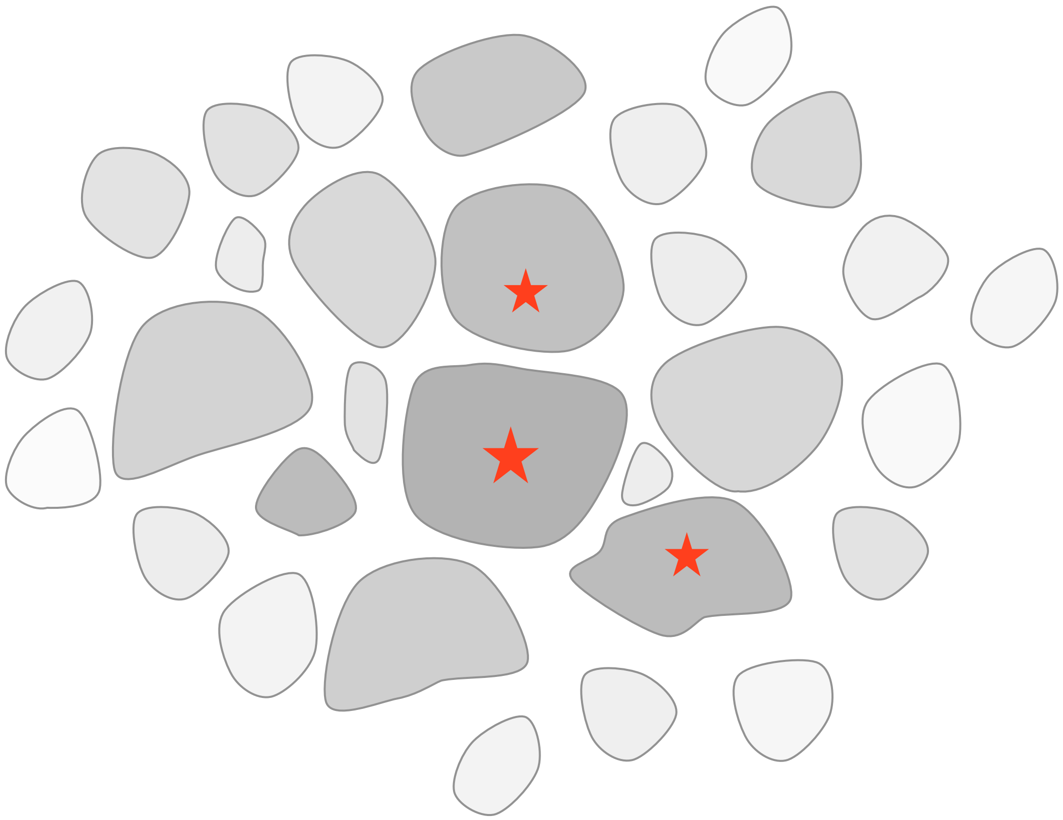

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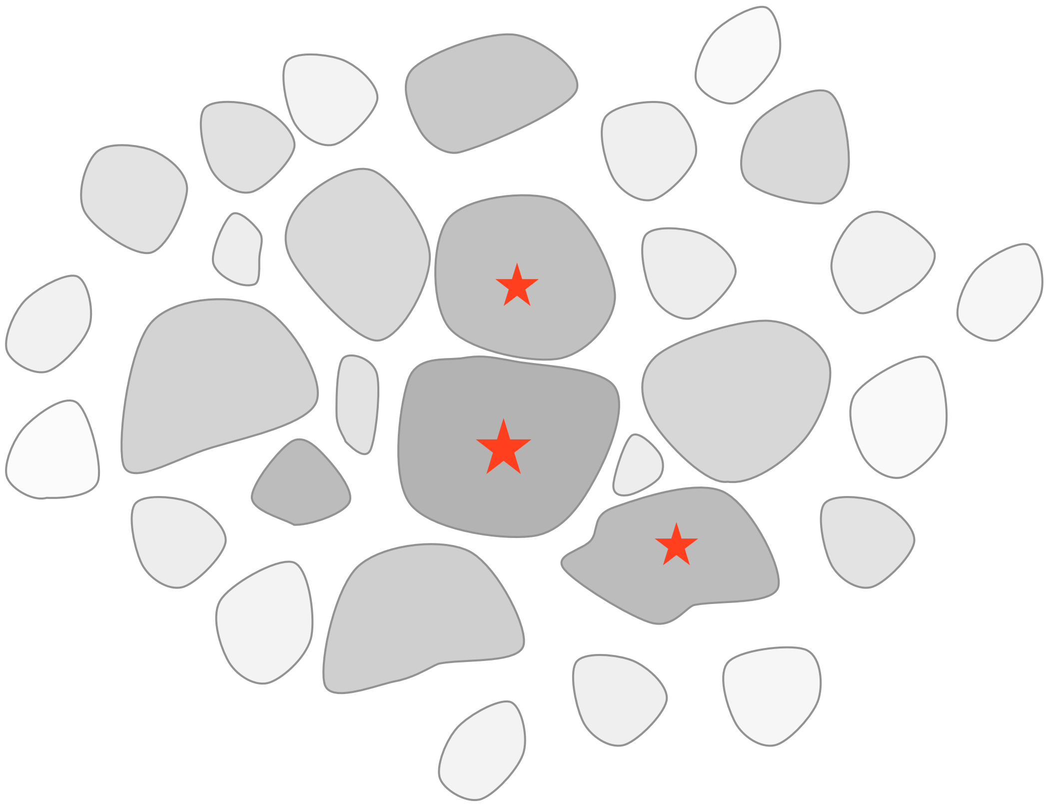

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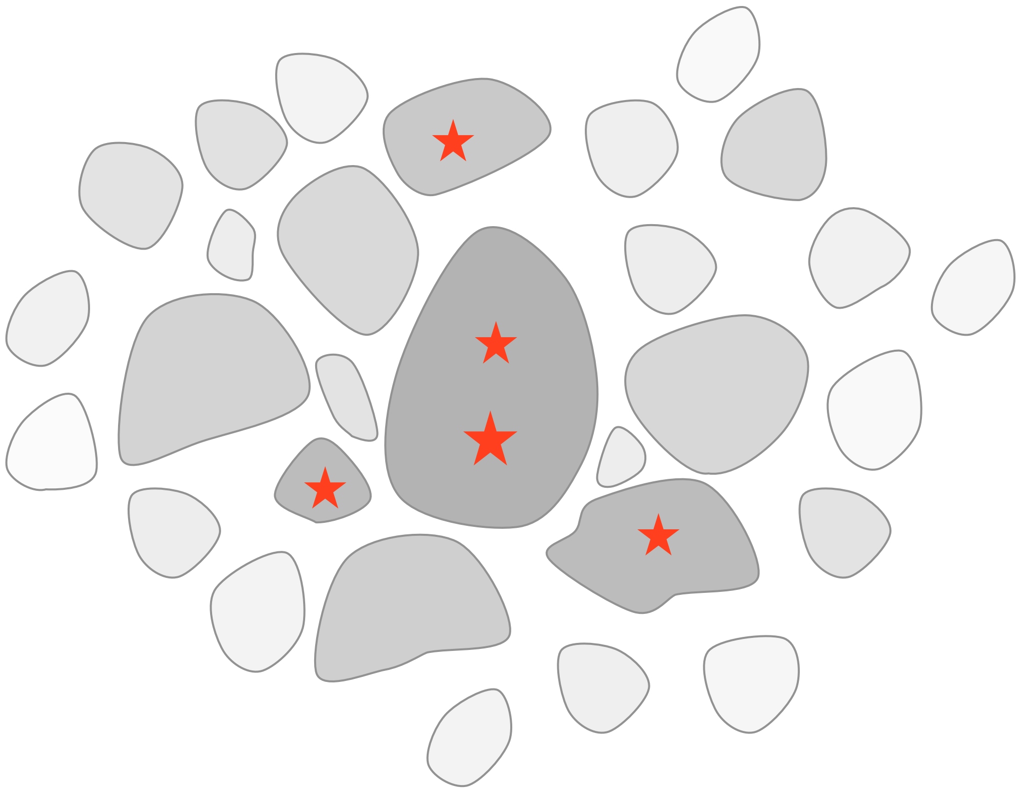
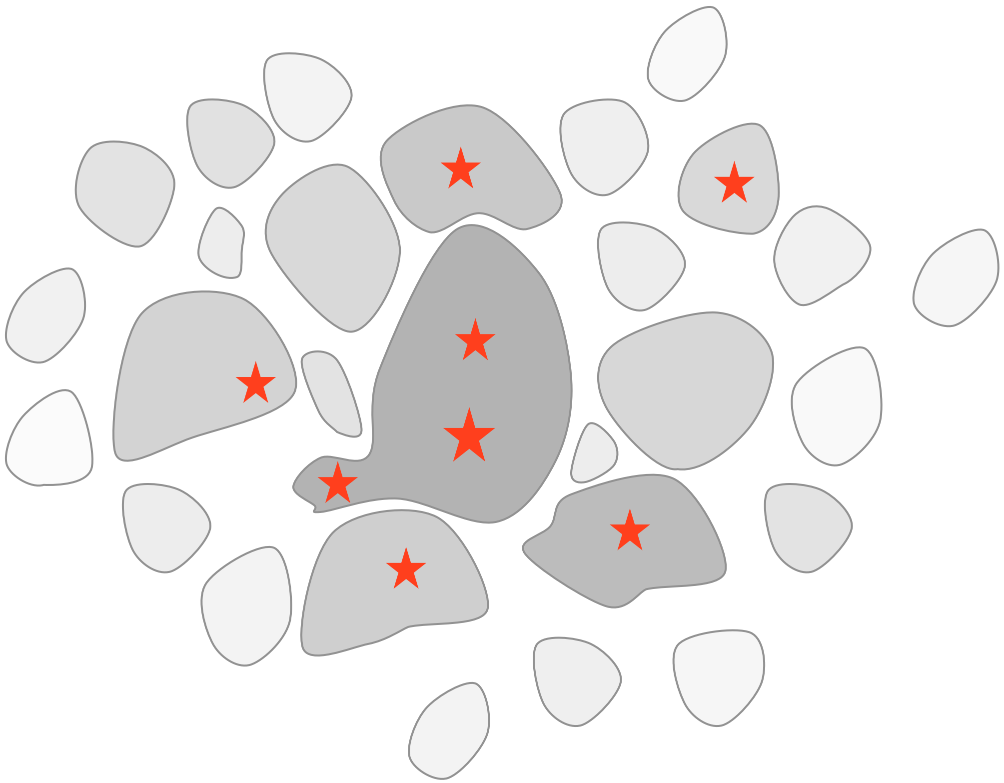


$\alpha = E_{kin}/|E_{pot}| < 1$

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



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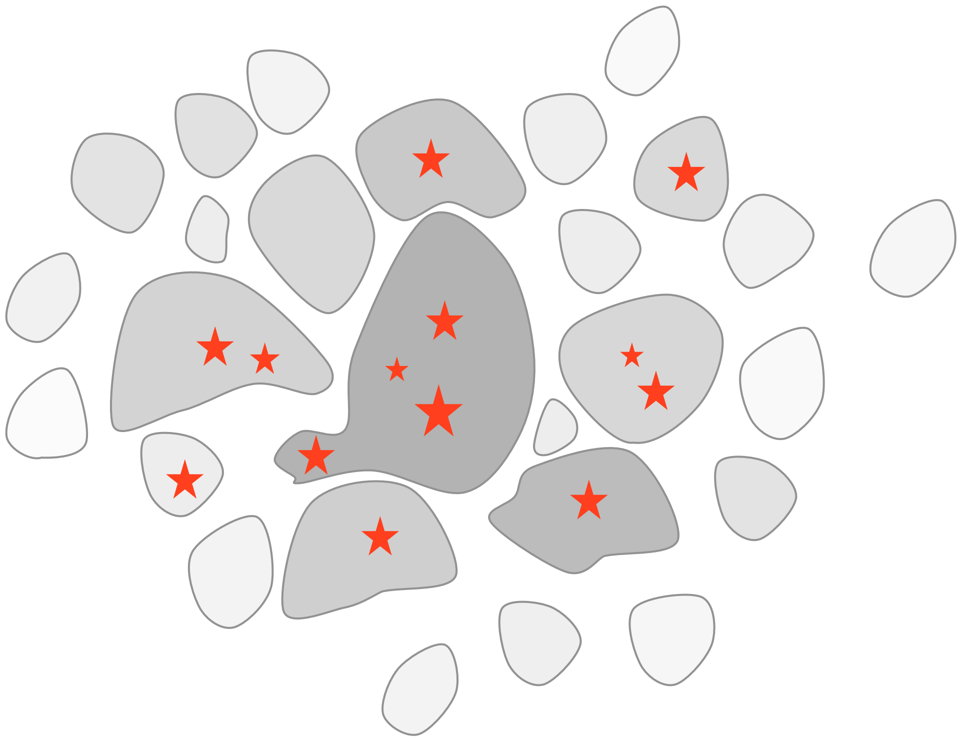

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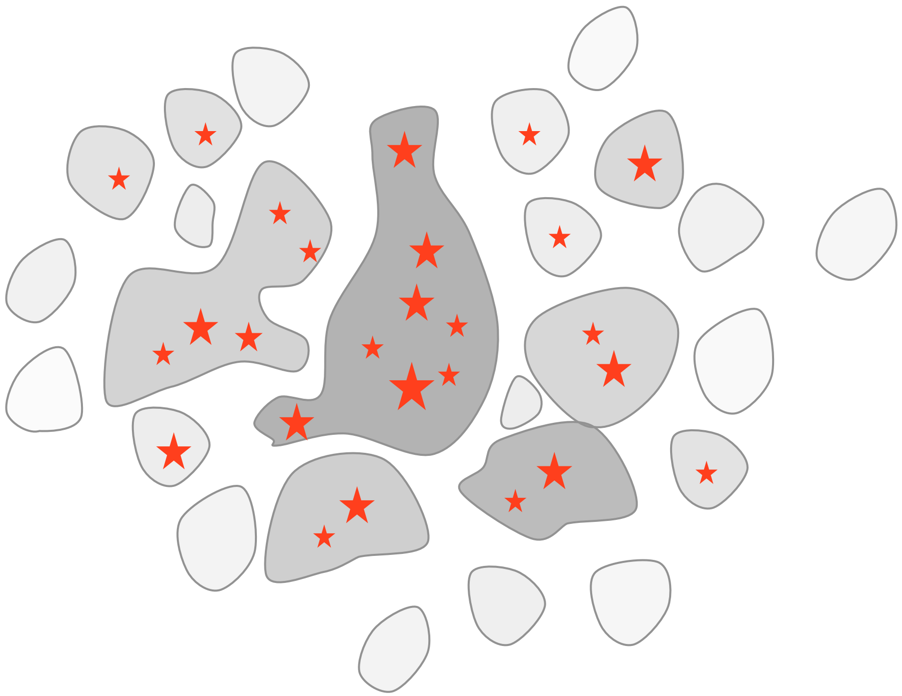
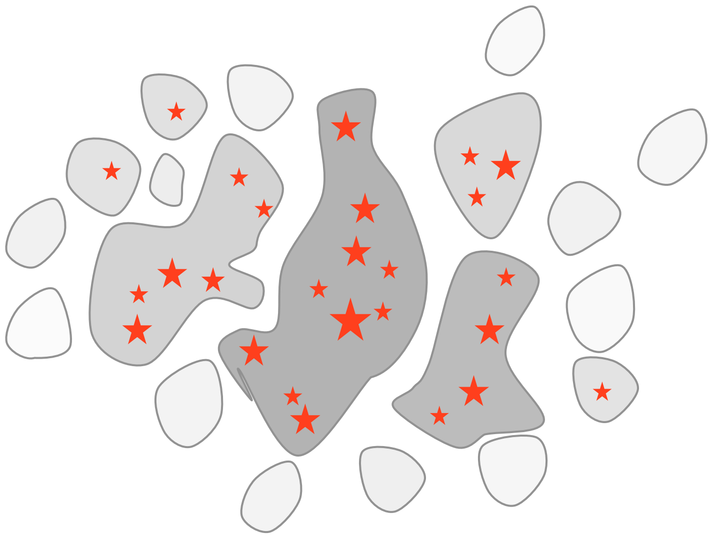


in *dense clusters*, competitive mass growth
becomes important



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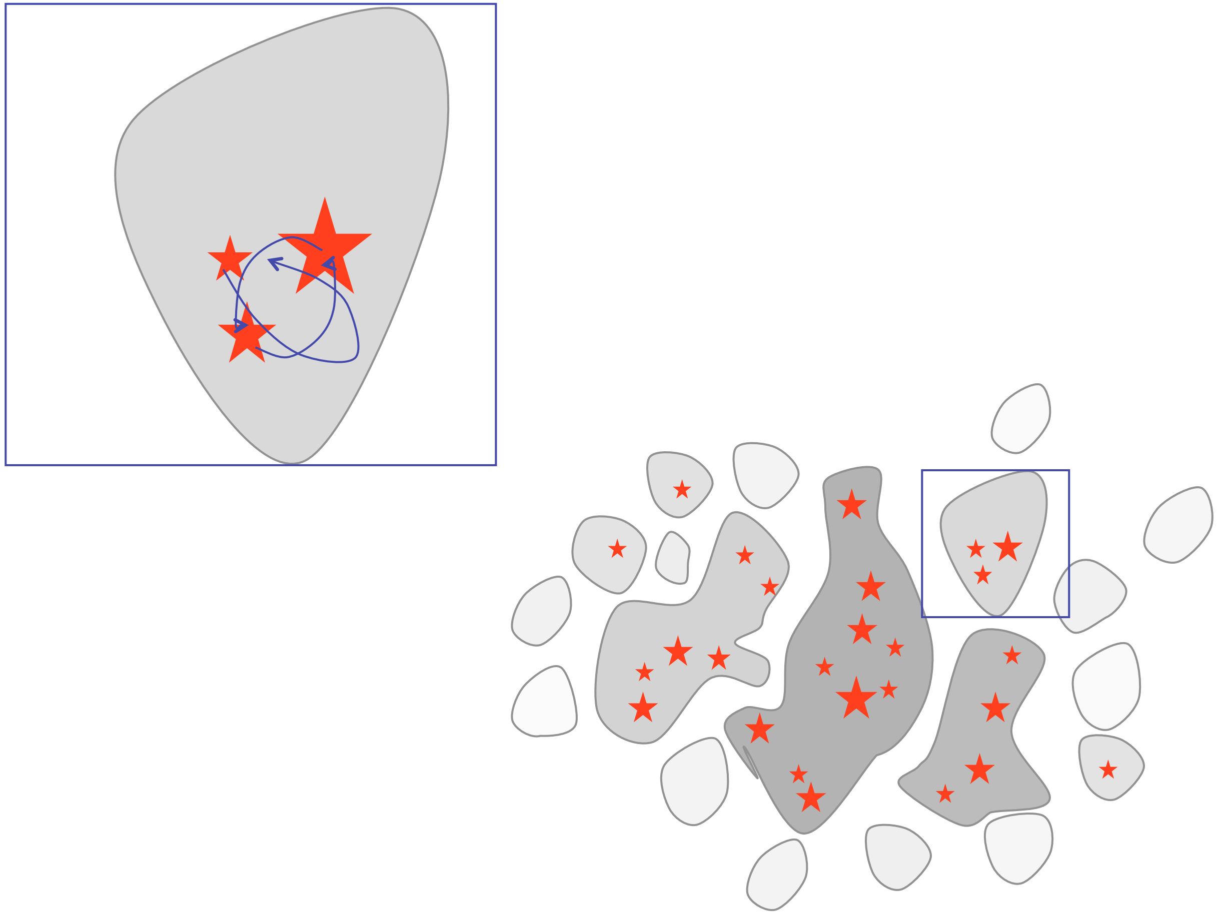
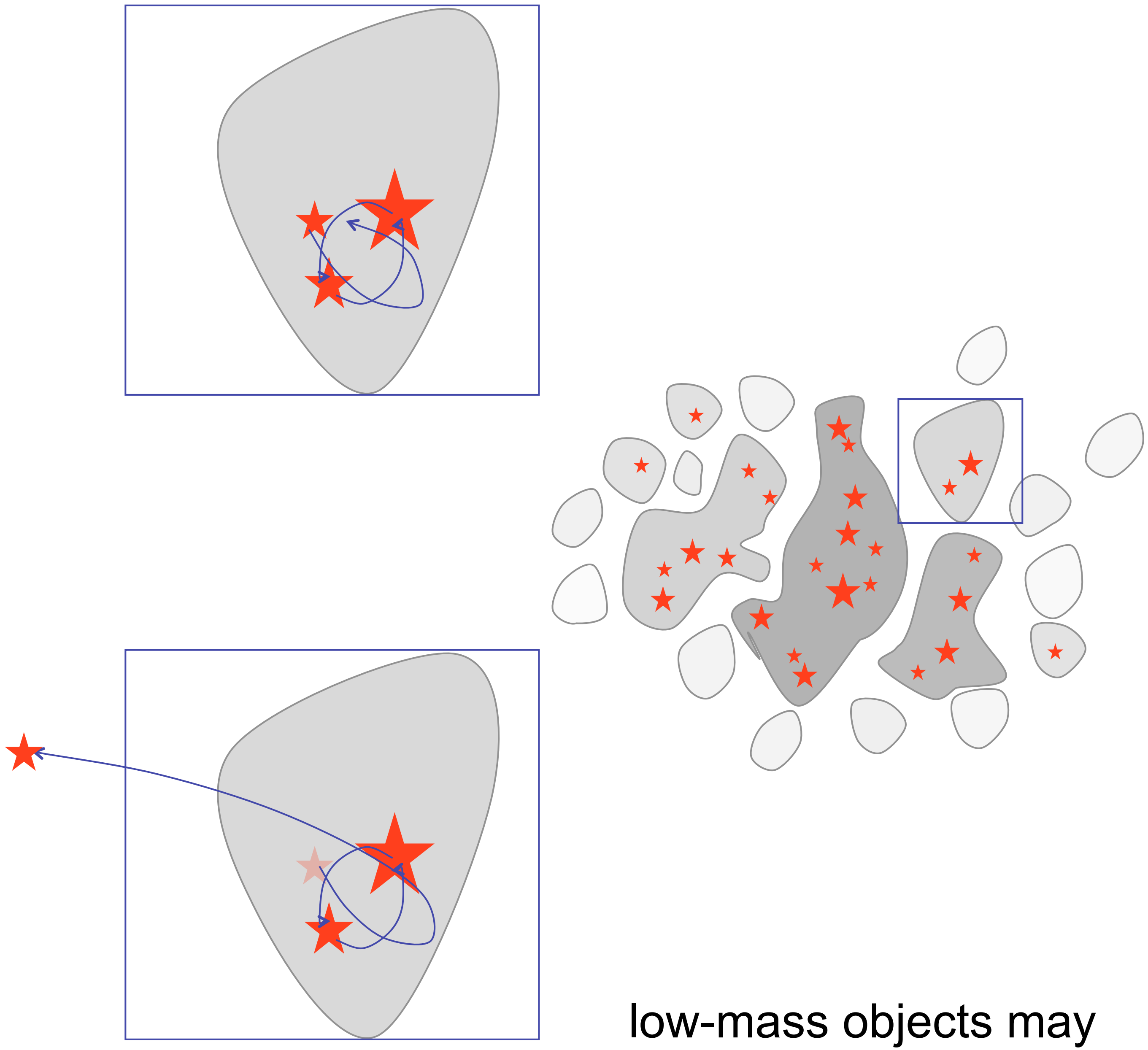
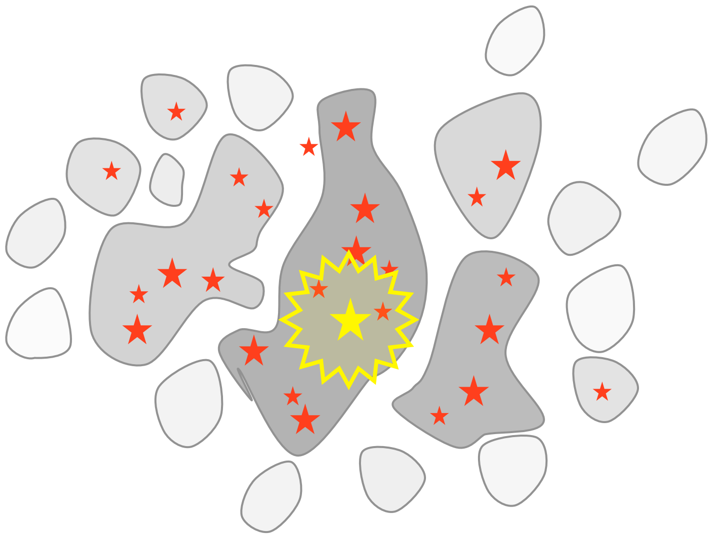


