Protostars and discs: Low-mass star formation in a magnetised medium

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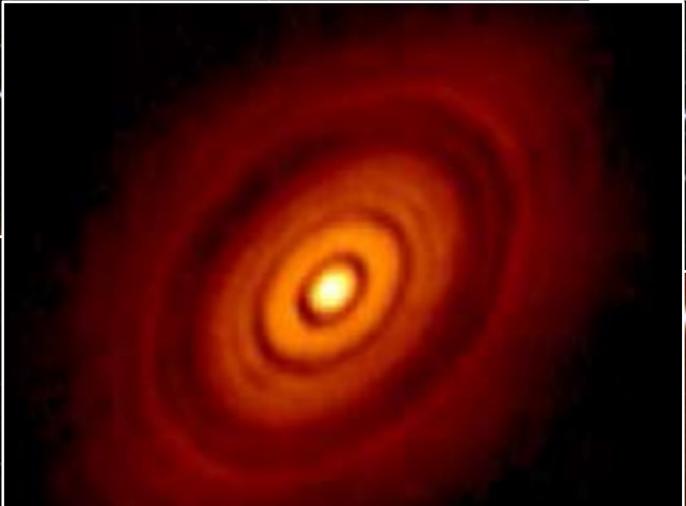
Importance of stars: The big picture

Stars as energetic events: SN 1994D near NGC 4526 (apod.nasa.gov)

Stars as light sources: Whirlpool Galaxy (M51; nasa.gov)



Stars hosting planetary systems: HL Tau dust disc (ALMA Partnership, 2015)

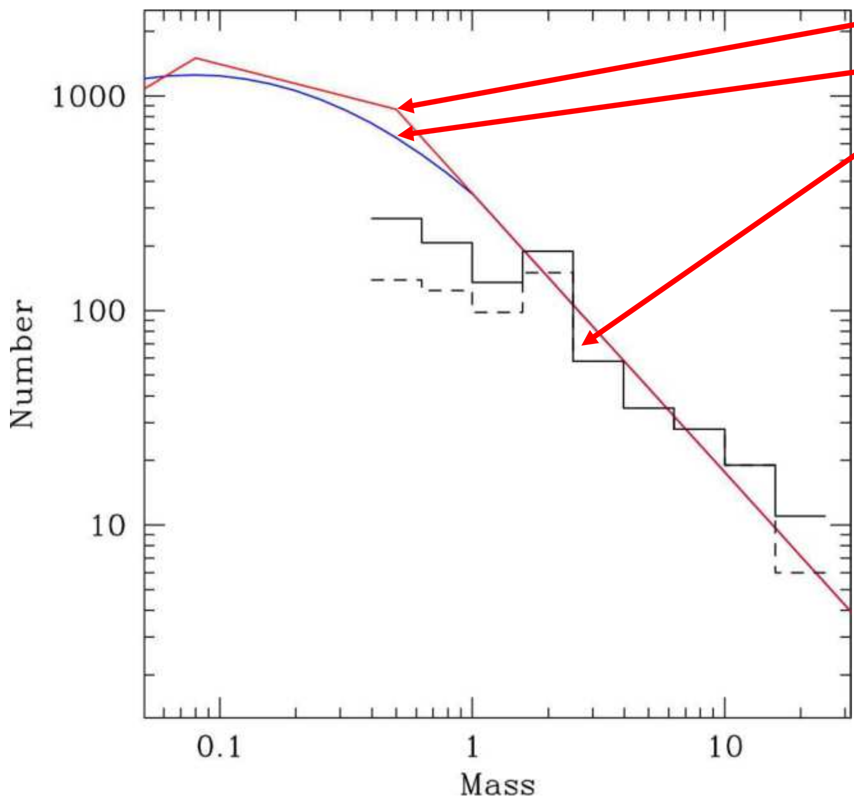
Stars as energetic events: Wolf-Rayet Star 124 (apod.nasa.gov)

Stars launching jets: Large scale HH jet driven by a proto-brown dwarf (Riaz et. al., 2017)

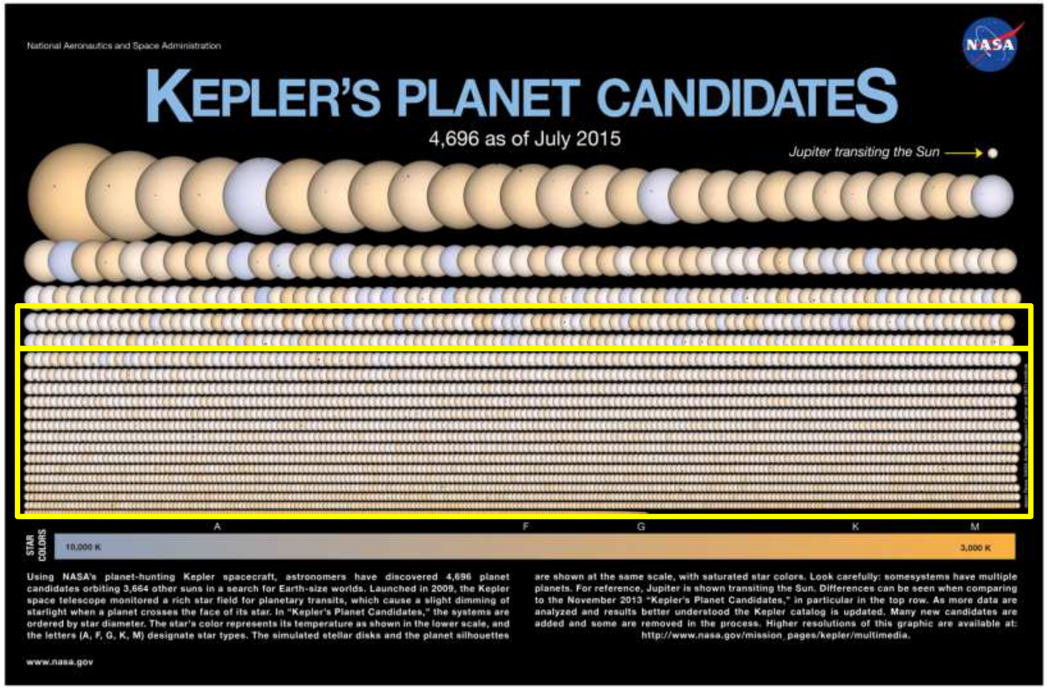
Stars as light sources: Hubble Ultra Deep Field (nasa.gov)

Importance of stars: Masses

- Initial mass function (IMF) of NCG 3603

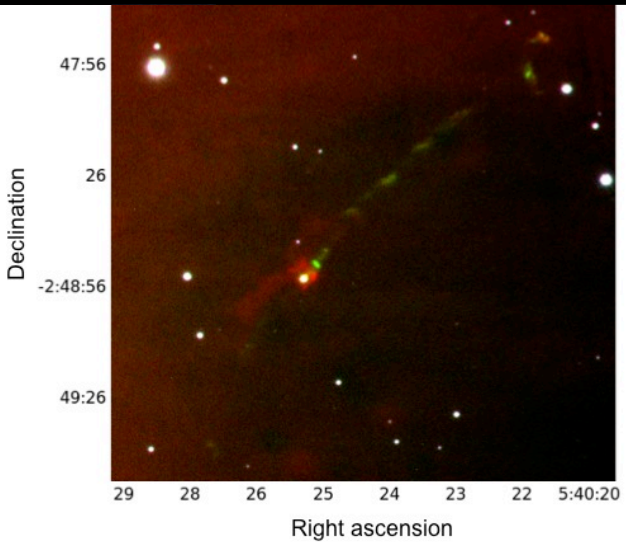


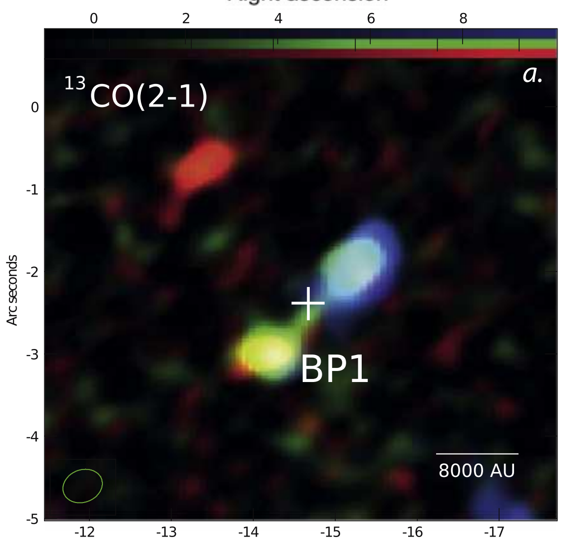
Kroupa IMF (2001)
Chabrier IMF (2003)
NCG 3603 (Stolte+ 2006)

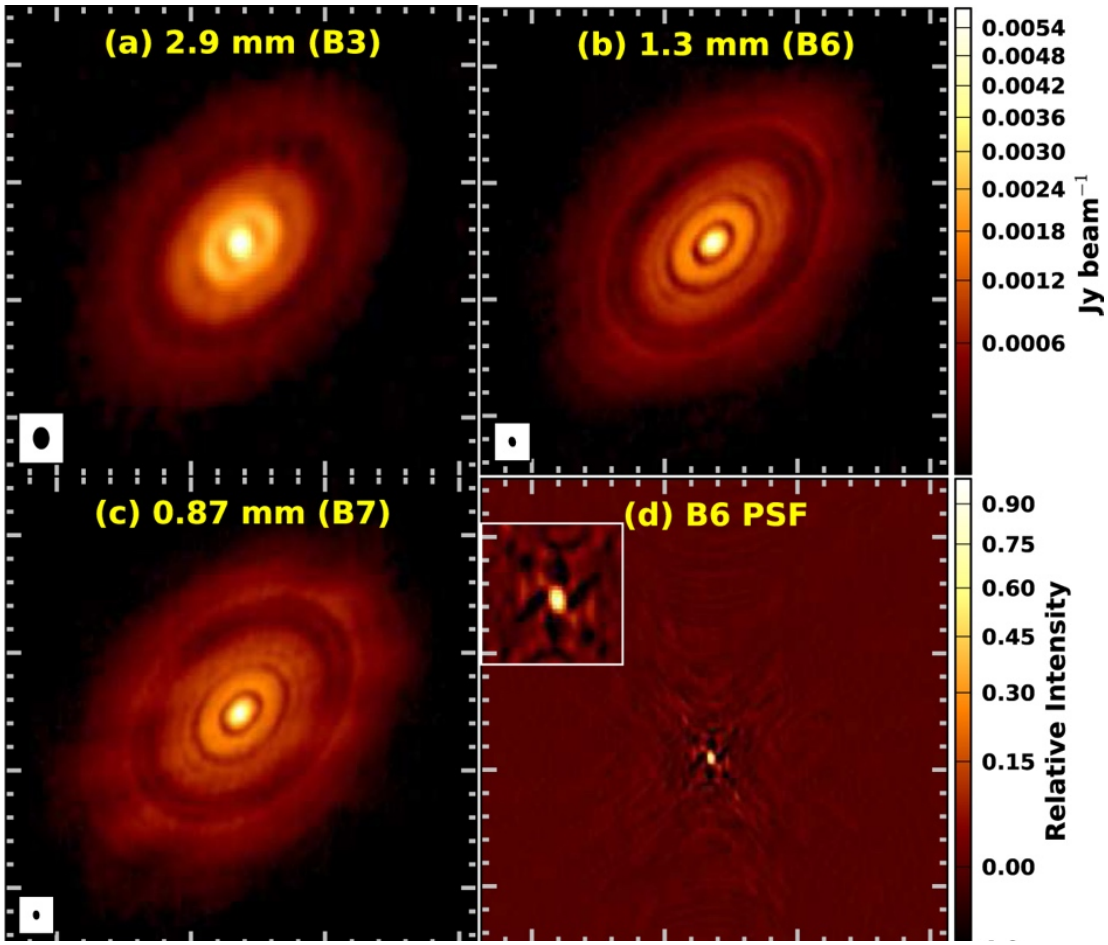


Left: Bonnell, Larson, Zinnecker (2007)

Importance of Low-stars: Outflows & Discs

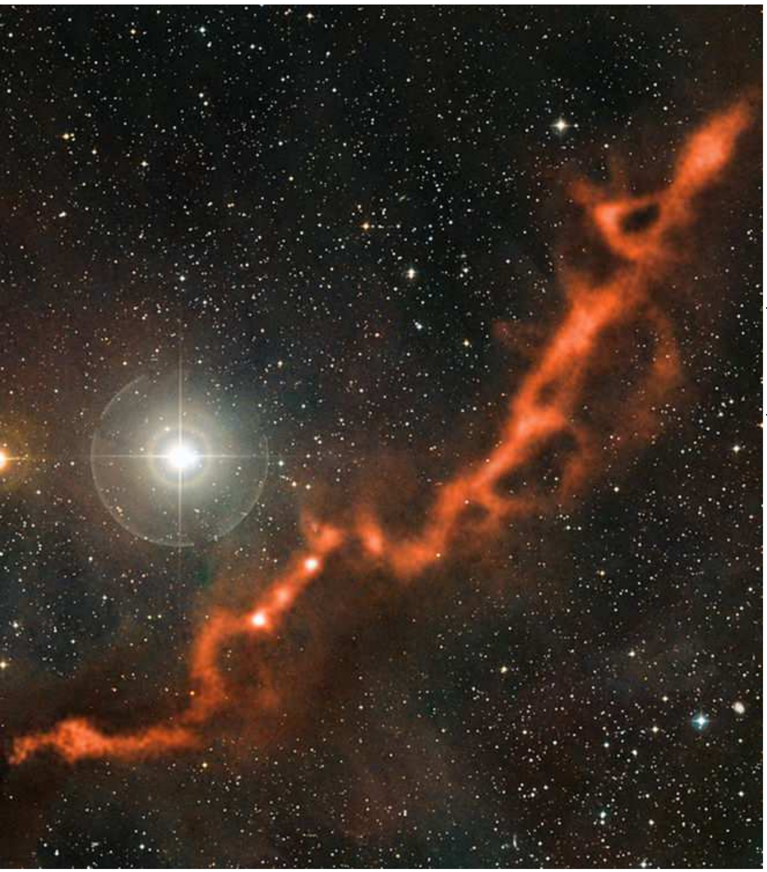




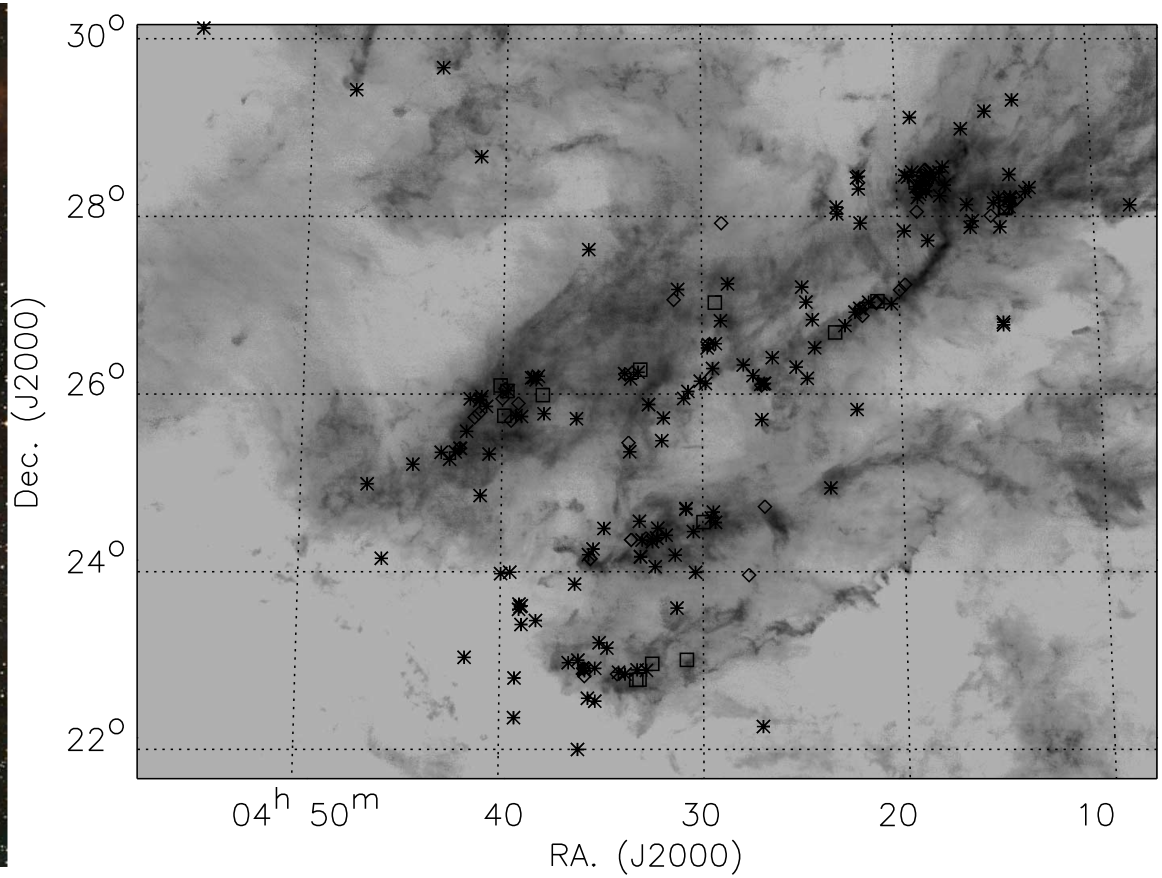


Top left: Large scale Herbig-Haro jet driven by a proto-brown dwarf (Riaz et. al., 2017)
Bottom left: CO outflows from low-mass stars with 1pc of Sgr A* (Yusef-Zadeh et. al., 2017)
Right: HL Tau dust disc (ALMA Partnership, 2015)

Importance of stars: Stellar nurseries

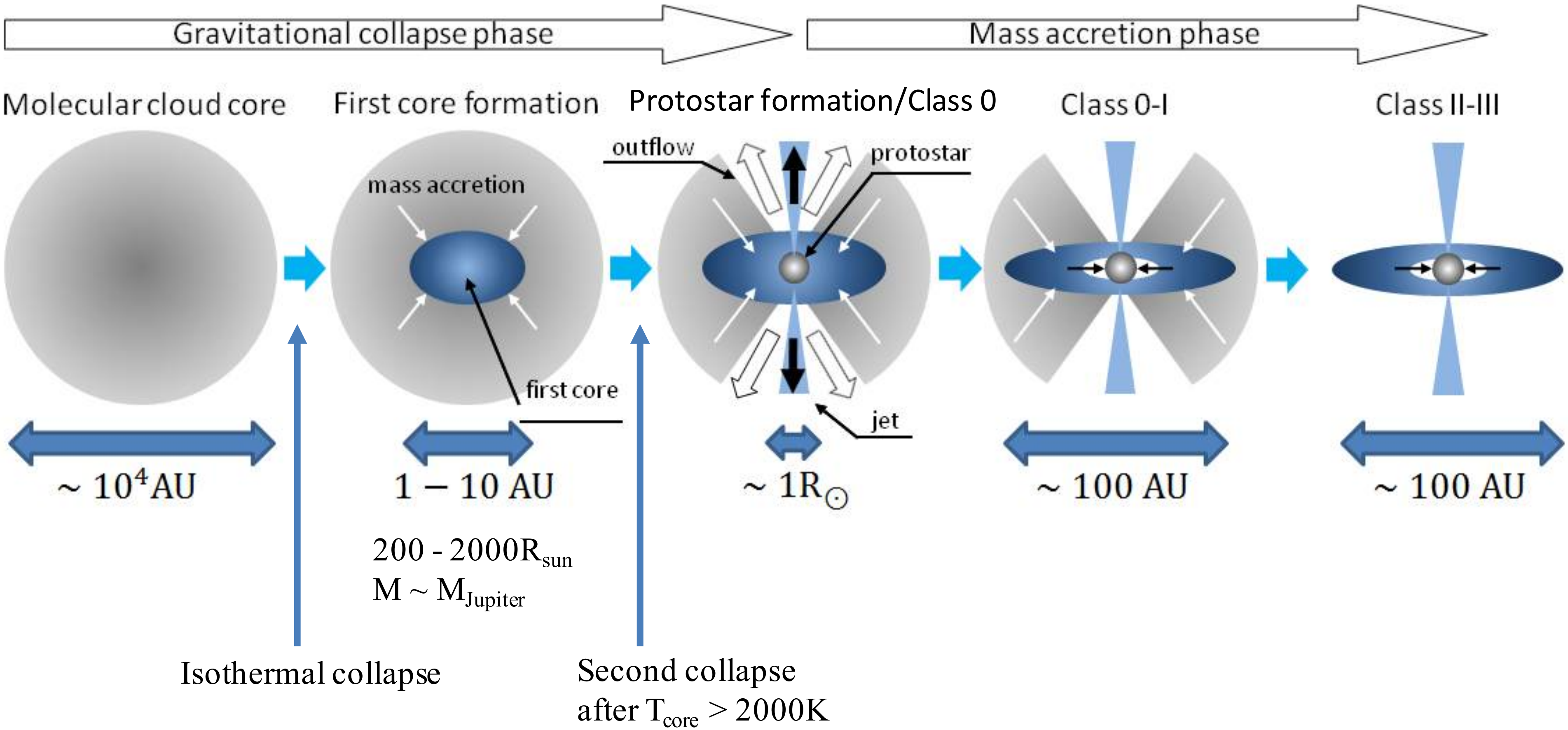


Taurus Molecular Cloud
(Credit: ESO/APEX (MPIfR/ESO/OSO)/A. Hacar et al./Digitized Sky Survey 2. Acknowledgment: Davide De Martin)



