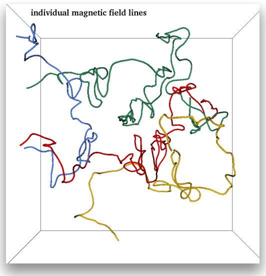
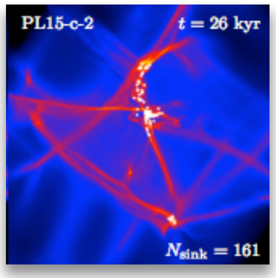
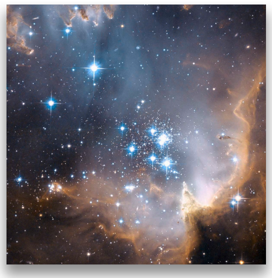
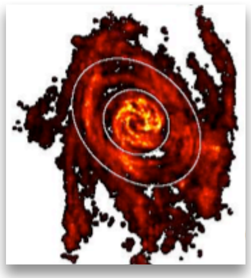
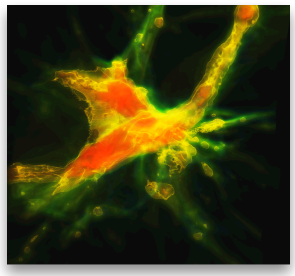
Modeling ISM Dynamics and Star Formation



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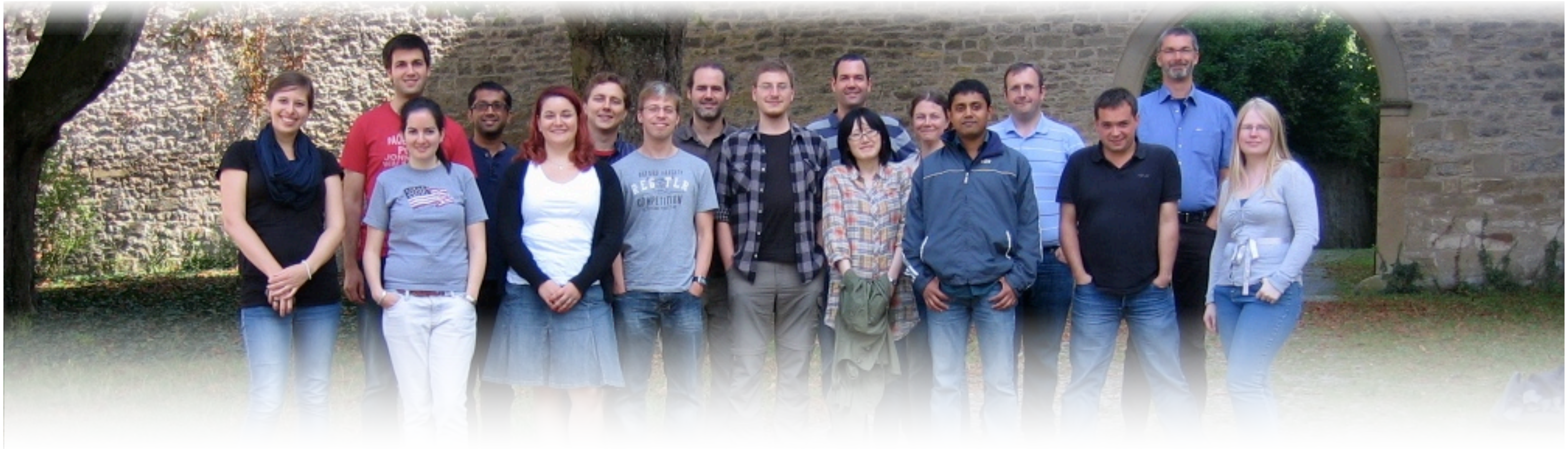
thanks to ...



... people in the group in Heidelberg:

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

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... many collaborators abroad!

Deutsche Forschungsgemeinschaft DFG

BADEN-WÜRTTEMBERG STIFTUNG Wir stiften Zukunft

HGSFP

IMPRS

Disclaimer

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

overview I

1. <u>Introduction</u> [~1h]
 -- phenomenology of stellar birth
 -- short historic overview
 -- complexity of star formation, overview of relevant physical processes

2. <u>ISM dynamics and of star formation</u> [~4h]

2.1 Turbulence
 -- turbulence in the interstellar medium (statistical characteristics)
 -- discussion of possible drivers of ISM turbulence
 -- *excursion: modeling turbulence*

2.2 Gravo-turbulent star formation models
 -- short overview of statistical (turbulence-based) star formation models
 -- competitive accretion vs. monolithic collapse vs. alternative approaches

2.3 Influence of density profile on star-cluster formation
 -- dependence of fragmentation on initial density profile of cluster forming cloud cores
 -- requirement for taking cloud formation into account

2.4 Radiative processes
 -- coupling between gas/dust and the radiation field
 -- *long excursion: modeling radiative transfer*

2.5 Thermodynamic properties of the ISM
 -- main heating and cooling mechanisms
 -- chemical processes in the ISM
 -- multi-phase ISM
 -- *excursion: modeling extinction in dense clouds*

2.6 Magnetic fields in the ISM
 -- influence of magnetic fields on molecular cloud dynamics
 -- protostellar collapse and magnetic fields

overview 2

3. <u>Star formation and feedback</u> [~1.5h]
  -- importance of feedback for locally terminating star formation
  -- *excursion: sink particles as subgrid-scale model of protostellar collapse*

3.1 Radiative feedback
  -- accretion heating
  -- ionizing radiation, HII regions
  -- *excursion: coupling (proto)stellar evolution to sink particles*

3.2 Mechanical feedback
  -- controversial role of outflows in star formation
  -- *excursion: modeling outflows*

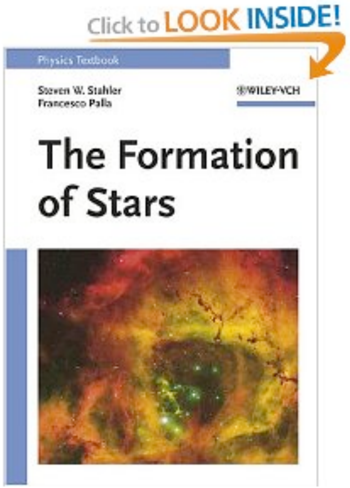
4. <u>Some selected applications</u> [~1.5h]

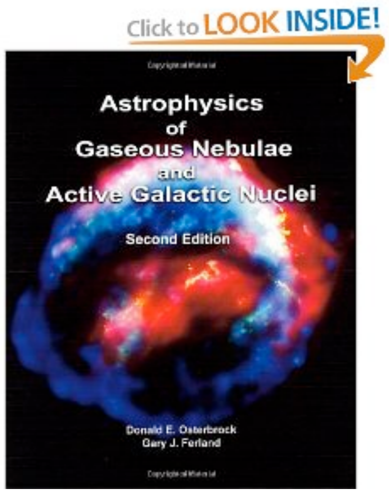
4.1 The stellar initial mass function
  -- theoretical models of the IMF
  -- universality

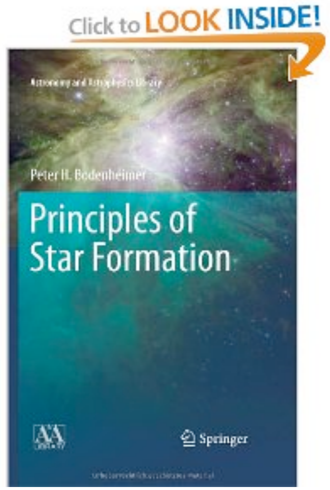
4.2 Star formation in the primordial universe
  -- formation of the first stars
  -- transition from Population III to Population II (dust vs. atomic cooling lines)
  -- observational constraints
  -- dark stars

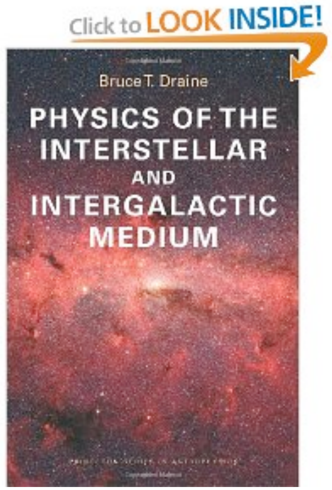
4.3 Magnetic field amplification in the early universe
  -- dynamo processes in primordial halos
  -- some notes on numerical resolution

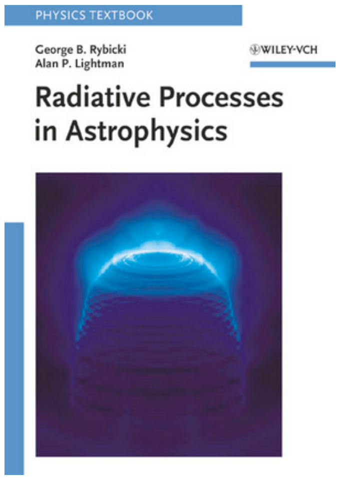
Literature

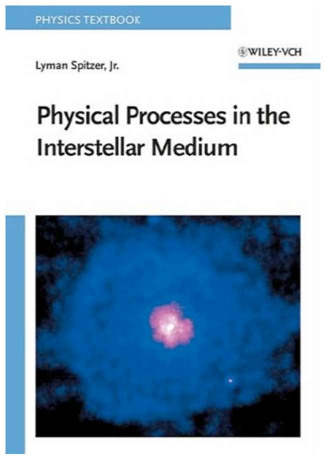

Click to LOOK INSIDE!
Physics Textbook
Steven W. Stahler
Francesco Palla
WILEY-VCH
The Formation of Stars

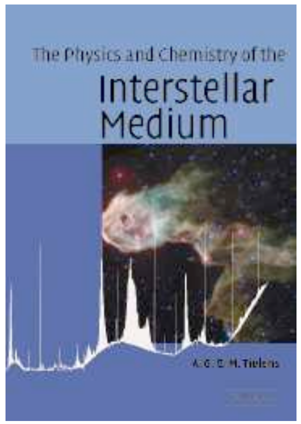

Click to LOOK INSIDE!
Astrophysics of Gaseous Nebulae and Active Galactic Nuclei
Second Edition
Donald E. Osterbrock
Gary J. Ferland

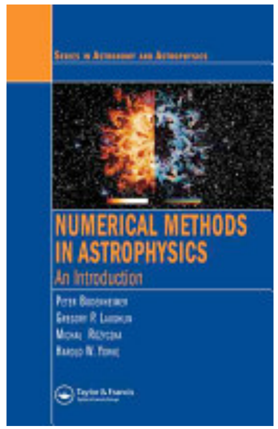

Click to LOOK INSIDE!
Peter H. Bodenheimer
Principles of Star Formation
Springer


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


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


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


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


NUMERICAL METHODS IN ASTROPHYSICS
An Introduction

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

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- Review Articles

  - Mac Low, M.-M., Klessen, R.S., 2004, "The control of star formation by supersonic turbulence", Rev. Mod. Phys., 76, 125
  - Elmegreen, B.G., Scalo, J., 2004, "Interstellar Turbulence 1", ARA&A, 42, 211
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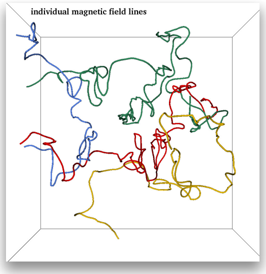
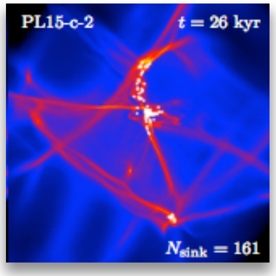
  - Zinnecker, H., Yorke, McKee, C.F., Ostriker, E.C., 2008, "Toward Understanding Massive Star Formation", ARA&A, 45, 481 - 563
  - McKee, C.F., Ostriker, E.C., 2008, "Theory of Star Formation", ARA&A, 45, 565
  - Kennicutt, R.C., Evans, N.J., 2012, "Star Formation in the Milky Way and Nearby Galaxies", ARA&A, 50, 531

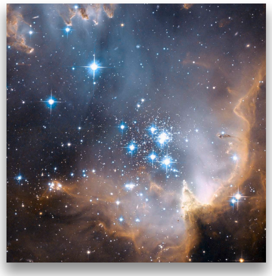
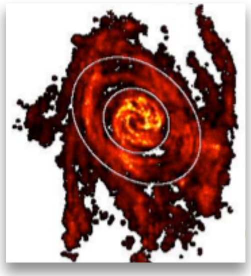
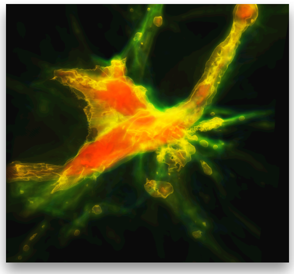
Further resources

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

Part 1: Introduction



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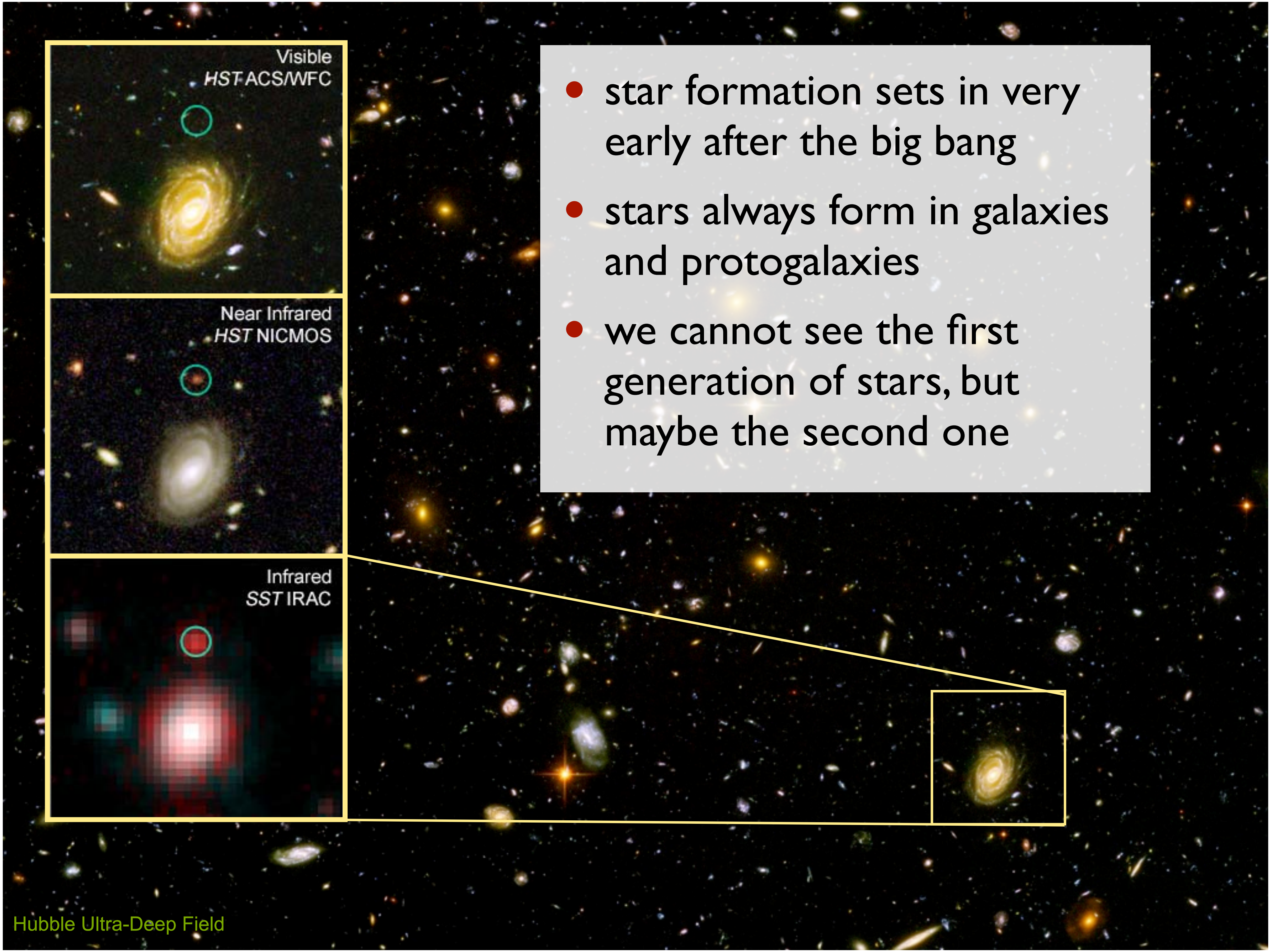
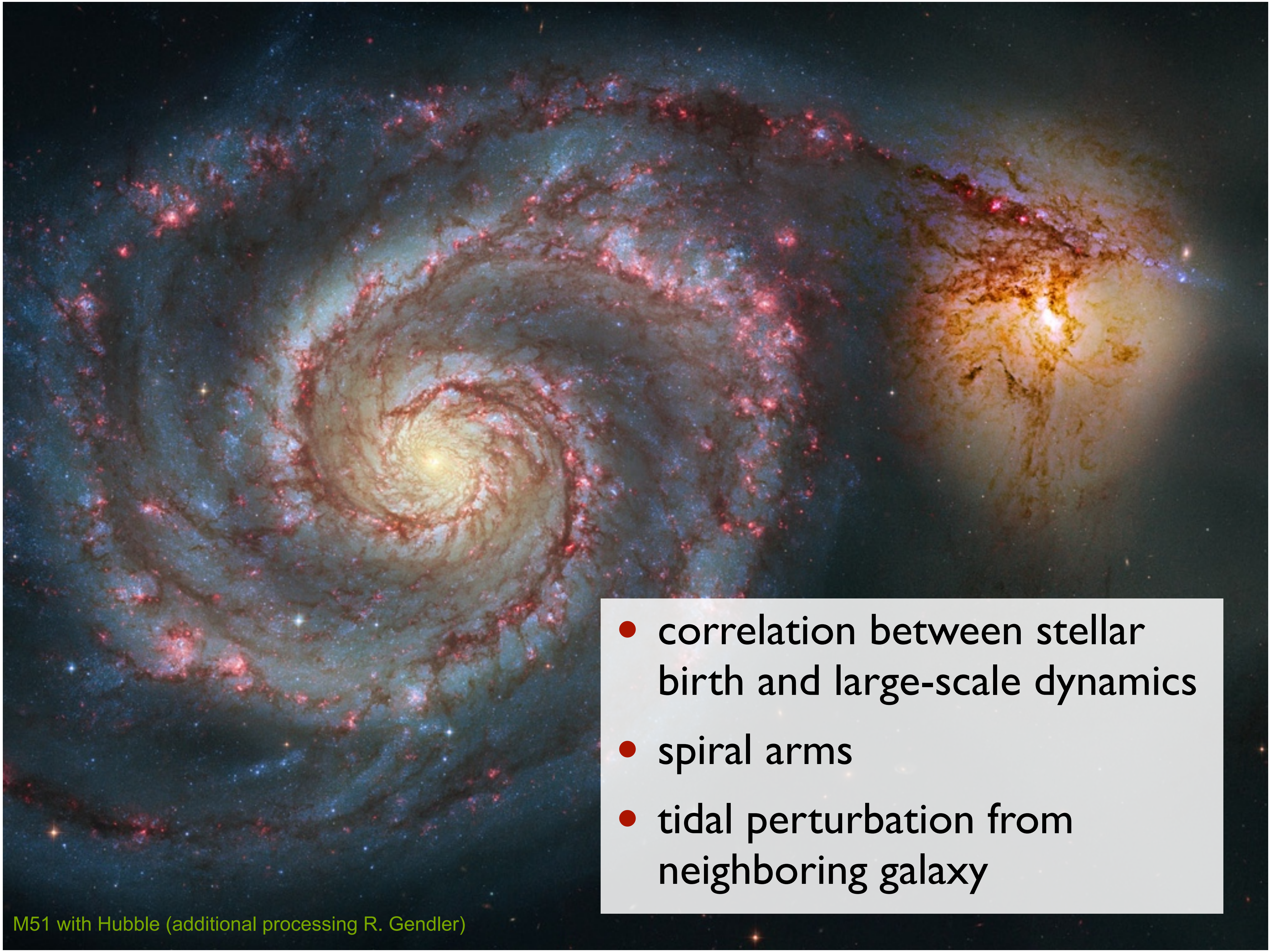
Phenomenology