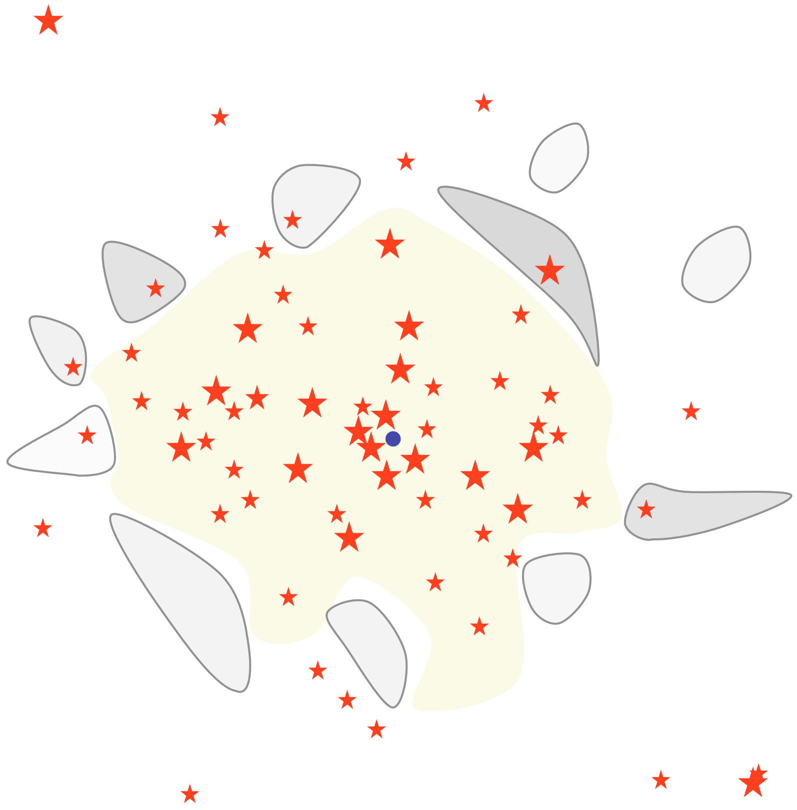
in *dense clusters*, *N*-body effects influence mass growth



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



feedback terminates star formation



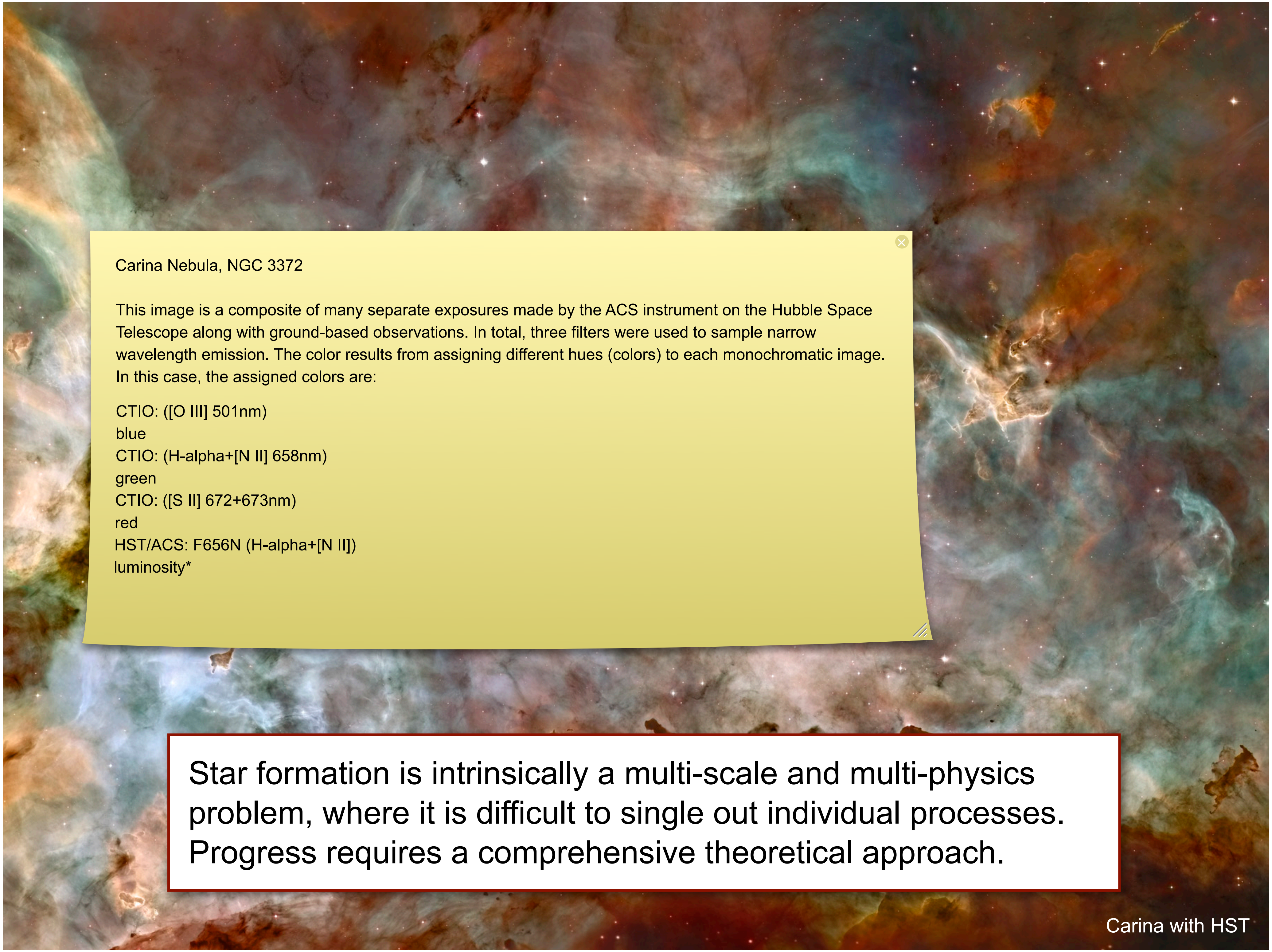
result: *star cluster*, possibly with HII region

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.



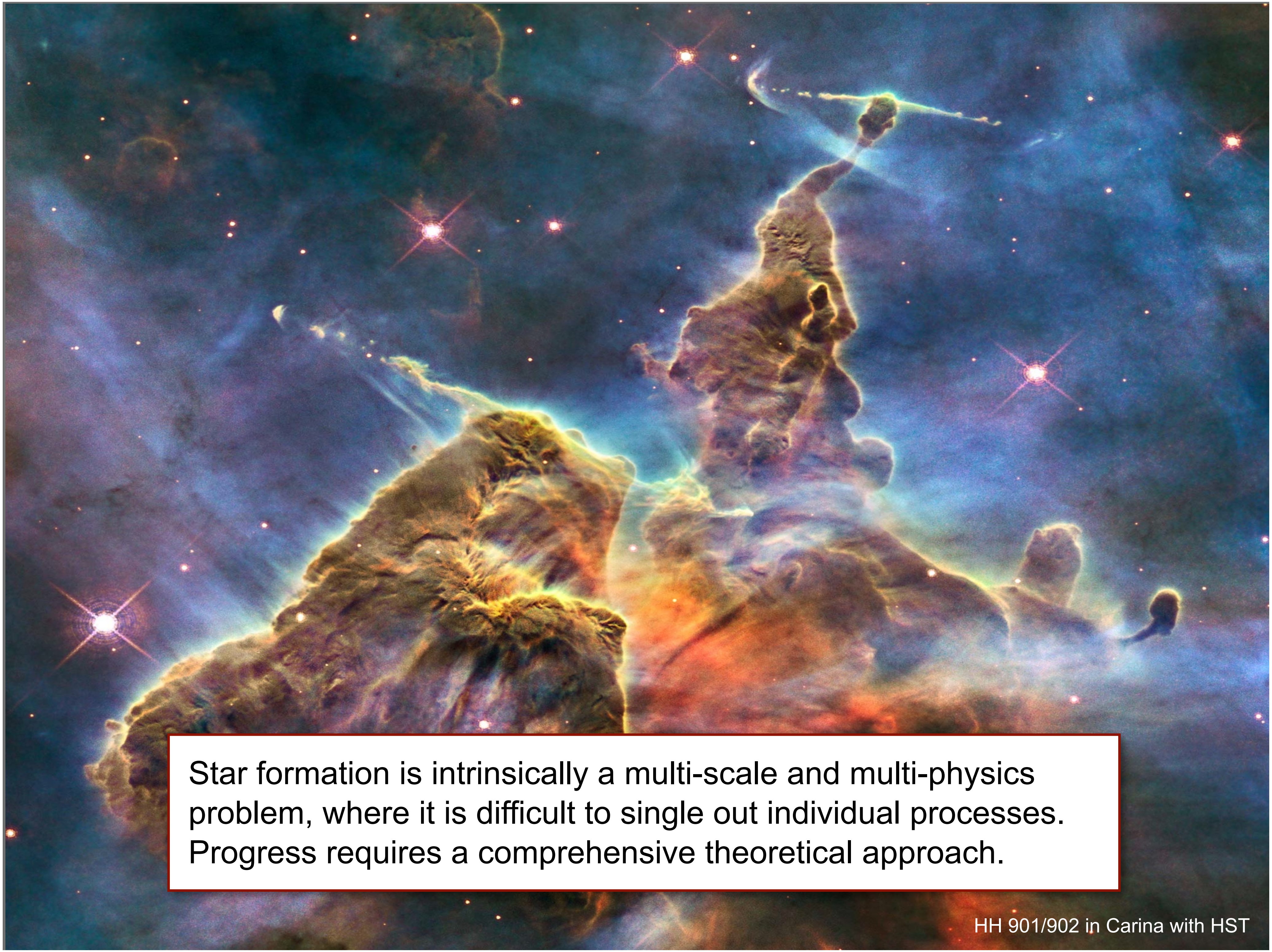
Carina Nebula, NGC 3372

This image is a composite of many separate exposures made by the ACS instrument on the Hubble Space Telescope along with ground-based observations. In total, three filters were used to sample narrow wavelength emission. The color results from assigning different hues (colors) to each monochromatic image. In this case, the assigned colors are:

CTIO: ([O III] 501nm)
blue
CTIO: (H-alpha+[N II] 658nm)
green
CTIO: ([S II] 672+673nm)
red
HST/ACS: F656N (H-alpha+[N II])
luminosity*

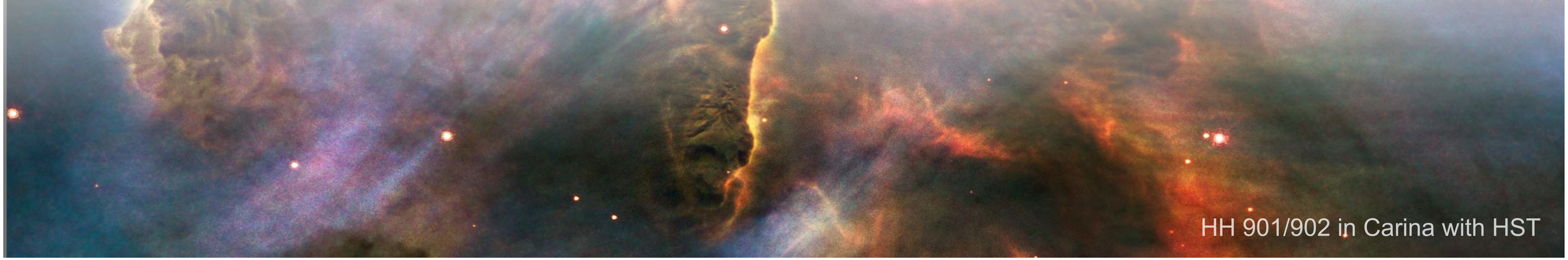
Star formation is intrinsically a multi-scale and multi-physics problem, where it is difficult to single out individual processes. Progress requires a comprehensive theoretical approach.

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?



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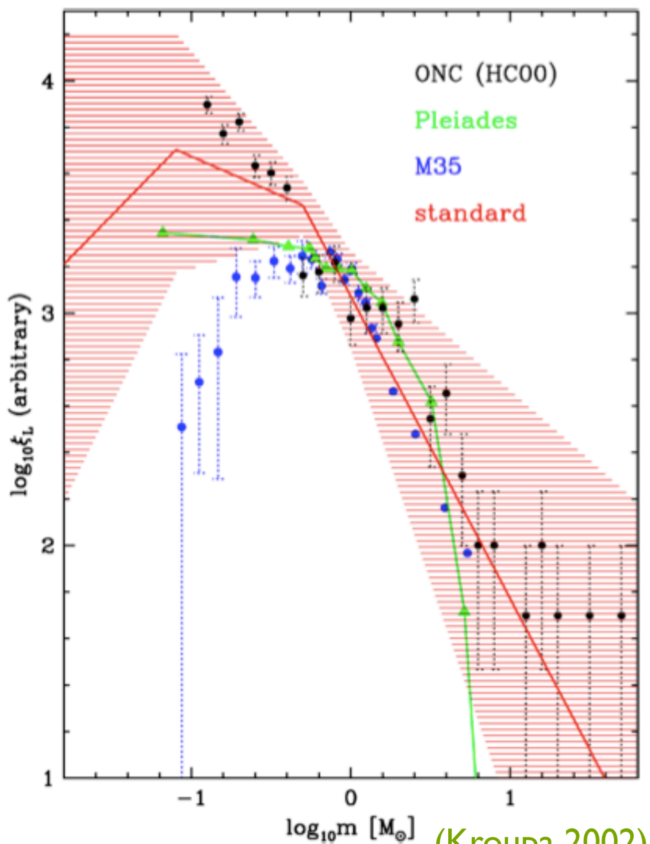
HH 901/902 in Carina with HST

stellar mass fuction

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



(Kroupa 2002)

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

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
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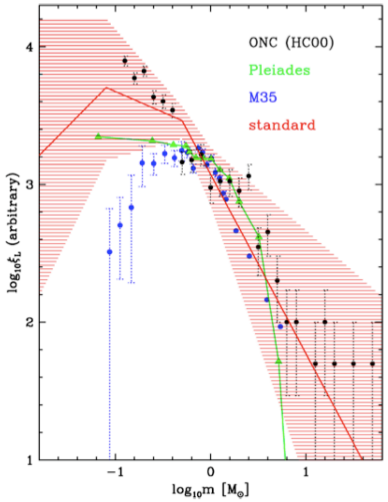
    ionizing radiation, bipolar outflows, winds, SN

(Kroupa 2002)



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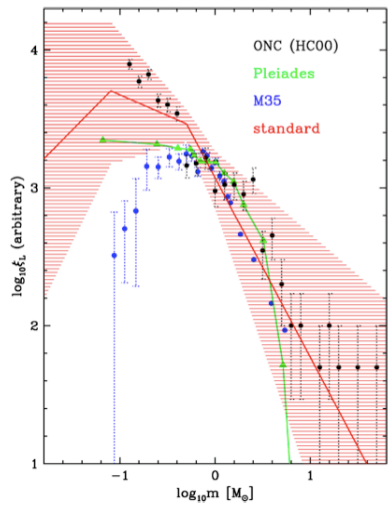
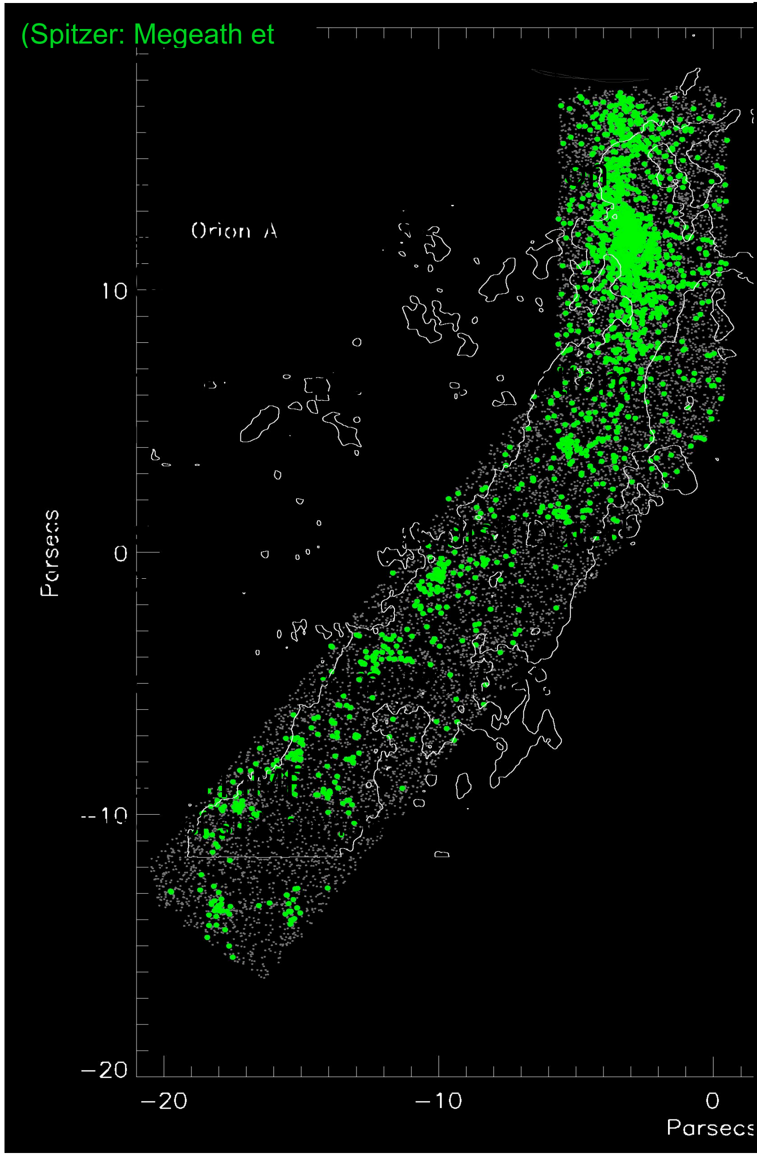
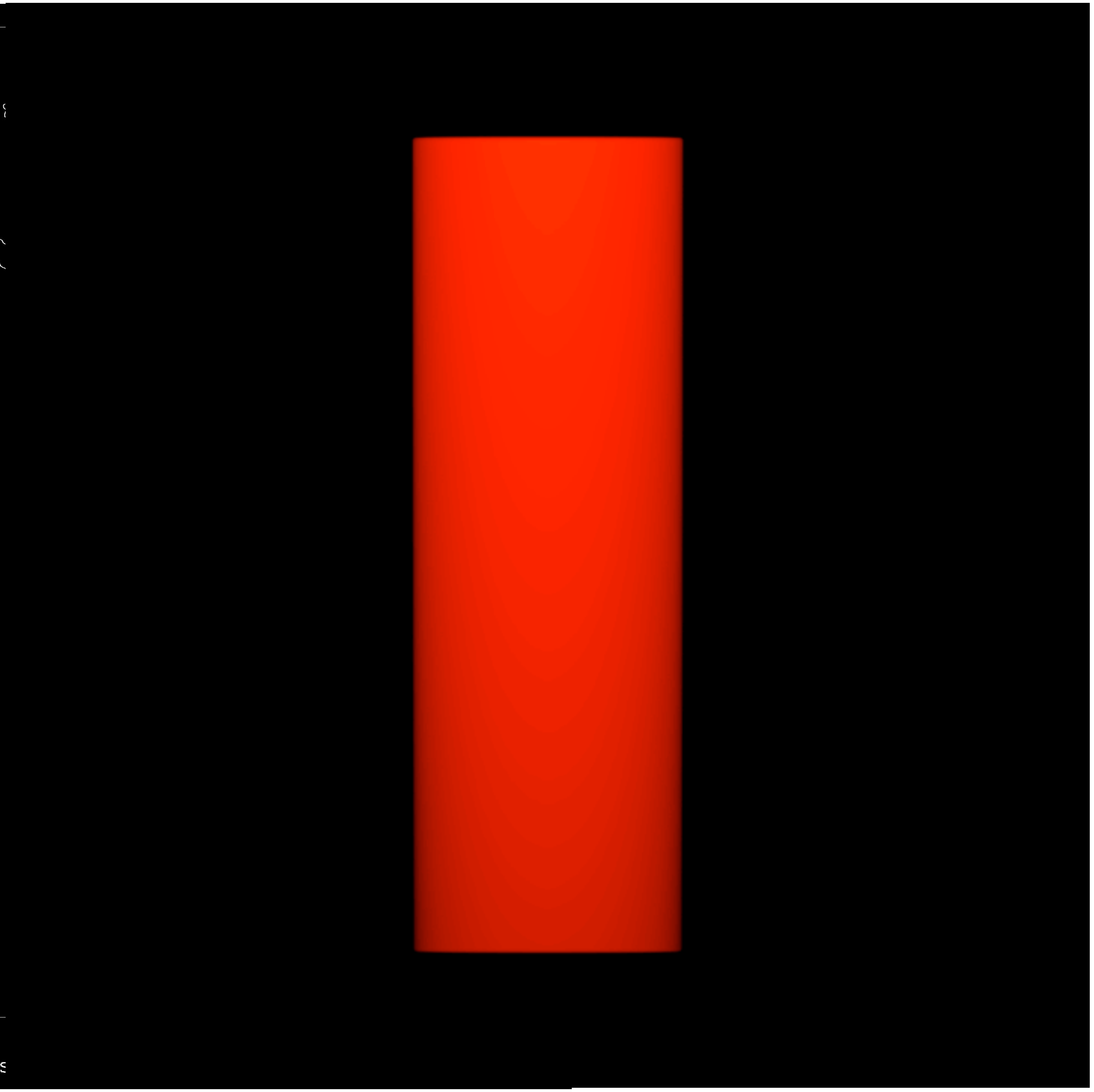


