ISM turbulence and star formation

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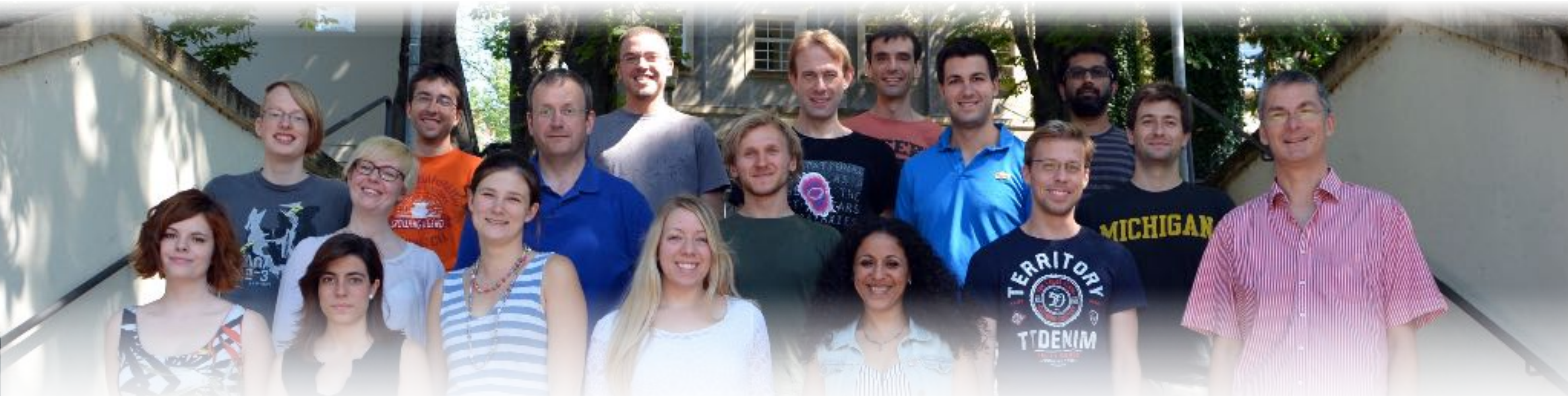
Star formation & ISM dynamics



... people in the star formation group at Heidelberg University:

Bhaskar Agarwal, Carla Bernhard, Daniel Ceverino, Max Disch, Sam Geen, Simon Glover, Dimitrios Gouliermis, Sacha Hony, Ondrej Jaura, Ralf Klessen, Besma Klinger-Araifa, Mattis Magg, Kiwan Park, Eric Pellegrini, Daniel Rahner, Stefan Reißl, Anna Schauer, Mattia Sormani, Robin Treß, Katharina Wollenberg

... former group members:

Christian Baczynski, Robi Banerjee, Erik Bertram, Paul Clark, Gustavo Dopcke, Christoph Federrath, Philipp Girichidis, Thomas Greif, Lionel Haemmerle, Tilman Hartwig, Lukas Konstandin, Thomas Peters, Claes-Erik Rydberg, Dominik Schleicher, Jennifer Schober, Daniel Seifried, Rahul Shetty, Rowan Smith, László Szűcs, Hsiang-Hsu Wang, Daniel Whalen, and many more ...

... many collaborators abroad!

Deutsche Forschungsgemeinschaft DFG

ISM-SPP

BADEN-WÜRTTEMBERG STIFTUNG

STARLIGHT

erc European Research Council

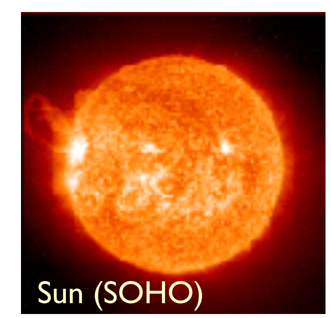

theoretical
considerations

decrease in spatial scale / increase in density


Andromeda (R. Gendler)


NGC 602 in LMC (Hubble)


Proplyd in Orion (Hubble)


Sun (SOHO)


Earth

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

decrease in spatial scale / increase in density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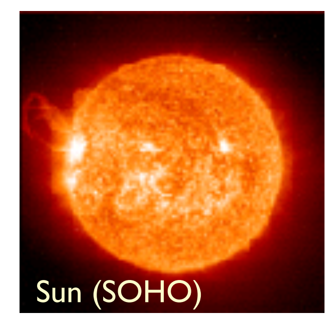

Sun (SOHO)


Earth

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

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

early theoretical models

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

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

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

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

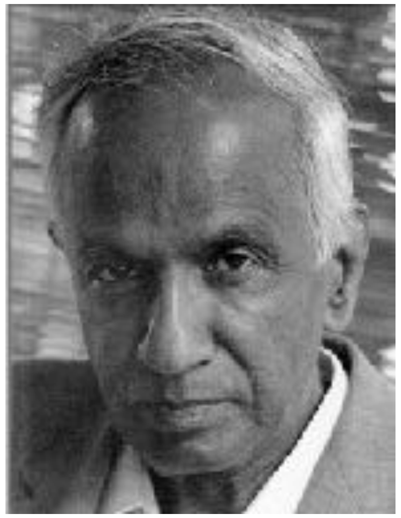
    $\ell_{turb} \ll \ell_{dyn}$

  - then turbulent velocity dispersion contributes to effective sound speed:

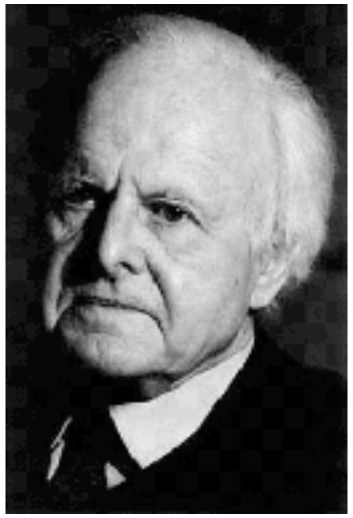
    $$\boxed{c_c^2 \mapsto c_c^2 + \sigma_{rms}^2}$$

  - → Larger effective Jeans masses → more stability
  - BUT: *(1) turbulence depends on k:* $\sigma_{rms}^2(k)$

    (2) supersonic turbulence → $\sigma_{rms}^2(k) >> c_s^2$ *usually*



S. Chandrasekhar, 1910 - 1995



C.F. von Weiszäcker, 1912 - 2007

problems of early dynamical theory

- molecular clouds are *highly Jeans-unstable,*
  yet, they do *NOT* form stars at high rate
  and with high efficiency (Zuckerman & Evans 1974 conundrum)
  (the observed global SFE in molecular clouds is *~5%*)
  → *something prevents large-scale collapse.*
- all throughout the early 1990's, molecular clouds had been thought to be long-lived quasi-equilibrium entities.
- molecular clouds are *magnetized*

magnetic star formation

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

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

  - Critical mass-to-flux ratio (Mouschovias & Spitzer 1976)

$$\left[\frac{M}{\Phi}\right]_{cr} = \frac{\zeta}{3\pi}\left[\frac{5}{G}\right]^{1/2}$$

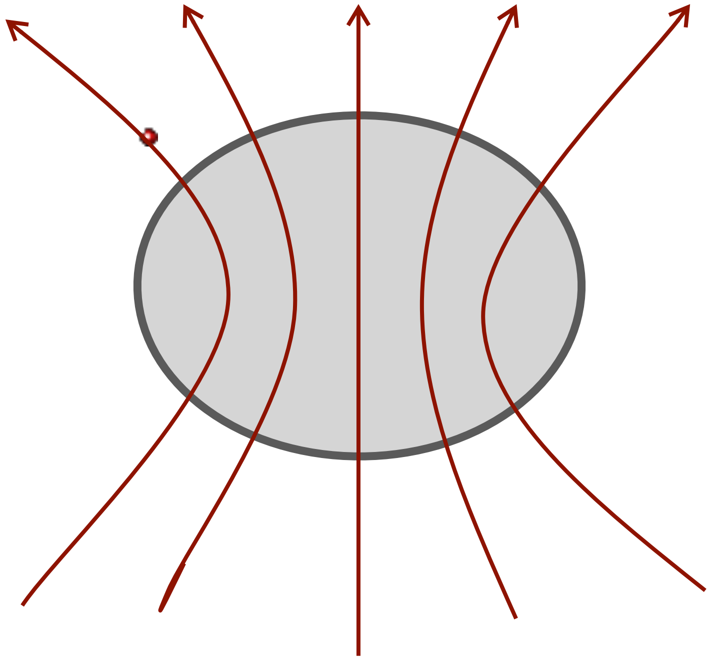
  - Ambipolar diffusion can initiate collapse

Lyman Spitzer, Jr., 1914 - 1997

“standard theory” of star formation

- BASIC ASSUMPTION: Stars form from magnetically highly subcritical cores
- Ambipolar diffusion slowly increases (M/Φ): $\tau_{AD} \approx 10\tau_{ff}$
- Once $(M/\Phi) > (M/\Phi)_{crit}$: dynamical collapse of SIS
    - Shu (1977) collapse solution
    - $dM/dt = 0.975\ c_s^3/G$ = 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
Klessen & Glover, 2016, Saas Fee Lecture, 43, 85)

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*
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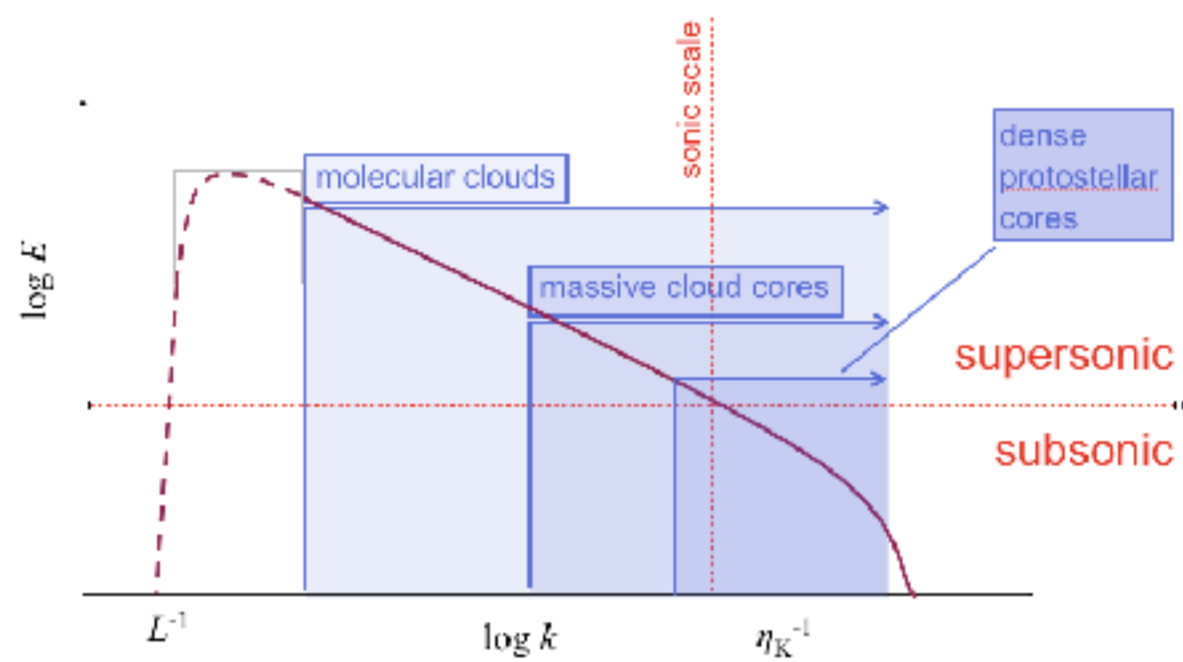
- some predictions:
  - dynamical star formation timescale τ_{ff}
  - high binary fraction
  - complex spatial structure of embedded star clusters
  - and many more . . .



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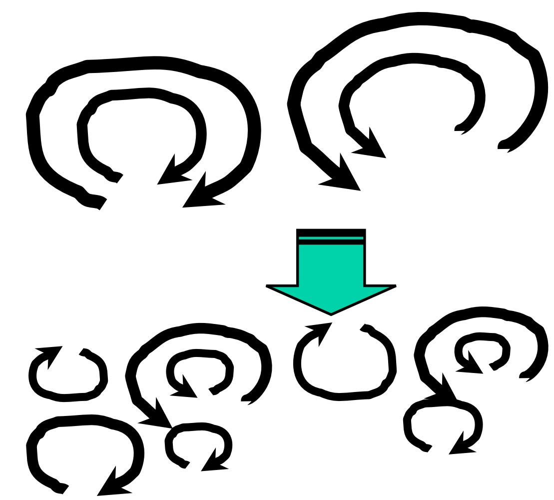
properties of turbulence

- laminar flows turn *turbulent* at *high* *Reynolds* numbers

$$Re = \frac{\text{advection}}{\text{dissipation}} = \frac{VL}{\nu}$$



V= typical velocity on scale L, $\nu = \eta/\rho$ = kinematic viscosity, turbulence for Re > 1000 → typical values in ISM 10^8-10^{10}

- Navier-Stokes equation (transport of momentum)

$$\rho\frac{d\vec{v}}{dt} = \rho\left(\frac{\partial\vec{v}}{\partial t} + (\vec{v}\cdot\vec{\nabla})\vec{v}\right) = -\vec{\nabla}P + \eta\,\vec{\nabla}^2\vec{v} + \left(\frac{\eta}{3} + \zeta\right)\vec{\nabla}(\vec{\nabla}\cdot\vec{v})$$

shear viscosity

bulk viscosity

$$\sigma_{ij} \equiv \eta\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} - \frac{2}{3}\,\delta_{ij}\frac{\partial v_k}{\partial x_k}\right) + \zeta\delta_{ij}\frac{\partial v_k}{\partial x_k}$$

viscous stress tensor

properties of turbulence

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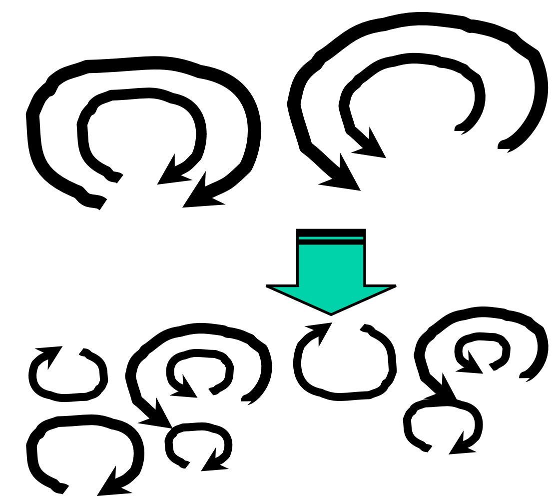


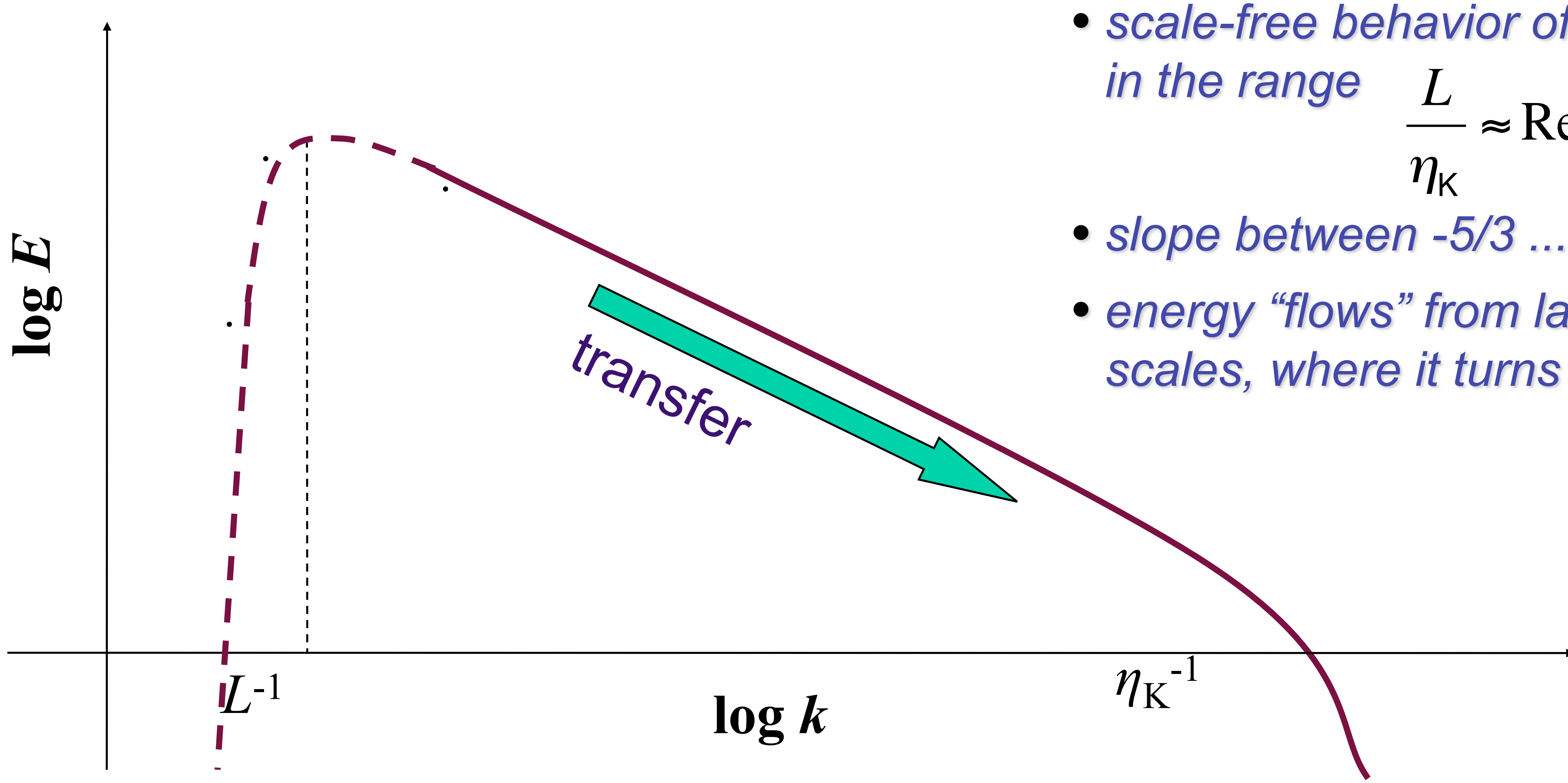
V= typical velocity on scale L, $\nu = \eta/\rho$ = kinematic viscosity,
turbulence for Re > 1000 → typical values in ISM 10^8-10^{10}

- vortex streching --> turbulence is intrinsically anisotropic
  (only on large scales you may get
  homogeneity & isotropy in a statistical sense;
  see Landau & Lifschitz, Chandrasekhar, Taylor, etc.)

Tornado over Portofino

(ISM turbulence: shocks & B-field
cause additional inhomogeneity)

turbulent cascade in the ISM



- *scale-free behavior of turbulence in the range* $\dfrac{L}{\eta_K} \approx \mathrm{Re}^{3/4}$
- *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?)

