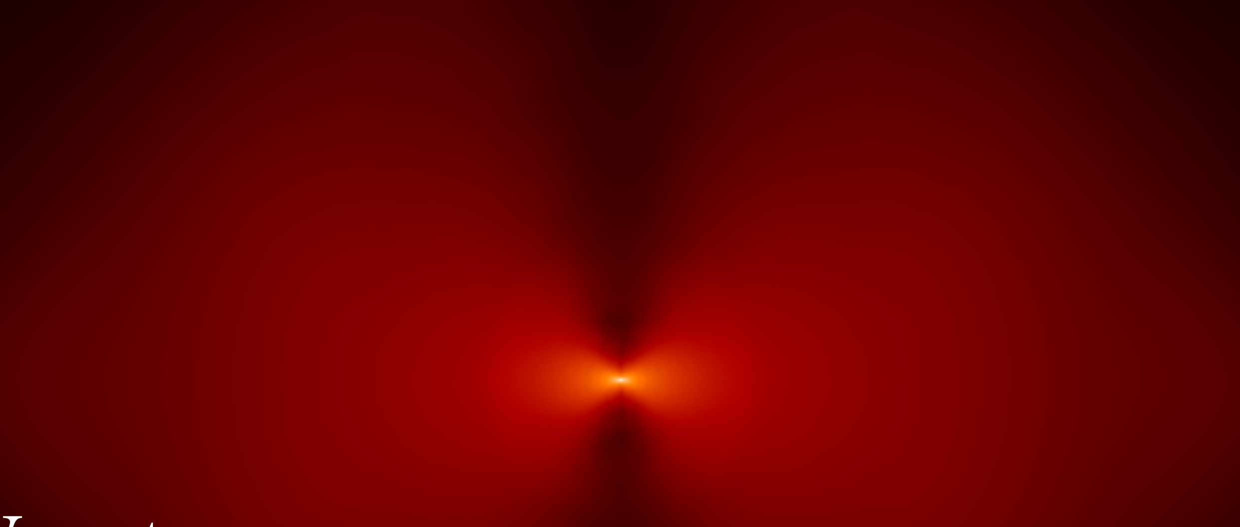
How cosmic rays shape a protostar: How cosmic rays effect the evolution of the magnetic field



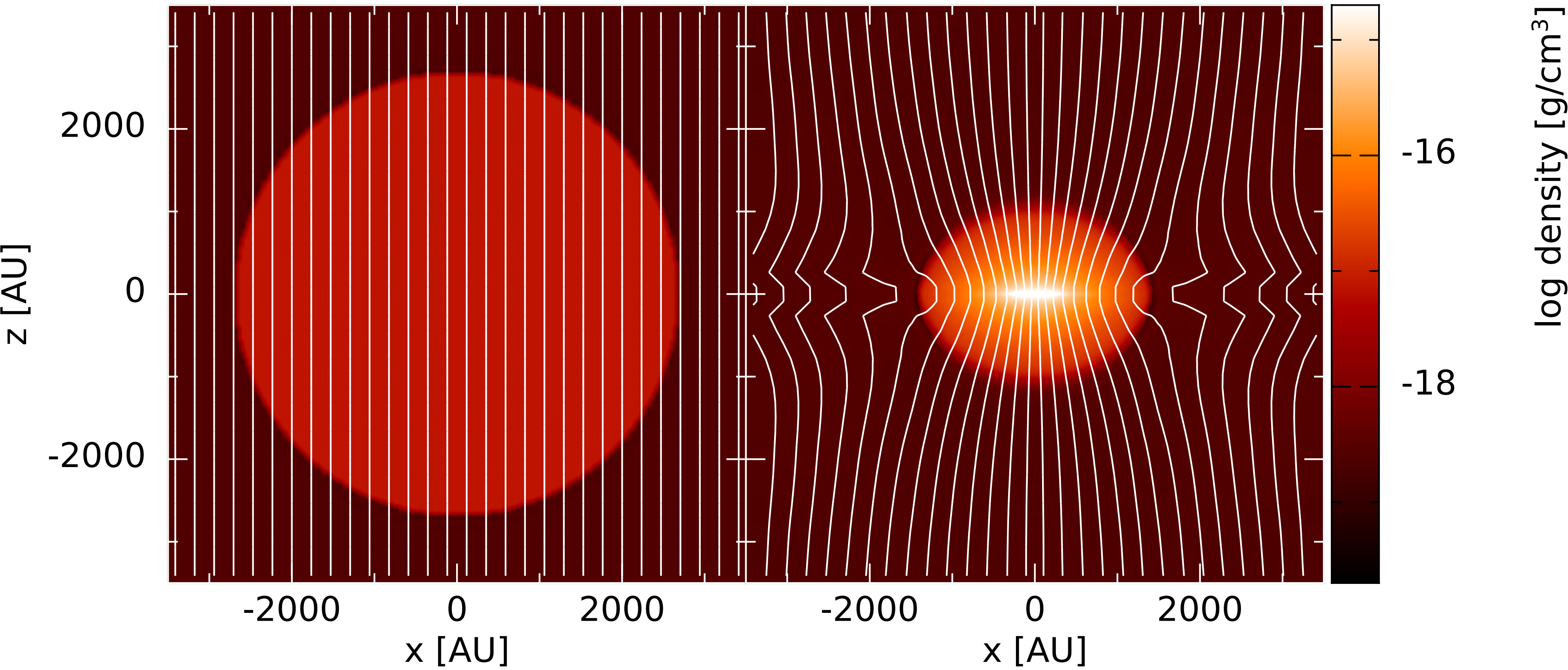
James Wurster

with Matthew Bate & Daniel Price

Cosmic rays: The salt of the star formation recipe
Arcetri, Florence, Italy
May 2, 2018