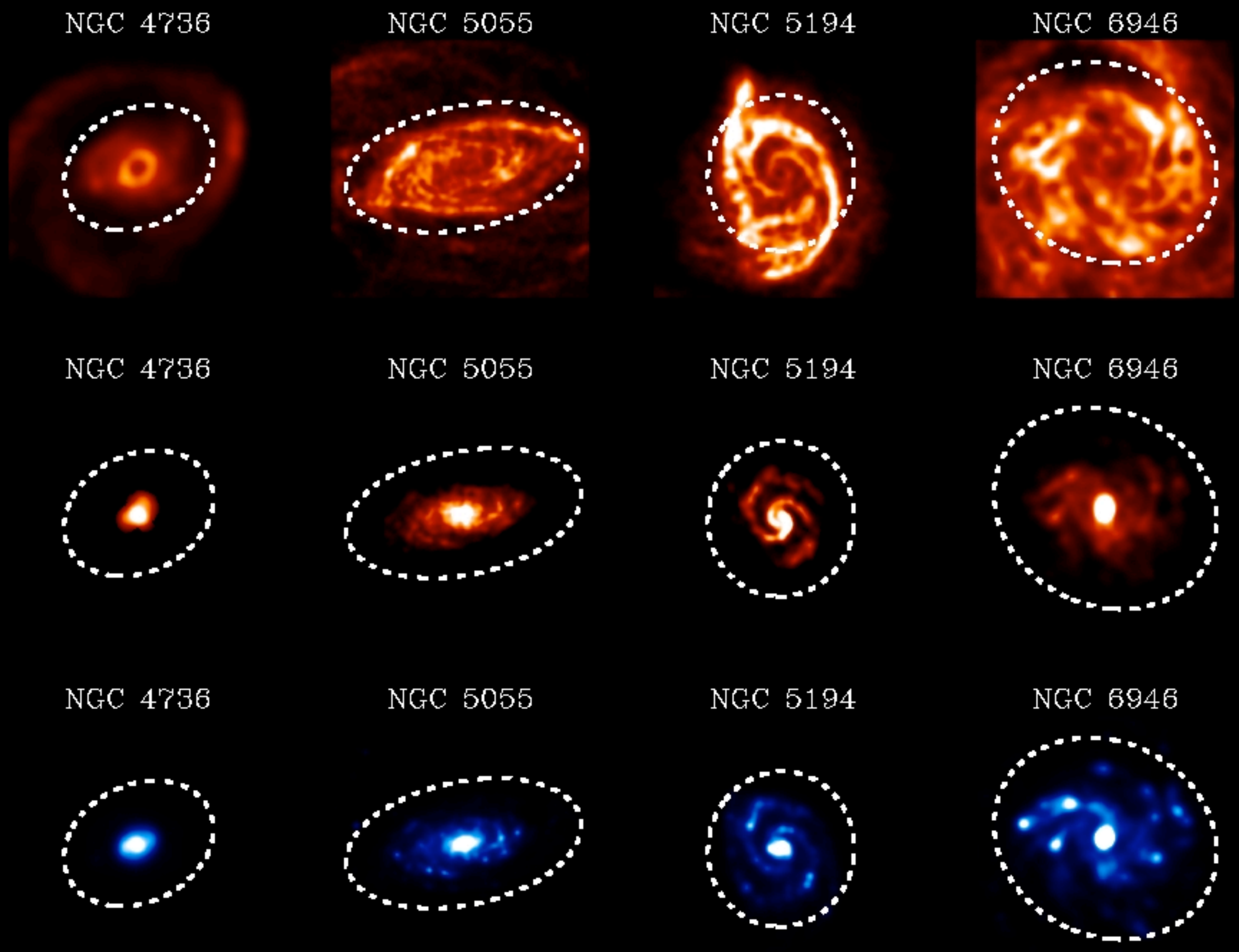


- star formation sets in very early after the big bang
- stars always form in galaxies and protogalaxies
- we cannot see the first generation of stars, but maybe the second one



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

M51 with Hubble (additional processing R. Gendler)



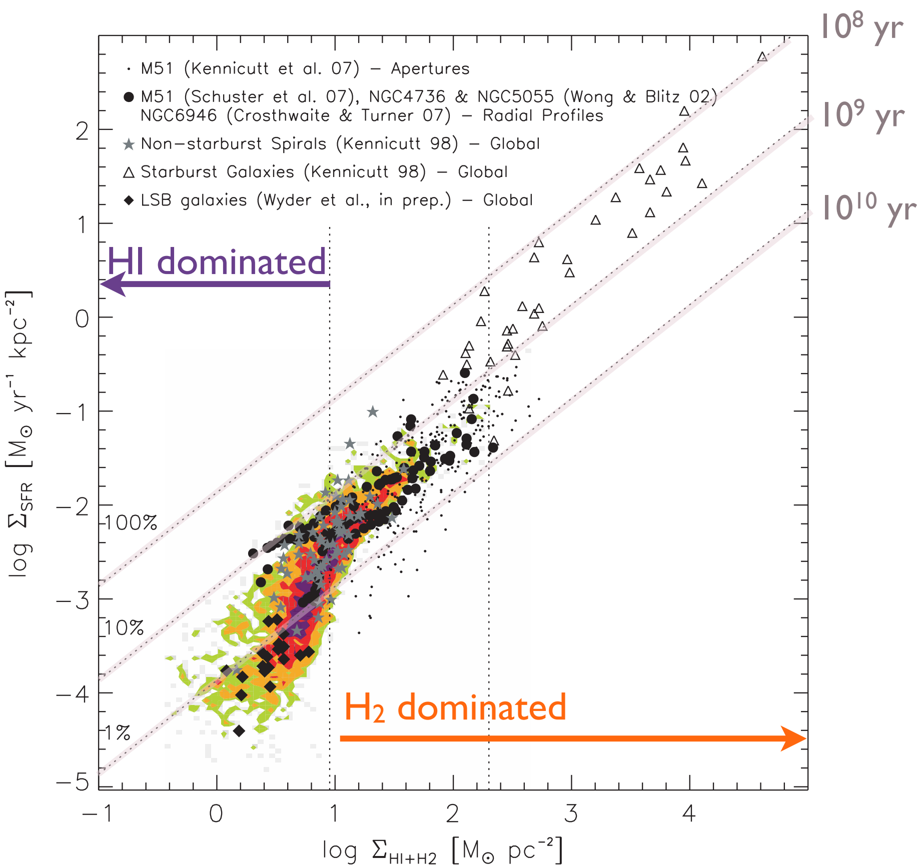
atomic hydrogen

molecular hydrogen

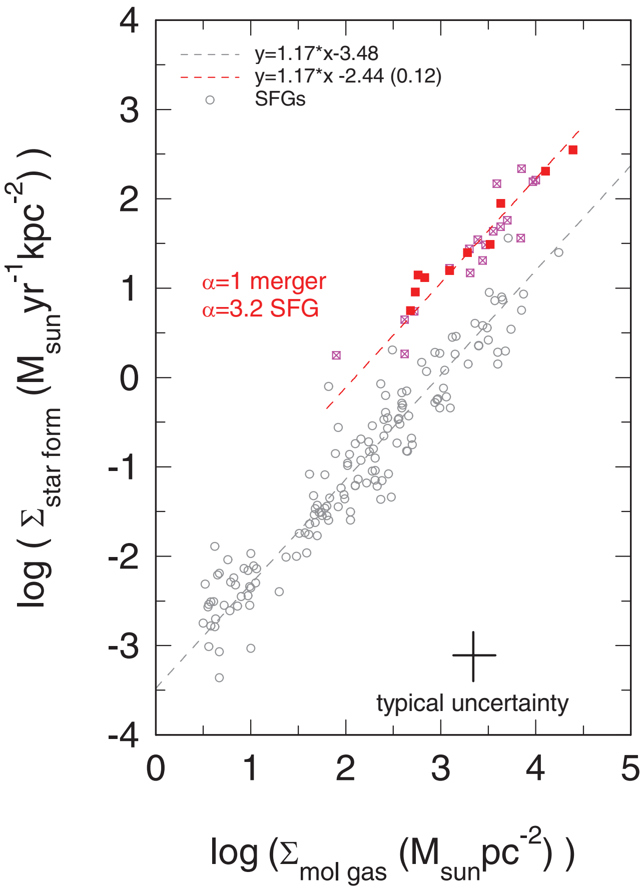
star formation

- HI gas more extended
- H2 and SF well correlated

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

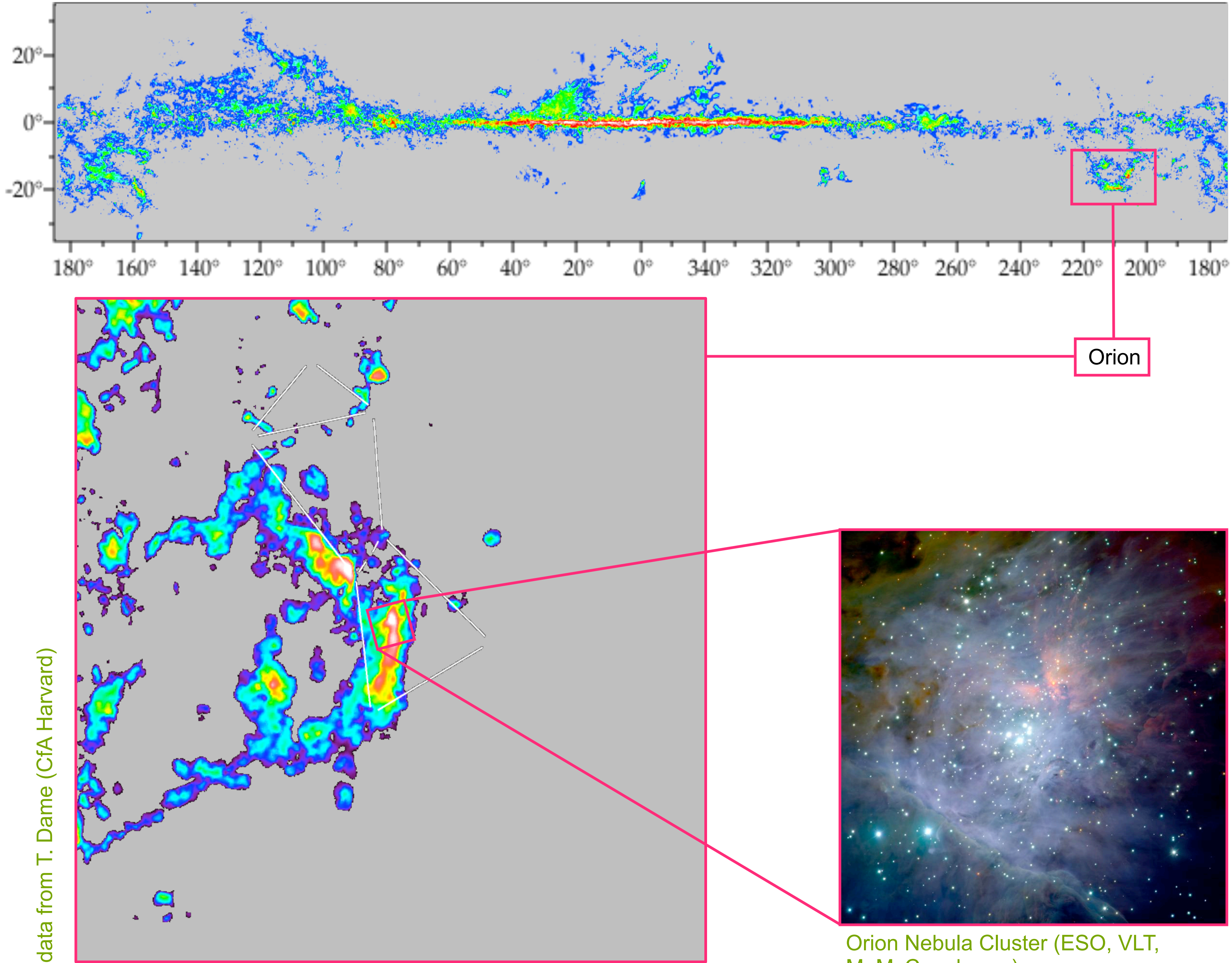


Bigiel et al. (2008, AJ, 136, 2846)



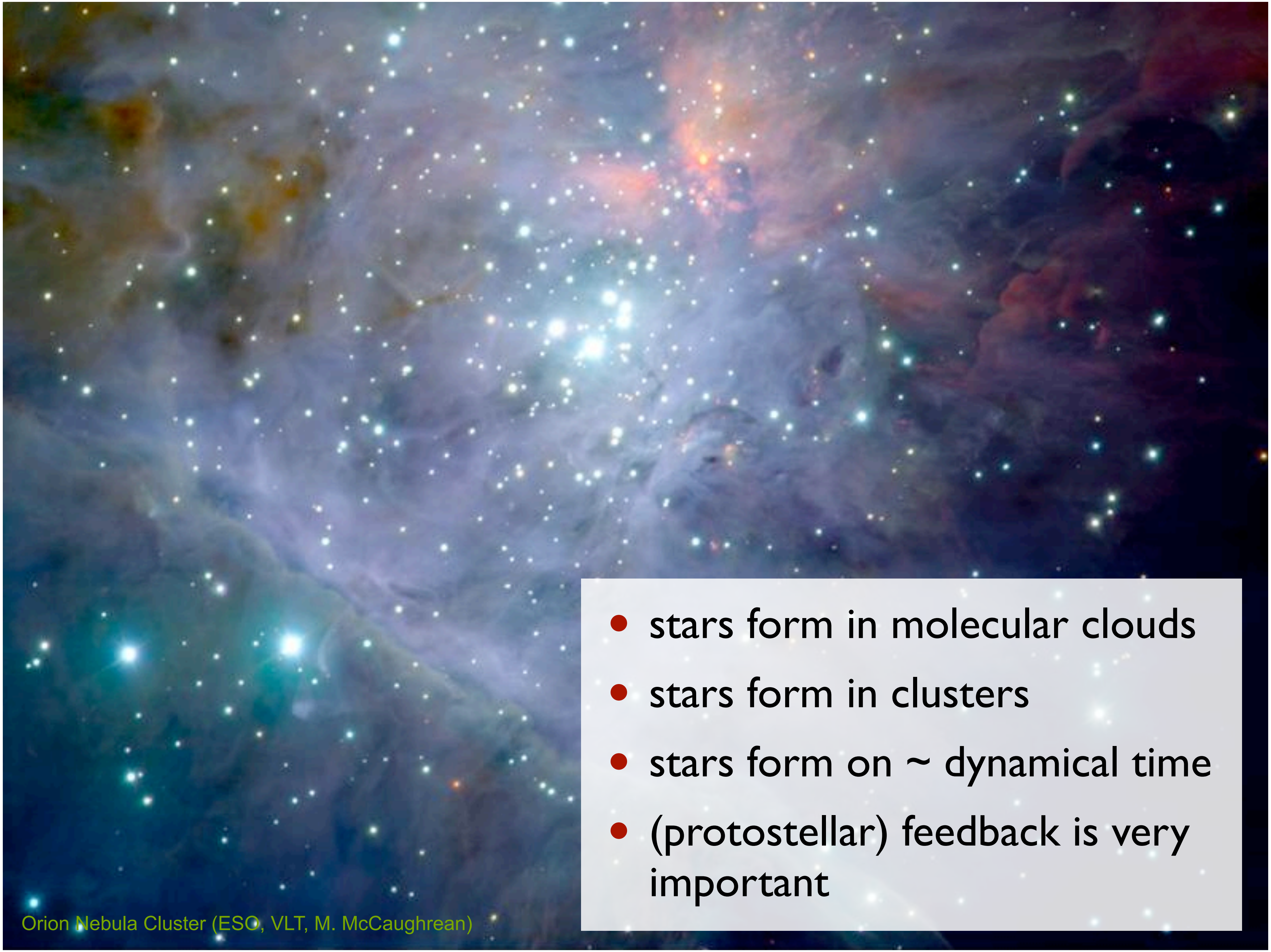
Genzel et al. (2010, MNRAS, AJ, 407, 2091)

- roughly linear relation between H_2 and SFR
- roughly constant depletion time: few x 10^9 yr
- super linear relation between total gas and SFR



data from T. Dame (CfA Harvard)

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

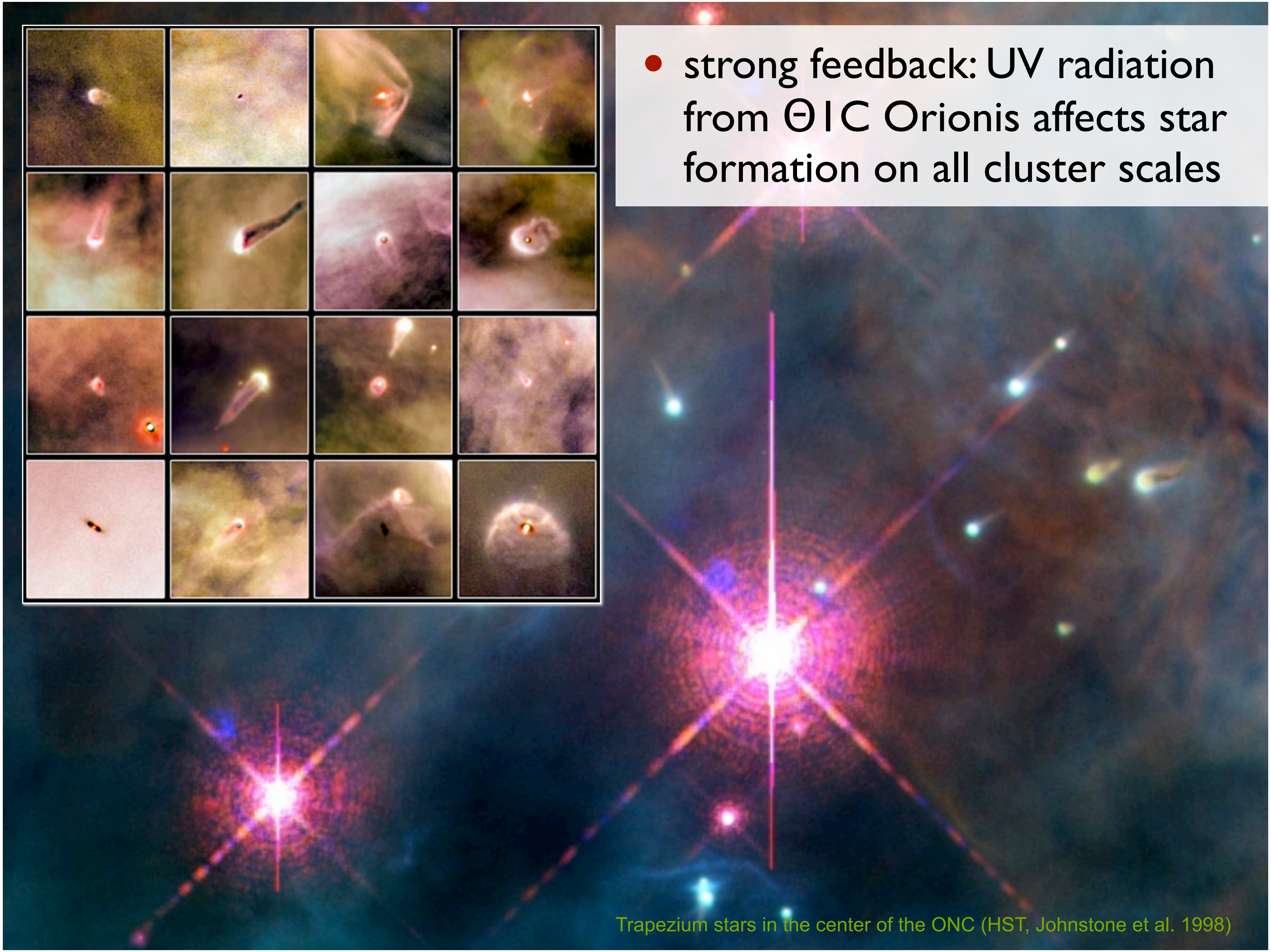


- stars form in molecular clouds
- stars form in clusters
- stars form on ~ dynamical time
- (protostellar) feedback is very important

