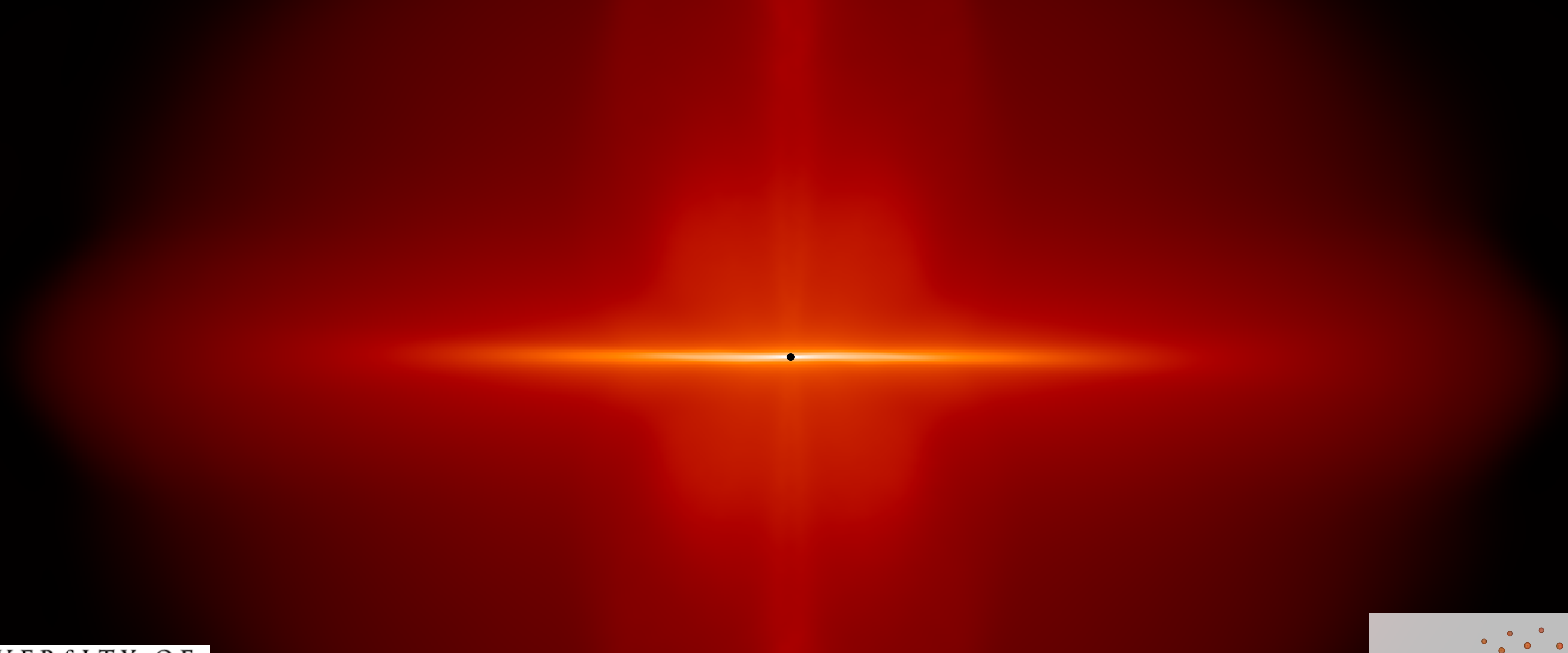
The implications of non-ideal magnetohydrodynamics on star formation



James Wurster

Collaborators: Matthew Bate & Daniel Price

University of Western Ontario

September 28, 2017

UNIVERSITY OF EXETER

MoCA Monash Centre for Astrophysics

MONASH University

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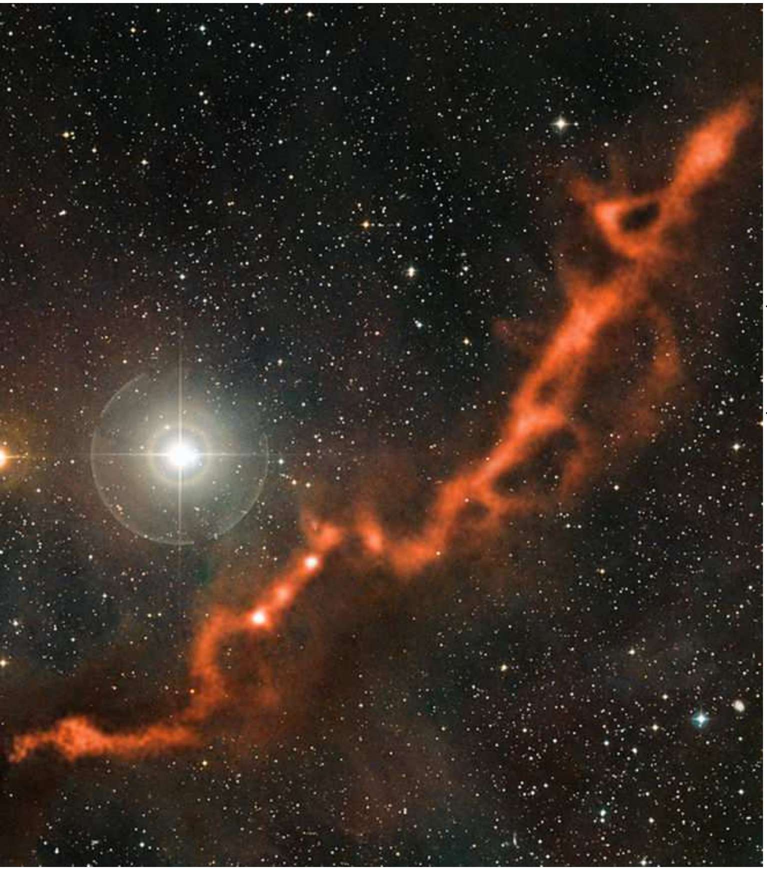
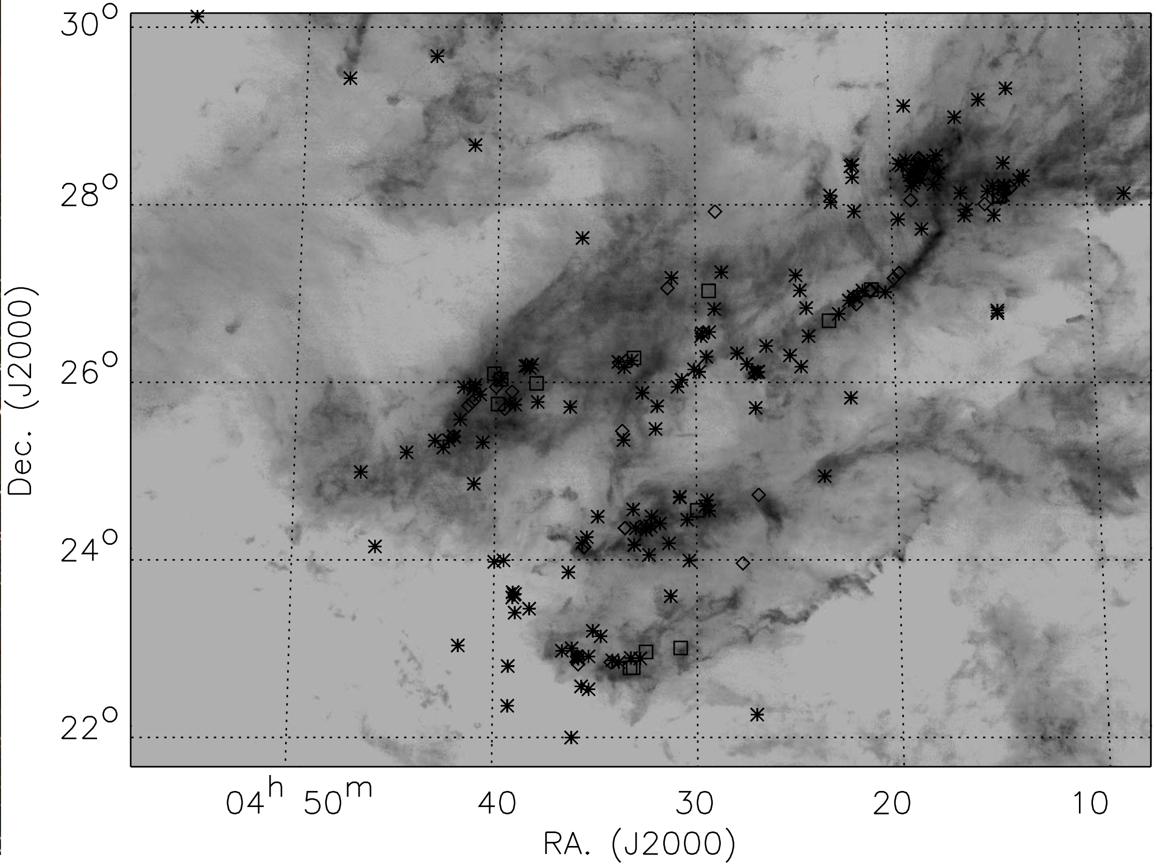
DiRAC

Importance of Stars: Stellar Nurseries

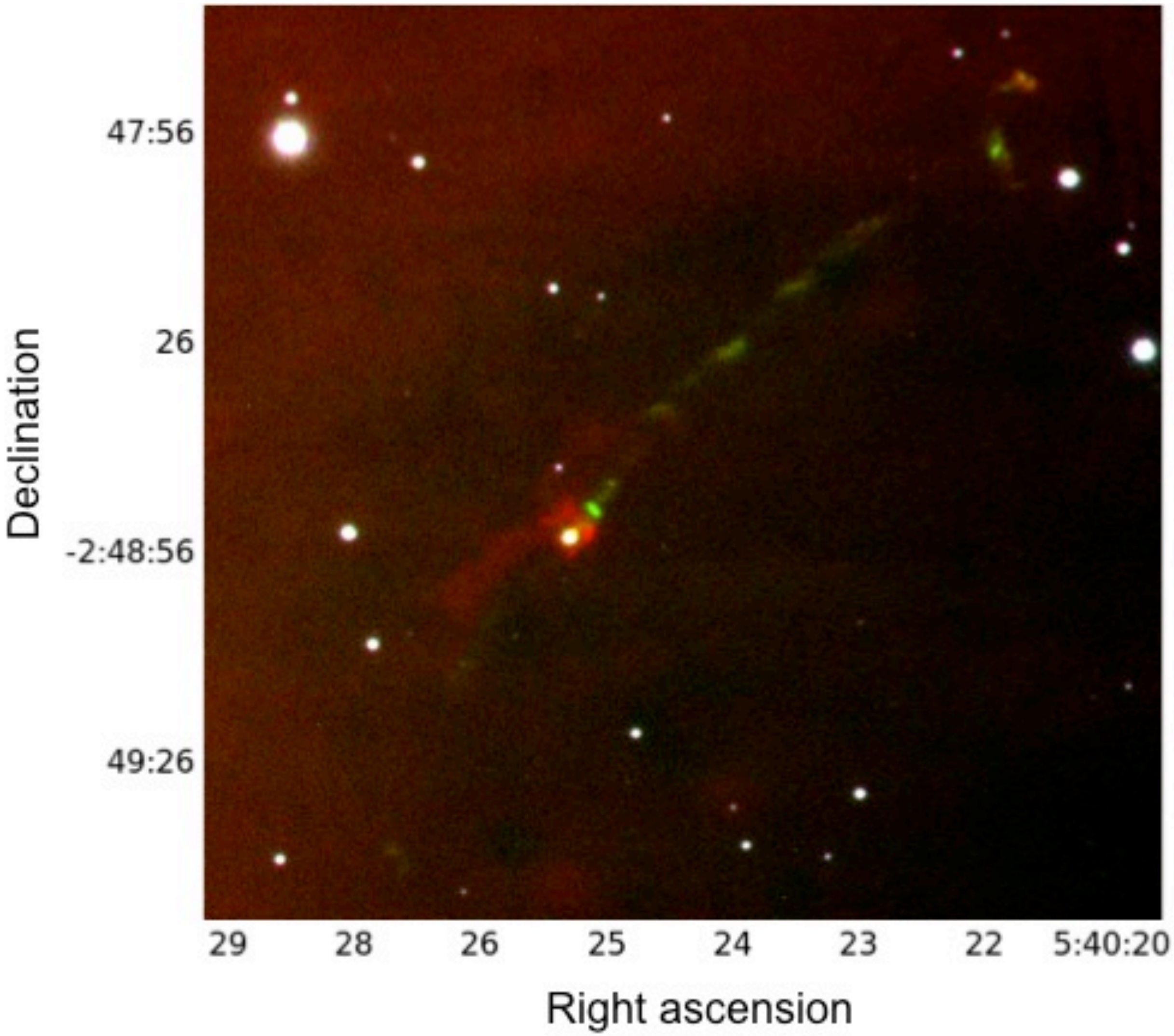


Taurus Molecular Cloud
(Source: Credit: ESO/APEX (MPIfR/ESO/OSO)/A. Hacar et al./Digitized Sky Survey 2. Acknowledgment: Davide De Martin)



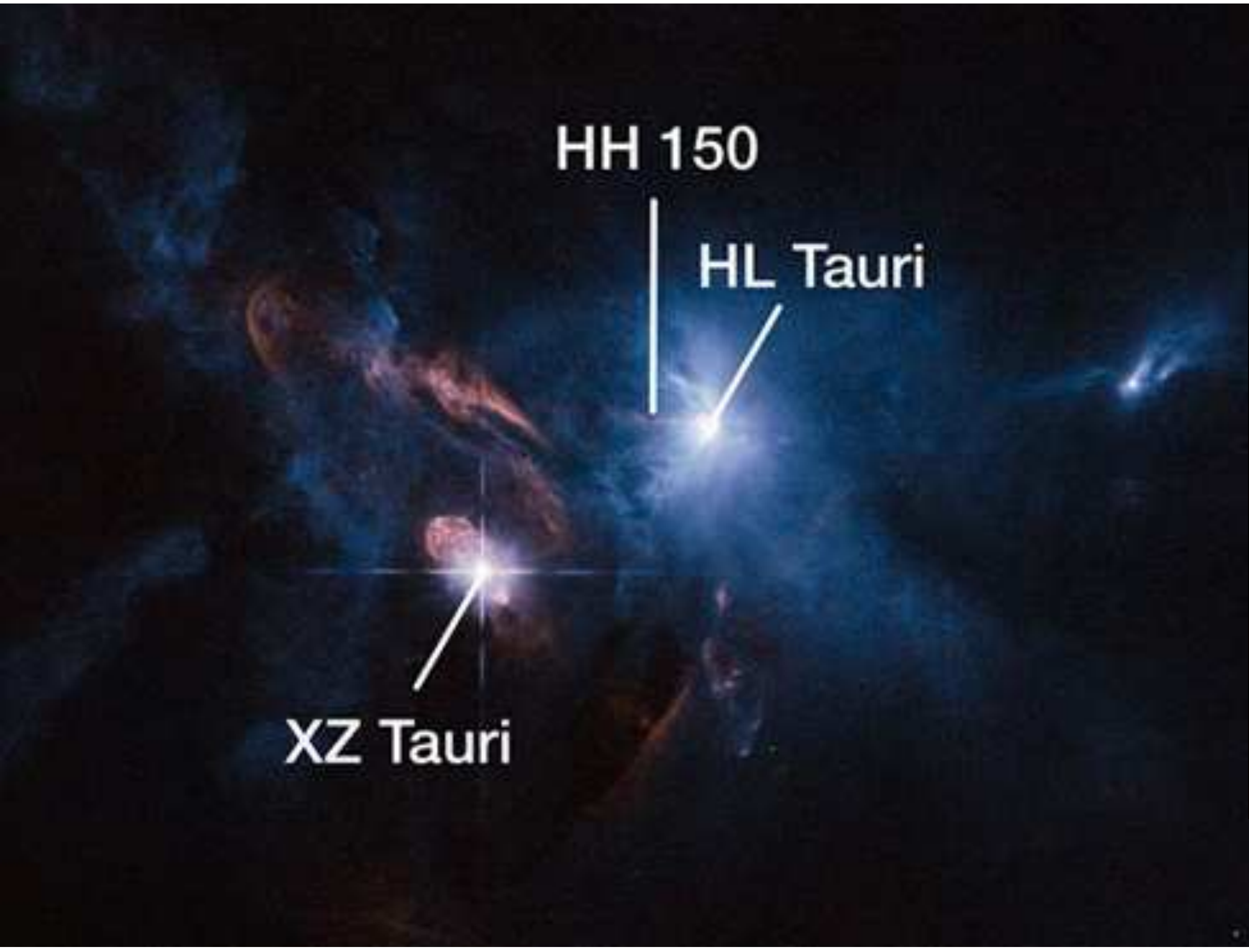
Taurus Molecular Cloud: H_2 column density map with positions of young stars (Goldsmith et. al., 2008)

