Brown Dwarf Formation Through Gravitational Collapse: Insights From 3D MHD Simulations

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(Under review at Apj letters)

CENTRE DE RECHERCHE ASTROPHYSIQUE DE LYON

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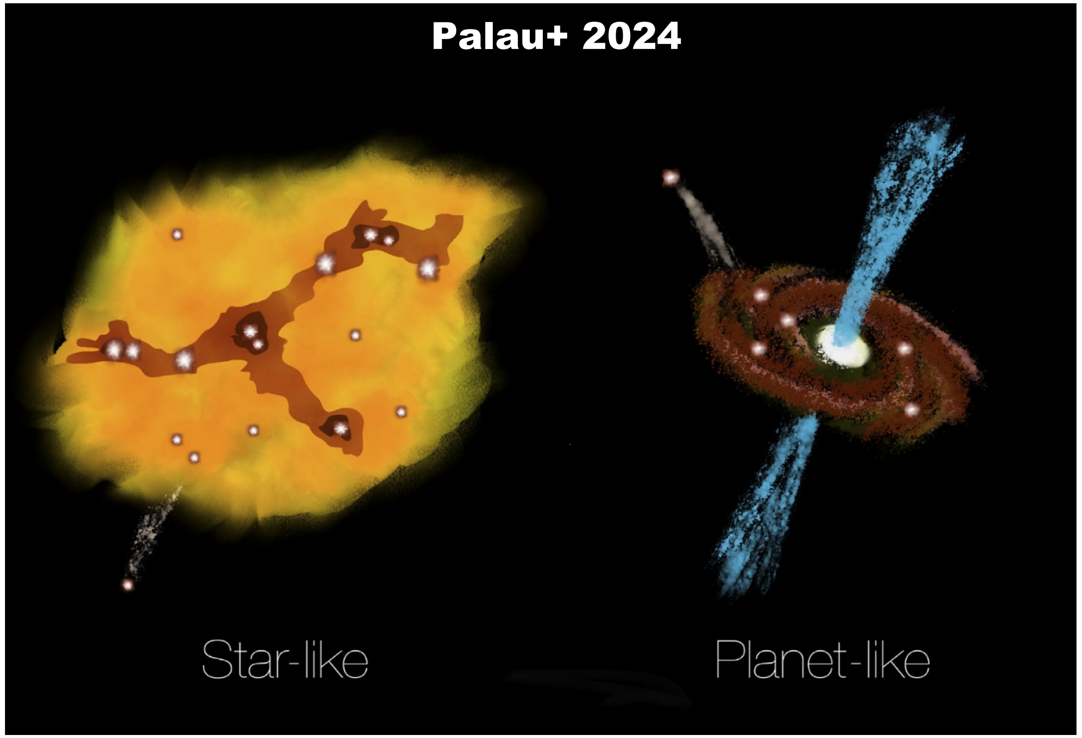
Context: Formation mechanism of Brown Dwarfs



Scaled-down version of low-mass star formation

Gravo-turbulent processes create the necessary density peaks in the ISM

(Padoan & Nordlund 2002, Hennebelle & Chabrier 2008, Chabrier & Hennebelle 2010, Hopkins 2012, Chabrier+ 2014, Haugbølle+ 2018, Vázquez-Semadeni+ 2019, Dhandha+ 2014)

Disk-fragmentation

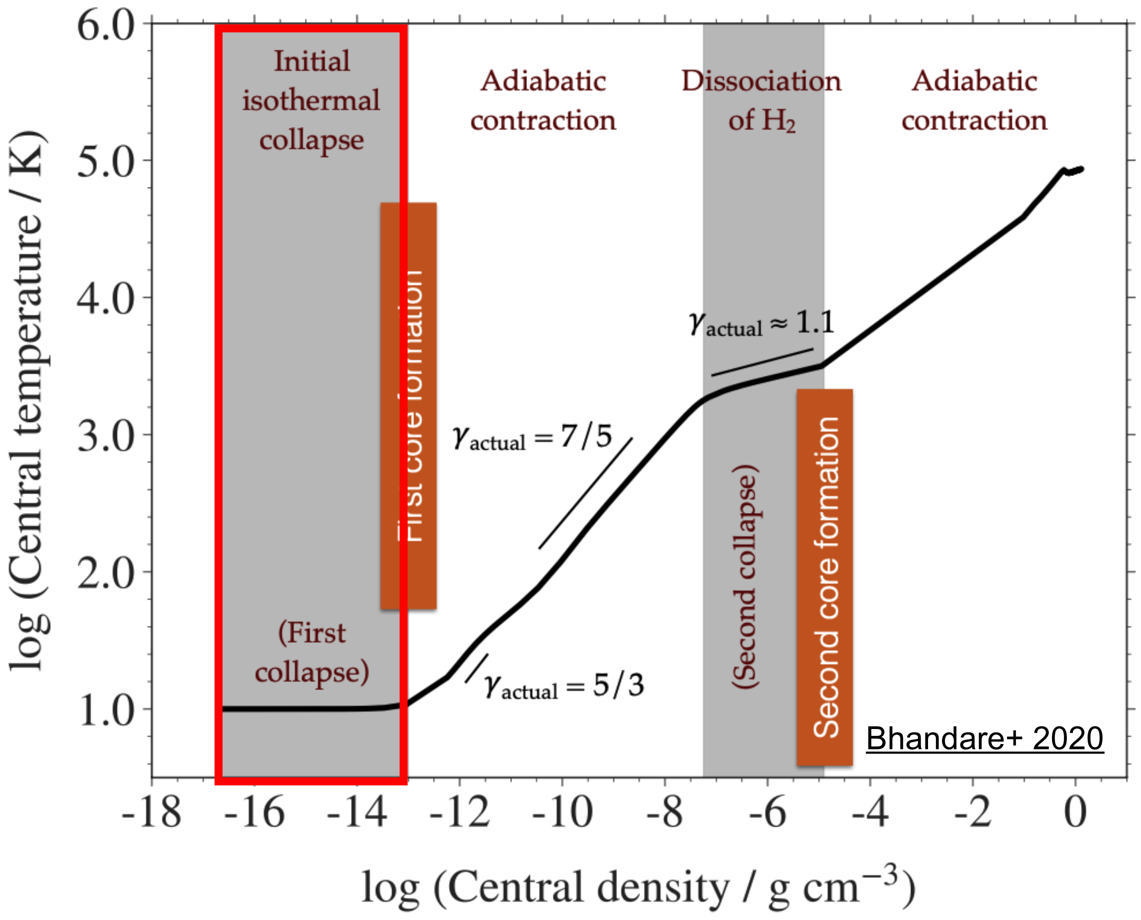
(Stamatellos+ 2007, Stamatellos & Whitworth 2008)

