The early stages of low-mass star formation: Formation and evolution of the protostar and its disc

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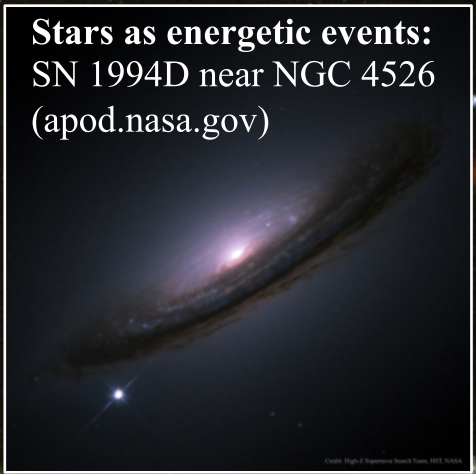
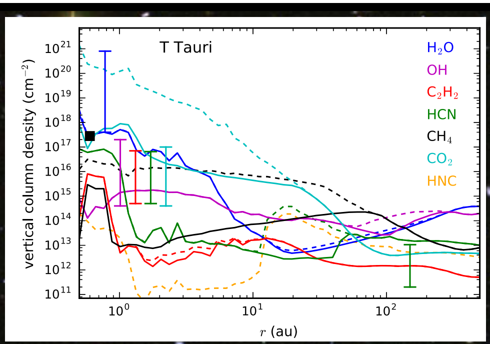
Importance of stars: The big picture

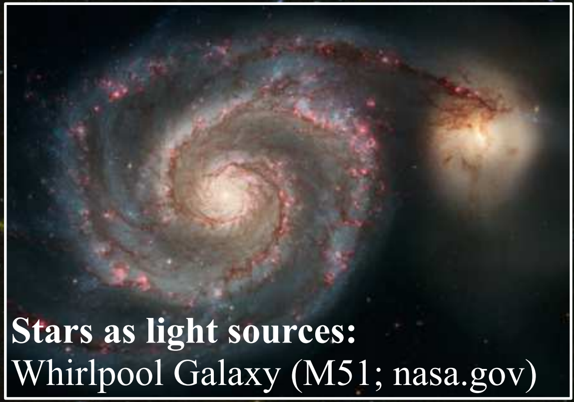


Stars as energetic events: SN 1994D near NGC 4526 (apod.nasa.gov)

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

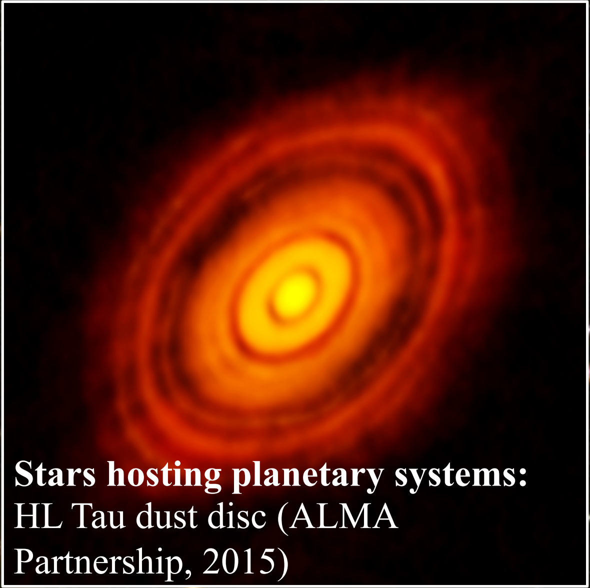


Chemical Evolution (Agundez + 2018)

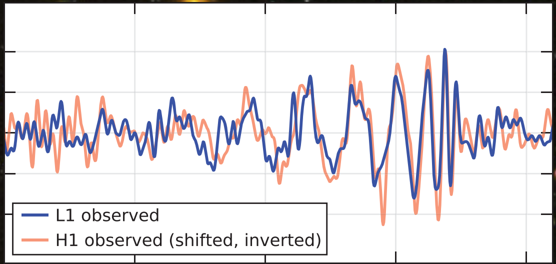


Stars as light sources: Whirlpool Galaxy (M51; nasa.gov)

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



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



Form black holes that can merge (Abbott + 2016)

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

Importance of stars: Masses

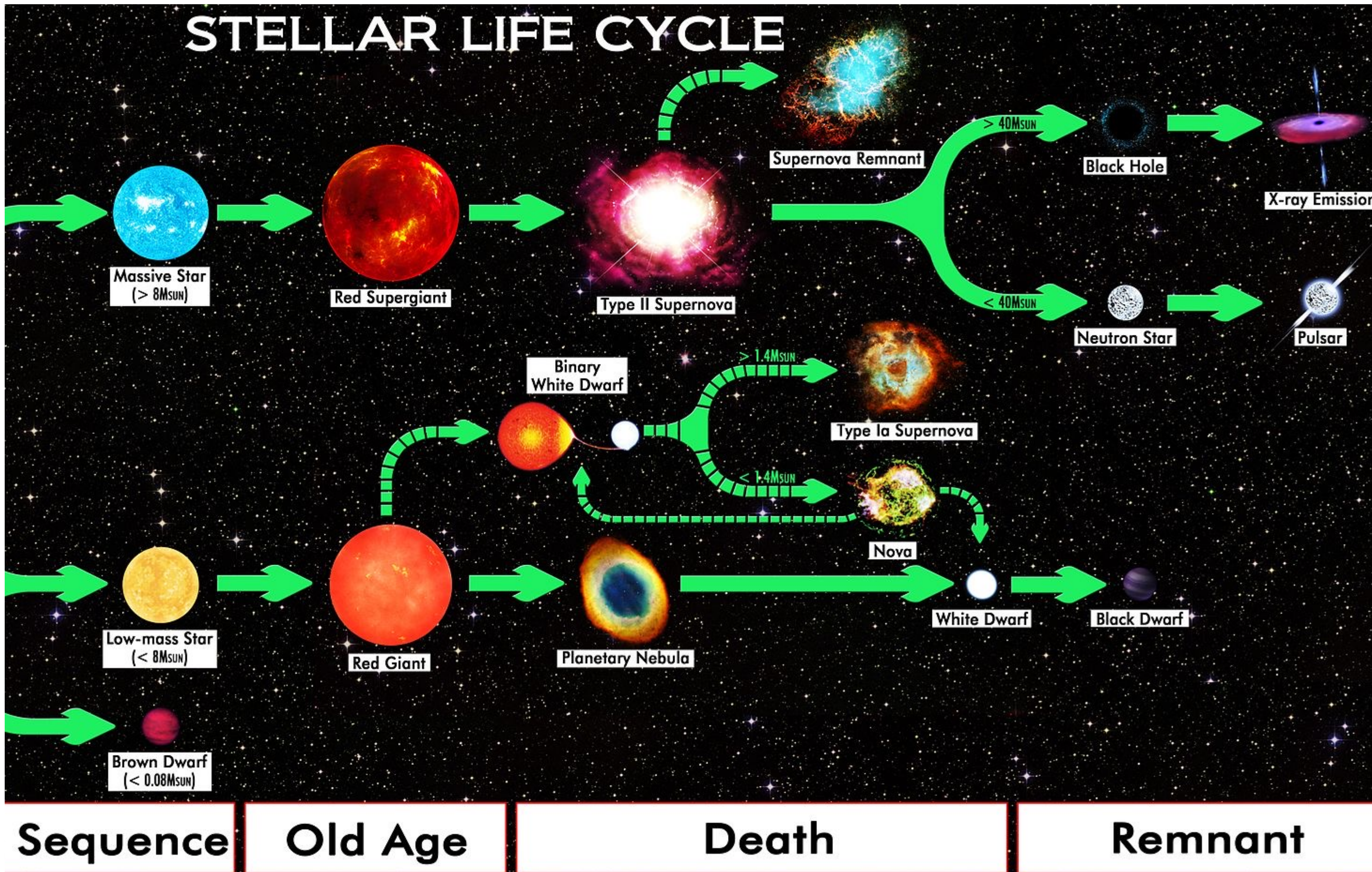
➢ Main classes of stellar masses

❖ Massive stars ($8M_{sun} < M$)

❖ Low-mass stars ($0.08M_{sun} < M < 8M_{sun}$)

❖ Brown Dwarfs ($M < 0.08M_{sun}$)

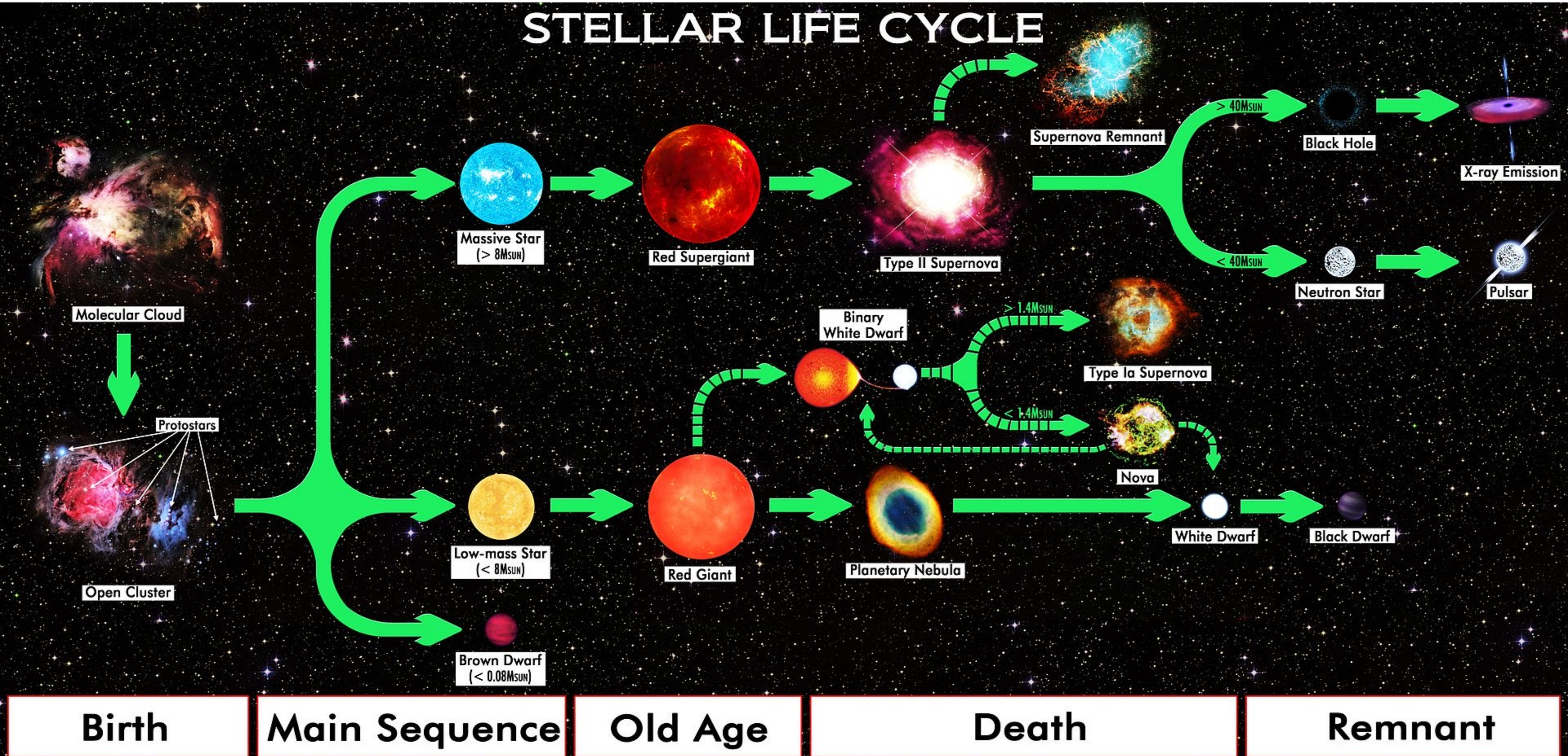
Importance of stars: Masses



Main

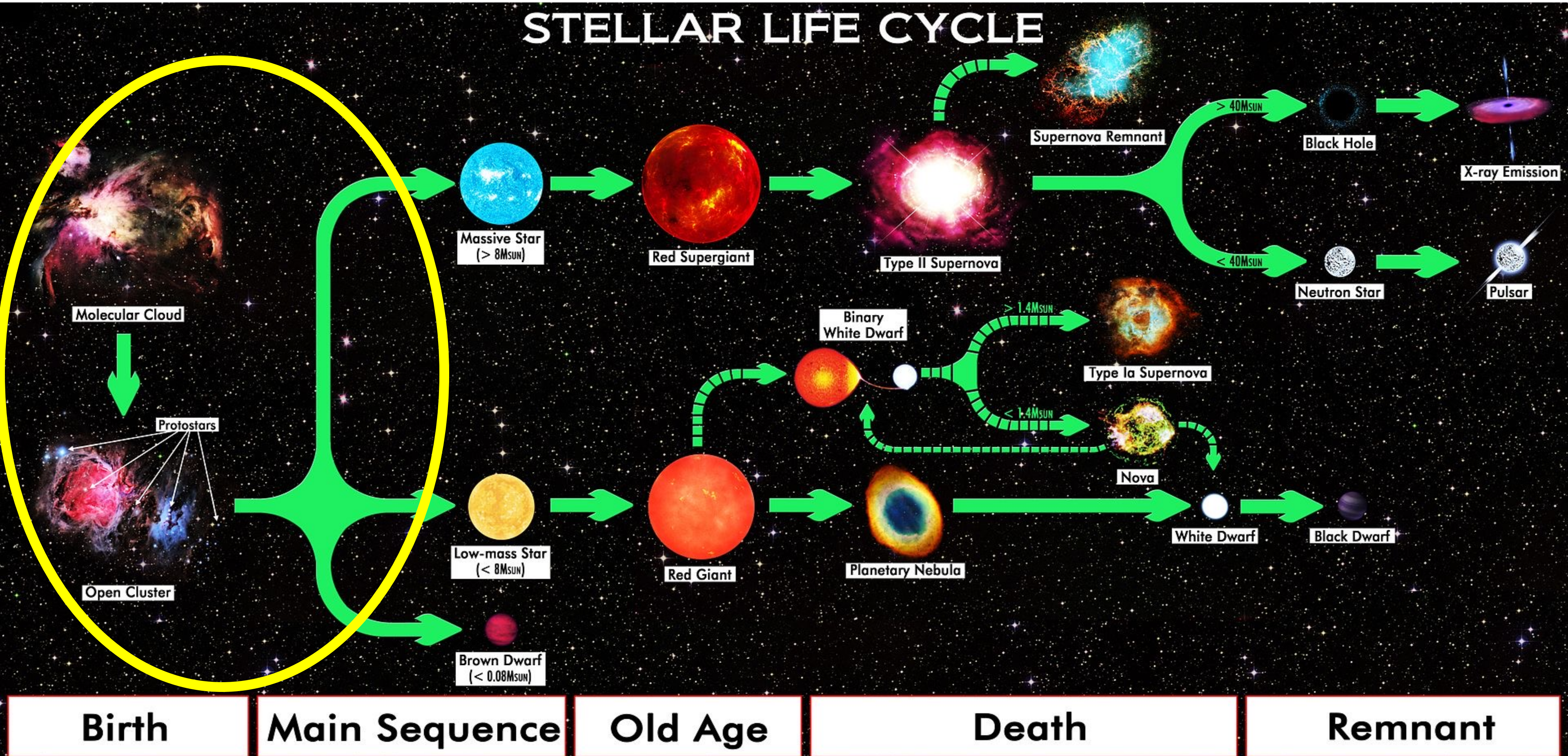
- ➢ Evolutionary path is determined by its mass

