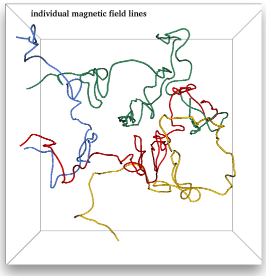
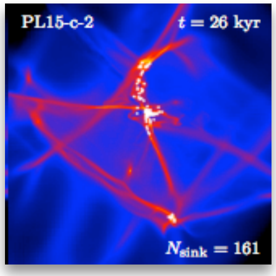
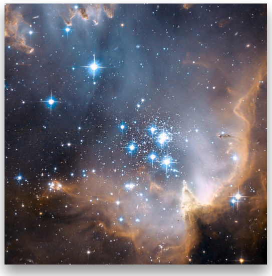
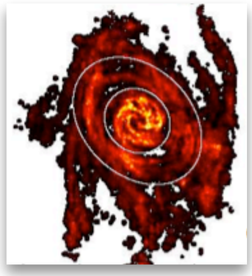
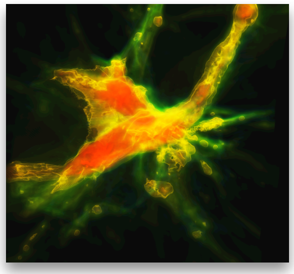
Open problems in star formation











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thanks to ...

... people in the group in Heidelberg:

Richard Allison, Gabriel Anorve, Christian Baczynski, Erik Bertram, Frank Bigiel, Paul Clark, Gustavo Dopcke, Jayanta Dutta, Philipp Girichidis, Simon Glover, Lukas Konstandin, Faviola Molina, Milica Micic, Mei Sasaki, Jennifer Schober, Rahul Shetty, Rowan Smith

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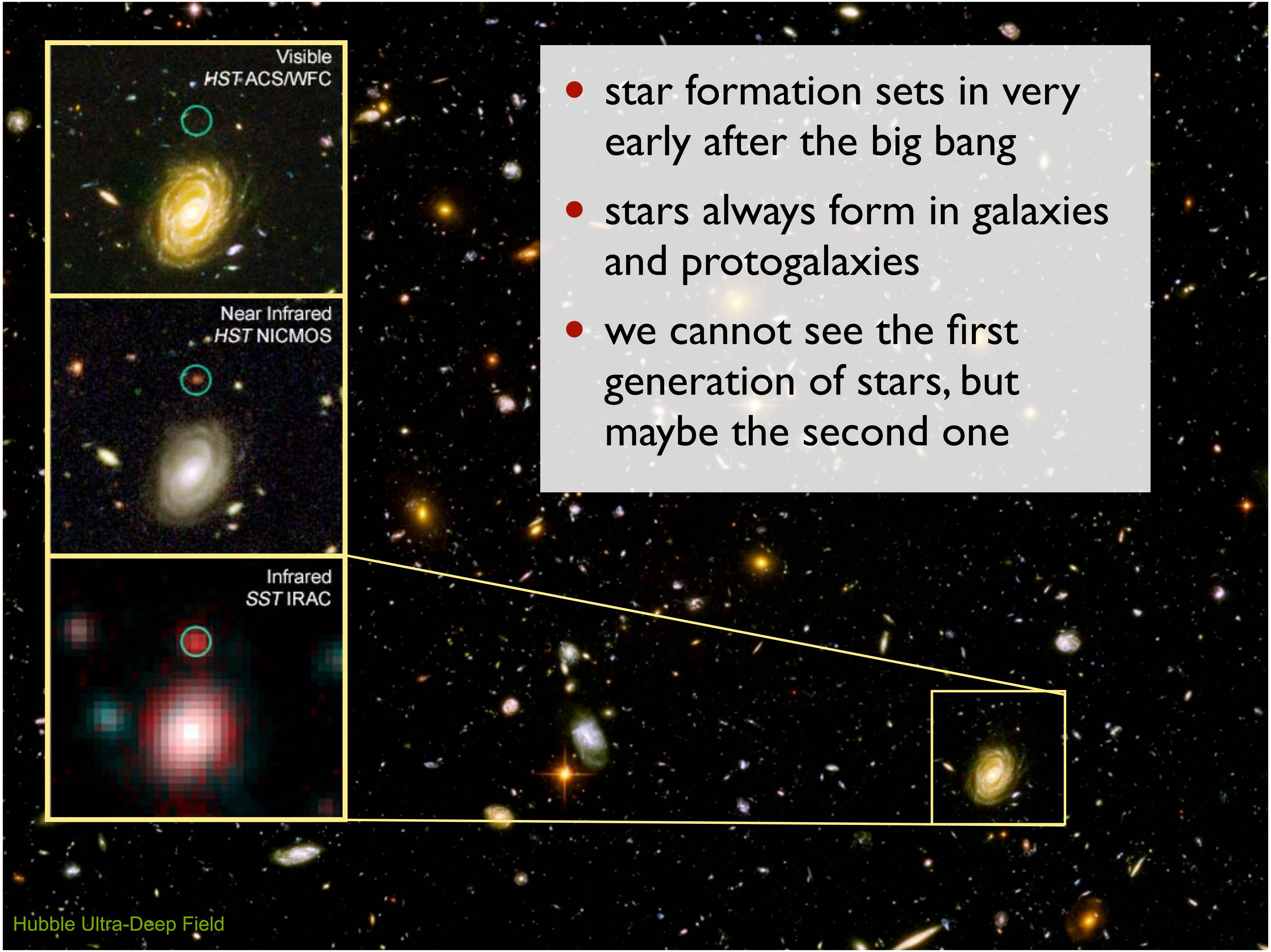
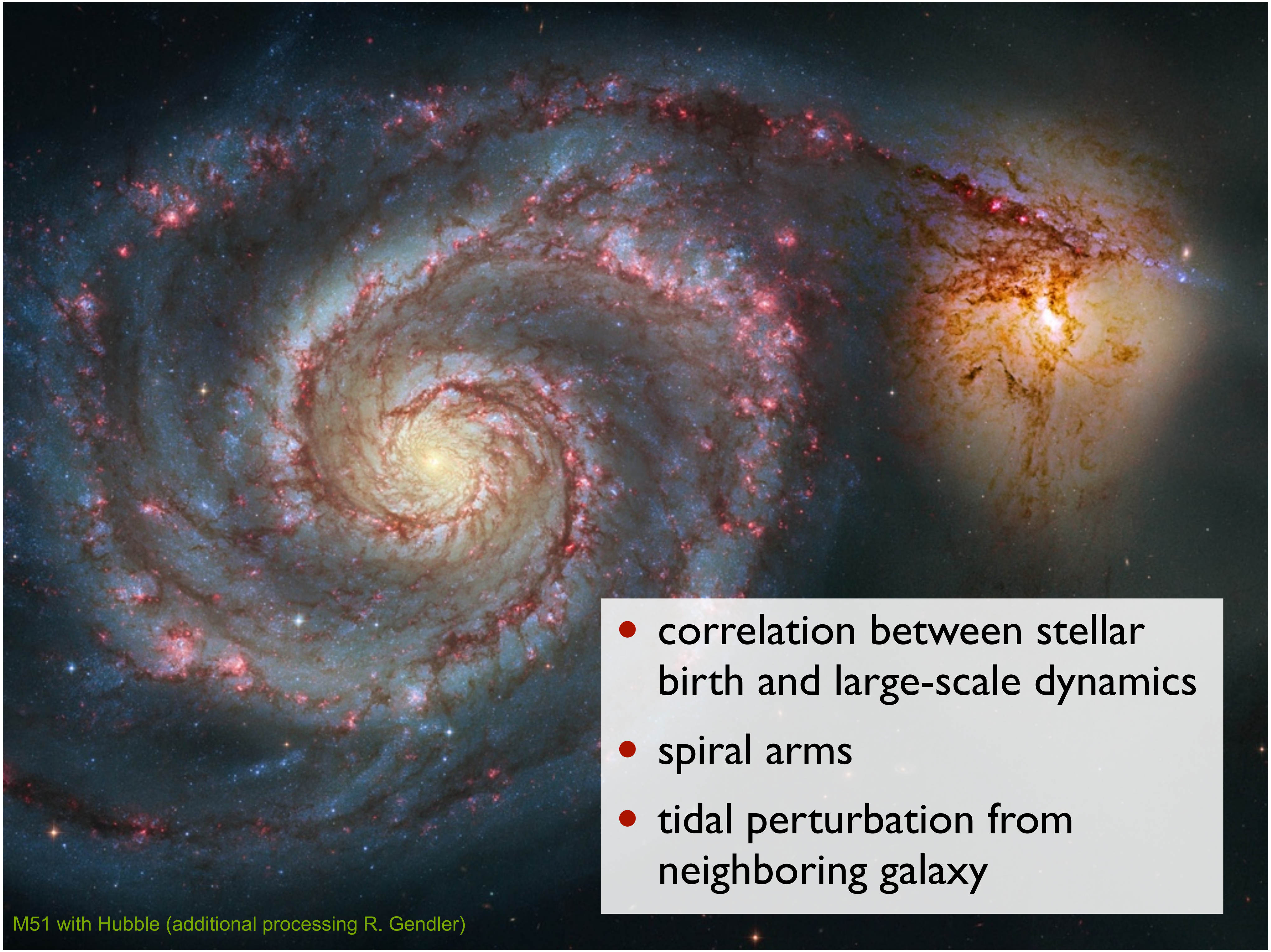
IMPRS

agenda

- star formation theory
  - phenomenology
  - historic remarks
  - our current understanding and its limitations
- open questions
  - can radiative feedback limit protostellar accretion?
  - what are the initial conditions for star cluster formation?
  - are molecules needed to form stars?

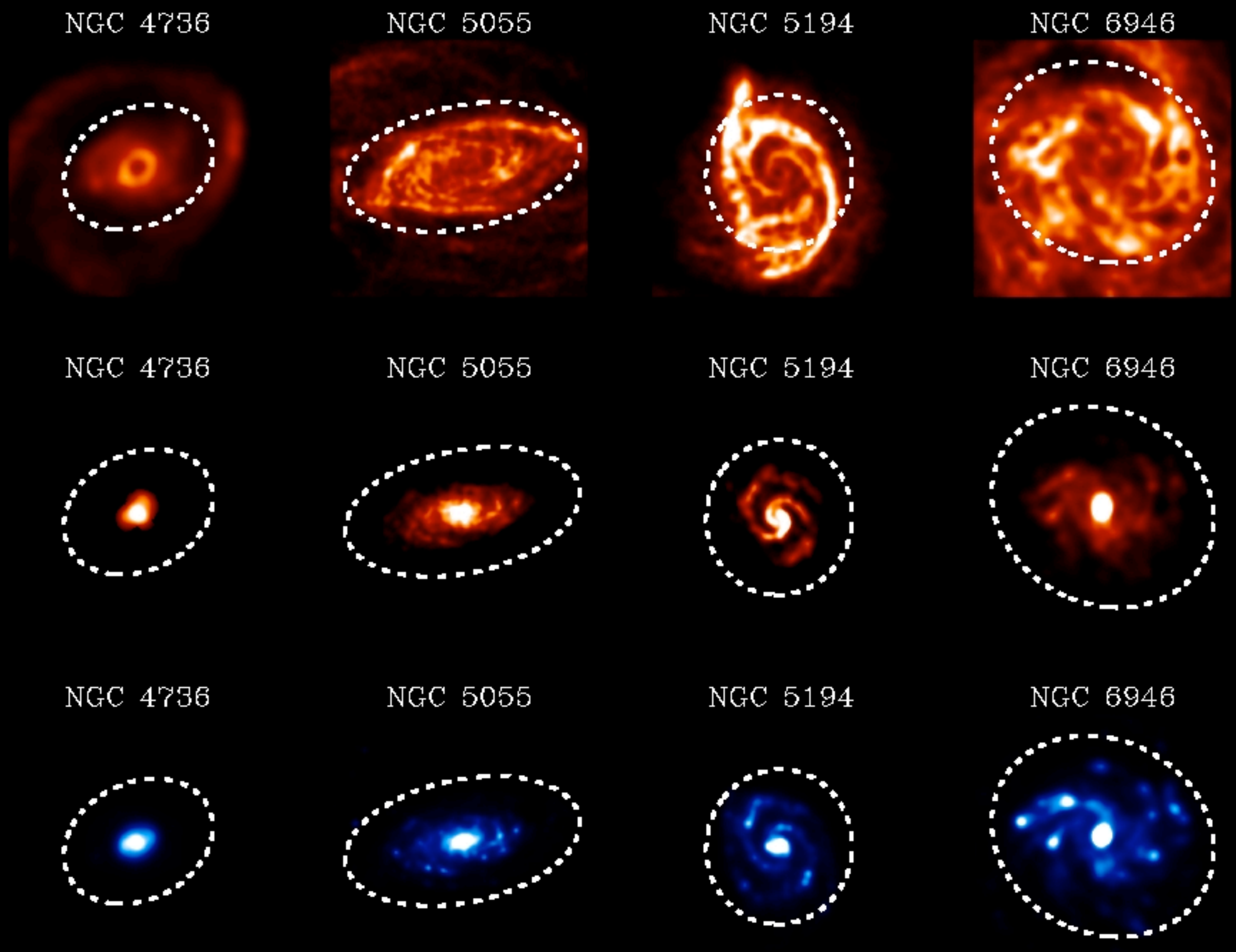
Phenomenology


Visible
HST ACS/WFC
Near Infrared
HST NICMOS
Infrared
SST IRAC
• star formation sets in very early after the big bang
• stars always form in galaxies and protogalaxies
• we cannot see the first generation of stars, but maybe the second one
Hubble Ultra-Deep Field