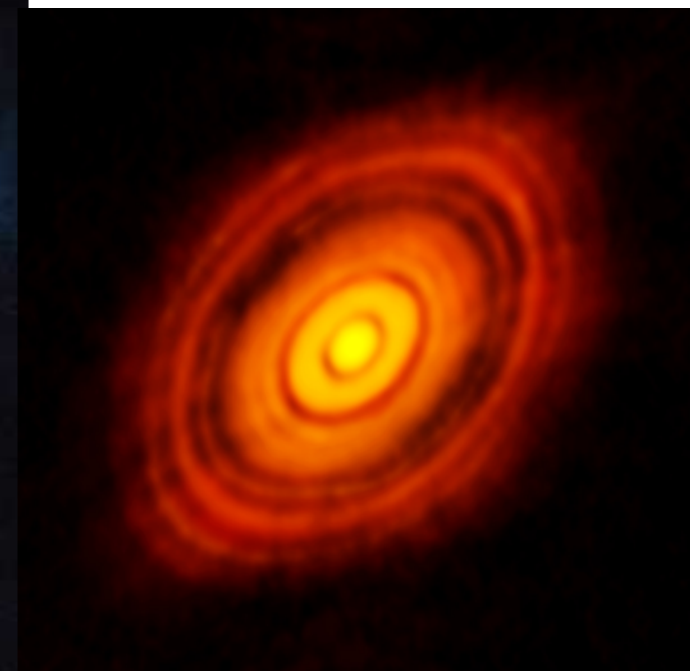
Importance of Stars: Outflows



Large scale Herbig-Haro jet driven by a proto-brown dwarf (Riaz et. al., 2017)

Importance of Stars: Planetary Discs



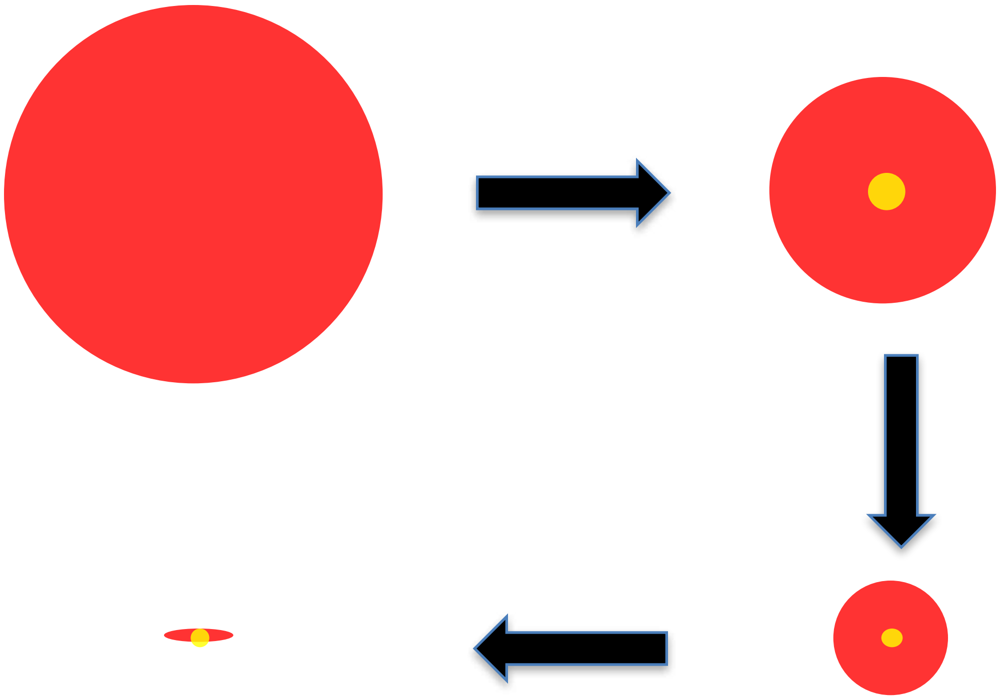


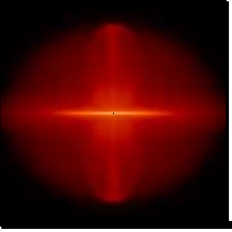
HL Tauri and surroundings (credit: NASA/HST)

HL Tau: Dust disc

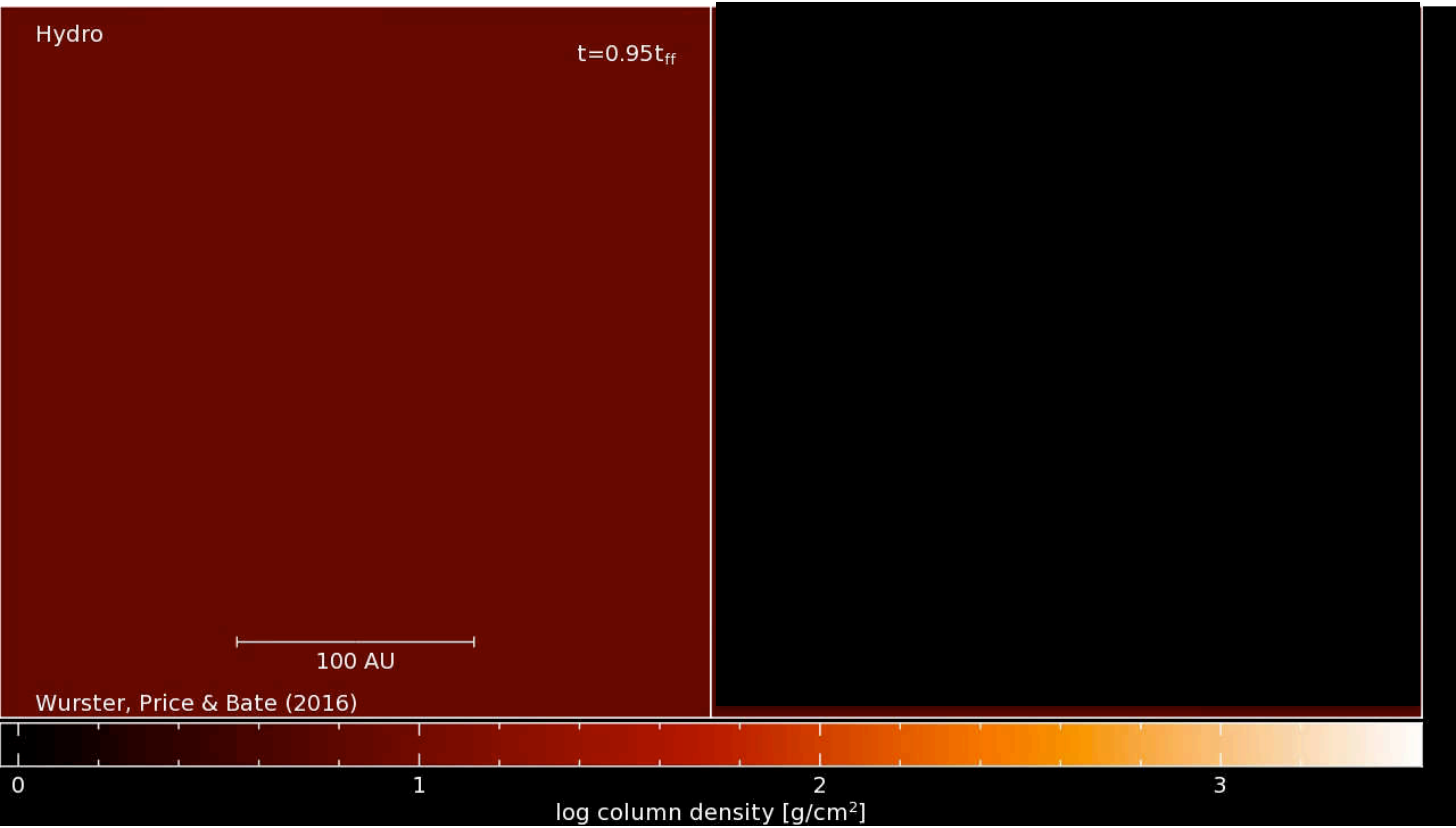
Star Formation: from the beginning

Richard Larson

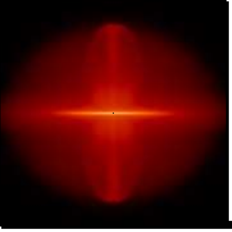




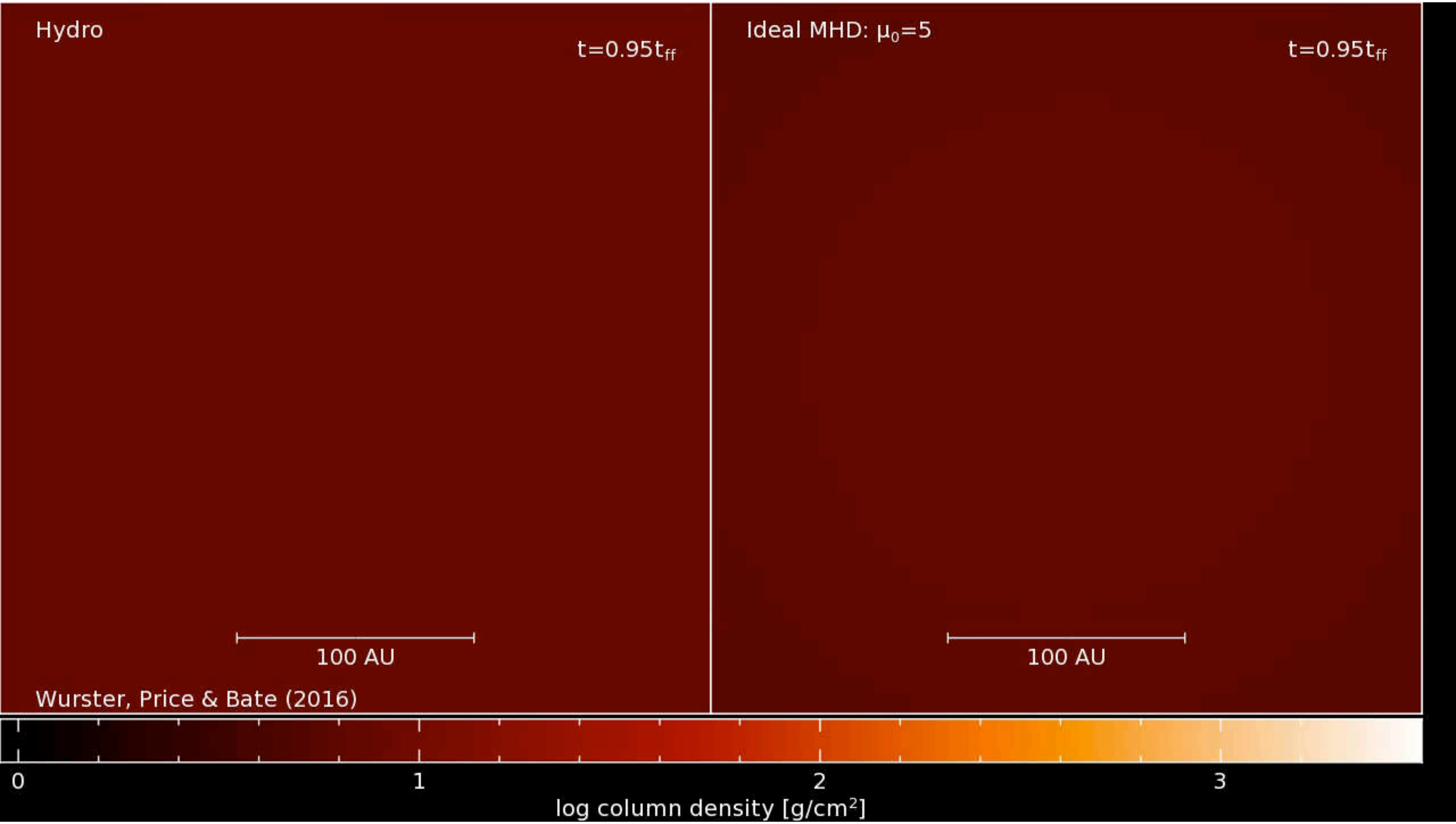
Disc Formation: Hydrodynamics



Video not publically available.



Disc Formation: Magnetohydrodynamics

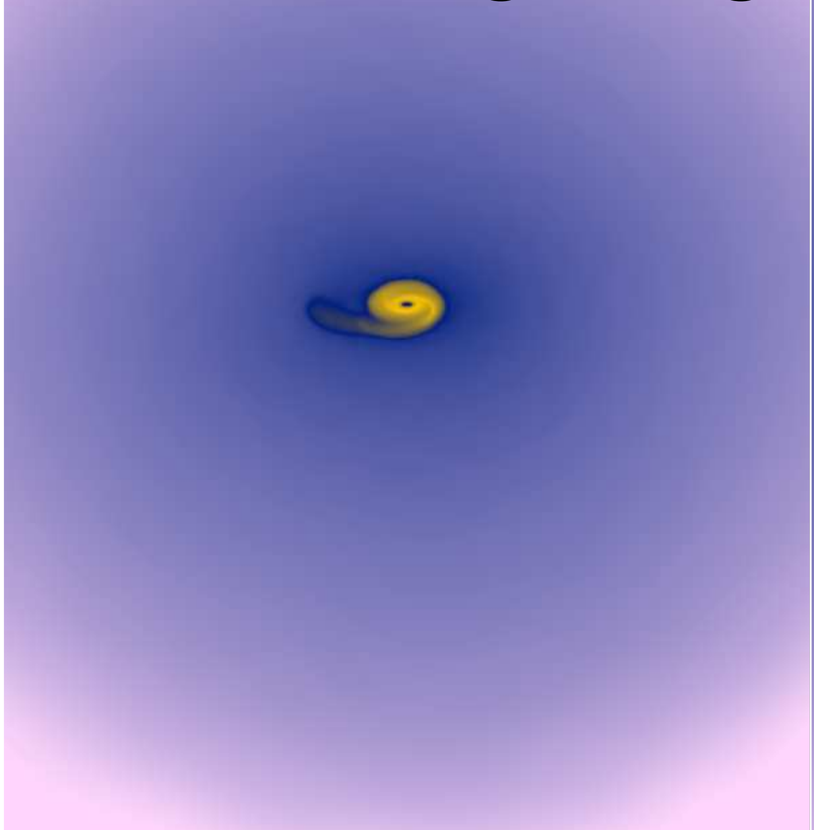


Video not publically available.