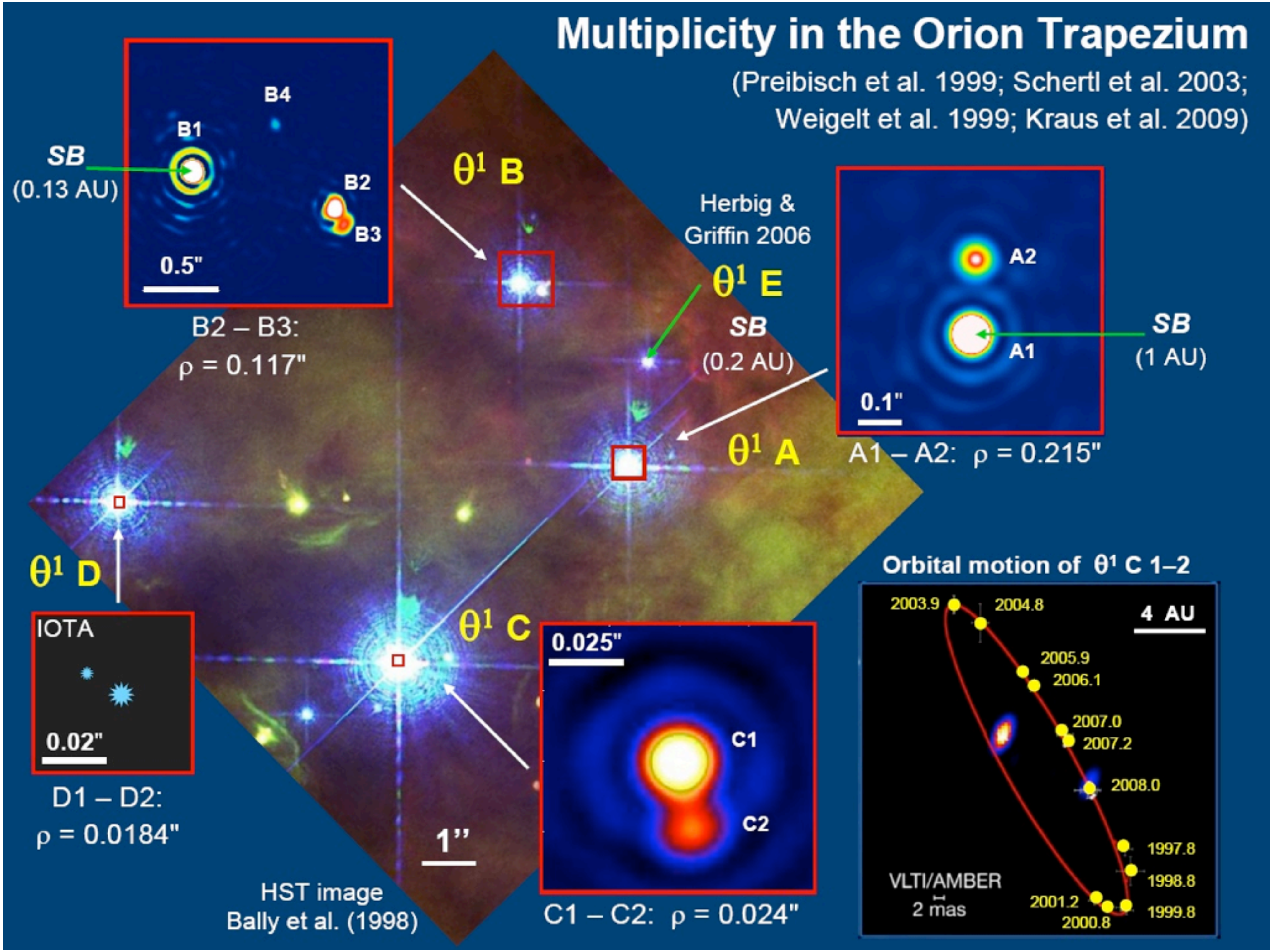
Orion Nebula Cluster (ESO, VLT, M. McCaughrean)

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

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



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


Multiplicity in the Orion Trapezium
(Preibisch et al. 1999; Schertl et al. 2003;
Weigelt et al. 1999; Kraus et al. 2009)
SB
(0.13 AU)
B1
B4
B2
B3
0.5"
B2 – B3:
ρ = 0.117"
θ1 B
Herbig &
Griffin 2006
θ1 E
SB
(0.2 AU)
A2
A1
SB
(1 AU)
0.1"
θ1 A
A1 – A2: ρ = 0.215"
θ1 D
IOTA
0.02"
D1 – D2:
ρ = 0.0184"
θ1 C
0.025"
C1
C2
C1 – C2: ρ = 0.024"
1"
HST image
Bally et al. (1998)
Orbital motion of θ1 C 1–2
4 AU
2003.9
2004.8
2005.9
2006.1
2007.0
2007.2
2008.0
1997.8
1998.8
1999.8
2000.8
2001.2
VLTI/AMBER
2 mas

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

Pleiades (DSS, Palomar Observatory Sky Survey)

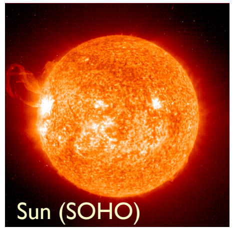
theoretical approach

decrease in spatial scale / increase in density


Andromeda (R. Gendler)


NGC 602 in LMC (Hubble)


Proplyd in Orion (Hubble)


Sun (SOHO)


Earth

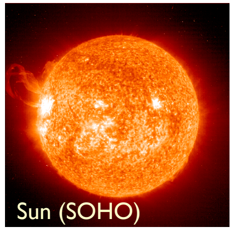
- density
  - density of ISM: few particles per cm^3
  - density of molecular cloud: few 100 particles per cm^3
  - density of Sun: 1.4 g/cm^3
- spatial scale
  - size of molecular cloud: few 10s of pc
  - size of young cluster: ~ 1 pc
  - size of Sun: 1.4×10^{10} cm

decrease in spatial scale / increase in density


Andromeda (R. Gendler)


NGC 602 in LMC (Hubble)

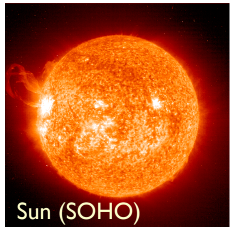

Proplyd in Orion (Hubble)


Sun (SOHO)


Earth

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

decrease in spatial scale / increase in density



- 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.

historic overview

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

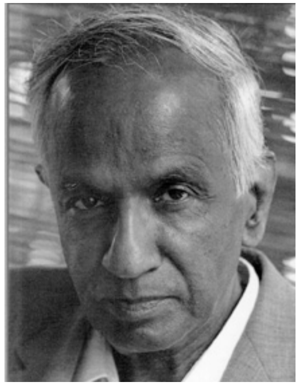
    $\ell_{\mathrm{turb}} \ll \ell_{\mathrm{dyn}}$

  - then turbulent velocity dispersion contributes to effective soundspeed:

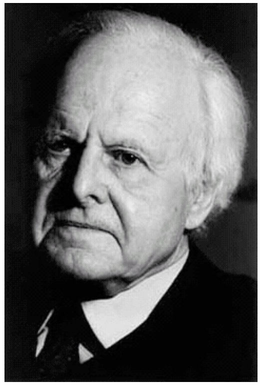
    $$c_{\mathrm{eff}}^2 \mapsto c_c^2 + \sigma_{rms}^2$$

  - → 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

Properties of IMS turbulence

ISM turbulence is:

- Supersonic (rms velocity dispersion >> sound speed)
- Anisotropic (shocks & magnetic field)
- Driven on large scales (power in mol. clouds always dominated by largest-scale modes)

Microturbulent approach is NOT valid in ISM

- No closed analytical/statistical formulation known
  --> necessity for numerical modeling

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

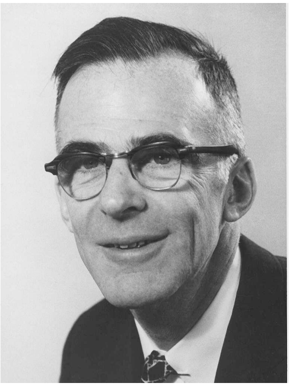
- *Mestel & Spitzer (1956):* Magnetic fields can prevent collapse*!!!*
  - Critical mass for gravitational collapse in presence of B-field

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

  - 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

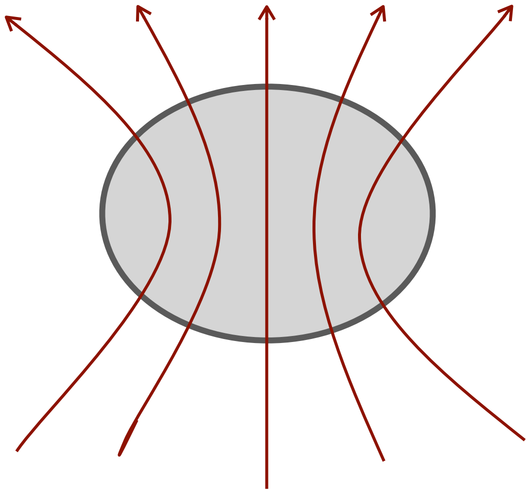


Lyman Spitzer, Jr., 1914 - 1997

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

observed B-fields are weak

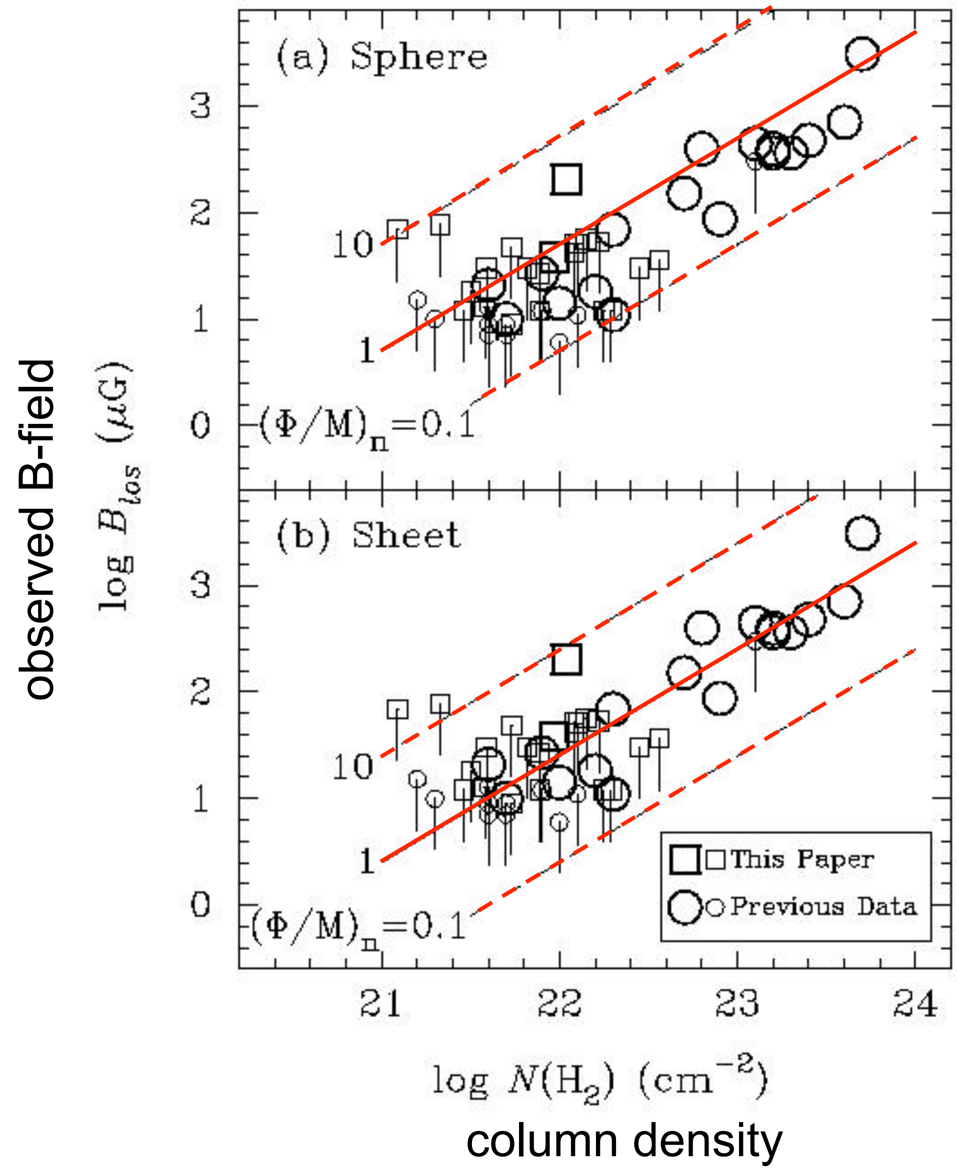
B versus ***N(H_2)*** from *Zeeman measurements*.

(from Bourke et al. 2001)

→ cloud cores are magnetically supercritical***!!!***

$(\Phi/M)_n > 1$ no collapse

$(\Phi/M)_n < 1$ collapse

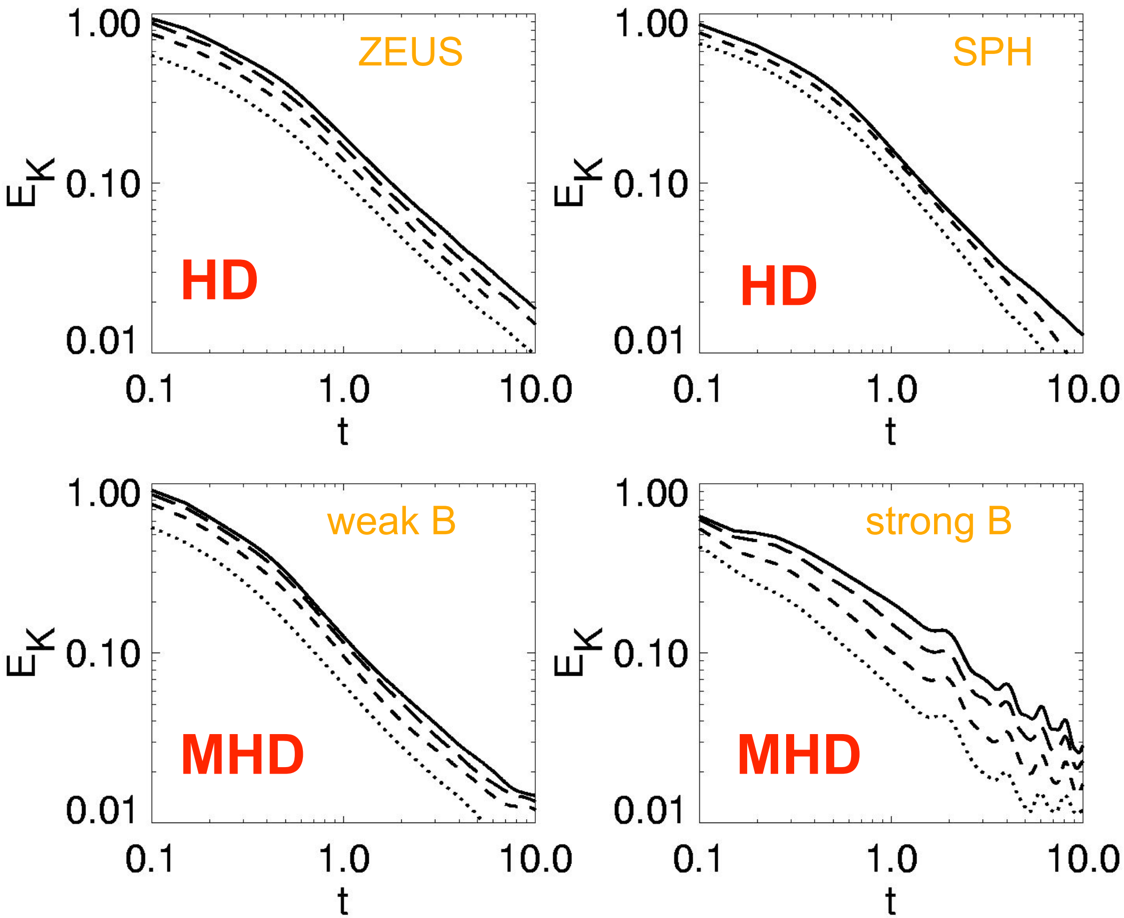


molecular cloud dynamics

- **Timescale problem:** Turbulence *decays* on timescales *comparable to the free-fall time* τ_{ff} ($E \propto t^{-\eta}$ with $\eta \approx 1$).

(Mac Low et al. 1998,
Stone et al. 1998,
Padoan & Nordlund 1999)

- Magnetic fields (static or wave-like) *cannot* prevent loss of energy.



