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

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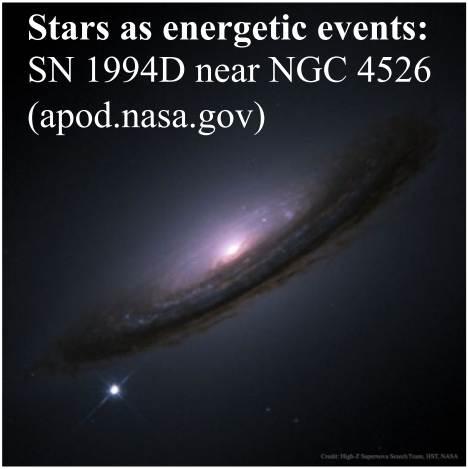
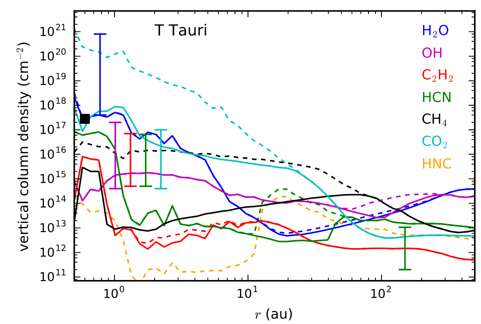
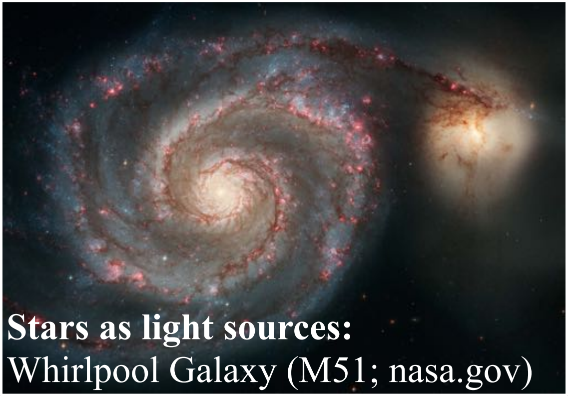
Importance of stars: The big picture



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

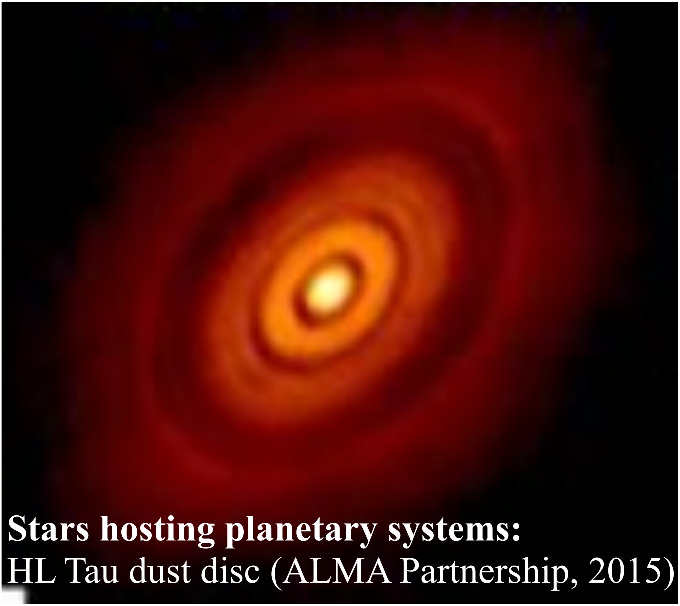


Chemical Evolution (Agundez + 2018)

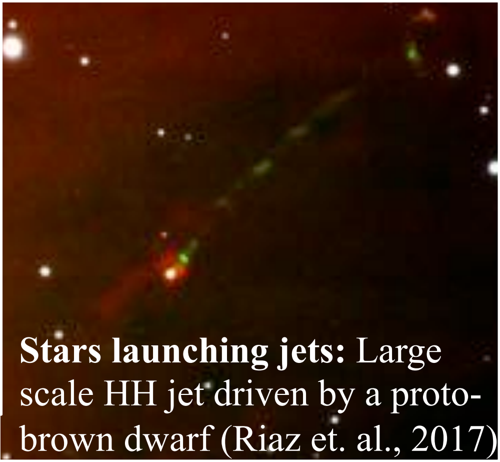


Stars as light sources: Whirlpool Galaxy (M51; nasa.gov)

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



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

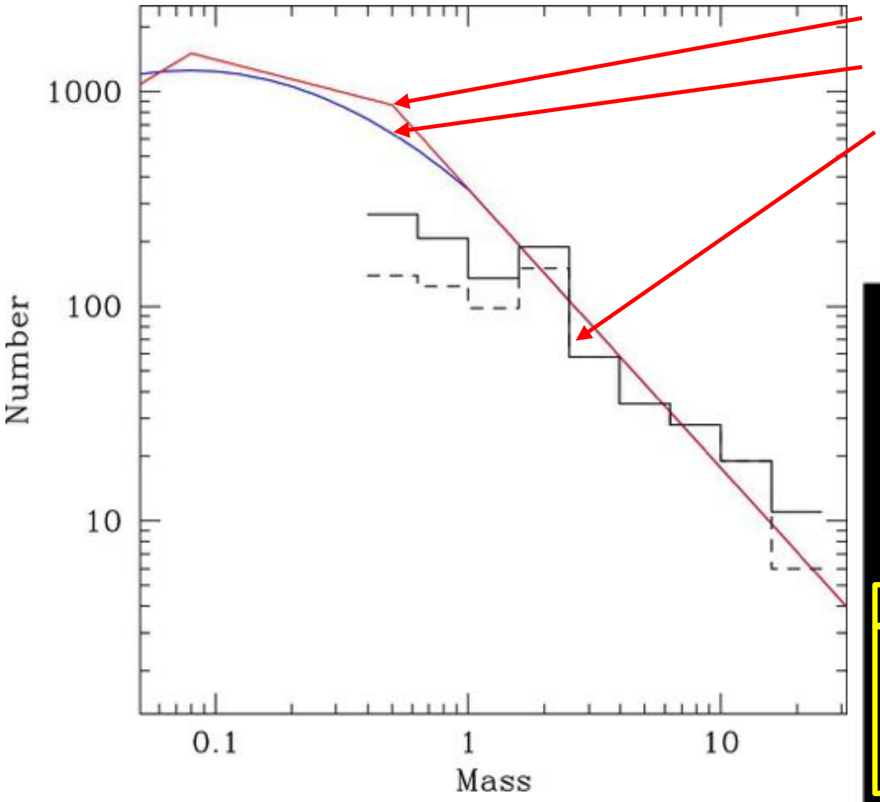


Stars launching jets: Large scale HH jet driven by a proto-brown dwarf (Riaz et. al., 2017)

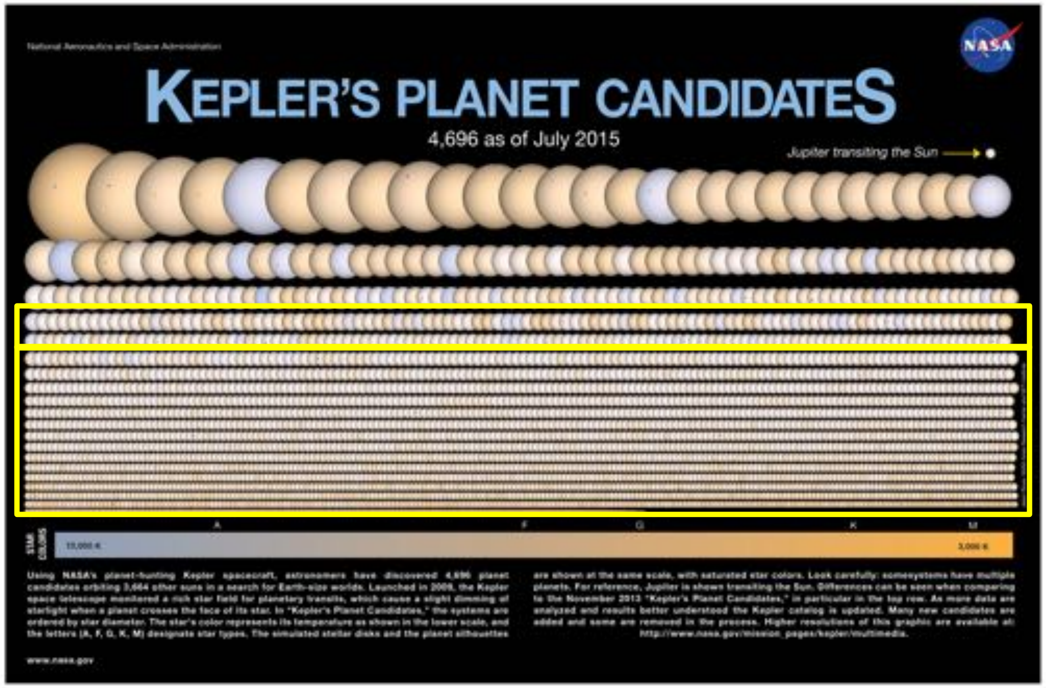
Stars as light sources: Hubble Ultra Deep Field (nasa.gov)

Importance of stars: Masses

- Initial mass function (IMF) of NCG 3603



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



National Aeronautics and Space Administration

KEPLER'S PLANET CANDIDATES

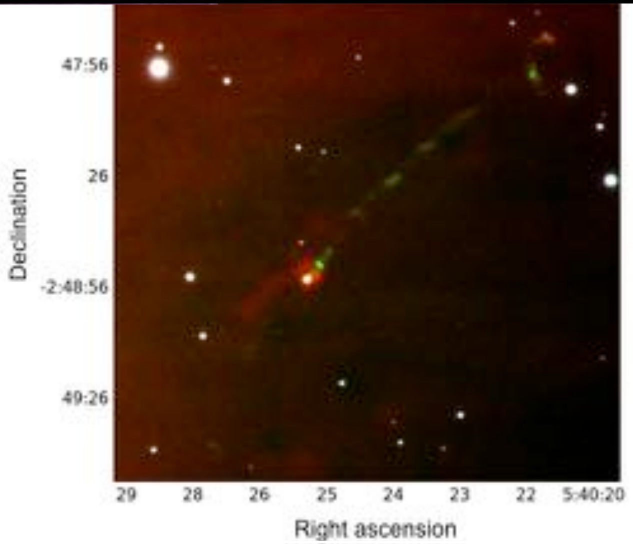
4,696 as of July 2015

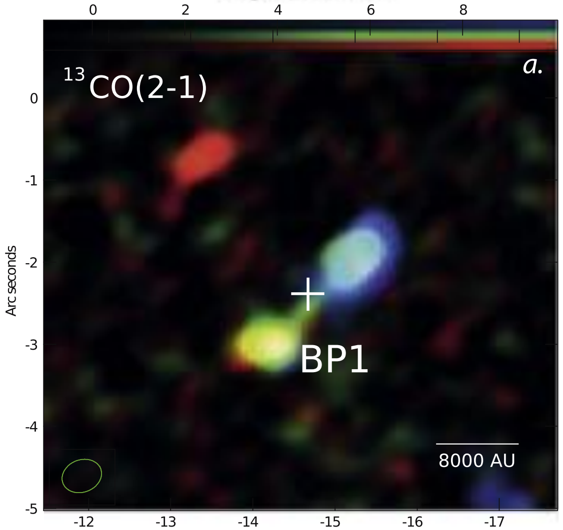
Using NASA's planet-hunting Kepler spacecraft, astronomers have discovered 4,696 planet candidates orbiting 3,664 other suns in a search for Earth-size worlds. Launched in 2009, the Kepler space telescope monitored a rich star field for planetary transits, which cause a slight dimming of starlight when a planet crosses the face of its star. In "Kepler's Planet Candidates," the systems are ordered by star diameter. The star's color represents its temperature as shown in the lower scale, and the letters (A, F, G, K, M) designate star types. The simulated stellar disks and the planet silhouettes are shown at the same scale, with saturated star colors. Look carefully: somesystems have multiple planets. For reference, Jupiter is shown transiting the Sun. Differences can be seen when comparing to the November 2013 "Kepler's Planet Candidates," in particular in the top row. As more data are analyzed and results better understood the Kepler catalog is updated. Many new candidates are added and some are removed in the process. Higher resolutions of this graphic are available at: http://www.nasa.gov/mission_pages/kepler/multimedia.

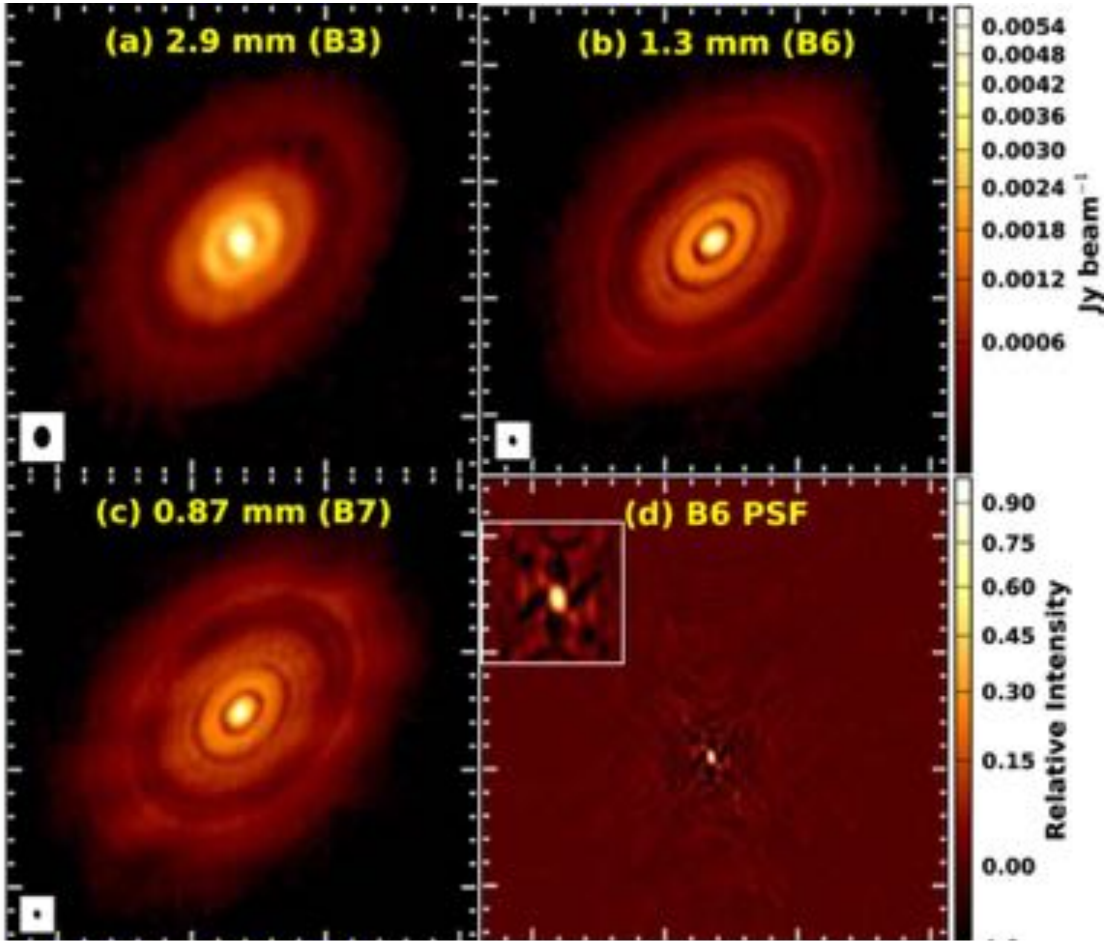
www.nasa.gov

Left: Bonnell, Larson, Zinnecker (2007)

Importance of Low-stars: Outflows & Discs

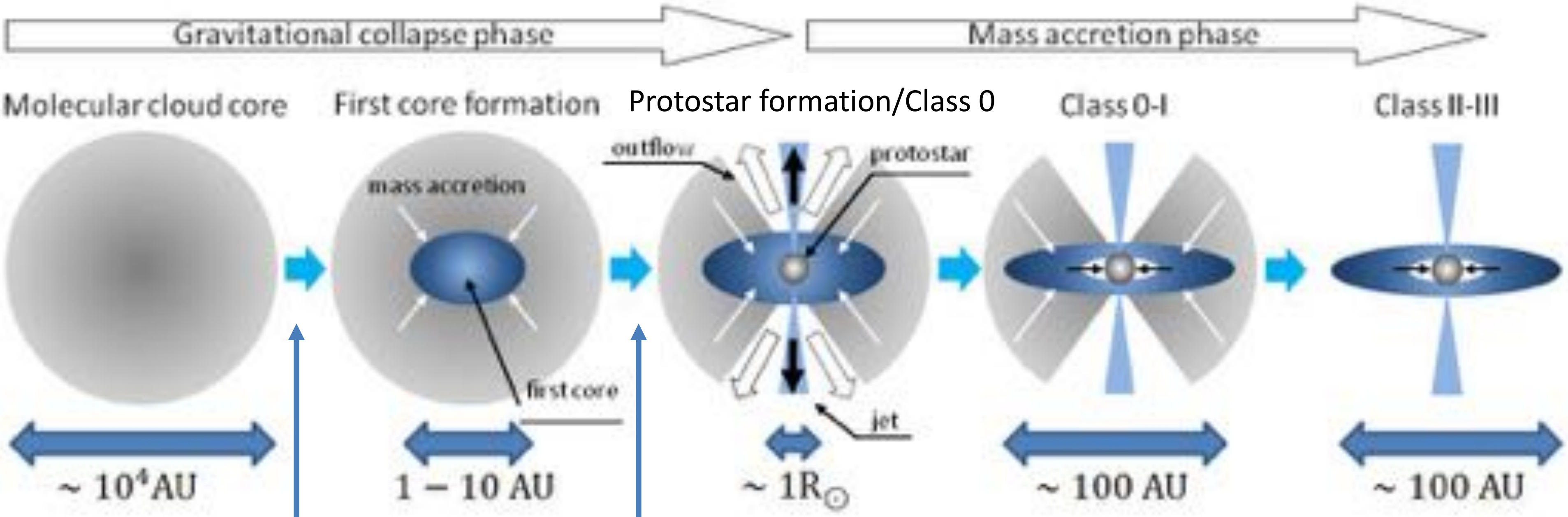






Top left: Large scale Herbig-Haro jet driven by a proto-brown dwarf (Riaz et. al., 2017)
Bottom left: CO outflows from low-mass stars with 1pc of Sgr A* (Yusef-Zadeh et. al., 2017)
Right: HL Tau dust disc (ALMA Partnership, 2015)

