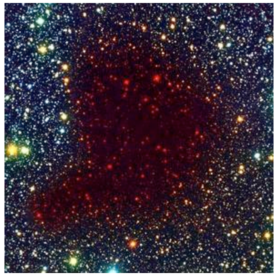
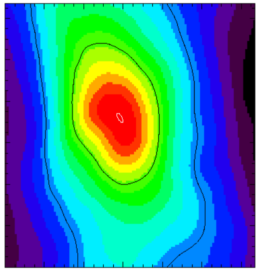
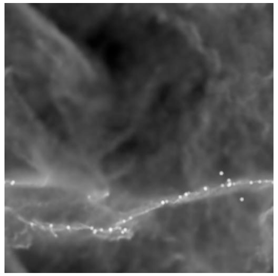
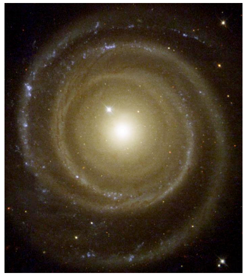
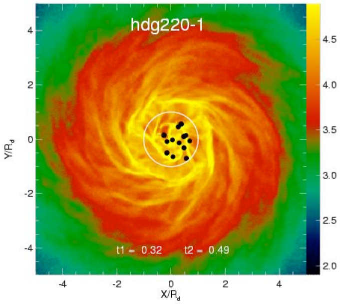
Star Formation











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Zentrum für Astronomie der Universität Heidelberg
Institut für Theoretische Astrophysik

thanks to ...

... people in the group in Heidelberg:

Robi Banerjee, Simon Glover, Rahul Shetty, Sharanya Sur, Daniel Seifried, Milica Milosavljevic, Florian Mandl, Christian Baczynski, Rowan Smith, Gustavo Dopcke, Jonathan Downing, Jayanta Dutta, Faviola Molina, Christoph Federrath, Erik Bertram, Lukas Konstandin, Paul Clark, Stefan Schmeja, Ingo Berentzen, Thomas Peters, Hsiang-Hsu Wang

... many collaborators abroad!

Deutsche Forschungsgemeinschaft DFG

Emmy Noether-Programm DFG

ASTRONET

LANDESSTIFTUNG Baden-Württemberg

HGSFP

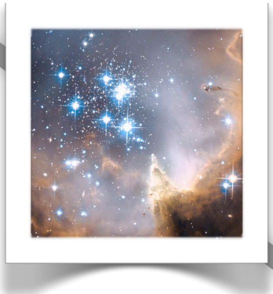
IMPRS

agenda

- a simple cartoon picture of dynamic star formation theory
- some applications, open issues, and questions

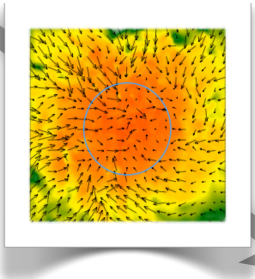
agenda

Accretion onto disk galaxies



High-mass star formation

First star formation



Magnetic fields in the primordial universe

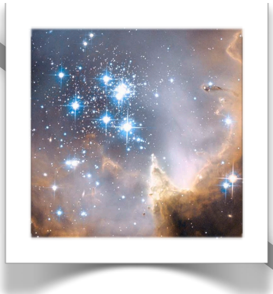
agenda

decreasing spatial scales

present days

early universe

Accretion onto disk galaxies



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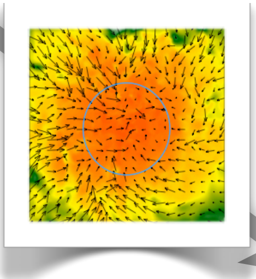
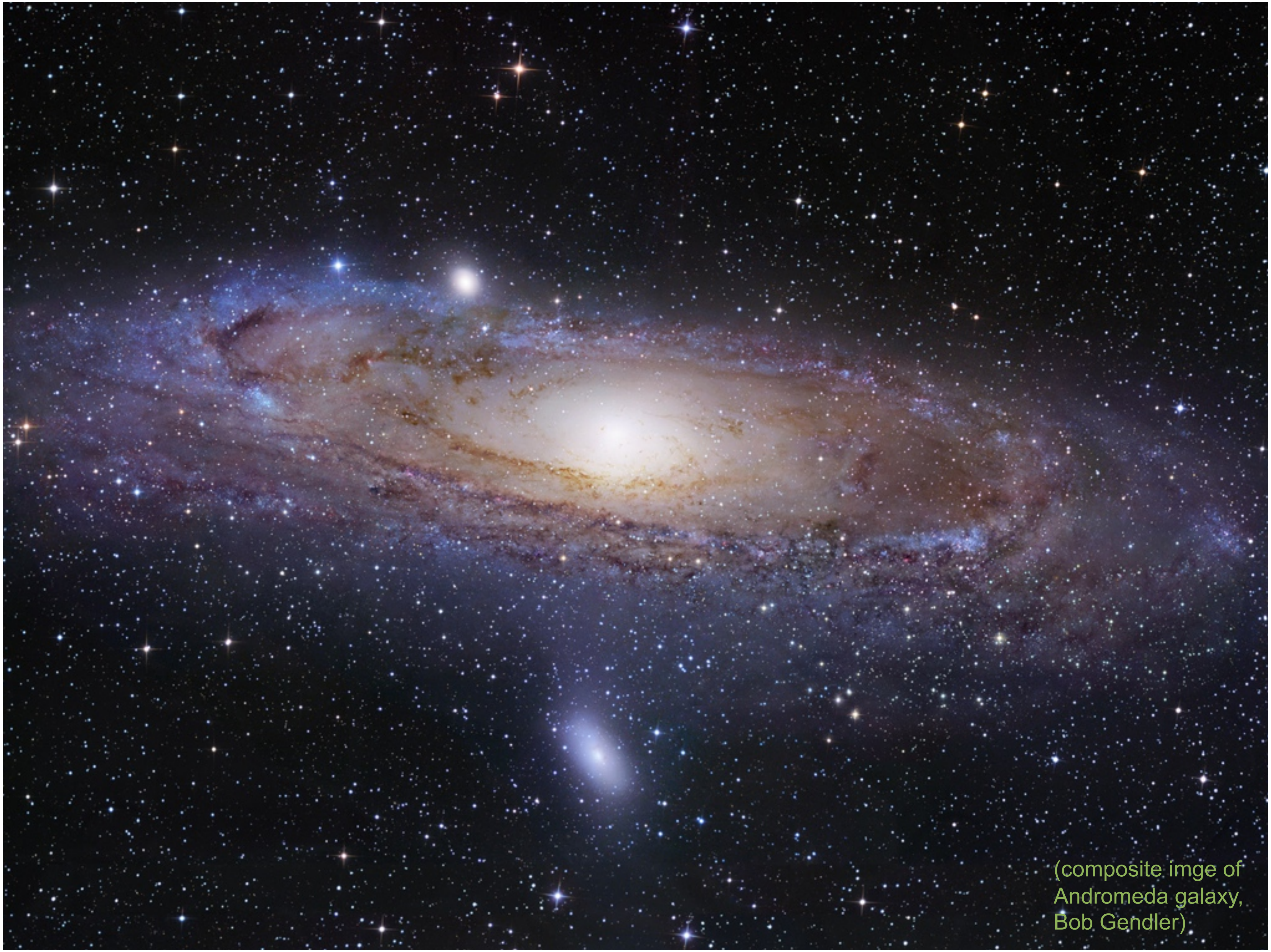


Magnetic fields in the primordial universe

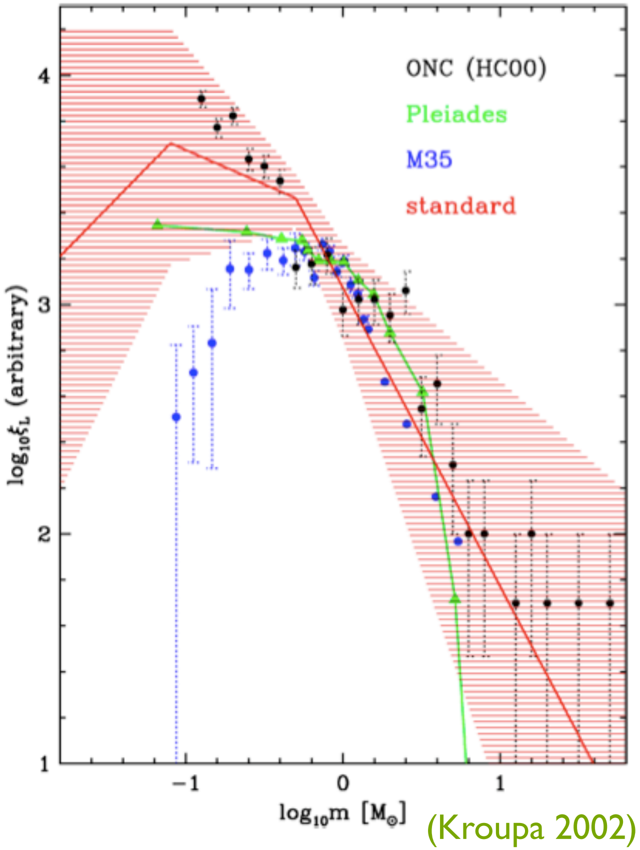


(composite imge of Andromeda galaxy, Bob Gendler)

NGC 602 in the LMC: Hubble Heritage Image

stellar mass fuction

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



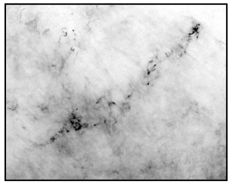
(Kroupa 2002)

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

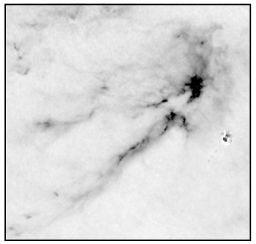
nearby molecular clouds

scales to same scale

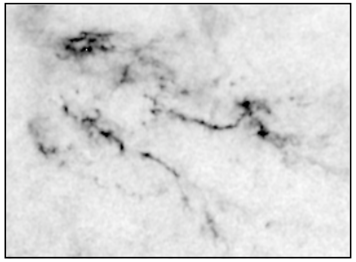
Pipe



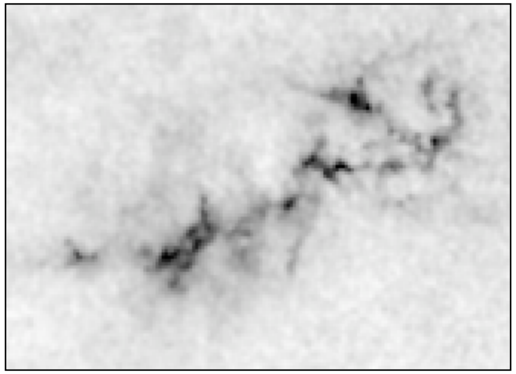
Ophiuchus

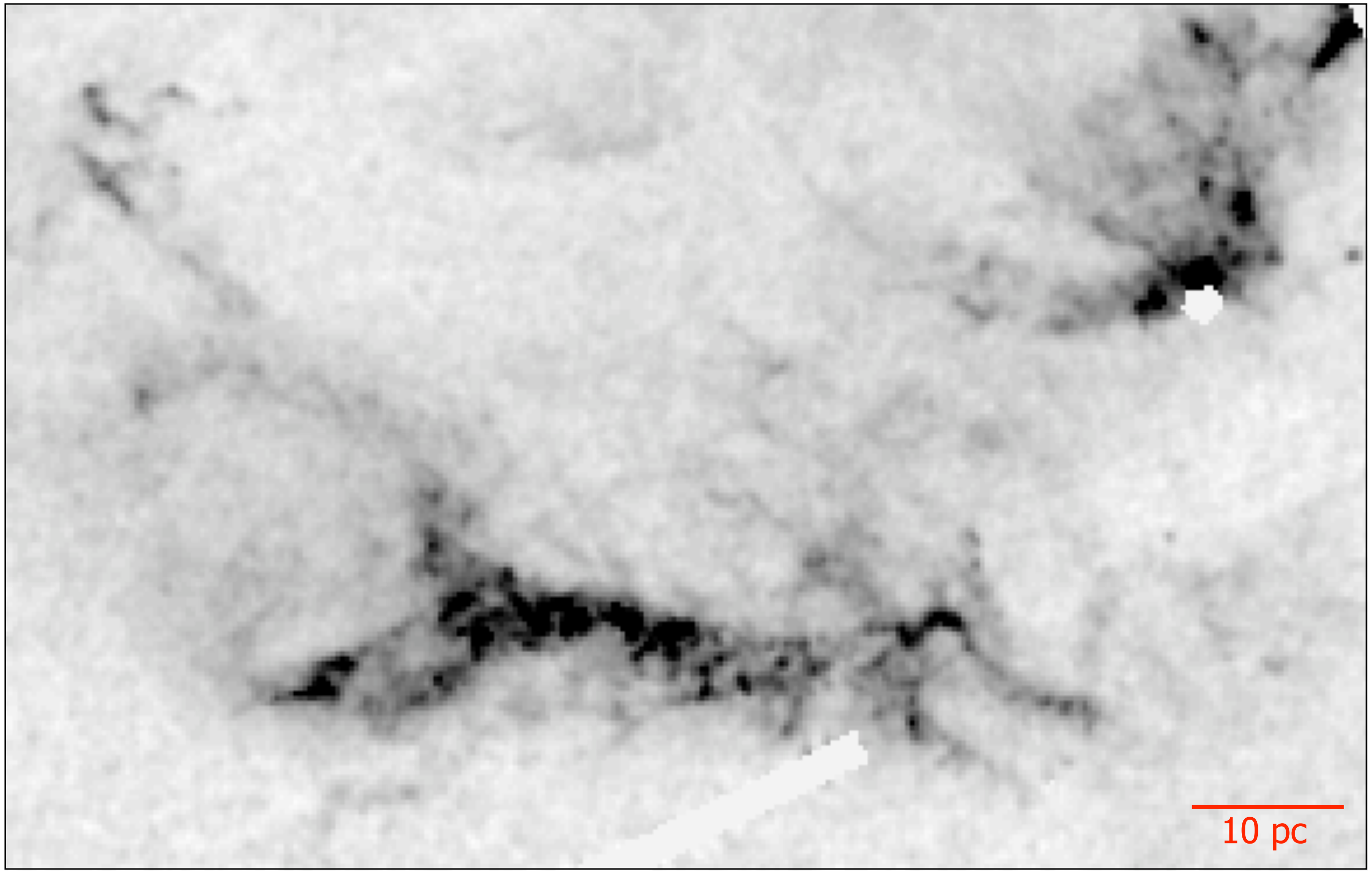


Taurus



Perseus

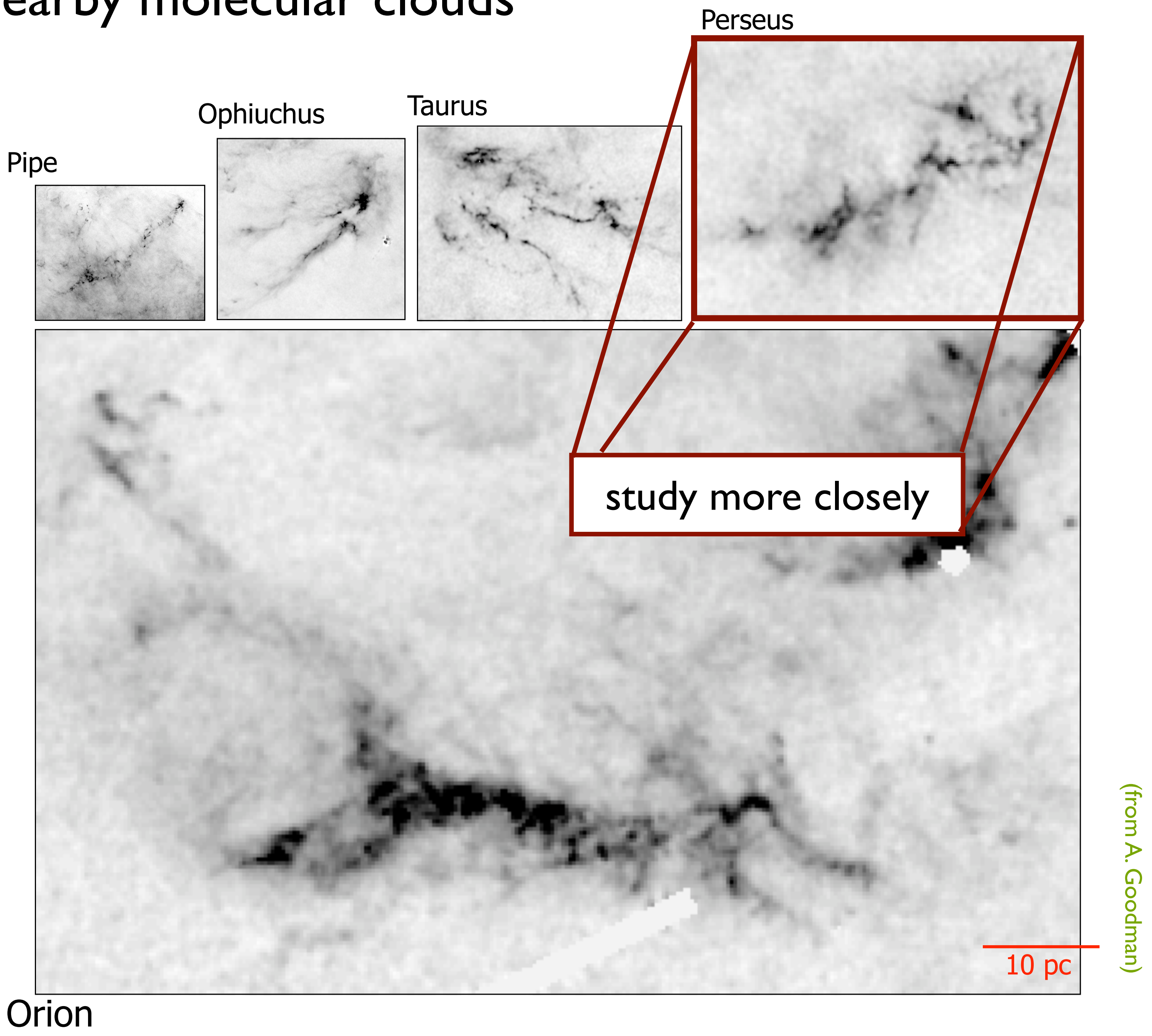




Orion

(from A. Goodman)

nearby molecular clouds



study more closely

scales to same scale

(from A. Goodman)

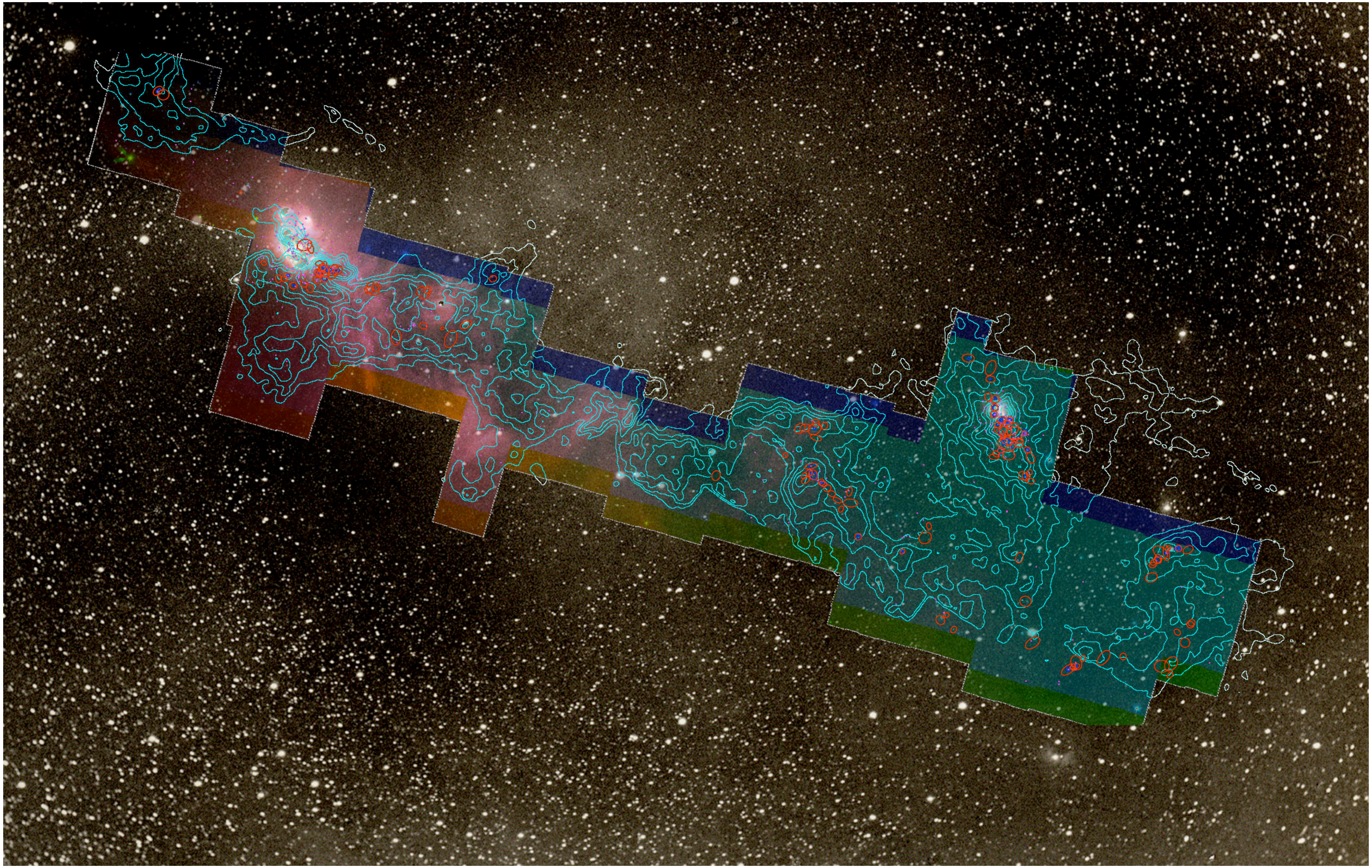
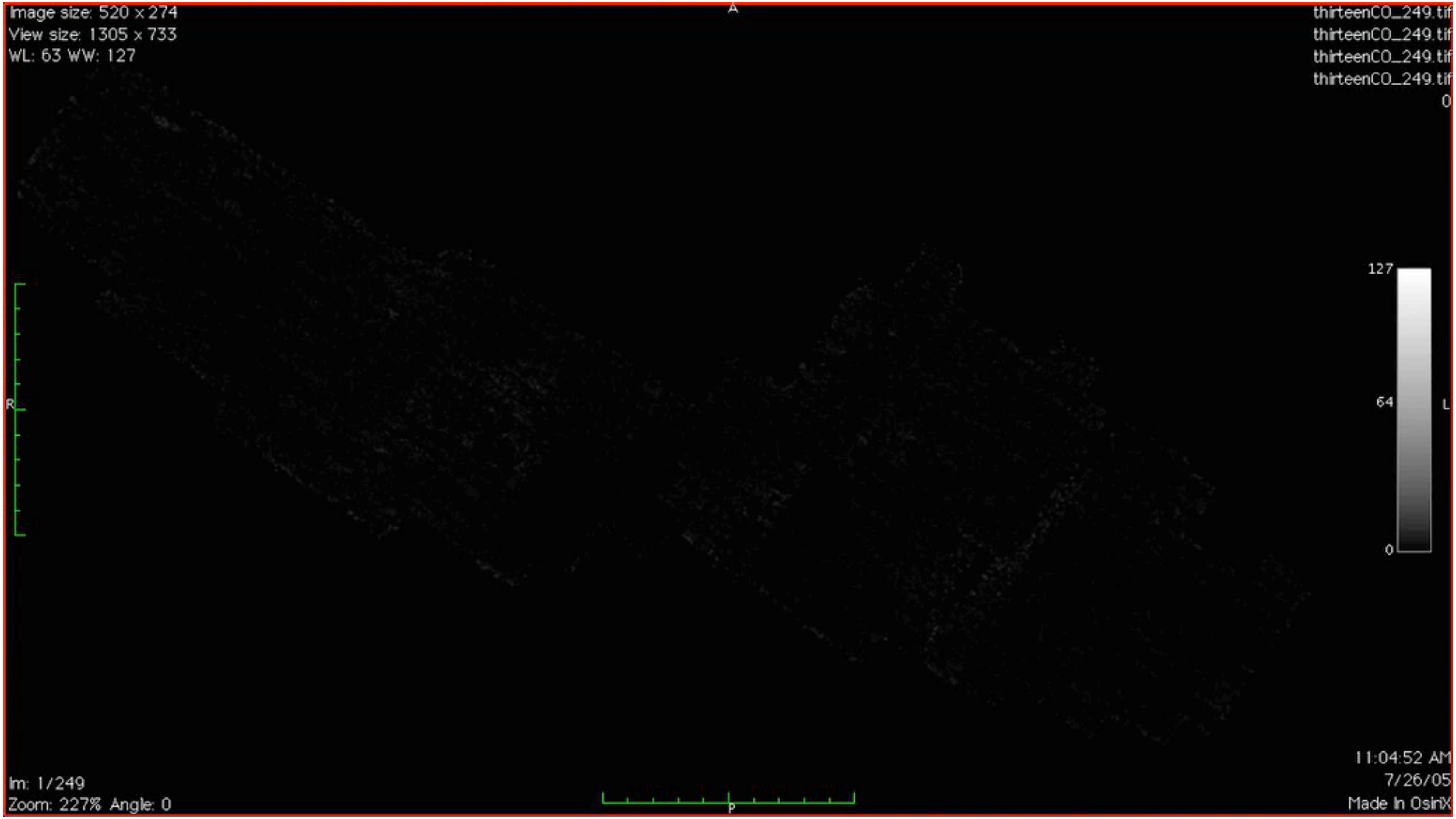
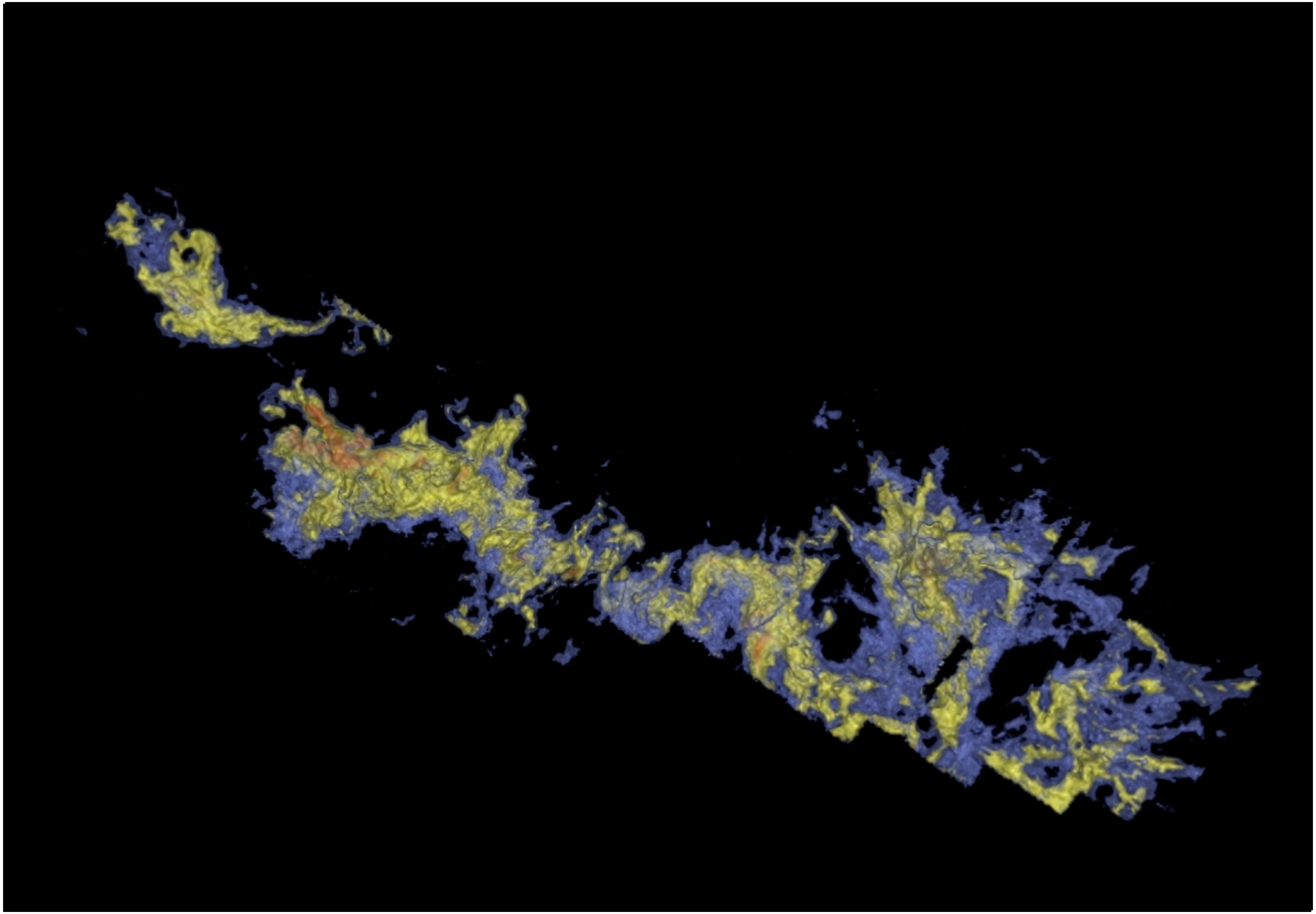


image from Alyssa Goodman: COMPLETE survey



velocity distribution in Perseus

velocity cube from Alyssa Goodman: COMPLETE survey



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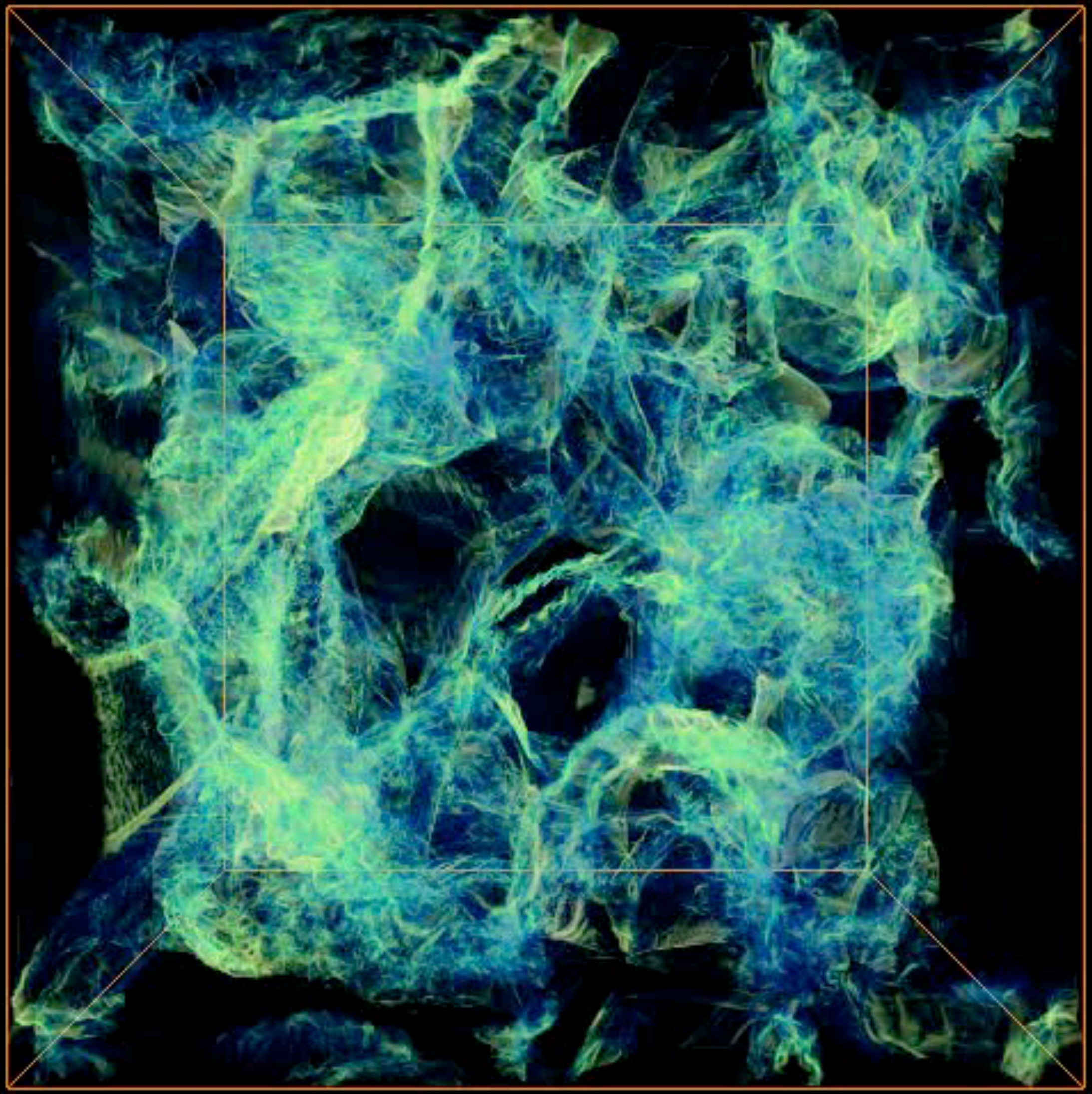
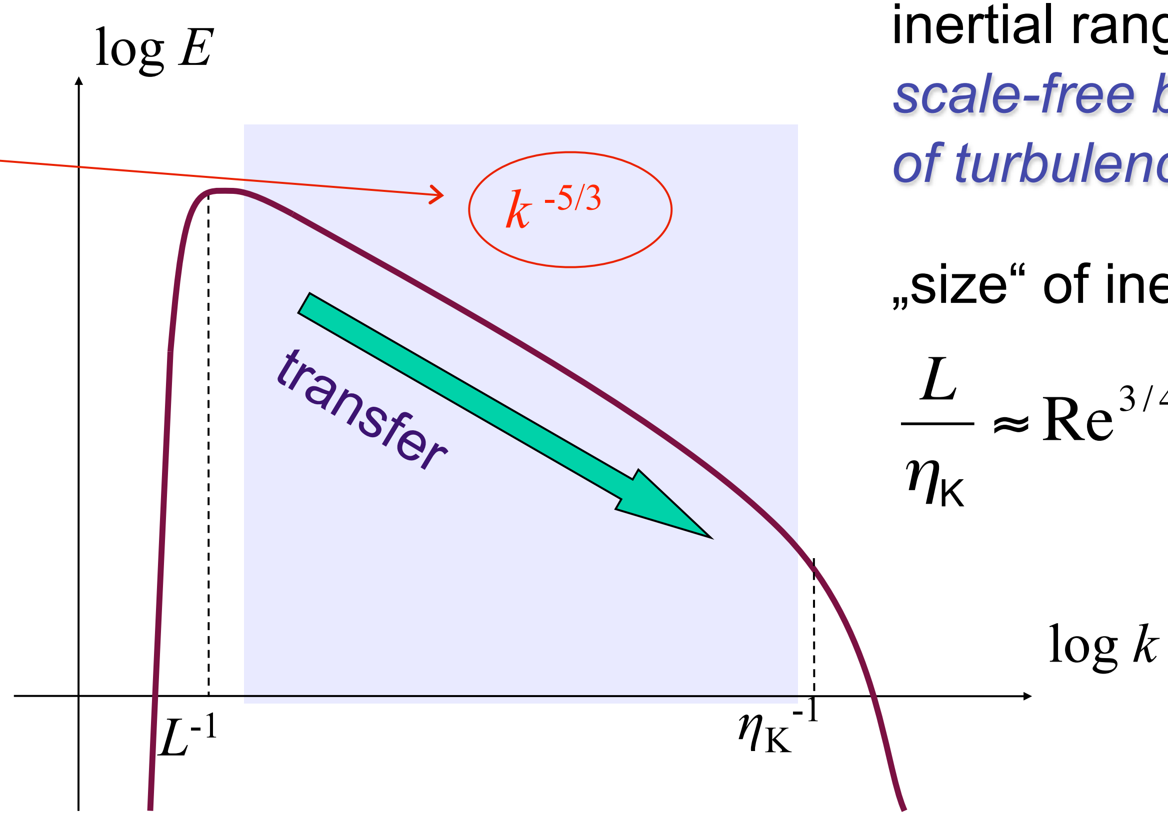


