Simulating Star Formation - an overview from the basics to the state-of-the-art -

Stefanie Walch
Universität zu Köln
Theoretische Astrophysik

GISM2
Banyuls-sur-mer
28.07.2023

Outline of the following lecture

1. Introduction: cores, disks, multiplicity and stellar initial mass function (IMF)
2. Fragmentation: Jeans mass & core fragmentation, disk fragmentation
3. Other physical processes shaping prestellar cores (magnetic fields, turbulence)
4. How to model star formation (also issues with resolution)
5. Initial conditions and their impact (density profiles, turbulence)
6. Stellar feedback
7. Getting the IMF and star formation efficiency in cores

Outline of the following lecture

1. Introduction: cores, disks, multiplicity and stellar initial mass function (IMF)
2. Fragmentation
3. Other physical processes shaping prestellar cores (magnetic fields, turbulence)
4. How to model star formation (also issues with resolution)
5. Initial conditions and their impact (density profiles, turbulence)
6. Stellar feedback
7. Getting the IMF and star formation efficiency in cores

Nearest GMC:
Orion Nebula
d ~ 1500 ly, i.e. 450 pc

l ~ 8pc
m ~ 2000 M_{sun}

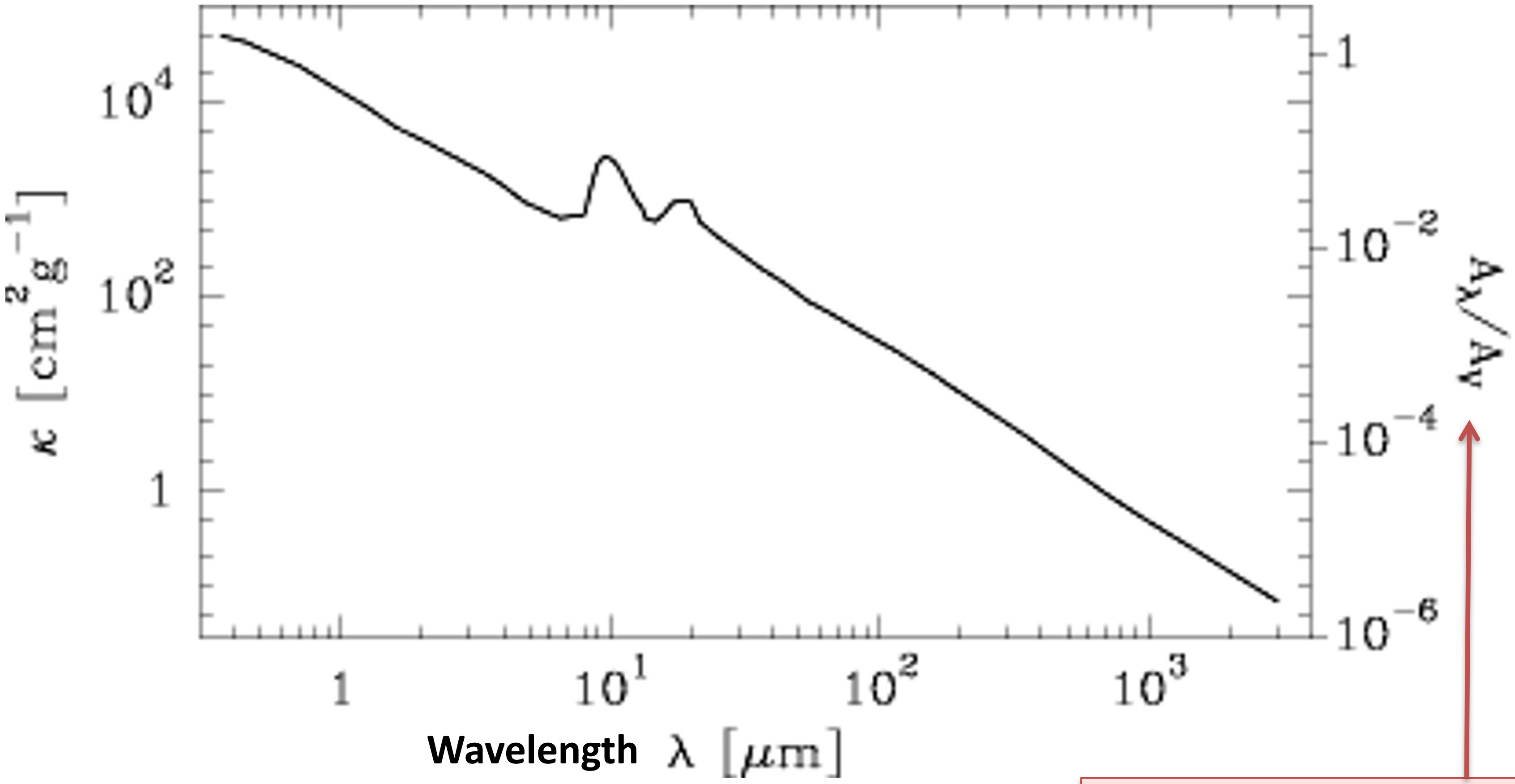
“Star factory”

Hubble Space Telescope
image of the
Orion Nebula
(visible light)

Dark dust lanes

Trapezium cluster

Interstellar extinction of light



Extinction normalized to visual extinction

Orion in the
INFRARED

Spitzer Space Telescope
IRAC

Credit:
NASA/ JPL Caltech/
T. Megeath (University
of Toledo) & M.Robberto
(STScI)

Star formation in a nutshell

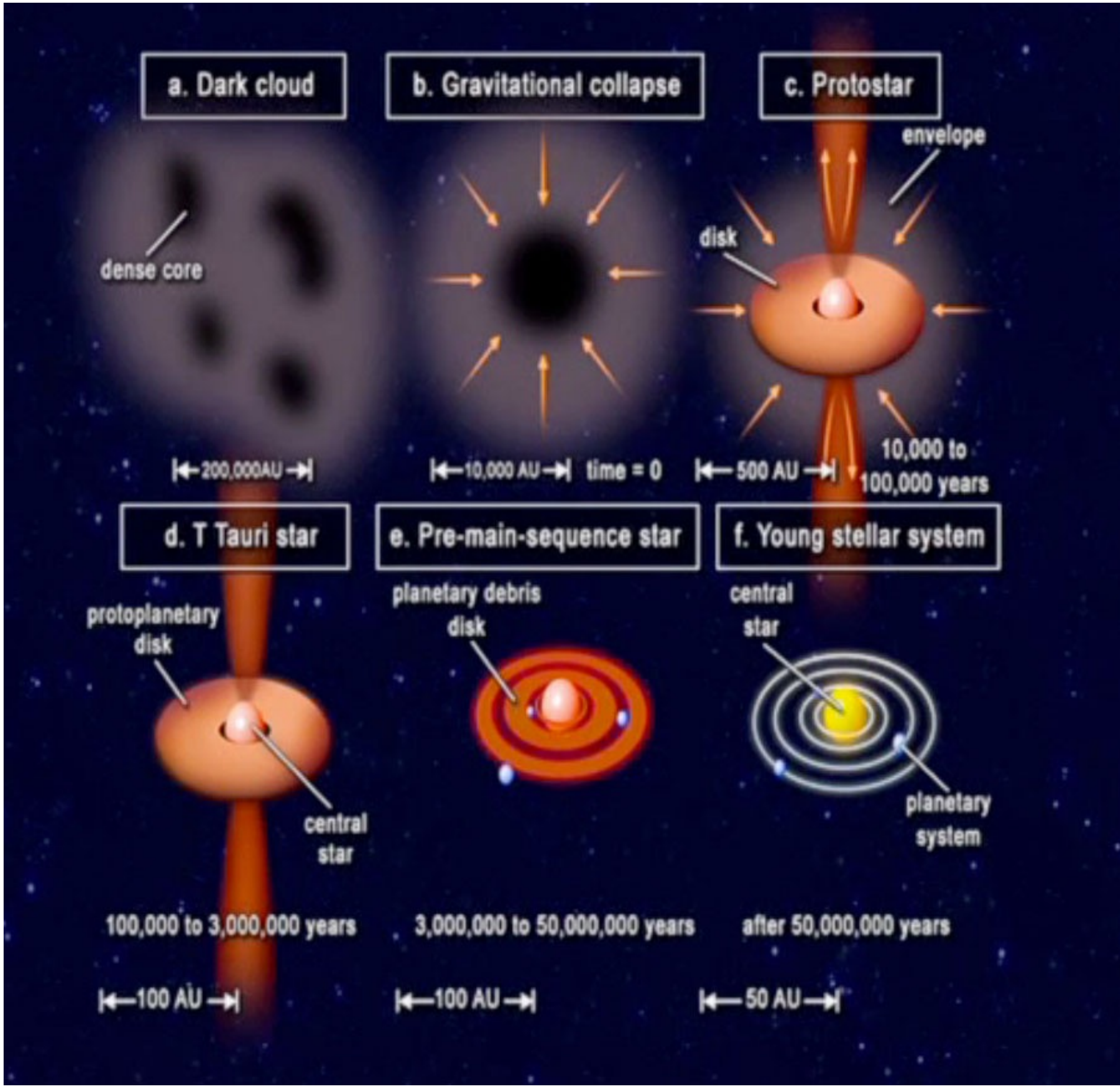
-> Cold & dense gas clouds become self-gravitating

-> Collapse & Star formation

-> Change in length scale during collapse:
core: 0.1 pc (3×10^{17} cm) =>
disk: 100 AU (1.5×10^{15}cm) =>
first core: < 1 AU (1.5×10^{13}cm) =>
star: stellar radius ($\sim10^{11}$ cm)

-> Change in density during collapse:
core: $10^{-18} - 10^{-20}$ g/cm^3 =>
first core: $>10^{-12}$ g/cm^3 =>
star: ~ 10^{0} g/cm^3 =>

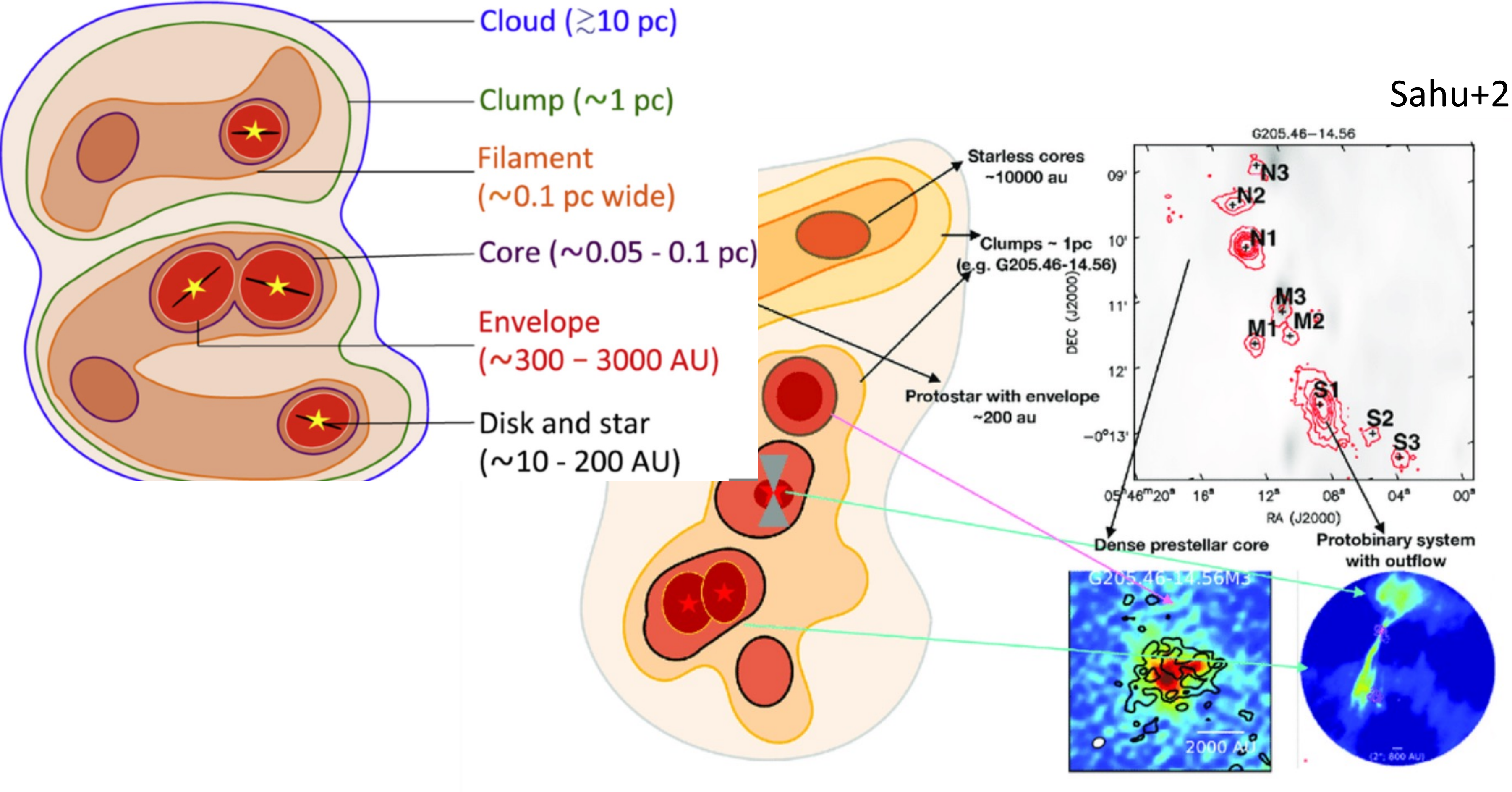
Massive stars (> 8 $M_\odot$) are rare!
~ 1 massive star per 100 $M_\odot$ of gas that forms stars



Problyds in Orion with HST

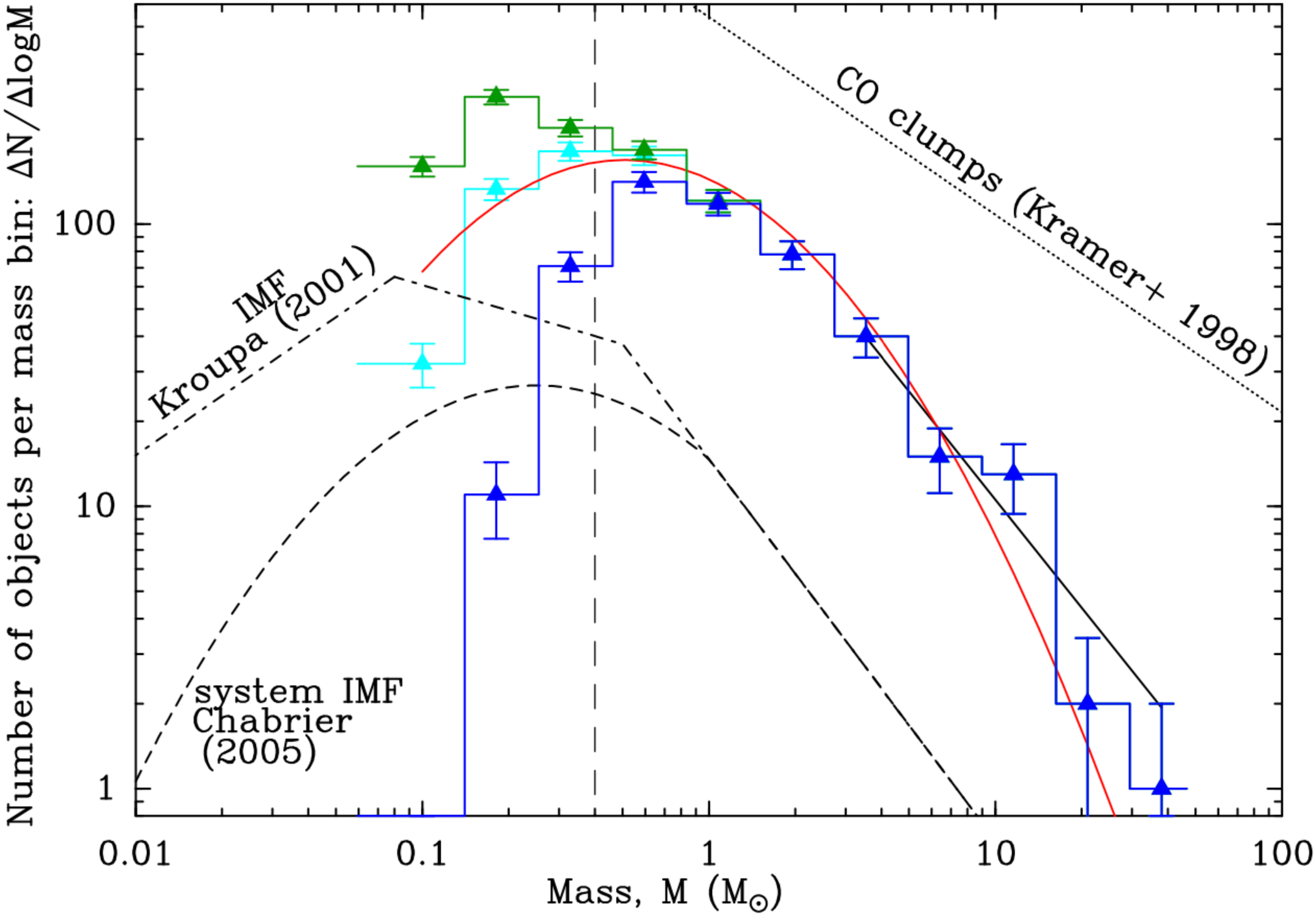
Star formation in dense cores which are embedded in clumps/ filaments / clouds