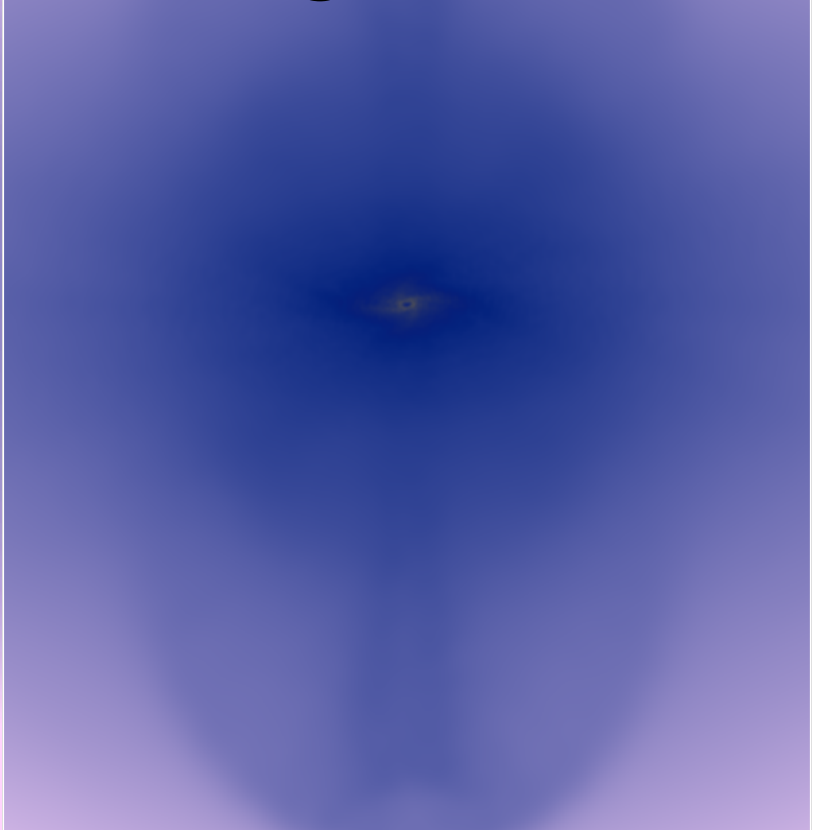
Disc Formation: Magnetohydrodynamics

The Magnetic Braking Catastrophe:

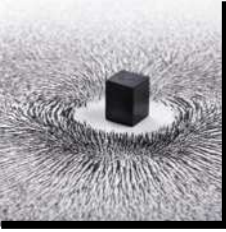
discs do not form in numerical simulations containing strong, ideal magnetic fields



No magnetic field



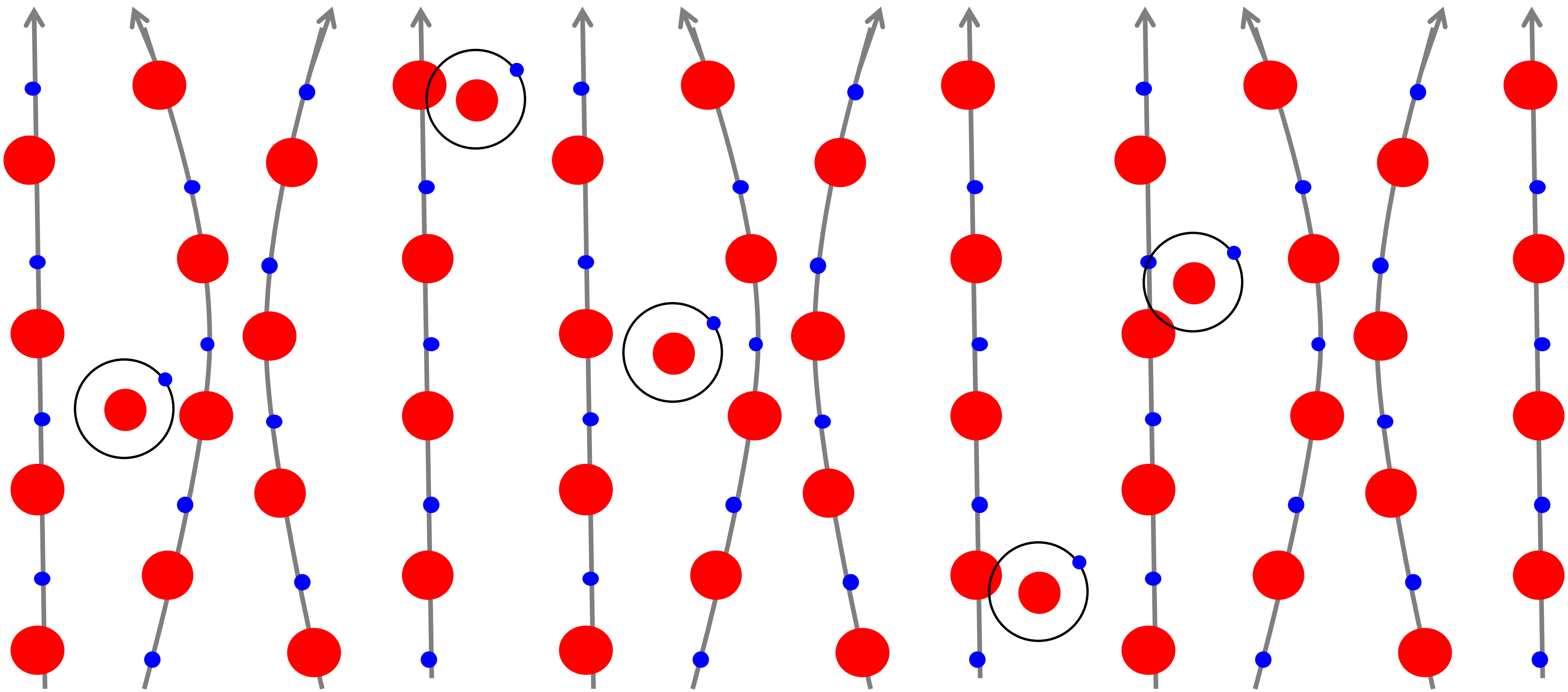
Strong magnetic field

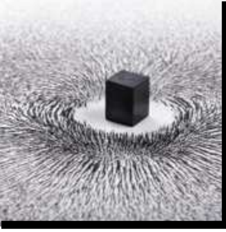


Ideal Magnetohydrodynamics

- ➢Fully ionised plasma 

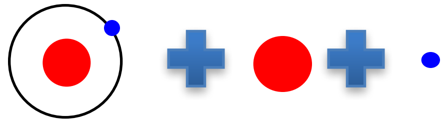
- ➢Zero resistivity & infinite conductivity
- ➢Ions & electrons are tied to the magnetic field

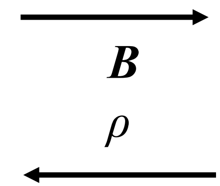




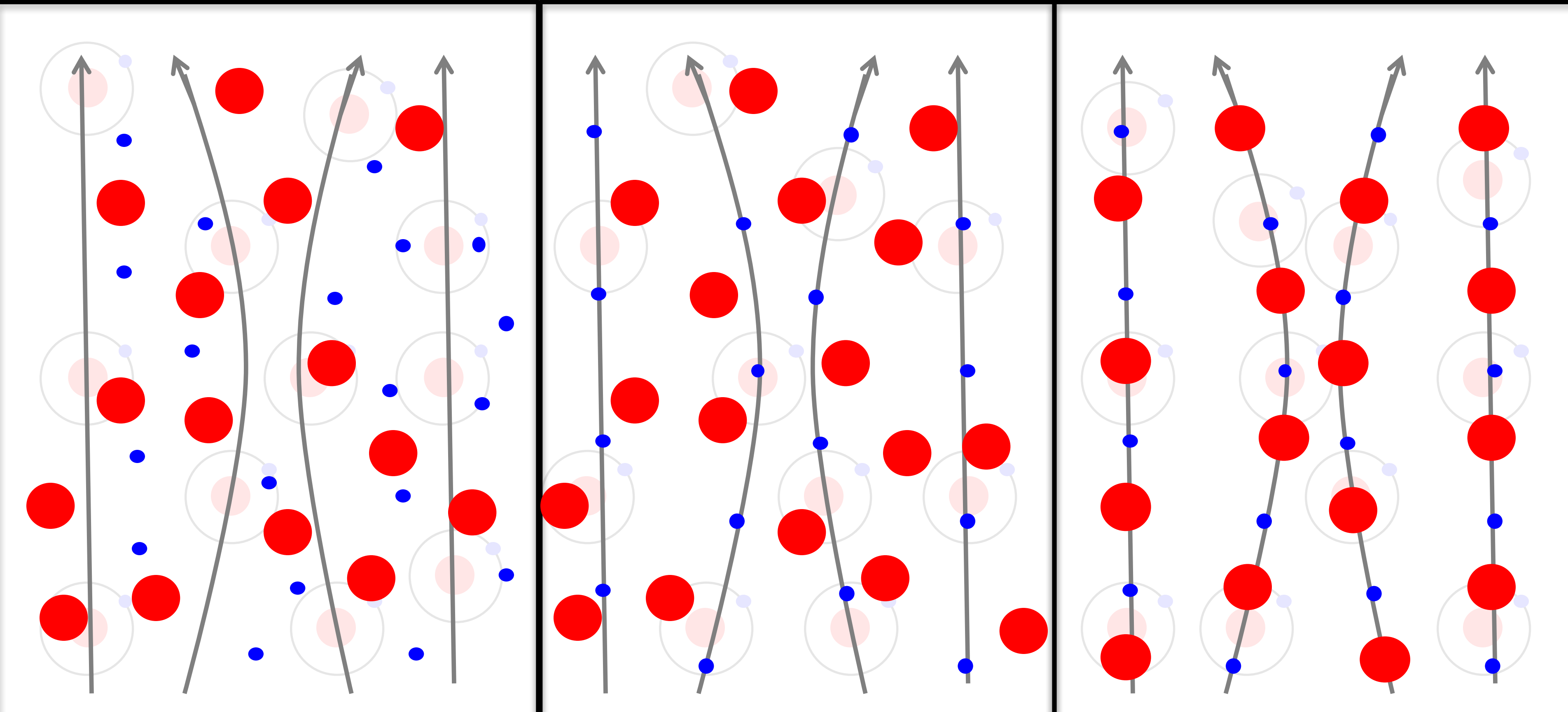
Non-ideal Magnetohydrodynamics

- Partially ionised plasma



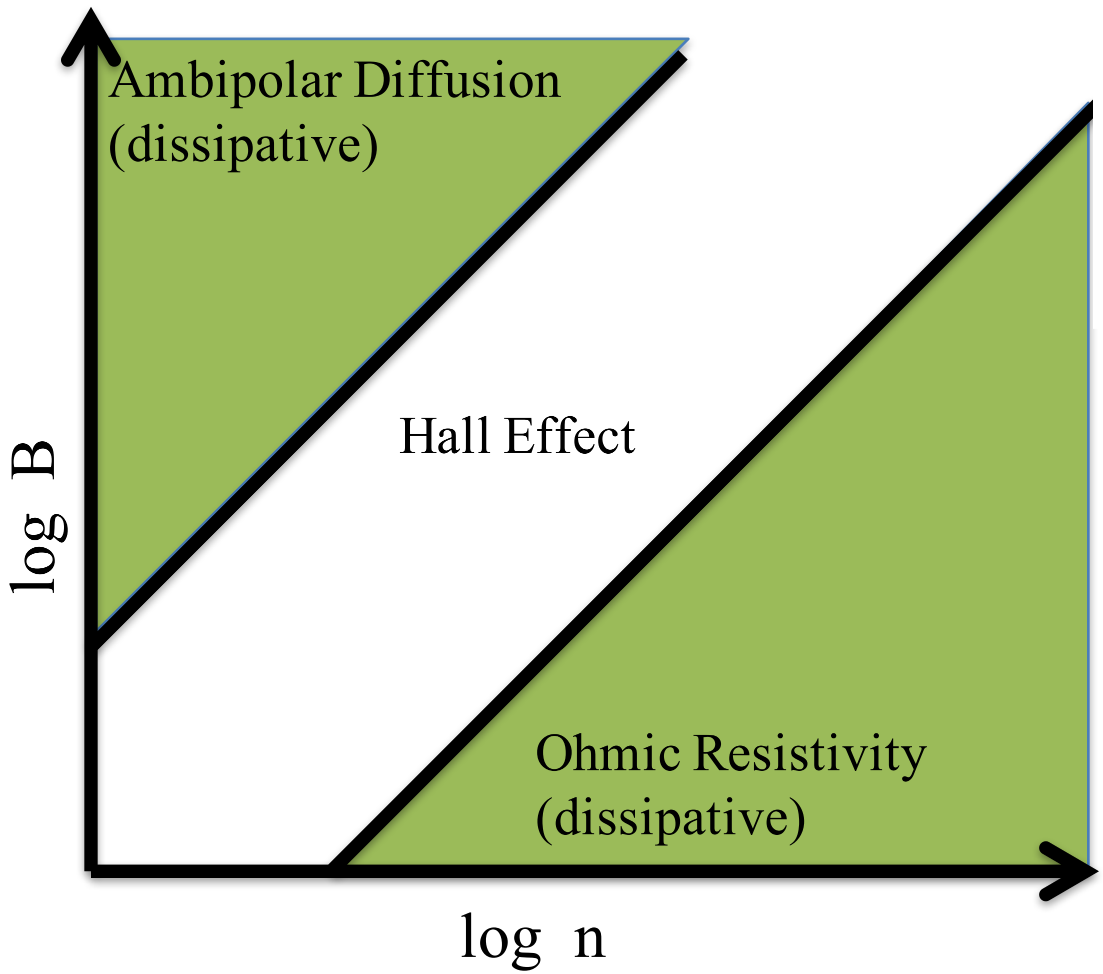


- Non-zero resistivity & conductivity
- Ions, electrons & neutrals behaviour is environment-dependent



Ohmic Resistivity | Hall Effect | Ambipolar Diffusion

Non-ideal Magnetohydrodynamics



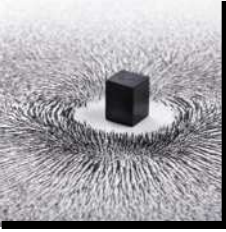
$$\left.\frac{\mathrm{d}\boldsymbol{B}}{\mathrm{d}t}\right|_{\mathrm{OR}} = -\boldsymbol{\nabla} \times \eta_{\mathrm{OR}} \left(\boldsymbol{\nabla} \times \boldsymbol{B}\right),$$

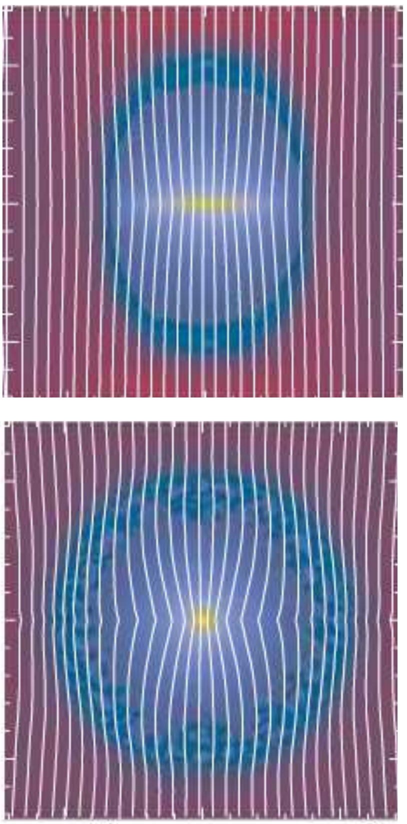
$$\left.\frac{\mathrm{d}\boldsymbol{B}}{\mathrm{d}t}\right|_{\mathrm{HE}} = -\boldsymbol{\nabla} \times \eta_{\mathrm{HE}} \left[\left(\boldsymbol{\nabla} \times \boldsymbol{B}\right) \times \hat{\boldsymbol{B}}\right],$$

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

Adapted from Wardle (2007)

Non-ideal Magnetohydrodynamics





Price & Bate (2007)