example: model of Orion cloud

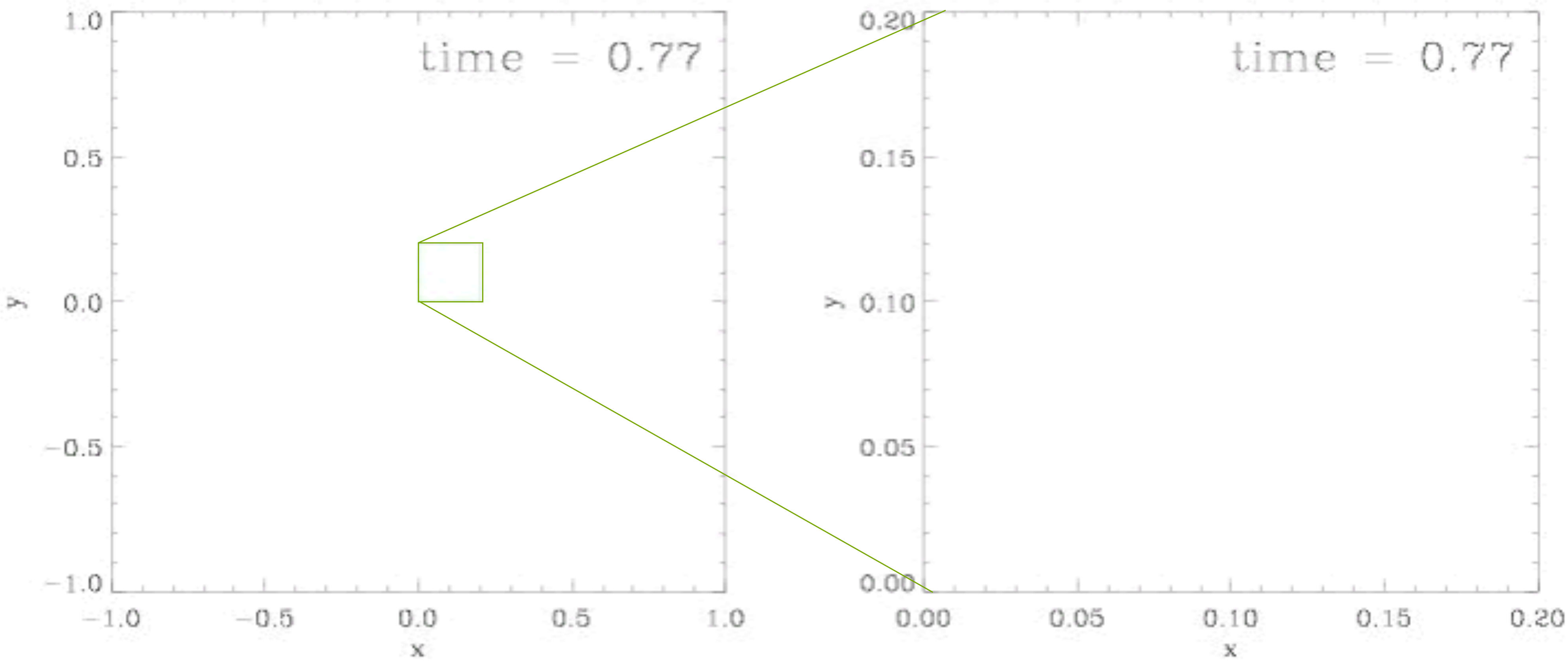




(Bonnell, Smith, Clark, & Bate 2010, MNRAS, 410, 2339)

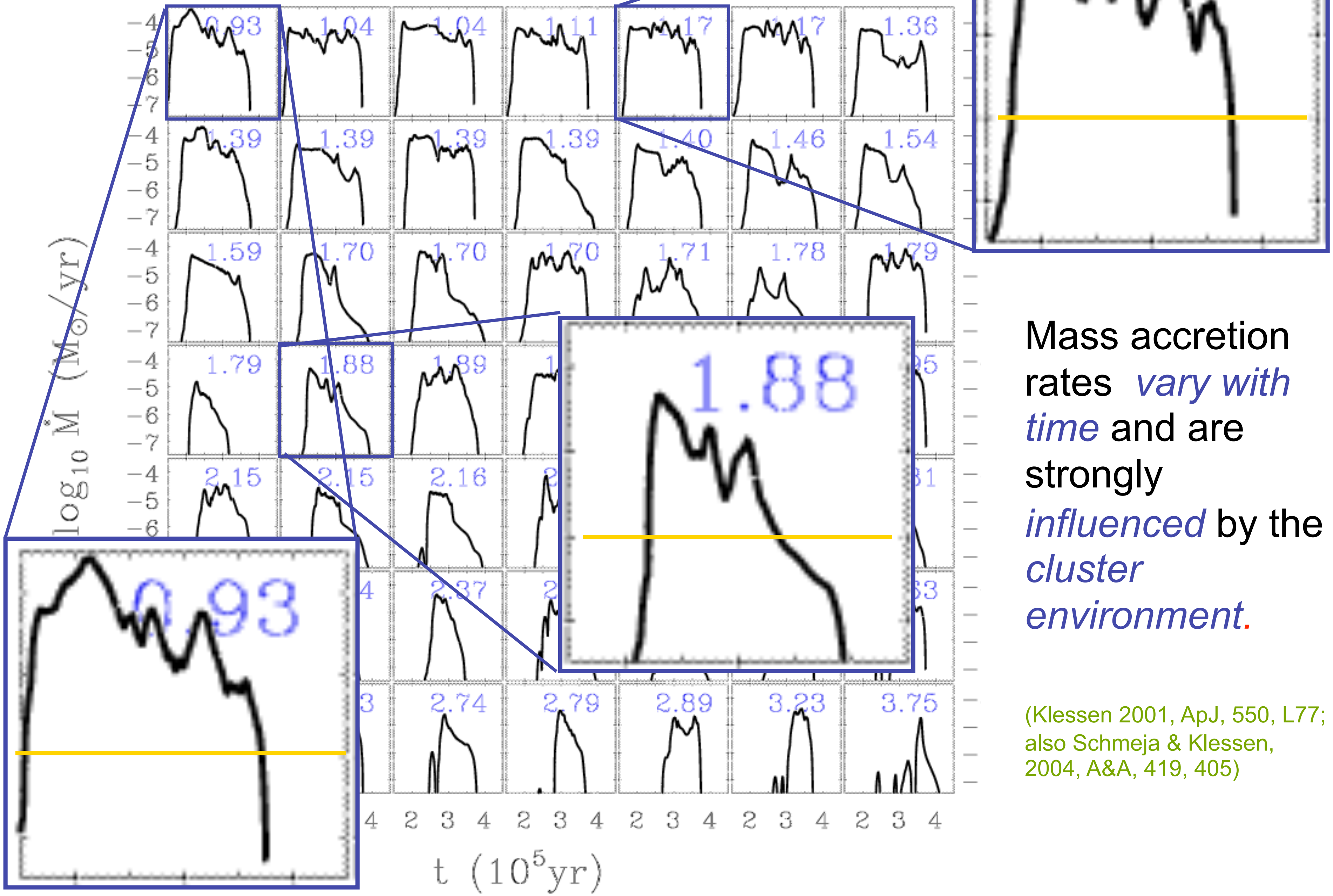
dynamics of nascent star cluster

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



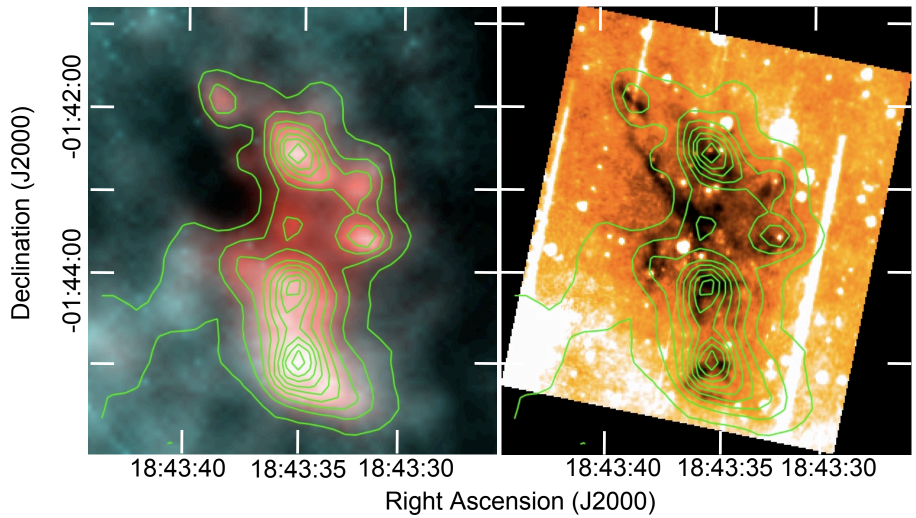
Mass accretion rates *vary with time* and are strongly *influenced* by the *cluster environment*.

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

important caveat:
initial conditions?

ICs of star cluster formation

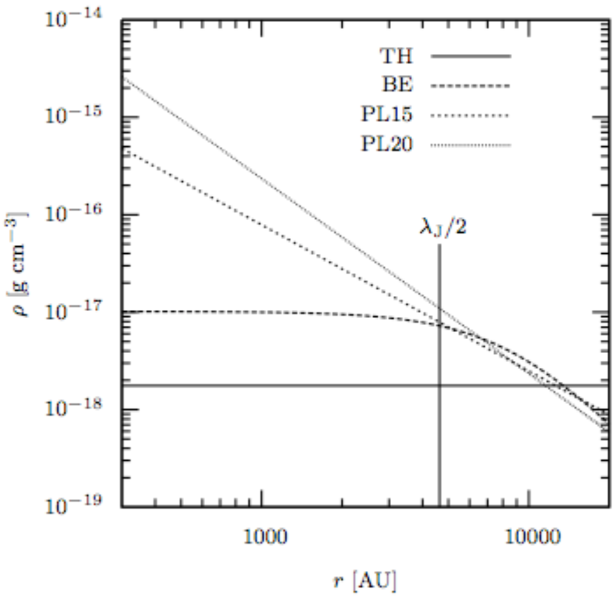
- key question:
  - what is the initial density profile of cluster forming cores? how does it compare low-mass cores?
- observers answer:
  - very difficult to determine!
    - most high-mass cores have some SF inside
    - infra-red dark clouds (IRDCs) are difficult to study
  - but: new results with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



IRDC observed with Herschel, Peretto et al. (2010)

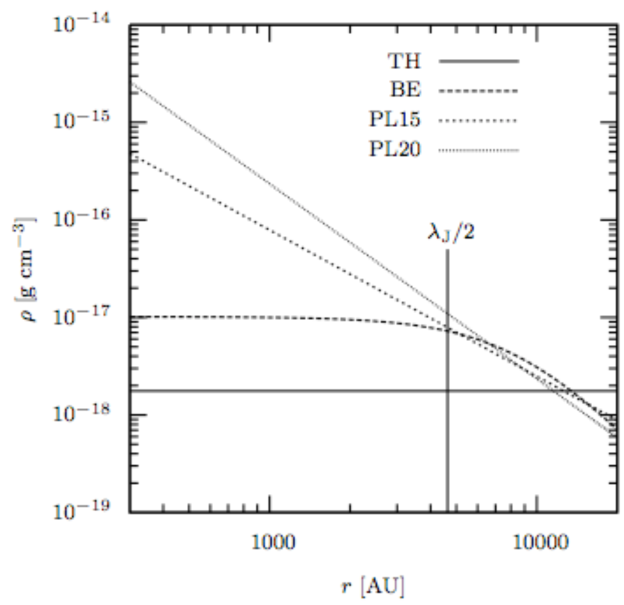
different density profiles

- 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



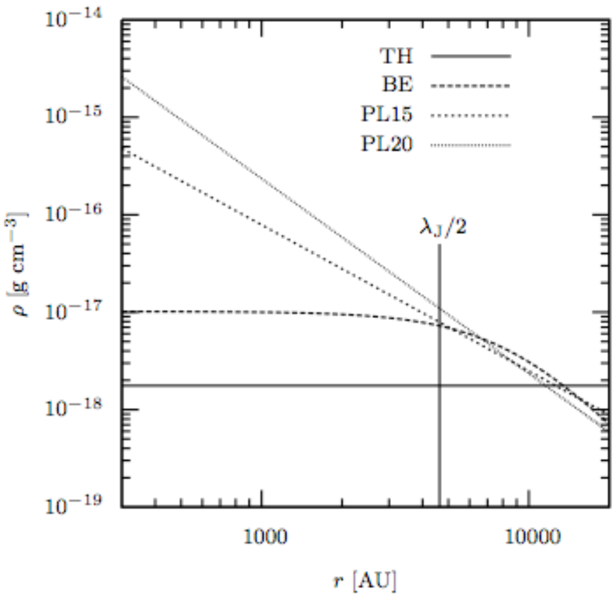
different density profiles

- does the density profile matter?
  - .
  - .
  - .
- in comparison to
  - turbulence ...
  - radiative feedback ...
  - magnetic fields ...
  - thermodynamics ...

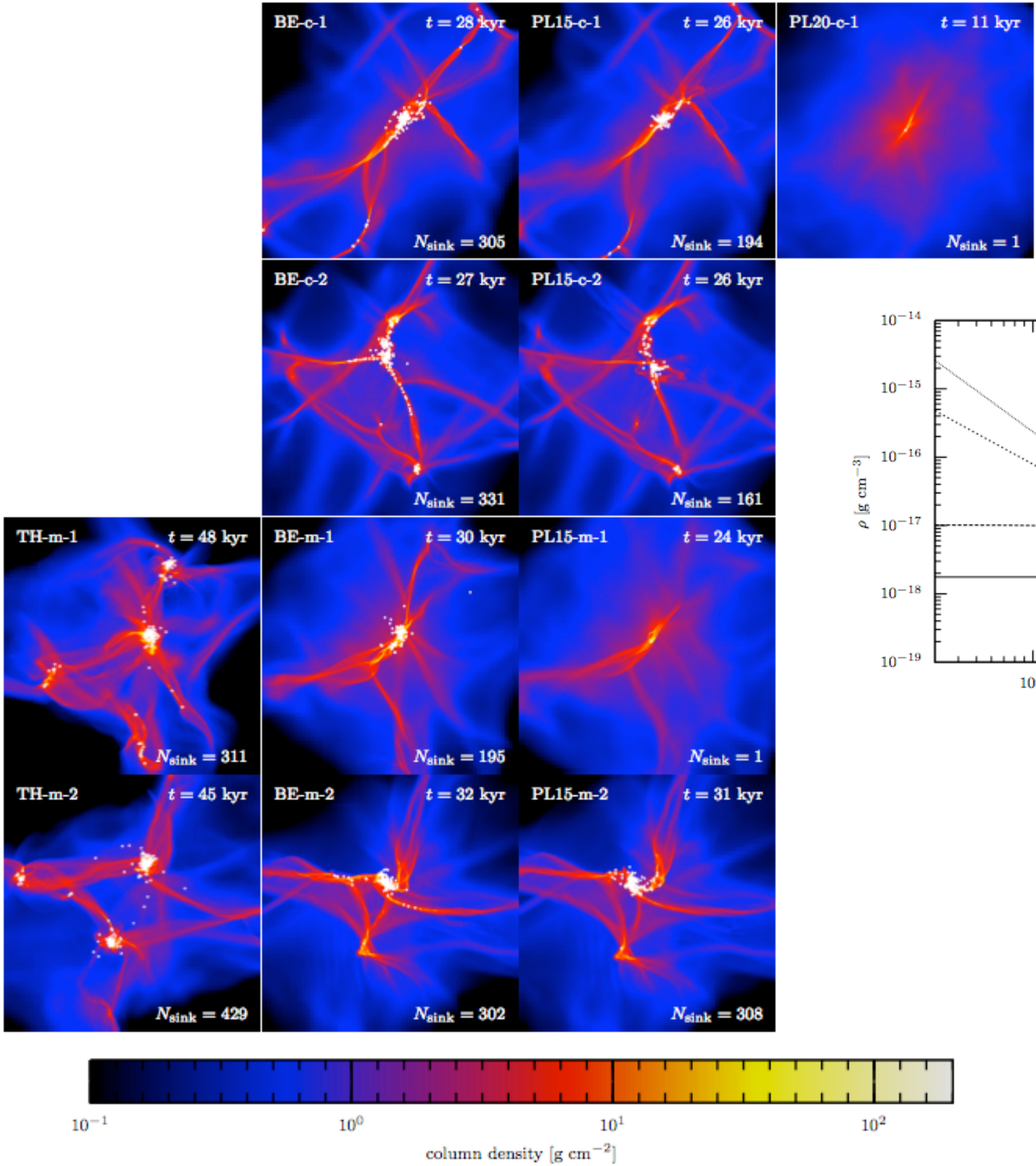


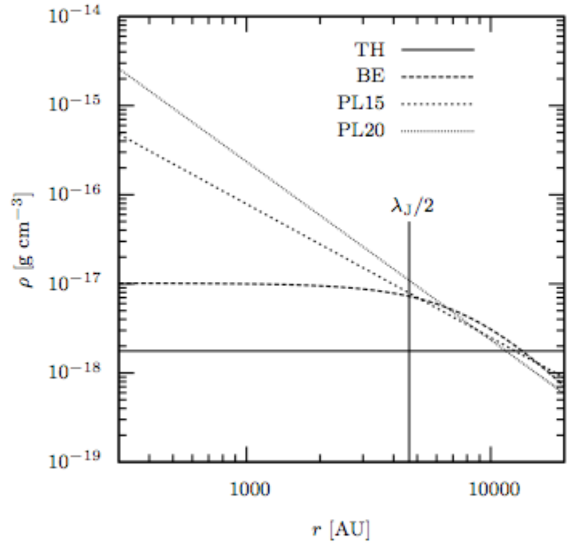
different density profiles

- 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)

Run	t_{sim} [kyr]	t_{sim}/t_{ff}^{core}	t_{sim}/t_{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

number of protostars

ICs with flat inner density profile on average form more fragments

Girichids et al. (2011abc)

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number of protostars

ICs with flat inner density profile on average form more fragments

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

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.
- *CONCLUSION:* take molecular cloud formation into account in theoretical / numerical models!

stellar mass fuction

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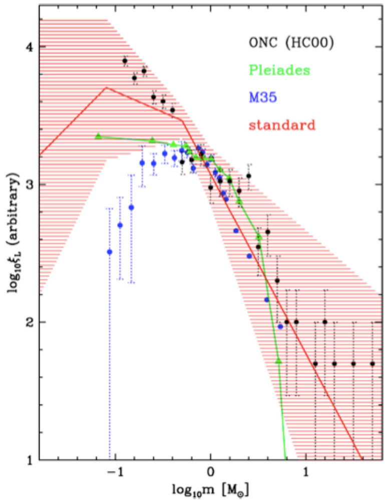
(Kroupa 2002)