(movie from Christoph Federrath)

Turbulent cascade

Kolmogorov (1941) theory
incompressible turbulence



inertial range:
scale-free behavior of turbulence

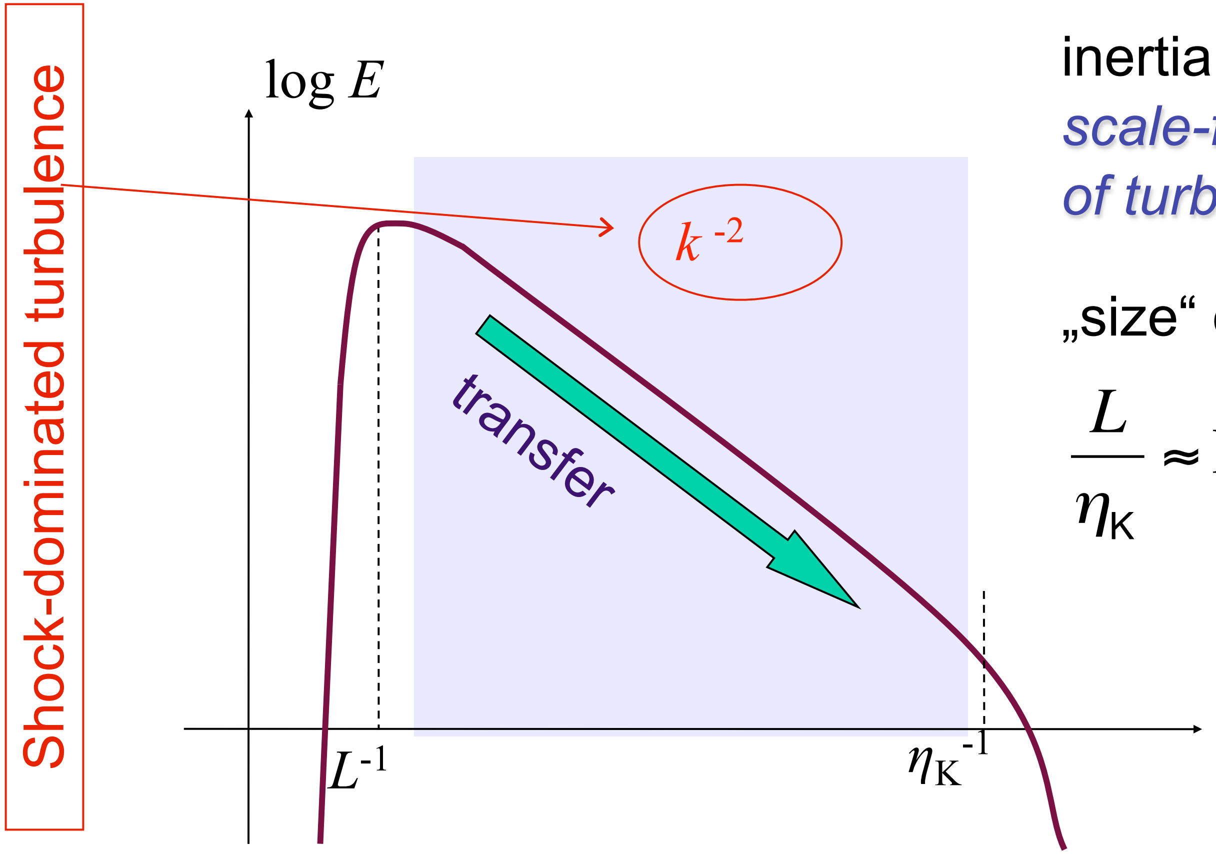
„size“ of inertial range:

$$\frac{L}{\eta_K} \approx \mathrm{Re}^{3/4}$$

energy
input
scale

energy
dissipation
scale

Turbulent cascade



inertial range:
scale-free behavior
of turbulence

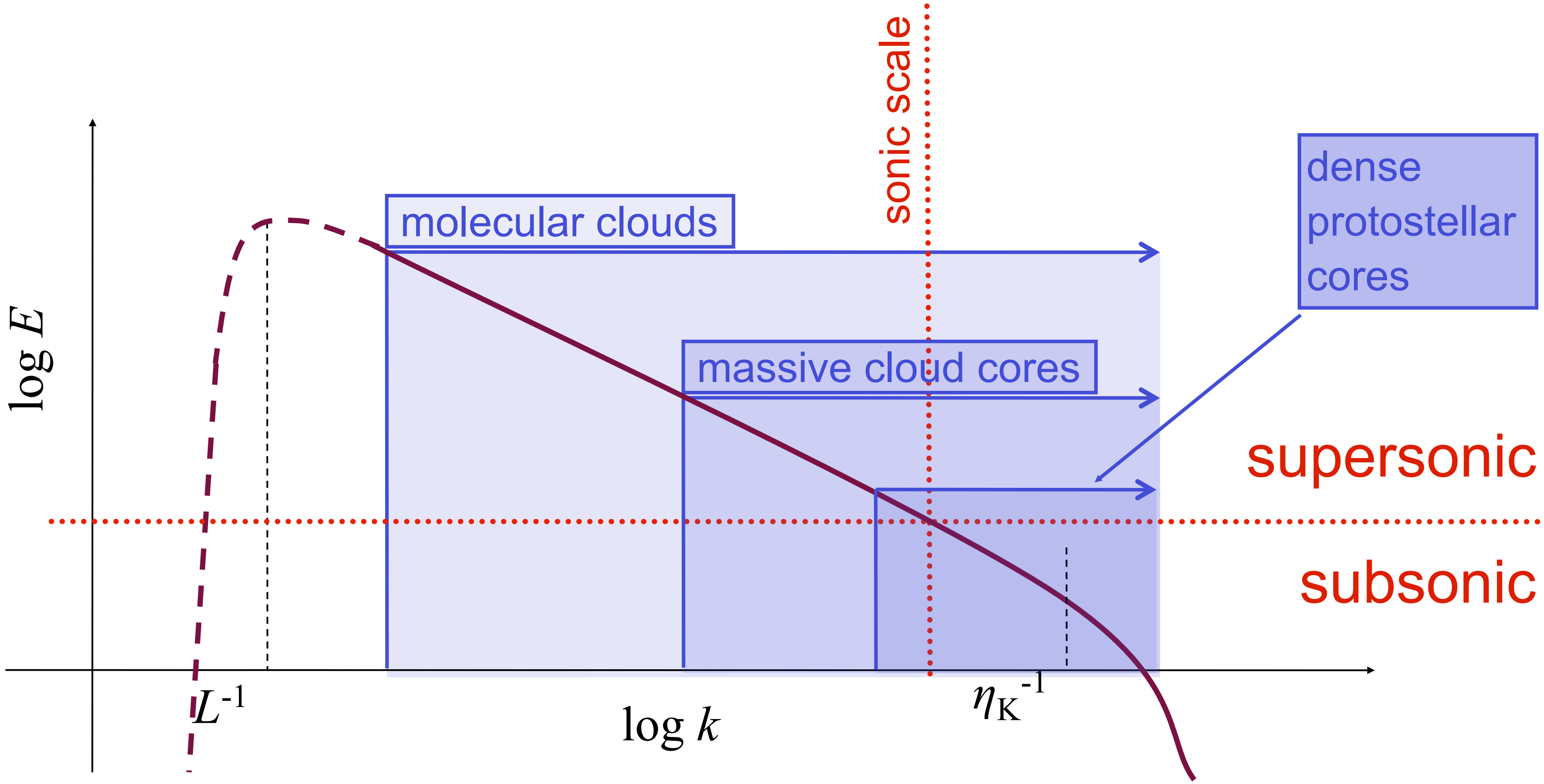
„size“ of inertial range:

$$\frac{L}{\eta_K} \approx \mathrm{Re}^{3/4}$$

energy
input
scale

energy
dissipation
scale

Turbulent cascade in ISM

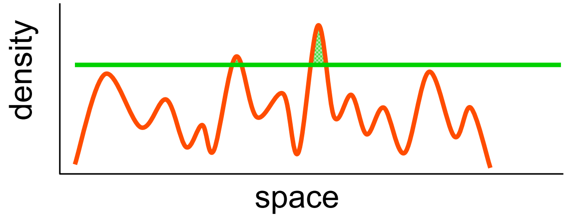


energy source & scale
NOT known
(supernovae, winds,
spiral density waves?)

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

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

dynamical SF in a nutshell



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

→ ***GRAVOTUBULENT FRAGMENTATION***

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

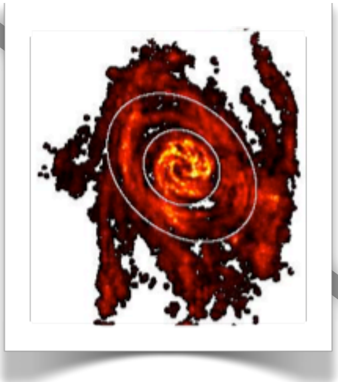
(e.g. Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194)

agenda

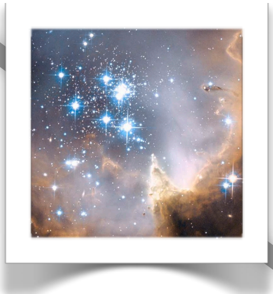
decreasing spatial scales

present days

early universe

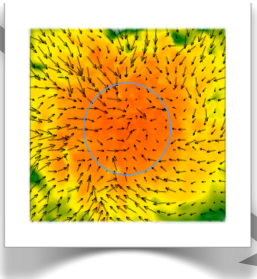


Accretion onto disk galaxies



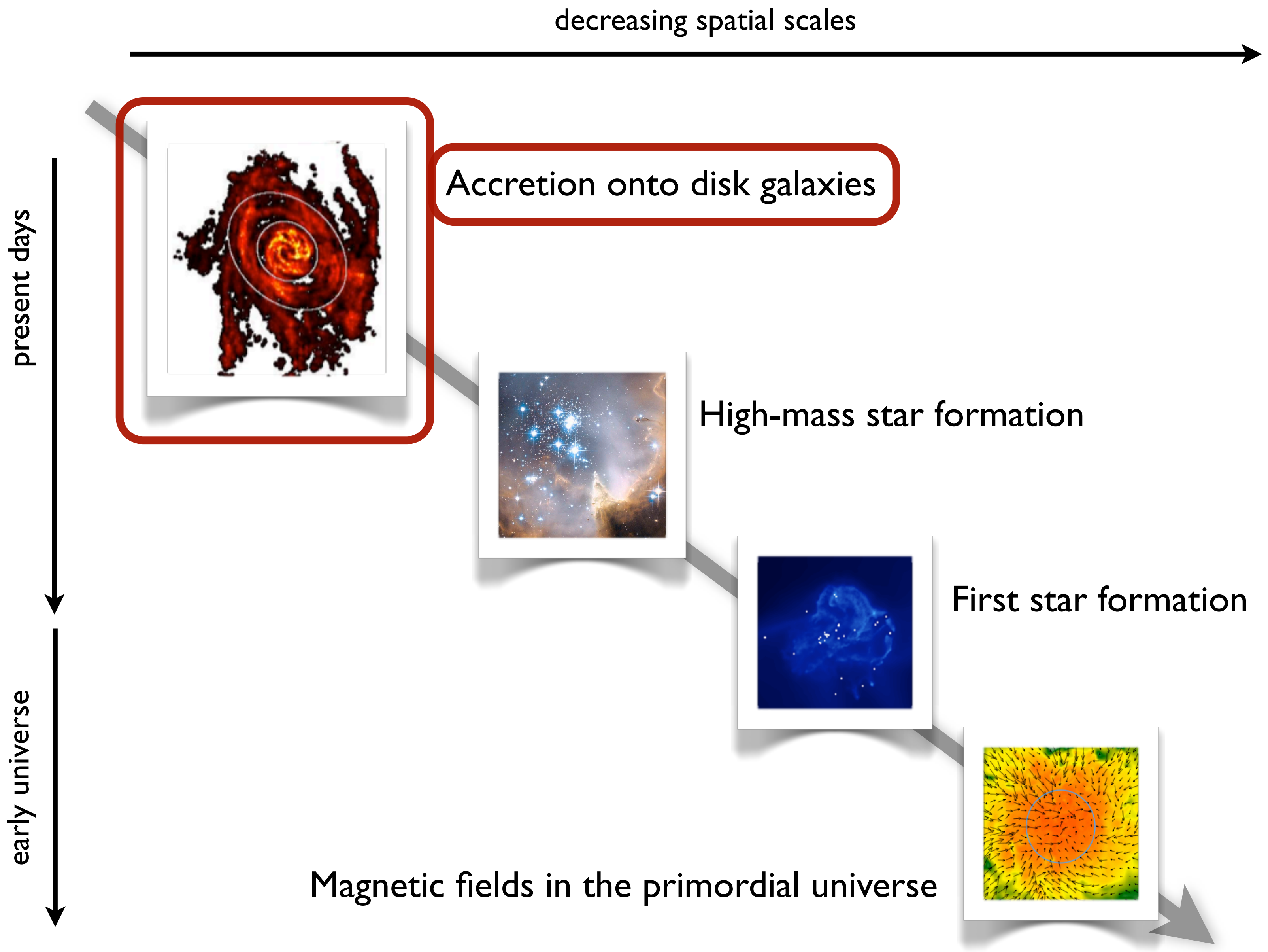
High-mass star formation

First star formation



Magnetic fields in the primordial universe

agenda



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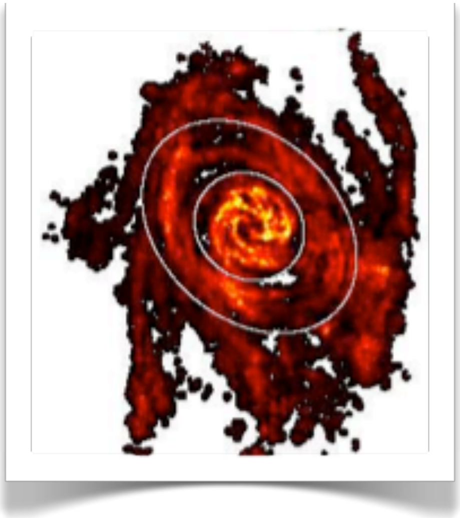
Magnetic fields in the primordial universe

what drives ISM turbulence?

- seems to be driven on large scales, and there is little difference between star-forming and non-SF clouds
    - *rules out internal sources*



- proposals in the literature
    - *supernovae*
    - *spiral density waves*
    - *magneto-rotational instability*
    - *expanding HII regions / stellar winds / outflows*
    - *new idea: accretion onto disk*

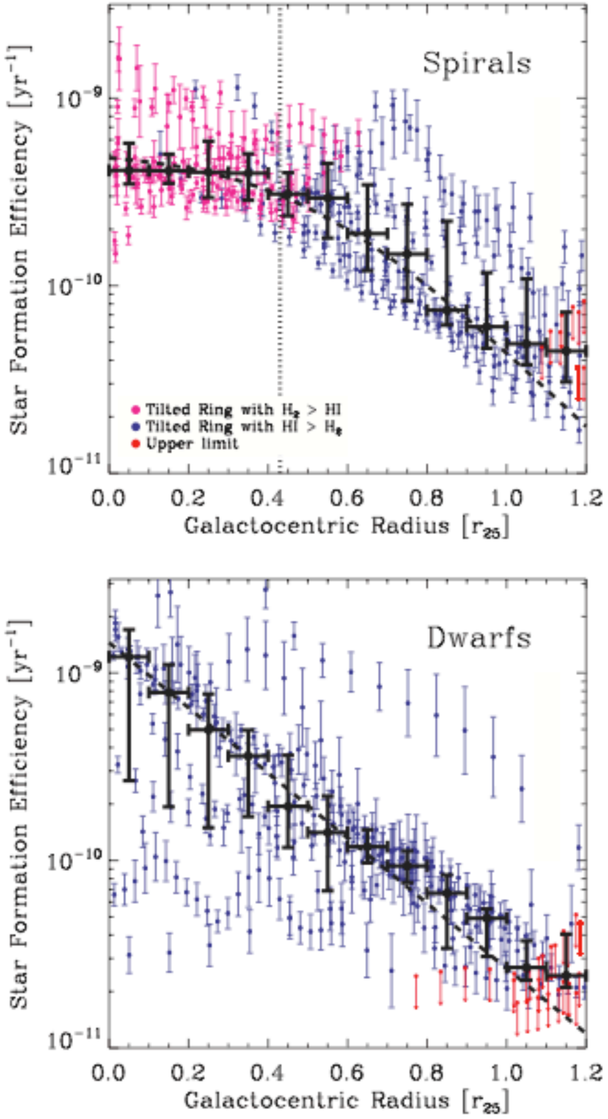
accretion driven turbulence

- idea:
  - astrophysical objects *form* by *accretion* of ambient material
  - the *kinetic energy* associated with this process is a key agent *driving internal turbulence*.
  - this works on *ALL* scales:
    - galaxies
    - molecular clouds
    - protostellar accretion disks

Klessen & Hennebelle (2010, A&A, 520, A17)

gas depletion times

- additional thoughts
  - typical gas depletion times in large spirals are of order of 10^9 yr
  - gas needs to be replenished from somewhere: *accretion of external gas?*
  - note, there is an alternative: *stellar mass loss*



Leroy et al. (2008, AJ, 136, 2782)

concept

turbulence decays on a crossing time $$\tau_\mathrm{d} \approx \frac{L_\mathrm{d}}{\sigma}$$

energy decay rate $$\dot{E}_\mathrm{decay} \approx \frac{E}{\tau_\mathrm{d}} = -\frac{1}{2}\frac{M\sigma^3}{L_\mathrm{d}}$$

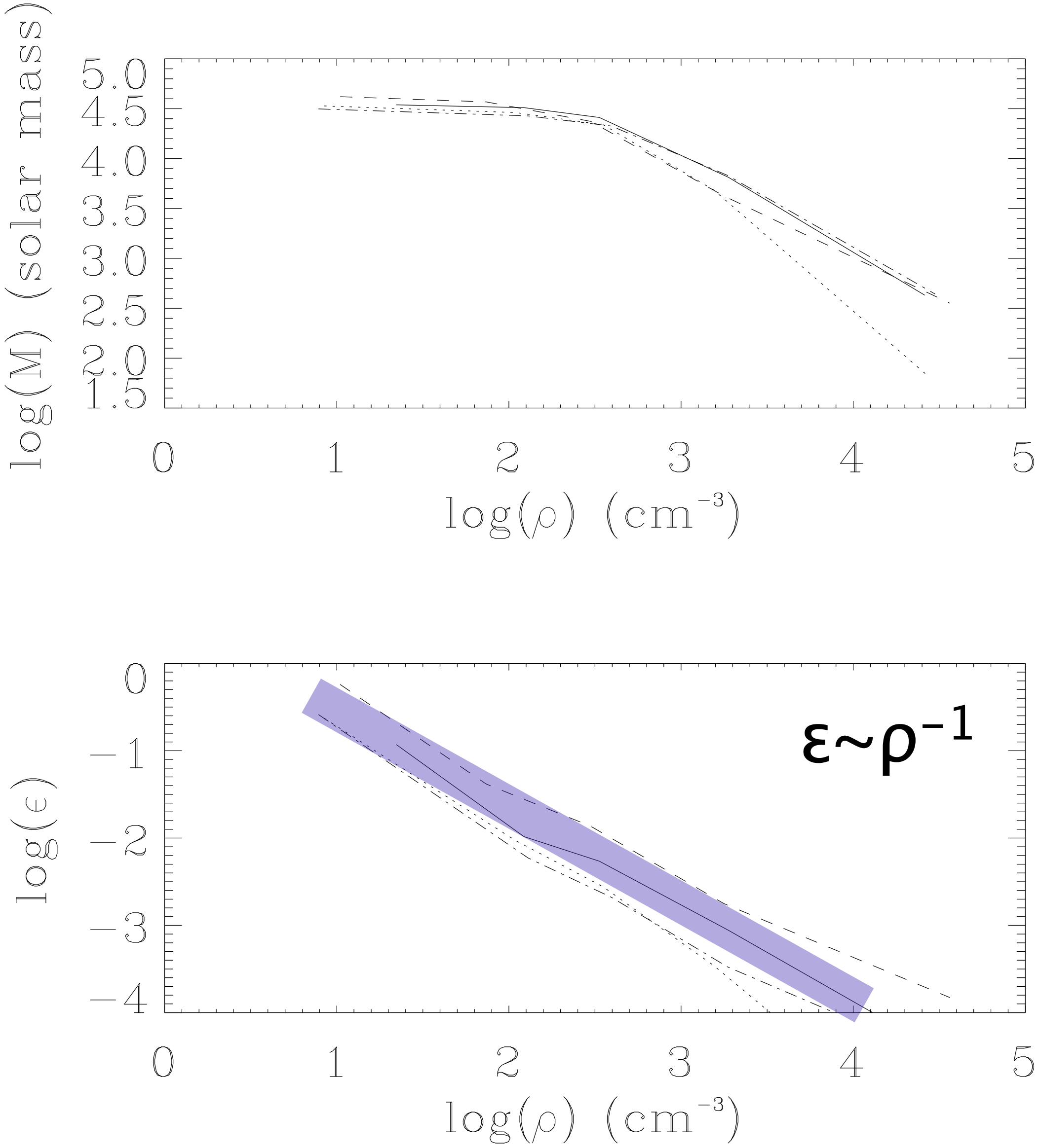
kinetic energy of infalling material $$\dot{E}_\mathrm{in} = \frac{1}{2}\dot{M}_\mathrm{in}v_\mathrm{in}^2$$

can both values match, modulo some efficiency?

$$\epsilon = \left|\frac{\dot{E}_\mathrm{decay}}{\dot{E}_\mathrm{in}}\right|$$

Klessen & Hennebelle (2010, A&A, 520, A17)

some estimates from convergent flow studies



$\epsilon \sim \rho^{-1}$

Klessen & Hennebelle (2010, A&A, 520, A17)

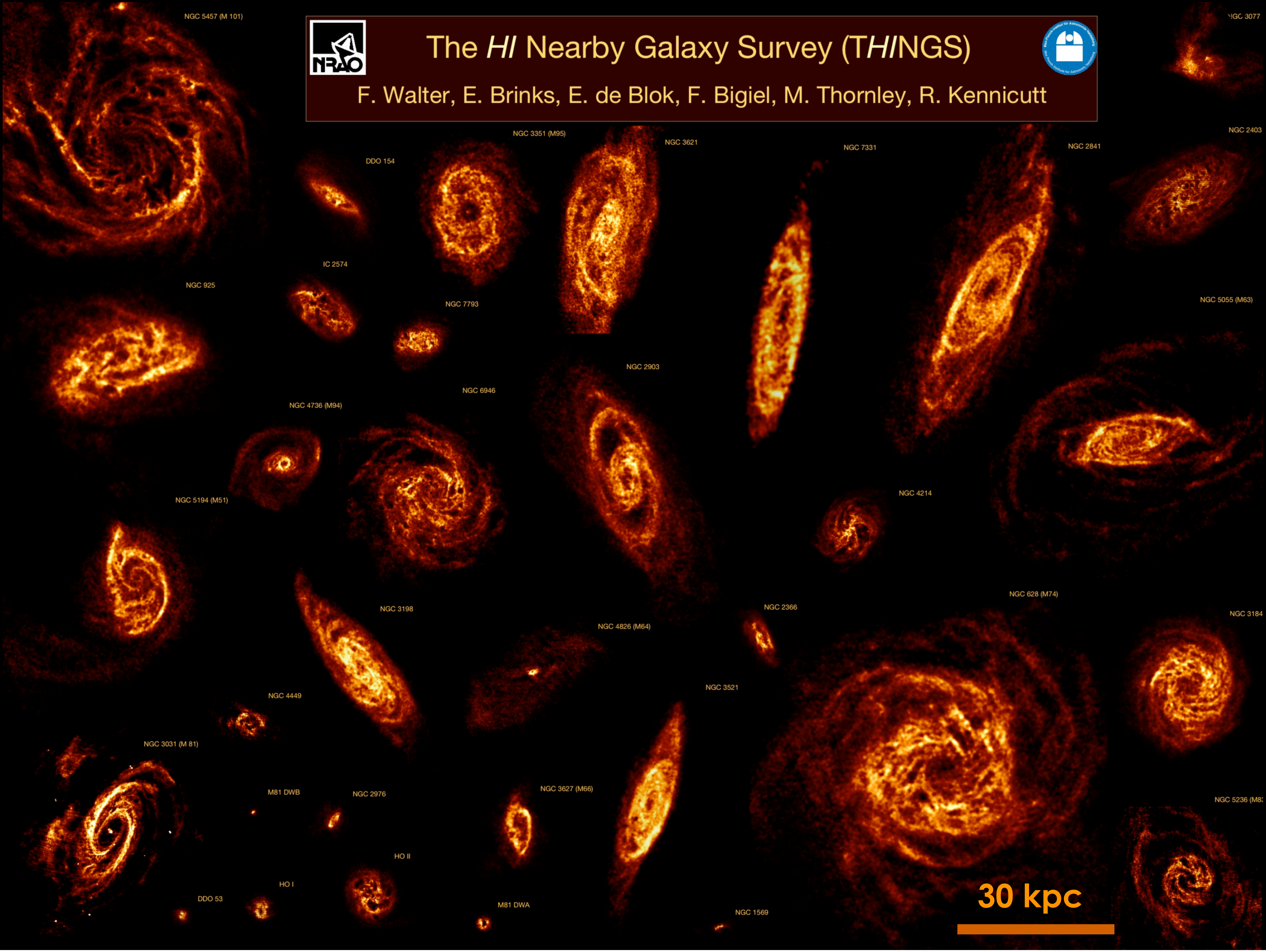
application to galaxies

- underlying assumption
  - galaxy is in steady state
    ---> accretion rate equals star formation rate
  - we ask: what is the required efficiency for the method to work?
- study Milky Way and 11 THINGS
  - excellent observational data in HI:
    velocity dispersion, column density, rotation curve

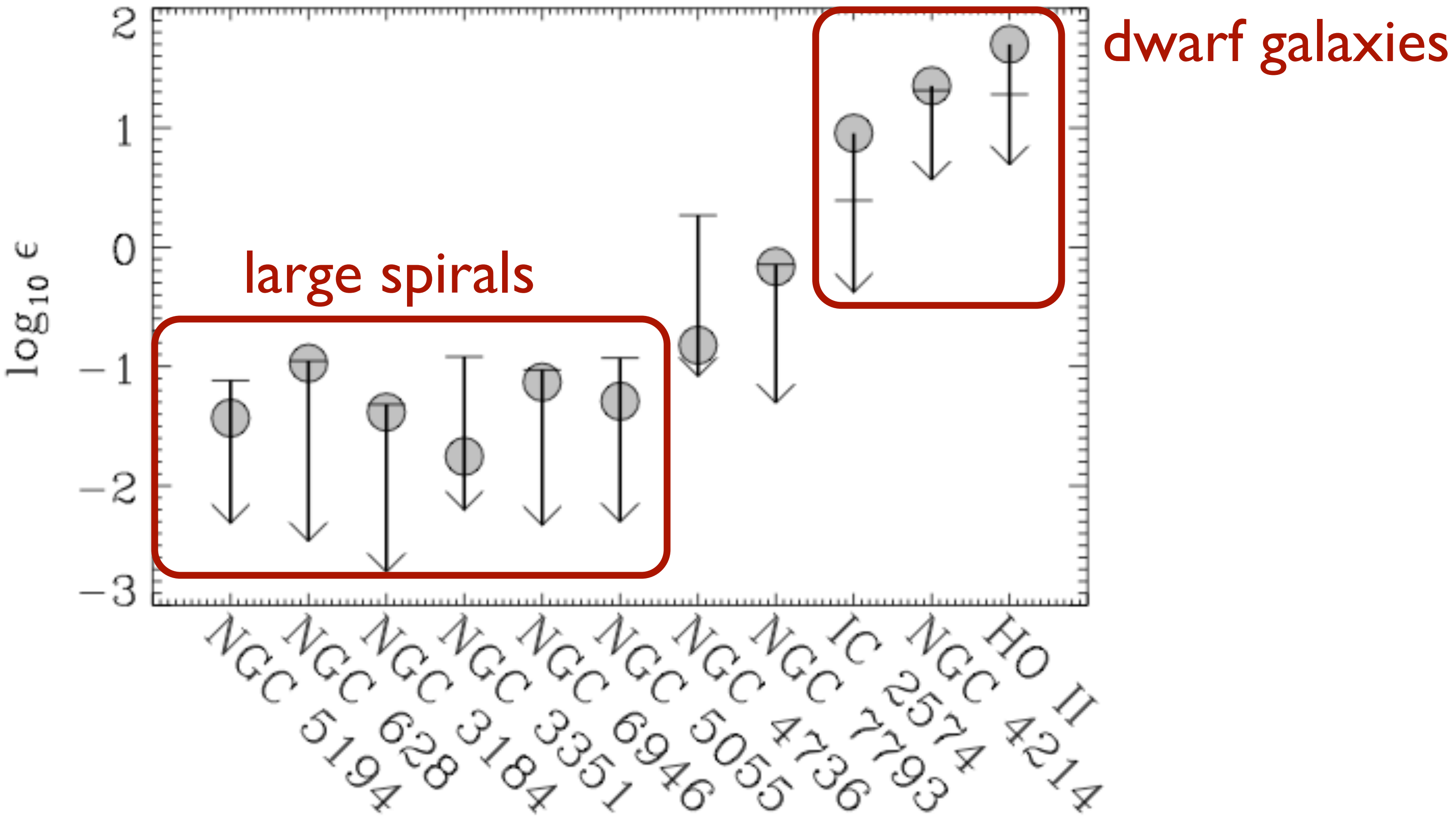
Klessen & Hennebelle (2010, A&A, 520, A17)

The *HI* Nearby Galaxy Survey (TH*I*NGS)

F. Walter, E. Brinks, E. de Blok, F. Bigiel, M. Thornley, R. Kennicutt

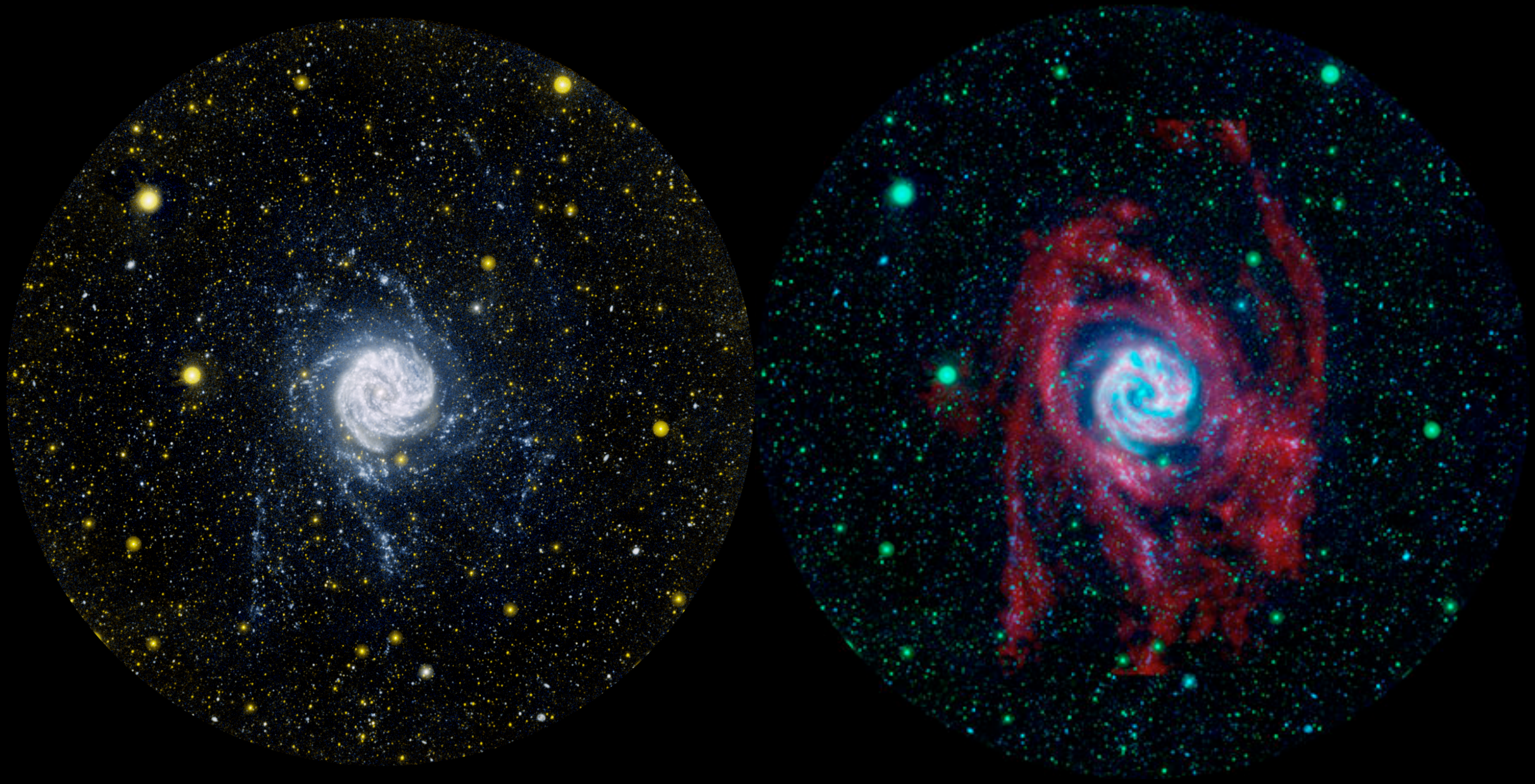


11 THINGS galaxies



Klessen & Hennebelle (2010, A&A, 520, A17)