Star formation: from the beginning



200 - $2000R_{sun}$
$M \sim M_{Jupiter}$

Isothermal collapse

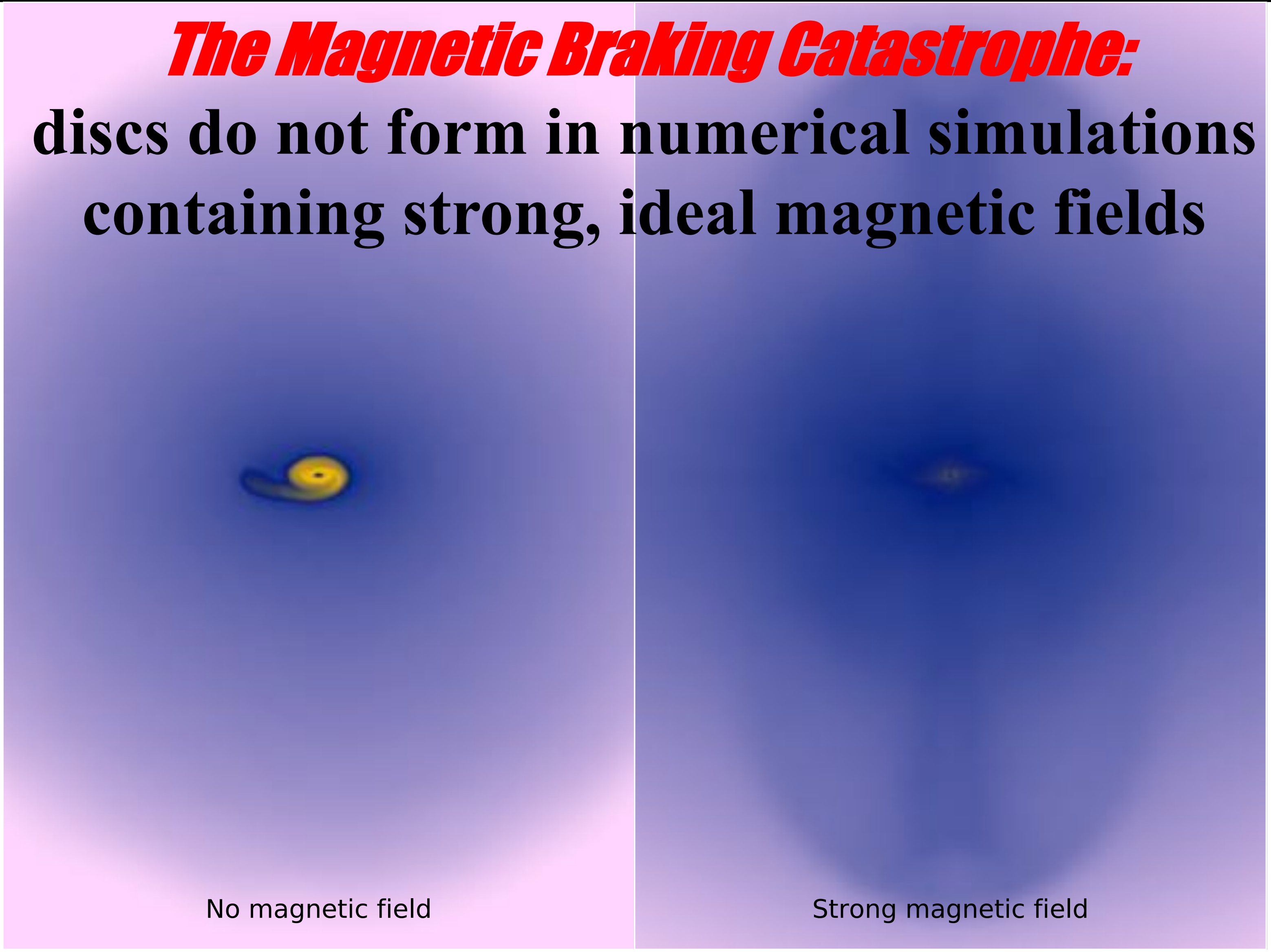
Second collapse
after $T_{core} > 2000K$

Larson (1969); Illustration by Y. Tsukamoto

Disc formation: Magnetohydrodynamics

The Magnetic Braking Catastrophe:

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



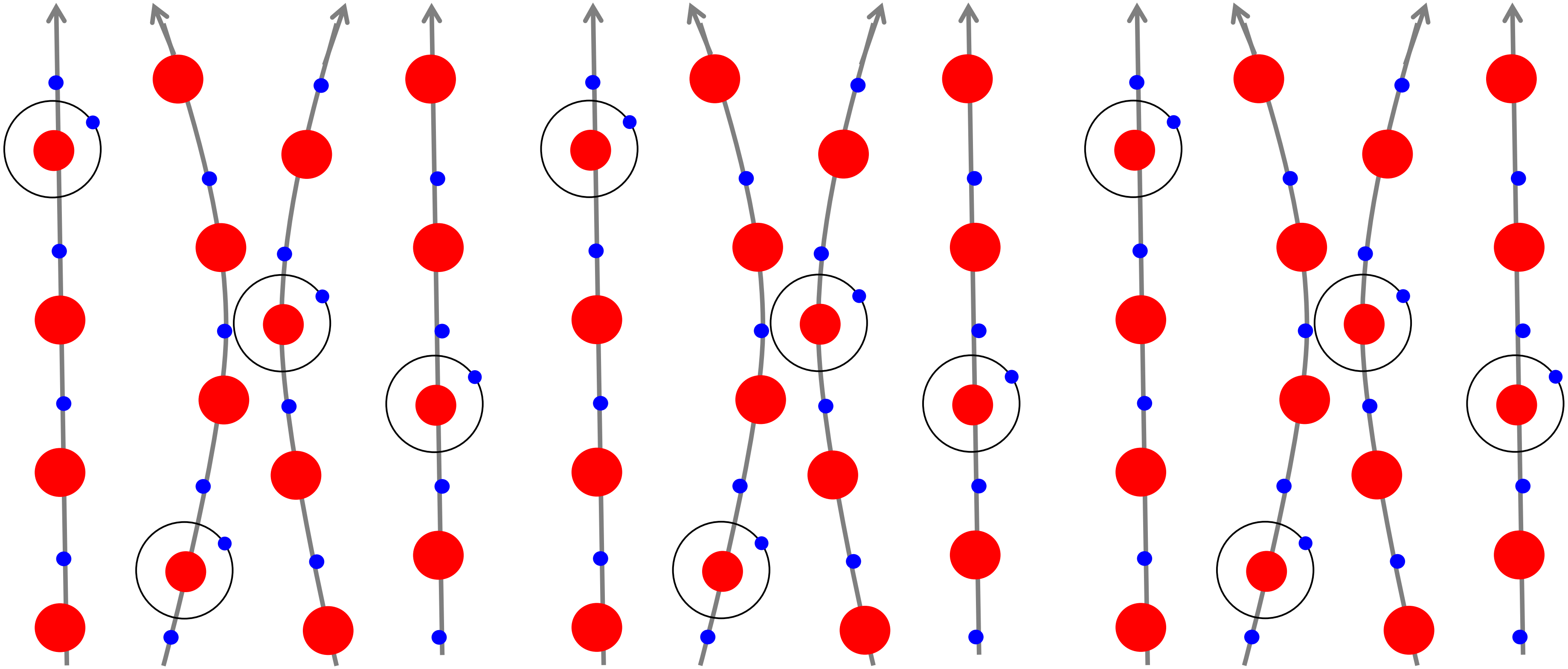
No magnetic field

Strong magnetic field

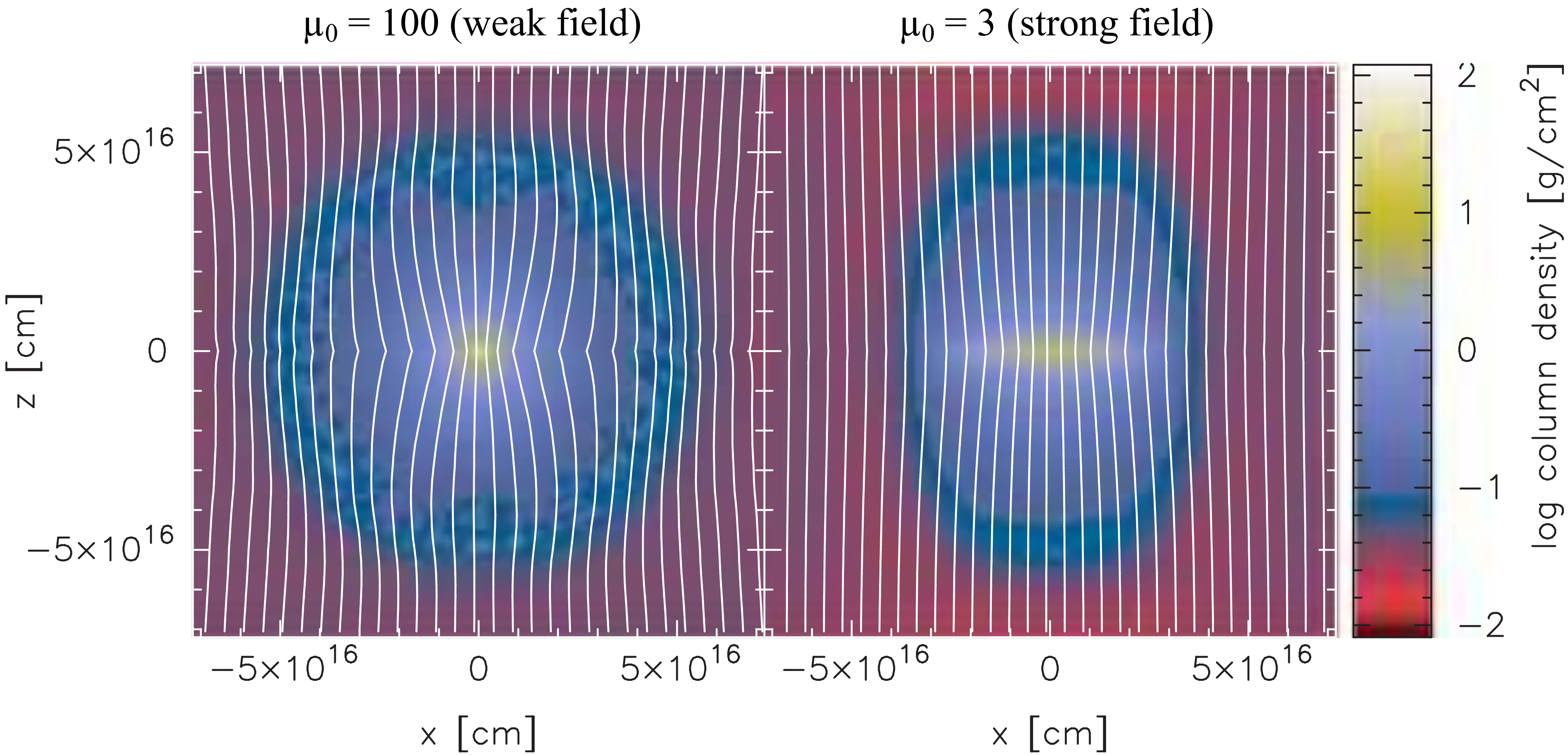
e.g. Allen, Li & Shu (2003); Galli+ (2006)

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



Star formation: with ideal magnetic fields



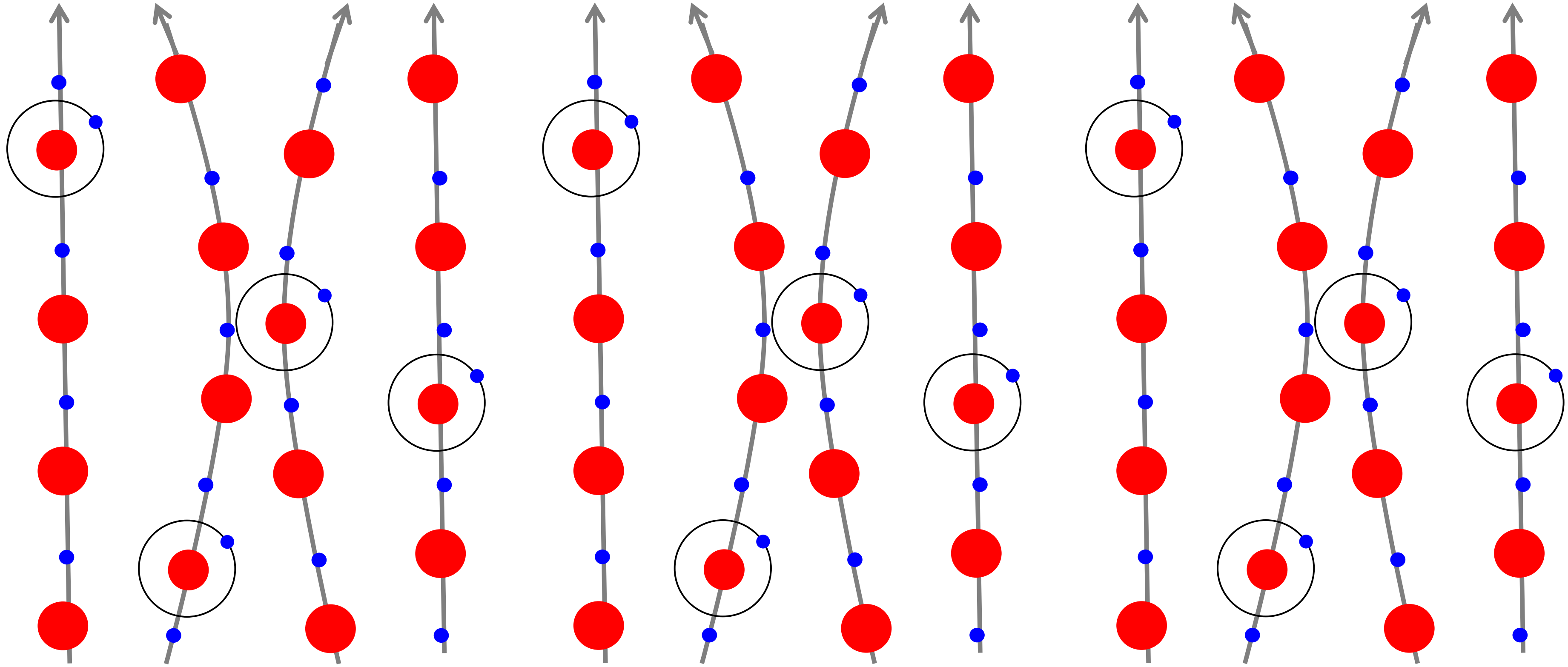
$\mu_0 = 100$ (weak field)

$\mu_0 = 3$ (strong field)

Price & Bate (2007)

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



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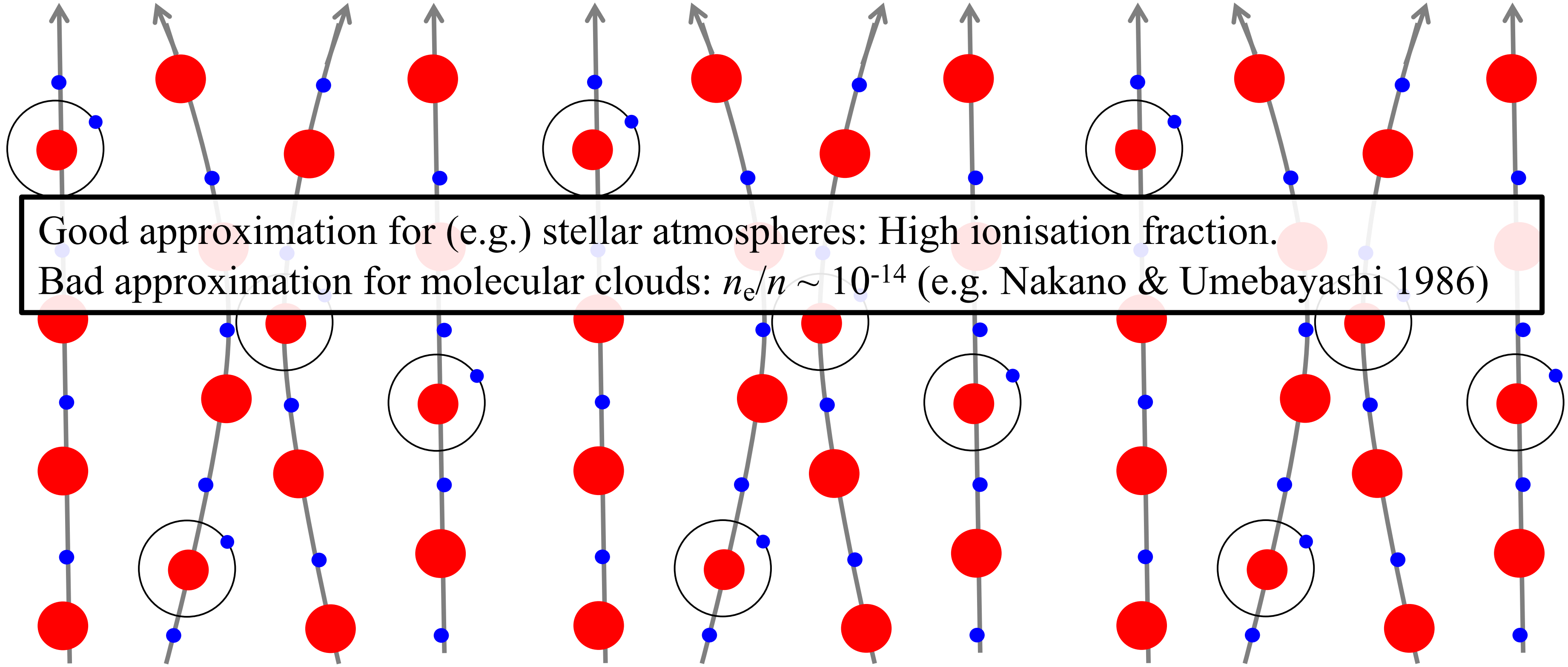
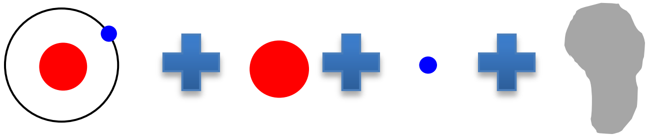
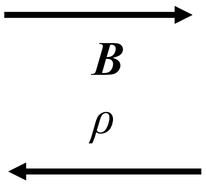


Good approximation for (e.g.) stellar atmospheres: High ionisation fraction.
Bad approximation for molecular clouds: $n_e/n \sim 10^{-14}$ (e.g. Nakano & Umebayashi 1986)

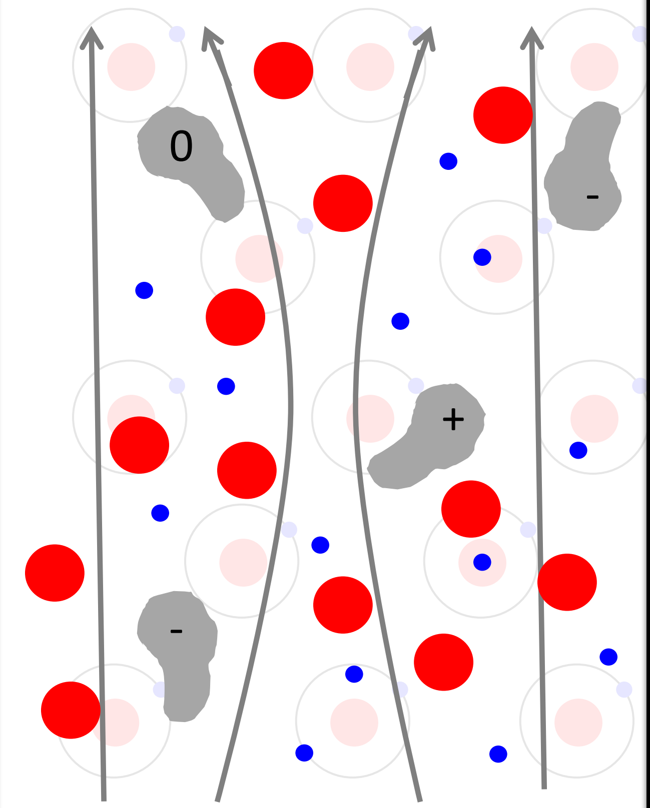
Non-ideal magnetohydrodynamics

- ➢Partially ionised plasma and dust:

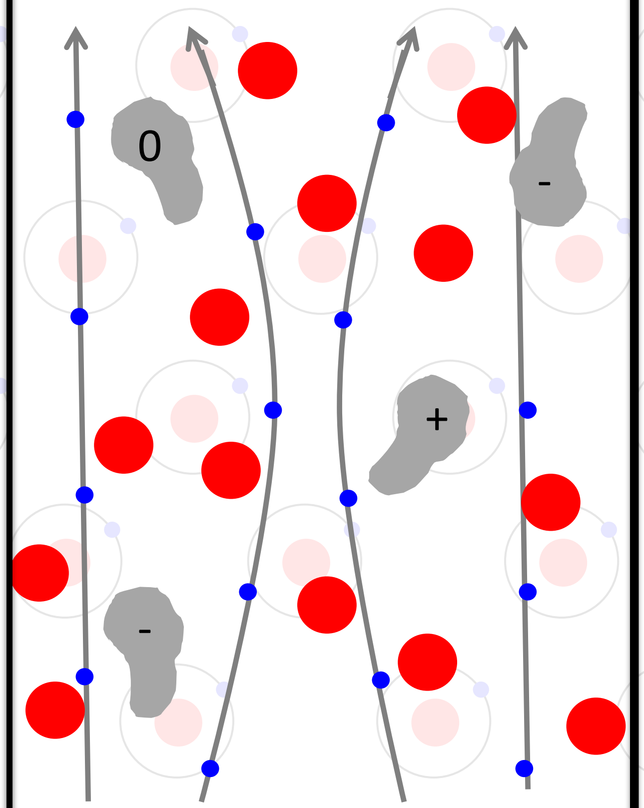




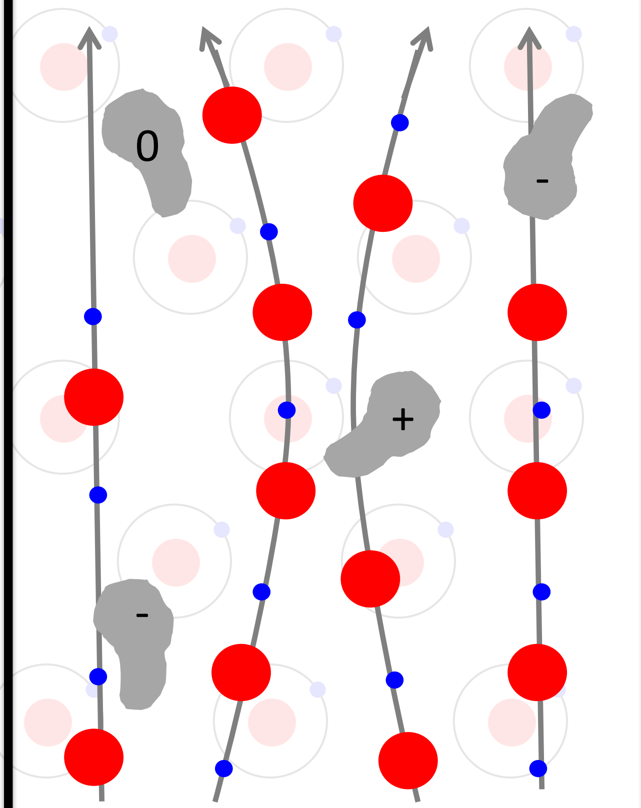
- ➢Non-zero resistivity & conductivity
- ➢Ions, electrons & neutrals behaviour is environment-dependent



Ohmic Resistivity



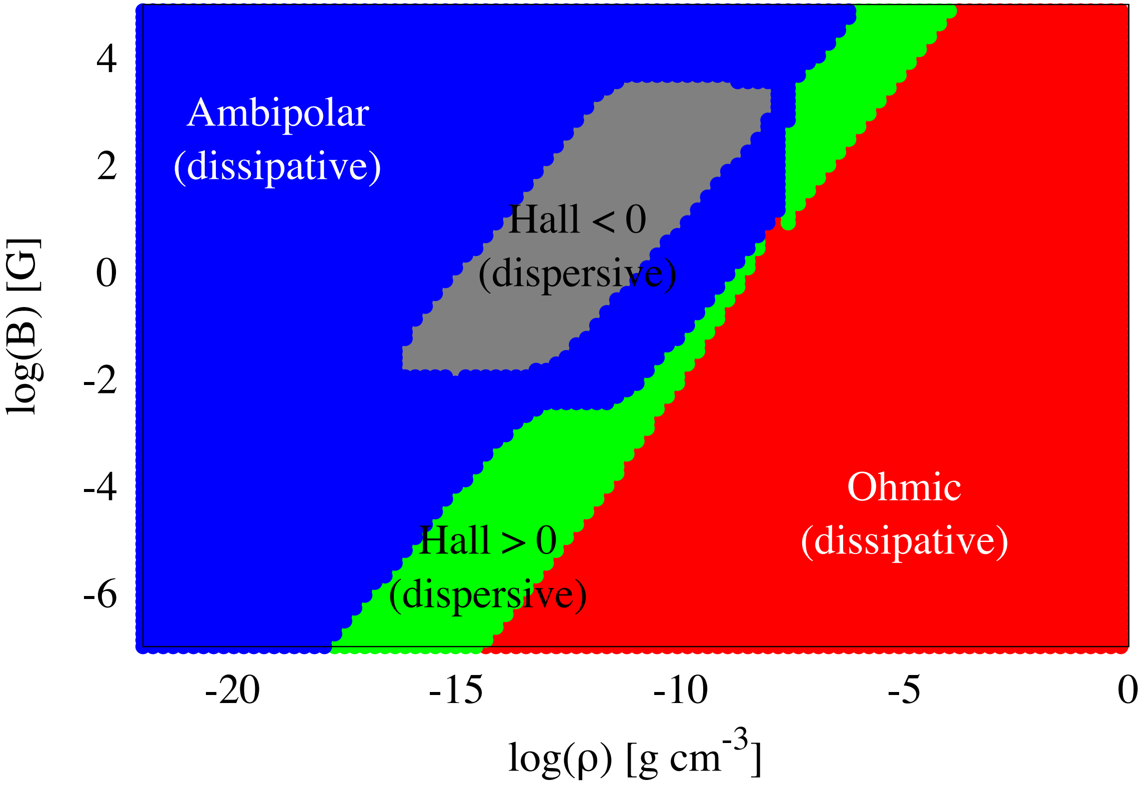
Hall Effect



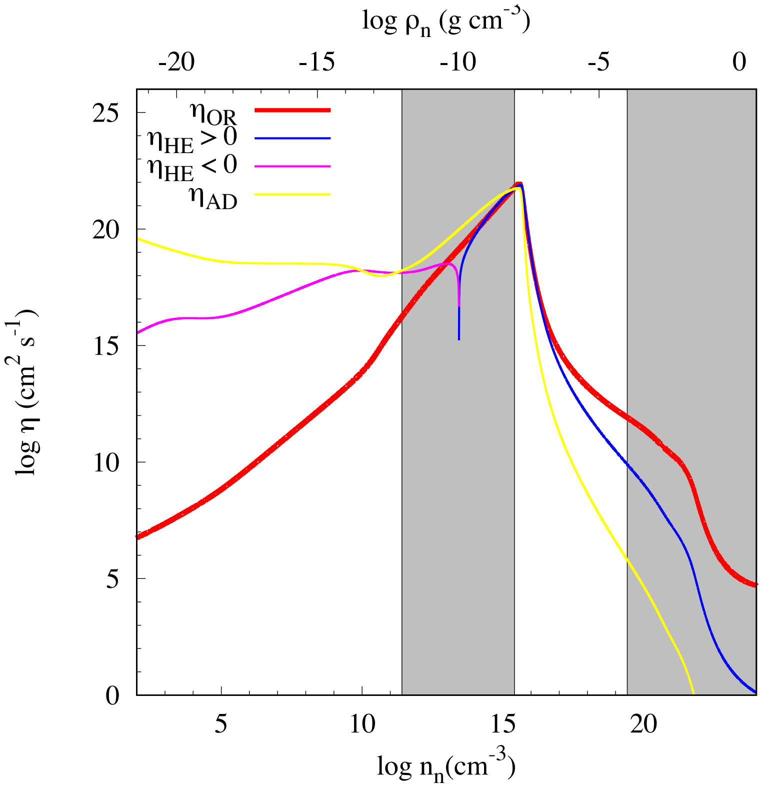
Ambipolar Diffusion

Non-ideal magnetohydrodynamics

Phase space diagram



Coefficients
(for a star-forming model)

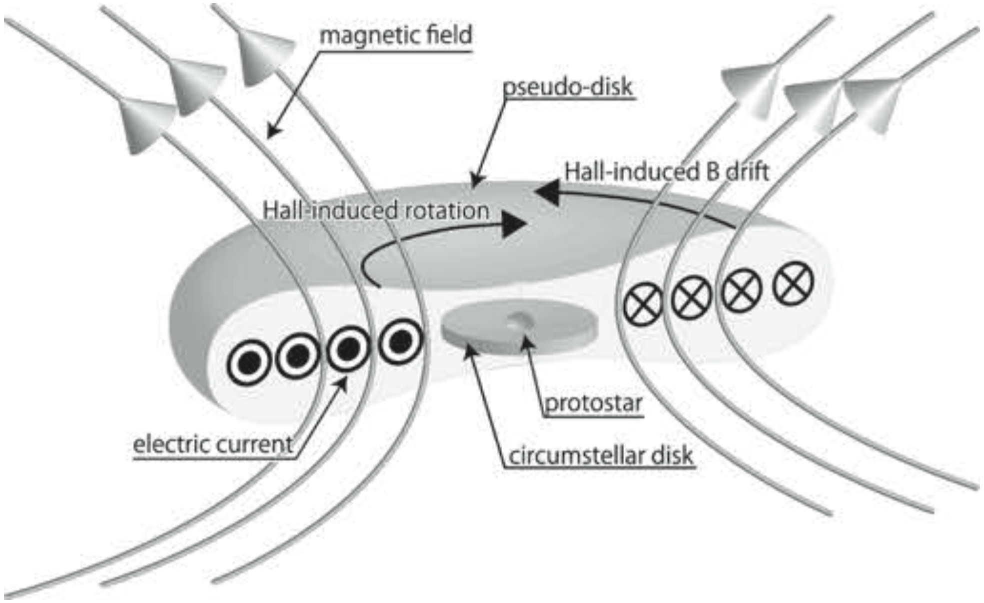


- ➢Values dependent on microphysics:
  - ➢Grain size, ionised species, cosmic ray ionisation rate

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

Non-ideal magnetohydrodynamics: The Hall effect

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



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

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

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

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

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

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

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

Simplify:

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

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

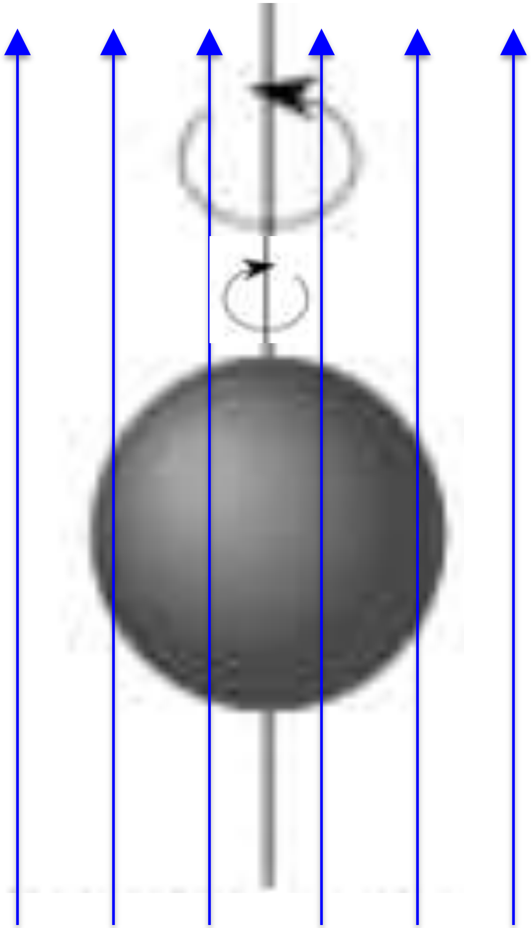
$$\left.\frac{\mathrm{d}\boldsymbol{B}}{\mathrm{d}t}\right|_{\mathrm{AD}} = \boldsymbol{\nabla}\times\left\{\eta_{\mathrm{AD}}\left[\left(\boldsymbol{\nabla}\times\boldsymbol{B}\right)\times\hat{\boldsymbol{B}}\right]\times\hat{\boldsymbol{B}}\right\}$$

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

Non-ideal magnetohydrodynamics: The Hall effect

- Depending on the relative orientation of L & B, the Hall-induced rotation will contribute to or detract from the initial rotation

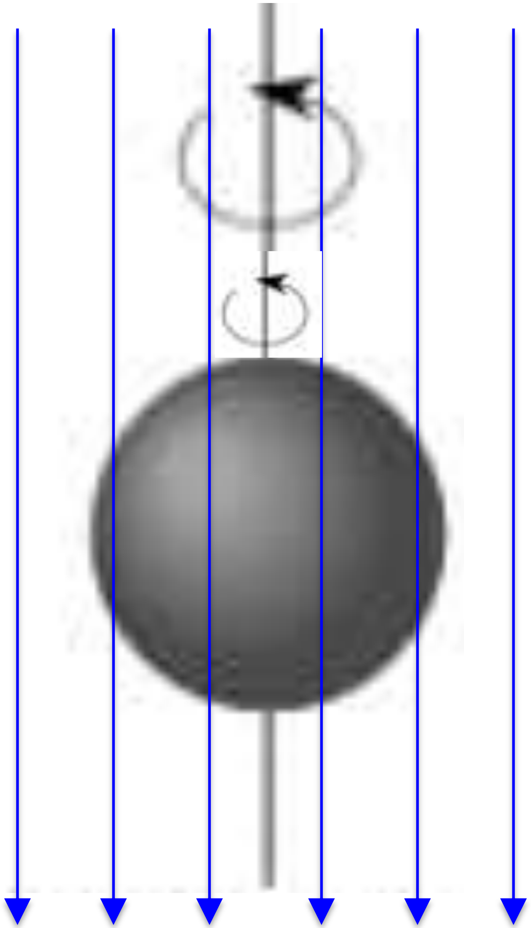
L & B are aligned



Direction of initial rotation

Hall-induced rotation

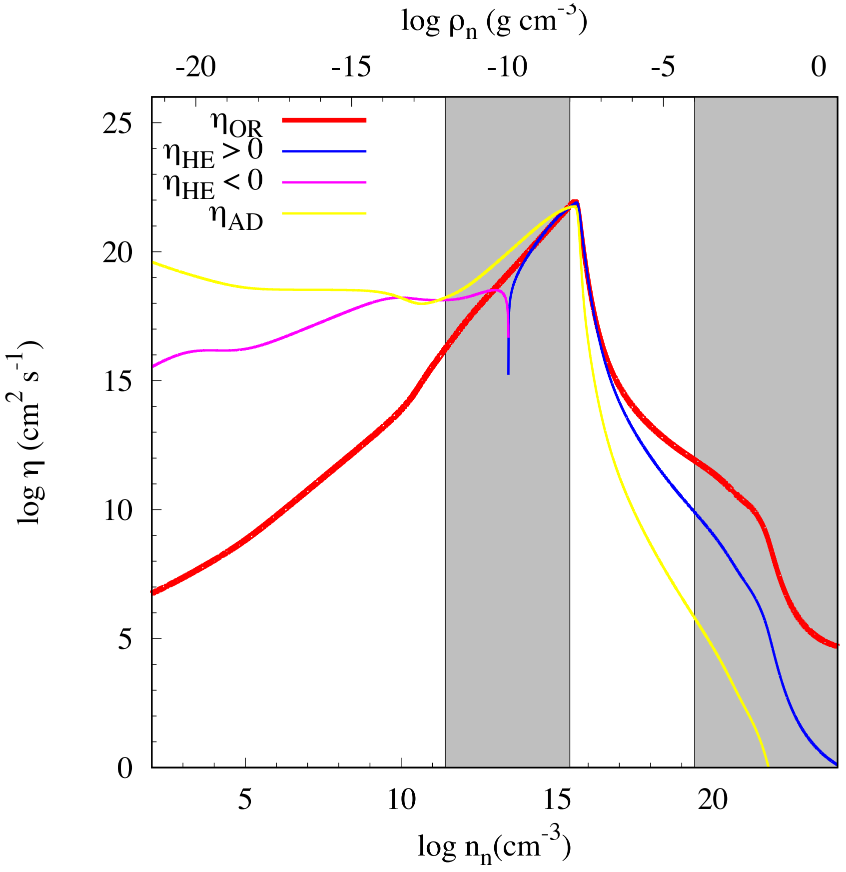
L & B are anti-aligned



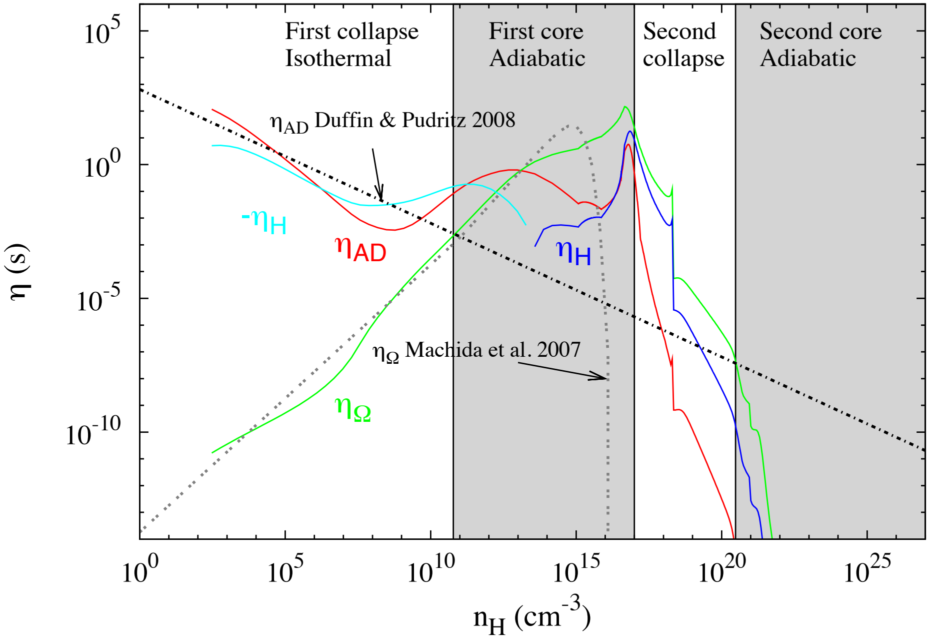
see also: Braiding & Wardle (2012a,b)

Non-ideal magnetohydrodynamics: Calculations

- Algorithm comparison (both models use their default parameters)



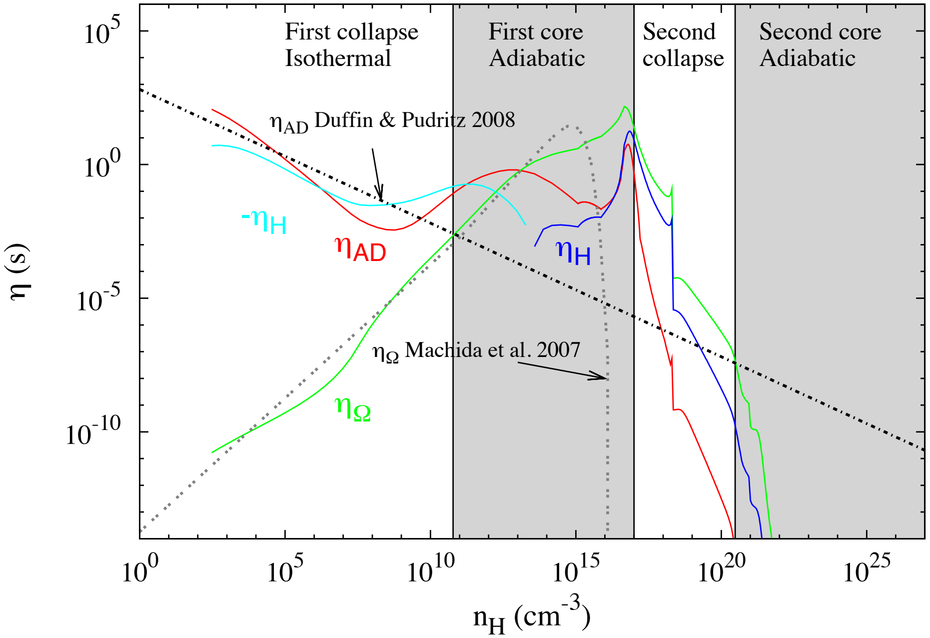
Wurster (2016)