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

Star formation: from the beginning

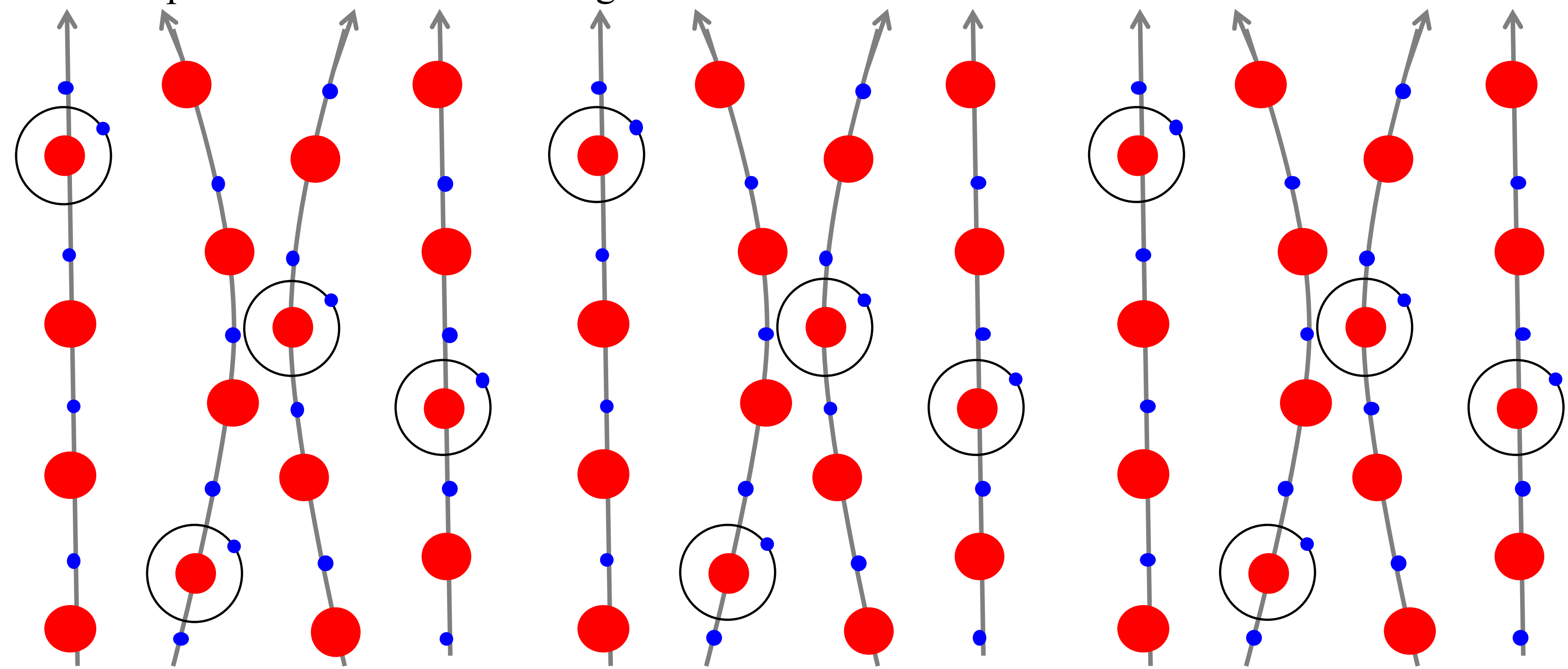


Larson (1969); Illustration by Y. Tsukamoto

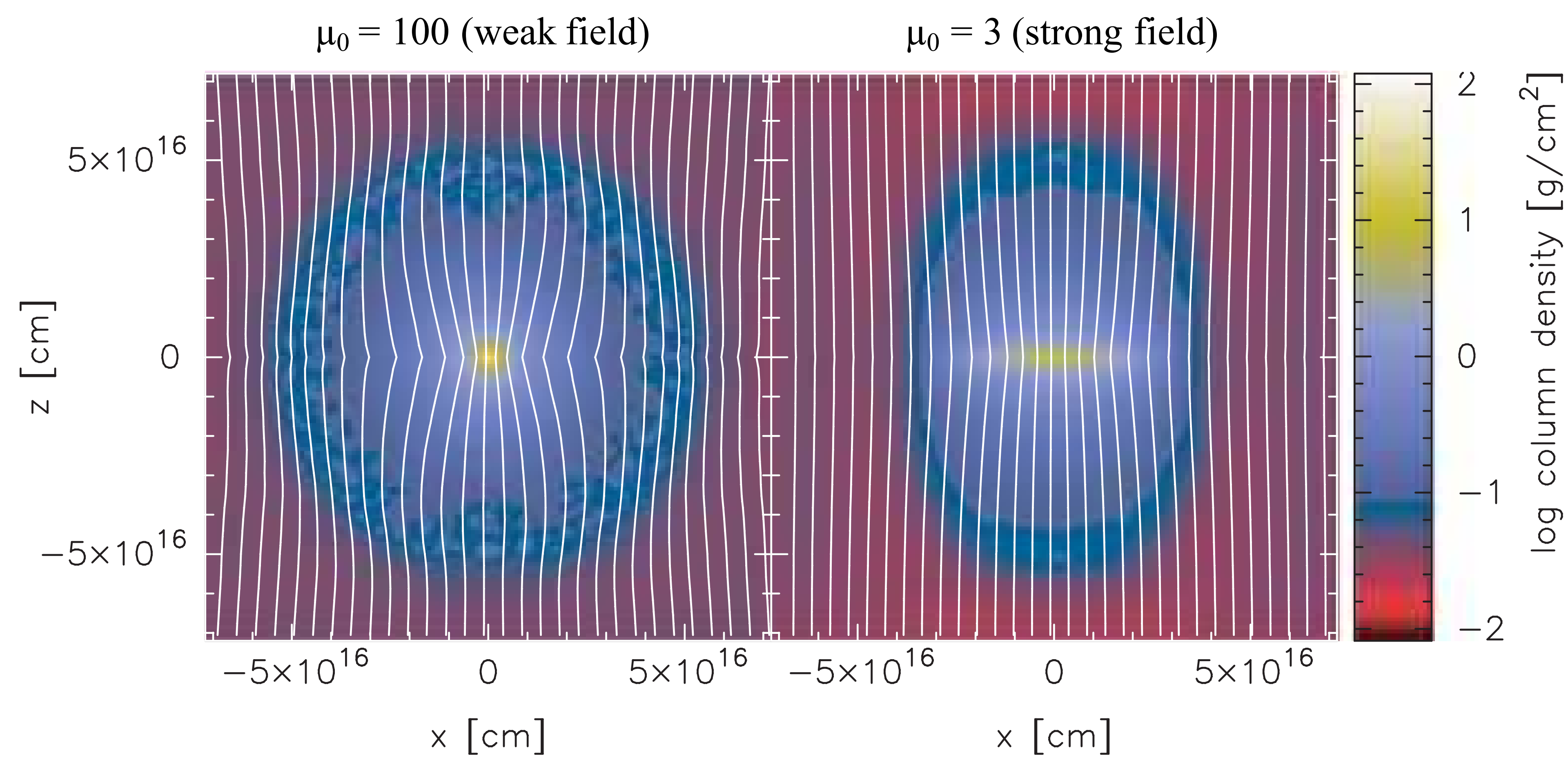
Ideal magnetic fields

- Highly ionised plasma: 

- Zero resistivity & infinite conductivity
- Ions & electrons are tied to the magnetic field
- Neutral particles are tied to the magnetic field due to interactions with the ions & electrons

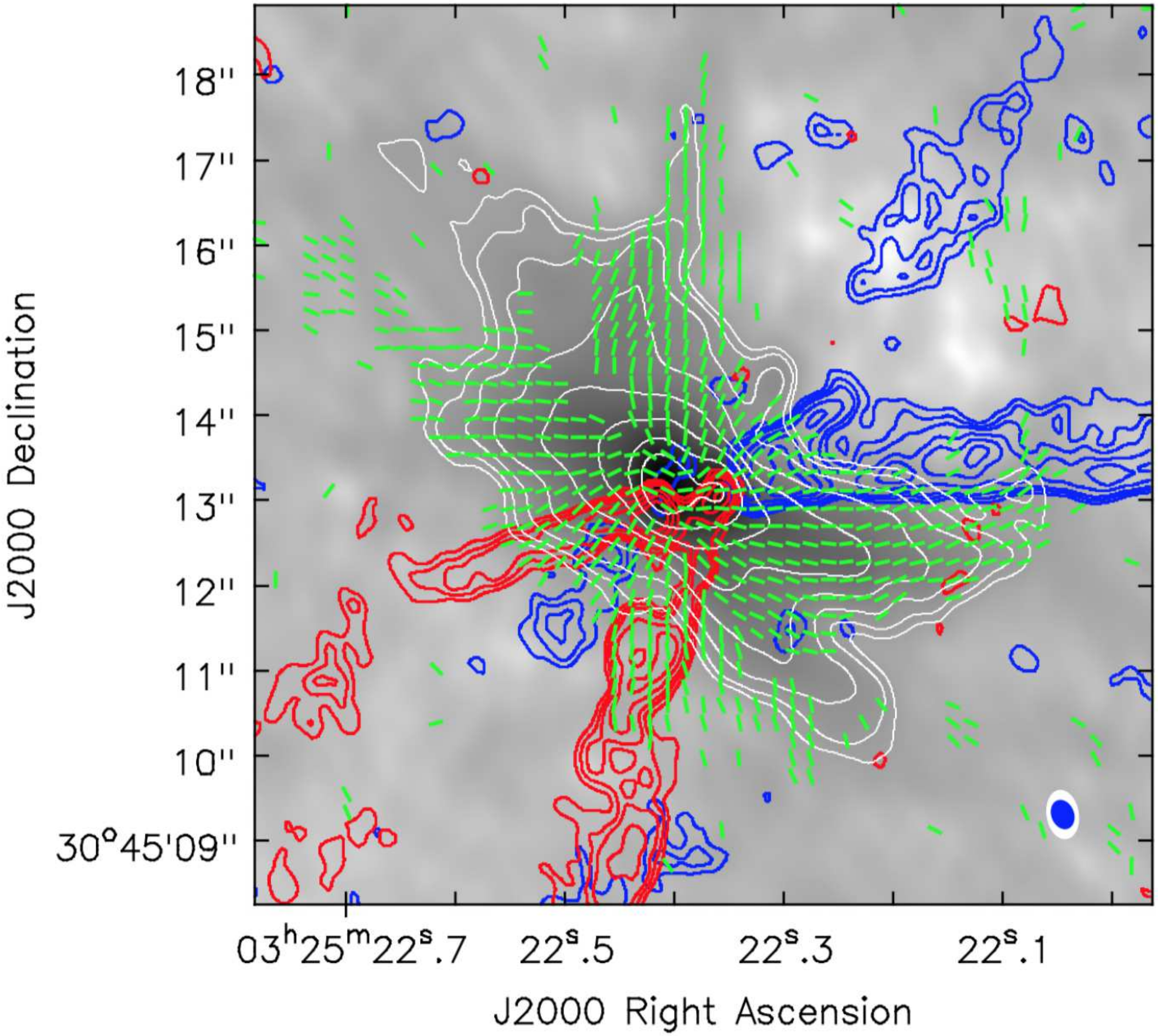


Star formation: with magnetic fields



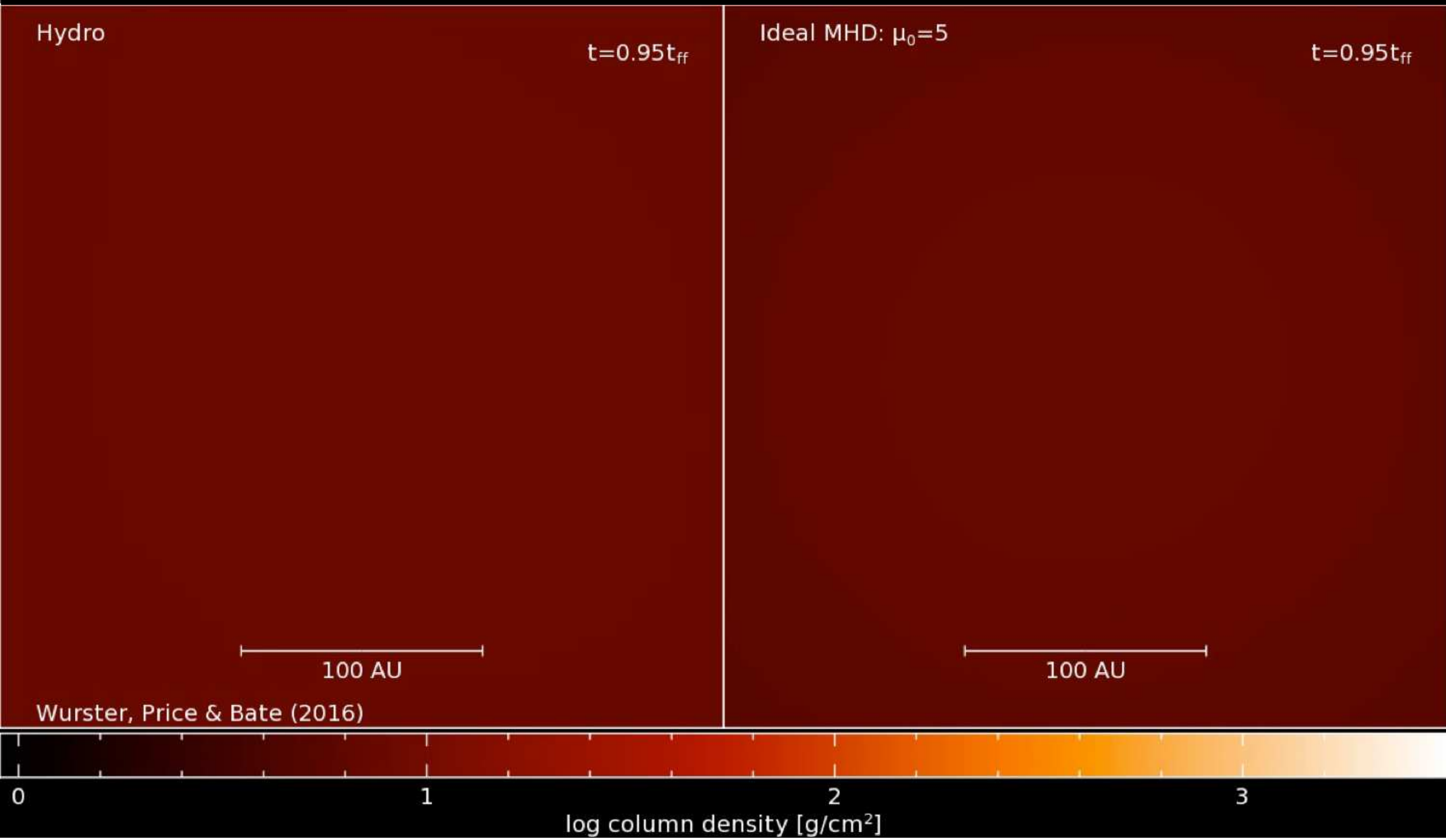
Price & Bate (2007)

Star formation: with magnetic fields



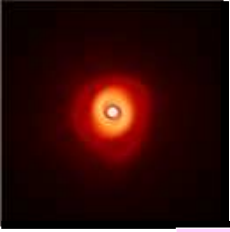
Kwon+ (2018)

Disc formation: Hydrodynamics vs Magnetohydrodynamics



Wurster, Price & Bate (2016)

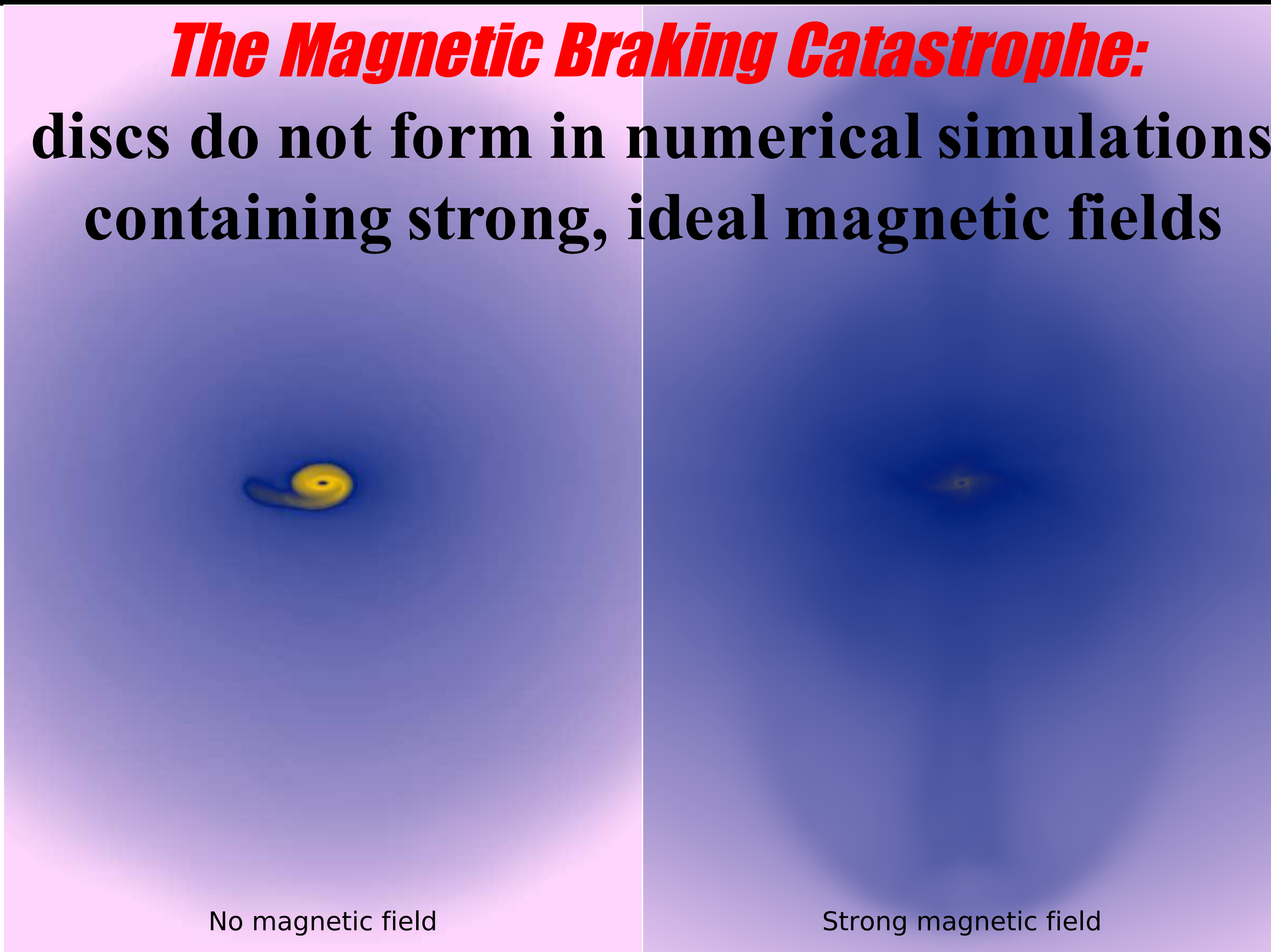
Video Available at:
https://youtu.be/WqfqYRUsYuQ?list=PLwI7am9c6sBi3yBP0Yp-8qMK414H5OPph



Disc formation: Magnetohydrodynamics

The Magnetic Braking Catastrophe:

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

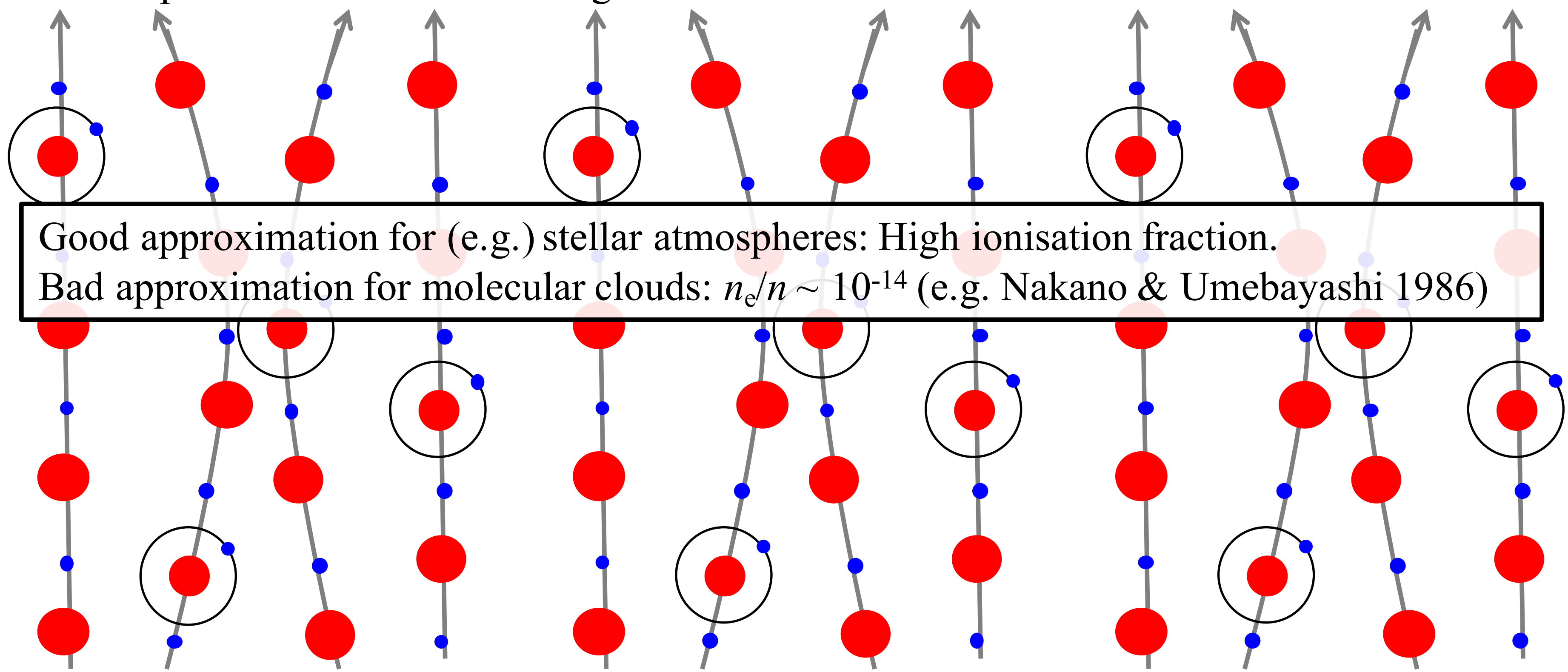


e.g. Allen, Li & Shu (2003); Galli+ (2006)

Ideal magnetohydrodynamics

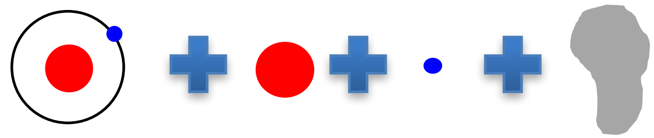
- Highly ionised plasma:

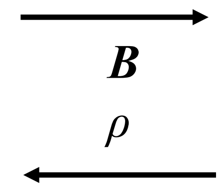
- Zero resistivity & infinite conductivity
- Ions & electrons are tied to the magnetic field
- Neutral particles are tied to the magnetic field due to interactions with the ions & electrons



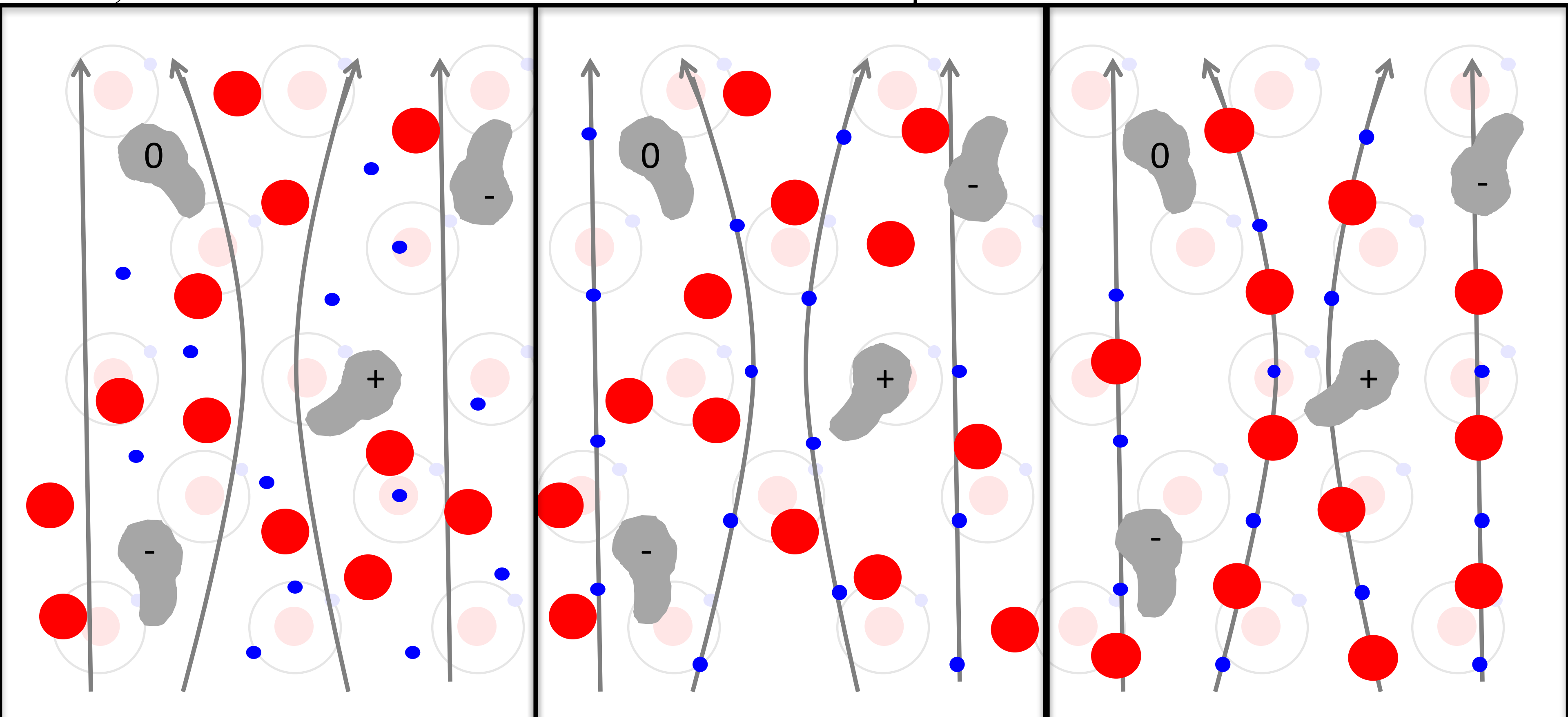
Good approximation for (e.g.) stellar atmospheres: High ionisation fraction.
Bad approximation for molecular clouds: $n_e/n \sim 10^{-14}$ (e.g. Nakano & Umebayashi 1986)

Non-ideal magnetohydrodynamics

- Partially ionised plasma and dust: 



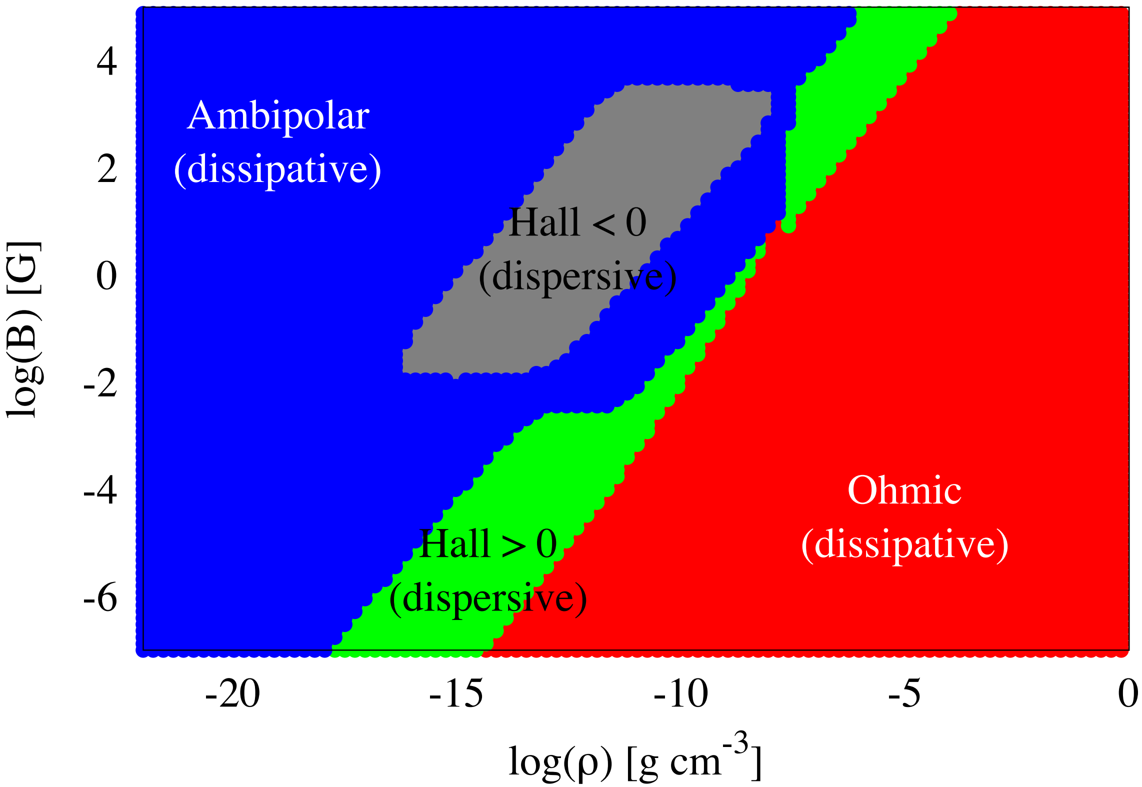
- Non-zero resistivity & conductivity
- Ions, electrons & neutrals behaviour is environment-dependent



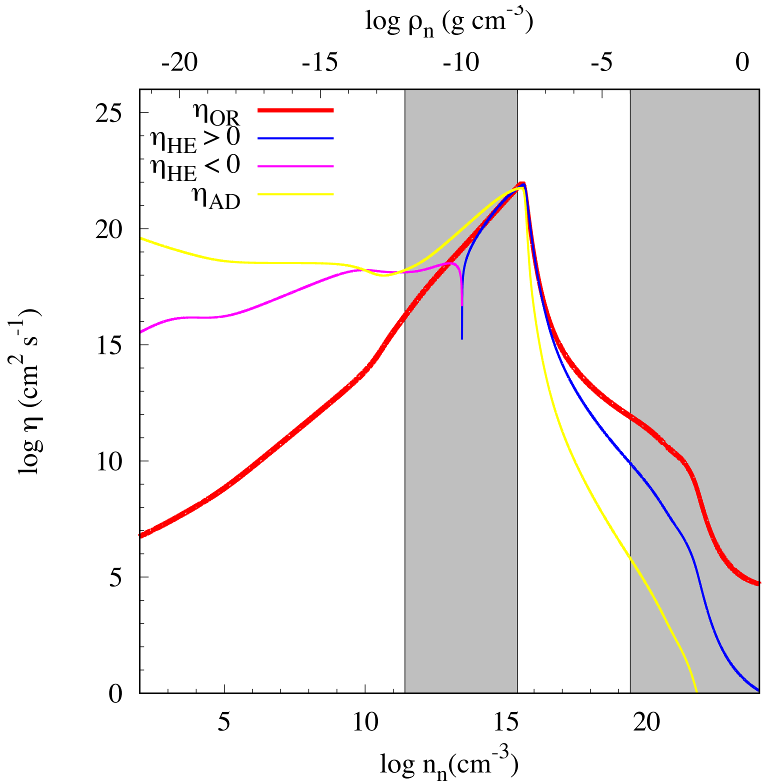
Ohmic Resistivity | Hall Effect | Ambipolar Diffusion

Non-ideal magnetohydrodynamics

Phase space diagram



Coefficients
(for a star-forming model)

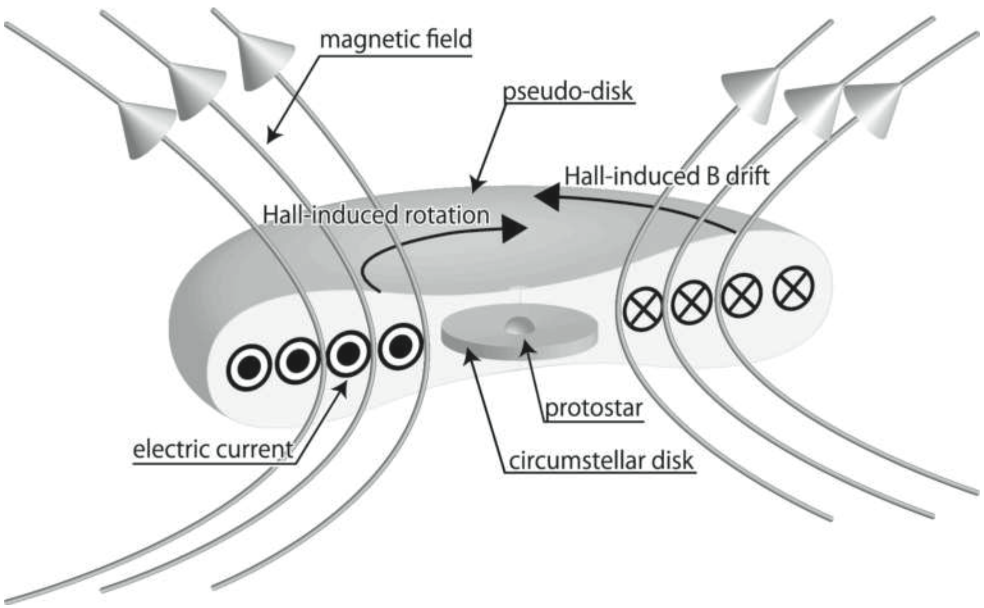


- Values dependent on microphysics:
  - Grain size, ionised species, cosmic ray ionisation rate

Adapted from Wardle (2007); constructed using NICIL (Wurster, 2016)

Non-ideal magnetohydrodynamics: The Hall effect

➢Image assumes $\boldsymbol{\eta}_{\rm HE} < 0$ (reasonable for star formation; Wurster 2016; Marchand + 2016)



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

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

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

For magnetic field reversal, substitute $\boldsymbol{B}\rightarrow-\boldsymbol{B}$:

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

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

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

Simplify:

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

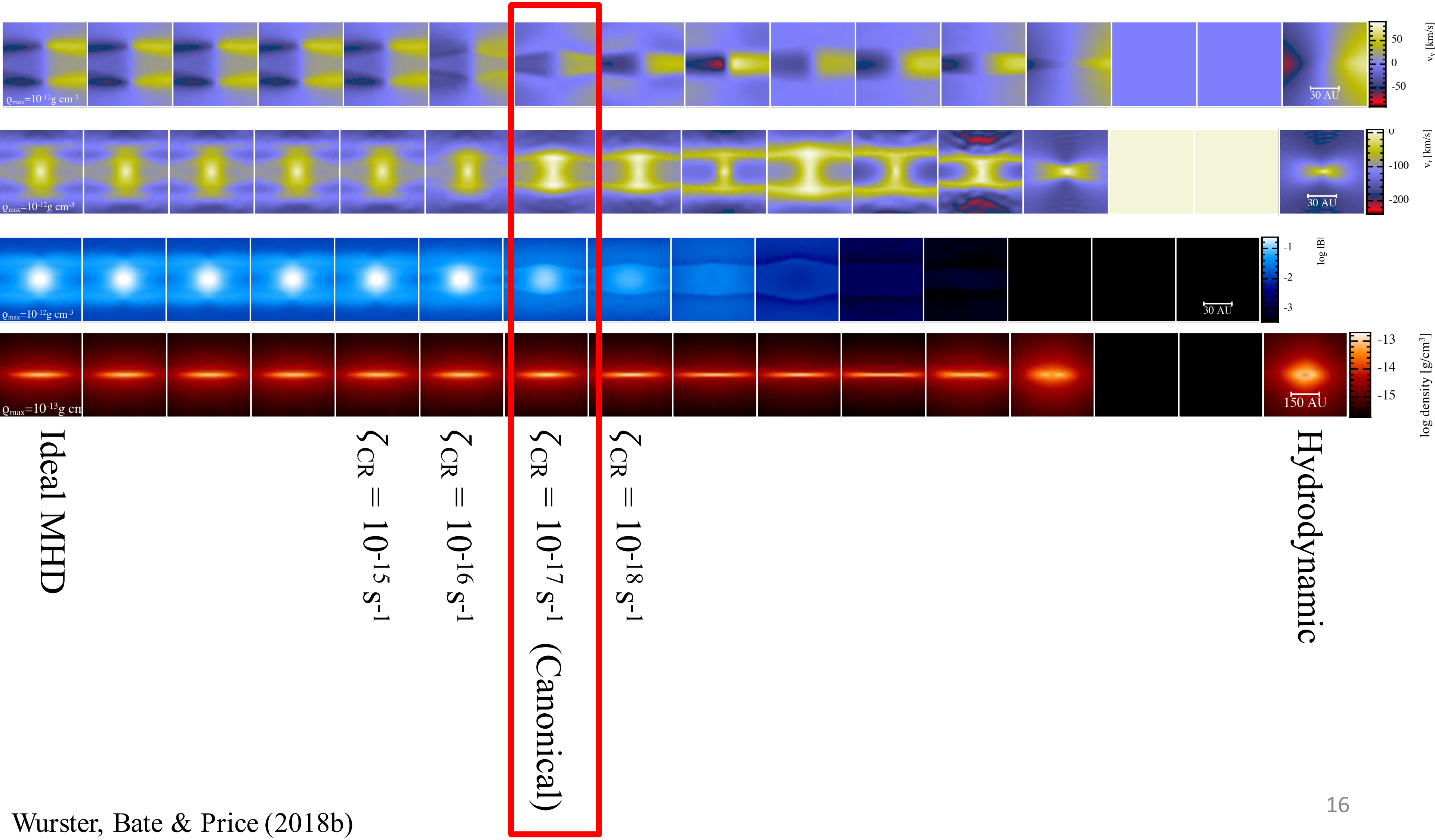
$$\left.\frac{\mathrm{d}\boldsymbol{B}}{\mathrm{d}t}\right|_{\rm HE} = \boldsymbol{\nabla}\times\left[\eta_{\rm HE}\left(\boldsymbol{\nabla}\times\boldsymbol{B}\right)\times\hat{\boldsymbol{B}}\right]$$

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

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

Cosmic ray ionisation rate

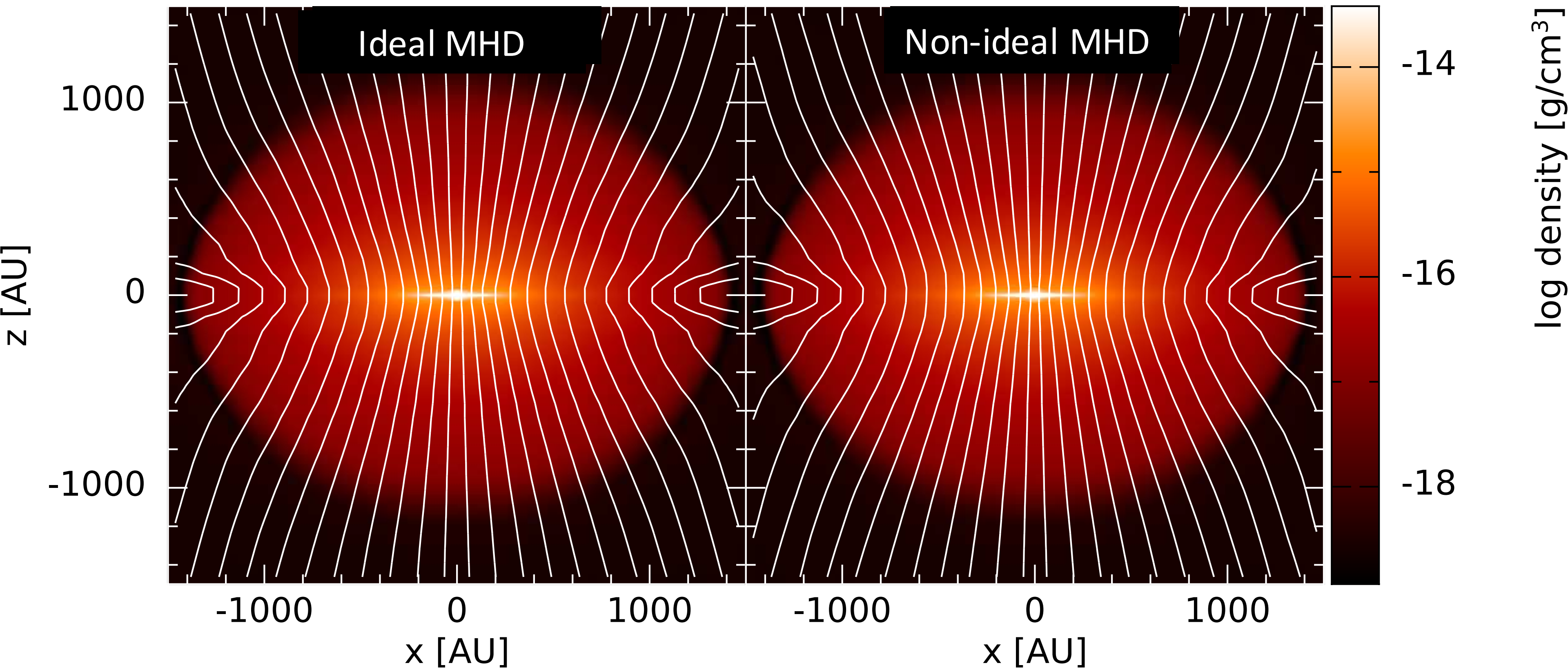
- Images: v_y, v_r, $\log(B)$, $\log(\rho)$ at $\rho_{max} = 10^{-12}$ g cm^{-3}