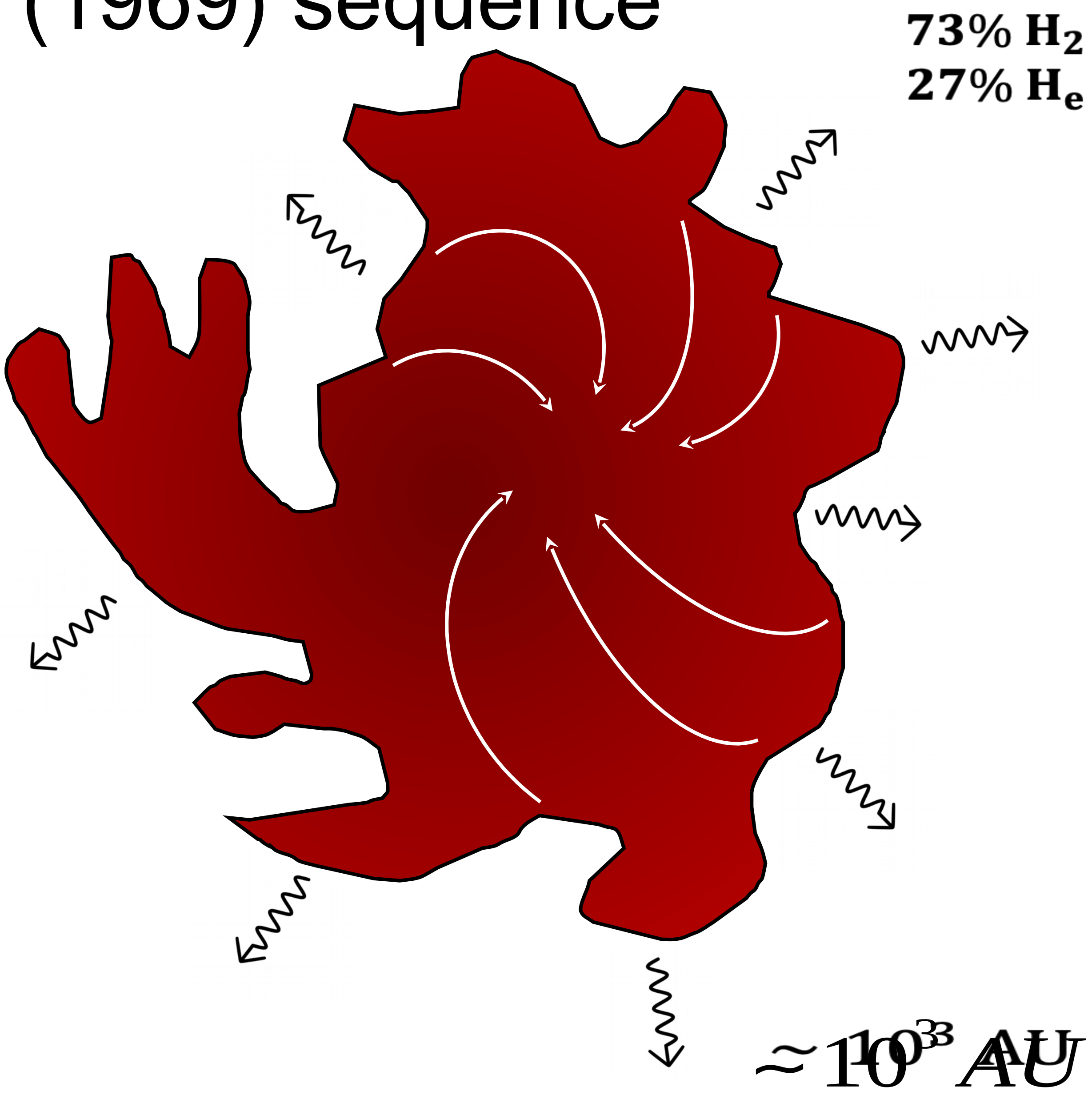
Stunted Growth (ejection, competition)

(Reipurth & Clarke 2001, Bate+ 2002, Bonnell & Bate 2006, Bonnell+ 2008, Basu & Vorobyov 2012, Reipurth & Mikkola 2015, Bate 2019, Coleman+ 2025)

Observational data supports both paradigms

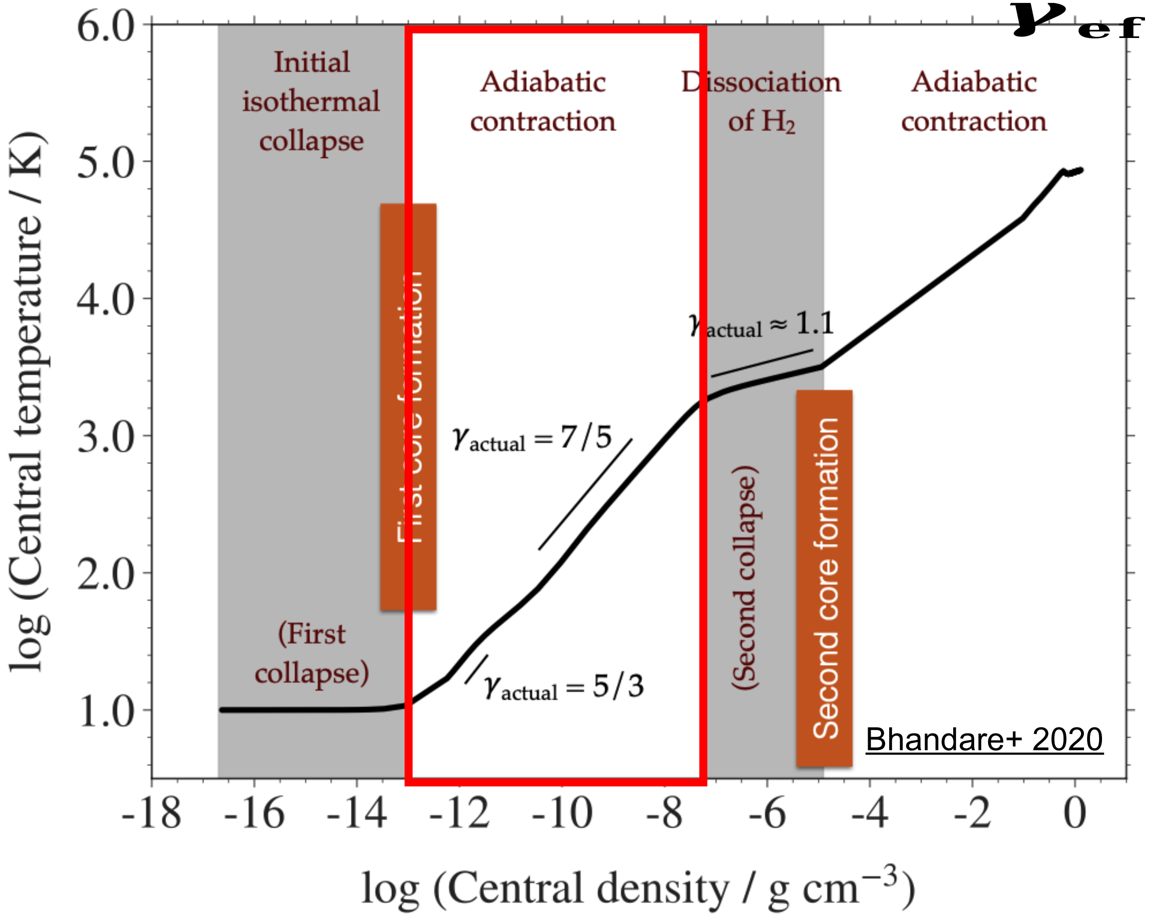
Star-like scenario: Larson (1969) sequence