Sahu+2021



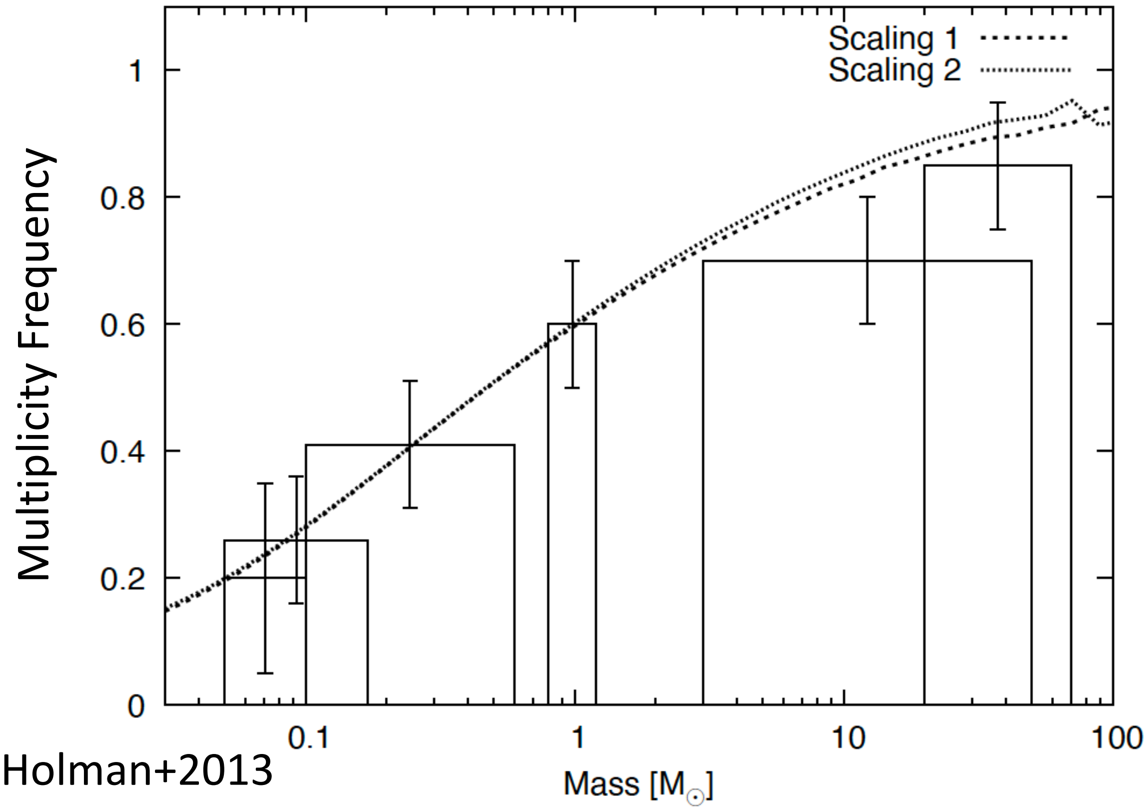
| The cartoon depicts how clumps to cores with hierarchical structures were observed in the ALMASOP survey. Red contours are cores of a PGCC, which were observed with JCMT (Yi et al., 2018) ~ 6,000 au resolutions. The cores were observed in detail with ALMA and revealed embedded protostars with multiplet and dense prestellar cores (Dutta et al., 2020; Sahu et al., 2021).

Core mass function in Orion & Stellar IMFs



Könyves+2020 Starless cores, candidate prestellar, robust prestellar cores, lognormal fit

Stellar multiplicity



Holman+2013

Fig. 4. The boxes represent the observational estimates of multiplicity frequency in different primary-mass intervals, due to Close et al. (2003); Basri & Reiners (2006); Fischer & Marcy (1992); Duquennoy & Mayor (1991); Preibisch et al. (1999); Mason et al. (1998). The error bars represent the observational uncertainties. The dashed and dotted line shows the multiplicity frequency as a function of primary mass for the best-fit models with $\mu_c = 0.0$ and – respectively – Scaling I and Scaling II; the noisy points at large and small M_1 are due to poor statistics.

Multiplicity frequency:

$$b_i = \frac{\mathcal{P}_i}{\mathcal{S}_i + \mathcal{P}_i}\,.$$

e.g. Hubber & Whitworth (2005)

i : bin number

P: number of primaries

S: number of singles

$\Rightarrow$ No dependence on higher-order multiples

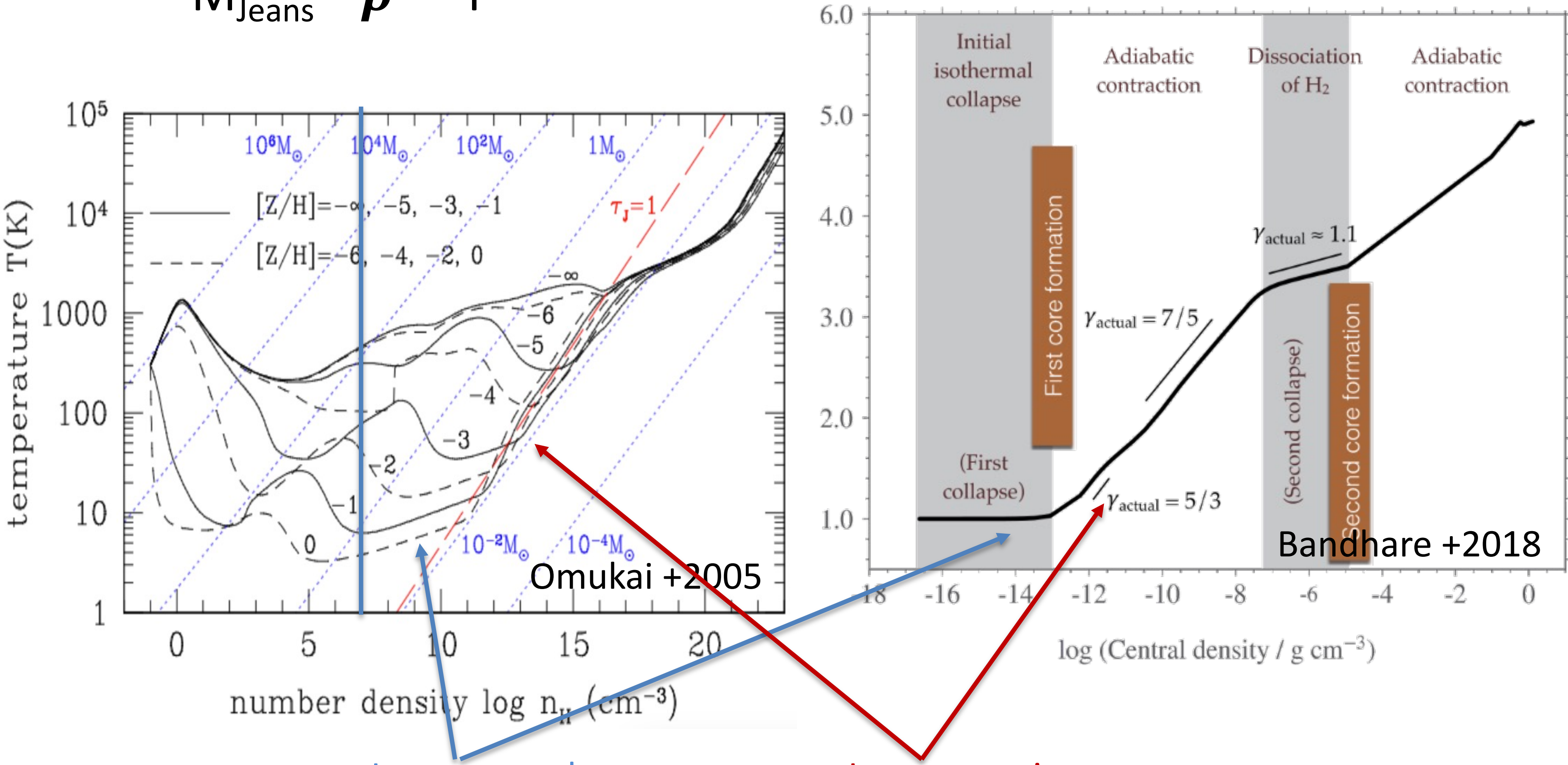
Stellar multiplicity frequency increases with stellar mass!

Outline of the following lecture

1. Introduction: cores, disks, multiplicity and stellar initial mass function (IMF)
2. Fragmentation: Jeans mass & core fragmentation, disk fragmentation
3. Other physical processes shaping prestellar cores (magnetic fields, turbulence)
4. How to model star formation (also issues with resolution)
5. Initial conditions and their impact (density profiles, turbulence)
6. Stellar feedback
7. Getting the IMF and star formation efficiency in cores

Fragmentation: Jeans mass

$M_{Jeans} \sim \rho^{-1/2} T^{3/2}$



Omukai +2005

Bandhare +2018

Jeans mass decreases

Jeans mass increases

Once the gas becomes optically thick in the infrared, T increases and M_{Jeans} increases

$\Rightarrow$ Minimum M_{Jeans} at the “opacity limit” is ~0.01 $M_\odot$

$\Rightarrow$ 20-30x lower than the peak of the stellar IMF (Low & Lynden-Bell, 1976)

Fragmentation: Disk fragmentation

Disk stability analysis: Toomre parameter Q: $$Q = \frac{c_s \kappa}{\pi G \Sigma}$$

Based on thin disk model

For Keplerian disk: $Q \approx 2 \frac{M_*}{M_d} \frac{H}{r}$ with $H = c_s / \Omega$

Spiral arms are signs of gravitational instability, but can also be triggered by perturbations (e.g. stellar companions)

Density in spiral arms highest => prone to gravitational instability

$\Rightarrow$ Disk fragmentation

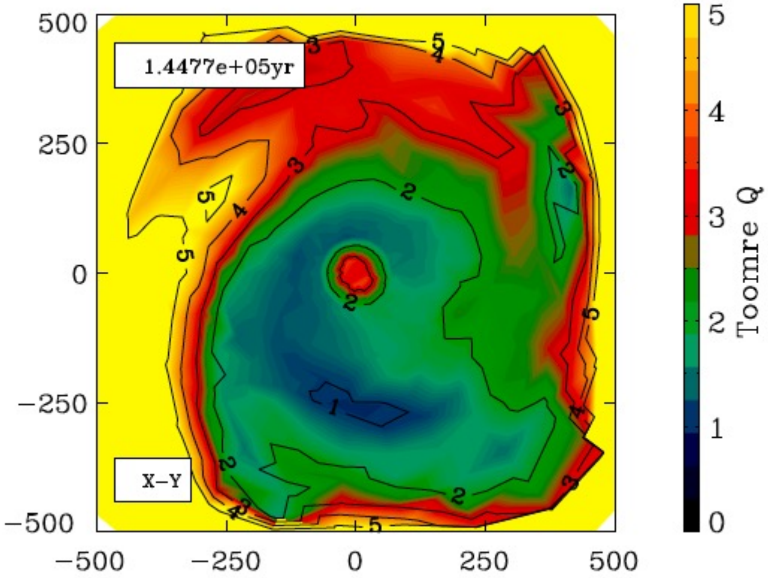
$\Rightarrow$ Often formation of brown dwarfs

$\Rightarrow$ Still unclear whether brown dwarfs can form "in isolation"

Also:

Angular momentum redistribution due to gravitational torques

=> Promoting accretion onto the central star



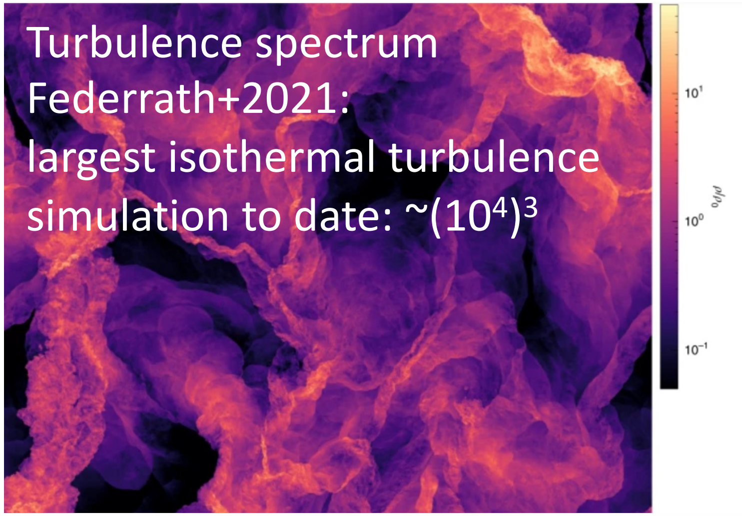
From Walch+2010

Outline of the following lecture

1. Introduction: cores, disks, multiplicity and stellar initial mass function (IMF)
2. Fragmentation
3. Other physical processes shaping prestellar cores (magnetic fields, turbulence)
4. How to model star formation (also issues with resolution)
5. Initial conditions and their impact (density profiles, turbulence)
6. Stellar feedback
7. Getting the IMF and star formation efficiency in cores