Wurster, Bate & Price (2018b)

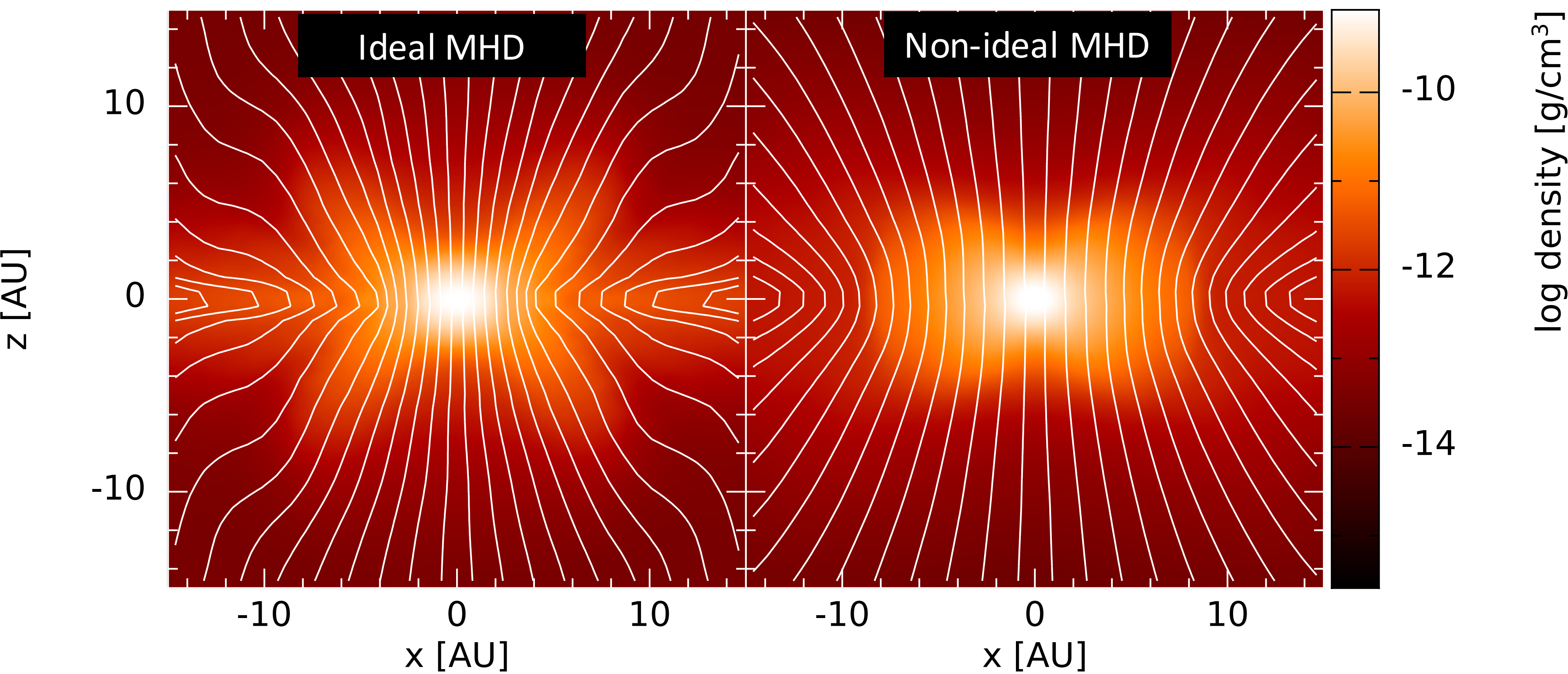
Non-ideal magnetohydrodynamics

➢ Strong field; large scale structure



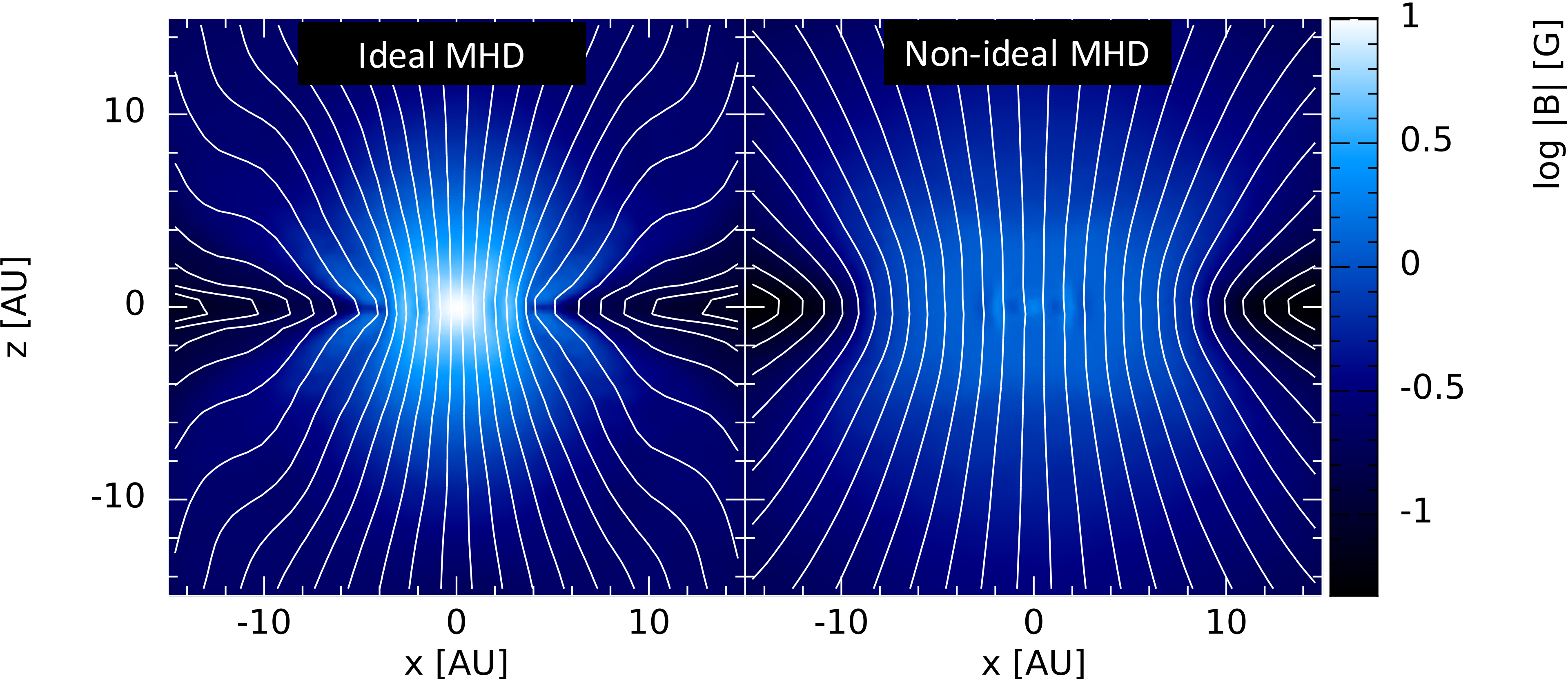
Non-ideal magnetohydrodynamics

➢ Strong field; small scale structure

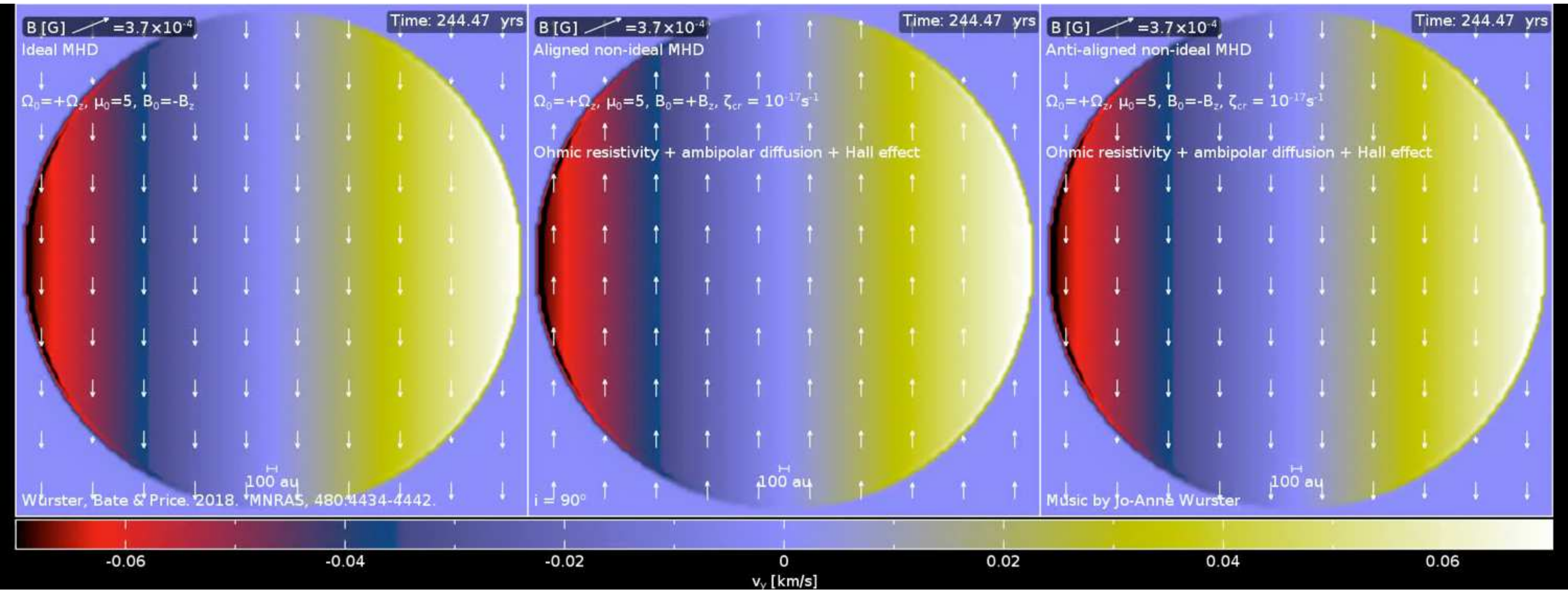


Non-ideal magnetohydrodynamics

- Strong field; small scale structure



Formation of a low-mass star



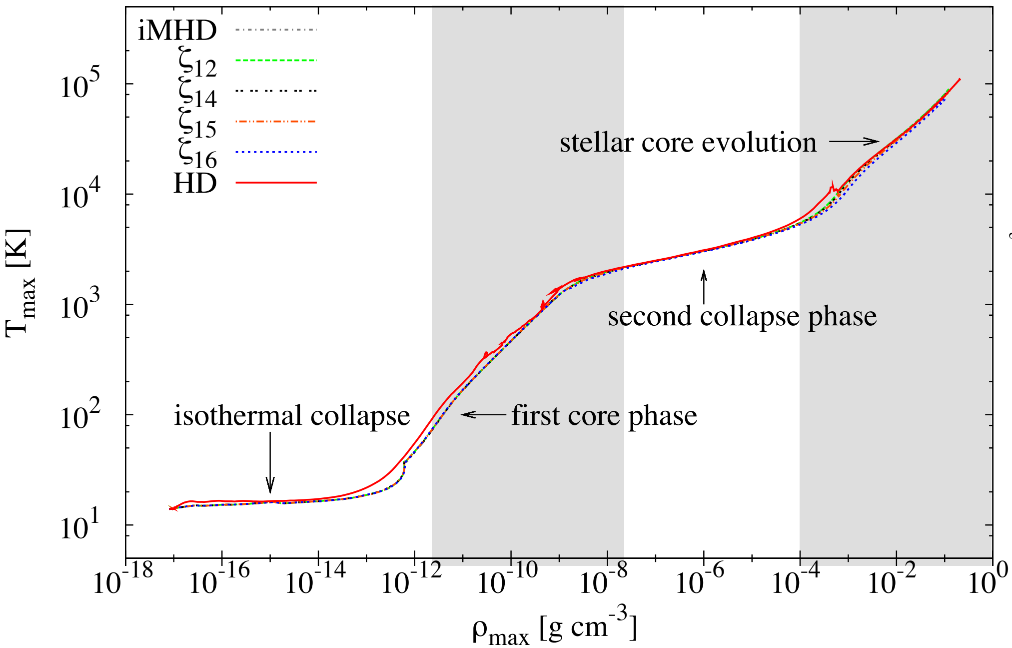
- Video available at https://youtu.be/2SQxgXbdJyg?list=PLwI7am9c6sBhhofuWPomUvqu9asfkKwCf

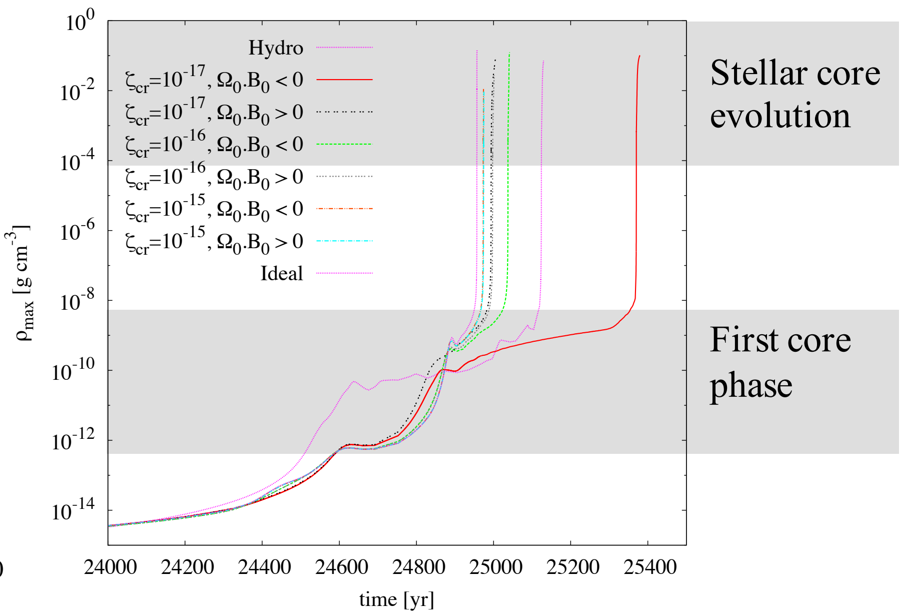
Wurster, Bate & Price (2018c)

Music: Jo-Anne Wurster

Collapse to stellar densities: Evolution

- Temperature evolution is independent of ionisation rates
- Time evolution is dependent on ionisation rates & magnetic field orientation

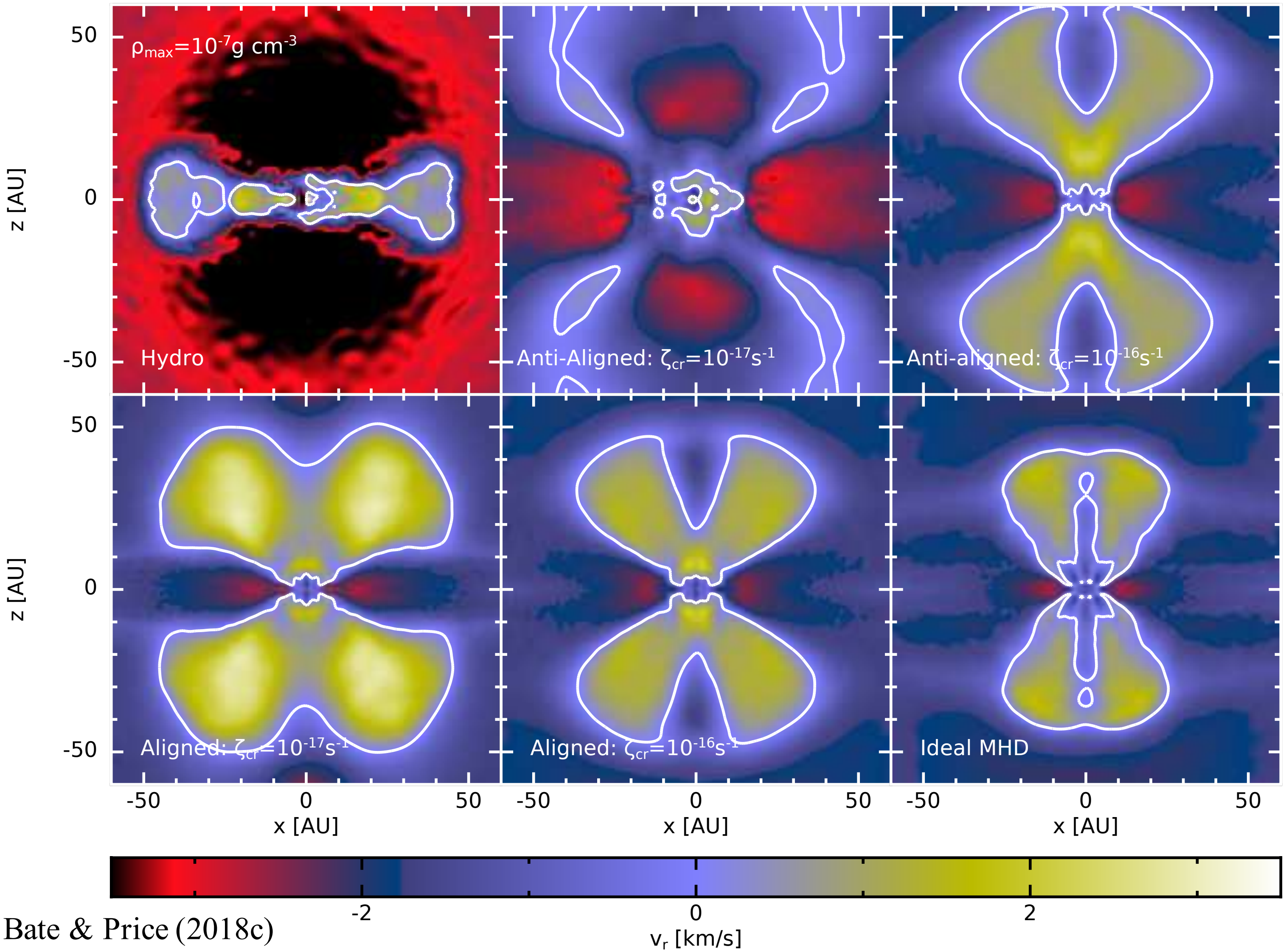




Wurster, Bate & Price (2018a,c)

First core outflows

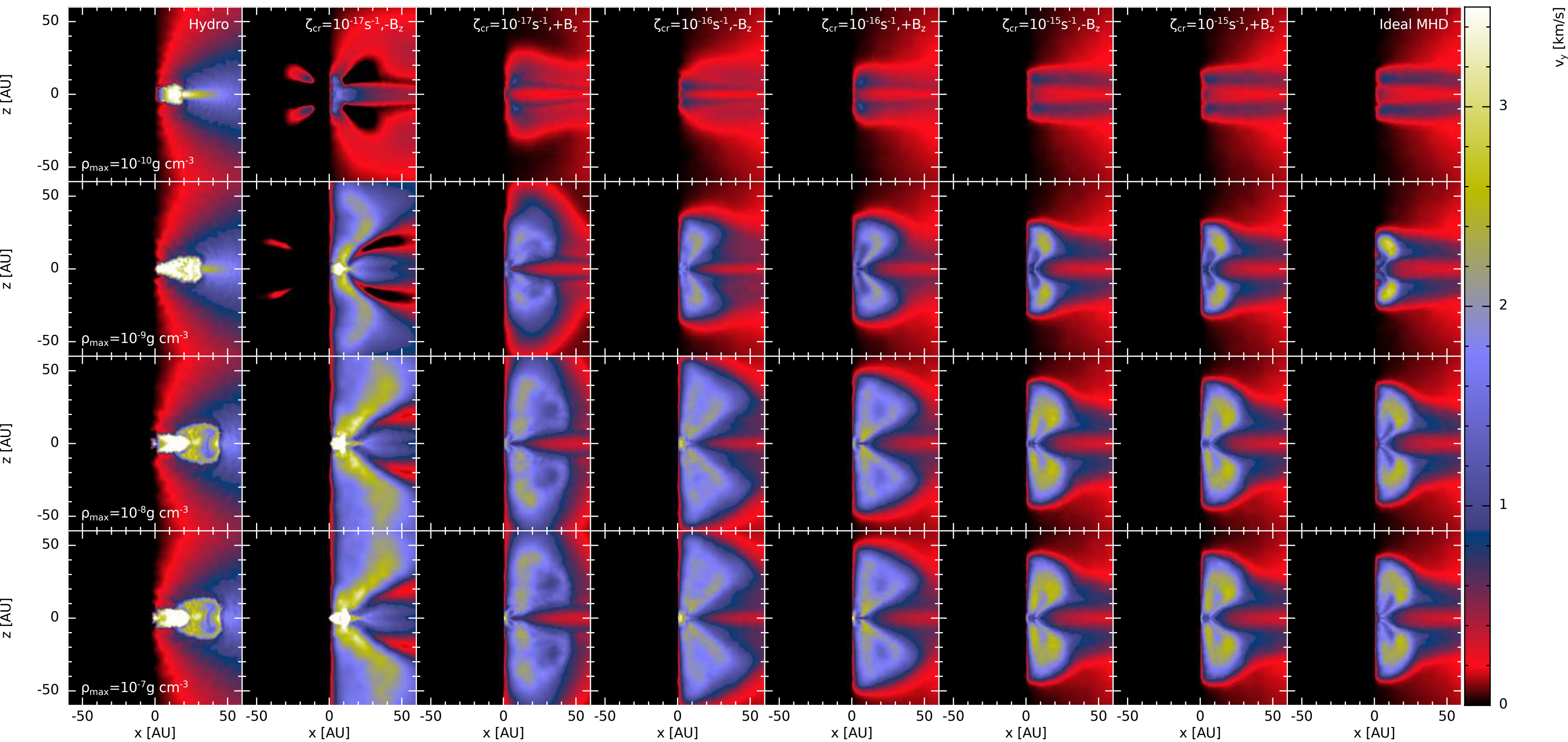
- Aligned magnetic fields enhance outflows; Anti-aligned magnetic fields suppress outflows