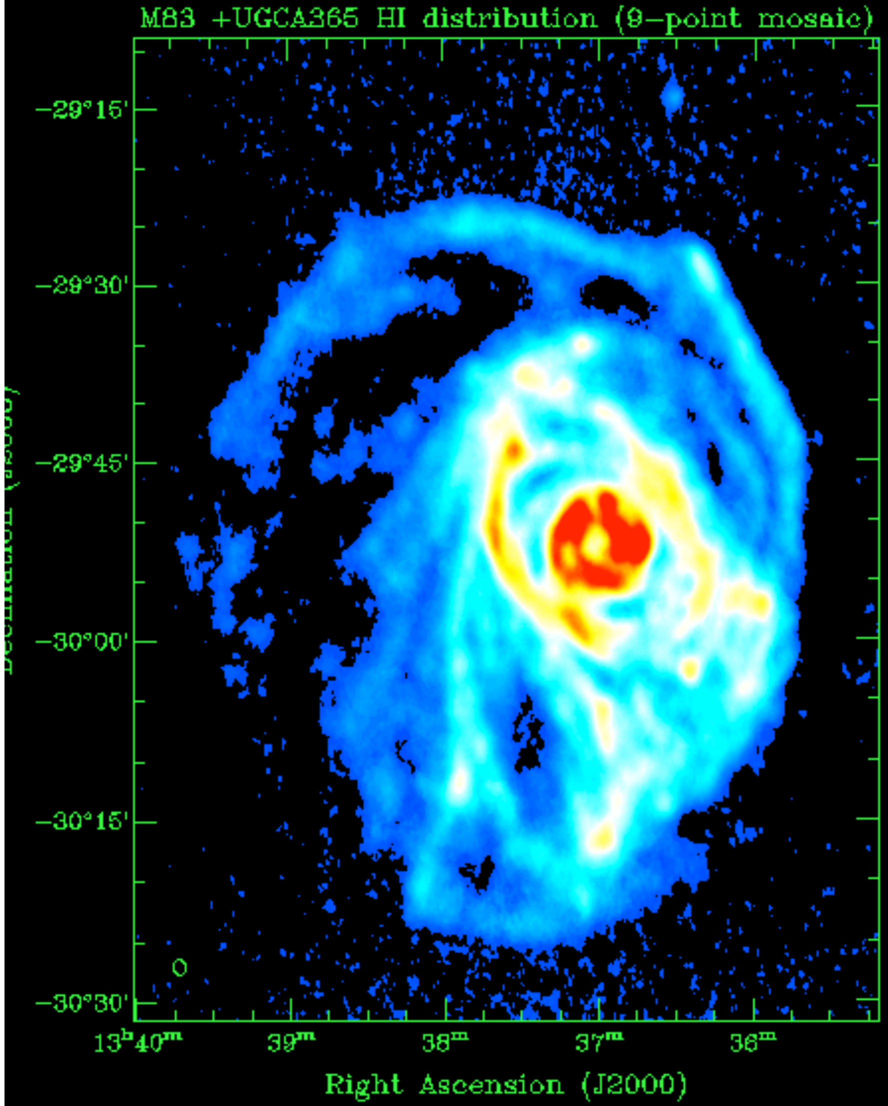
M83



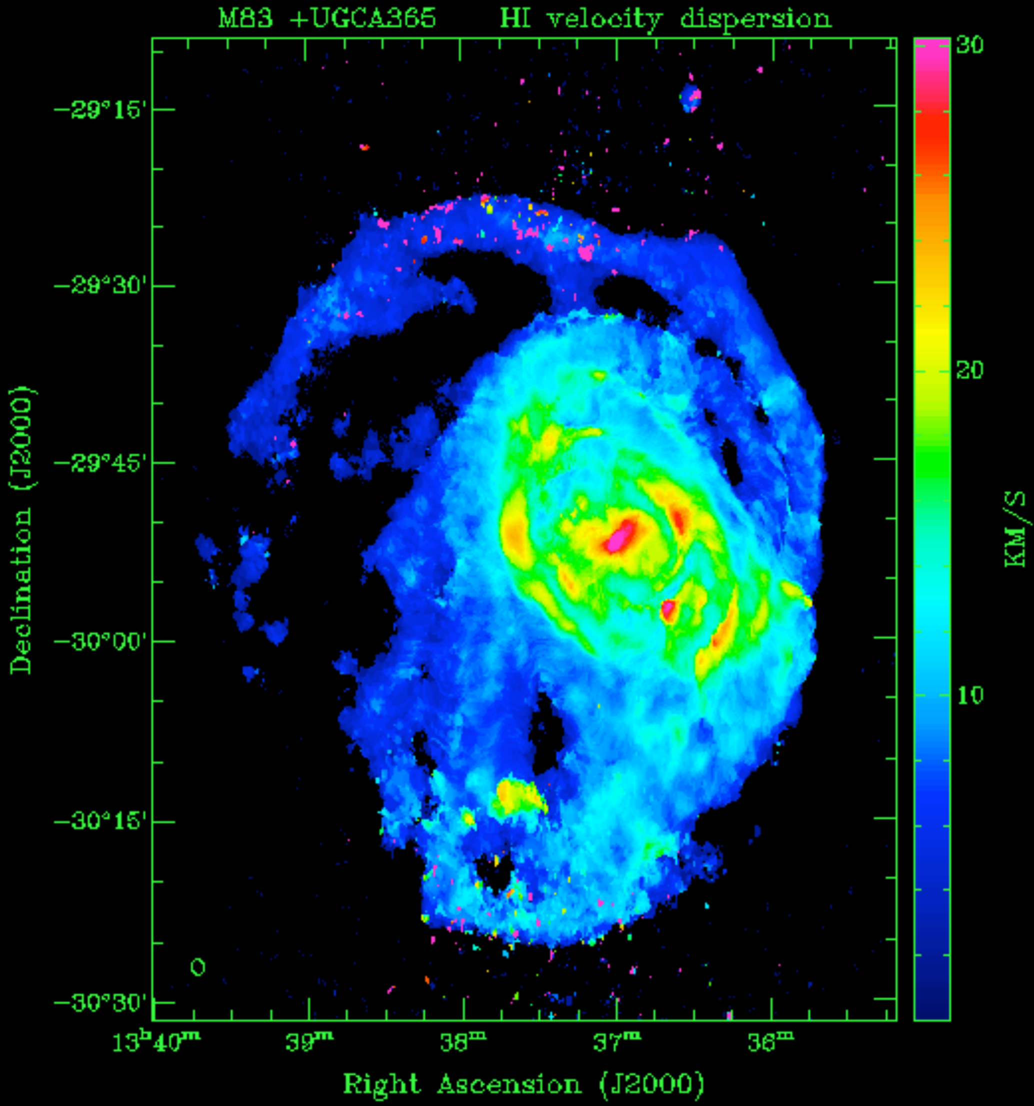
Do we actually see the gas flow through the disk?
ANSWER: Yes in M83!

M83

M83 HI column



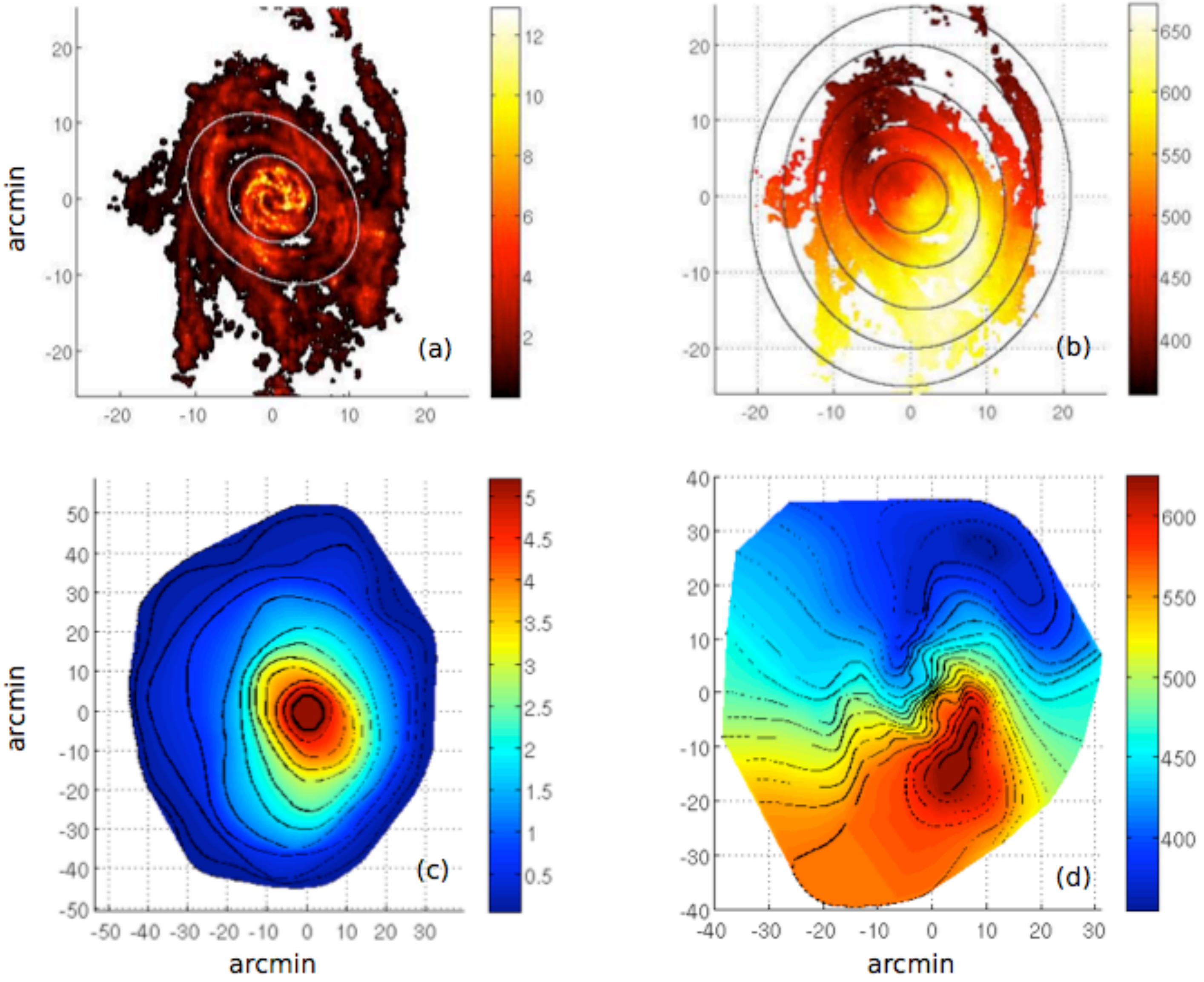
M83 HI velocity dispersion



M83

HI intensity

HI velocity dispersion



THINGS

Effelsberg

M83

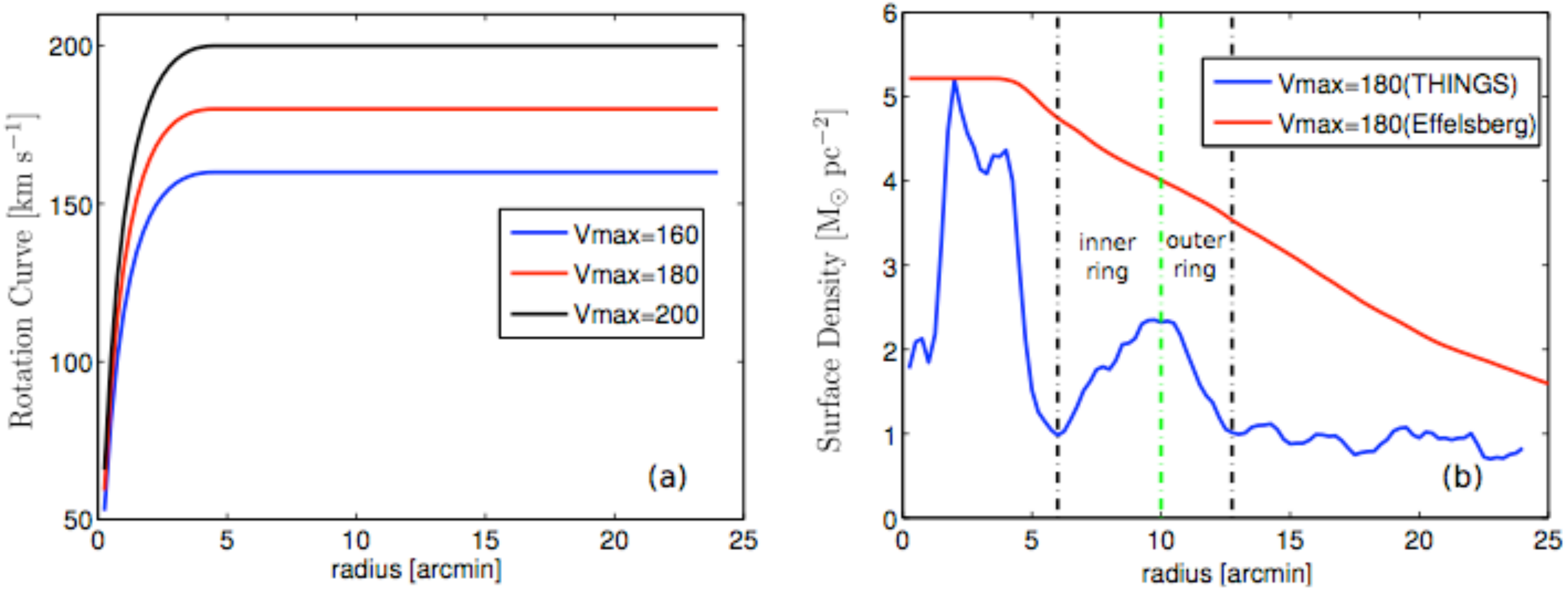


Figure 3. (a) The Brandt-type flat rotation curves as described in Eq. (13). Due to the low inclination of M83, we bracket the real situation with a range of different rotation curves and corresponding fit parameters from the tilted ring model. We assume $n = 0.8$, $R_{\rm max} = 4.5'$, $V_{\rm max} = 160, 180, 200$ km s^{-1}. As suggested in HB81, we take the model with $V_{\rm max} = 180$ as our fiducial case, which will then be justified in § 5. (b) The averaged surface density of the THINGS map (blue curve) and of the Effelsberg map (red curve). They are extracted from the fiducial model. The black vertical lines situated at $6'$ and $12.75'$ define the region of ring structure, which is also shown as the area enclosed by the white ellipses in Fig. 1a and the black ellipses in Fig. 7. The green vertical line marks the location of the density peak and further divides the ring into an inner ring and an outer ring.

M83

averaged radial velocity

radial mass flux

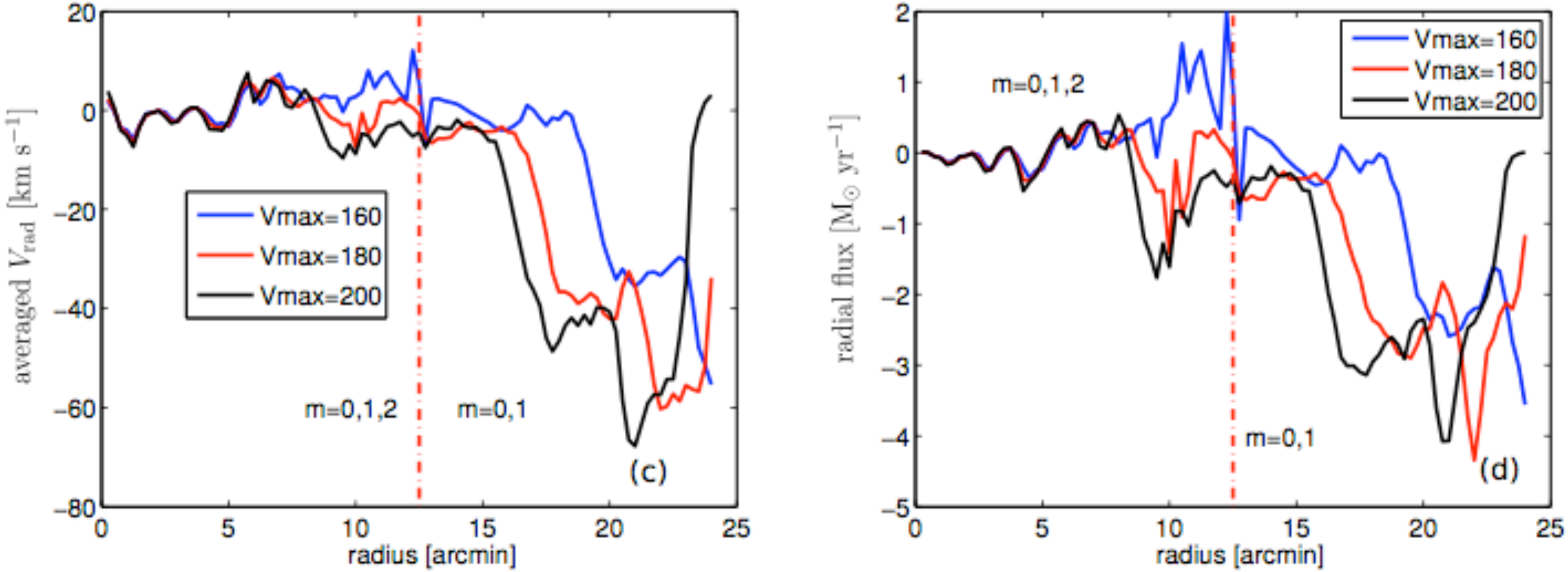
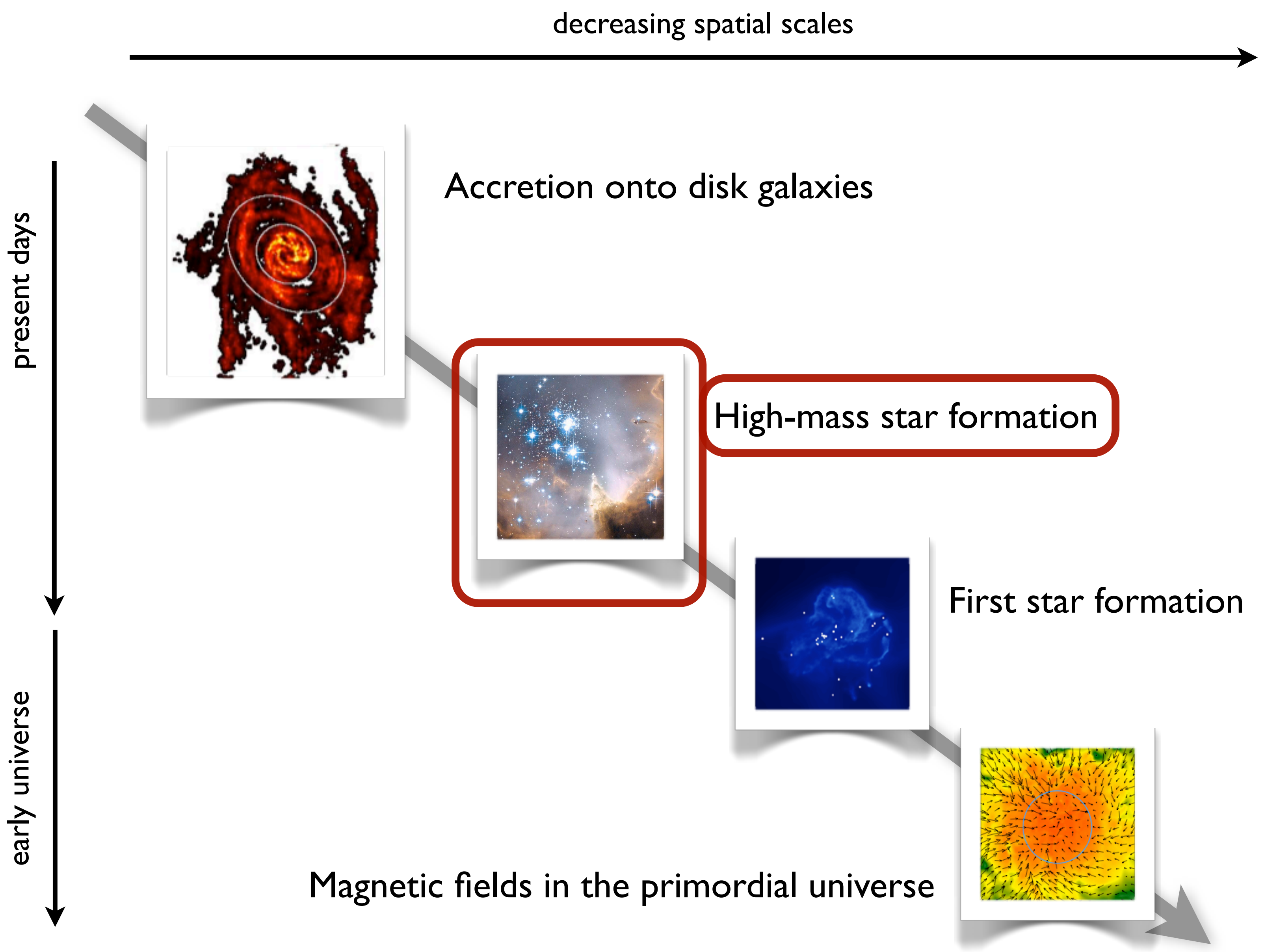


Figure 5. (a) PA and (b) inclination models used to infer radial motion of the gas in the THINGS map. (c) The inferred radial velocity. (d) The inferred radial mass flow. PA and inclination inside the vertical line ($R = 12.5'$) are extracted from the THINGS map, while in the other part we extrapolate these quantities from the Effelsberg map. The Fourier coefficients are fitted for the harmonics $m = 0, 1, 2$ for the radial regime to the left of the vertical line, while only $m = 0, 1$ for the outer parts of the map. In the outer disk, the radial shift is due the different inclinations corresponding to the different models. In all models, the common features are the prominent radial inflow in the outer disk, epicyclic motion in the transition zone (where the HI is organized into a ring like structure, see also Fig. 7 and an indication of moderate radial inflow in the inner disk.

questions

- what is the expected accretion rate onto spiral galaxies?
- how is this mass accreted?
  - in big lumps (e.g. high-velocity clouds)?
  - rains down gently at interface halo / thick disk?
- can we see this mass transfer in other galaxies?

agenda



decreasing spatial scales

present days

early universe

Accretion onto disk galaxies

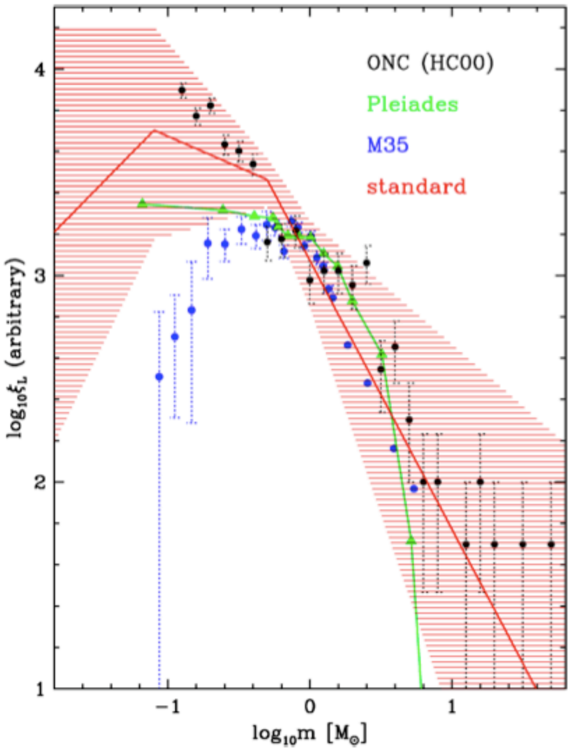
High-mass star formation

First star formation

Magnetic fields in the primordial universe

We want to address the following questions:

- how do massive stars (and their associated clusters) form?
- what determines the upper stellar mass limit?
- what is the physics behind observed HII regions?



IMF (Kroupa 2002)

Rosetta nebula (NGC 2237)

(proto)stellar feedback processes

- radiation pressure on dust particles
- ionizing radiation
- stellar winds
- jets and outflows

- radiation pressure on dust particles
  - has gained most attention in the literature (see e.g. Krumholz et al. 2007, 2008, 2009)
- ionization
  - few numerical studies so far (e.g. Dale 2007, Gritschneder et al. 2009), detailed collapse calculations with ionizing and non-ionizing feedback still missing
  - HII regions around massive stars are directly observable --> direct comparison between theory and observations

our (numerical) approach

- focus on collapse of individual high-mass cores...
  - massive core with 1,000 $M_\odot$
  - Bonnor-Ebert type density profile
    (flat inner core with 0.5 pc and rho ~ $r^{-3/2}$ further out)
  - initial m=2 perturbation, rotation with $\beta = 0.05$
  - sink particle with radius 600 AU and threshold density of 7×10^{-16} g cm^{-3}
  - cell size 100 AU

Peters et al. (2010a, ApJ, 711, 1017), Peters et al. (2010b, arXiv:1003.4998), Peters et al. (2010c, 1005.3271)

our (numerical) approach

- method:
    - FLASH with ionizing and non-ionizing radiation using raytracing based on hybrid-characteristics
    - protostellar model from Hosokawa & Omukai
    - rate equation for ionization fraction
    - relevant heating and cooling processes
    - some models include magnetic fields
    - *first 3D MHD calculations that consistently treat both ionizing and non-ionizing radiation in the context of high-mass star formation*

Peters et al. (2010a,b,c)

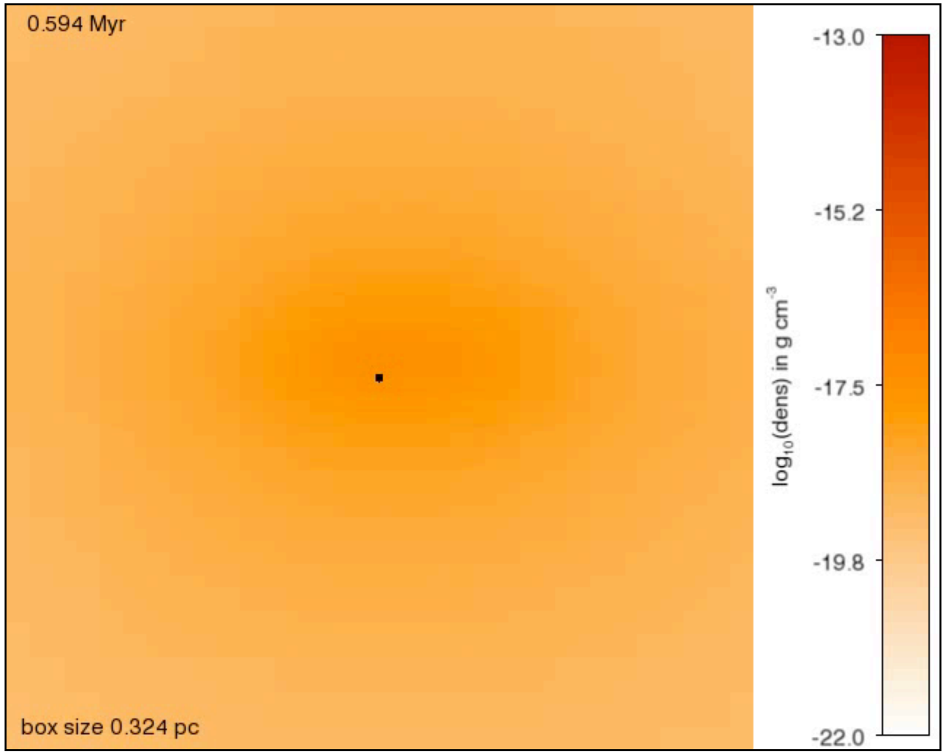
model with suppressed disk frag.

Disk edge on

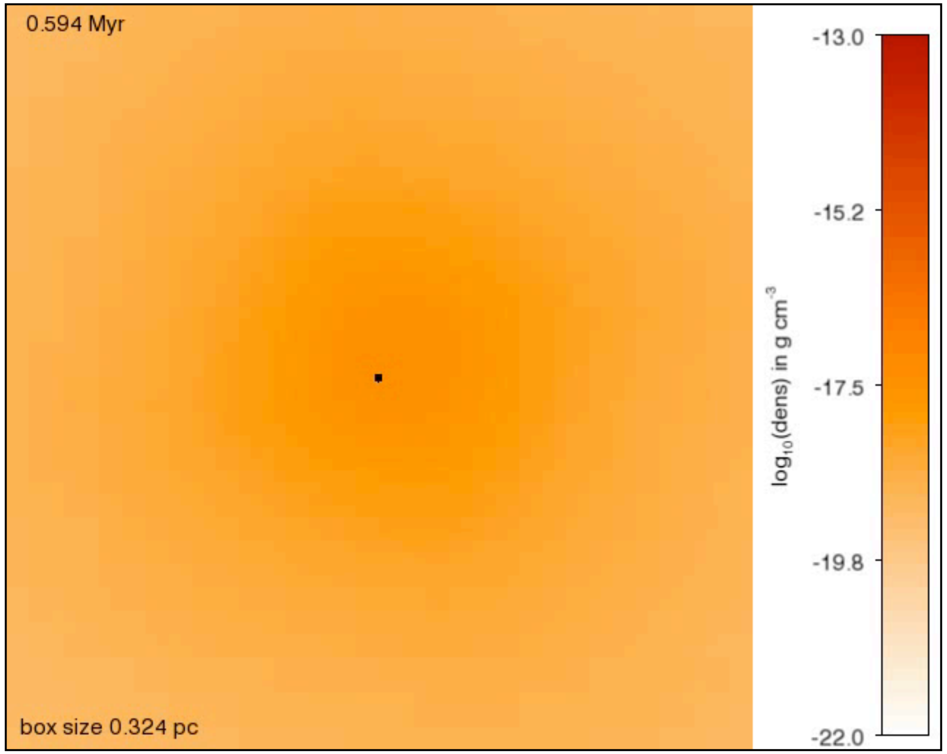
Disk plane

Peters et al. (2010a,b,c)

model with multiple protostars

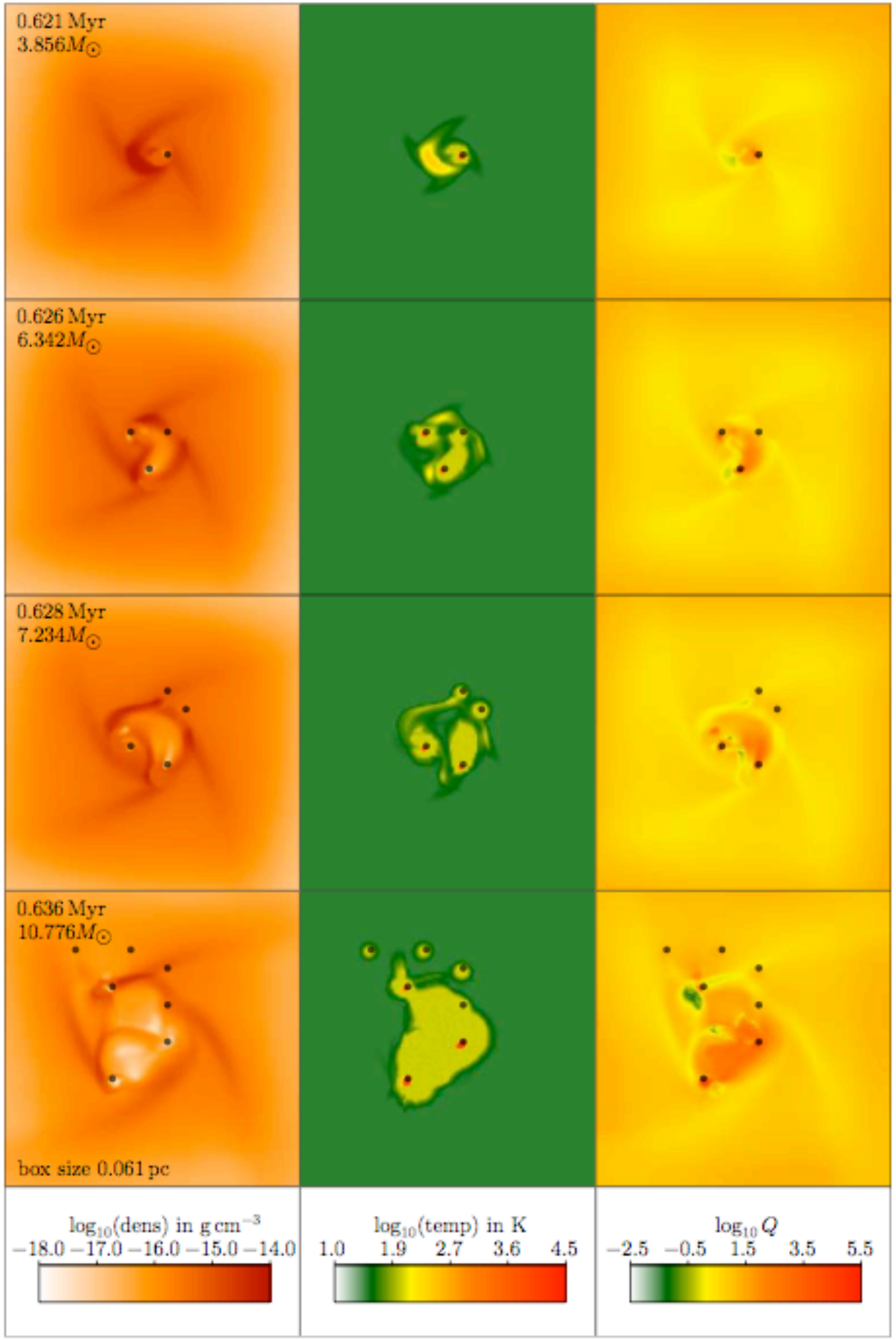


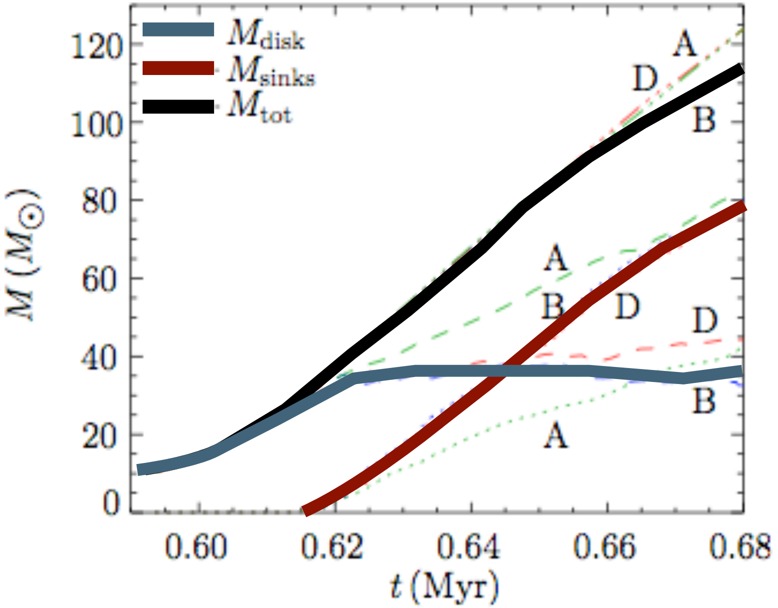
Disk edge on



Disk plane

Peters et al. (2010a,b,c)