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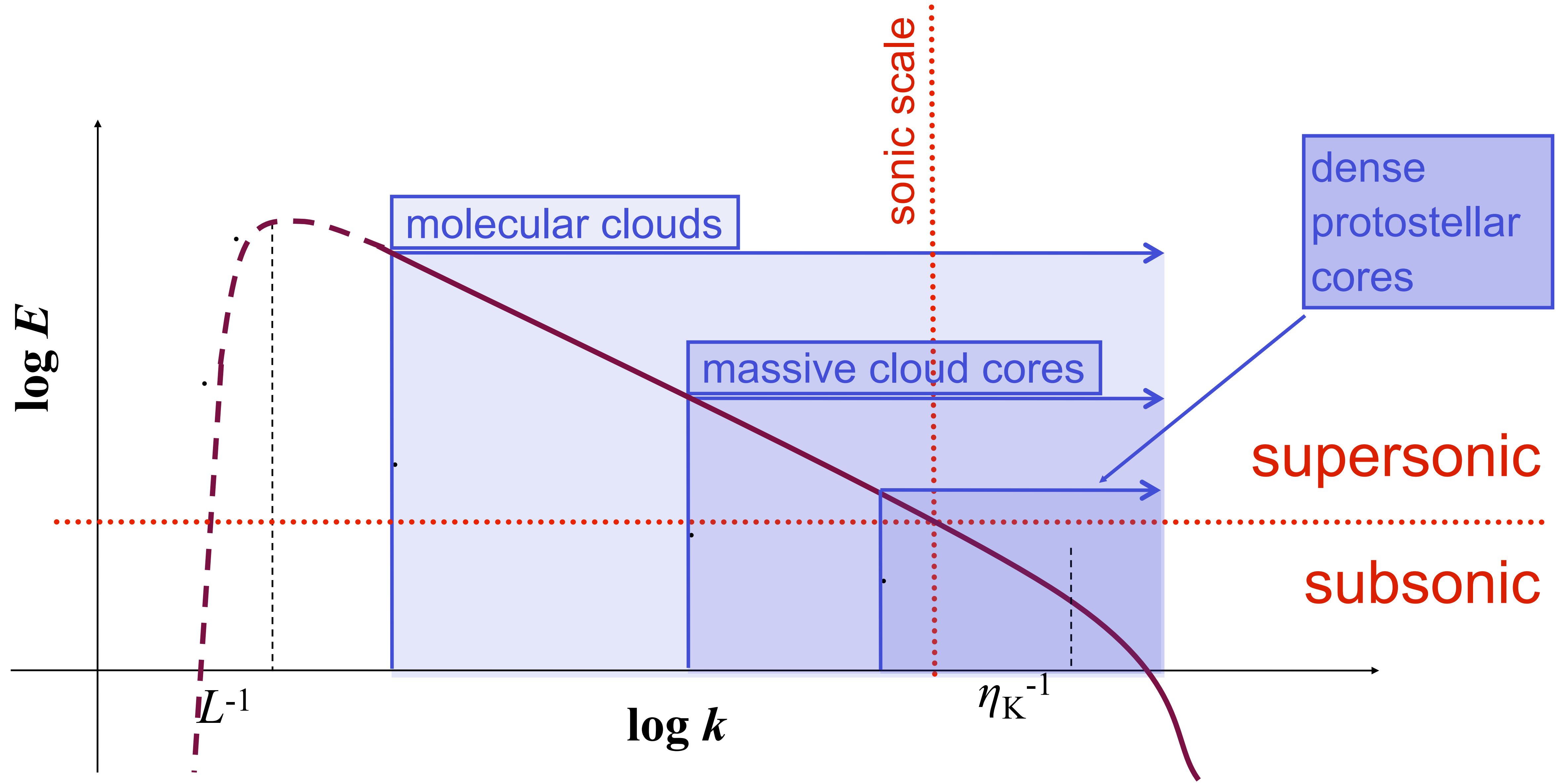


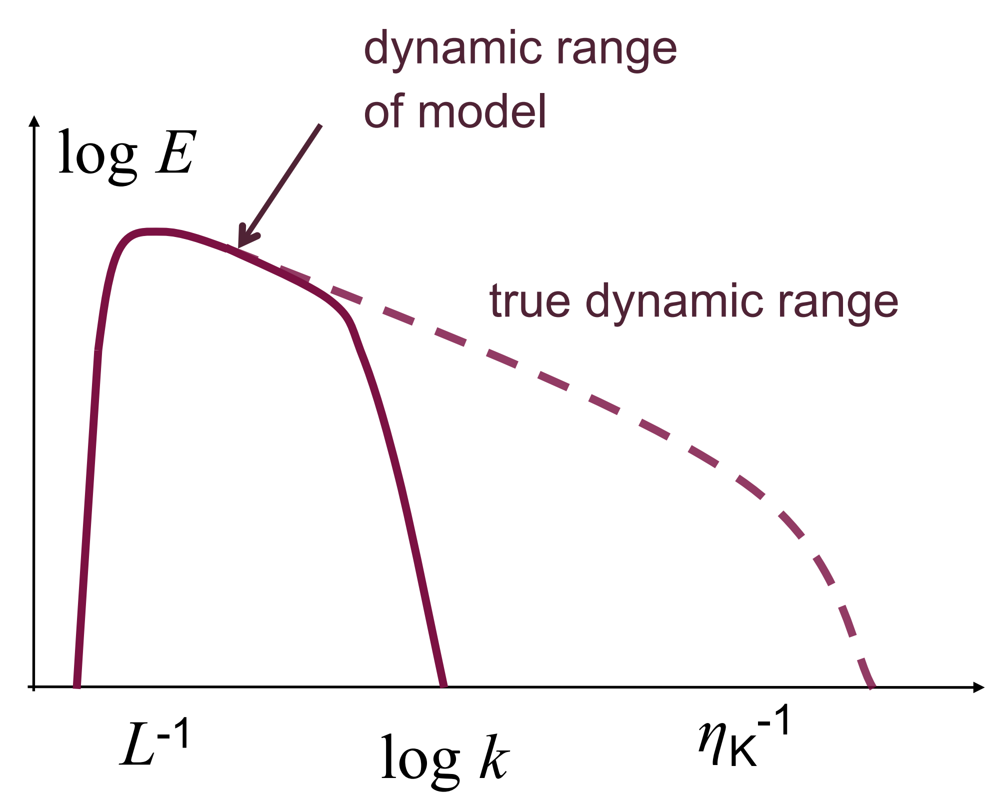
energy source & scale
NOT known
(supernovae, winds,
spiral density waves?)

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

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

large eddie simulations - caveats!

- We use ***LES*** to model the large-scale dynamics
- Principal problem: only large scale flow properties
  - Reynolds number: Re = LV/ν ***(Re_{nature} >> Re_{model})***
  - dynamic range much smaller than true physical one
  - need *subgrid model* (in our case simple: only dissipation)
  - but what to do for more complex when processes on subgrid scale determine large-scale dynamics (chemical reactions, nuclear burning, etc)
  - Turbulence is "space filling" --> difficulty for AMR (don't know what criterion to use for refinement)
- How *large* a Reynolds number do we need to catch basic dynamics right?



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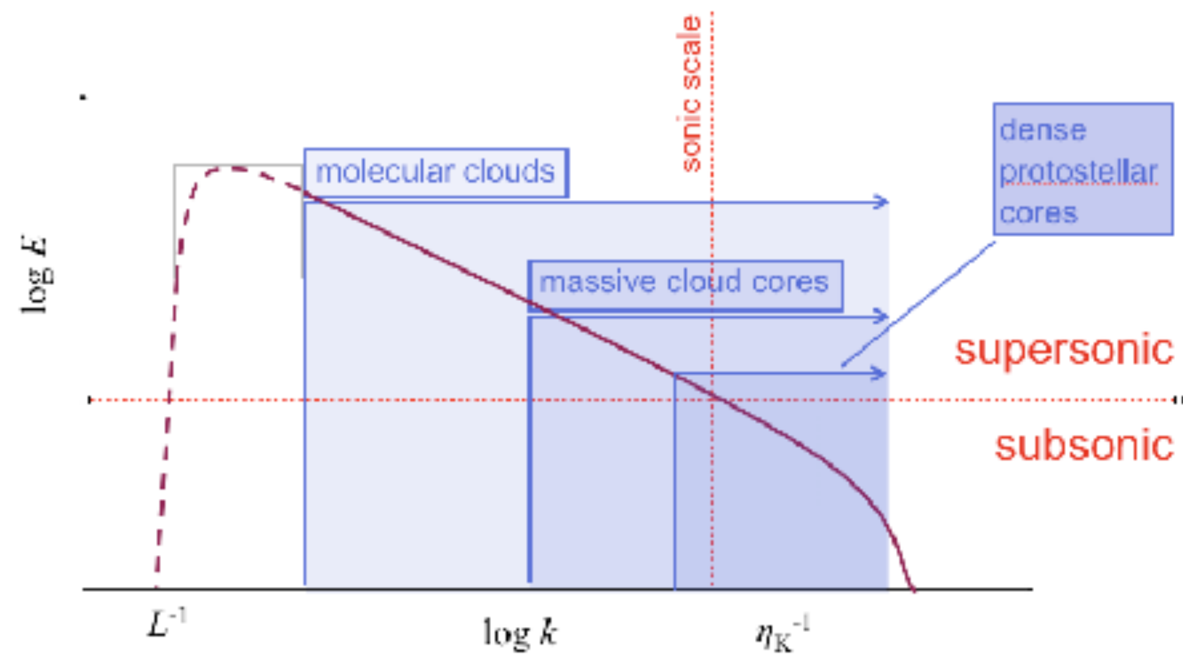

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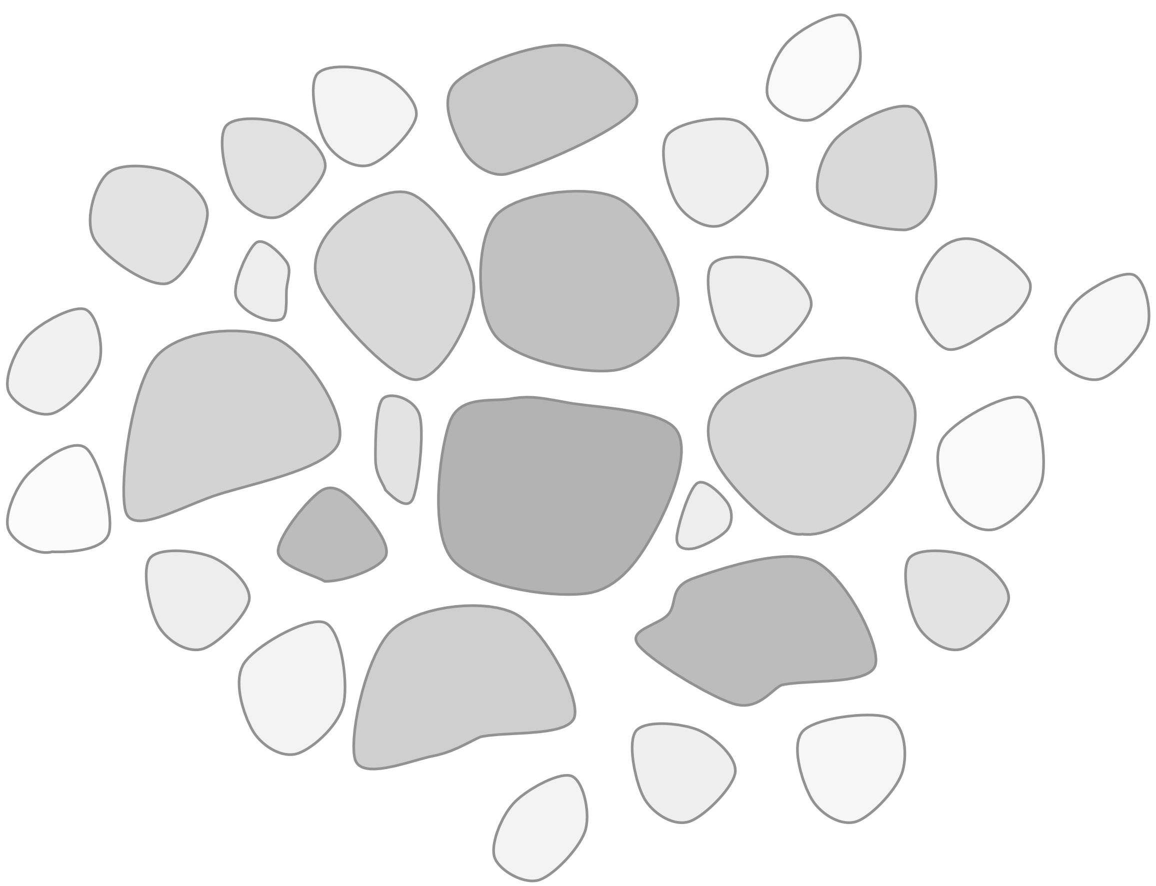
Klessen & Glover 2014, Saas Fee Lecture, arXiv:1412.5182, 1-191

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:

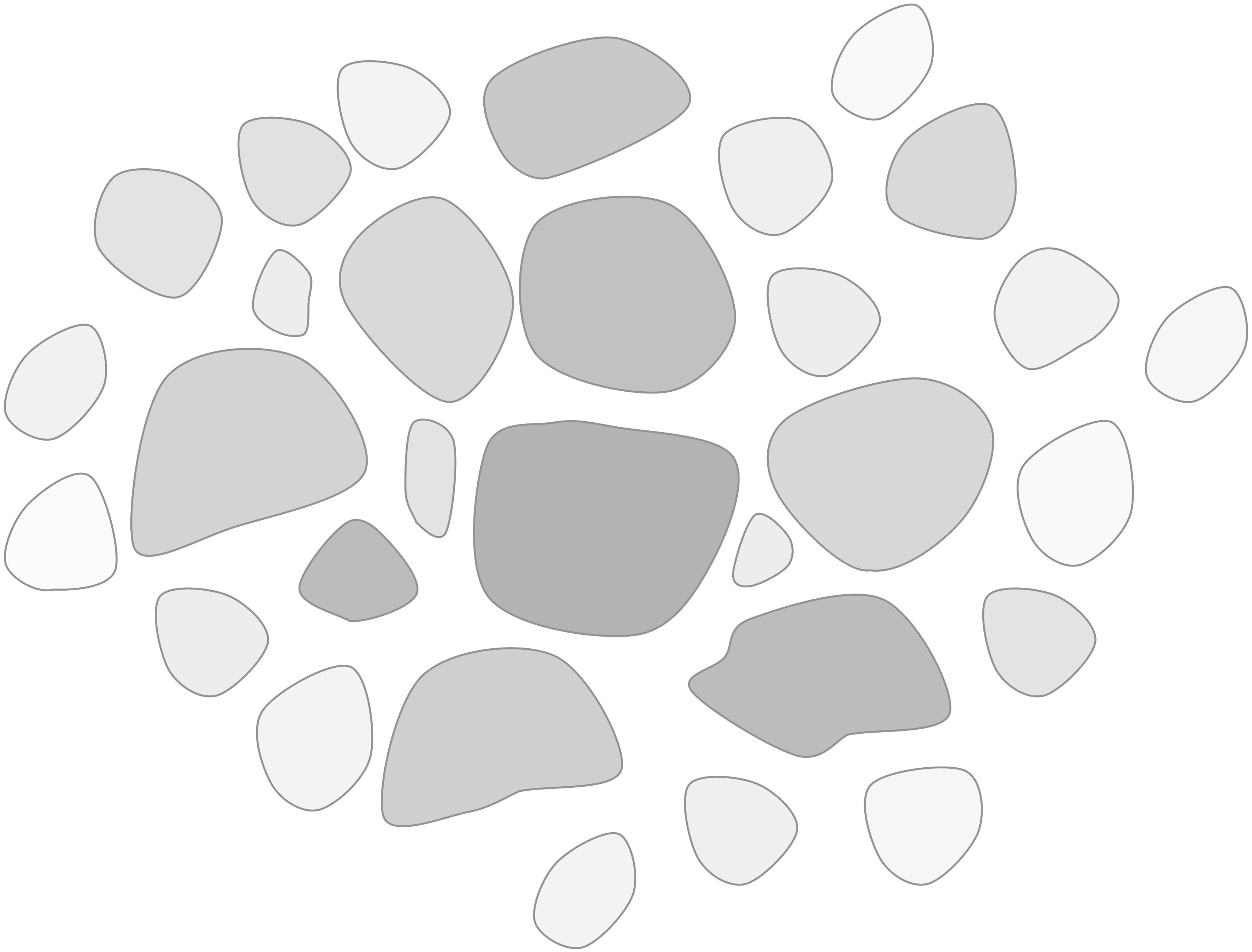
$\alpha = E_{kin}/|E_{pot}| < 1$

--> *global contraction*

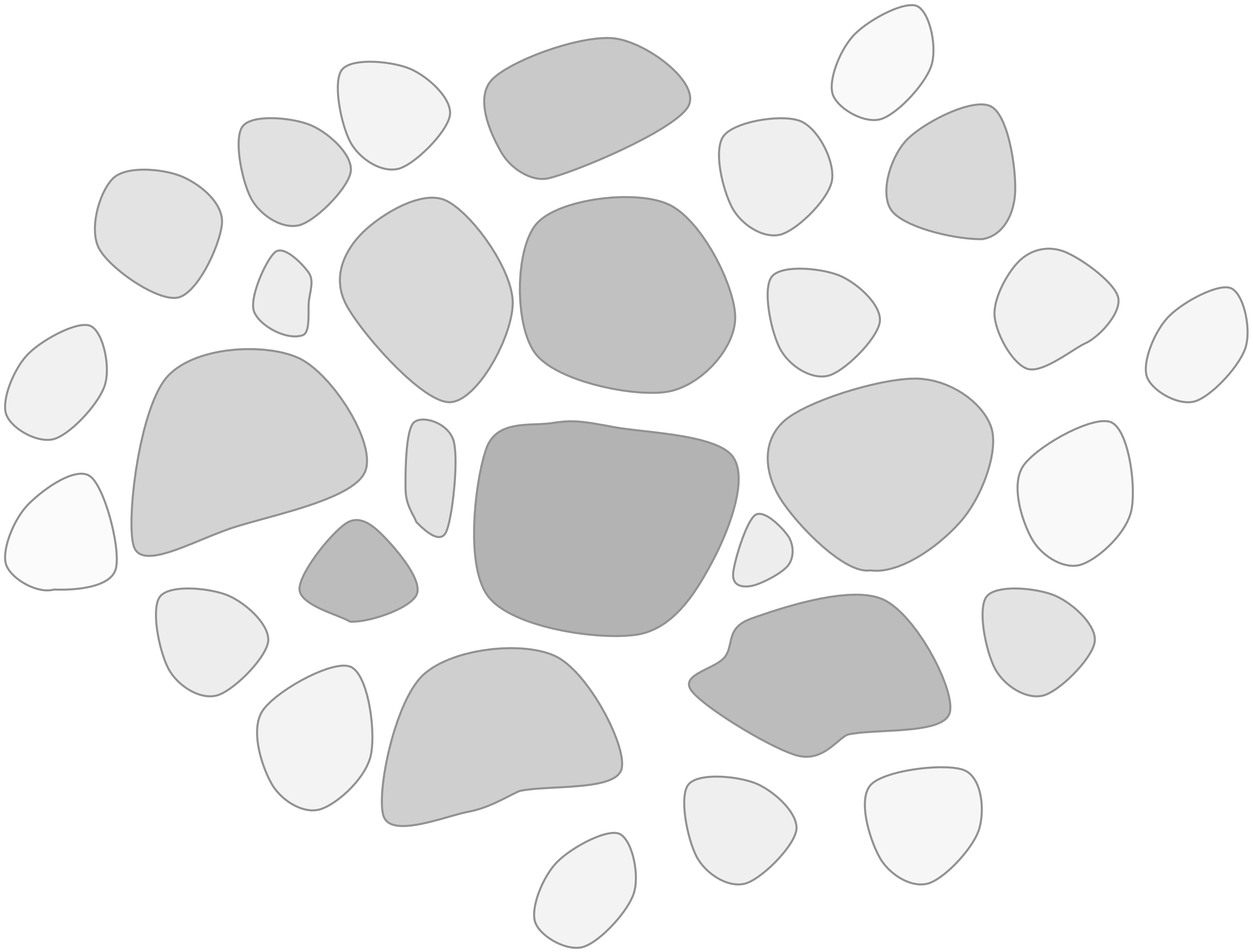
--> core do *interact* while collapsing

--> *competition* influences *mass growth*

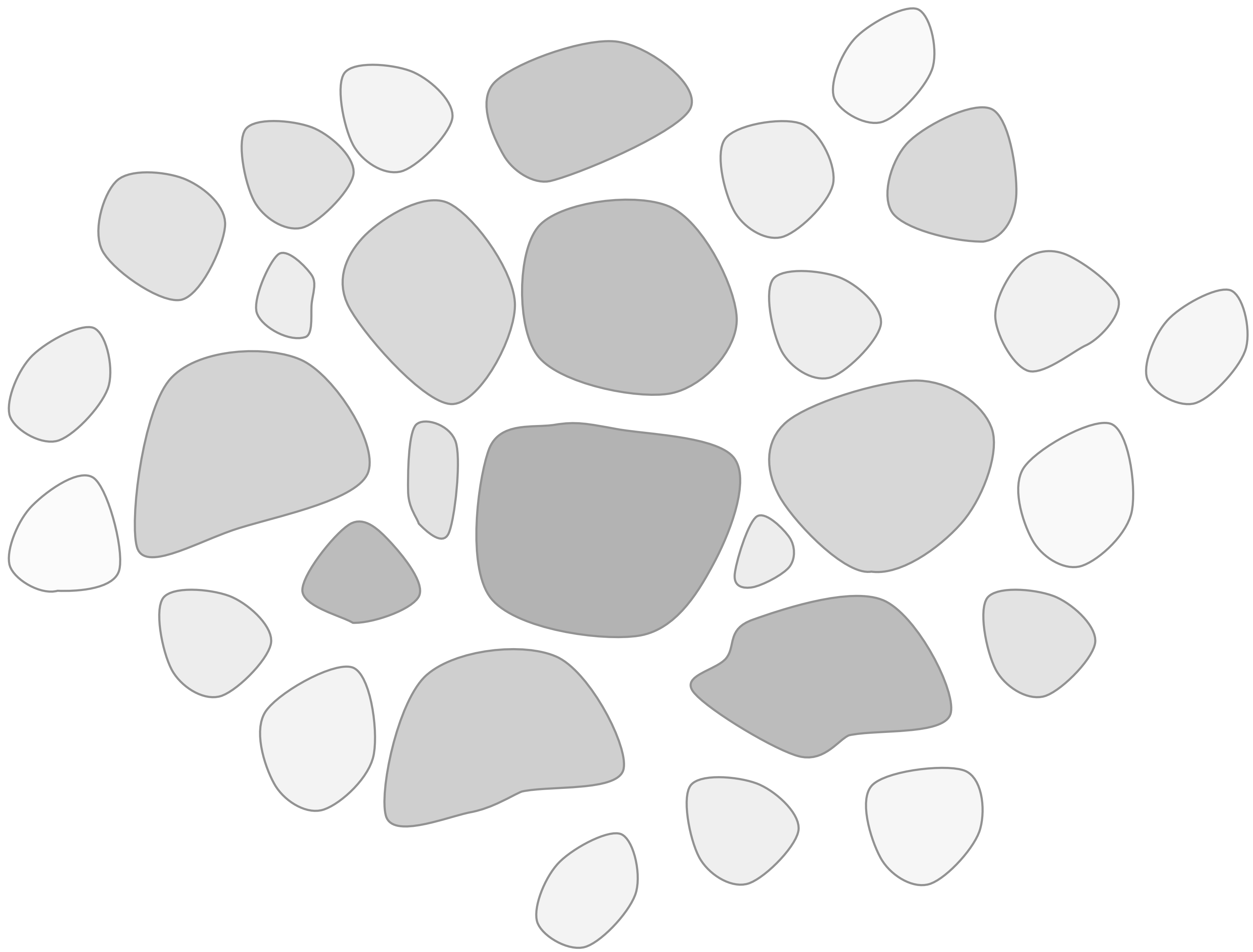
--> *dense cluster with high-mass stars*



