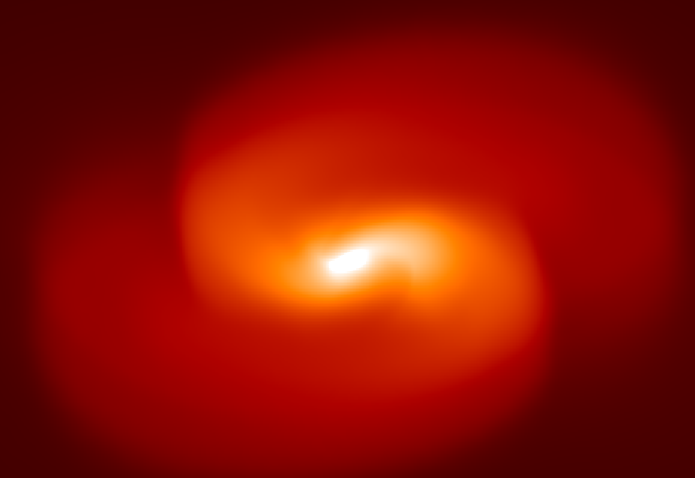
Low-mass star formation with non-ideal magnetohydrodynamics



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with Matthew Bate & Daniel Price

The Wonders of Star Formation
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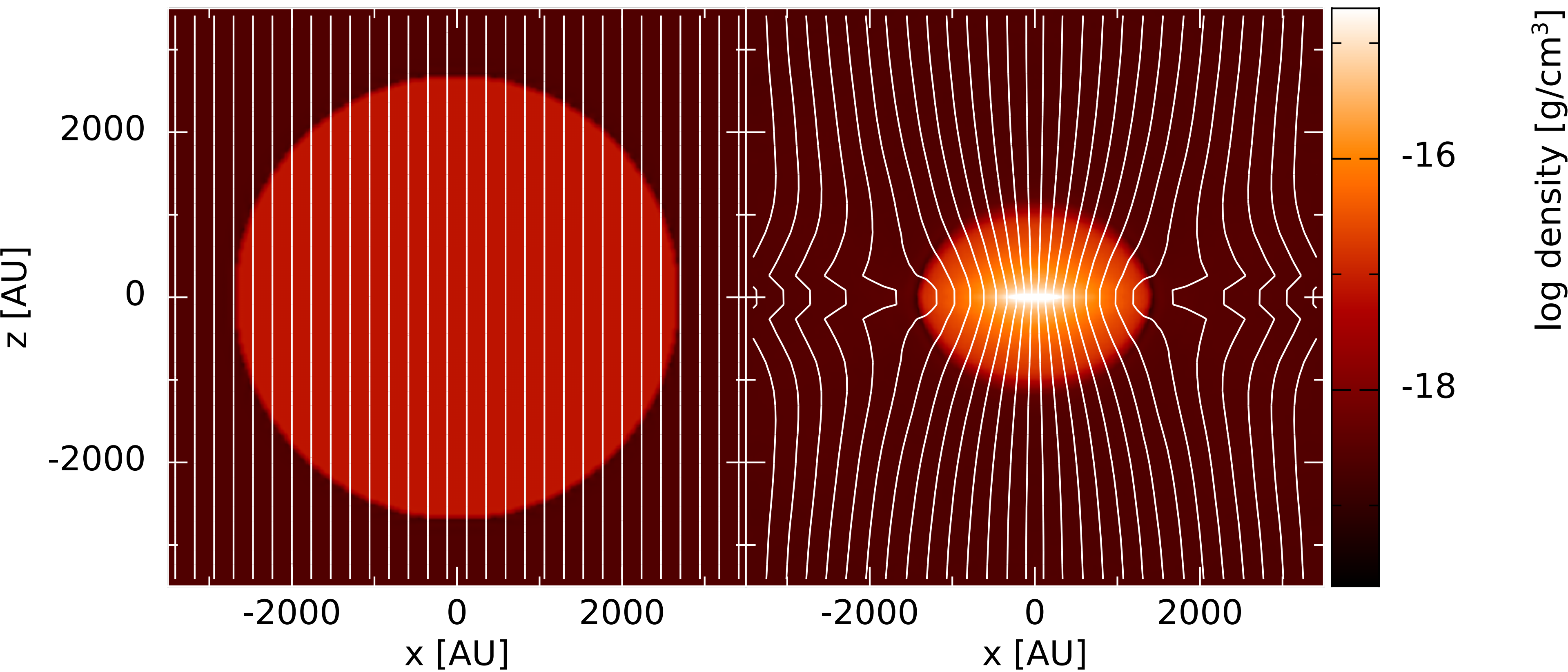
Magnetic fields in molecular clouds

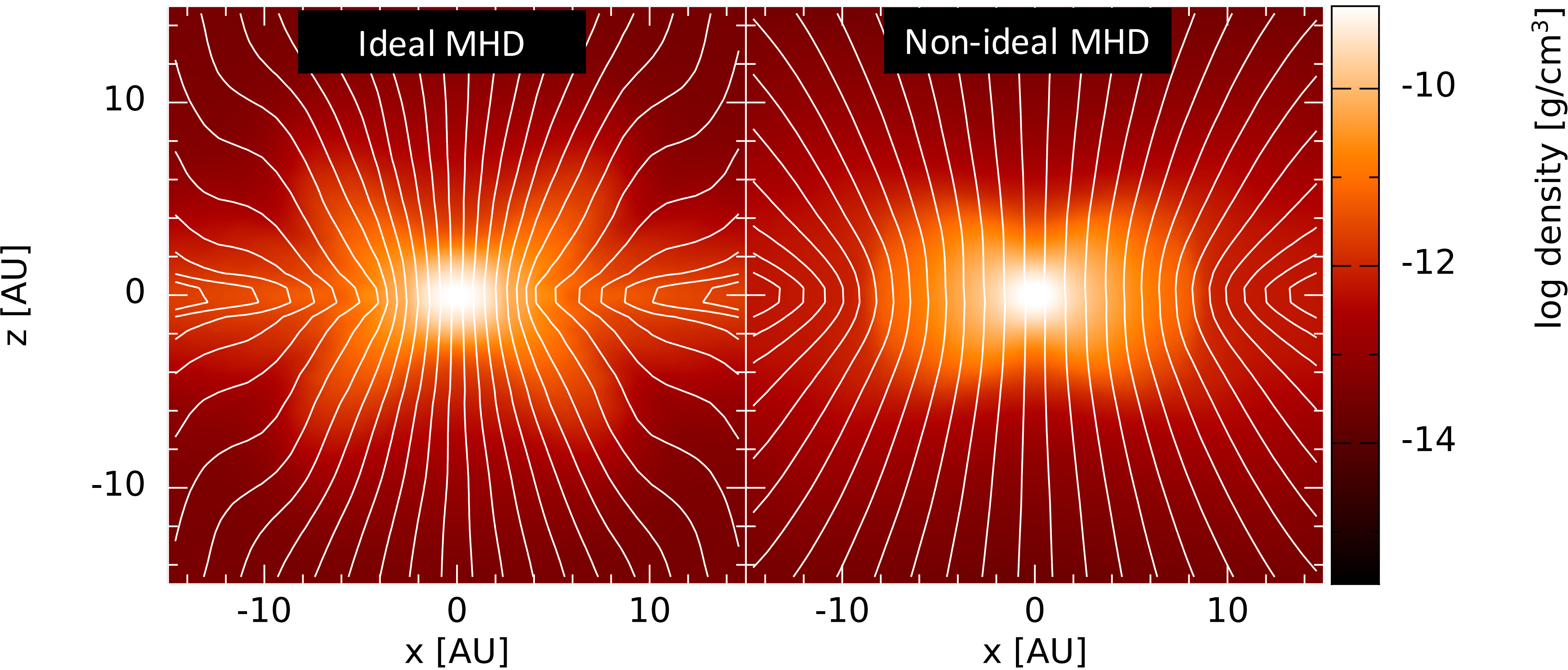
- Strong field; large scale structure



Density (rendered) + Magnetic field lines. Ideal MHD.
Left: Typical (idealised) initial conditions in numerical simulations (collapsing spherical clouds).
Right: at $\rho_{max} = 10^{-9}$ g cm^{-3}