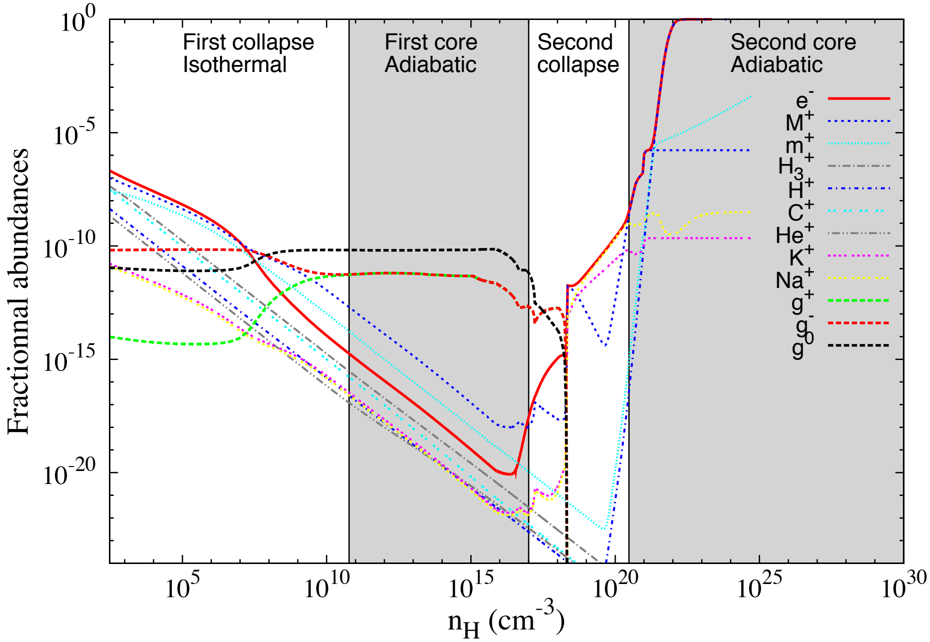


Marchand+ (2016)

Non-ideal magnetohydrodynamics: Chemical models

- ➢Models are chemically dependent
  - ➢More precise chemical network and abundance yields more precise coefficients
  - ➢Still highly dependent on cosmic ray ionisation rate (results not shown here)

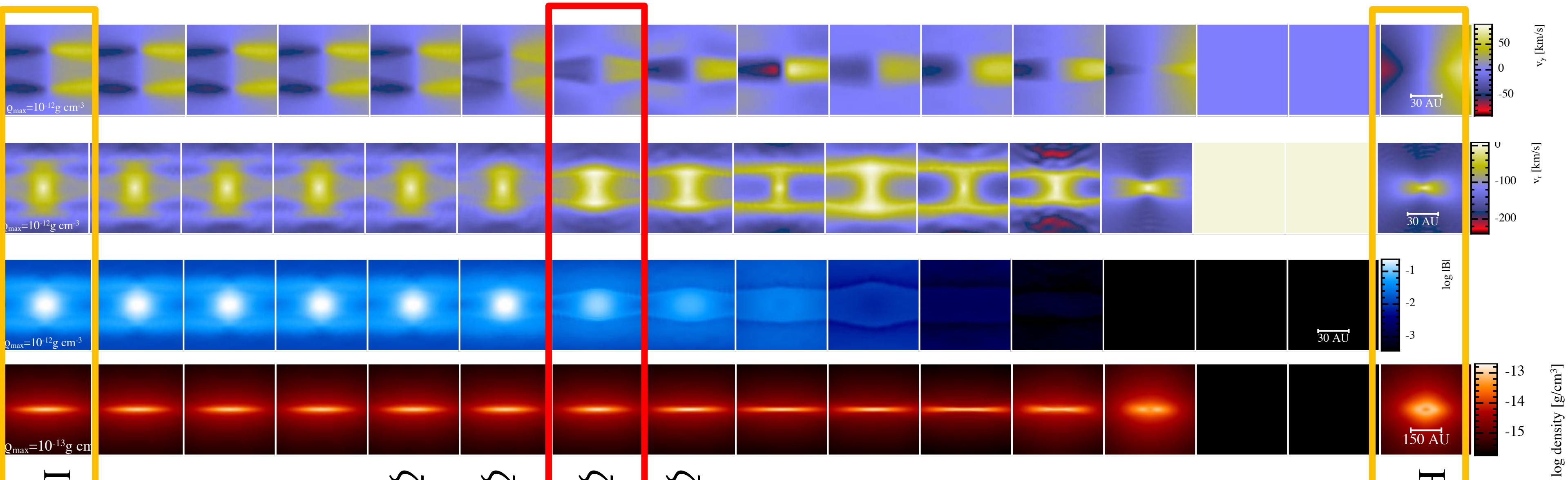




Marchand+ (2016)

Non-ideal magnetohydrodynamics: Cosmic ray ionisation rate

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



Ideal MHD

$\zeta_{\rm CR} = 10^{-15}\ {\rm s}^{-1}$

$\zeta_{\rm CR} = 10^{-16}\ {\rm s}^{-1}$

$\zeta_{\rm CR} = 10^{-17}\ {\rm s}^{-1}$ (Canonical)

$\zeta_{\rm CR} = 10^{-18}\ {\rm s}^{-1}$

Hydrodynamic

Legend:

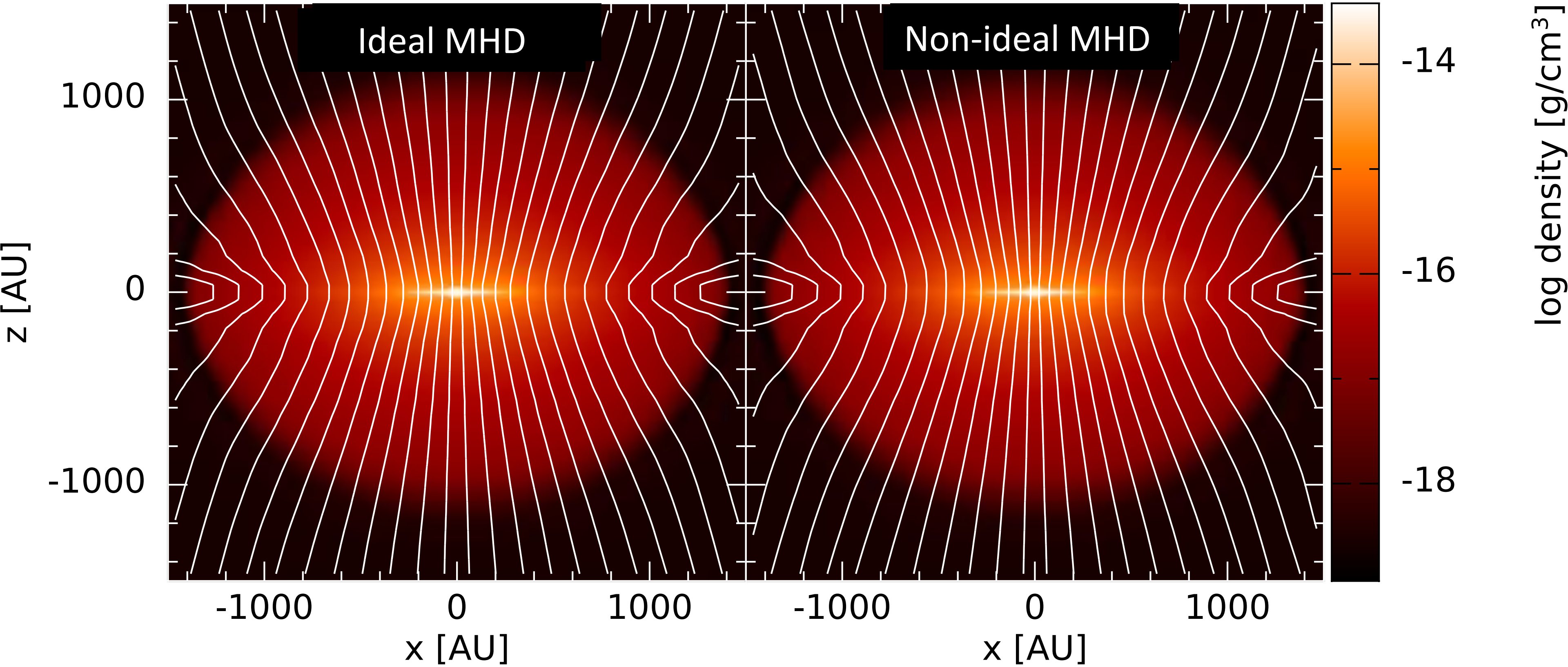
Canonical

Extreme cases

Wurster, Bate & Price (2018b)

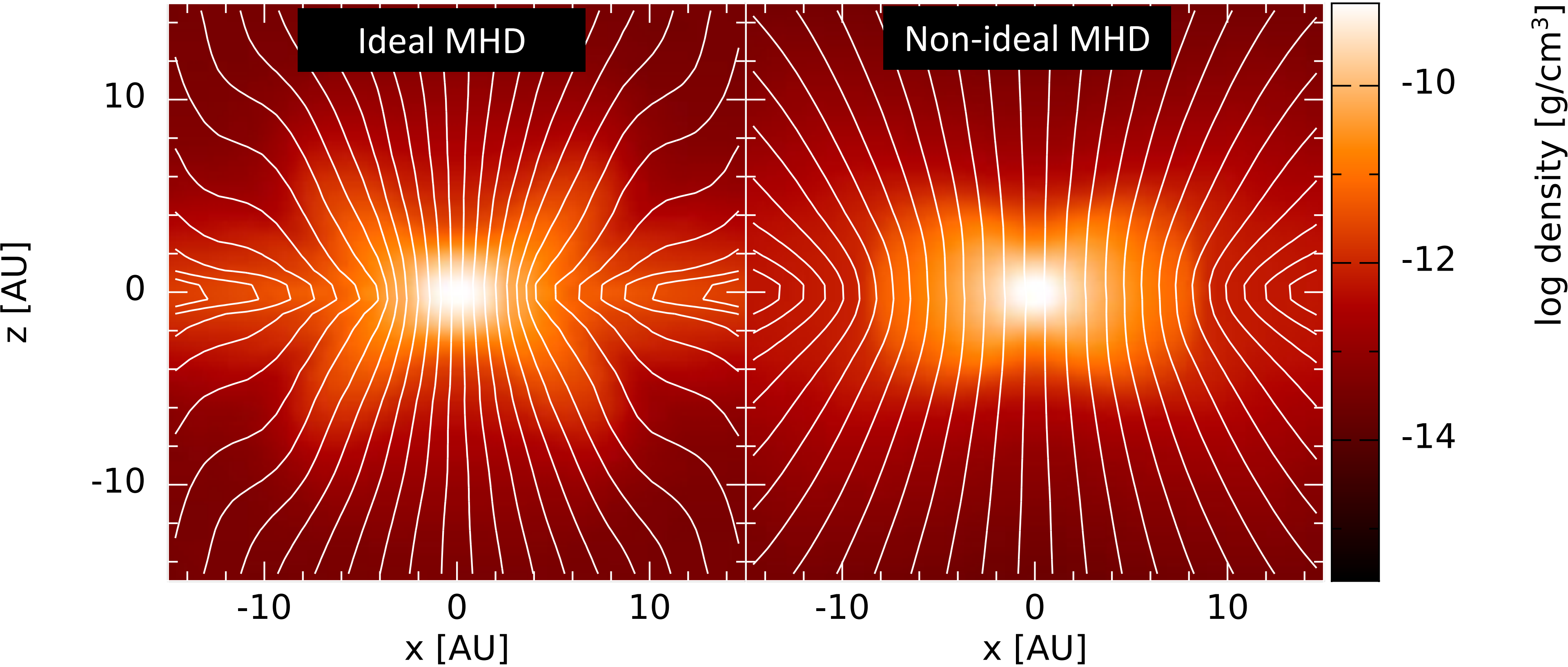
Non-ideal magnetohydrodynamics

- Strong field; large scale structure



Non-ideal magnetohydrodynamics

- Strong field; small scale structure



Non-ideal magnetohydrodynamics

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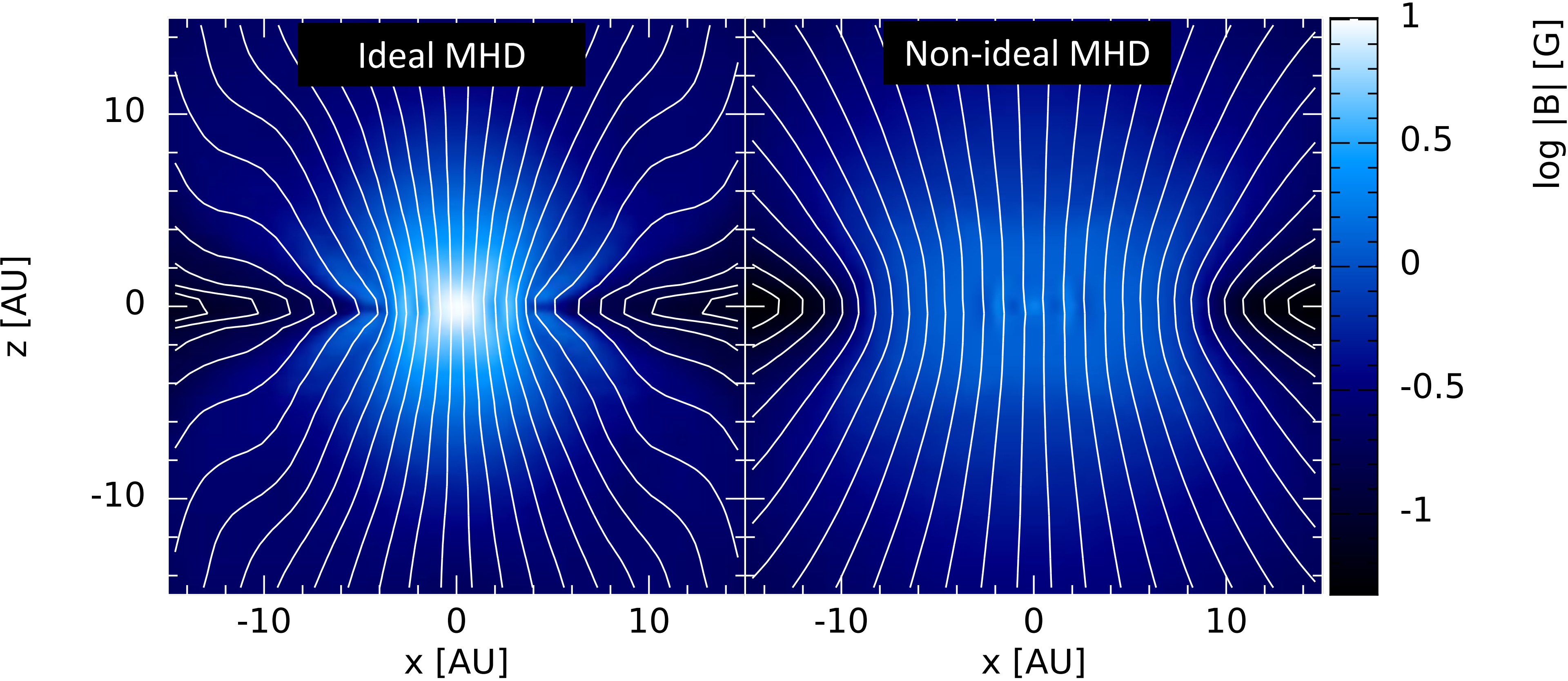
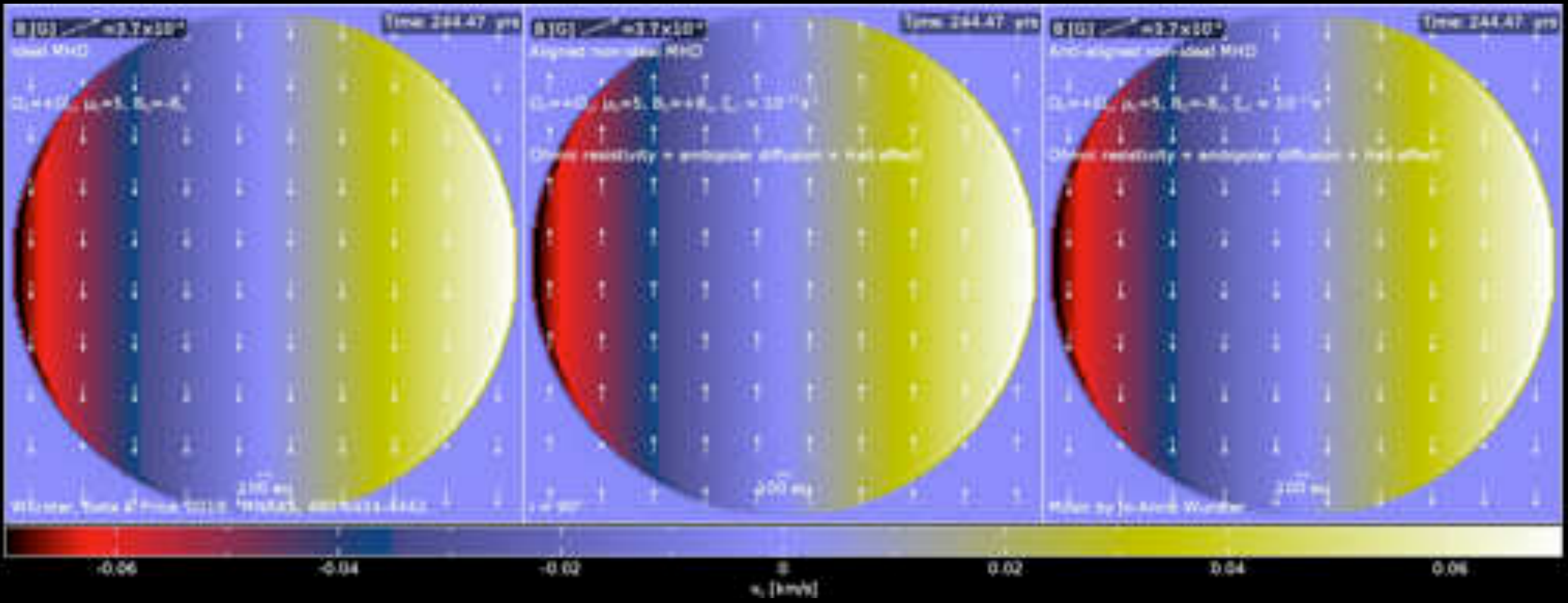