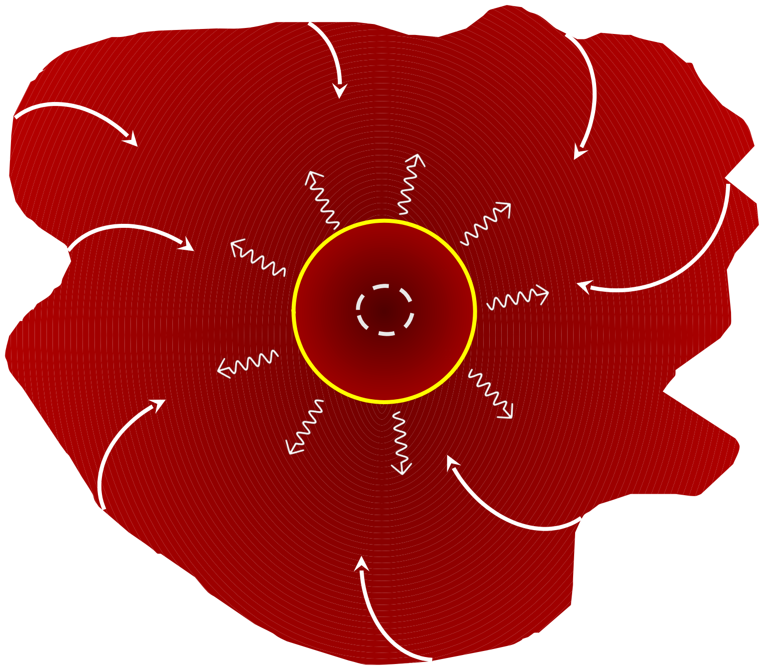




Star-like scenario: Larson (1969) sequence

$$\gamma_{eff} \approx \frac{5}{3} \ (T < 100\ K); \ \gamma_{eff} \approx \frac{7}{5} \ (T > 100\ K)$$





$\sim 5\ AU$

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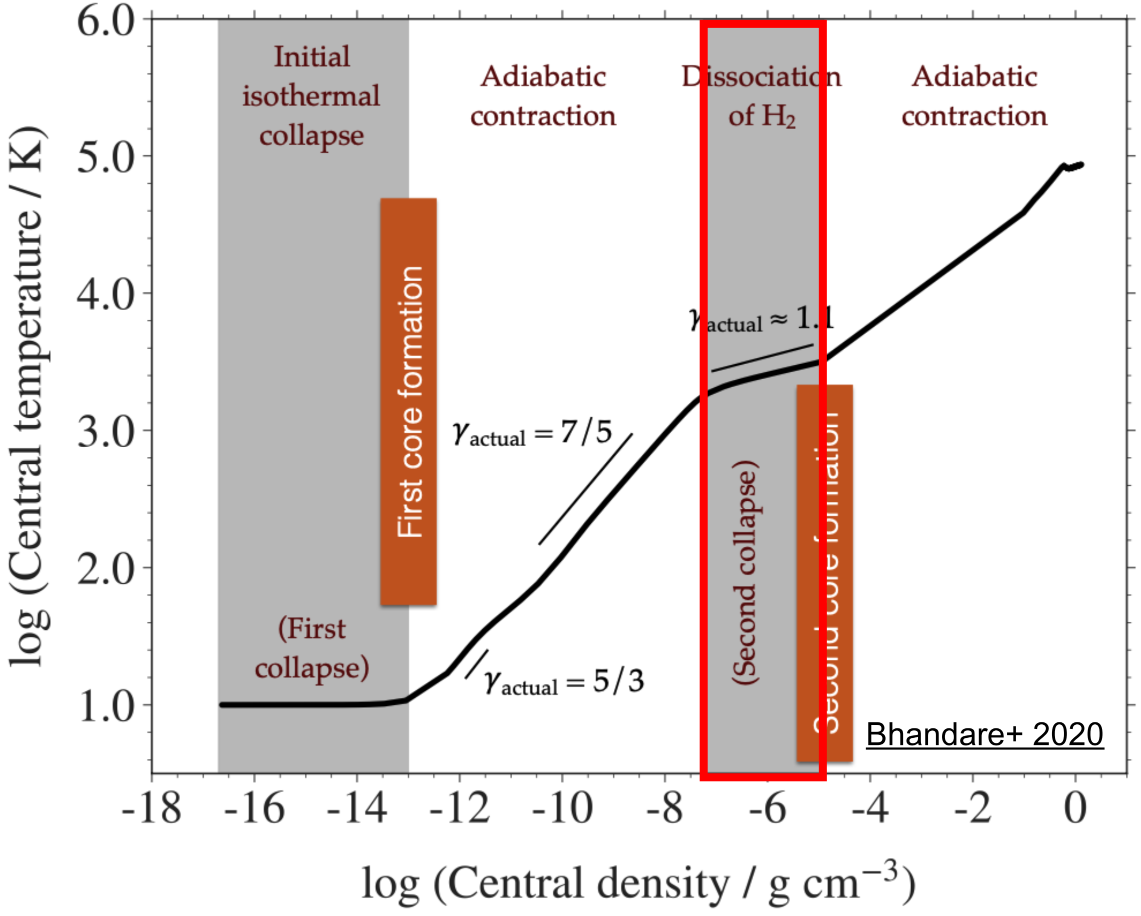
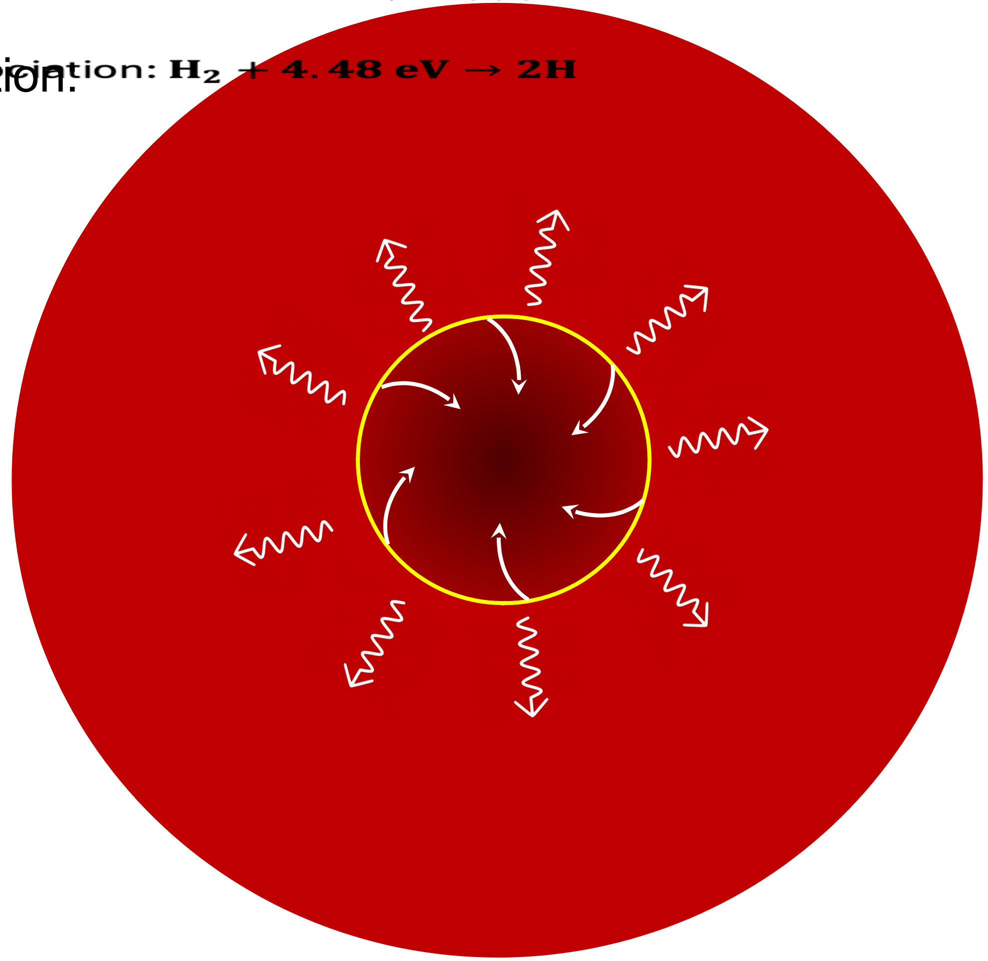