(Mac Low, Klessen, Burkert, & Smith, 1998, PRL)

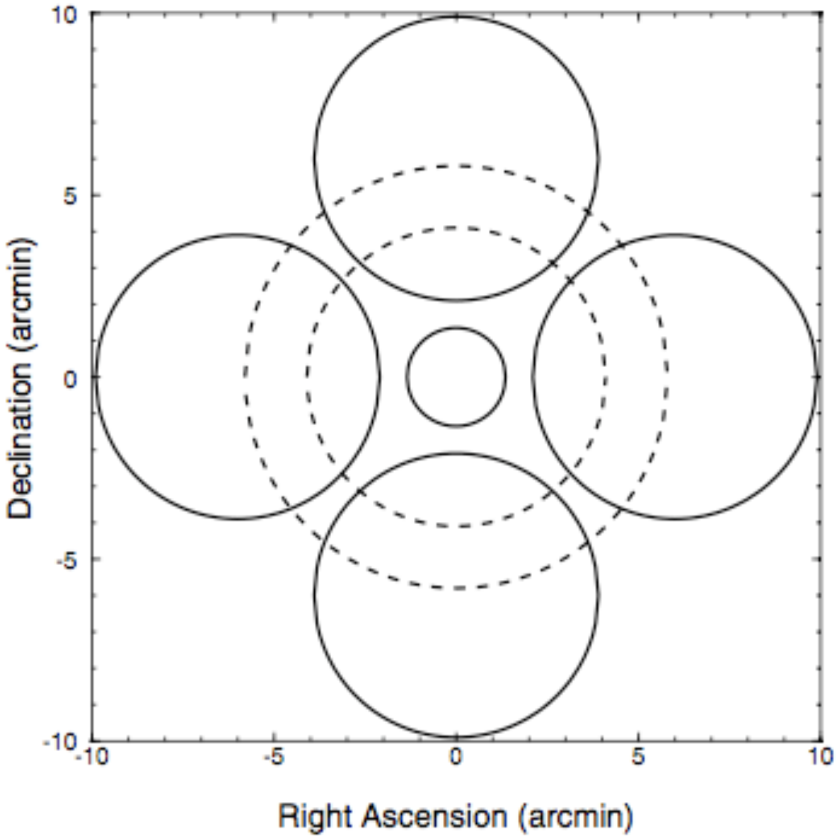
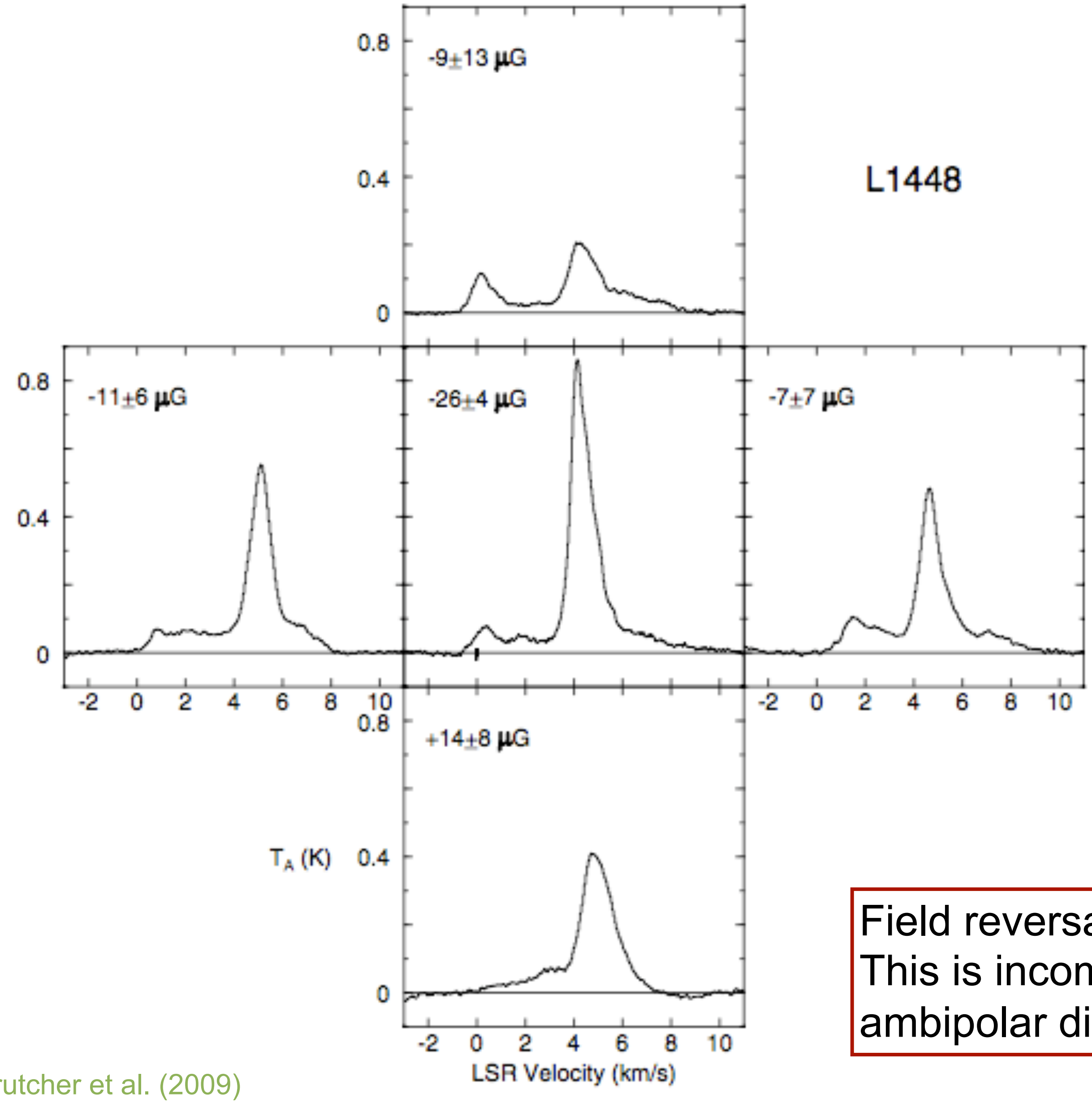


Fig. 1.— The Arecibo telescope primary beam (small circle centered at 0,0) and the four GBT telescope primary beams (large circles centered 6′ north, south, east, and west of 0,0. The dotted circles show the first sidelobe of the Arecibo telescope beam. All circles are at the half-power points.

Crutcher et al. (2009)



Crutcher et al. (2009)

Fig. 2.— OH 1667 MHz spectra toward the core of L1448CO obtained with the Arecibo telescope (center panel) and toward each of the envelope positions 6′ north, south, east, and west of the core, obtained with the GBT. In the upper left of each panel is the inferred B_{LOS} and its 1σ uncertainty at that position. A negative B_{LOS} means the magnetic field points toward the observer, and vice versa for a positive B_{LOS}.

Field reversal in the outer parts. This is incompatible with “standard” ambipolar diffusion theory!

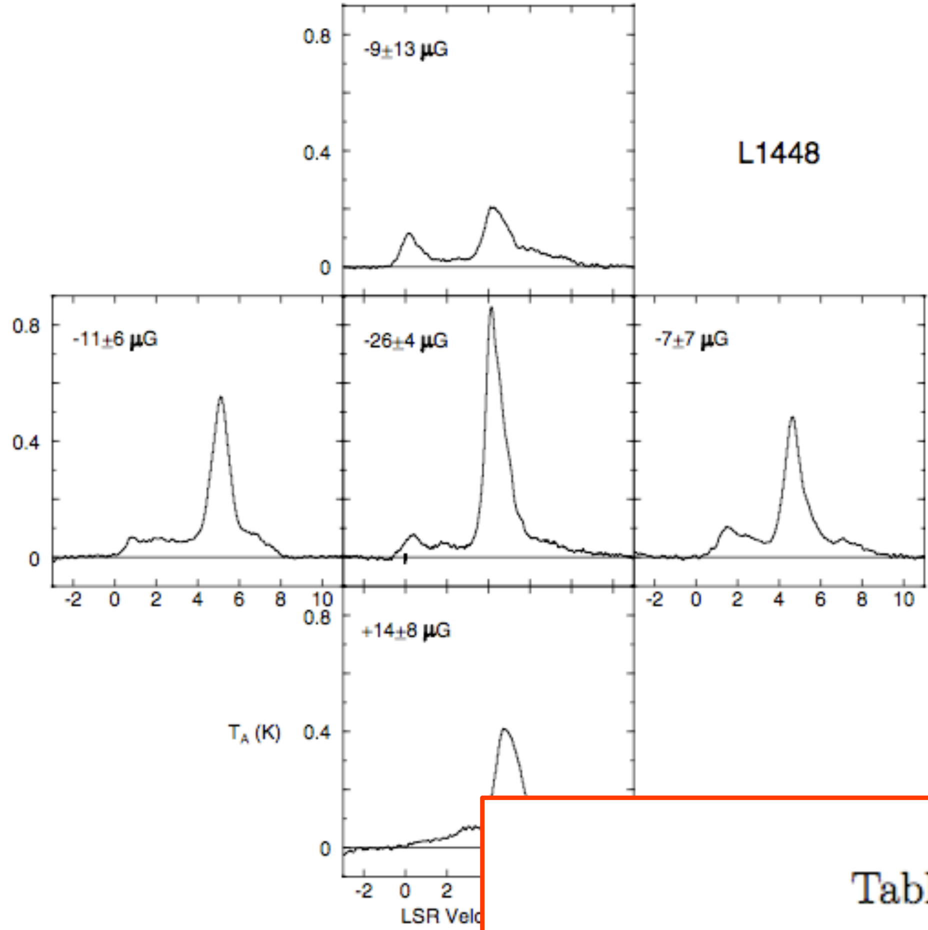


Fig. 2.— OH 1667 MHz spectra toward the
telescope (center panel) and toward each of the
west of the core, obtained with the GBT. In the
and its 1σ uncertainty at that position. A neg
toward the observer, and vice versa for a positi

example: L1448

Table 2. Relative Mass/Flux

Cloud	$\mathcal{R}$	$\mathcal{R}'$	Probability $\mathcal{R}$ or $\mathcal{R}' > 1$
L1448CO	0.02 ± 0.36	0.07 ± 0.34	0.005
B217-2	0.15 ± 0.43	0.19 ± 0.41	0.05
L1544	0.42 ± 0.46	0.46 ± 0.43	0.11
B1	0.41 ± 0.20	0.44 ± 0.19	0.010

Crutcher et al. (2009)

Lunttila et al. (2008)

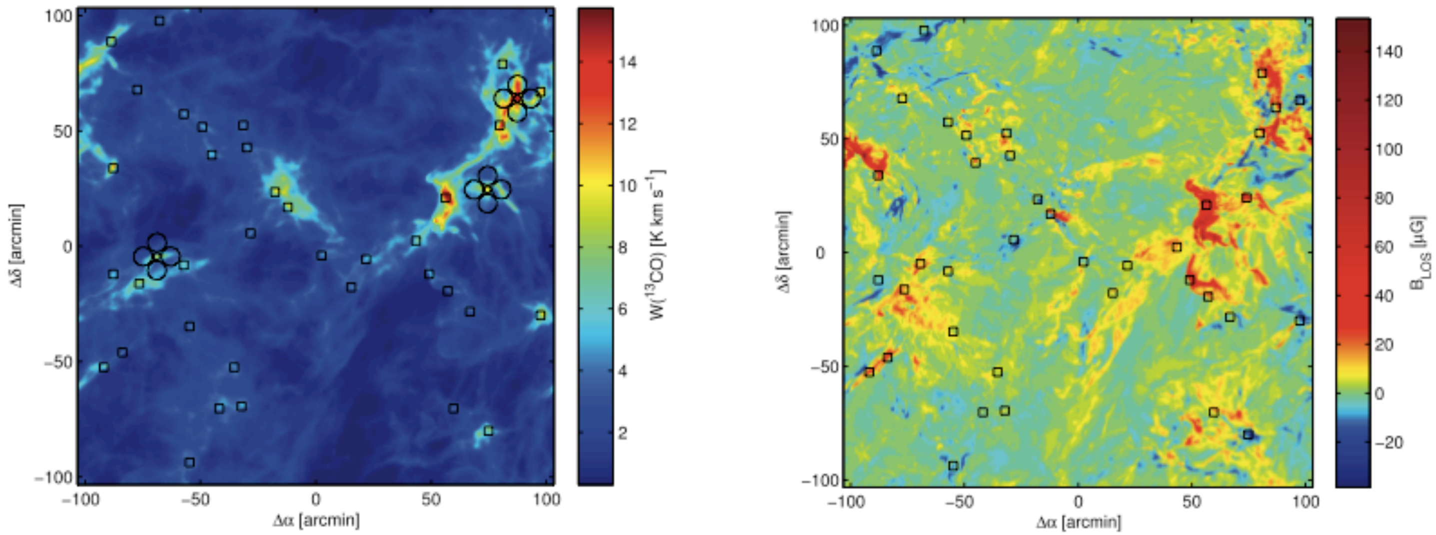
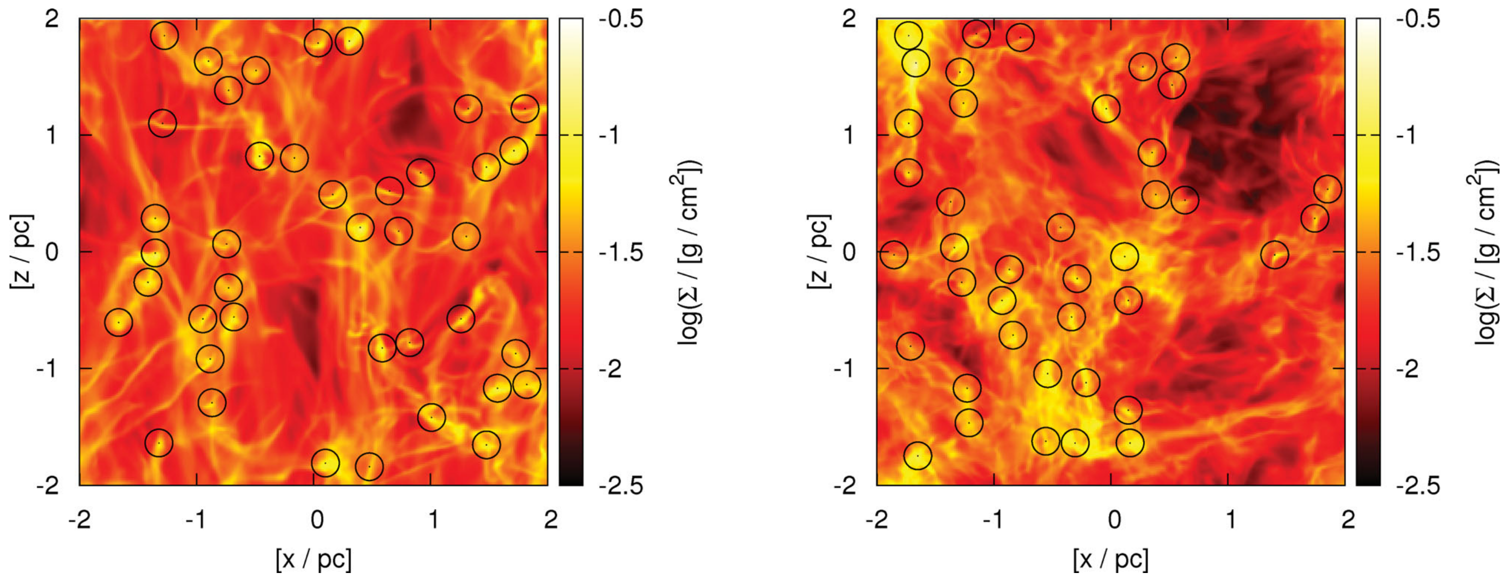
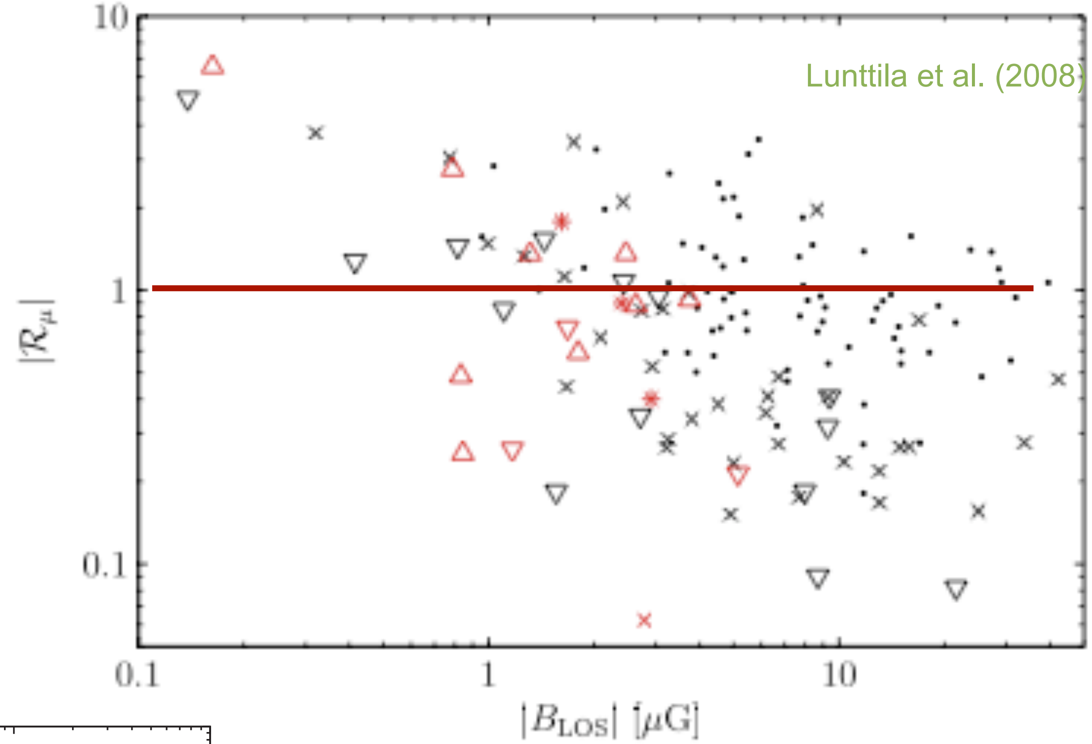
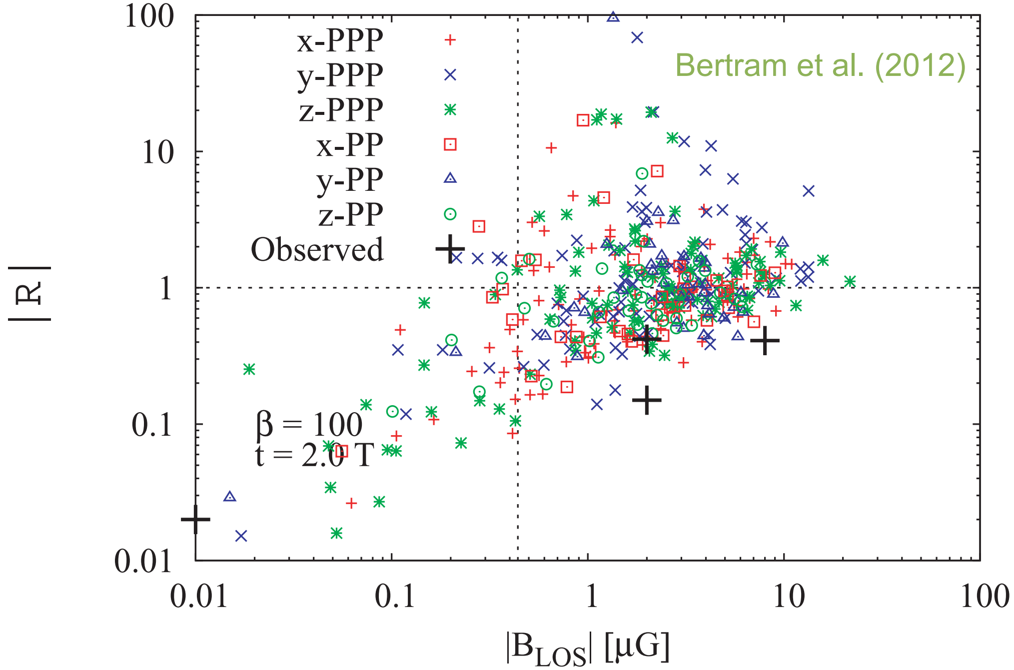


FIG. 1.—*Left*: Simulated ^{13}CO (1–0) map of the model in the *z*-axis direction. The locations of the cloud cores are shown with squares. The circles indicate the locations of telescope beams used in the synthetic observations of three cores. *Right*: Line-of-sight magnetic field strength as calculated from Zeeman splitting.