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

M51 with Hubble (additional processing R. Gendler)



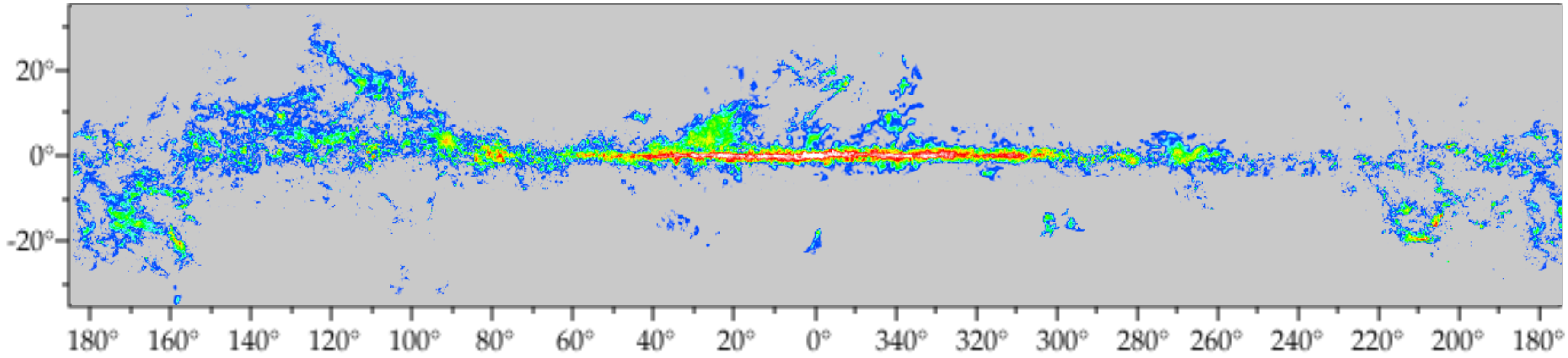
atomic hydrogen

molecular hydrogen

star formation

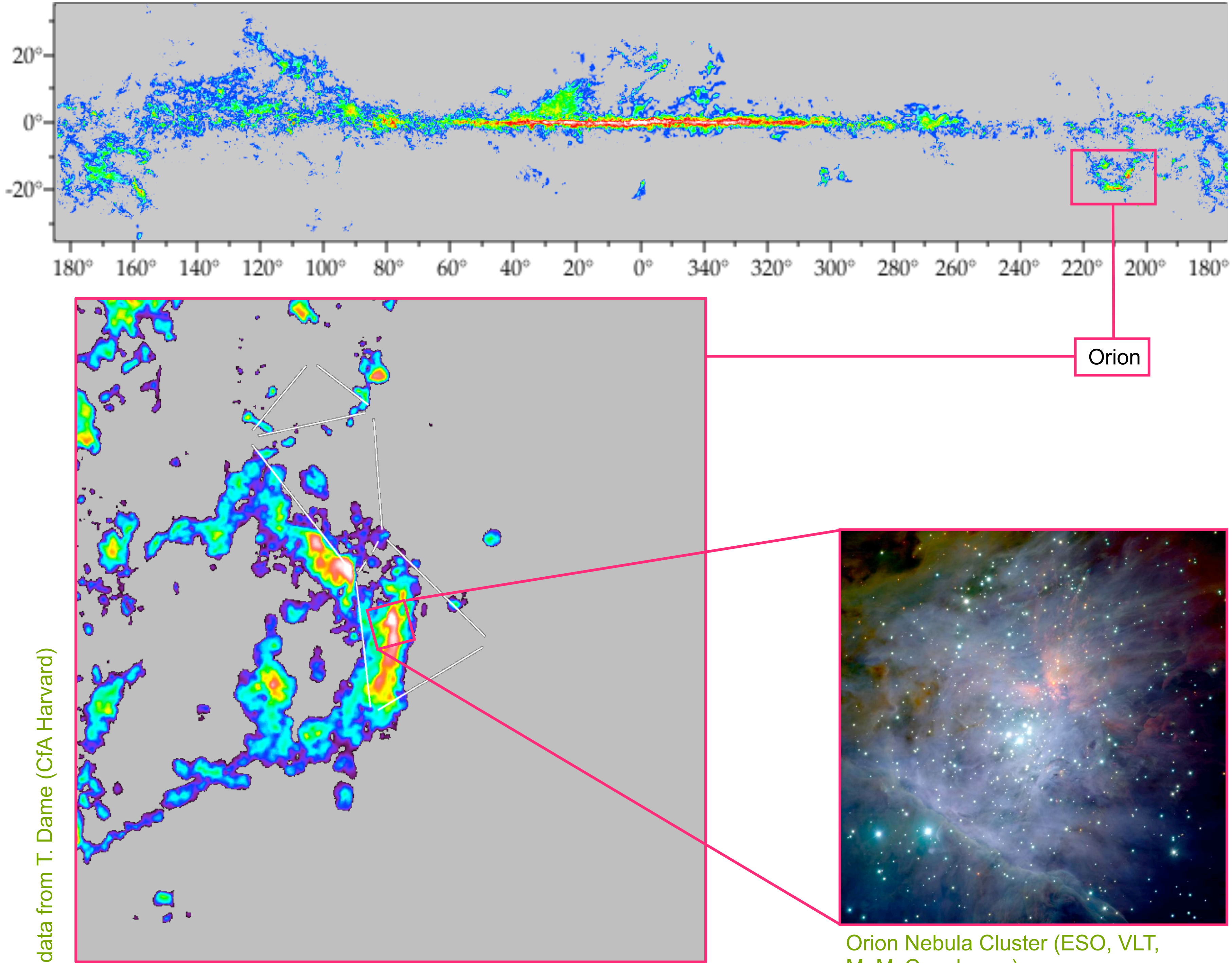
- HI gas more extended
- H2 and SF well correlated

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

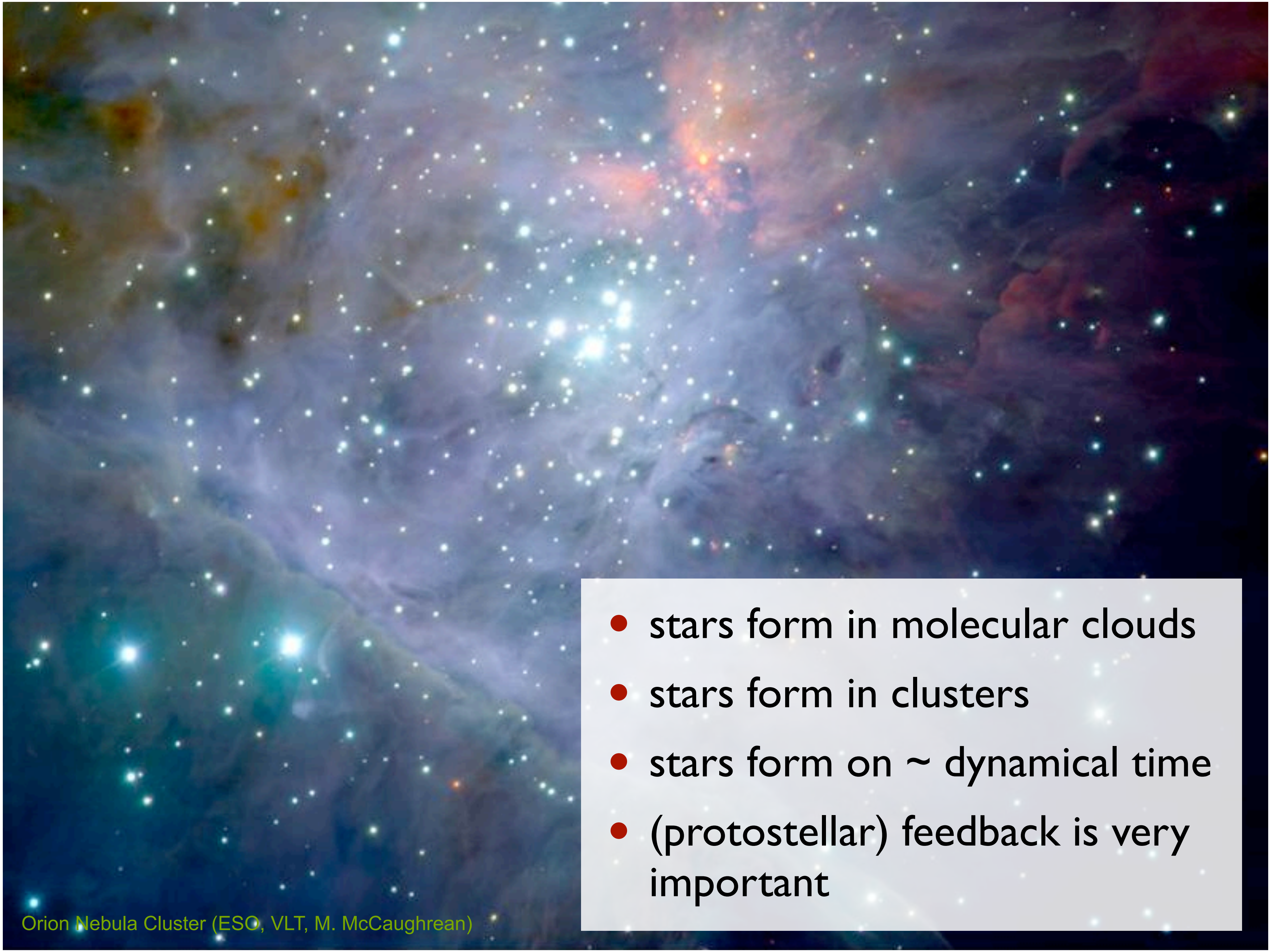


distribution of molecular gas in the Milky Way as traced by CO emission

data from T. Dame (CfA Harvard)



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

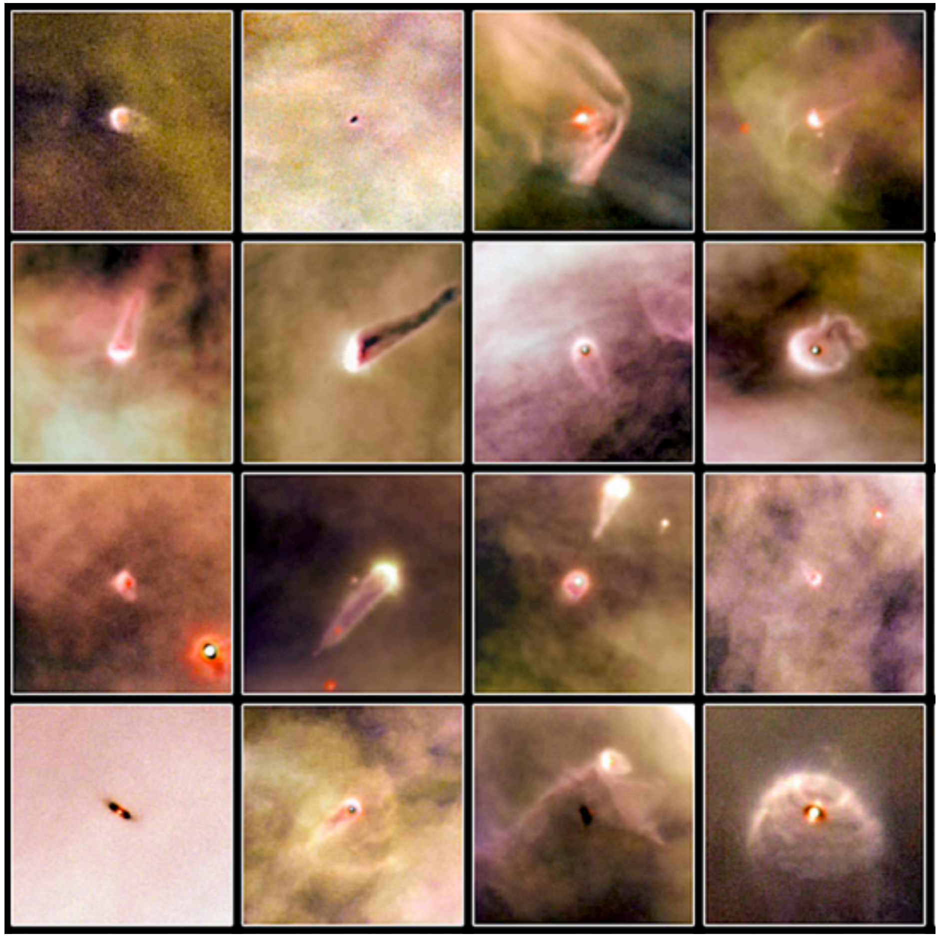


- stars form in molecular clouds
- stars form in clusters
- stars form on ~ dynamical time
- (protostellar) feedback is very important

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

Trapezium Cluster: Central Region

Ionizing radiation from central star **Θ1C Orionis**



Proplyds: Evaporating ``protoplanetary´´ disks around young low-mass protostars

(Johnstone et al. 1998, Hubble)