$\gamma_{eff} \approx 1.1$

$T > 2000$ K

dissociation: $H_2 + 4.48$ eV $\rightarrow 2H$



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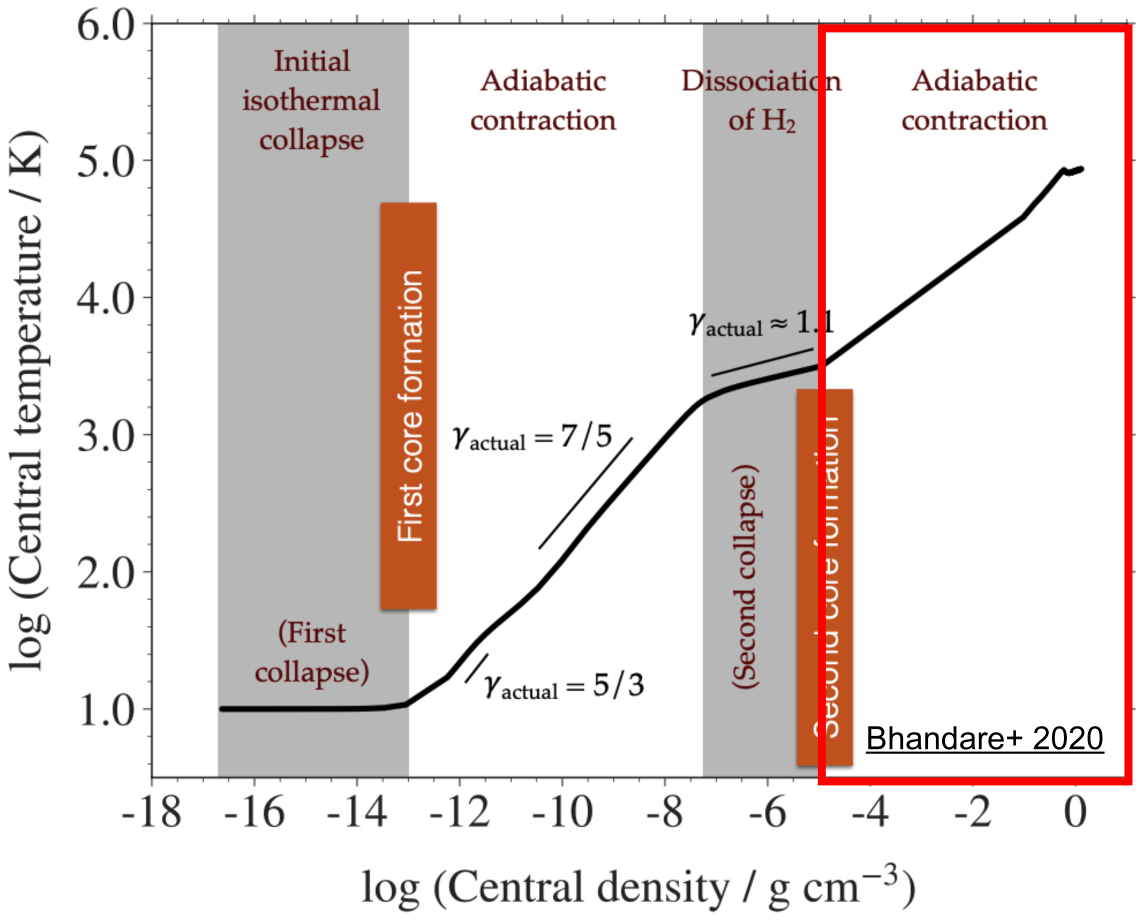