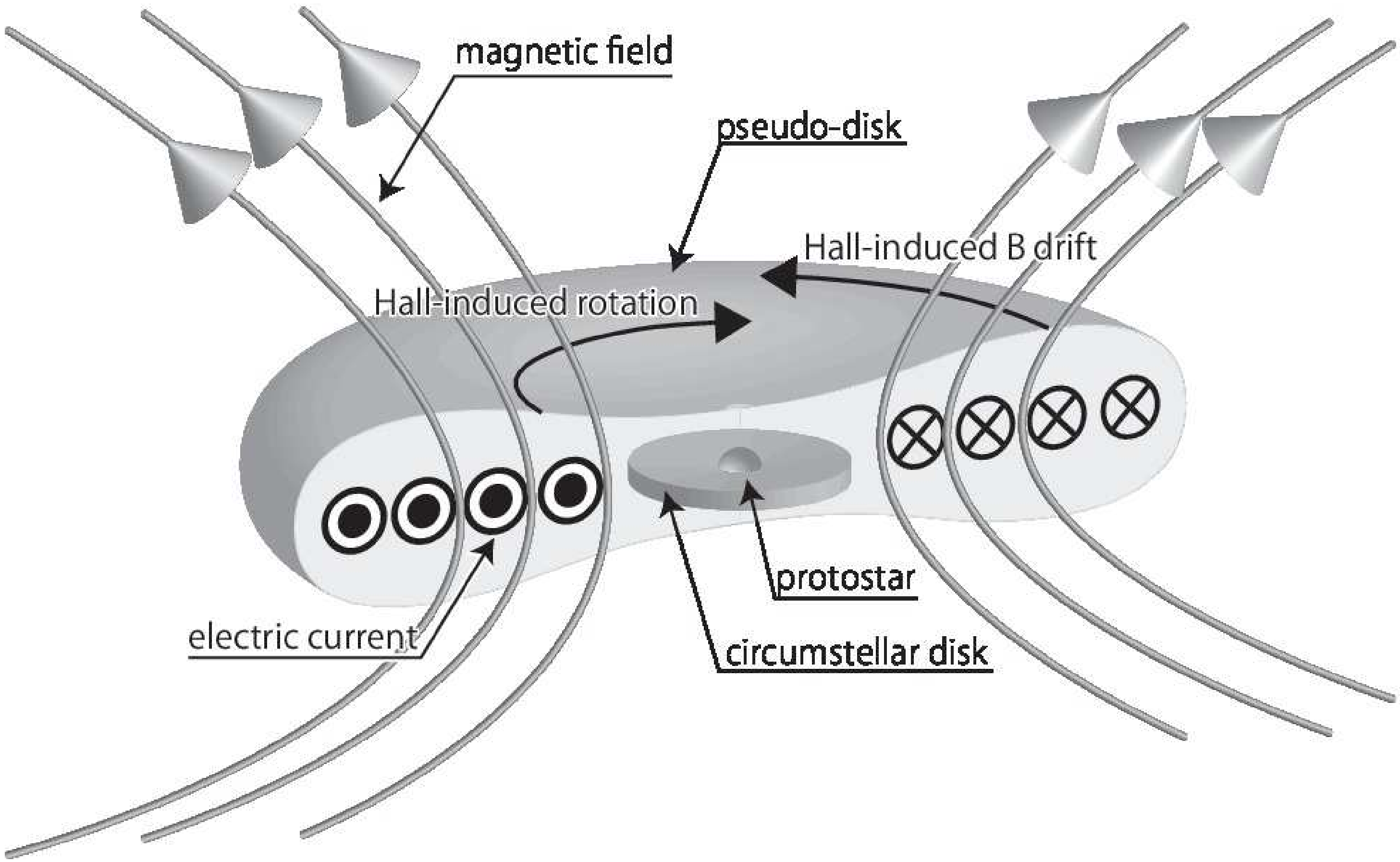
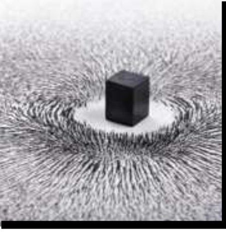
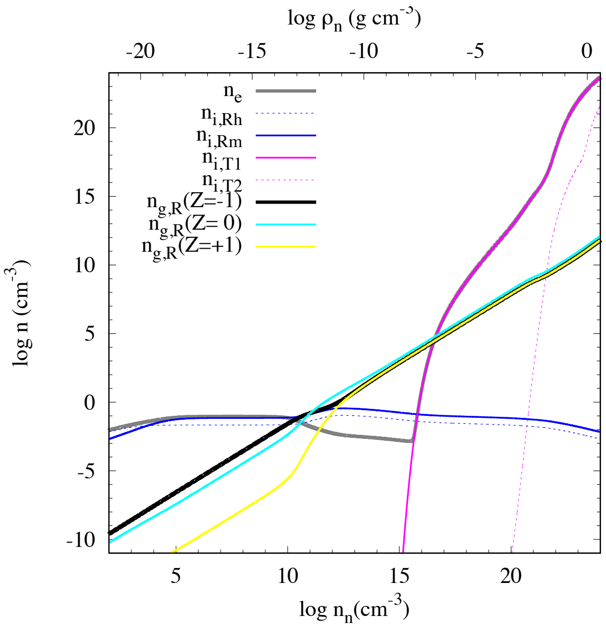


Image credit: Tsukamoto et al (2017); see also: Braiding & Wardle (2012a,b)



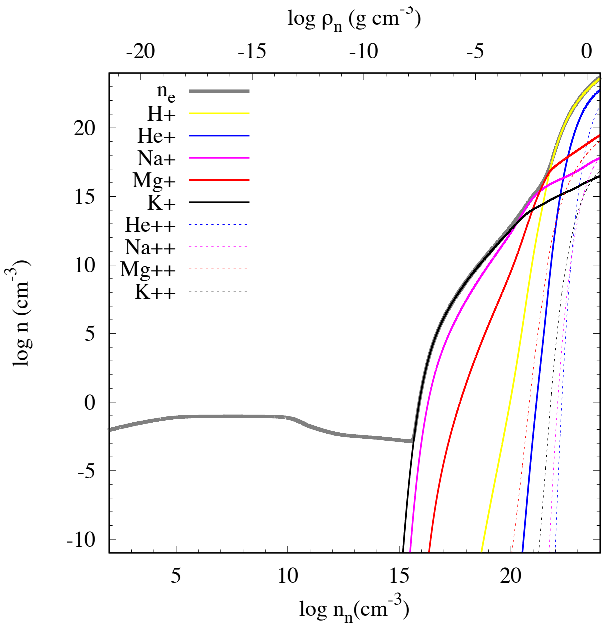
Non-ideal Magnetohydrodynamics

Cosmic ray ionisation:



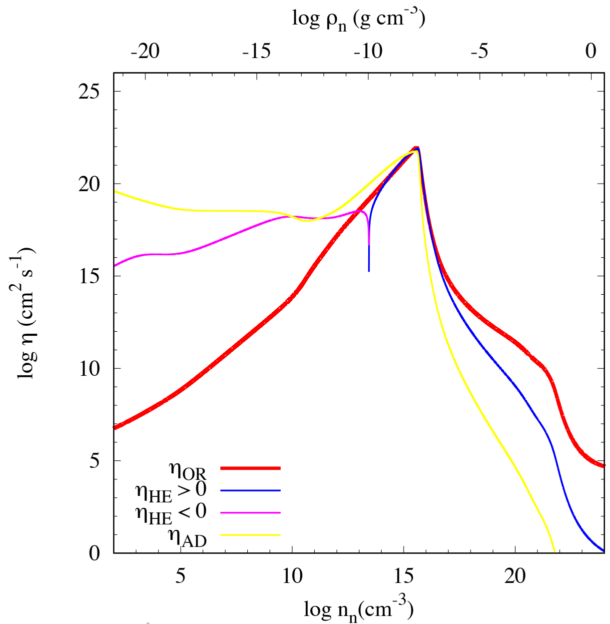
- Includes
  - Heavy & light ions
  - grains

Thermal ionisation:



- Includes
  - 5 singly ionised elements
  - 4 doubly ionised elements

Coefficients:



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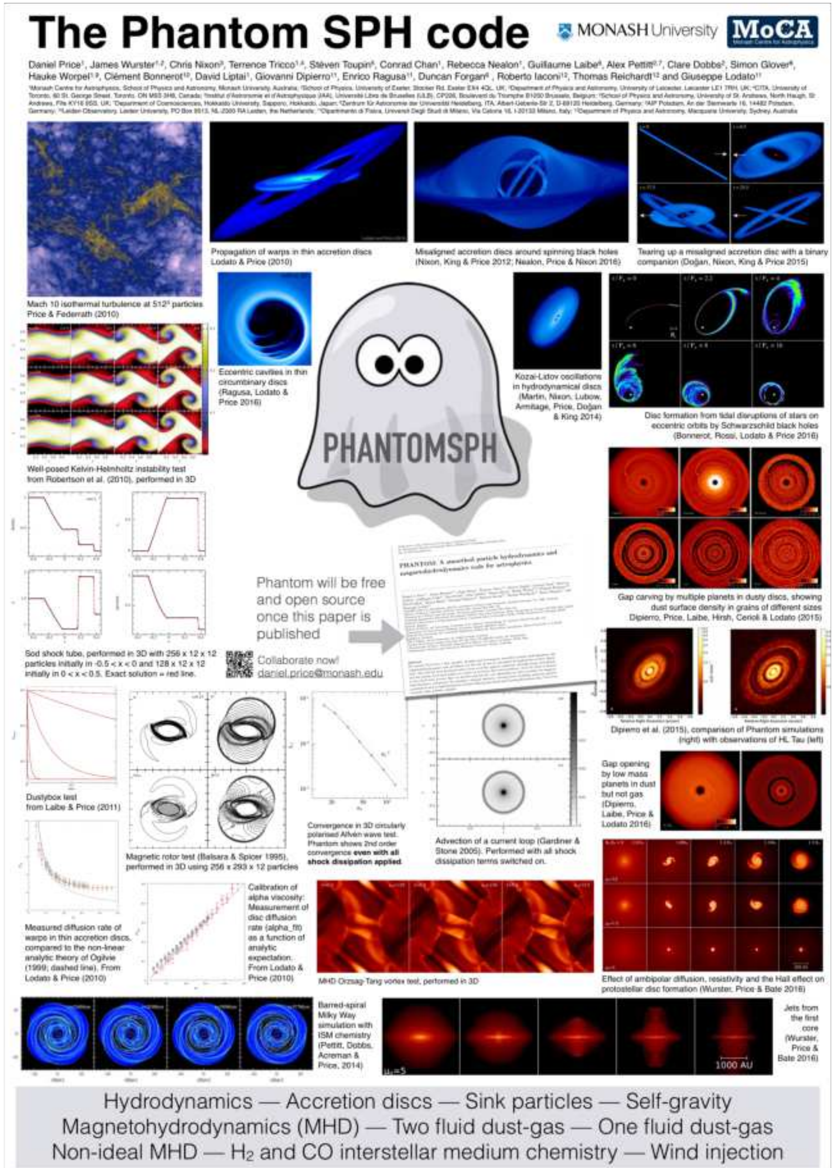
$$\left.\frac{\mathrm{d}\boldsymbol{B}}{\mathrm{d}t}\right|_{\mathrm{HE}} = -\boldsymbol{\nabla}\times\eta_{\mathrm{HE}}\left[\left(\boldsymbol{\nabla}\times\boldsymbol{B}\right)\times\hat{\boldsymbol{B}}\right],$$

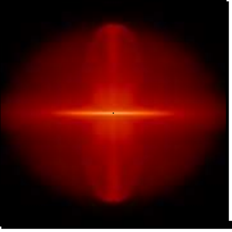
$$\left.\frac{\mathrm{d}\boldsymbol{B}}{\mathrm{d}t}\right|_{\mathrm{AD}} = \boldsymbol{\nabla}\times\eta_{\mathrm{AD}}\left\{\left[\left(\boldsymbol{\nabla}\times\boldsymbol{B}\right)\times\hat{\boldsymbol{B}}\right]\times\hat{\boldsymbol{B}}\right\}.$$

Wurster (2016): NICIL code. Available at https://bitbucket.org/jameswurster/nicil/wiki/Home

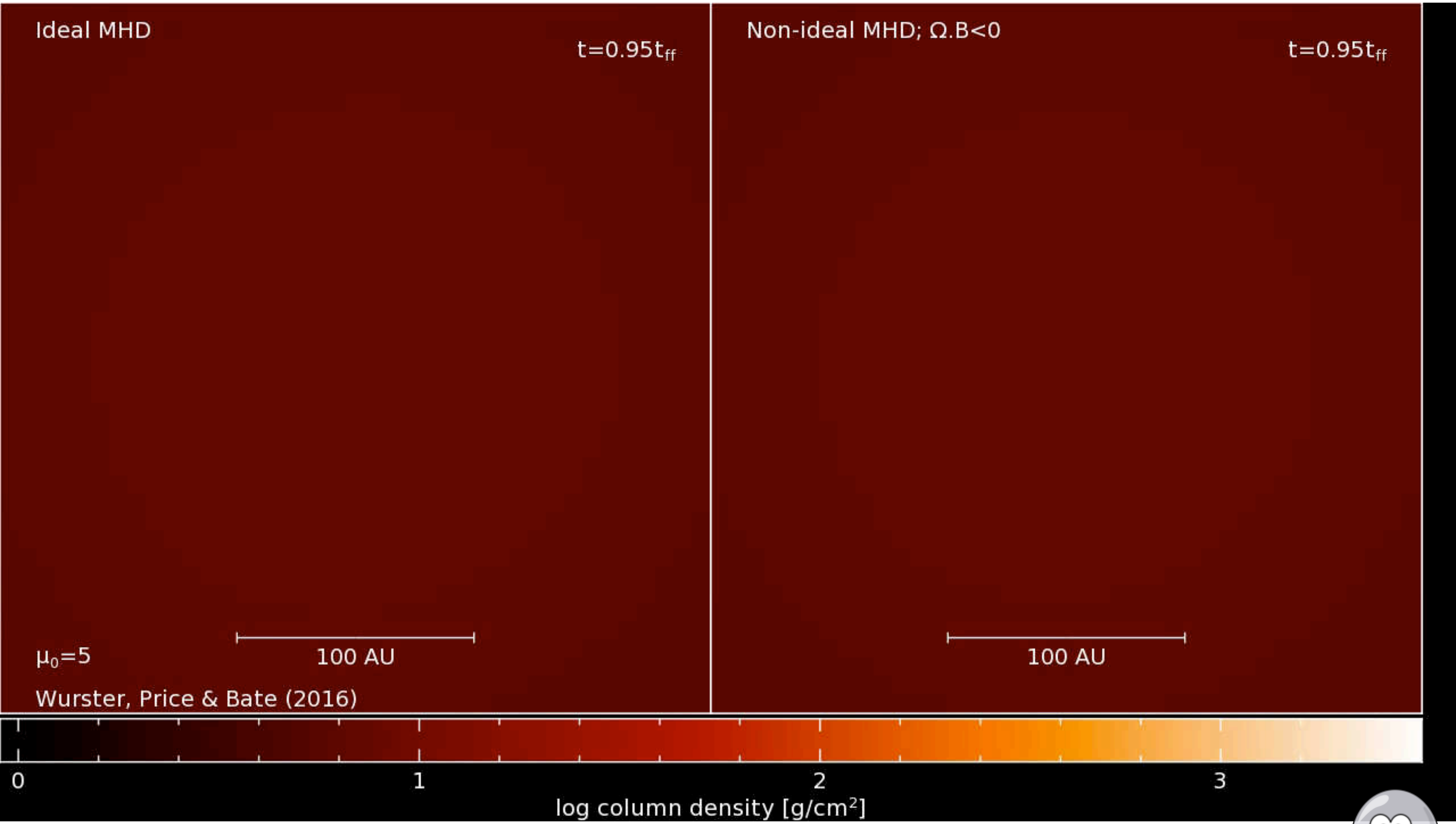
Phantom



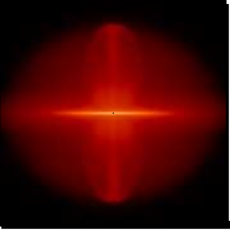
- Phantom
  - Publically available at https://phantomsph.bitbucket.io
  - Reference:
  - D. J. Price, J. Wurster, C. Nixon, T. S. Tricco, and 22 others. (arXiv:1702.03930)