Importance of stars: Masses



- Evolutionary path is determined by its *birth* mass

Importance of stars: Masses

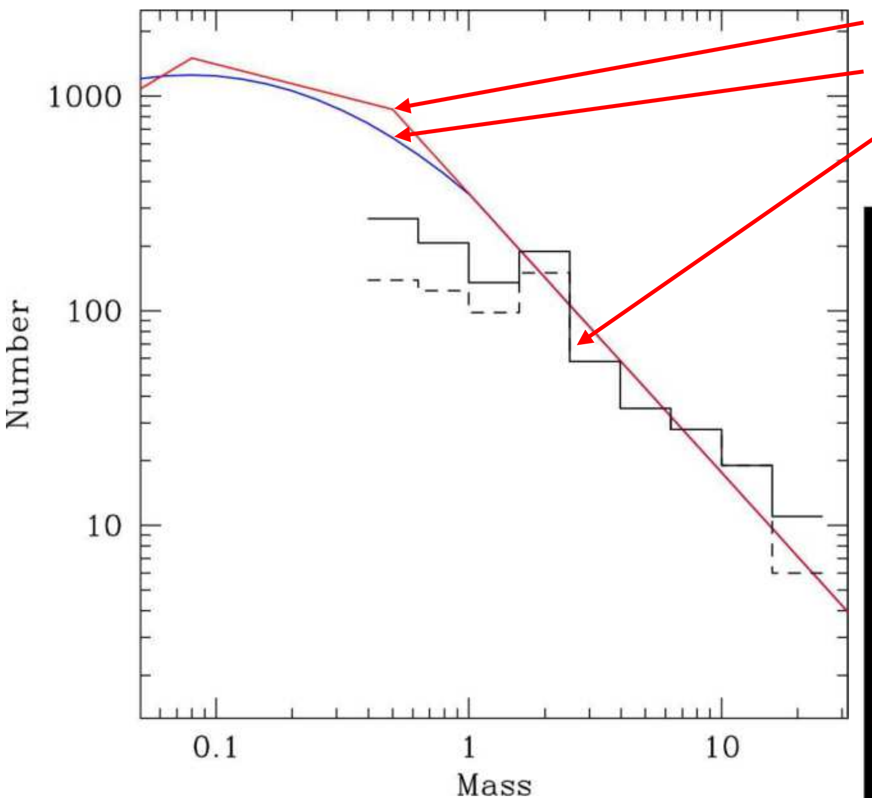


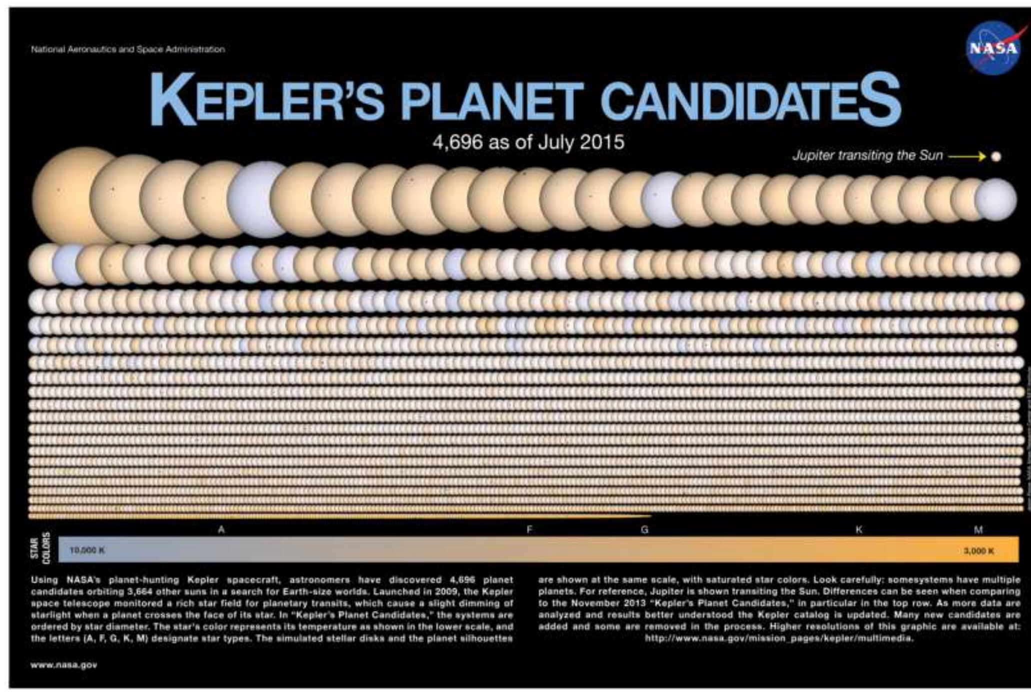
- Evolutionary path is determined by its *birth* mass

Image: R.N. Bailey (Own work, CC BY 4.0, https://commons.wikimedia.org/w/index.php?curid=59672008)

Importance of stars: Masses

- Initial mass function (IMF) of NCG 3603

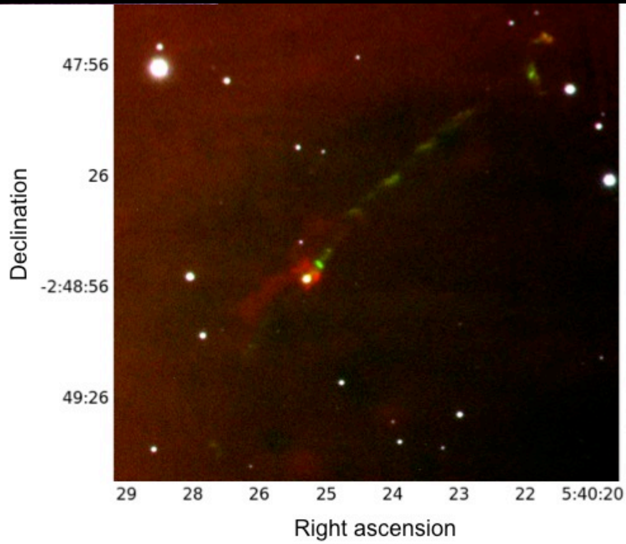


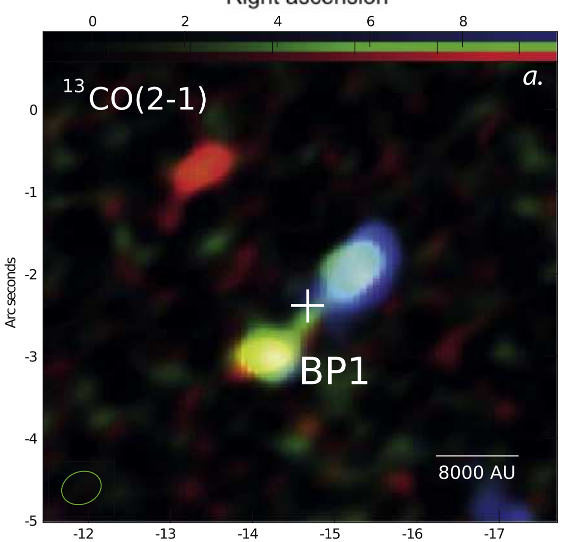


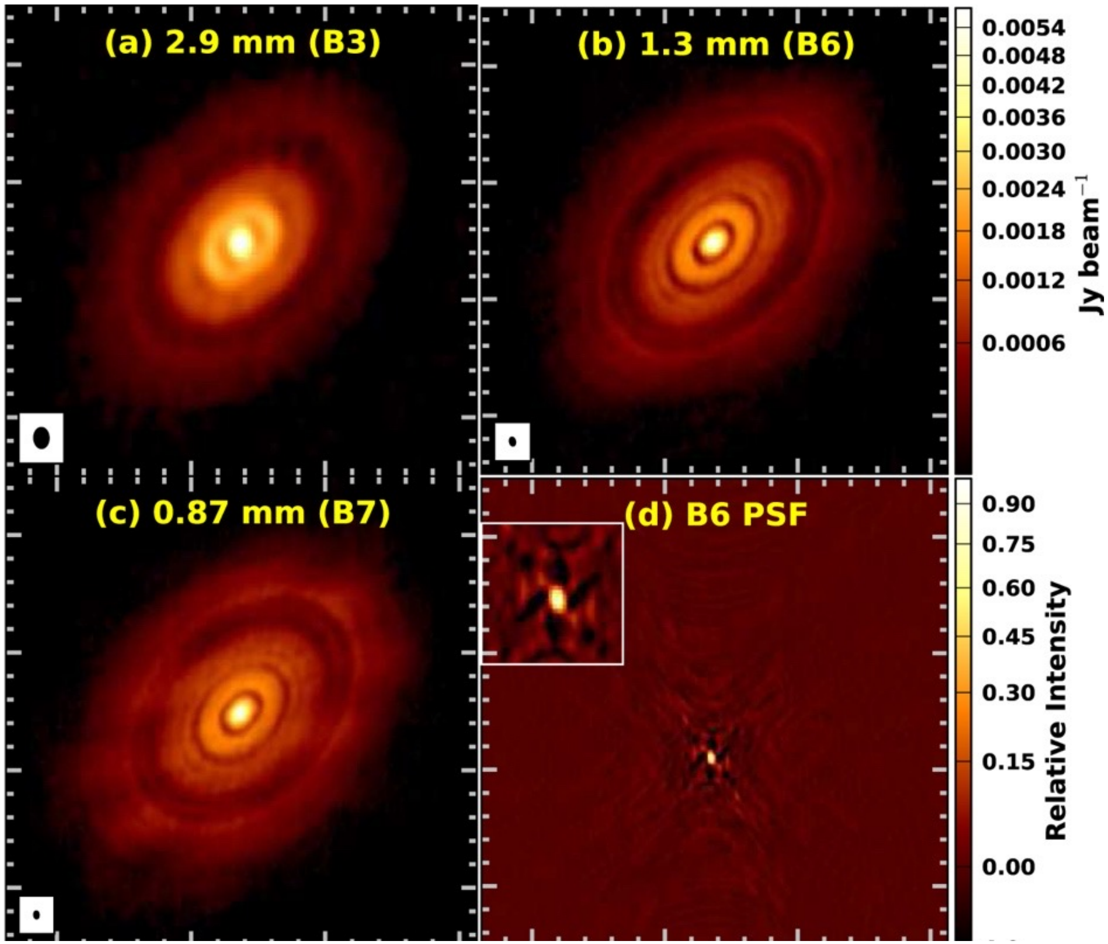
- Low mass stars are much more plentiful than high-mass stars

Left: Bonnell, Larson, Zinnecker (2007)

Importance of Low-stars: Outflows & Discs







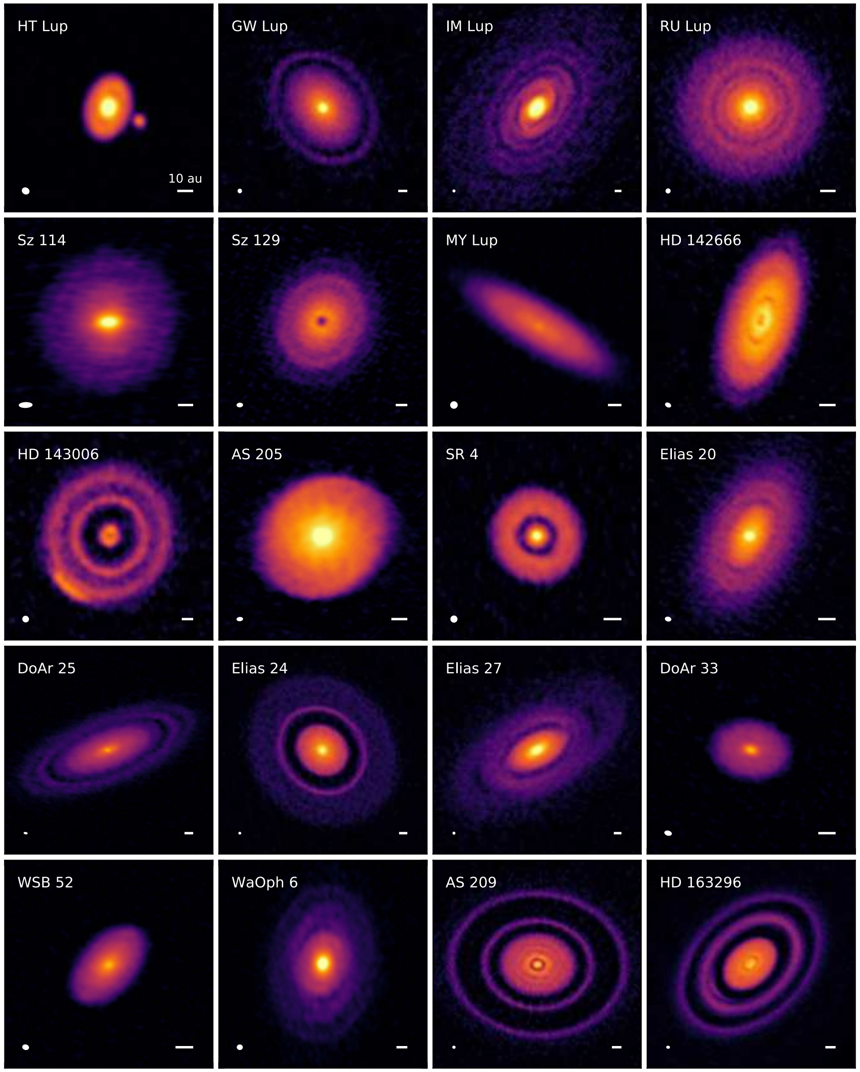
Top left: Large scale Herbig-Haro jet driven by a proto-brown dwarf (Riaz et. al., 2017)

Bottom left: CO outflows from low-mass stars with 1pc of Sgr A* (Yusef-Zadeh et. al., 2017)