Bertram et al. (2012)





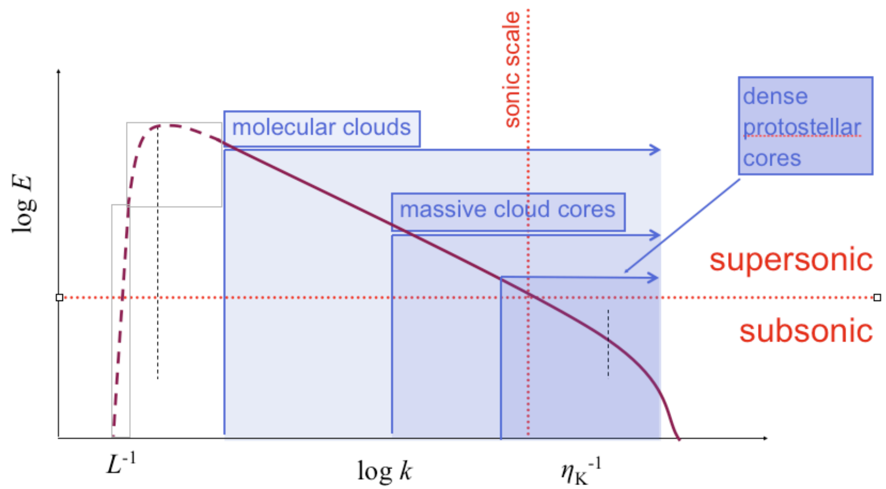
Also numerical models of prestellar cores forming in turbulent MHD simulations of ISM dynamics show a large number of field reversals.

gravoturbulent star formation

- BASIC ASSUMPTION:

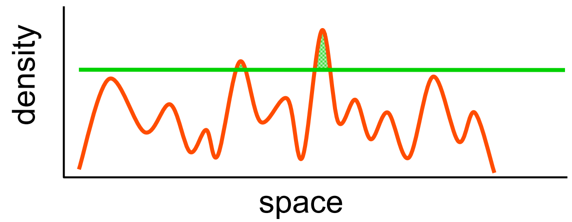
star formation is controlled by interplay between supersonic turbulence and self-gravity

- 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

gravoturbulent star formation



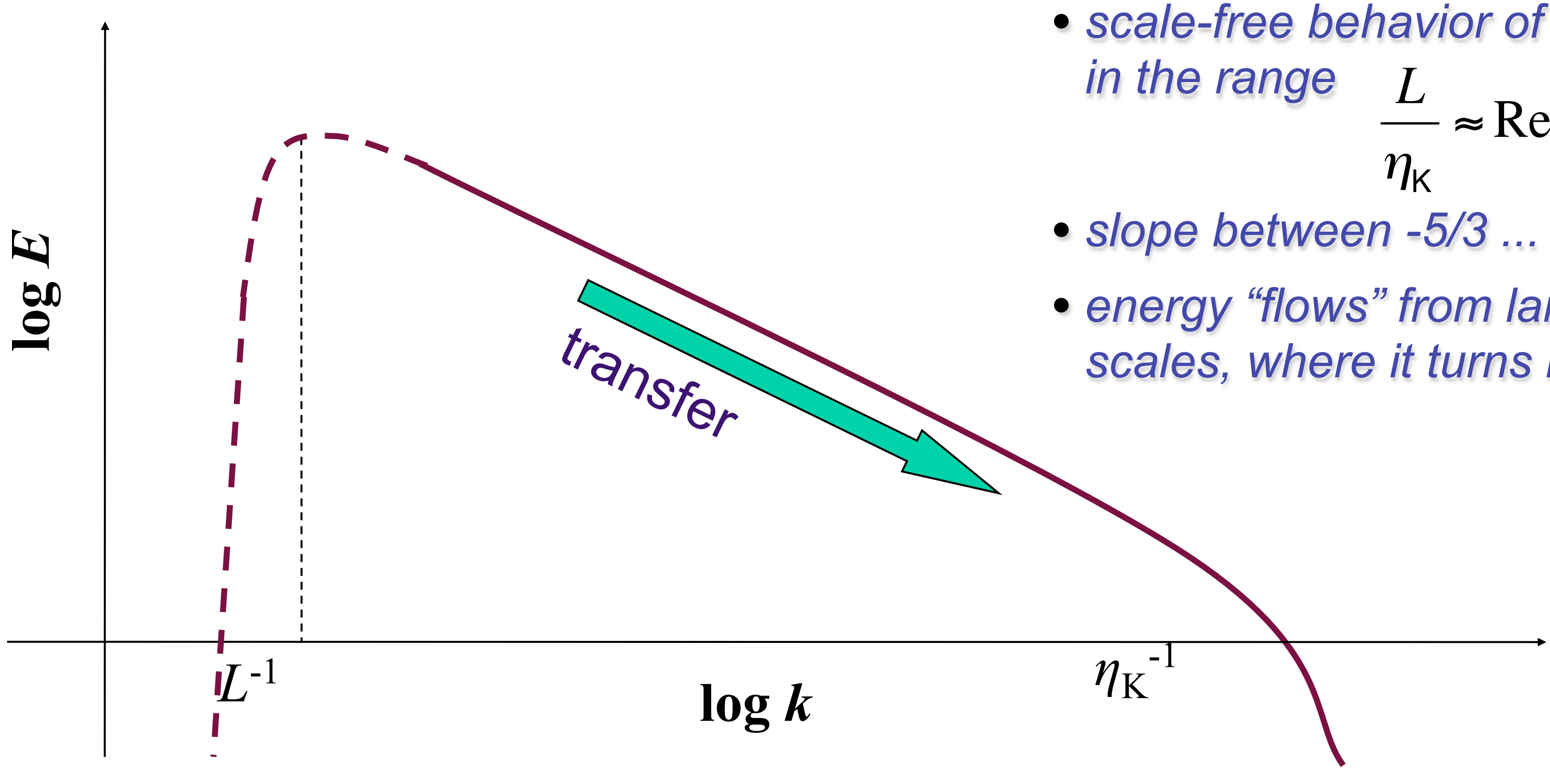
- interstellar gas is highly *inhomogeneous*
  - *thermal instability*
  - *gravitational instability*
  - *turbulent compression* (in shocks $\delta\rho/\rho \propto \mathcal{M}^2$; in atomic gas: $\mathcal{M} \approx 1...3$)
- cold *molecular clouds* can form rapidly in high-density regions at *stagnation 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)

turbulent cascade in the ISM

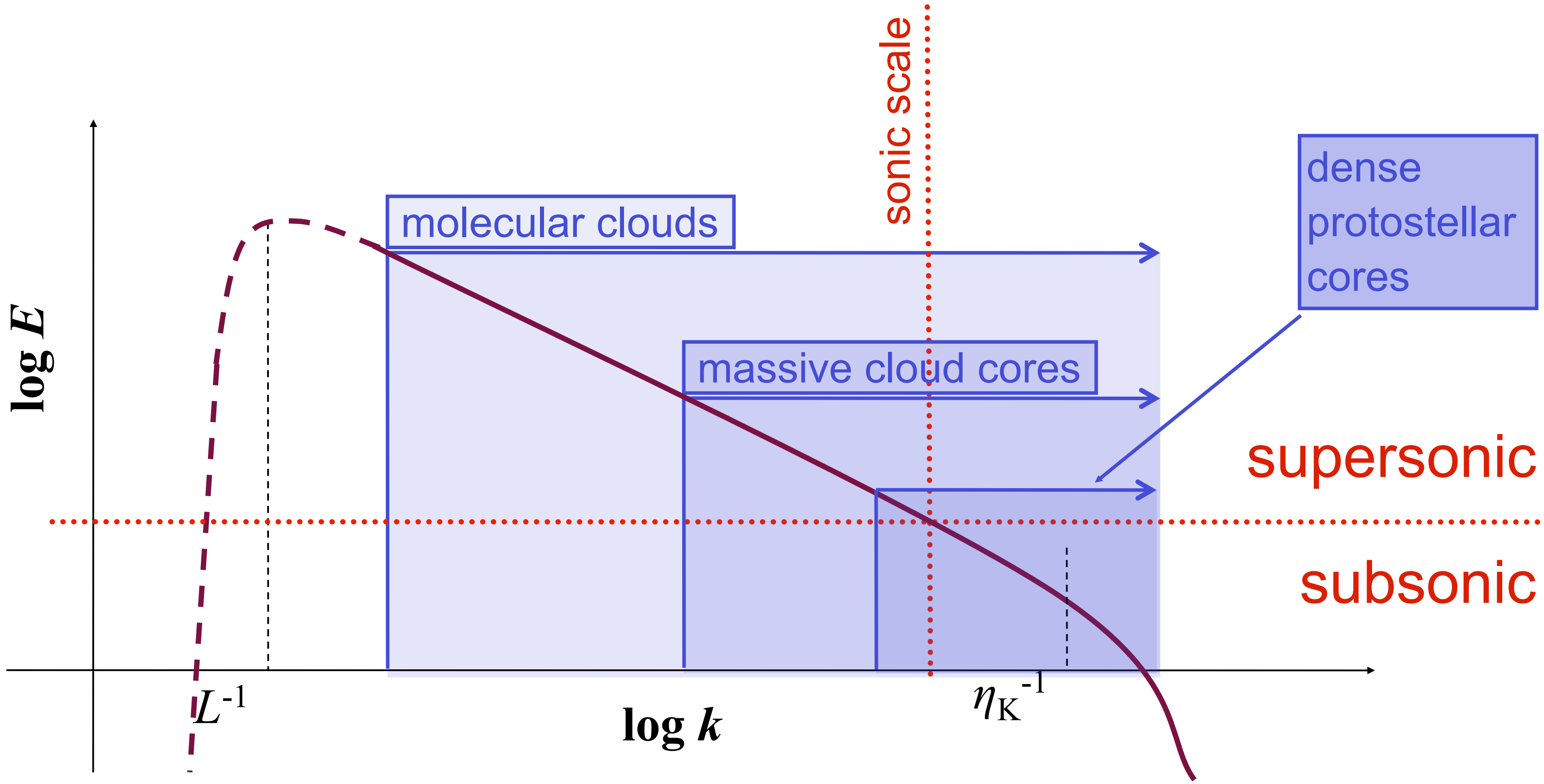


- *scale-free behavior of turbulence in the range* $\frac{L}{\eta_K} \approx \mathrm{Re}^{3/4}$
- *slope between -5/3 ... -2*
- *energy "flows" from large to small scales, where it turns into heat*

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

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

turbulent cascade in the ISM



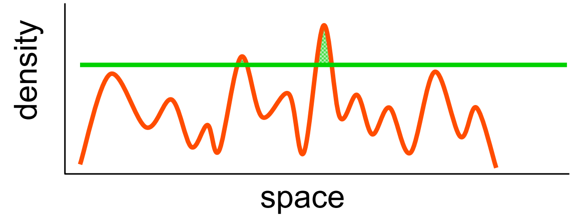
energy source & scale
NOT known
(supernovae, winds, spiral density waves?)

σ_{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: $\mathcal{M} \approx 1...3$)



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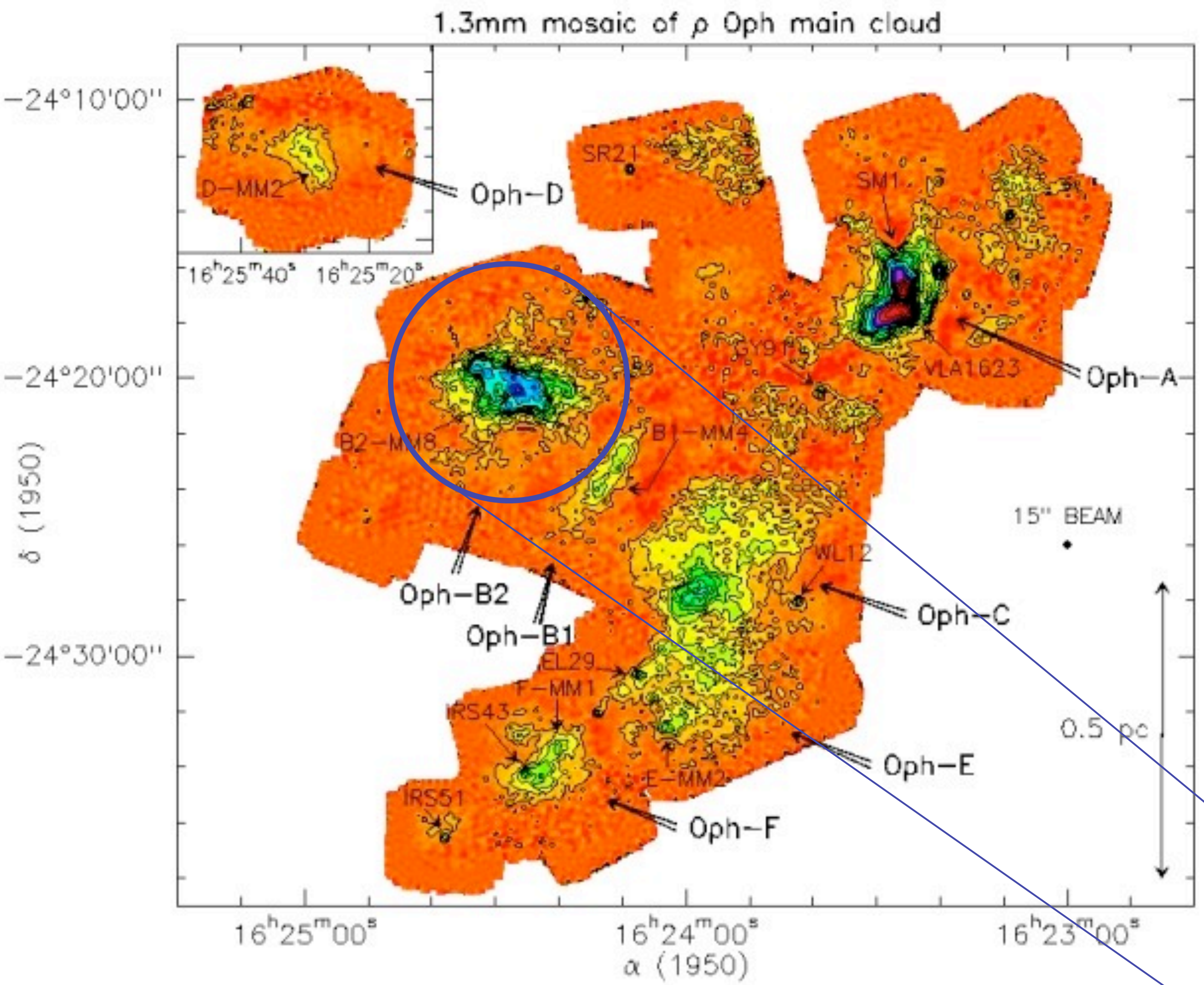
Density structure of MC's



(Motte, André, & Neri 1998)

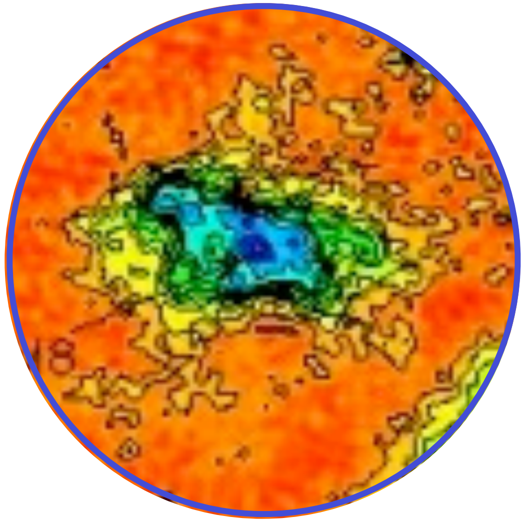
molecular clouds are highly inhomogeneous

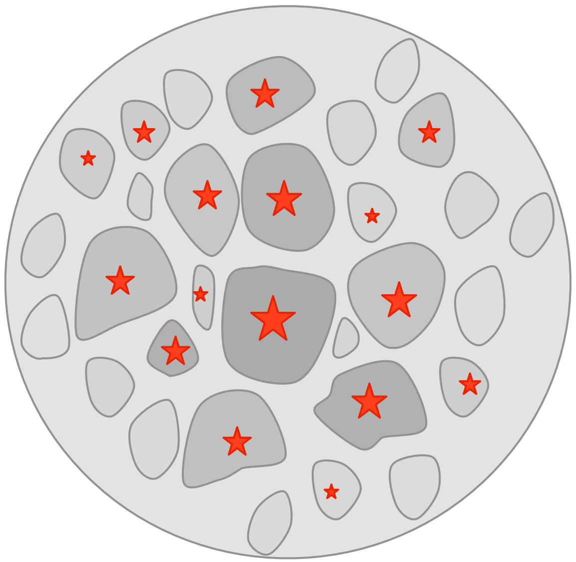
stars form in the densest and coldest parts of the cloud

ρ-Ophiuchus cloud seen in dust emission

let's focus on a cloud core like this one

Evolution of cloud cores

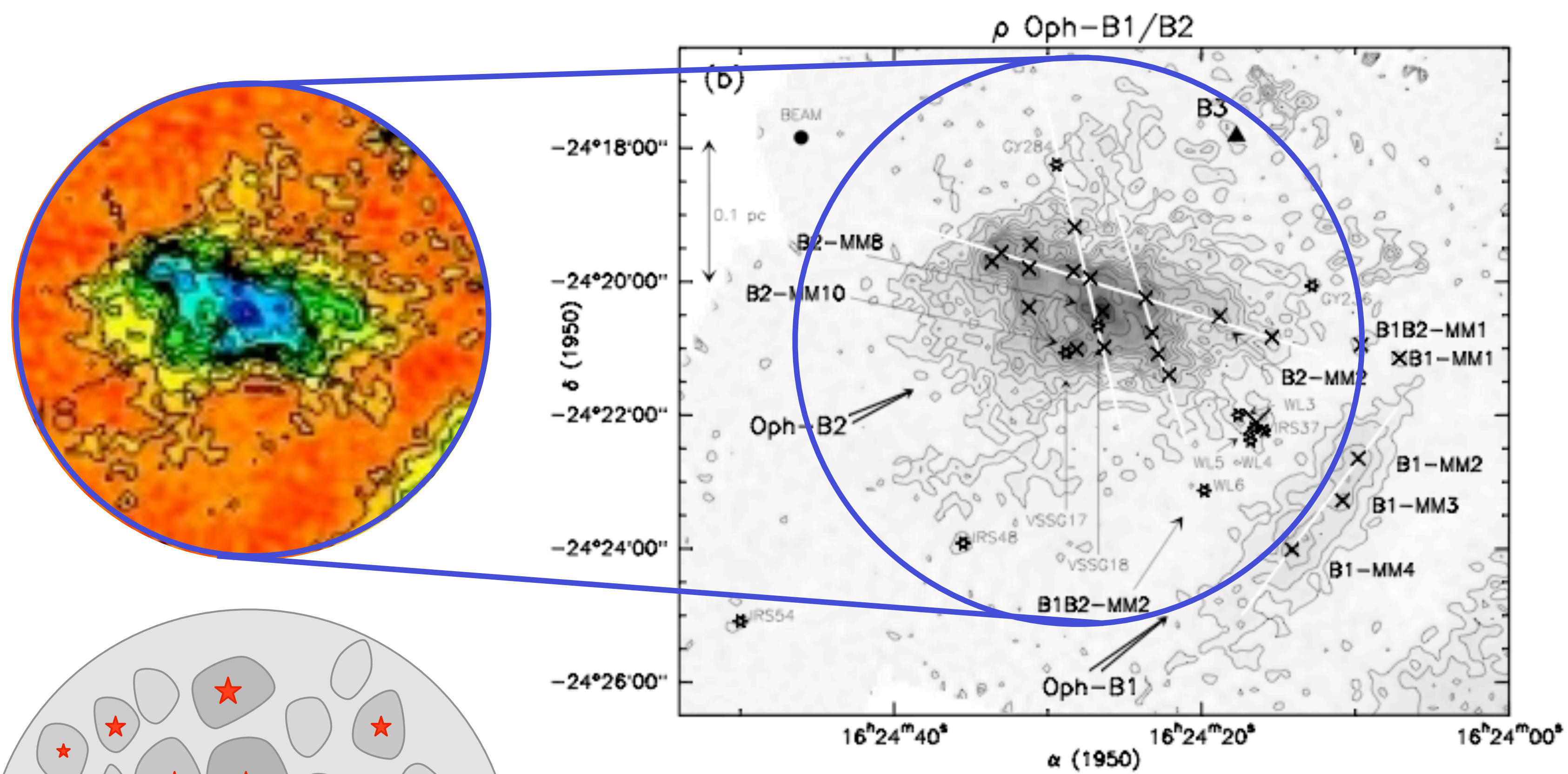


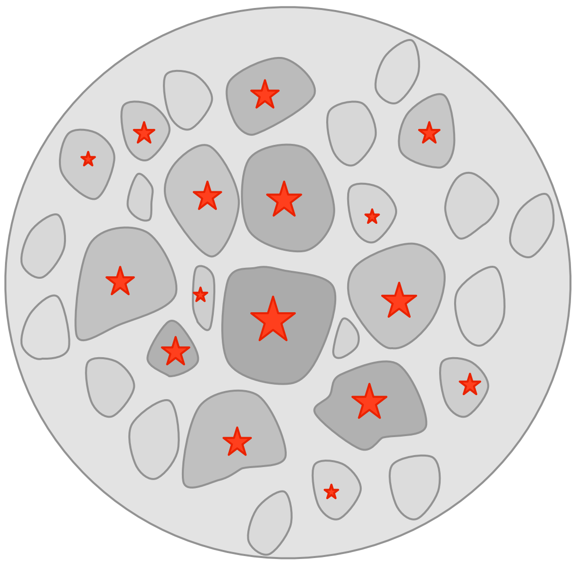


- How does this core evolve?
  Does it form one single massive star or cluster with mass distribution?