(Ricci et al. 2008, Hubble)

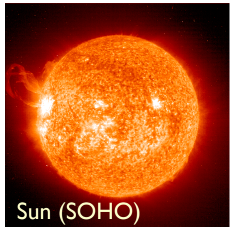
theoretical approach

decrease in spatial scale / increase in density


Andromeda (R. Gendler)


NGC 602 in LMC (Hubble)


Proplyd in Orion (Hubble)


Sun (SOHO)


Earth

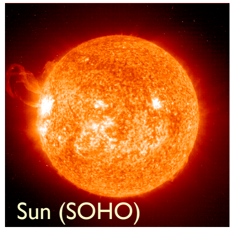
- density
  - density of ISM: few particles per cm^3
  - density of molecular cloud: few 100 particles per cm^3
  - density of Sun: 1.4 g/cm^3
- spatial scale
  - size of molecular cloud: few 10s of pc
  - size of young cluster: ~ 1 pc
  - size of Sun: 1.4×10^{10} cm

decrease in spatial scale / increase in density


Andromeda (R. Gendler)


NGC 602 in LMC (Hubble)


Proplyd in Orion (Hubble)


Sun (SOHO)


Earth

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

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

early theoretical models

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

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

  - 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

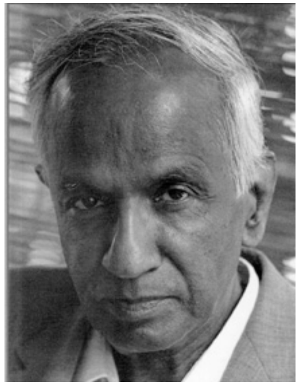
first approach to turbulence

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

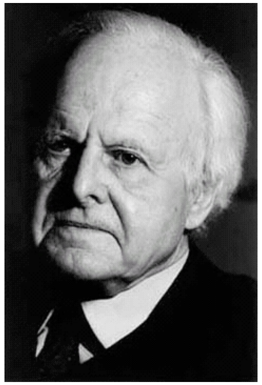
    $\ell_{turb} \ll \ell_{dyn}$
  - then turbulent velocity dispersion contributes to effective soundspeed:

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

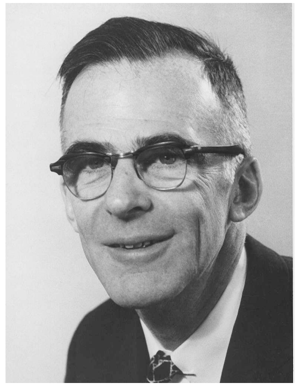
- *Mestel & Spitzer (1956):* Magnetic fields can prevent collapse***!!!***
  - Critical mass for gravitational collapse in presence of B-field

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

  - 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

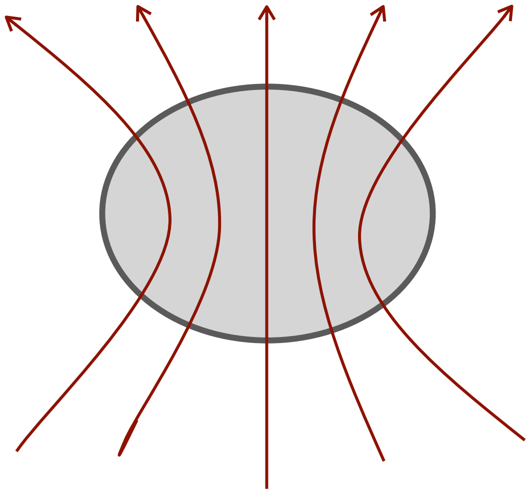


Lyman Spitzer, Jr., 1914 - 1997

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

Frank Shu, 1943 -



magnetic field

problems of “standard theory”

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

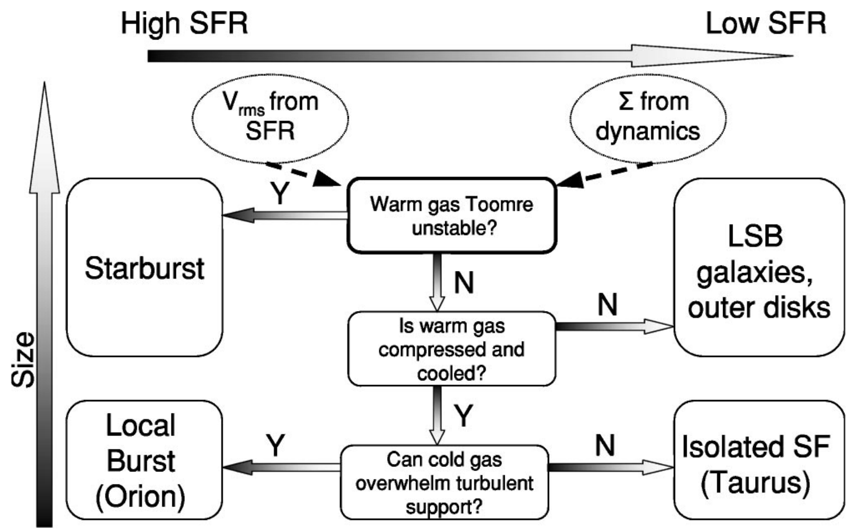
(see, e.g. the overview by Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194)

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

some concerns

- *energy balance*
  - in molecular clouds:

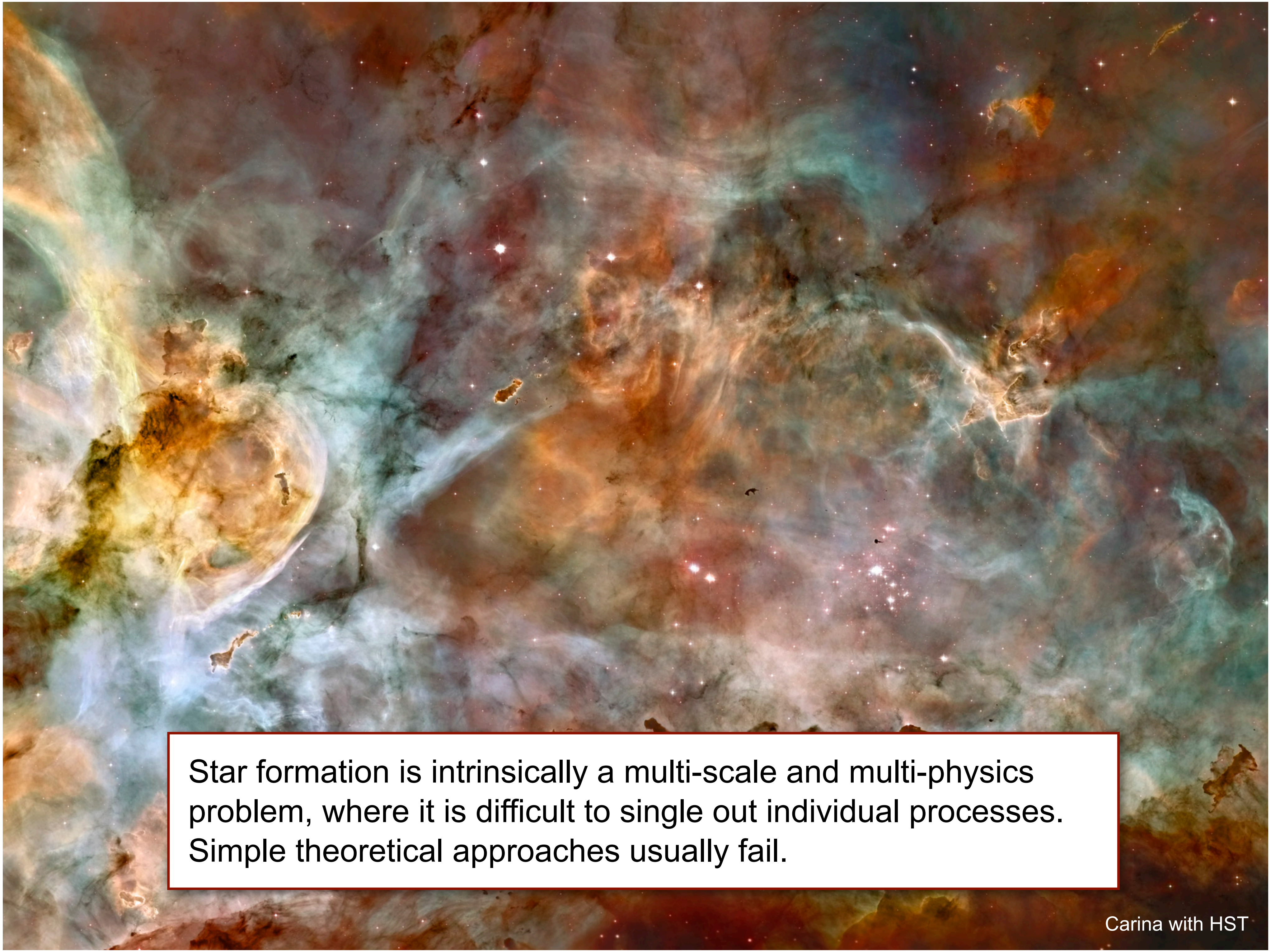
    kinetic energy ~ potential energy ~ magnetic energy > thermal energy

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

current status

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

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



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

Carina with HST


HH 901/902 in Carina with HST

selected open questions

- how do high-mass stars form?
  can radiation stop accretion?
- what are the initial conditions for star cluster formation?
  how does core structure translate into cluster structure?
- how do molecular clouds form?
  are molecules needed for star formation?
- what drives turbulence?
- what triggers / regulates star formation on galactic scales?
- how does star formation depend on metallicity?
  how do the first stars form?
- what processes generate strong magnetic fields in the early universe?

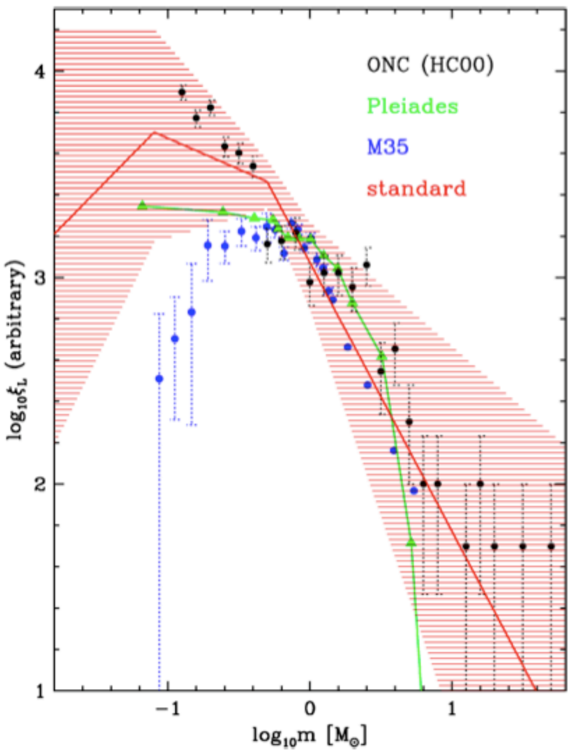
high-mass

stars formation

high-mass star formation

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

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

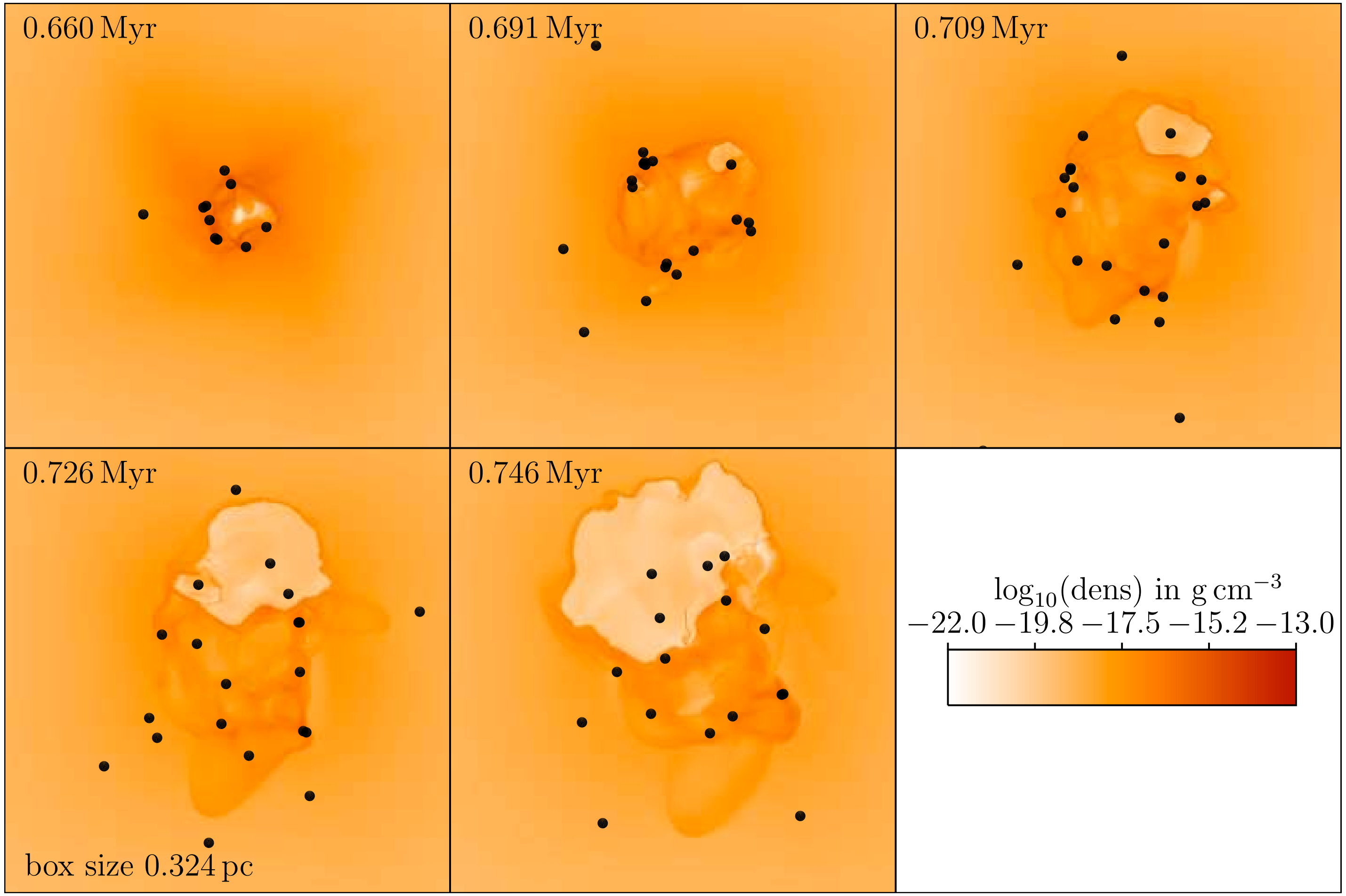
- focus on collapse of individual high-mass cores...
  - massive core with 1,000 $M_\odot$
  - Bonnor-Ebert type density profile
    (flat inner core with 0.5 pc and rho ~ $r^{-3/2}$ further out)
  - initial m=2 perturbation, rotation with $\beta = 0.05$
  - sink particle with radius 600 AU and threshold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