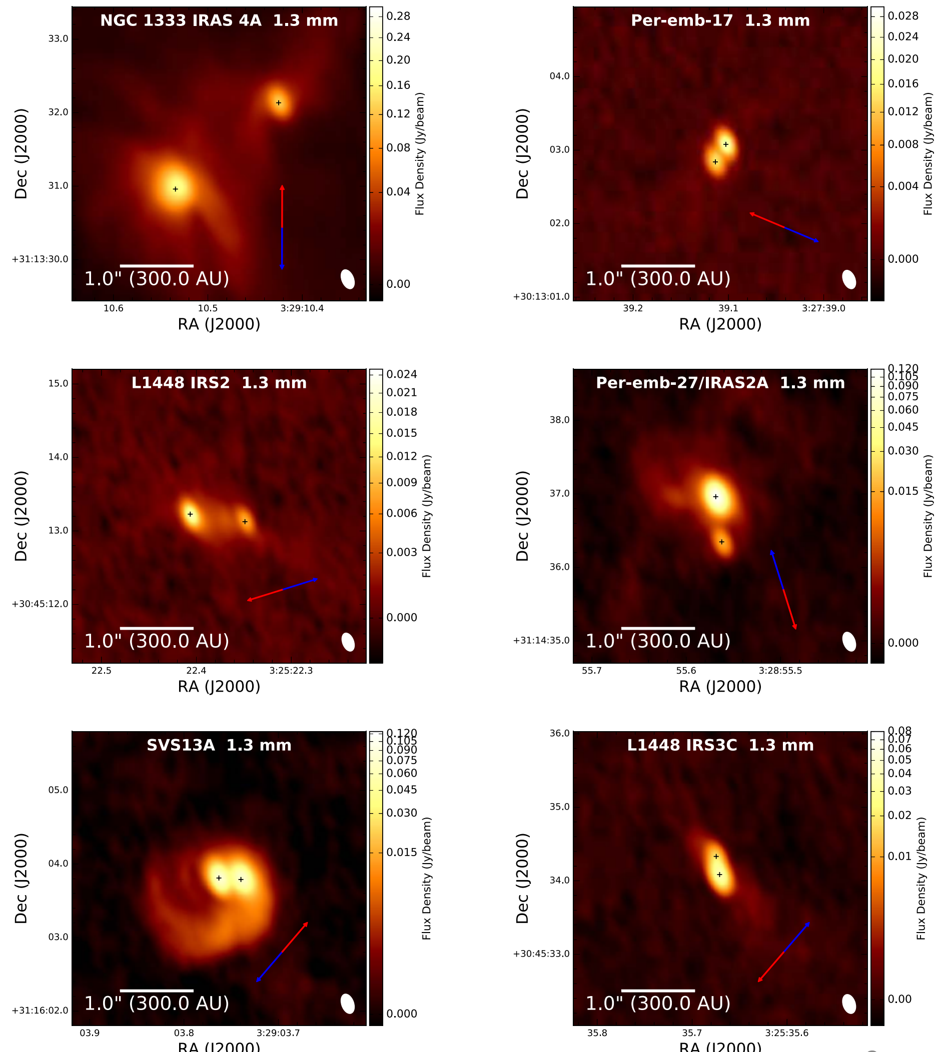
Right: HL Tau dust disc (ALMA Partnership, 2015)

Importance of Low-stars: Discs

- Considerable observational focus on discs

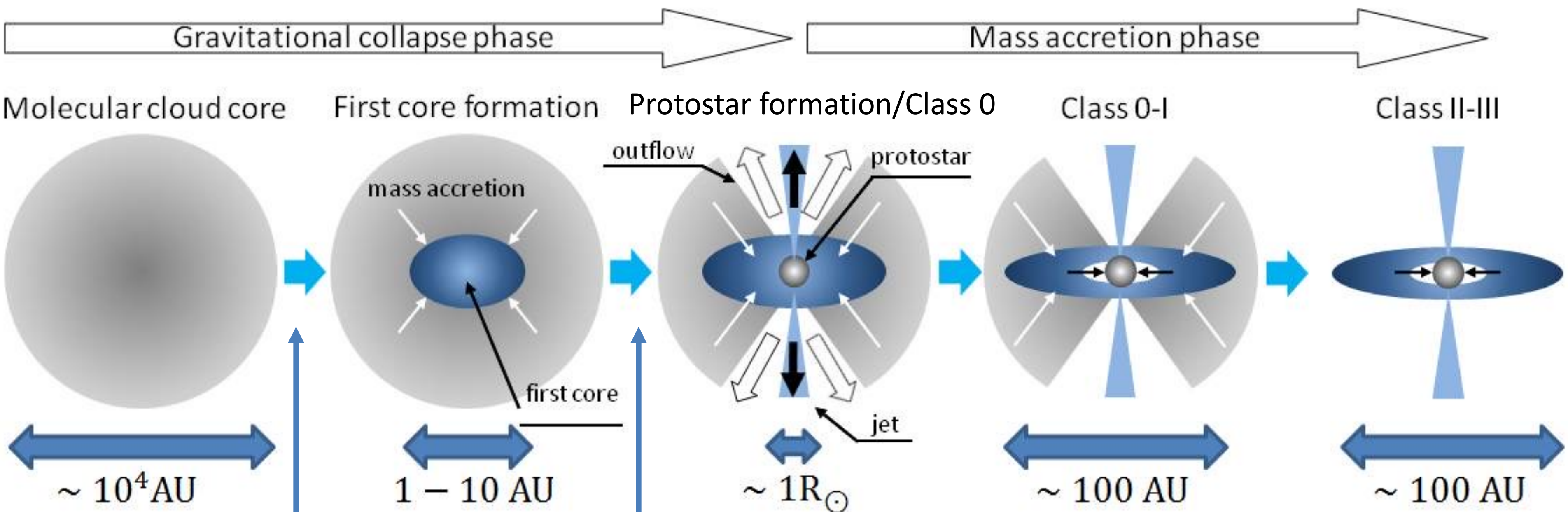


DSHARP sample (Andrews+2018)



Discs in Perseus (Tobin+2018)

Star formation: From the beginning



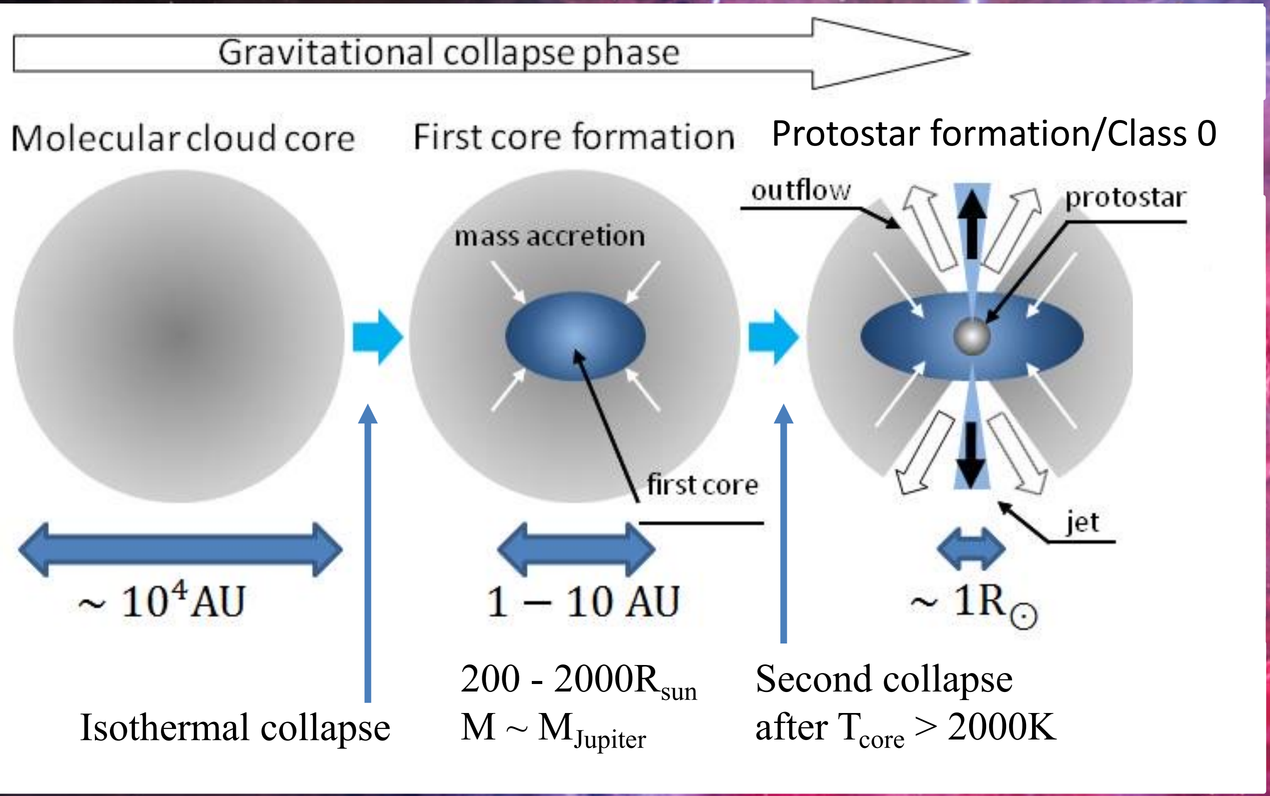
Isothermal collapse

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

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

Larson (1969); Illustration by Y. Tsukamoto
Background: Orion Molecular Cloud. (image credit: Drudis & Goldman via APOD)

Star formation: From the beginning

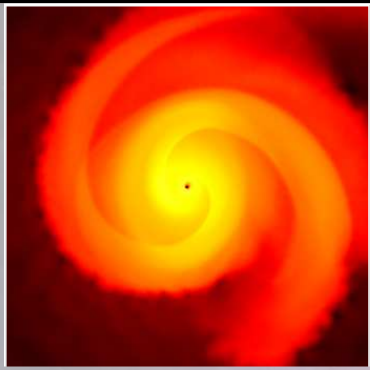


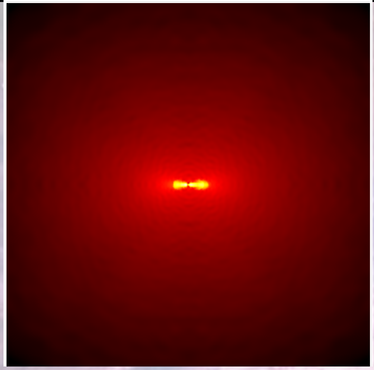
- Relevant processes:
  - Gas
  - Dust
  - Radiation
  - Magnetic fields
  - Kinematics: Rotation
  - Kinematics: Turbulence
  - Etc…

- Disc formation is a natural consequence of star formation

Larson (1969); Illustration by Y. Tsukamoto
Background: Orion Molecular Cloud. (image credit: Drudis & Goldman via APOD)

Star formation: Numerical results: Challenges

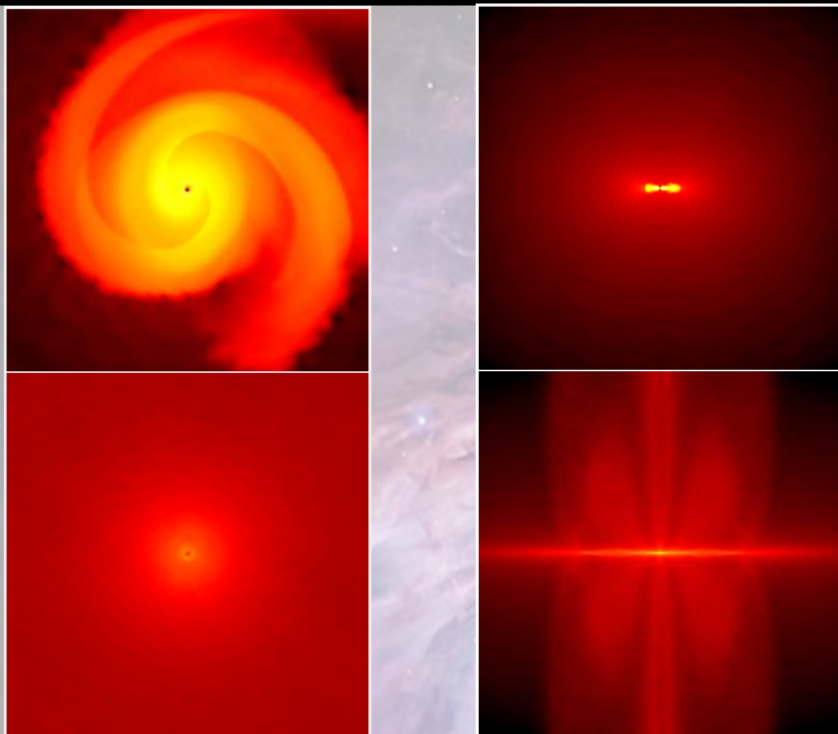




- Hydro + radiation
  - Large disc & no outflows
  - Not realistic since no magnetic fields

Foreground: Wurster & Lewis (2020a); see also Wurster+ (2016, 2018c)
Background: Orion Molecular Cloud. (image credit: Drudis & Goldman via APOD)

Star formation: Numerical results: Challenges

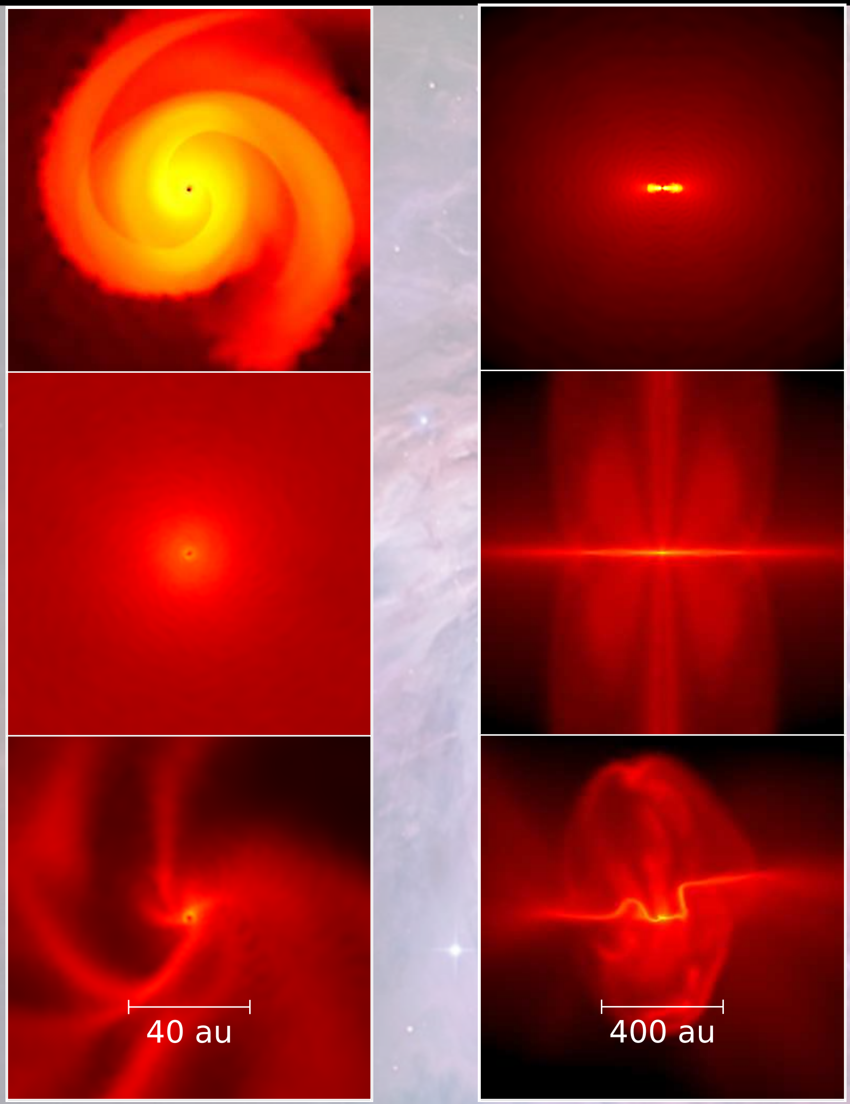


- Hydro + radiation
  - Large disc & no outflows
  - Not realistic since no magnetic fields

- Ideal MHD + radiation
  - Outflows & no disc

Foreground: Wurster & Lewis (2020a); see also Wurster+ (2016, 2018c)
Background: Orion Molecular Cloud. (image credit: Drudis & Goldman via APOD)