Magnetic fields in molecular clouds

- Strong field; large scale structure

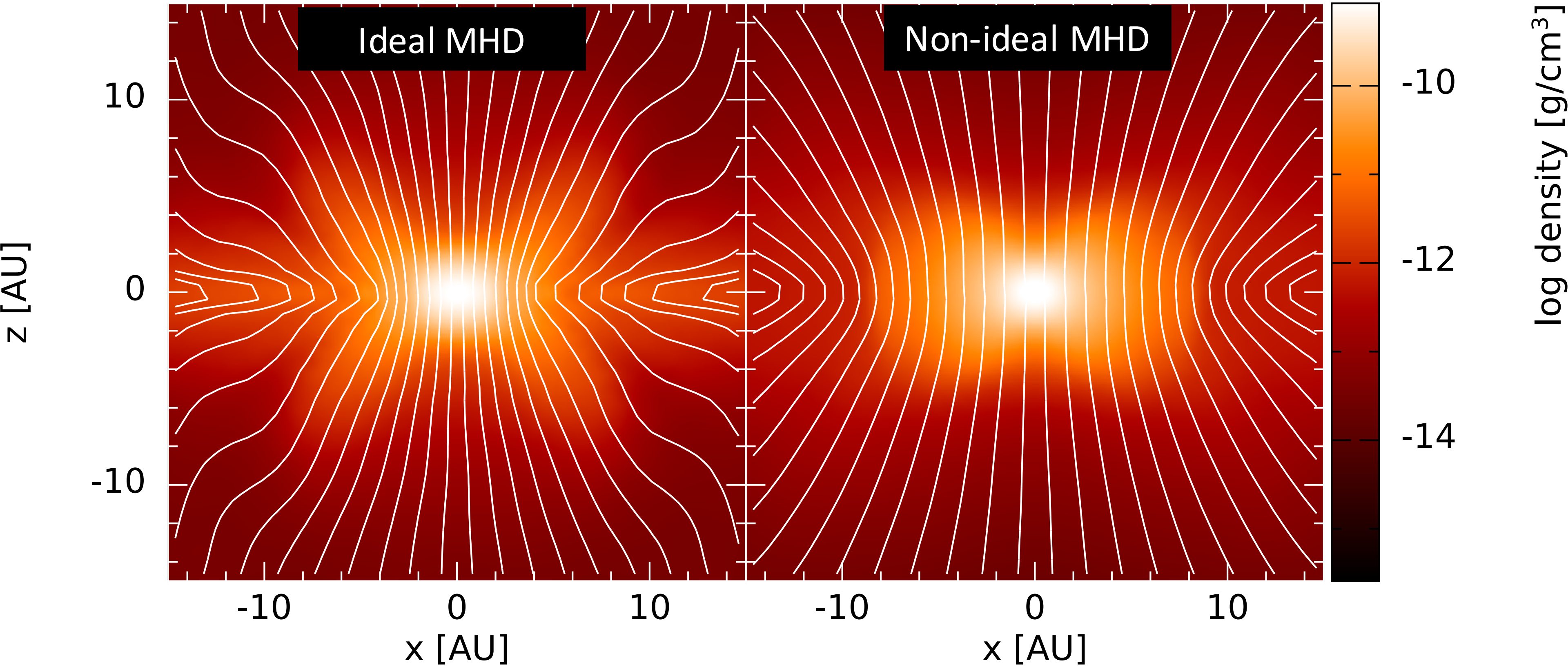


Density (rendered) + Magnetic field lines

Ideal MHD. Left: Typical initial conditions in numerical simulations. Right: at $\rho_{max} = 10^{-9}$g cm^{-3}

Magnetic fields in molecular clouds

- ➢ Strong field; small scale structure

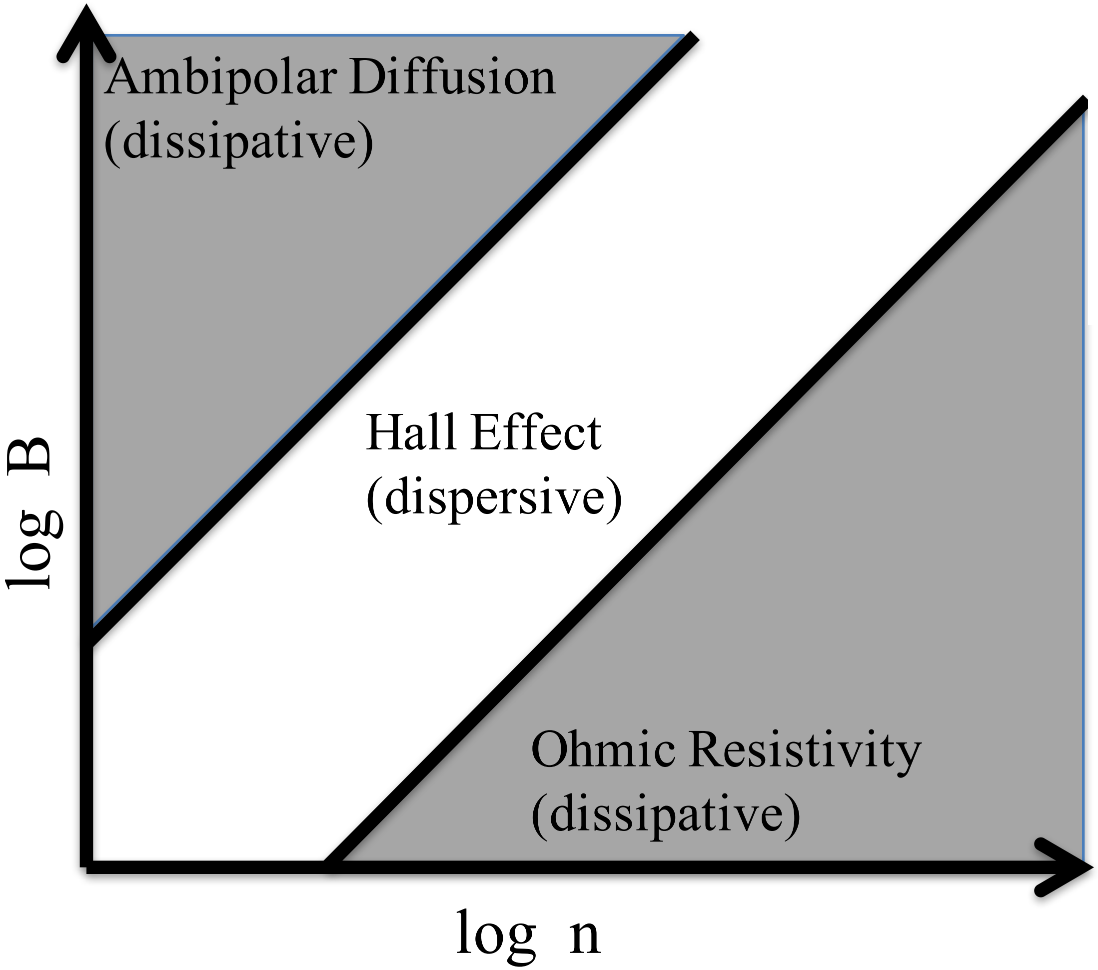


Non-ideal MHD processes:

- ➢ Ohmic resistivity (diffusive)
- ➢ Ambipolar diffusion (diffusive)
- ➢ Hall effect (dispersive)

Non-ideal magnetohydrodynamics

Simplistic view: assumes only ions and electrons (i.e. no dust grains):



Ambipolar Diffusion
(dissipative)

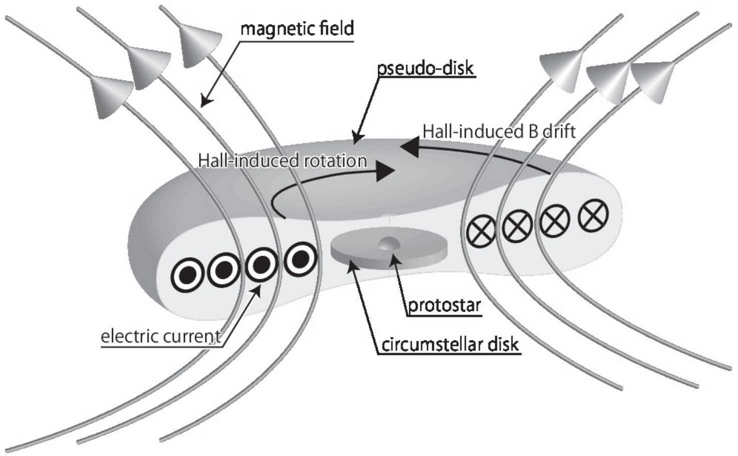
Hall Effect
(dispersive)

Ohmic Resistivity
(dissipative)

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

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

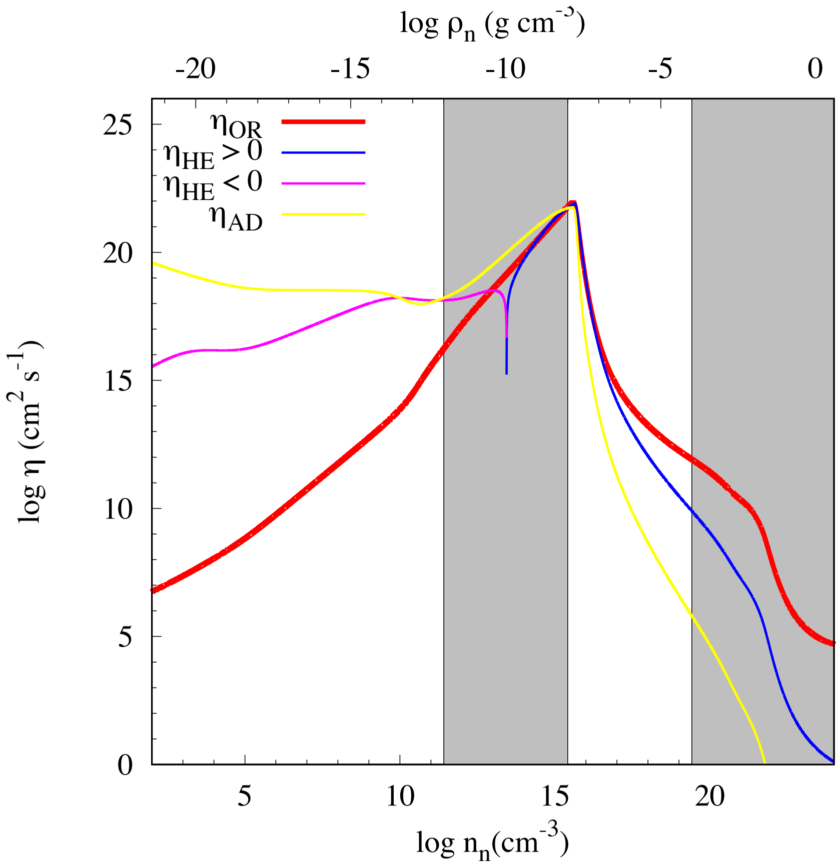
$$\left.\frac{\mathrm{d}\boldsymbol{B}}{\mathrm{d}t}\right|_{\mathrm{AD}} = \boldsymbol{\nabla}\times\eta_{\mathrm{AD}}\left\{\left[\left(\boldsymbol{\nabla}\times\boldsymbol{B}\right)\times\hat{\boldsymbol{B}}\right]\times\hat{\boldsymbol{B}}\right\}.$$

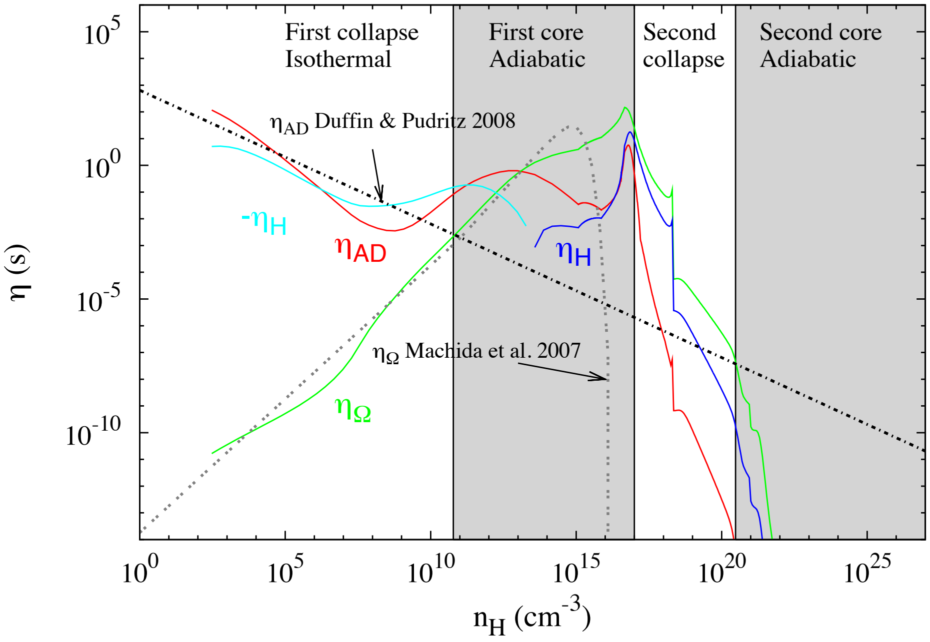


Adapted from Wardle (2007)