Wurster, Bate & Price (2018c)

Large scale rotational velocity

- ➢Rotational speed increases as ionisation rate decreases
- ➢Counter-rotating envelops are a transient feature in the model with $\boldsymbol{\zeta}_{cr} = 10^{-17}$ s^{-1} with -B_z

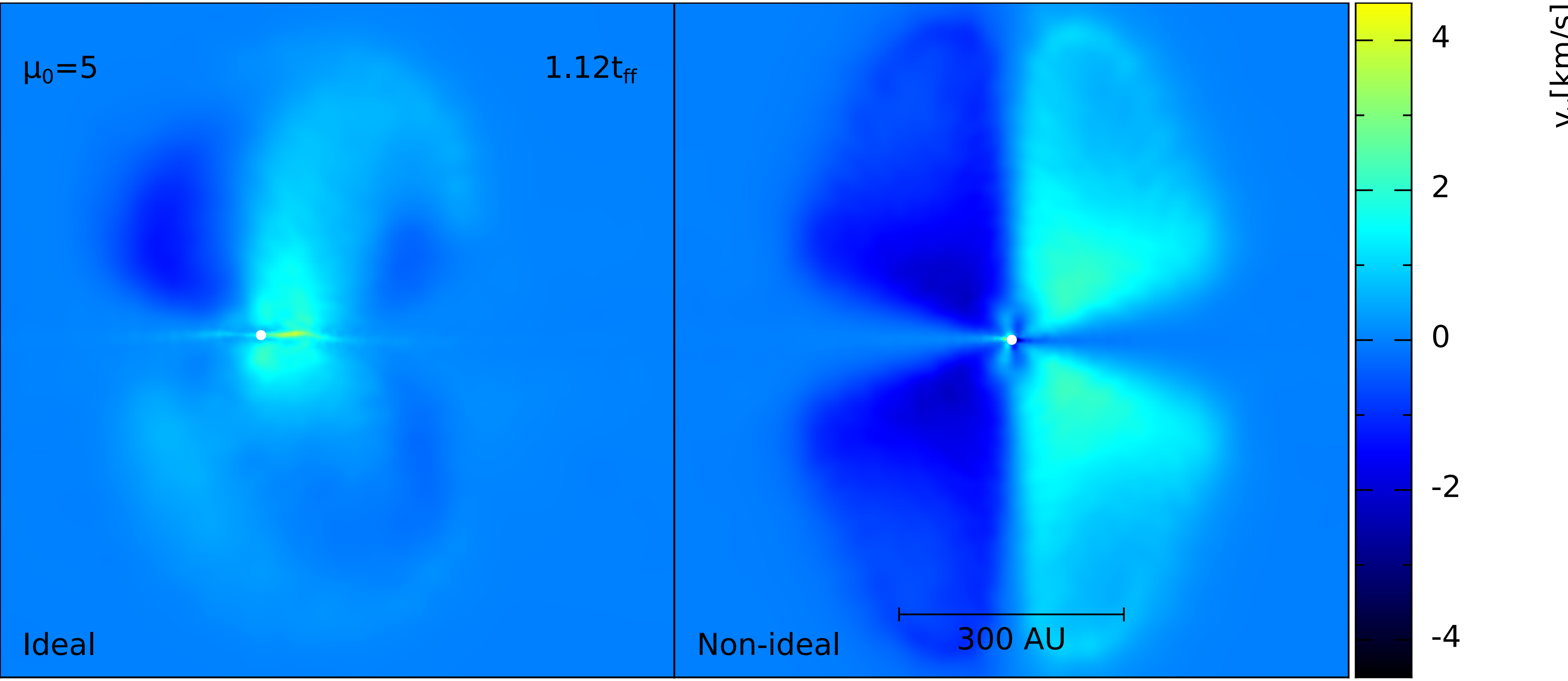


Wurster, Bate & Price (2018c) +

For counter-rotation, see also Krasnopolsky, Li &Shang (2011), Wurster, Price & Bate (2016), Tsukamoto et al. (2015,2017)

Envelopes: Induced rotation

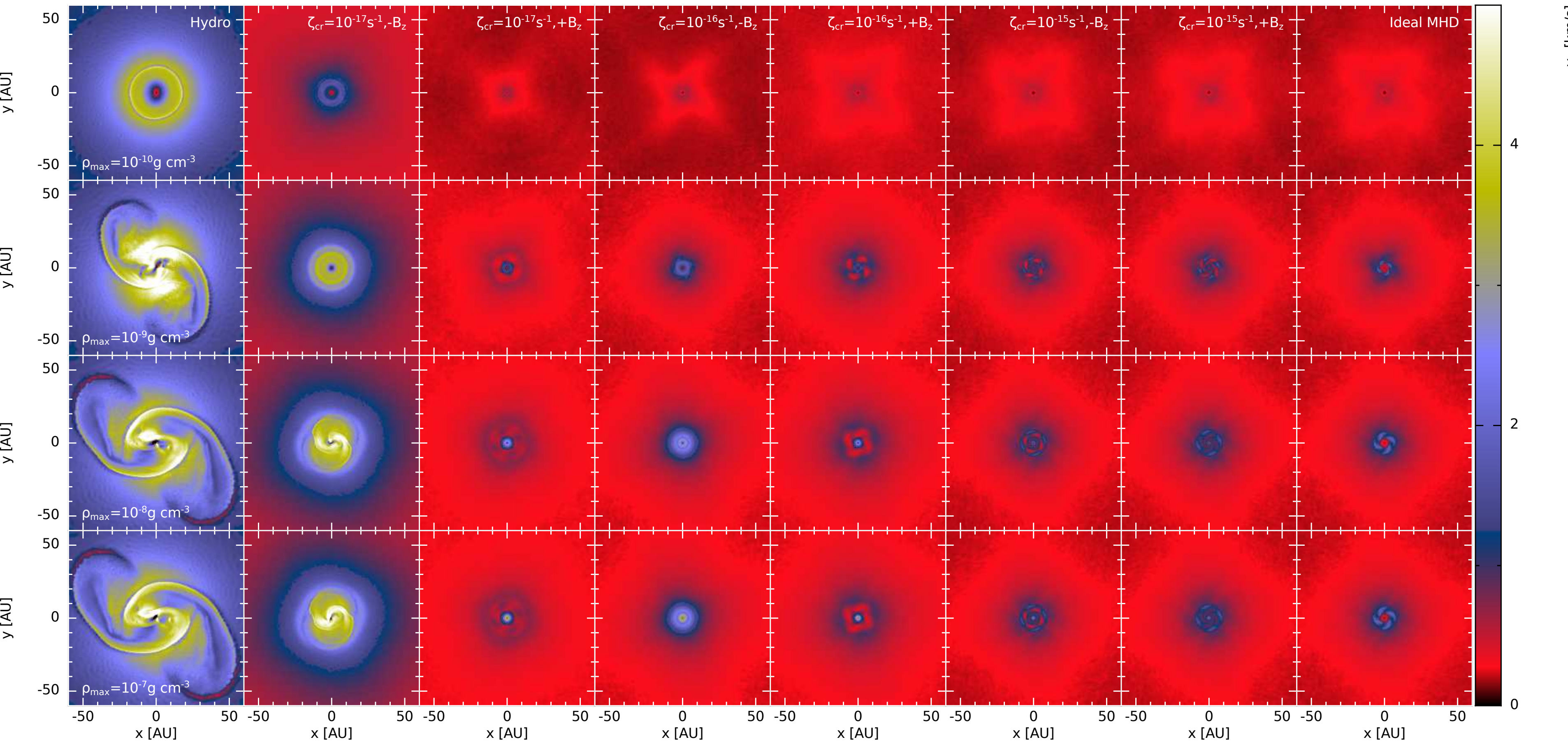
➢ Hall effect can induce coherent rotation from a zero-angular momentum initial condition



For counter-rotation, see also Krasnopolsky, Li &Shang (2011), Wurster, Price & Bate (2016), Tsukamoto et al. (2015,2017)

Rotationally supported discs

- ➢Discs form in the hydrodynamics model and the non-ideal model with $\zeta_{cr} = 10^{-17}$ s^{-1} with $-B_z$

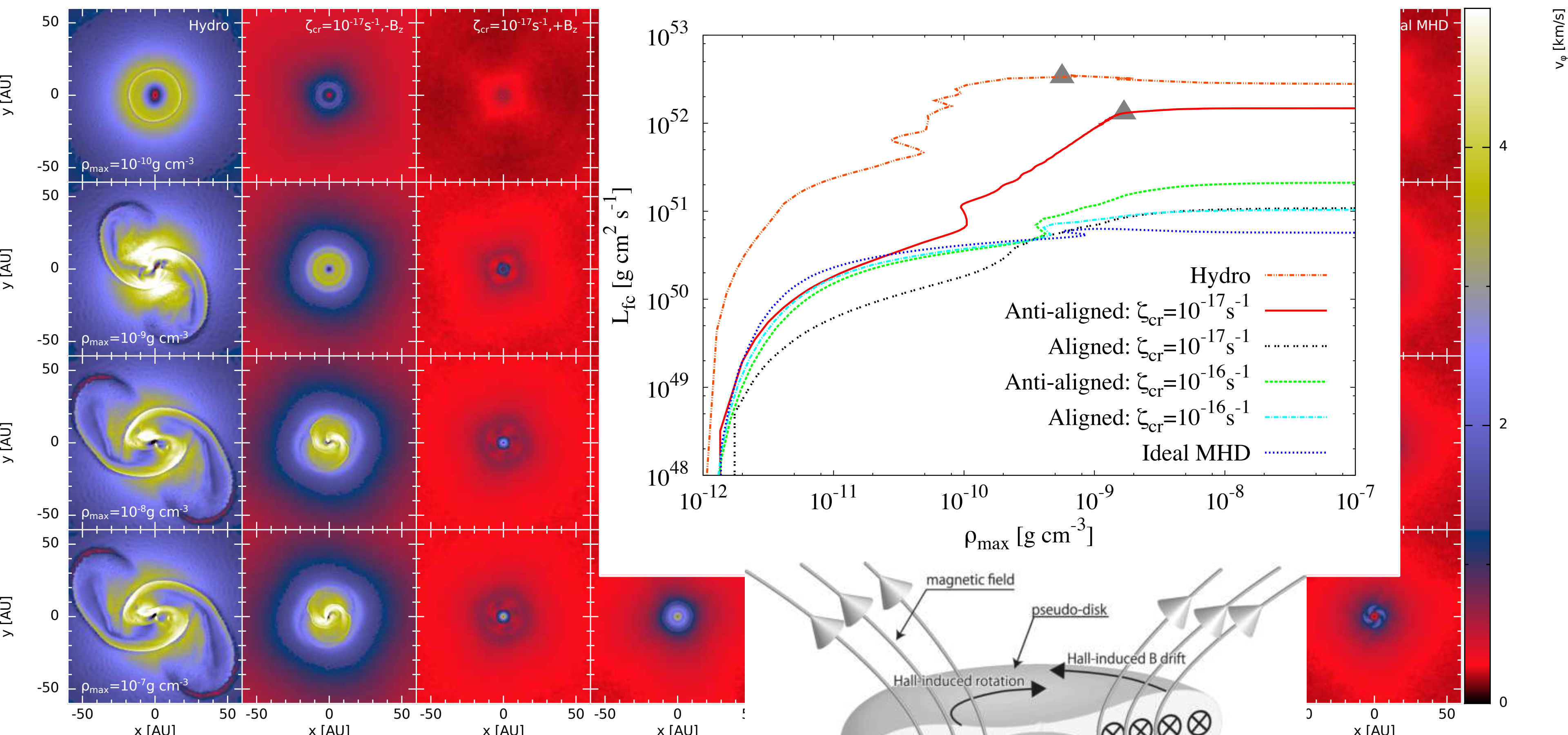


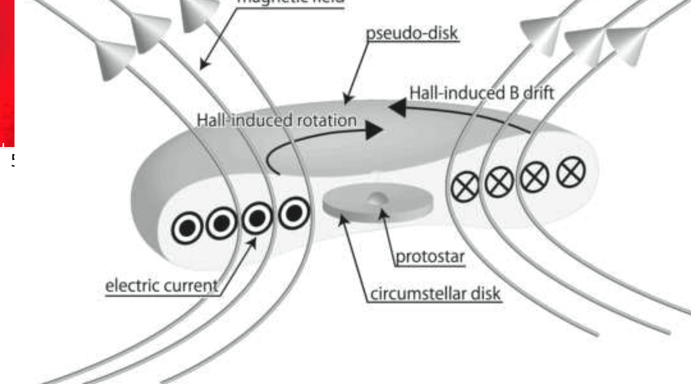
- ➢Discs form during the first hydrostatic core phase
- ➢Similar disc structure obtained by Tsukamoto+ (2015a) for $\zeta_{cr} = 10^{-17}$ s^{-1} with $\pm B_z$

Wurster, Bate & Price (2018c) +

Rotationally supported discs

➢Discs form in the hydrodynamics model and the non-ideal model with $\boldsymbol{\zeta}_{cr} = 10^{-17}\ s^{-1}$ with $-B_z$





Wurster, Bate & Price (2018c) +

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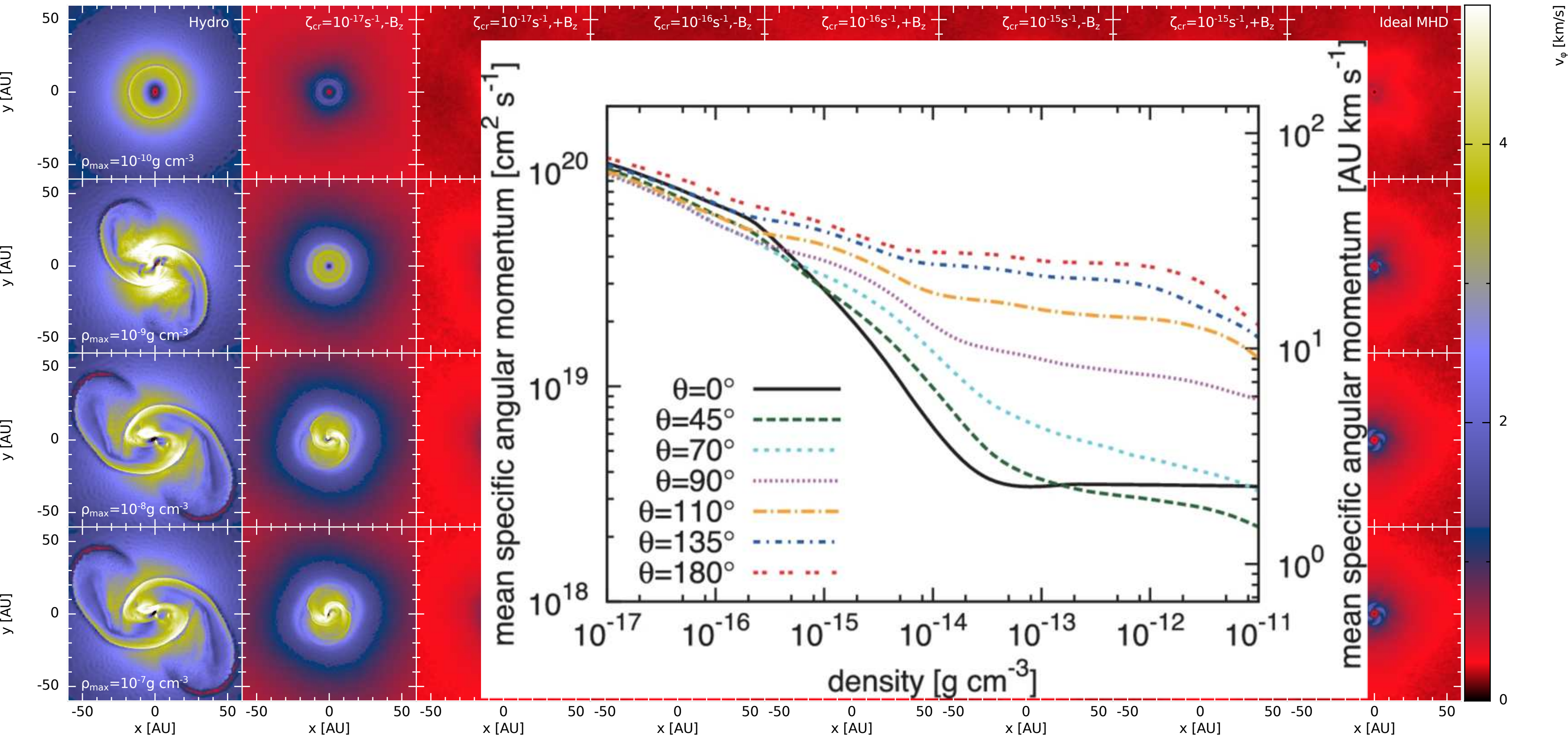
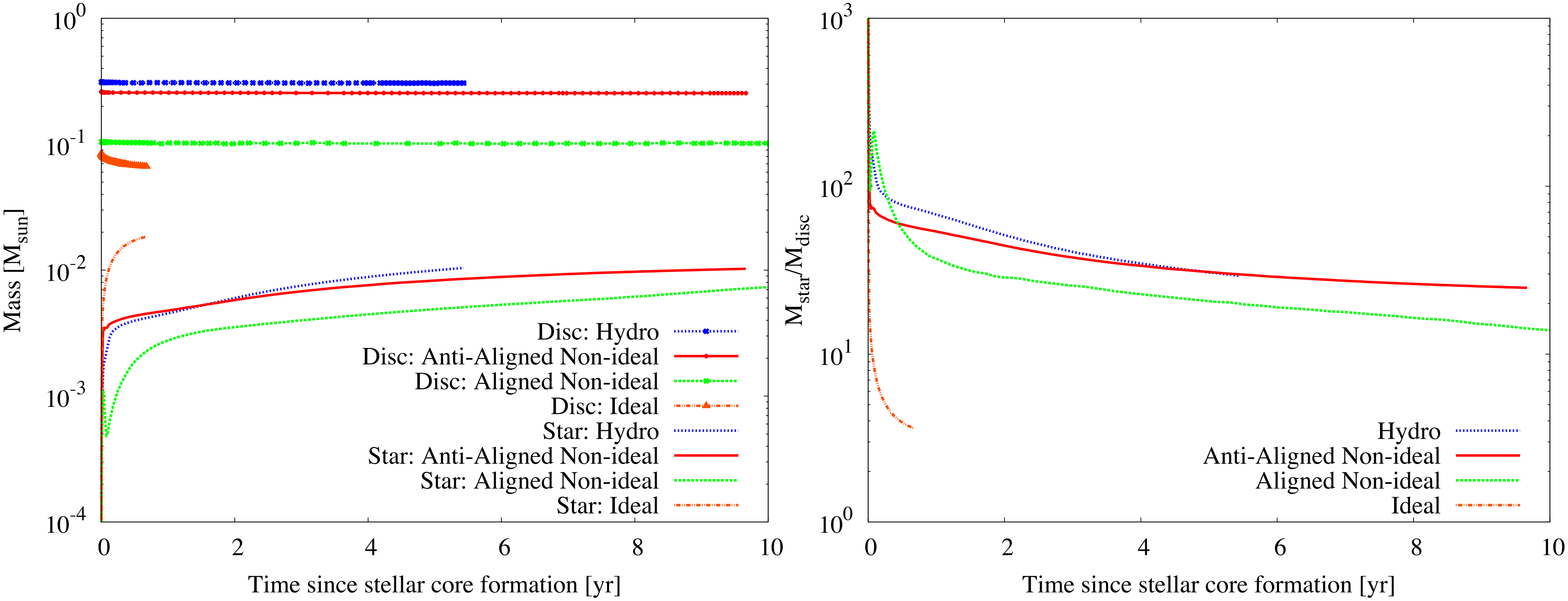


Wurster, Bate & Price (2018c) +; inset: Tsukamoto+ (2017)