Magnetic fields in molecular clouds

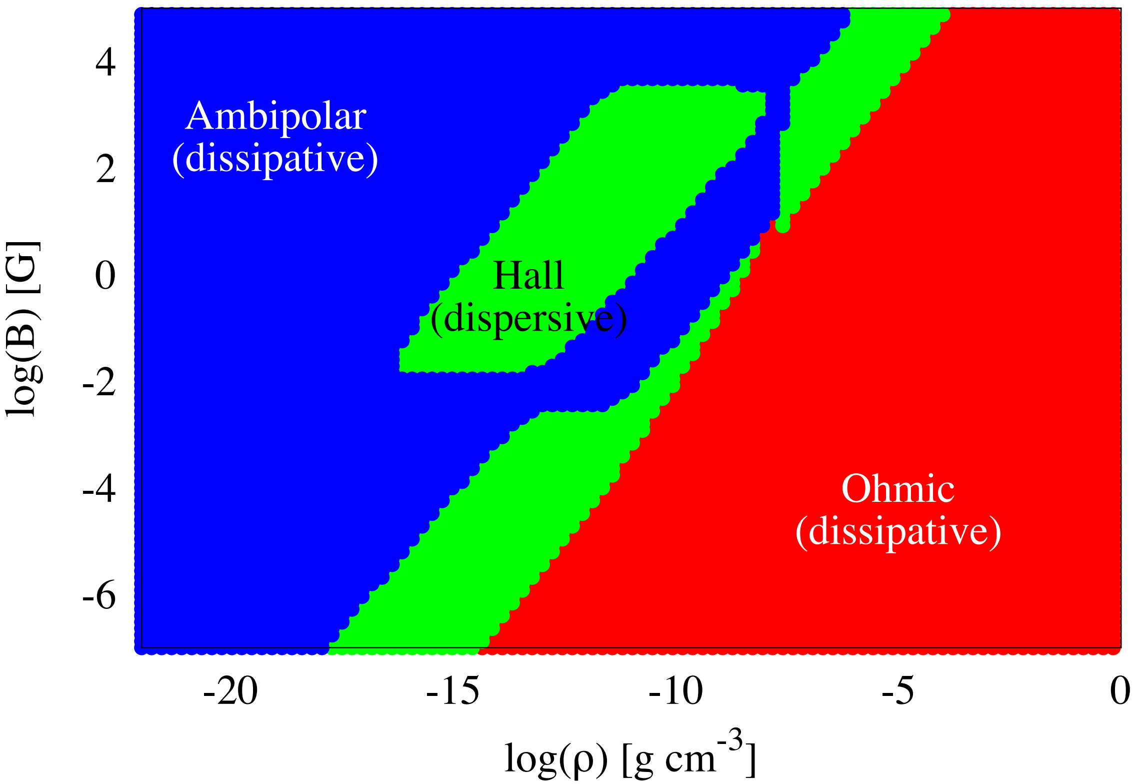
- Strong field; small scale structure



Leads to:
- Very high central magnetic field strength
- Efficient transport of angular momentum
- Discs not forming

Leads to:
- Weak central magnetic field strengths
- Weak surrounding magnetic fields
- Rotationally supported discs

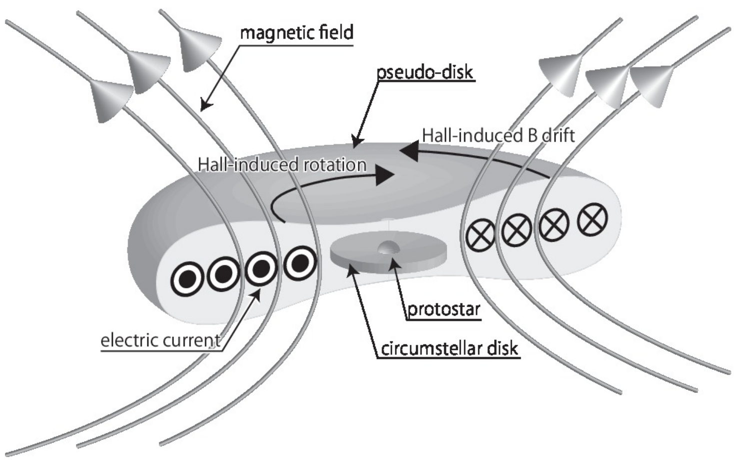
Non-ideal magnetohydrodynamics



$$\left.\frac{\mathrm{d}\boldsymbol{B}}{\mathrm{d}t}\right|_{\mathrm{OR}} = -\boldsymbol{\nabla} \times \eta_{\mathrm{OR}} \left(\boldsymbol{\nabla} \times \boldsymbol{B}\right),$$

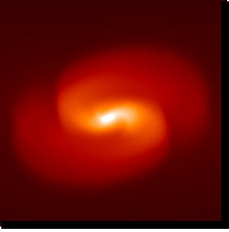
$$\left.\frac{\mathrm{d}\boldsymbol{B}}{\mathrm{d}t}\right|_{\mathrm{HE}} = -\boldsymbol{\nabla} \times \eta_{\mathrm{HE}} \left[\left(\boldsymbol{\nabla} \times \boldsymbol{B}\right) \times \hat{\boldsymbol{B}}\right],$$

$$\left.\frac{\mathrm{d}\boldsymbol{B}}{\mathrm{d}t}\right|_{\mathrm{AD}} = \boldsymbol{\nabla} \times \eta_{\mathrm{AD}} \left\{\left[\left(\boldsymbol{\nabla} \times \boldsymbol{B}\right) \times \hat{\boldsymbol{B}}\right] \times \hat{\boldsymbol{B}}\right\}.$$