turbulence creates a hierarchy of clumps



as turbulence decays locally, contraction sets in



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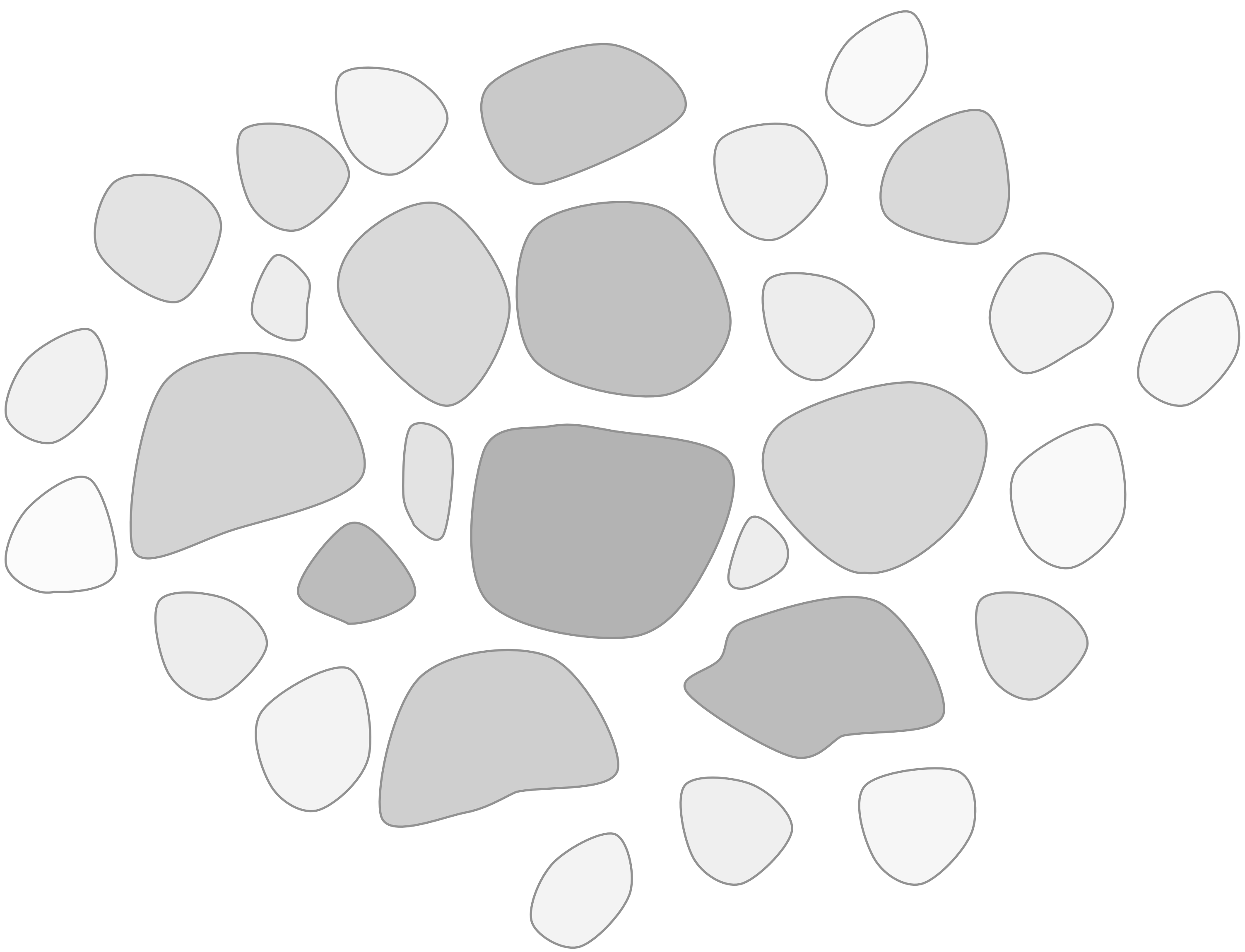
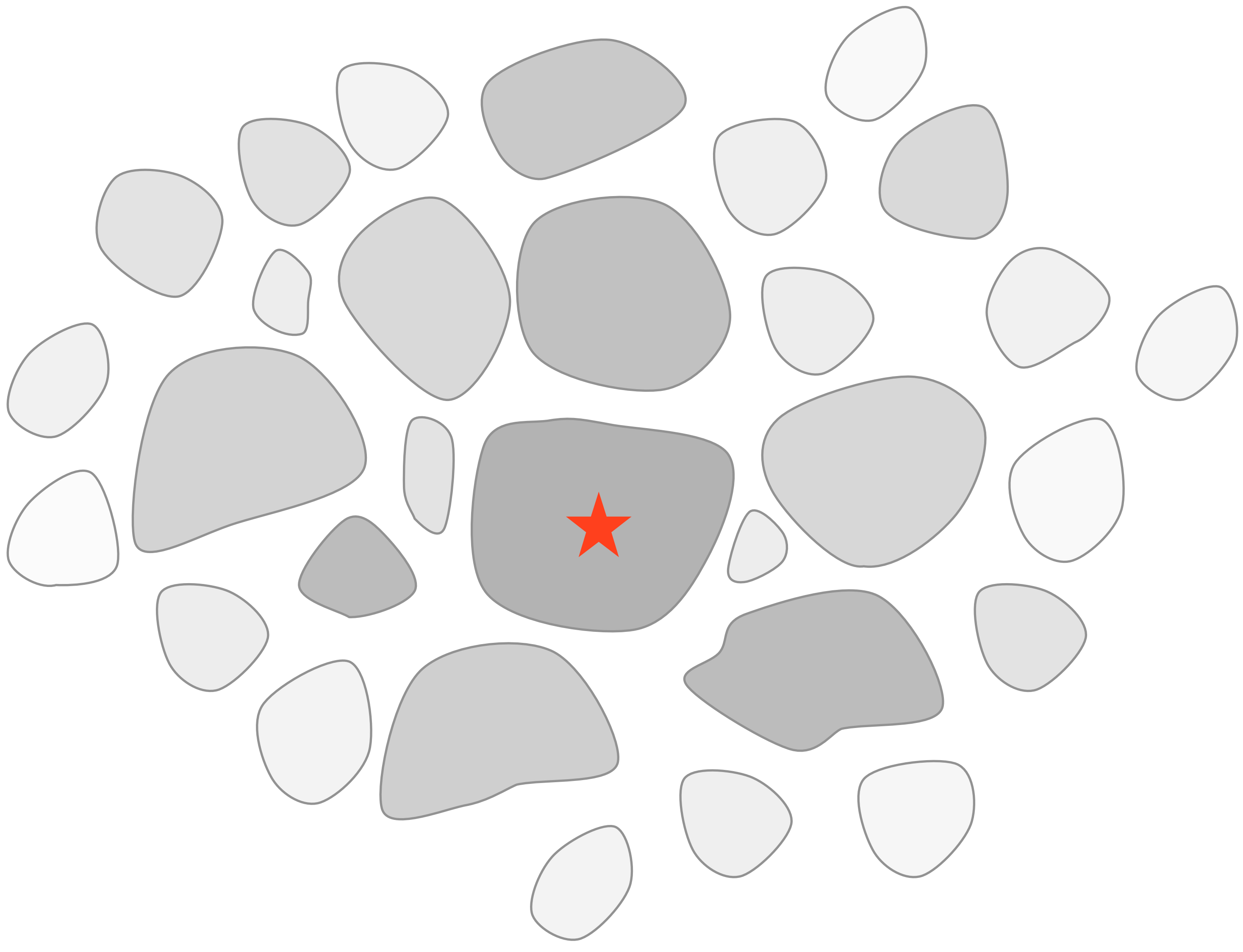


while region contracts, individual clumps collapse to form stars



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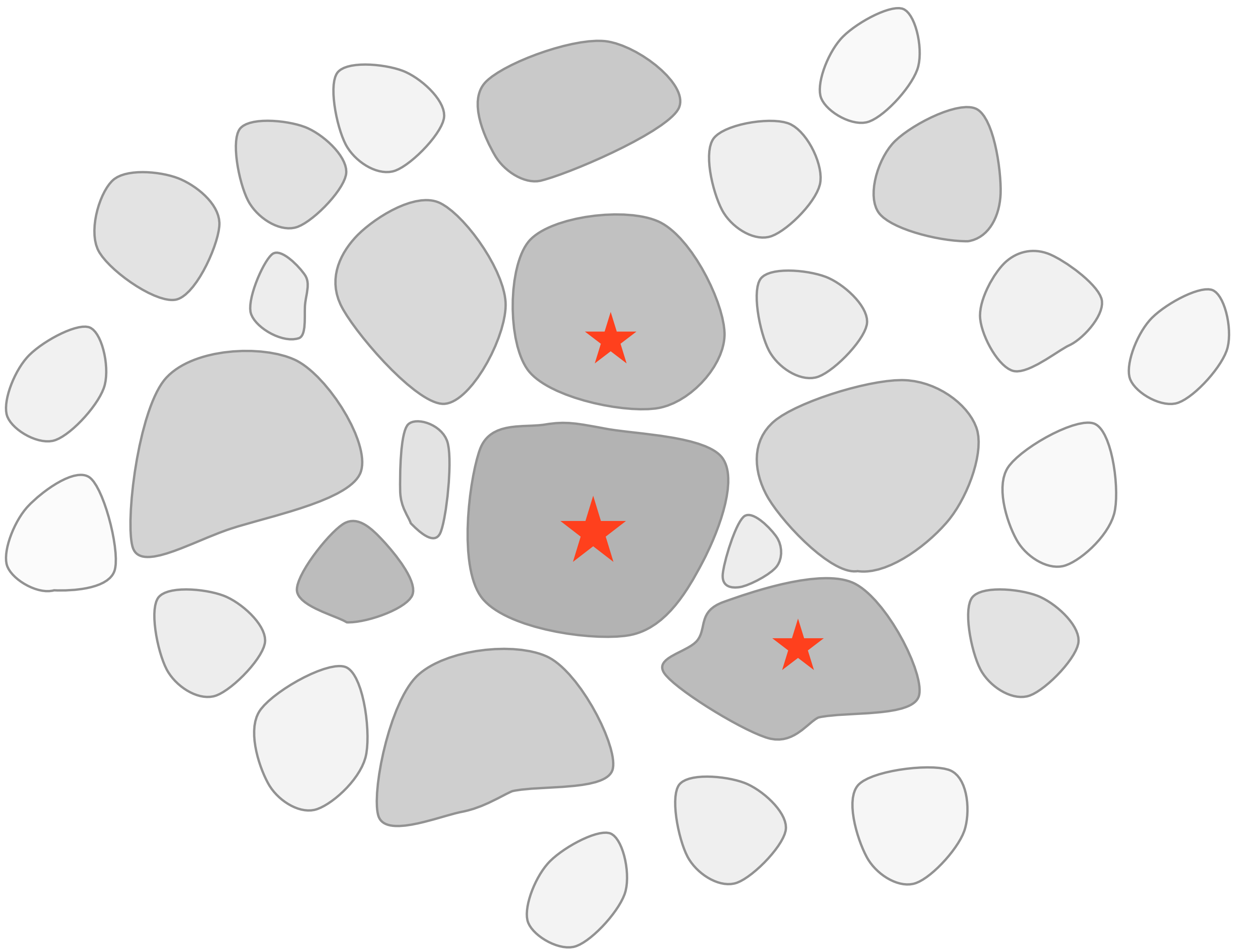
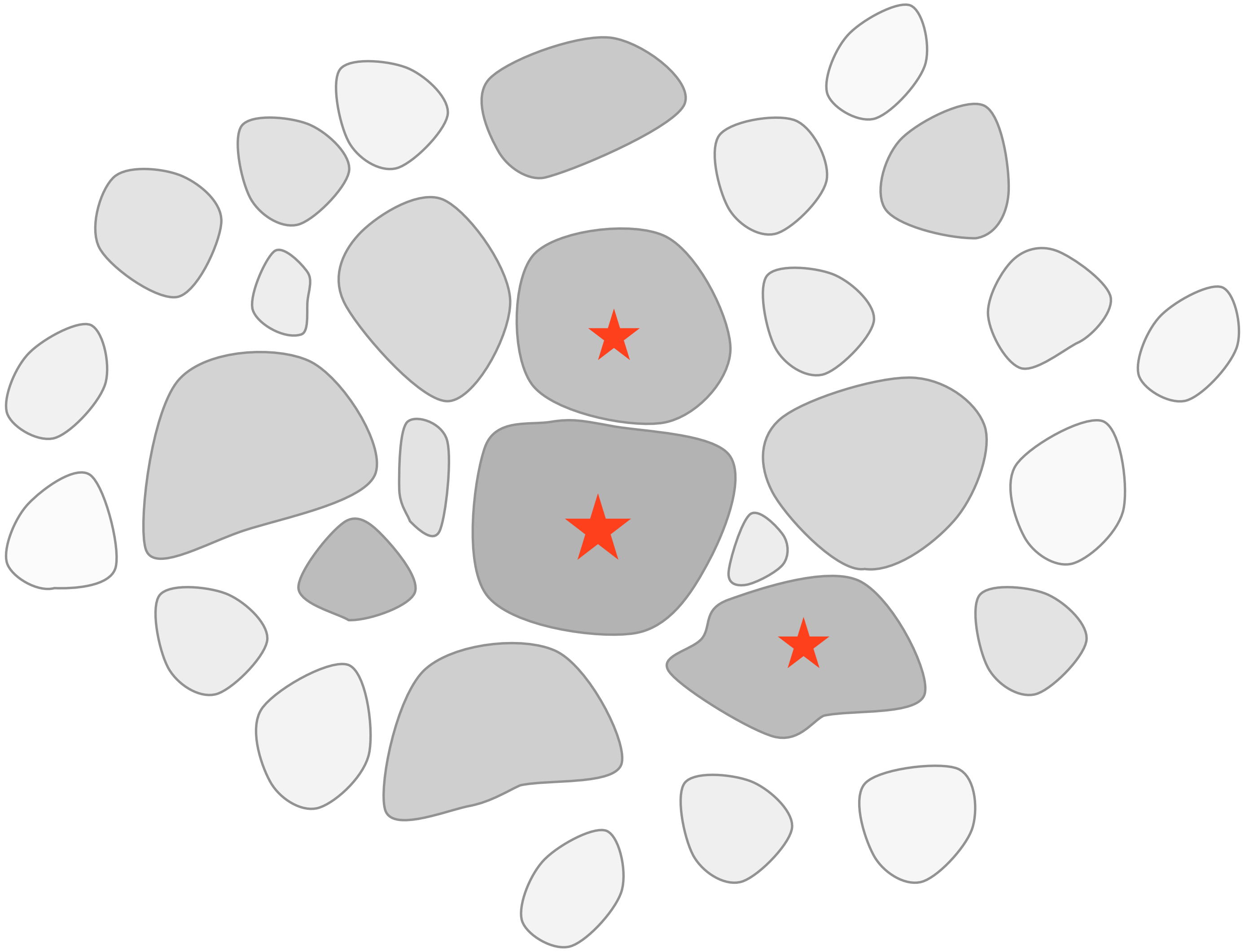


individual clumps collapse to form stars



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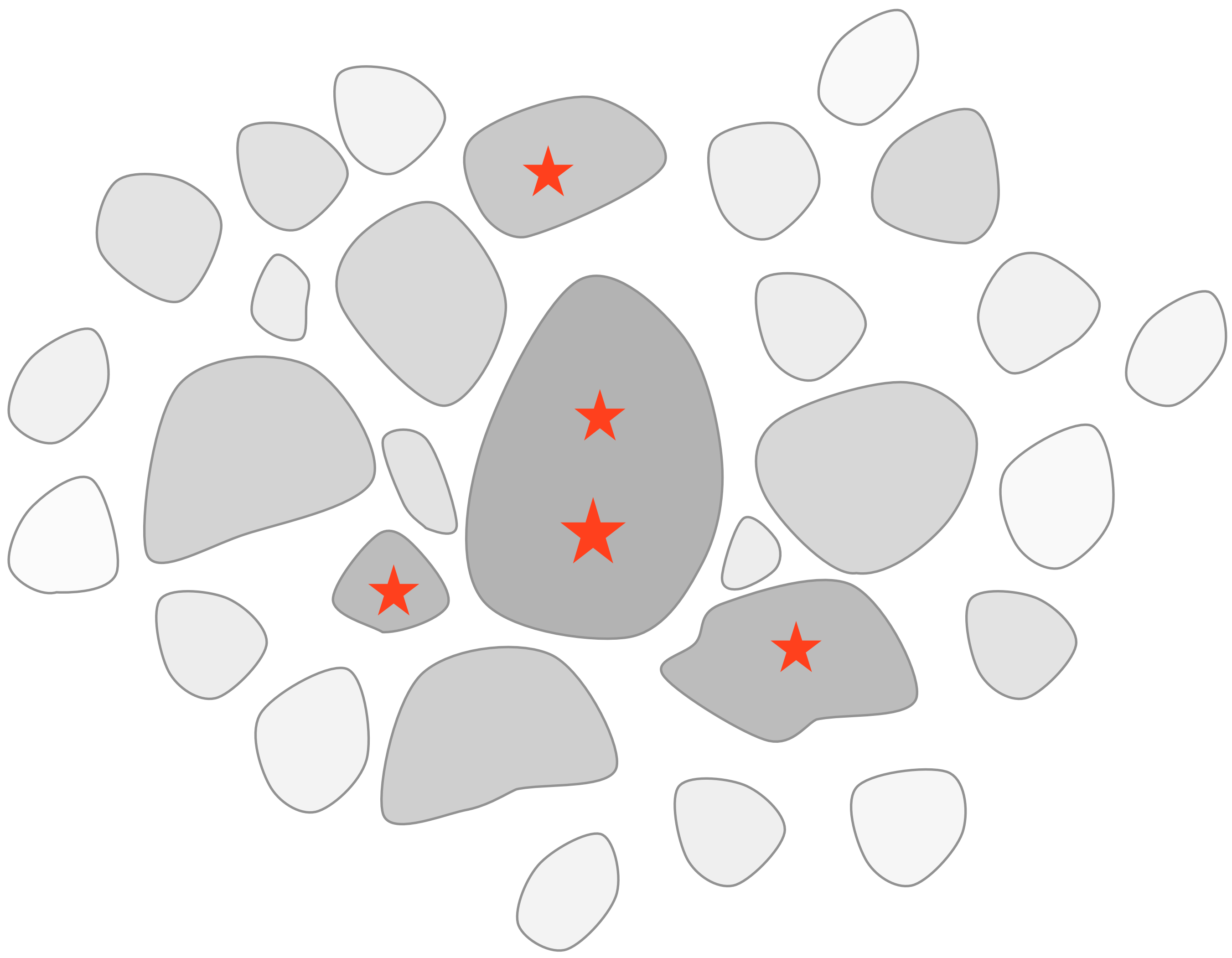
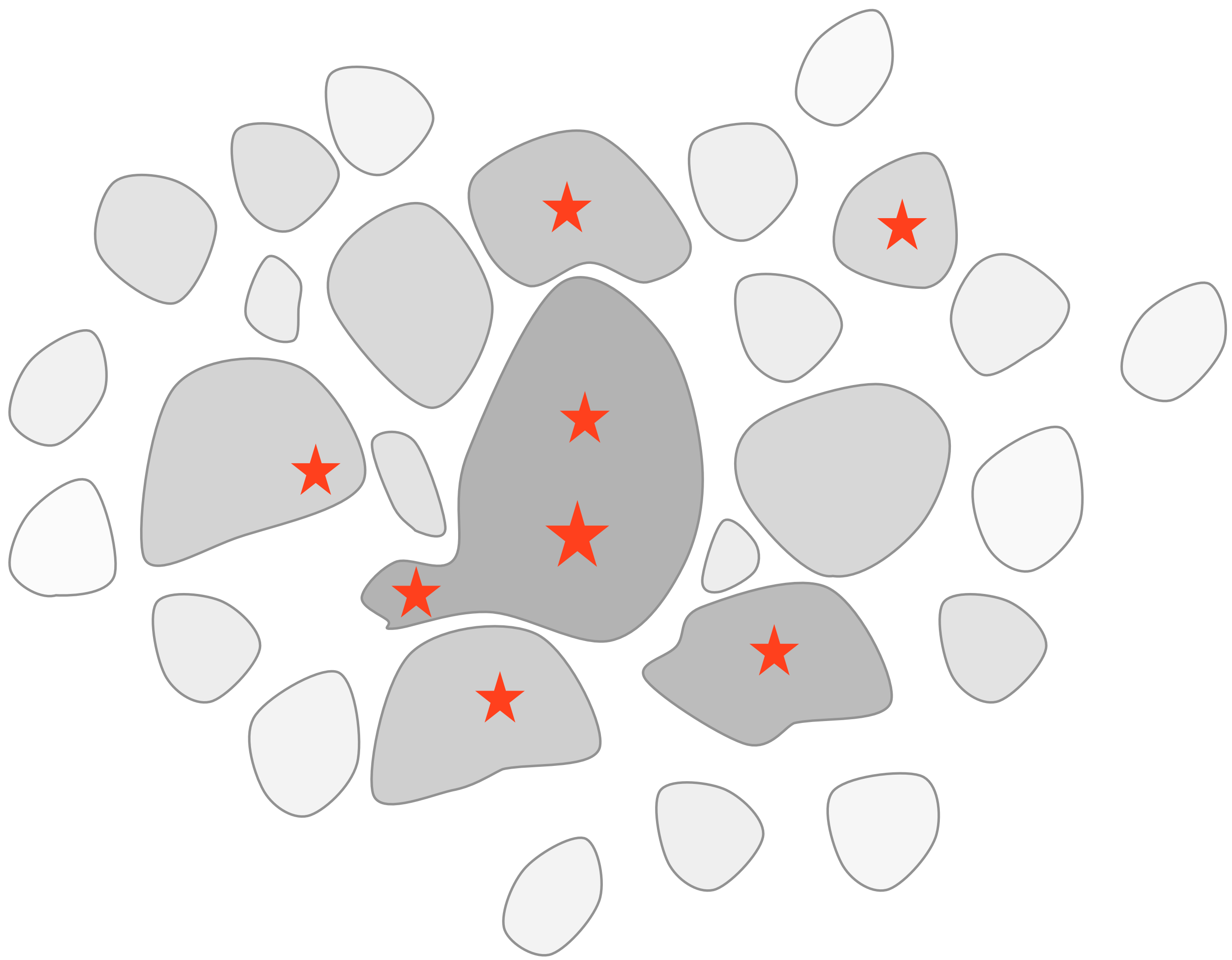