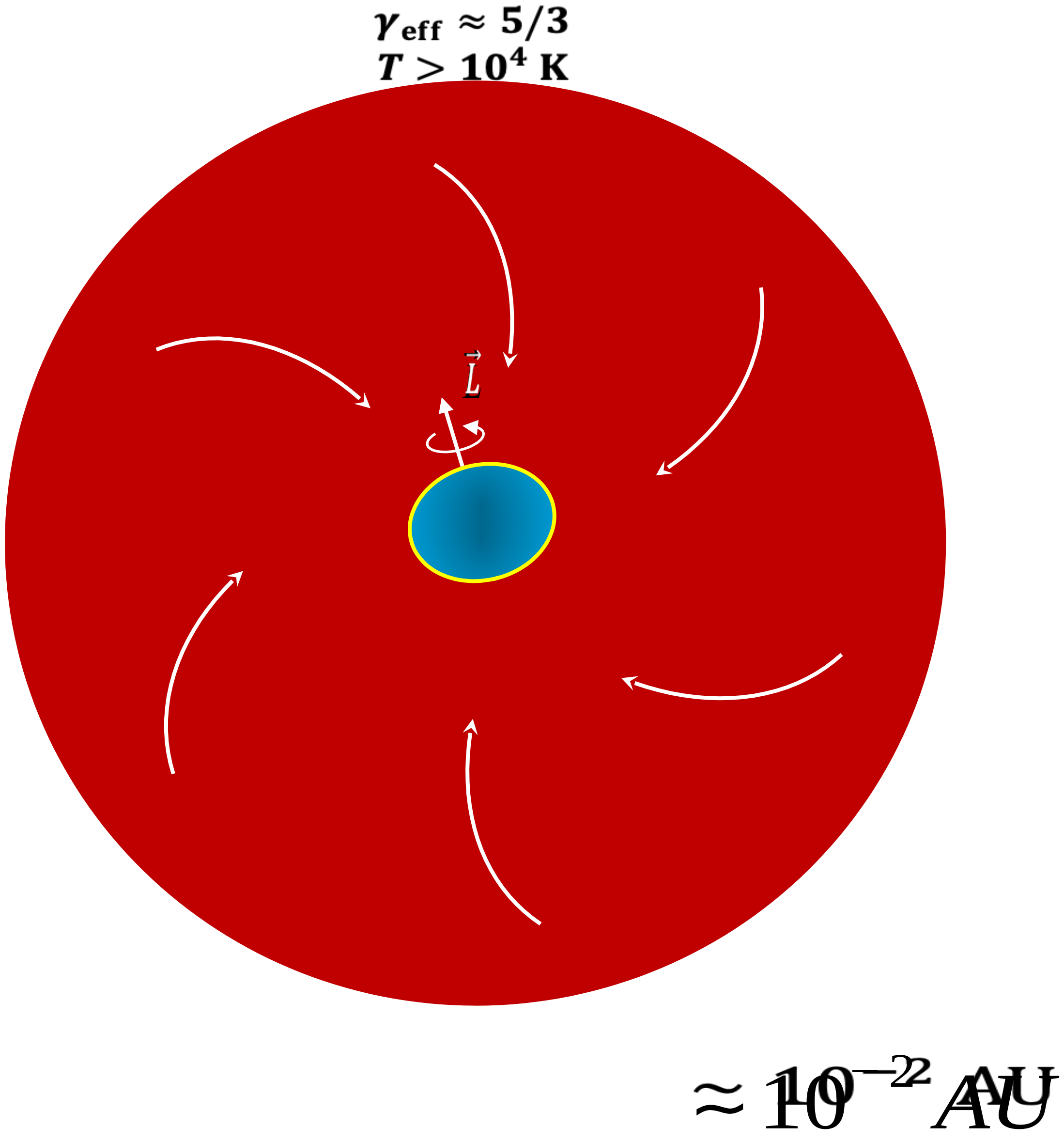

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