Peters et al. (2010a, ApJ, 711, 1017), Peters et al. (2010b, ApJ, 719, 831), Peters et al. (2010c, ApJ, 725, 134)

our (numerical) approach

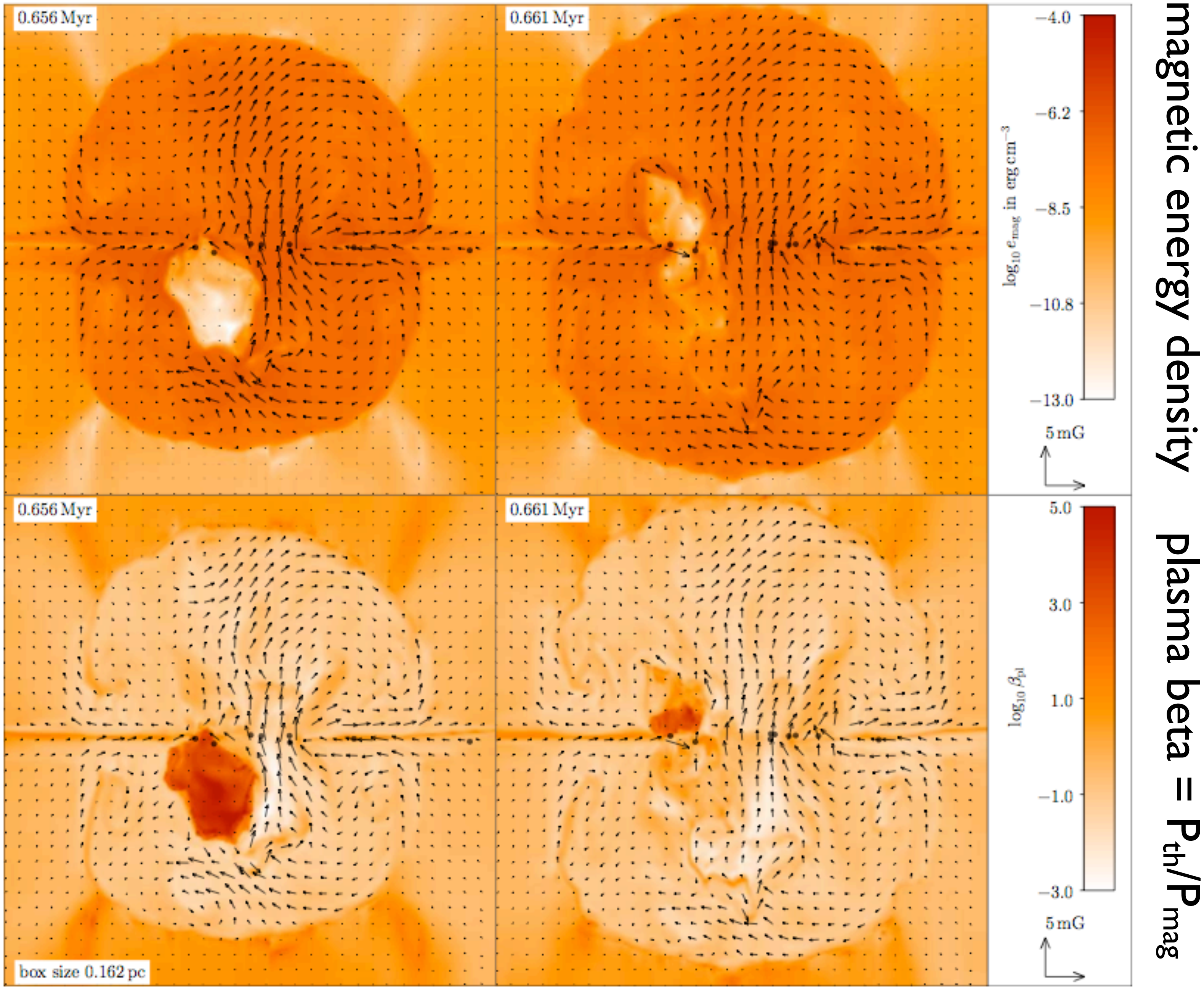
- method:
  - FLASH with ionizing and non-ionizing radiation using raytracing based on hybrid-characteristics
  - protostellar model from Hosokawa & Omukai
  - rate equation for ionization fraction
  - relevant heating and cooling processes
  - some models include magnetic fields
  - *first 3D MHD calculations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

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



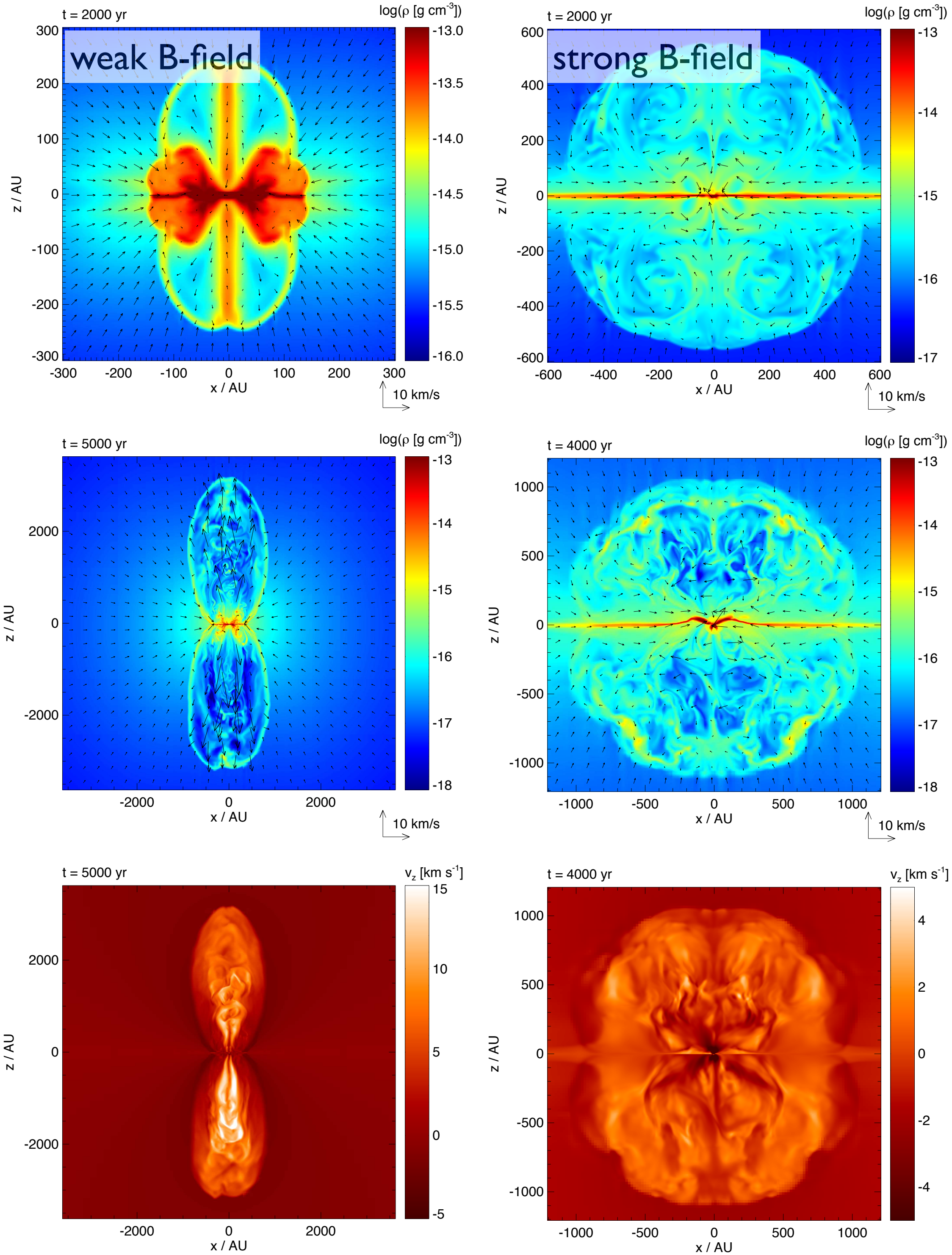
- all protostars accrete from common gas reservoir
- accretion flow suppresses expansion of ionized bubble
- cluster shows “fragmentation-induced starvation”
- halting of accretion flow allows bubble to expand

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



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

Peters et al. (2011, ApJ, 729, 72)