Perturbations?
Turbulence in star forming cores

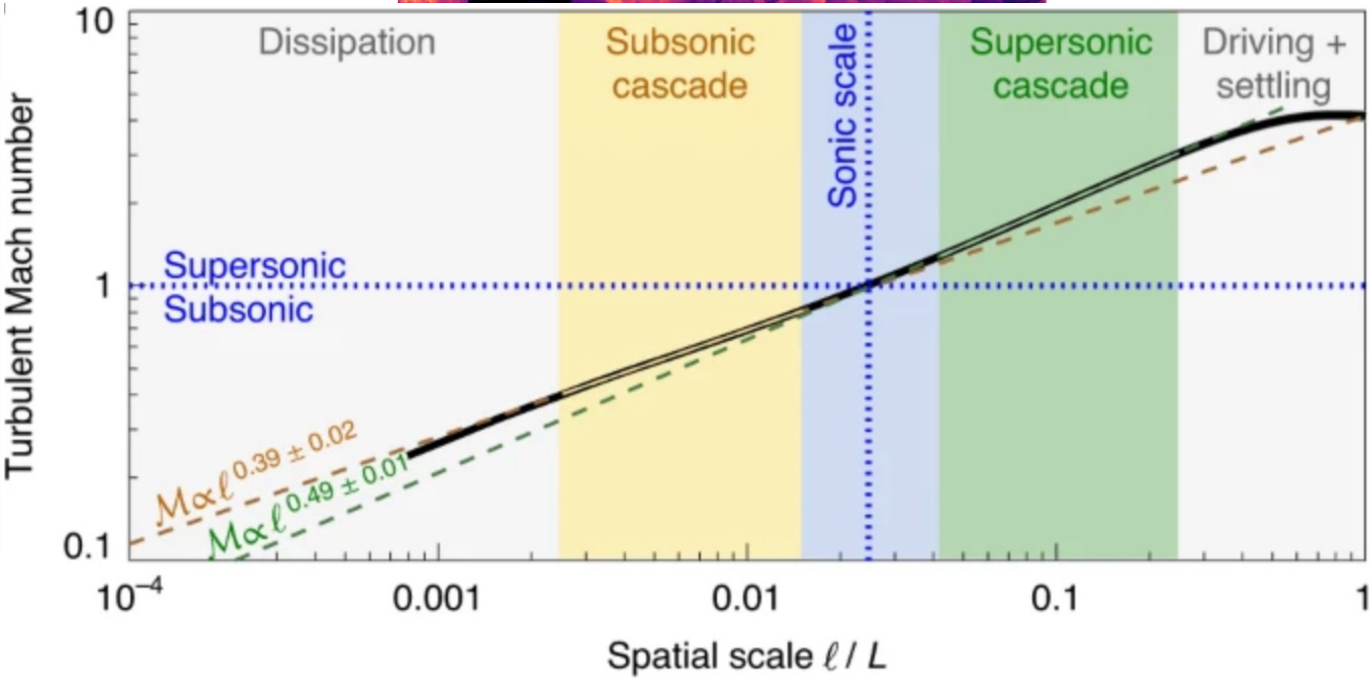
Turbulent motions



Turbulence spectrum Federrath+2021:
largest isothermal turbulence simulation to date: ~$(10^4)^3$

Interstellar gas turbulence is generally supersonic!

The cores condense out of a lower density medium and are therefore perturbed on large scales!

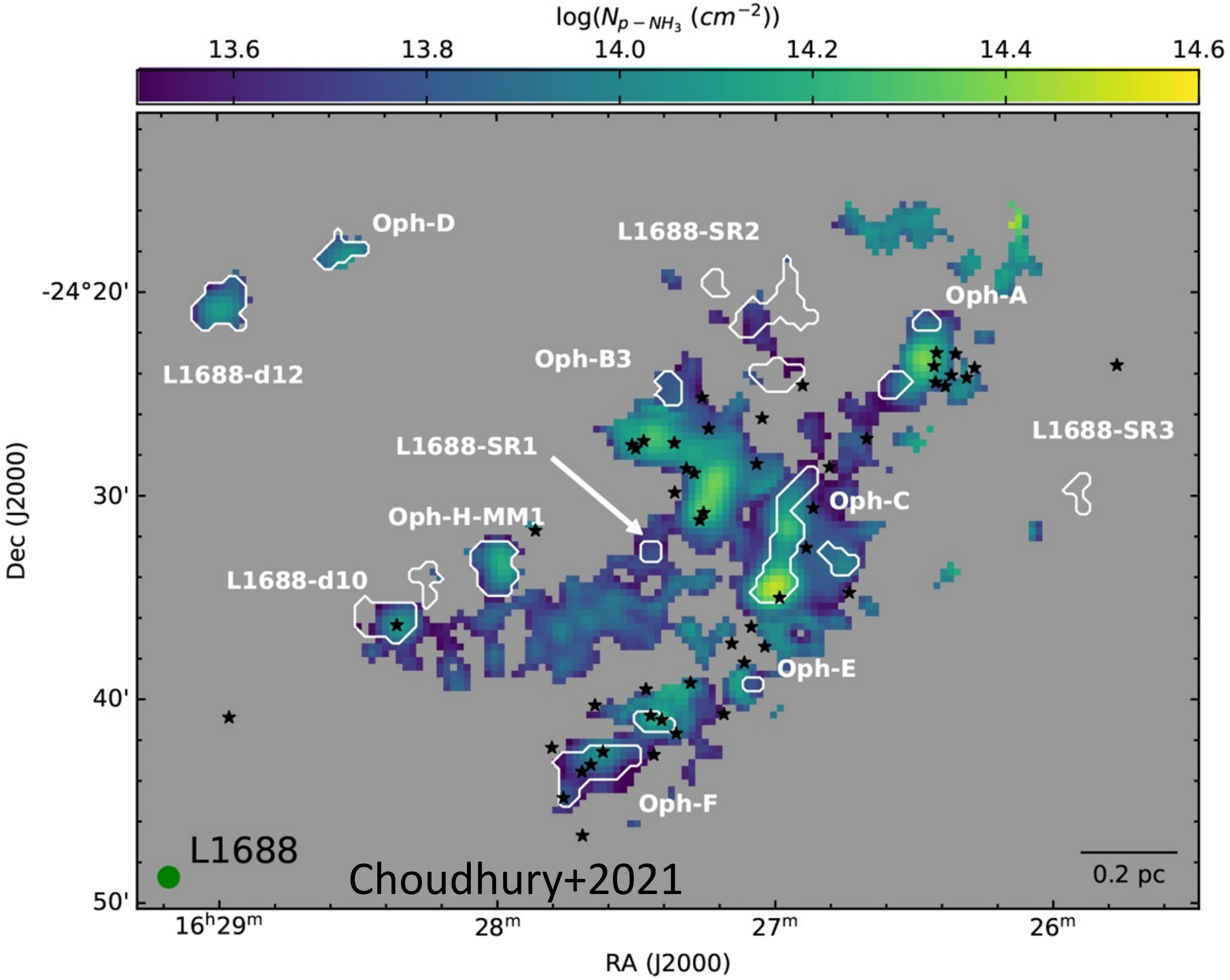


Transition to coherence

Observations:
non-thermal vs thermal linewidths

Cores seem to be islands of coherent motion (sub-thermal turbulence), see e.g.,
Goodman+1998
Pineda+2010
Chen+2019
Choudhury+2021

Turbulence also causes angular momentum!



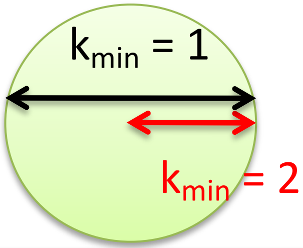
Choudhury+2021

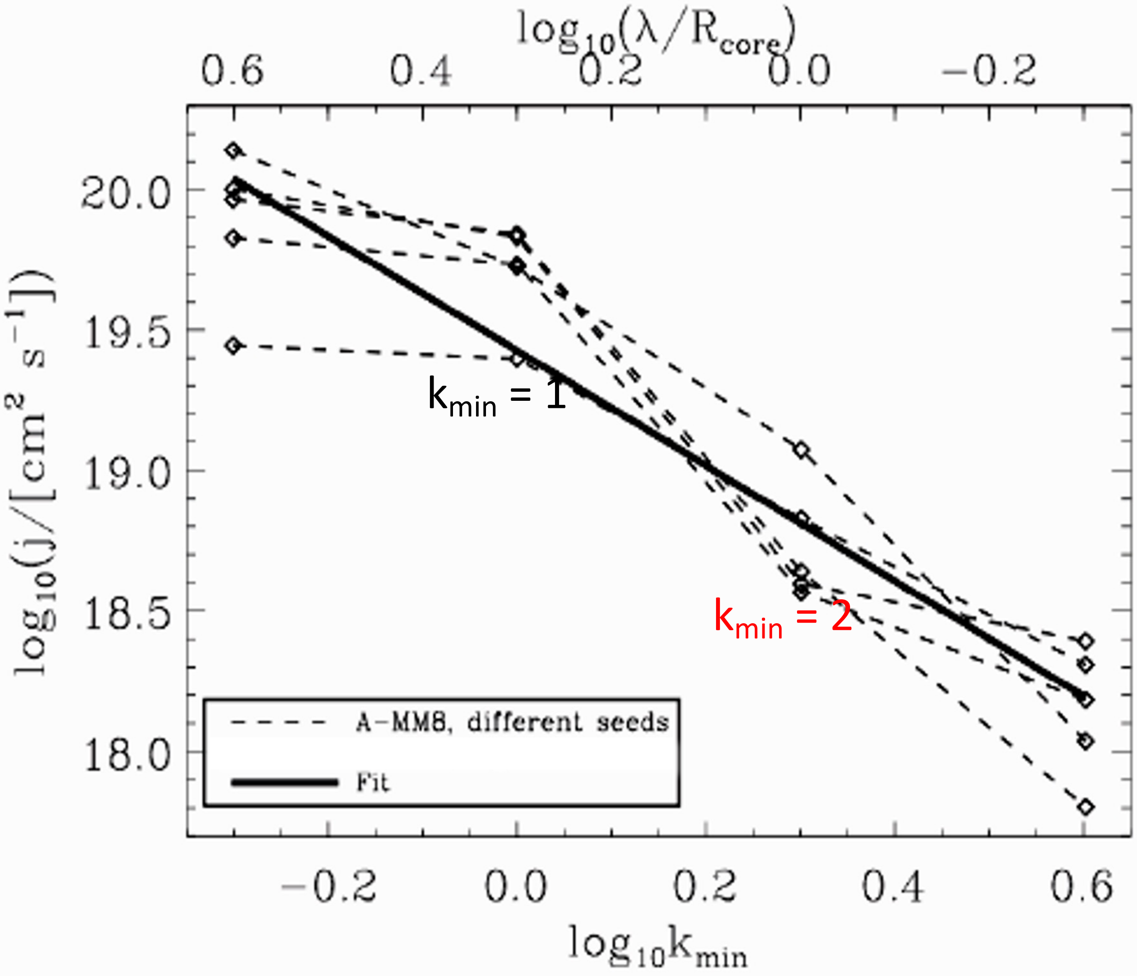
Turbulence scale and angular momentum

Turbulent motions

In interstellar gas
turbulence is supersonic!

The cores condense out of a
lower density medium and are
therefore perturbed on large scales!





$$j_{\mathrm{CORE}} \simeq 4\times10^{19}\,\mathrm{cm}^2\,\mathrm{s}^{-1}\,k_{\mathrm{MIN}}^{-2}$$

Magnetic fields

Critical mass-to-flux ratio of cores (based on uniform density):
$$\left.\frac{M}{\Phi_B}\right|_{\mathrm{mag,crit}} \equiv \frac{1}{2\pi\sqrt{G}}$$

Magnetic Jeans mass (spherical):
e.g. Chen & Ostriker (2014)

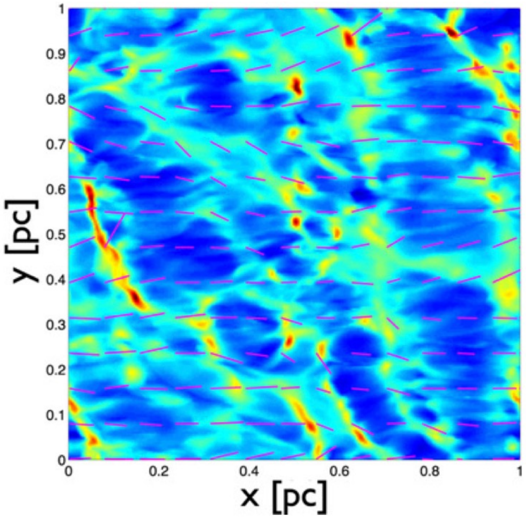
$$M_{\mathrm{mag,sph}} = \frac{9}{128\pi^2 G^{3/2}}\frac{B^3}{\rho^2}$$
$$= 14\,M_\odot\left(\frac{B}{10\,\mu\mathrm{G}}\right)^3\left(\frac{n}{1000\,\mathrm{cm}^{-3}}\right)^{-2}$$

Subcritical: magnetic field important
Supercritical: magnetic field small

Interesting result: Priestley+2022
Testing criticality with molecular gas chemistry

- Molecules that freeze-out (e.g., CS, HCN) have lower line intensities in subcritical cores due to longer collapse times
- Also, line widths in subcritical cores are more narrow

$\Rightarrow$ Better fit to observations



In subcritical case: Non-ideal MHD effects are important!
Collapse: mostly ambipolar diffusion

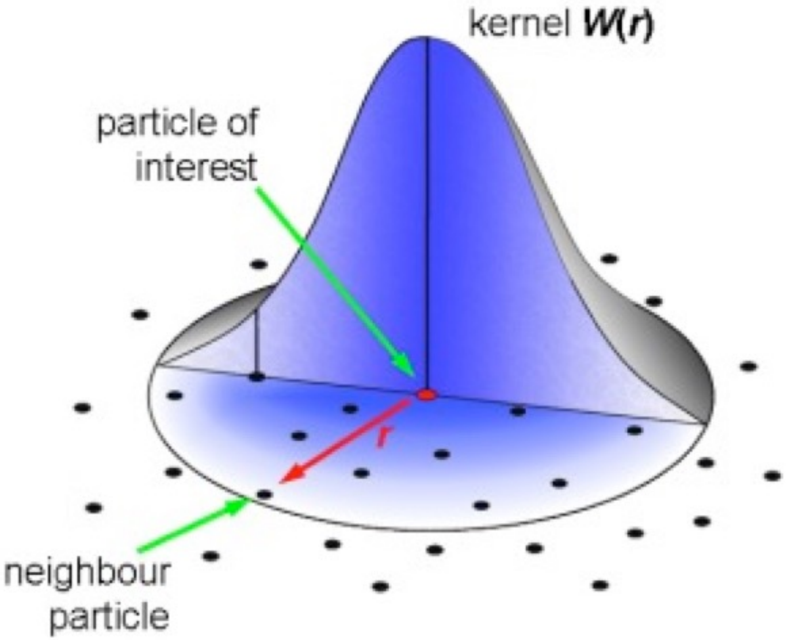
Outline of the following lecture

1. Introduction: cores, disks, multiplicity and stellar initial mass function (IMF)
2. Fragmentation
3. Other physical processes shaping prestellar cores (magnetic fields, turbulence)
4. How to model star formation (also issues with resolution)
5. Initial conditions and their impact (density profiles, turbulence)
6. Stellar feedback
7. Getting the IMF and star formation efficiency in cores