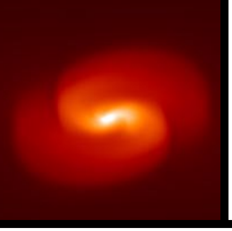
Formation of a low-mass star



https://www.youtube.com/watch?v=2SQxgXbdJyg&t=4s

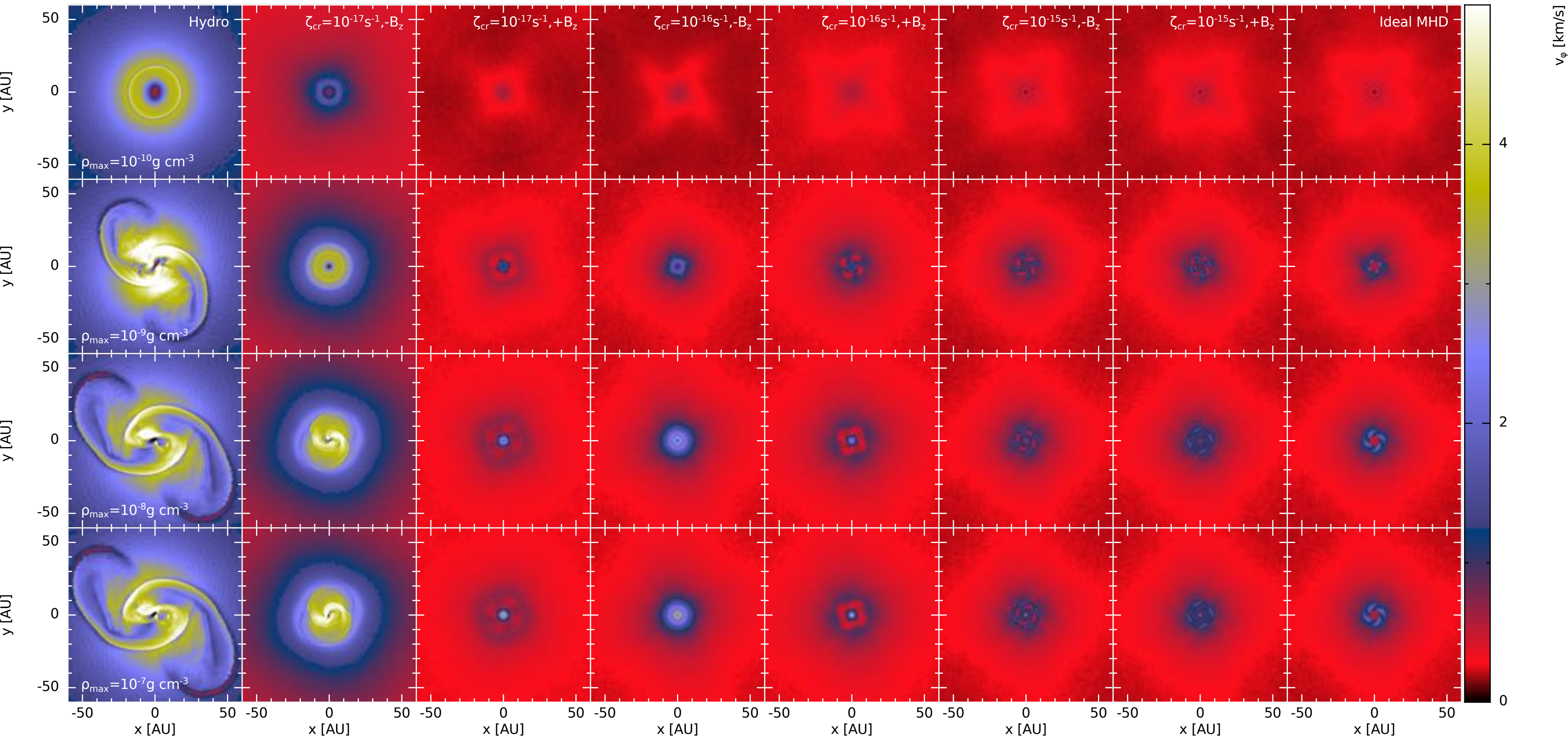
Wurster, Bate & Price (2018c)

Music: Jo-Anne Wurster



Rotationally supported discs

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



- ➢Discs form during the first hydrostatic core phase
- ➢Similar disc structure obtained by Tsukamoto+ (2015a) for $\boldsymbol{\zeta}_{cr} = 10^{-17}$ s^{-1} with ±B$_z$

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

Rotationally supported discs

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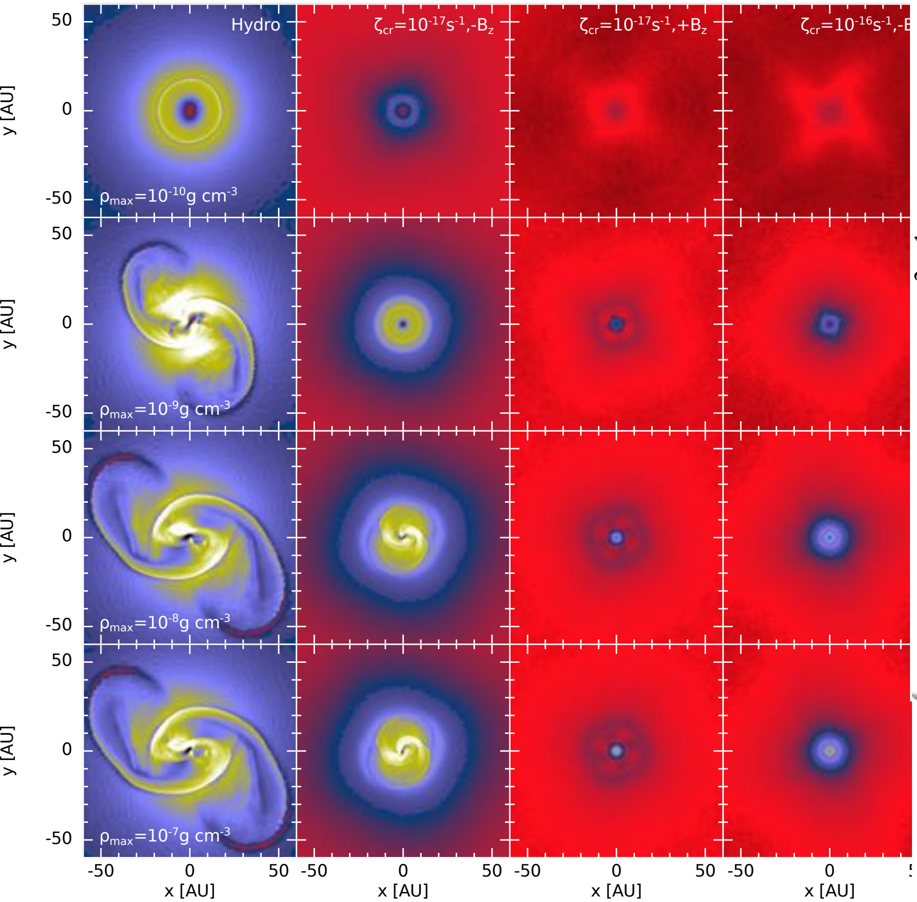
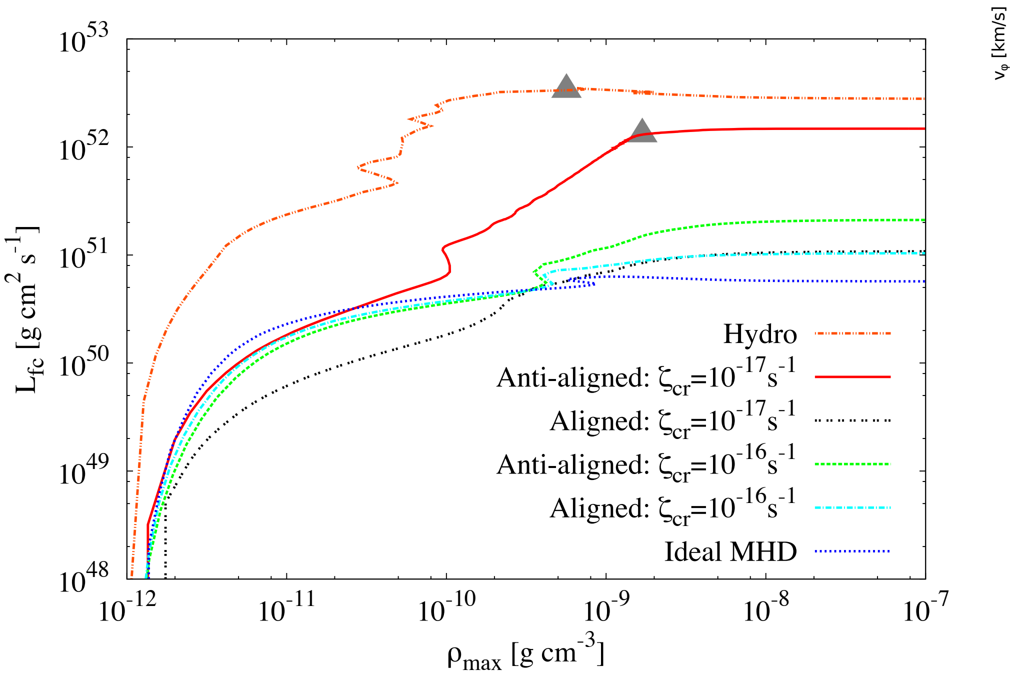
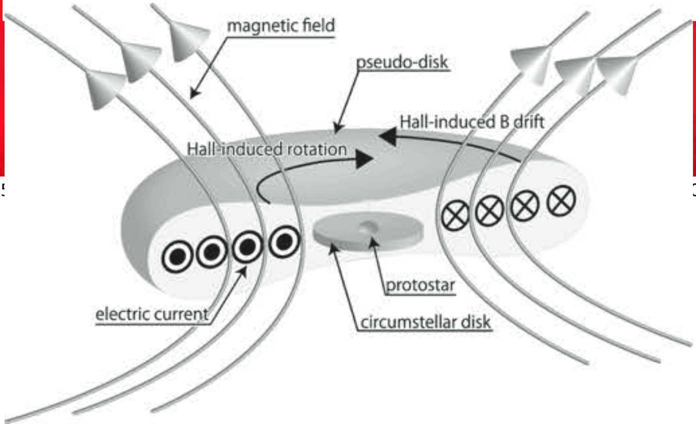
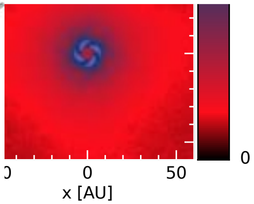
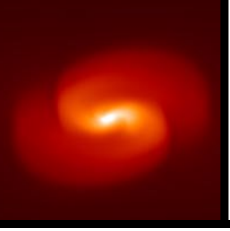






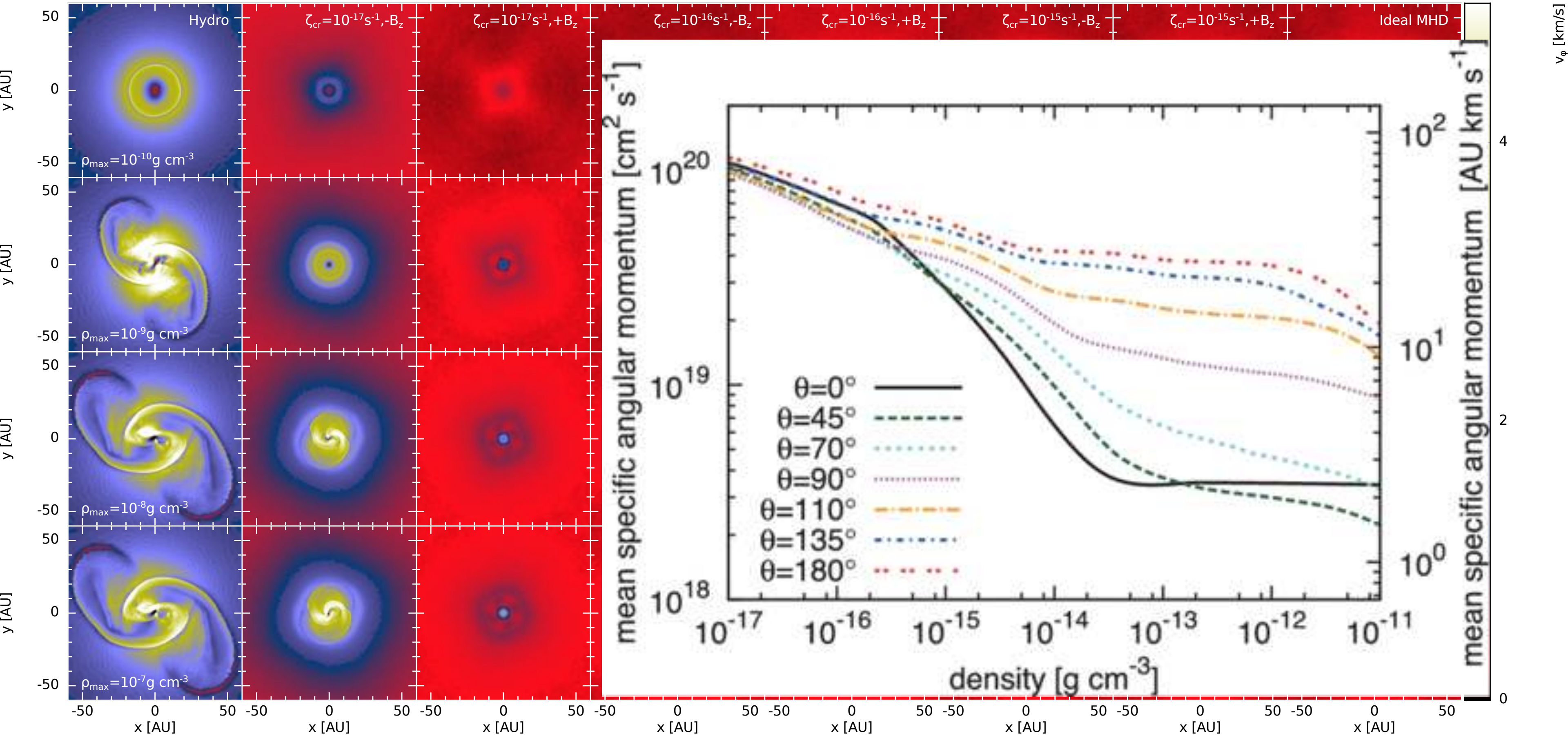


Wurster, Bate & Price (2018a,c) +

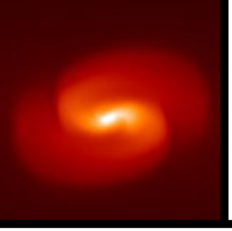


Rotationally supported discs

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

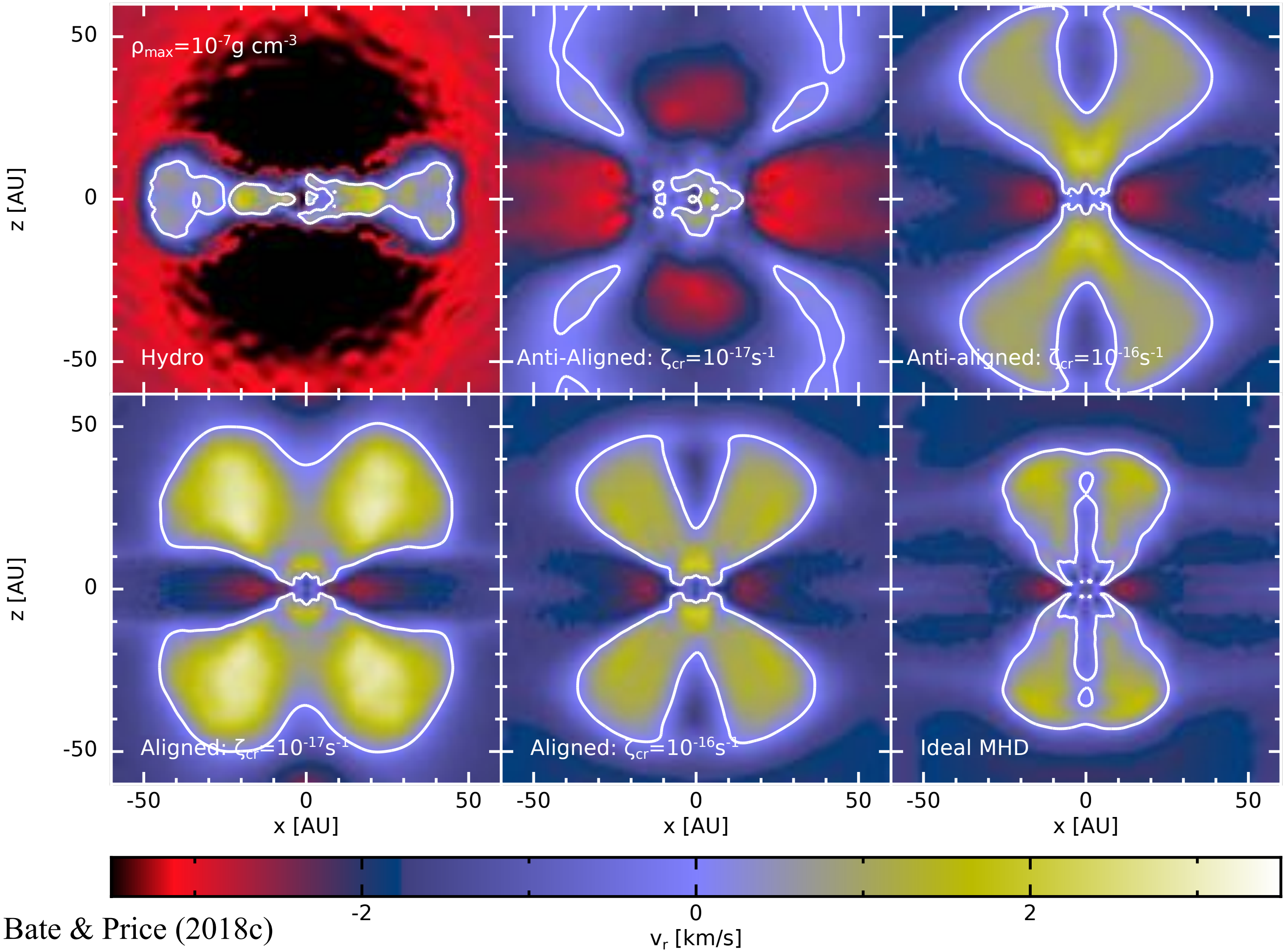


Wurster, Bate & Price (2018a,c) +; inset: Tsukamoto+ (2017)

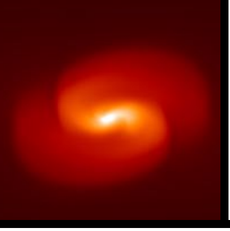


First core outflows

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

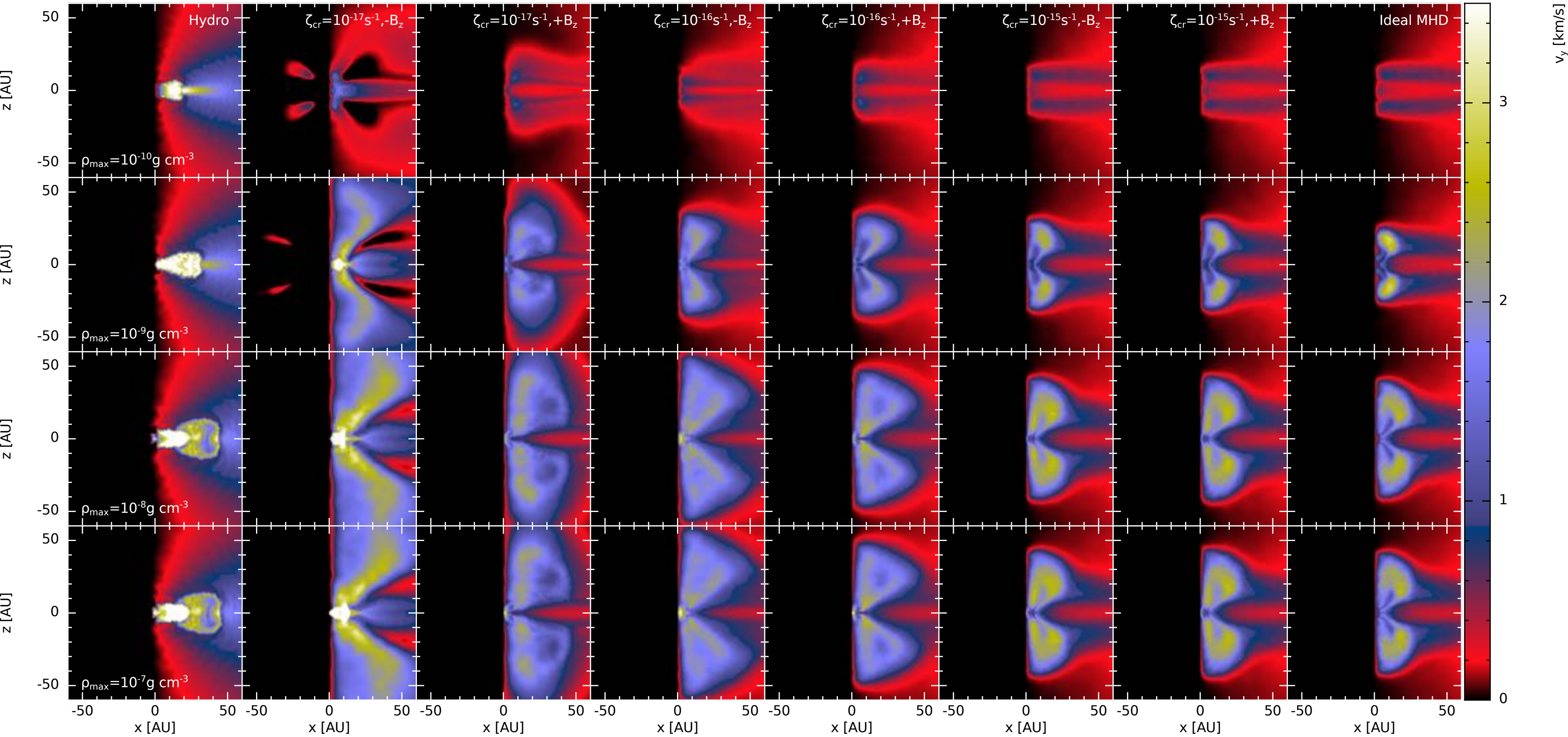


Wurster, Bate & Price (2018c)