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

Non-ideal magnetohydrodynamics



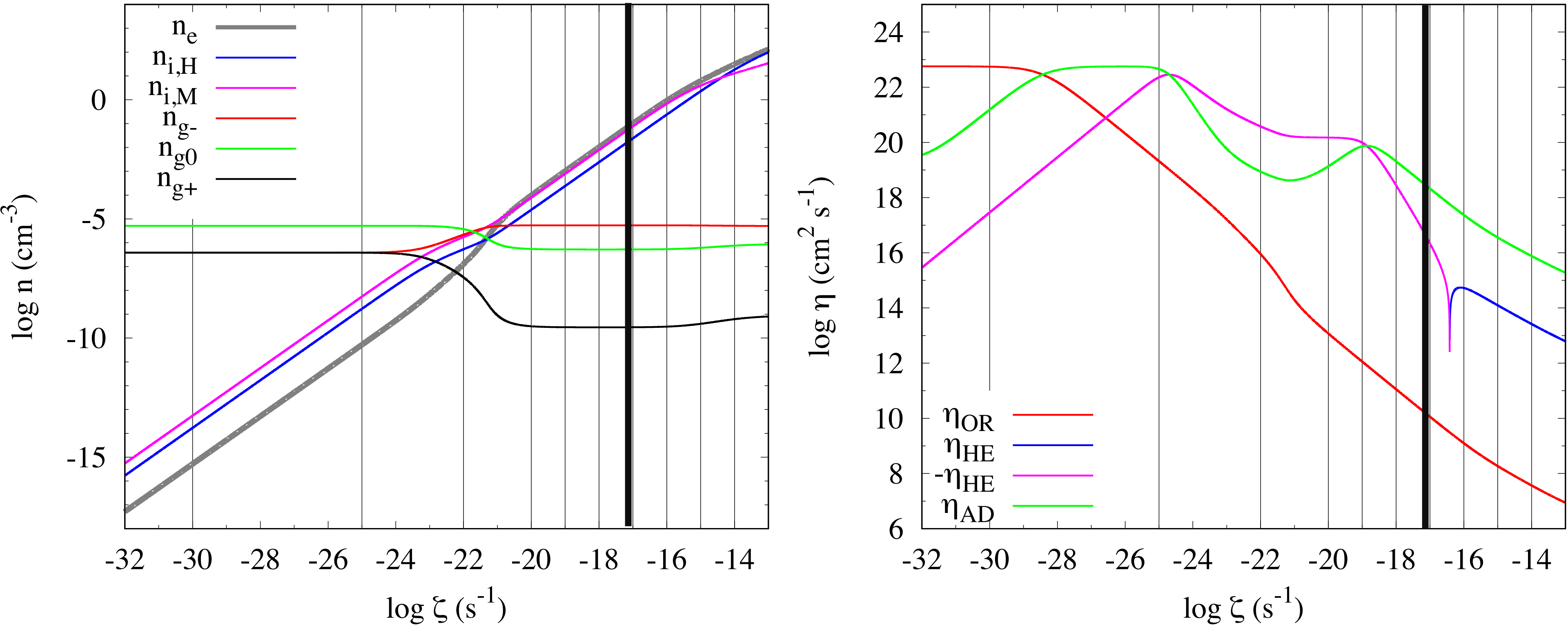


Wurster (2016):NICIL

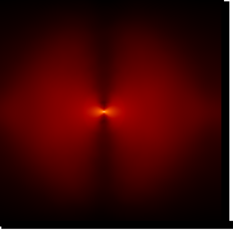
Marchand+ (2016)

Ionisation Rates

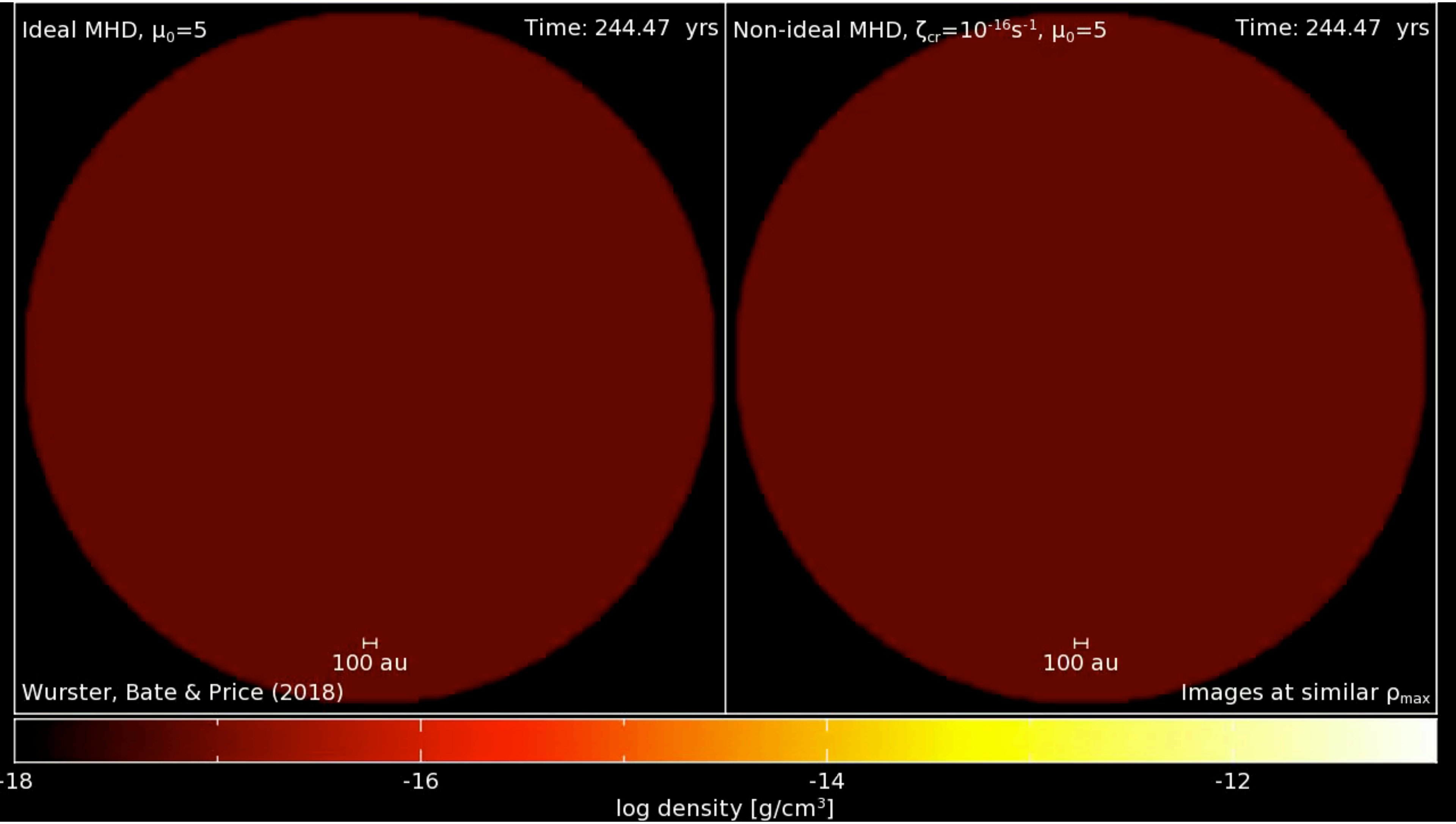
For typical initial conditions in numerical simulations:



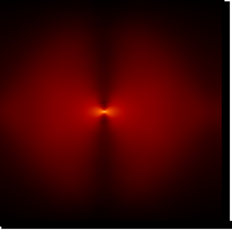
Wurster, Bate & Price (2018b)



Collapse to stellar densities: Evolution of the density



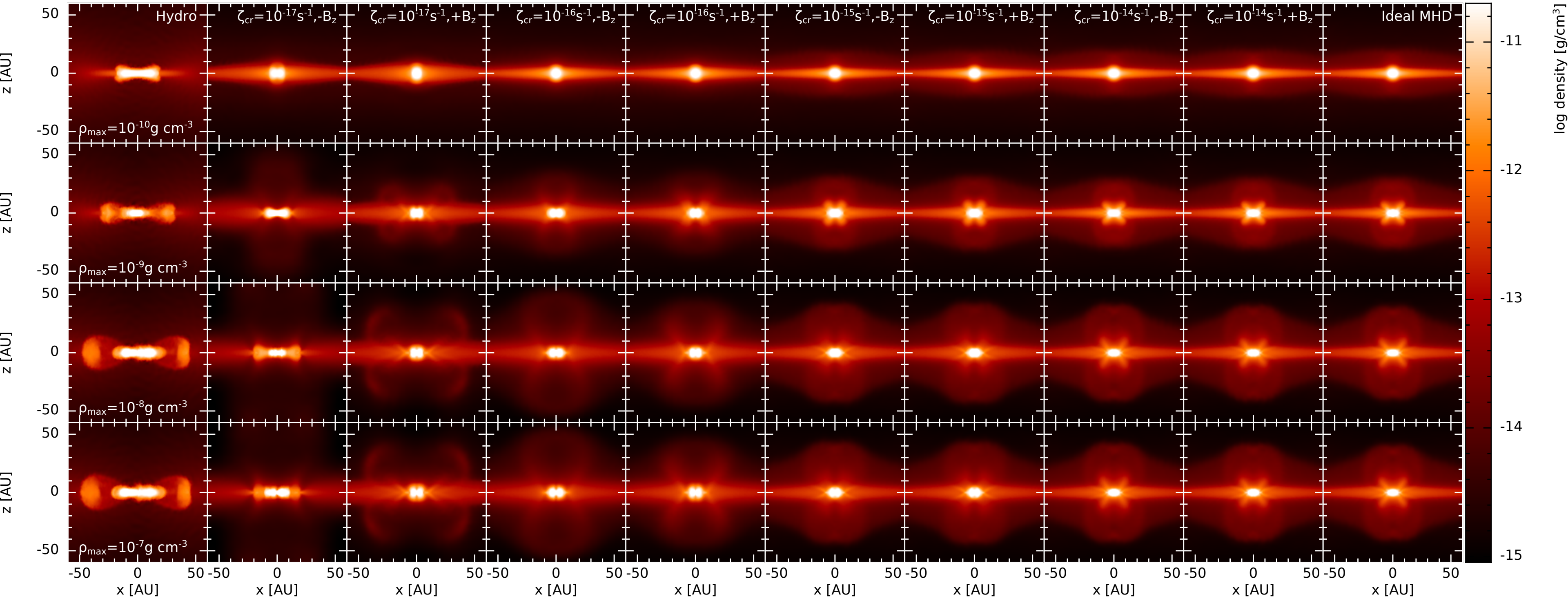
Wurster, Bate & Price (2018a). Video available at https://www.youtube.com/watch?v=CgErHuWdcPw&t=8s



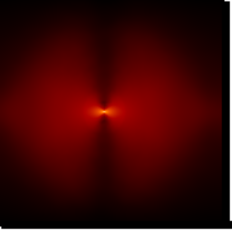
First hydrostatic core: Density

Hydro $\zeta_{cr} = 10^{-17}\ s^{-1}$ $\zeta_{cr} = 10^{-16}\ s^{-1}$ $\zeta_{cr} = 10^{-15}\ s^{-1}$ $\zeta_{cr} = 10^{-14}\ s^{-1}$ Ideal