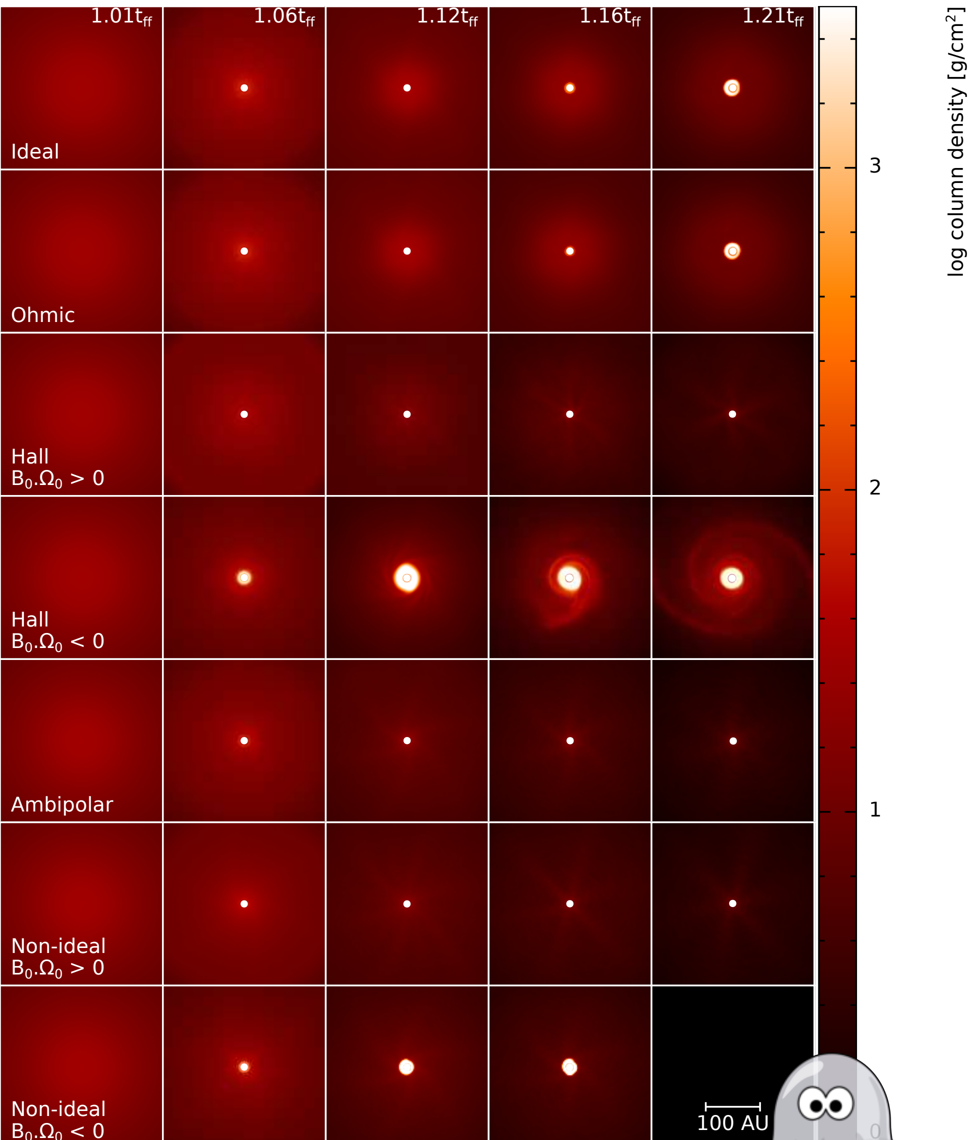
Disc Masses

- Disc mass: sum of the gas with 10^{-13} g cm^{-3} < ρ < 10^{-4} g cm^{-3}
- Stellar mass: sum of the gas with ρ > 10^{-4} g cm^{-3}



data from Wurster, Bate & Price (2018c)

Non-Ideal MHD Components

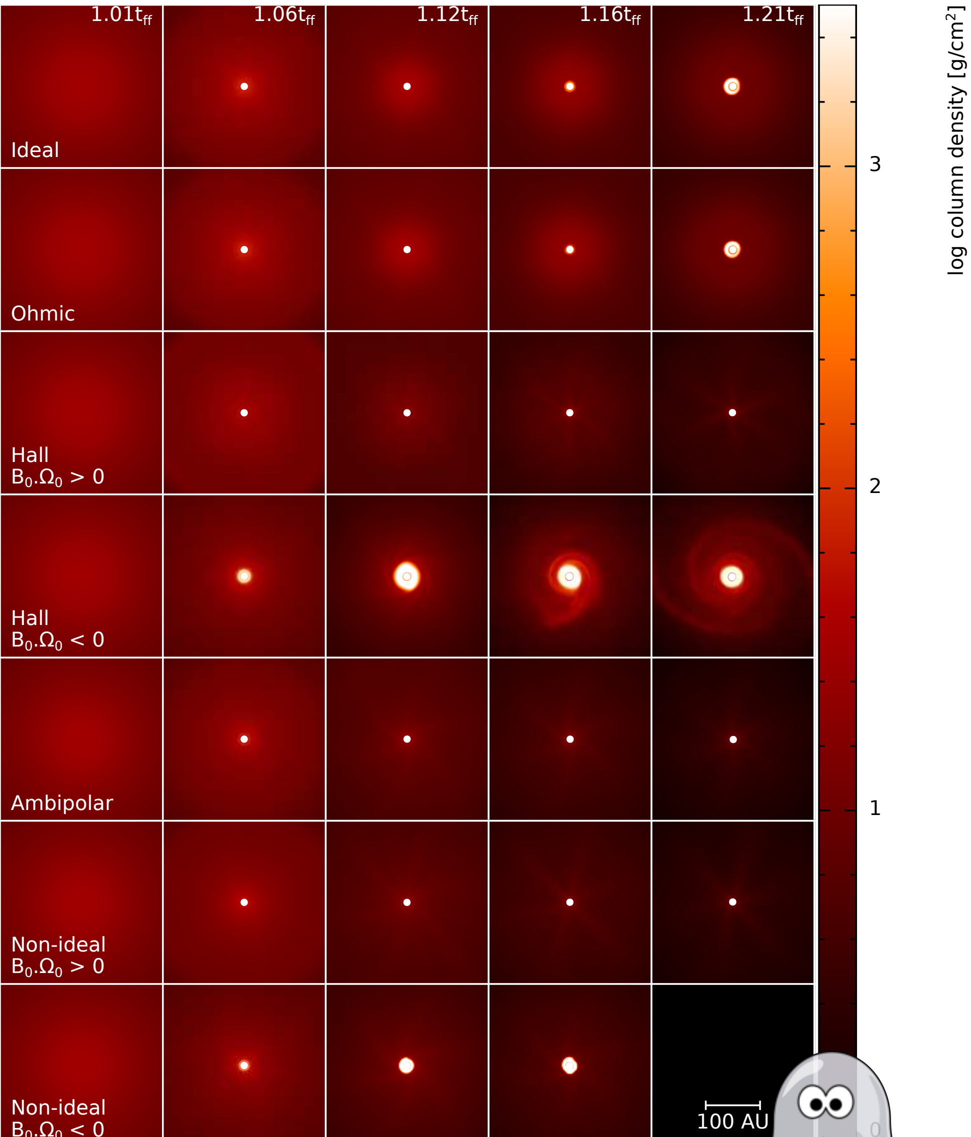


Wurster, Price & Bate (2016)

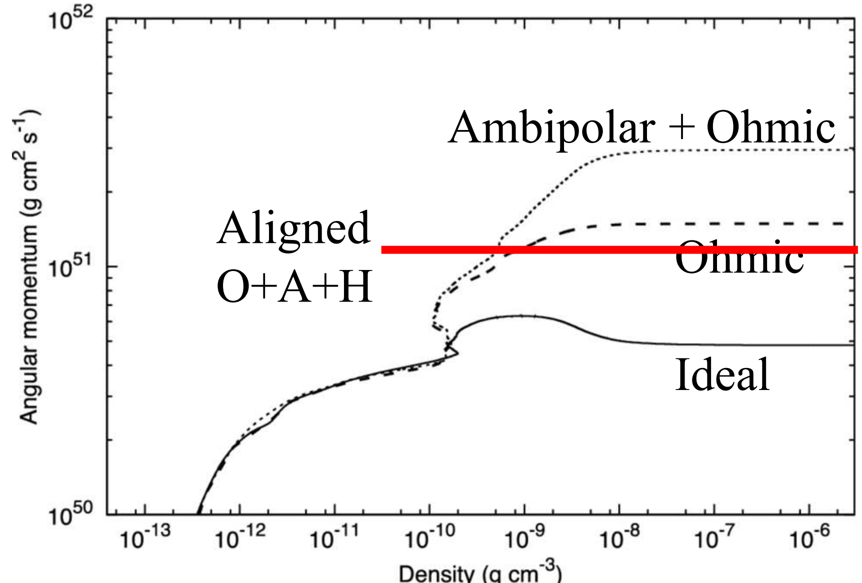
- Multiple conclusions in the literature regarding disc formation with Ohmic resistivity and/or ambipolar diffusion
- Likely possible to form small 1-5au discs in the long term with only Ohmic and/or ambipolar (Dapp and Basu 2010, Machida+ 2011, Dapp+ 2012, Tomida+ 2015, Tsukamoto+ 2015a, Masson+ 2016)
- Hennebelle et al. (2016) predicts 18au discs for ambipolar diffusion only
- Models to the left include a 6.7au sink particle
- Open question: *When do discs form?*

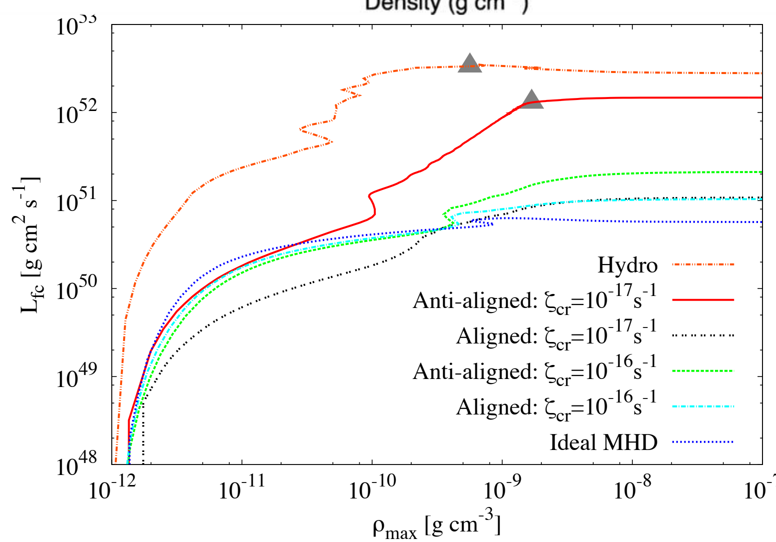
Non-Ideal MHD Components

Anti-aligned O+A+H



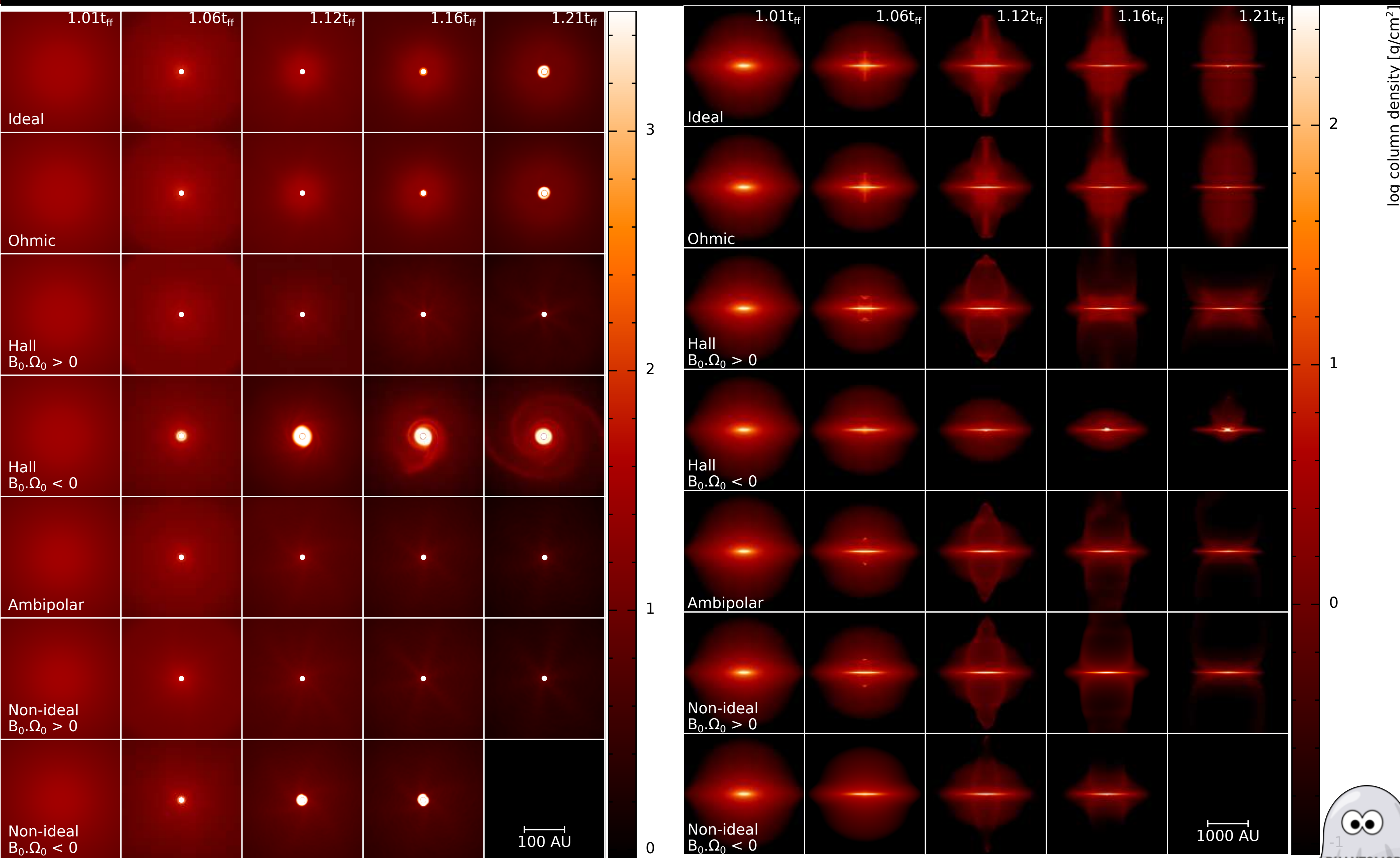
Wurster, Price & Bate (2016)



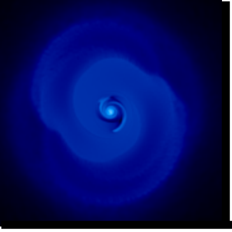


Top: Tsukamoto+ (2015b)
Bottom: Wurster, Bate & Price (2018c)

Non-Ideal MHD Components

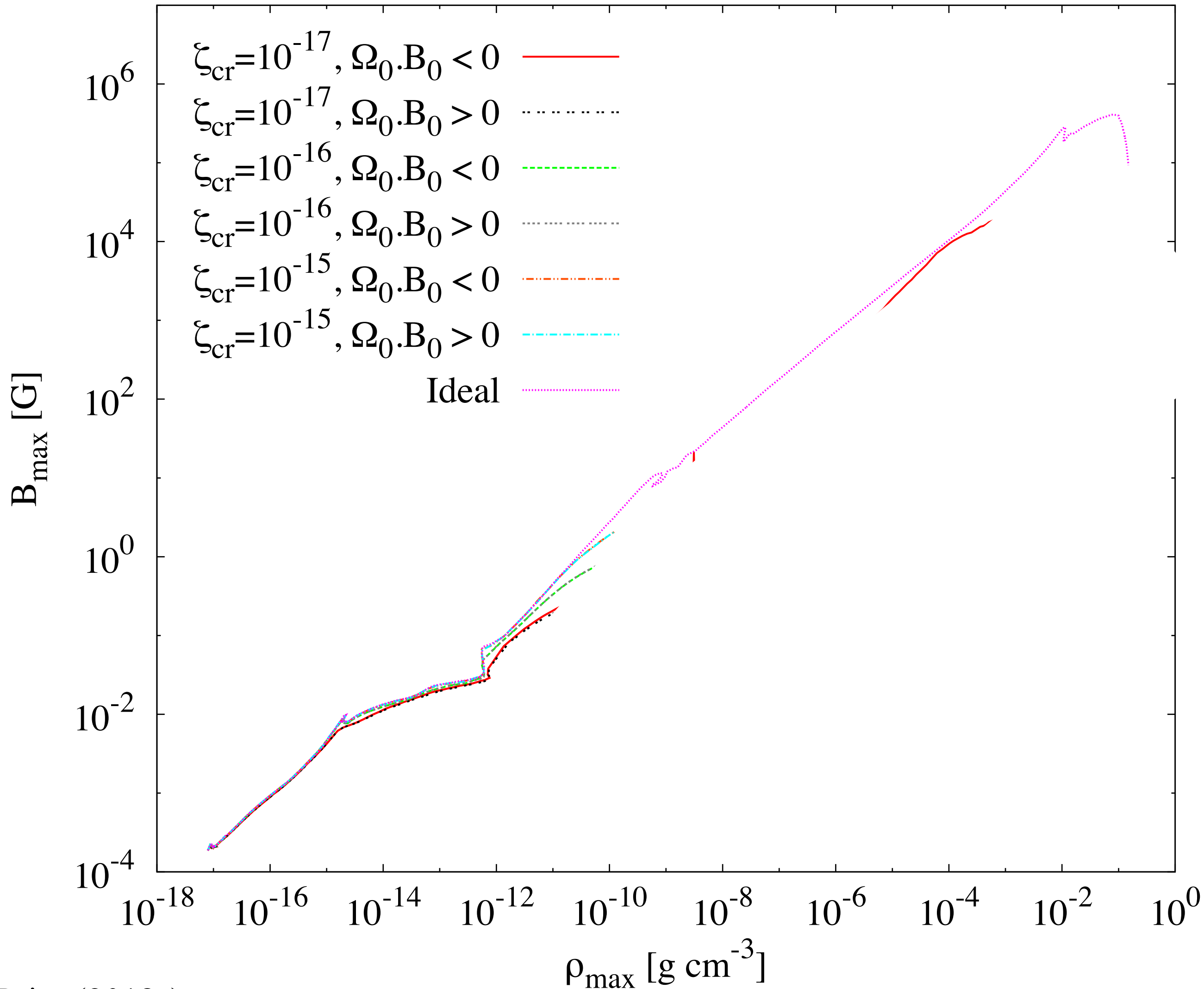


Wurster, Price & Bate (2016)

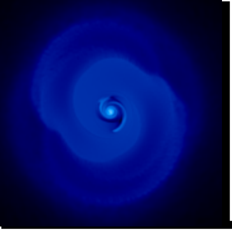


Magnetic field evolution

- Ideal MHD: Magnetic fields grow with density; mostly suggests spherical collapse

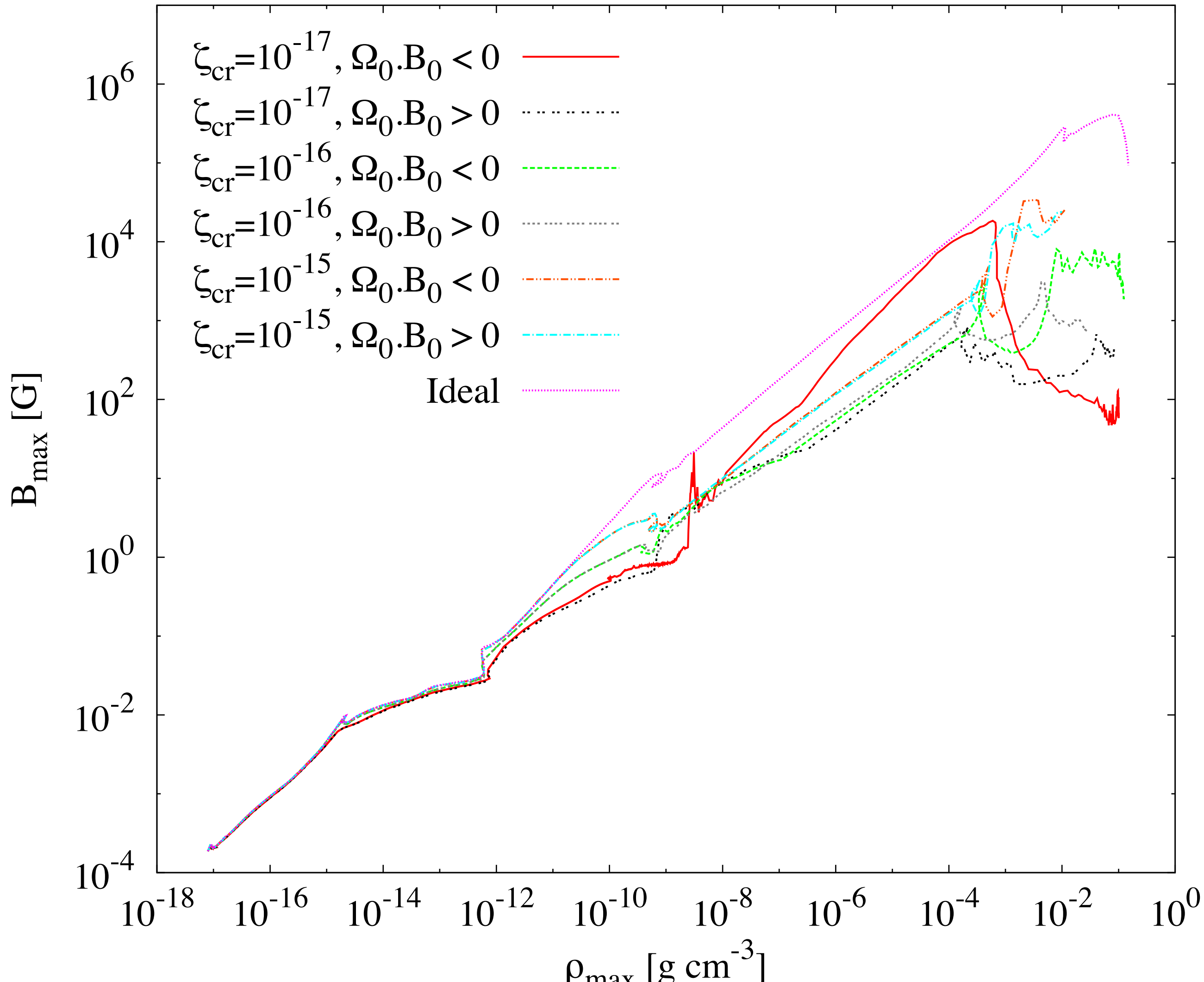


Wurster, Bate & Price (2018c) +

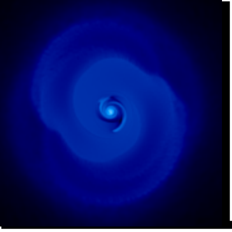


Magnetic field evolution

- Non-ideal effects decrease the magnetic field strength, starting in the first core phase