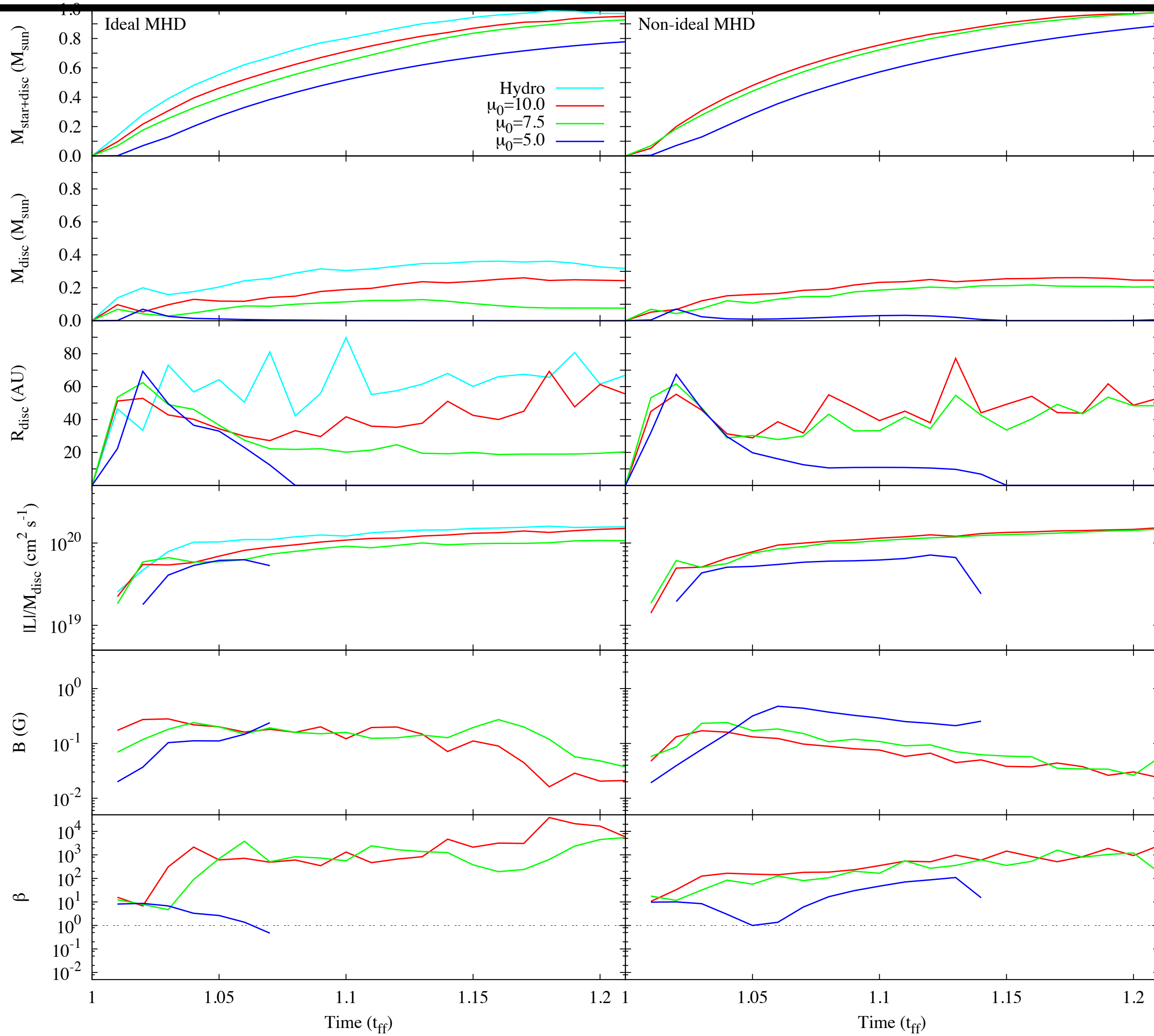
Disc Formation: Ideal & Non-ideal MHD



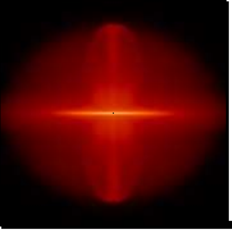
Video available at https://www.youtube.com/watch?v=j2032OTknvY



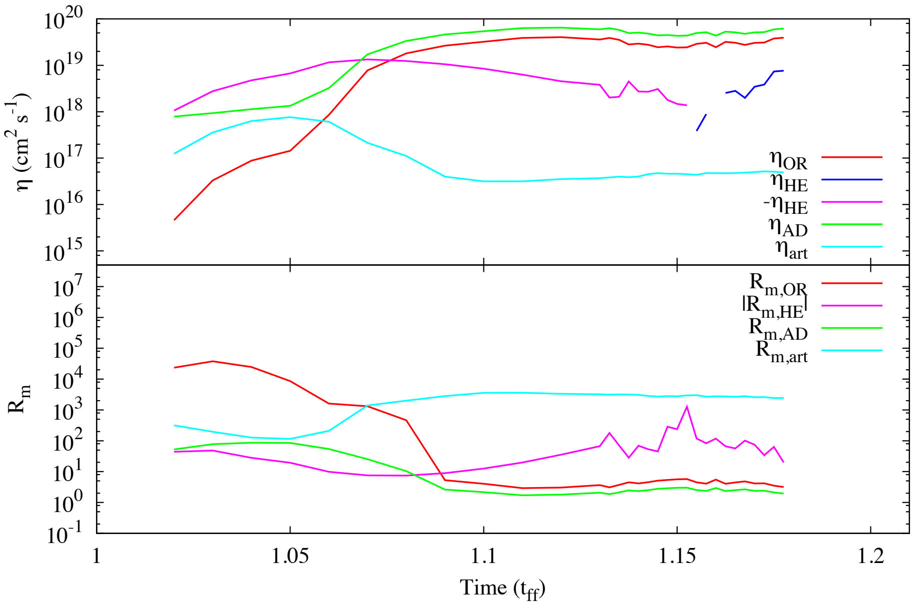
Disc Properties

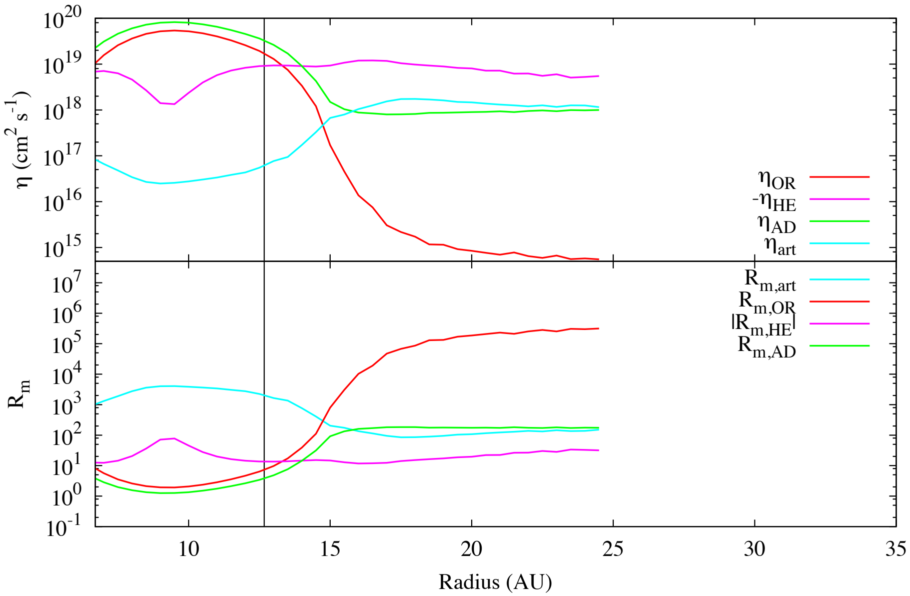


Wurster, Price & Bate (2016)

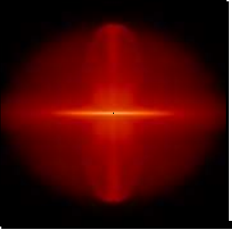


Disc Properties

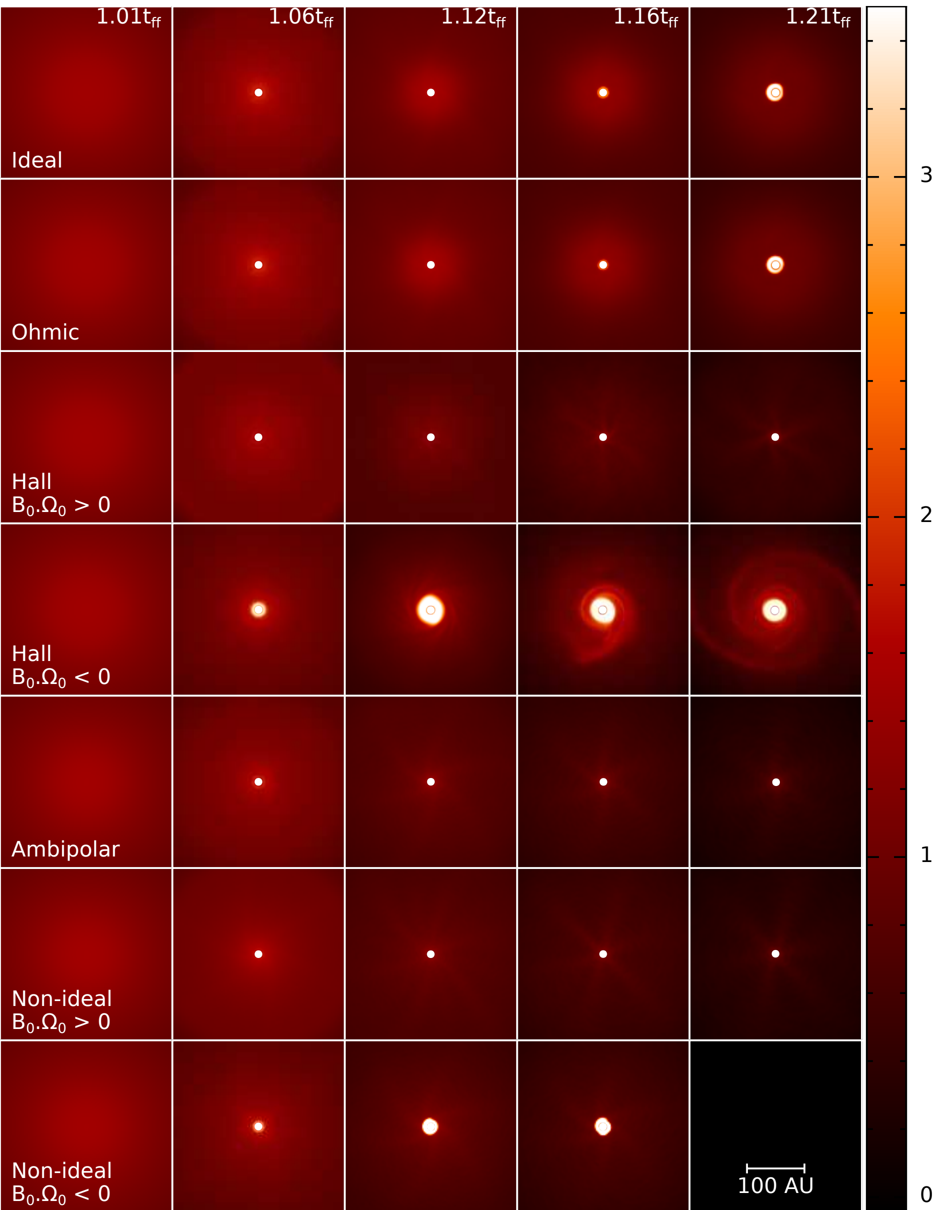


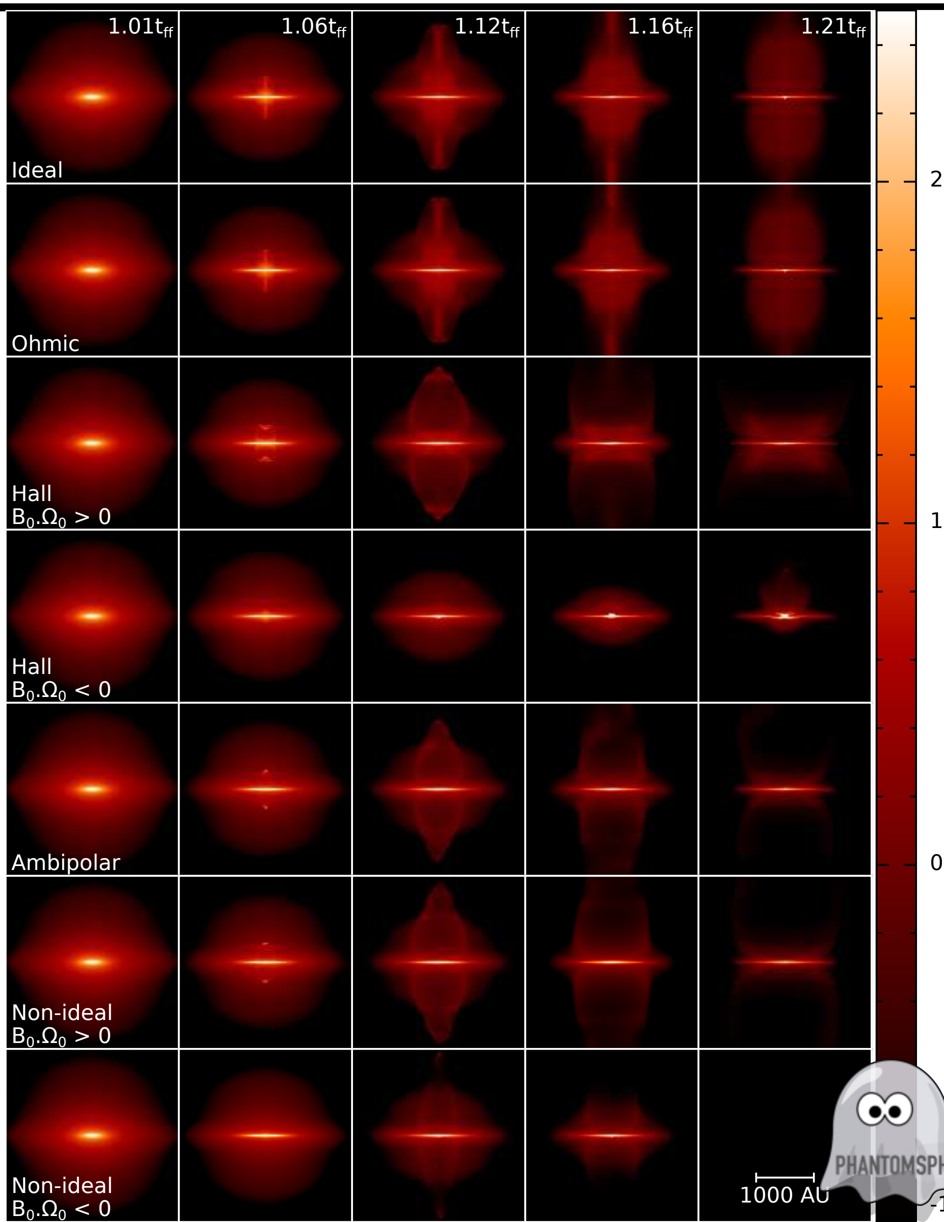


Wurster, Price & Bate (2016)