$-B_z$ $+B_z$ $-B_z$ $+B_z$ $-B_z$ $+B_z$ $-B_z$ $+B_z$



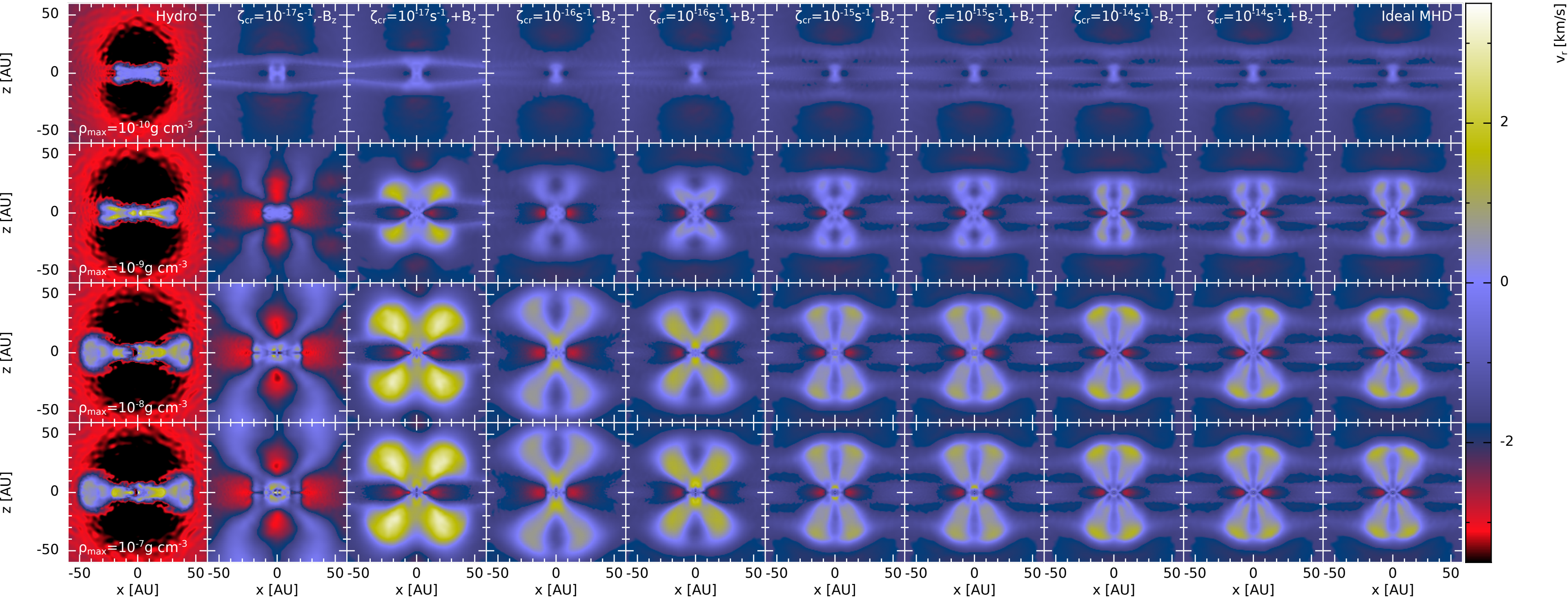
Wurster, Bate & Price (2018a, in prep)



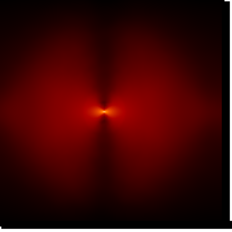
First hydrostatic core: Radial outflows

Hydro $\zeta_{cr} = 10^{-17}$ s^{-1} $\zeta_{cr} = 10^{-16}$ s^{-1} $\zeta_{cr} = 10^{-15}$ s^{-1} $\zeta_{cr} = 10^{-14}$ s^{-1} Ideal

$-B_z$ $+B_z$ $-B_z$ $+B_z$ $-B_z$ $+B_z$ $-B_z$ $+B_z$



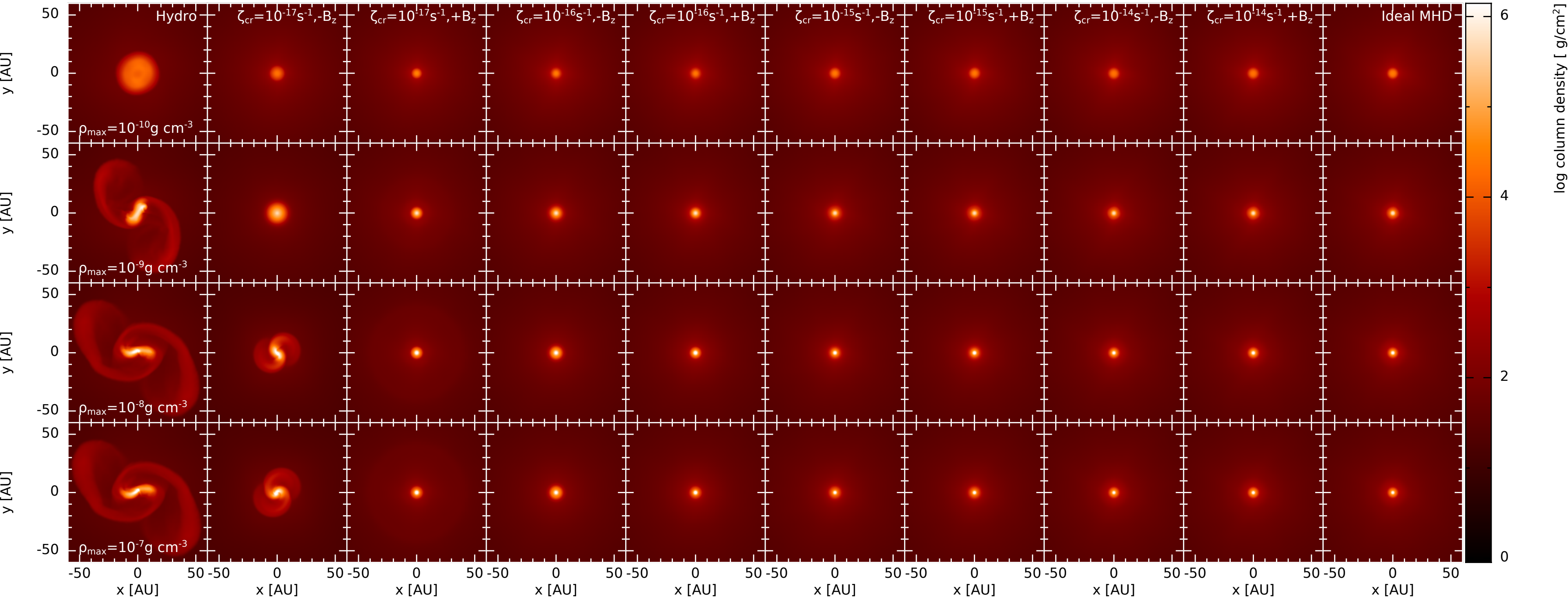
Wurster, Bate & Price (2018a, in prep)



First hydrostatic core: Disc formation

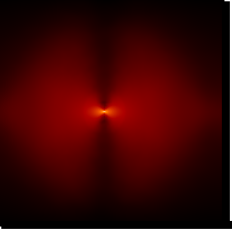
Hydro $\zeta_{cr} = 10^{-17}$ s^{-1} $\zeta_{cr} = 10^{-16}$ s^{-1} $\zeta_{cr} = 10^{-15}$ s^{-1} $\zeta_{cr} = 10^{-14}$ s^{-1} Ideal

$-B_z$ $+B_z$ $-B_z$ $+B_z$ $-B_z$ $+B_z$ $-B_z$ $+B_z$



- ➢For disc formation, a realistic cosmic ray ionisation rate is as important as the Hall effect (and initial magnetic field geometry)