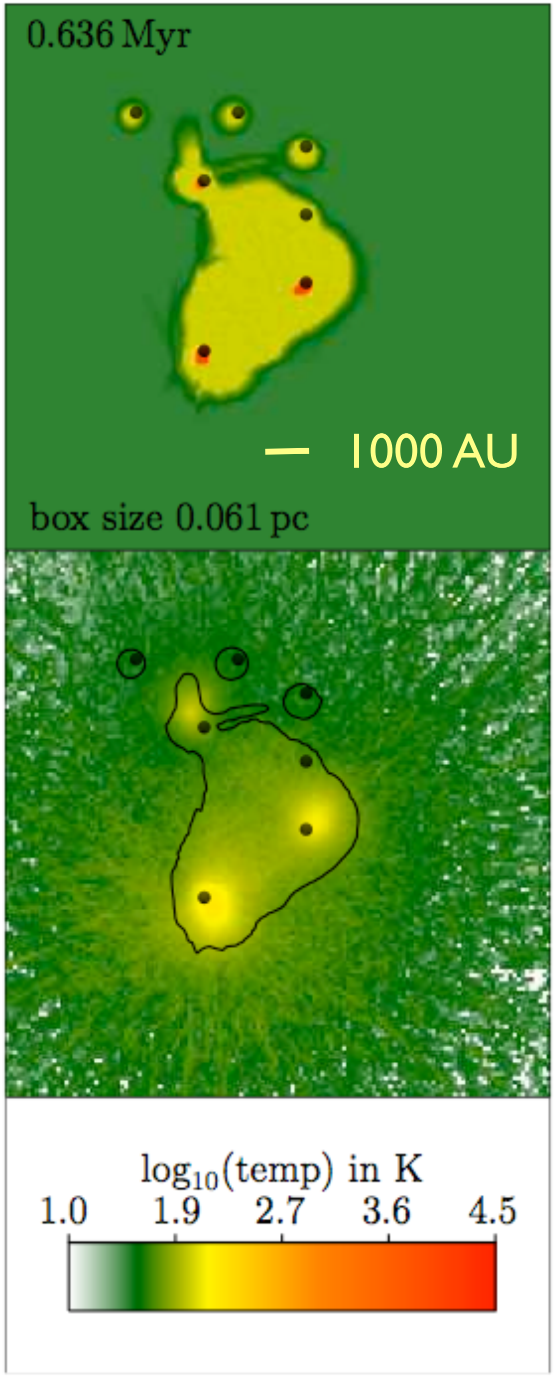


density in inner region and early times

density on larger scales and later times

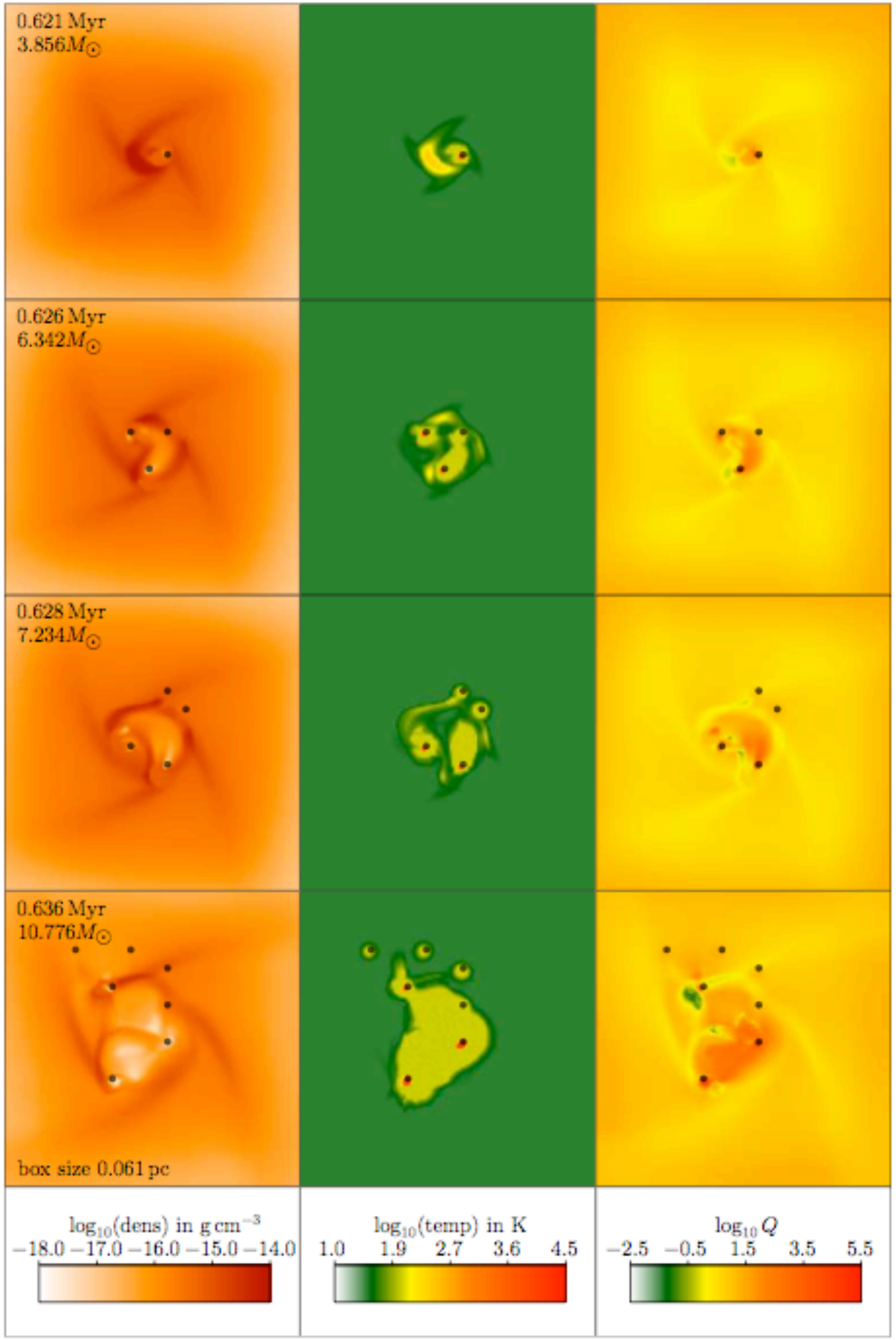
velocity on larger scales and later times

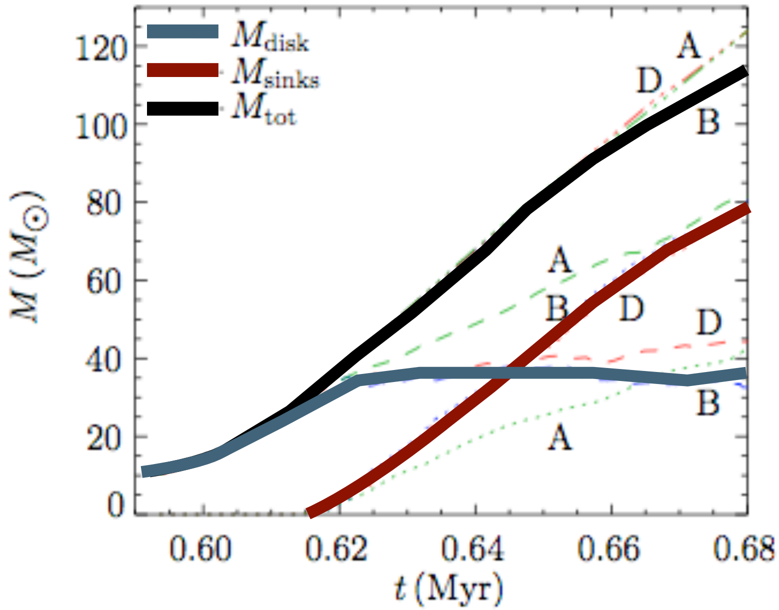
Seifried, Pudrith, Banerjee, Duffin, Klessen (2011)



ray tracing method
(hydrid characteristics)

Monte Carlo: full RT
(with scattered radiation)

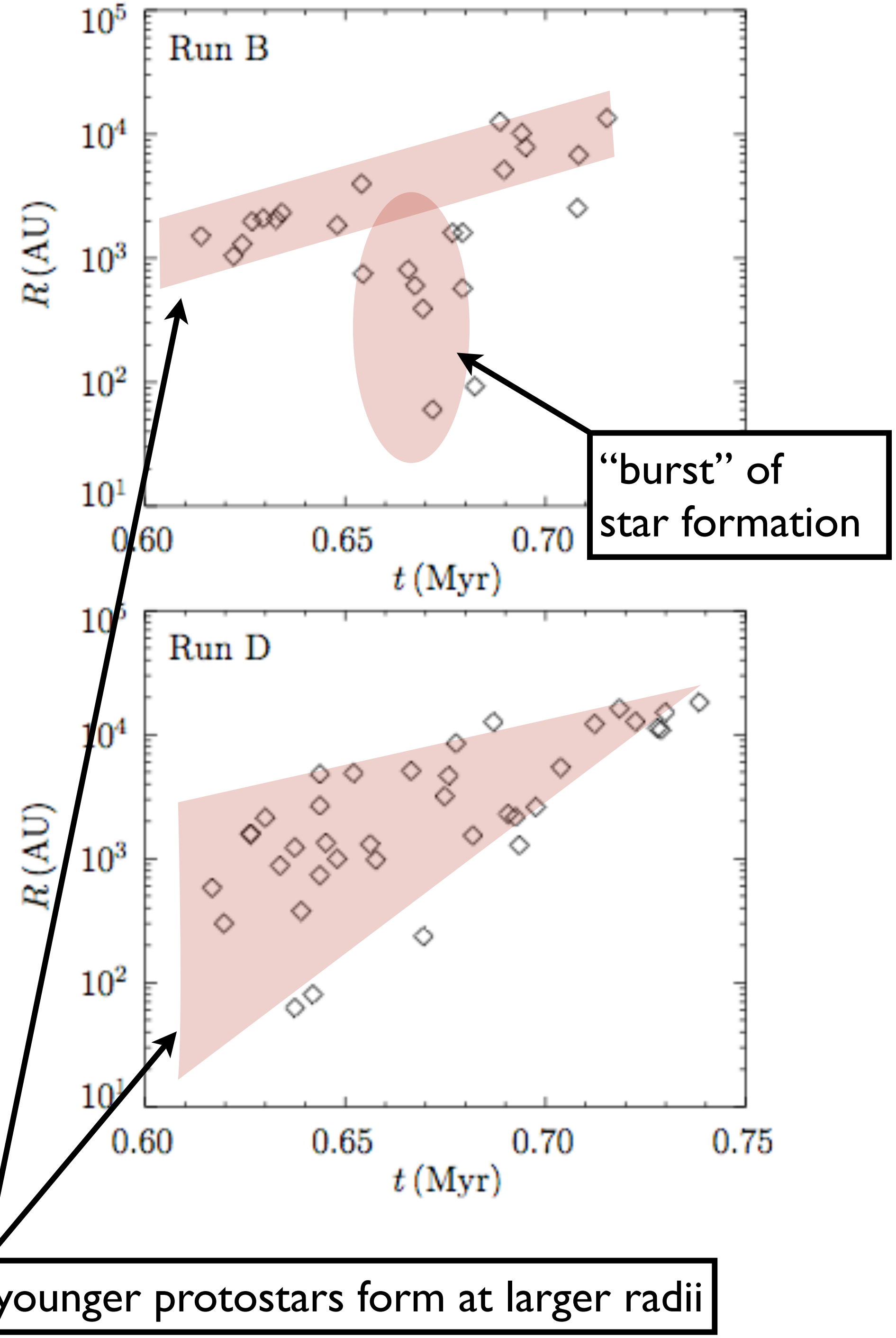


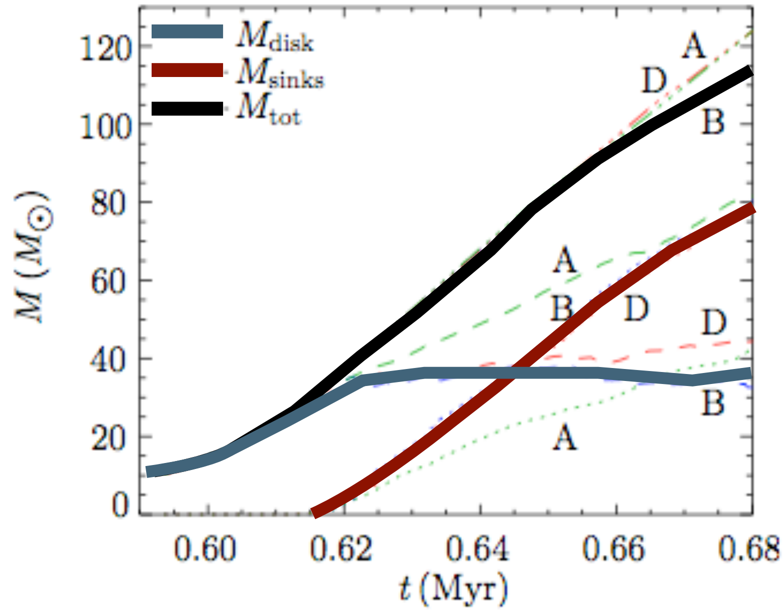


mass load onto the disk exceeds inward transport
--> becomes gravitationally unstable (see also Kratter & Matzner 2006, Kratter et al. 2010)

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

Peters et al. (2010a, ApJ, 711, 1017),
Peters et al. (2010b, ApJ, 719, 831),
Peters et al. (2010c, ApJ, 725, 134)