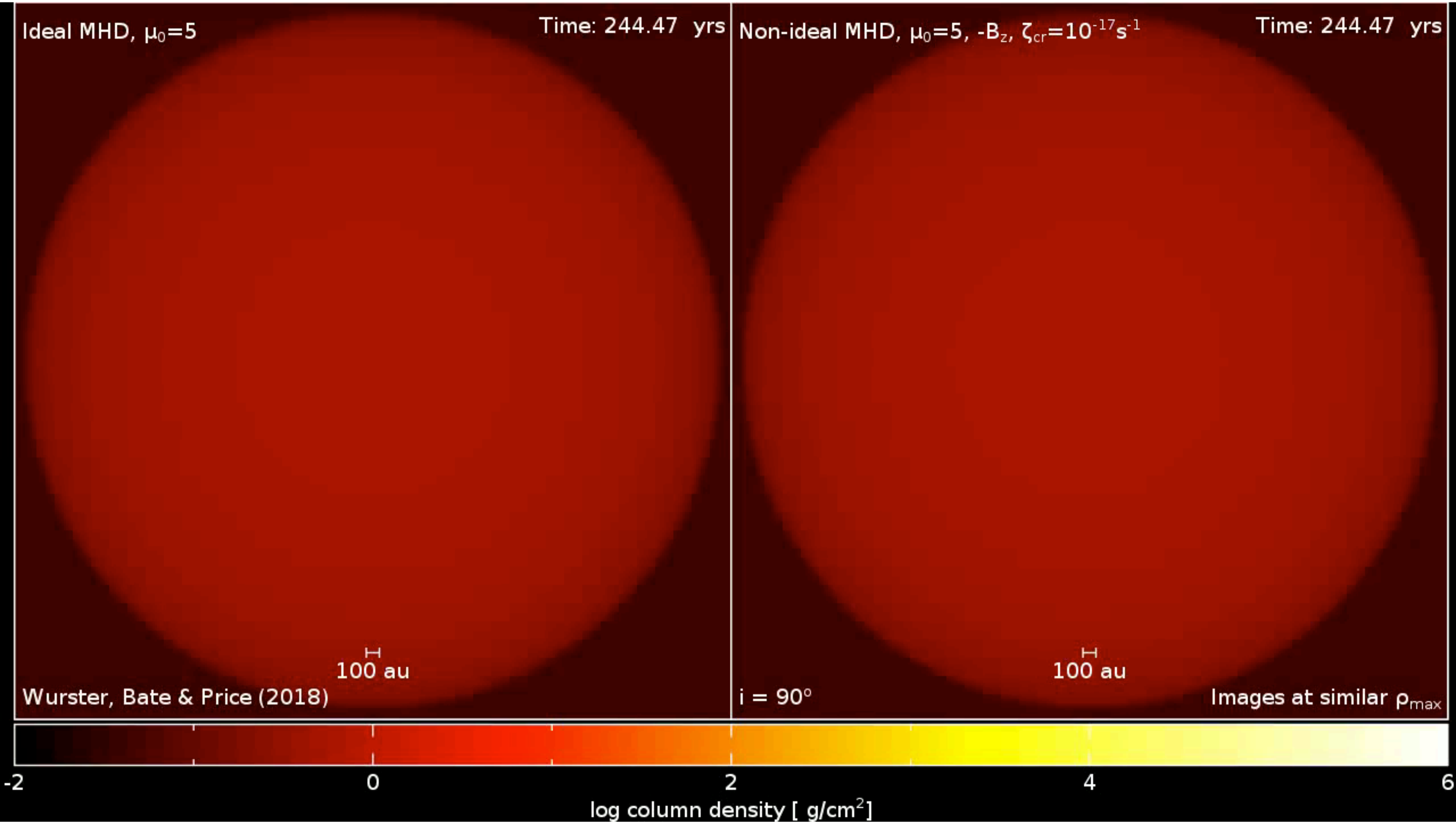


Adapted from Wardle (2007)
Made using NICIL (Wurster, 2016)

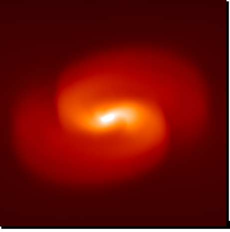
Image credit: Tsukamoto et al (2017);
see also: Braiding & Wardle (2012a,b)



Collapse to stellar densities: Evolution of the density

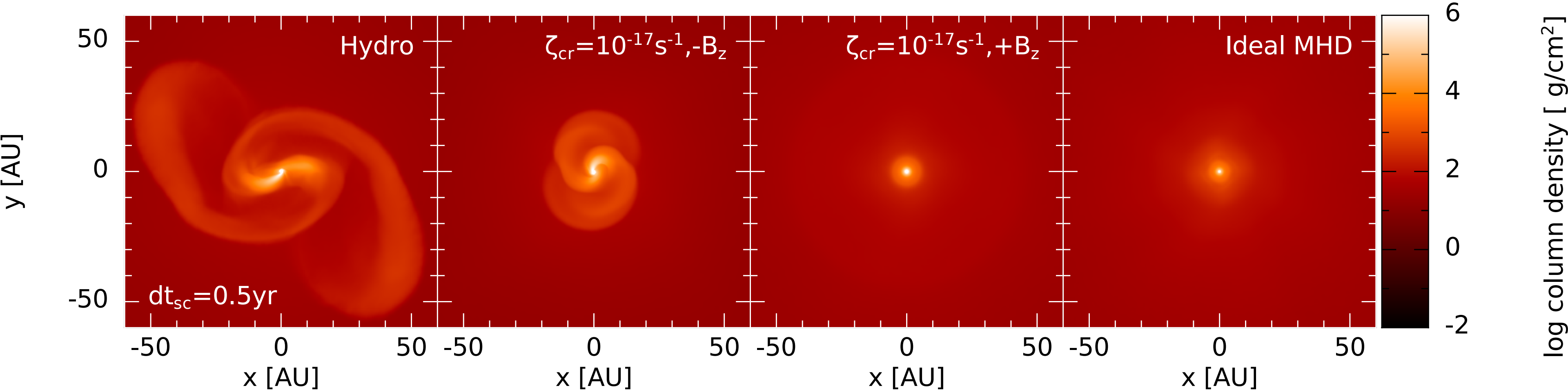


Wurster, Bate & Price (2018c). Video available at https://www.youtube.com/watch?v=duaA1bu2wf8



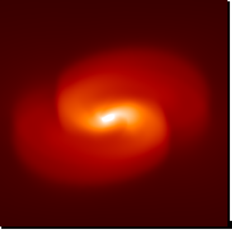
Density

- After stellar core formation



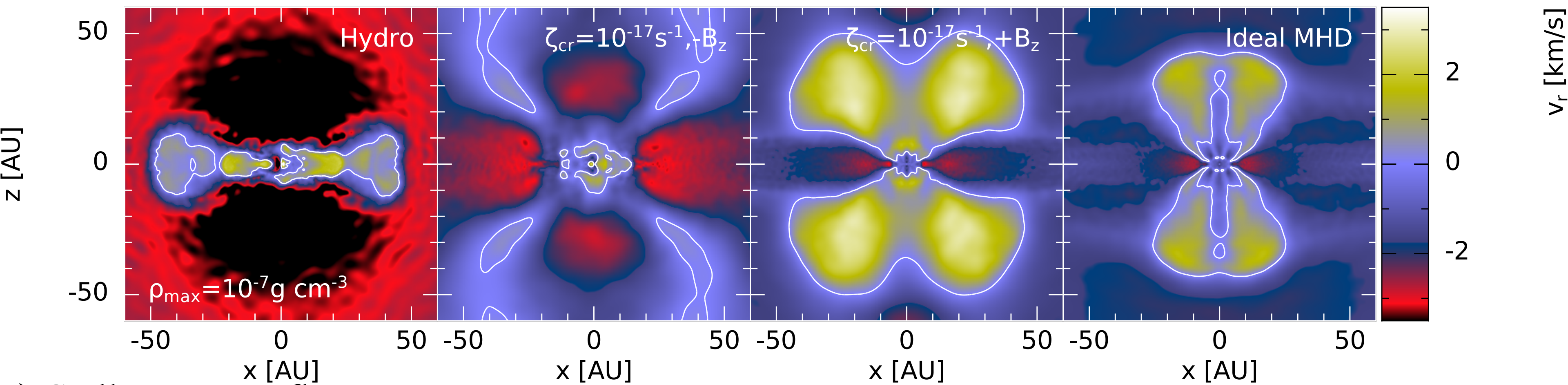
- Hydro: forms a 50au disc early during the first hydrostatic core phase
- Non-ideal with $-B_z$: forms a 25au disc during the first hydrostatic core phase
- Non-ideal with $+B_z$: forms a 1au disc by the stellar core phase
- Ideal: never forms a rotationally supported disc

Wurster, Bate & Price (2018a,c,d)