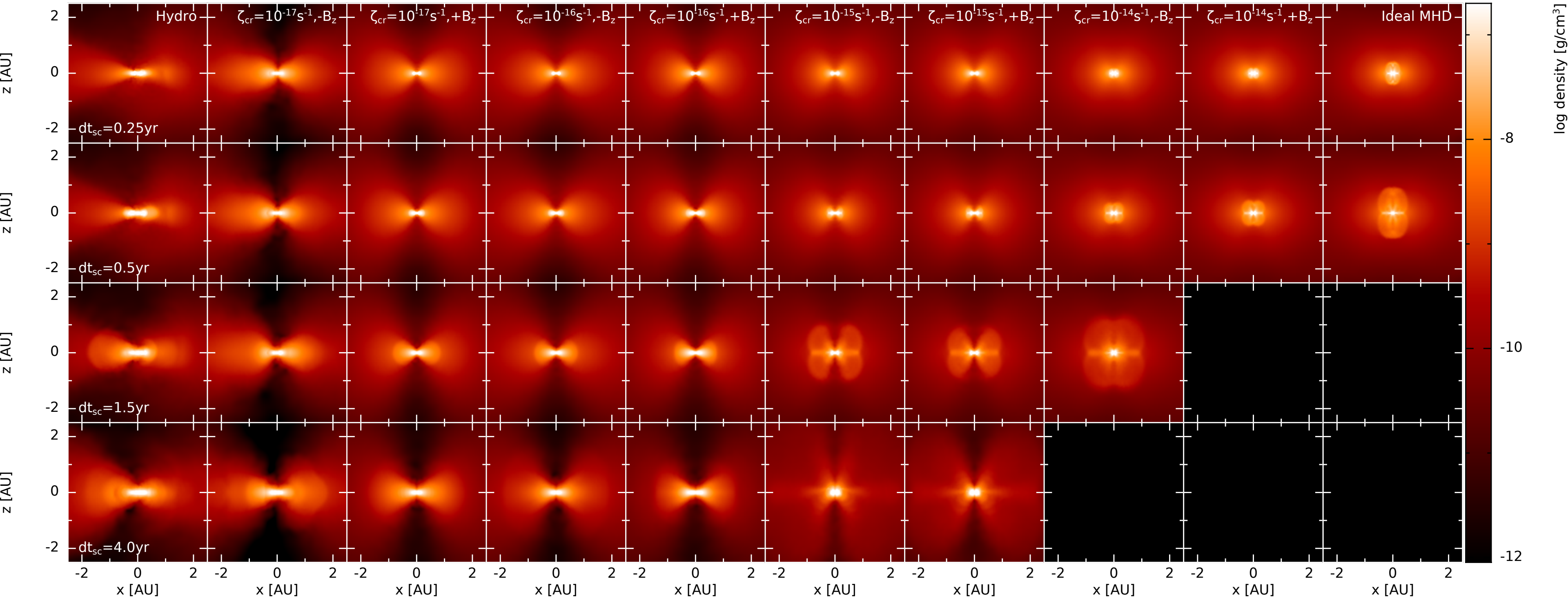
Wurster, Bate & Price (2018a, in prep)



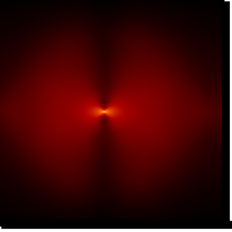
Stellar core: Density

Hydro $\zeta_{cr} = 10^{-17}$ s^{-1} $\zeta_{cr} = 10^{-16}$ s^{-1} $\zeta_{cr} = 10^{-15}$ s^{-1} $\zeta_{cr} = 10^{-14}$ s^{-1} Ideal

-B$_z$ +B$_z$ -B$_z$ +B$_z$ -B$_z$ +B$_z$ -B$_z$ +B$_z$



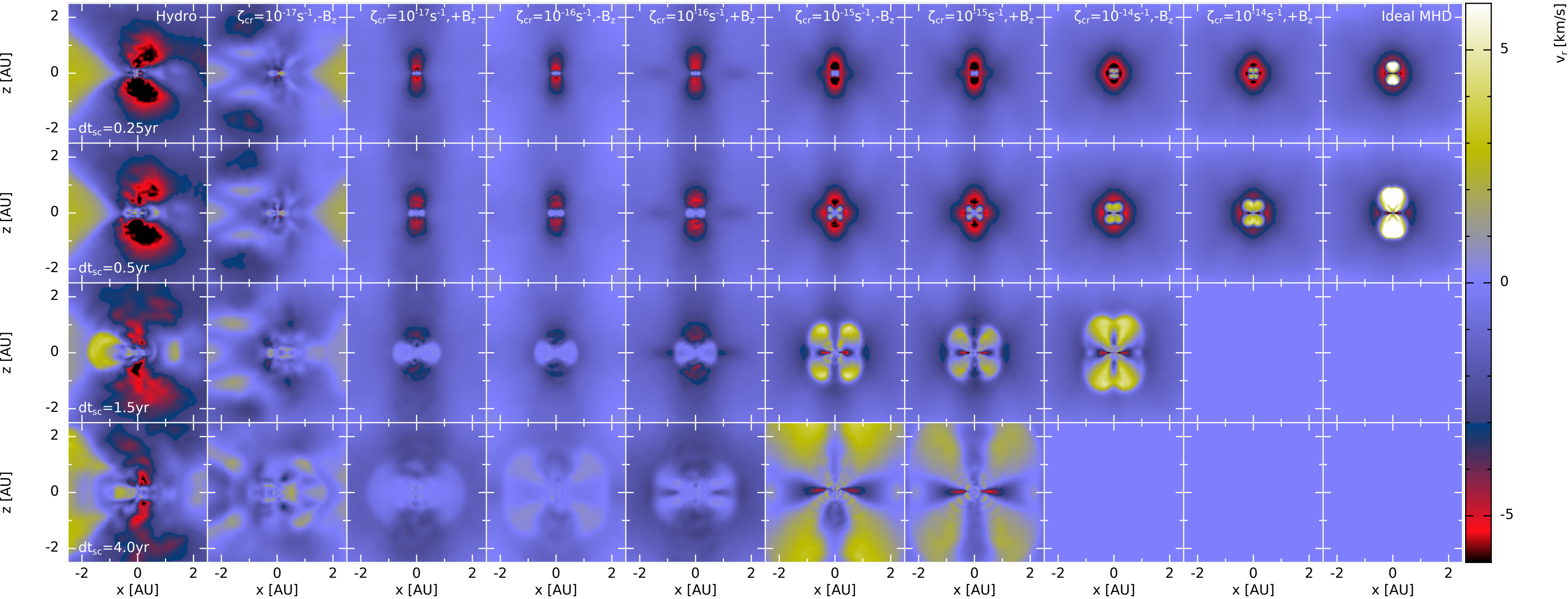
Wurster, Bate & Price (2018a, in prep)