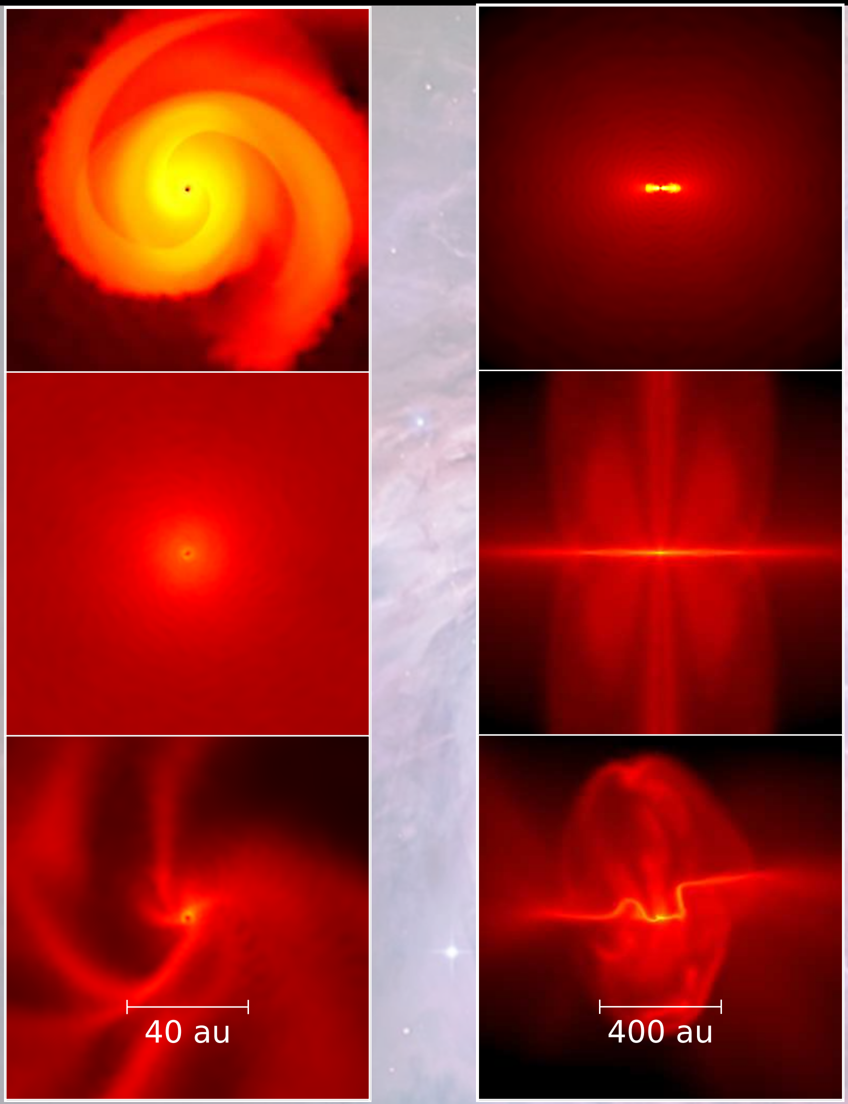
Star formation: Numerical results: Challenges



- Hydro + radiation
  - Large disc & no outflows
  - Not realistic since no magnetic fields
- Ideal MHD + radiation
  - Outflows & no disc
- Ideal MHD + radiation + turbulence
  - Some outflows & no disc

Foreground: Wurster & Lewis (2020a); see also Wurster+ (2016, 2018c)
Background: Orion Molecular Cloud. (image credit: Drudis & Goldman via APOD)

Star formation: Numerical results: Challenges



- The ideal MHD models demonstrate the ***Magnetic Braking Catastrophe***: discs do not form in numerical simulations containing strong, ideal magnetic fields (e.g., Allen, Li & Shu (2003); Galli+ (2006))

- From top to bottom:
  - Hydro + radiation
  - Ideal MHD + radiation
  - Ideal MHD + radiation + turbulence

Foreground: Wurster & Lewis (2020a); see also Wurster+ (2016, 2018c)
Background: Orion Molecular Cloud. (image credit: Drudis & Goldman via APOD)

Ideal magnetohydrodynamics

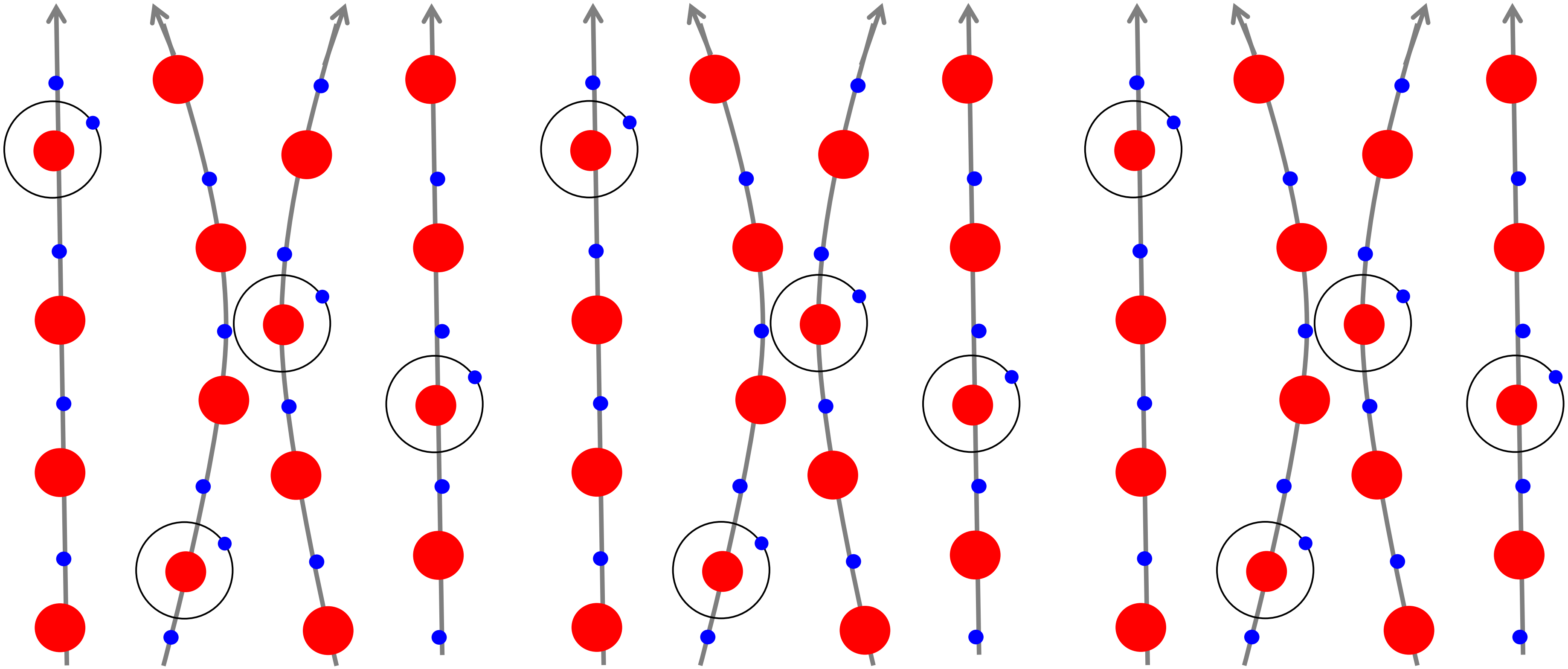
➢Highly ionised plasma:

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B})$$

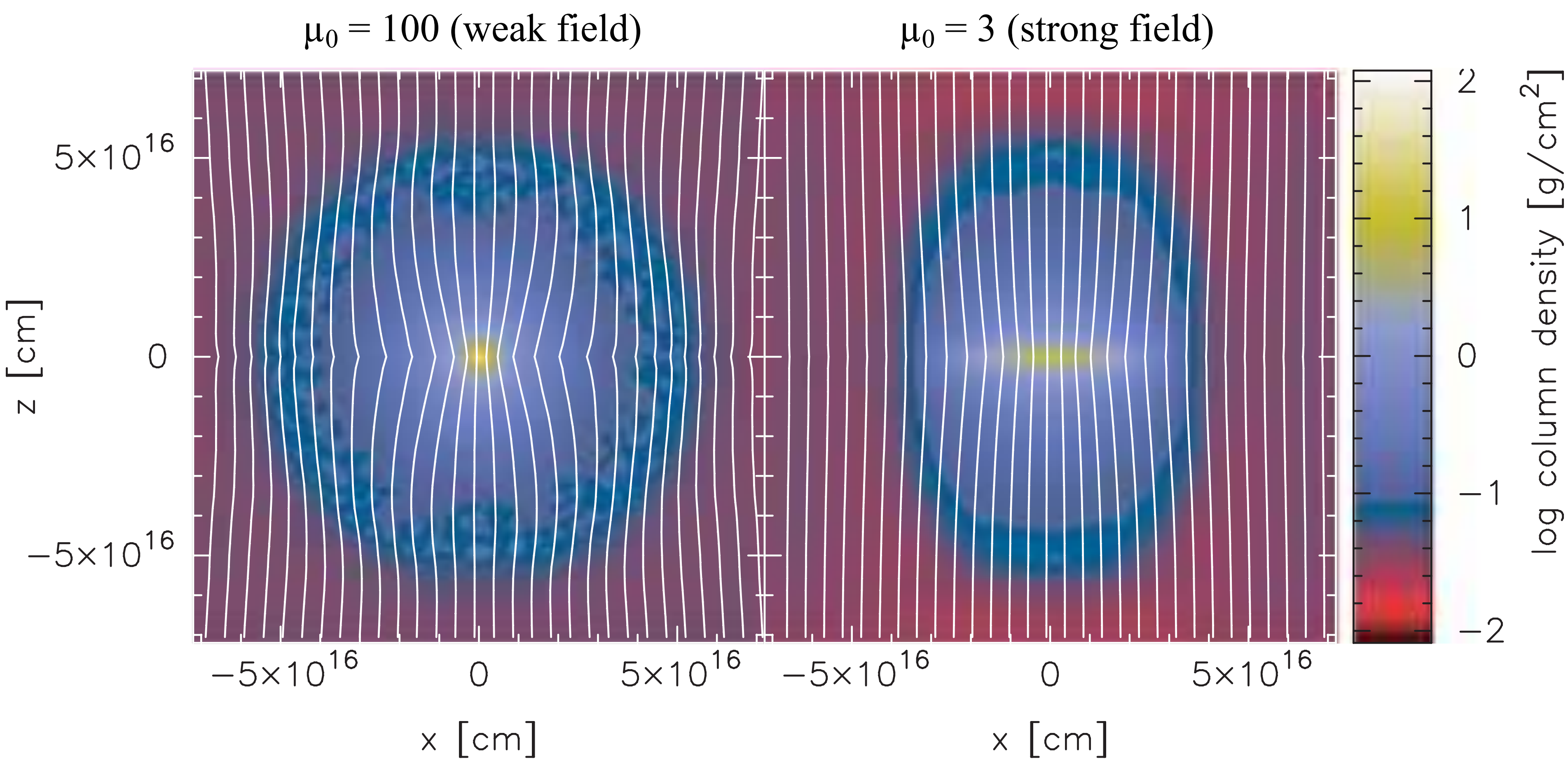
➢Zero resistivity & infinite conductivity

➢Ions & electrons are tied to the magnetic field

➢Neutral particles are tied to the magnetic field due to interactions with the ions & electrons



Ideal magnetohydrodynamics



Price & Bate (2007)

Ideal magnetohydrodynamics

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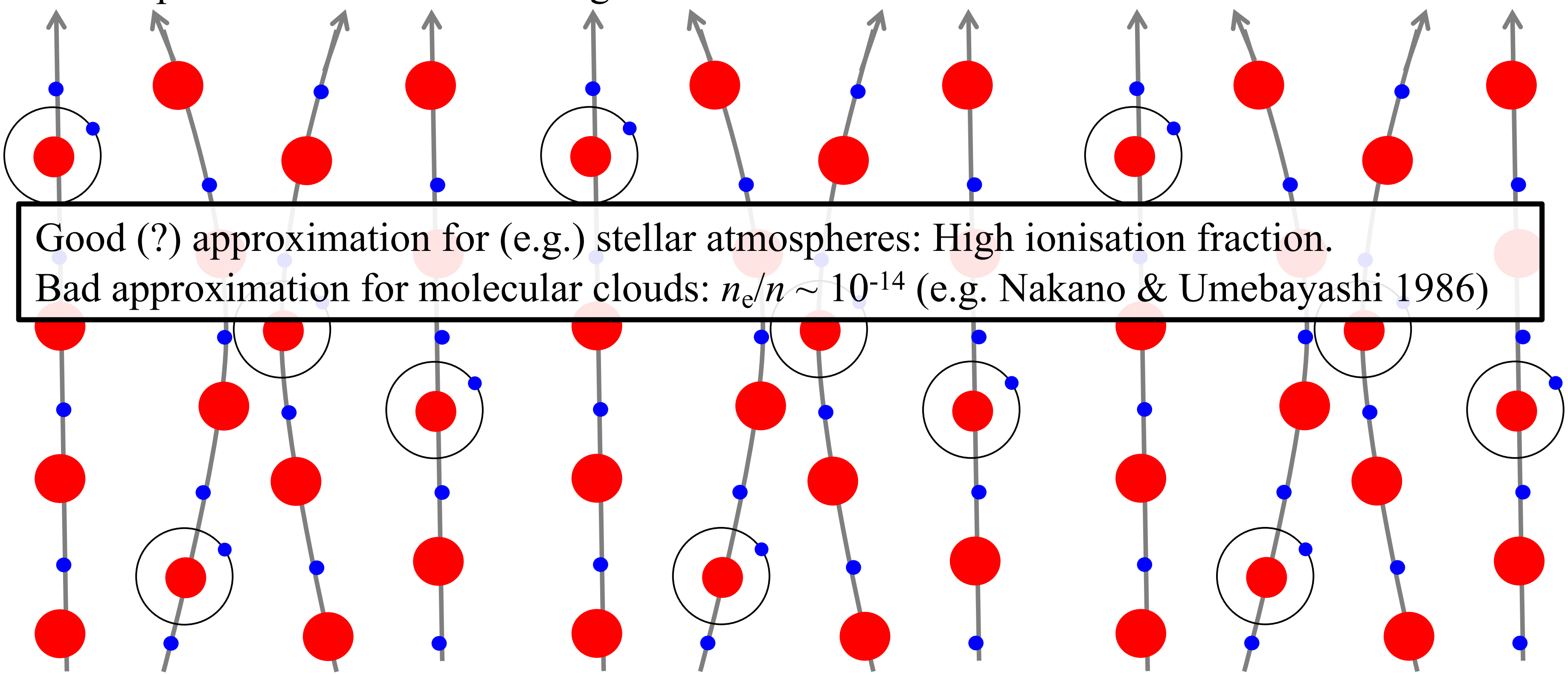
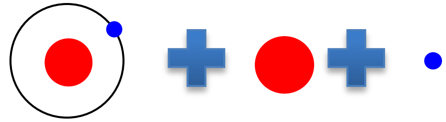
- Neutral particles are tied to the magnetic field due to interactions with the ions & electrons