$\alpha = E_{kin}/|E_{pot}| < 1$

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



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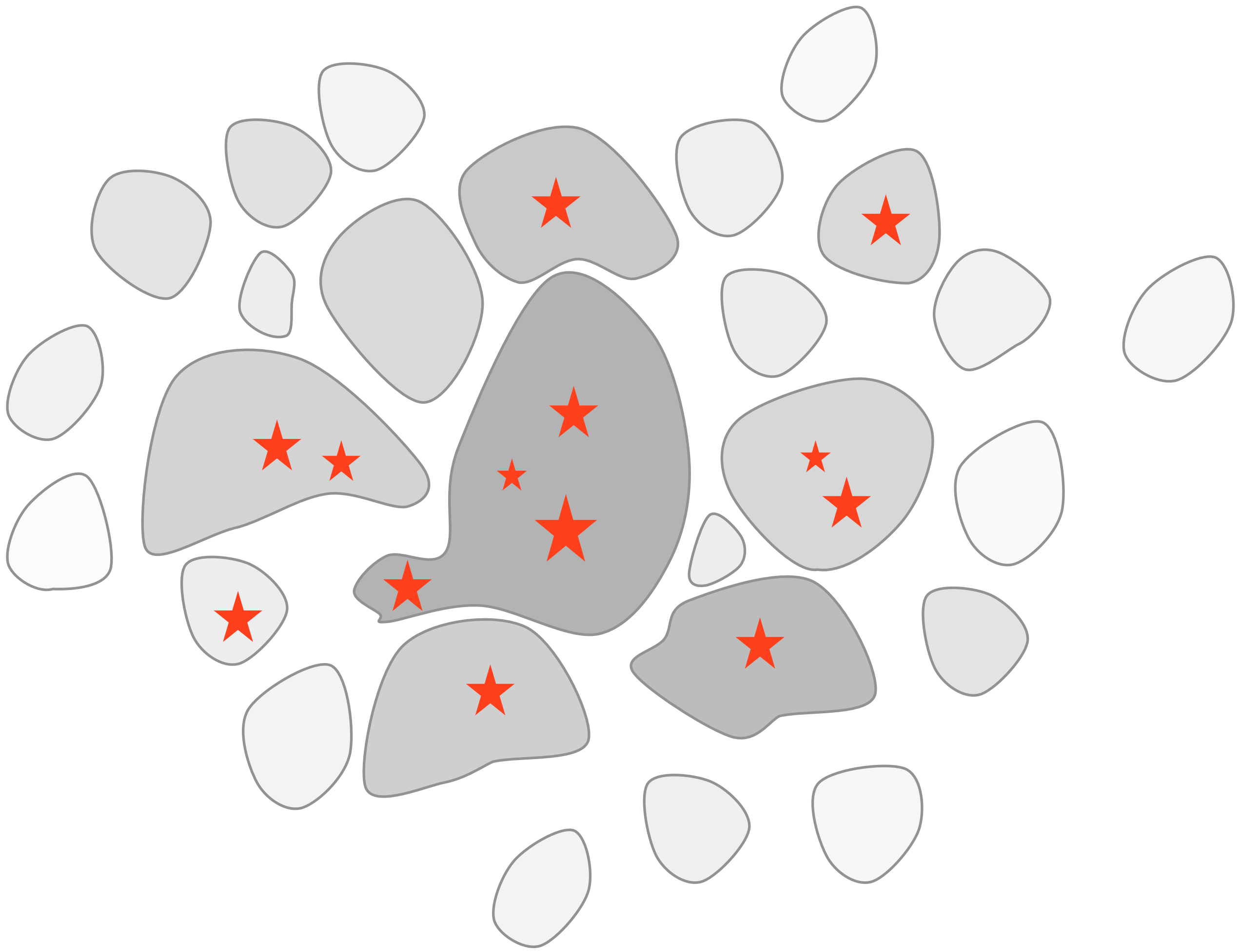

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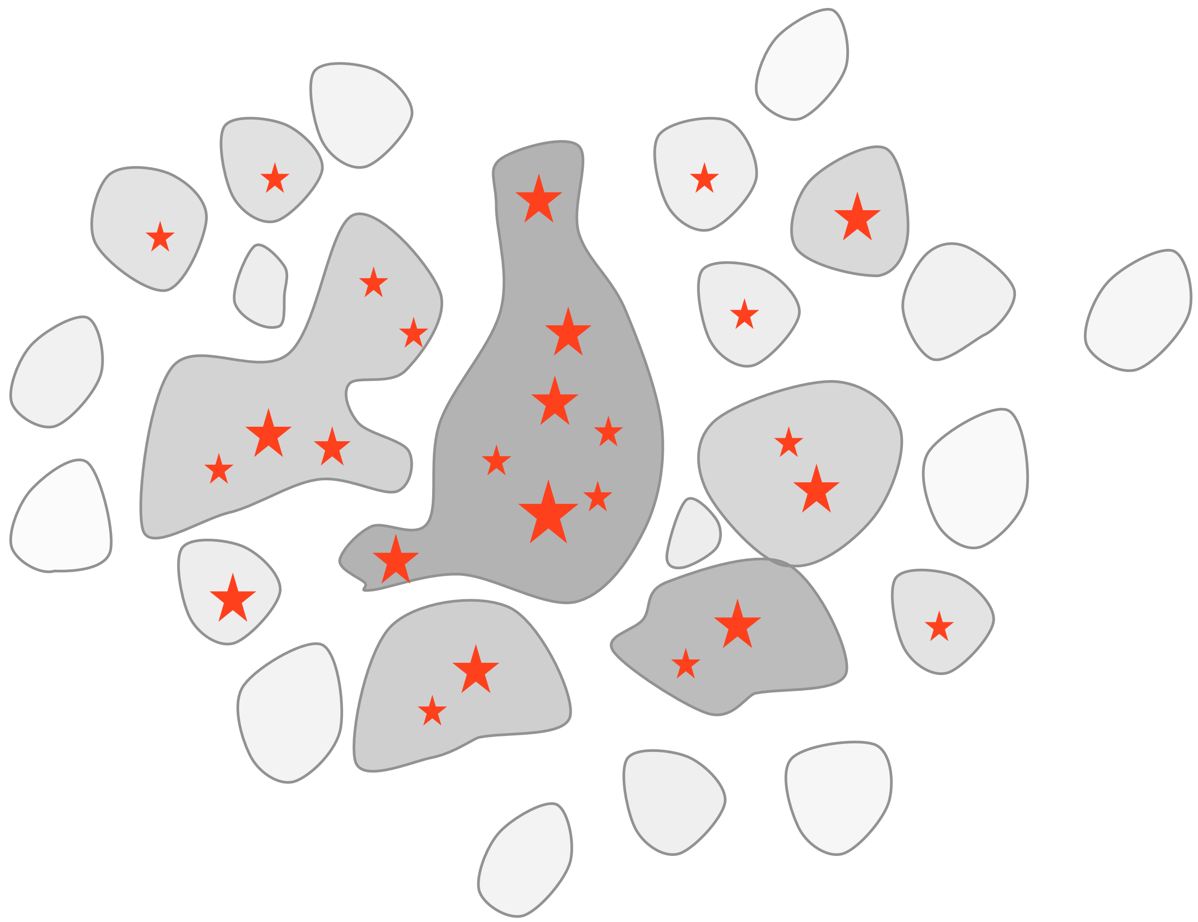

in *dense clusters*, competitive mass growth becomes important

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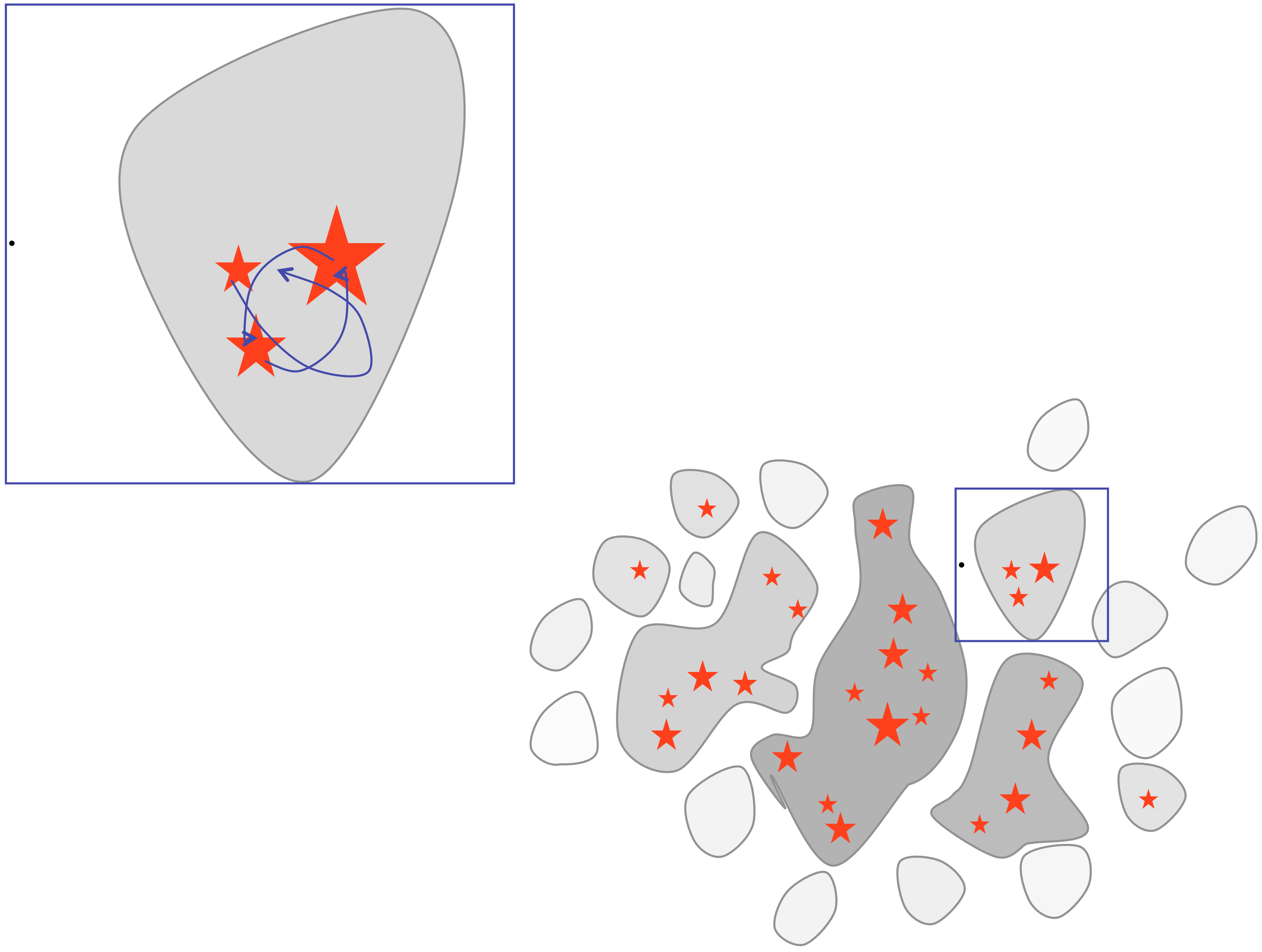
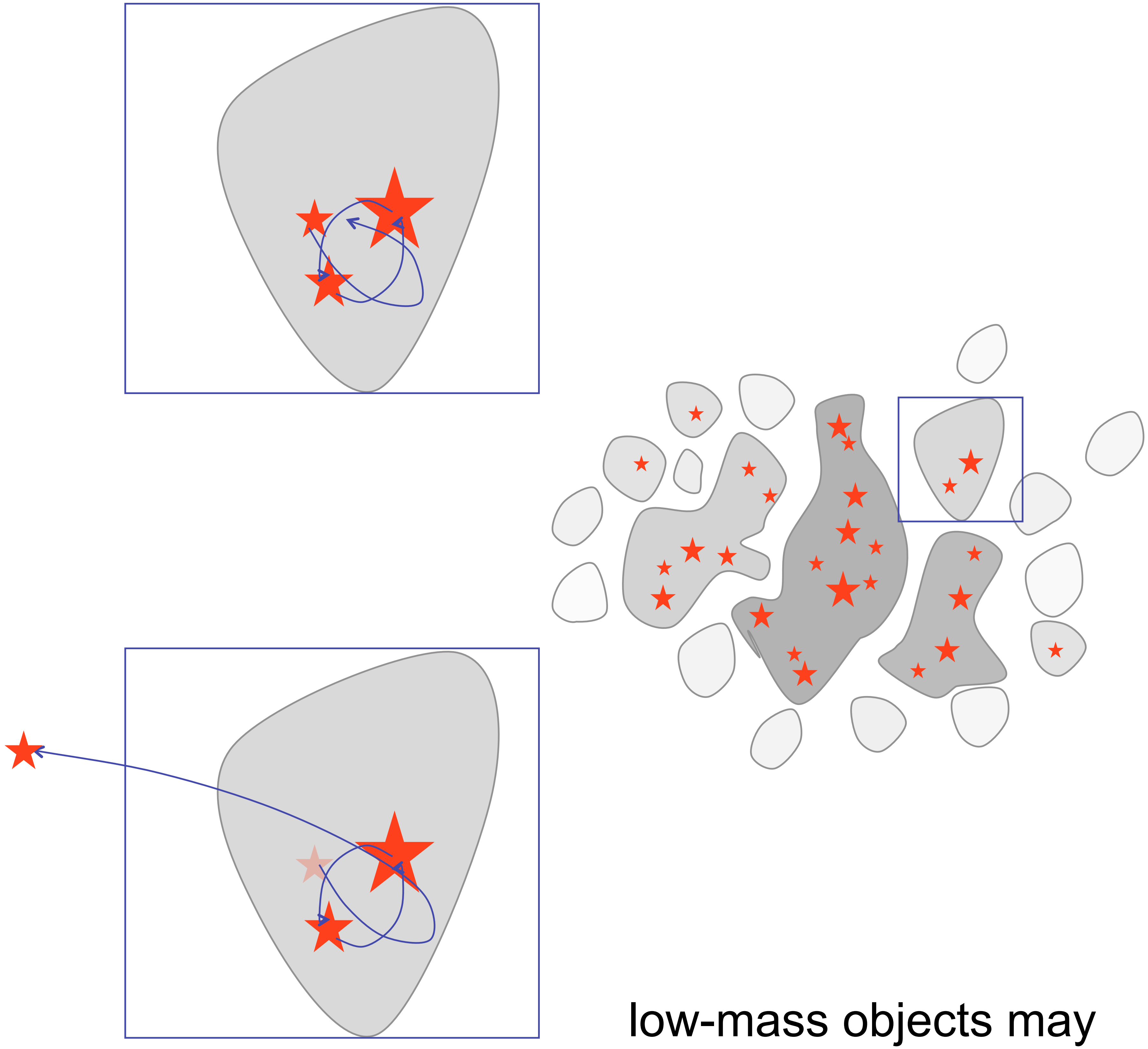
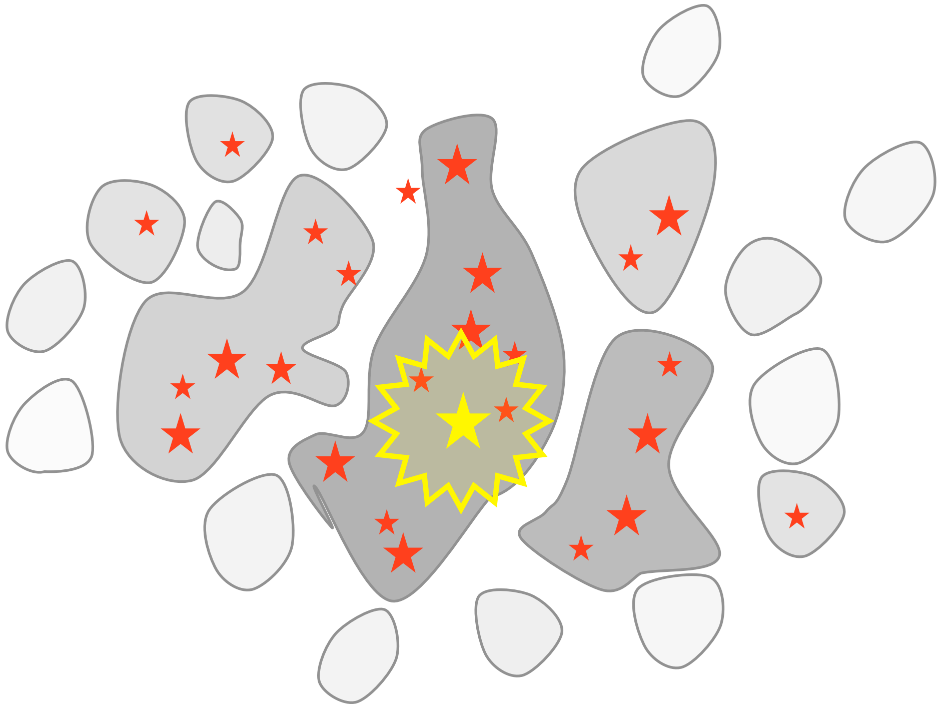


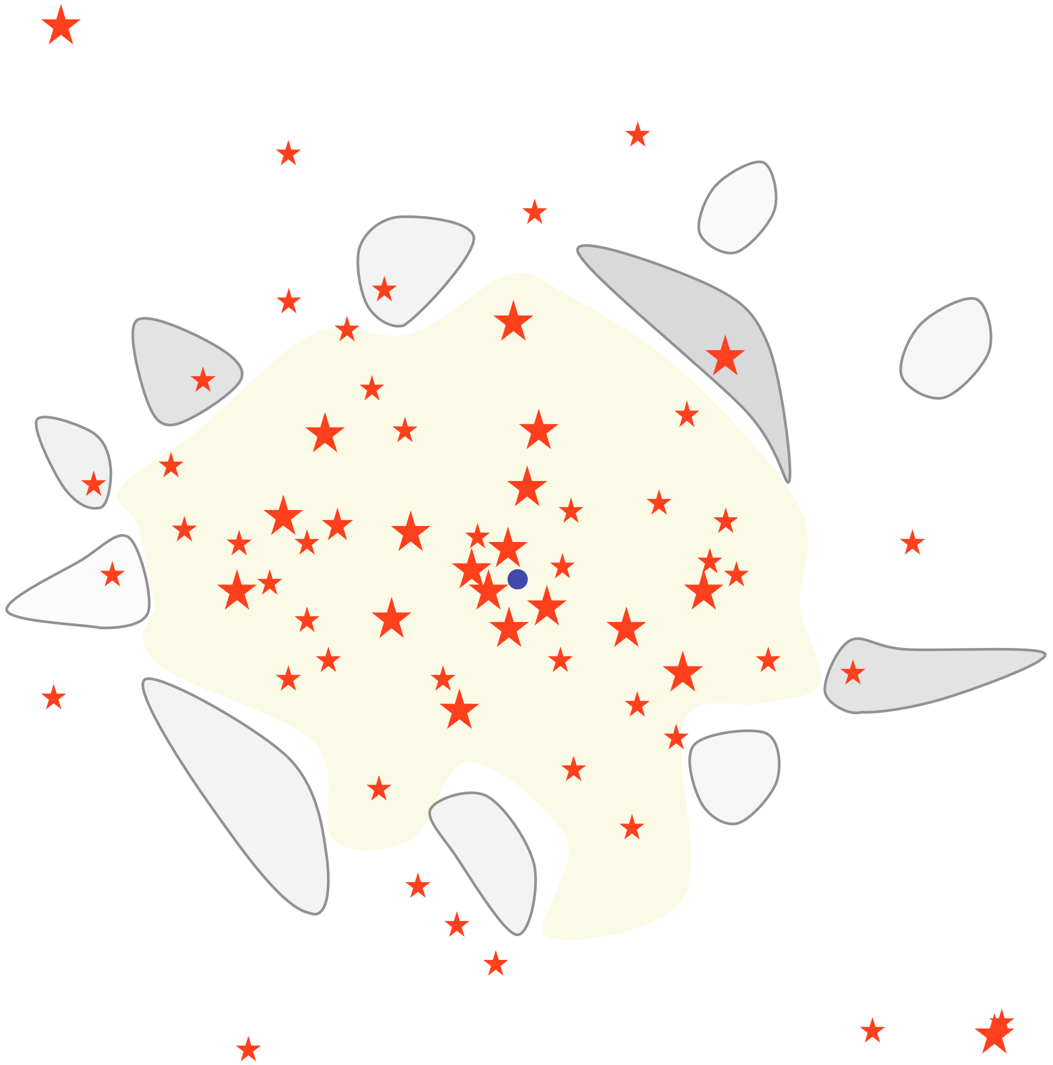
in *dense clusters*, *N*-body effects influence mass growth