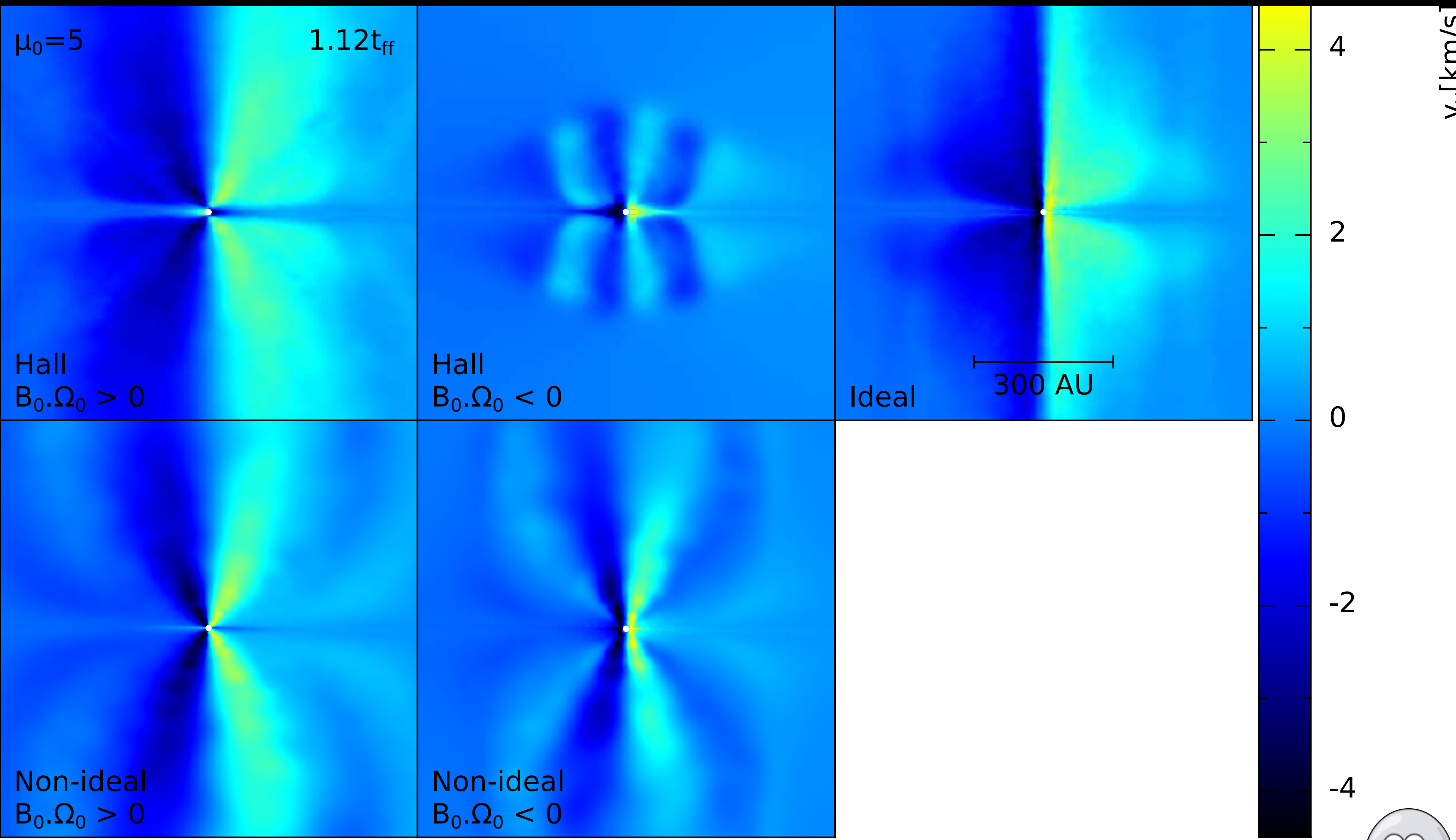


Non-Ideal MHD Components





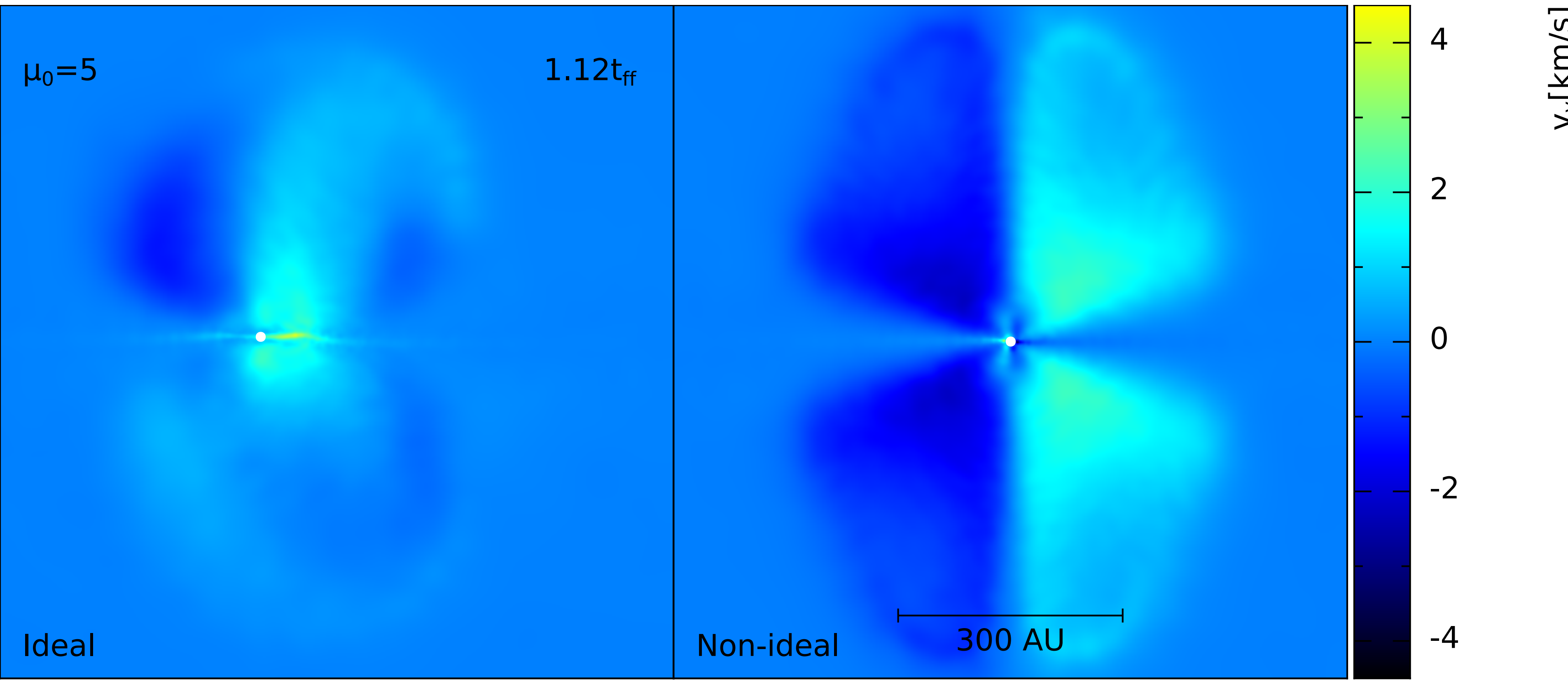
Counter-rotating Envelope



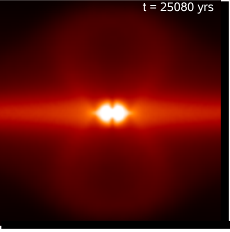
Wurster, Price & Bate (2016); see also Tsukamoto et al (2015)

- Hall effect induces the formation of a counter-rotating envelope

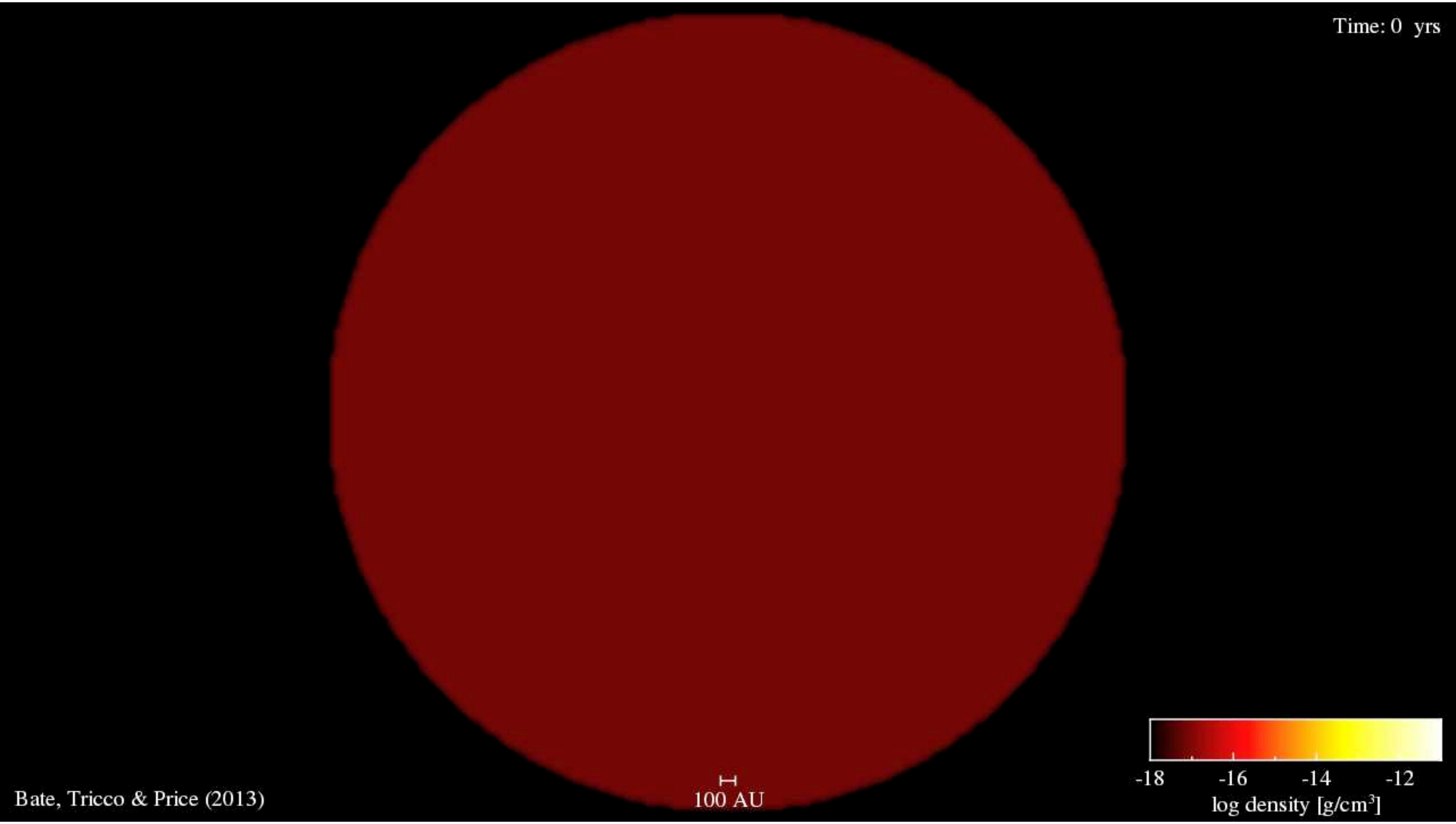
Induced Rotation



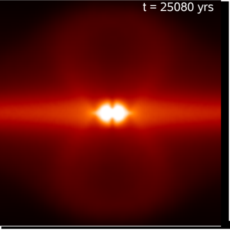
- Hall effect can induce coherent rotation from a zero-angular momentum initial condition



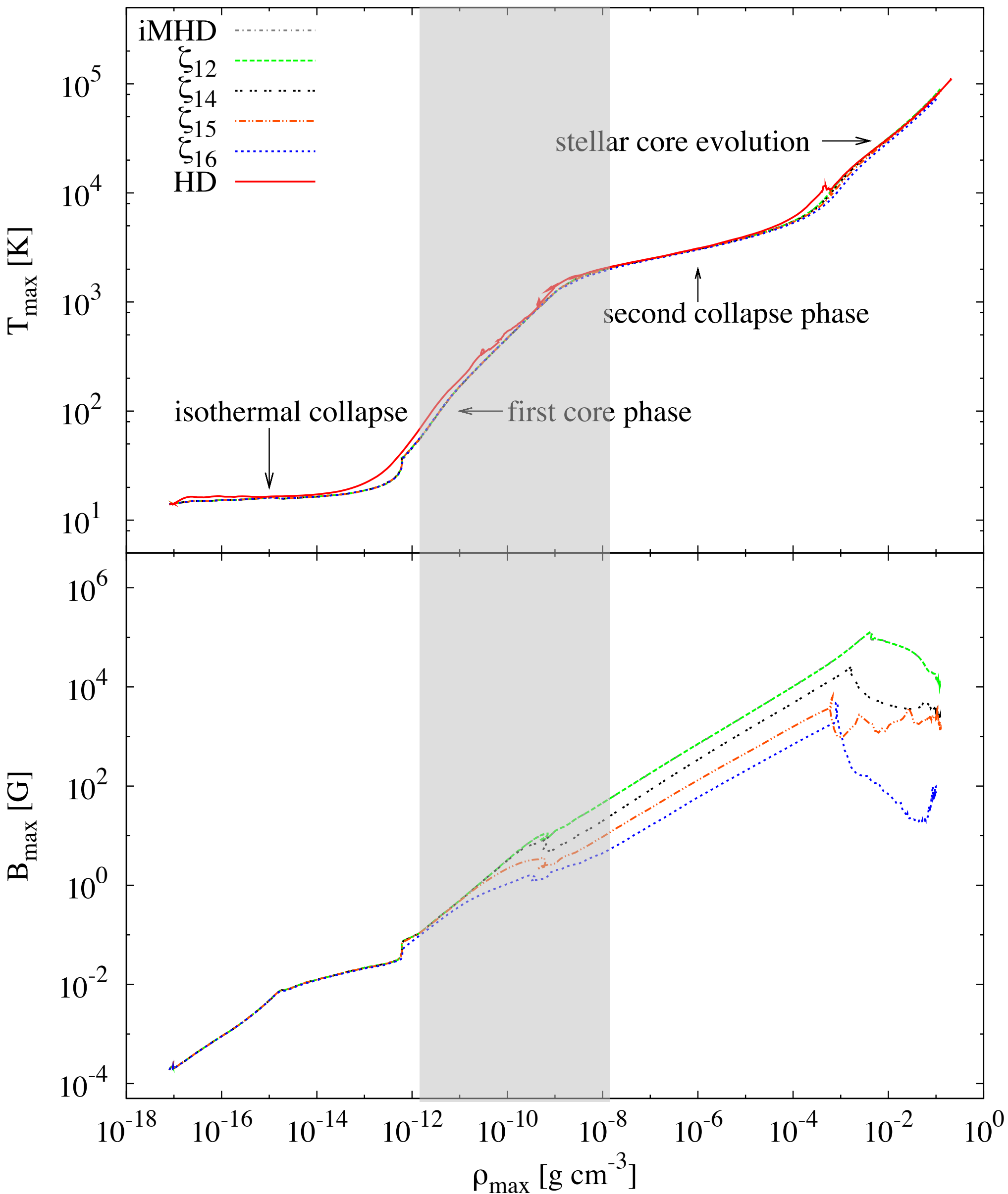
Collapse to stellar densities

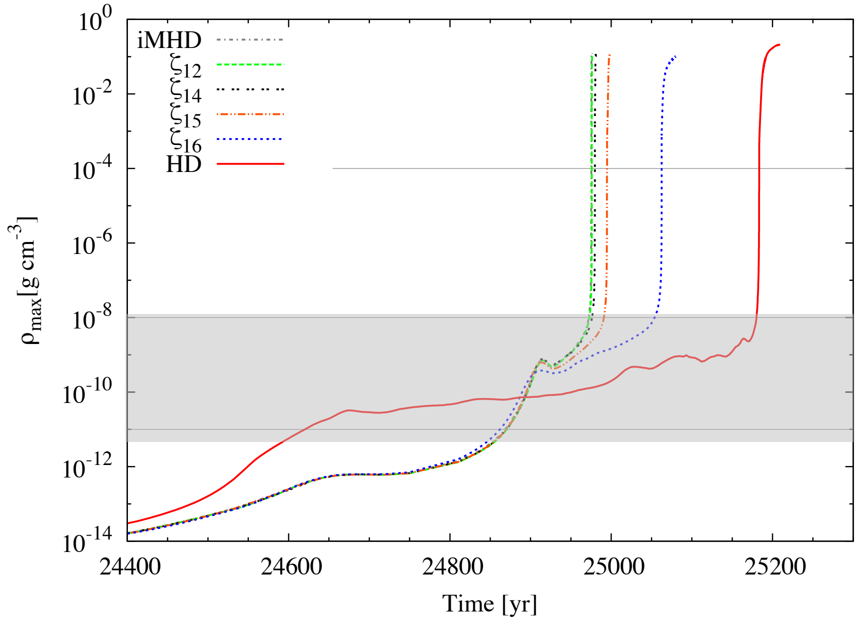


- Ideal MHD. Video available at https://www.astro.ex.ac.uk/people/mbate/Animations/BateTriccoPrice2013_MF05.mov

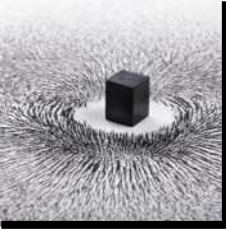


Collapse to stellar densities: First Hydrostatic Core



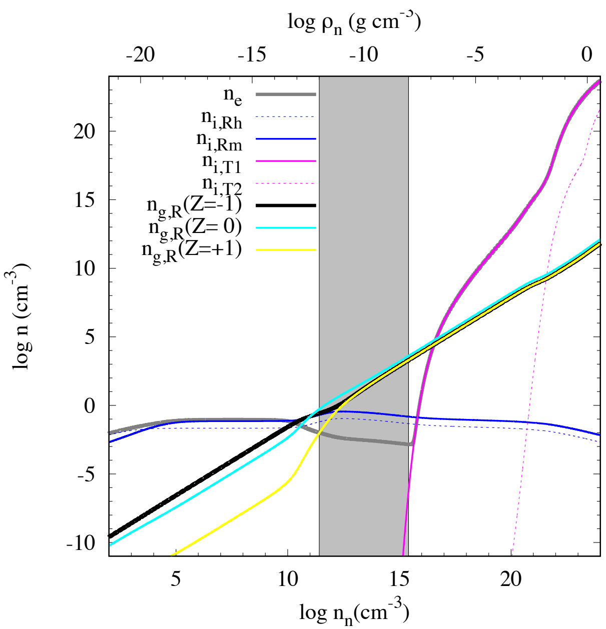


Wurster, Bate & Price (submitted)