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

Evolution of cloud cores

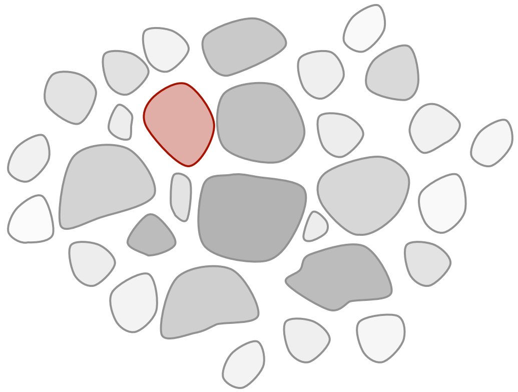




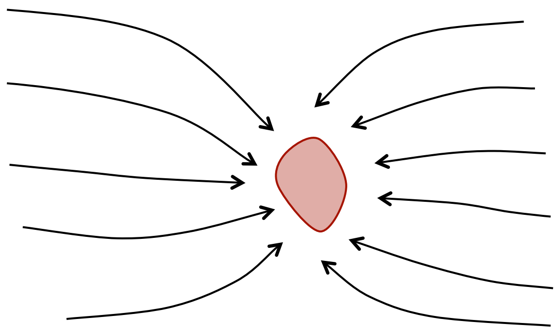
indeed ρ-Oph B1/2 contains several cores ("starless" cores are denoted by ×, cores with embedded protostars by ☆)

(Motte, André, & Neri 1998)

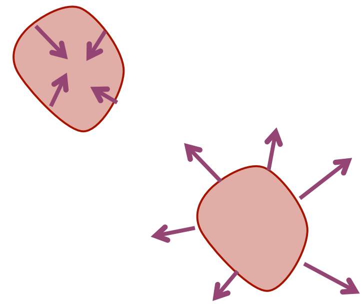
Formation and evolution of cores



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



- if $M > M_{crit} \propto \rho^{-1/2} T^{3/2}$: collapse & star formation
- if $M < M_{crit} \propto \rho^{-1/2} T^{3/2}$: reexpansion after end of external compression

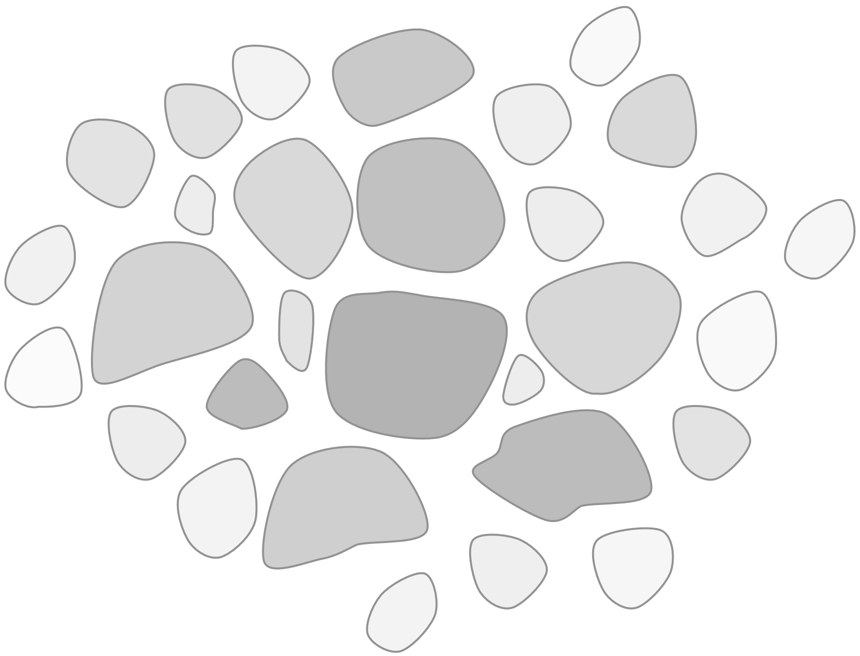


(e.g. Vazquez-Semadeni et al 2005)

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

Formation and evolution of cores

What happens to distribution of cloud cores?



Two exteme cases:

(1) turbulence dominates energy budget:

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

--> individual cores do *not* interact

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

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

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

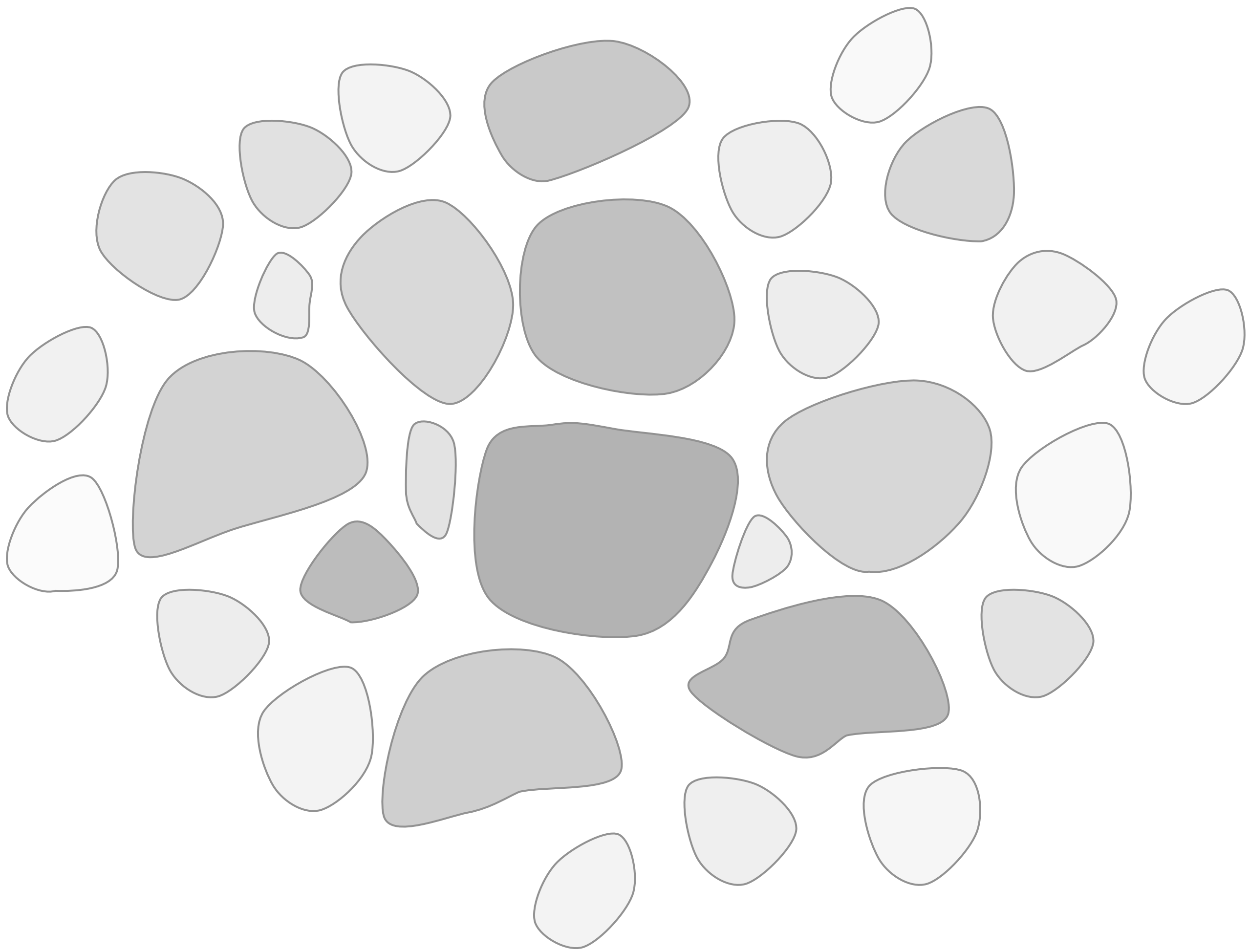
$\alpha = E_{kin}/|E_{pot}| < 1$

--> *global contraction*

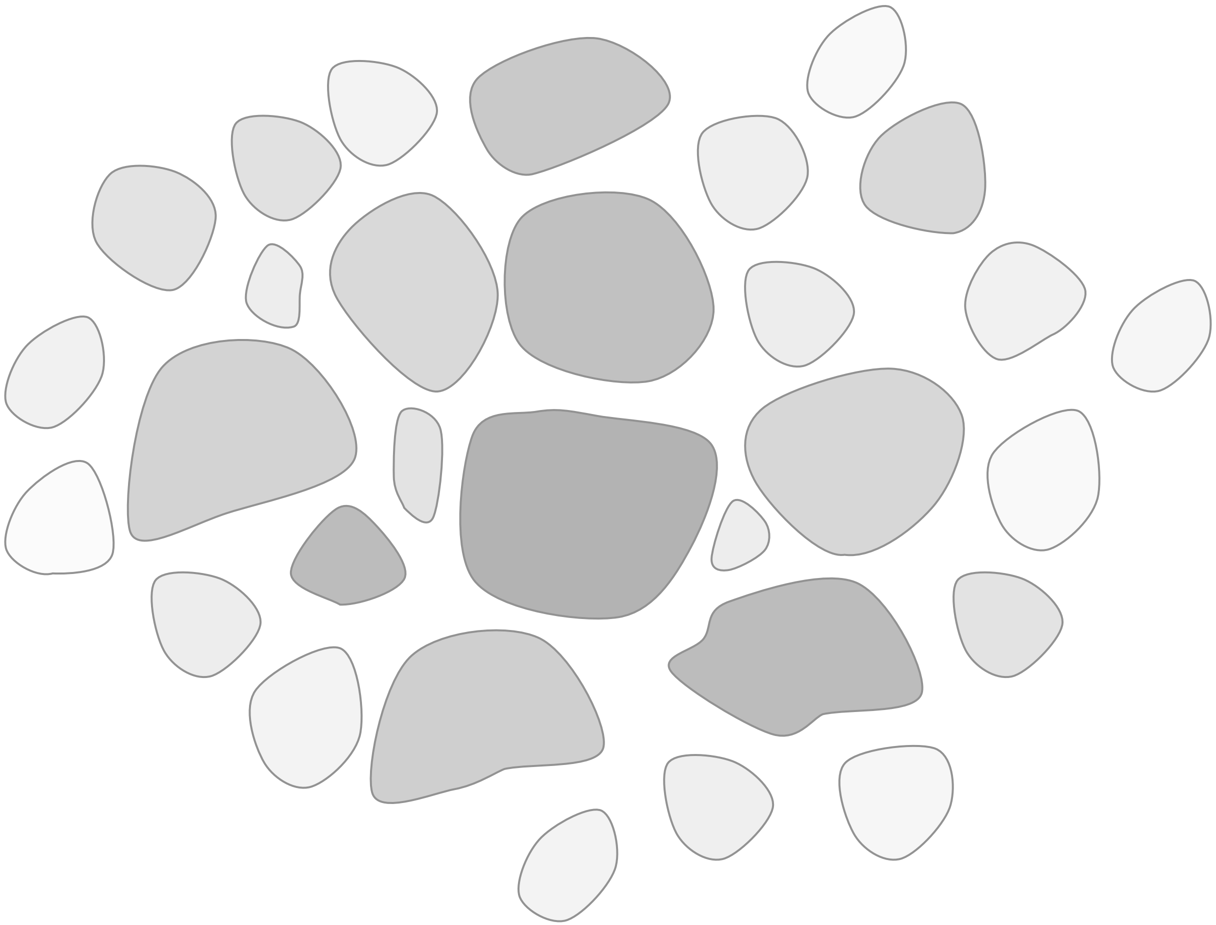
--> core do *interact* while collapsing

--> *competition* influences *mass growth*

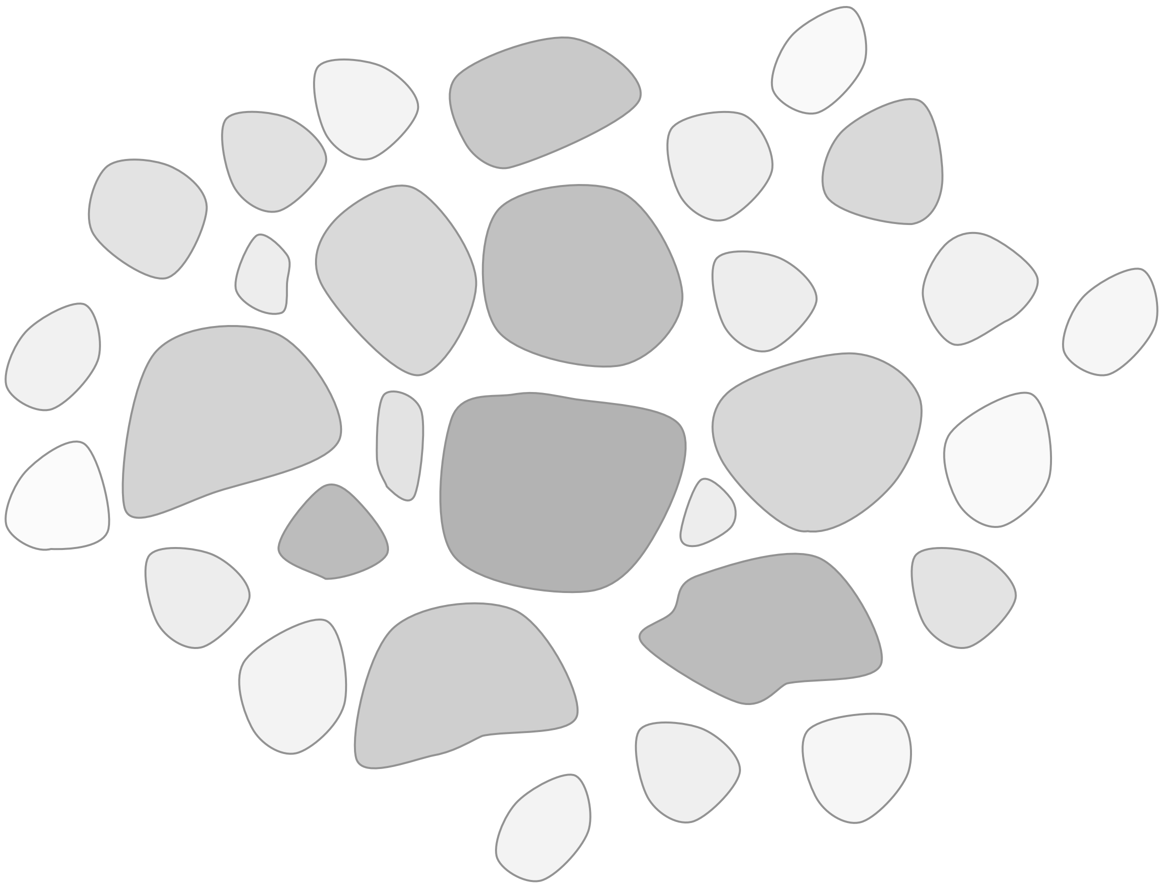
--> *dense cluster with high-mass stars*



turbulence creates a hierarchy of clumps



as turbulence decays locally, contraction sets in



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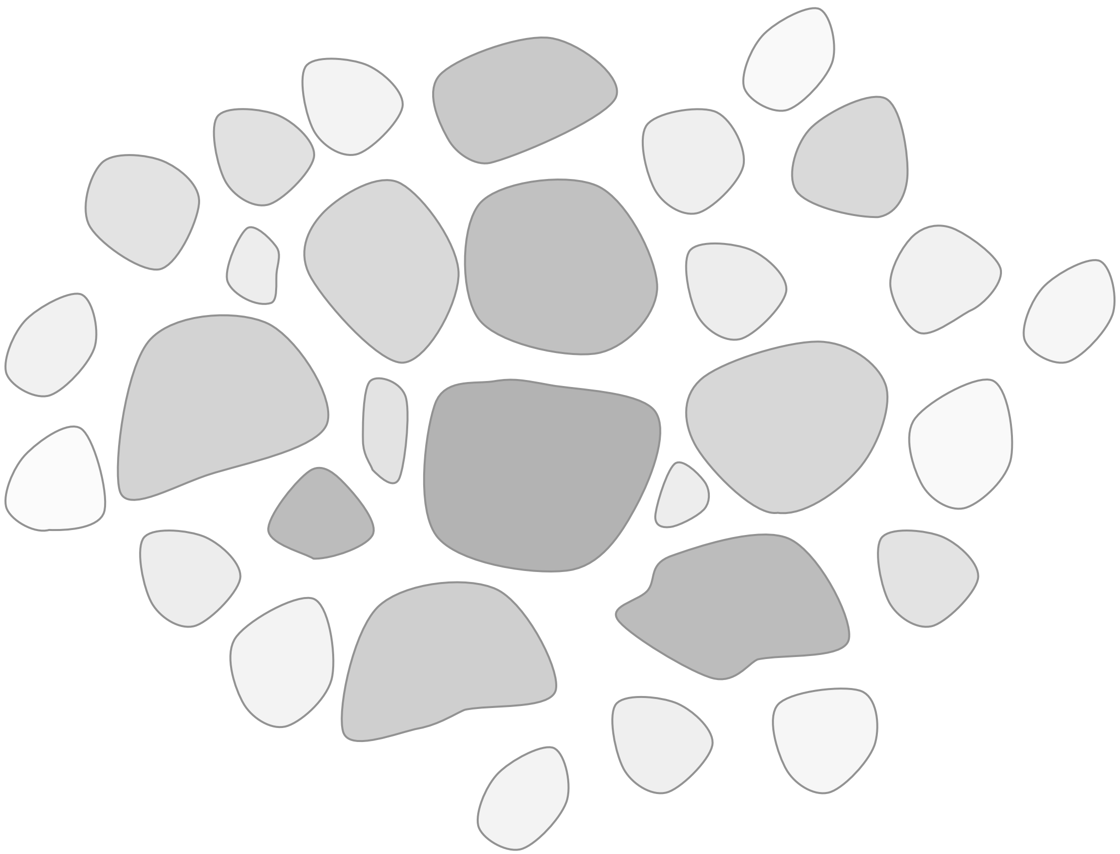
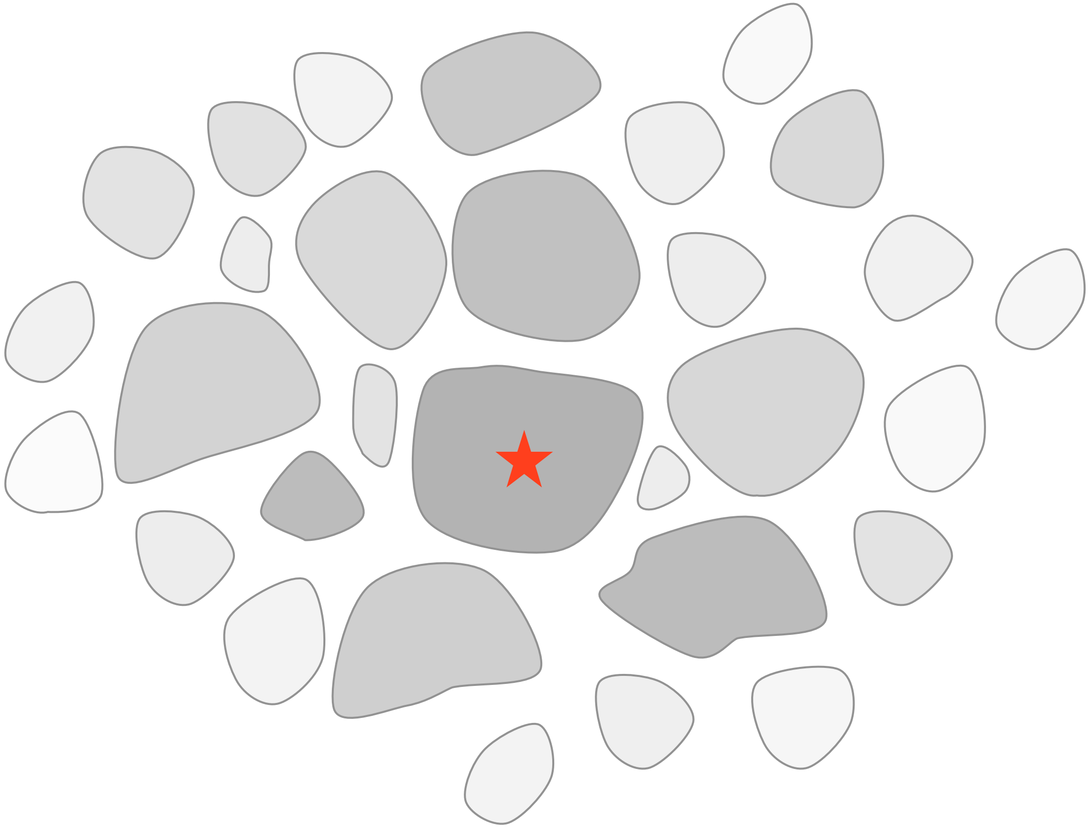