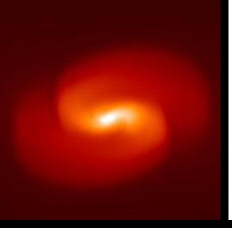


Large scale rotational velocity

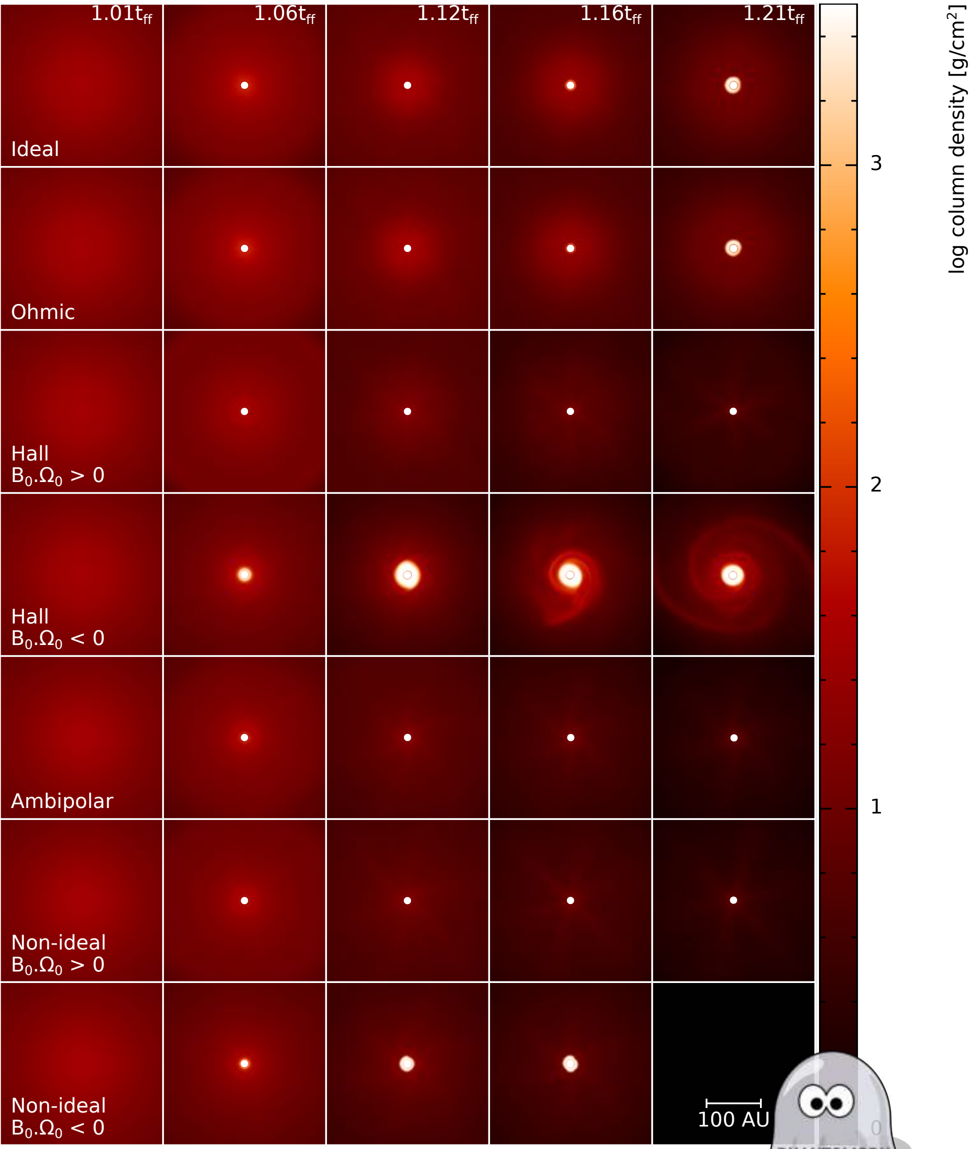
- Rotational speed increases as ionisation rate decreases
- Counter-rotating envelops are a transient feature in the model with $\boldsymbol{\zeta}_{cr} = 10^{-17}\ s^{-1}$ with $-B_z$



Wurster, Bate & Price (2018a,c) +
For counter-rotation, see also Krasnopolsky, Li &Shang (2011), Wurster, Price & Bate (2016), Tsukamoto et al. (2015,2017)



Non-Ideal MHD Components

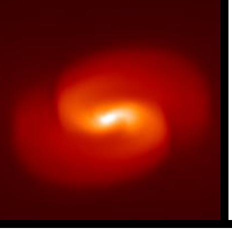


Wurster, Price & Bate (2016)

- 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

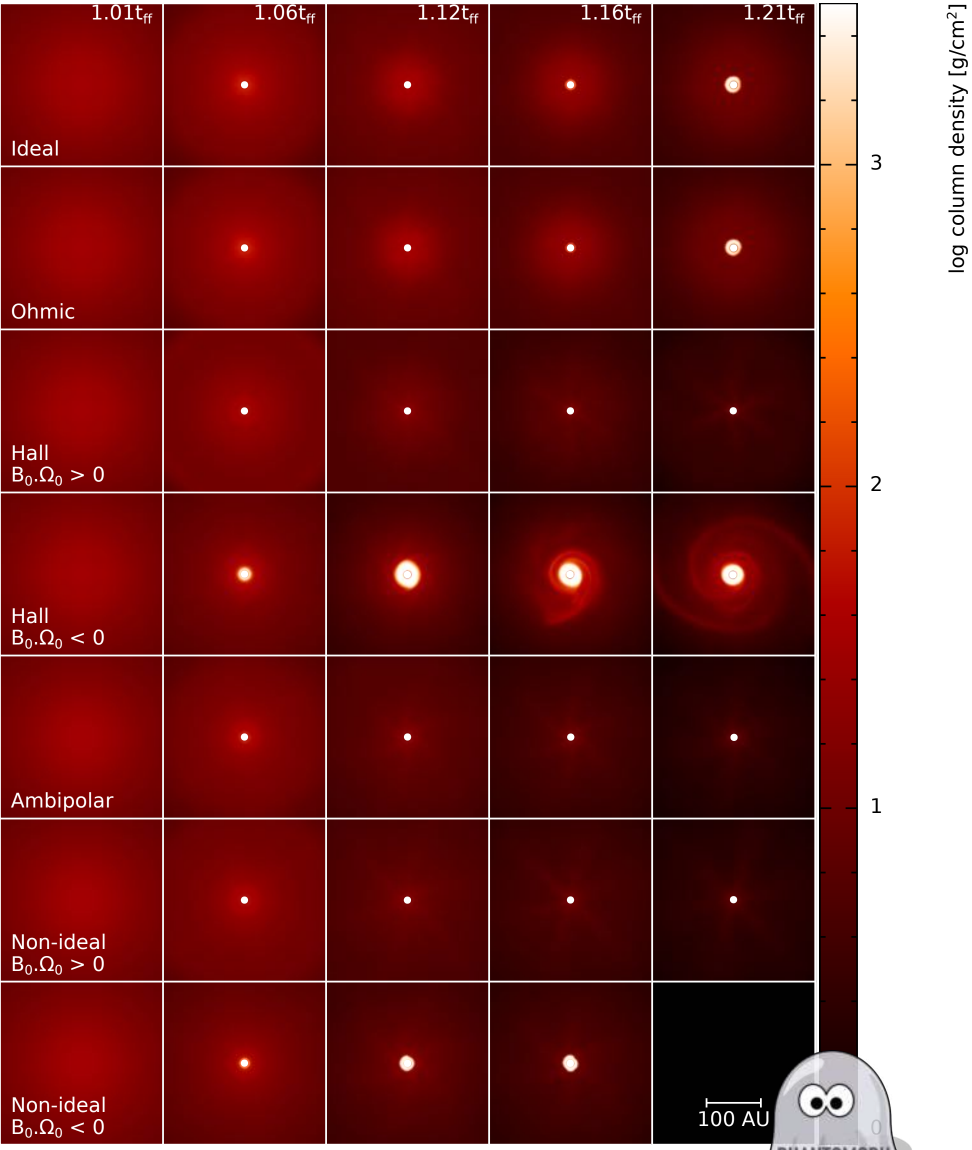
- Models to the left include a 6.7au sink particle

- Open question: *When do discs form?*

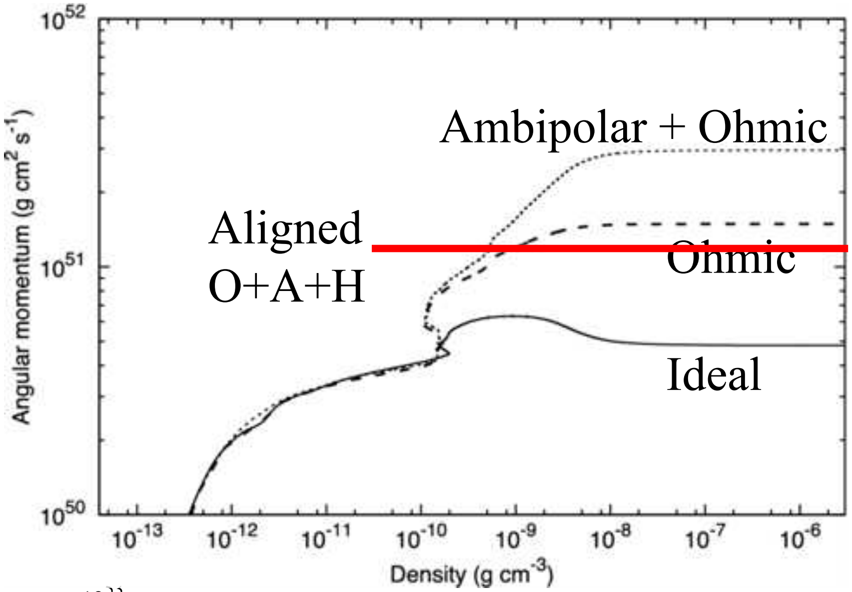


Non-Ideal MHD Components

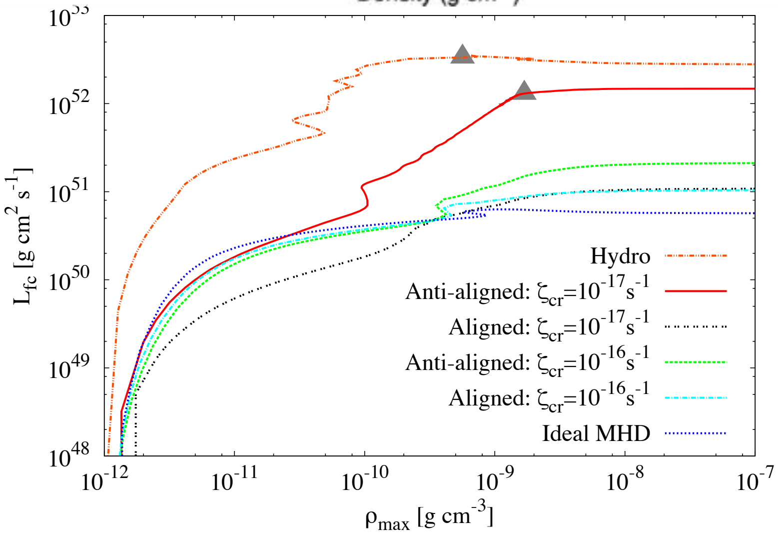
Anti-aligned O+A+H



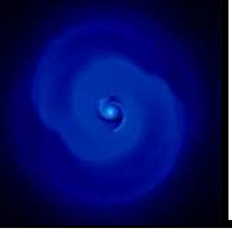
Wurster, Price & Bate (2016)



Aligned O+A+H

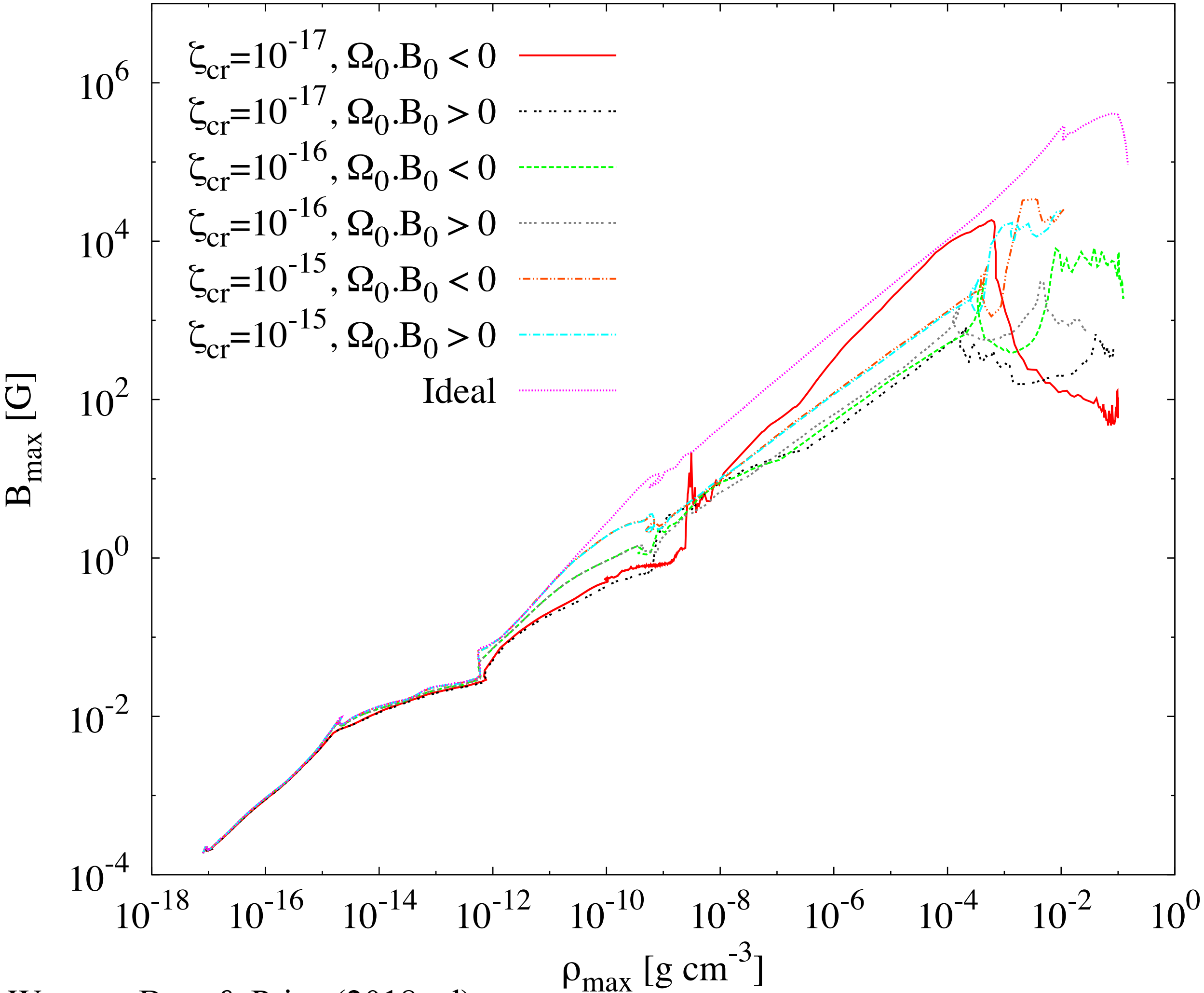


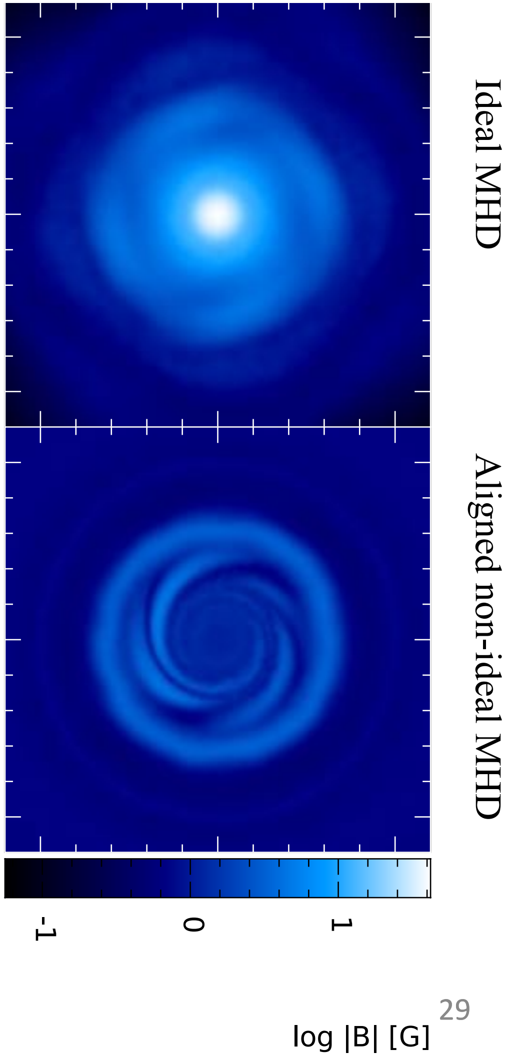
Top: Tsukamoto+ (2015b)
Bottom: Wurster, Bate & Price (2018c)