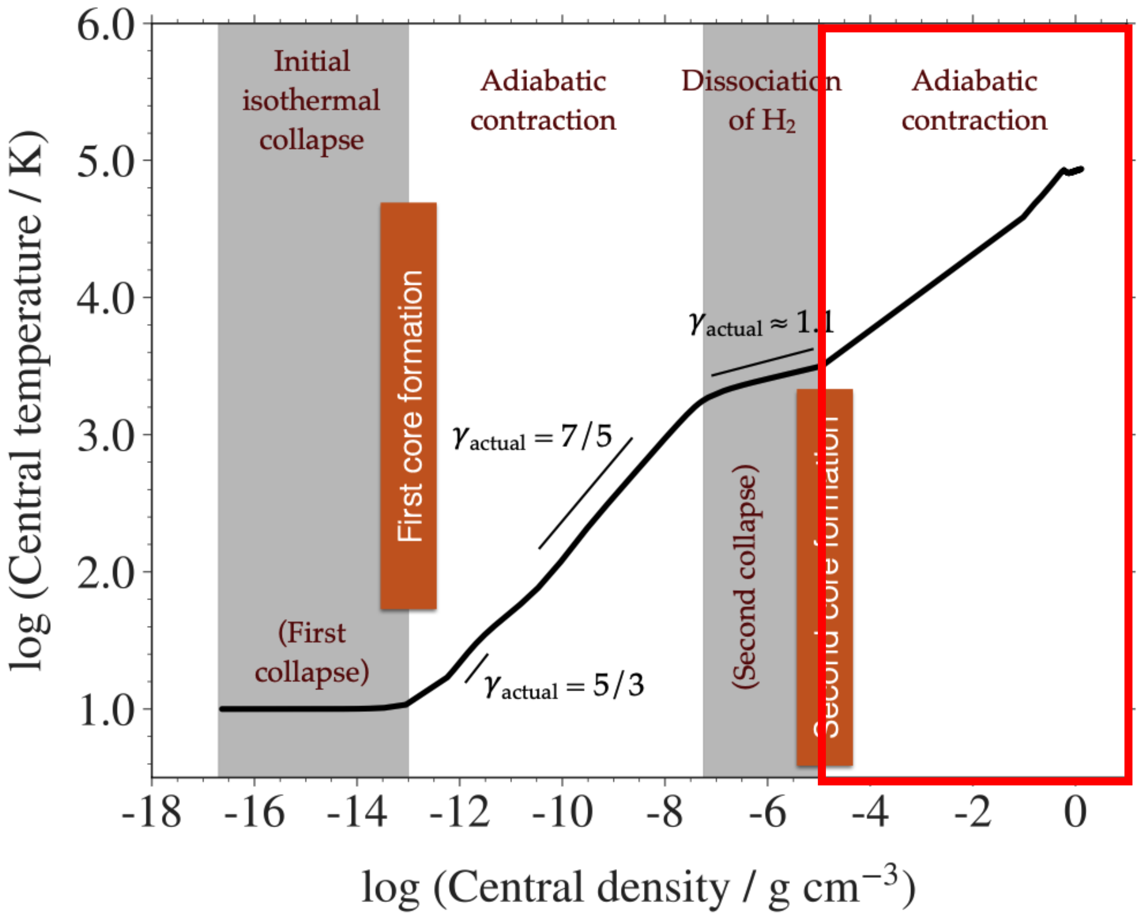
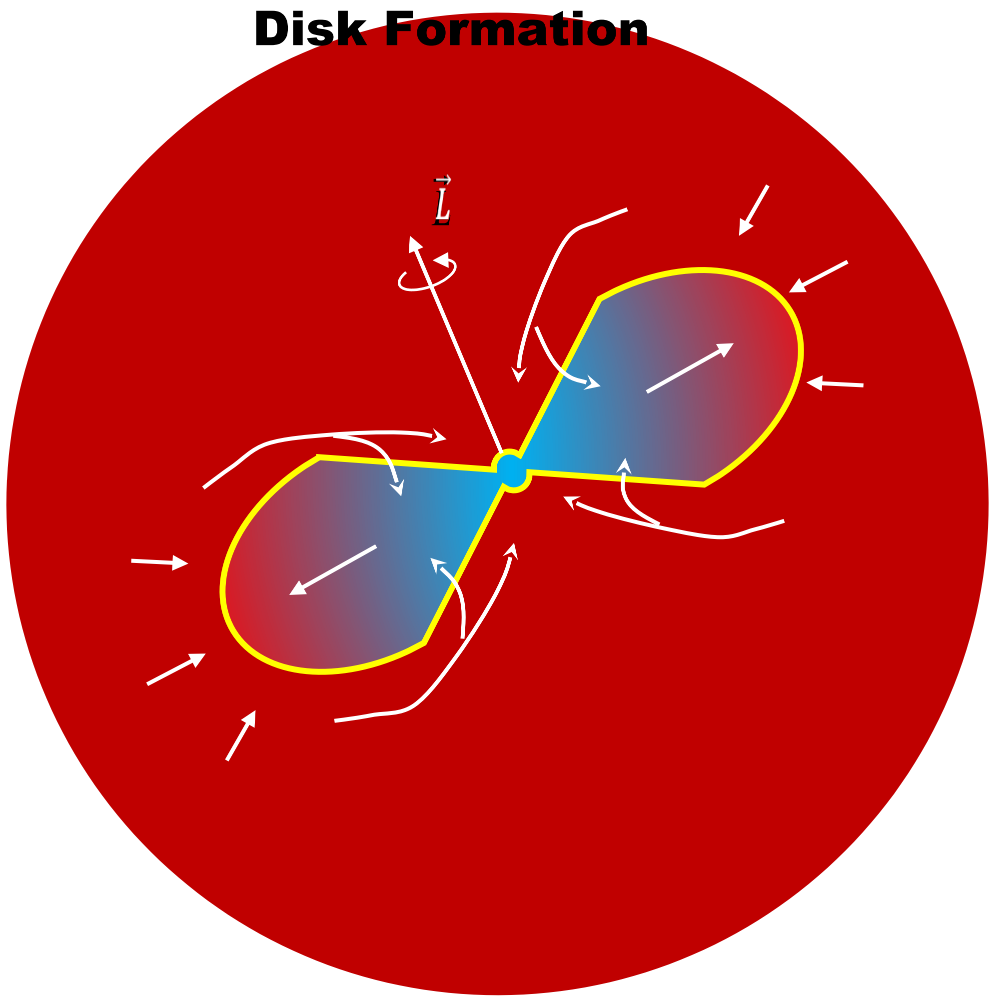
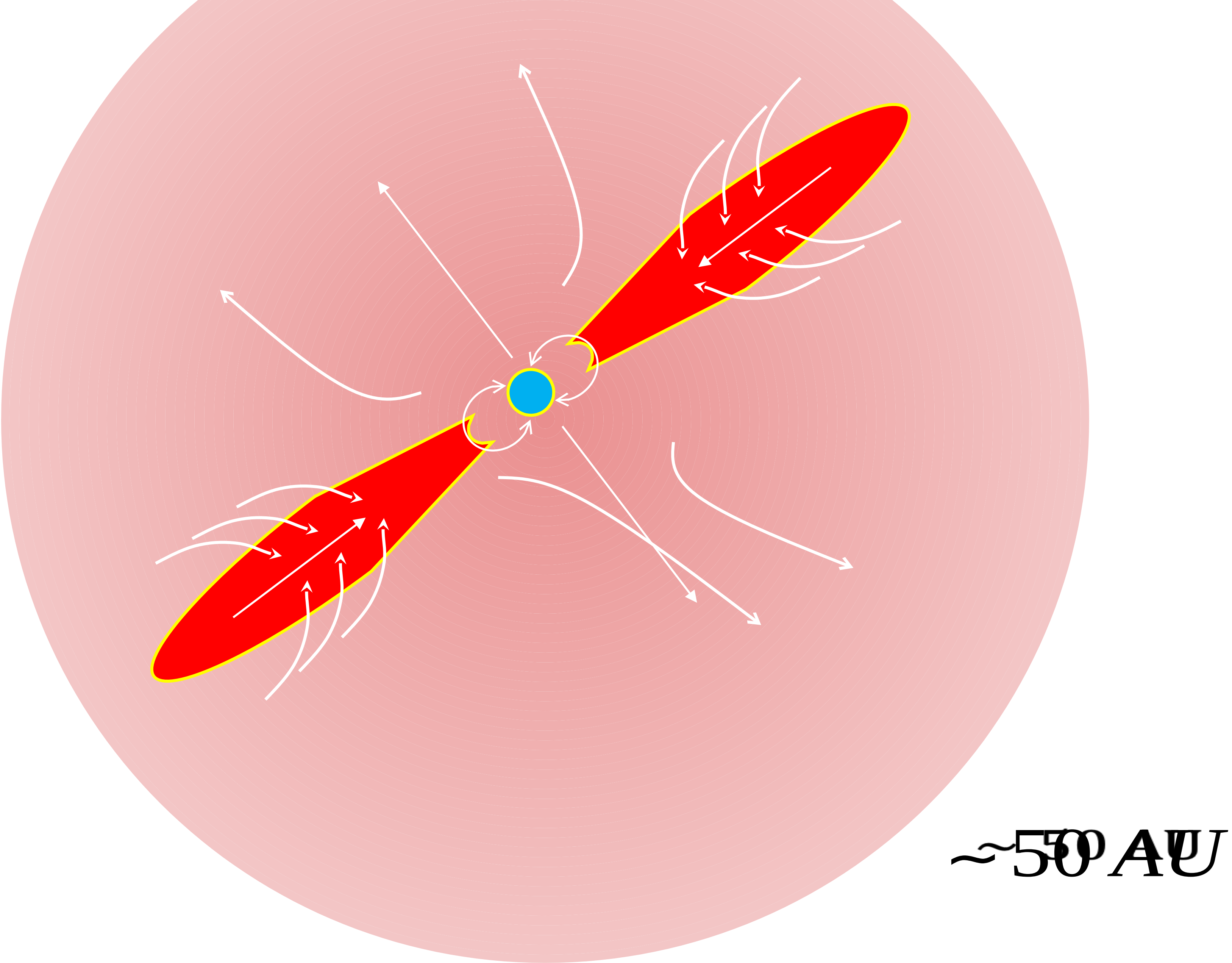