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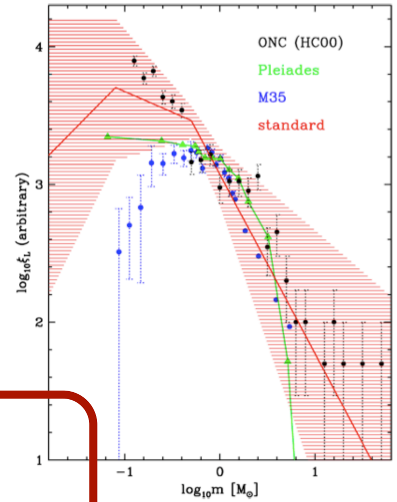


application to early star formation

thermodynamics & fragmentation

degree of fragmentation depends on *EOS!*

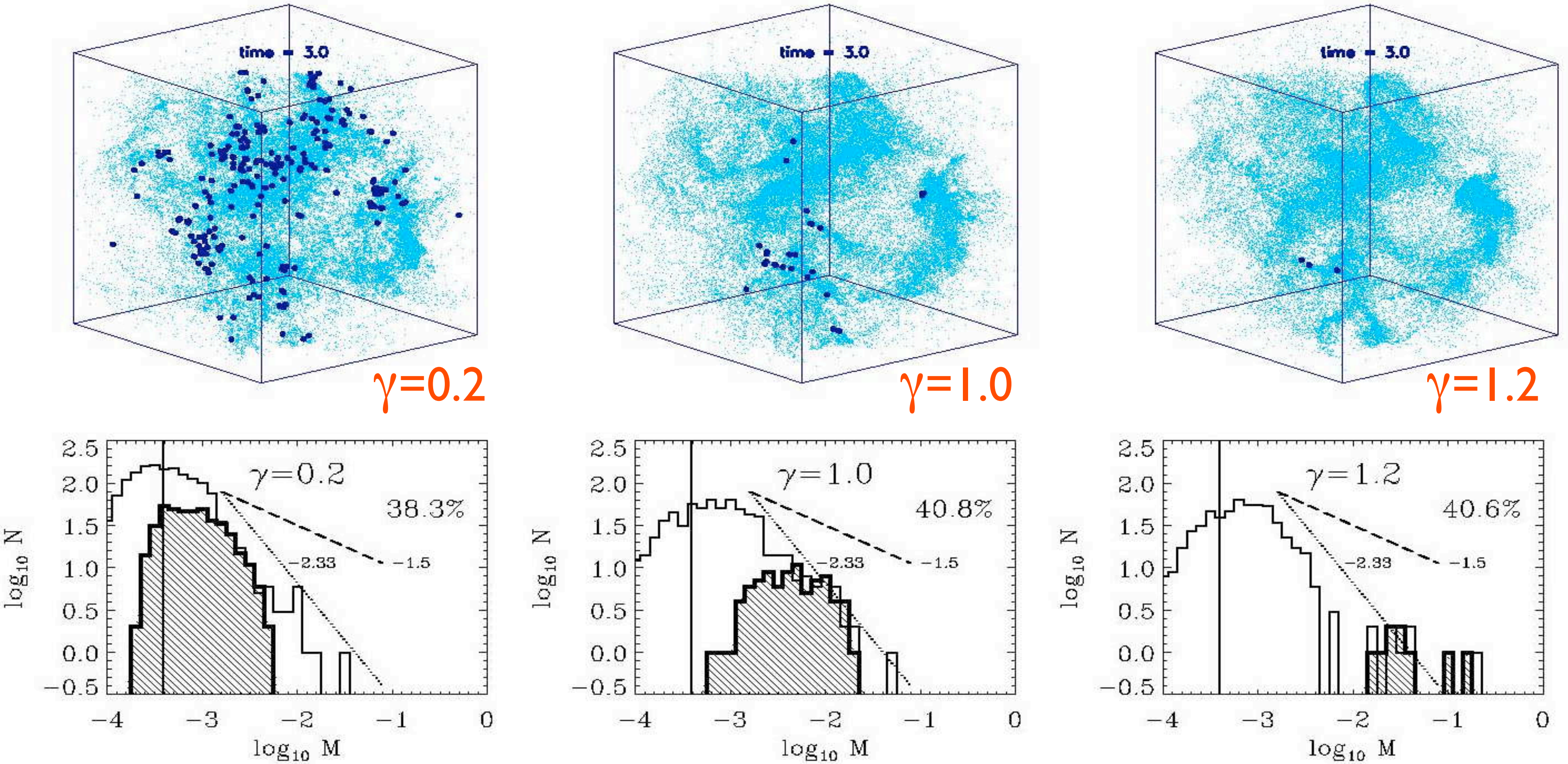
polytropic EOS: $\mathbf{p} \propto \rho^{\gamma}$

$\gamma<1$: 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*

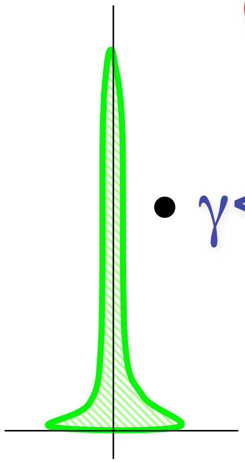
for $\gamma>1$ it is suppressed → *isolated massive stars*

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

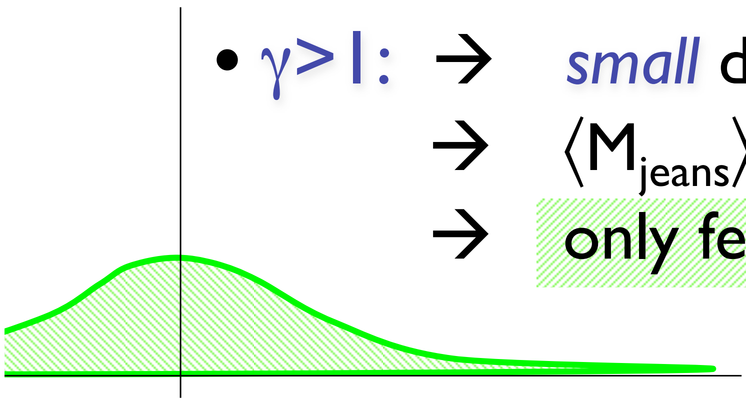
how does that work?

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

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

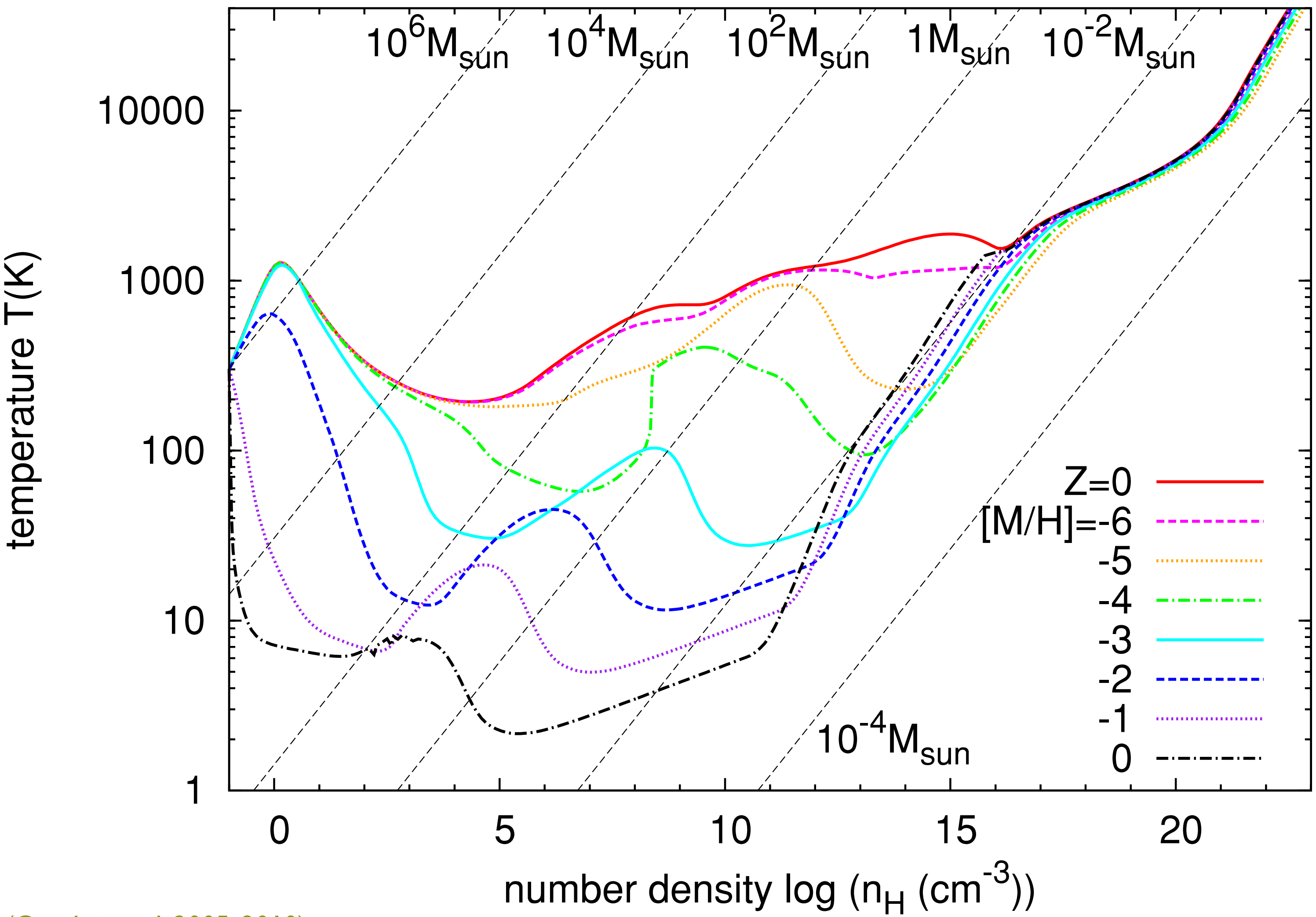


- $\gamma<1$: → *large* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ becomes small
  → number of fluctuations with $M > M_{jeans}$ is large



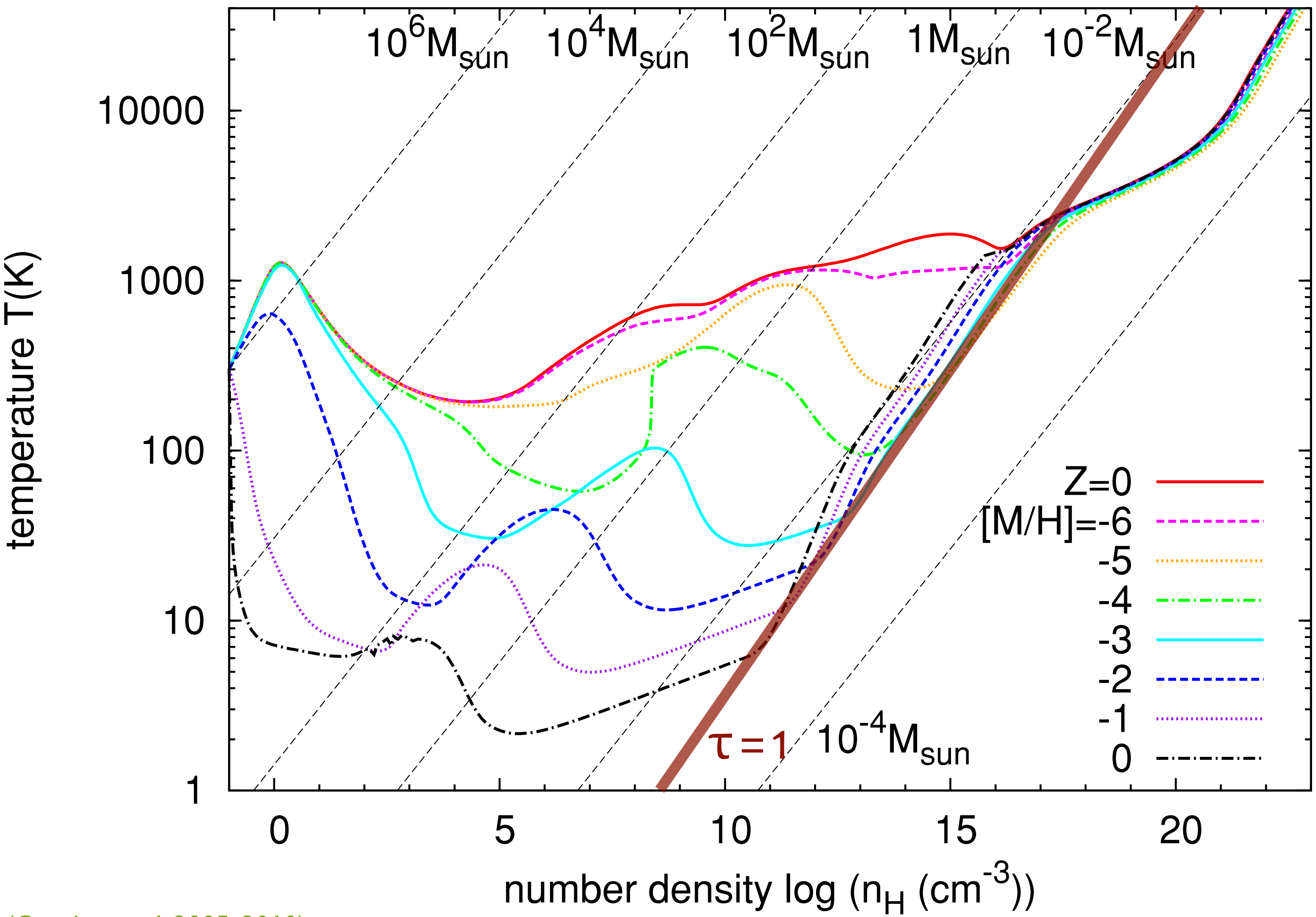
- $\gamma>1$: → *small* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ is large
  → only few and massive clumps exceed M_{jeans}

EOS as function of metallicity



(Omukai et al. 2005, 2010)

EOS as function of metallicity



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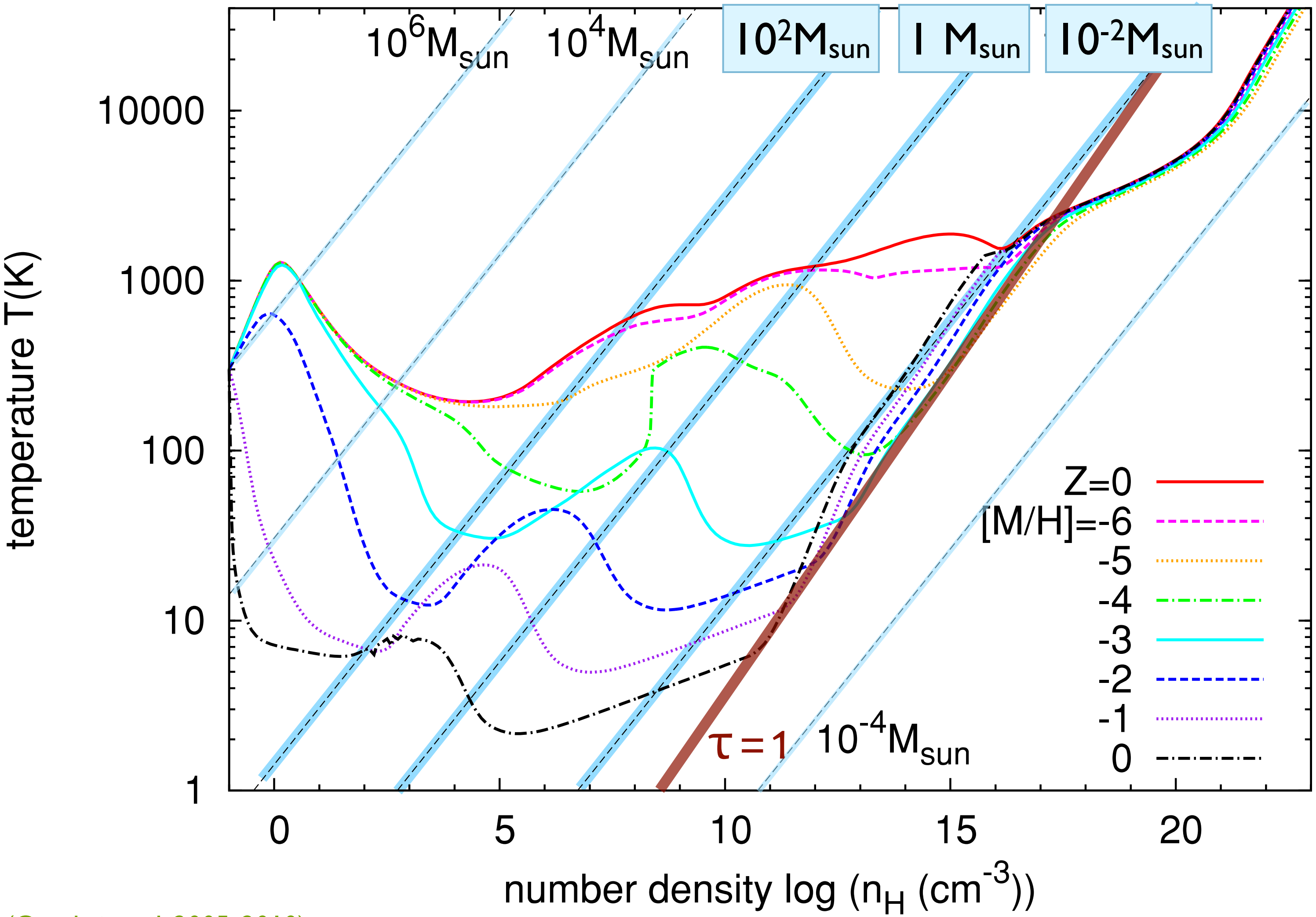

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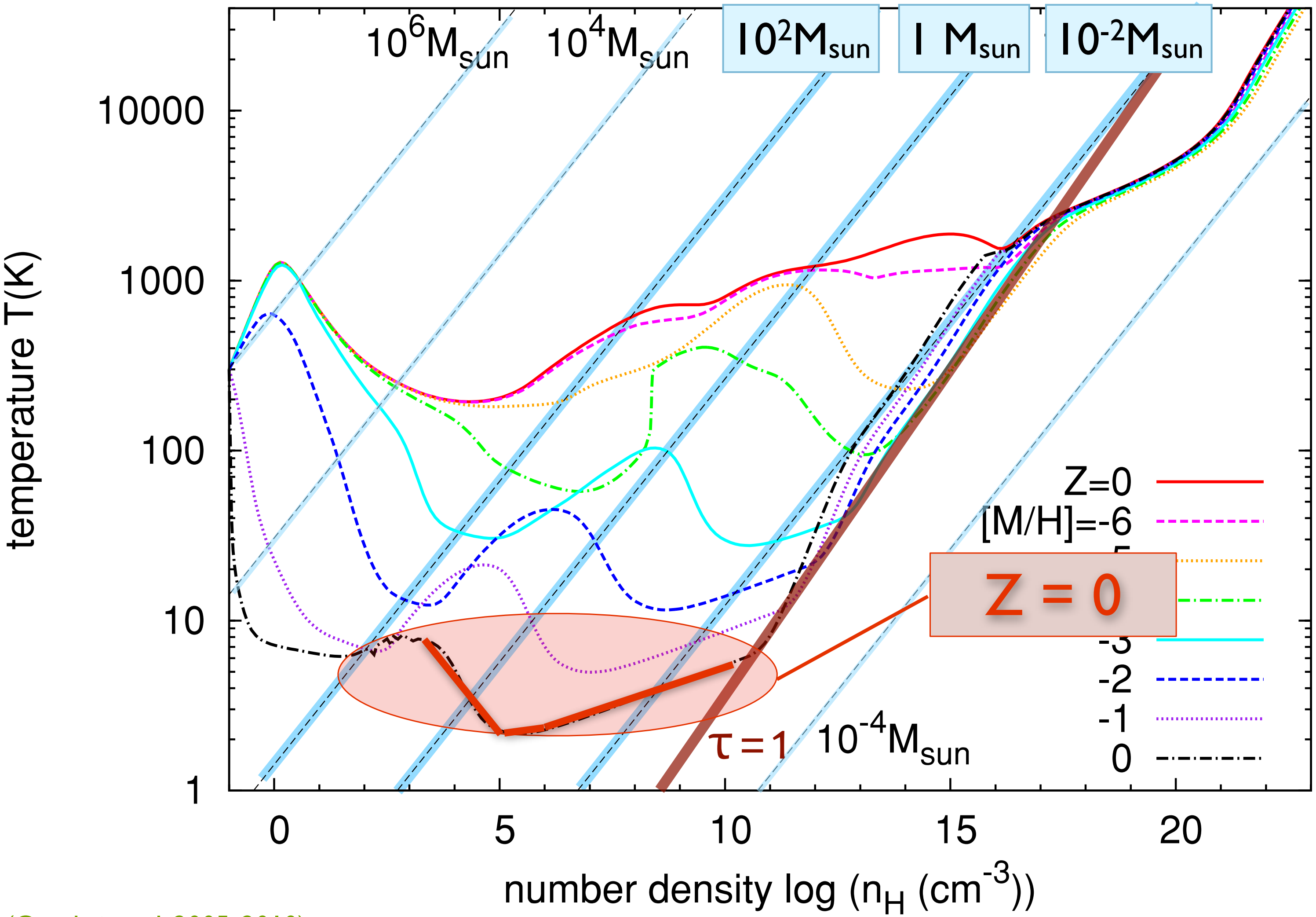
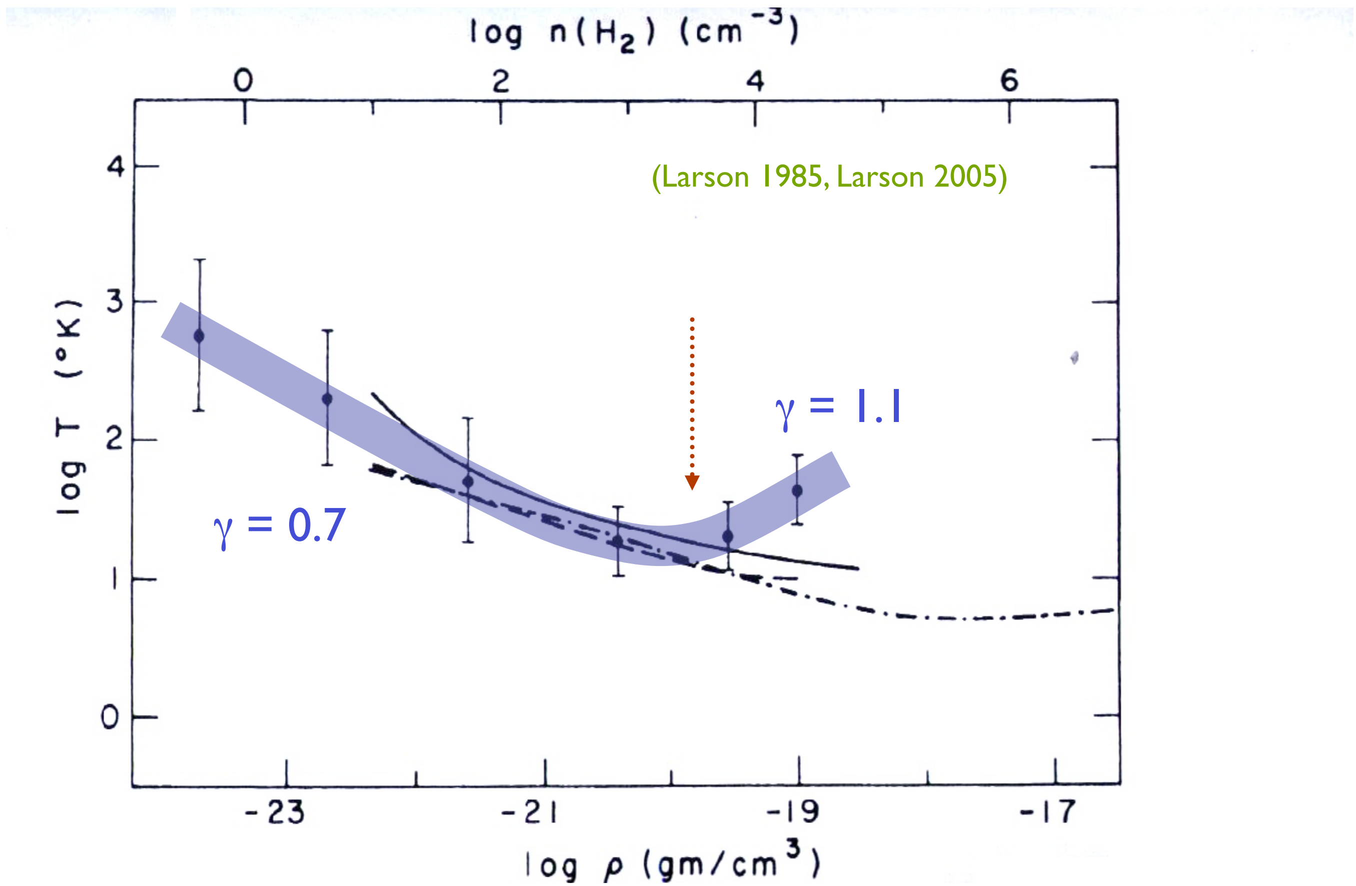
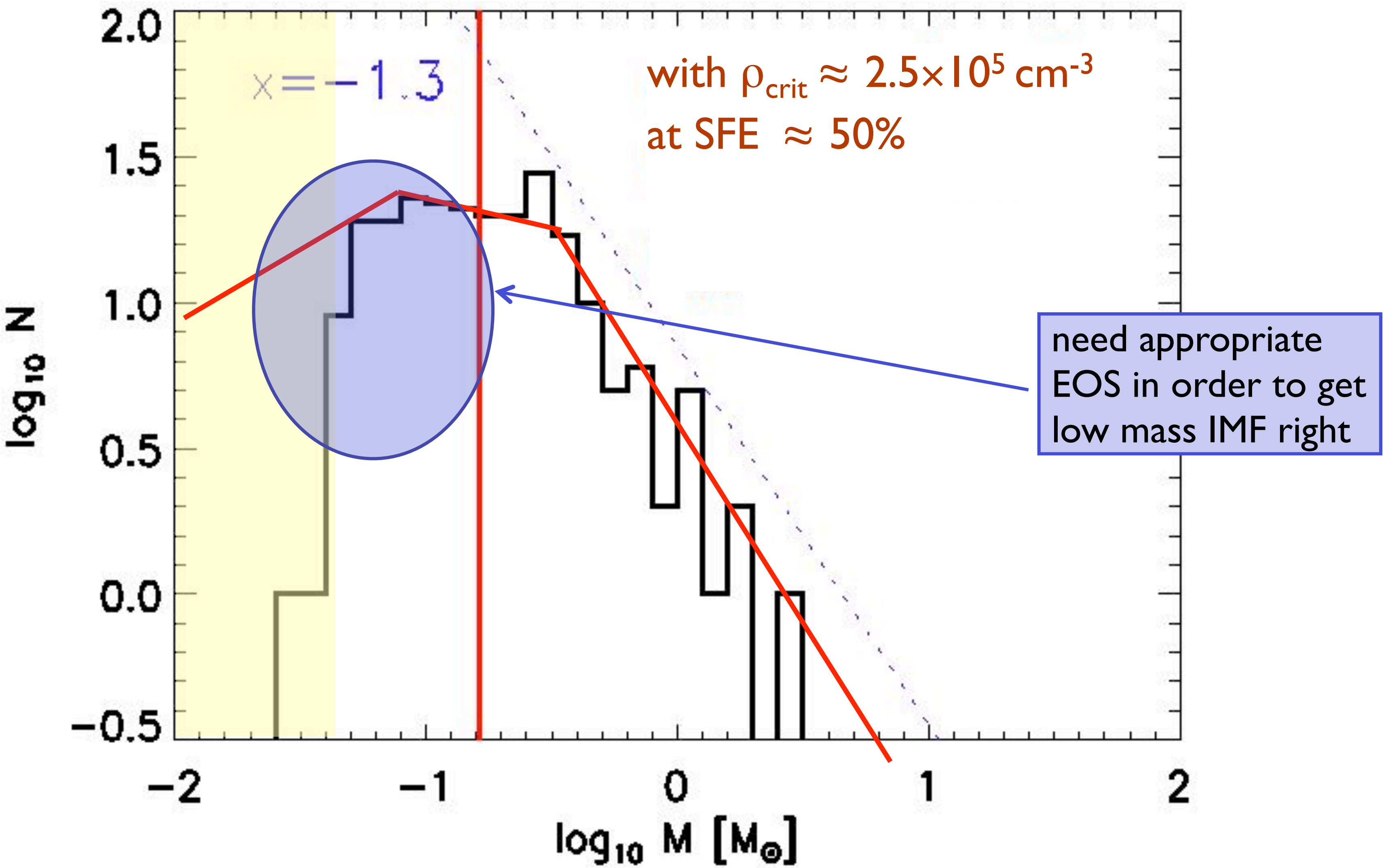