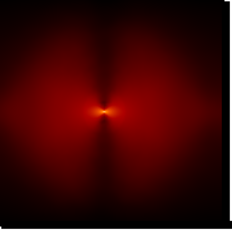
Stellar core: Radial outflows

Hydro $\zeta_{cr} = 10^{-17}$ s^{-1} $\zeta_{cr} = 10^{-16}$ s^{-1} $\zeta_{cr} = 10^{-15}$ s^{-1} $\zeta_{cr} = 10^{-14}$ s^{-1} Ideal

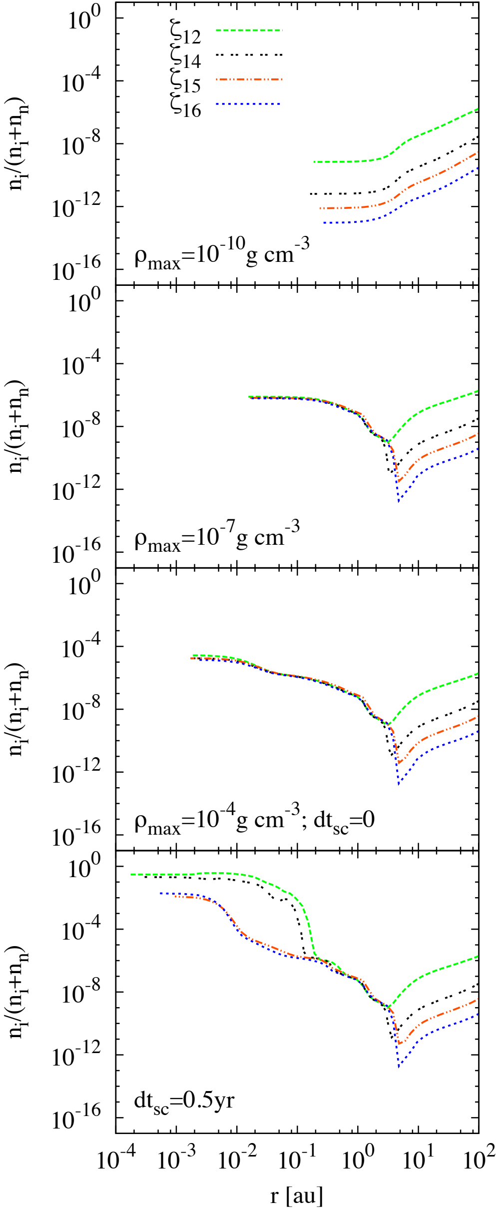
-B_z +B_z -B_z +B_z -B_z +B_z -B_z +B_z

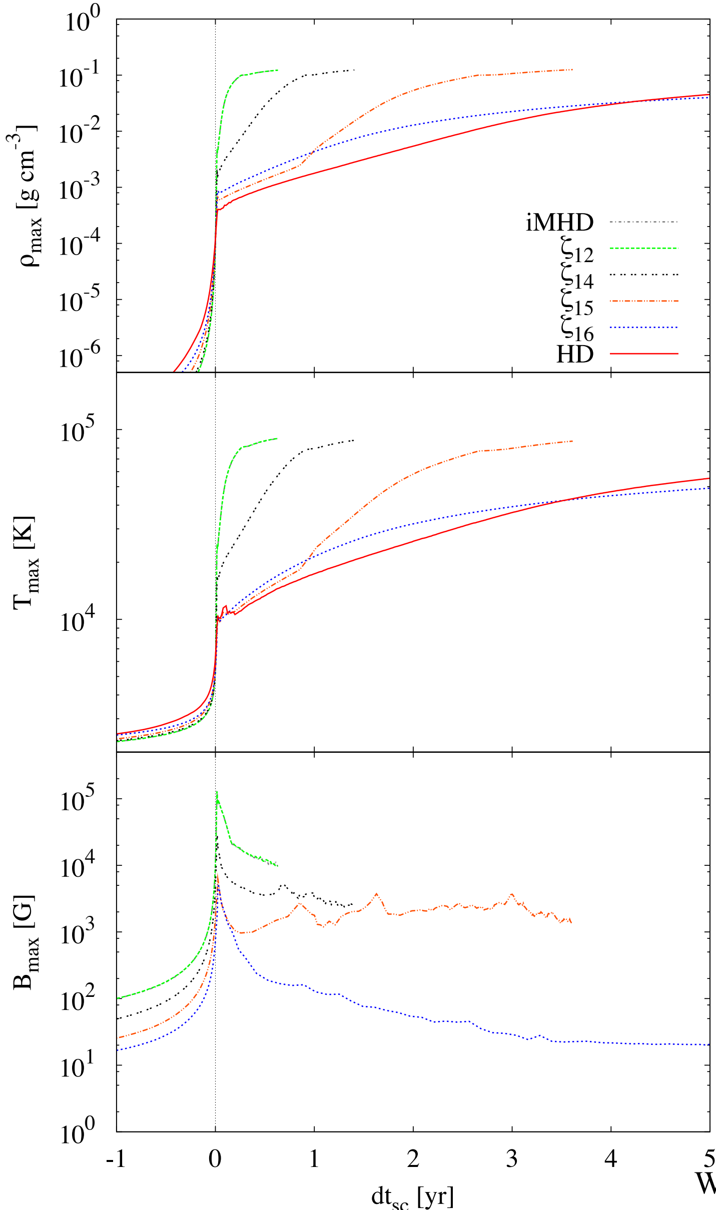


Wurster, Bate & Price (2018a, in prep)



Core evolution





Wurster, Bate & Price (2018a)

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
- Varied the cosmic ray ionisation rate, while keeping the chemistry the same

- Decreasing the cosmic ionisation rate increases the lifetime of the first hydrostatic core
- The first and second hydrostatic cores become thermally ionised, but the accreting material is still only ionised by cosmic rays
- The first core outflows are suppressed for realistic cosmic ray ionisation rates and anti-aligned magnetic and rotation vectors
- Large, gravitationally unstable discs form only for realistic cosmic ray ionisation rates and anti-aligned magnetic and rotation vectors
- The second core outflow is suppressed at low cosmic ray ionisation rates

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