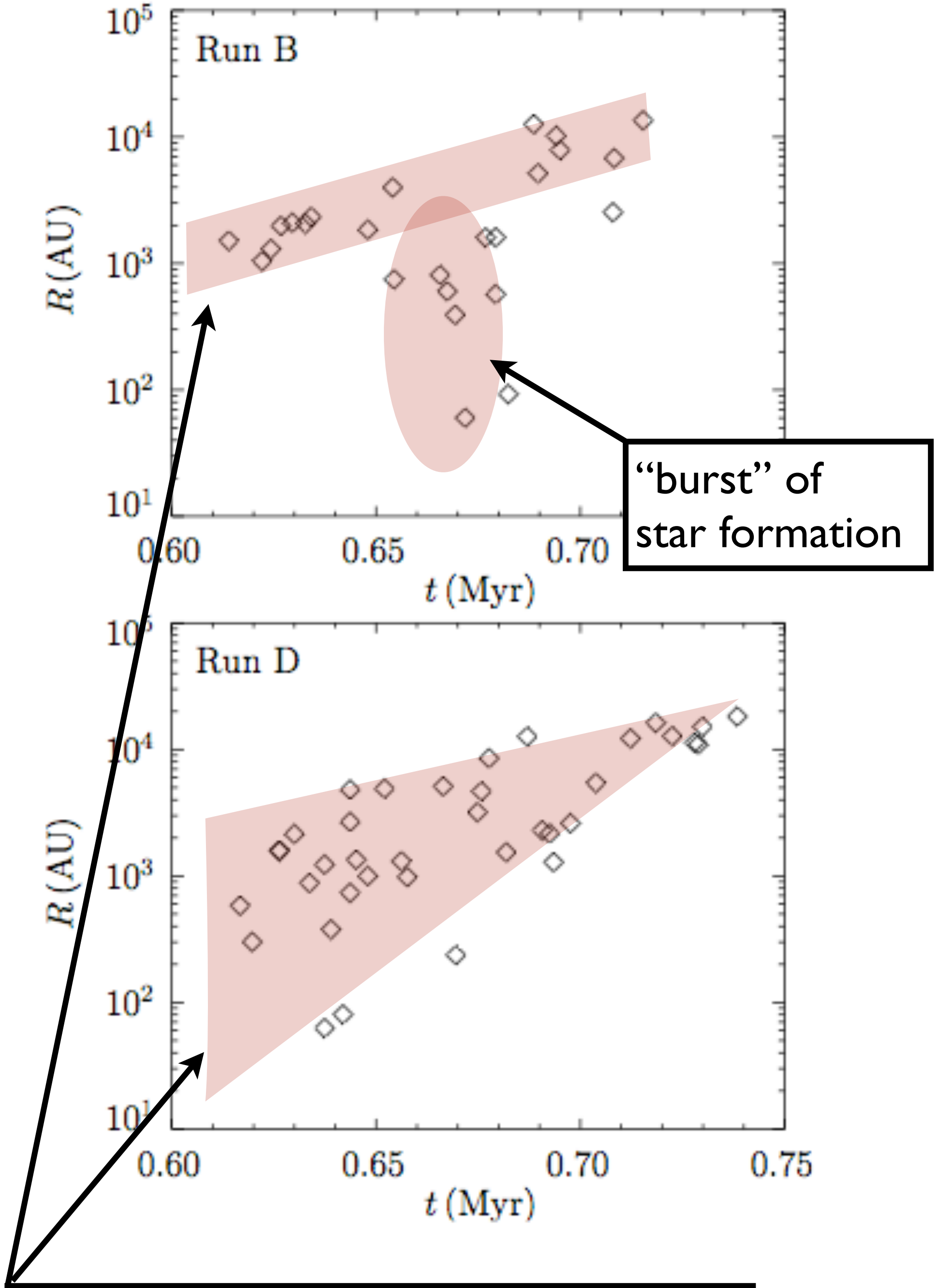




mass load onto the disk exceeds inward transport
--> becomes gravitationally unstable (see also Kratter & Matzner 2006, Kratter et al. 2010)

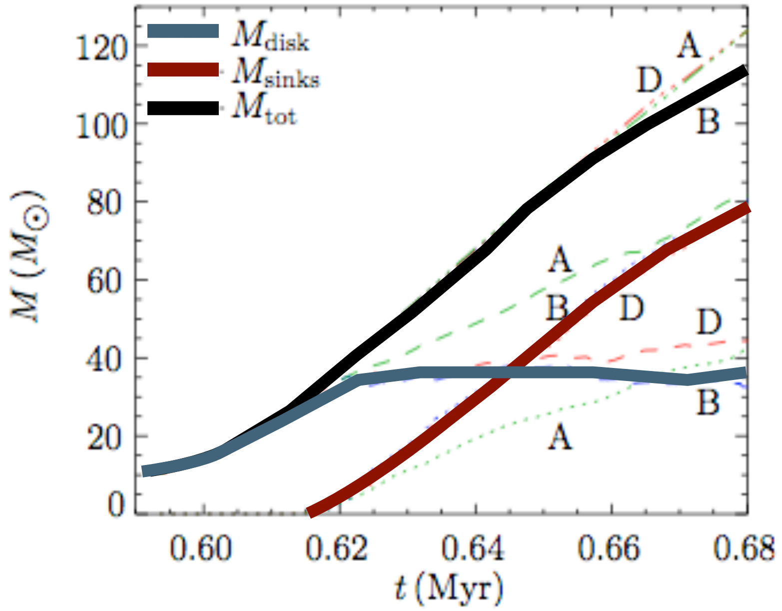
fragments to form multiple stars --> explains why high-mass stars are seen in clusters

Peters et al. (2010a,b,c)



“burst” of star formation

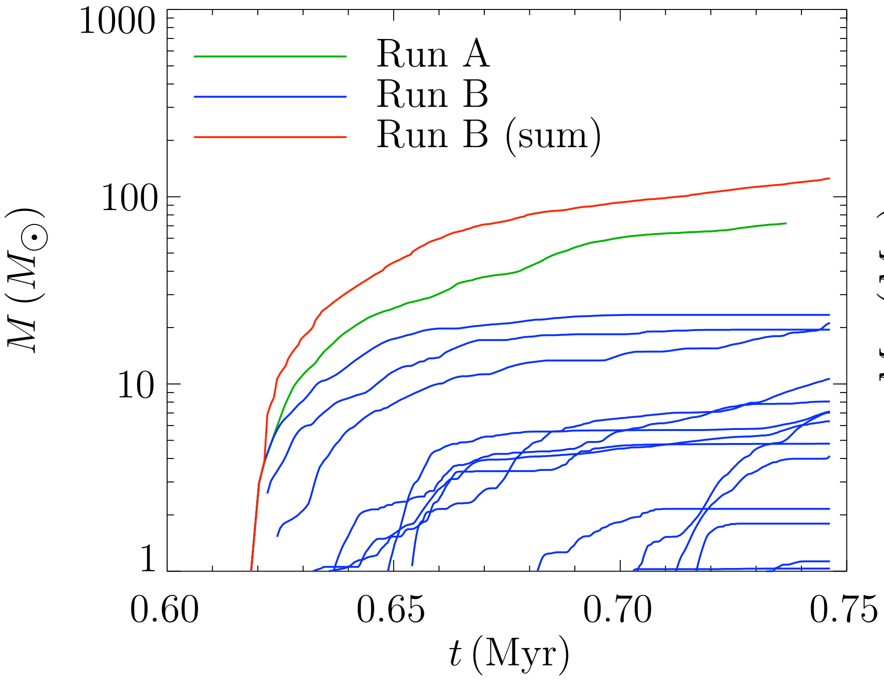
younger protostars form at larger radii

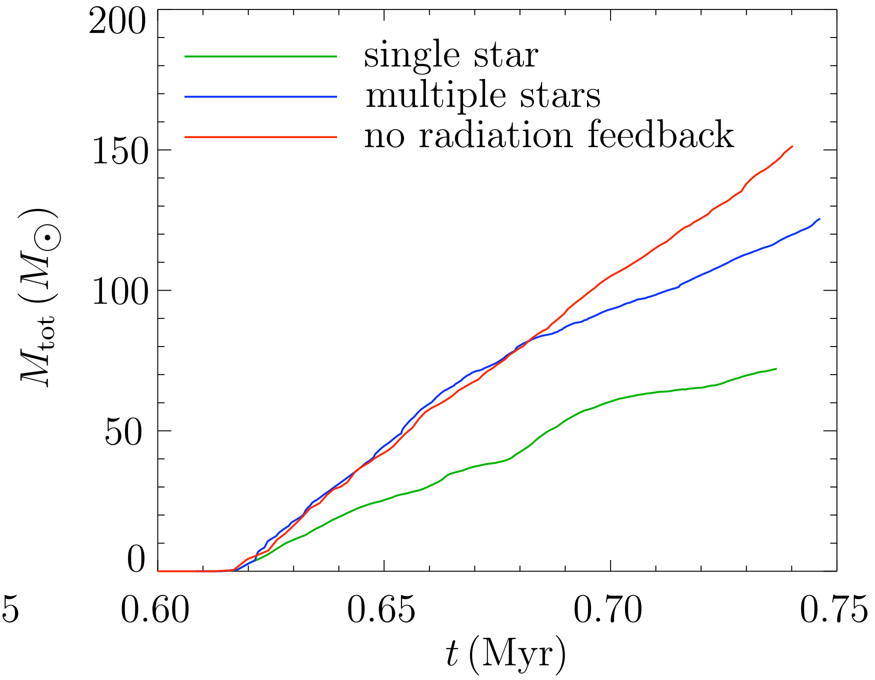


mass load onto the disk exceeds inward transport
--> becomes gravitationally unstable (see also Kratter & Matzner 2006, Kratter et al. 2010)

fragments to form multiple stars --> explains why high-mass stars are seen in clusters

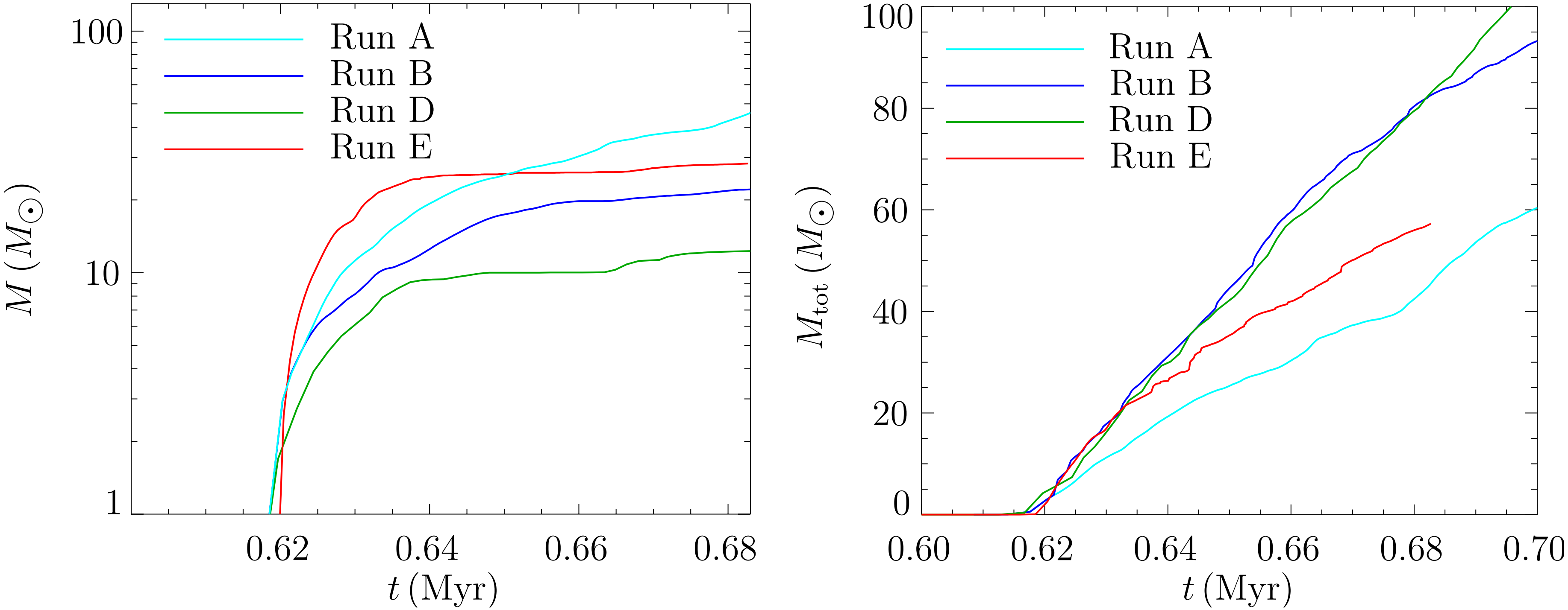
Peters et al. (2010a,b,c)





- compare with control run without radiation feedback
- total accretion rate does not change with accretion heating
- expansion of ionized bubble causes turn-off
- no triggered star formation by expanding bubble

Peters et al. (2010a,b,c,d)

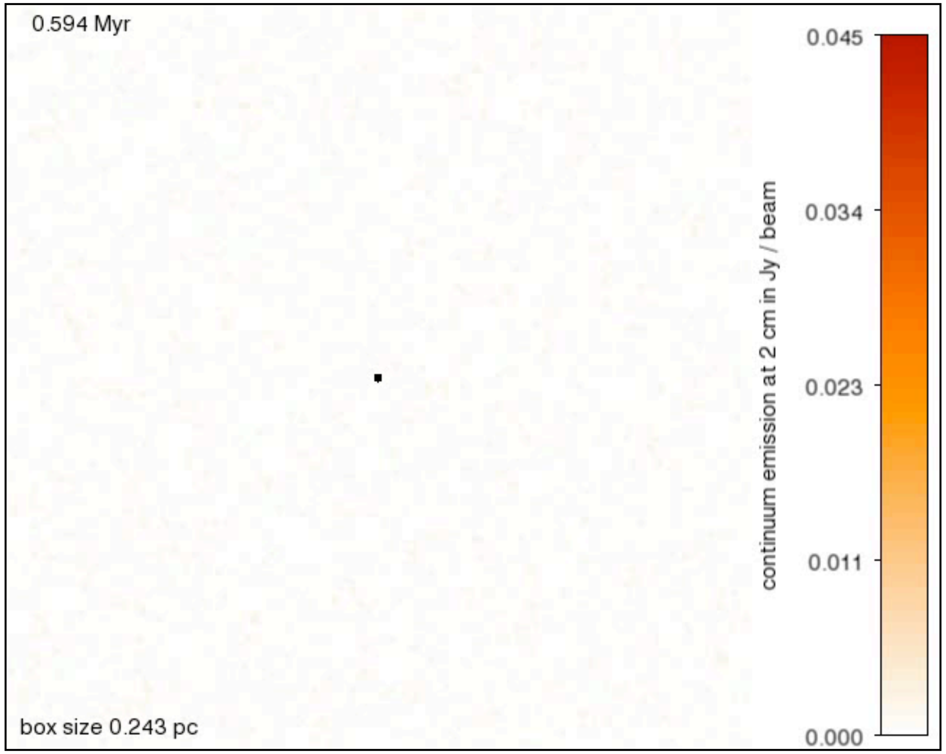


- magnetic fields lead to weaker fragmentation
- central star becomes more massive (magnetic breaking

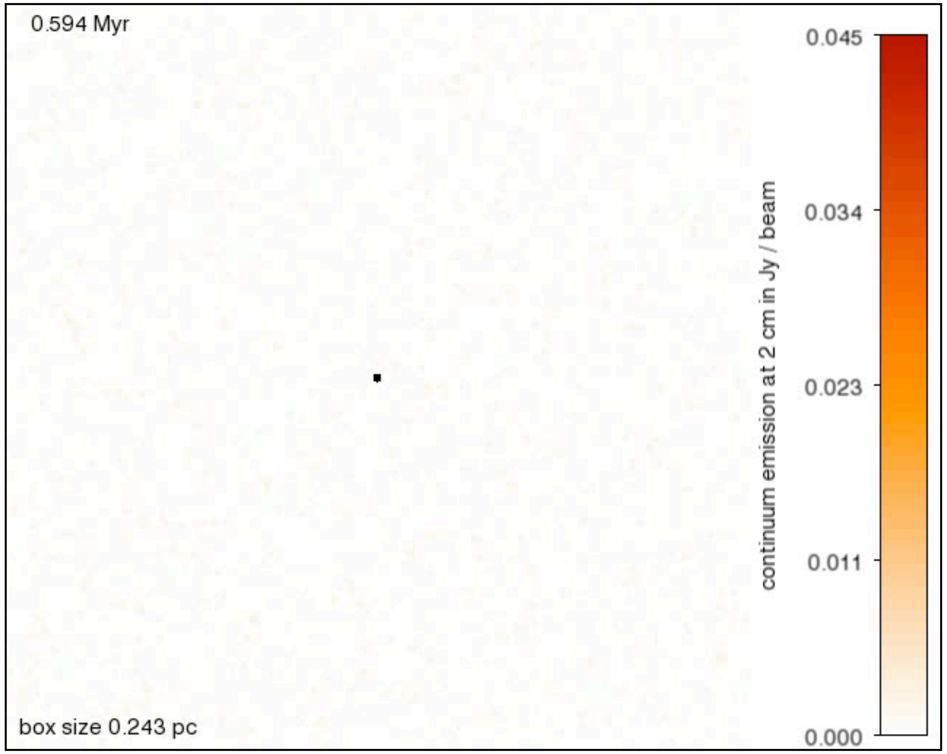
Peters et al. (2010a,b,c,d)

- numerical data can be used to generate continuum maps
- calculate free-free absorption coefficient for every cell
- integrate radiative transfer equation (neglecting scattering)
- convolve resulting image with beam width
- VLA parameters:
    - distance $2.65\,\mathrm{kpc}$
    - wavelength $2\,\mathrm{cm}$
    - FWHM $0''.14$
    - noise $10^{-3}\,\mathrm{Jy}$

Peters et al. (2010a,b,c)

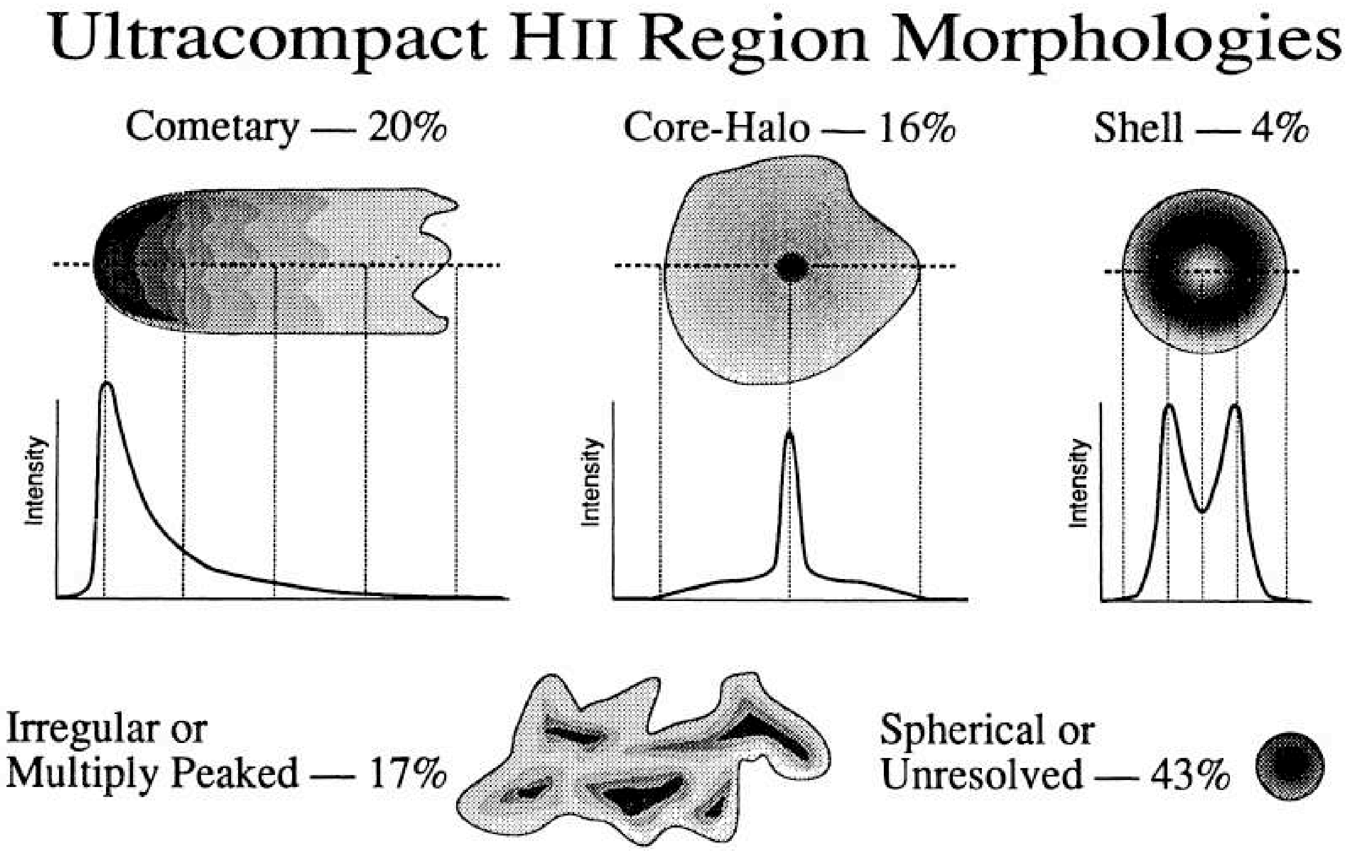


Disk face on

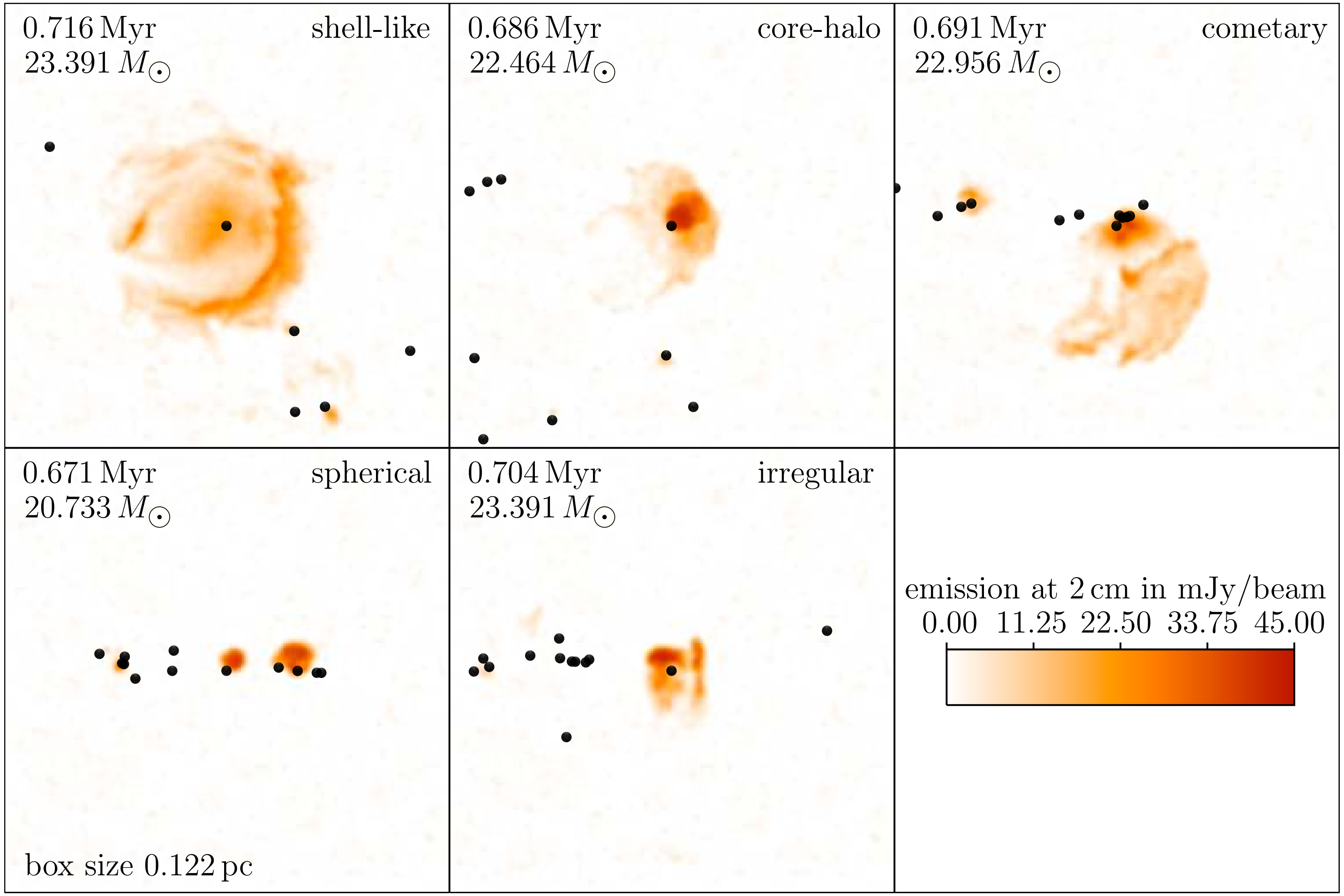


Disk edge on

Peters et al. (2010a,b,c)

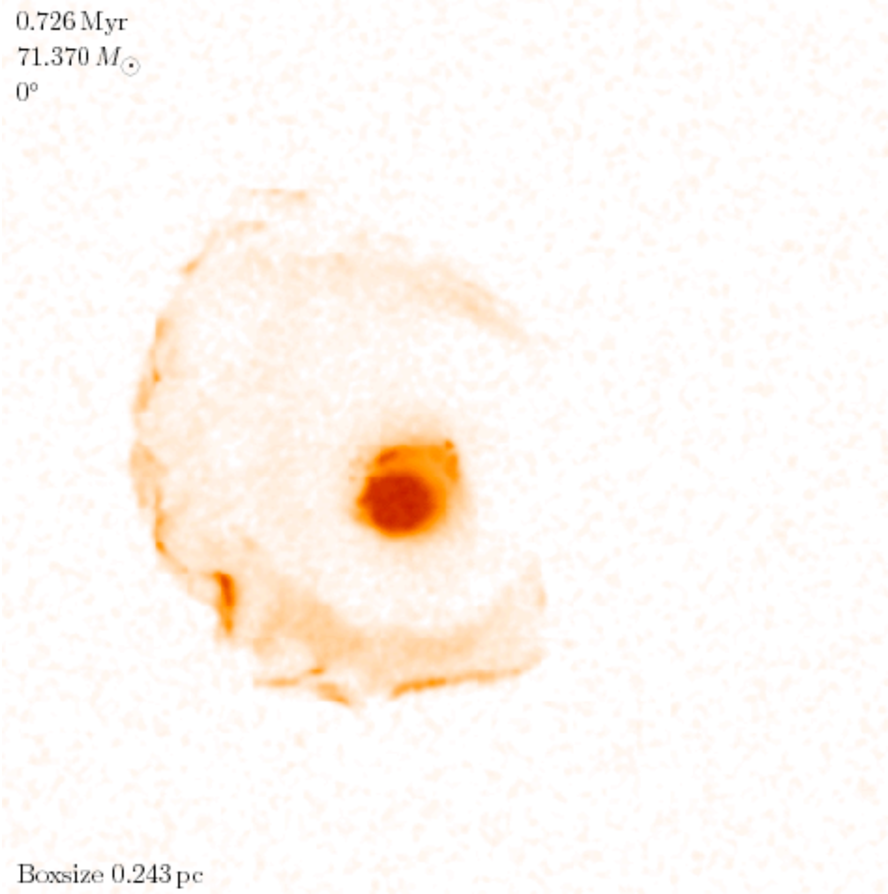


- Wood & Churchwell 1989 classification of UC H II regions
- Question: What is the origin of these morphologies?
- UC H II lifetime problem: Too many UC H II regions observed!



- synthetic VLA observations at $2\,\mathrm{cm}$ of simulation data
- interaction of ionizing radiation with accretion flow creates high variability in time and shape
- flickering resolves the lifetime paradox!

Peters et al. (2010a,b,c)



Morphology of HII region depends on viewing angle

Peters et al. (2010a,b,c)

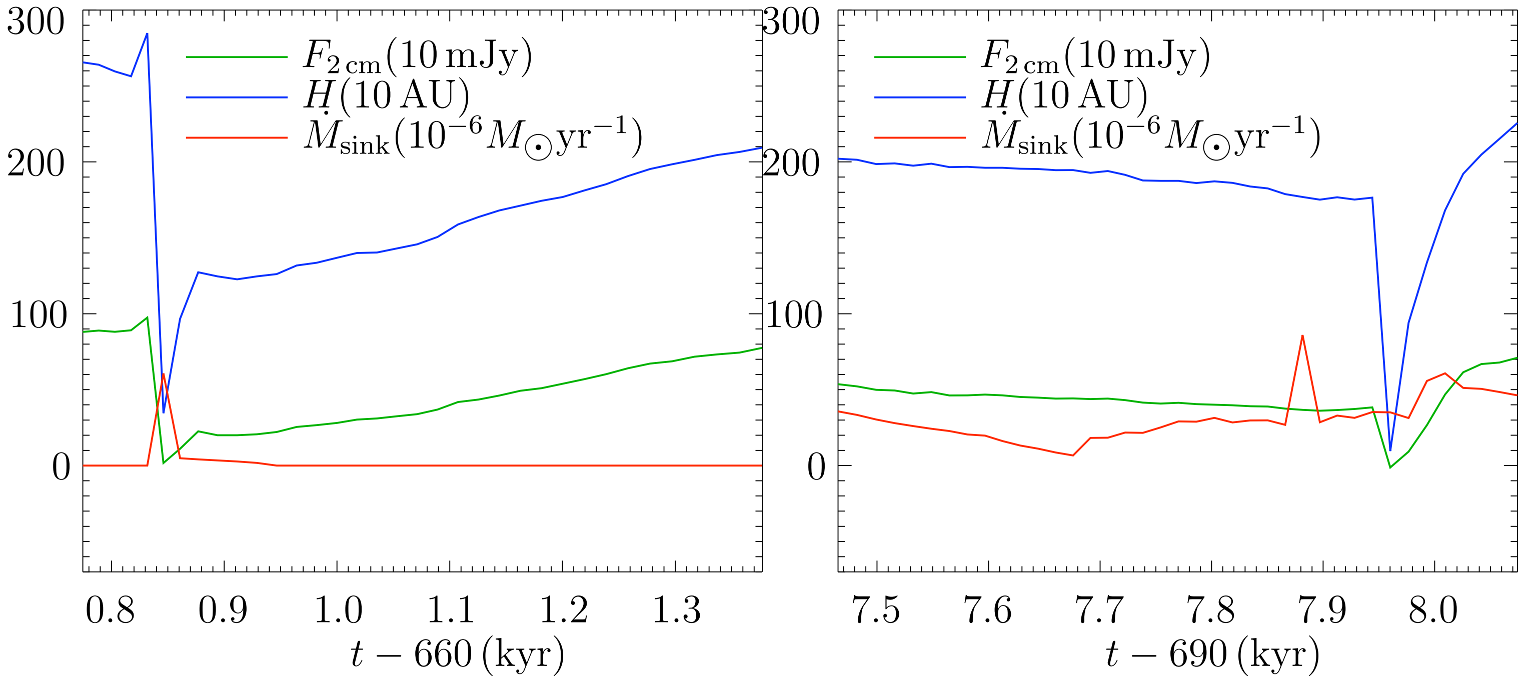
Type	WC89	K94	single	multiple
Spherical/Unresolved	43	55	19	60 ± 5
Cometary	20	16	7	10 ± 5
Core-halo	16	9	15	4 ± 2
Shell-like	4	1	3	5 ± 1
Irregular	17	19	57	21 ± 5

WC89: Wood & Churchwell 1989, K94: Kurtz et al. 1994

- statistics over 25 simulation snapshots and 20 viewing angles
- statistics can be used to distinguish between different models
- single sink simulation does not reproduce lifetime problem

Peters et al. (2010a,b,c)

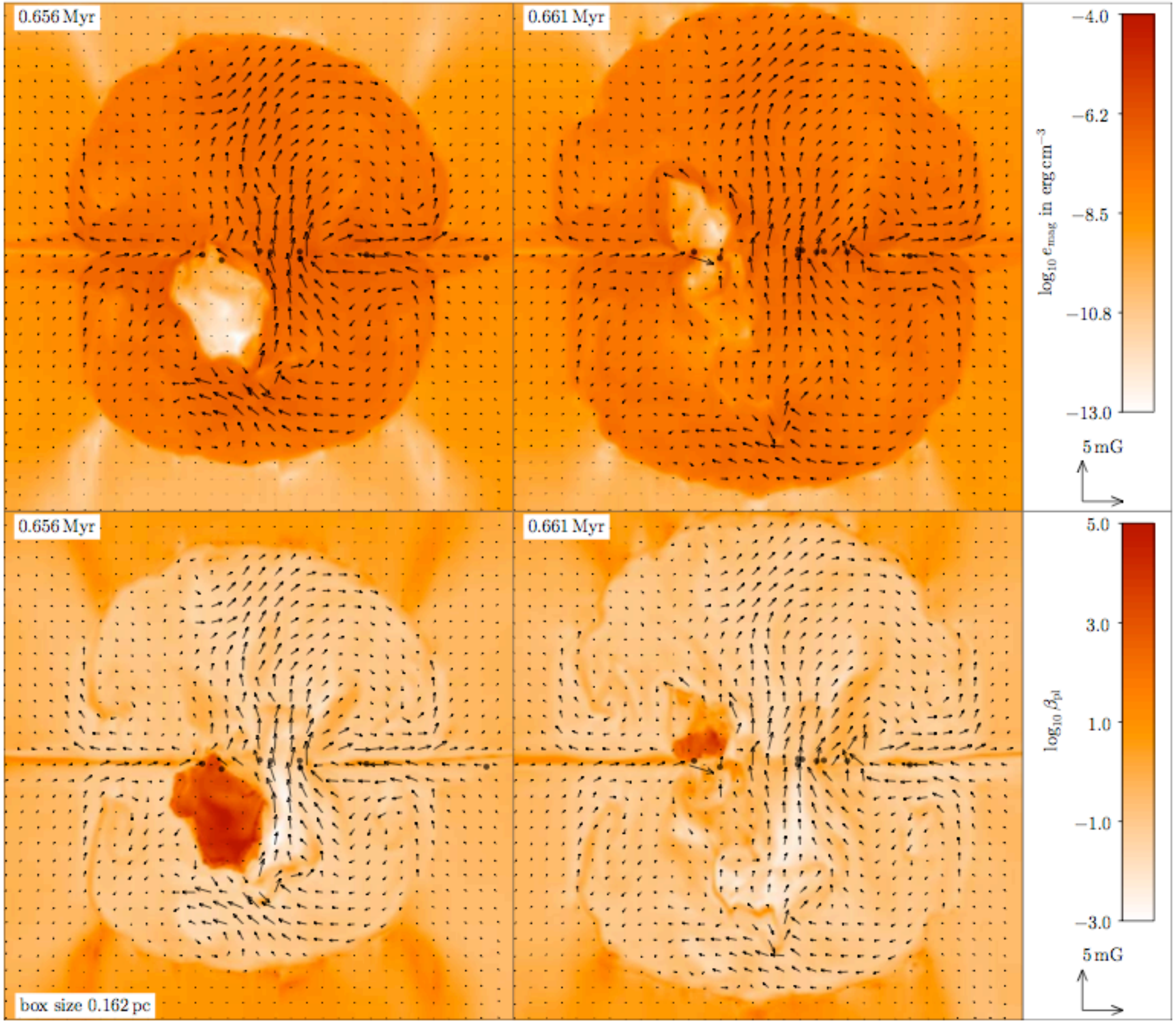
time variability



- correlation between accretion events and H II region changes
- time variations in size and flux have been observed
- changes of size and flux of 5–$7\%\mathrm{yr}^{-1}$ match observations