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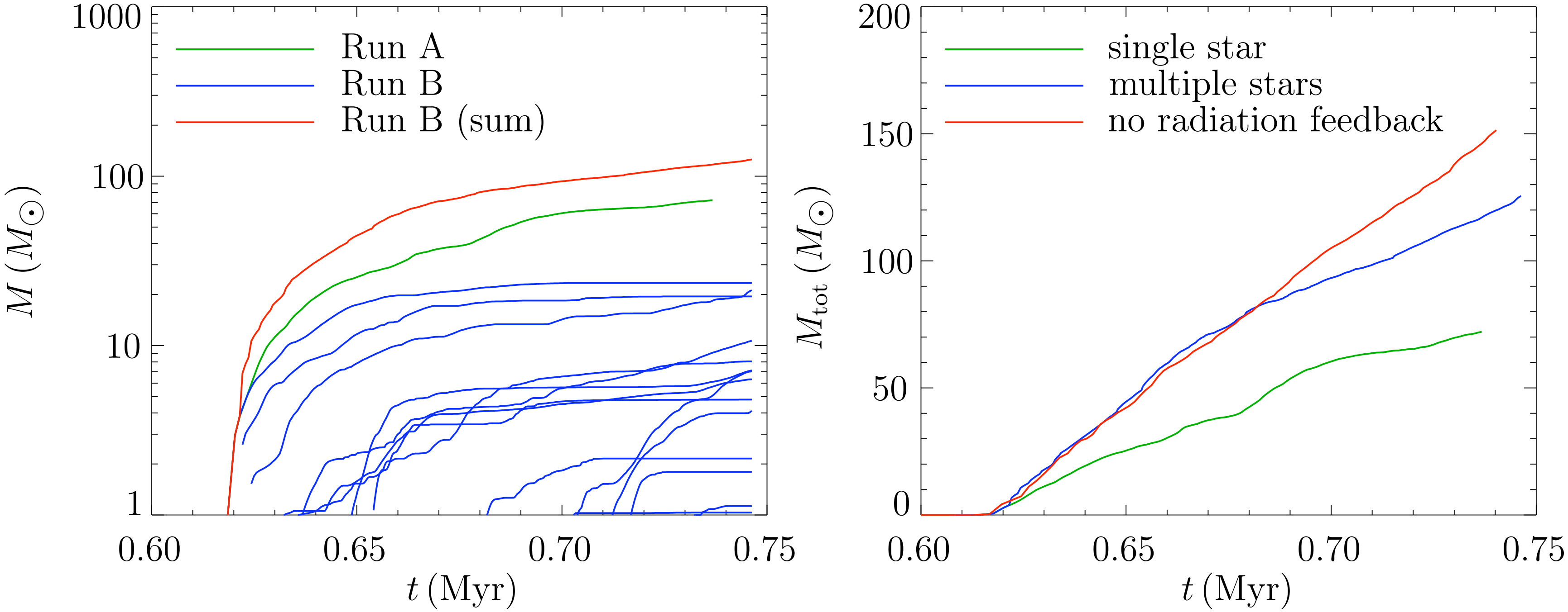
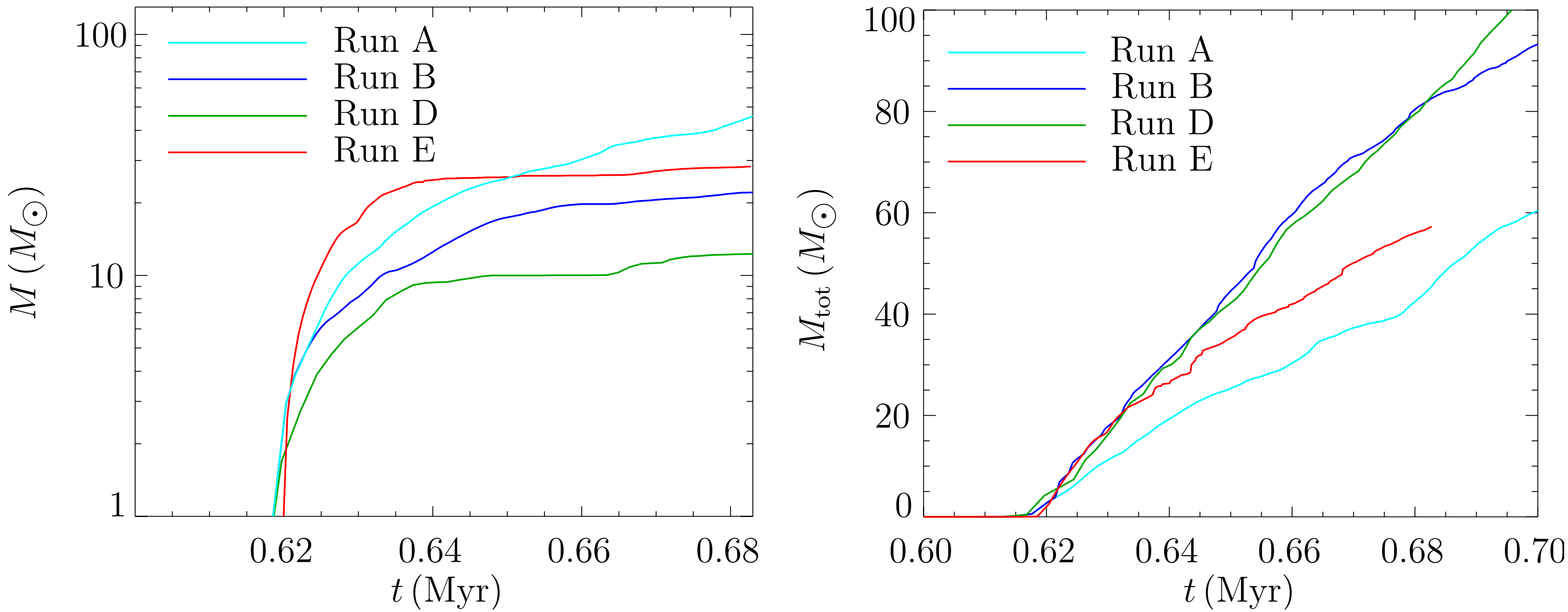


- compare with control run without radiation feedback
- total accretion rate does not change with accretion heating
- expansion of ionized bubble causes turn-off
- no triggered star formation by expanding bubble

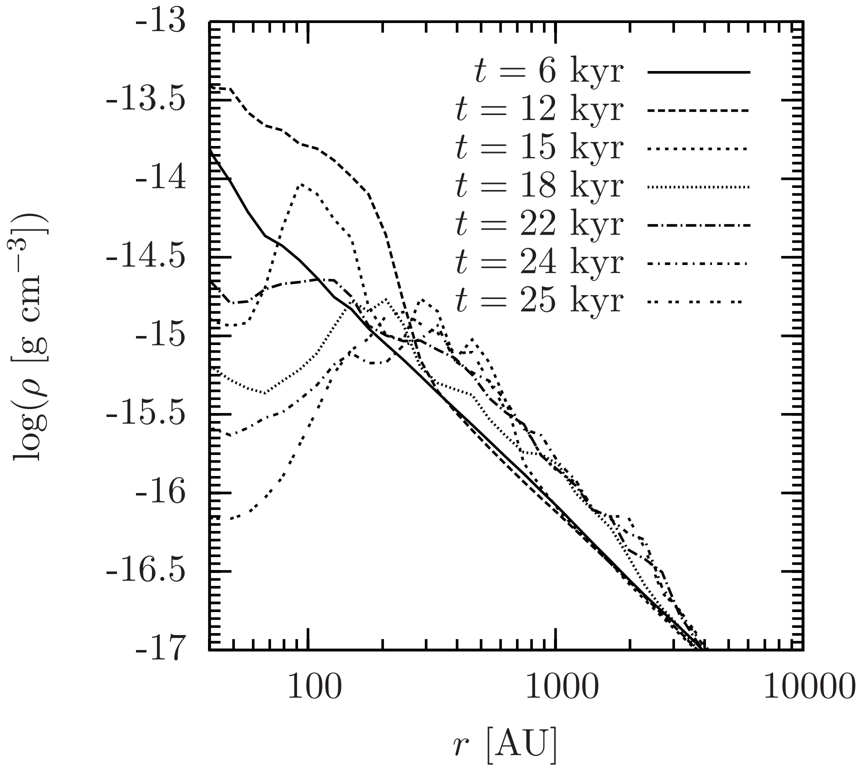
Peters et al. (2010a, ApJ, 711, 1017), Peters et al. (2010b, ApJ, 719, 831), Peters et al. (2010c, ApJ, 725, 134)



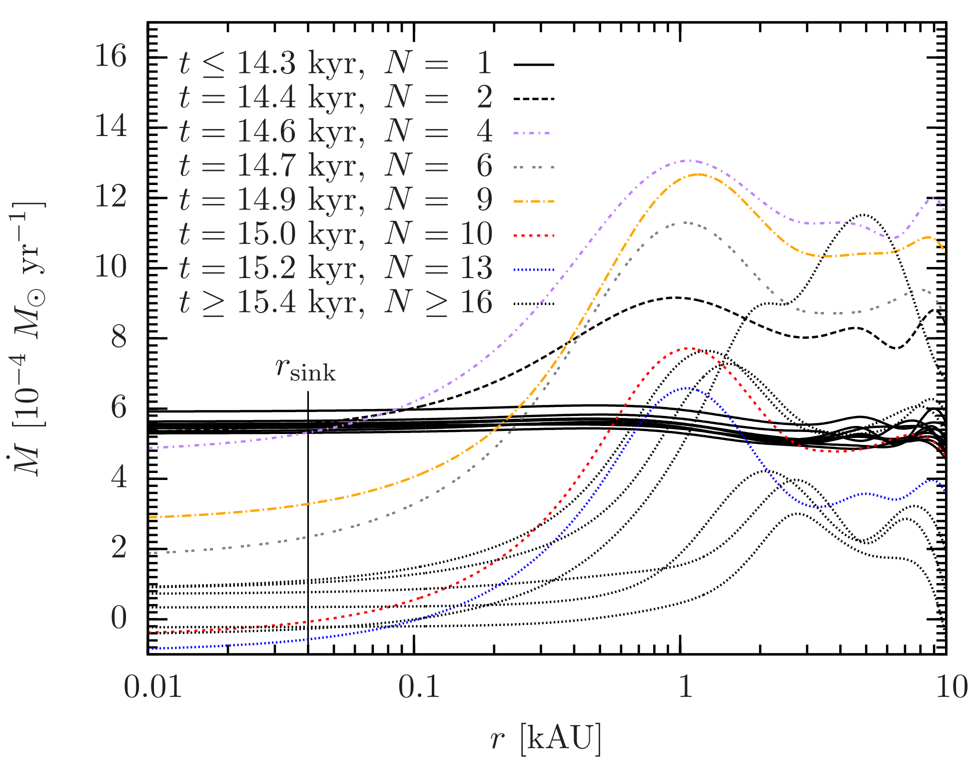
- magnetic fields lead to weaker fragmentation
- central star becomes more massive (magnetic breaking

Peters et al. (2010a, ApJ, 711, 1017), Peters et al. (2010b, ApJ, 719, 831), Peters et al. (2010c, ApJ, 725, 134), Peters et al. (2011, ApJ, 729, 72