while region contracts, individual clumps collapse to form stars



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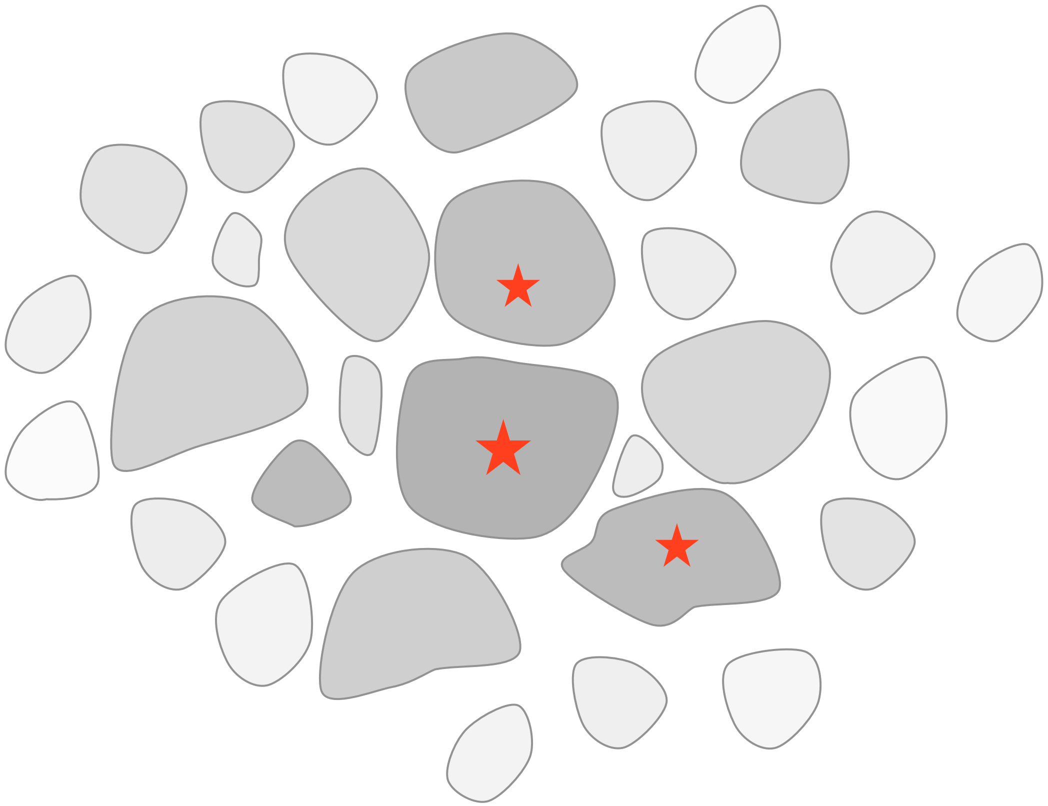

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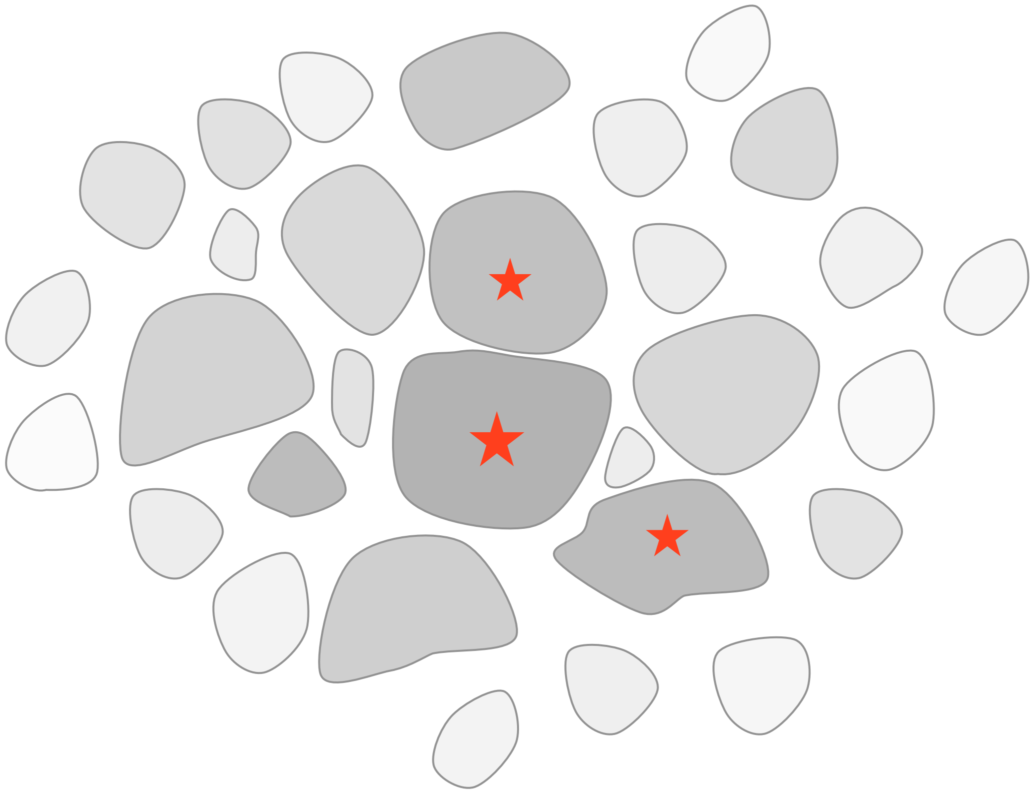

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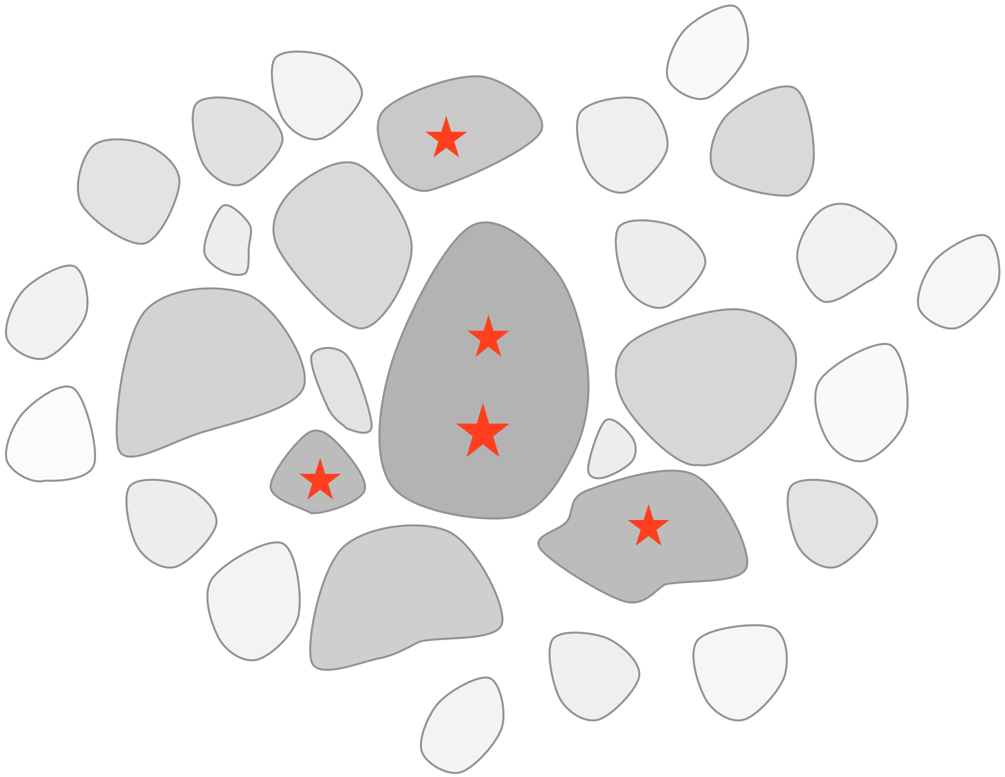
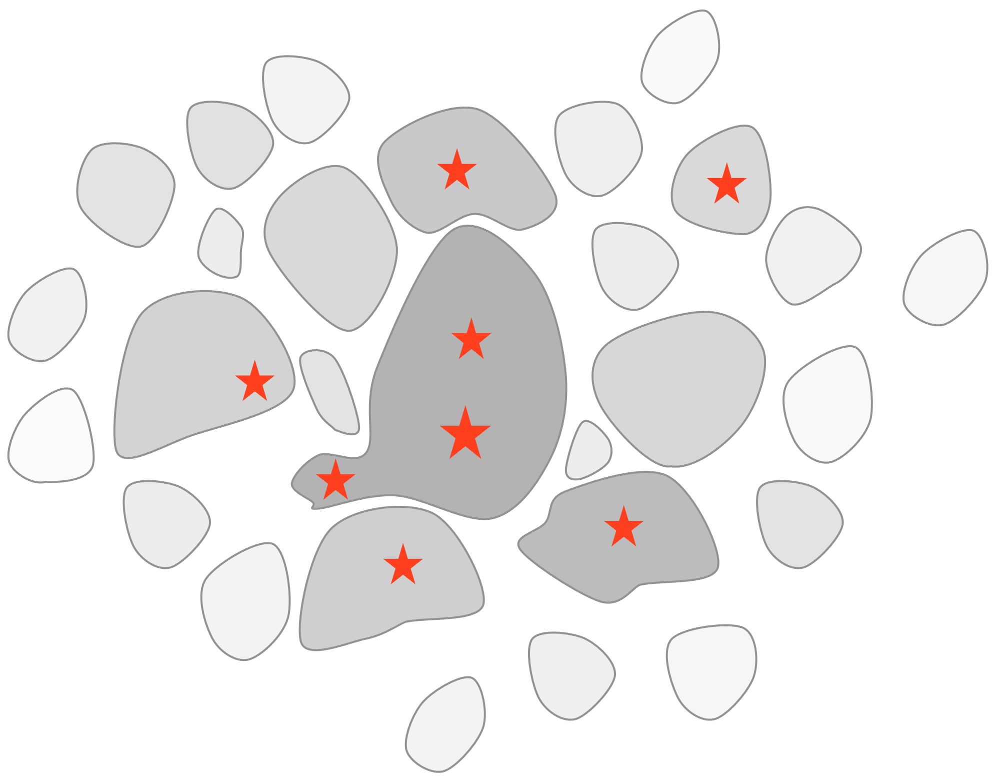


$\alpha = E_{kin}/|E_{pot}| < 1$

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



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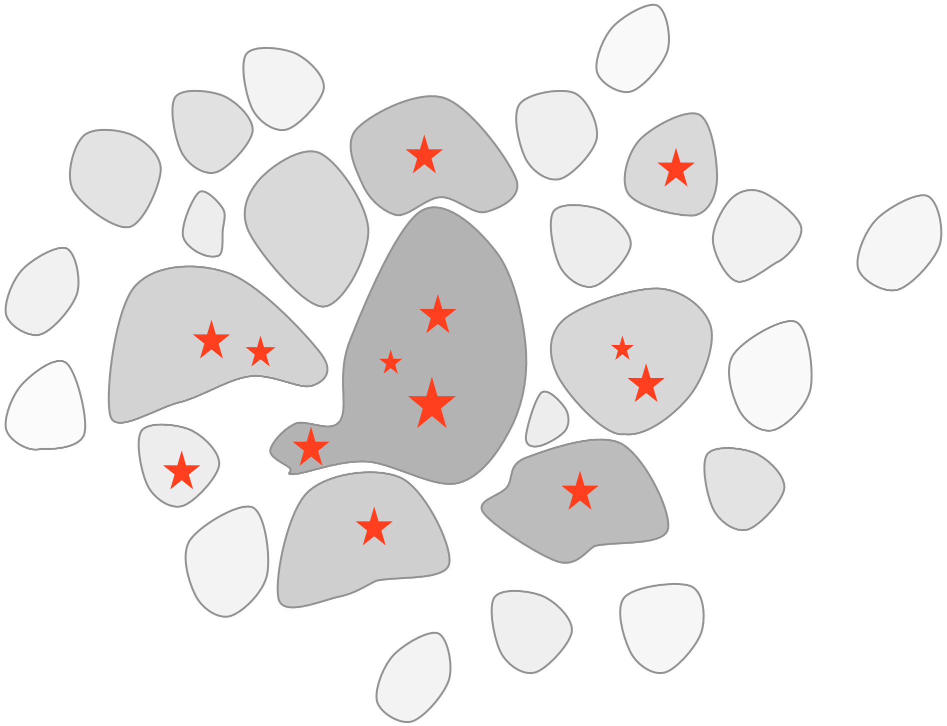

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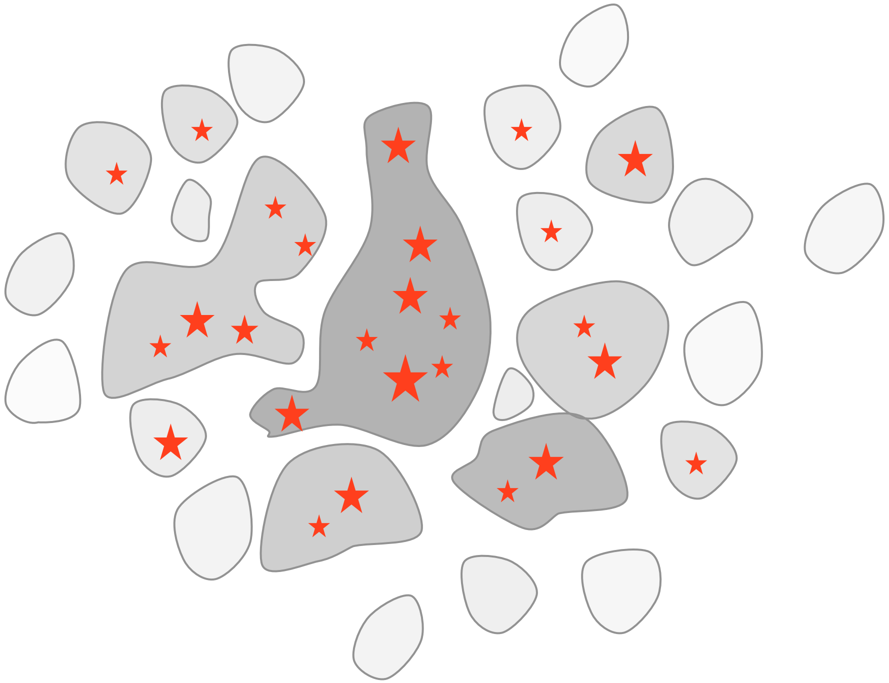
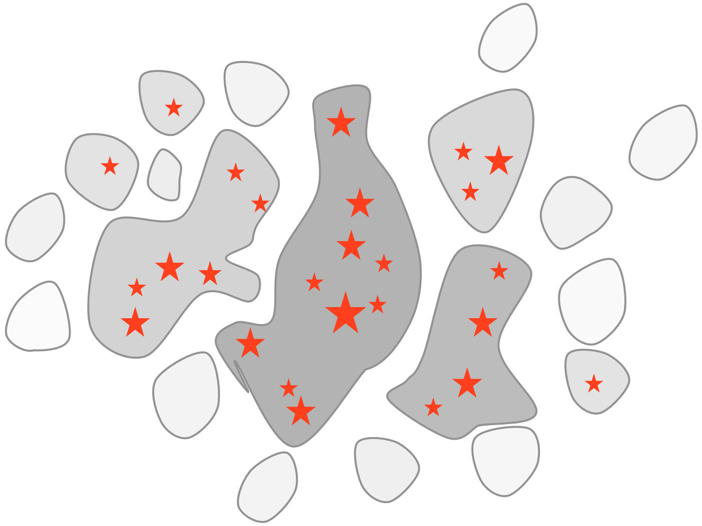