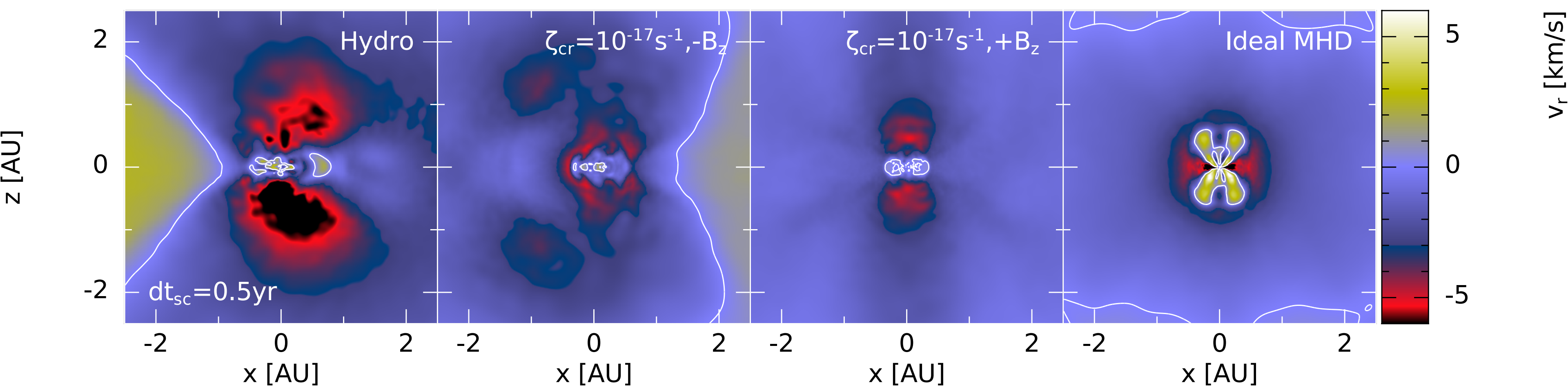


Radial outflows

- First core outflows:

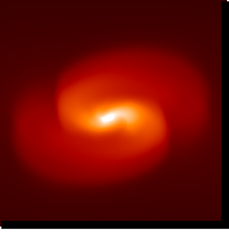


- Stellar core outflows:



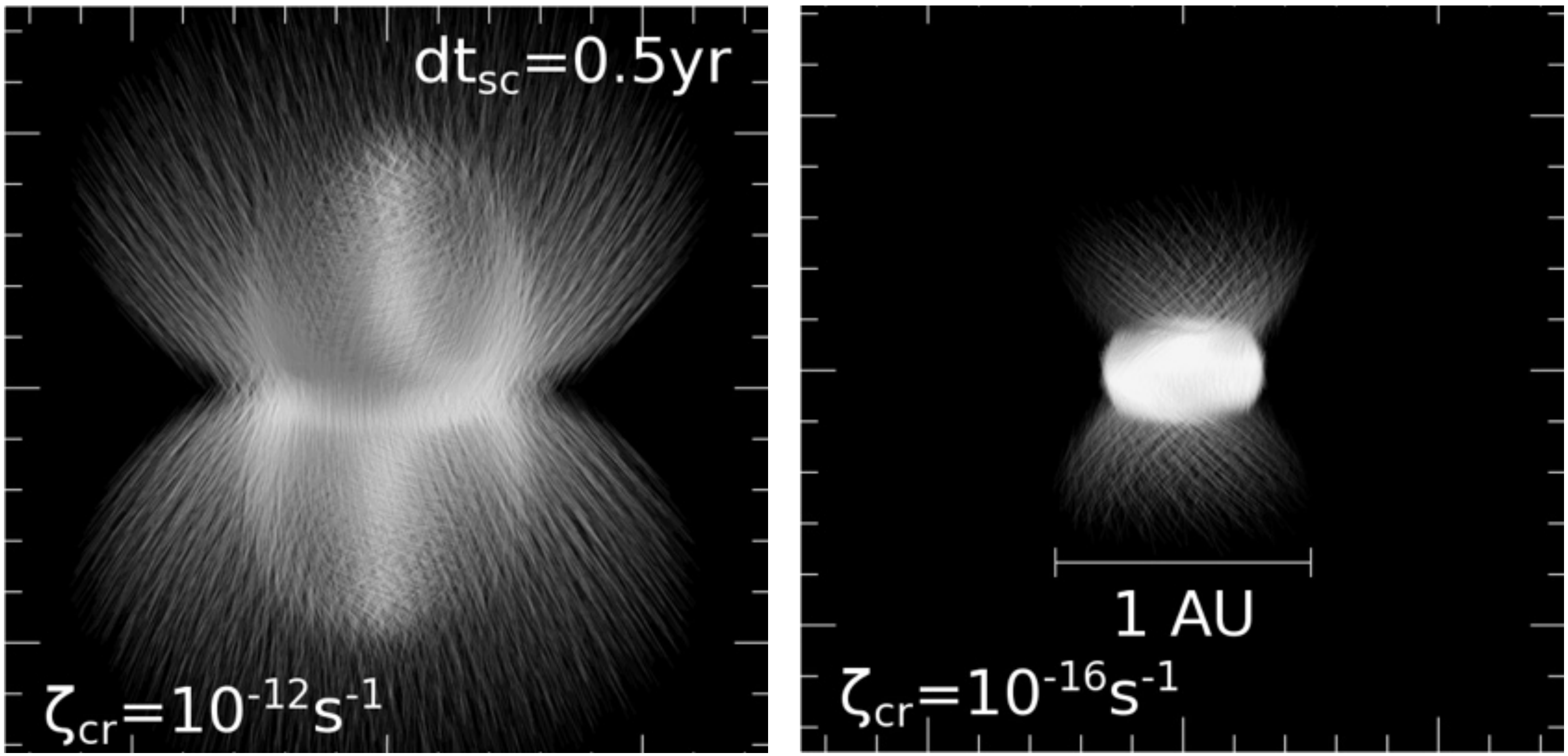
- Outflow speed is dependent on realistic $\boldsymbol{\zeta}_{cr}$ and the Hall effect

Wurster, Bate & Price (2018a,c)

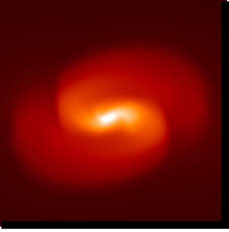


Core evolution

➢Strong kG magnetic fields are observed in stars. Are they fossil, or dynamo-generated?