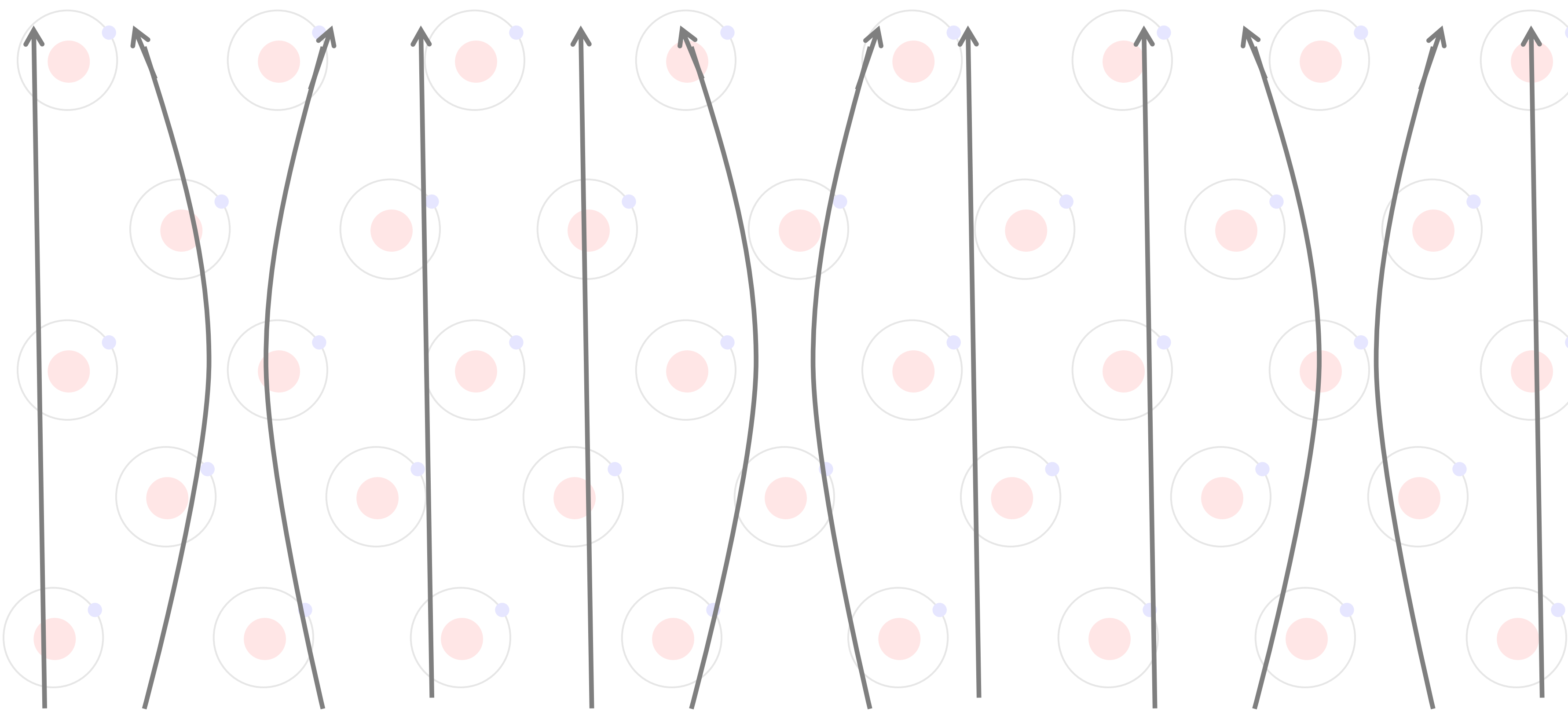


Good (?) approximation for (e.g.) stellar atmospheres: High ionisation fraction.
Bad approximation for molecular clouds: $n_e/n \sim 10^{-14}$ (e.g. Nakano & Umebayashi 1986)

Non-ideal magnetohydrodynamics

- Partially ionised plasma: 

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



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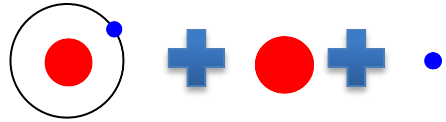

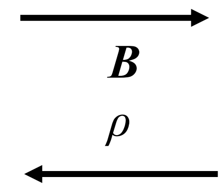

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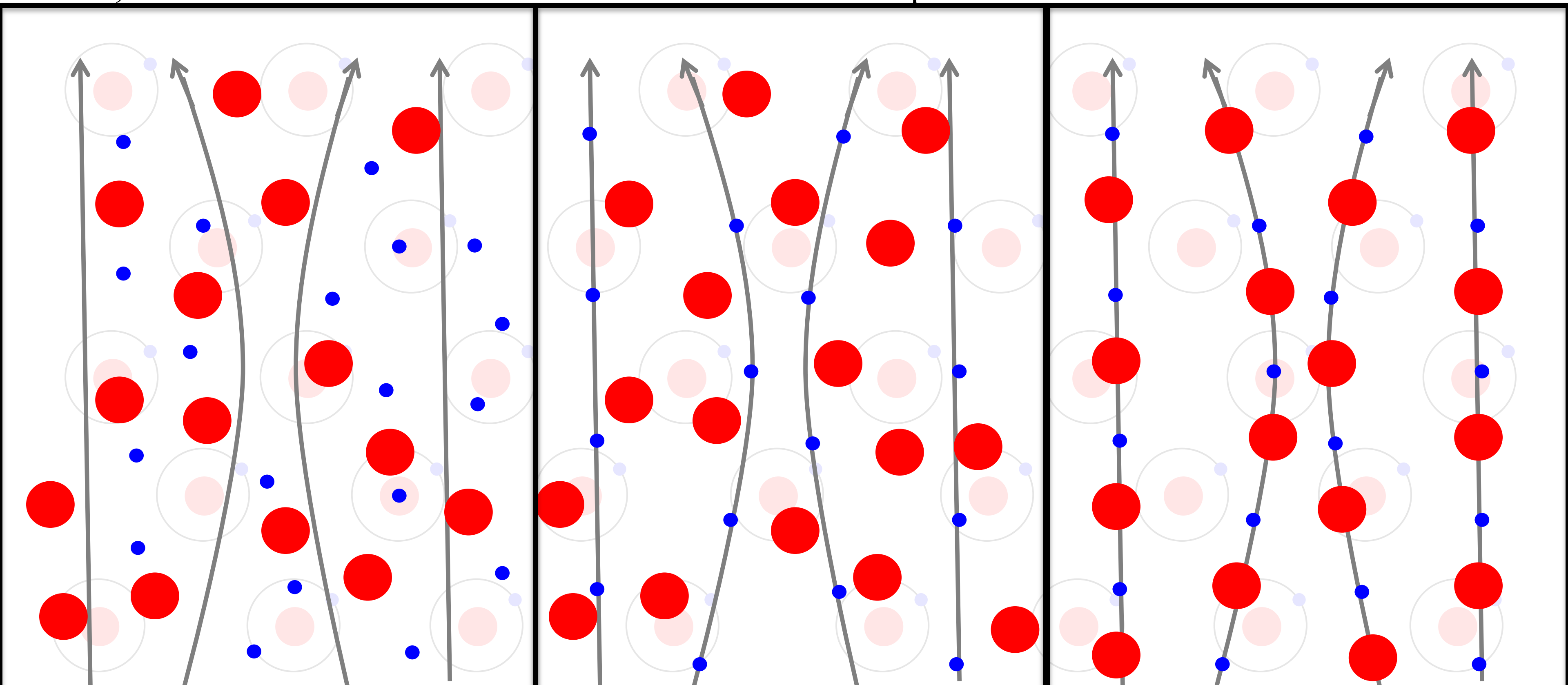
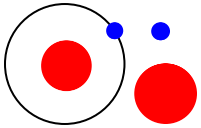
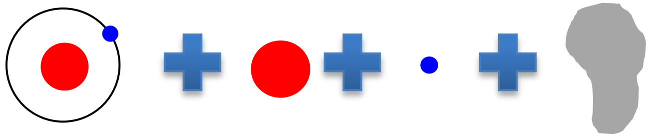


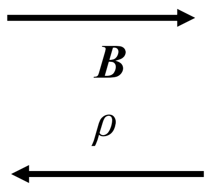
Ohmic Resistivity (diffusive) | Hall Effect (dispersive) | Ambipolar Diffusion (diffusive)

Non-ideal magnetohydrodynamics



- Partially ionised plasma and dust:





- Non-zero resistivity & conductivity
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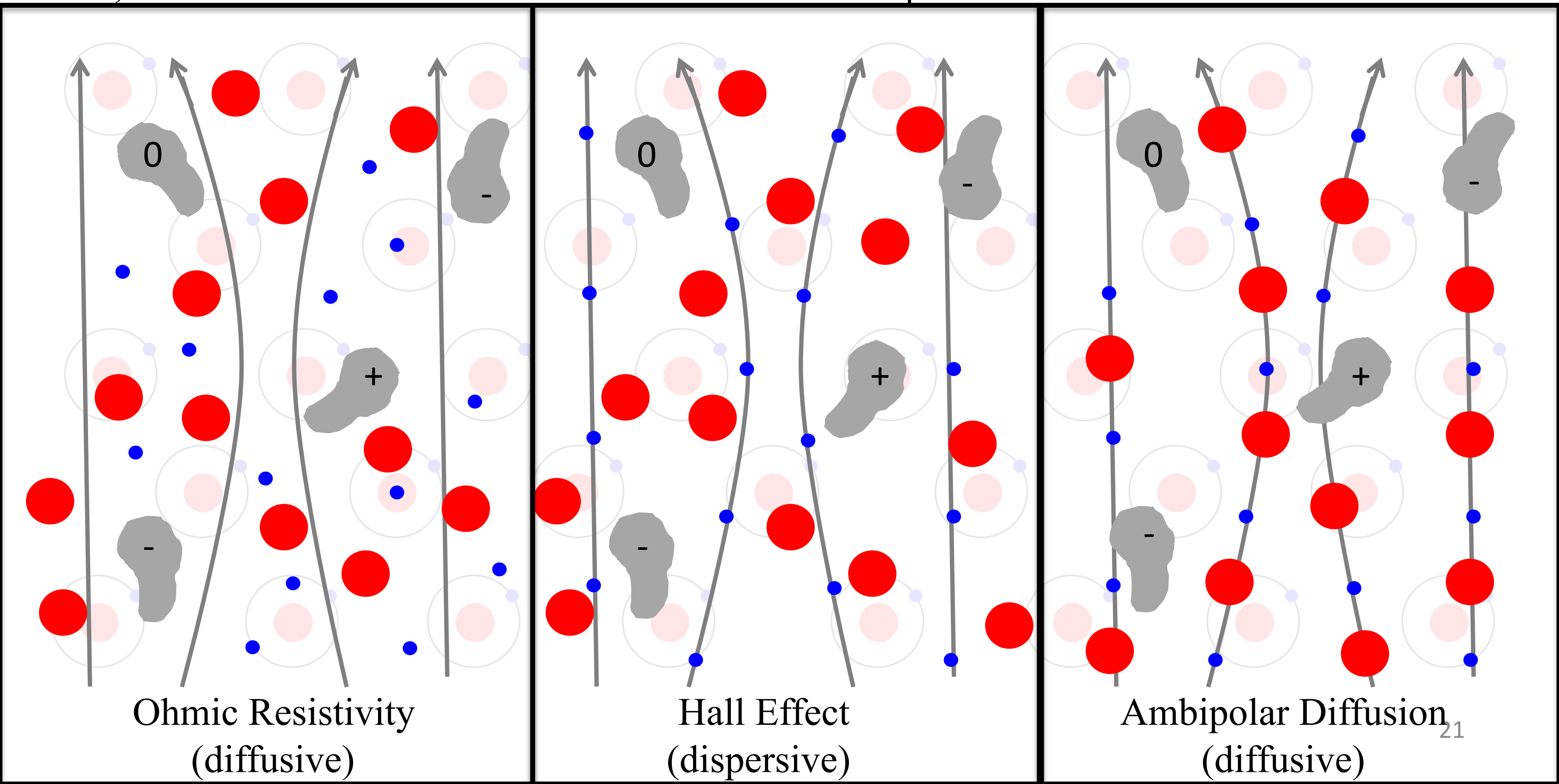
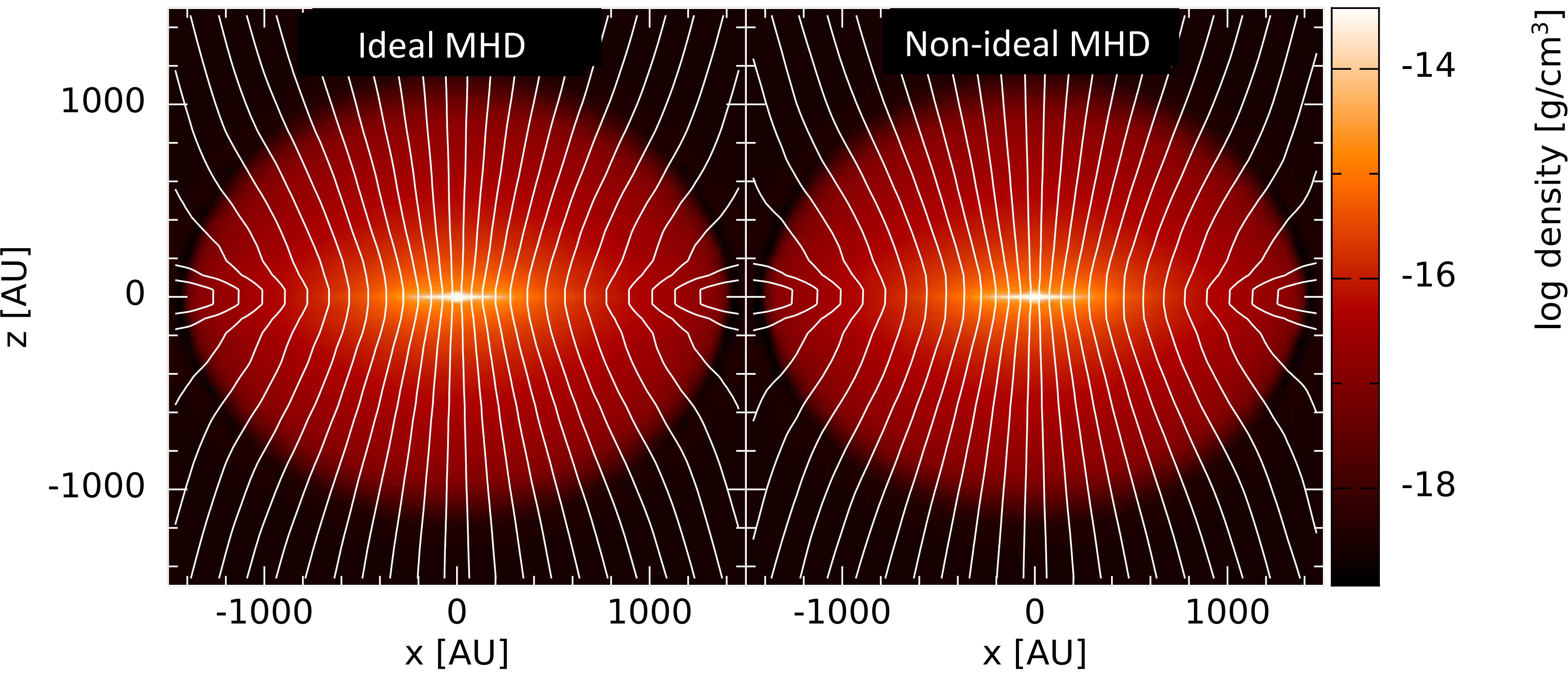