in *dense clusters*, competitive mass growth becomes important



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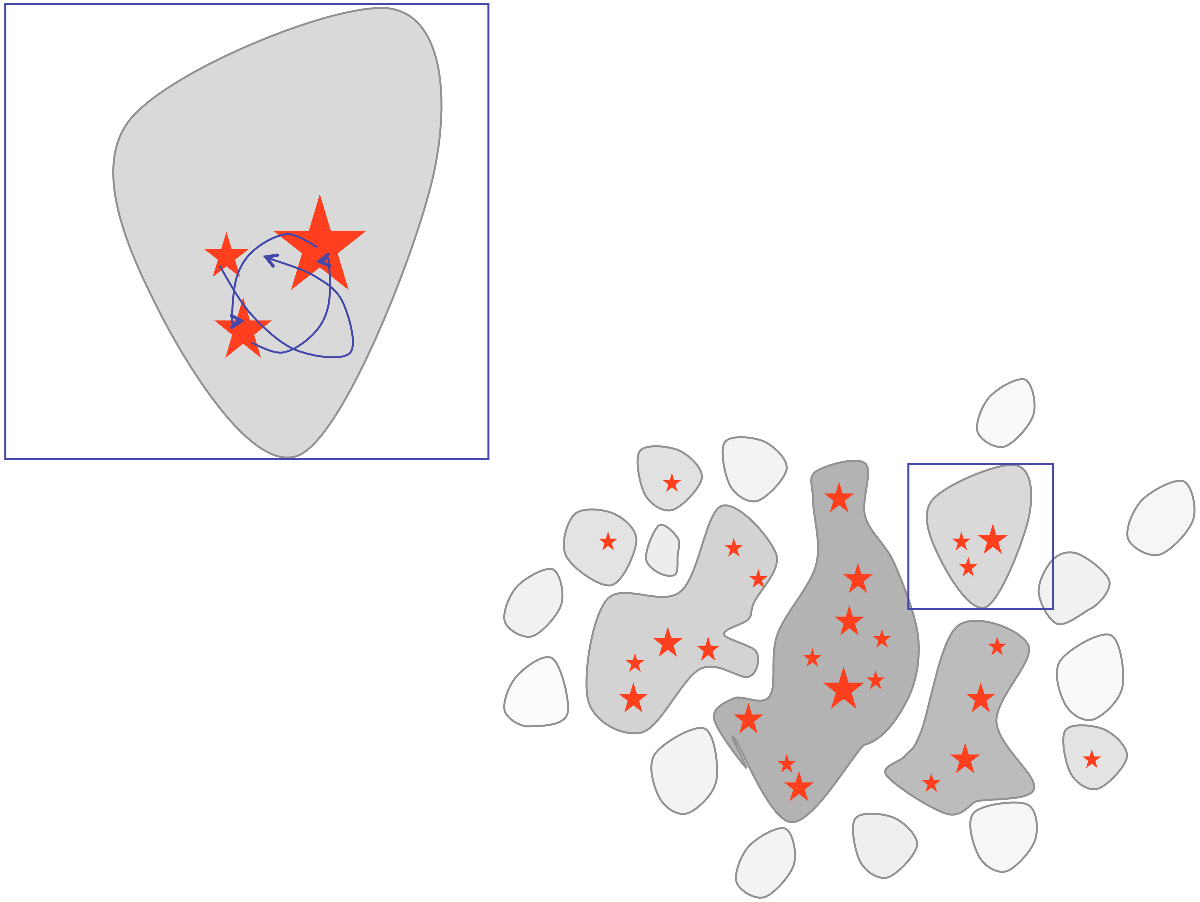
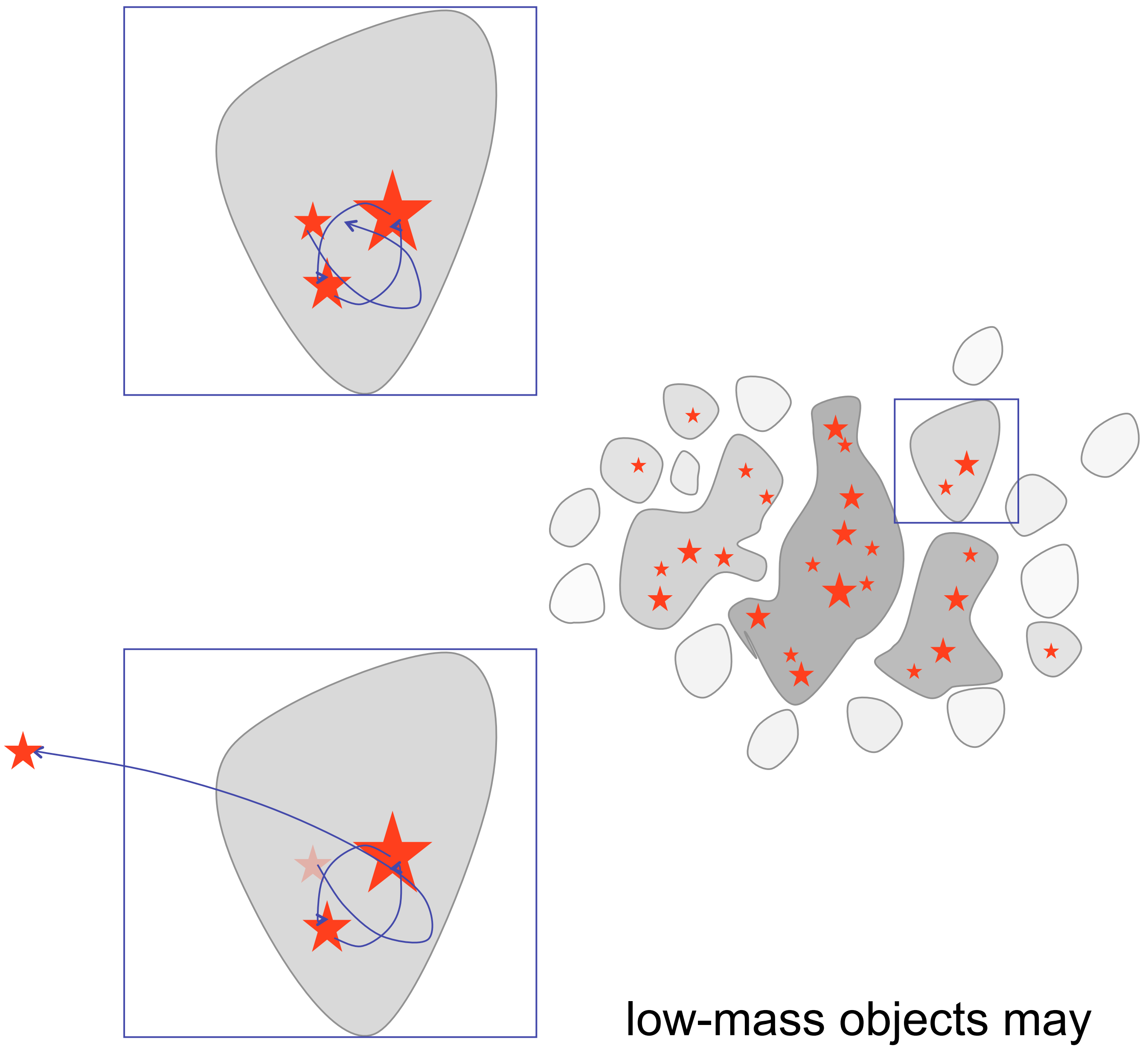
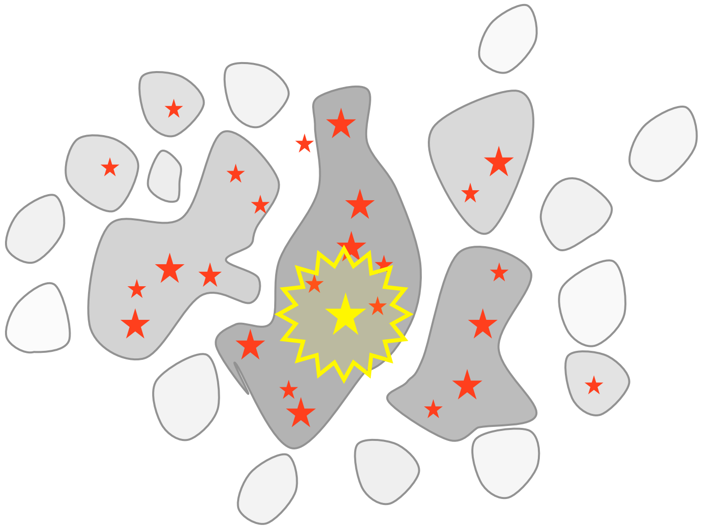


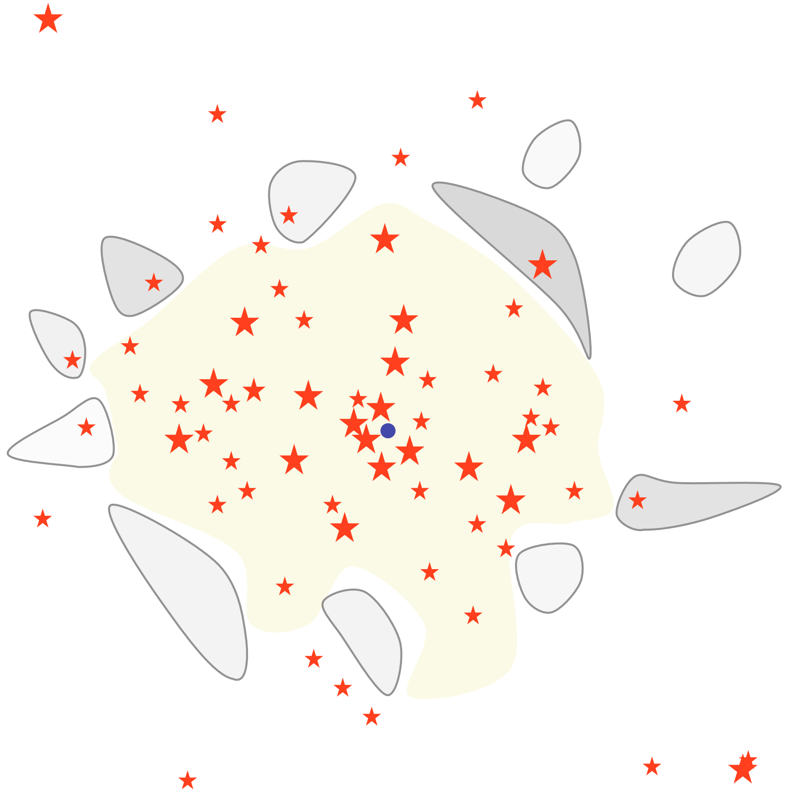
in *dense clusters*, *N*-body effects influence mass growth



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

some concerns of simple model

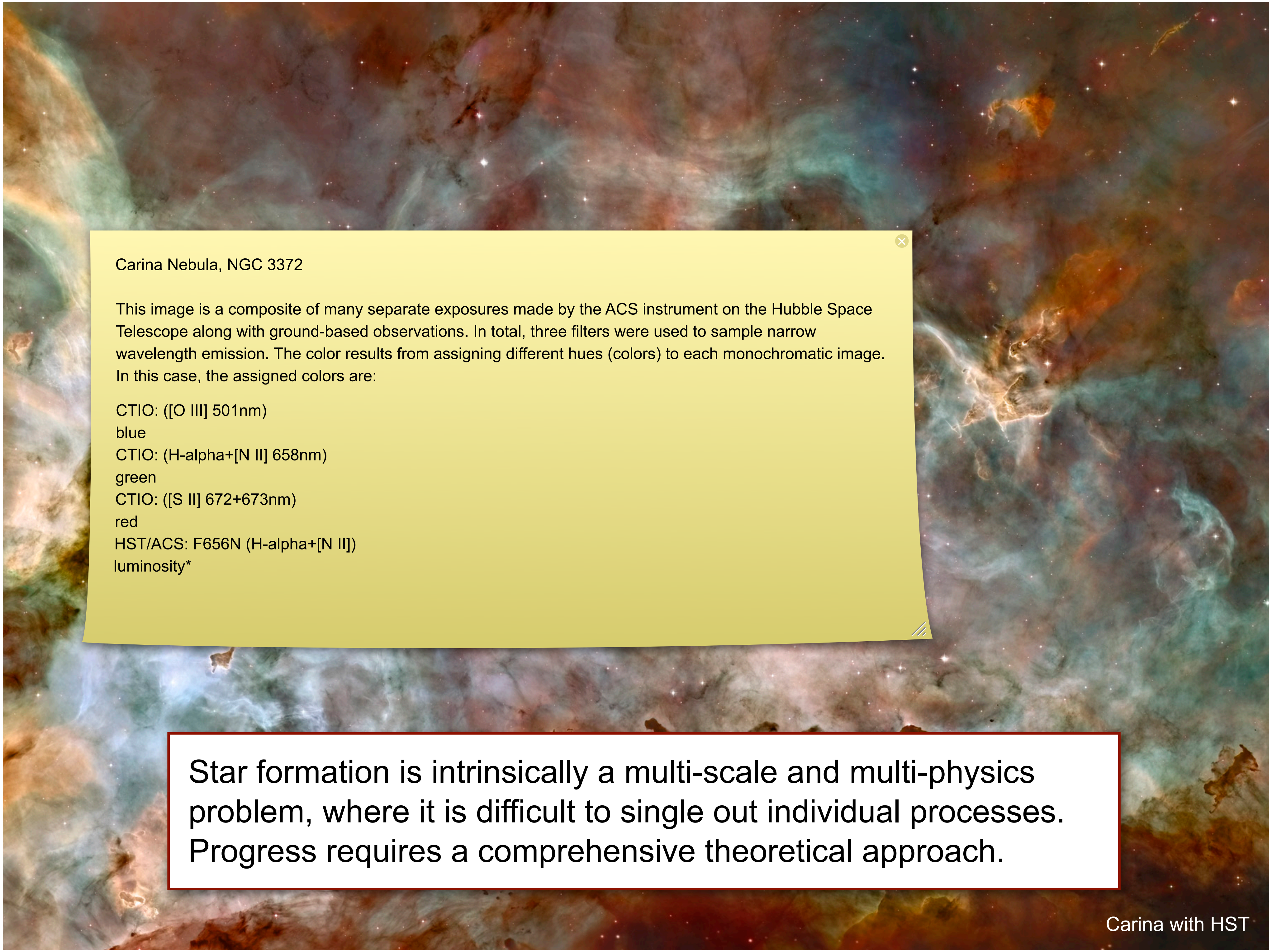
- *energy balance*
  - in molecular clouds:

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

current status

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

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



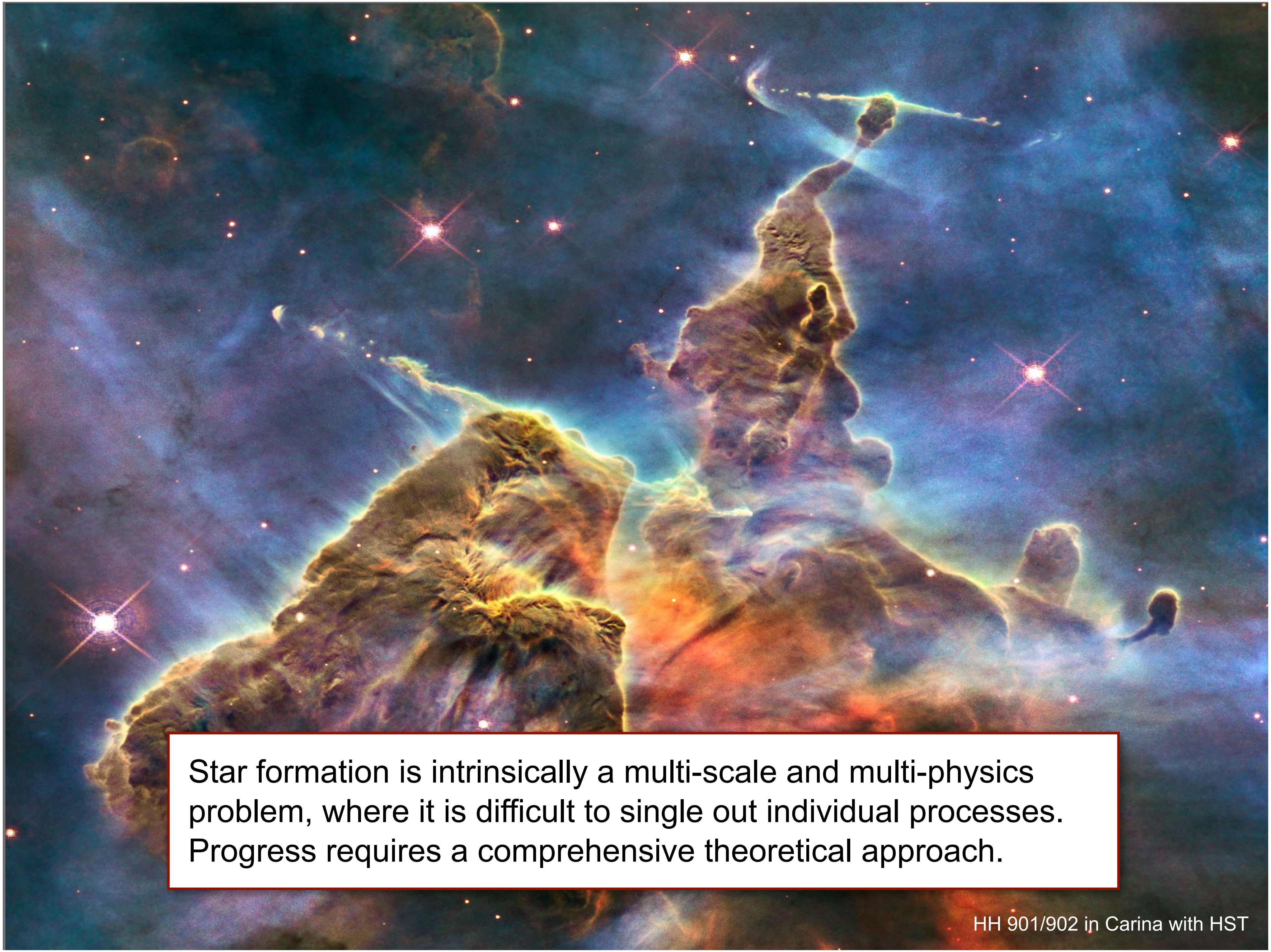
Carina Nebula, NGC 3372

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

theoretical approach

ISM dynamics and SF

magneto-hydrodynamics
(multi-phase, non-ideal MHD, turbulence)

chemistry (gas + dust, heating + cooling)

radiation (continuum + lines)

stellar dynamics
(collisional: star clusters, collisionless: galaxies, DM)

stellar evolution
(feedback: radiation, winds, SN)

\+ **laboratory work**
(reaction rates, cross sections, dust coagulation properties, etc.)

theoretical approach

- massive parallel codes
- particle-based: SPH with improved algorithms (XSPH with turb. subgrid model, GPM, particle splitting, MHD-SPH?)
- grid-based: AMR (FLASH, ENZO, RAMSES, Nirvana3, etc), subgrid-scale models (FEARLESS)
- BGK methods

magneto-hydrodynamics
(multi-phase, non-ideal MHD, turbulence)

chemistry (gas + dust, heating + cooling)

radiation (continuum + lines)

stellar dynamics
(collisional: star clusters, collisionless: galaxies, DM)

stellar evolution
(feedback: radiation, winds, SN)

theoretical approach

- ever increasing chemical networks
- working reduced networks for time-dependent chemistry in combination with hydro-dynamics
- improved data on reaction rates (laboratory + quantum mechanical calculations)

magneto-hydrodynamics
(multi-phase, non-ideal MHD, turbulence)

chemistry (gas + dust, heating + cooling)

radiation (continuum + lines)

stellar dynamics
(collisional: star clusters, collisionless: galaxies, DM)

stellar evolution
(feedback: radiation, winds, SN)

theoretical approach

- continuum vs. lines
- Monte Carlo, characteristics
- approximative methods
- combine with hydro

↔

magneto-hydrodynamics (multi-phase, non-ideal MHD, turbulence)

chemistry (gas + dust, heating + cooling)

radiation (continuum + lines)

stellar dynamics (collisional: star clusters, collisionless: galaxies, DM)

stellar evolution (feedback: radiation, winds, SN)

theoretical approach

- statistics: number of stars (collisional: 10^6, collisionless: 10^{10})
- transition from gas to stars
- binary orbits
- long-term integration

magneto-hydrodynamics (multi-phase, non-ideal MHD, turbulence)

chemistry (gas + dust, heating + cooling)

radiation (continuum + lines)

stellar dynamics (collisional: star clusters, collisionless: galaxies, DM)

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theoretical approach

magneto-hydrodynamics
(multi-phase, non-ideal MHD, turbulence)

chemistry (gas + dust, heating + cooling)

radiation (continuum + lines)

stellar dynamics
(collisional: star clusters, collisionless: galaxies, DM)

- very early phases (pre main sequence tracks)
- massive stars at late phases
- role of rotation
- primordial star formation

stellar evolution
(feedback: radiation, winds, SN)

theoretical approach

methods need to be combined!

magneto-hydrodynamics
(multi-phase, non-ideal MHD, turbulence)

chemistry (gas + dust, heating + cooling)

radiation (continuum + lines)

stellar dynamics
(collisional: star clusters, collisionless: galaxies, DM)

stellar evolution
(feedback: radiation, winds, SN)

\+ **laboratory work**
(reaction rates, cross sections, dust coagulation properties, etc.)

end


Carina with HST