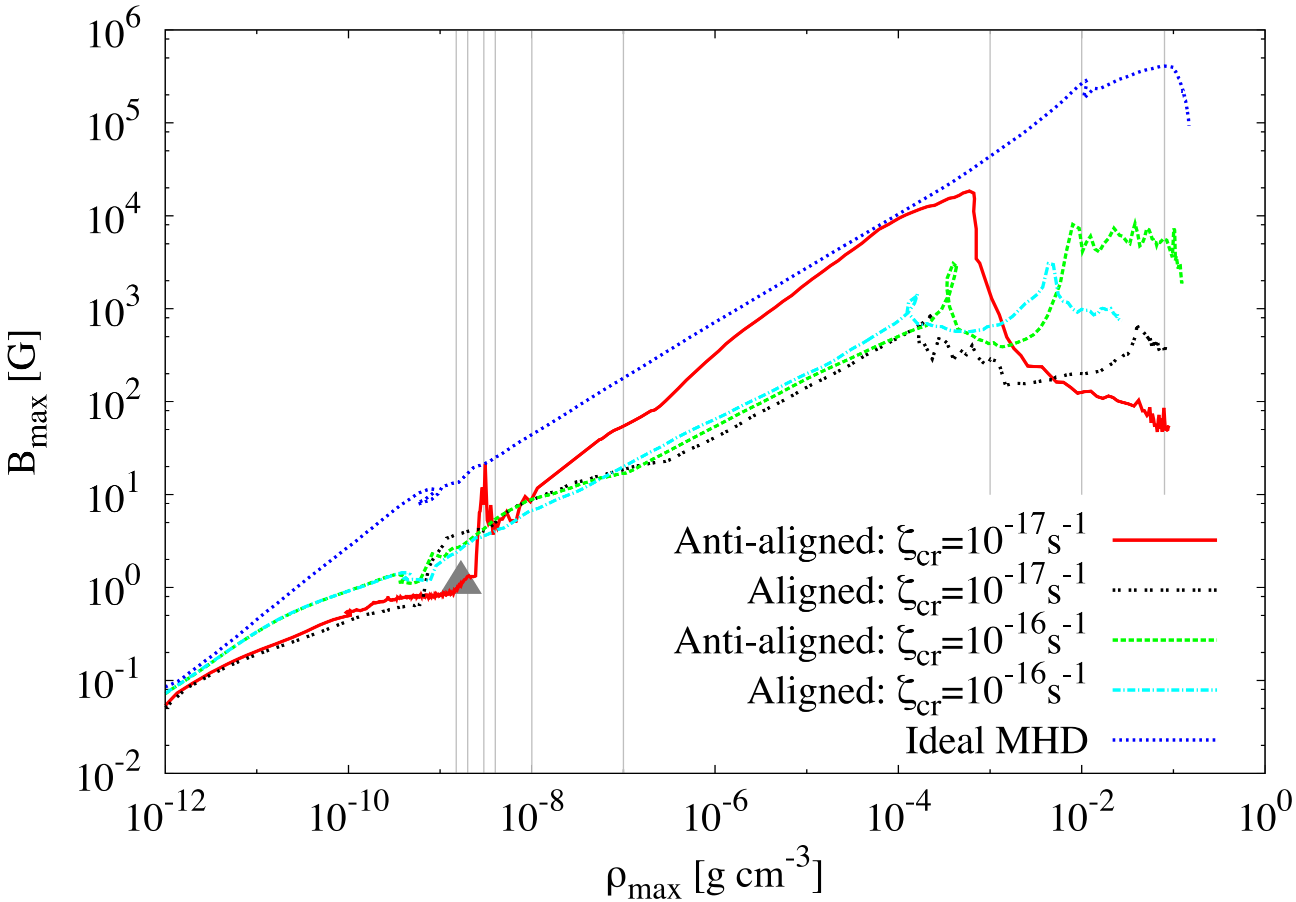


Wurster, Bate & Price (2018a)

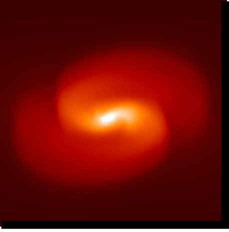


Magnetic field strength

- The maximum magnetic field strength is stronger in the ideal MHD model than when using non-ideal MHD

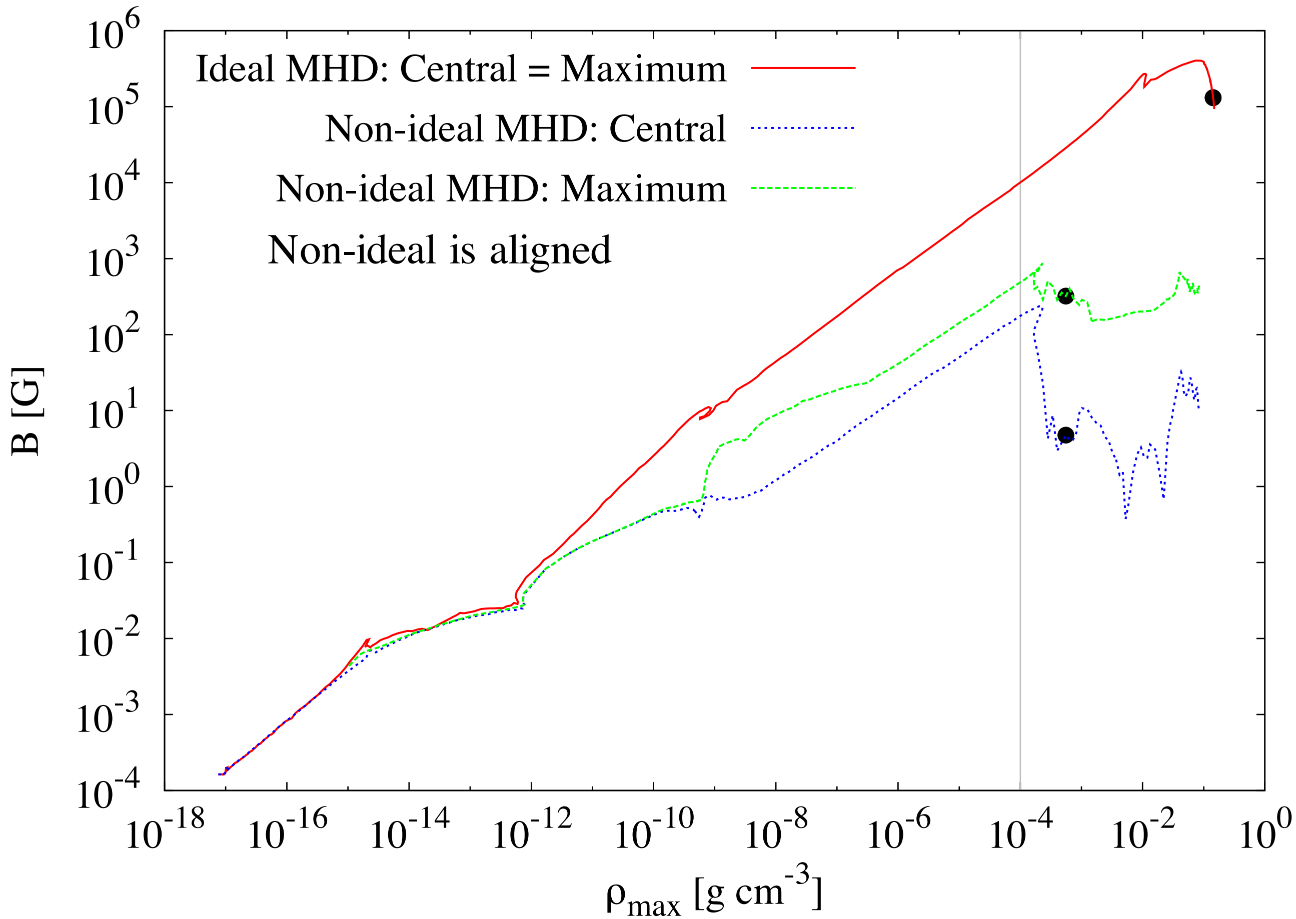


Wurster, Bate & Price (2018c)



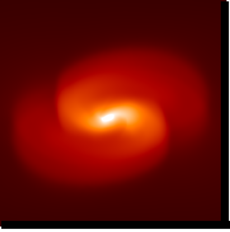
Magnetic field strength

- ➢The maximum magnetic field strength is not coincident with the central magnetic field strength in non-ideal MHD