(Omukai et al. 2005, 2010)

present-day star formation

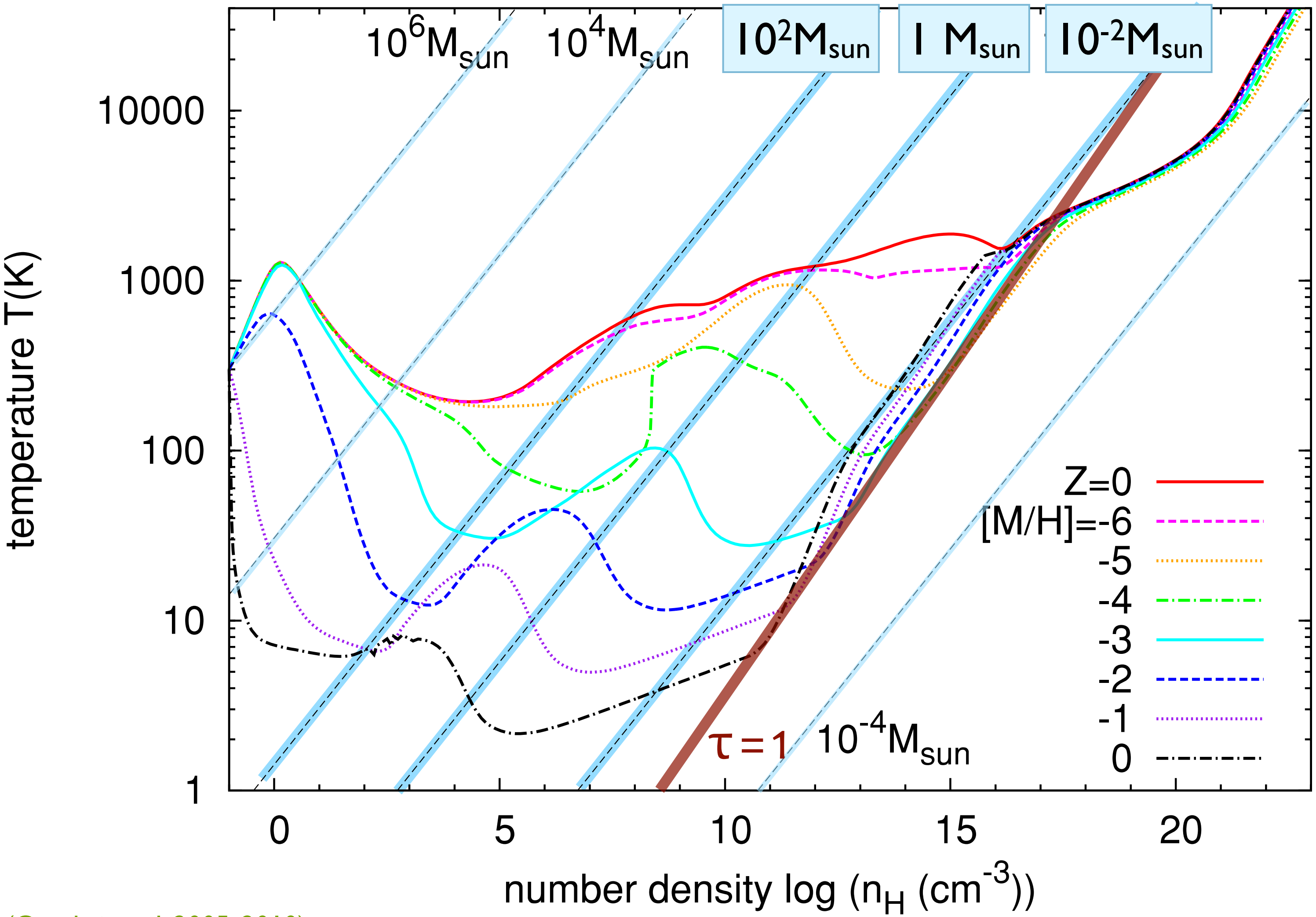


IMF in nearby molecular clouds



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

EOS as function of metallicity



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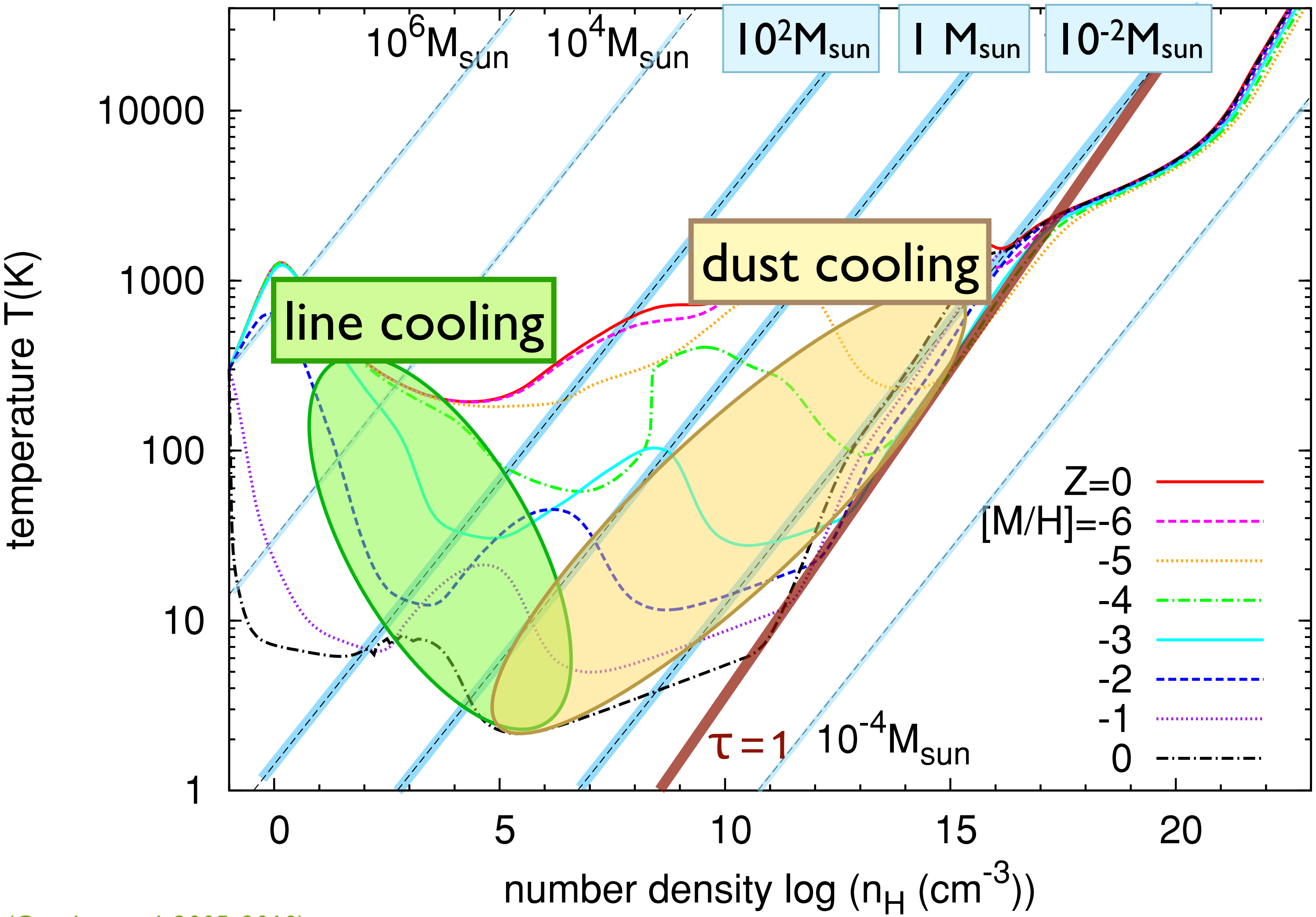

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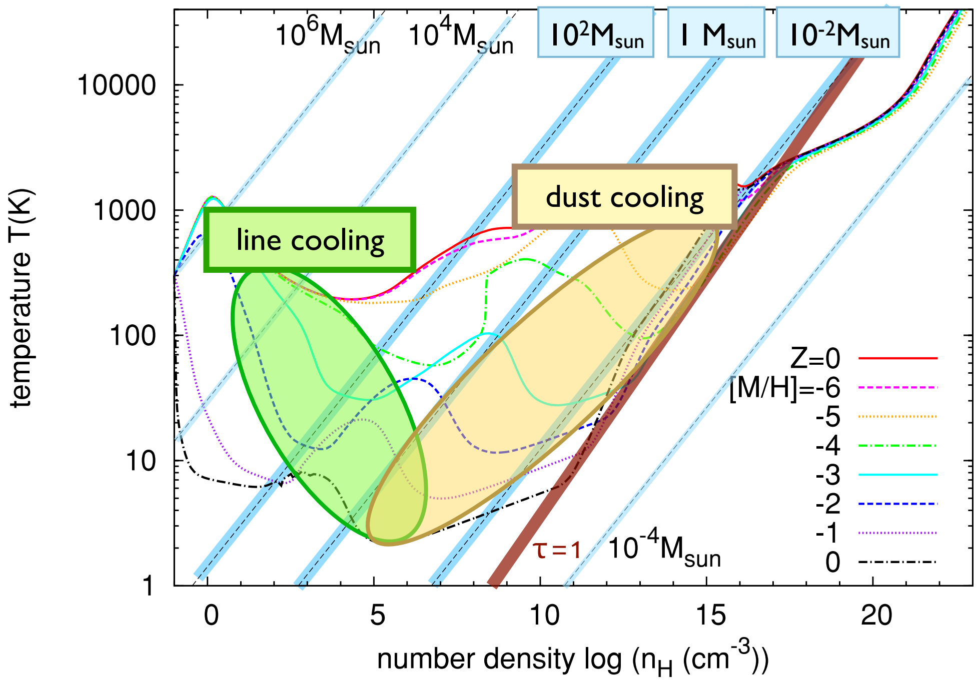
transition: Pop III to Pop II.5



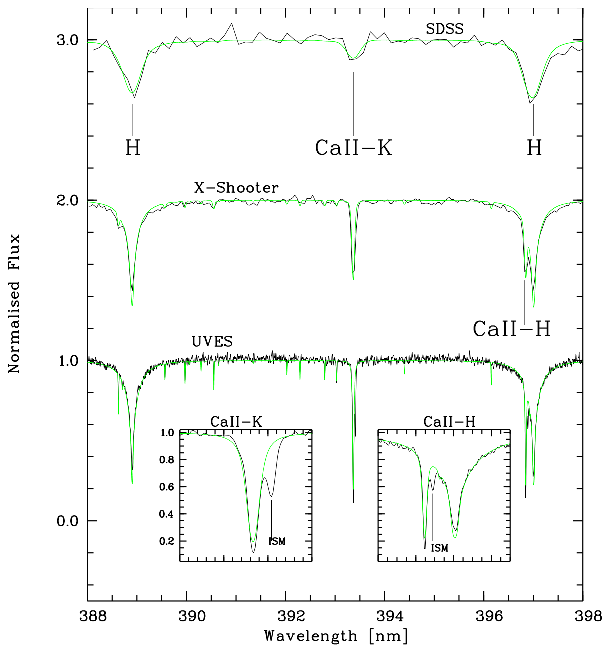
two competing models:

- 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}.

(Omukai et al. 2005, 2010)

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]

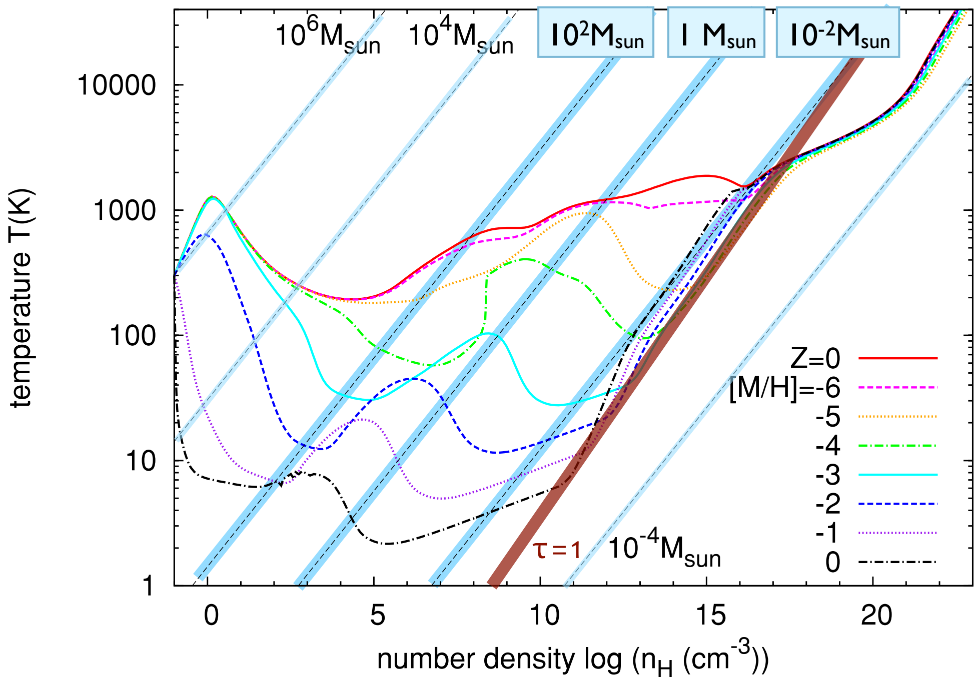
- new ESO large program to find more of these stars (120h x-shooter, 30h UVES)
  [PI E. Caffau]

Element	$[X/H]_{1D}$	+3Dcor.	+NLTE cor.	+ 3D cor + NLTE cor	N lines	S_H	$A(X)_\odot$
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)

transition: Pop III to Pop II.5

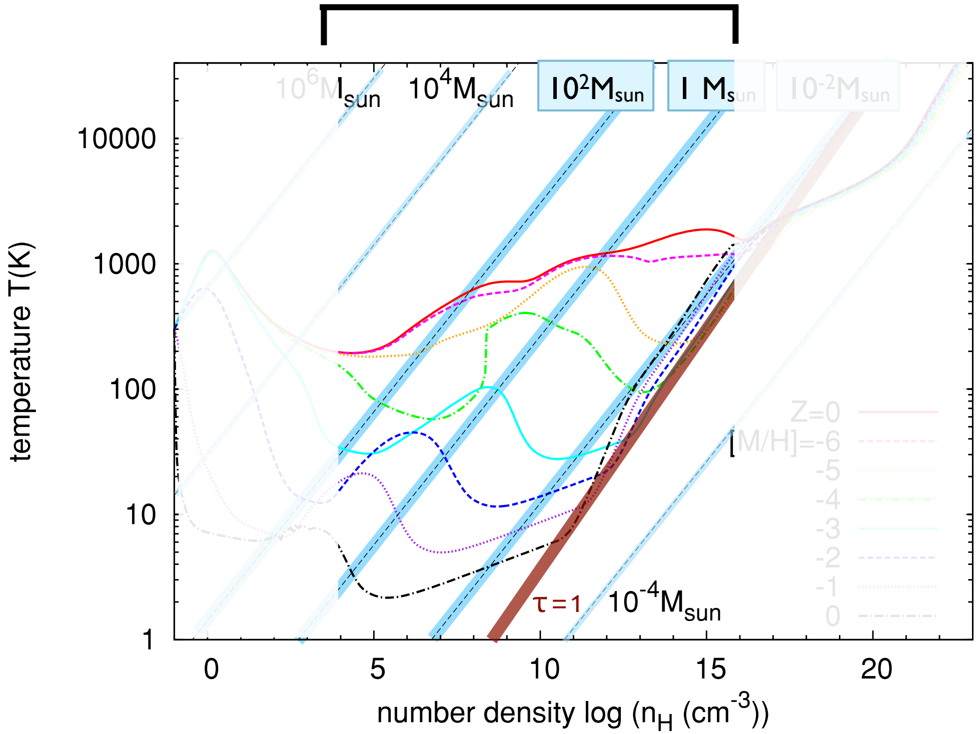


approach problem with high-resolution hydrodynamic calculations of central parts of high-redshift halos

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

(Omukai et al. 2005, 2010)