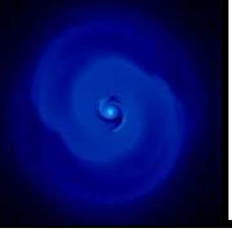
Magnetic field evolution

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



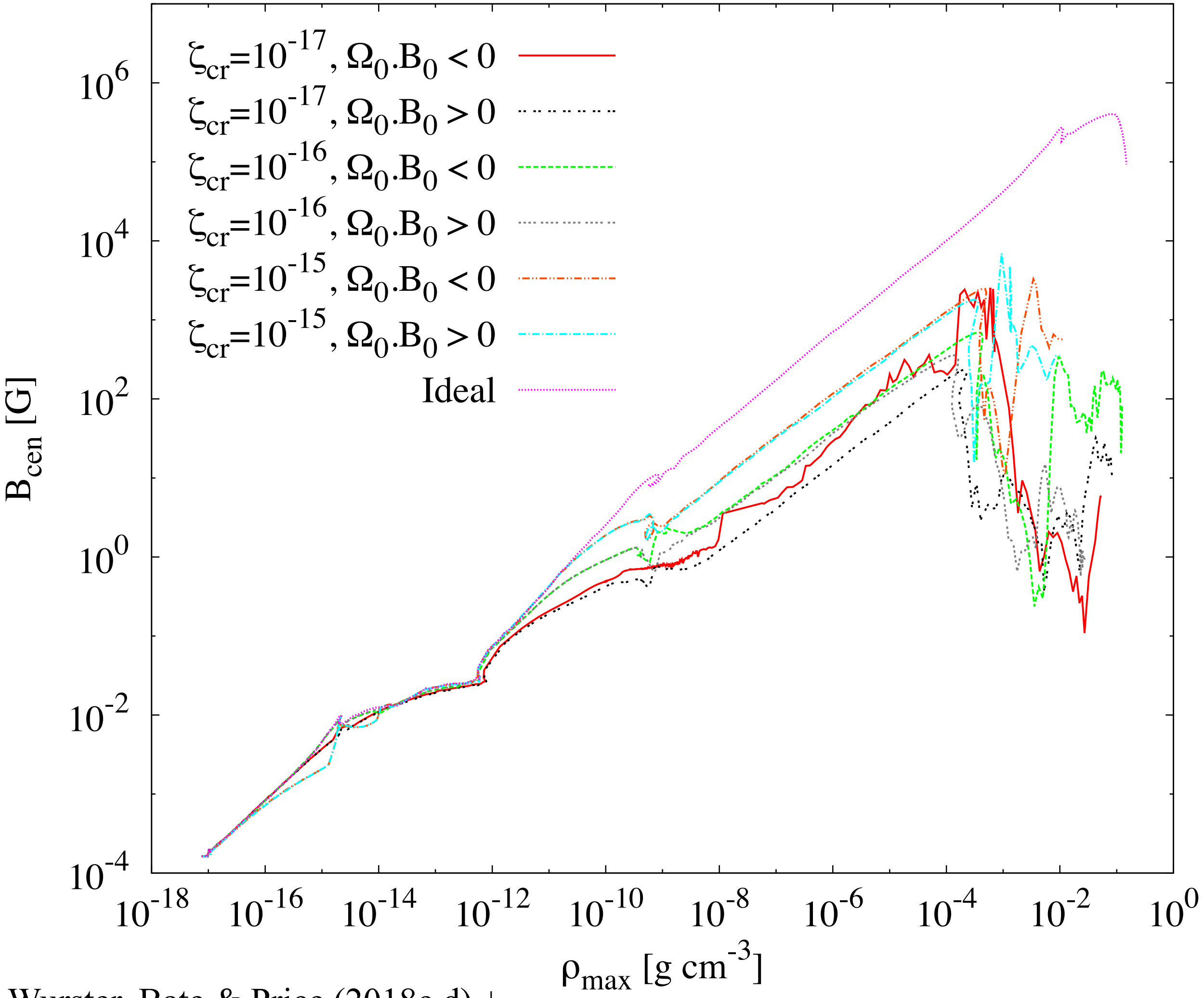


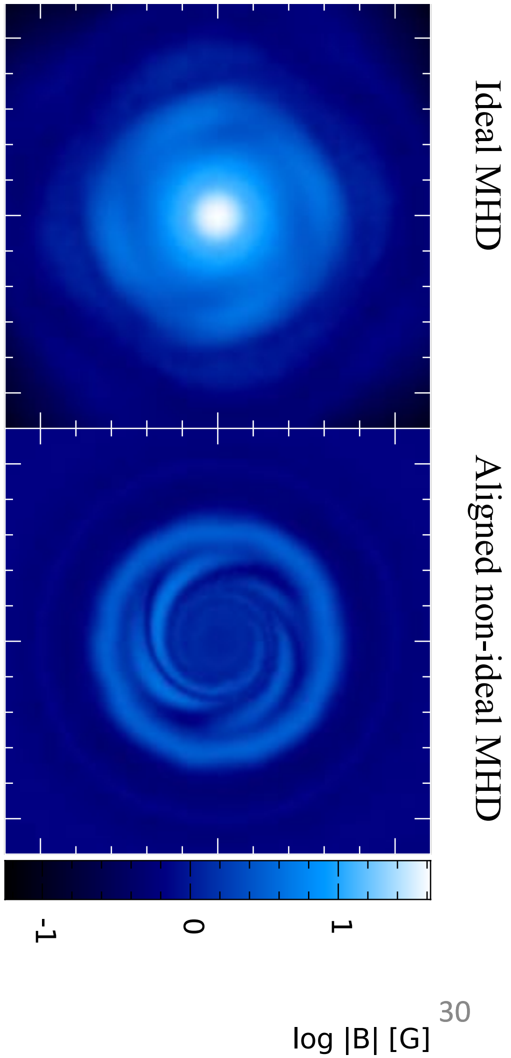
Wurster, Bate & Price (2018c,d) +



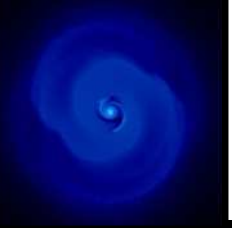
Magnetic field evolution

- ➢ The maximum magnetic field strength is not at the centre of the core in the non-ideal models
- ➢ Magnetic wall forms in non-ideal MHD models (Tassis &Mouschovias, 2005)



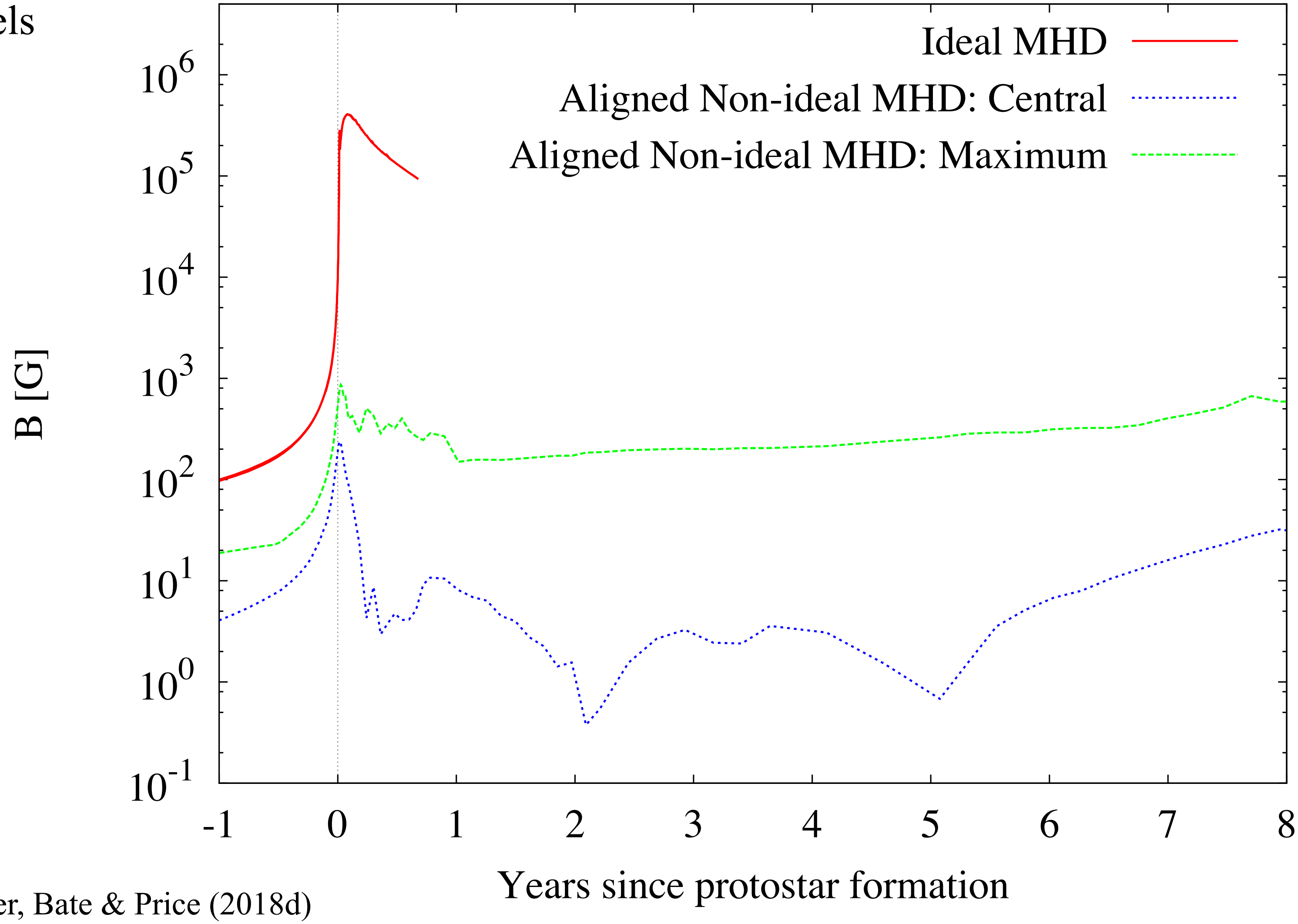


Wurster, Bate & Price (2018c,d) +



Magnetic field evolution

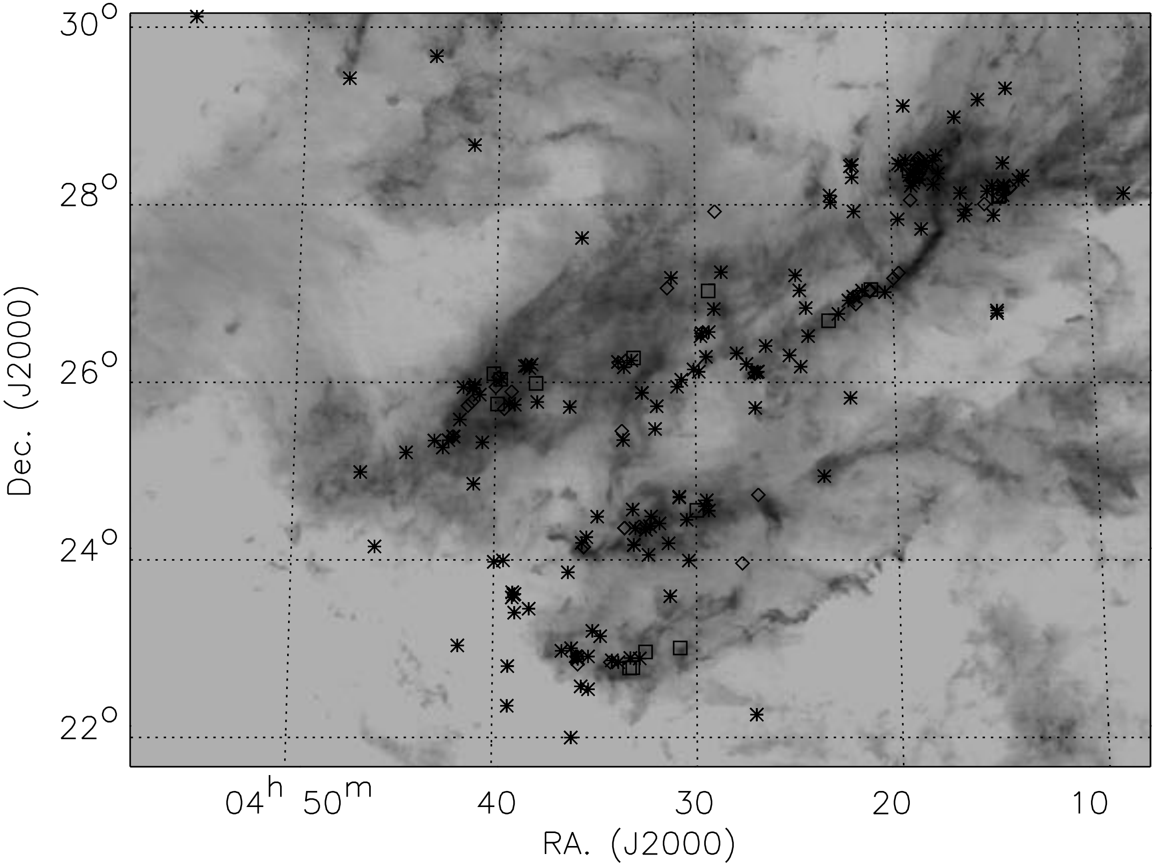
- Strong kG magnetic fields are observed in stars. Are they fossil, or dynamo-generated?
- Most likely dynamo-generated since the fossil magnetic field is << 1000G in the non-ideal models



Wurster, Bate & Price (2018d)

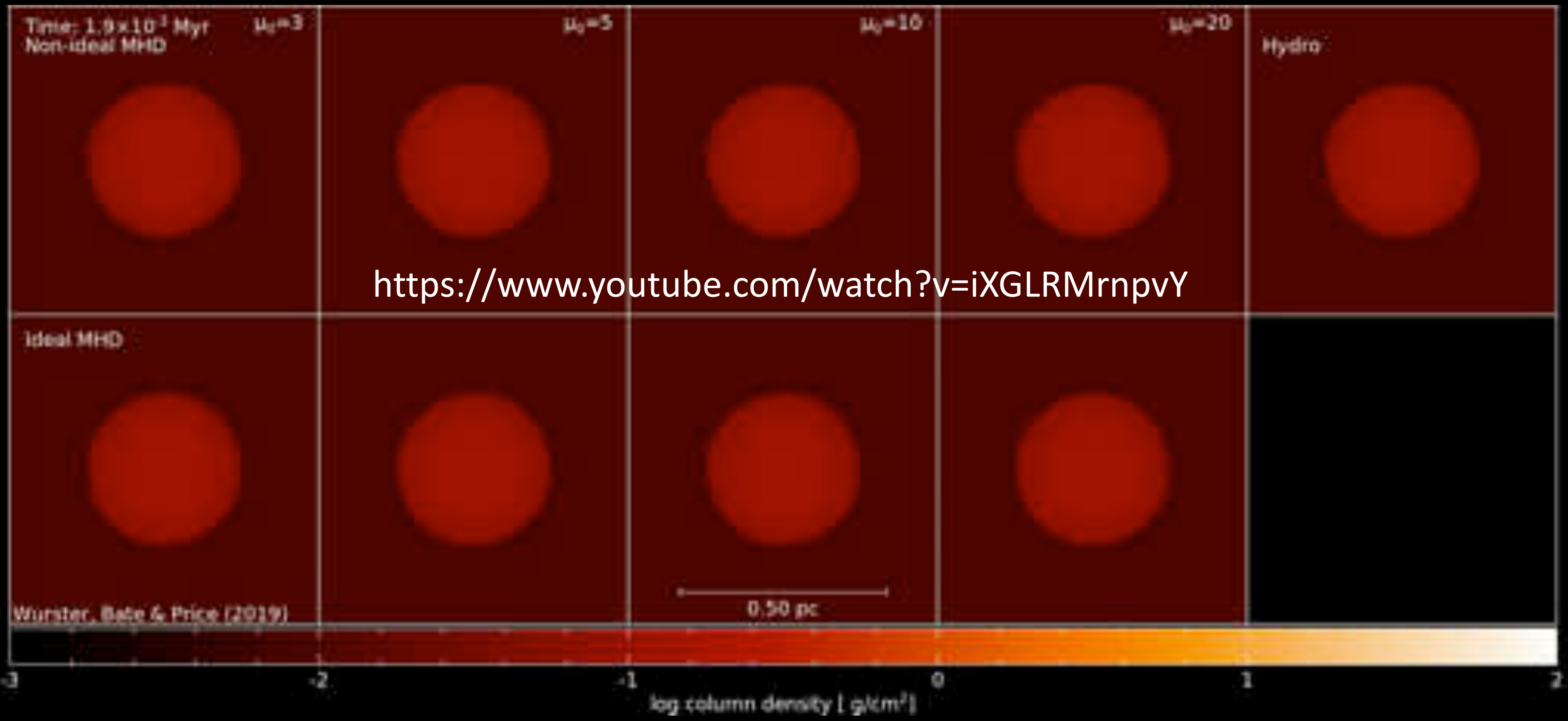
Importance of stars: Stellar nurseries

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



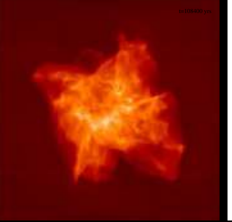
Taurus Molecular Cloud: H_2 column density map with positions of young stars (Goldsmith et. al., 2008)

Cluster Formation: Effect of Magnetic Fields

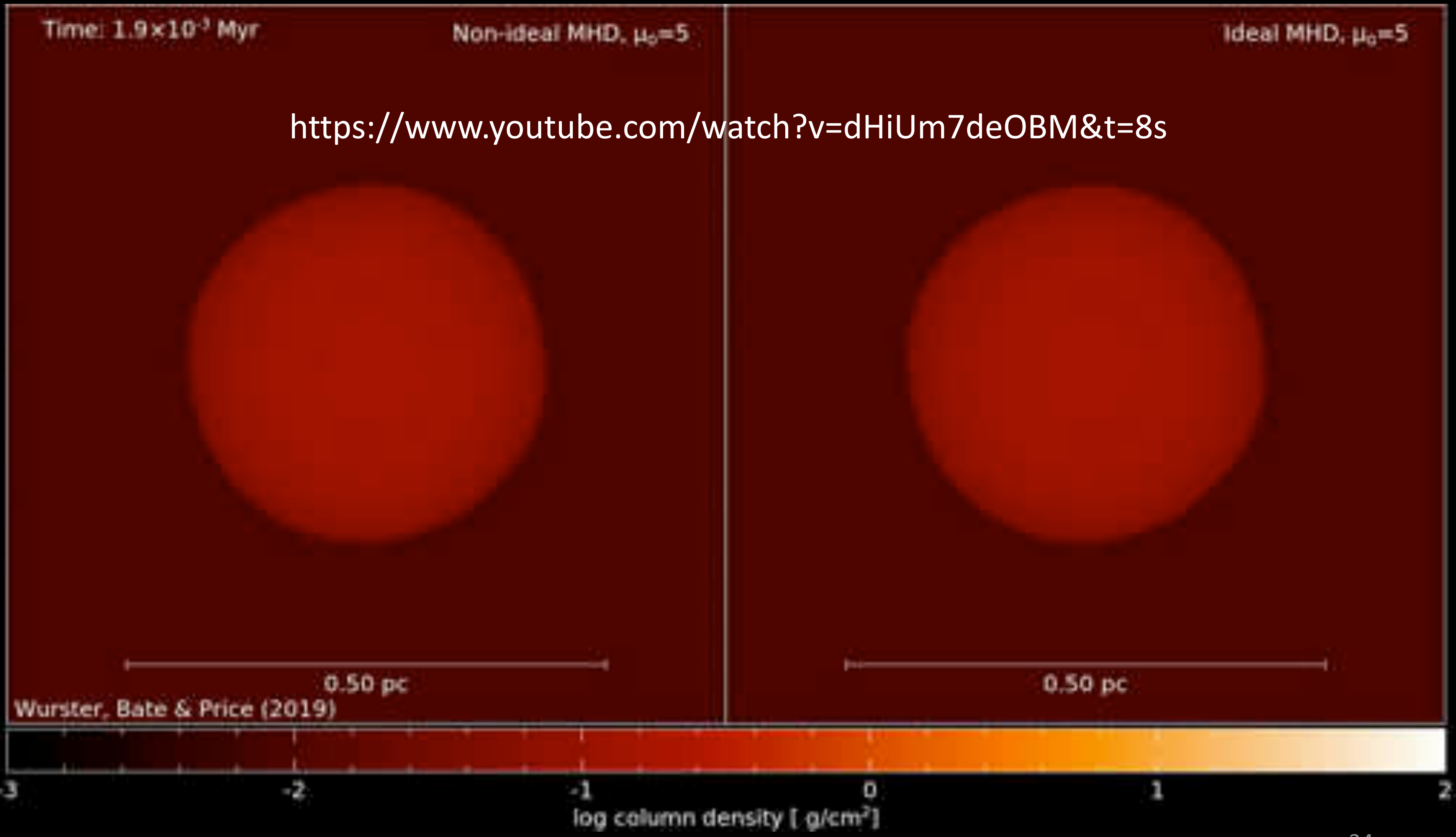


https://www.youtube.com/watch?v=iXGLRMrnpvY

Wurster, Bate & Price (submitted)