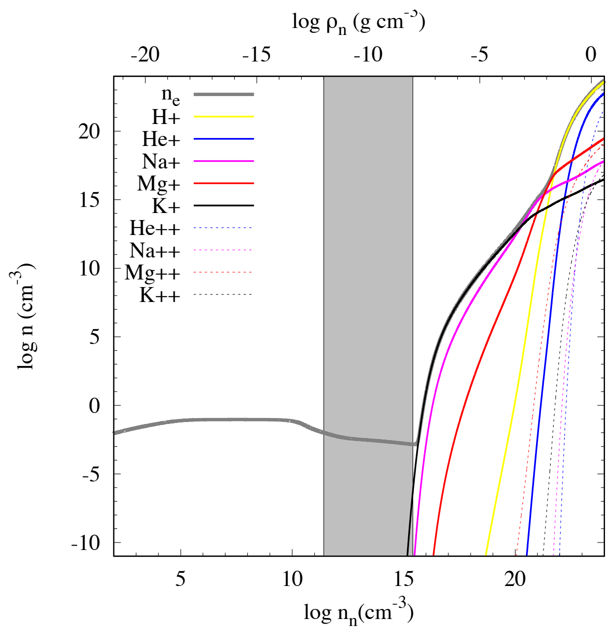
Collapse to stellar densities: FHC: Non-ideal Magnetohydrodynamics

Cosmic ray ionisation:



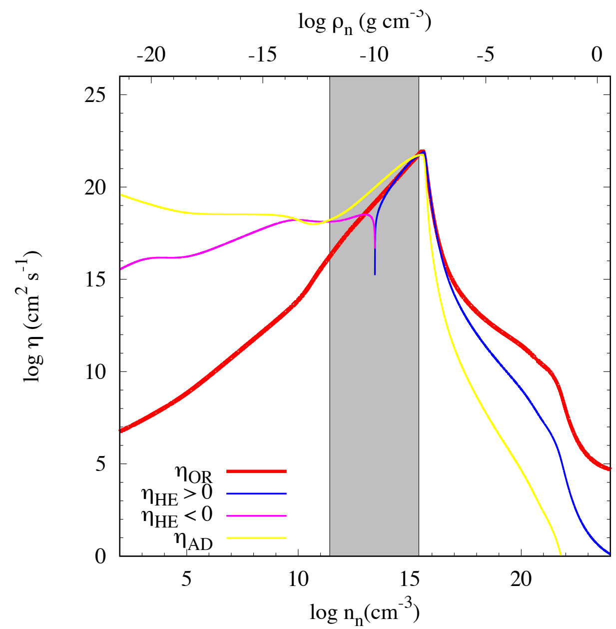
- Includes
  - Heavy & light ions
  - grains

Thermal ionisation:



- Includes
  - 5 singly ionised elements
  - 4 doubly ionised elements

Coefficients:

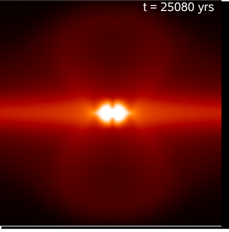


$$\left.\frac{\mathrm{d}\boldsymbol{B}}{\mathrm{d}t}\right|_{\mathrm{OR}} = -\boldsymbol{\nabla}\times\eta_{\mathrm{OR}}\left(\boldsymbol{\nabla}\times\boldsymbol{B}\right),$$

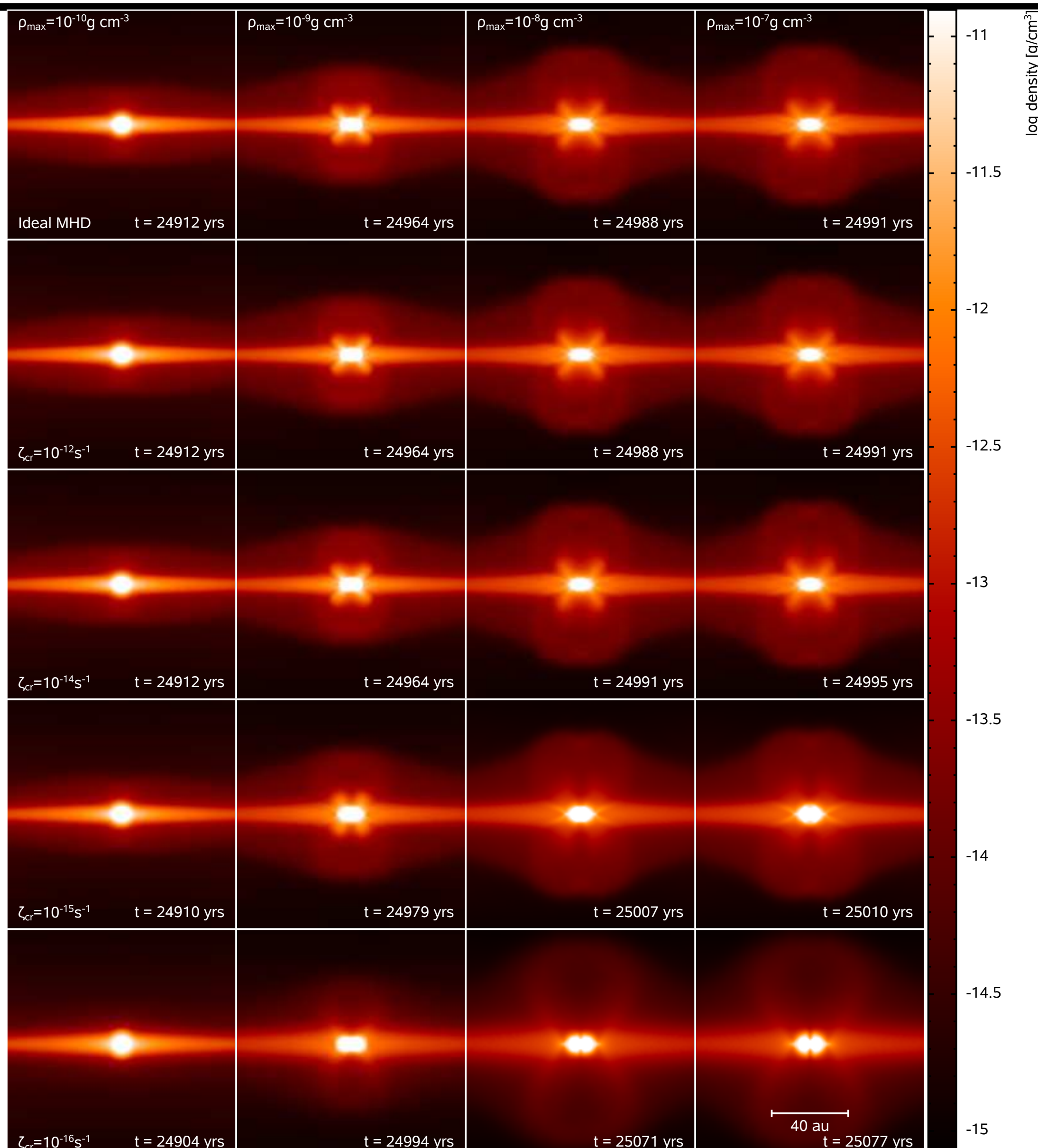
$$\left.\frac{\mathrm{d}\boldsymbol{B}}{\mathrm{d}t}\right|_{\mathrm{HE}} = -\boldsymbol{\nabla}\times\eta_{\mathrm{HE}}\left[\left(\boldsymbol{\nabla}\times\boldsymbol{B}\right)\times\hat{\boldsymbol{B}}\right],$$

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

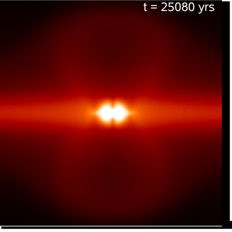
Wurster (2016)



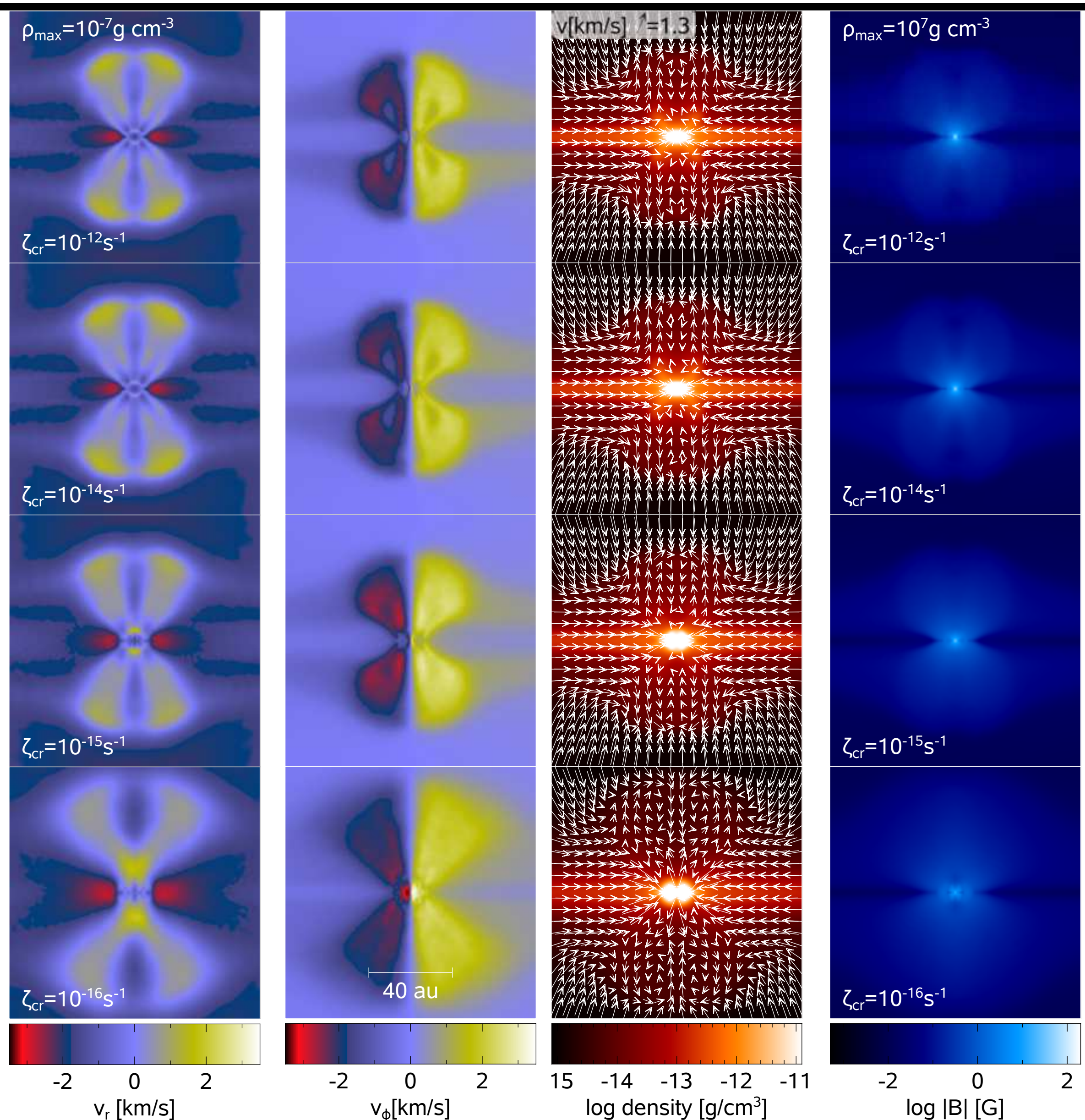
Collapse to stellar densities: First Hydrostatic Core



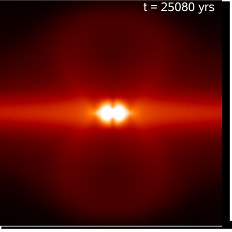
Wurster, Bate & Price (submitted)



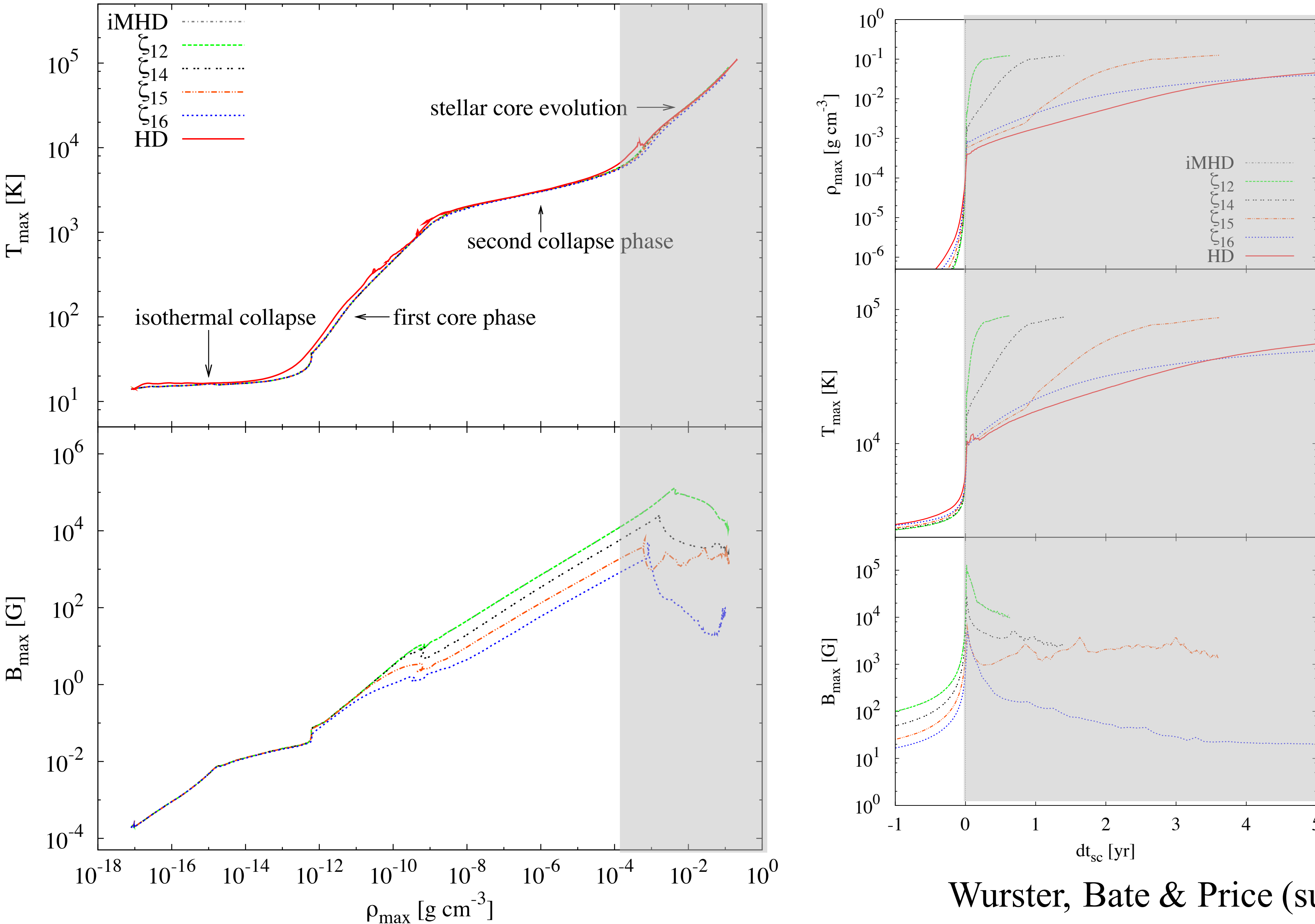
Collapse to stellar densities: First Hydrostatic Core



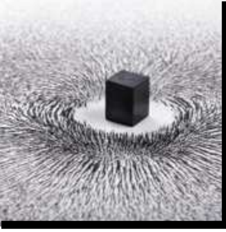
Wurster, Bate & Price (submitted)



Collapse to stellar densities: Stellar core

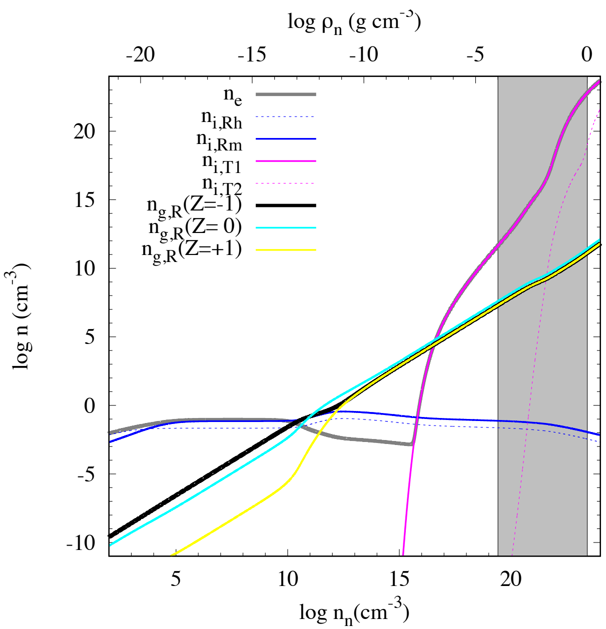


Wurster, Bate & Price (submitted)