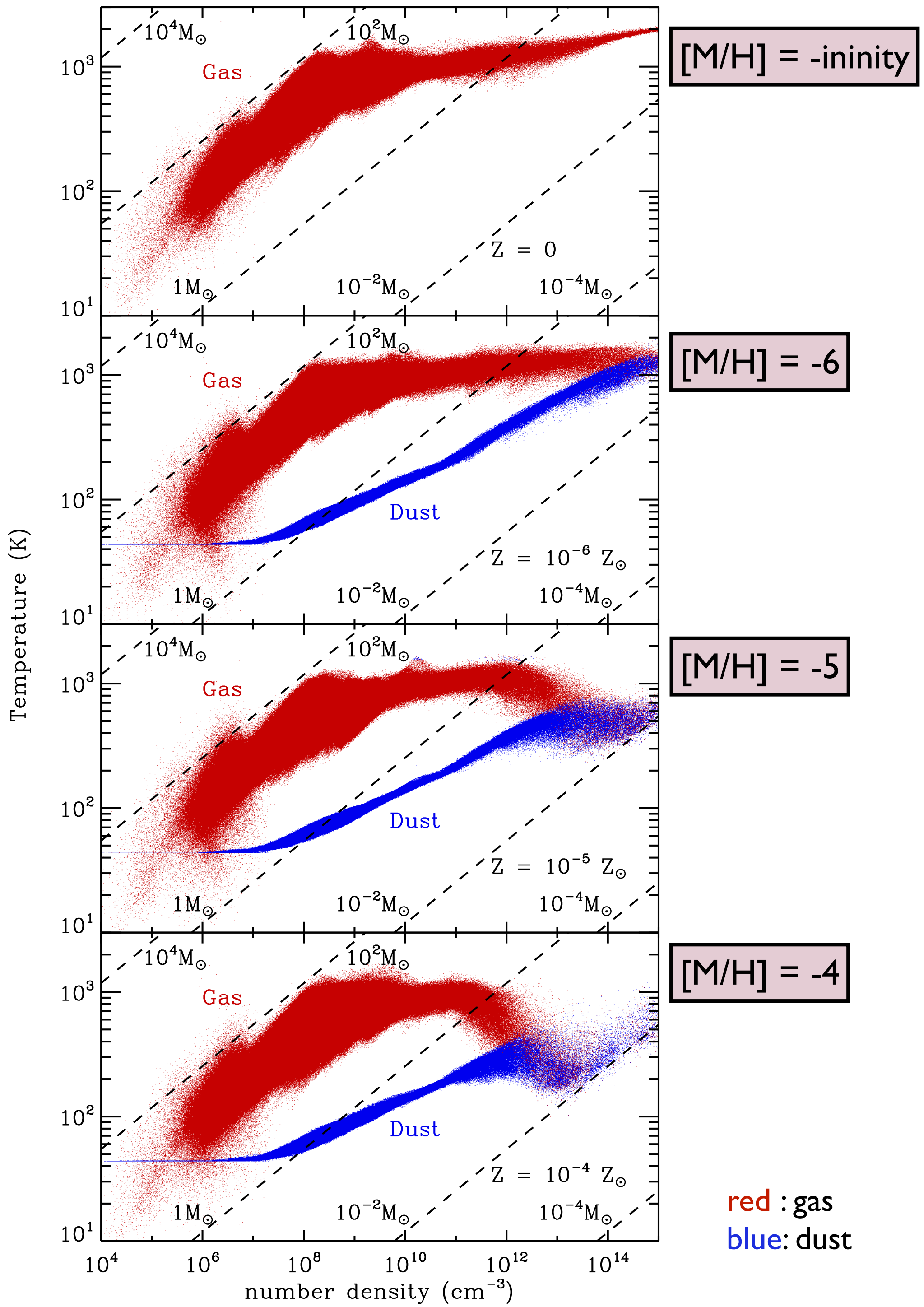
transition: Pop III to Pop II.5

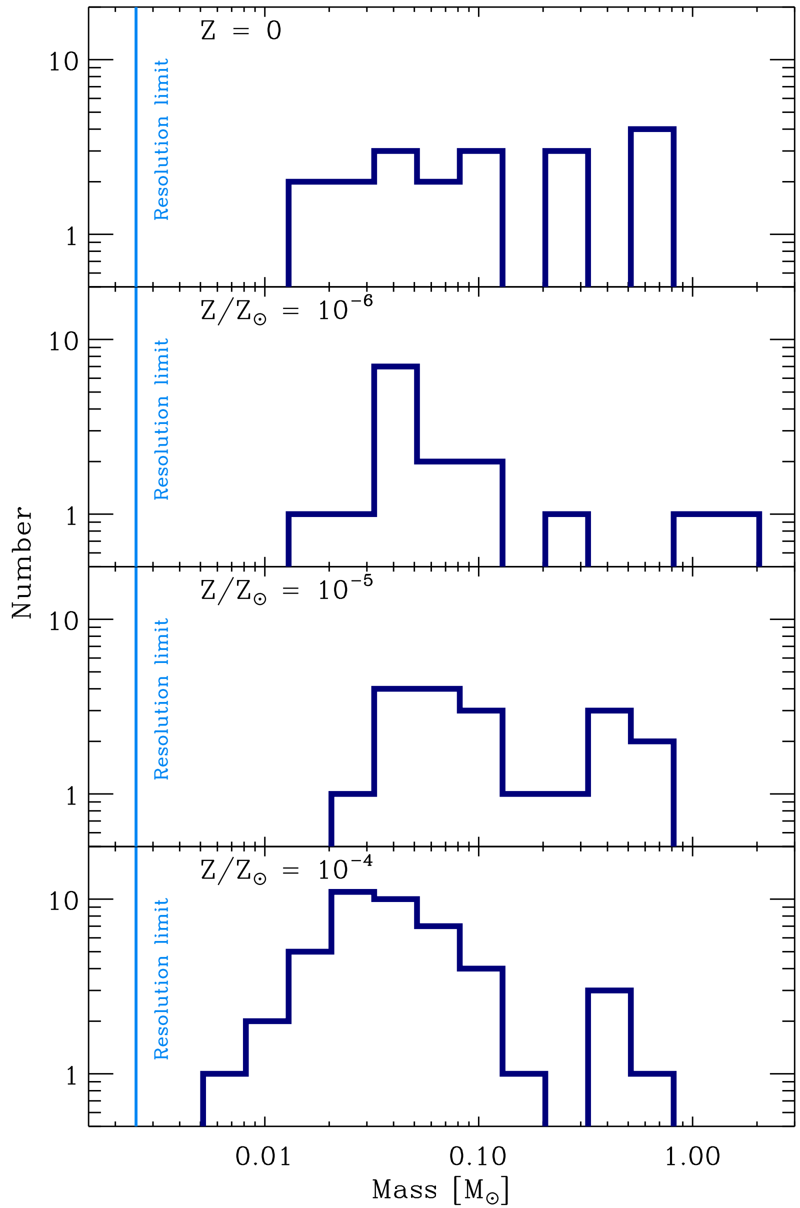


approach problem with high-resolution hydrodynamic calculations of central parts of high-redshift halos

- 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)

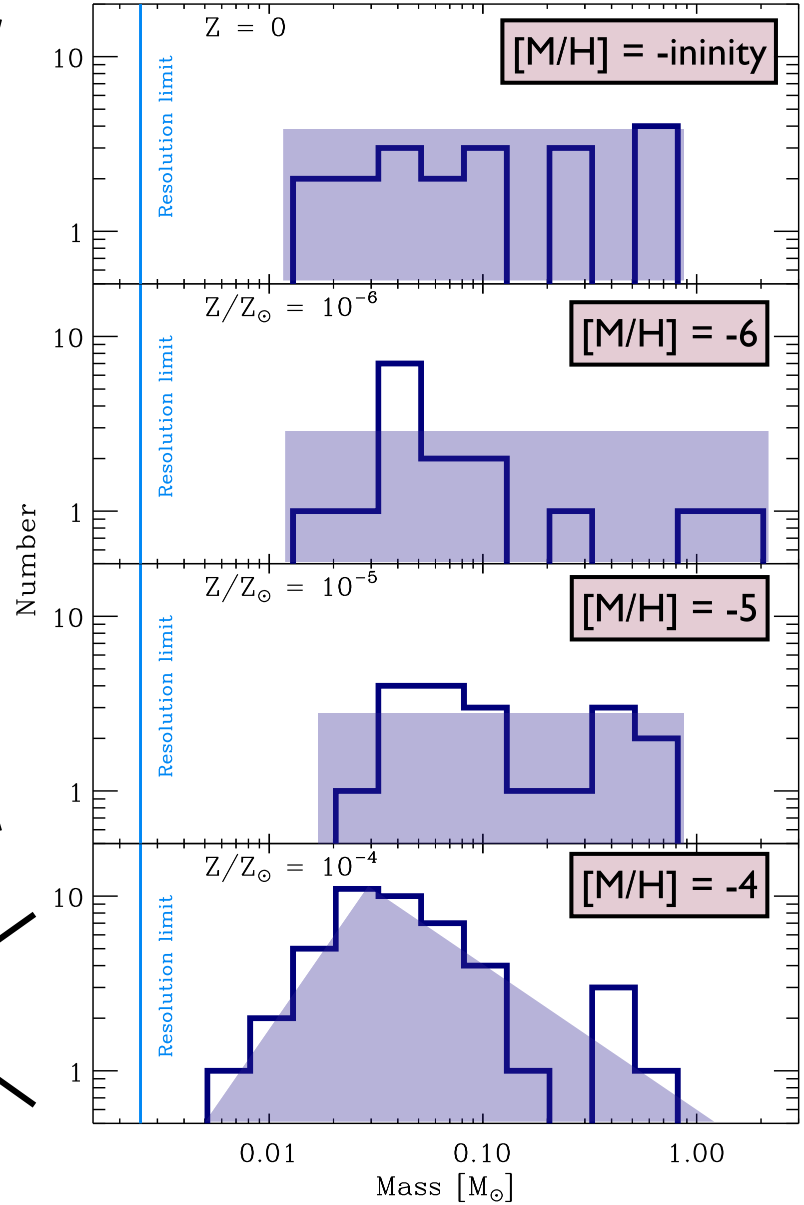




Dopcke et al., 2012, submitted to ApJ, arXiv:1203.6842) hints for differences in mass spectrum

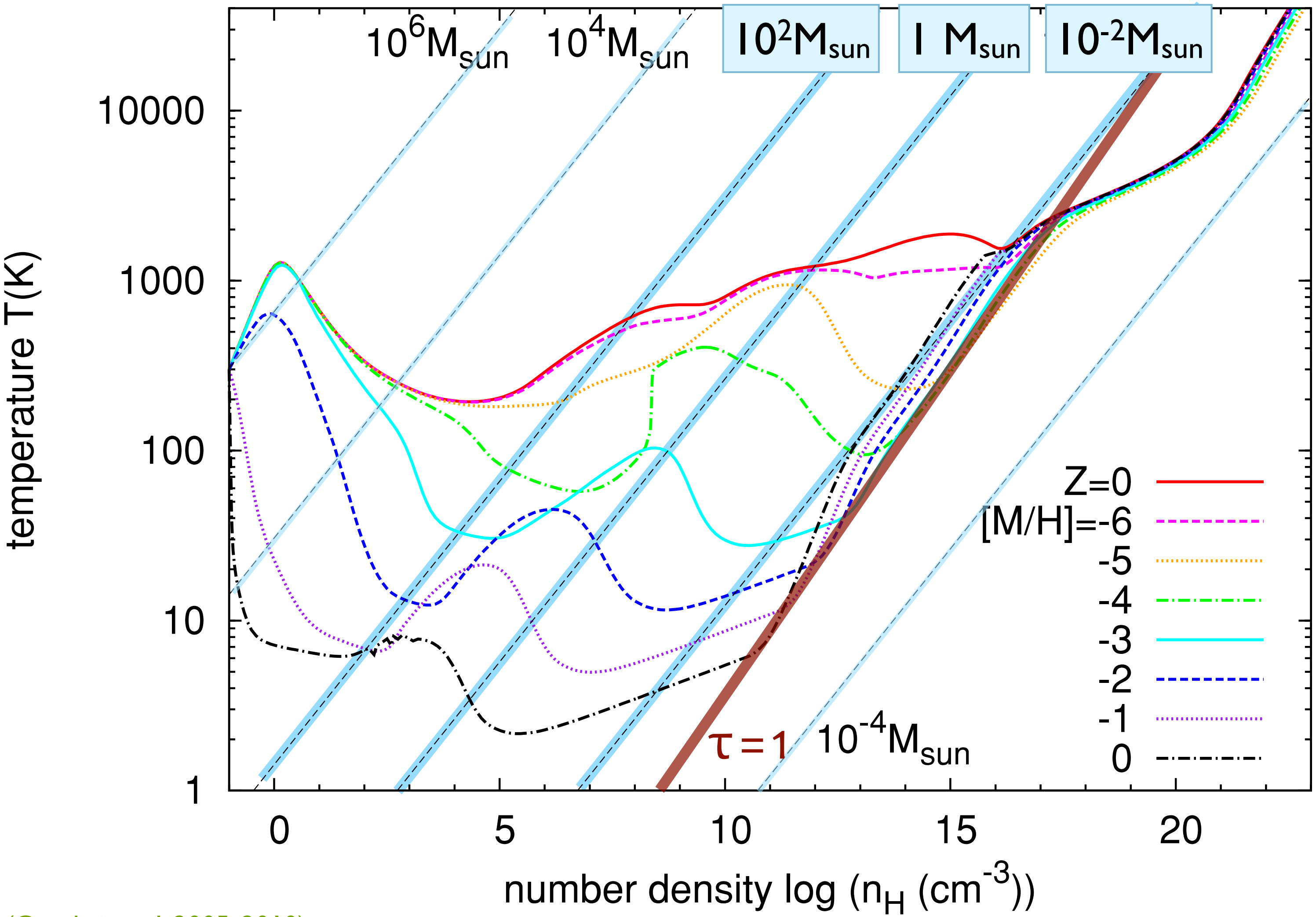
disk fragmentation mode

gravoturbulent fragmentation mode



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

EOS as function of metallicity



(Omukai et al. 2005, 2010)

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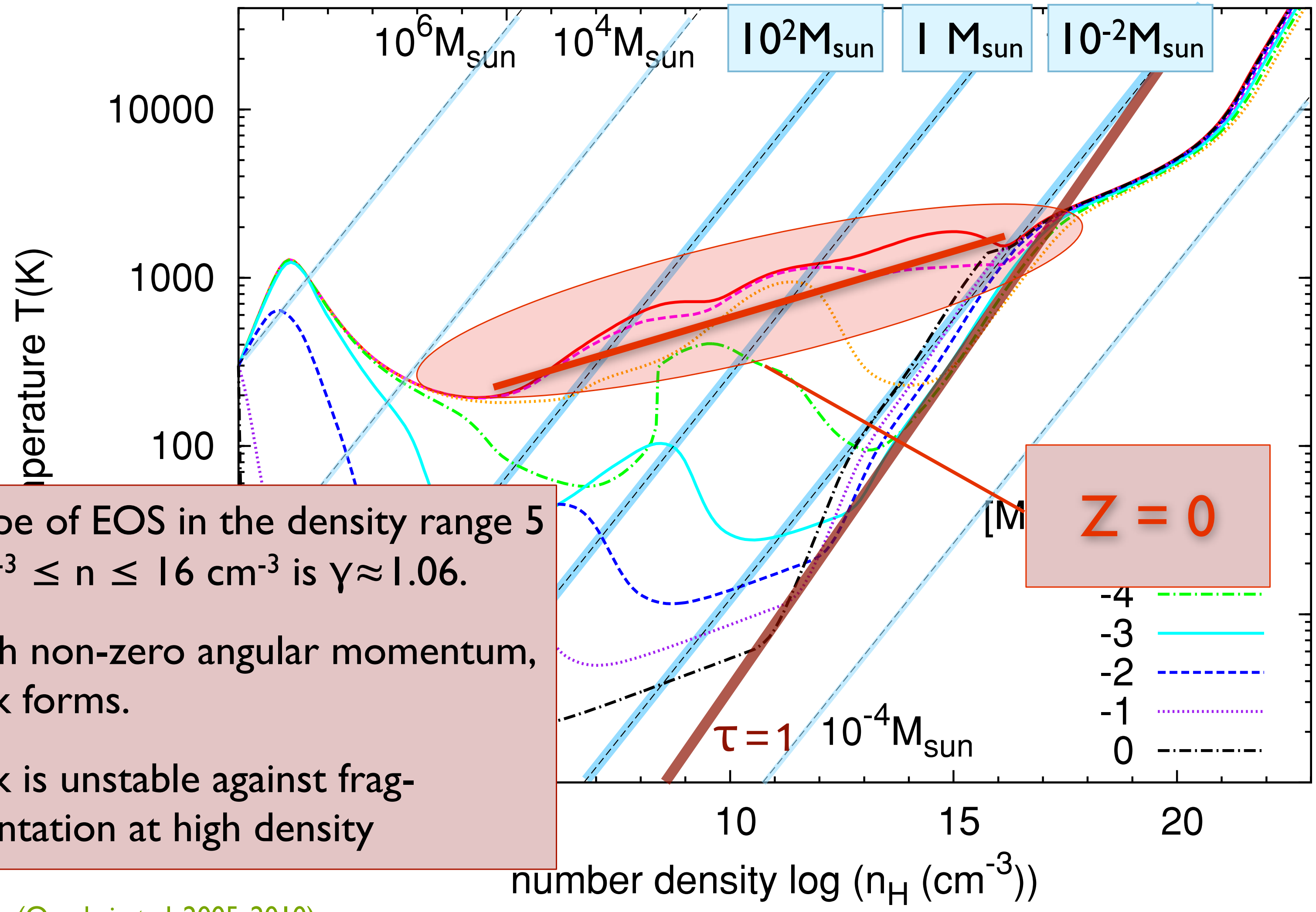
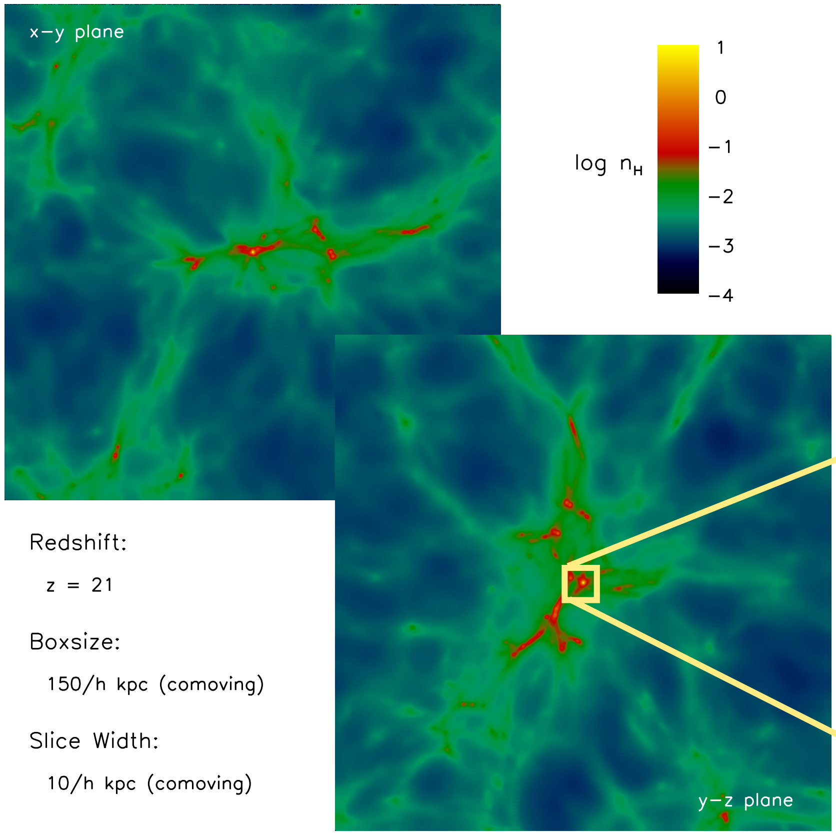


- slope of EOS in the density range 5 cm^{-3} $\leq$ n $\leq$ 16 cm^{-3} is $\gamma \approx 1.06$.
- with non-zero angular momentum, disk forms.
- disk is unstable against fragmentation at high density

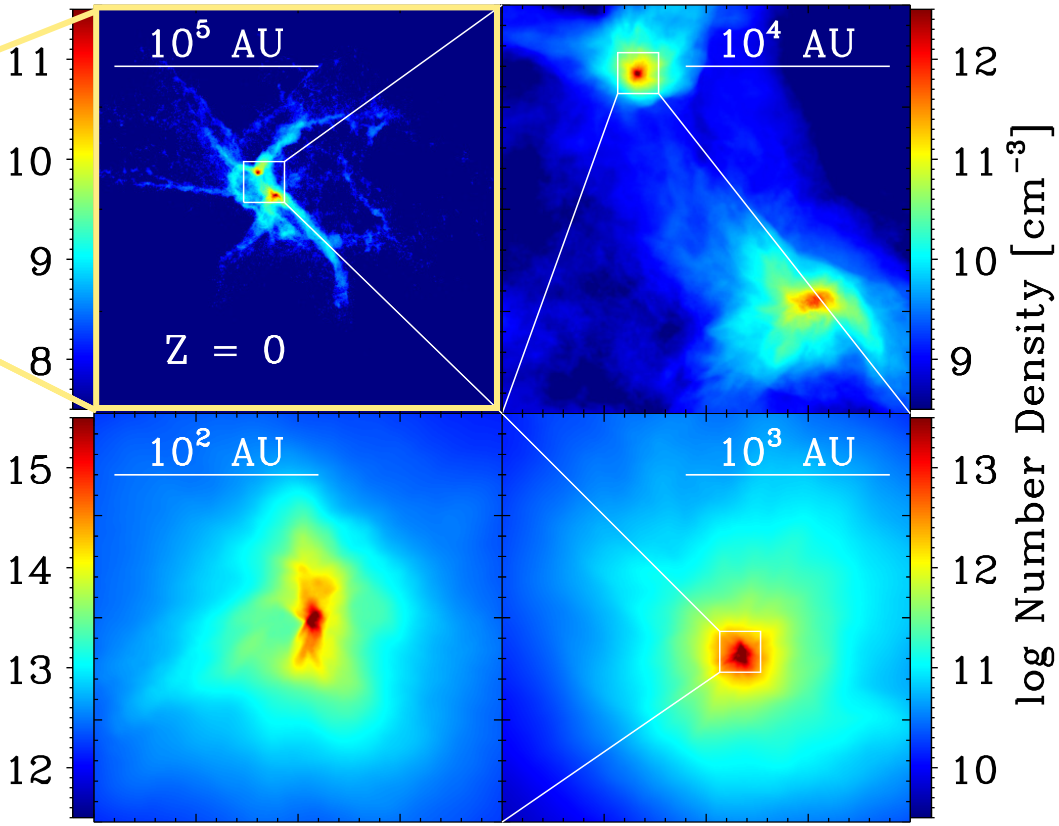
(Omukai et al. 2005, 2010)

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)

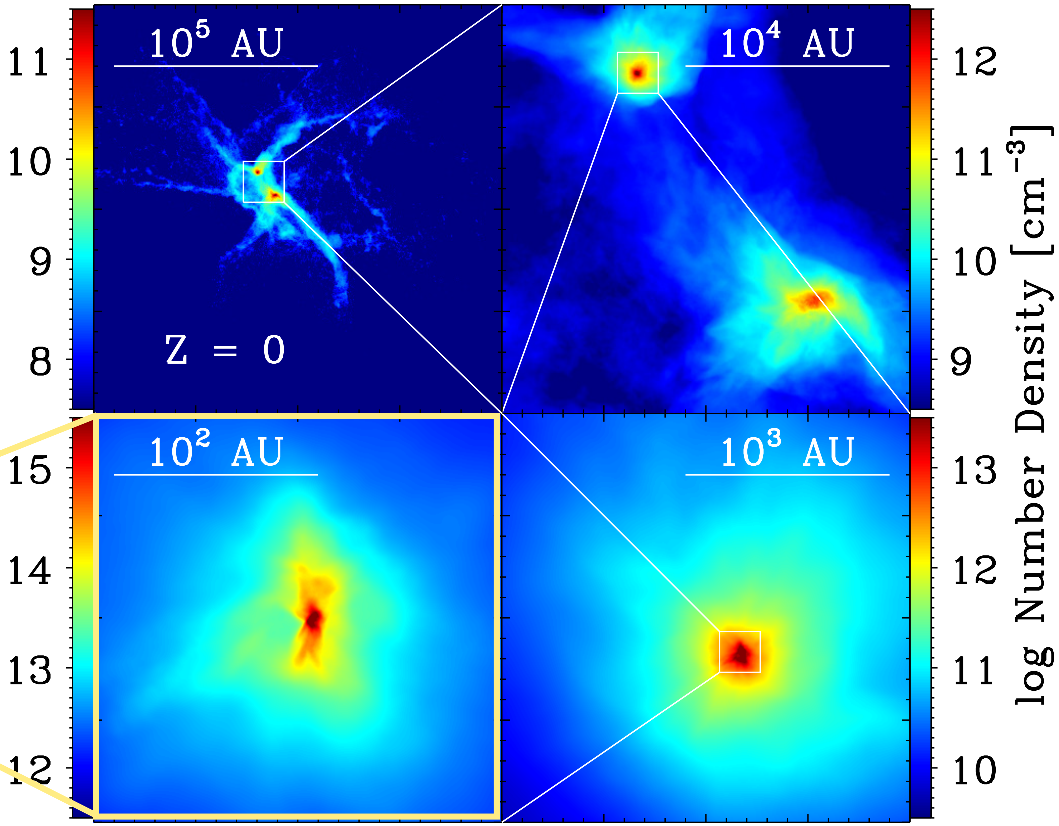


(Greif et al. 2011, ApJ, 737, 75, Greif et al. 2012, MNRAS, 424, 399, Dopcke et al. 2012, ApJ submitted, arXiv1203.6842)

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?