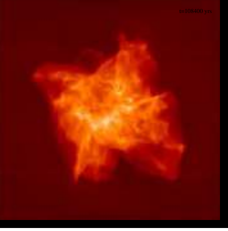


Cluster Formation: Effect of non-ideal MHD



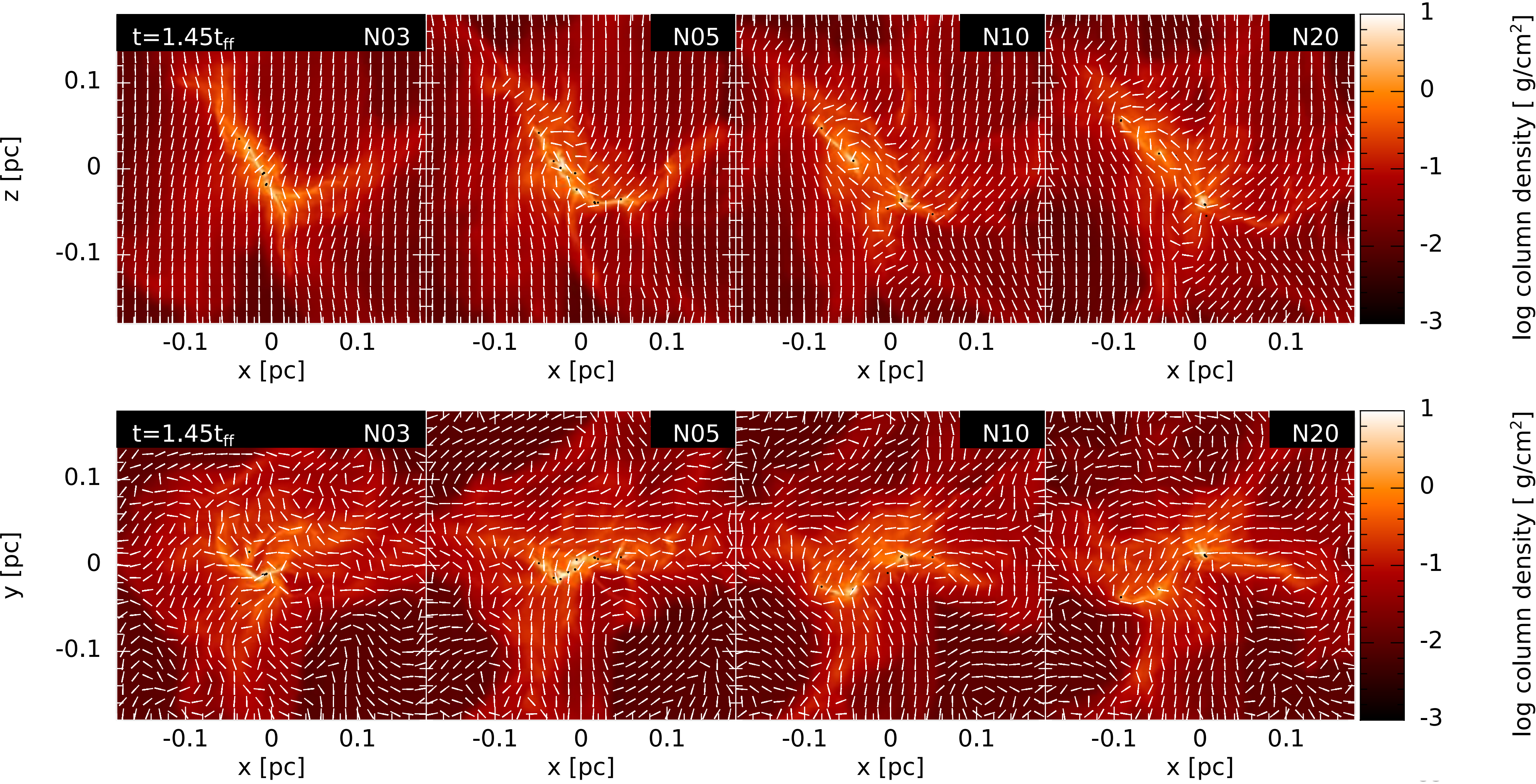
https://www.youtube.com/watch?v=dHiUm7deOBM&t=8s

Wurster, Bate & Price (submitted)



Cluster Formation: Magnetic field lines

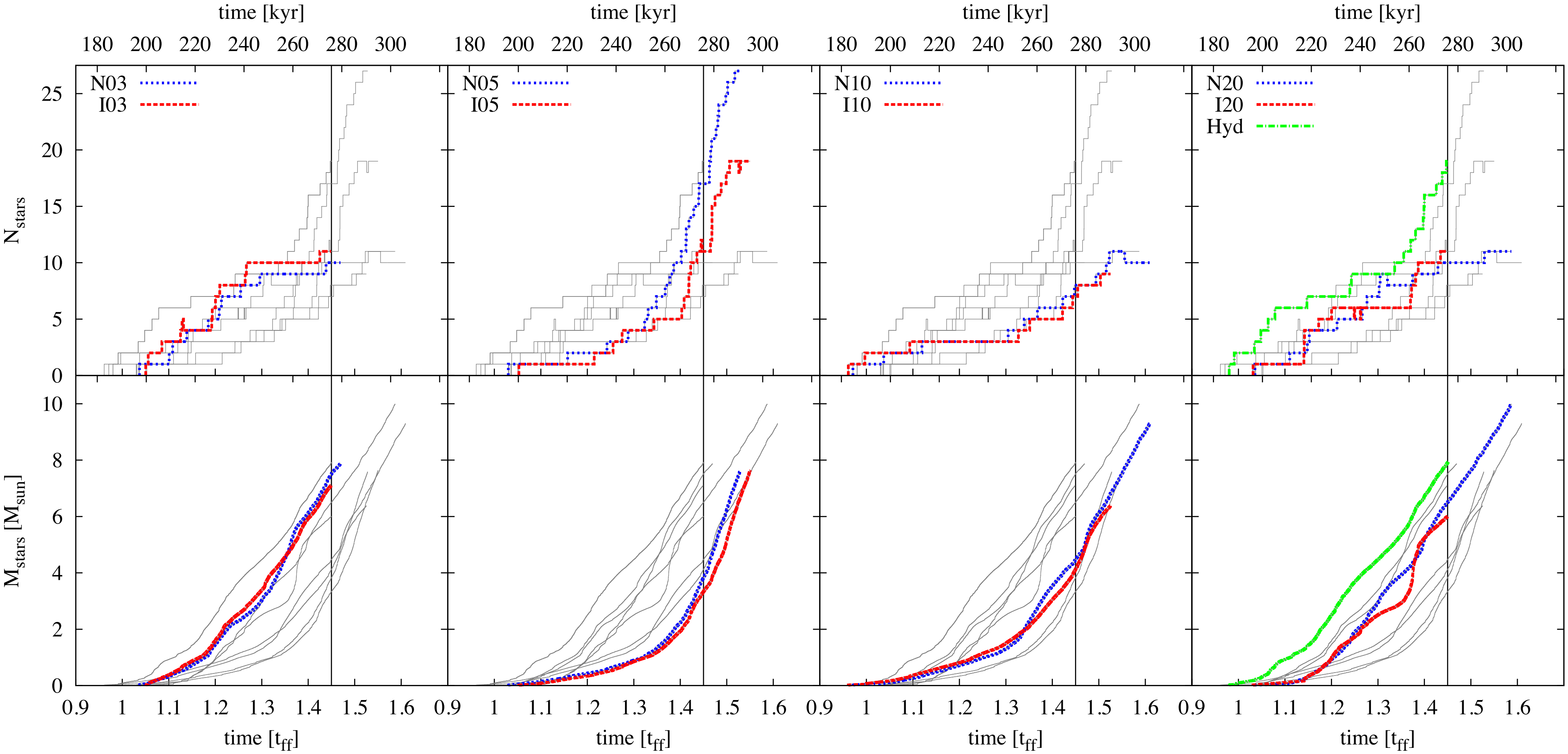
- Magnetic fields cross dense filaments approximately perpendicularly
- Magnetic fields are approximately parallel to low-density filaments



Wurster, Bate & Price (submitted)

Cluster Formation: Stellar Mass

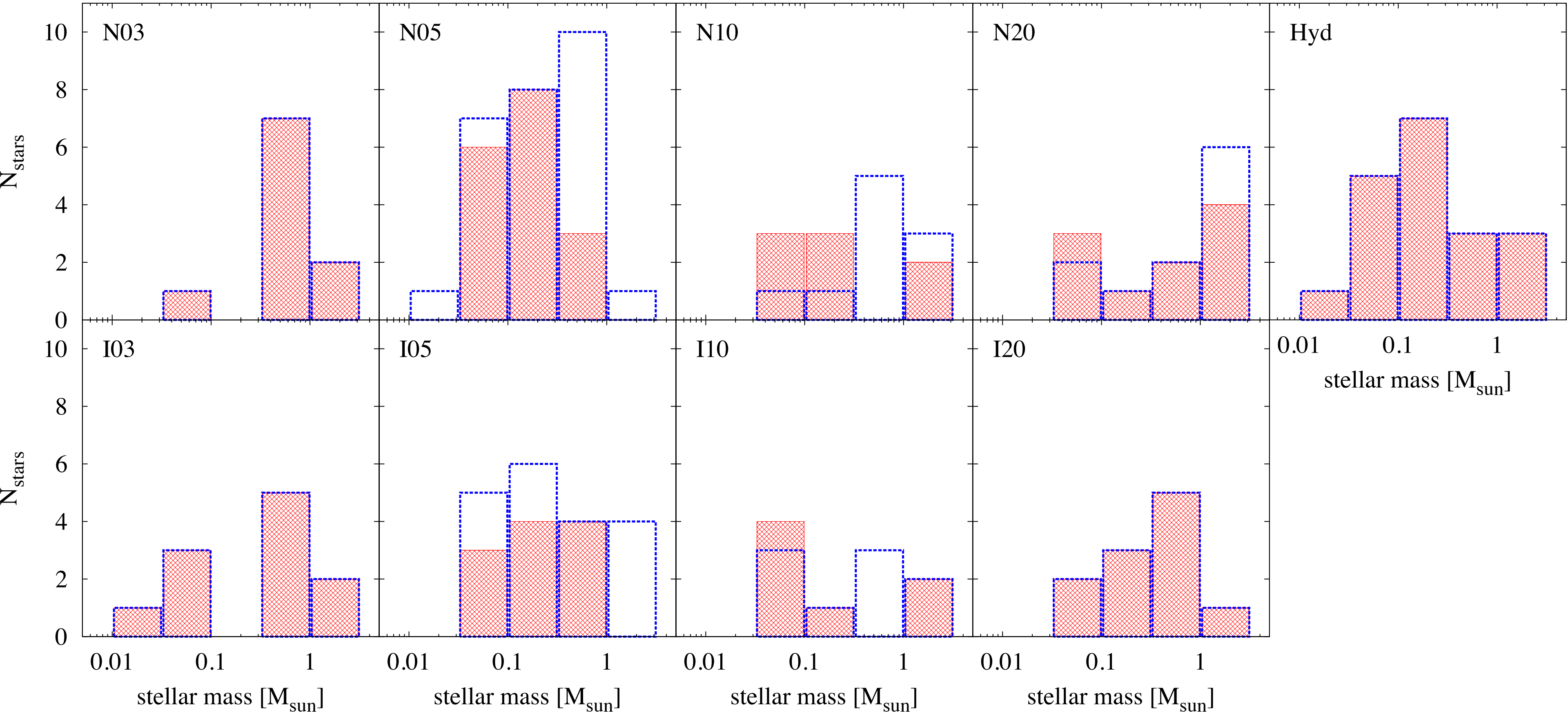
- ➢No trend when stars form
- ➢Excluding N03 & I03, there is more mass in stars with weaker initial magnetic field strengths



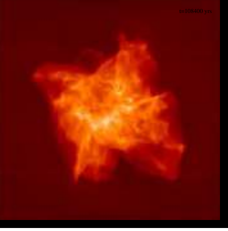
Wurster, Bate & Price (submitted)

Cluster Formation: Stellar Mass

- No trend in IMF (although this is low-number statistics)
- red is at common time of $1.45t_{ff}$; blue is at end of the respective simulations

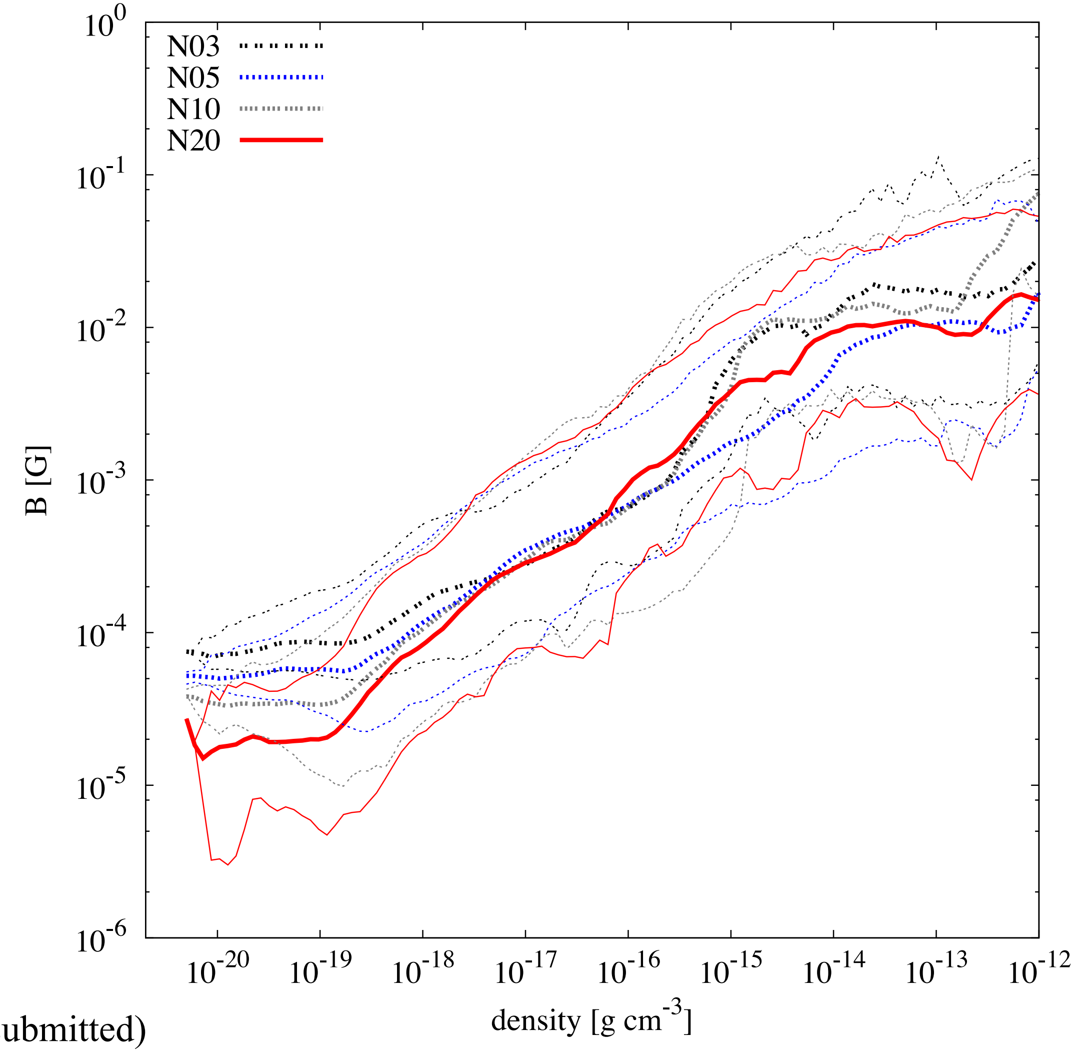


Wurster, Bate & Price (submitted)

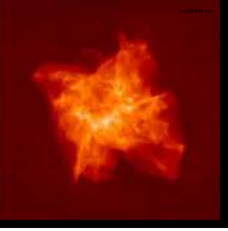


Cluster Formation: Star forming regions

➢Star forming regions have a wide range of initial magnetic field strengths, that are approximately independent of the global environment

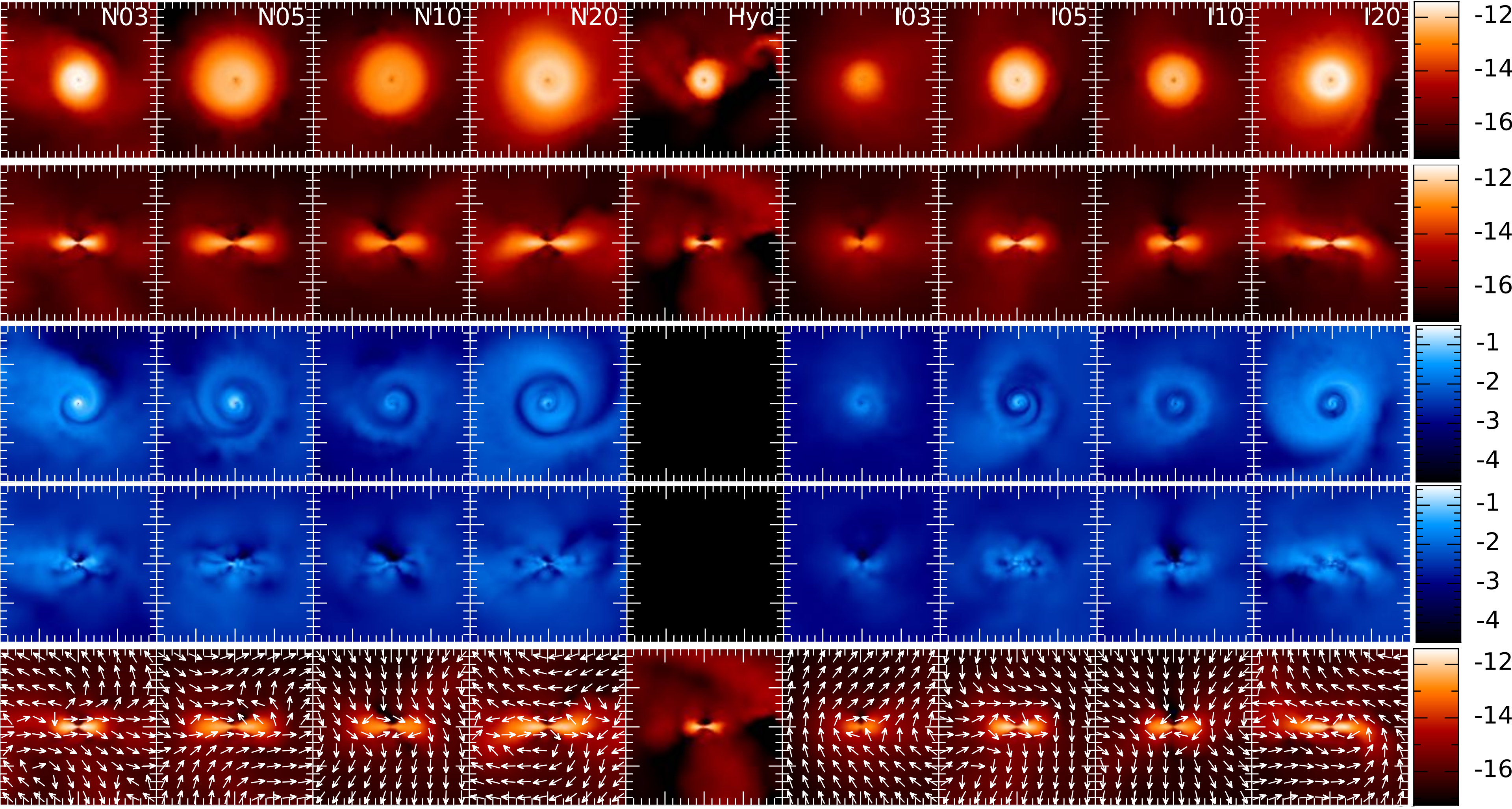


Wurster, Bate & Price (submitted)



Cluster Formation: Protostellar discs

- Large protostellar discs form in *all* our models
- Major tics are 103au



Wurster, Bate & Price (submitted)

Conclusions

- Isolated, low-mass star formation:
  - Large discs only form in the hydrodynamic and $\zeta_{cr} = 10^{-17}$ s^{-1} with -B_z models.
    - *this resolved the magnetic braking catastrophe*
  - 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

- Star cluster formation:
  - No trends amongst most of our parameters
  - Discs form in all of our models, *suggesting that the magnetic braking catastrophe is a result of poor initial conditions*

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