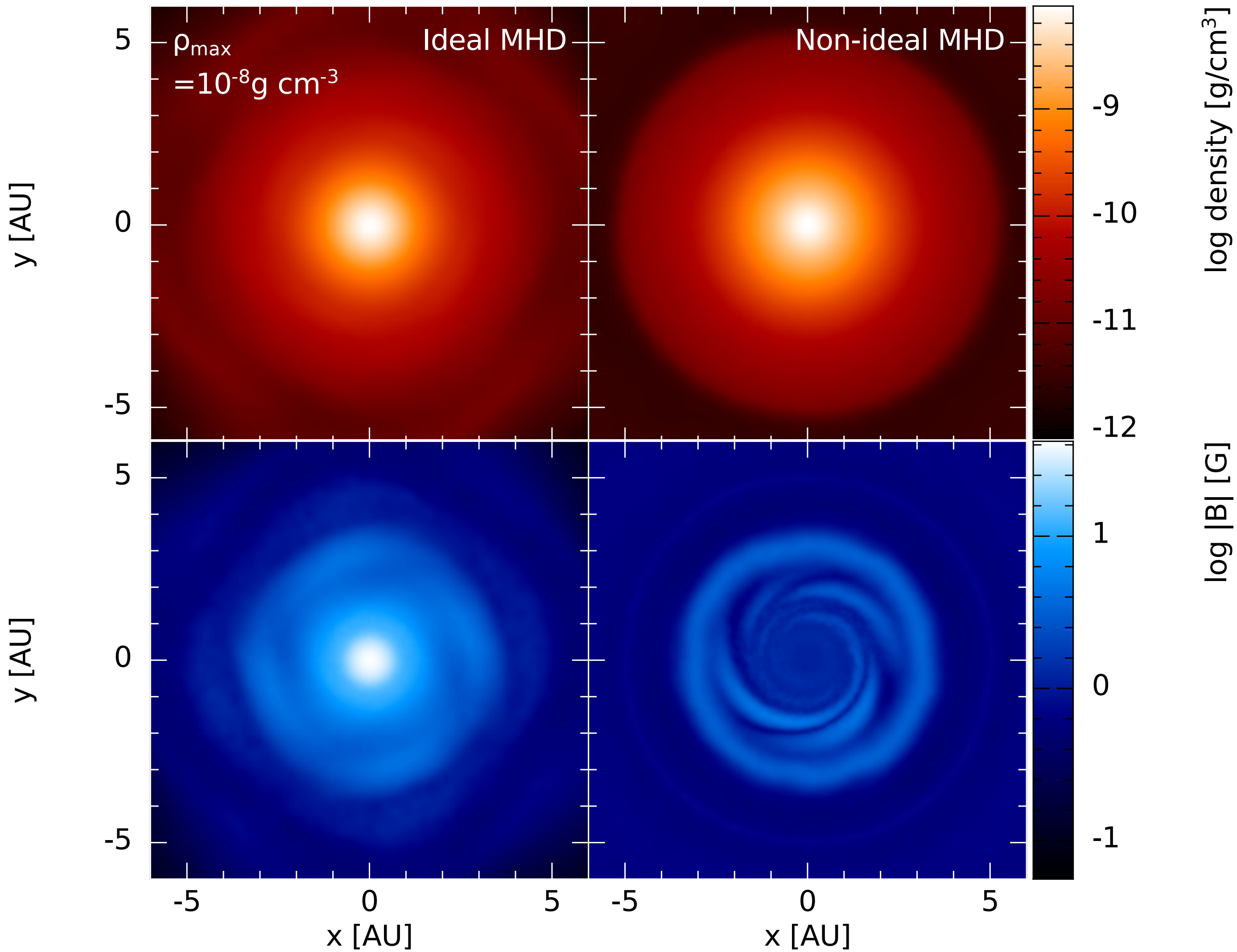
- ➢Black dots represent 6mo after stellar core formation

Wurster, Bate & Price (2018d)



Magnetic field structure

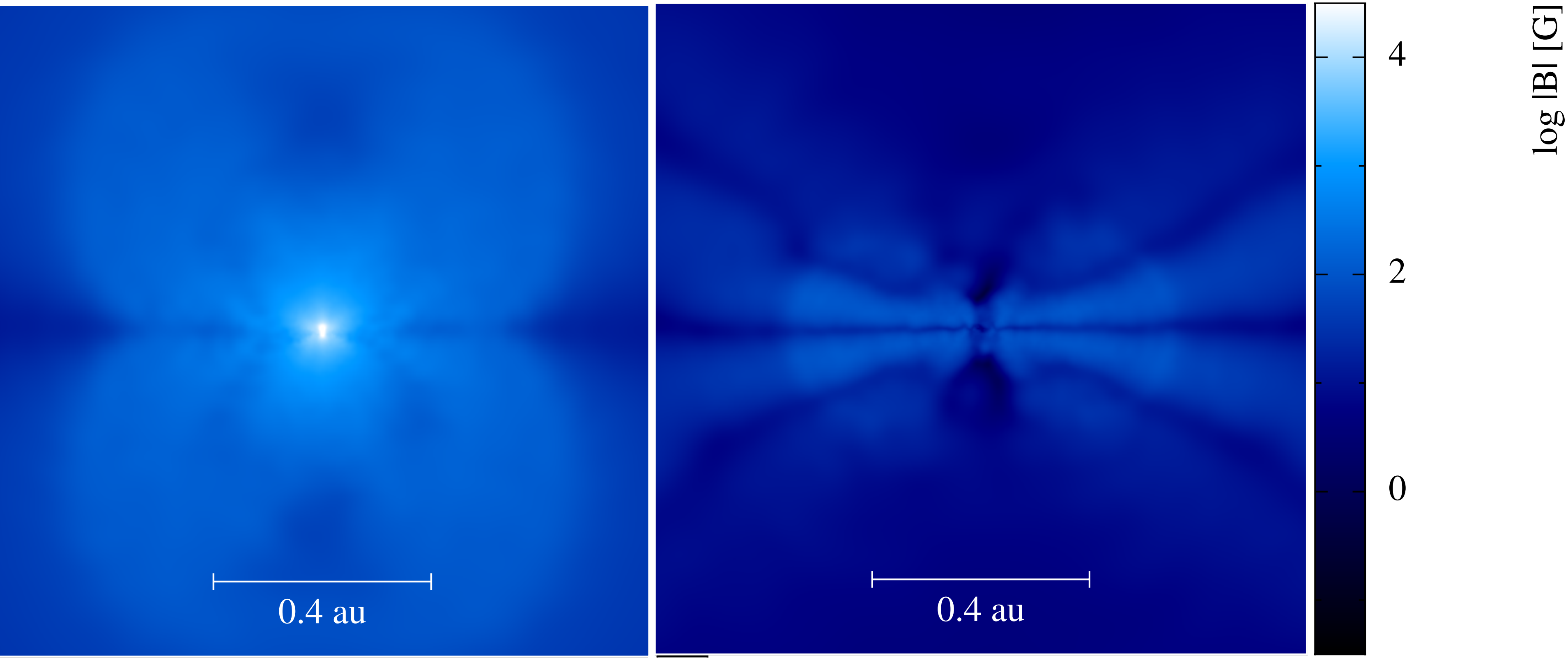
➢Ideal vs aligned non-ideal MHD: during the first hydrostatic core phase



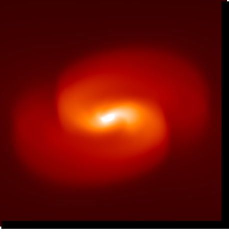
Wurster, Bate & Price (2018d)

Magnetic field structure

➢Ideal vs aligned non-ideal MHD: 6mo after stellar core formation (x-z plane)