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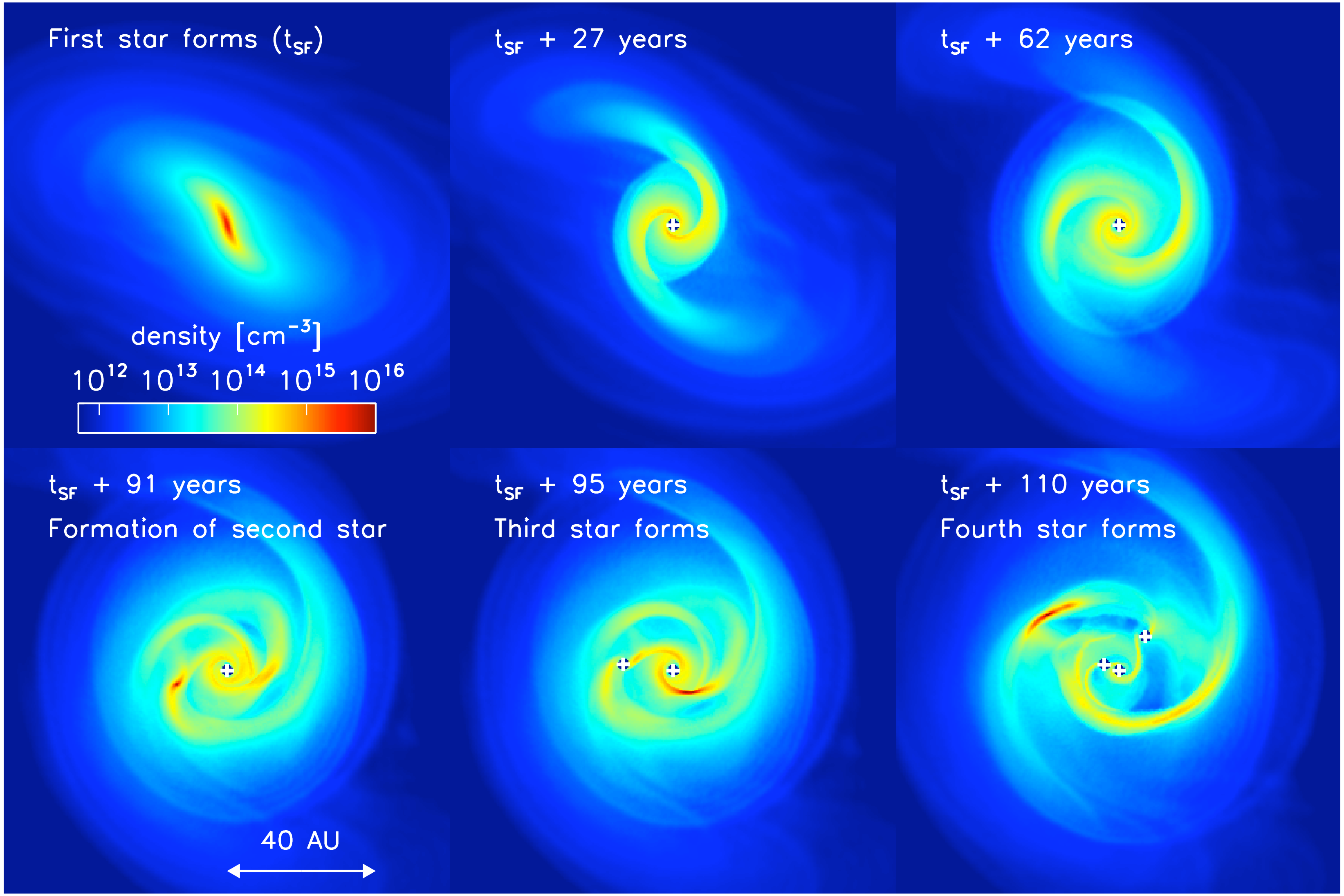
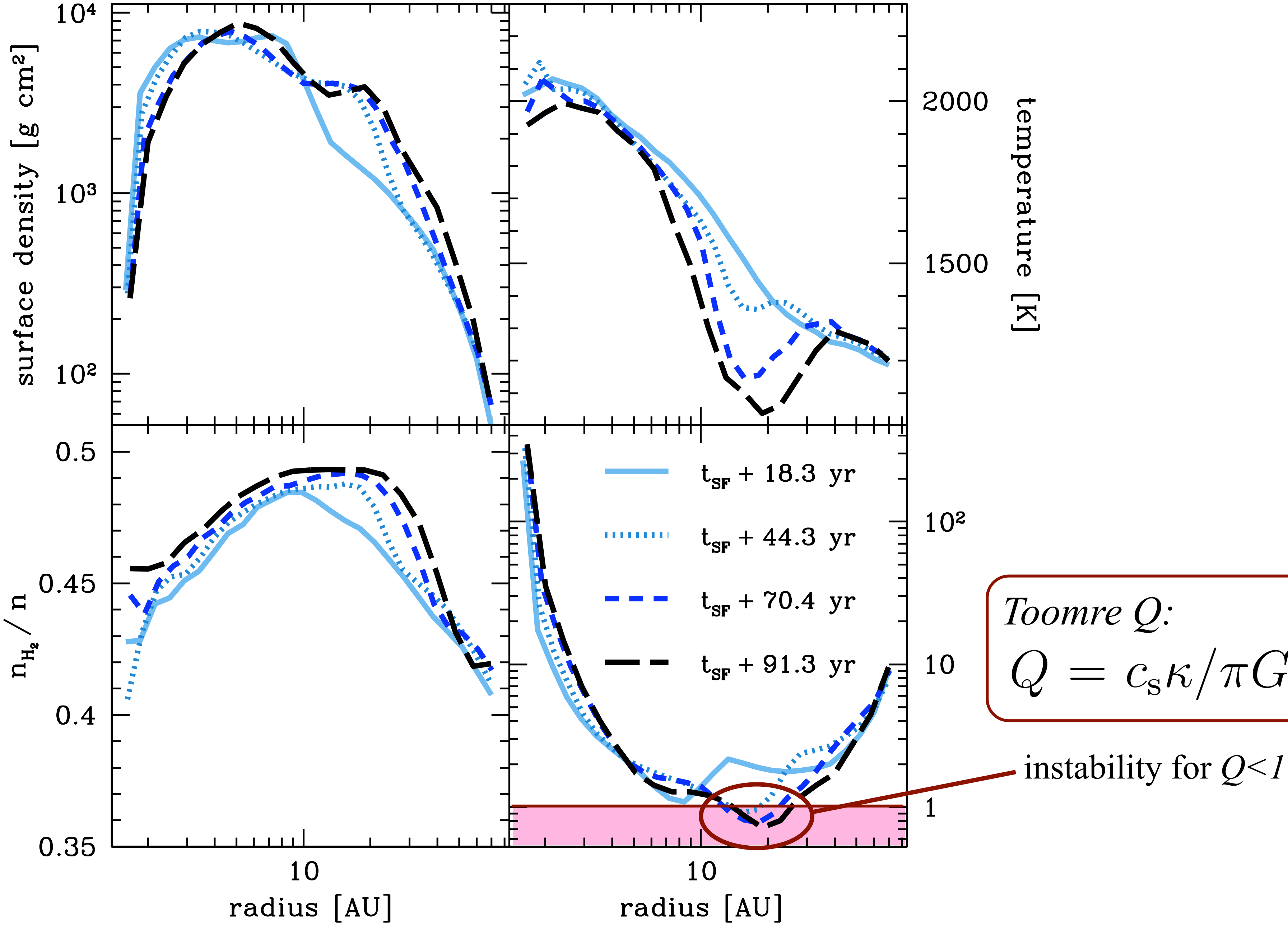


detailed look at accretion disk

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



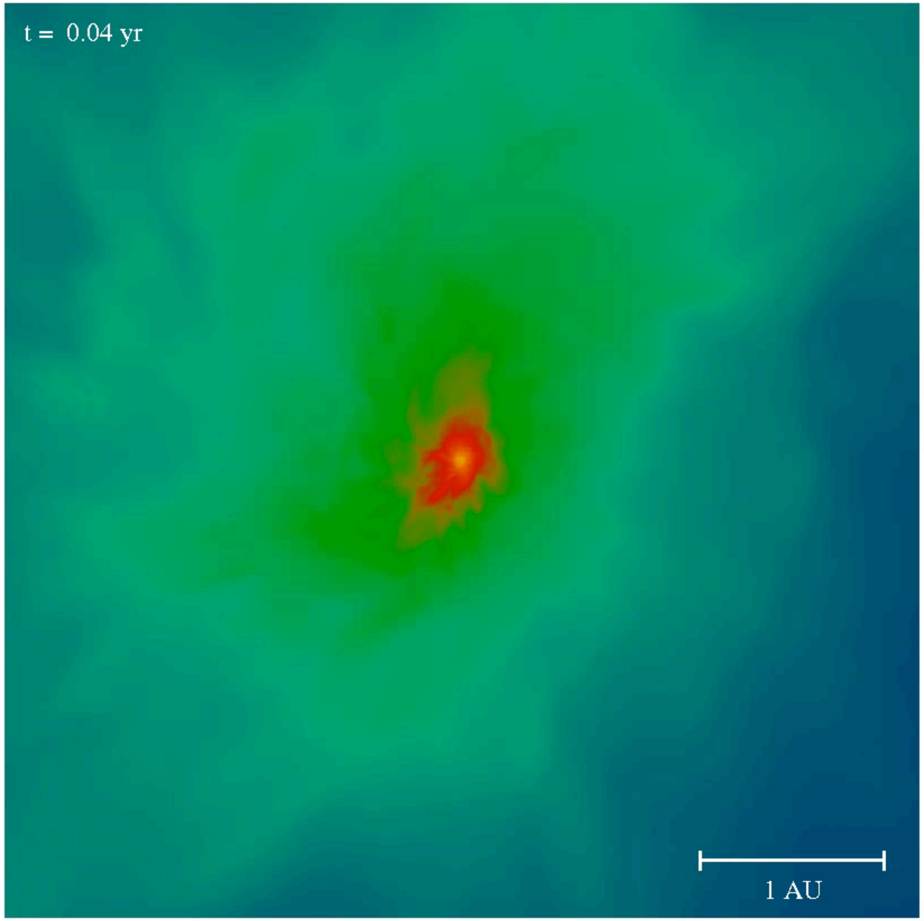
Toomre Q:

$$Q = c_{\mathrm{S}}\kappa/\pi G\Sigma$$

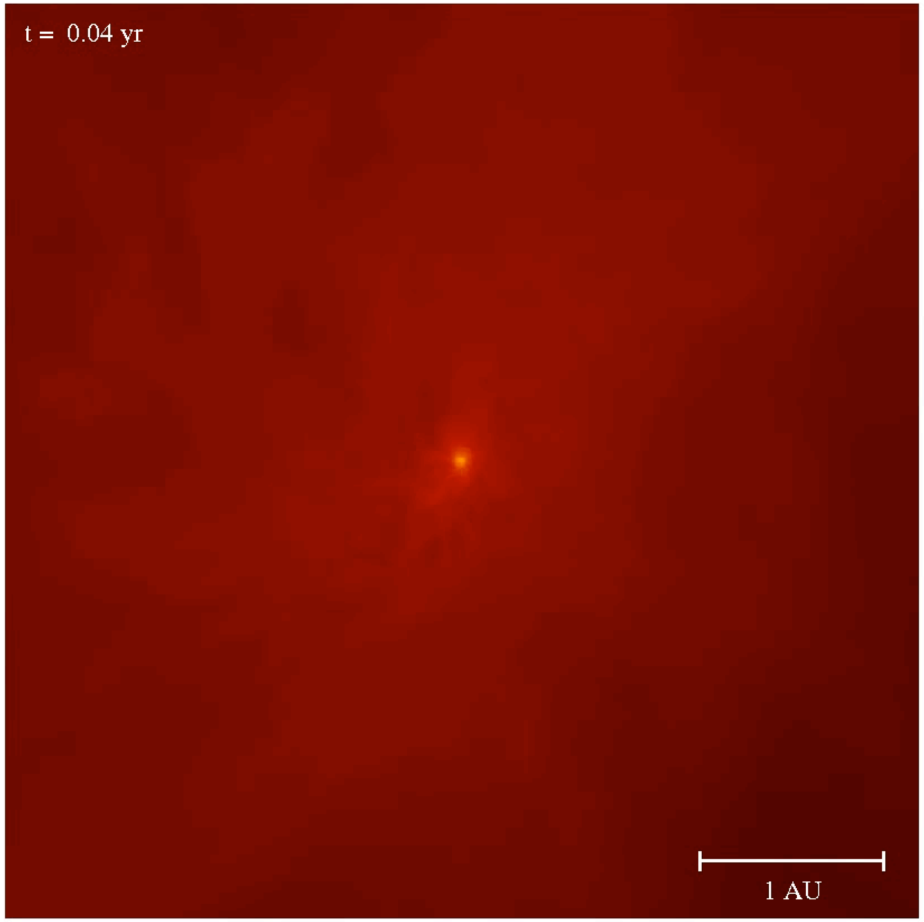
(Clark et al. 2011b, Science, 331, 1040)

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

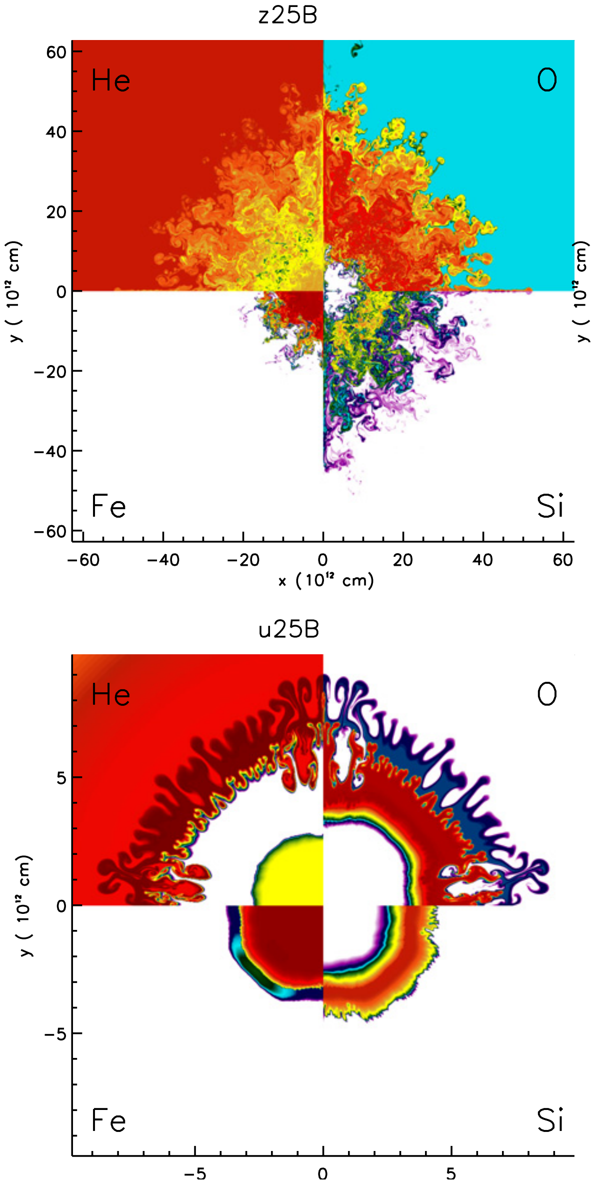


temperature

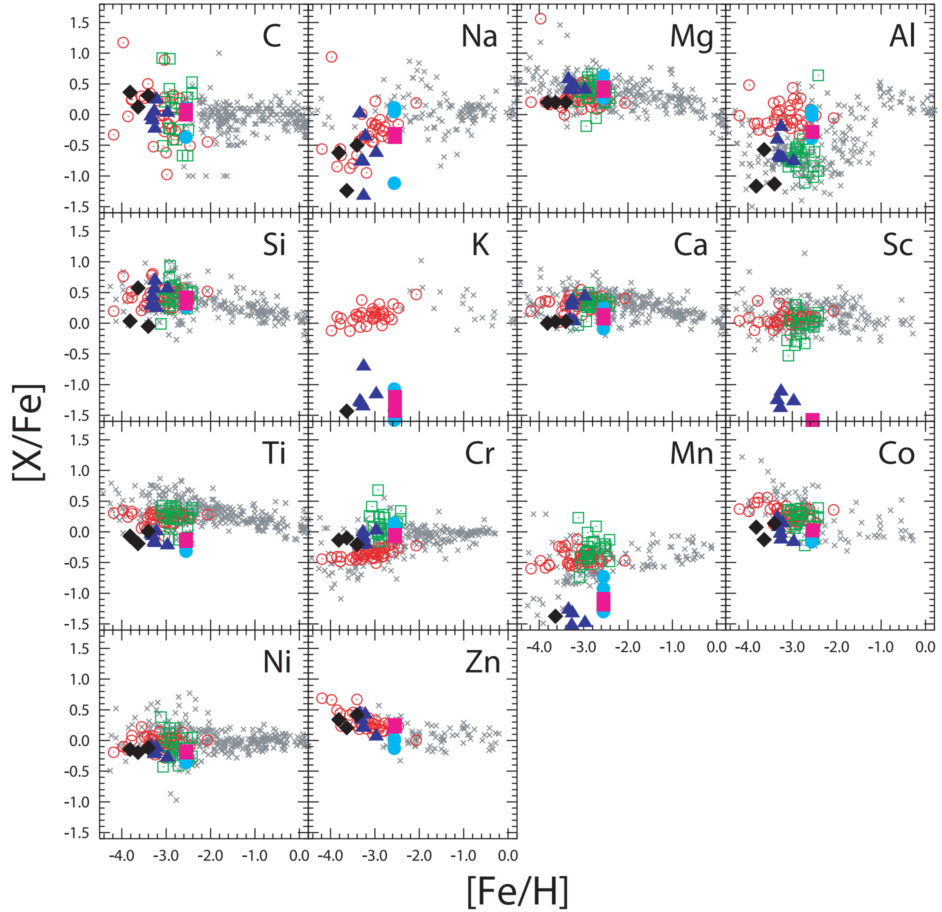
(Greif et al., submitted to MNRAS, MNRAS, 424, 399)

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)

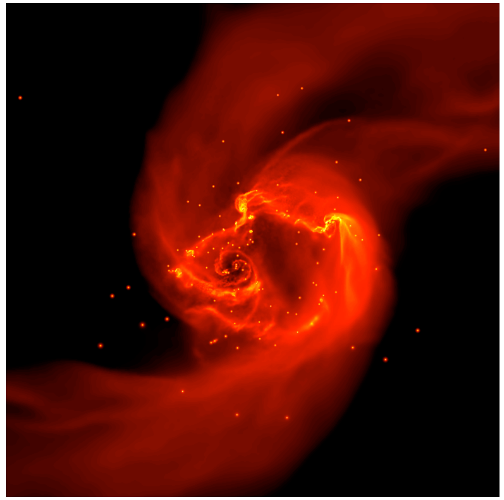


(Tominaga et al. 2007)

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)

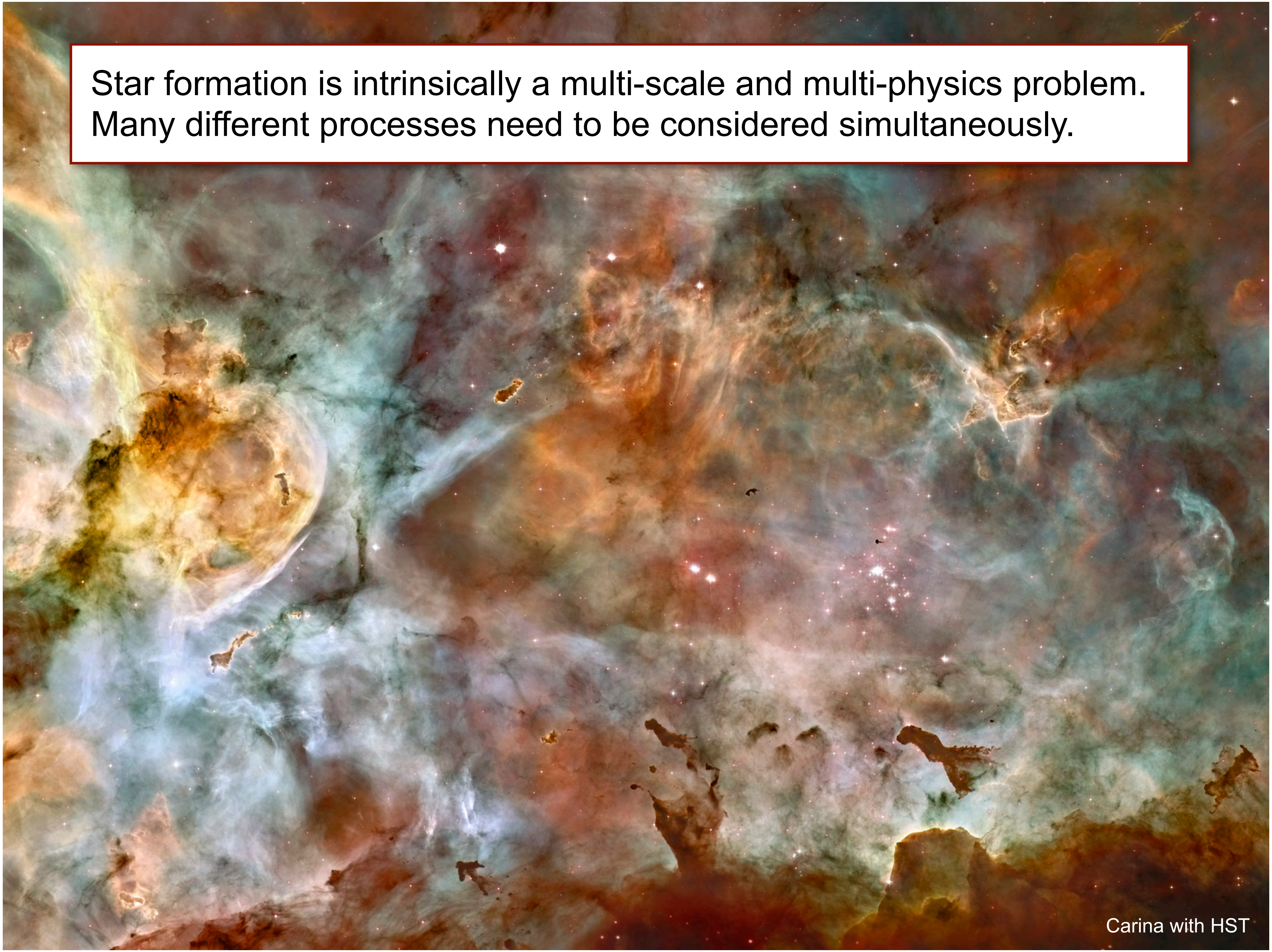
primordial star formation



- 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*?