  Franco-Hernández et al. 2004, Rodríguez et al. 2007, Galván-Madrid et al. 2008

(Galvan-Madrid et al. 2010, in preparation)



magnetic energy density

plasma beta = P_{th}/P_{mag}

- magnetic tower flow creates roundish bubble
- magnetic field does not change HII morphology

Some results

- Ionization feedback cannot stop accretion
- Ionization drives bipolar outflow
- H II region shows high variability in time and shape
- All classified morphologies can be observed in one run
- Lifetime of H II region determined by accretion time scale
- Rapid accretion through dense, unstable flows
- Fragmentation-induced mass limits of massive stars

questions

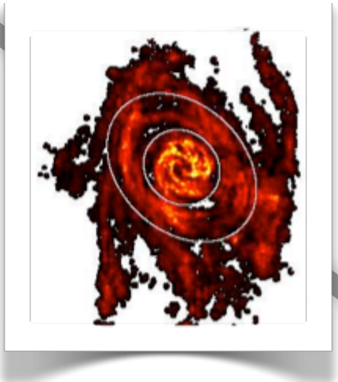
- what determines the upper mass limit of stars?
- can the models reproduce the SEDs of UC HII regions?
- is the predicted statistics of the time variability of UC HII regions correct?

agenda

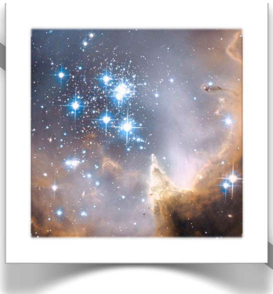
decreasing spatial scales

present days

early universe

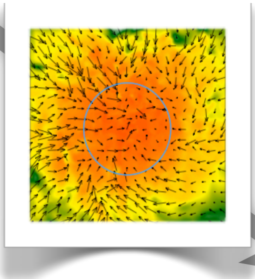


Accretion onto disk galaxies



High-mass star formation

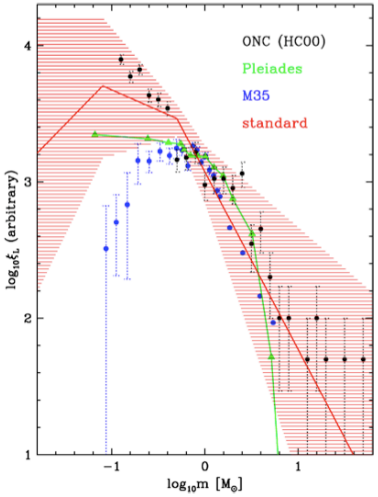
First star formation



Magnetic fields in the primordial universe

stellar masses

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



stellar masses

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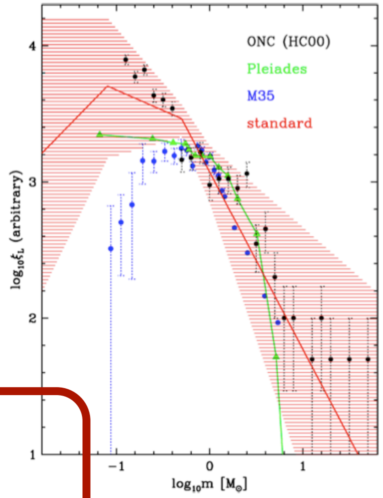


application to first star formation

thermodynamics & fragmentation

degree of fragmentation depends on *EOS!*

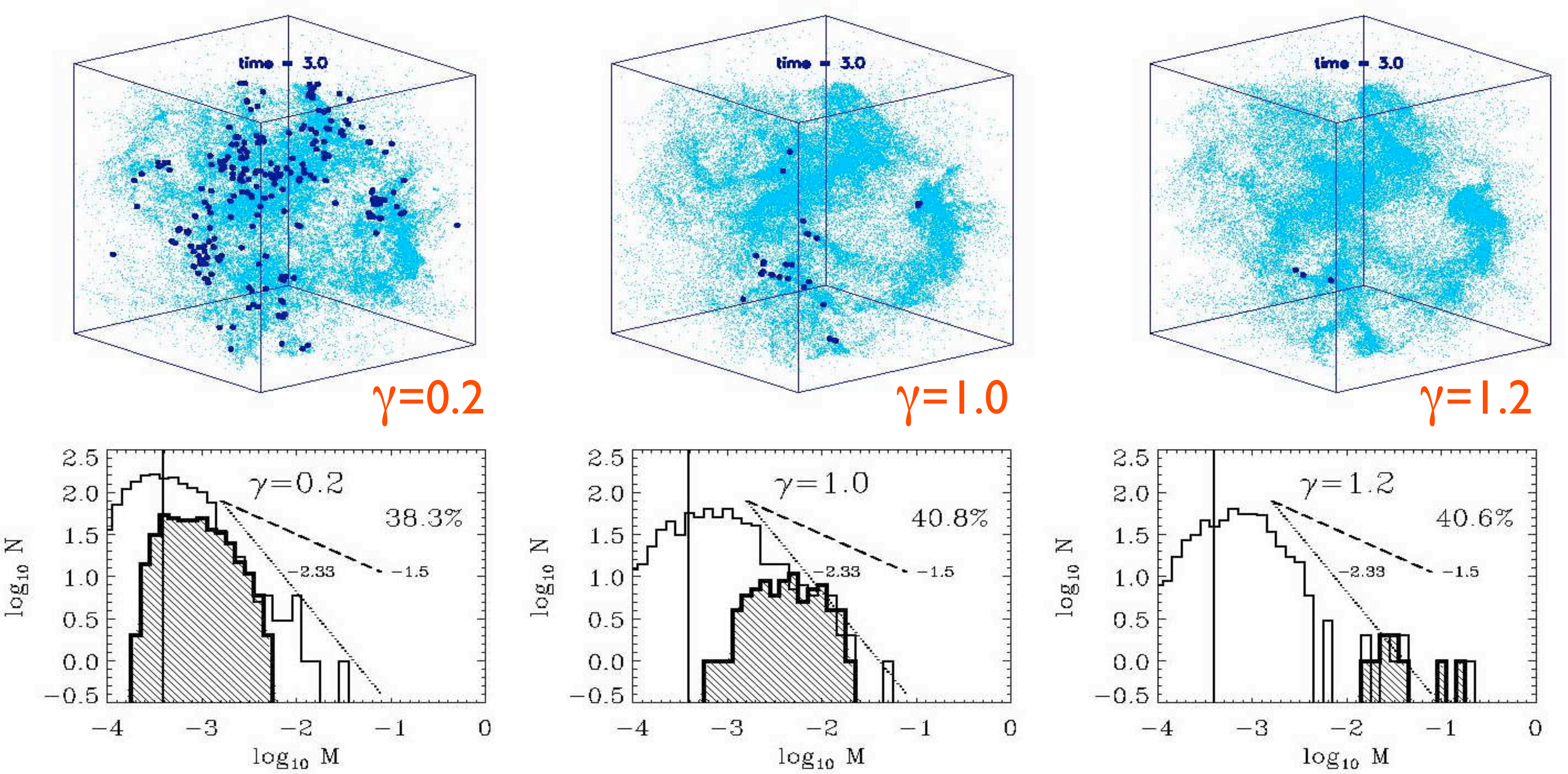
polytropic EOS: $\mathbf{p} \propto \rho^{\gamma}$

$\gamma < 1$: 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*

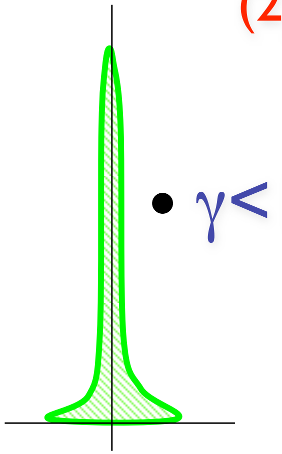
for $\gamma>1$ it is suppressed → formation of *isolated massive stars*

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

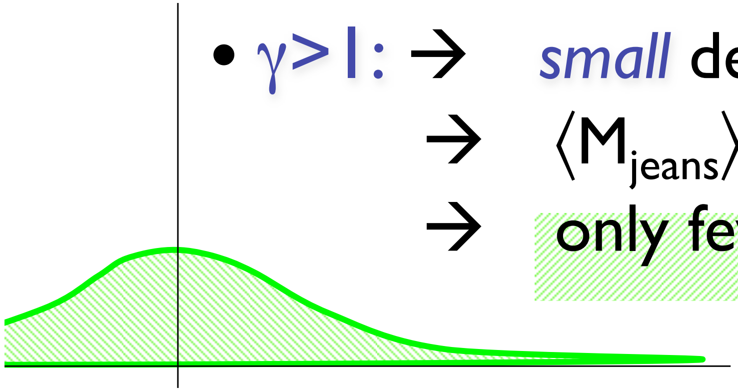
how does that work?

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

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

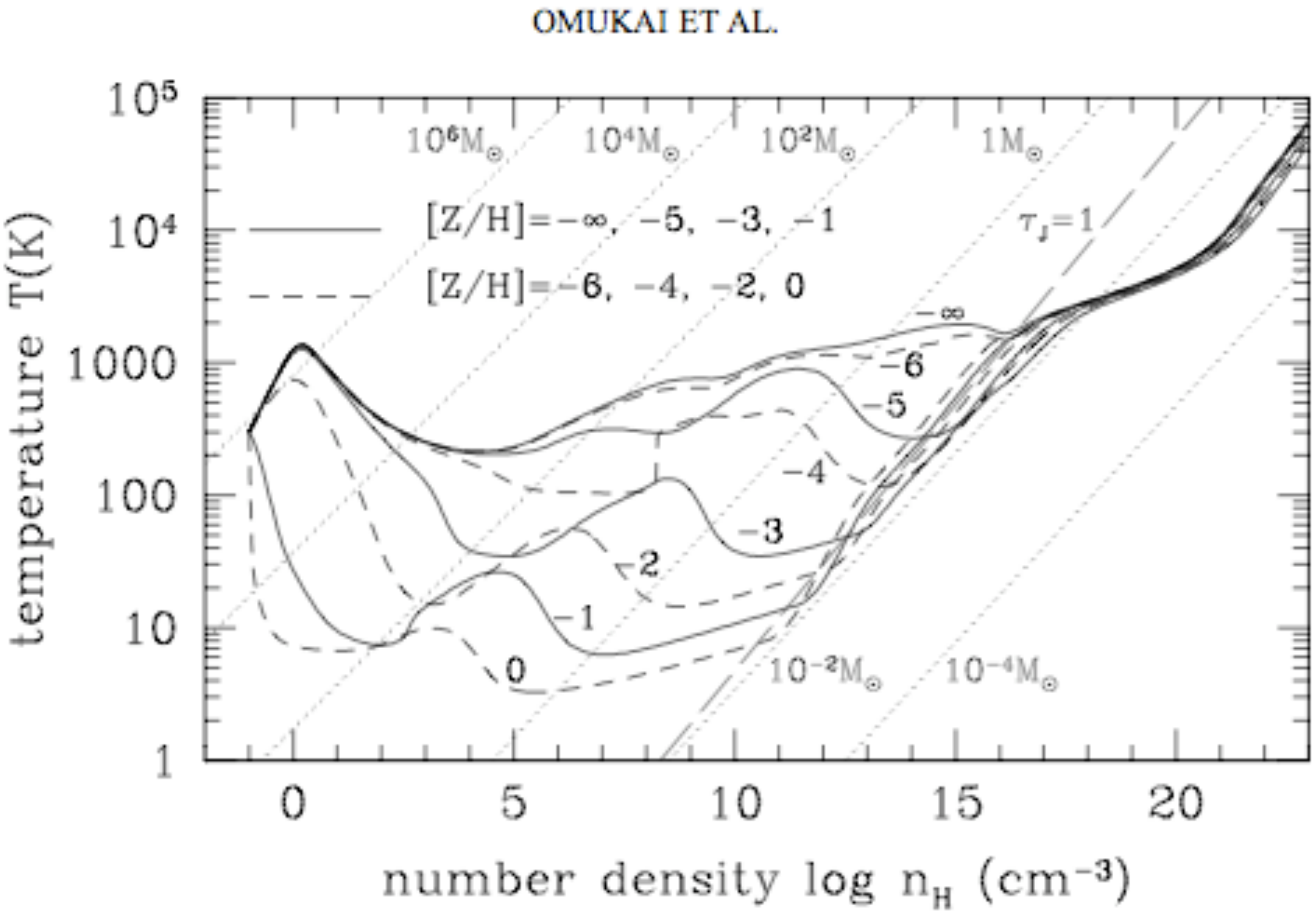


- $\gamma<1$: → *large* density excursion for given pressure
  - → ⟨M_{jeans}⟩ becomes small
    - → number of fluctuations with $M > M_{jeans}$ is large



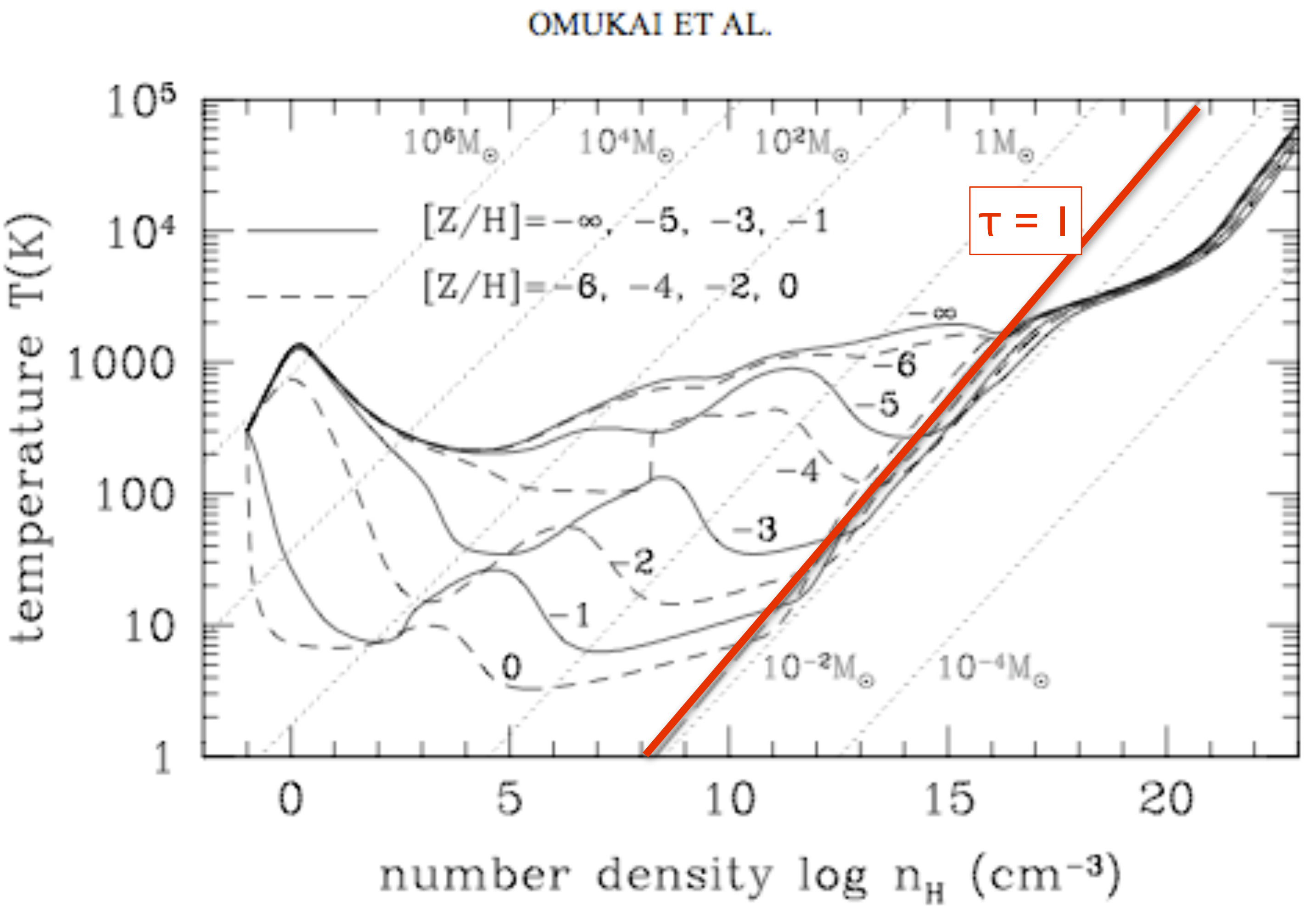
- $\gamma>1$: → *small* density excursion for given pressure
  - → ⟨M_{jeans}⟩ is large
  - → only few and massive clumps exceed M_{jeans}

EOS as function of metallicity



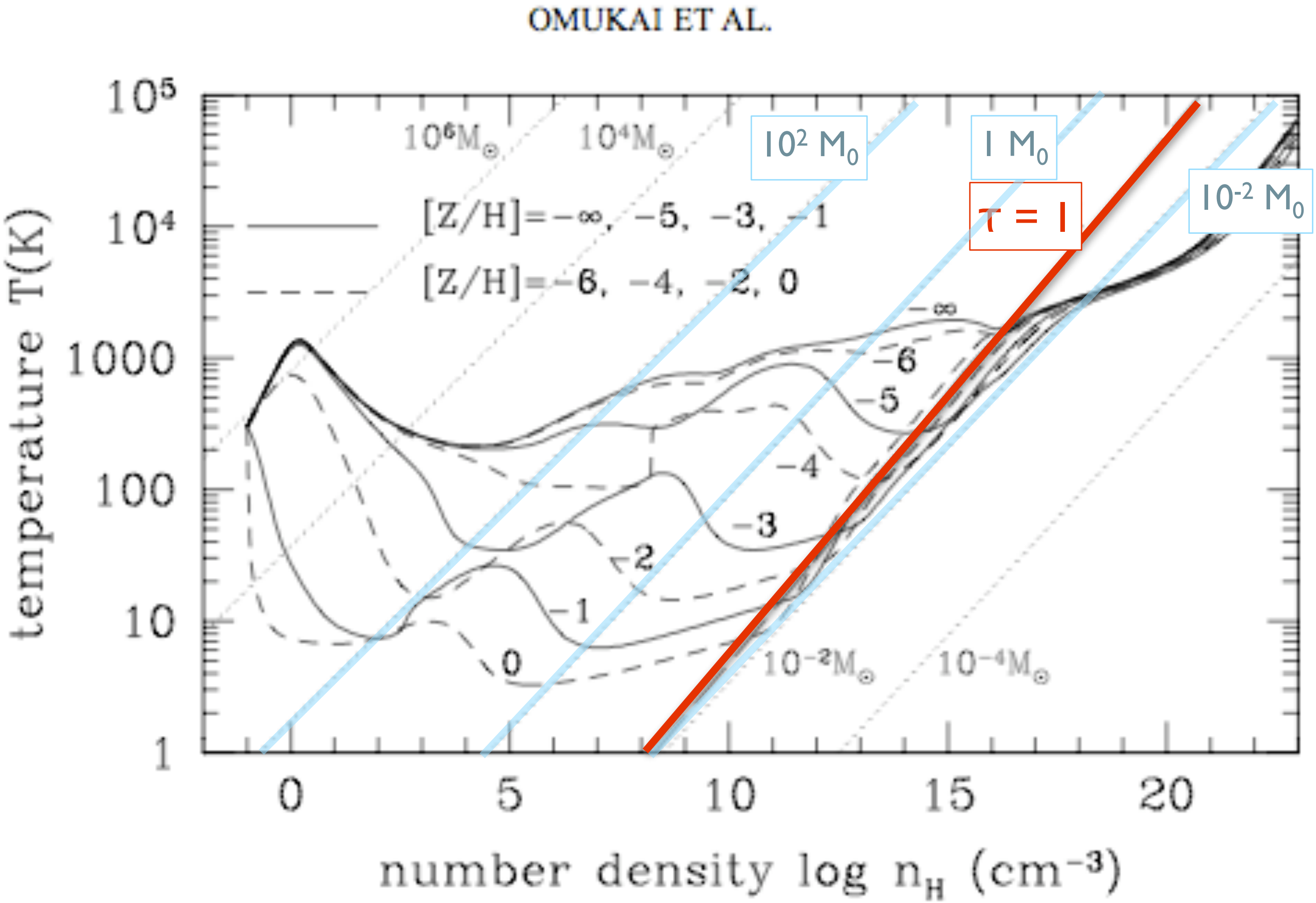
(Omukai et al. 2005)

EOS as function of metallicity



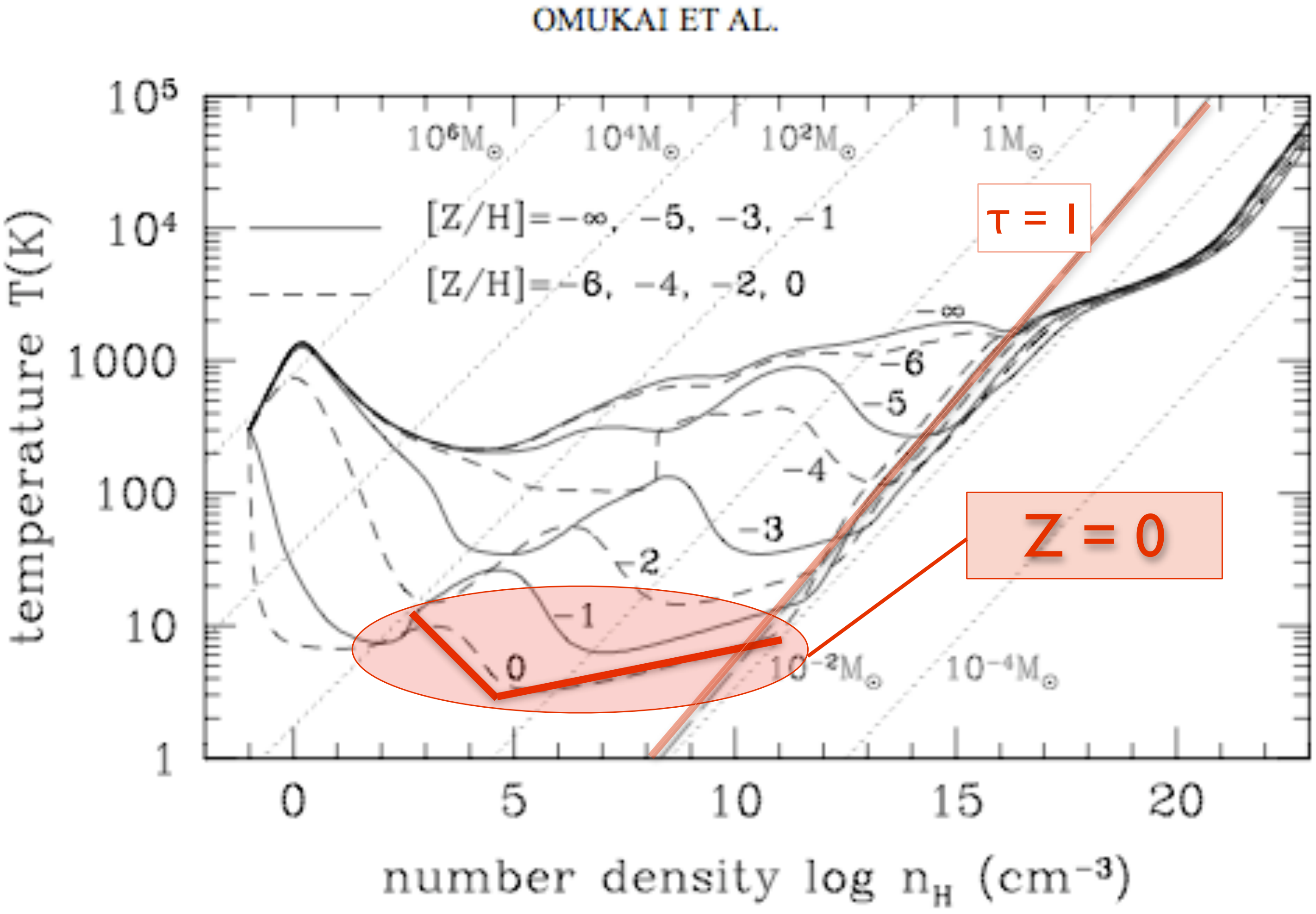
(Omukai et al. 2005)

EOS as function of metallicity



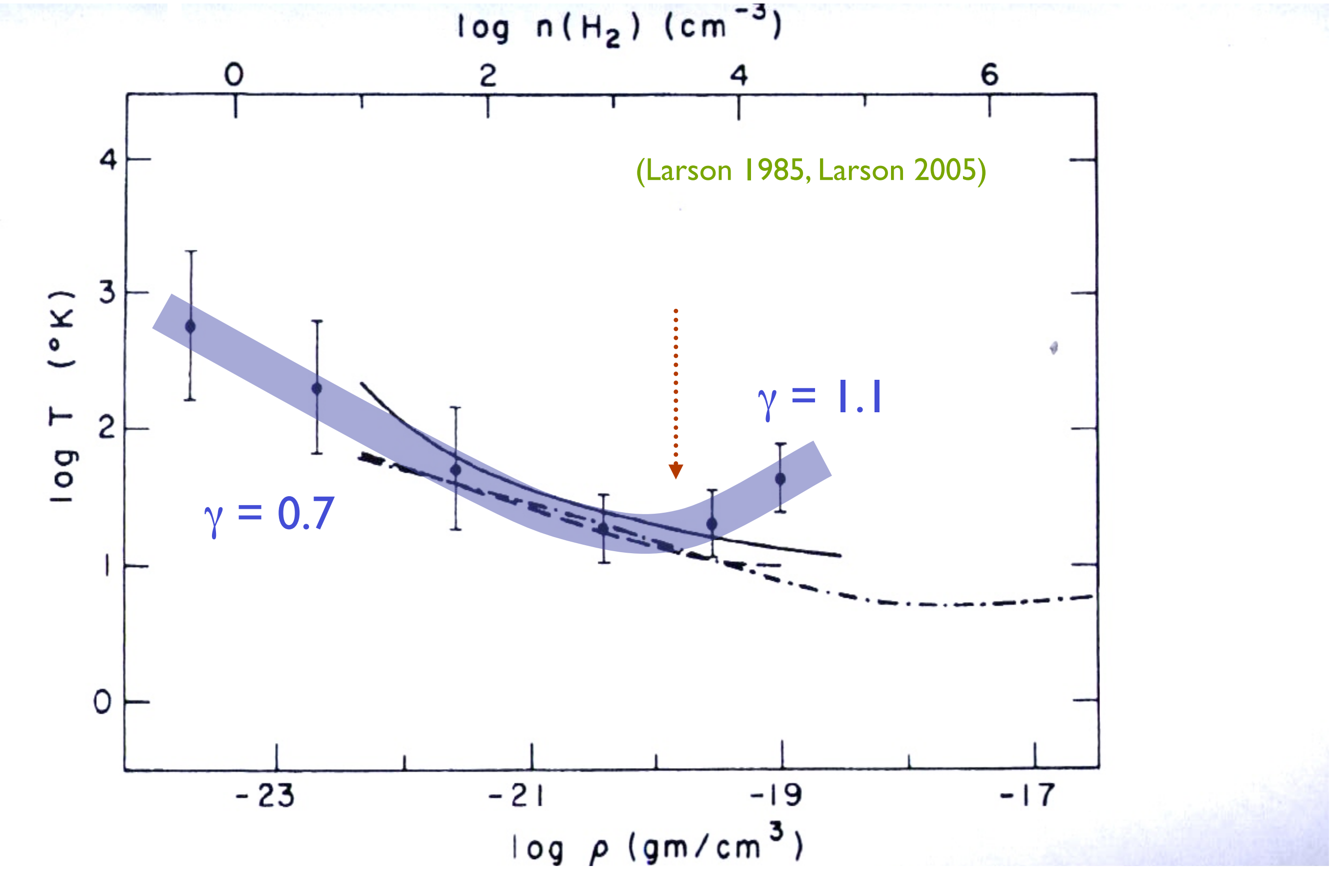
(Omukai et al. 2005)

present-day star formation



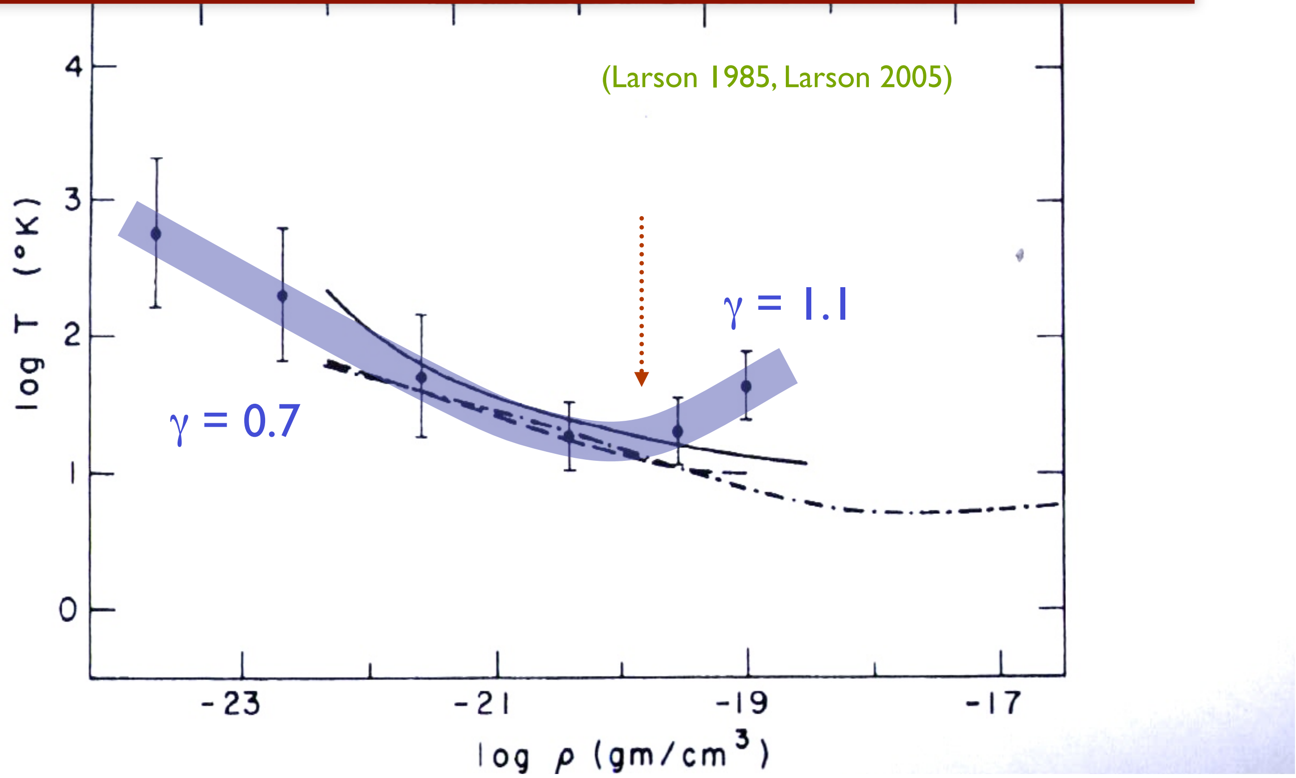
(Omukai et al. 2005, Jappsen et al. 2005, Larson 2005)

present-day star formation


(Larson 1985, Larson 2005)

present-day star formation

This kink in EOS is very insensitive to environmental conditions such as ambient radiation field
--> reason for universal for of the (Elmegreen et al. 2008)



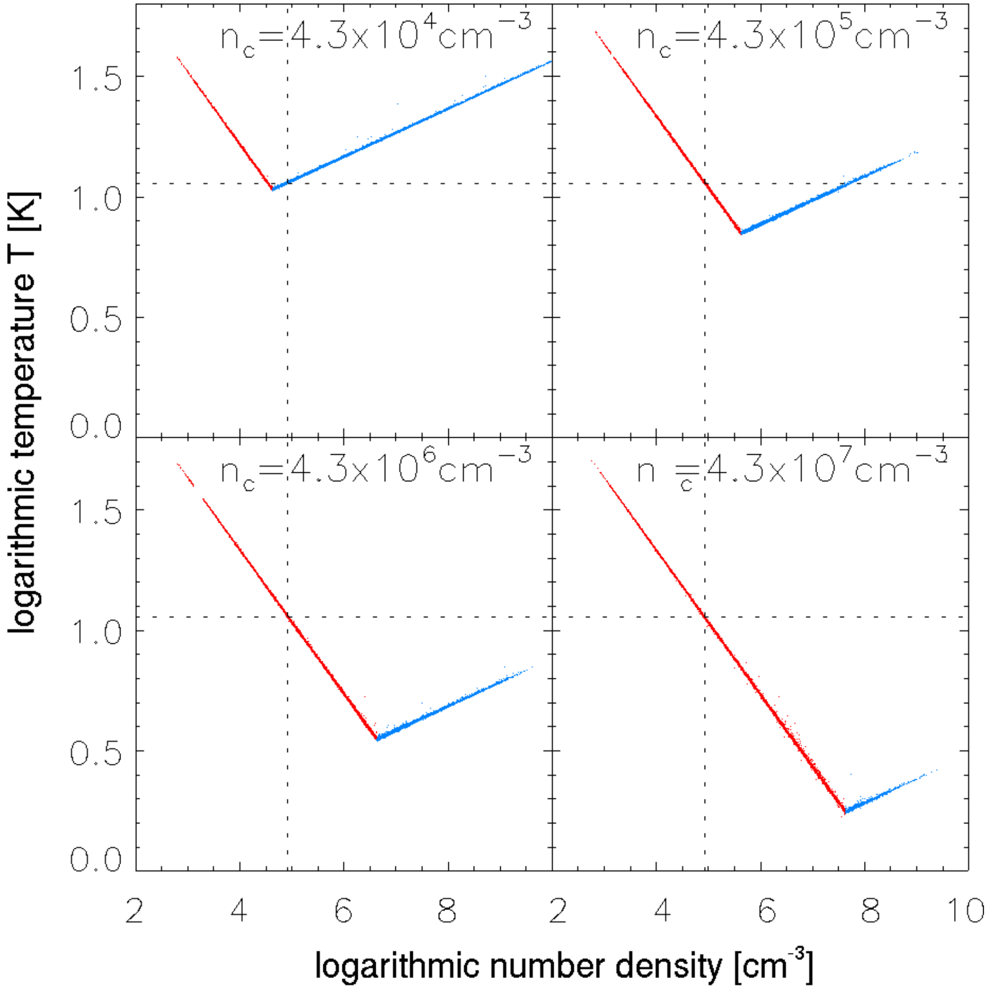
(Larson 1985, Larson 2005)

IMF from simple piece-wise polytropic EOS

$\gamma_1 = 0.7$

$\gamma_2 = 1.1$

$$\boxed{T \sim \rho^{\gamma-1}}$$



EOS and Jeans Mass:

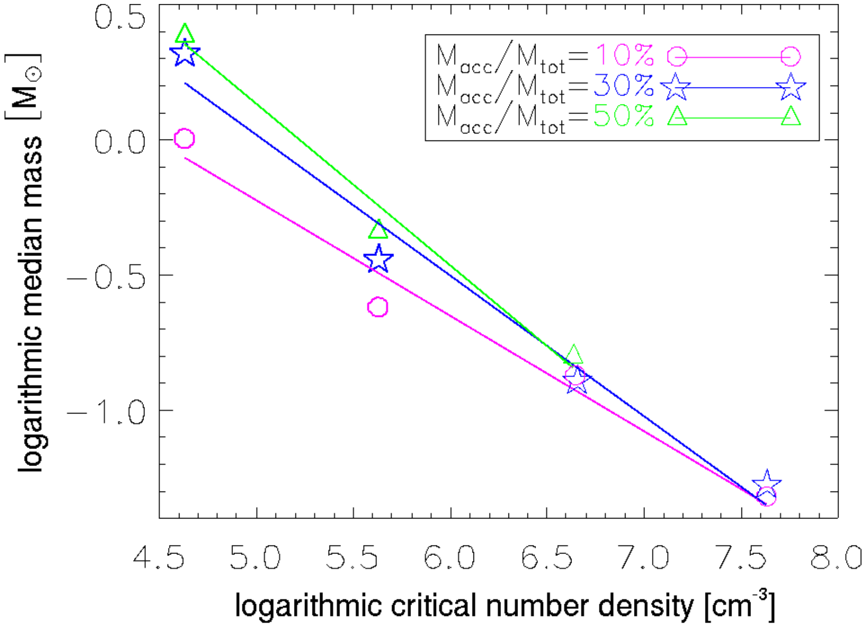
$\mathbf{p} \propto \rho^{\gamma} \rightarrow \rho \propto \mathbf{p}^{1/\gamma}$

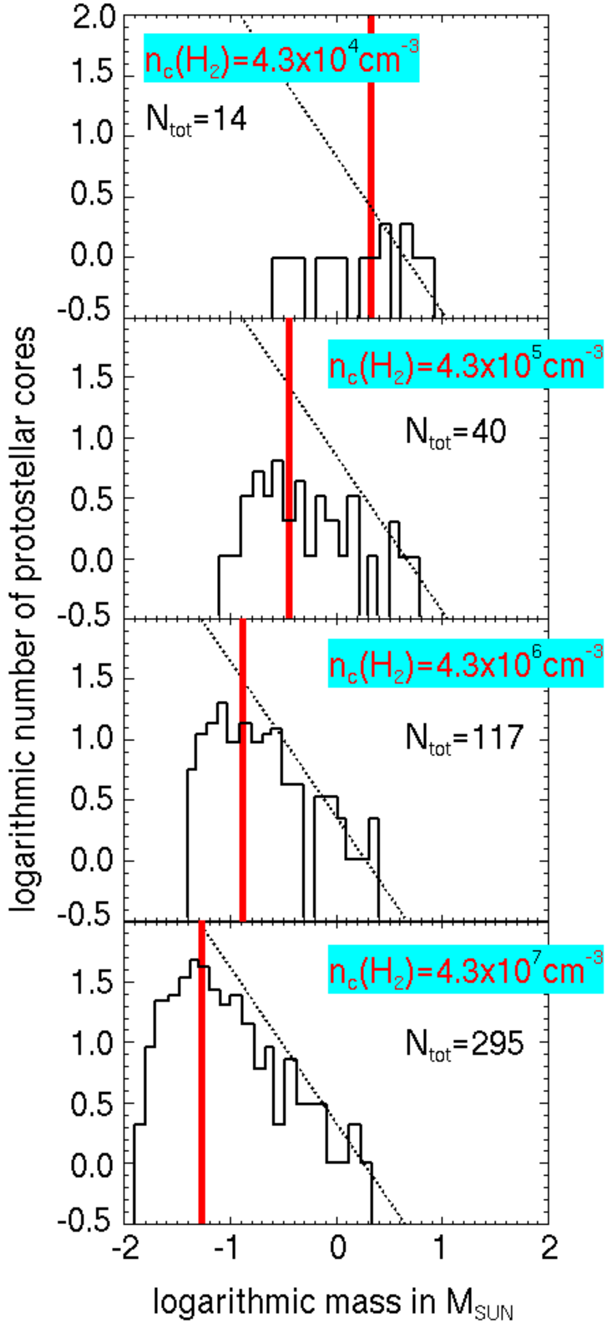
$\mathbf{M}_{\mathbf{jeans}} \propto \gamma^{3/2} \rho^{(3\gamma-4)/2}$

(Jappsen et al. 2005)

IMF from simple polytropic EOS

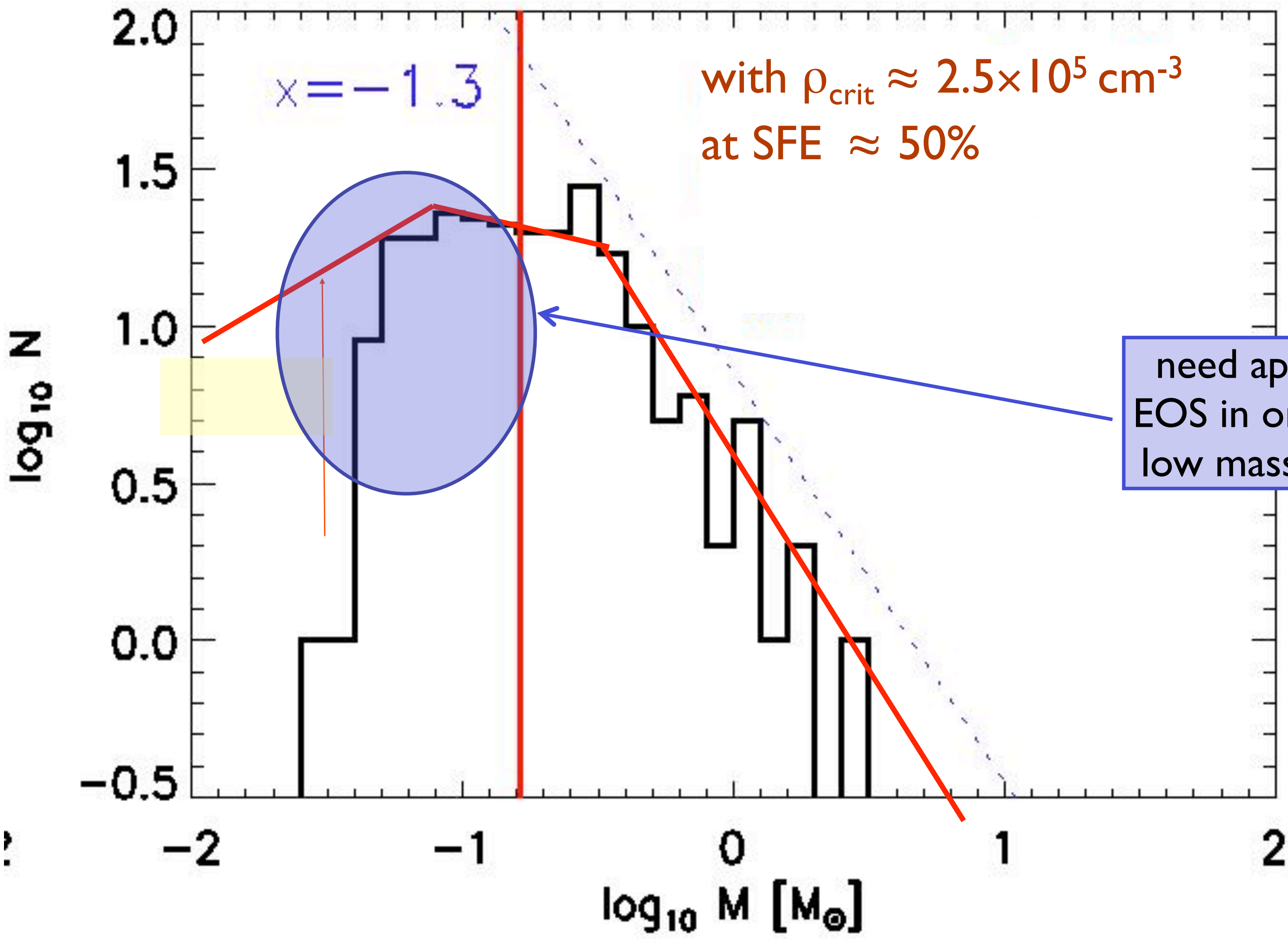
critical density ⬆ ⟹ median mass ⬇





(Jappsen et al. 2005)

IMF in nearby molecular clouds

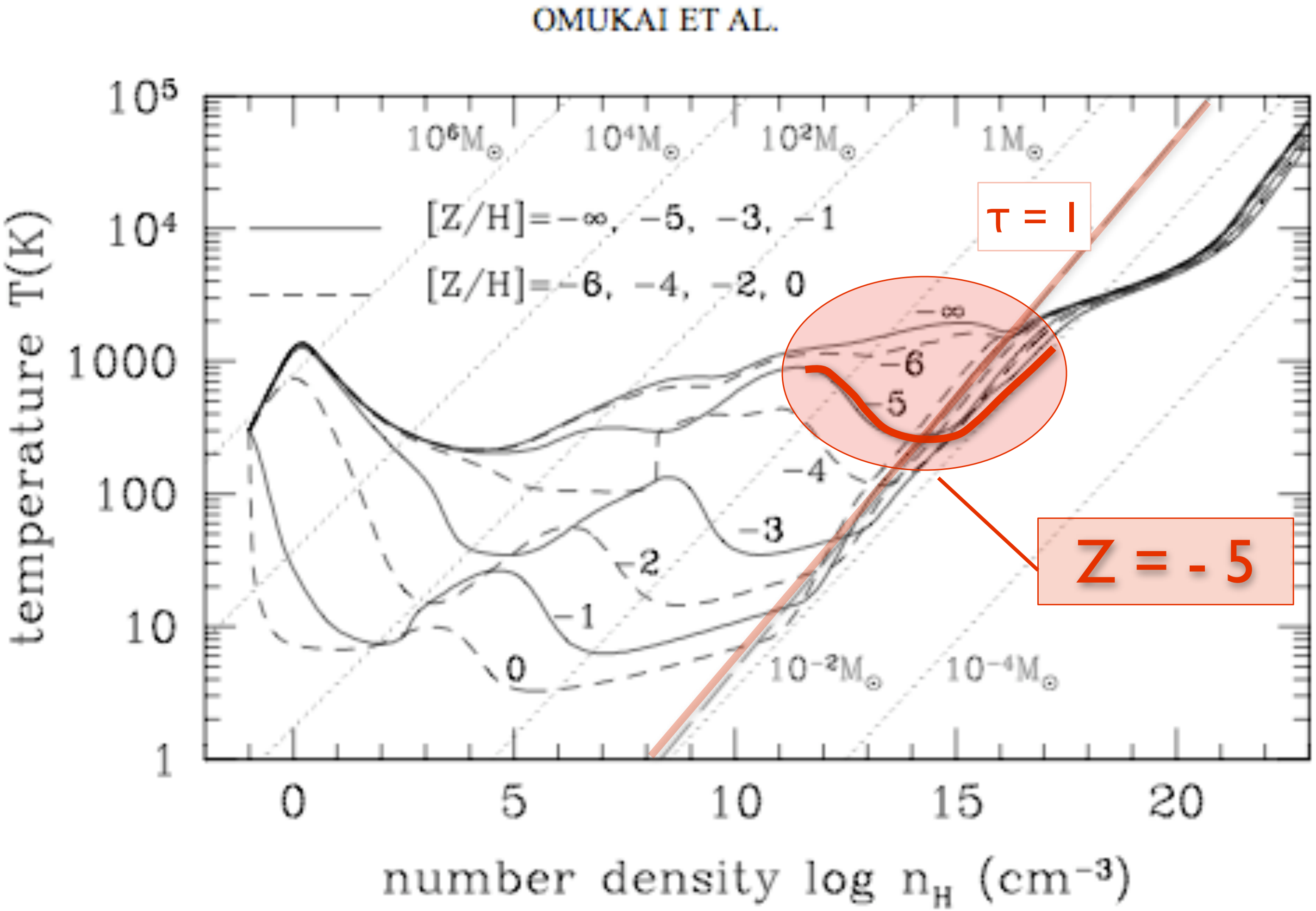


with $\rho_{crit} \approx 2.5\times10^5$ cm^{-3}
at SFE ≈ 50%

need appropriate EOS in order to get low mass IMF right

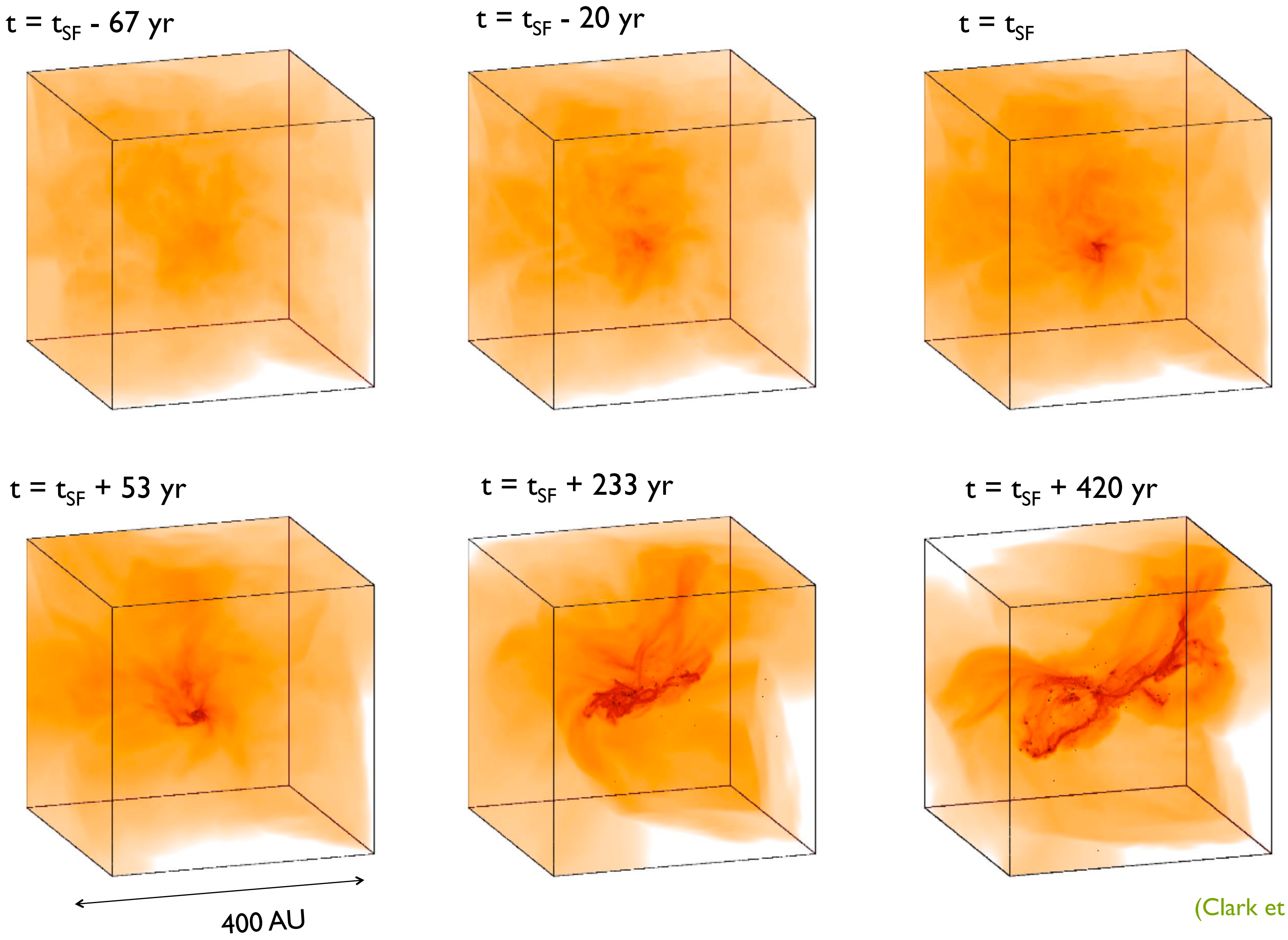
(Jappsen et al. 2005, A&A, 435, 611)

transition: Pop III to Pop II.5



(Omukai et al. 2005)

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



$t = t_{SF} - 67$ yr

$t = t_{SF} - 20$ yr

$t = t_{SF}$

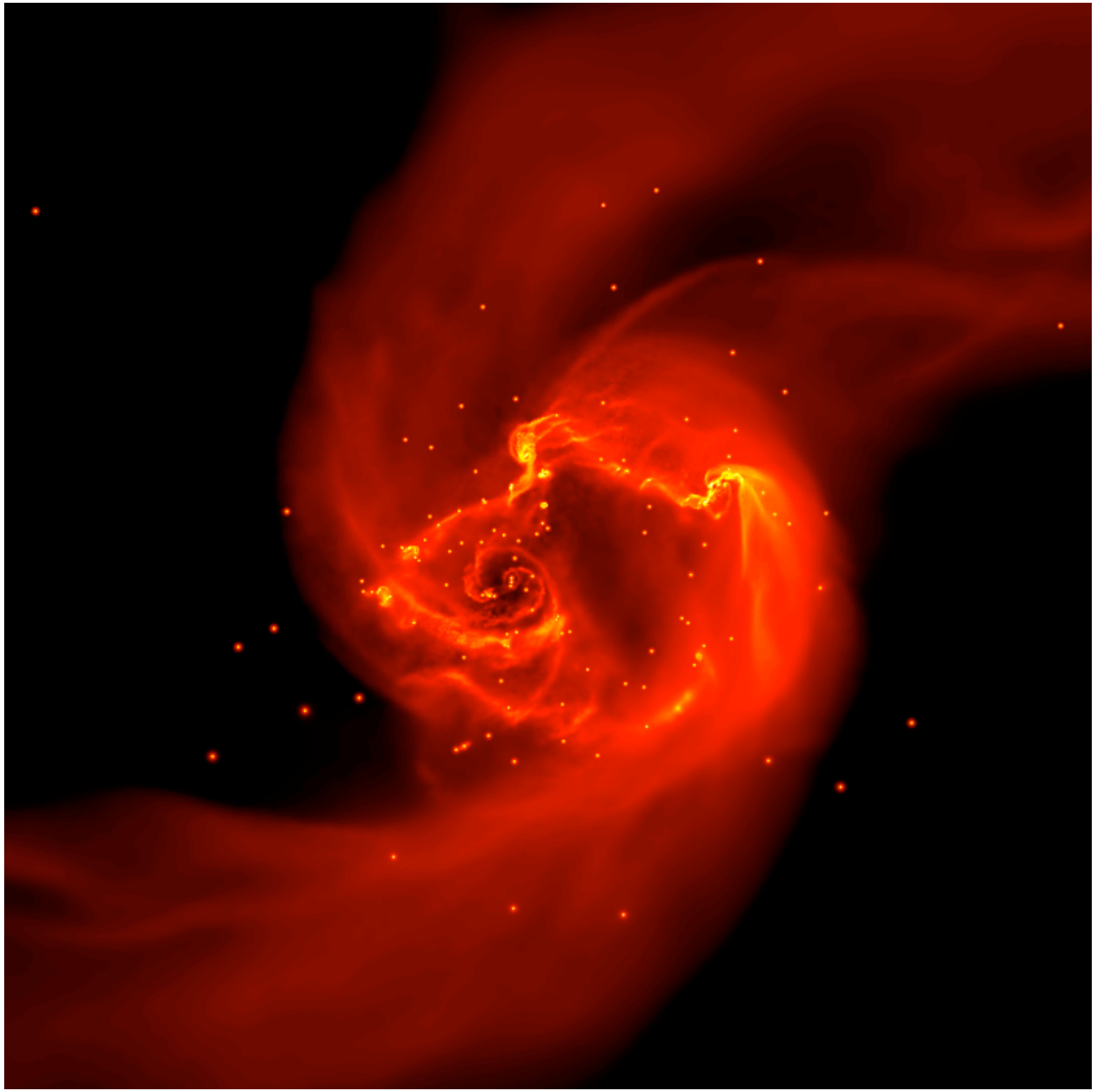
$t = t_{SF} + 53$ yr

$t = t_{SF} + 233$ yr

$t = t_{SF} + 420$ yr

(Clark et al. 2007)

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

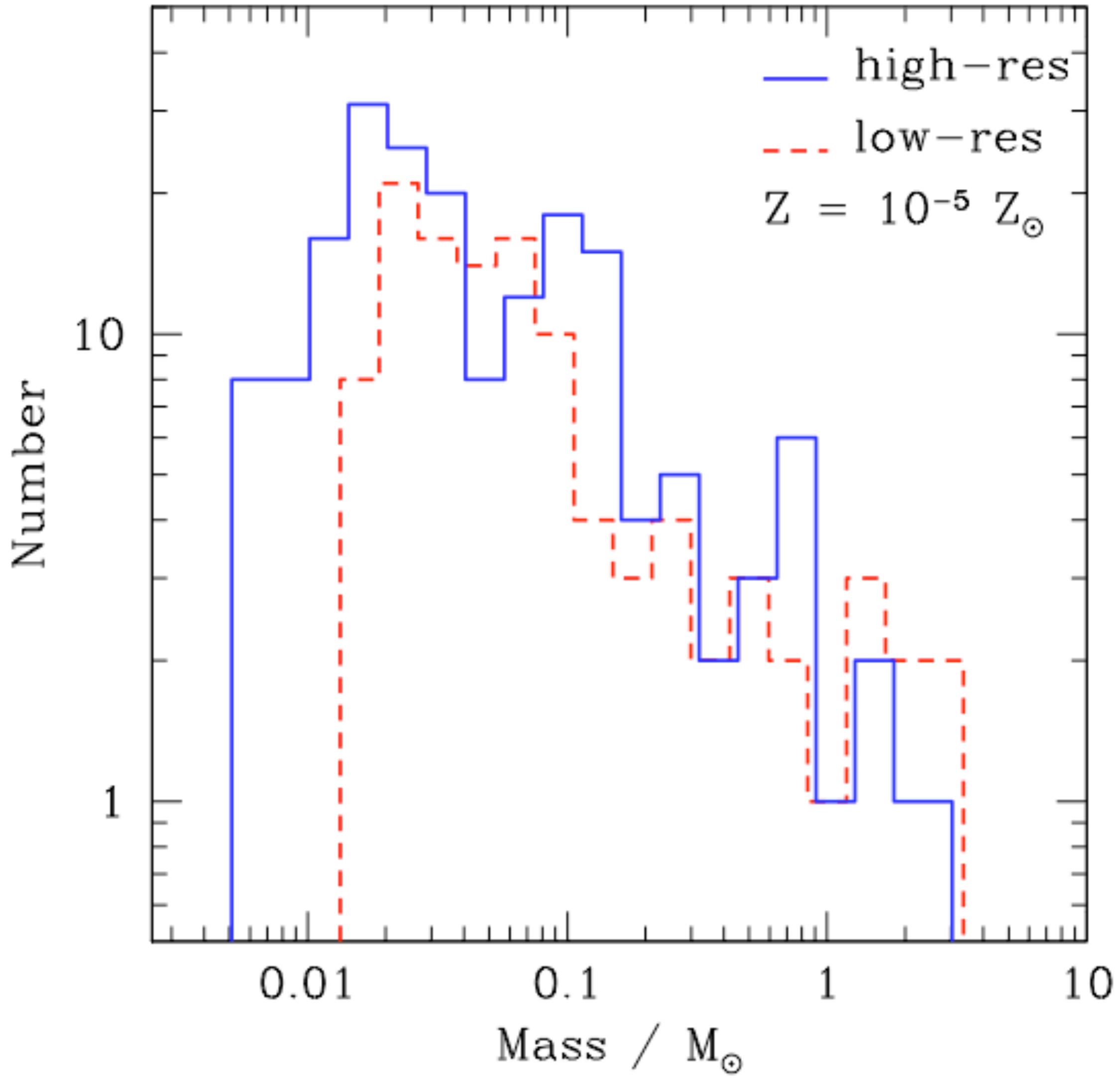


dense cluster of low-mass protostars builds up:

- 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)

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



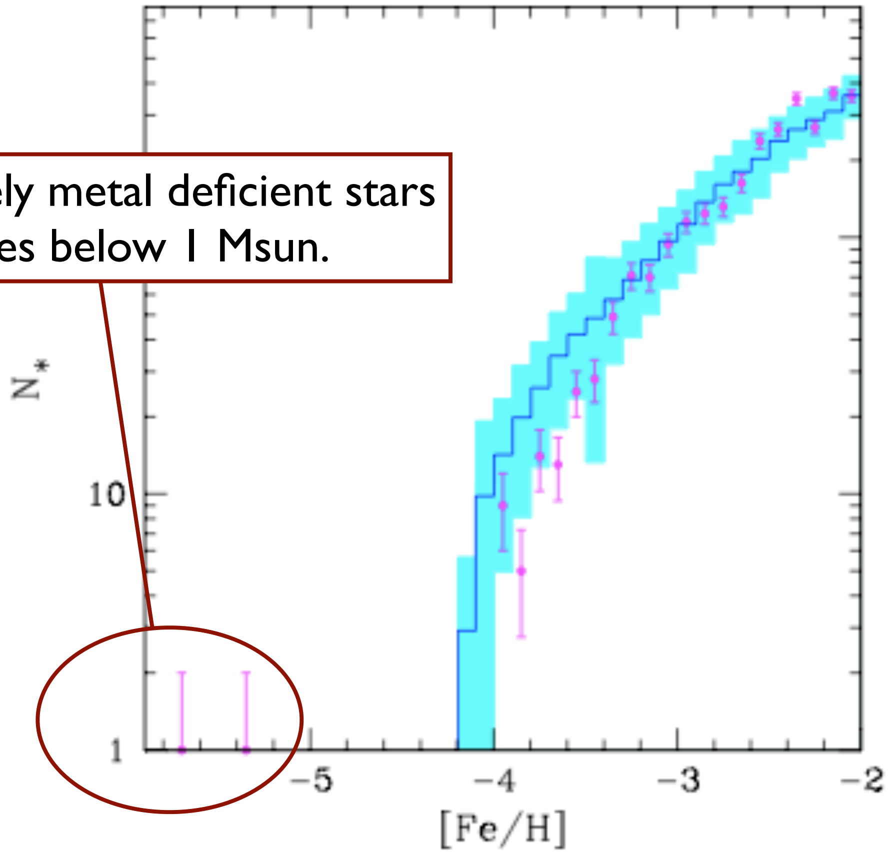
dense cluster of low-mass protostars builds up:

- mass spectrum peaks below 1 M_{sun}
- cluster VERY dense n_{stars} = 2.5 x 10^9 pc^{-3}

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

(Clark et al. 2008)

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



2 extremely metal deficient stars with masses below 1 Msun.

(plot from Salvadori et al. 2006, data from Frebel et al. 2005)

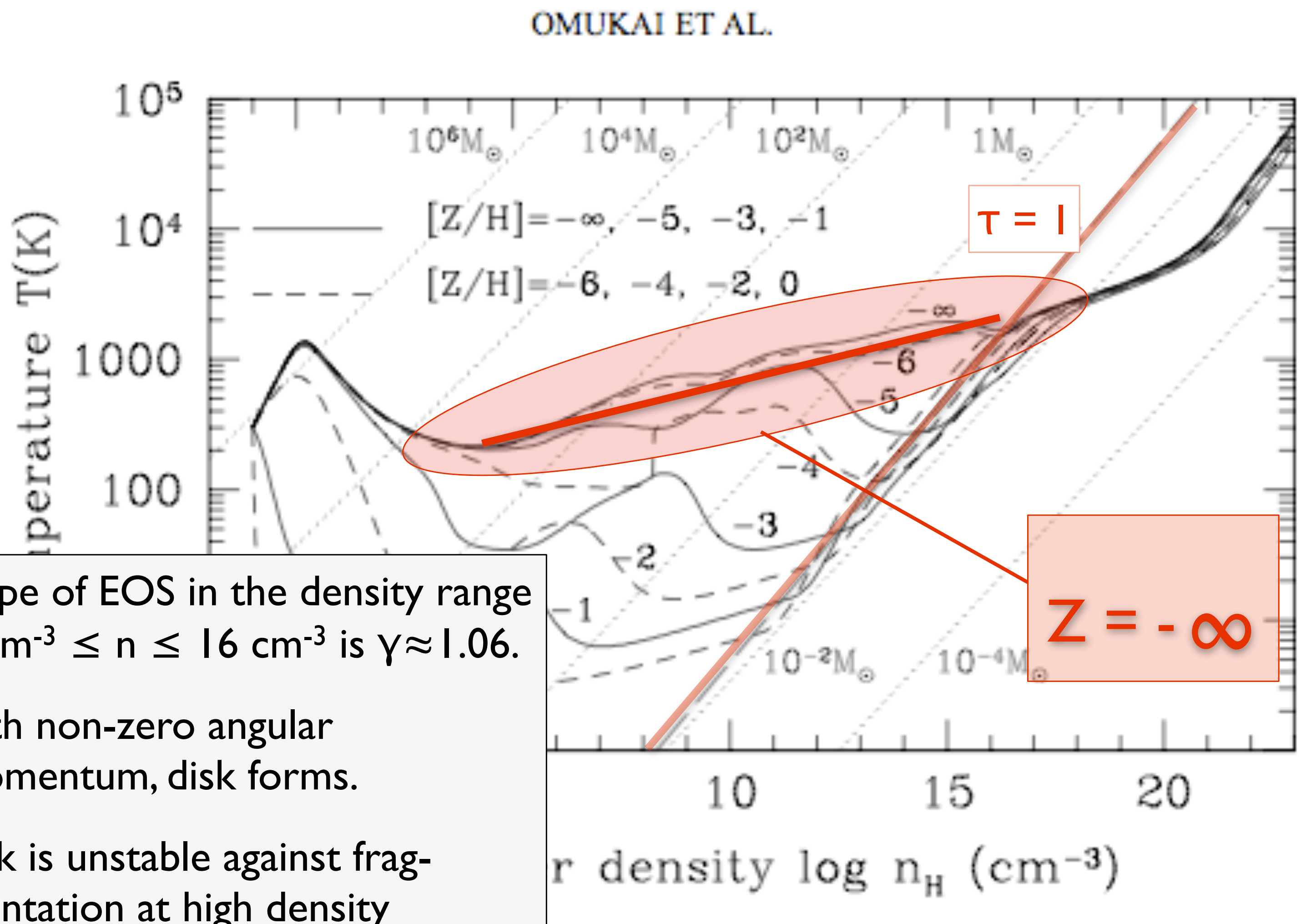
dense cluster of low-mass protostars builds up:

- mass spectrum peaks below 1 M_{sun}
- cluster VERY dense $n_{stars} = 2.5 \times 10^9\ pc^{-3}$

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

(Clark et al. 2008)

metal-free star formation



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

(Omukai et al. 2005)

metal-free star formation

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)

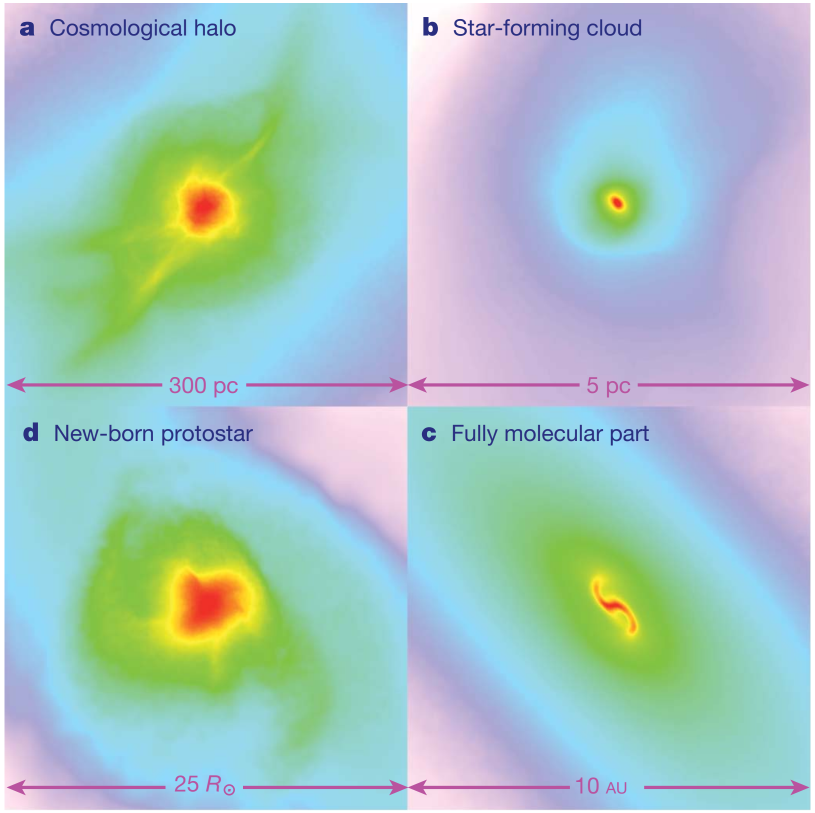
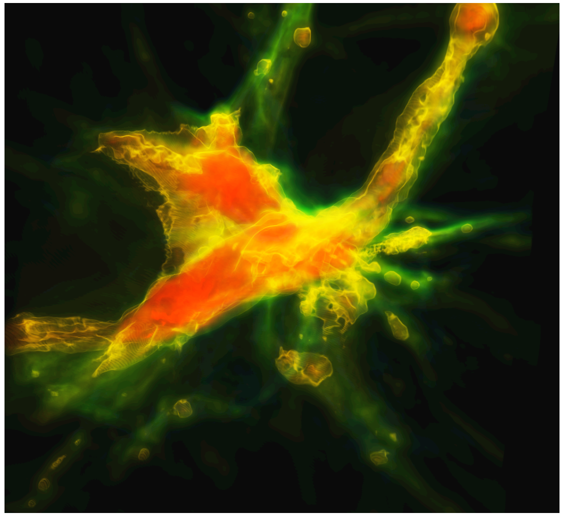


Figure 1 | Projected gas distribution around a primordial protostar. Shown is the gas density (colour-coded so that red denotes highest density) of a single object on different spatial scales. **a**, The large-scale gas distribution around the cosmological minihalo; **b**, a self-gravitating, star-forming 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
- speculation: *differences in stellar mass function*, just like in present-day star formation



(Greif et al. 2008)

turbulence in Pop III halos

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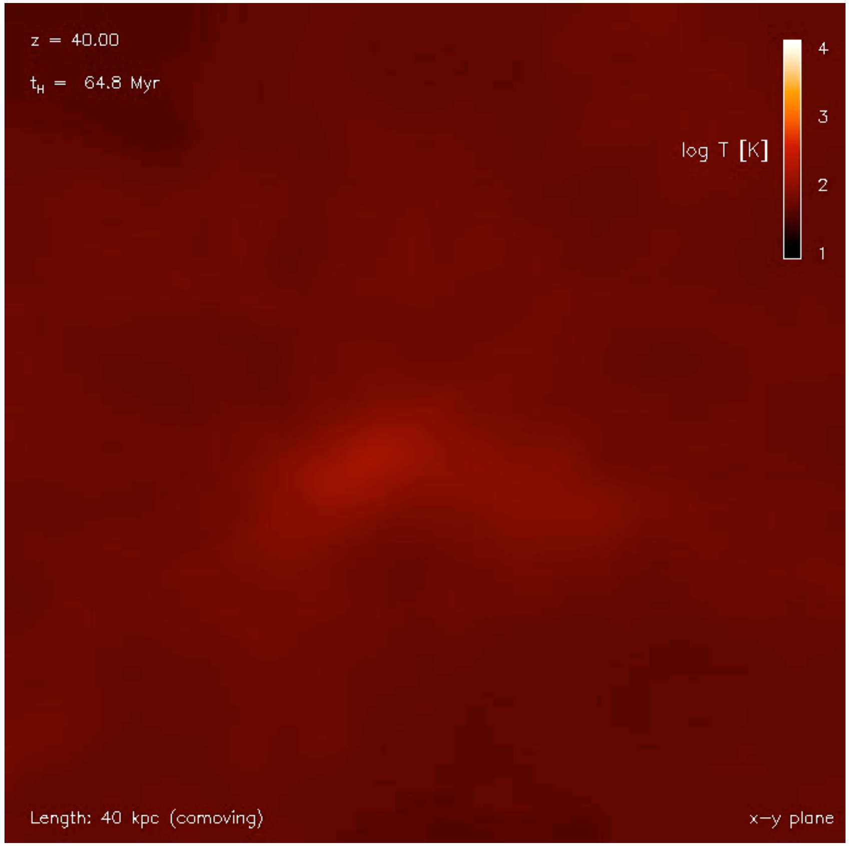
- speculation: *differences in stellar mass function*, just like in present-day star formation

turbulence developing in an atomic cooling halo

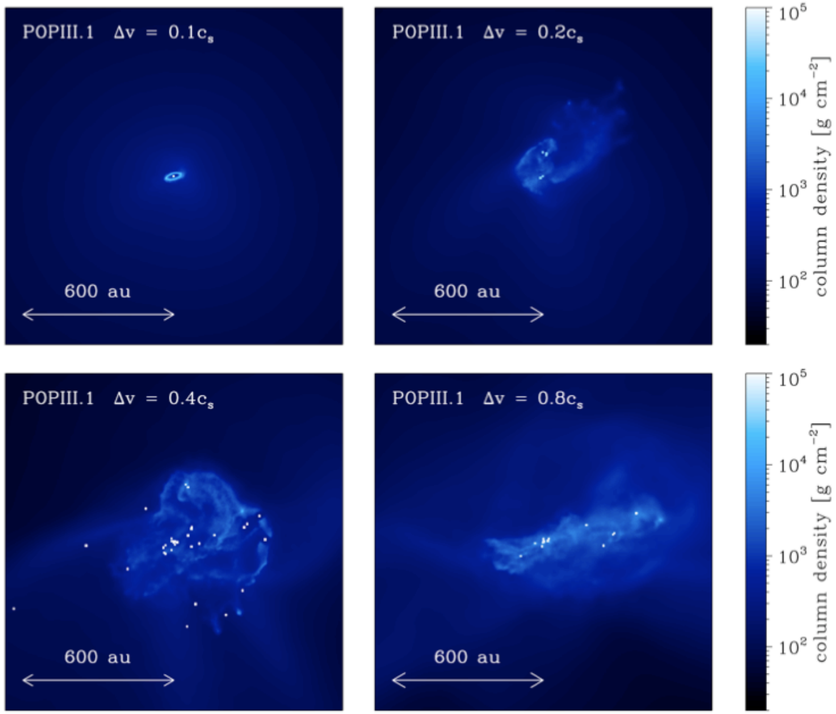


(Greif et al. 2008)

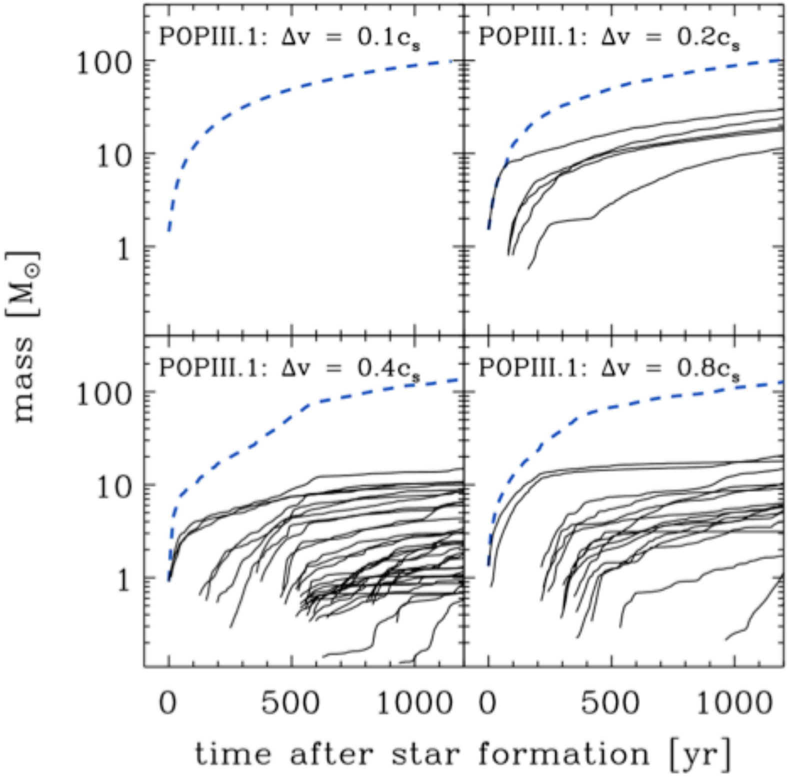
multiple Pop III stars in halo

- parameter study with different strength of turbulence using SPH: study Pop III.1 and Pop III.2 case (Clark et al., 2010a, submitted)
- 2 very high resolution studies of Pop III star formation in cosmological context
  - SPH: Clark et al. 2010b, submitted
  - Arepo: Greif et al. 2010, submitted
  - complementary approaches with interesting similarities and differences....