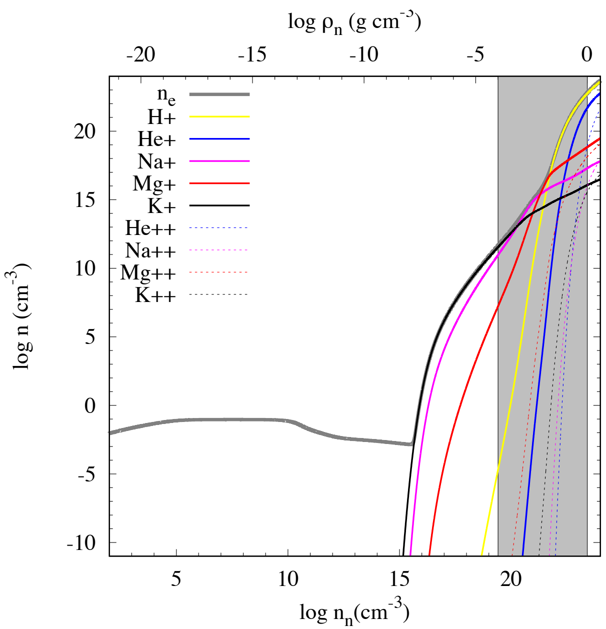
Collapse to stellar densities: SHC: Non-ideal Magnetohydrodynamics

Cosmic ray ionisation:



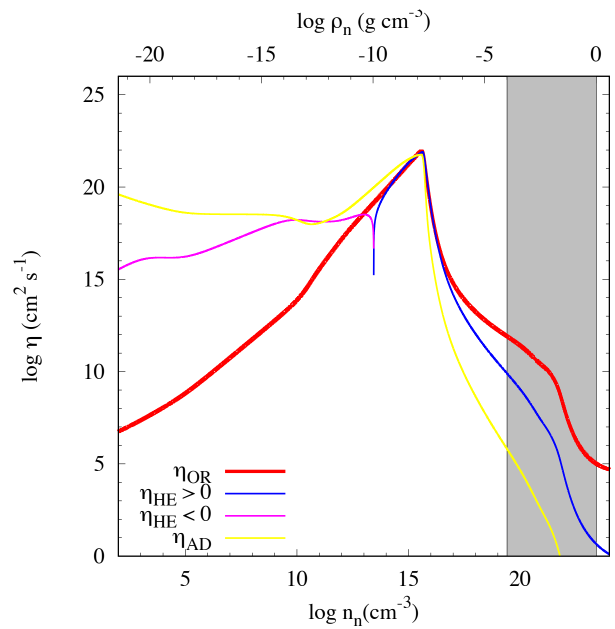
- Includes
  - Heavy & light ions
  - grains

Thermal ionisation:



- Includes
  - 5 singly ionised elements
  - 4 doubly ionised elements

Coefficients:



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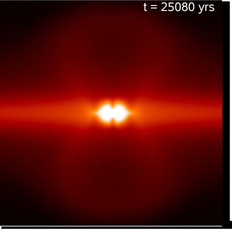
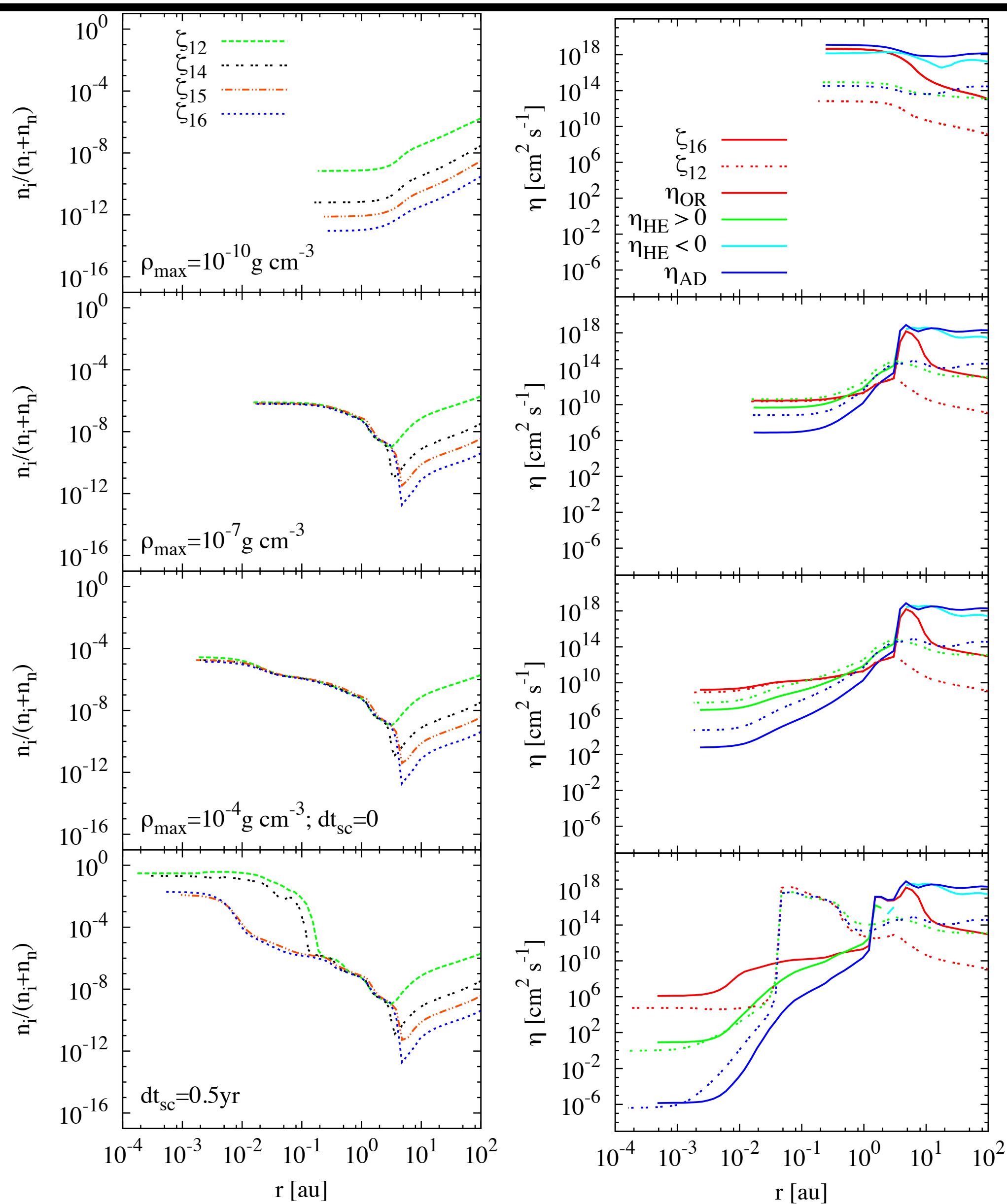
$$\left.\frac{\mathrm{d}\boldsymbol{B}}{\mathrm{d}t}\right|_{\mathrm{HE}} = -\boldsymbol{\nabla}\times\eta_{\mathrm{HE}}\left[\left(\boldsymbol{\nabla}\times\boldsymbol{B}\right)\times\hat{\boldsymbol{B}}\right],$$

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

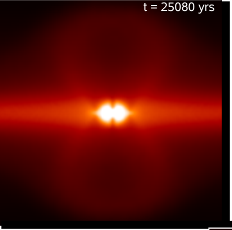
Wurster (2016)



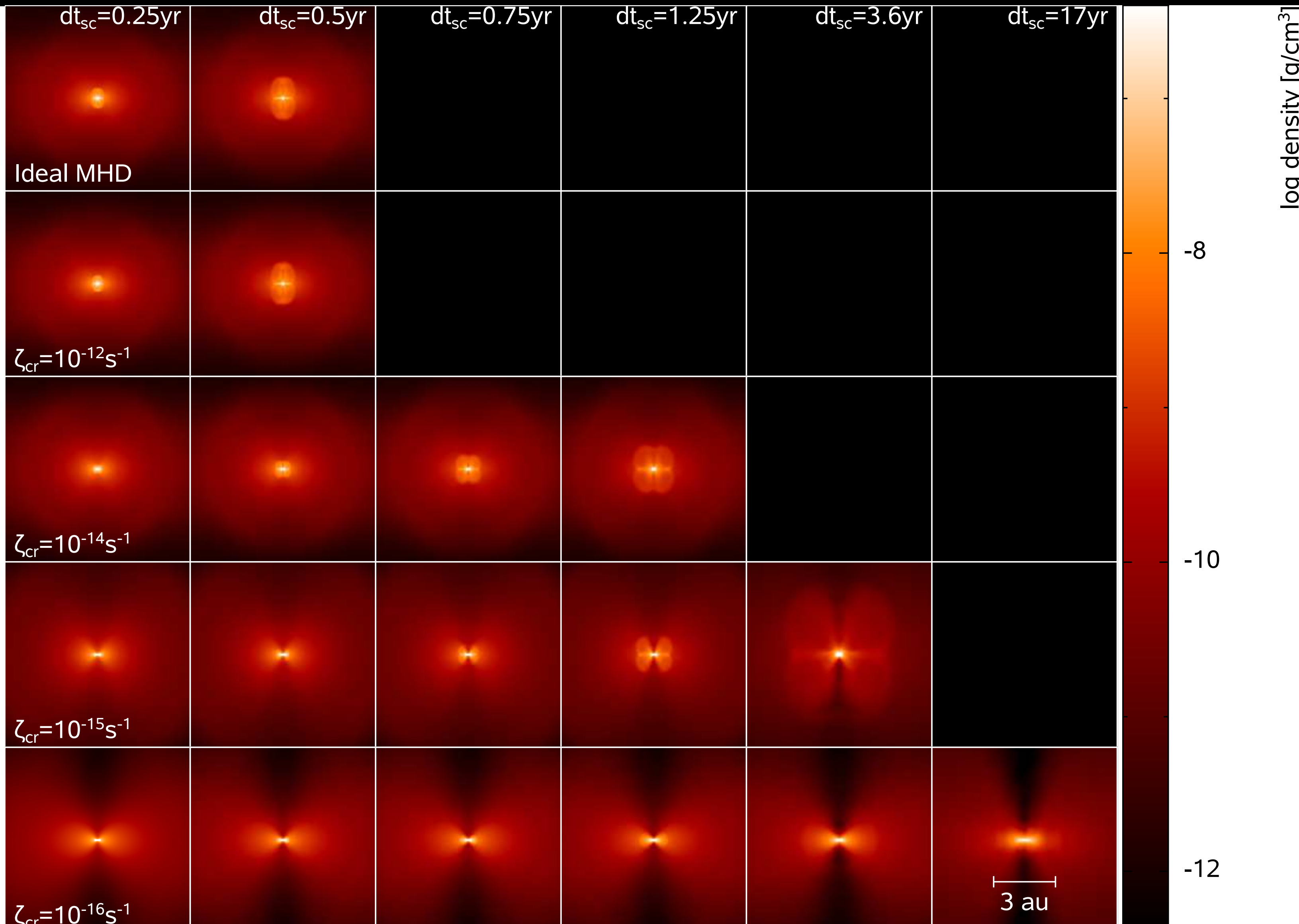
Collapse to stellar densities



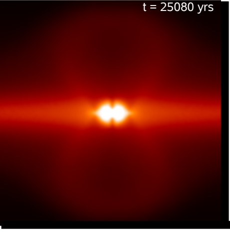
Wurster, Bate & Price (submitted)



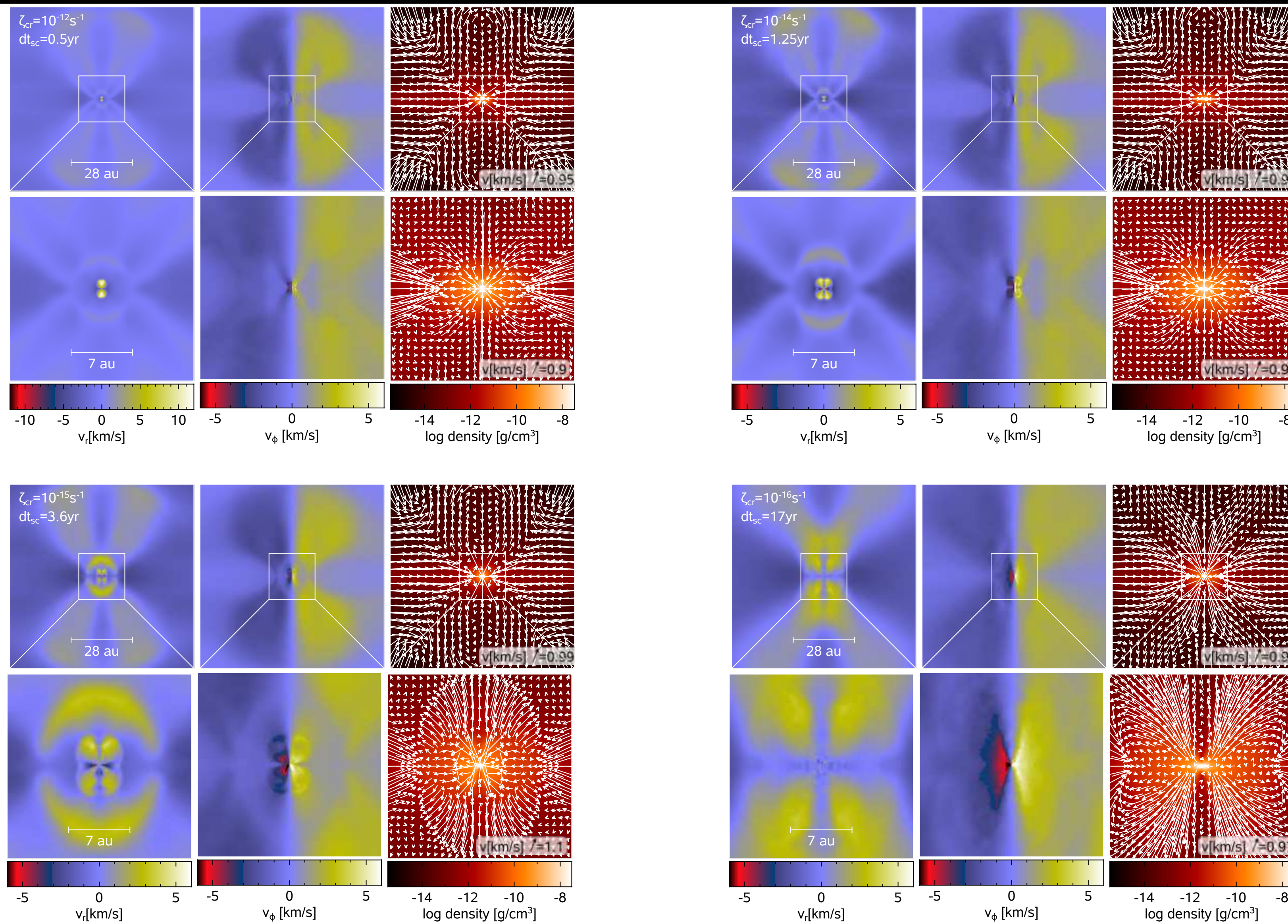
Collapse to stellar densities: Stellar core



Wurster, Bate & Price (submitted)



Collapse to stellar densities: Stellar core



Wurster, Bate & Price (submitted)

Conclusions

- Large disc forms with no magnetic fields
- No disc forms with strong, ideal magnetic fields
    - Large discs with strong magnetic fields are observed

- Decreasing M/Φ decreases mass and size of resulting disc
- Formation of discs and outflows is anti-correlated
- Changing initial magnetic field direction + Hall effect is strongest affect
- Larger discs form with lower ionisation rate
- Hall Effect causes the formation of a counter-rotating envelope

- Non-ideal MHD suppresses first and second core outflows

- This is just the beginning!

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