$\sim 1\,AU$

Star-like scenario: Larson (1969) sequence

Transition to class I system



Simulating a proto-Brown Dwarf with RAMSES (Teyssier 2002)

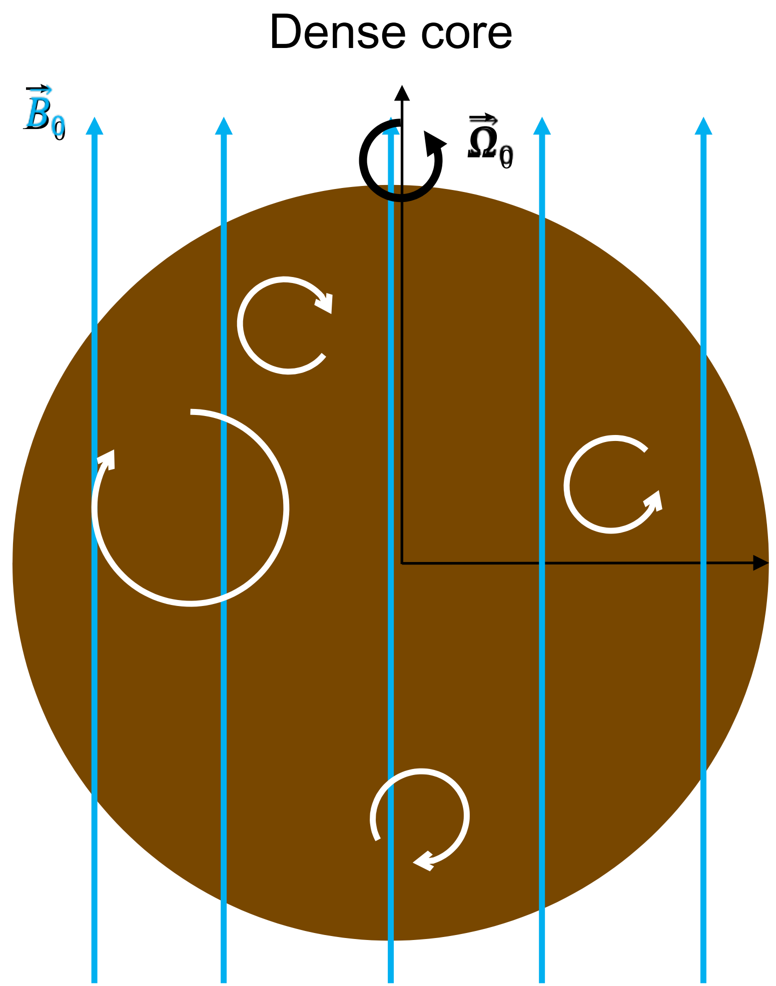
Physics included

- **Self-gravity**
- **Gray flux limited diffusion** (FLD) (Commerçon+ 2011,2014, González+ 2015)
- **Non-ideal MHD** with **Ambipolar diffusion** (NIMHD) (Teyssier+ 2006, Fromang+ 2006, Masson+ 2012)

Initial conditions

- Uniform density sphere with M_0, T_0
- Thermal to gravitational energy ratio $\alpha = 0.25$
- Turbulent Mach number $\mathcal{M}$
- Mass-to-flux ratio $\mu_m = \frac{(M/\phi)}{(M/\phi)_{crit}}$
- Very high resolution: AMR with $\ell_{\min} = 6, \ell_{\max} = 23$
  - $\Delta x_{\min} \sim 10^{-2}\ \mathrm{R}_\odot$
- 4 runs

R1	$0.05\ \mathrm{M}_\odot,\ \mathcal{M} = 0.4,\ \mu_m = 4,\ \Delta x_{\min} \approx 1.2\times10^{-2}\ \mathrm{R}_\odot$
R2	$0.1\ \mathrm{M}_\odot,\ \mathcal{M} = 0.4,\ \mu_m = 4,\ \Delta x_{\min} \approx 5\times10^{-2}\ \mathrm{R}_\odot$
R3	$0.1\ \mathrm{M}_\odot,\ \mathcal{M} = 0.1,\ \mu_m = 4,\ \Delta x_{\min} \approx 2.5\times10^{-2}\ \mathrm{R}_\odot$
R4	$0.1\ \mathrm{M}_\odot,\ \mathcal{M} = 0.4,\ \mu_m = 8\ \Delta x_{\min} \approx 2.5\times10^{-2}\ \mathrm{R}_\odot$



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R4 $0.1\ \mathrm{M}_\odot,\ \mathcal{M} = 0.4,\ \mu_m = 8,\ \Delta x_{\min} \approx 2.5\times10^{-2}\ \mathrm{R}_\odot$