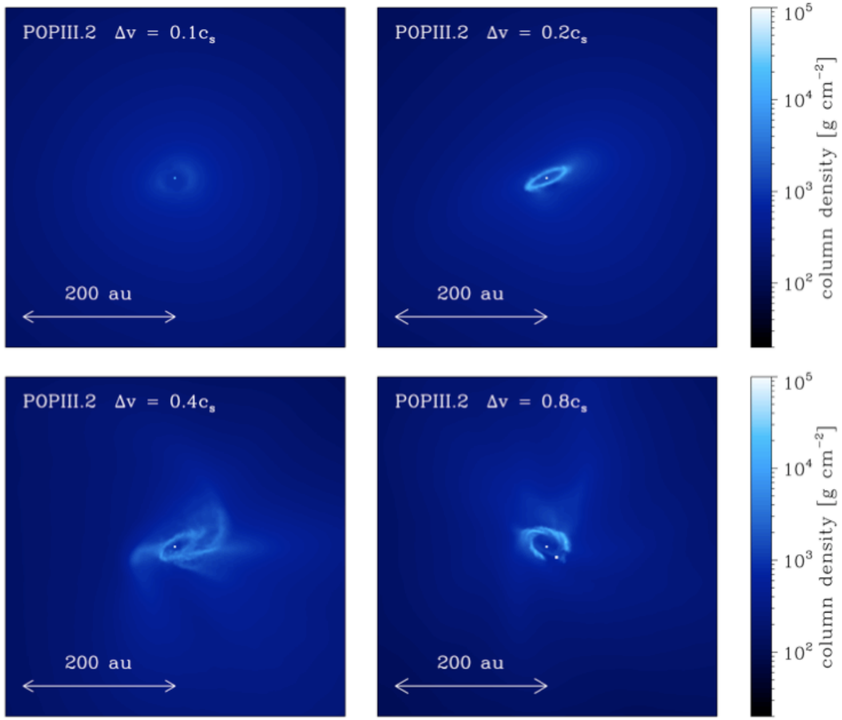
Pop III.1



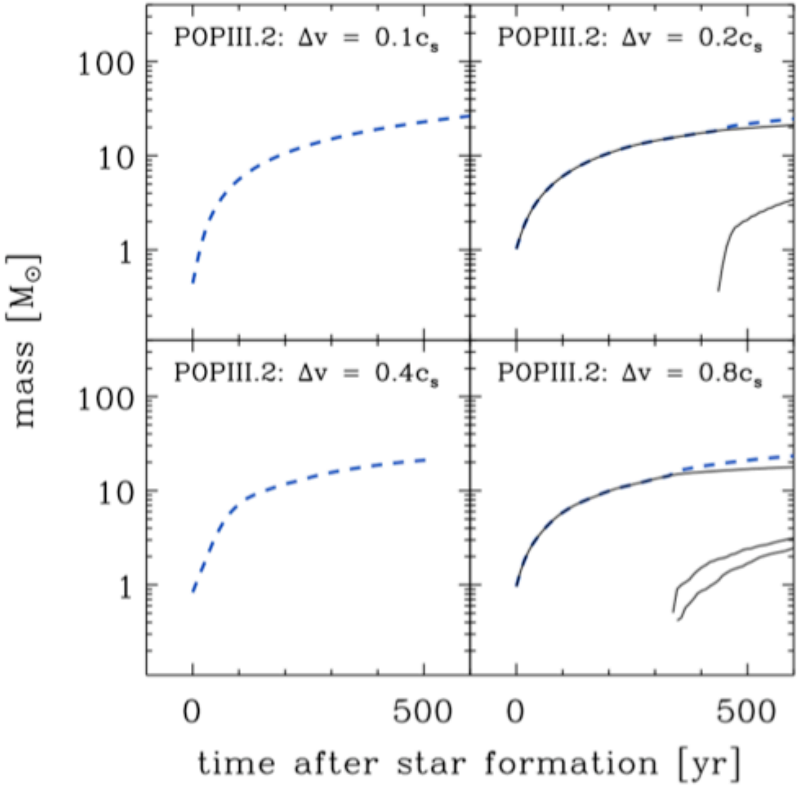
(Clark et al, 2010a, submitted)



Pop III.2



(Clark et al, 2010a, submitted)



SPH study: face on look at accretion disk

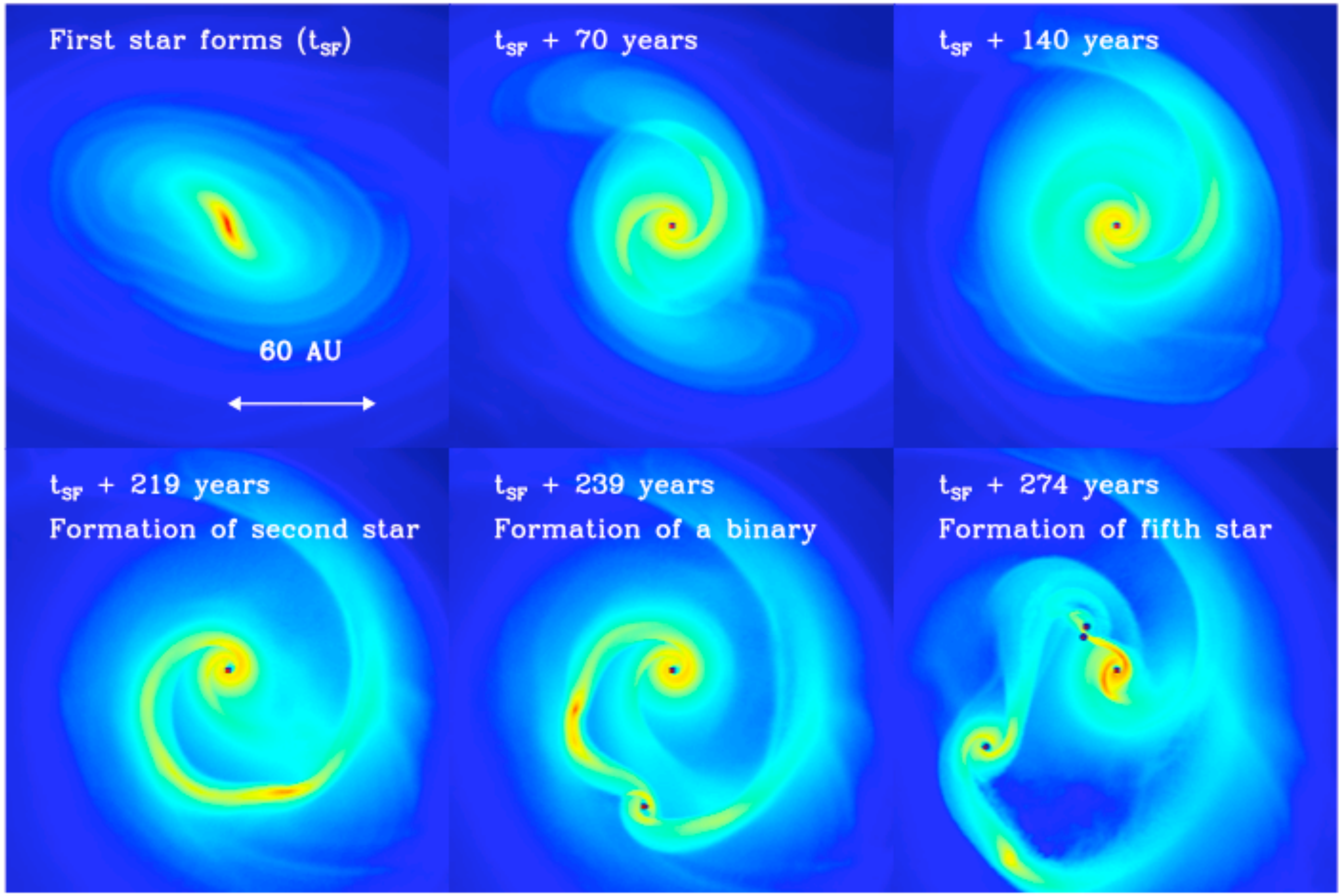


Figure 1: Density evolution in a 180 AU region around the first protostar, showing the build-up of the protostellar disk and its eventual fragmentation. The prominent two-arm spiral structure is caused by the gravitational instability in the disk, and the resulting gravitational torques provide the main source of angular momentum transport that allows disk material to accrete onto the protostar. Eventually, as mass continues to pour onto the disk from the in-falling envelope, the disk becomes so unstable that regions in the spiral arms become self-gravitating in their own right: the disk fragments and a multiple system is formed. The color table is stretched over number densities ranging from 10^{11} (dark blue) to 10^{16} cm^{-3} (red).

(Clark et al. 2010b, submitted)

SPH study: some disk parameters

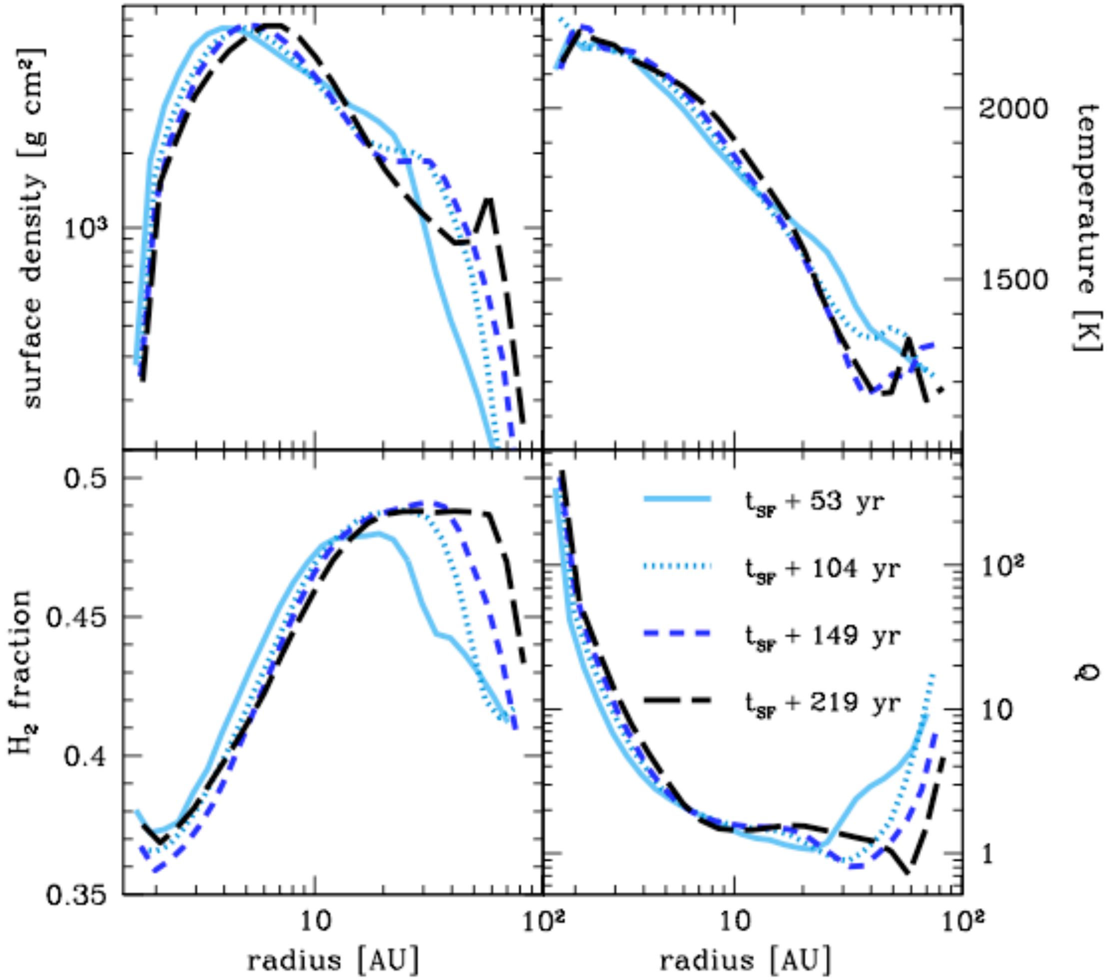


Figure 2: Radial profiles of the disk's physical properties, centered on the first protostellar core to form. The quantities are mass-weighted and taken from a slice through the midplane of the disk. In the lower right-hand plot we show the radial distribution of the disk's Toomre parameter, $Q = c_s\kappa/\pi G\Sigma$, where c_s is the sound speed and κ is the epicyclic frequency. Since our disk is Keplerian, we adopt the standard simplification, and replace κ with the orbital frequency.

(Clark et al. 2010b, submitted)

SPH study: mass accretion onto disk and onto protostars

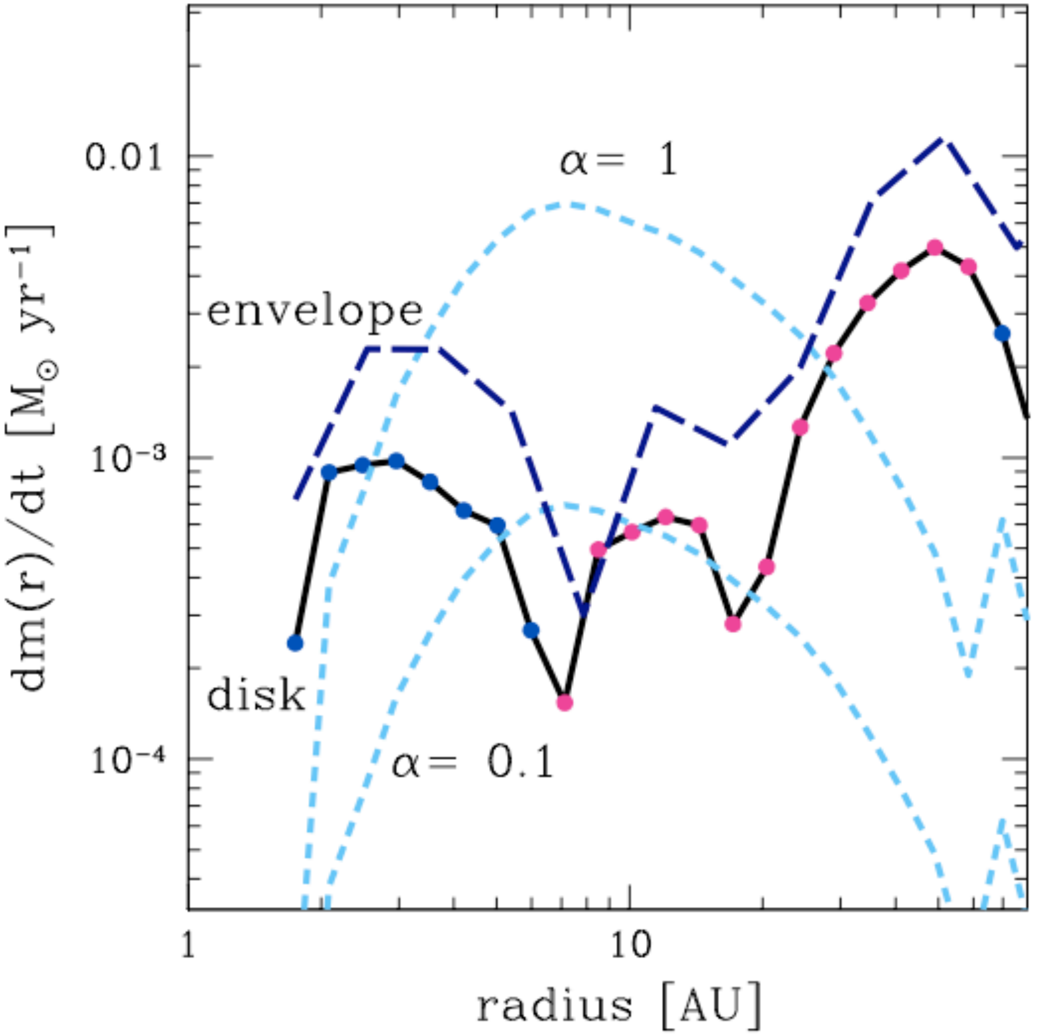
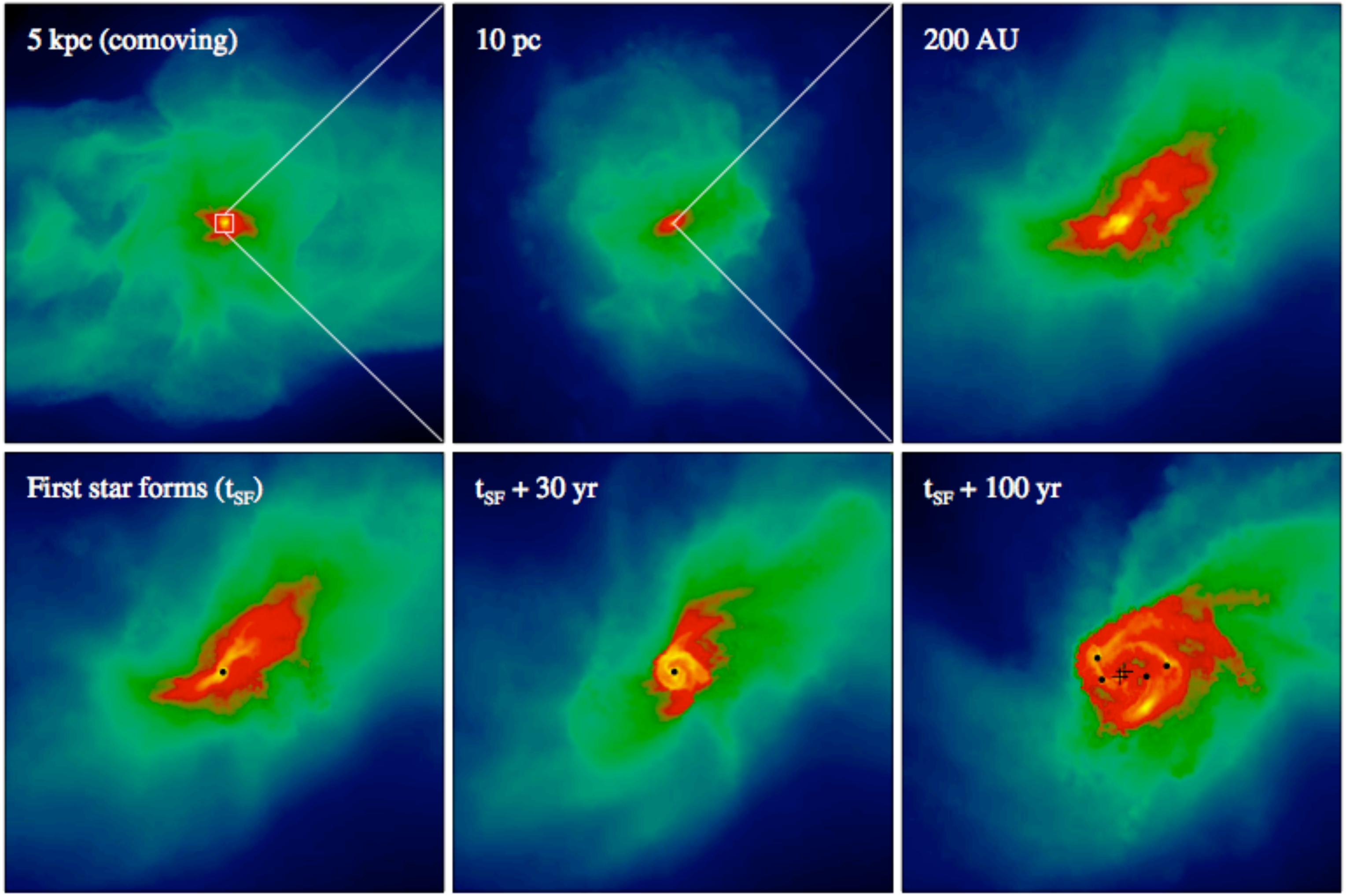


Figure 3: Mass transfer through the disk and in-falling envelope as a function of radius from the central protostar at the onset of disk fragmentation. In the case of the disk we have denoted annuli that are moving towards the protostar with blue dots, and those moving away in pink. The light blue dashed lines show the accretion rates expected from an 'alpha' (thin) disk model, where $\dot{M}(r) = 3\,\pi\,\alpha\,c_{\rm s}(r)\,\Sigma(r)\,H(r)$, with two global values of alpha and where $c_{\rm s}(r)$, $\Sigma(r)$, and $H(r)$ are (respectively) the sound speed, surface density and disk thickness at radius r.

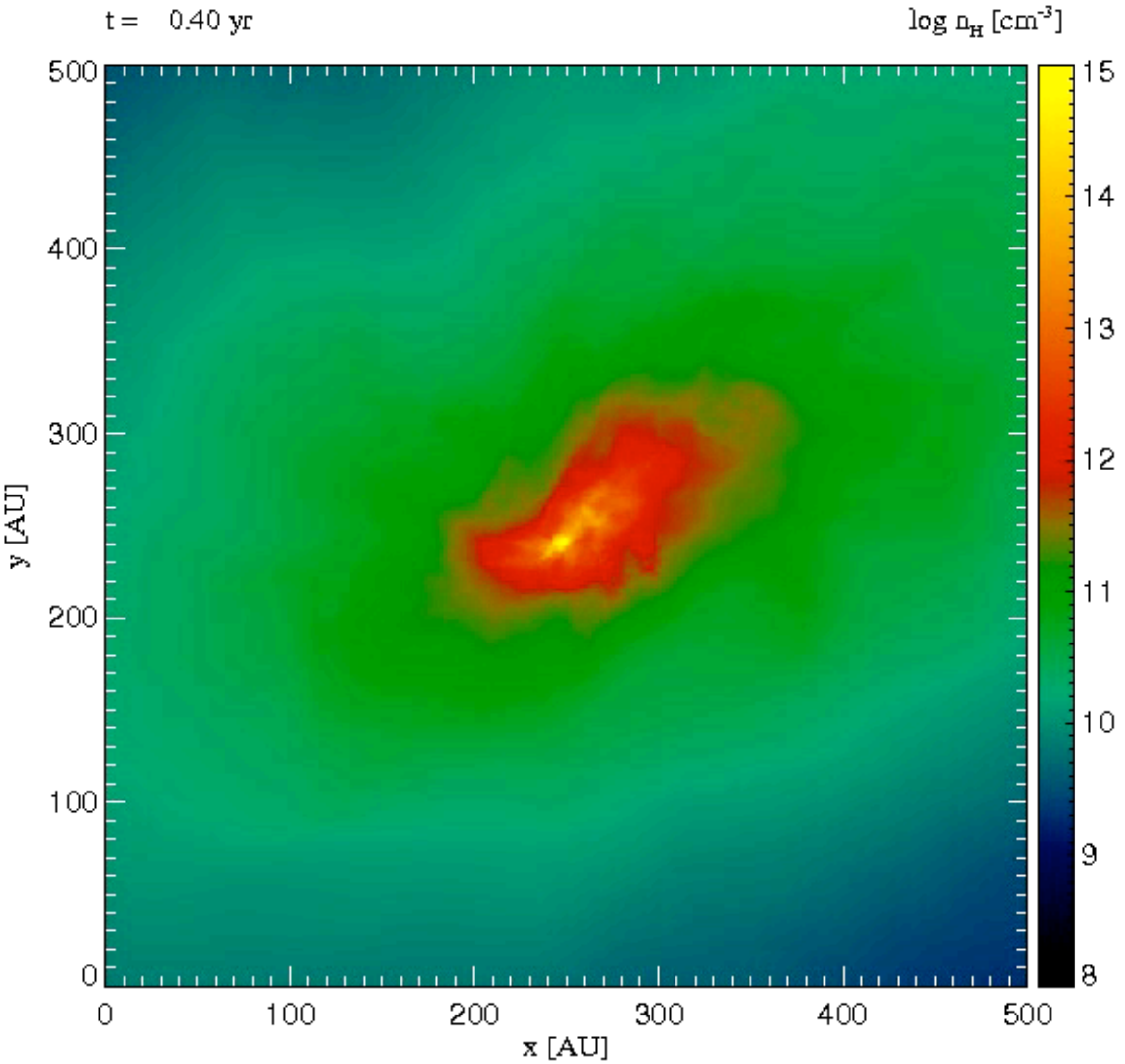
(Clark et al. 2010b, submitted)

Arepo study: surface density at different times



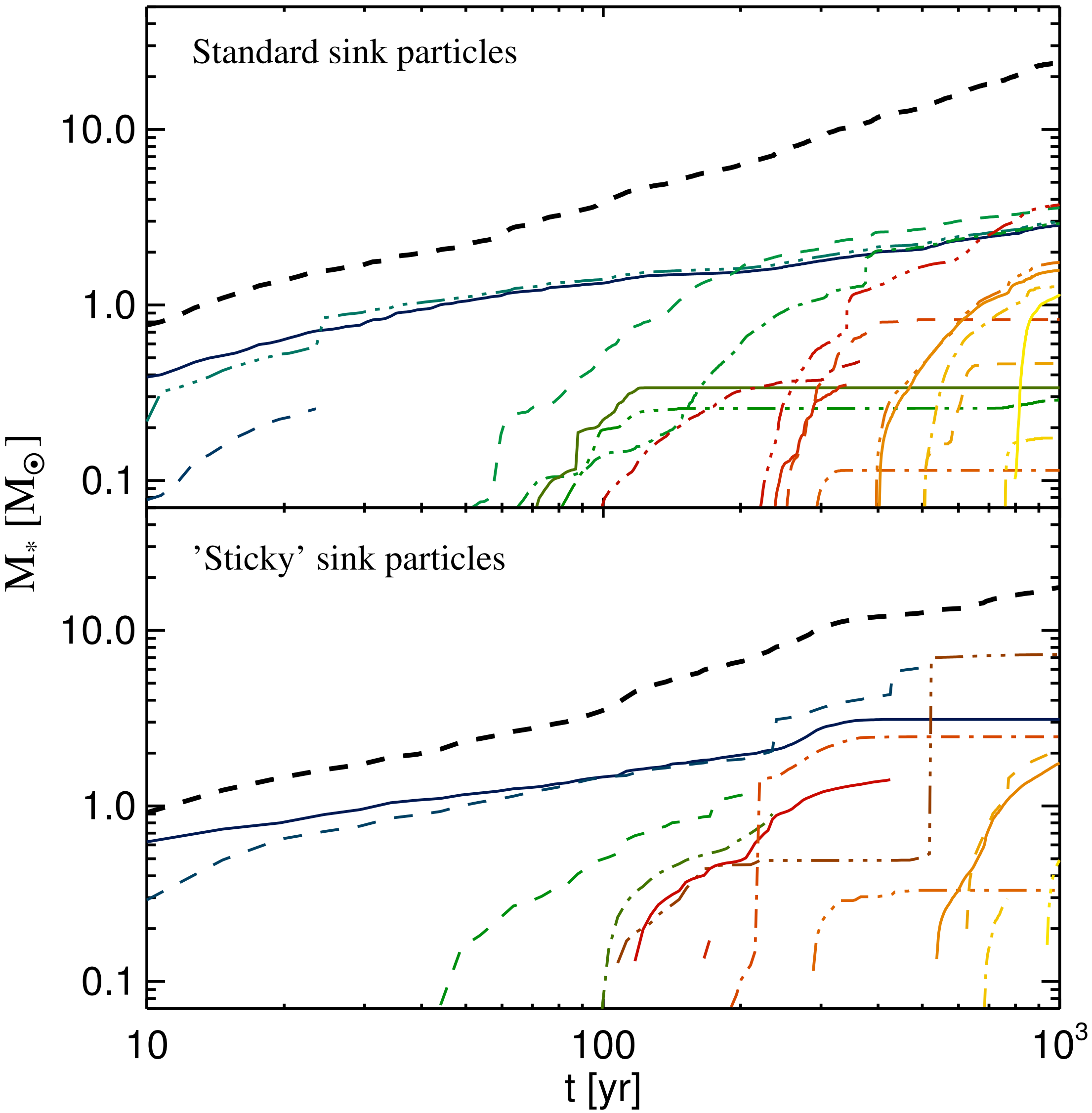
one out of five halos

(Greif et al. 2010, submitted)



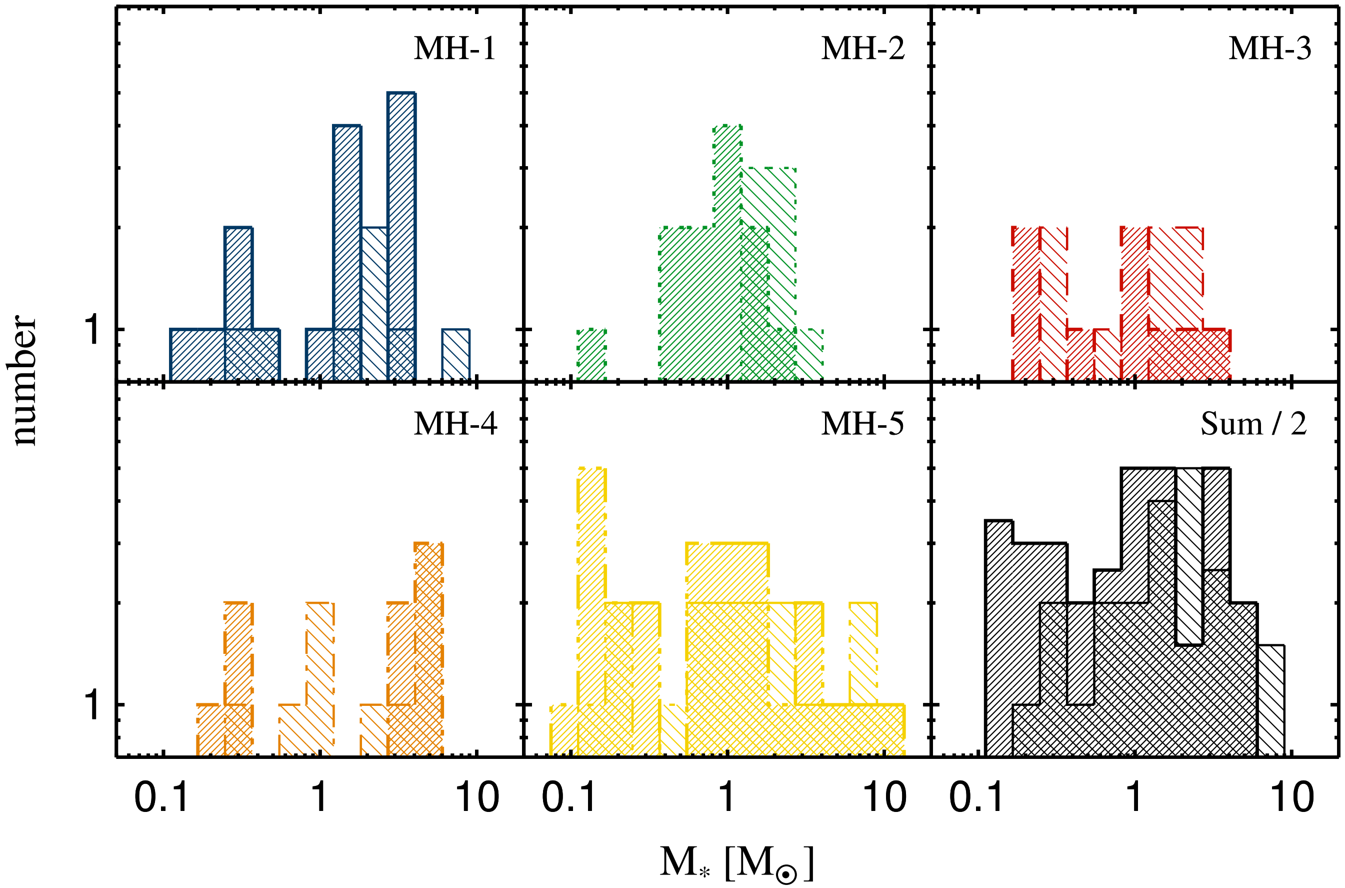
(Greif et al. 2010, submitted)