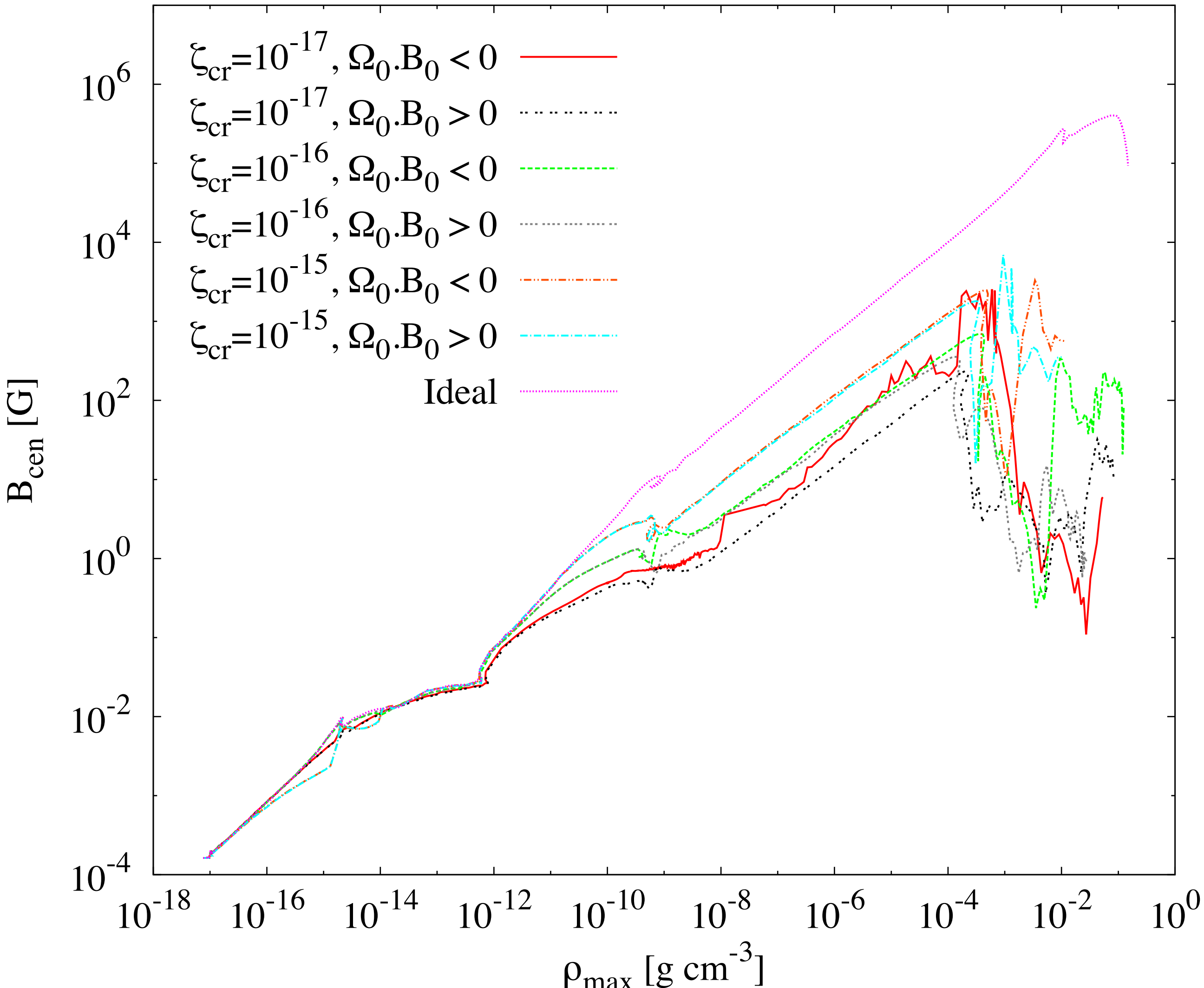


Wurster, Bate & Price (2018c) +



Magnetic field evolution

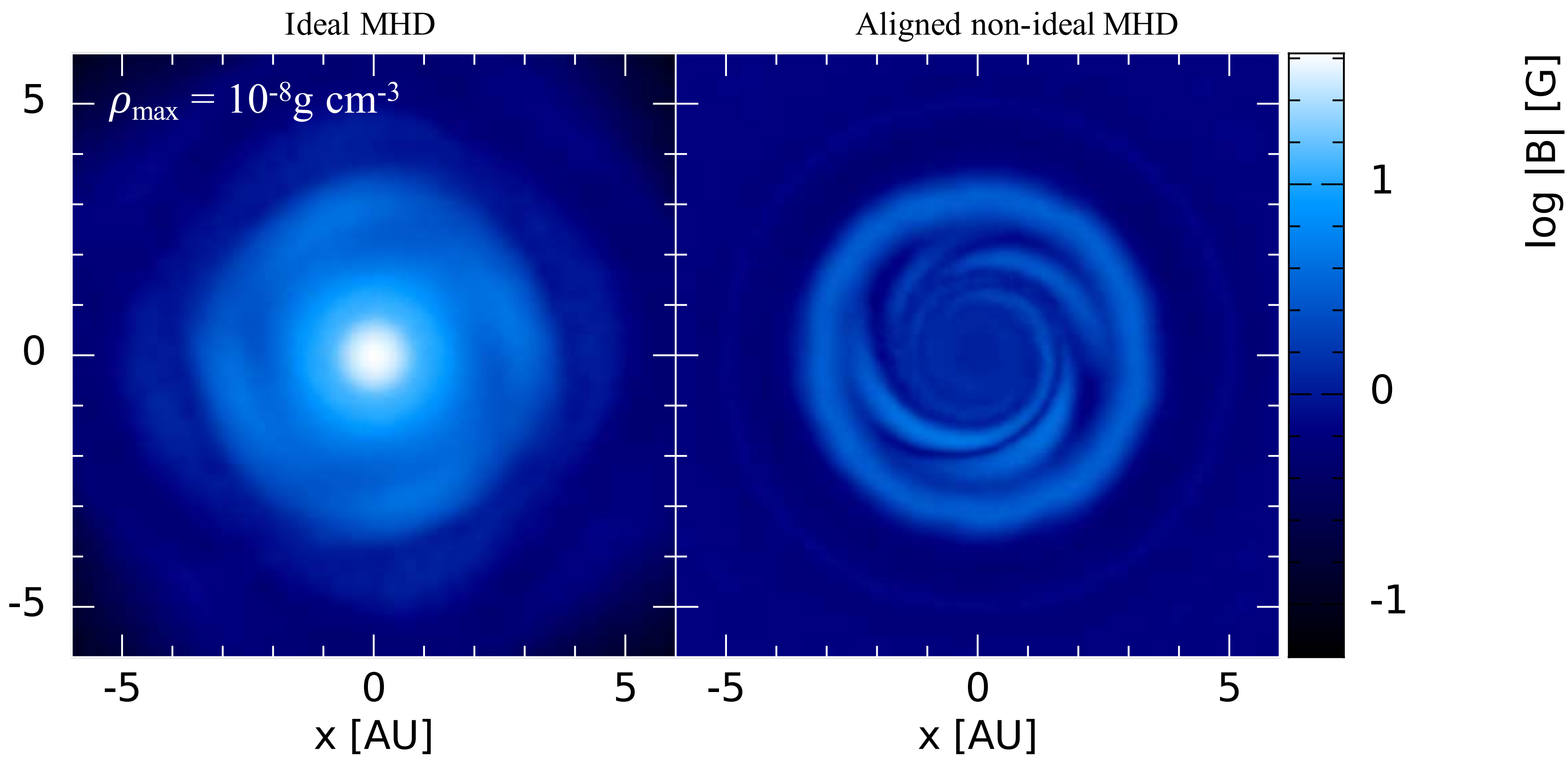
- The maximum magnetic field strength is not at the centre of the core in the non-ideal models



Wurster, Bate & Price (2018c) +

Magnetic field evolution

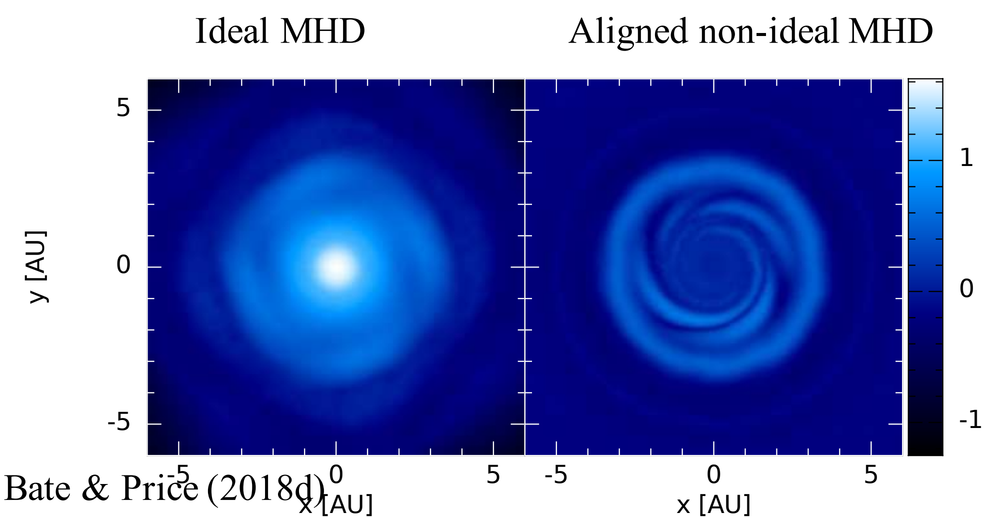
➢Magnetic wall forms in non-ideal MHD models (Tassis &Mouschovias, 2005)

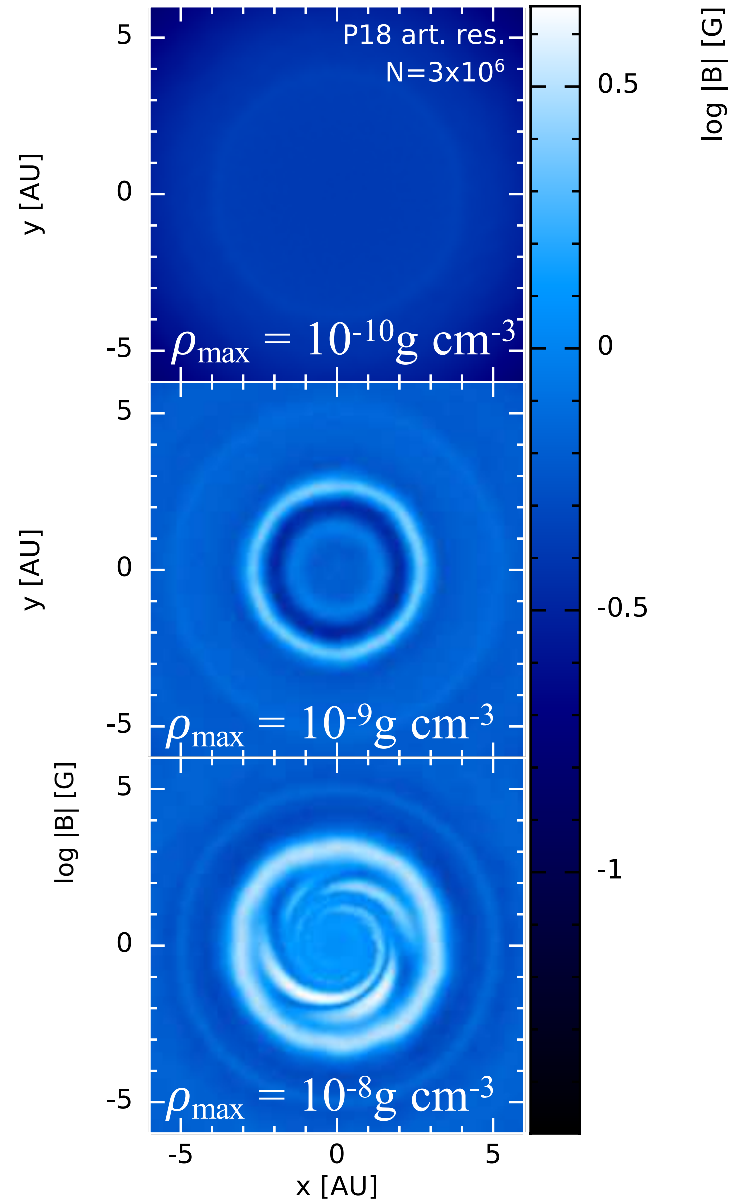


Wurster, Bate & Price (2018d)

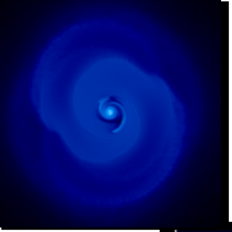
Magnetic field evolution

- Magnetic wall forms in non-ideal MHD models (Tassis &Mouschovias, 2005)

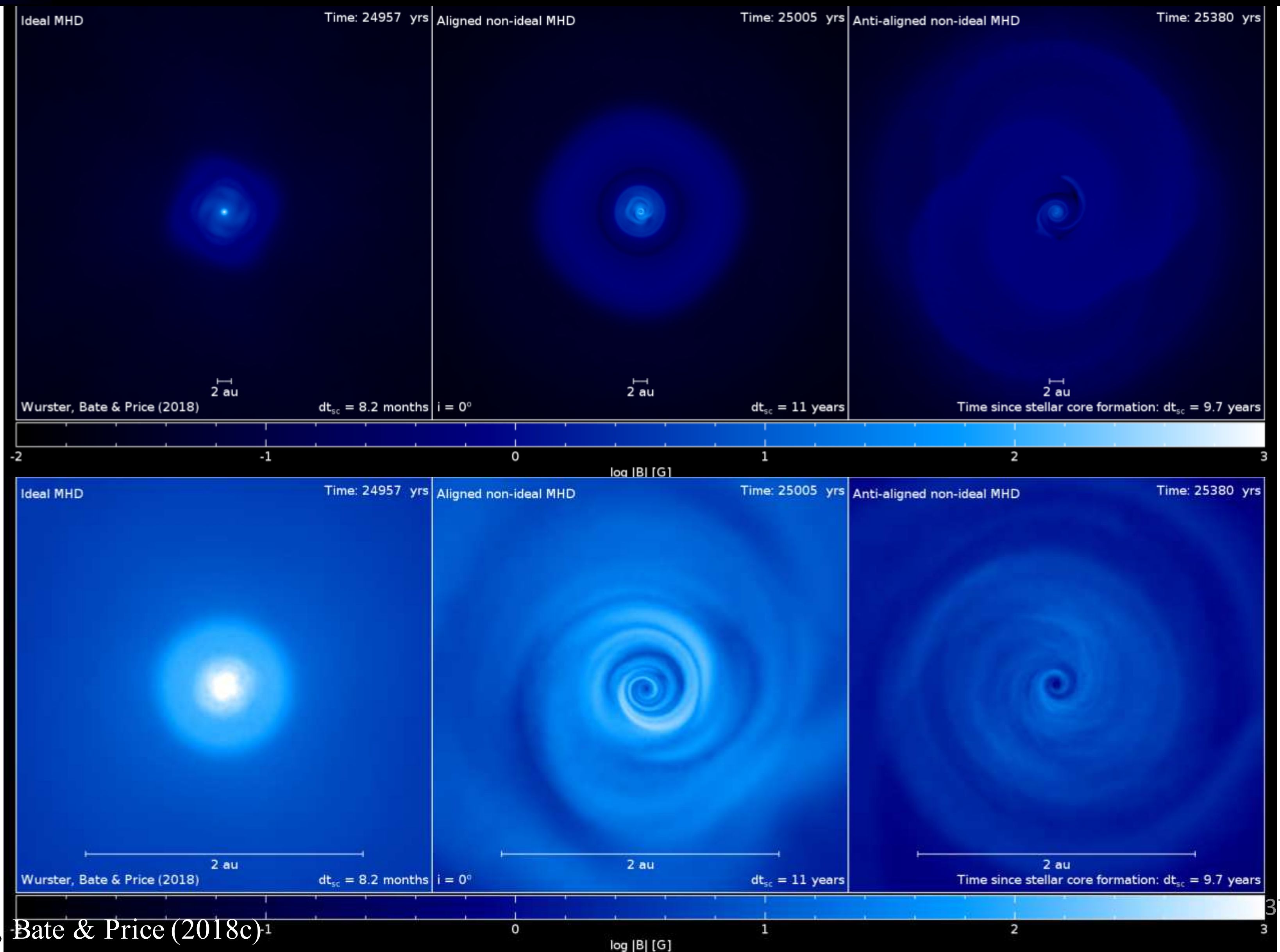




Wurster, Bate & Price (2018d)



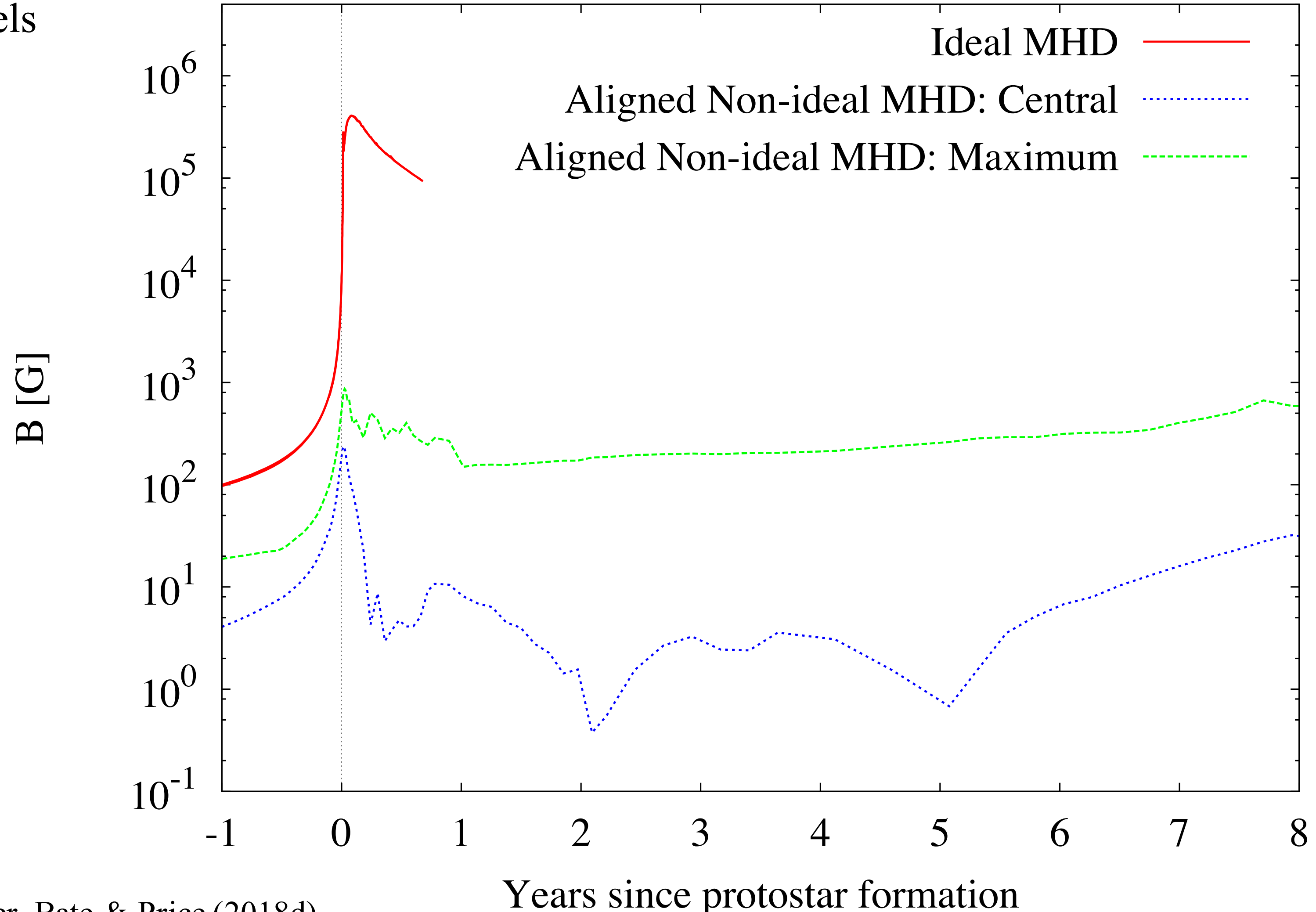
Magnetic field evolution



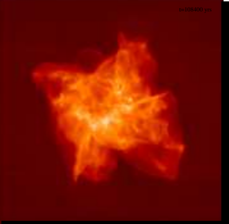
Wurster, Bate & Price (2018c)