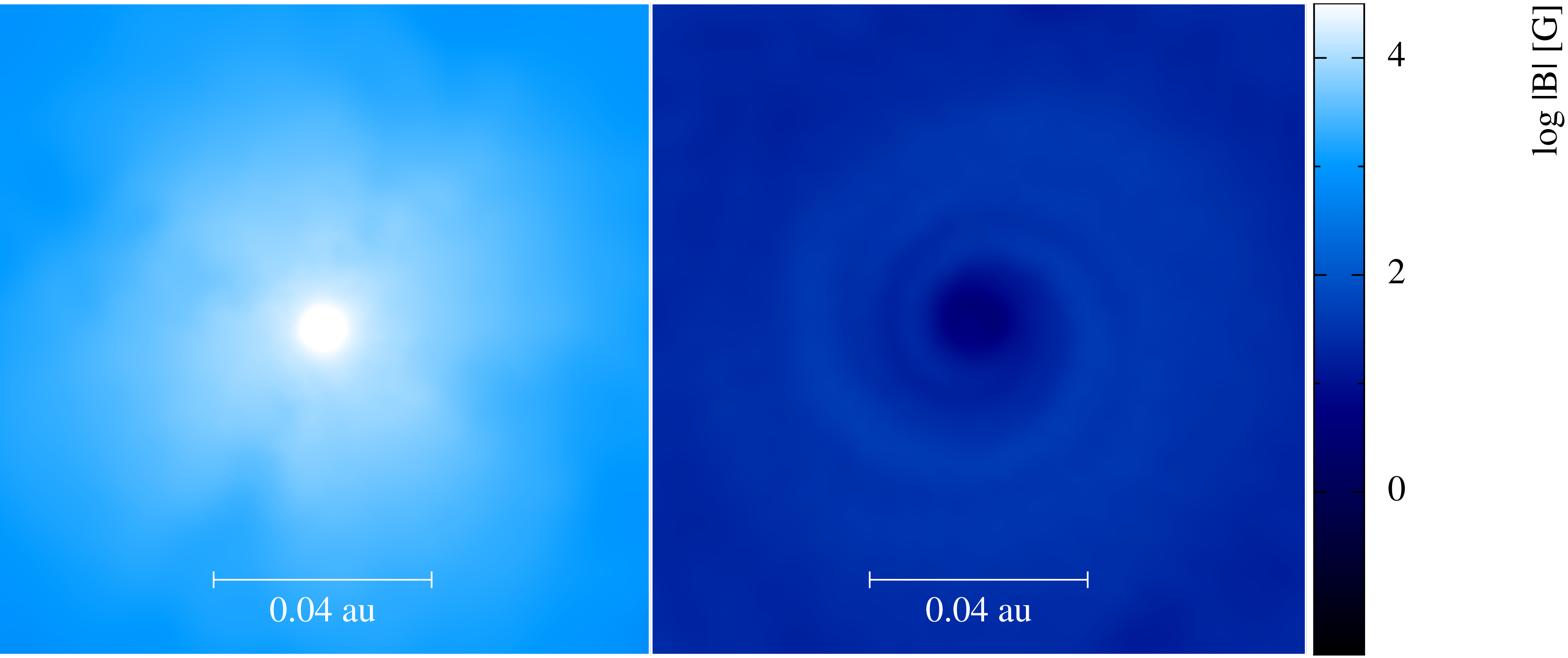


Wurster, Bate & Price (2018d)



Magnetic field structure

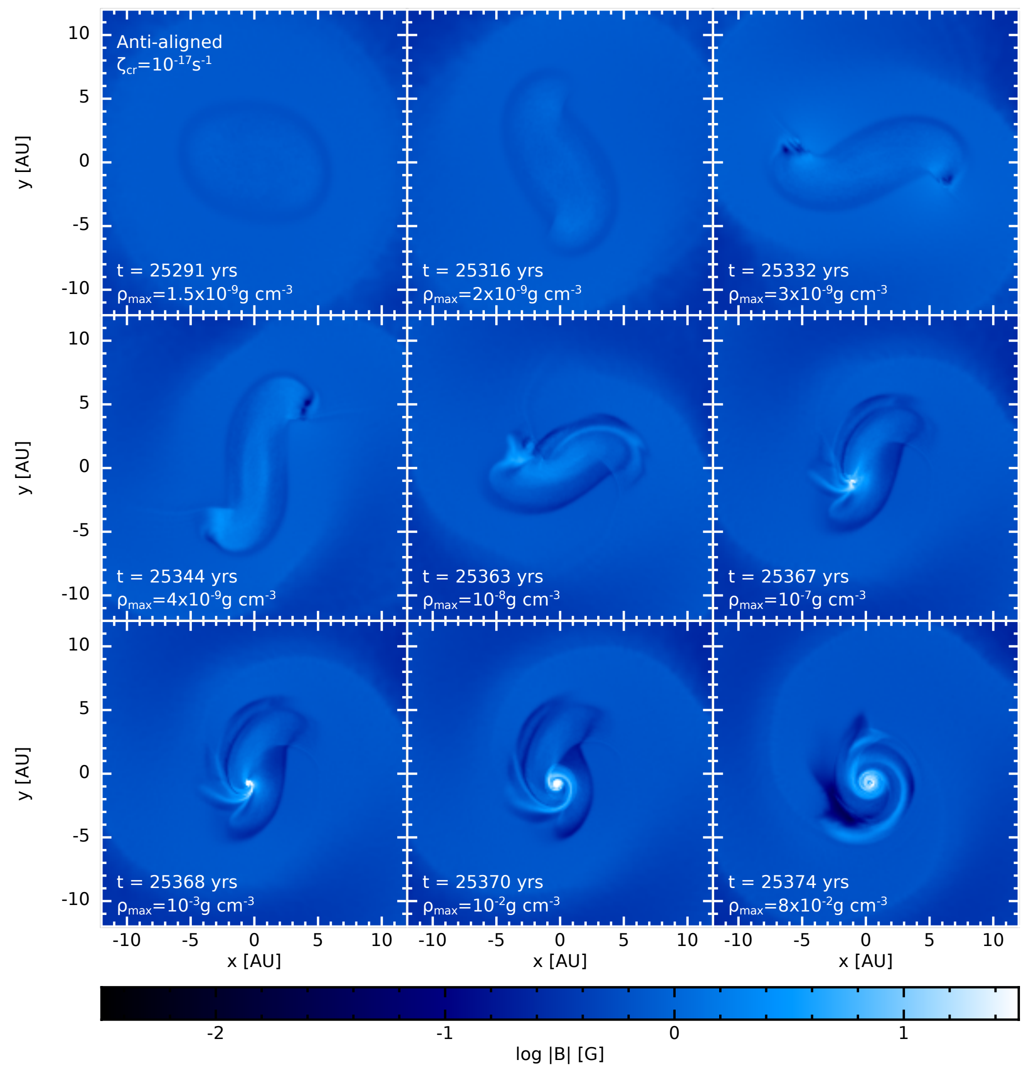
➢Ideal vs aligned non-ideal MHD: 6mo after stellar core formation (x-y plane)



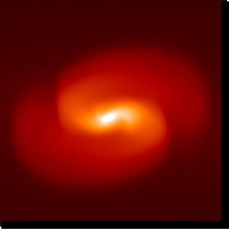
Wurster, Bate & Price (2018d)