Fragmentation-induced starvation in a complex cluster



gas density as function of radius
at different times

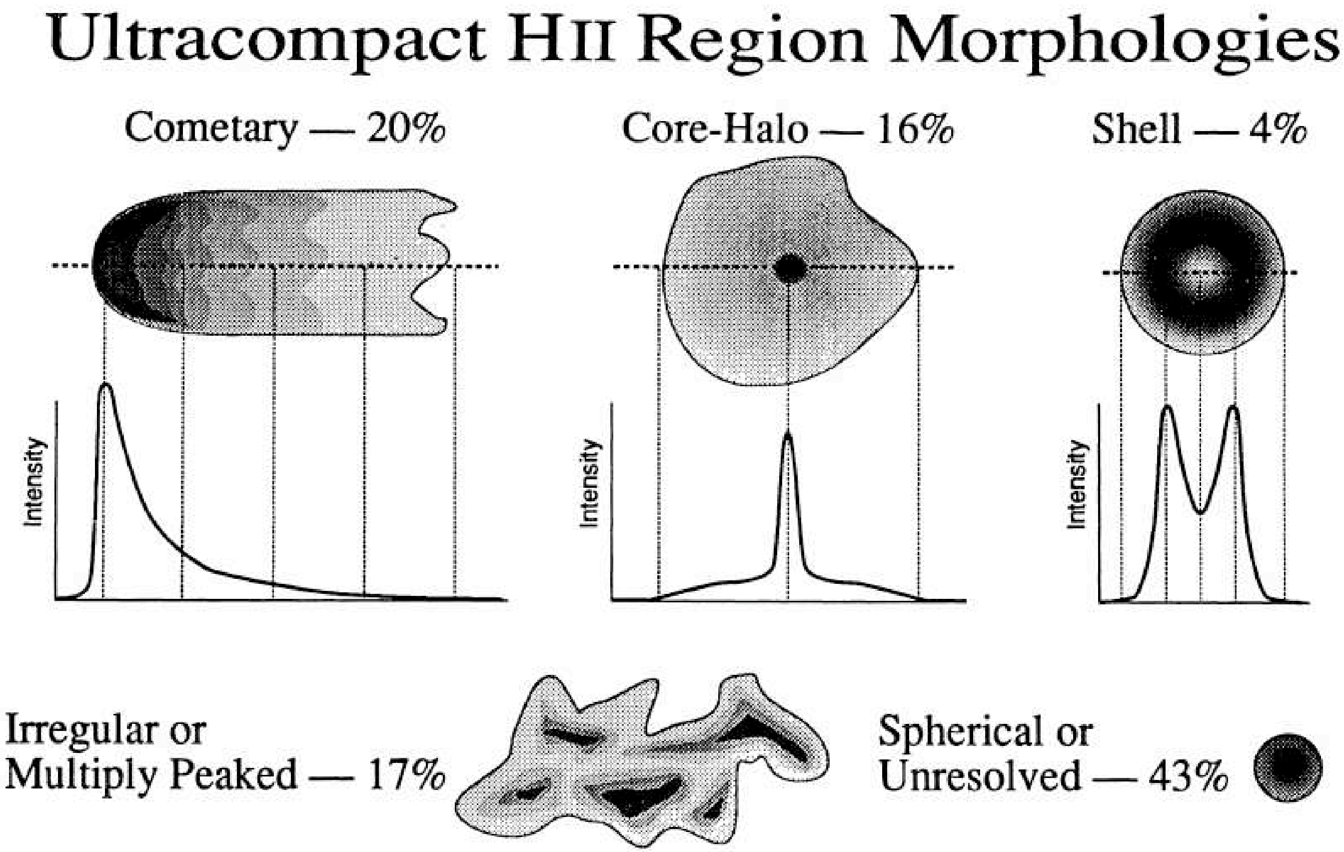


mass flow towards the center as
function of radius at different times

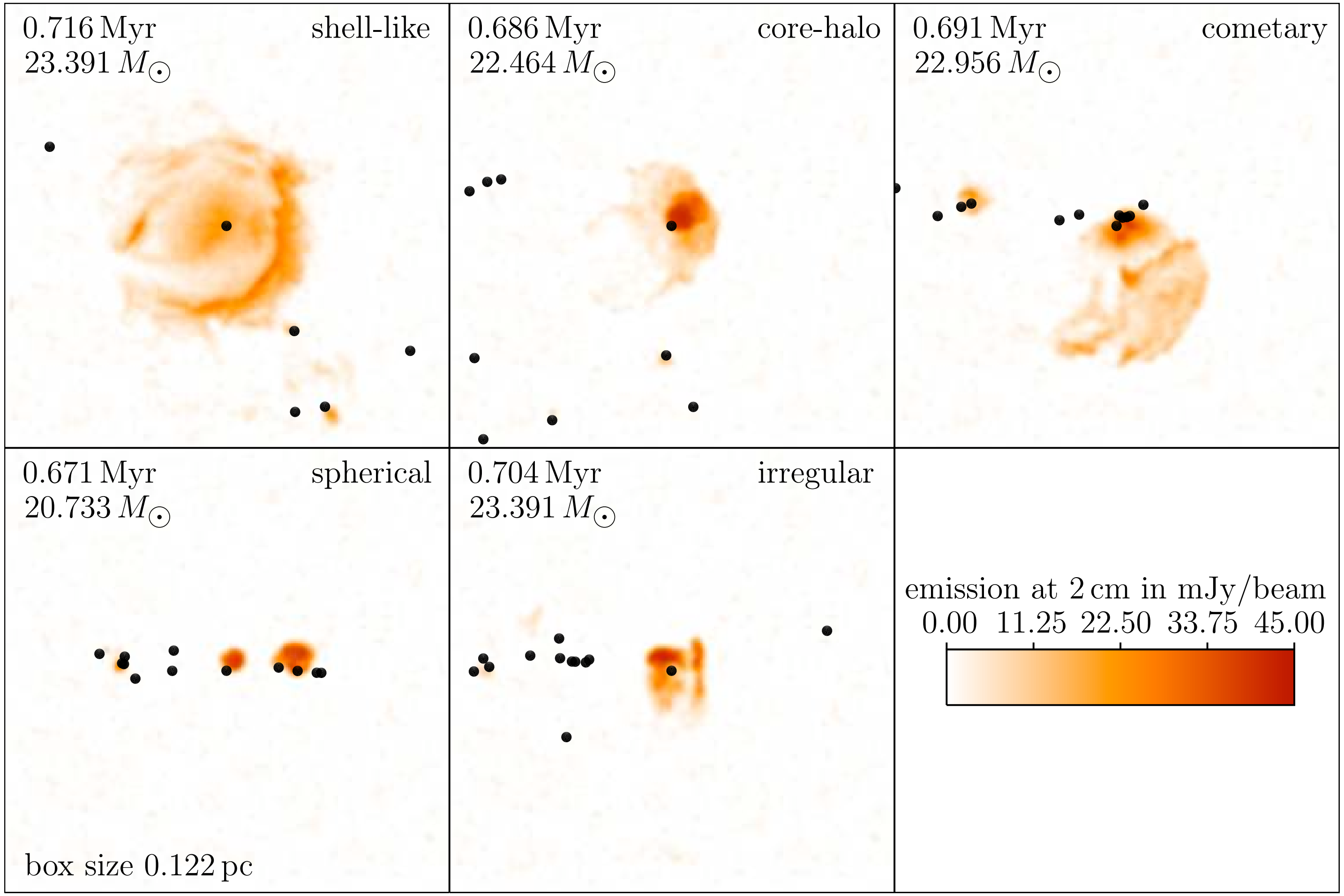
Girichidis et al. (2011a,b)

- 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 $0\farcs14$
  - noise $10^{-3}\,\mathrm{Jy}$

Peters et al. (2010a, ApJ, 711, 1017), Peters et al. (2010b, ApJ, 719, 831), Peters et al. (2010c, ApJ, 725, 134)



- 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)

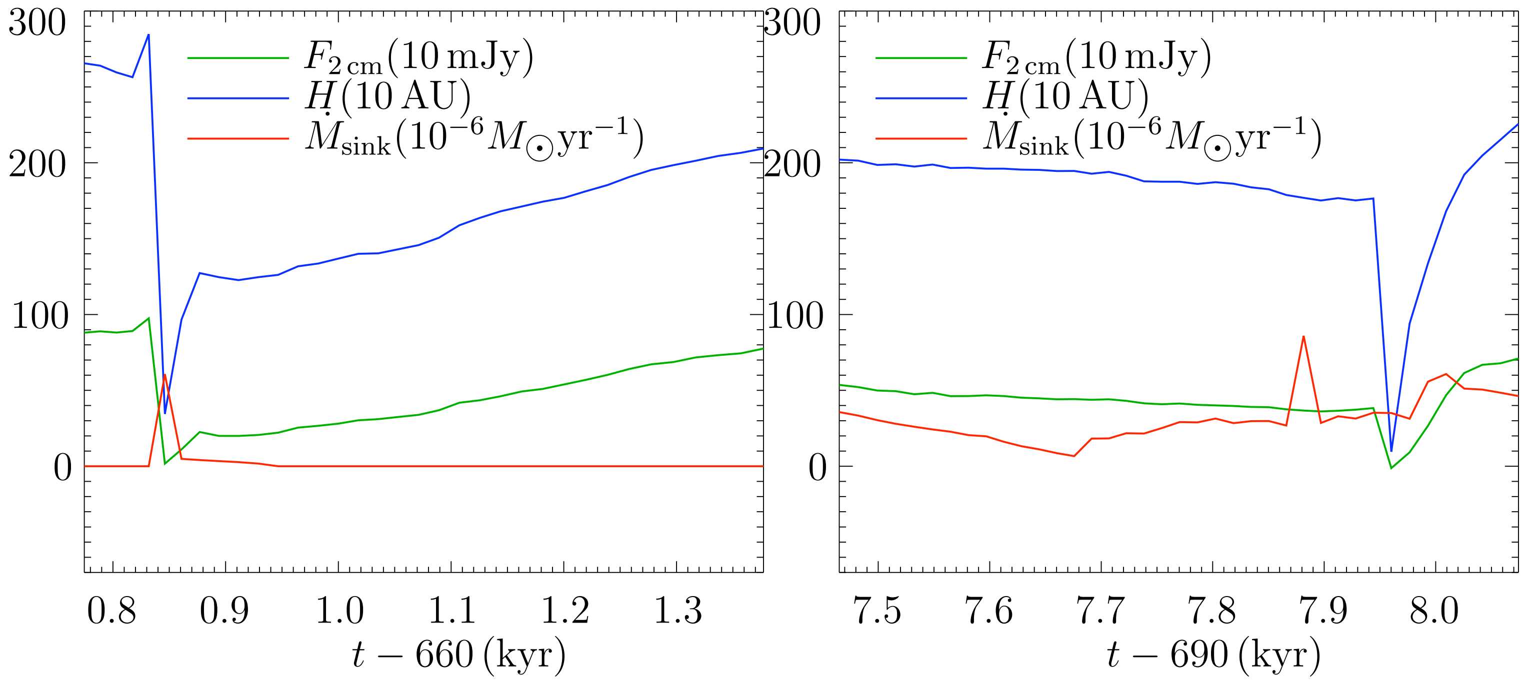
Type	WC89	K94	single	multiple
Spherical/Unresolved	43	55	19	60 ± 5
Cometary	20	16	7	10 ± 5
Core-halo	16	9	15	4 ± 2
Shell-like	4	1	3	5 ± 1
Irregular	17	19	57	21 ± 5

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. 2011)

Some results

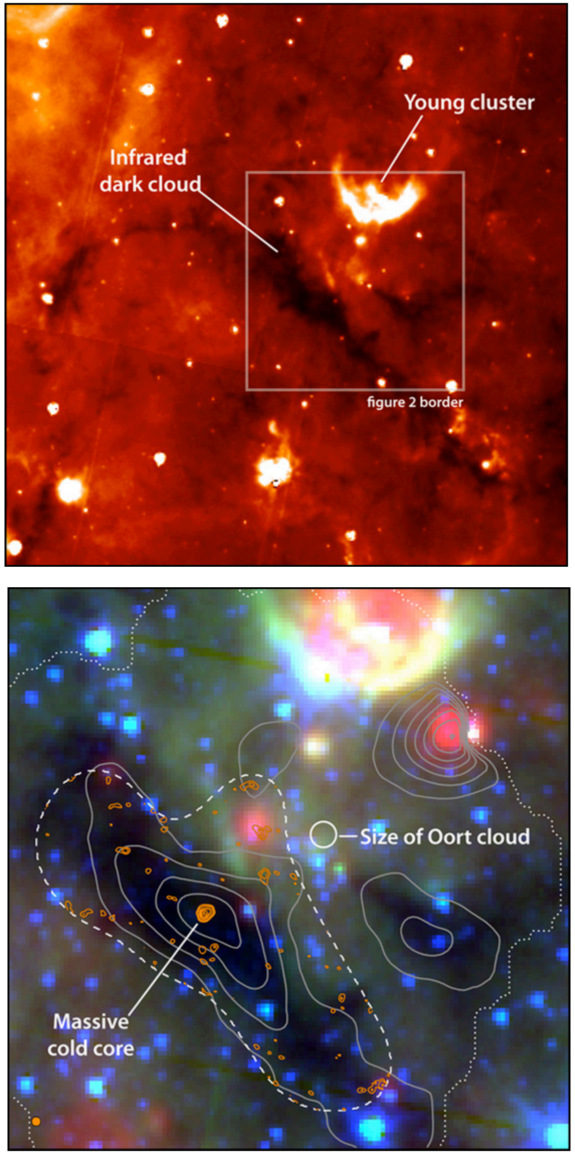
- ionization feedback cannot stop accretion
- ionization drives bipolar outflows
- HII regions show high variability in time and shape
- all classified morphologies can be observed in one run
- lifetime of HII regions determined by accretion timescale (and not by expansion time)
- rapid accretion through dense and unstable flows
- fragmentation limits further accretion of massive stars

Peters et al. (2010a, ApJ, 711, 1017), Peters et al. (2010b, ApJ, 719, 831), Peters et al. (2010c, ApJ, 725, 134), Peters et al. (2011, ApJ, 729, 72

initial conditions for cluster formation

ICs of star cluster formation

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



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

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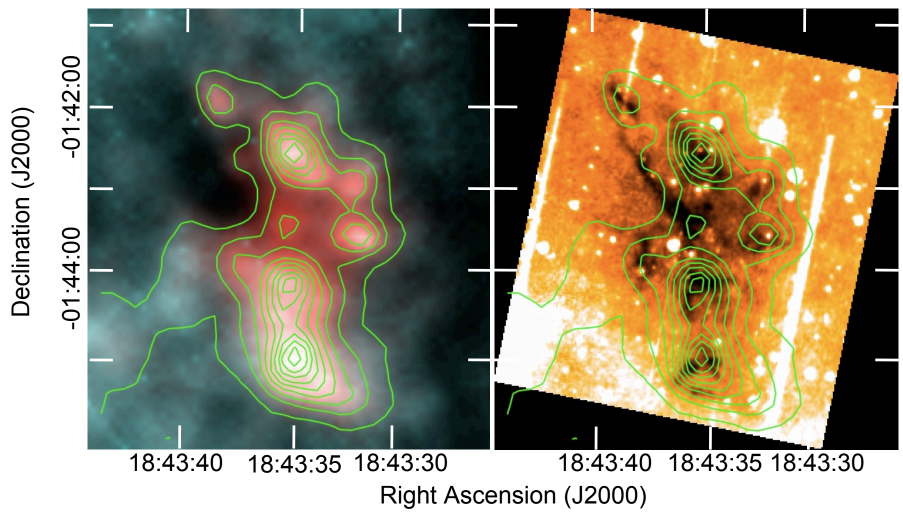
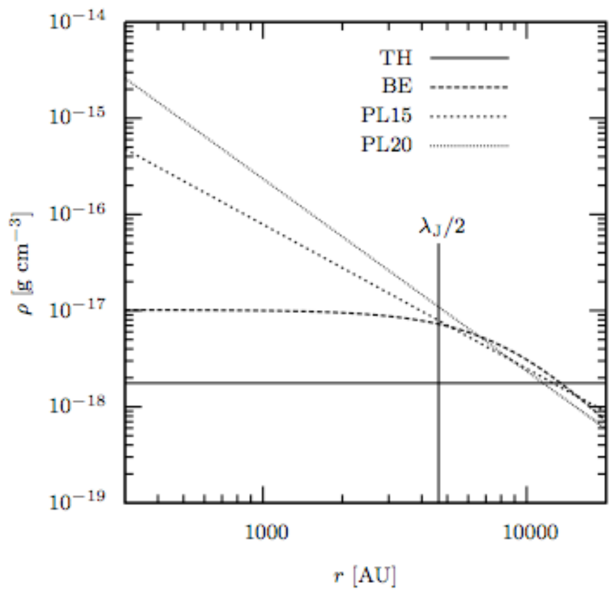


IRDC observed with Herschel, Peretto et al. (2010)