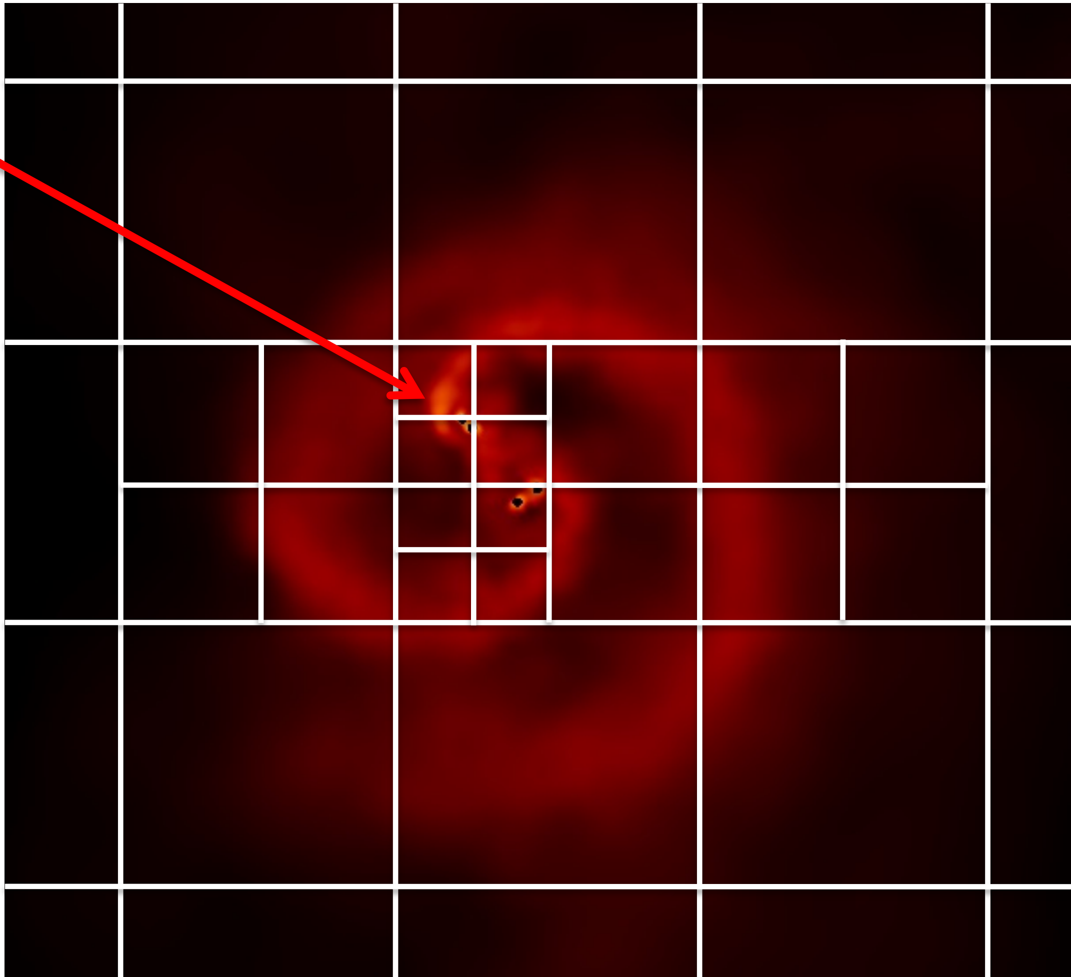
How do we model star formation?

Lagrangian approach:
Smoothed Particle Hydrodynamics

Fluid quantities in 3D
(In every cell / particle):
Mass or Density ρ
Velocity v_x,v_y,v_z
Temperature or pressure
Ionisation state
Magnetic field, …



Eulerian approach:
Grid-based method with Adaptive Mesh Refinement (AMR)



What do we want to simulate?

- Gas evolution: hydrodynamics
- Magnetic fields: magneto-hydrodynamics
- (Self-)Gravity!
- Turbulence
- Gas chemistry: Neutral species, ions, electrons, dust, cosmic rays
- Gas metallicity: how many elements more heavy than He? Which ones?

⇒ Gas cooling (continuum and lines)
⇒ Gas heating (collisions and radiation, e.g. photoelectric heating)

- Star formation: How massive? Surrounded by discs?
- Feedback from stars:
  - ✧ protostellar jets & outflows (all stars, low- and high-mass)

  Only massive stars:
  - ✧ stellar winds
  - ✧ stellar radiation (non-ionizing, ionizing radiation)
  - ✧ supernova explosions

⇒Modelling radiation requires radiative transfer!

What do we want to simulate?

- Gas evolution: hydrodynamics => Euler equations
- Magnetic fields: magneto-hydrodynamics => MHD equations
- (Self-)Gravity! => Poisson equation
- Turbulence
- Gas chemistry: Neutral species, ions, electrons, dust, cosmic rays => multi-fluid MHD!
- Gas metallicity: how many elements more heavy than He? Which ones?

⇒ Gas cooling (continuum and lines)

⇒ Gas heating (collisions and radiation, e.g. photoelectric heating)

⇒Chemical networks (coupled PDEs of species formation/destruction using rates)

- Star formation: How massive? Surrounded by discs? => Sink particles with subgrid models
- Stellar evolution modeling
- Feedback from stars:
  - ✧ protostellar jets & outflows (all stars, low- and high-mass) (Momentum feedback)

  Only massive stars:
  - ✧ stellar winds (Momentum feedback)
  - ✧ stellar radiation (non-ionizing, ionizing radiation) (radiative transfer)
  - ✧ supernova explosions (Thermal energy/ momentum feedback)

⇒Modeling radiation requires solving the radiative transfer equation!

What do we want to simulate?

Star formation is a multi-scale and multi-physics problem:

Which numerical techniques have to be used?

What can we simulate on today's largest supercomputers?

Wish list:

(1) (magneto-)hydrodynamics
(2) (self-)gravity
(3) chemistry, heating & cooling
(4) (multi-wavelength) radiative transfer

⇒ Everything coupled together and time evolved for many Myrs!

⇒ Is this possible?!

Let's have a look at the equations…
Ideal MHD equations + (self-)gravity

Continuity equation: $$\frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\mathbf{v}) = 0,$$

Conservation of momentum: $$\rho\left(\frac{\partial}{\partial t} + \mathbf{v}\cdot\nabla\right)\mathbf{v} = \frac{(\mathbf{B}\cdot\nabla)\mathbf{B}}{4\pi} - \nabla P_{\mathrm{tot}} + \rho\mathbf{g},$$

Conservation of total energy: $$\frac{\partial E}{\partial t} + \nabla\cdot\left[(E + P_{\mathrm{tot}})\mathbf{v} - \frac{(\mathbf{B}\cdot\mathbf{v})\,\mathbf{B}}{4\pi}\right] = \rho\mathbf{v}\cdot\mathbf{g},$$

Induction equation: $$\frac{\partial\mathbf{B}}{\partial t} = \nabla\times(\mathbf{v}\times\mathbf{B})\,,\quad \nabla\cdot\mathbf{B} = 0,$$

Additional constraint from Maxwell:
no magnetic monopoles!

where: $E = E_{int} + E_{kin} + E_{mag}$

Closure relation: Ideal gas: $P = (\gamma - 1)\rho\epsilon$

gravitational acceleration : $\mathbf{g}(\mathbf{x}) = -\nabla\phi(\mathbf{x})$

Information travels with the speed of sound / the Alfven speed << speed of light!

$c_{sound} \sim T^{1/2}$

$c_{Alfven} \sim B\,\rho^{-1/2}$

=> Mach number, Alfvenic Mach number

(Self-)Gravity

Solve the Poisson equation:
relating density and
gravitational potential

$$\nabla^2 \phi(\mathbf{x}) = 4\pi G \rho(\mathbf{x})$$

Can be gas + stars + dark matter

Gravity is a long-range force!
The exact solution requires solving an N^2 problem.

Solution using the **Green's function**:

$$\nabla^2 u(\mathbf{x}) = f(\mathbf{x})$$

Laplacian is linear operator =>

$$u(\mathbf{x}) = \int_{\mathbf{x}'} d\mathbf{x}' G(\mathbf{x}, \mathbf{x}') f(\mathbf{x}')$$

with response of system at x
to point source at x' :
(where δ is the Dirac delta function)

$$\nabla^2 G(\mathbf{x}, \mathbf{x}') = \delta(\mathbf{x} - \mathbf{x}')$$

Solution: **Newtonian potential**:

$$G(\mathbf{x}, \mathbf{x}') = -\frac{1}{4\pi} \cdot \frac{1}{|\mathbf{x} - \mathbf{x}'|}$$

(Self-)Gravity

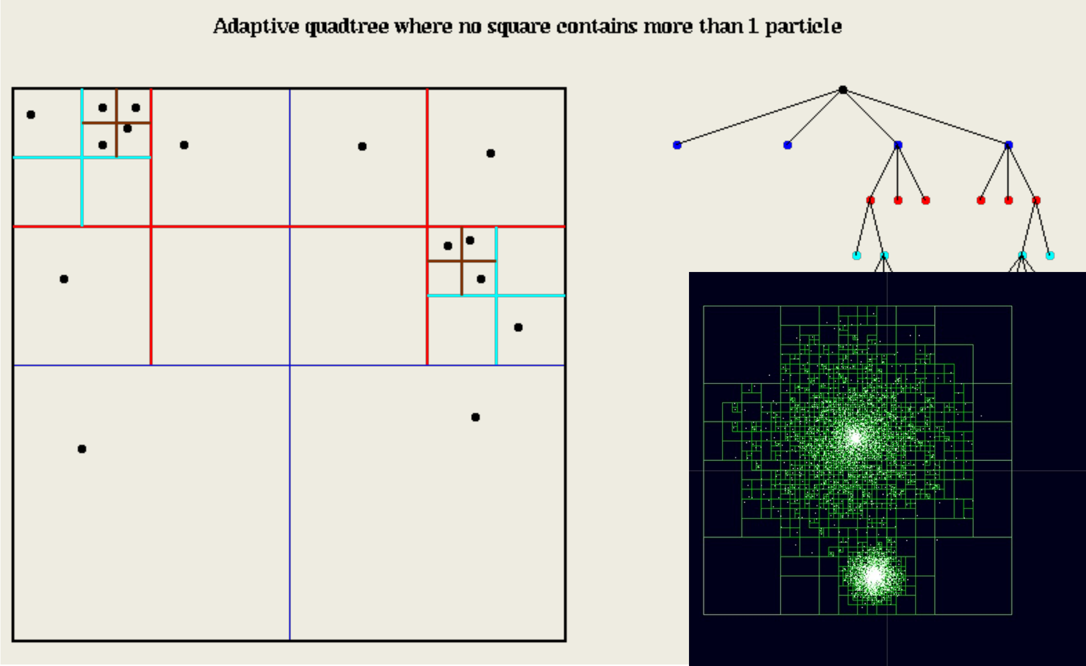
Solve the Poisson equation:
relating density and
gravitational potential

$$\nabla^2 \phi(\mathbf{x}) = 4\pi G \rho(\mathbf{x})$$

Gravity is a long-range force!
The exact solution requires solving an N^2 problem.

FLASH implements a multigrid method using V-Cycles

Tree-structure most efficient,
e.g. Octal-spatial tree
(Barnes & Hut 1986)
for neighbor search and
short/long-range
gravitational forces



(Self-)Gravity: Boundary conditions

Ewald method:

Ewald (1921)

1st application in Dark Matter simulations: Hernquist et al. (1999)

- Split up potential in short- and long-range part:

$$\varphi(\mathbf{r}) \overset{\mathrm{def}}{=} \varphi_{sr}(\mathbf{r}) + \varphi_{\ell r}(\mathbf{r})$$

- Short-range part: sum converges relatively quickly in real space
- Long-range part: sum converges quickly in Fourier space

Selected codes to model star formation

Grid codes (with AMR: adaptive mesh refinement): e.g., FLASH, Ramses, Enzo, Athena++, Orion

⇒ Accurate solutions with good convergence (order of scheme)

⇒ problems with resolution due to high dynamic range needed for star formation

Smoothed Particle Hydrodynamics: e.g., Gadget, Phantom

⇒ Bad convergence behaviour ($\sim N_{part}^{1/2}$), quite dissipative

⇒ Highly adaptive mass resolution, symplectic time integration: good conservation properties (e.g. angular momentum), no grid artefacts

⇒ Problems with magnetic fields (although scheme in Phantom is very good)

Improved SPH: e.g.,

⇒ Gandalf: Riemann SPH: solve Riemann problem across particle interfaces

⇒ Gizmo: Meshless finite mass / meshless finite volume (Gaburov+2011) => magnetic field implementation only proven for MFV

Moving Mesh: Arepo

⇒ Highly adaptive

⇒ Remeshing needs to be carefully done

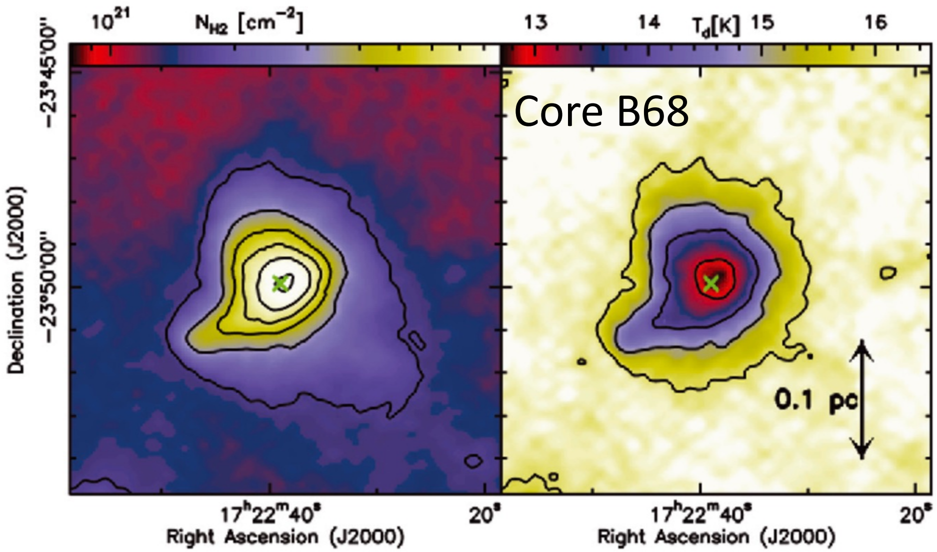
⇒ Voronoi mesh: more difficult implementations

All codes:

- Adaptive time stepping great for star formation
- BUT: be careful once stellar feedback (in particular radiation) turns on!

Prototypical core structure

Roy+2018



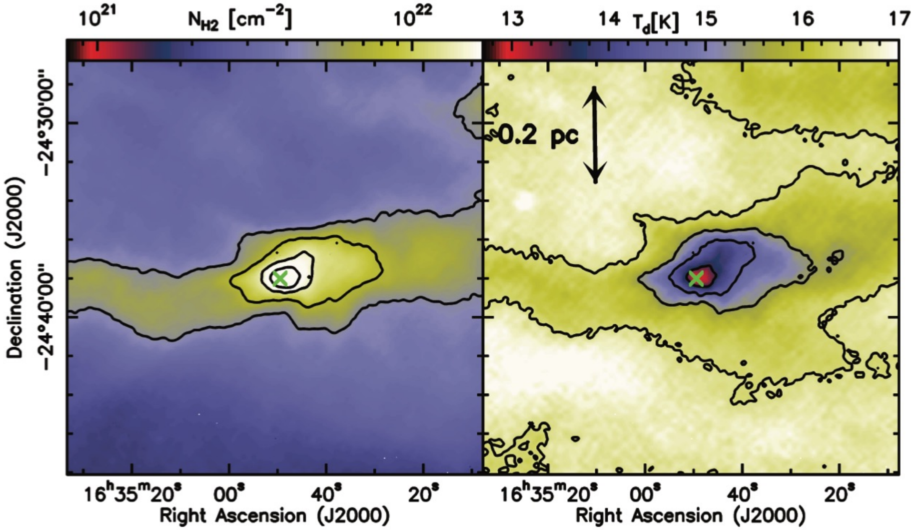
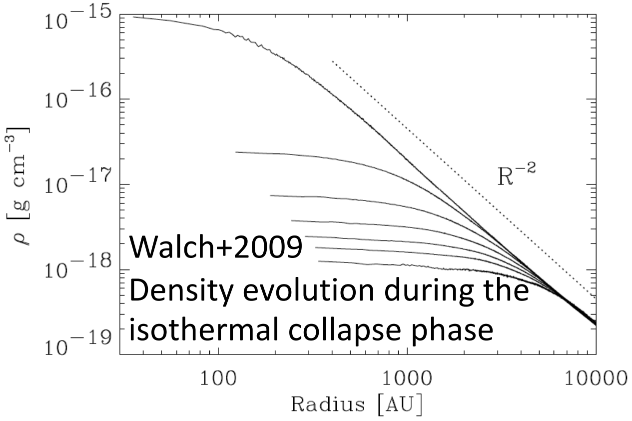


Fig. 3. Same as Fig. 1 but for L1689B. The column density contours are $6{\times}10^{21}$, $1{\times}10^{22}$, $1.4{\times}10^{22}$, $1.8{\times}10^{22}$, and $2.6{\times}10^{22}$ H_2 cm^{-2} (left), and the temperature contours are 16.5, 15.5, 14.5, and 13.5 K (right). The column density image shows that L1689B is embedded inside a filamentary structure.