Magnetic field evolution

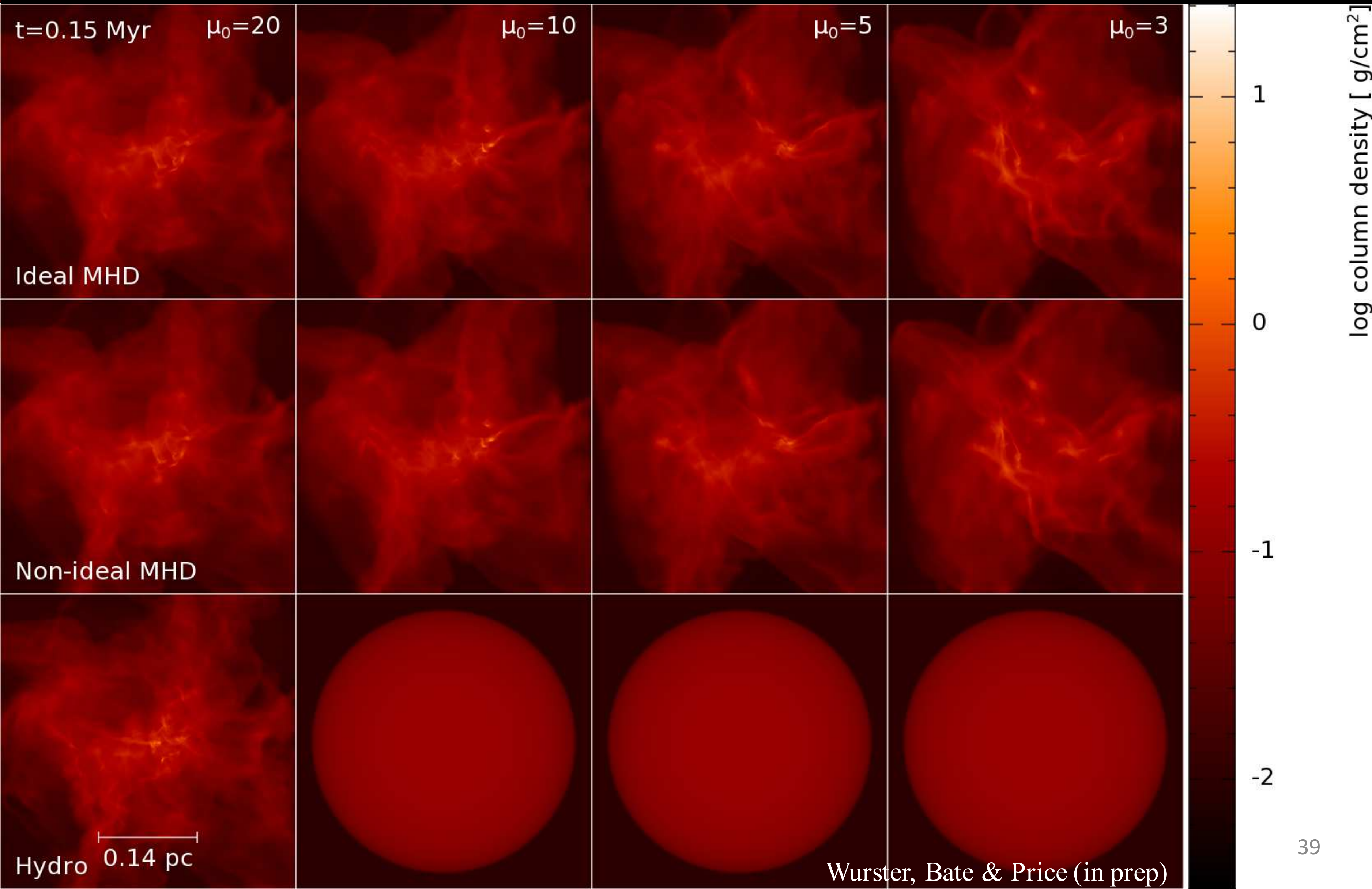
➢Strong kG magnetic fields are observed in stars. Are they fossil, or dynamo-generated?
➢Most likely dynamo-generated since the fossil magnetic field is << 1000G in the non-ideal models



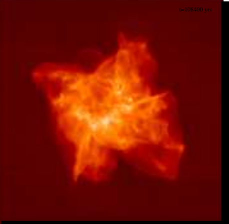
Wurster, Bate & Price (2018d)



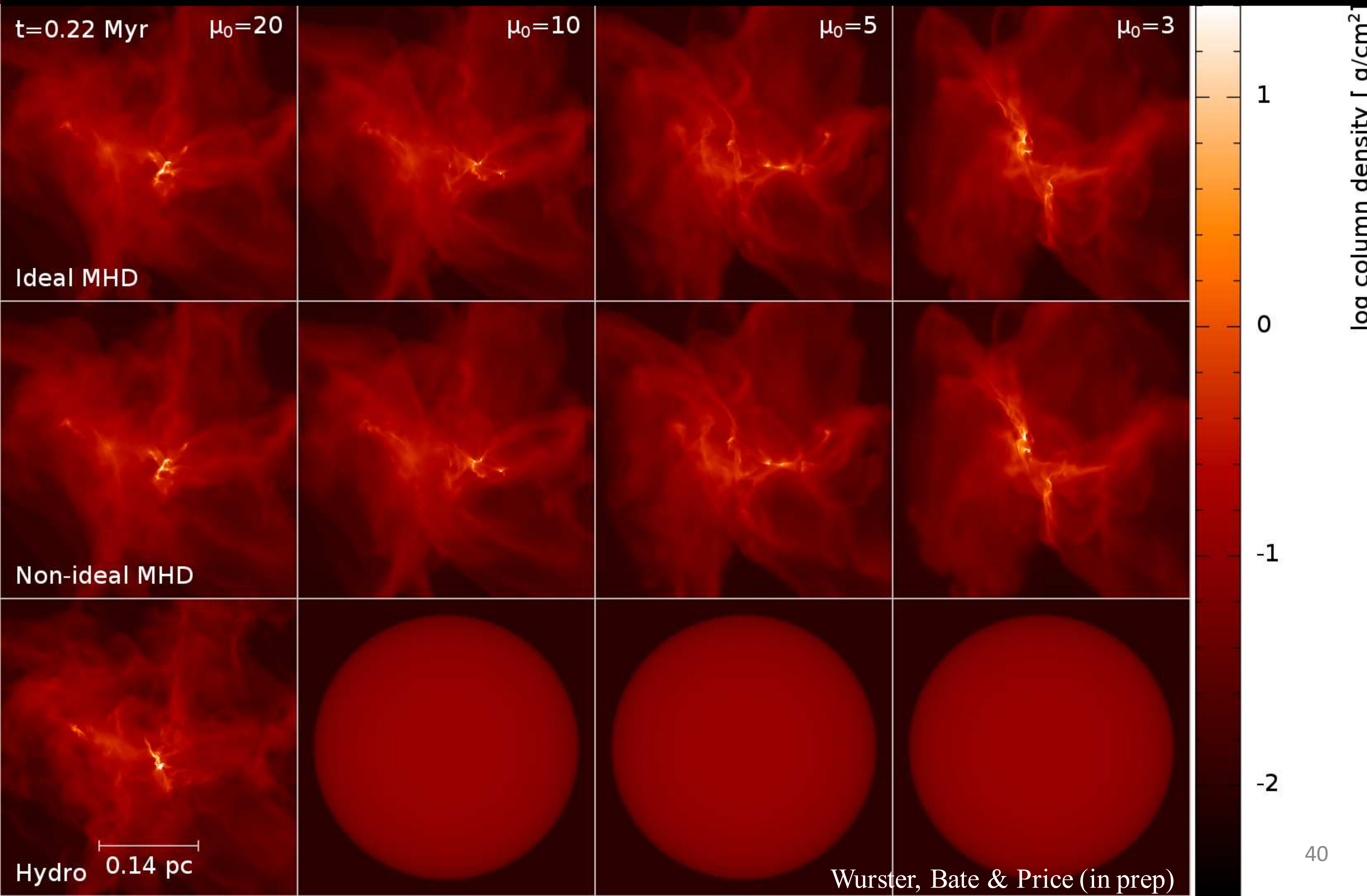
Cluster Formation



Wurster, Bate & Price (in prep)

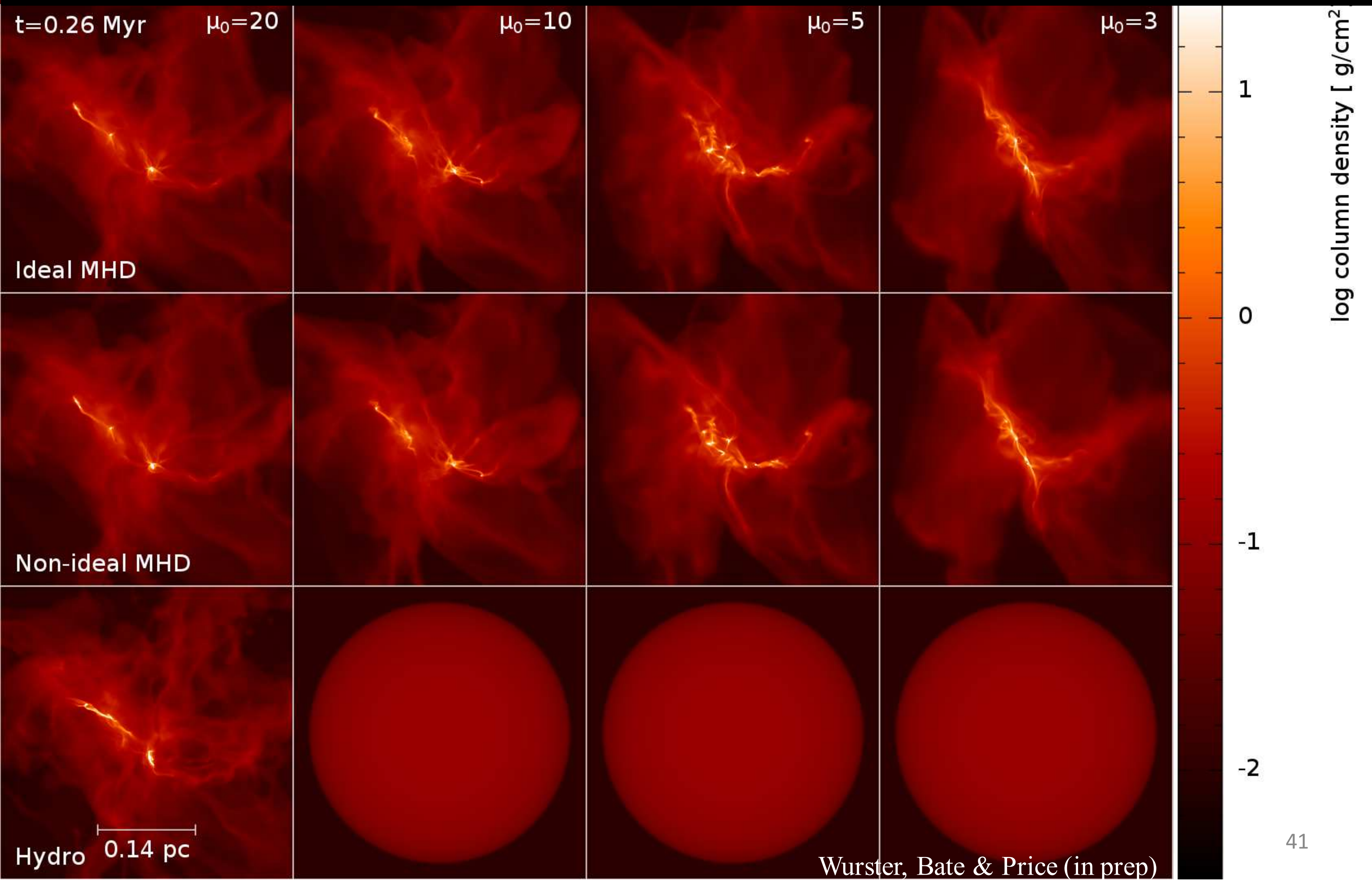


Cluster Formation

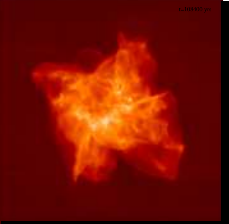


Wurster, Bate & Price (in prep)

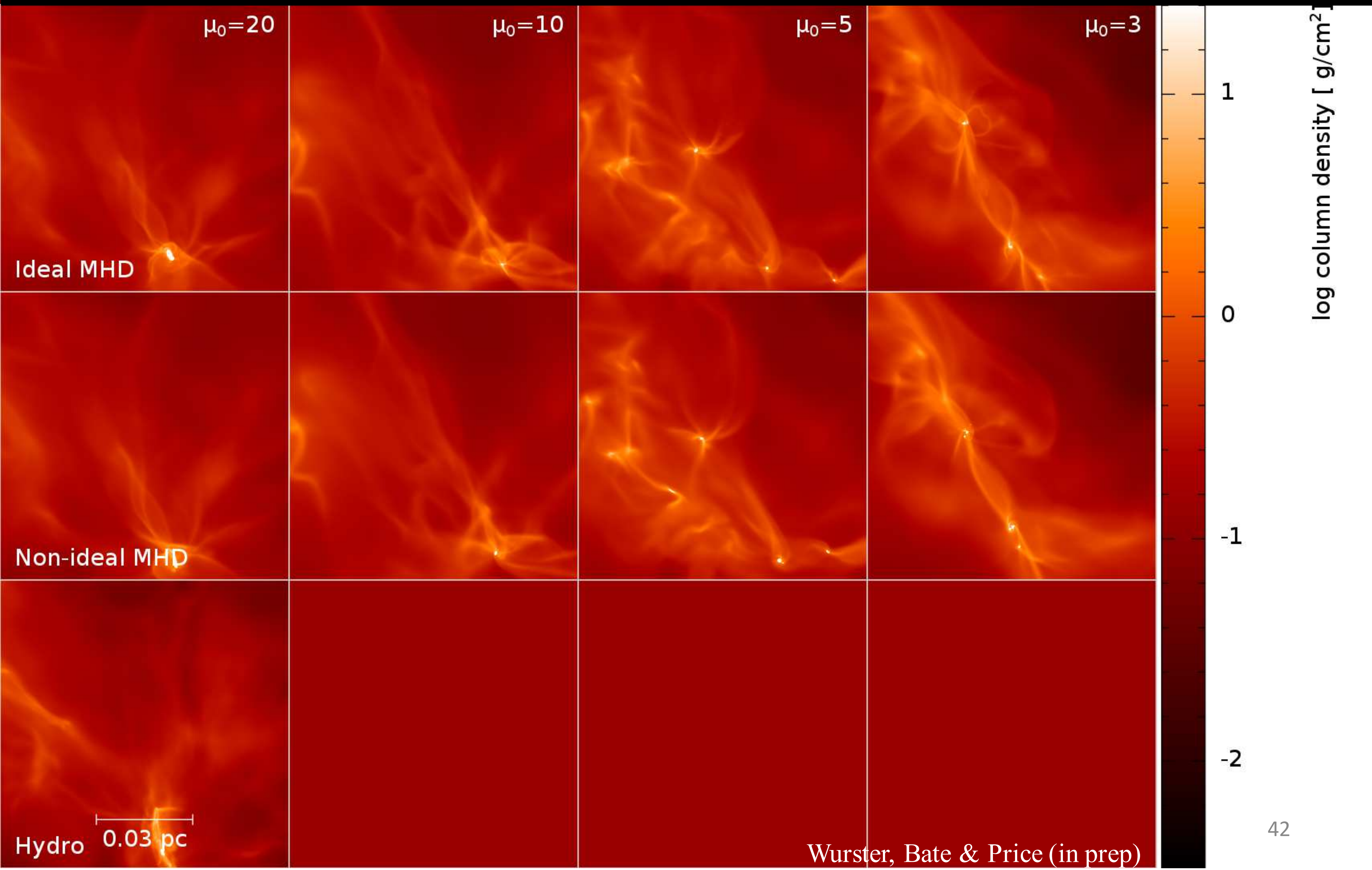
Cluster Formation



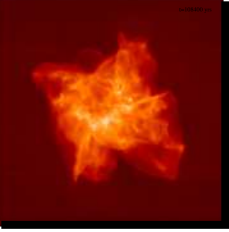
Wurster, Bate & Price (in prep)



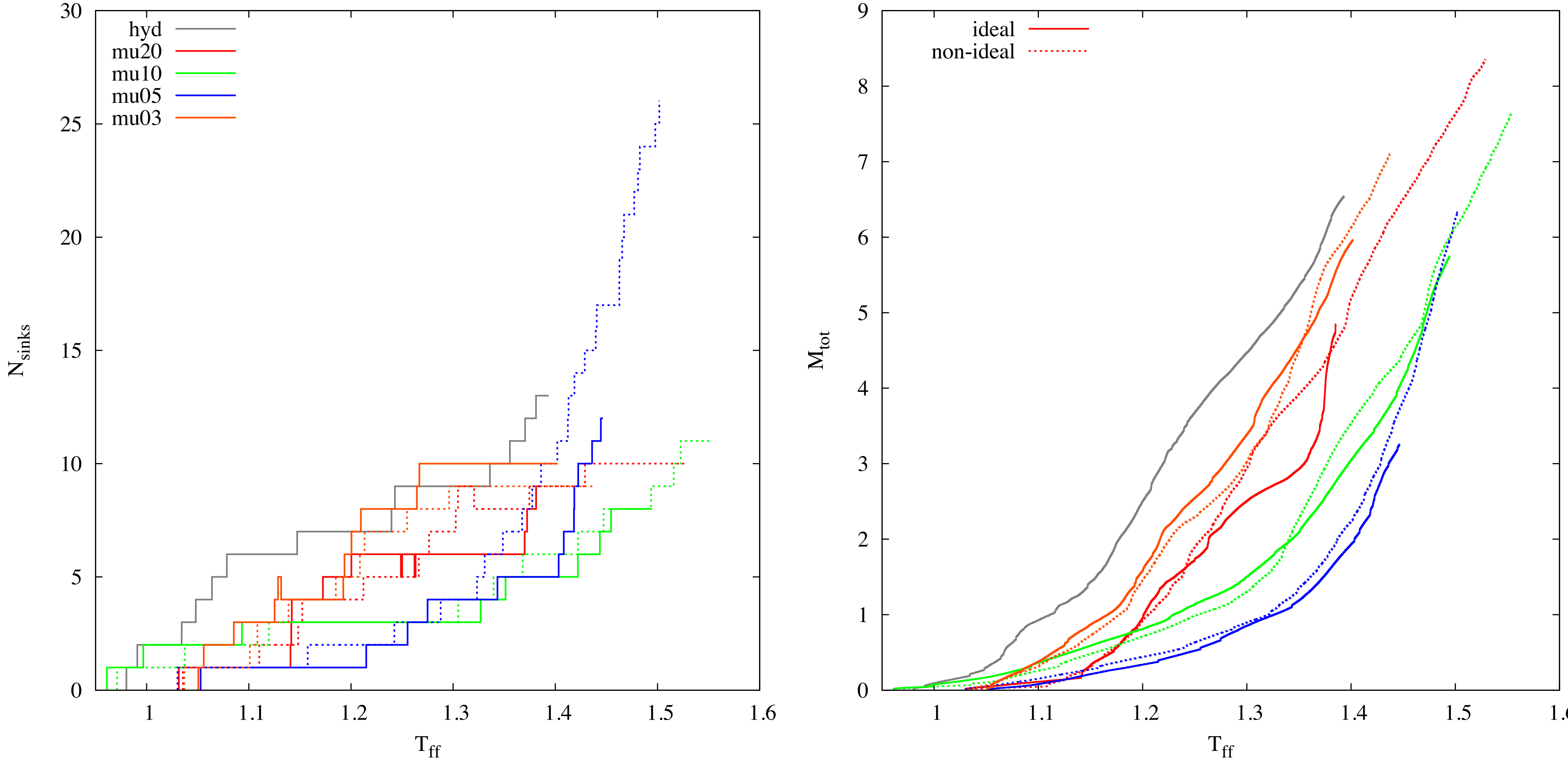
Cluster Formation



Wurster, Bate & Price (in prep)



Cluster Formation



Wurster, Bate & Price (in prep)

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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