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



feedback terminates star formation



result: *star cluster*, possibly with HII region


NGC 602 in the LMC: Hubble Heritage Image

current status

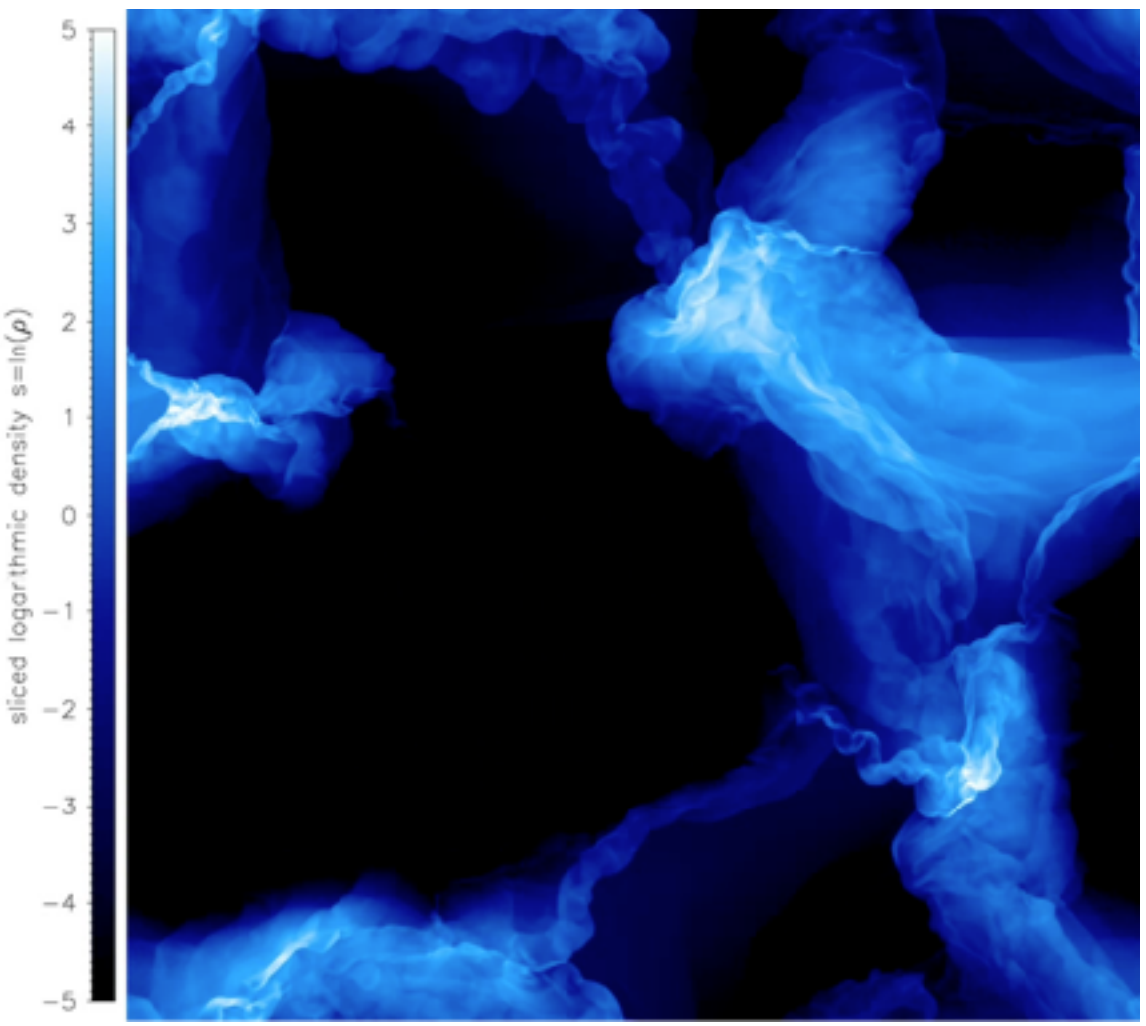
- *stars form from the complex interplay of self-gravity and a large number of competing processes (such as turbulence, magnetic fields, radiative and mechanical feedback, thermal pressure, cosmic rays, etc.)*
- *the relative importance of these processes depends on the environment*
  - prestellar cores --> 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.

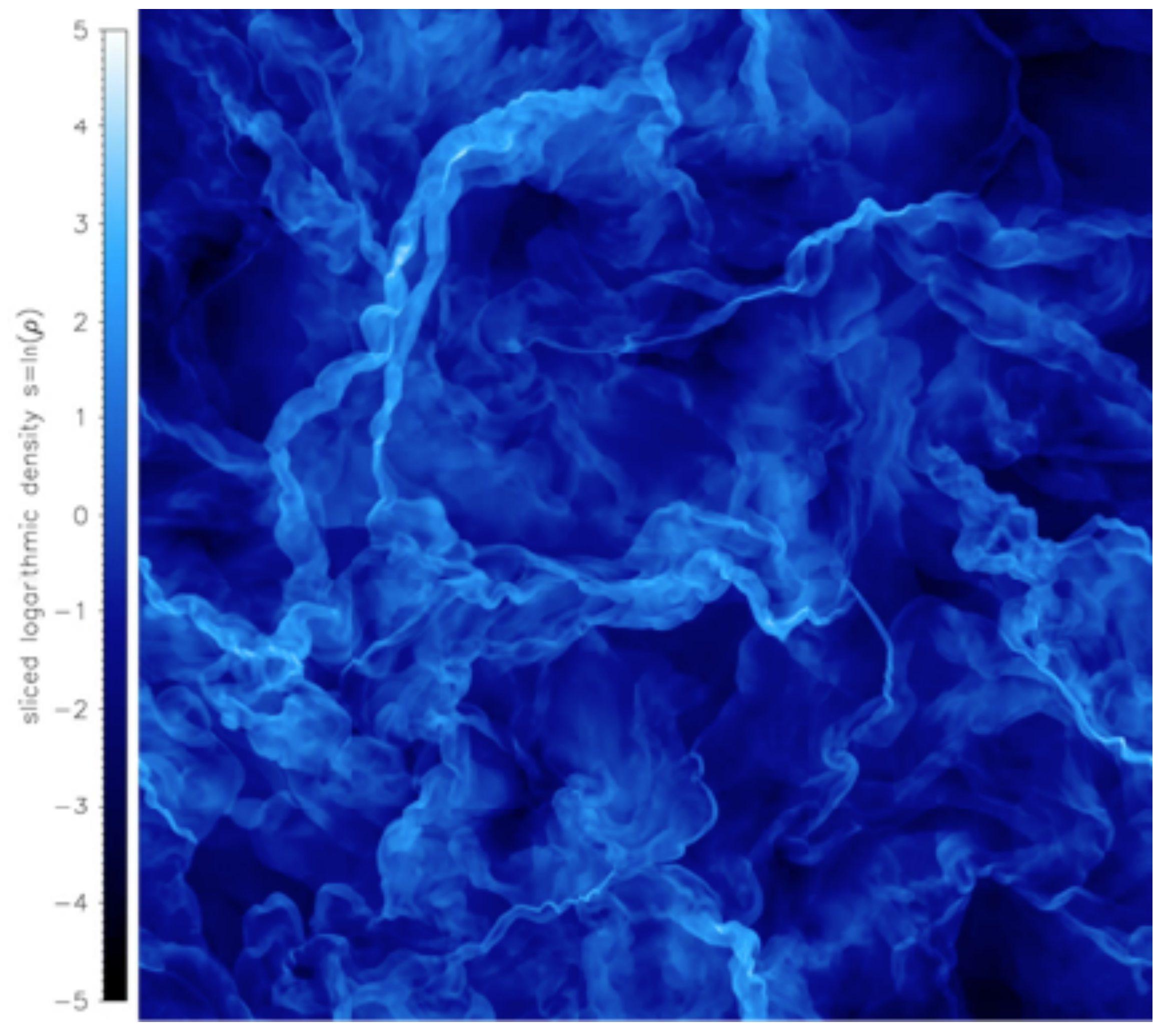

comments on
turbulence

dilatational vs. solenoidal driving

density as function of time / cut through 1024^3 cube simulation (FLASH)



compressive
larger structures, higher ρ-contrast



rotational
smaller structures, small ρ-pdf

Federrath, Klessen, Schmidt (2008a,b)

dilatational vs. solenoidal driving

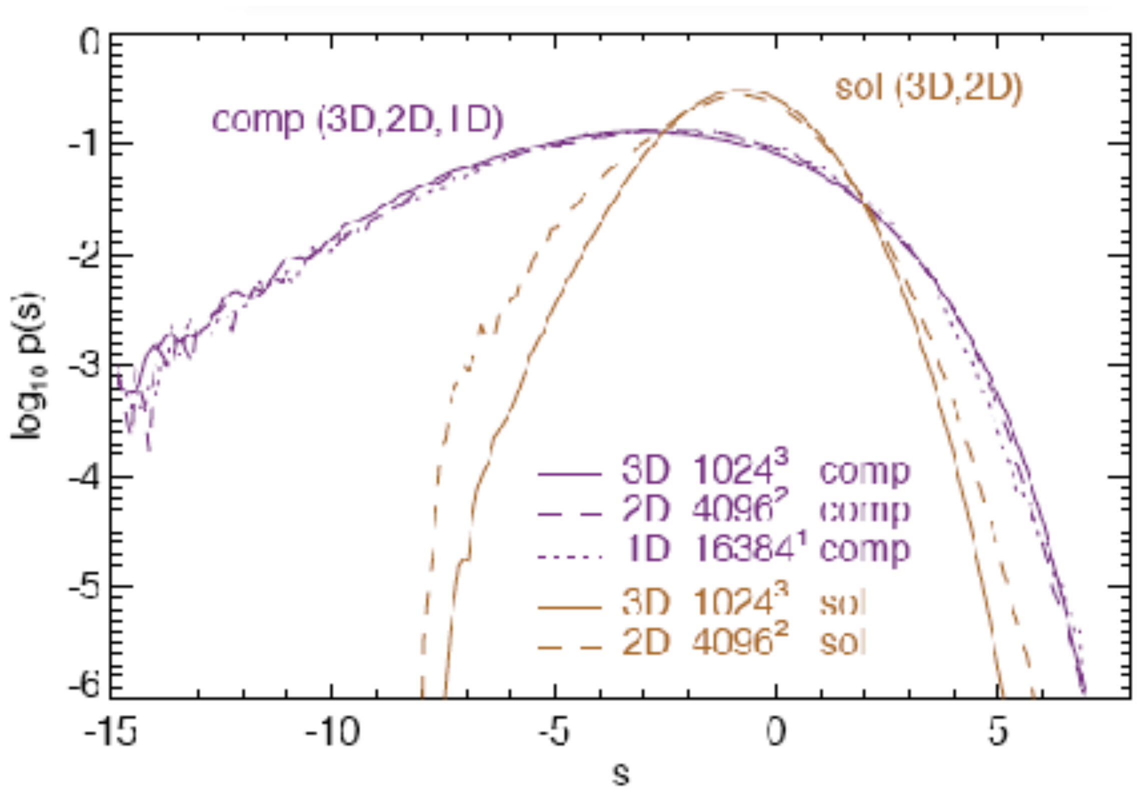


FIG. 3.— Volume-weighted density PDFs $p(s)$ obtained from 3D, 2D and 1D simulations with compressive forcing and from 3D and 2D simulations using solenoidal forcing. Note that in 1D, only compressive forcing is possible as in the study by Passot & Vázquez-Semadeni (1998). As suggested by eq. (5), compressive forcing yields almost identical density PDFs in 1D, 2D and 3D with $b\sim 1$, whereas solenoidal forcing leads to a density PDF with $b\sim 1/2$ in 2D and with $b\sim 1/3$ in 3D.

Federrath, Klessen, Schmidt (2008a)

- density pdf depends on "dimensionality" of driving
  - relation between width of pdf and Mach number

$$\boxed{\sigma_\rho/\rho_0 = b\mathcal{M}}$$

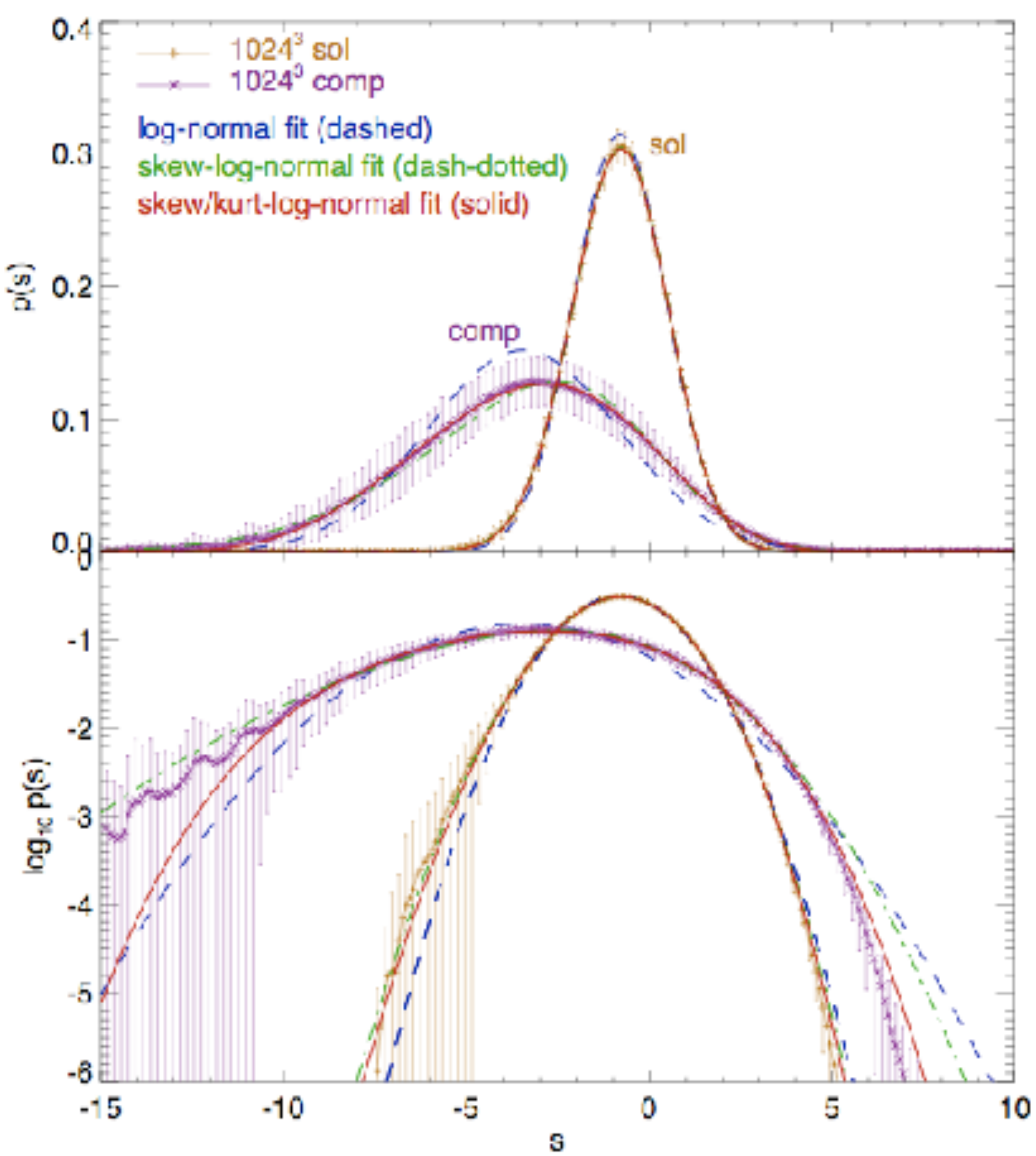
  - with b depending on ζ via

$$\boxed{b = 1 + \left[\frac{1}{D} - 1\right]\zeta = \begin{cases} 1 - \frac{2}{3}\zeta & \text{, for } D = 3 \\ 1 - \frac{1}{2}\zeta & \text{, for } D = 2 \\ 1 & \text{, for } D = 1 \end{cases}}$$

  - with ζ being the ratio of dilatational vs. solenoidal modes:

$$\mathcal{P}_{ij}^{\zeta} = \zeta\mathcal{P}_{ij}^{\perp} + (1-\zeta)\mathcal{P}_{ij}^{||} = \zeta\delta_{ij} + (1-2\zeta)\frac{k_i k_j}{|k|^2}$$

dilatational vs. solenoidal driving

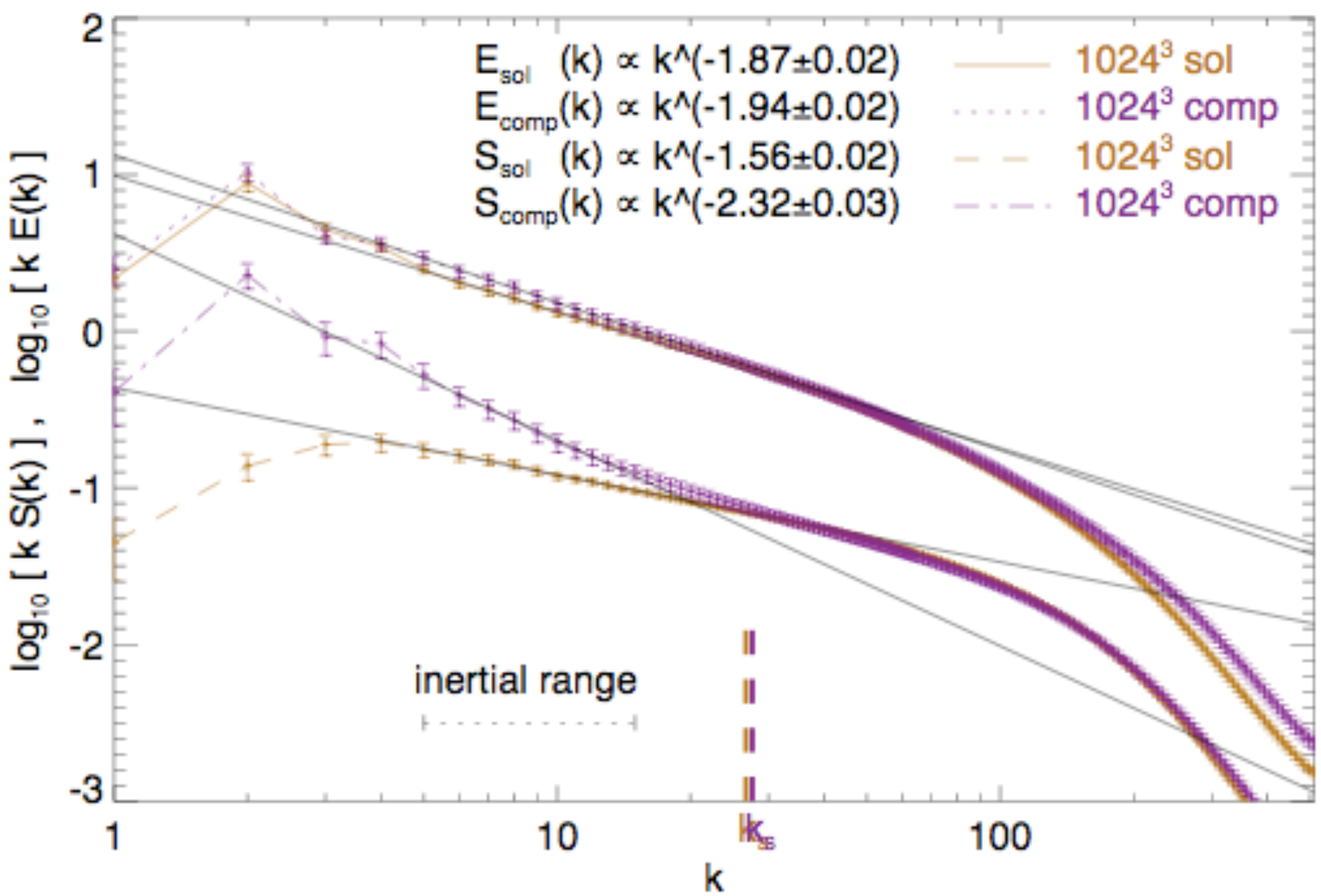


good fit needs 3rd and 4th moment of distribution!

Federrath, Klessen, Schmidt (2008b)

- density pdf depends on “dimensionality” of driving
  → is that a problem for the Krumholz & McKee model of the SF efficiency?
- density pdf of compressive driving is *NOT log-normal*
  → is that a problem for the Padoan & Nordlund, or Hennebelle & Chabrier IMF model?
- most “physical” sources should be *compressive* (convergent flows from spiral shocks or SN)

dilatational vs. solenoidal driving



compensated density spectrum kS(k) shows clear break at sonic scale. below that shock compression no longer is important in shaping the power spectrum ...