Prototypical core: B68:
Modeled as a Bonnor-Ebert sphere:
Hydrostatic sphere stabilized by external pressure



Walch+2009
Density evolution during the isothermal collapse phase

Are cores quasi-static entities?
Or are they dynamically evolving on short time scales?

Free-fall time
(uniform core, pressureless collapse)

$$t_{ff} = \sqrt{\frac{3\pi}{32 G \rho_0}}$$

Example:
SPH simulation of low-mass star formation

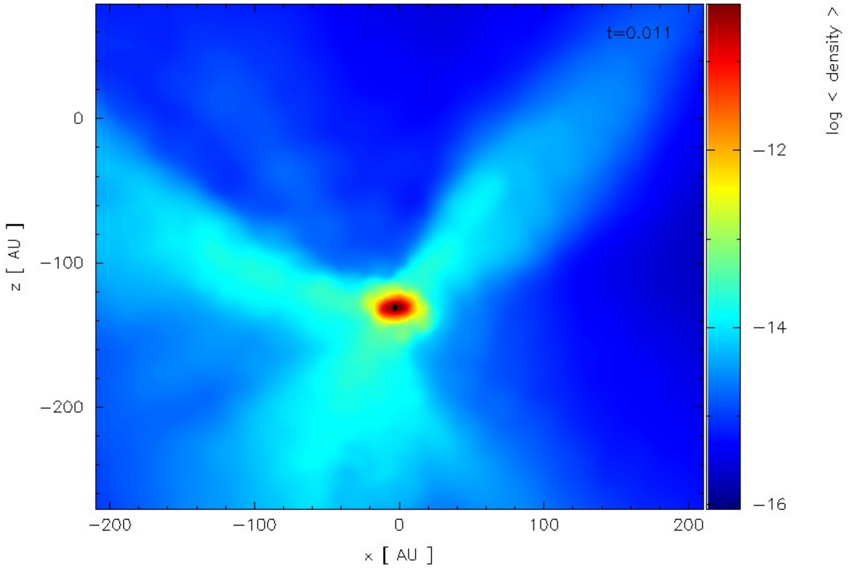
Initial conditions: Core with…

- $M=1.3\ M_{sun}$
- R=5,000 AU (1 AU= distance Earth – Sun ≈ 150 million km)
- Centrally condensed initial density profile
- Turbulent velocity field

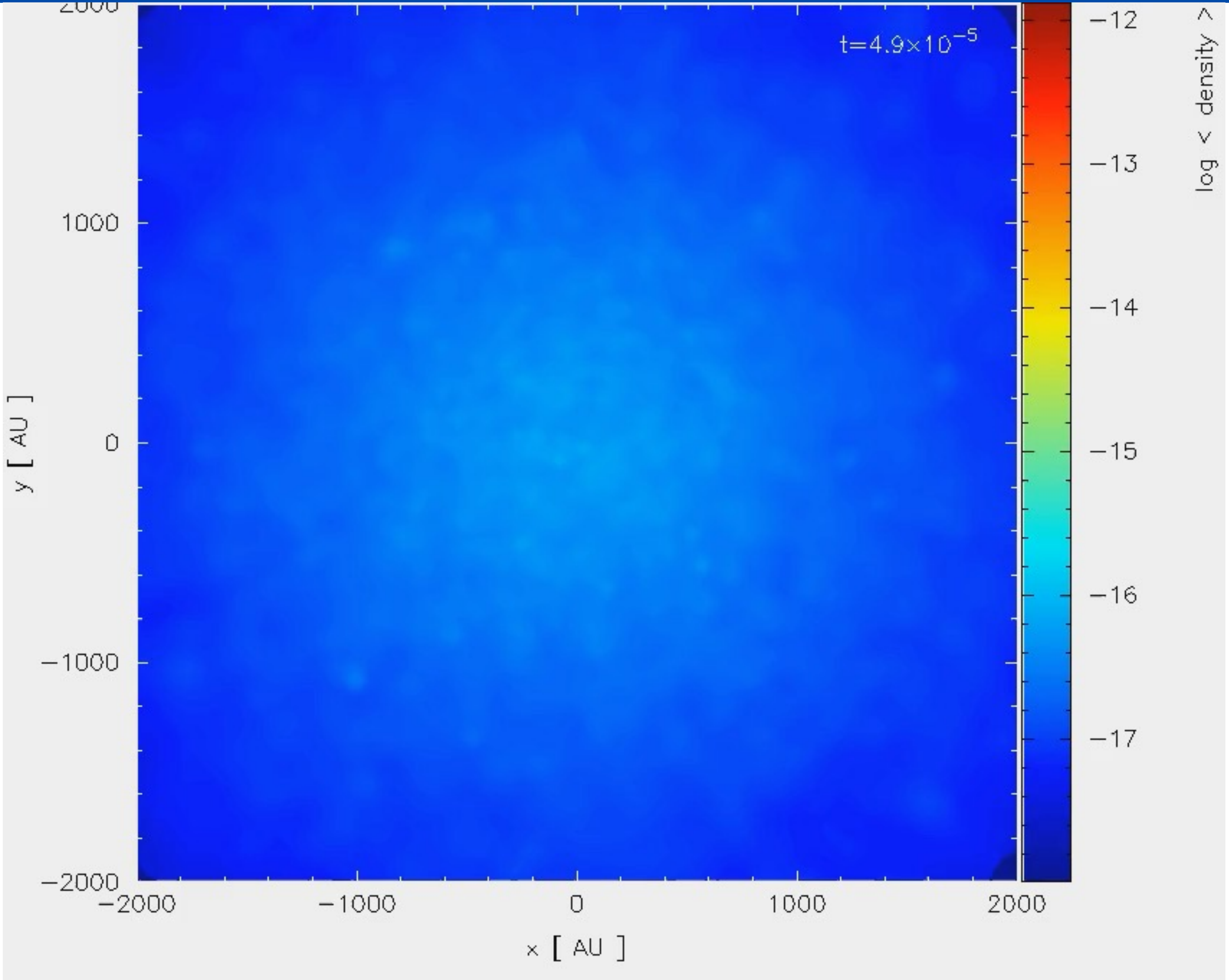
2 Movies:

1. **Collapse of the prestellar core**
2. **Zoom into the central 400 x 400 AU**

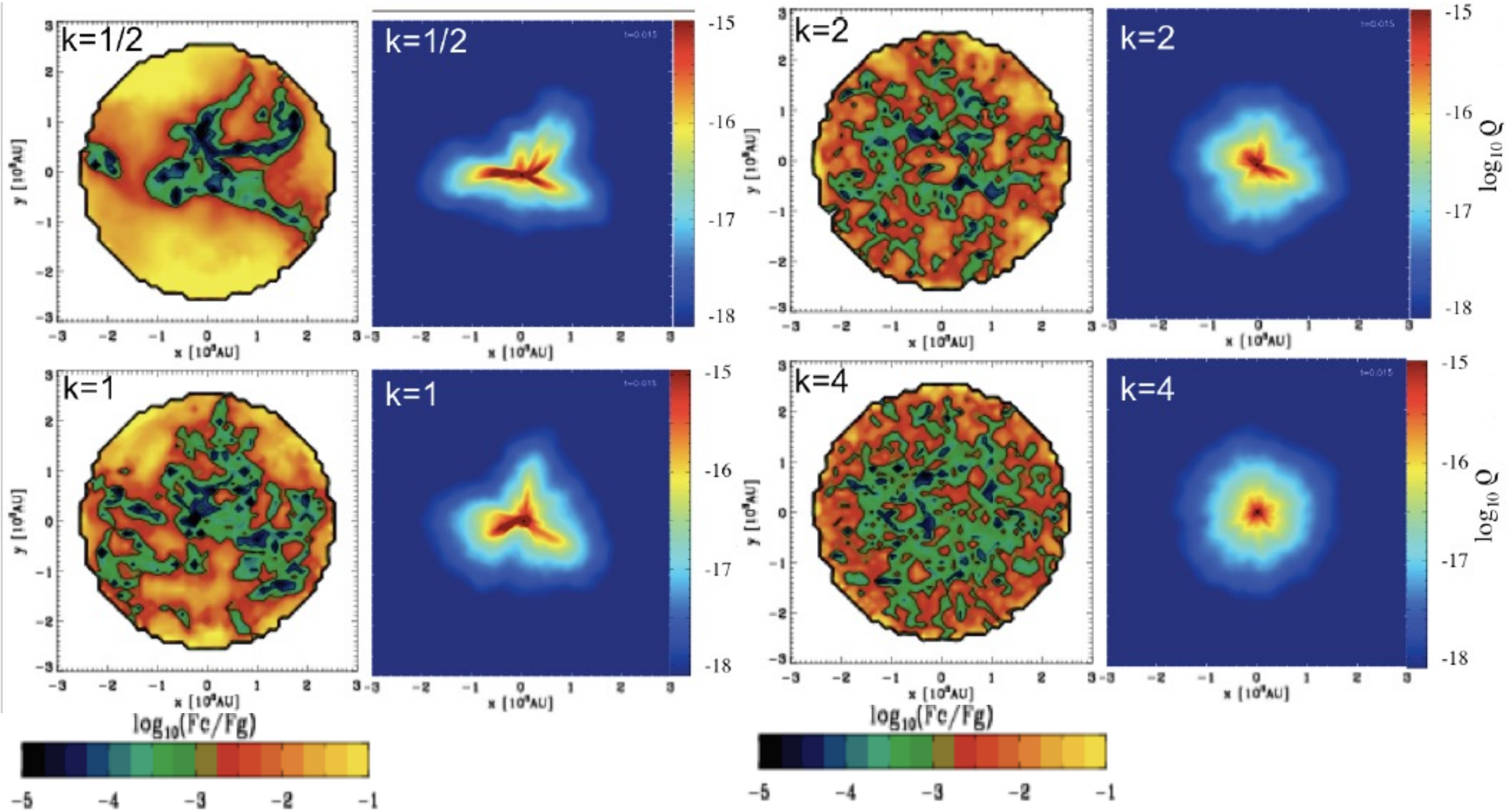
- Density is colour-coded
- Time scale ~ 10,000 years
- Star formation is modeled with sink particles!! (Black dots)