Non-ideal magnetohydrodynamics

- Strong field, initially vertical magnetic field
- Large scale structure



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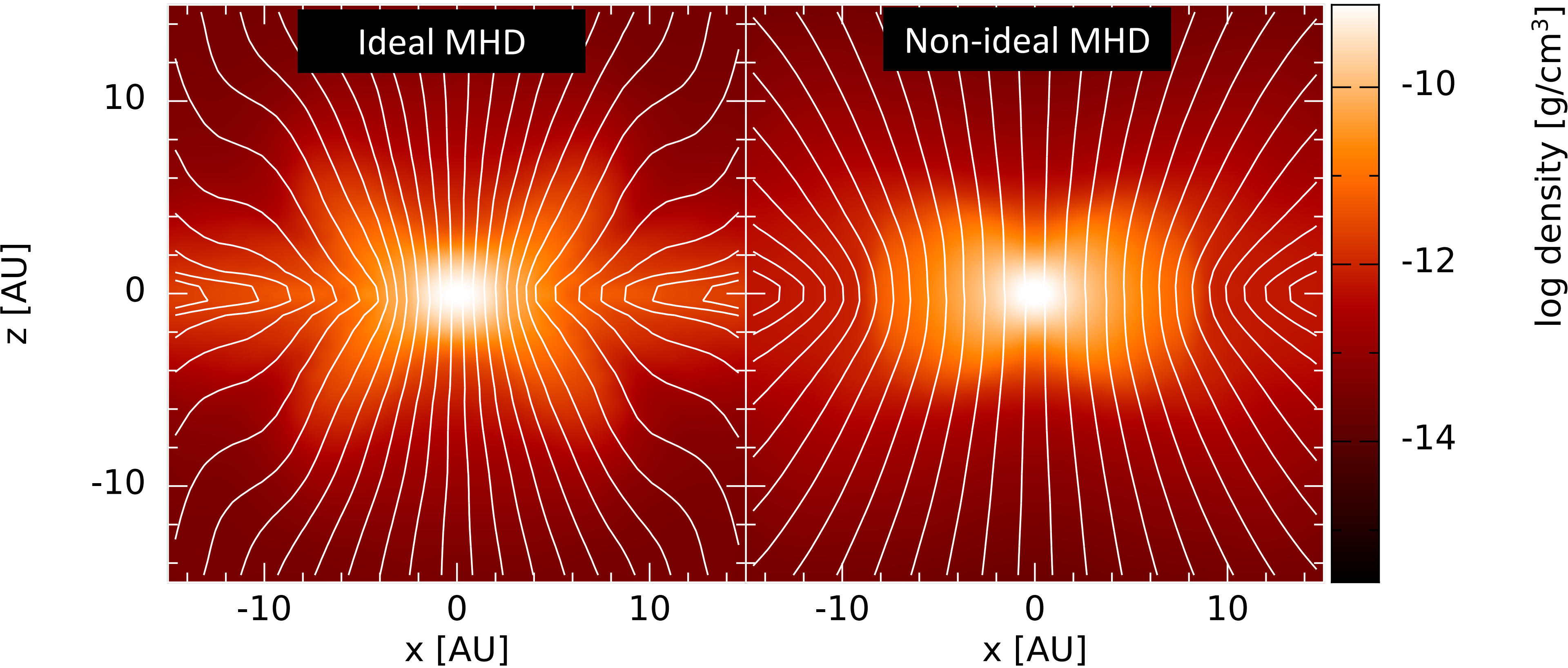

Non-ideal magnetohydrodynamics

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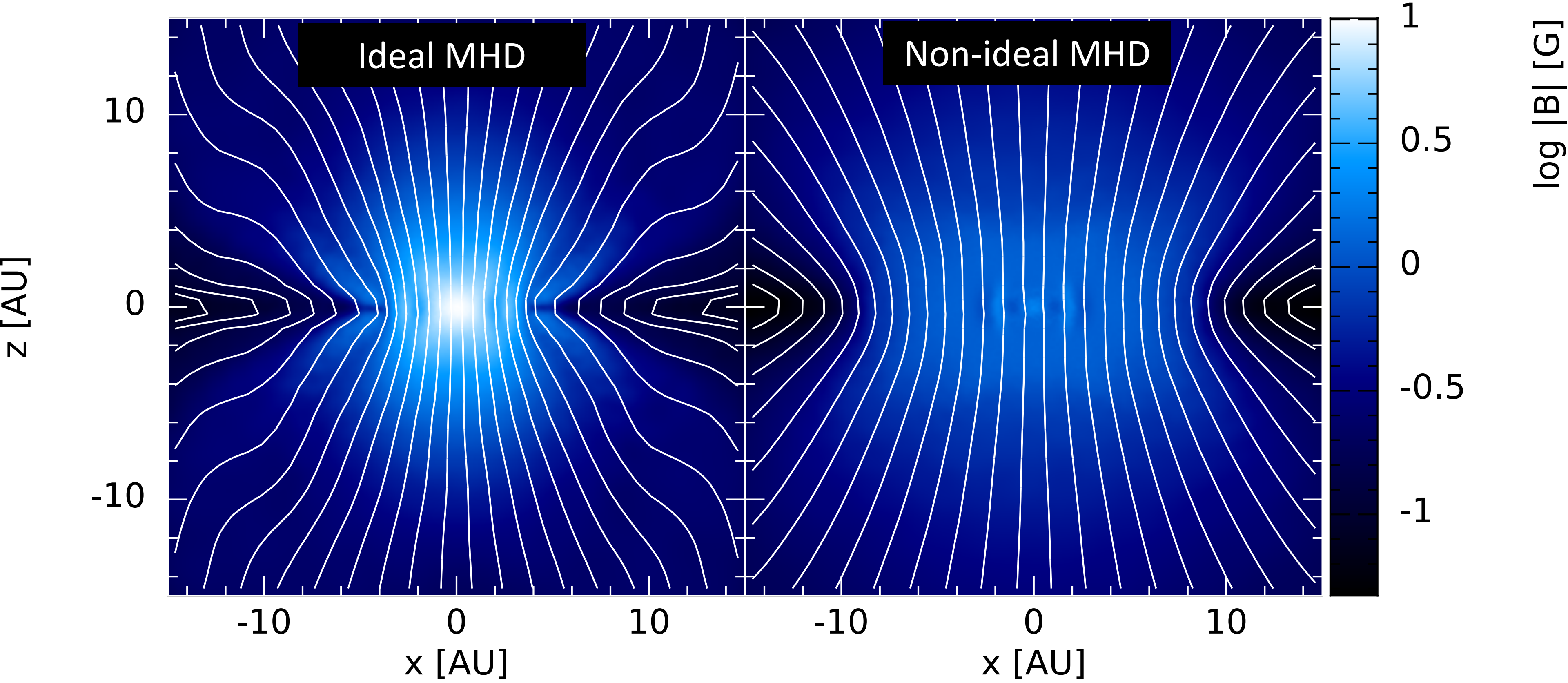
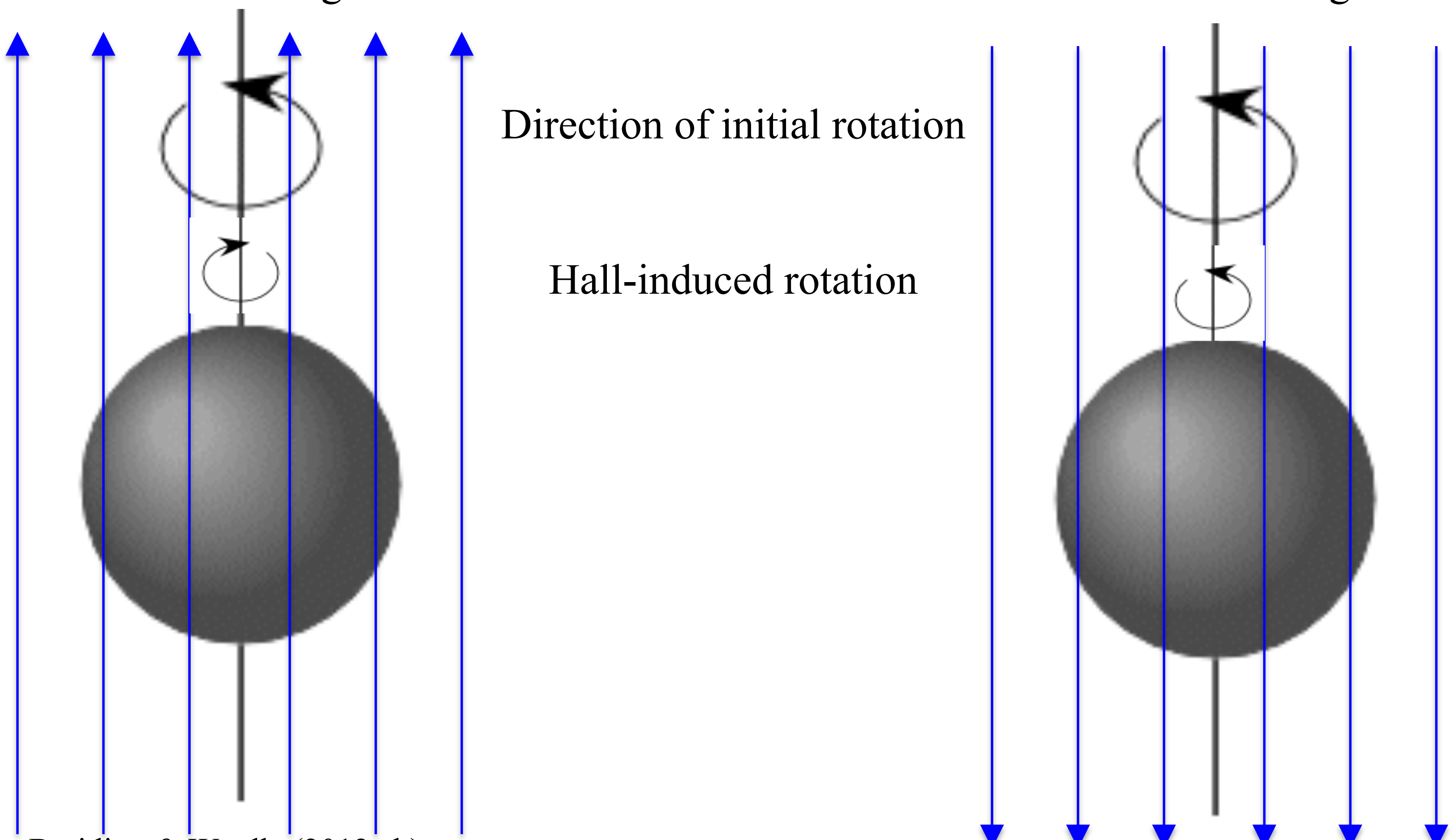