Magnetic field structure

➢Ideal vs anti-aligned non-ideal MHD

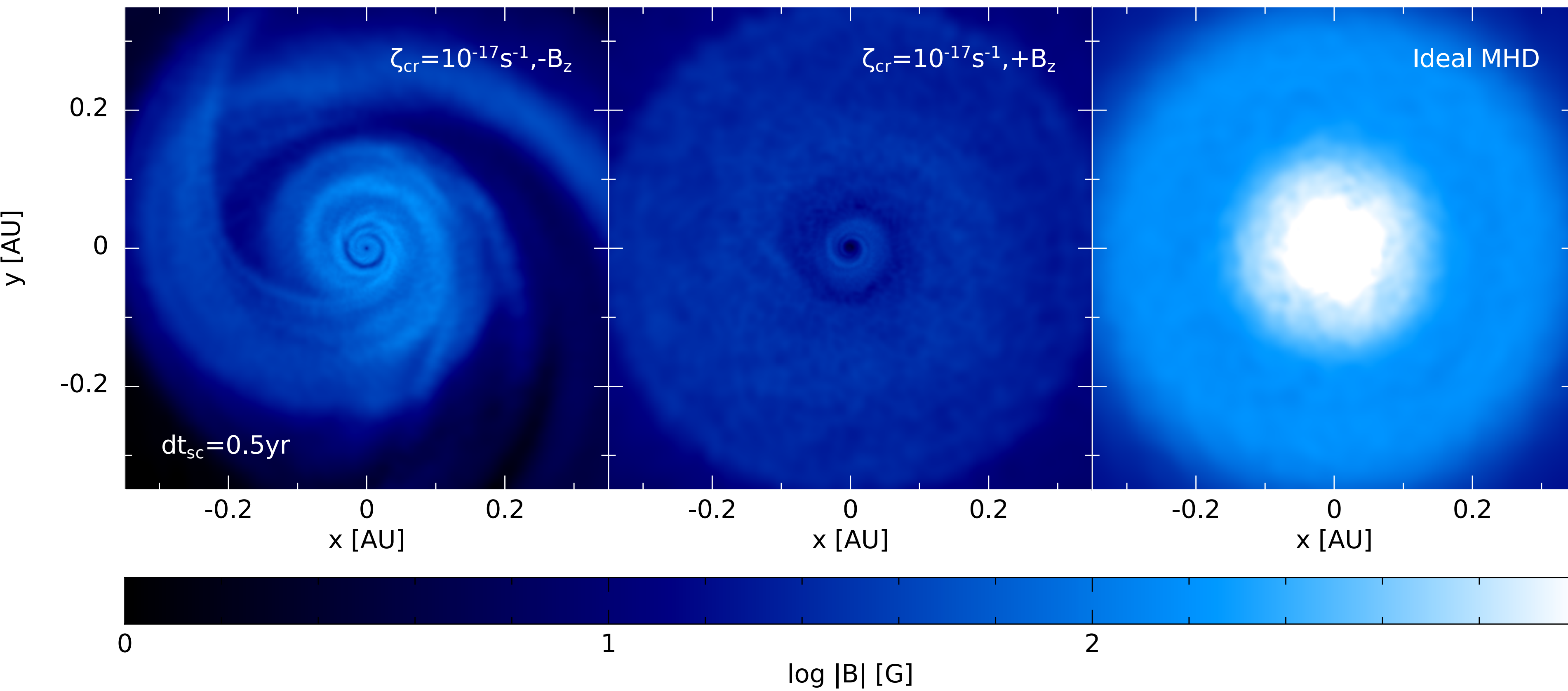


Wurster, Bate & Price (2018c)



Magnetic field structure

- Ideal vs anti-aligned non-ideal MHD: 6 mo after stellar core formation

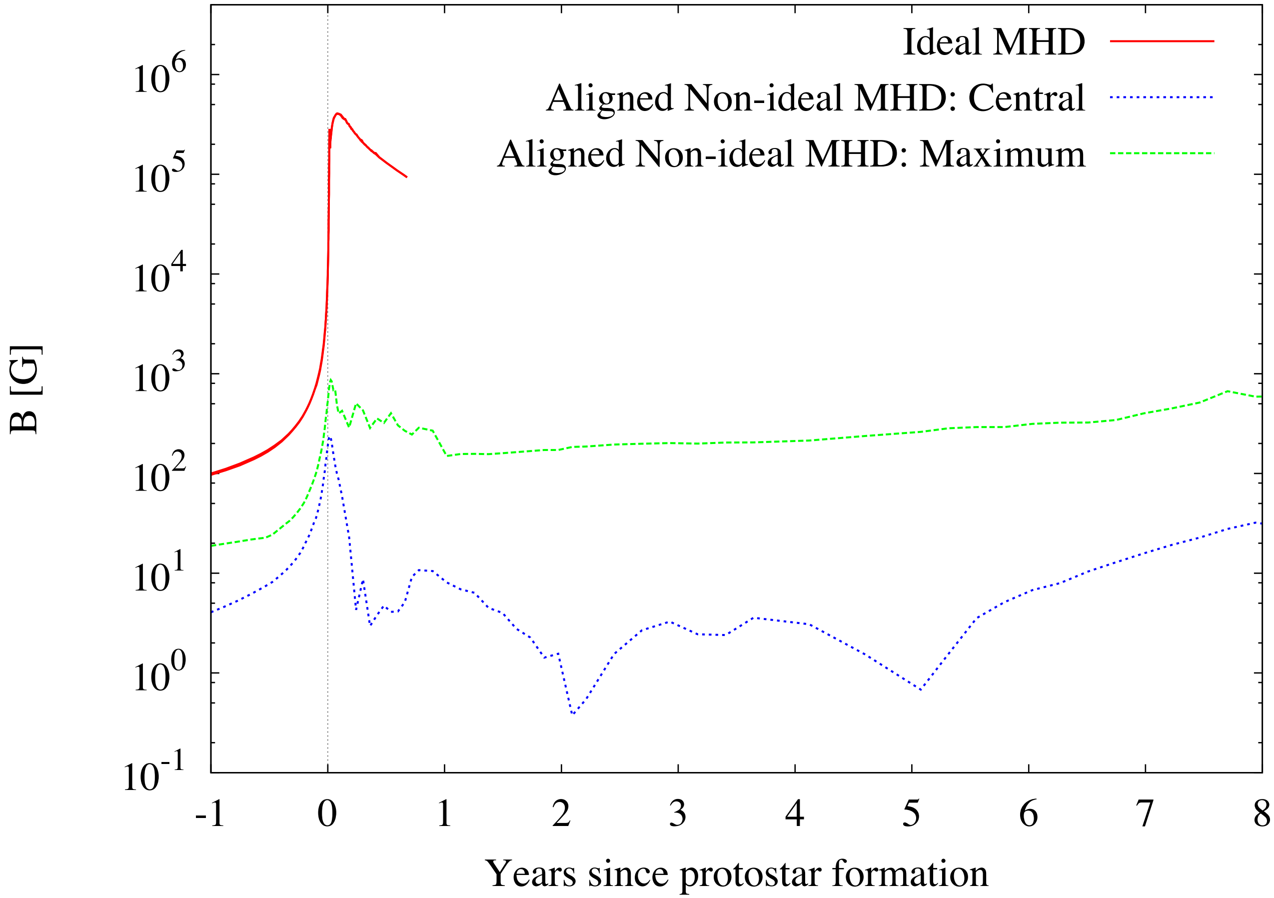


Wurster, Bate & Price (2018c,d)

Core evolution

➢Strong kG magnetic fields are observed in stars. Are they fossil, or dynamo-generated?

➢Most likely dynamo-generated since the fossil magnetic field is << 1000G in the non-ideal models



Wurster, Bate & Price (2018d)

Conclusions

➢Modelled the collapse of a strongly magnetised molecular cloud core through the first core to stellar densities; included Ohmic resistivity, ambipolar diffusion, the Hall effect.

- Large discs only form in the hydrodynamic and $\zeta_{cr} = 10^{-17}$ s^{-1} with -B_z models.
- In the $\zeta_{cr} = 10^{-17}$ s^{-1} with -B_z model, the maximum magnetic field strength is not coincident with the maximum density.
- First core outflows are suppressed in the hydrodynamic and $\zeta_{cr} = 10^{-17}$ s^{-1} with -B_z models.
- A fast first core outflow exists for the $\zeta_{cr} = 10^{-17}$ s^{-1} with +B_z model.
- Stellar core outflows exist only when using ideal magnetohydrodynamcis
- When using non-ideal MHD, the maximum magnetic field strength is not coincident with the central magnetic field strength
- The magnetic fields in stars must be generated by a dynamo action, rather than being fossil in origin

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