1. Collapse of the turbulent core

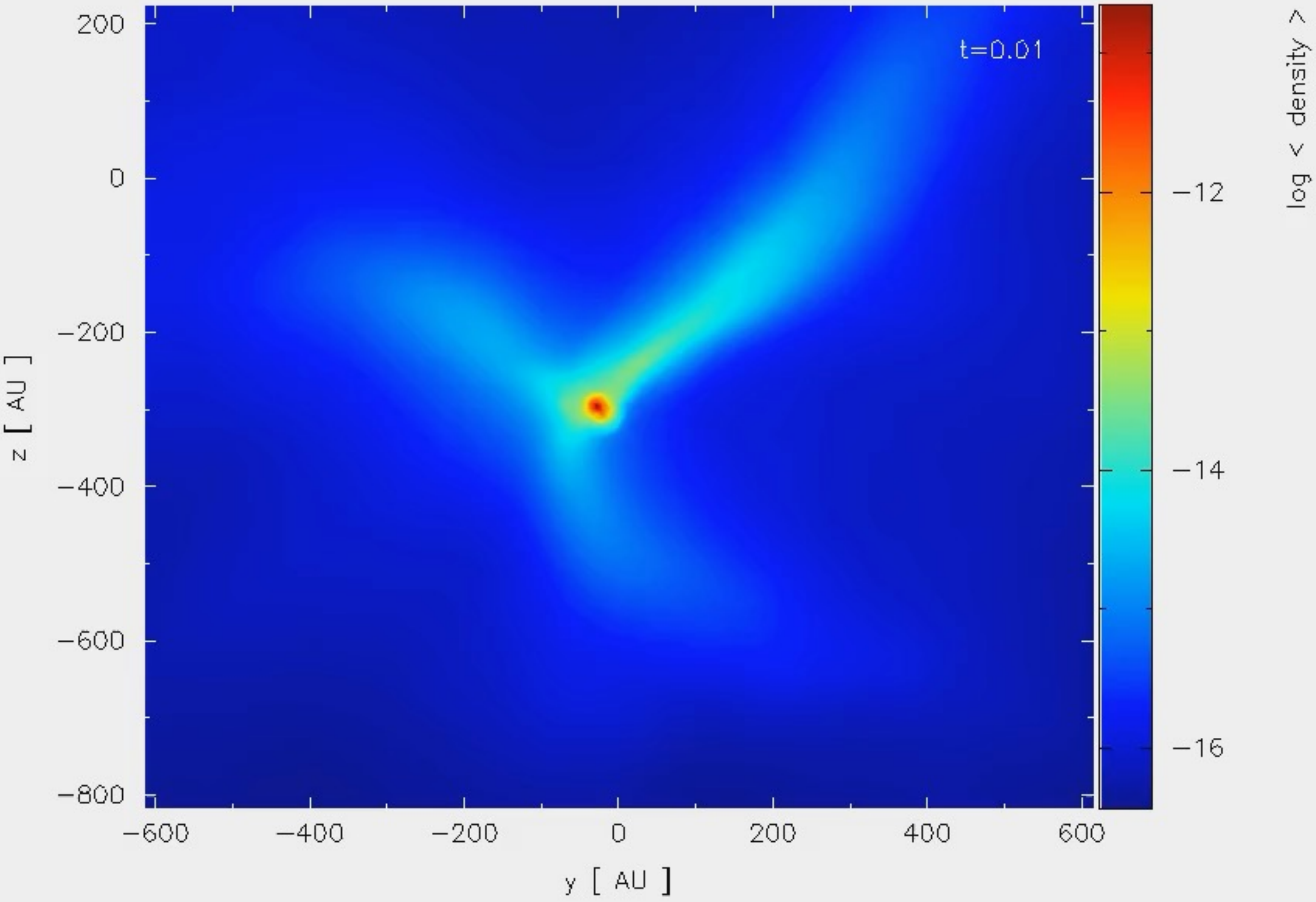


Filament formation explained with a simple force balance analysis

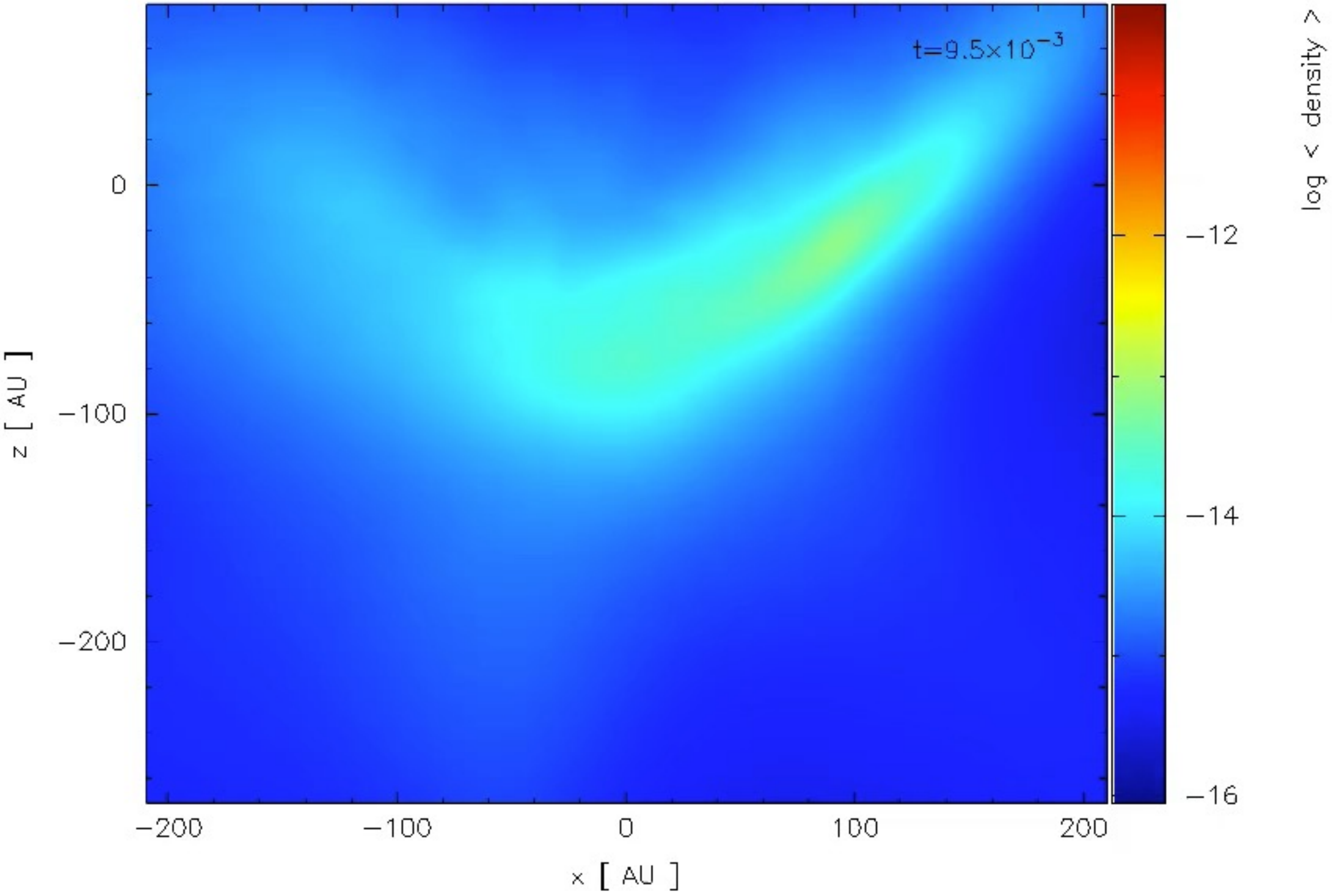


centrifugal force / gravitational force: blue color = no support; red color = centrifugal support

2. Zoom into the central 400 x 400 AU



Another example:
Triple system forming by disk fragmentation:
Highly unstable configuration

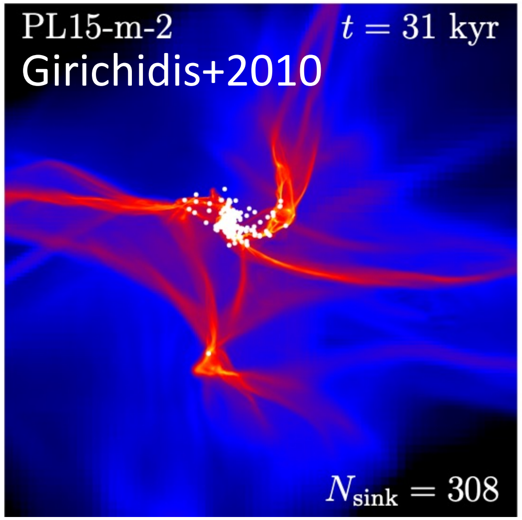


Outline of the following lecture

1. Introduction: cores, disks, multiplicity and stellar initial mass function (IMF)
2. Fragmentation
3. Other physical processes shaping prestellar cores (magnetic fields, turbulence)
4. How to model star formation (also issues with resolution)
5. Initial conditions and their impact (density profiles, turbulence)
6. Stellar feedback
7. Getting the IMF and star formation efficiency in cores

Impact of initial conditions

Density profile & turbulence: both impact fragmentation (Boss, A., 1987; Girichidis+2010)



$\Rightarrow$ The flatter the **density profile** the more likely is fragmentation

$\Rightarrow$ Steep, centrally condensed density profiles lead to high-mass stars

More **turbulence**: expressed with higher α_{vir}:
Ratio of turbulent kinetic E / gravitational E

$\Rightarrow$ Range of possible turbulent kinetic E is limited due to transition to coherence (see before)

Influence of the turbulent perturbation scale on star and disk formation

- **Top – to – bottom:**

Different turbulent seed.

- **Left – to – right:**

Different perturbation scale k_{min}

- **Small k_{min} (left)**

= large scale turbulence:

More angular momentum

=> big disks

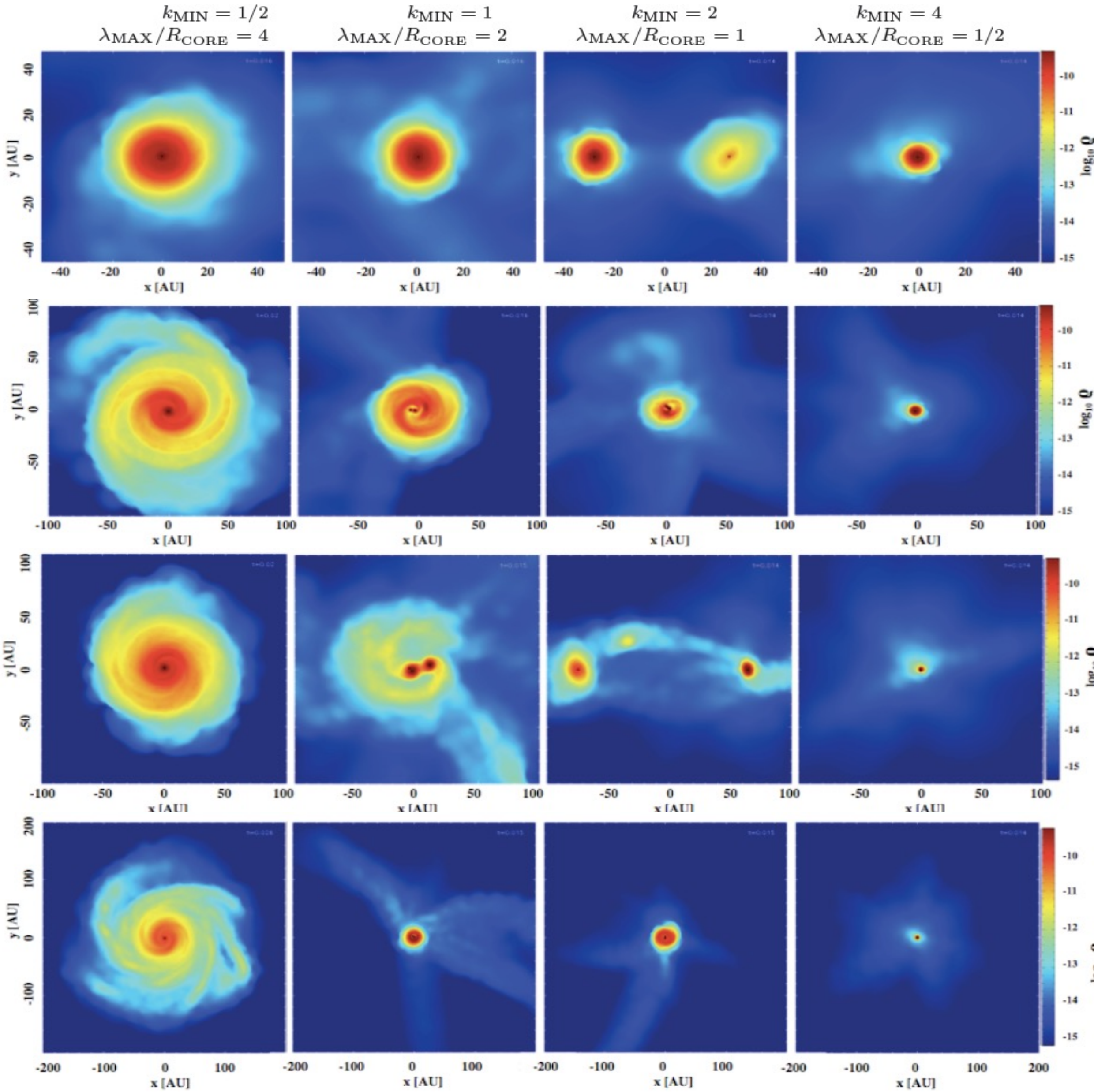
- **Intermediate k_{min}:**

More fragmentation; fragmentation ONLY in filaments!

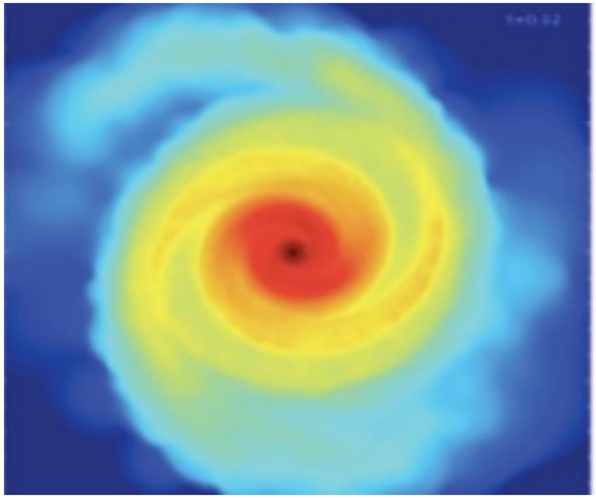
- **Large k_{min} (right)**

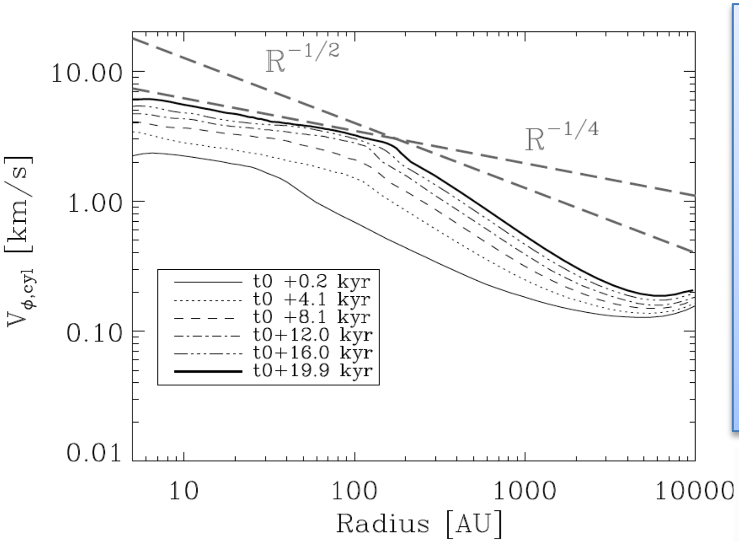
= small scale turbulence:

No fragmentation/big disks



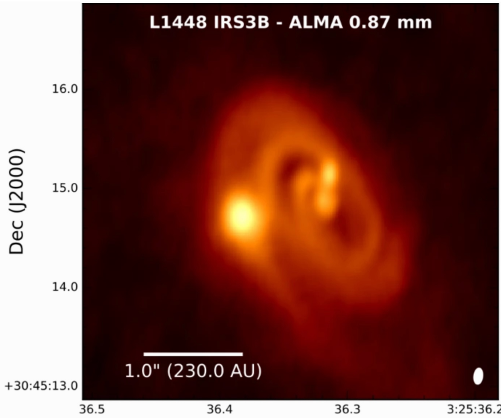
Disk angular velocity profiles

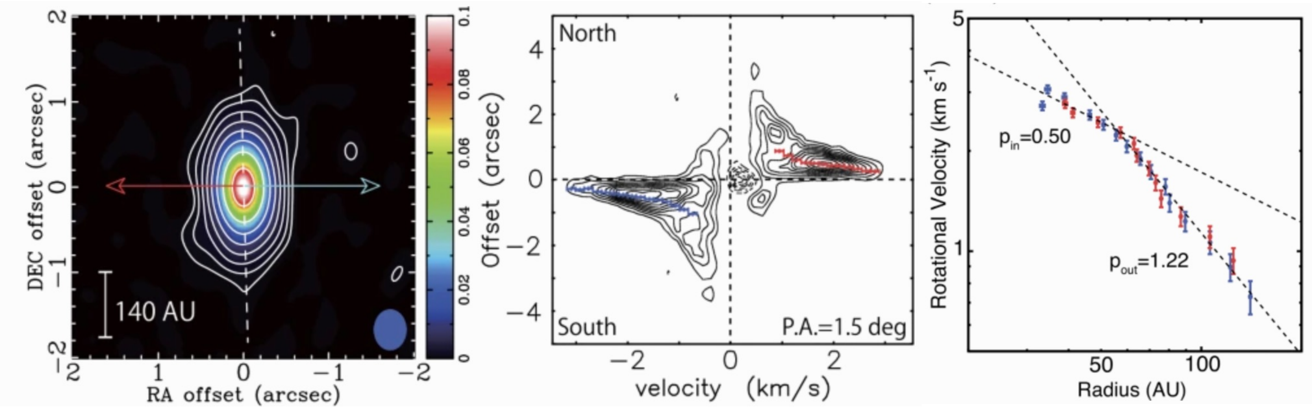


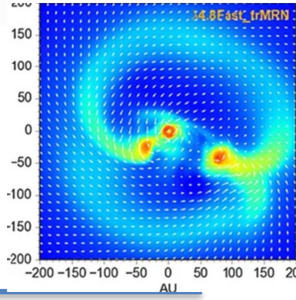


Walch+2009:
Self-gravitating young discs often show flatter than Keplerian rotation profiles

Keplerian v ~ $R^{-1/2}$







But also Keplerian disks are found in later stages and around higher mass protostars (e.g., Ginsburg+2018, Moscadelli+2019)
Zhao+2020 review: also discussing recent findings with respect to non-ideal MHD and magnetic breaking

Outline of the following lecture

1. Introduction: cores, disks, multiplicity and stellar initial mass function (IMF)
2. Fragmentation
3. Other physical processes shaping prestellar cores (magnetic fields, turbulence)
4. How to model star formation (also issues with resolution)
5. Initial conditions and their impact (density profiles, turbulence)
6. Stellar feedback
7. Getting the IMF and star formation efficiency in cores

Stellar feedback

Mechanical feedback:

- Protostellar jets and outflows
- Stellar winds

Radiative feedback:

- Non-ionizing radiation => heats dust => heats gas via gas-dust coupling & photoelectric effect
- Ionizing radiation => primarily ionizes and heats hydrogen gas, also heats dust
- X-rays => mostly heat gas
- Radiation pressure => associated with all absorptions / scatterings of photons => net outward force

Supernovae:

- Stars with $M > 8\ M_\odot$
- Depends on stellar lifetime => first explosions in a cluster after ~ 3 Myr or longer

Stellar feedback

Feedback from low-mass stars
Feedback from high-mass stars

Mechanical feedback:

- Protostellar jets and outflows
- Stellar winds

Radiative feedback:

- Non-ionizing radiation => heats dust => heats gas via gas-dust coupling & photoelectric effect
- Ionizing radiation => primarily ionizes and heats hydrogen gas, also heats dust
- X-rays => mostly from accretion => heating gas
- Radiation pressure => associated with all absorptions / scatterings of photons => net outward force
- accretion and intrinsic luminosities

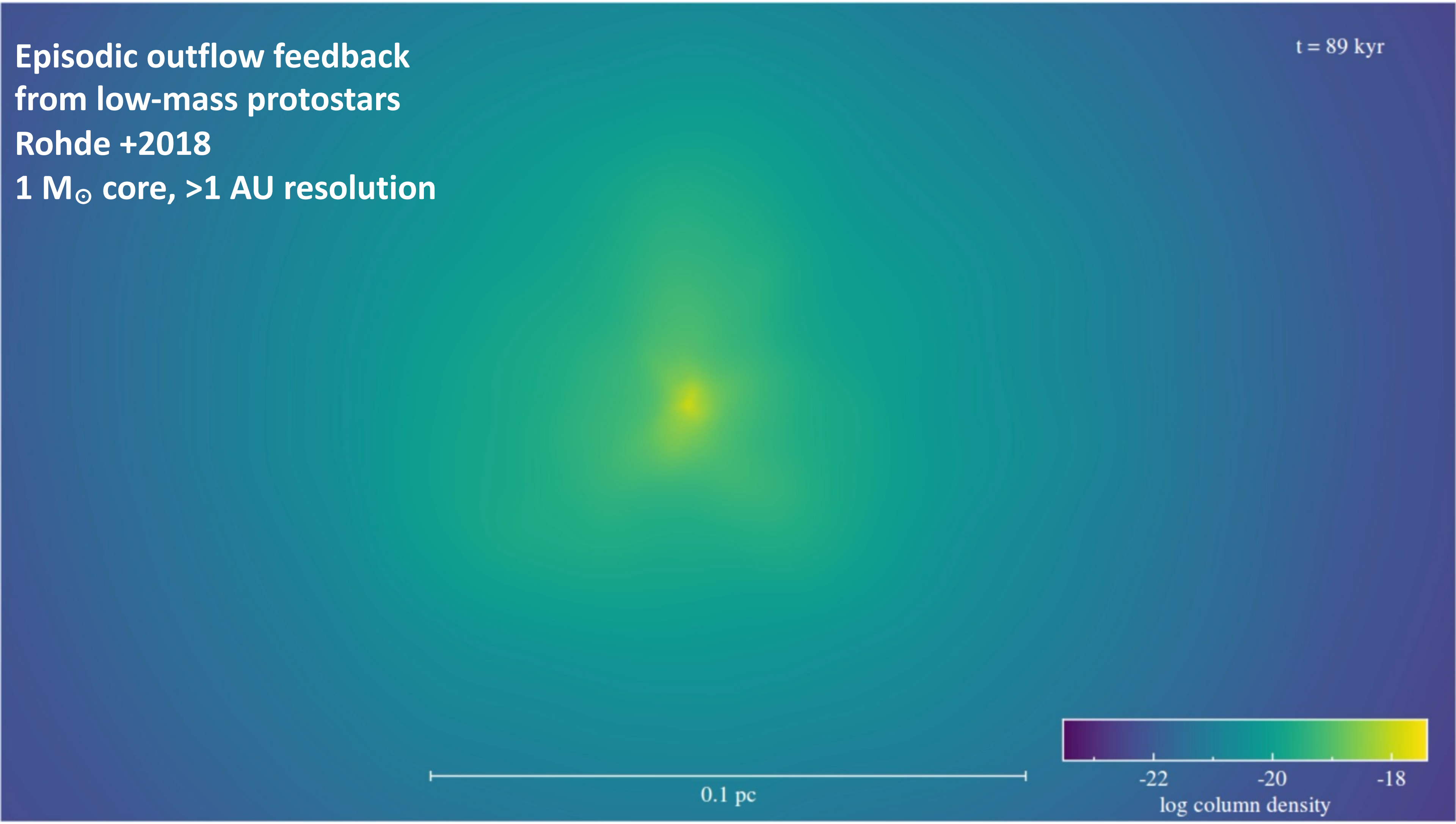
Talk by Mélanie

Supernovae:

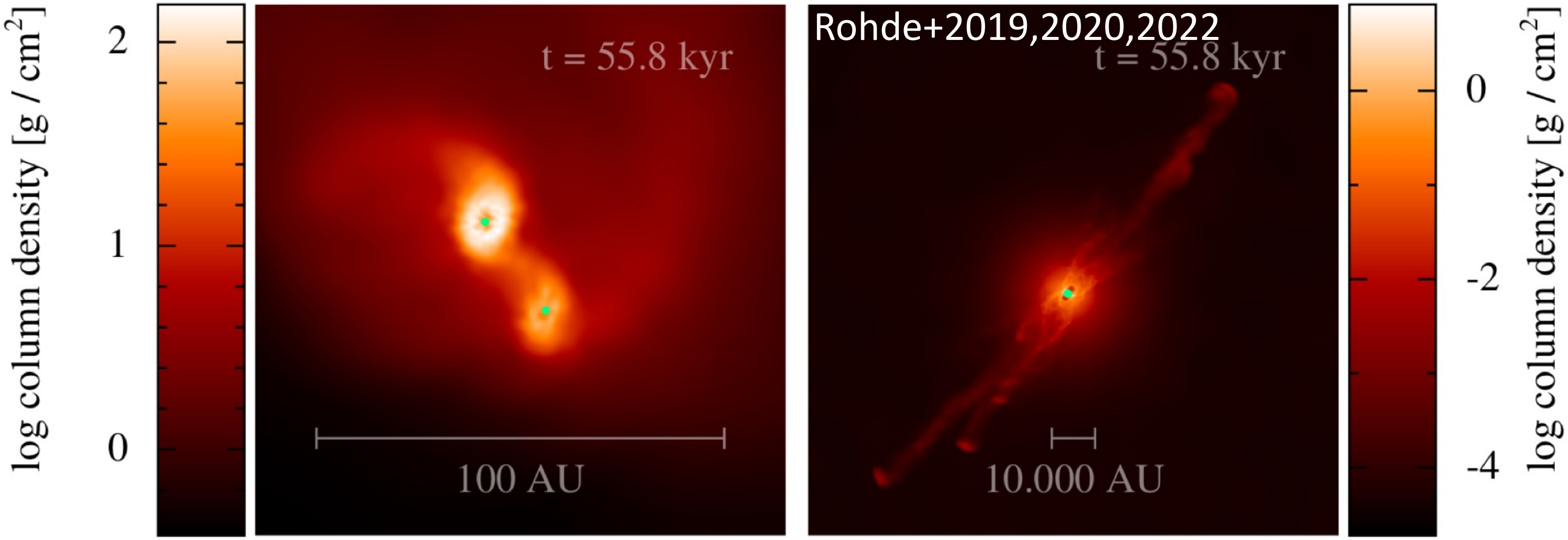
- Stars with M > 8 $M_\odot$
- Depends on stellar lifetime => first explosions in a cluster after ~ 3 Myr or longer

Protostellar outflow model

Episodic outflow feedback from low-mass protostars
Rohde +2018
1 $M_\odot$ core, >1 AU resolution



Protostellar outflow model



Rohde+2019,2020,2022

$$M_{\rm SINK} = M_{\rm IAD} + M_\star$$
$$L_{\rm SINK} = L_{\rm IAD} + L_\star$$

$$\frac{dM_\star}{dt} = \left.\frac{dM}{dt}\right|_{\rm BG} + \left.\frac{dM}{dt}\right|_{\rm MRI}$$

See also
Stamatellos+2005
Zhu+2019,+2020
+ protostellar
evolution model

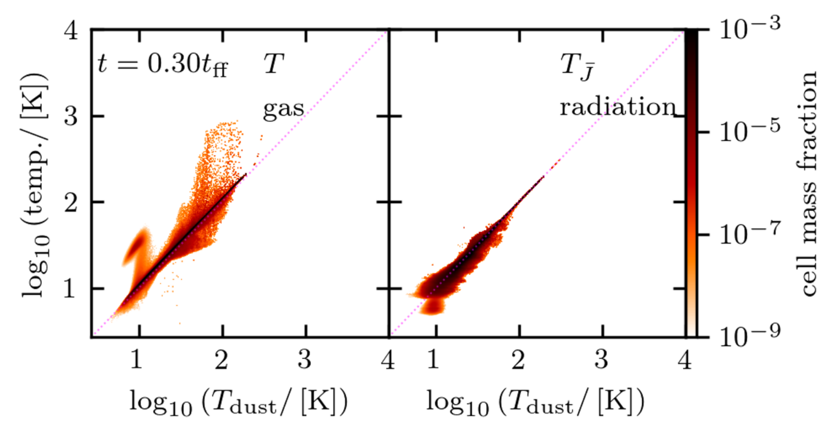
Results of simulations with episodic outflows by Rhode et al.:

- SFE efficiency reduced by ~2
- Entrainment factors ~7 ± 2
- More twin binaries with outflow feedback!
- Apparently setting the peak of the IMF!

Massive star formation

Massive star formation (< 1 pc) requires modeling additional feedback

- Rosen+2022: stellar winds are important
- Kuiper+2018: ionizing radiation and radiative heating is important, stellar winds not so much
- Klepitko+2023: radiative heating of dust more important than radiation pressure, then ionizing radiation



Zimmermann et al., in prep., simulations with FLASH
Klepitko+2023

Outline

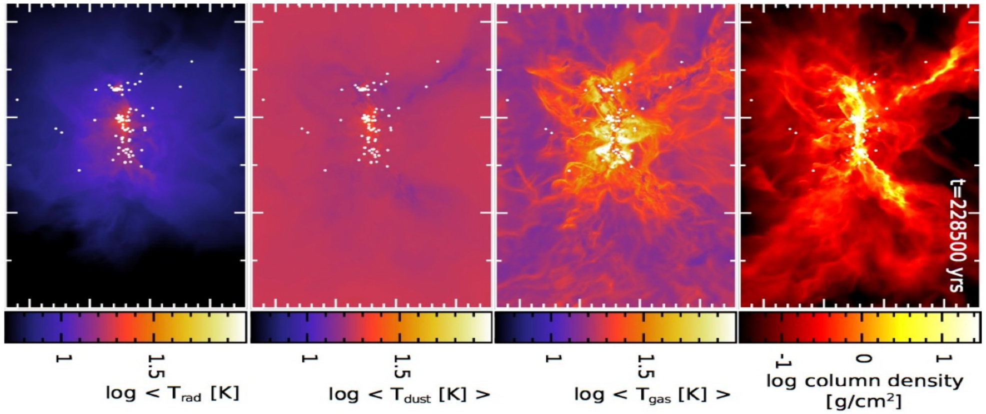
1. Introduction: cores, disks, multiplicity and stellar initial mass function (IMF)
2. Fragmentation
3. Other physical processes shaping prestellar cores (magnetic fields, turbulence)
4. How to model star formation (also issues with resolution)
5. Initial conditions and their impact (density profiles, turbulence)
6. Stellar feedback
7. Getting the IMF and star formation efficiency in cores

Getting the stellar IMF

Krumholz +2016: RMHD simulations:

⇒ radiative heating and thermal pressure set the peak of the IMF

Bate+2019:
Radiative feedback, different Z
$\sim 10^{-5}\ M_\odot$/particle

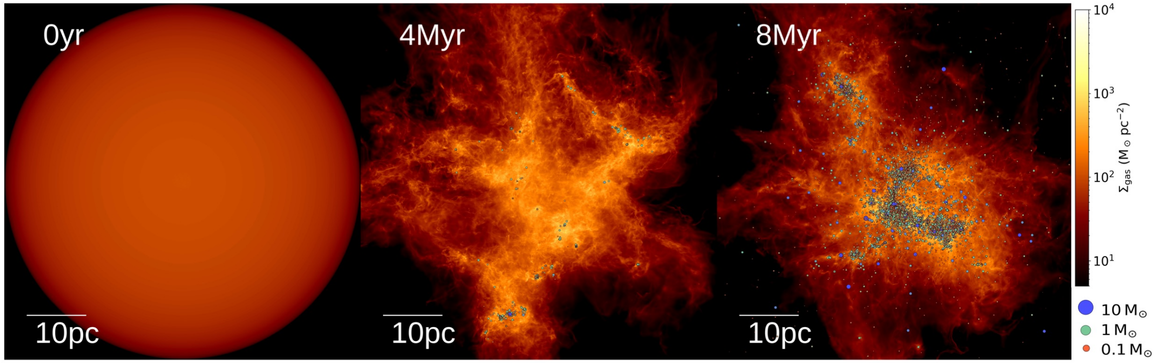


Starforge: Guszejnov +2020, +2022

⇒ Protostellar jets are important for setting the peak of the IMF

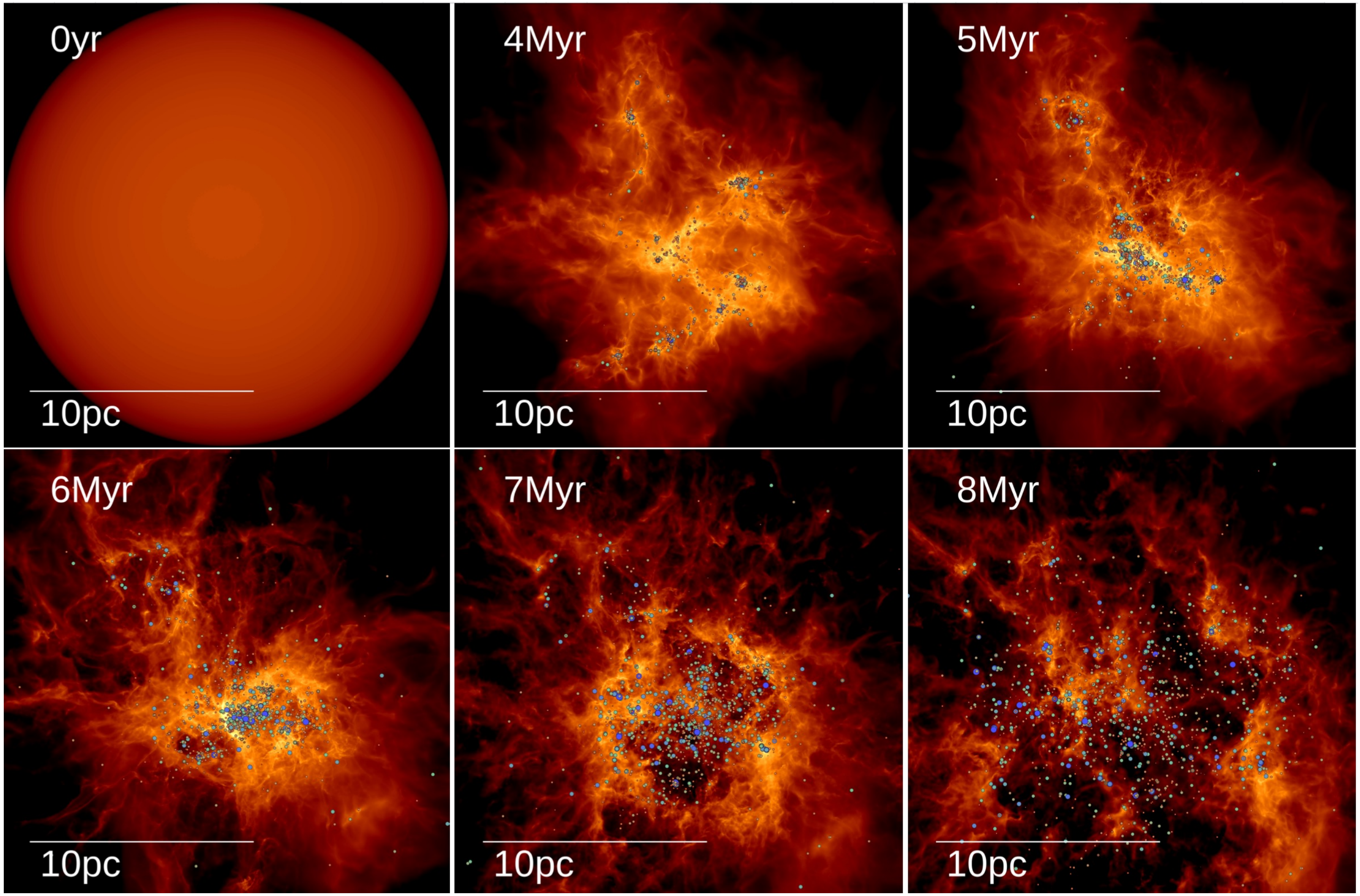
⇒ Still IMF variation too large: need additional physics