Arepo study: protostellar mass accretion rates



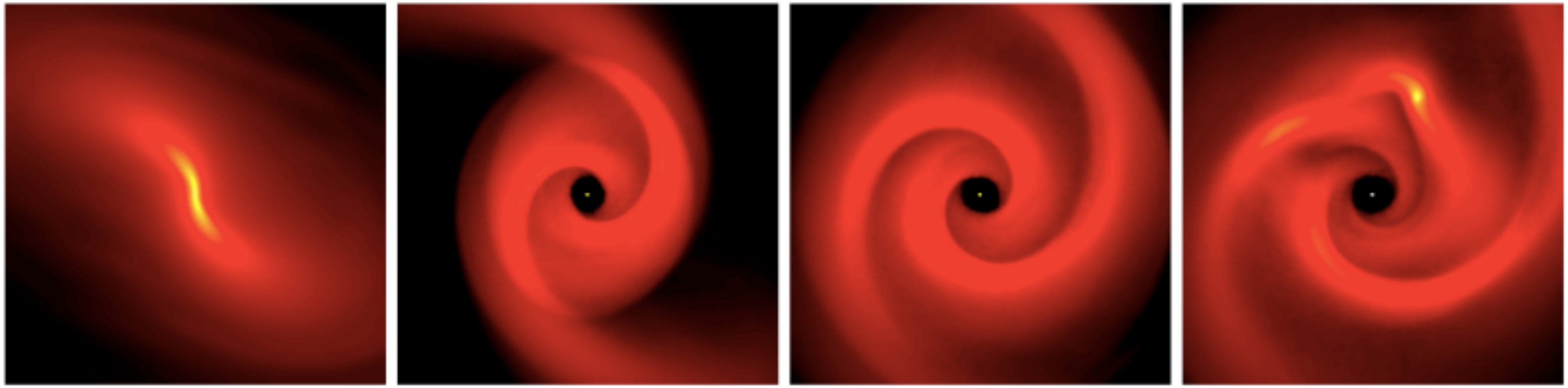
(Greif et al. 2010, submitted)

Arepo study: mass spectrum of fragments



(Greif et al. 2010, submitted)

primordial star formation



- first star formation is not less complex than present-day star formation
- brave claim: *all* Pop III stars form in multiple systems
- even braver claim: some Pop III stars fall in the mass range < 0.5 $M_\odot$ ---> they should still *be around*!!!!

questions

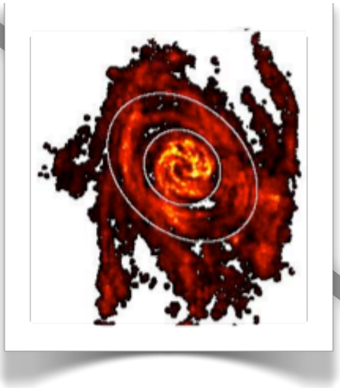
- is claim of Pop III stars with $M \sim 0.5\ M_\odot$ really justified?
  - stellar collisions
  - magnetic fields
  - radiative feedback
- how would we find them?
  - spectral features
- where should we look?
- what about magnetic fields?

agenda

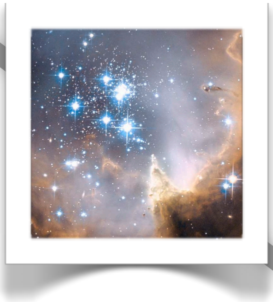
decreasing spatial scales

present days

early universe

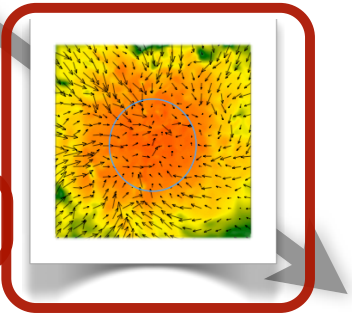


Accretion onto disk galaxies



High-mass star formation

First star formation



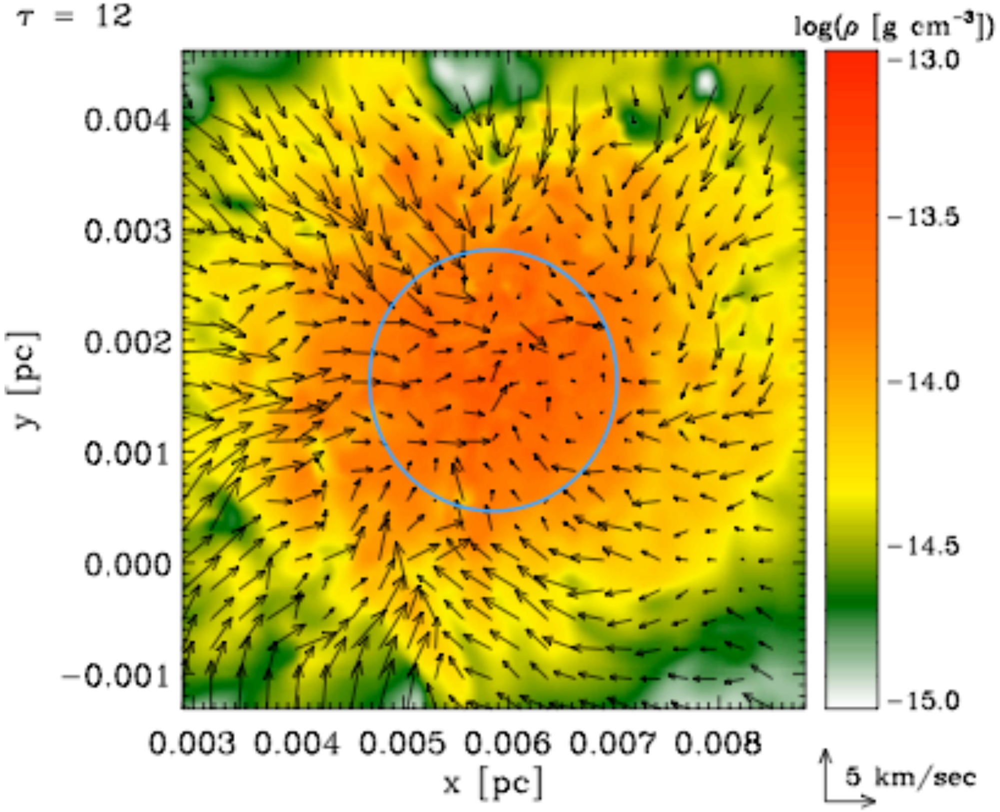
Magnetic fields in the primordial universe

B fields in the early universe?

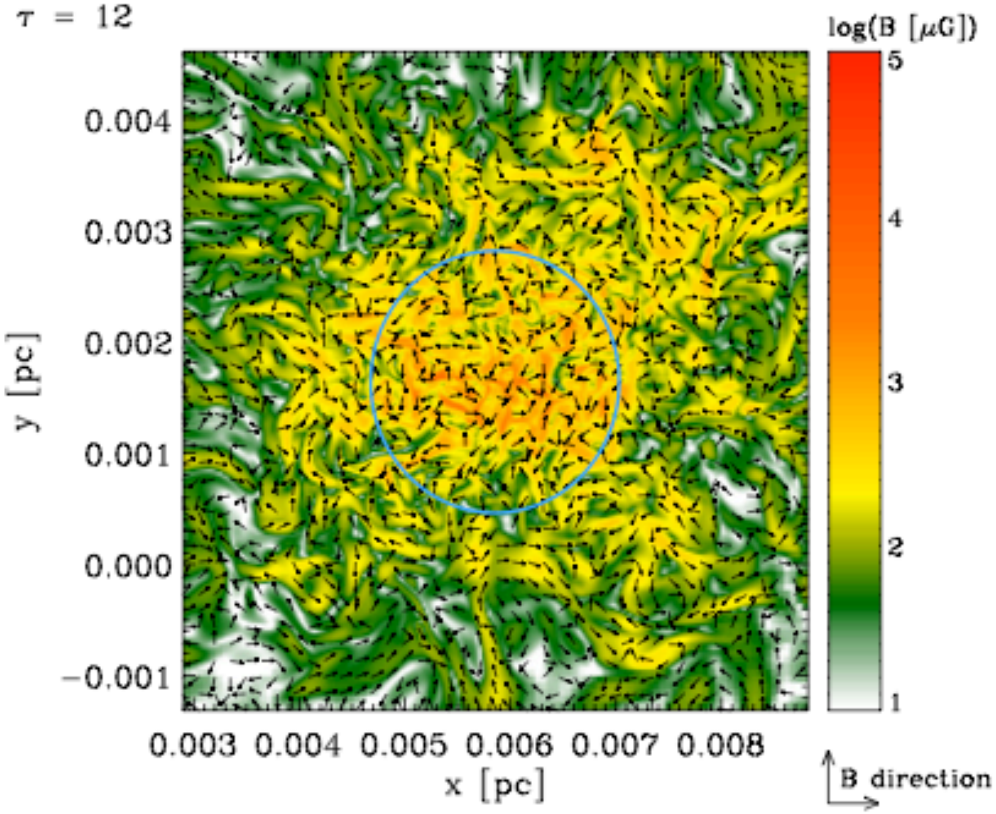
- we know the universe is magnetized (now)
- knowledge about B-fields in the high-redshift universe is extremely uncertain
  - inflation / QCD phase transition / Biermann battery / Weibel instability
- they are thought to be extremely small
- however, THIS MAY BE WRONG!

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 at redshift z ~ 20
- *method:* solve ideal MHD equations with very high resolution
  - grid-based AMR code FLASH (effective resolution 65536^3)

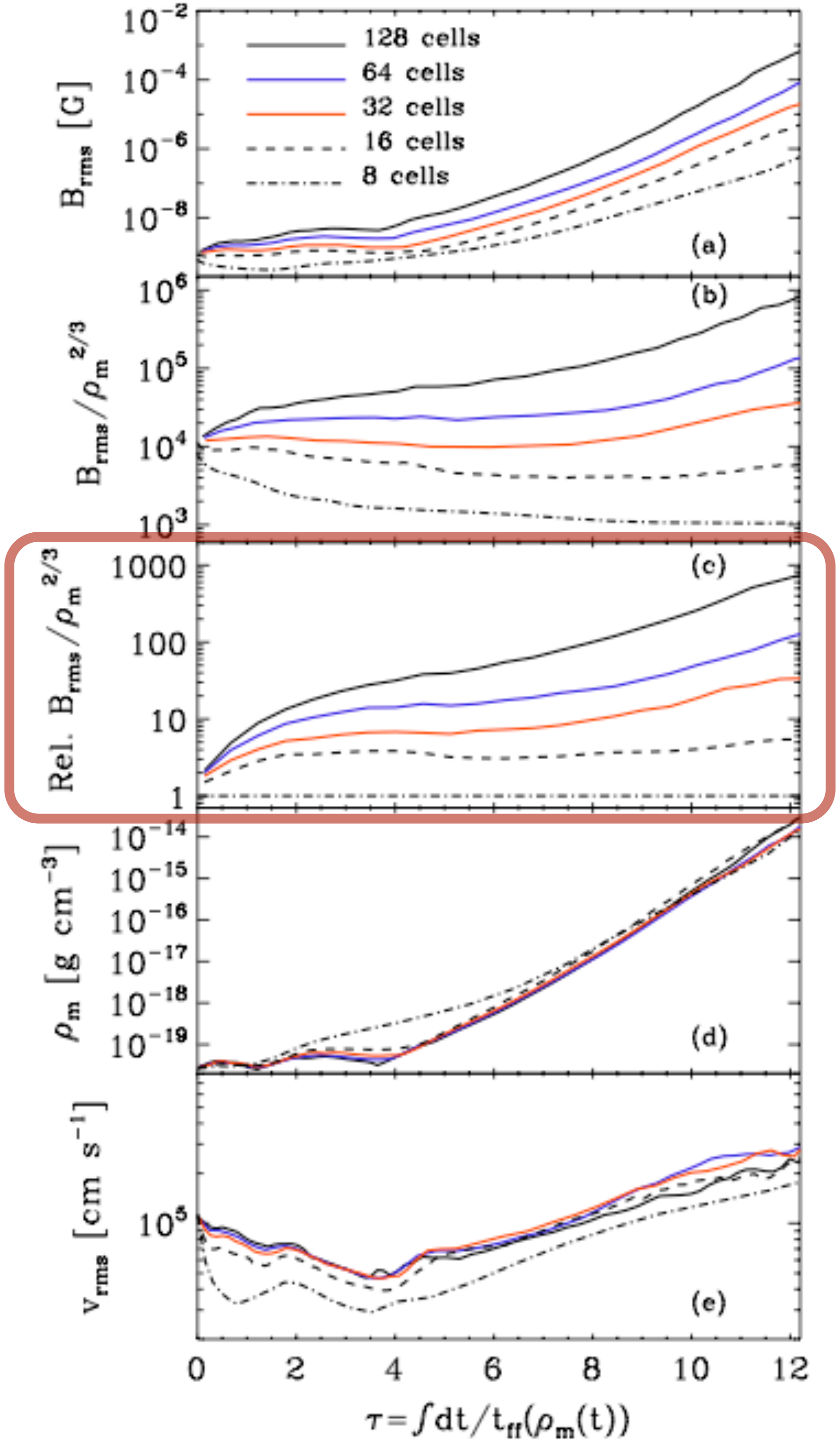


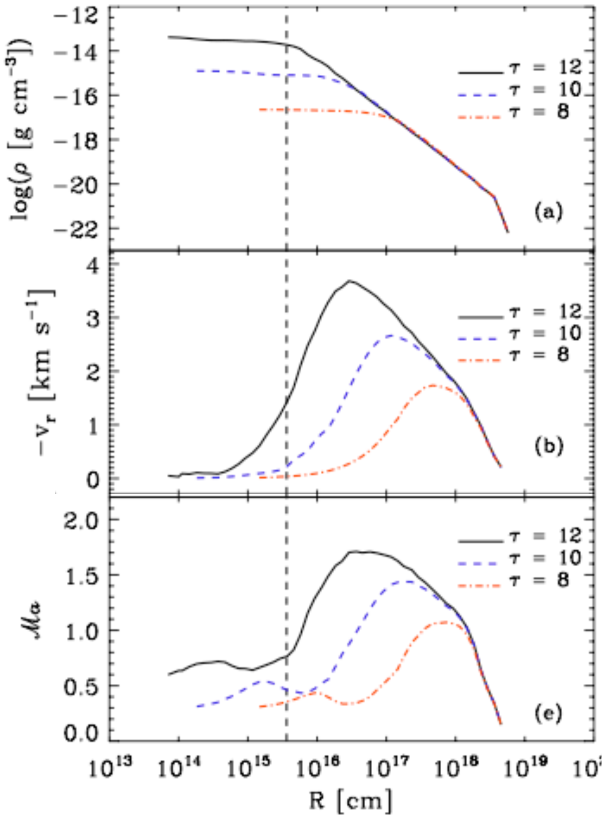
magnetic field structure



density structure

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





radial density profile

radial velocity profile

Mach number profile

Field amplification during first collapse seems unavoidable.

QUESTIONS:

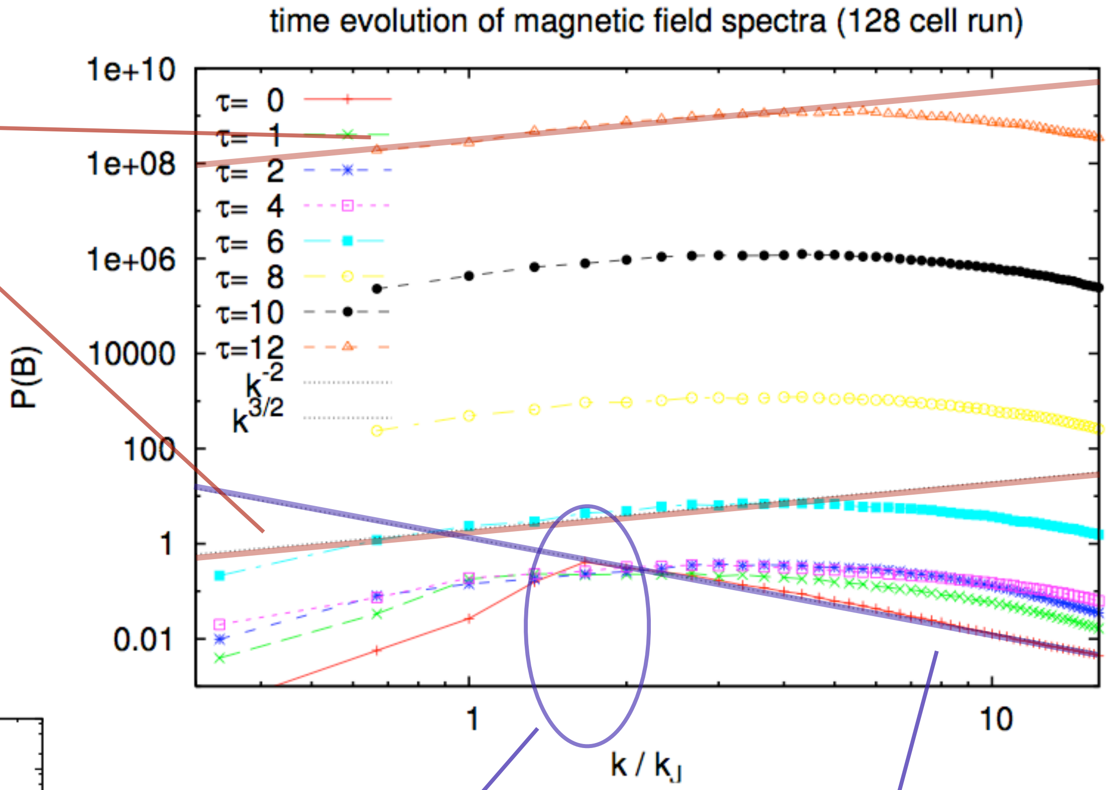
- Is it really the small scale dynamo?
- What is the saturation value?
  Can the field reach dynamically important strength?

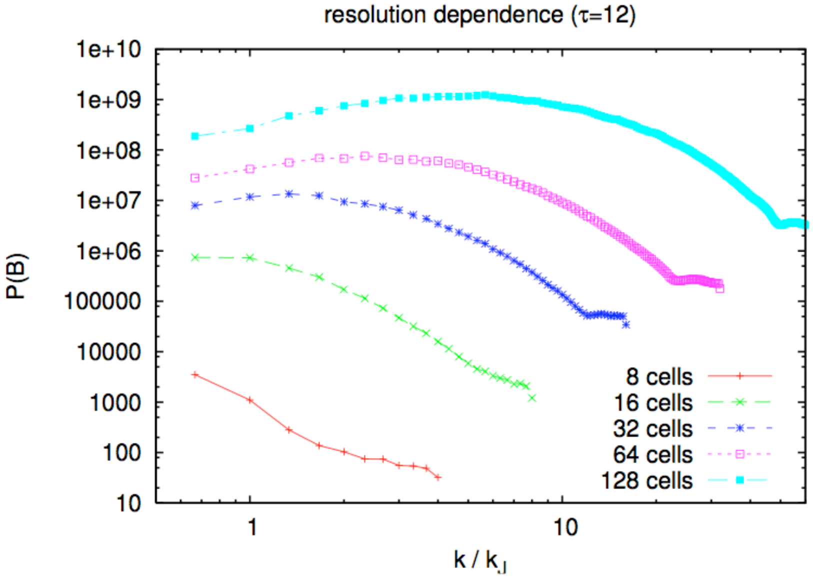
(Sur et al. 2010, ApJ, 721, L734)

analysis of magnetic field spectra

Slope +3/2 of Kazantsev theory

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



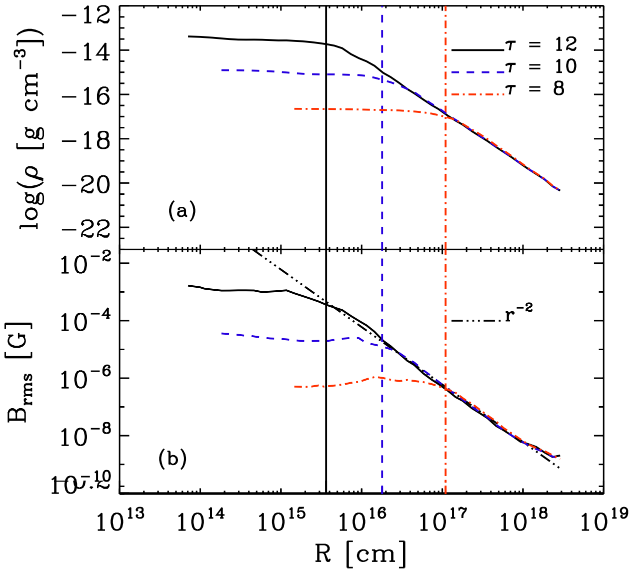


initial peak of B fluctuation spectrum

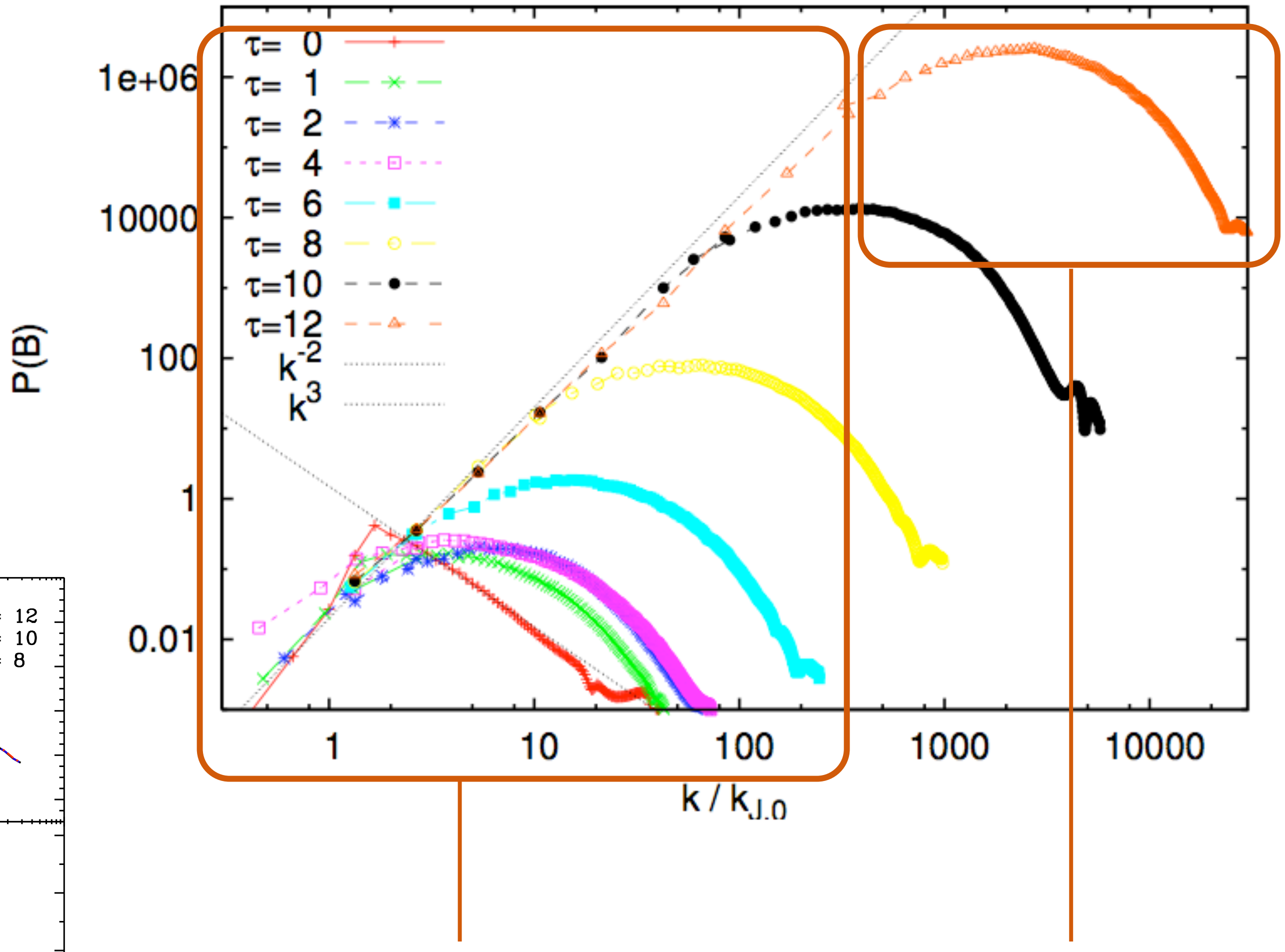
initial slope of B fluctuations

(Federrath et al., in prep.)

analysis of magnetic field spectra



time evolution of magnetic field spectra (128 cell run)

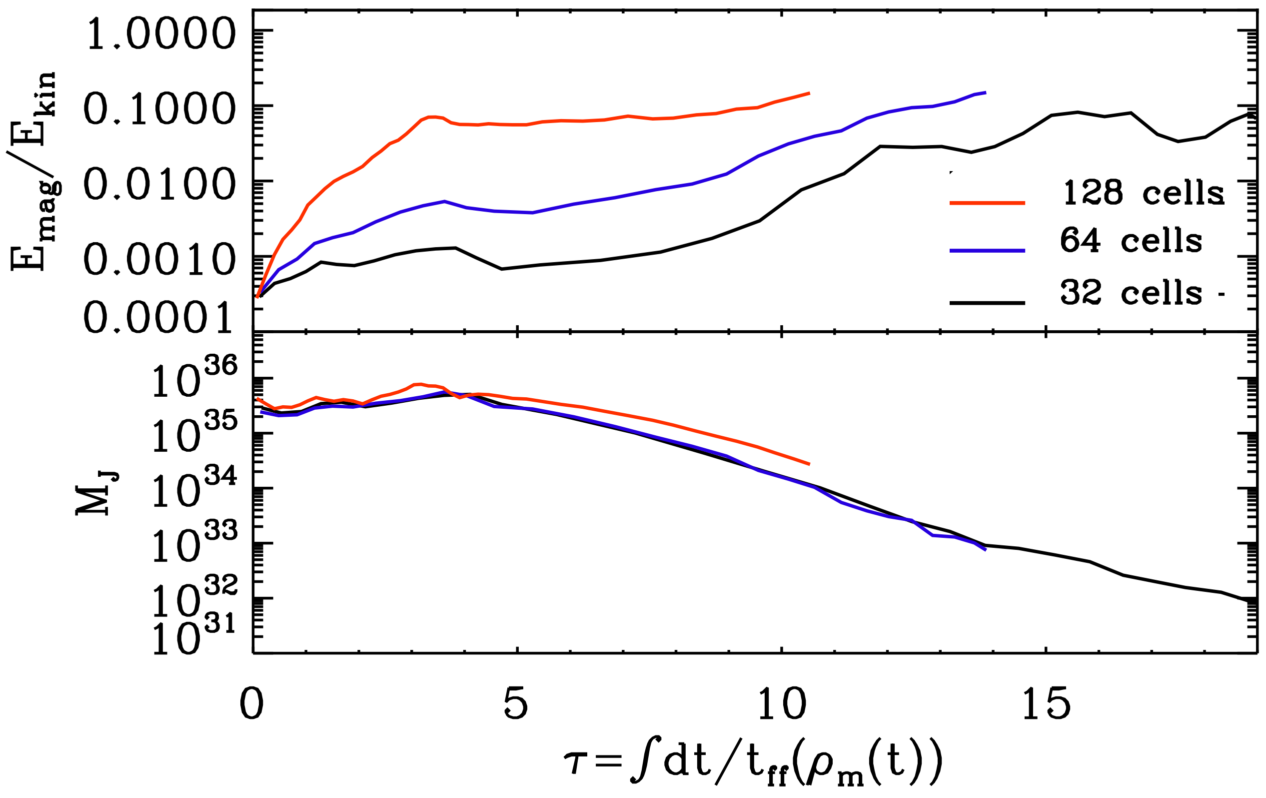


B fluctuation spectrum in $1/r^2$ fall-off

B fluctuation spectrum in flat inner core

(Federrath et al., in prep.)

first attempts to calculate the saturation level.



ratio of magnetic to kinetic energy

Jeans mass

We seem to get a saturation level of ~10%

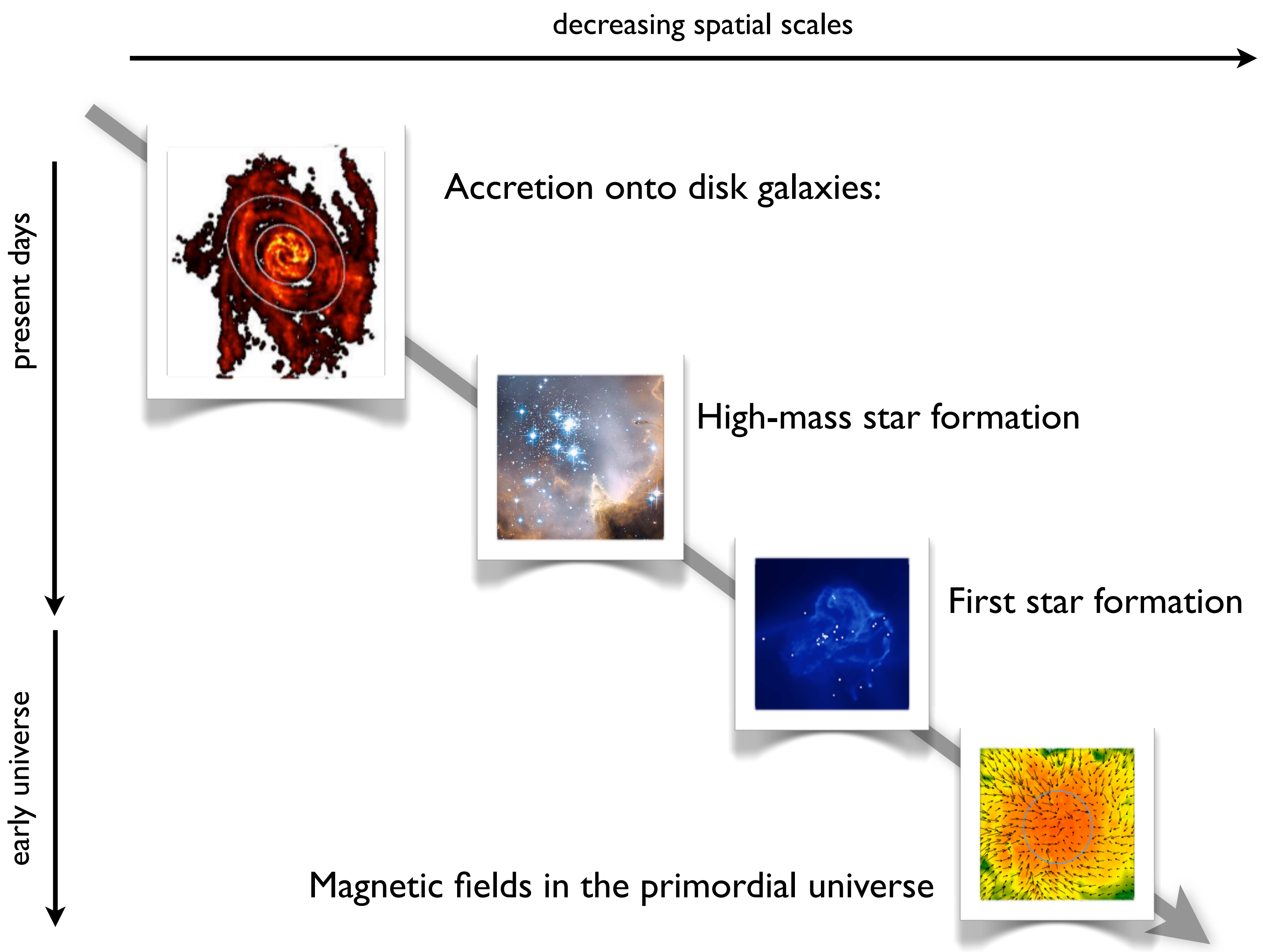
QUESTIONS:
- Is this true in a proper cosmological context?
- What does it mean for the formation of the first stars

(Sur et al., in prep.)

questions

- *small-scale turbulent dynamo* is expected to operate during Pop III star formation
- simple models indicate *saturation levels of ~10%*
  --> larger values via $\alpha\Omega$ dynamo?
- *QUESTIONS:*
  - does this hold for "proper" halo calculations (with chemistry and cosmological context)?
  - what is the strength of the seed magnetic field?

summary



decreasing spatial scales

present days

early universe

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First star formation

Magnetic fields in the primordial universe

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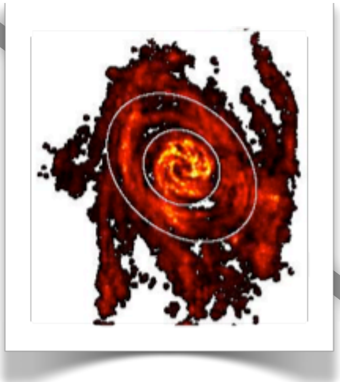
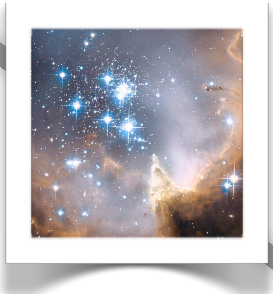


Accretion onto disk galaxies:

Can we see this accretion?

Can we see the mass flow through the galaxy?



High-mass star formation:

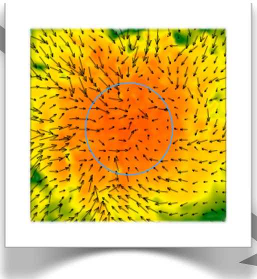
What set upper stellar mass limit?

Can we see UC HII regions flicker?

First star formation:

Are there still Pop III stars around?

How can we see them? And where?



Magnetic fields in the primordial universe:

Is there a minimum primordial field?

What is the influence of B on Pop III star?