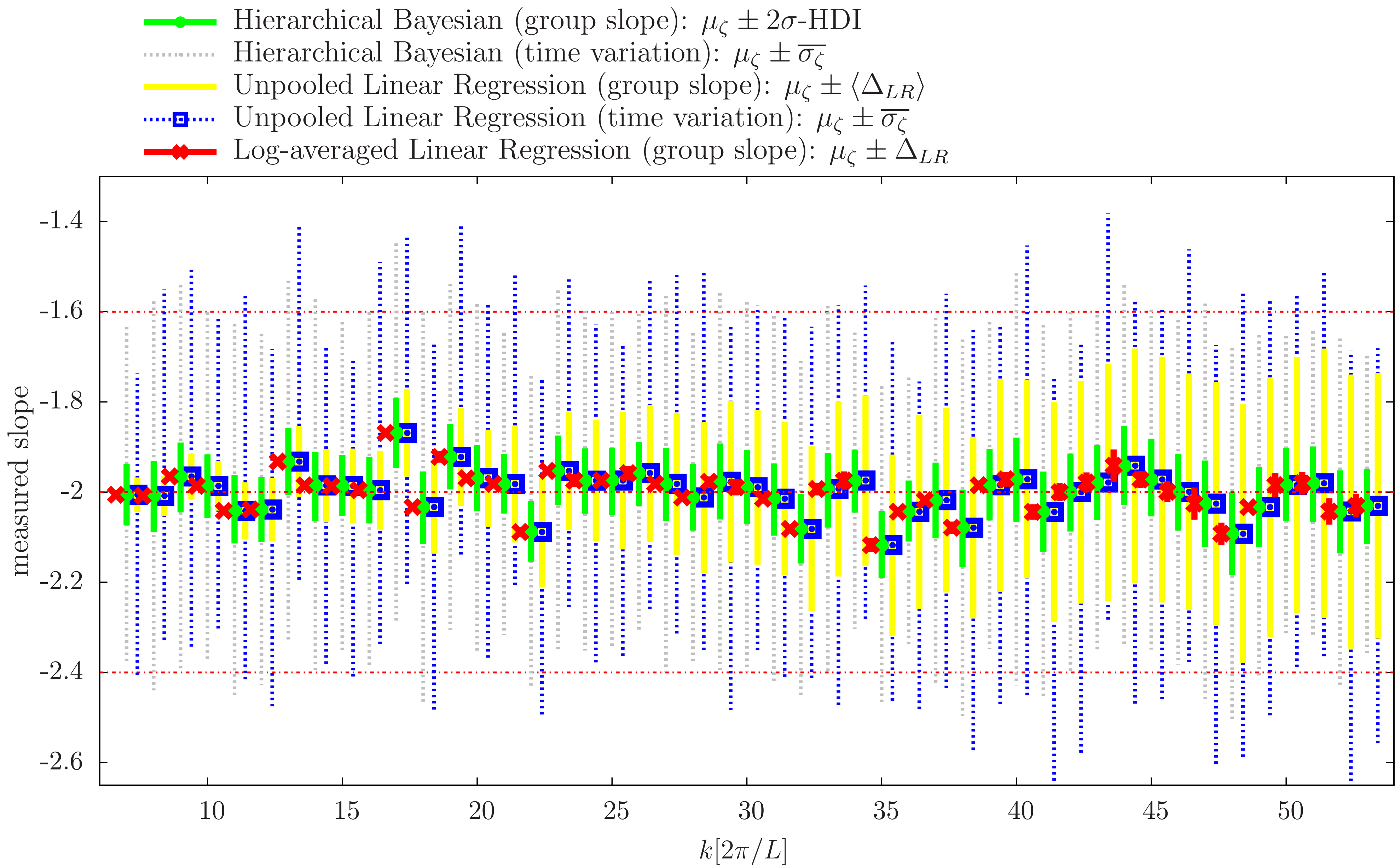
- density power spectrum differs between dilatational and solenoidal driving!

  → dilatational driving leads to break at sonic scale!

- can we use that to determine driving sources from observations ?

Federrath, Klessen, Schmidt (2008b)

caveat: really power law?



Konstandin et al. (2015, MNRAS, 446, 1775)

caveat: really power law?

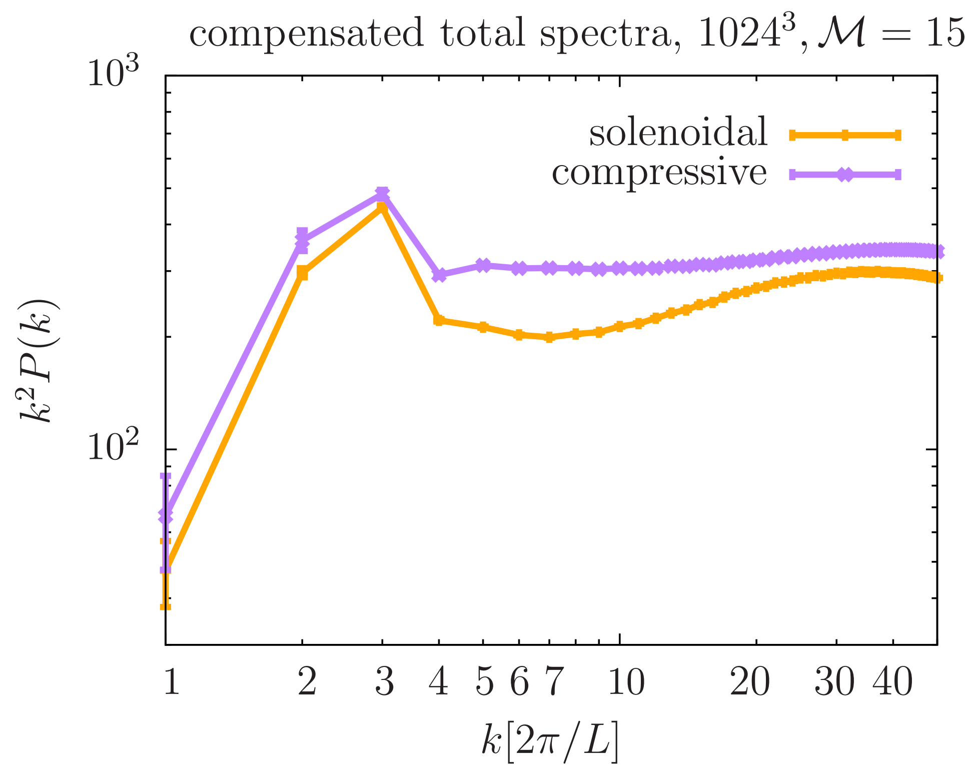


Figure 3. Total spectra for solenoidal (orange) and compressive (purple) forcing, compensated with k^2, and 1024^3 resolution.

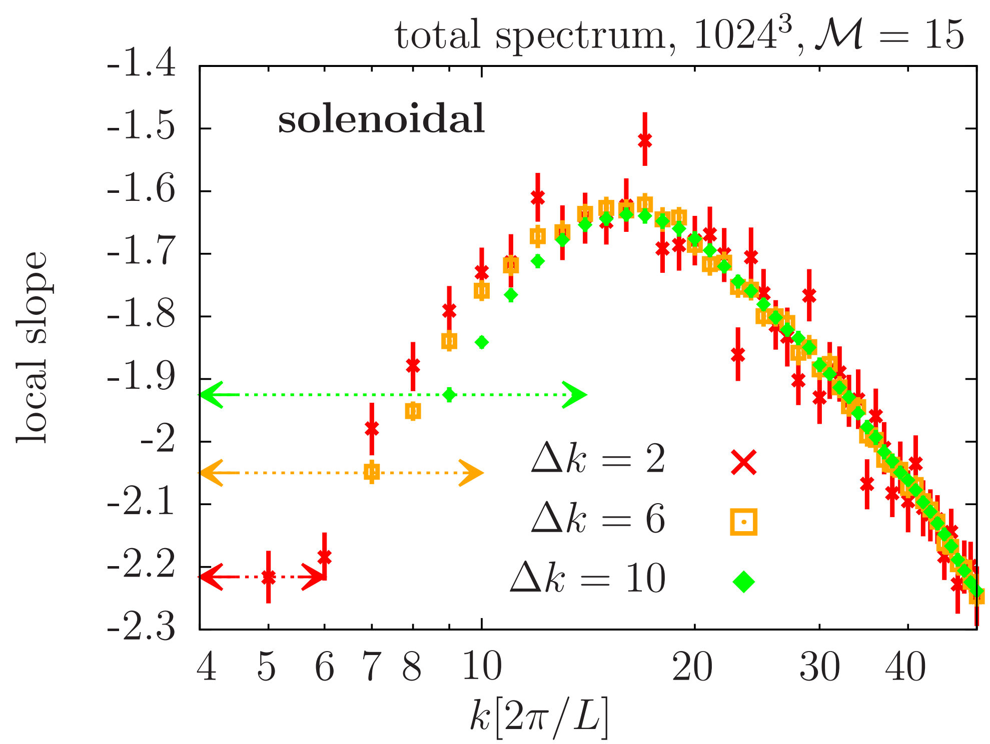


Figure 4. Measured Local Group slope of the Bayesian method as a function of the window centre k for three different fitting window sizes $\Delta k = 2, 6, 10$ (red, orange, green) performed on the total spectrum of the simulation with 1024^3 grid points and solenoidal forcing.

Konstandin et al. (2015, MNRAS, 446, 1775)

caveat: really power law?

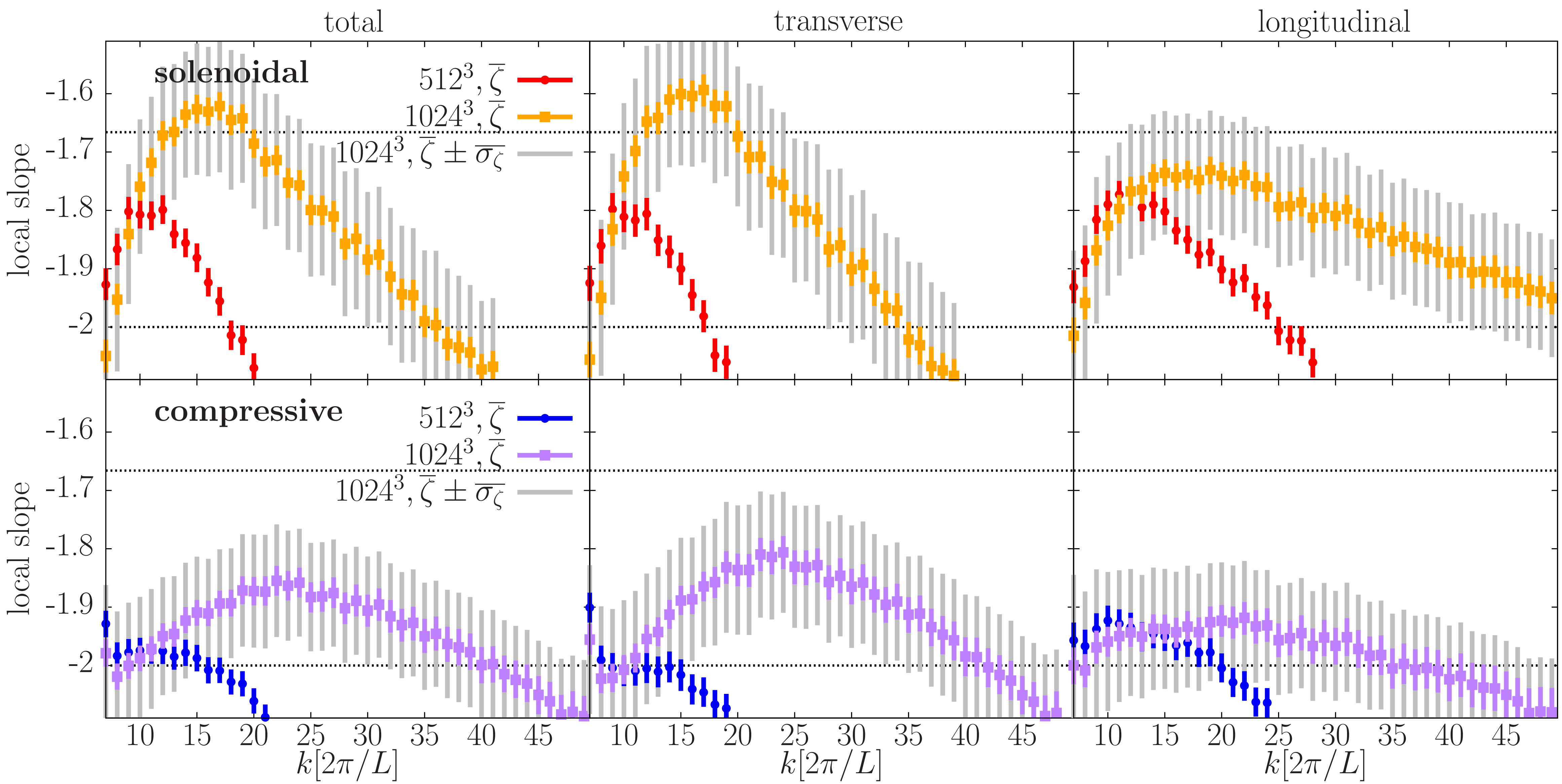


Figure 5. Local group slope as a function of the centre of the fitting window k with a size of $\Delta k = 6$ applied to the total (left), transverse (middle), and longitudinal (right) spectra of the simulations with $512^3, 1024^3$ resolution (red/orange and blue/purple), solenoidal (upper panels) and compressive (bottom panels) forcing. The grey error bars indicate the time variation of the slope at each k for the 1024^3 simulations. The horizontal dotted lines indicate Kolmogorov $-5/3$ scaling and a Burgers -2 scaling behaviour.

Konstandin et al. (2015, MNRAS, 446, 1775)

what drives ISM turbulence?

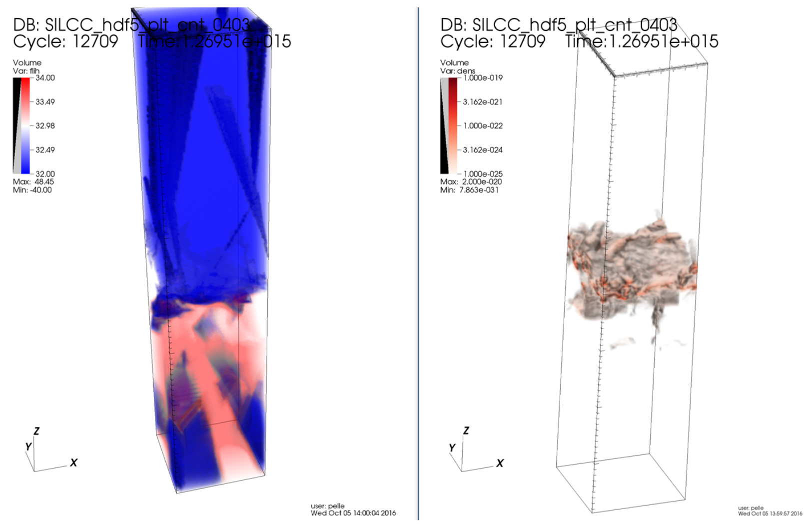
- seems to be driven on large scales, little difference between star-forming and non-SF clouds
  ---> rules out internal sources
- proposals in the literature
  - supernovae
  - expanding HII regions / stellar winds / outflows
  - spiral density waves
  - magneto-rotational instability
  - accretion onto disk

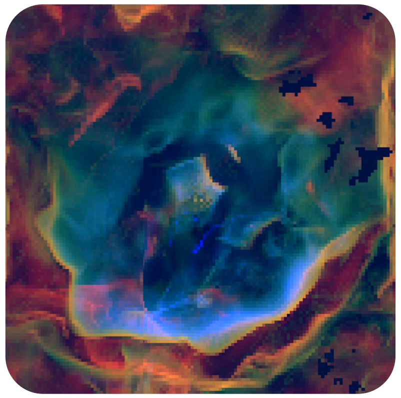

some tools

OPIATE postprocessing

Optimized Postprocessing Iterative Approach to EmissivitieS – V1

OPIATE translates local gas conditions of RMHD into reduced CLOUDY input
Provides new modules to Converts CLOUDY results of local gas into POLARIS input (or RADMC3D)
General frame work to provide a 1:1 match of simulations, microphysics and ray tracing





Radiative MHD
- Radiation
- Density
- Temperatures
- Chemistry
- Dust

OPIATE: RMHD to CLOUDY

Cloudy
- Radiative fluxes
- Complex Chemistry
- Multi-phase ISM
  - Subgrid IF/PDRs
- Excitation
  - Ion
  - Atomic
  - Molecular

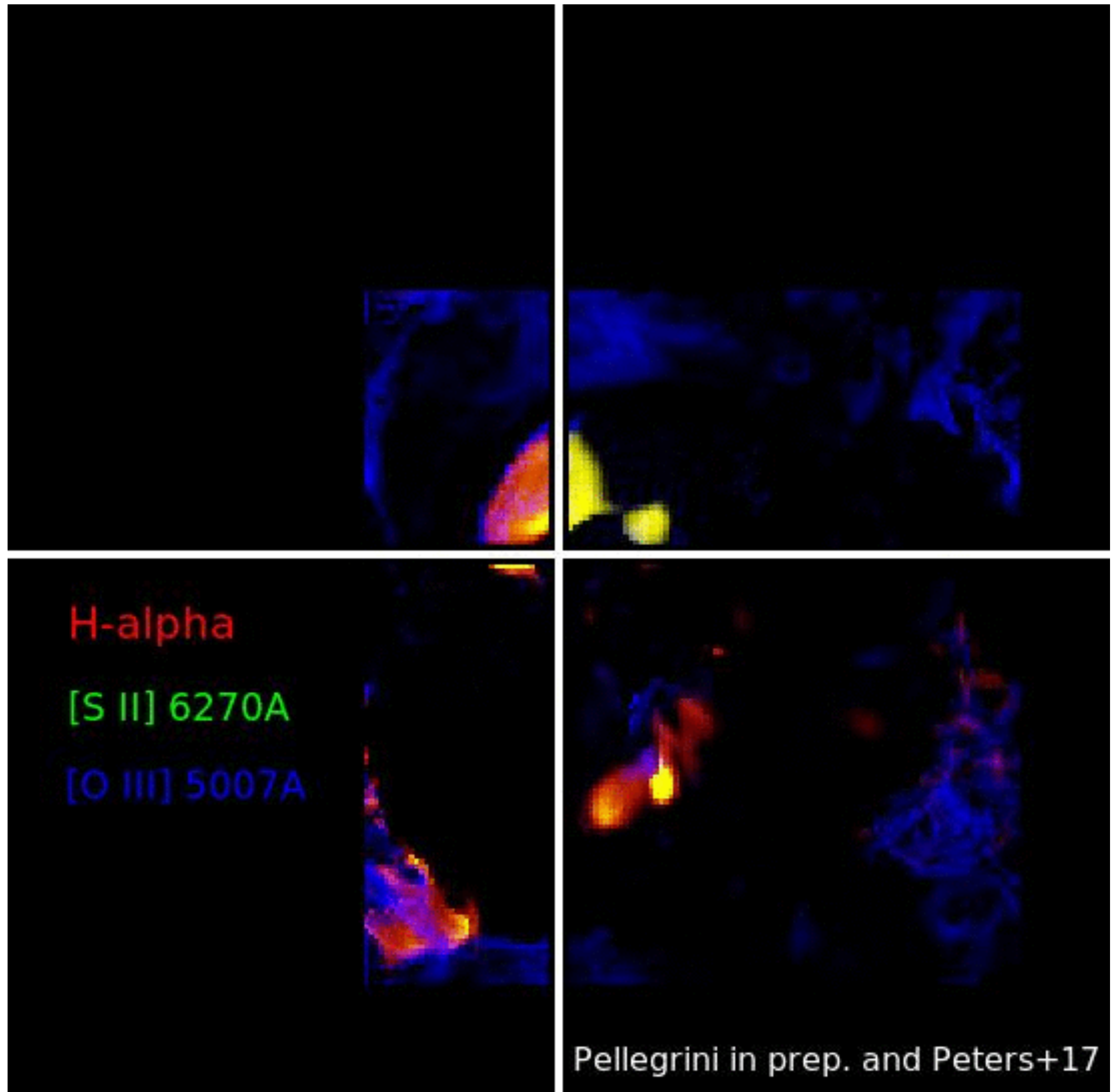
OPIATE: CLOUDY to POLARIS

POLARIS
- Ray tracing
- Monte Carlo of diffuse emission
- Polarization

OPIATE postprocessing

Optimized Postprocessing Iterative Approach to EmissivitieS

Functions to provided for Beginning-to-End processing of simulations
Resulting multi-line fitsCubes directly comparable with velocity resolved IFU data



Optimized Postprocessing Iterative Approach to EmissivitieS

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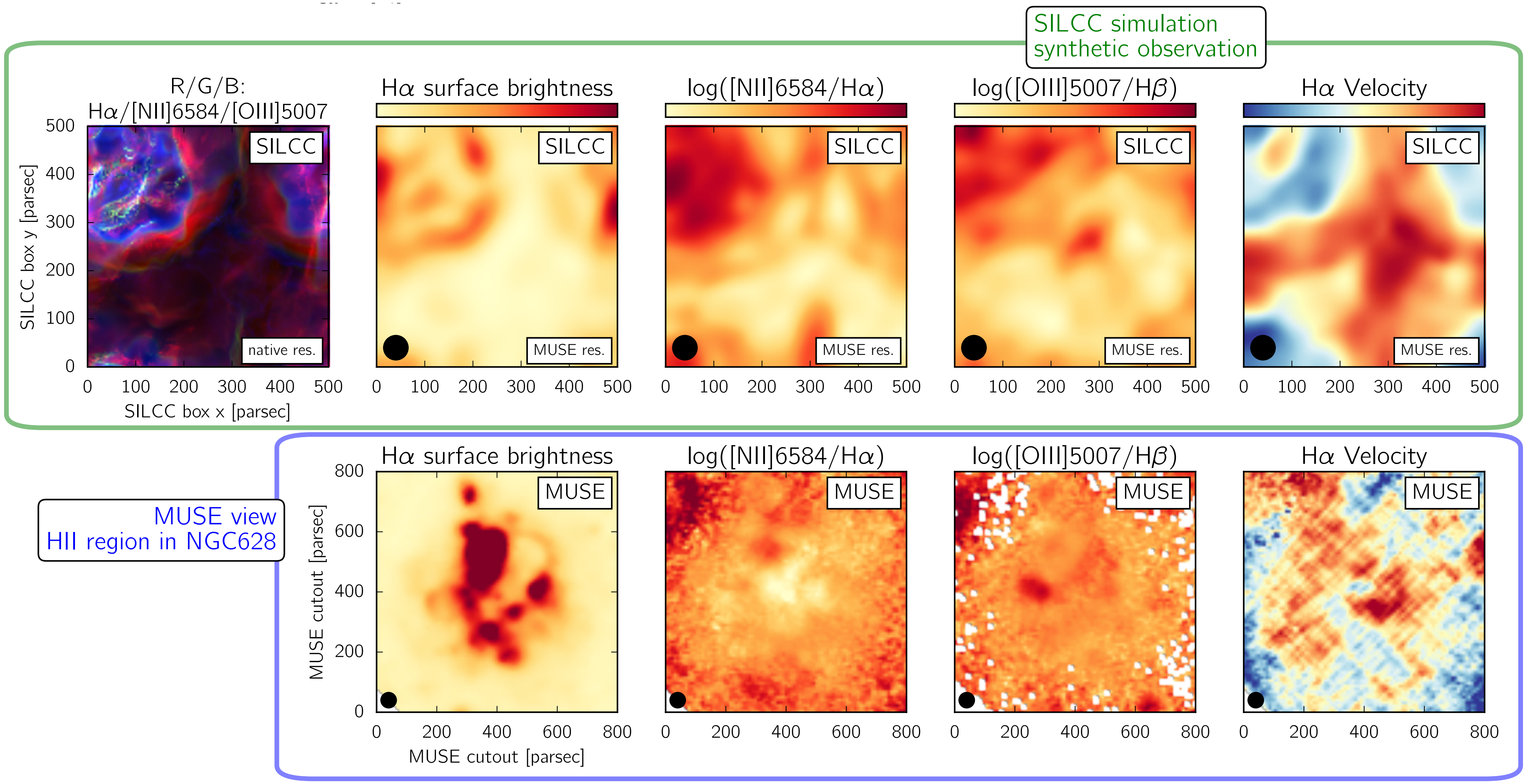

Fig. 3: First comparison between synthetic observation of an simulated HII region complex (SILCC; top row) and that extracted from the MUSE observation of NGC 628 (PI: Kreckel, Blanc; bottom row). Data cubes produced from synthetic observations of SILCC using the new OPIATE software (Pellegrini et al. in prep.) can be directly compared with MUSE data cubes to test the input physics. The SILCC simulation also contains time-domain information. Only one snapshot is presented here. Mock data from simulations of entire galactic disks will be generated by coIs Glover, Klessen and Emsellem.