Non-ideal magnetohydrodynamics: Hall effect

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

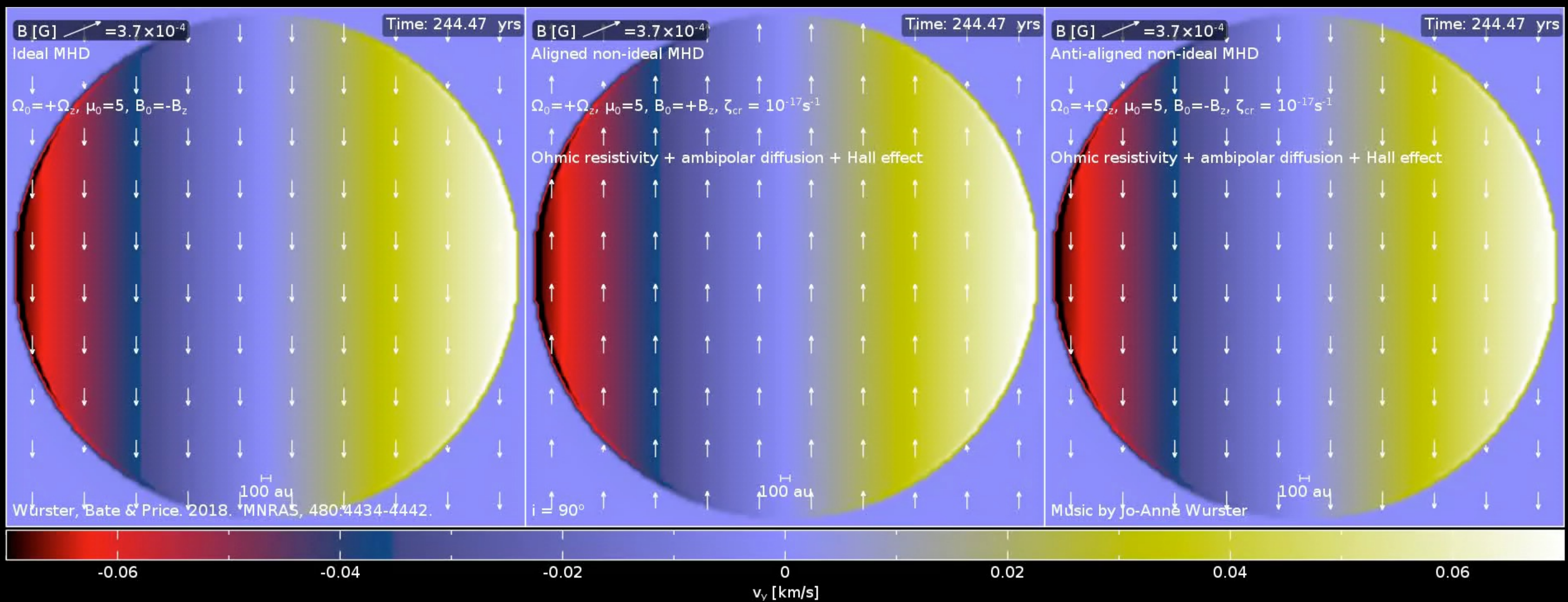
L & *B* are aligned

L & *B* are anti-aligned



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

Formation of a low-mass star



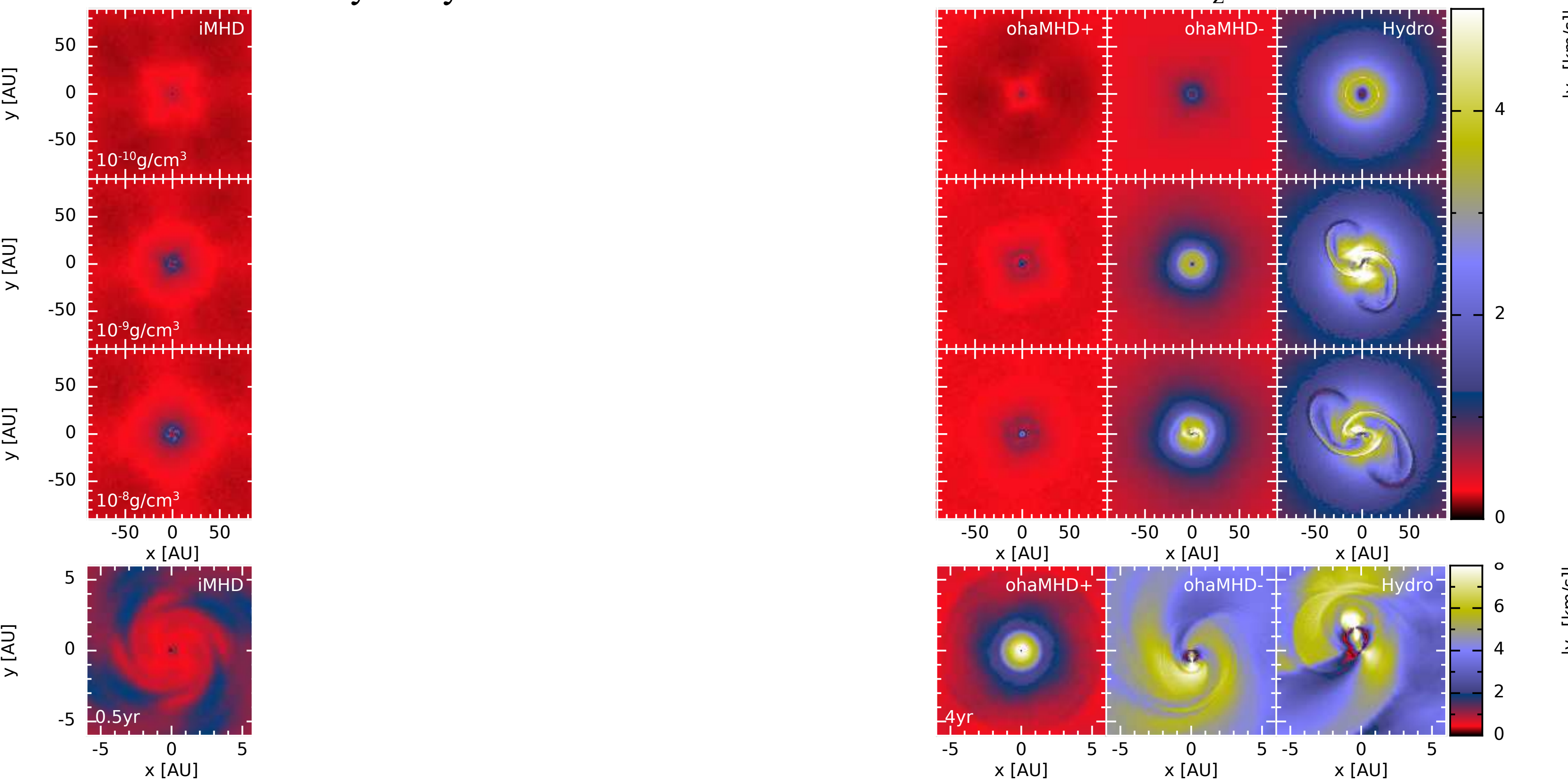
Available at: https://youtu.be/2SQxgXbdJyg

Wurster, Bate & Price (2018c)

Music: Jo-Anne Wurster

Rotationally supported discs

- ➢Discs form in the hydrodynamics model and the non-ideal model with $-B_z$



- ➢Discs form during the first hydrostatic core phase
- ➢Similar disc structure obtained by Tsukamoto+ (2015a) with $\pm B_z$

Wurster, Bate & Bonnell (2021); Wurster, Bate & Price (2018a,c)

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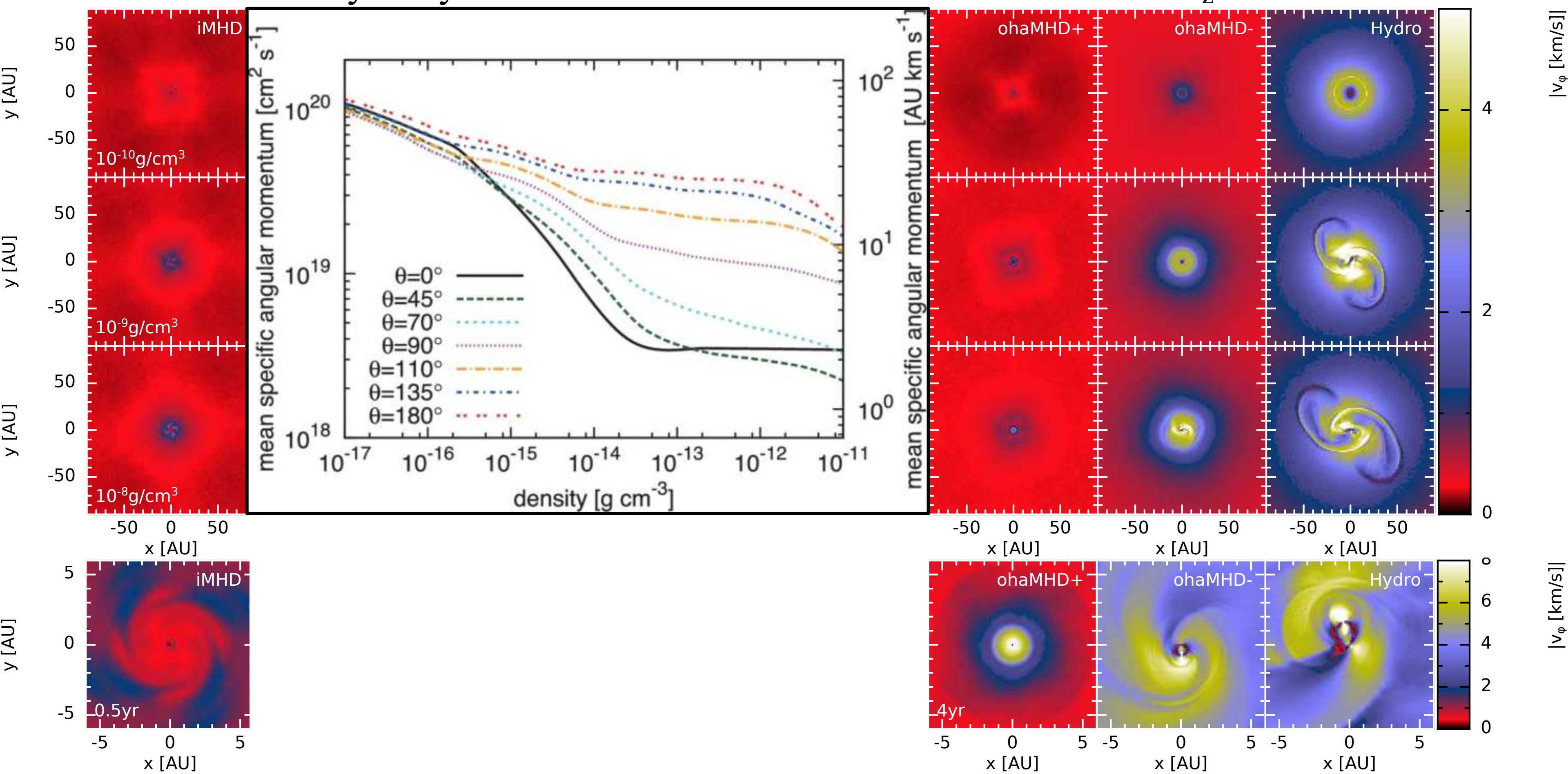

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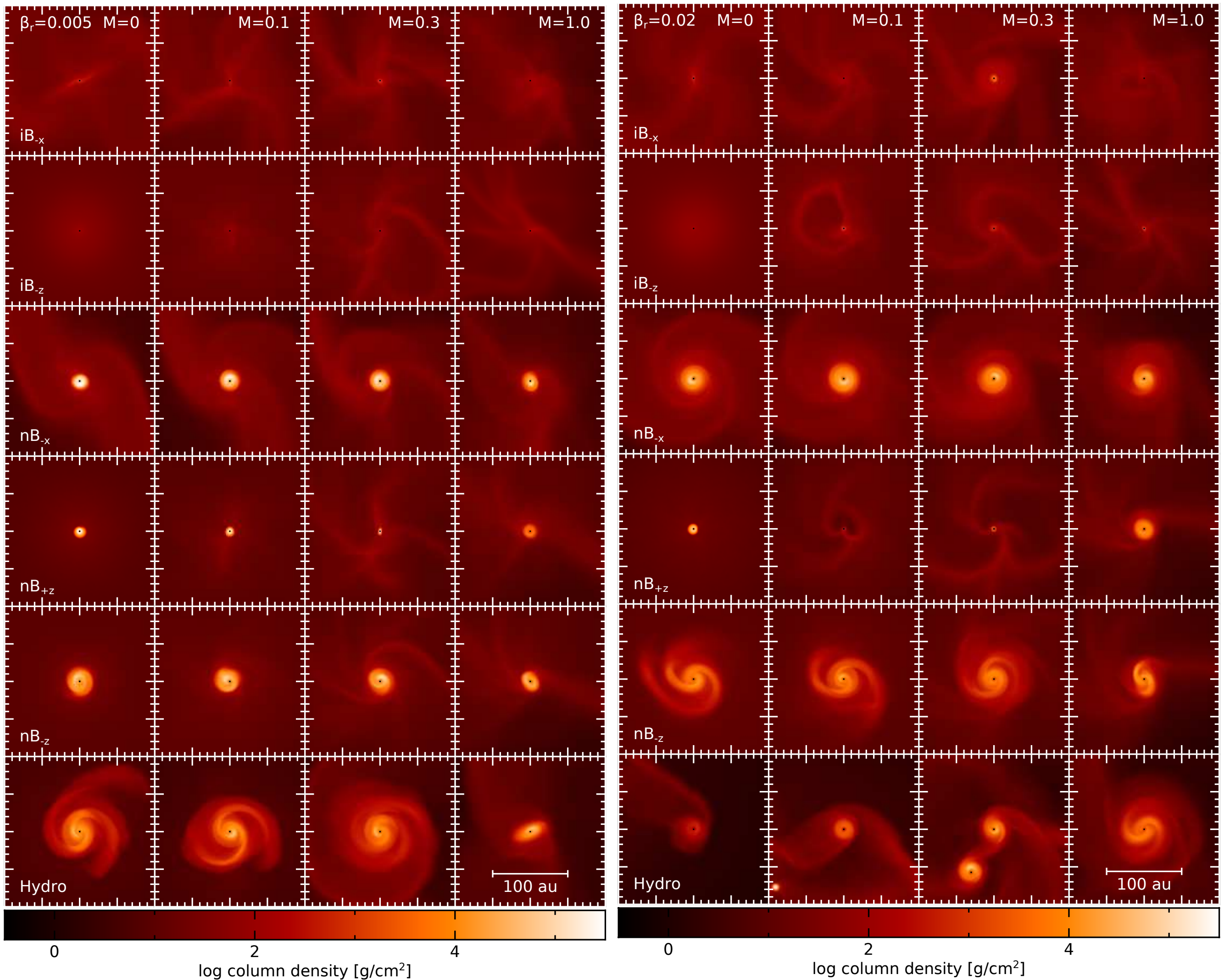
Wurster, Bate & Bonnell (2021); Wurster, Bate & Price (2018a,c); inset: Tsukamoto+ (2017)

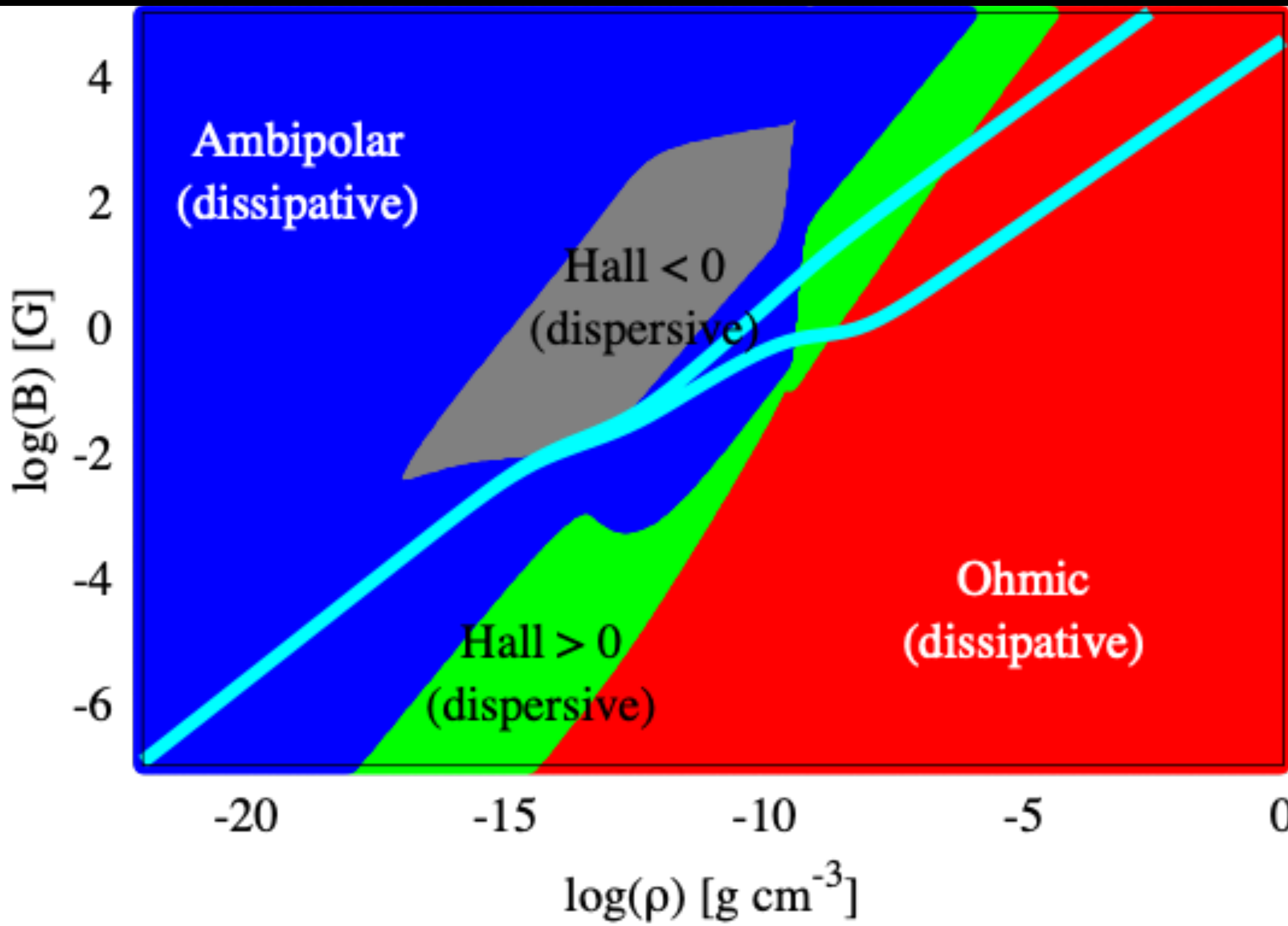
Rotationally supported discs

➢Sub- and trans-sonic turbulence is not enough to permit the formation of rotationally supported discs when employing ideal MHD



Wurster & Lewis (2020a)