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



Carina with HST

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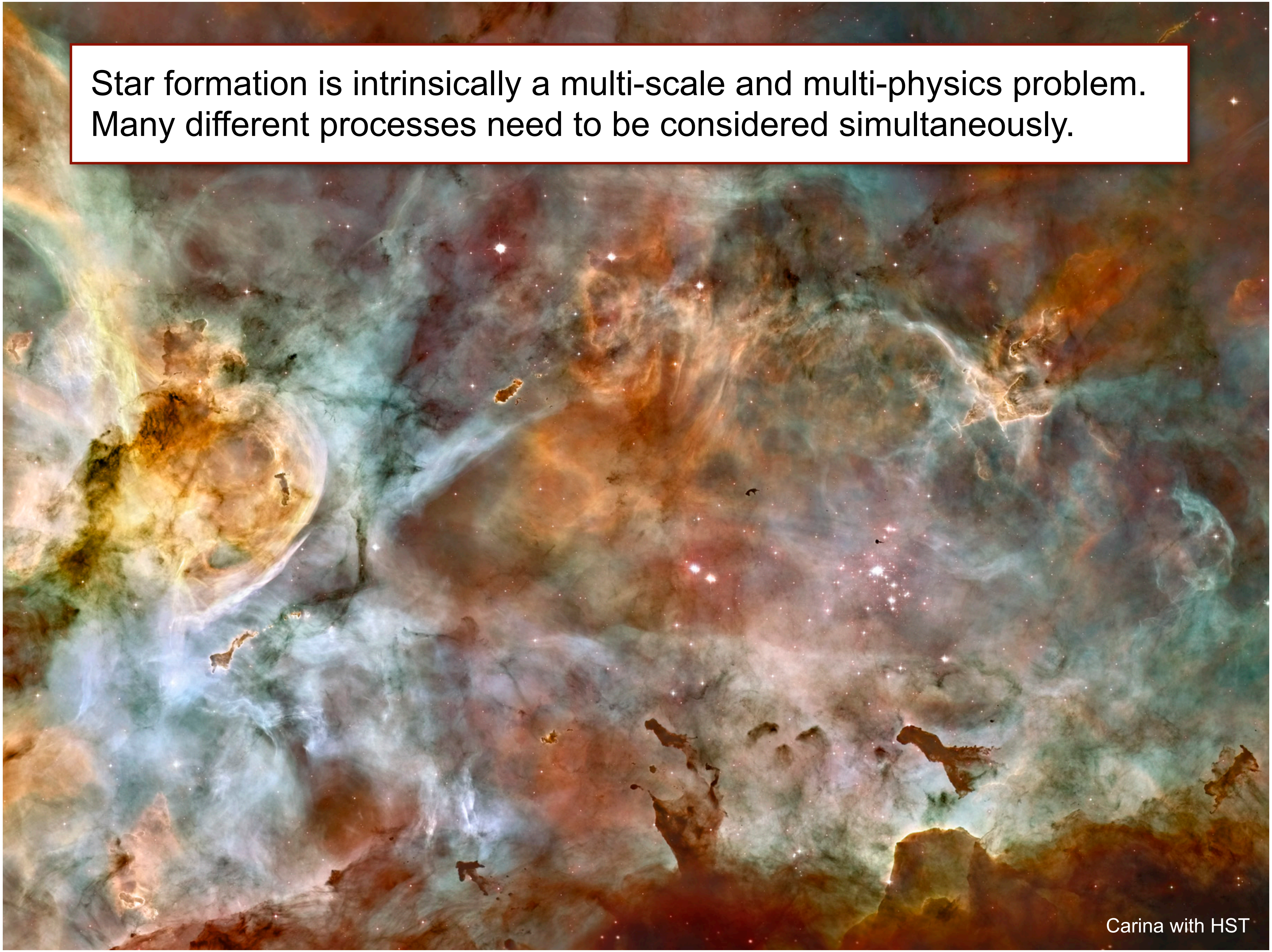

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Star formation is intrinsically a multi-scale and multi-physics problem, where it is difficult to single out individual processes.

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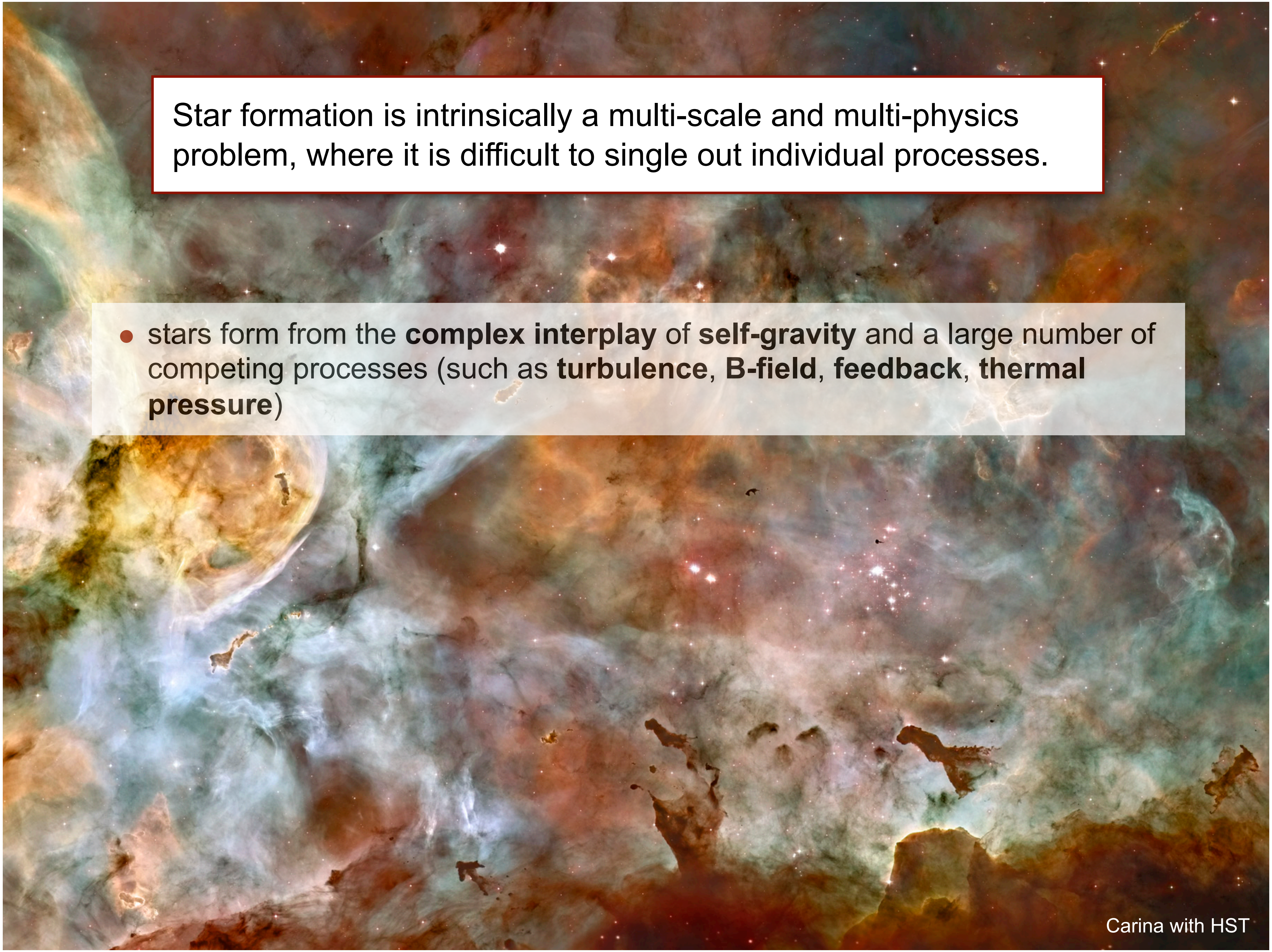

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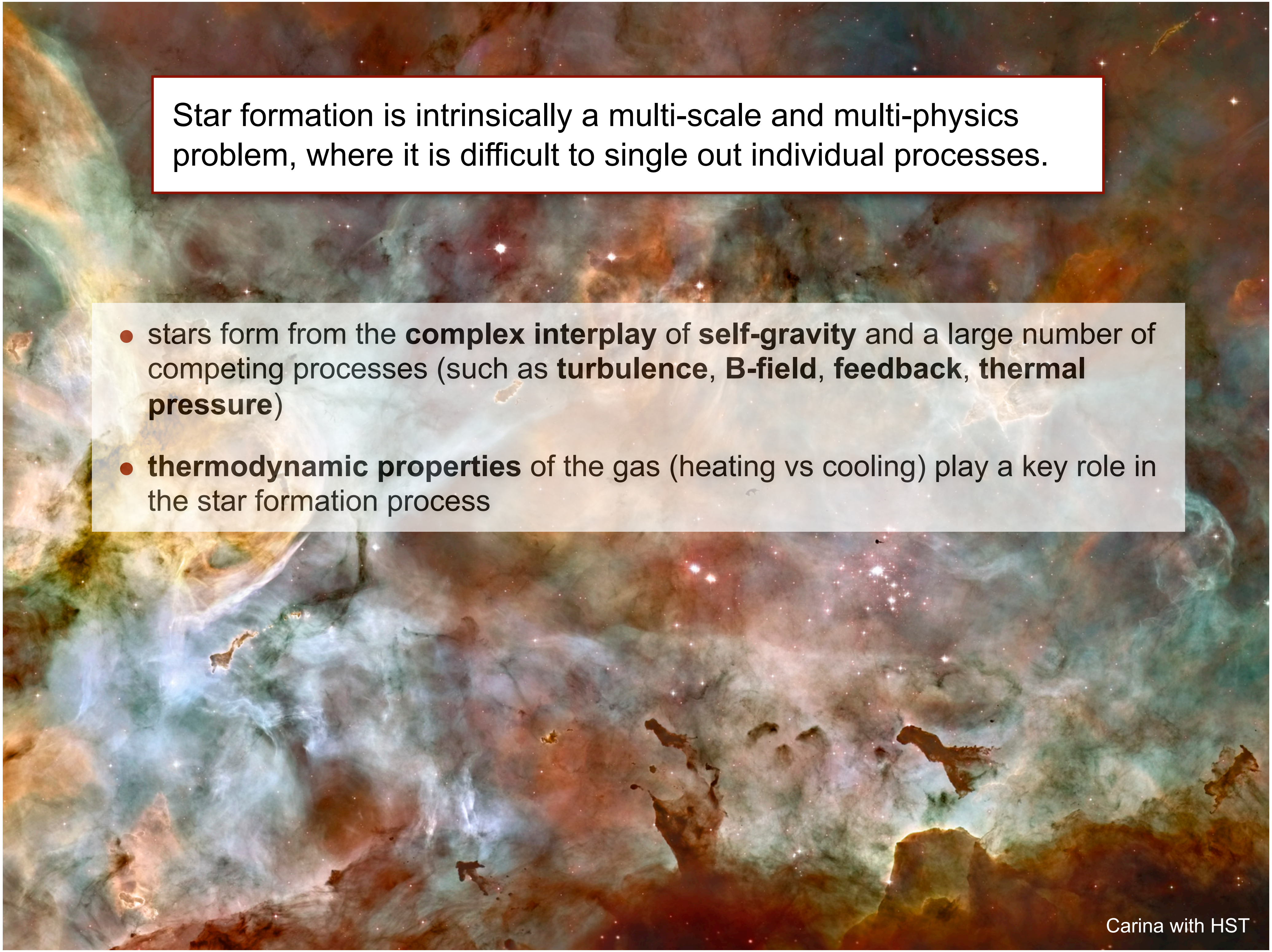

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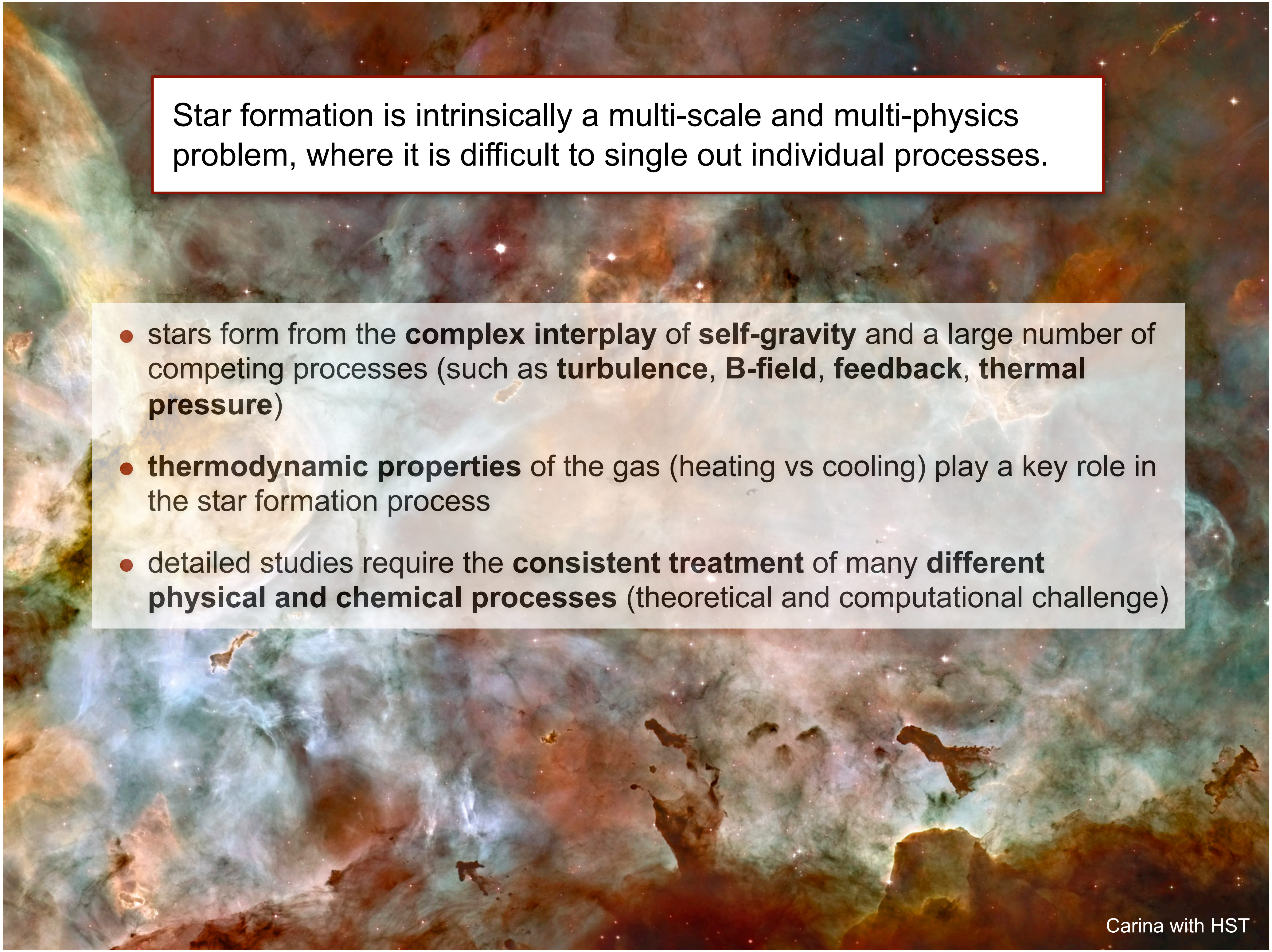
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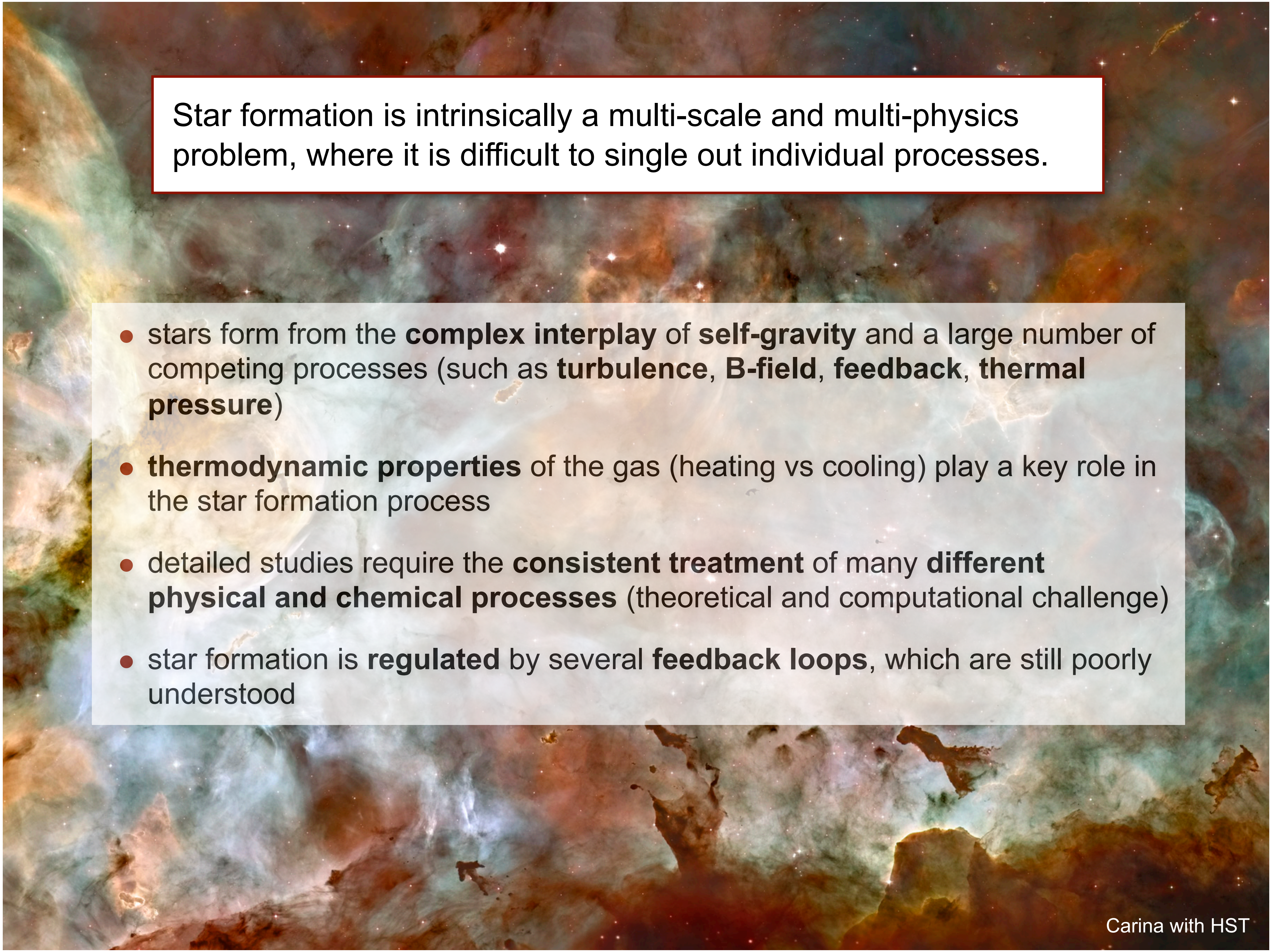

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- detailed studies require the **consistent treatment** of many **different physical and chemical processes** (theoretical and computational challenge)
- star formation is **regulated** by several **feedback loops**, which are still poorly understood
- **primordial star formation** shares the same **complexities** as present-day star formation

Carina with HST


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