Polaris postprocessing

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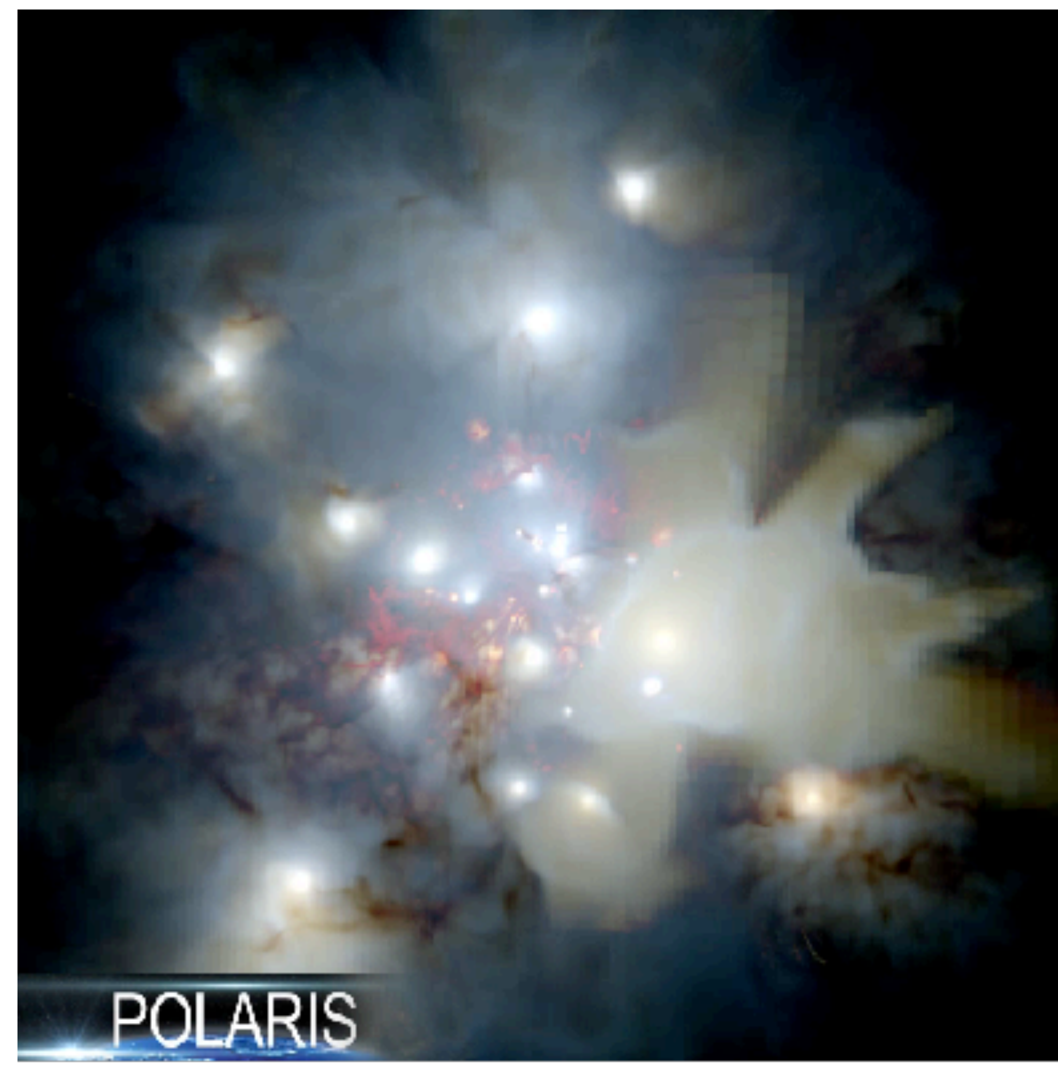
Polaris

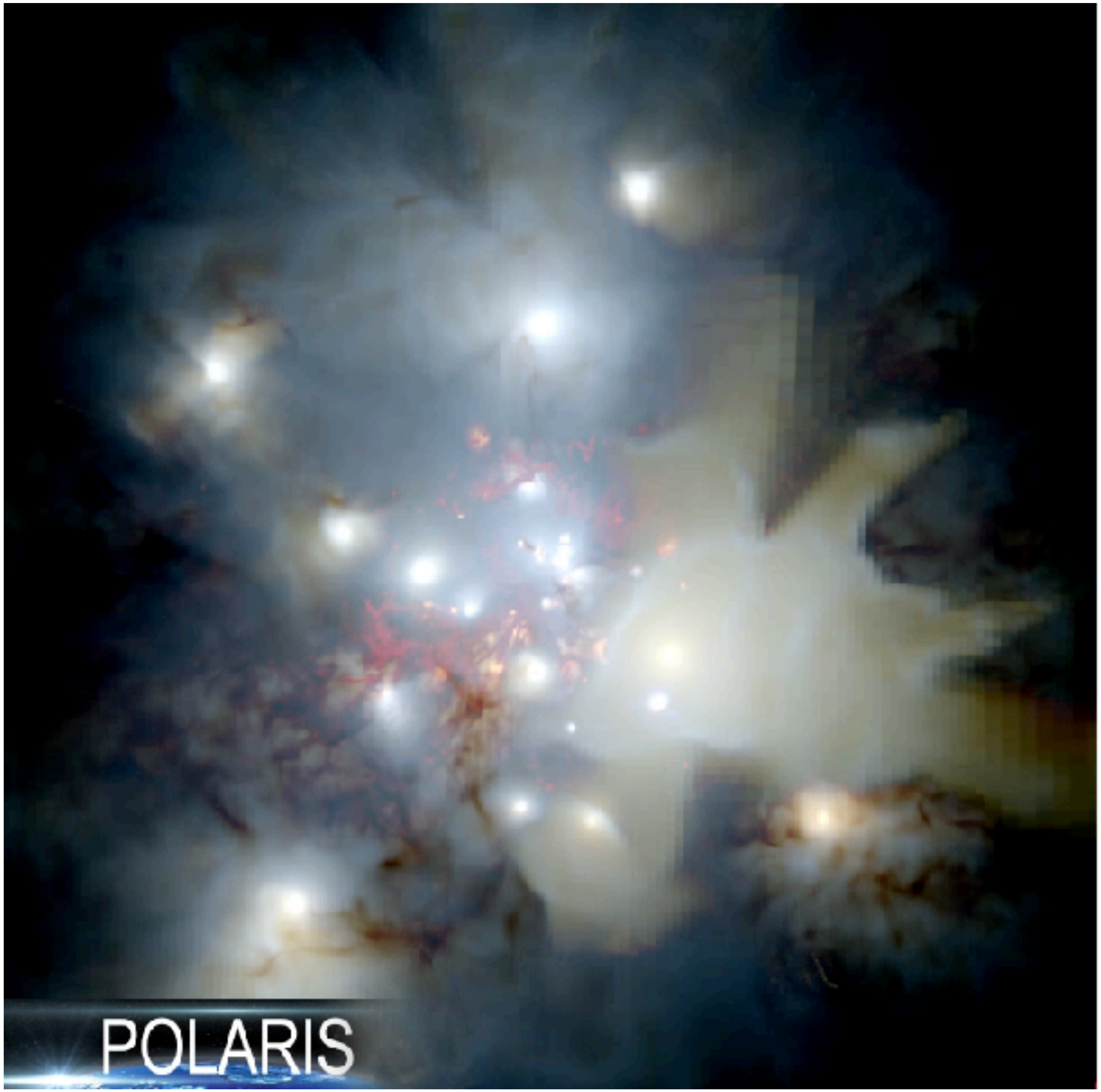
RT tool

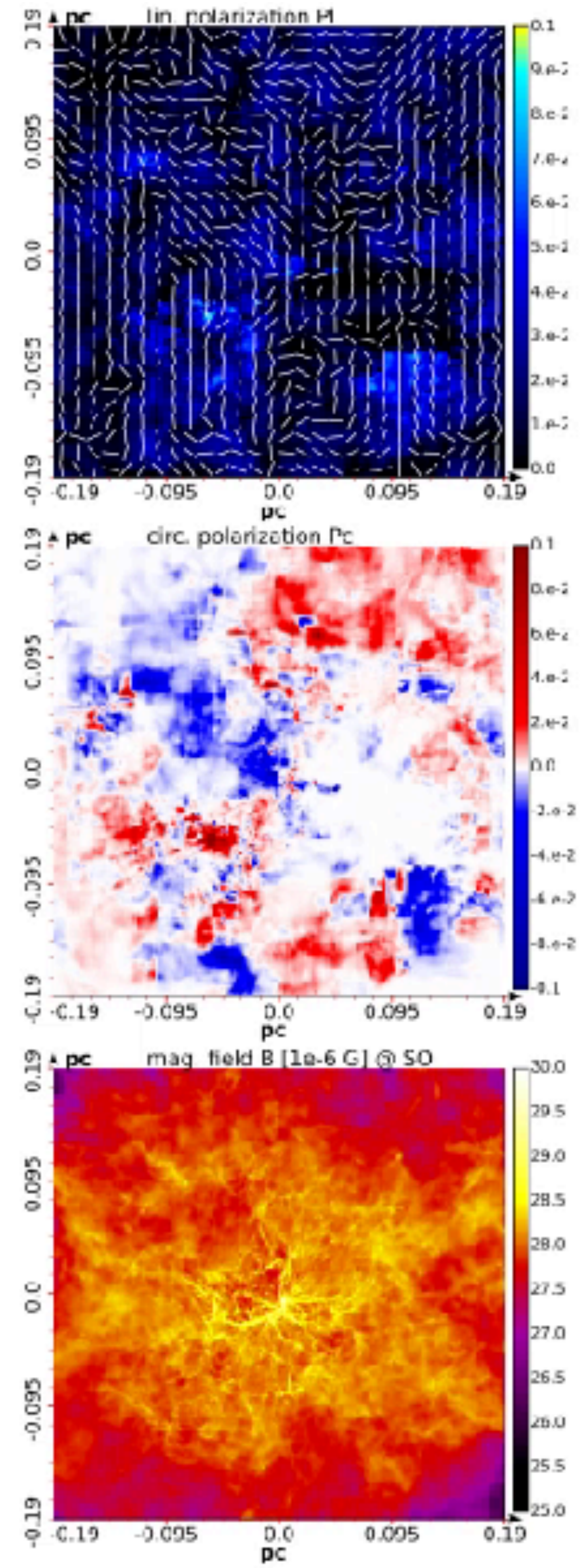
- MC dust heating: Combined heating algorithm of continuous absorption and immediate temperature correction
- Grid: Octree-grid with adaptive refinement
- Polarization mechanism: Dichroic extinction, thermal reemission, and scattering
- Dust grain alignment mechanisms:
  - Imperfect Davis-Greenstein (IDG)
  - Radiative torques (RAT)
  - Mechanical alignment (GOLD)
  - Imperfect internal alignement
  - Independent dust grain composition
- Optimization: Enforced scattering, wavelength range selection, and modified random walk



Polaris website in Kiel: http://www1.astrophysik.uni-kiel.de/~polaris/

Polaris postprocessing





Polaris website in Kiel: http://www1.astrophysik.uni-kiel.de/~polaris/

WARPFIELD

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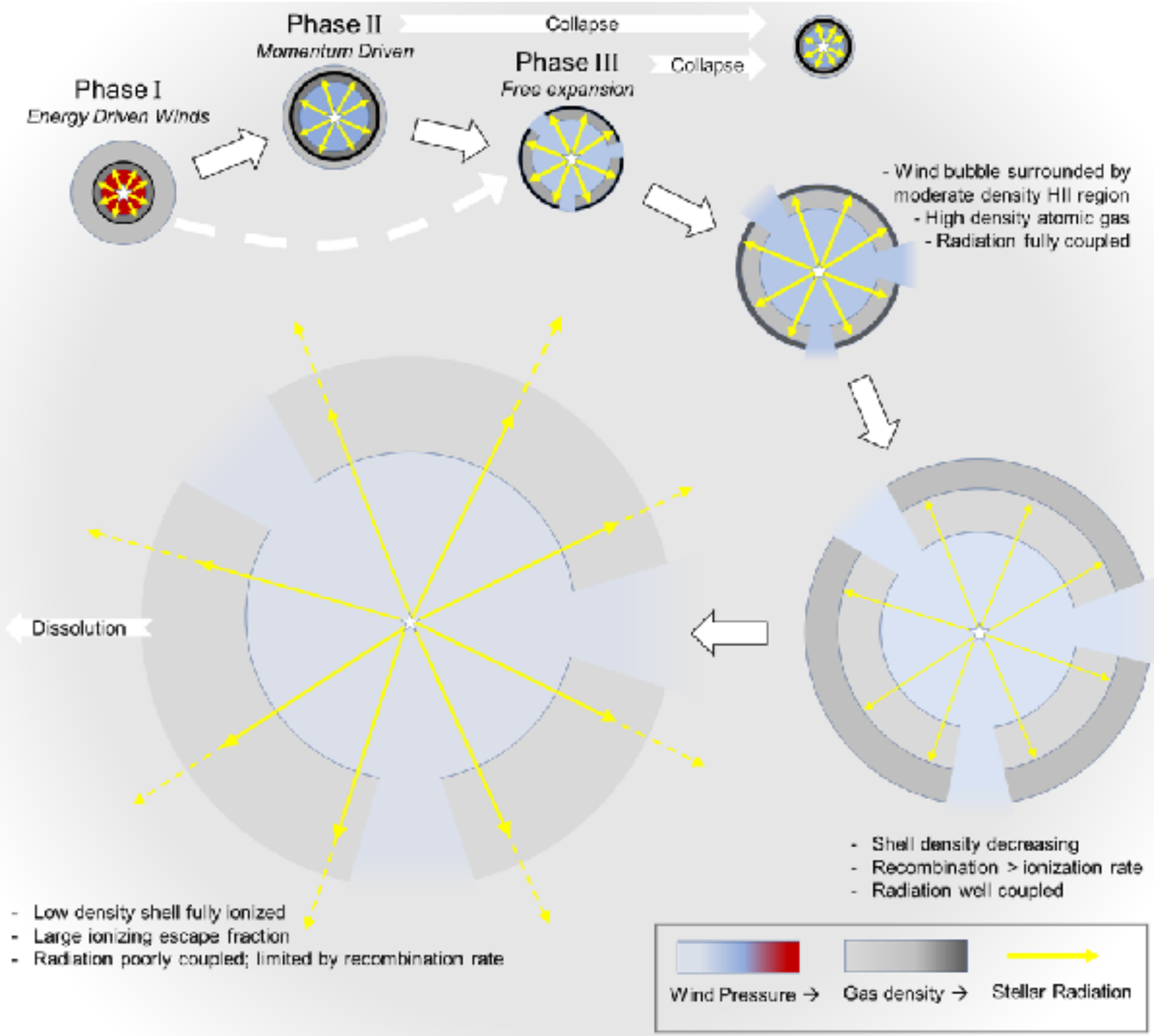
1D cloud/cluster model

WARPFIELD:

- 1D model of cluster embedded in spherical cloud
- starburst99 cluster evolution
- dynamics of think shell is calculated consistently
- with all relevant forms of stellar feedback
- fast, allowing for large parameter studies



Rahner et al. (2017, MNRAS, 470, 4453)

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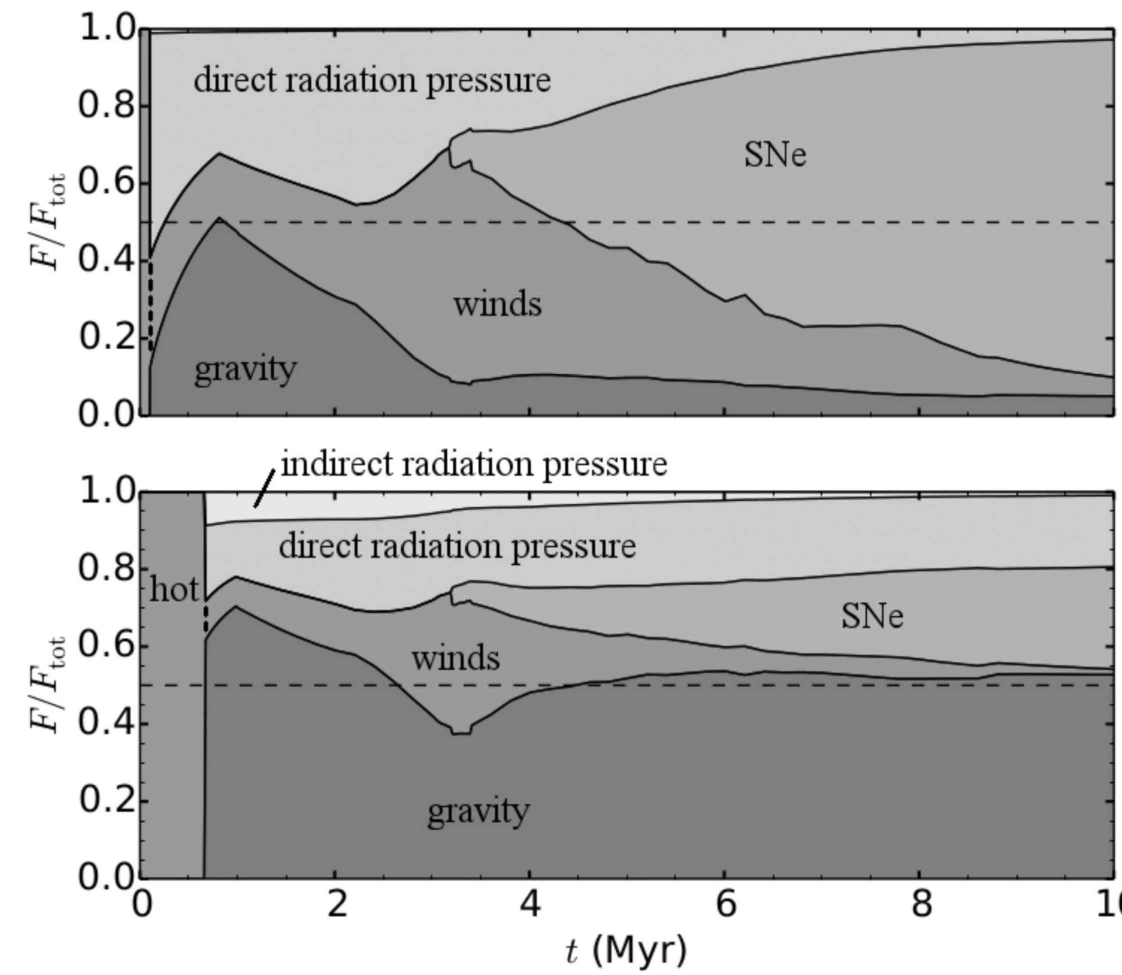

Figure 5. Comparison of relative forces from direct and indirect radiation pressure, winds, SNe, and gravity. If the contribution from gravity is above the 50 per cent margin (dashed horizontal line), the shell loses momentum. *Top*: $M_{\rm cl} = 10^5\,{\rm M}_\odot$, $\epsilon = 0.1$, $Z = {\rm Z}_\odot$, and $n_{\rm cl} = 1000\,{\rm cm}^{-3}$ (same parameters as in Fig. 3). The contribution from indirect radiation pressure fraction is so small, it is barely visible (<1 per cent). *Bottom*: same $n_{\rm cl}$ and Z as in the top panel, but with a higher cloud mass and star formation efficiency ($M_{\rm cl} = 3 \times 10^7\,{\rm M}_\odot$ and $\epsilon = 0.25$). For more information see Section 5.