⇒ Jets cannot regulate high-mass star formation



Getting the star formation efficiency

Low-mass clouds are easily dispersed by stellar feedback (ionizing radiation)



Role of ionizing radiation for dispersing individual clouds:

Whitworth, 1979
Walch+2012,+2013
Dale +2015
Geen +2016
JG Kim, Ostriker+21

Example by Guszejnov+2022 Starforge: clouds with 20,000 $M_\odot$

Sheets and filaments: cloud sub-structure

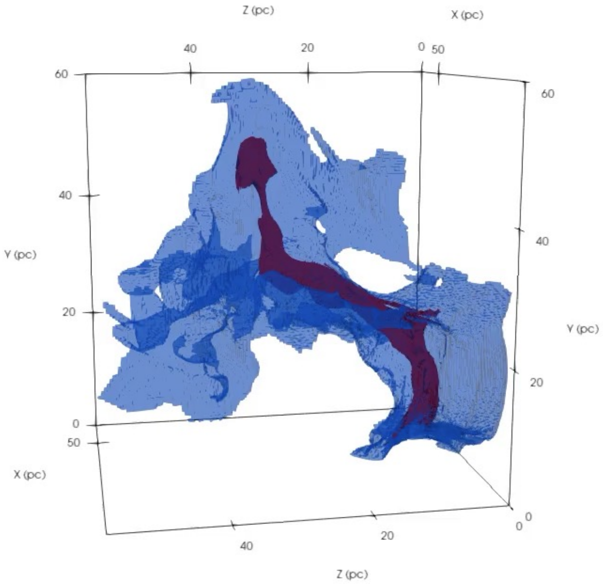
★ **magnetic fields slow down the cloud formation process** Despite overall similar ISM properties (phase distribution) with and without B on scales of several 100 pc; see SW+2015

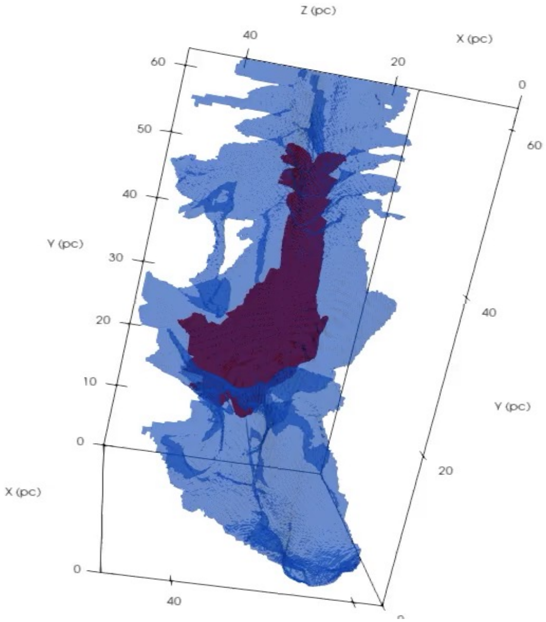
★ **Evolutionary sequence**

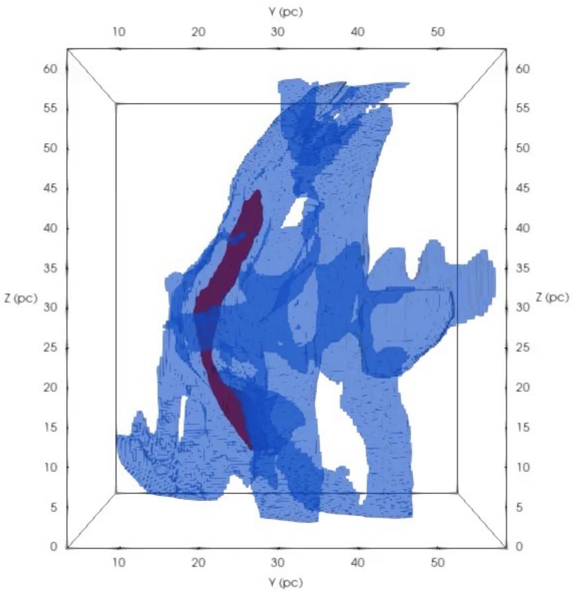
⇒ **Sheets (flying carpets)**

⇒ **filaments (cigars)**

Movies for 3 different magnetized SILCC-Zoom clouds



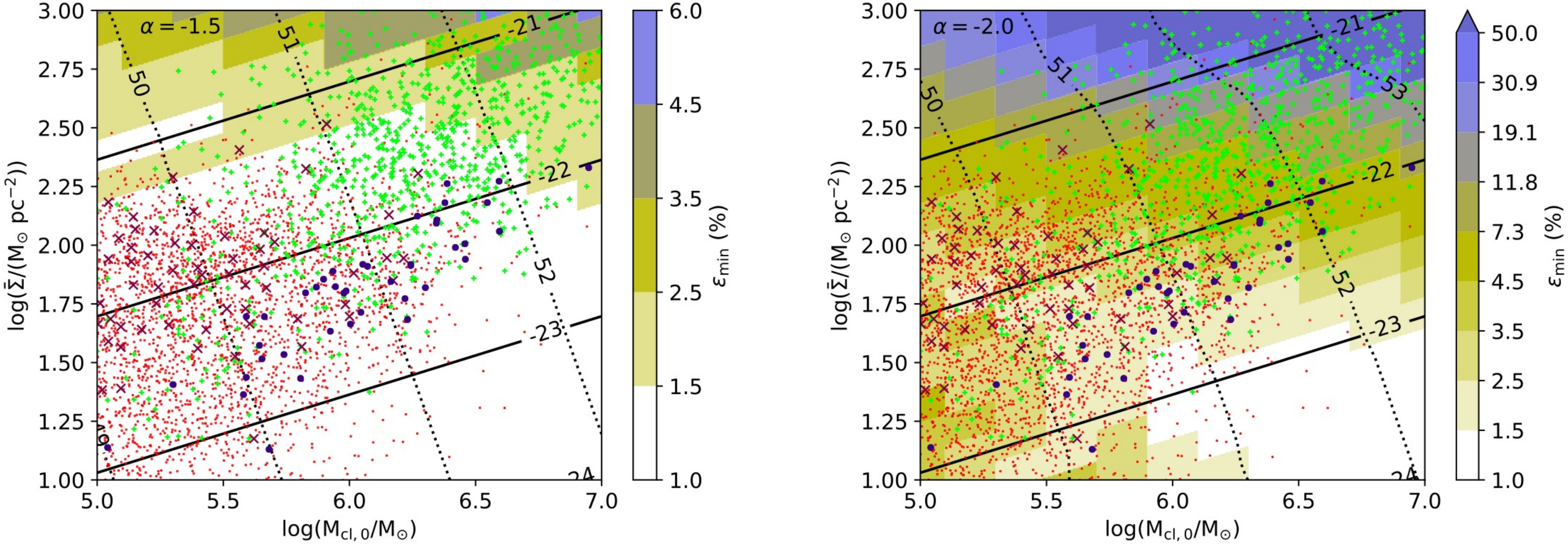




Ganguly, SW+2023;
see e.g. observations by Sara Rezaei: Rezaei Kh. & Kainulainen, 2022

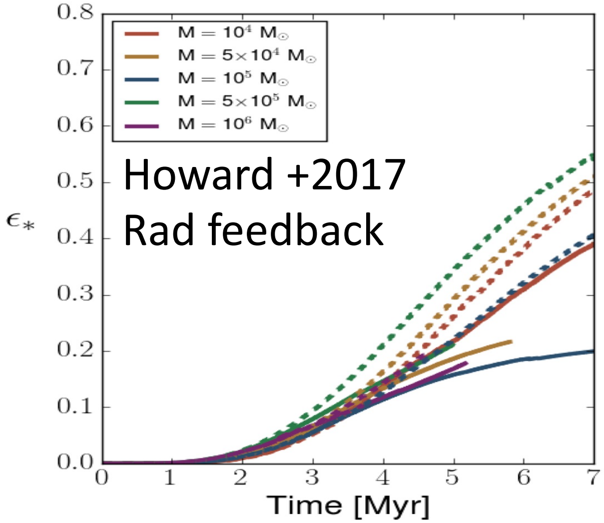
Efficiency of stellar feedback depends on cloud geometry / density profile

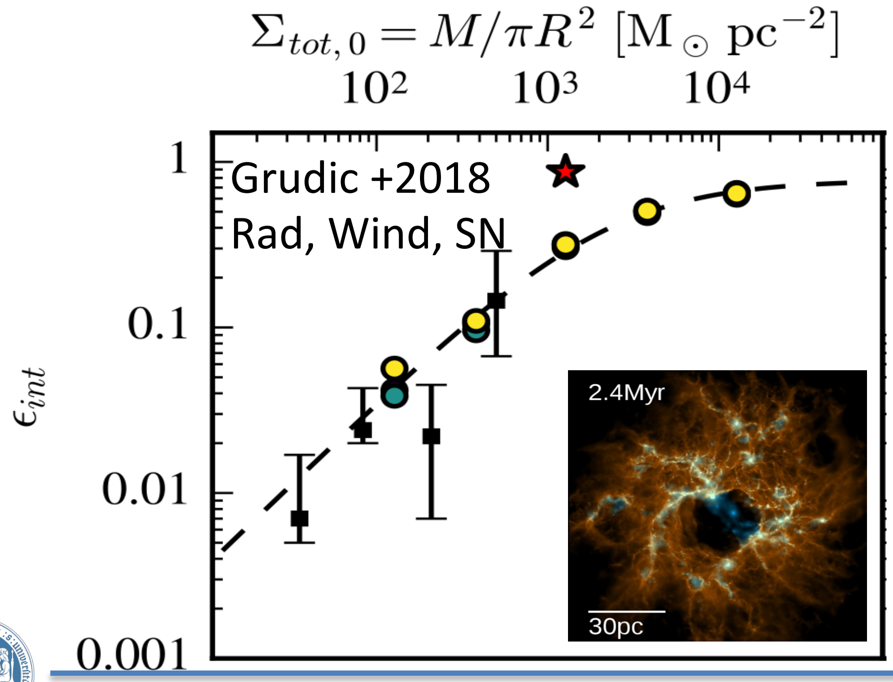
Rahner+2019 Warpfield 1D model: SFE sensitive to initial cloud density profile

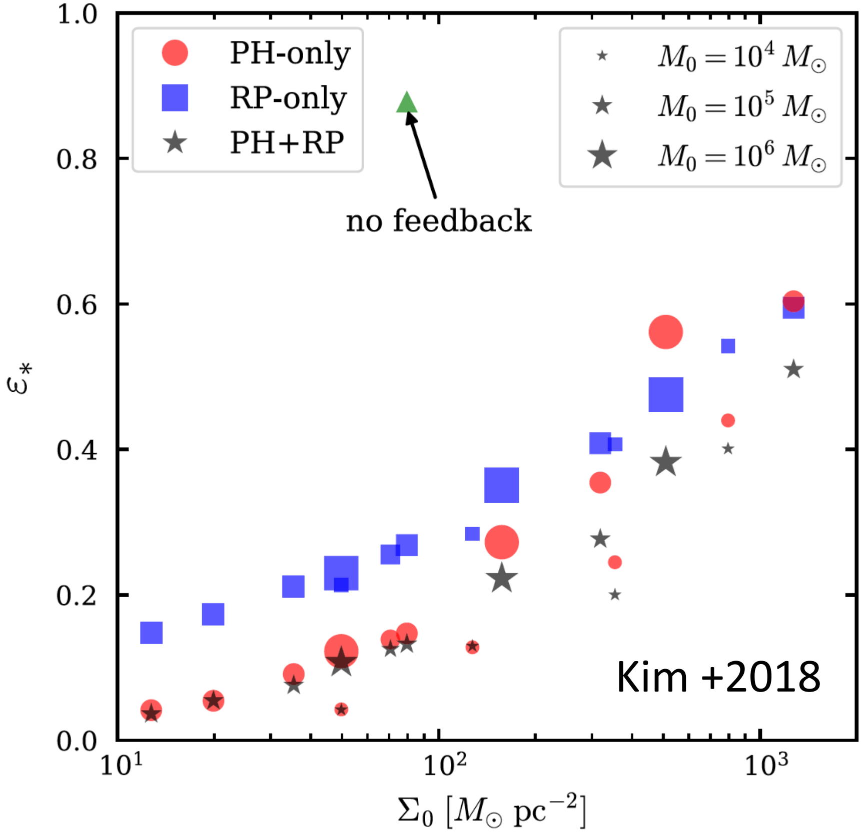


Cloud geometry: sheet-like / filamentary clouds vs. spherical clouds impacts boundedness of clouds (e.g. Zamora-Avilés +2019; Ganguly+2023)

SFE for different GMC surface densities







Very high SFE in clouds with high initial gas surface density!

Radiation pressure seems to help here but unsolved so far

Open question: Mapping of CMF -> IMF and SFE

Star formation efficiency?

Result of Könyves+2015, +2019: ~10%-20% of dense gas mass is in cores => perhaps no need to limit SFE in cores

In cores ~30% => mapping of CMF -> IMF
(*Padoan & Nordlund*, 2002; *Hennebelle & Chabrier*, 2008, 2009; *Oey*, 2011; *Hopkins*, 2012)

Or: CMF and IMF don't need to be related: dynamical interaction and stochastic accretion.
For massive stars: competitive accretion
(Bonnell +2001; *Bate* +2003; *Clark* +2007)

This issue is still unsolved:
Are cores stable objects? Or are they dynamical fluctuations with no "identity"?

Some models are trying to go down from larger scales, e.g. Haugbolle+2018, Pelkonen+2021 (but isothermal)

Need high-resolution, longer-term simulations with substantial physics!

Conclusions & Open questions

- **Fragmentation**:
  - Depends on core density profile and magnetic field strength, virial parameter, etc
  - We need to still better constrain these parameters!
  - Are cores actually real “objects” or just fluctuations? How much does their mass evolve over time within a star-forming molecular cloud?

- **Modeling star formation**:
  - How can we improve beyond the state-of-the-art to get a self-consistent model where jets & outflows are launched and disks are resolved (scale height)?
  - How can we achieve this if we need to model the larger-scale cloud environment at the same time in order to avoid the “initial condition problem”?
  - Are we missing some physics?

- **IMF and star formation efficiency**
  - Does the CMF map onto the IMF?
  - What is the SFE in cores?
  - Where and when (in the cluster evolution) do massive stars form?
  - Can we reproduce the multiplicity fraction as a function of mass? -> also needs more firm insights from observations of young clusters.

The SILCC project

SFB1601

We are hiring!