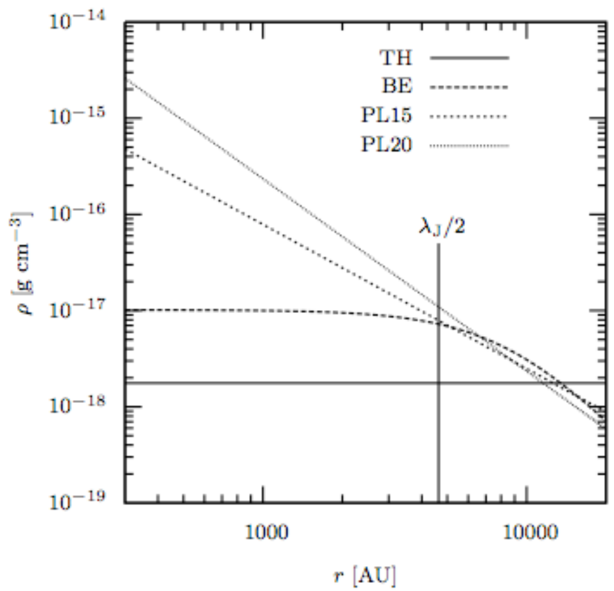
ICs of star cluster formation

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



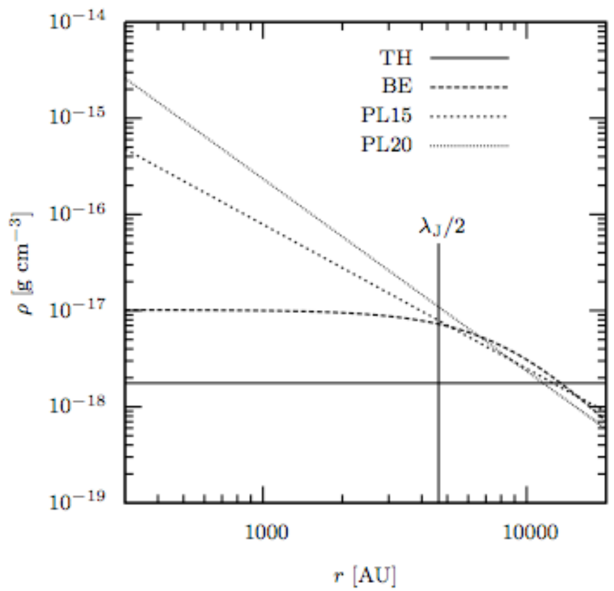
different density profiles

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

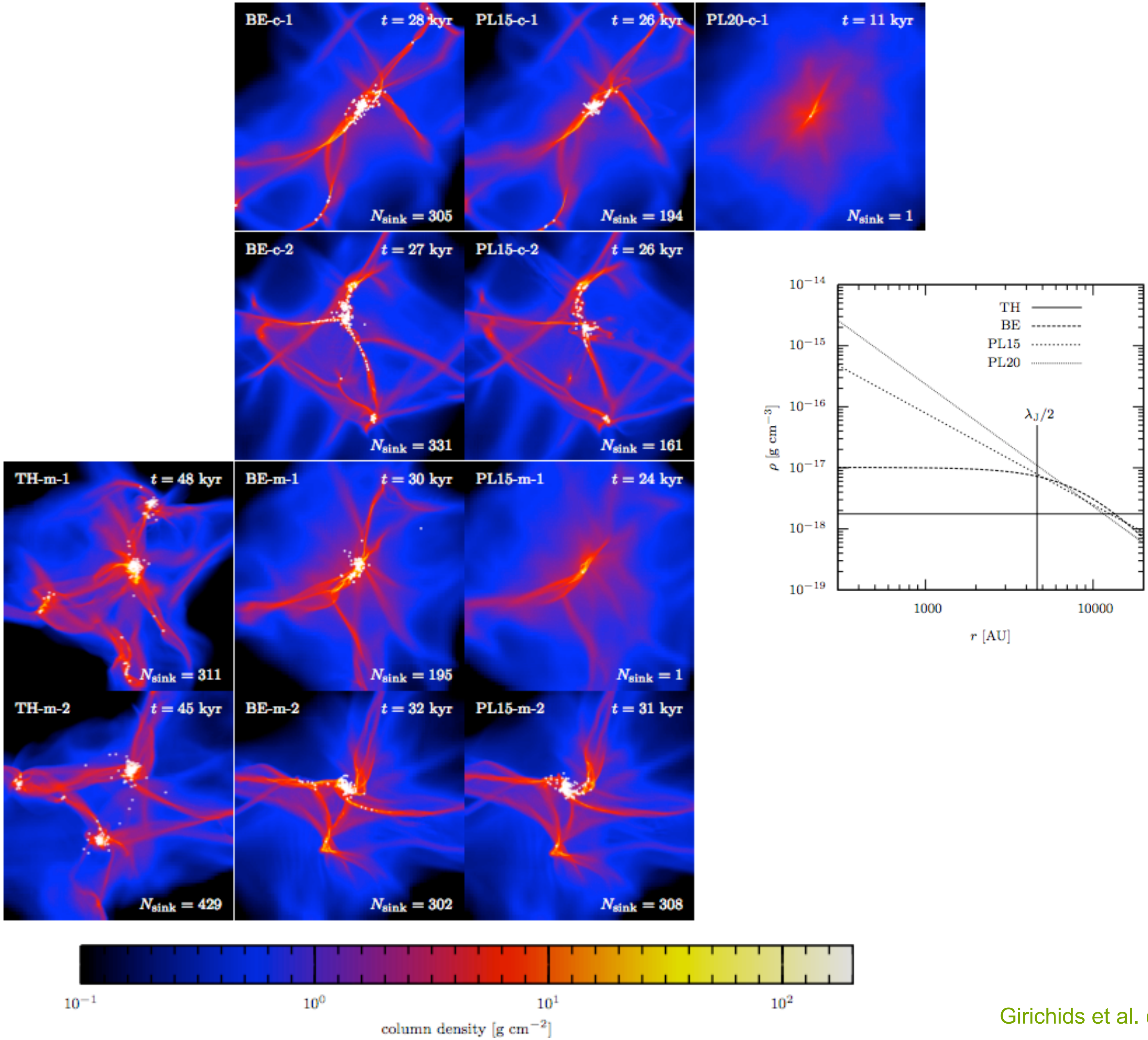


different density profiles

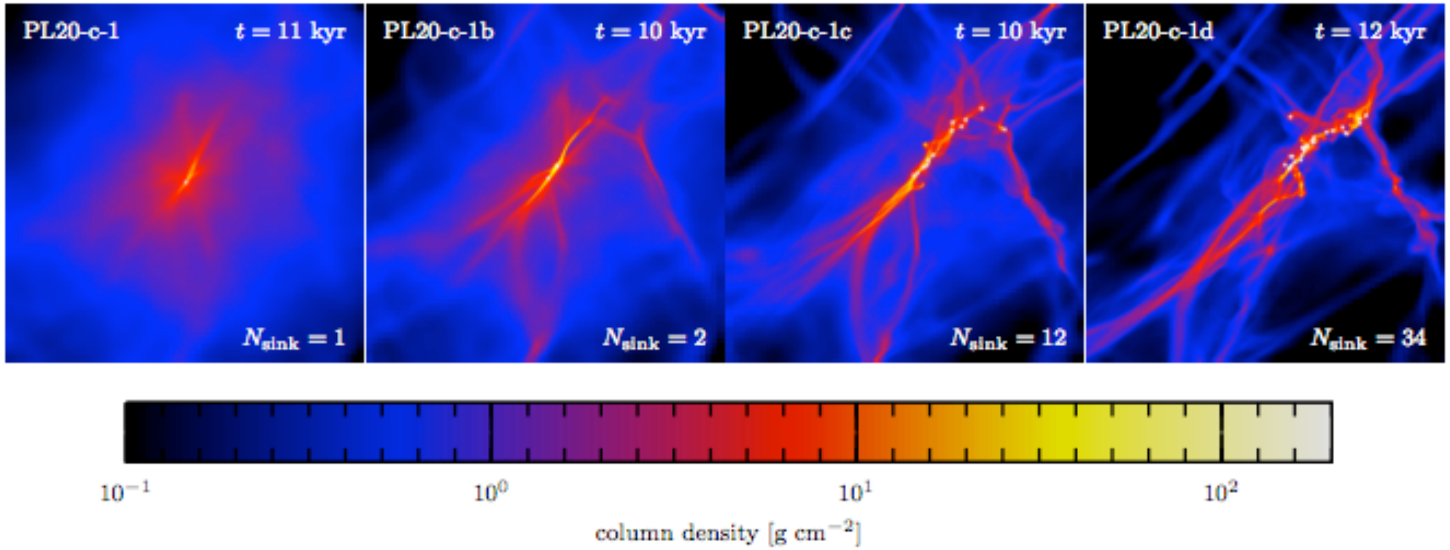
- address question in simple numerical experiment
- perform extensive parameter study
  - different profiles (top hat, BE, $r^{-3/2}$, r^{-3})
  - different turbulence fields
    - different realizations
    - different Mach numbers
    - solenoidal turbulence
      dilatational turbulence
      both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



Girichids, Federrath, Banerjee, Klessen (2011abc)



Girichids et al. (2011abc)



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

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

Girichids et al. (2011abc)

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

number of protostars

ICs with flat inner density profile form more fragments

Girichids et al. (2011abc)

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number of protostars

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

very high Mach numbers are needed to make SIS fragment

Girichids et al. (2011abc)

different density profiles

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

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

Girichids et al. (2011abc)


Carina with HST

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

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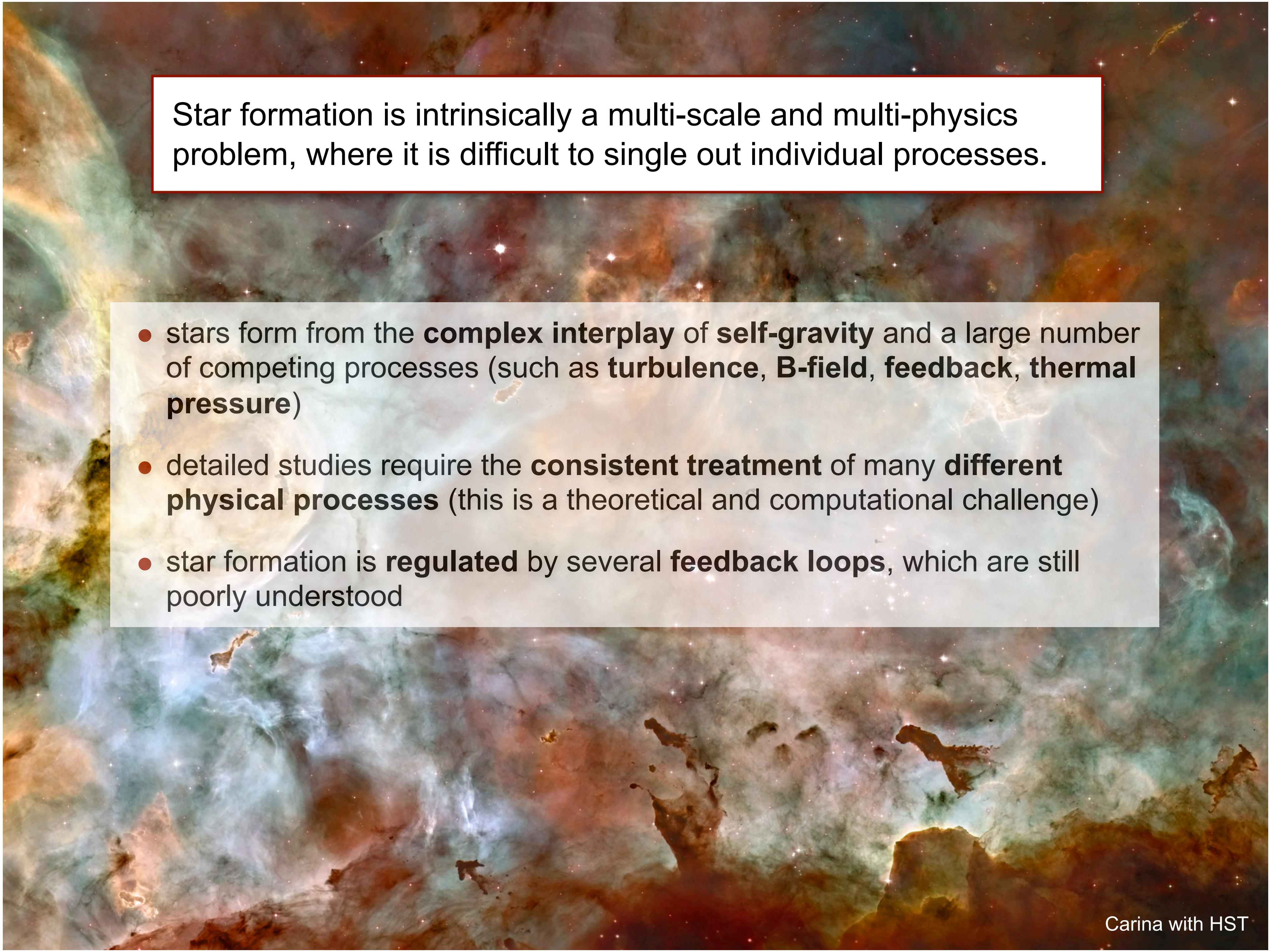
- stars form from the **complex interplay** of **self-gravity** and a large number of competing processes (such as **turbulence**, **B-field**, **feedback**, **thermal pressure**)
- detailed studies require the **consistent treatment** of many **different physical processes** (this is a theoretical and computational challenge)
- star formation is **regulated** by several **feedback loops**, which are still poorly understood



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- can radiation stop accretion onto high-mass stars? ➤ *probably not*
- what are the ICs of star cluster formation? ➤ *more work needed*
- are molecules required to form stars? ➤ *no*

Carina with HST


PPVI comes to Heidelberg
in summer 2013
... hope to see you there!!!