Rahner et al. (2017, MNRAS, 470, 4453)

WARPFIELD

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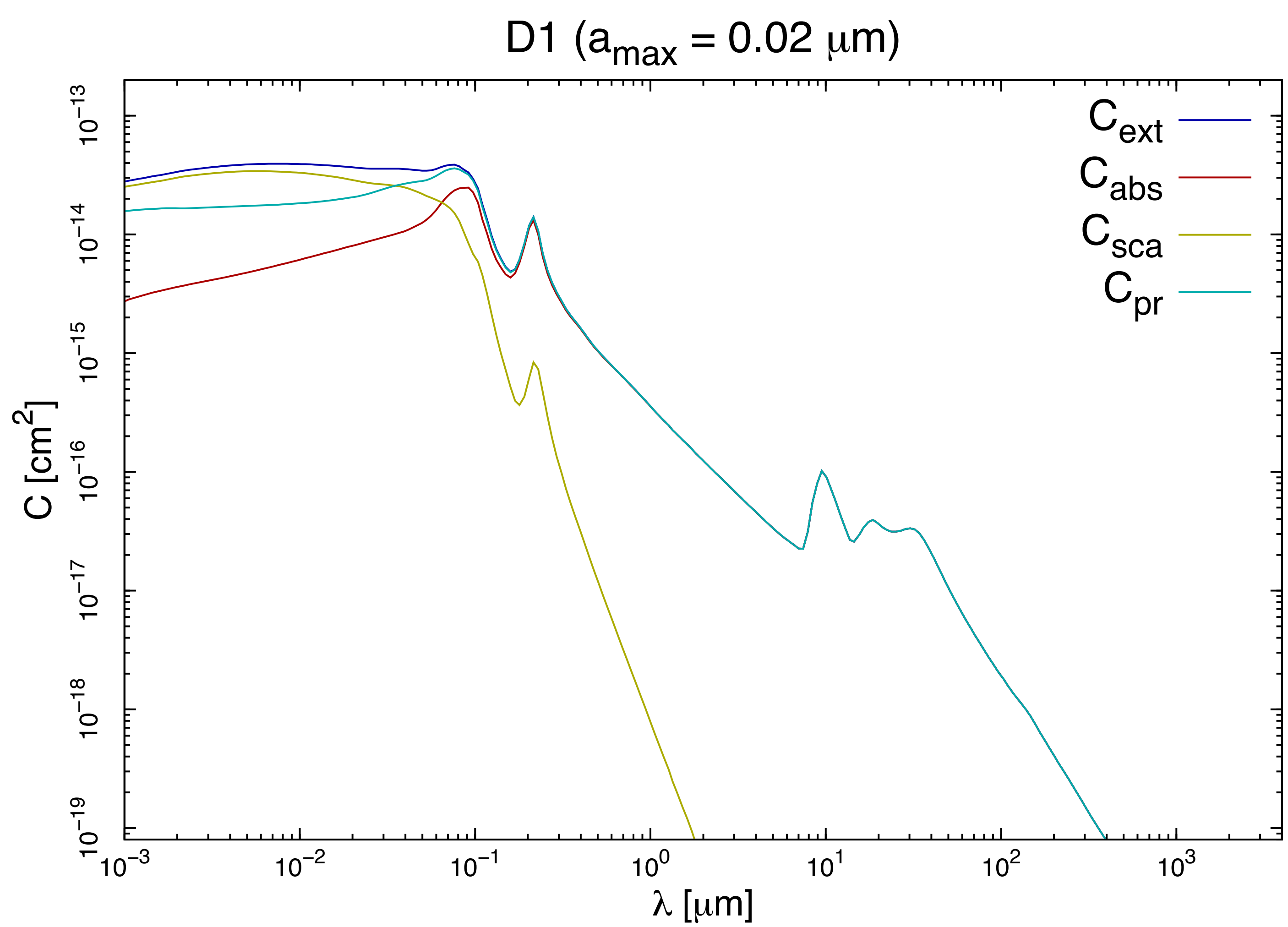
Polaris for microphysics

1D cloud/cluster model

Polaris:
- detailed dust scattering and absorption model
- 120 frequency bin
- Monte Carlo RT



Reissl et al. (2018, A&A in press, arXiv171002854)

Polaris for microphysics

1D cloud/cluster model

Polaris:

- detailed dust scattering and absorption model
- 120 frequency bin
- Monte Carlo RT

—> for Milky Way clouds, radiation pressure is not dominating over gravity!

red: gravity
blue: radiation pressure
purple: ratio

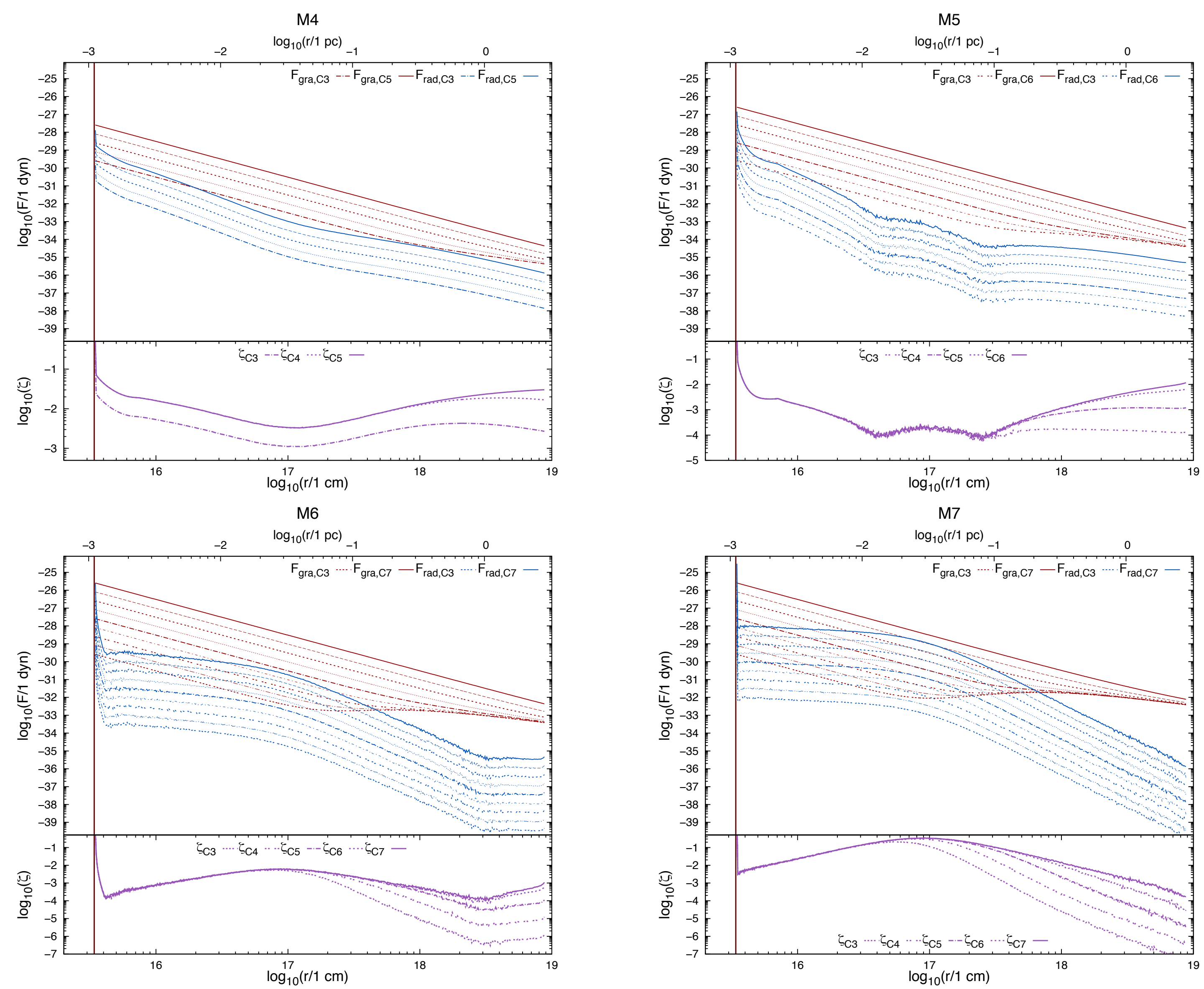


Fig. 5: Gravity (F_{gra}, red lines) in comparison to radiative forces (F_{rad}, blue lines) for models M4 (top left), M5 (top right left), M6 (bottom left), and M7 (bottom right). The ratio of forces is defined as $\zeta = F_{\mathrm{rad}}/F_{\mathrm{gra}}$ (purple lines). All cases have a *constant* dust temperature of $T_{\mathrm{d}} = 20$ K, an outer radius of $R_{\mathrm{out}} = 5$ pc and use dust model D2. Note that $\zeta < 1$ everywhere, implying that radiation pressure does not support the cloud against gravitational contraction. The vertical black line marks the sublimation radius.

Reissl et al. (2018, A&A in press, arXiv171002854)

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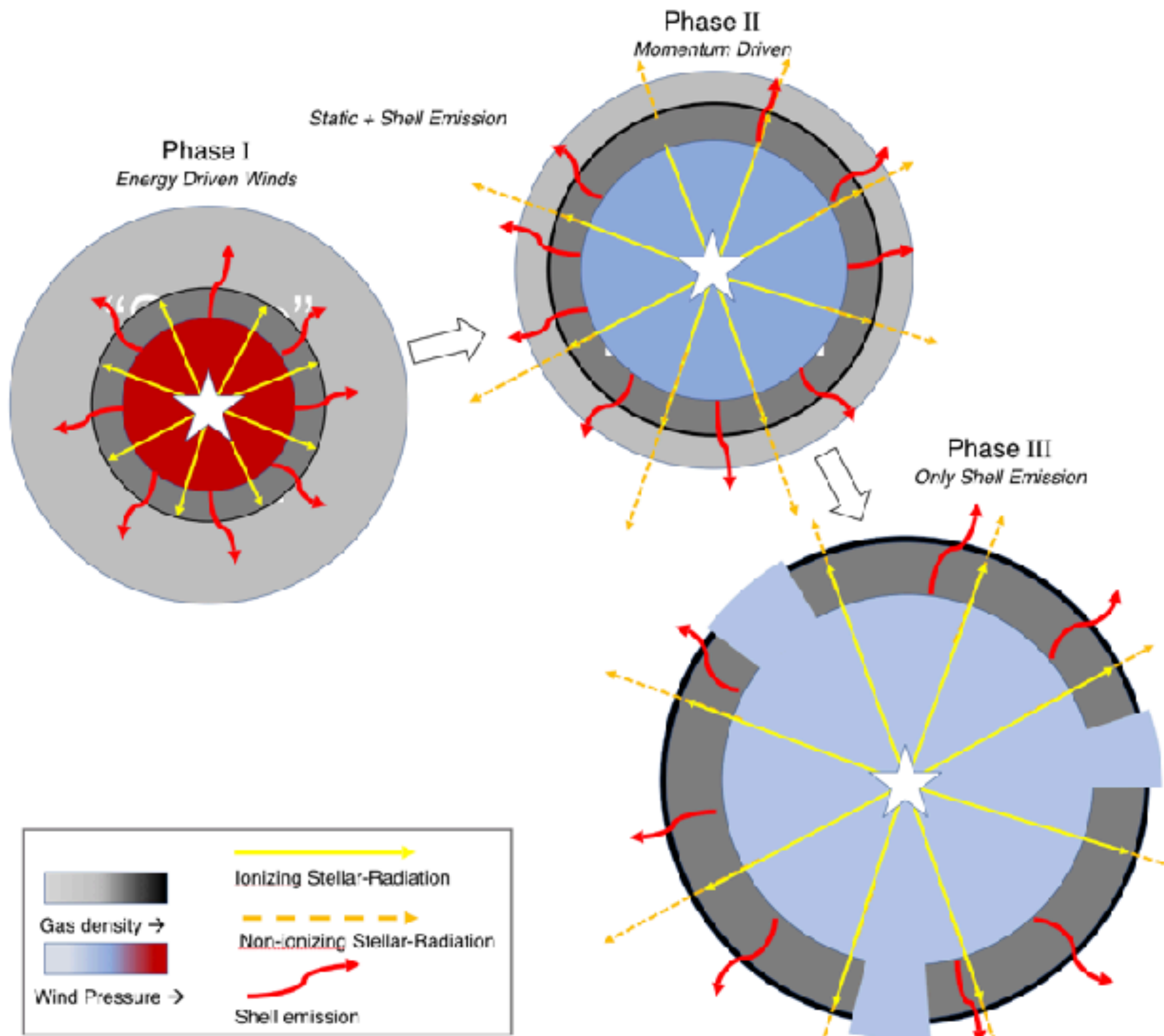
1D cloud/cluster model

WARPFIELD-EMP:
- 1D model of cluster embedded in spherical cloud
- starburst99 cluster evolution
- dynamics of think shell is calculated consistently
- with all relevant forms of stellar feedback
- fast, allowing for large parameter studies
- coupled to CLOUDY and 1D RT
- many different emission diagnostics

work by Daniel Rahner, Eric Pellegrini



Pellegrini et al. (2018, to be submitted)

WARPFIELD-EMP

synthetic BPT diagrams

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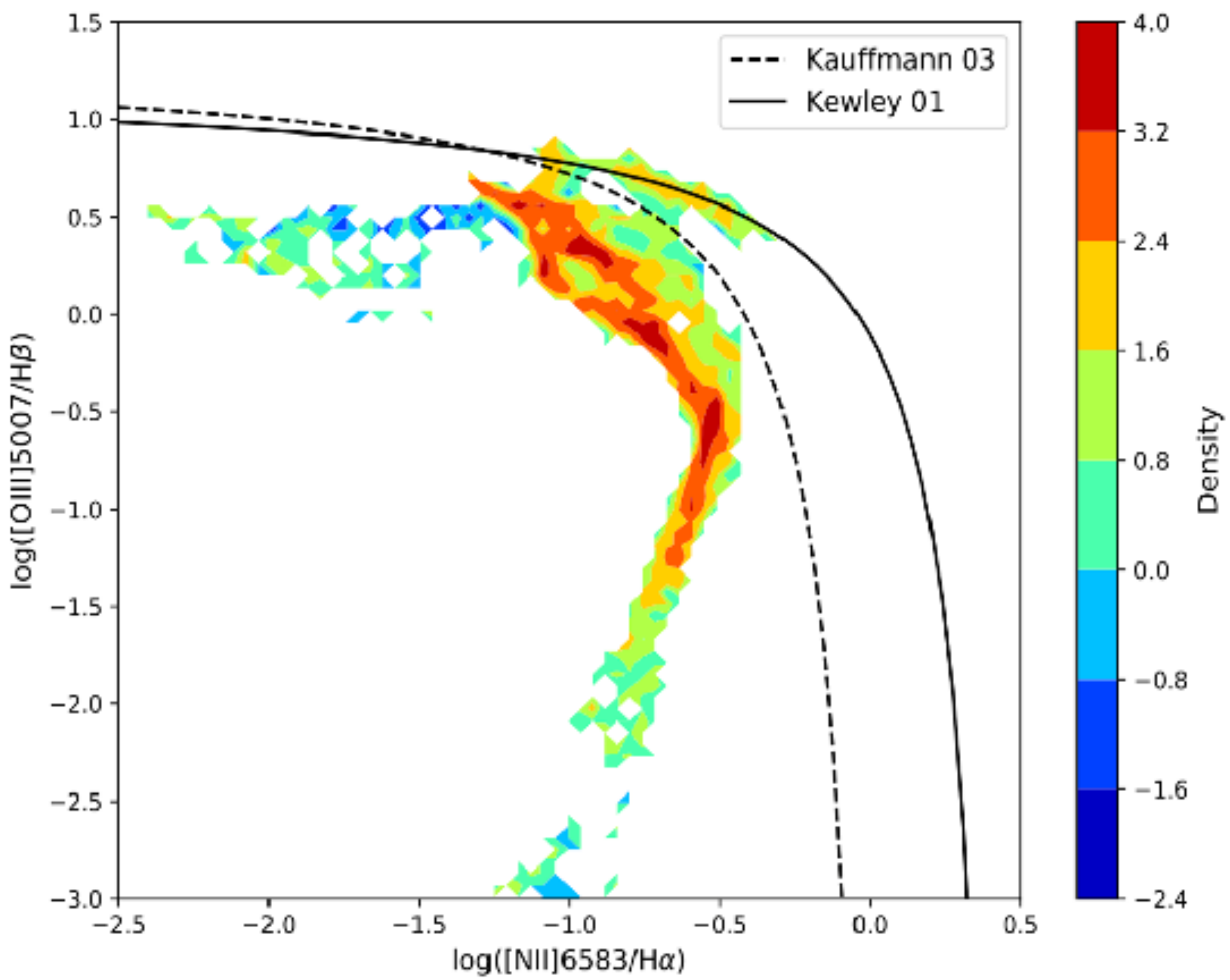
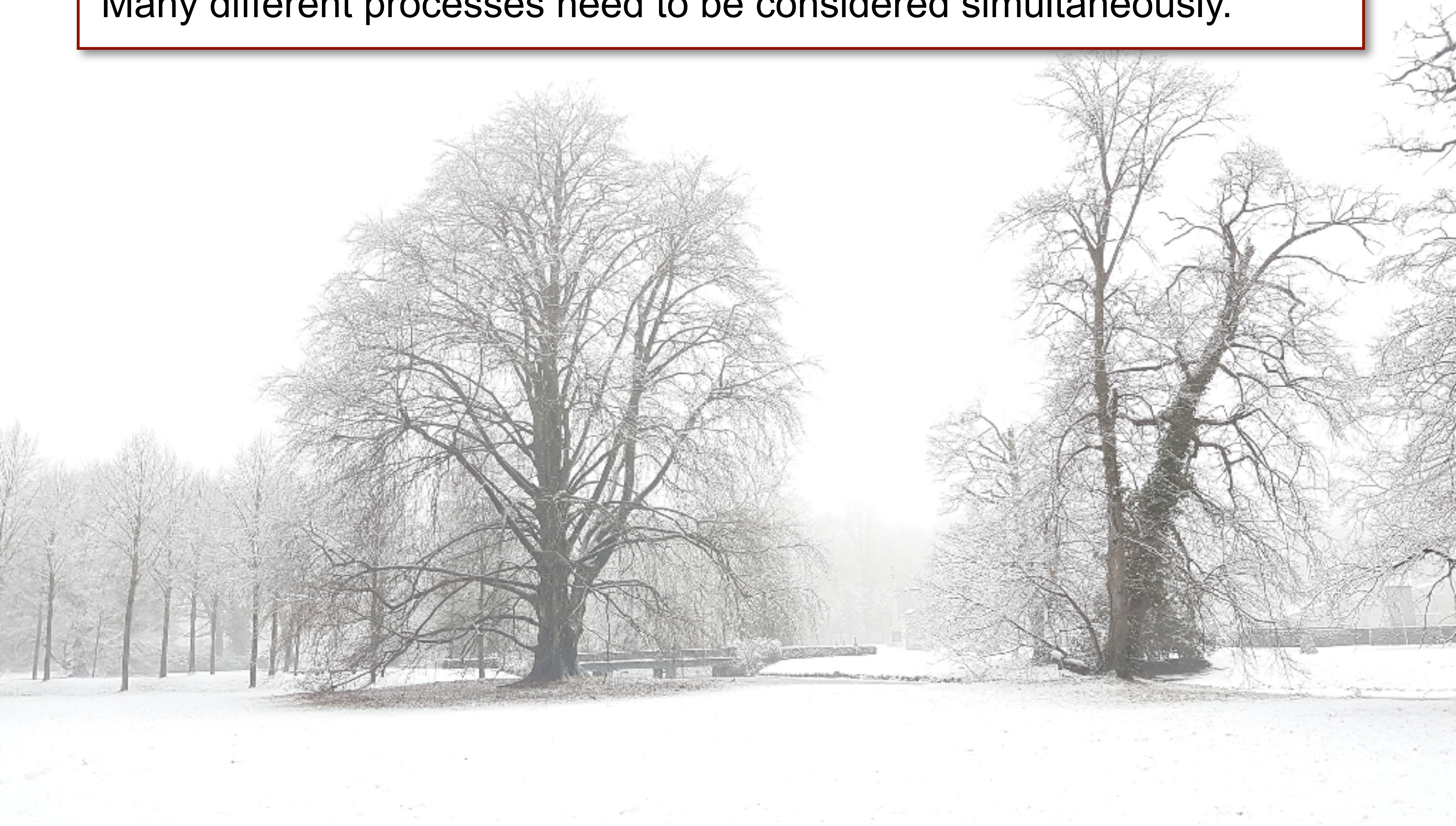


- heat diagram of synthetic BPT diagram for a (small) sample of cluster/cloud models at different ages

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



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

- 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
- **tools** for postprocessing simulations and for interpreting observations are available: **Polaris, OPIATE, WARPFIELD-EMP**