- Classical Larson sequence followed by all runs

- **First core lifetimes differ significantly**

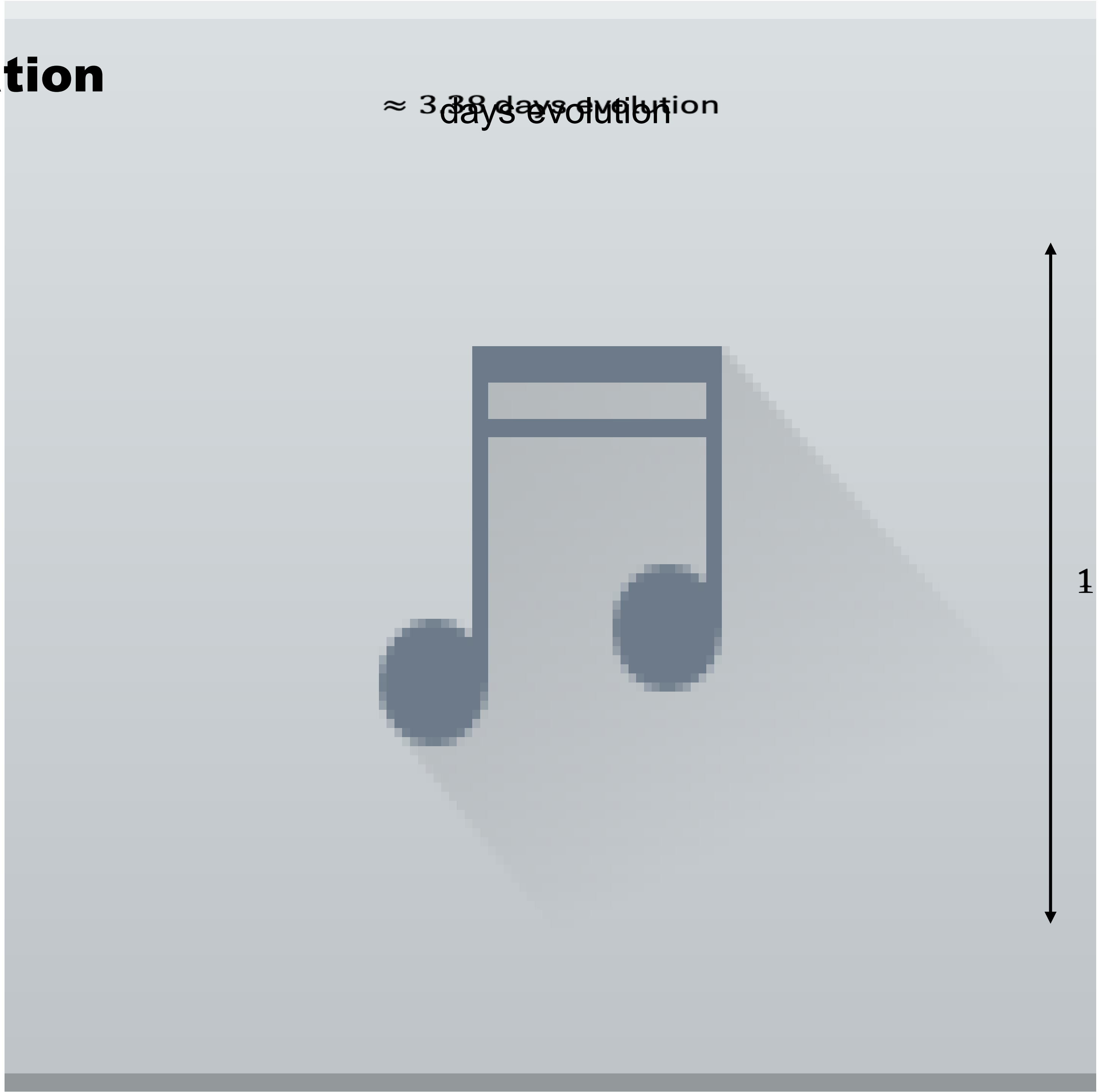
Magnetic Fields & $\mathcal{M}_0$ primary factors

Magnetic Fields & primary factors

Proto-Brown Dwarf formation

Properties at birth:

$$R_* \approx 0.75\ \mathrm{R_\odot}$$
$$M_* \approx 0.8\ \mathrm{M_{Jup}}$$



Proto-Brown Dwarf early evolution

- Similar evolution of **global properties** (M_*, R_*) after birth

Similar evolution of global properties () after birth

Accretion causes swelling

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Proto-Brown Dwarf structure

R1 $0.05\ M_\odot,\ \mathcal{M} = 0.4,\ \mu_m = 4,\ \Delta x_{\rm min} \approx 1.2\times10^{-2}\ R_\odot$

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R1 **R2** **R3** **R4**

Specific entropy

- Interior stucture of proto-Brown Dwarfs is sensitive to initial conditions
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- Proto-Brown Dwarfs are **radiatively stable**, $\frac{ds}{dr} > 0$ (Ledoux criterion)
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Proto-Brown Dwarf 3D structure

Strong toroidal & poloidal interior field $\frac{B_\phi}{B_p} \sim 3$

$\frac{B_\phi}{B_p} \sim 3$

MHD turbulence

Surface magnetic loops

Dipolar surface field ~ kG strength

Dipolar surface field strength

Entropy mixing by turbulence

Conclusion

- Brown Dwarf formation through gravitational collapse indeed possible
- Nascent proto-BDs early evolution is highly dynamical
- Interior structure of proto-BDs sensitive to initial conditions
- Nascent BDs should have magnetic fields of strength

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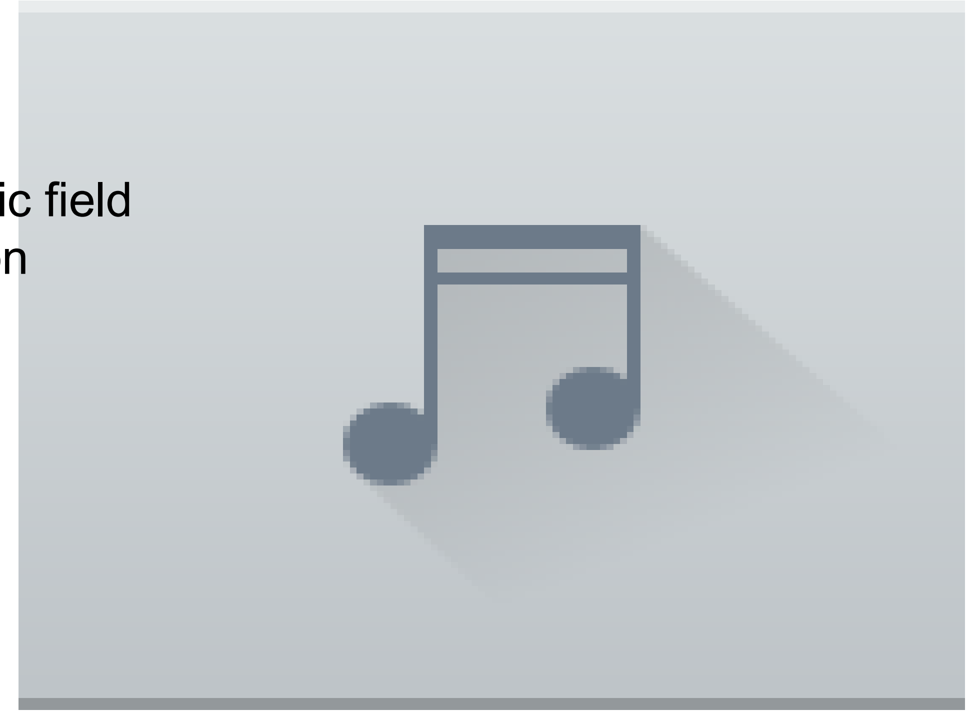
Perspectives

Magnetic field evolution



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Low velocity outflow at first core scales

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Disk formation around proto-BD