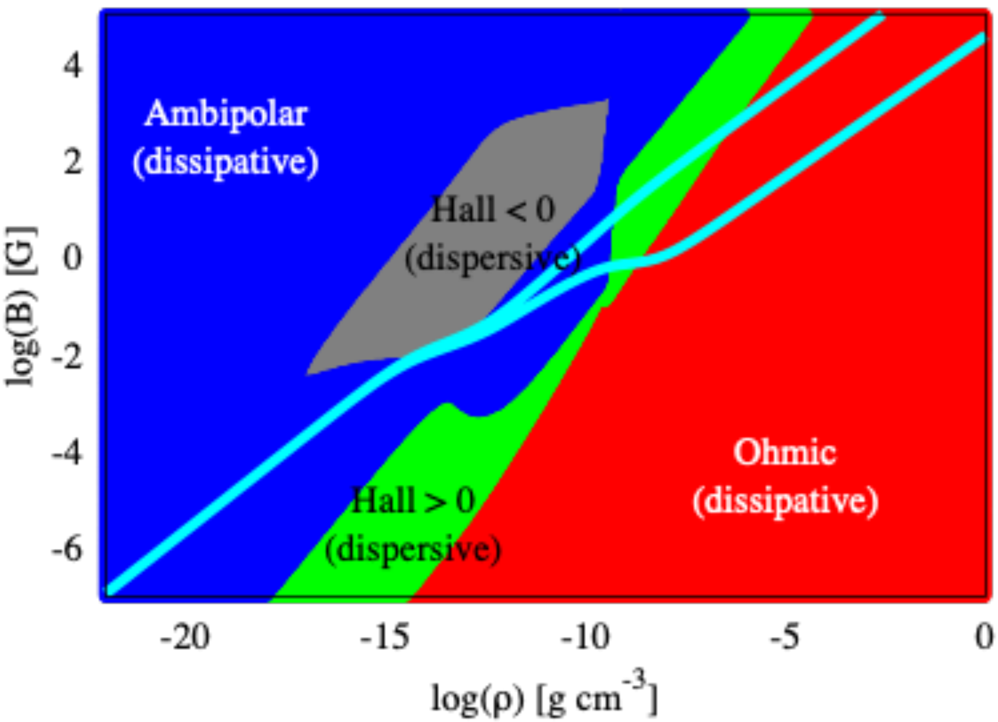
Non-ideal MHD



- Cyan lines is typical star forming tracks
- Values dependent on microphysics: Grain size, ionised species, cosmic ray ionisation rate

Adapted from Wardle (2007); constructed using NICIL v2.0 (Wurster, 2016)

Non-ideal MHD: Components



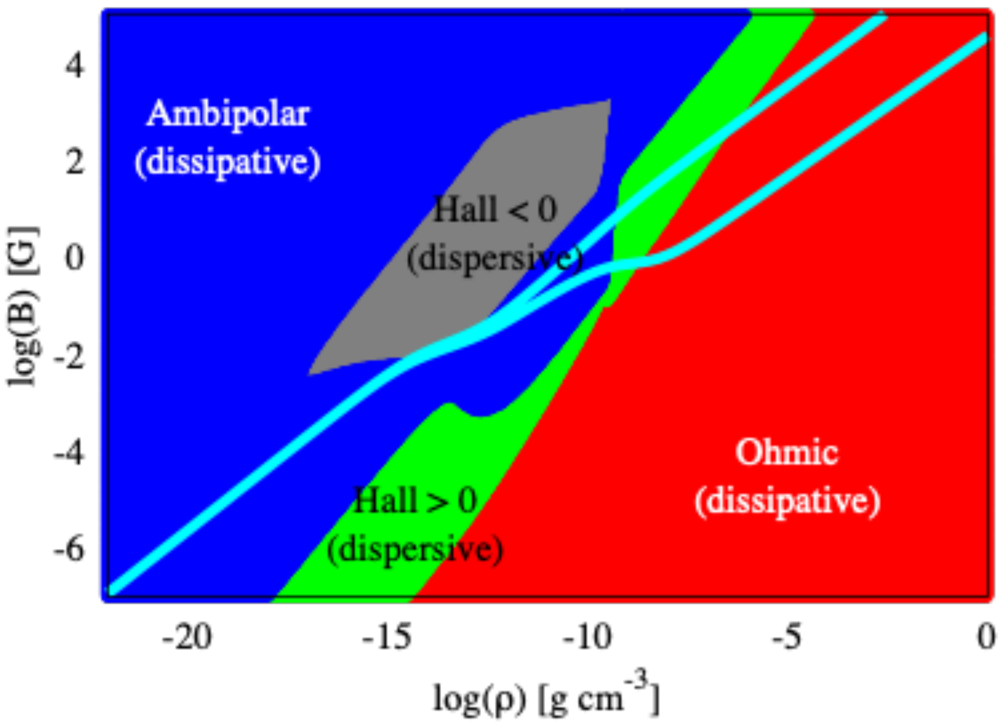
- Multiple conclusions in the literature regarding disc formation with Ohmic resistivity and/or ambipolar diffusion
- Likely possible to form small 1-5au discs in the long term with only Ohmic and/or ambipolar (Dapp and Basu 2010, Machida+ 2011, Dapp+ 2012, Tomida+ 2015, Tsukamoto+ 2015a, Masson+ 2016)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

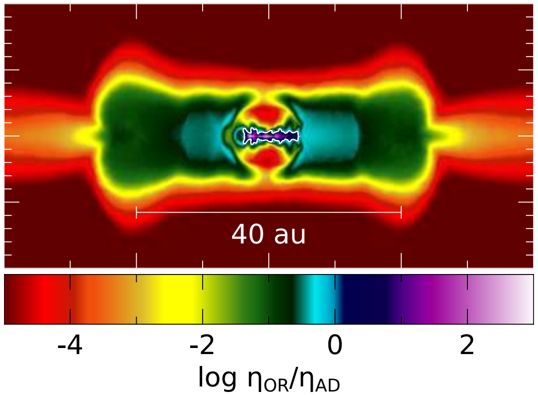
- Open question: *When do discs form?*

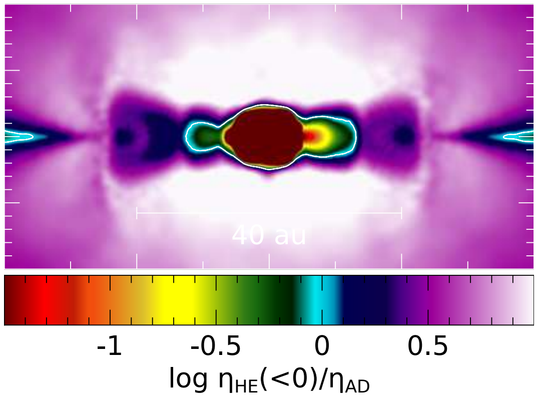
Adapted from Wardle (2007); constructed using NICIL v2.0 (Wurster, 2016)

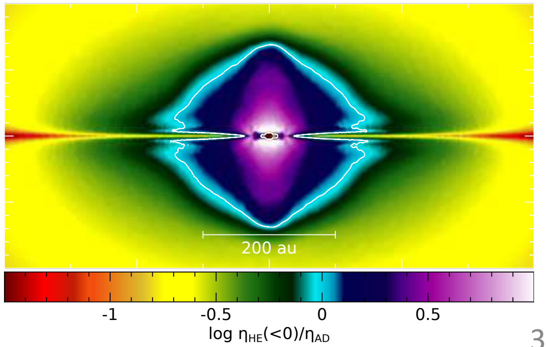
Non-ideal MHD: Components

➢Despite the apparent simplified phase space, many processes are important simultaneously, specifically the Hall effect & ambipolar diffusion







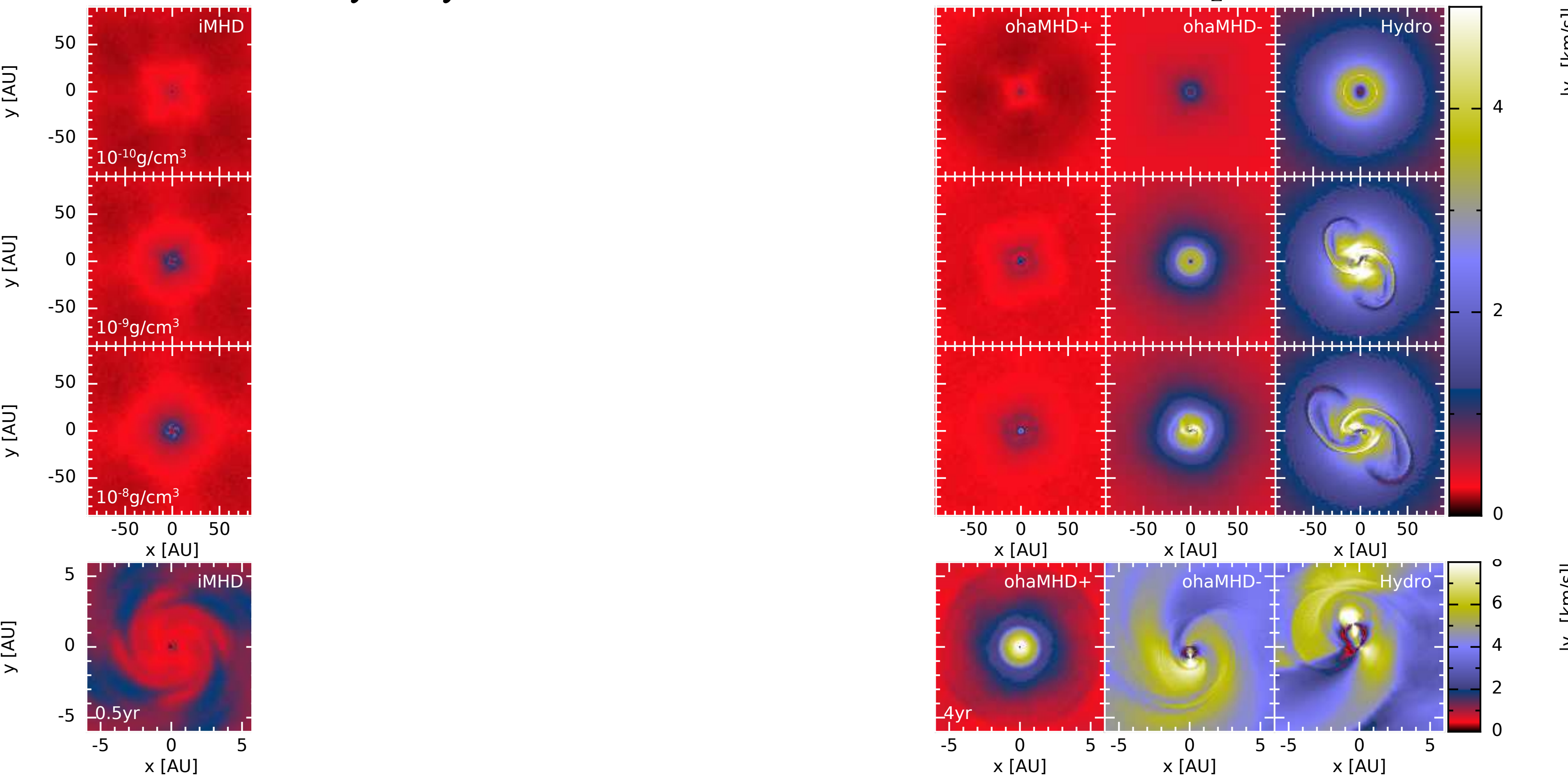


Adapted from Wardle (2007); constructed using NICIL v2.0 (Wurster, 2016)

Wurster (2021)

Non-ideal MHD Components: Rotationally supported discs

- Discs form in the hydrodynamics model and the non-ideal model with $-B_z$

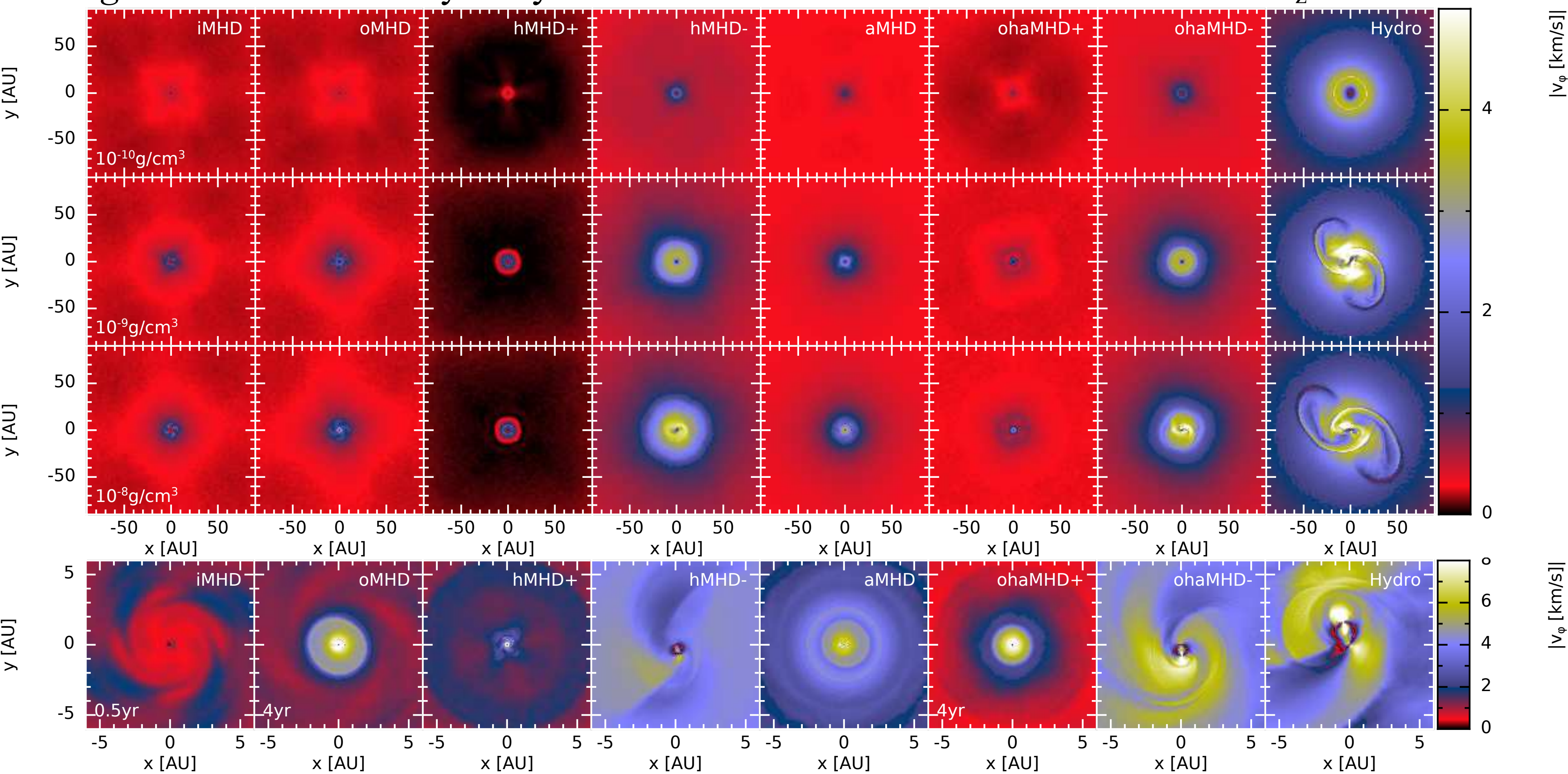


- Discs form during the first hydrostatic core phase
- Similar disc structure obtained by Tsukamoto+ (2015a) with $\pm B_z$

Wurster, Bate & Bonnell (2021); Wurster, Bate & Price (2018a,c)

Non-ideal MHD Components: Rotationally supported discs

- *Large* discs form in the hydrodynamics model and the non-ideal model with $-B_z$

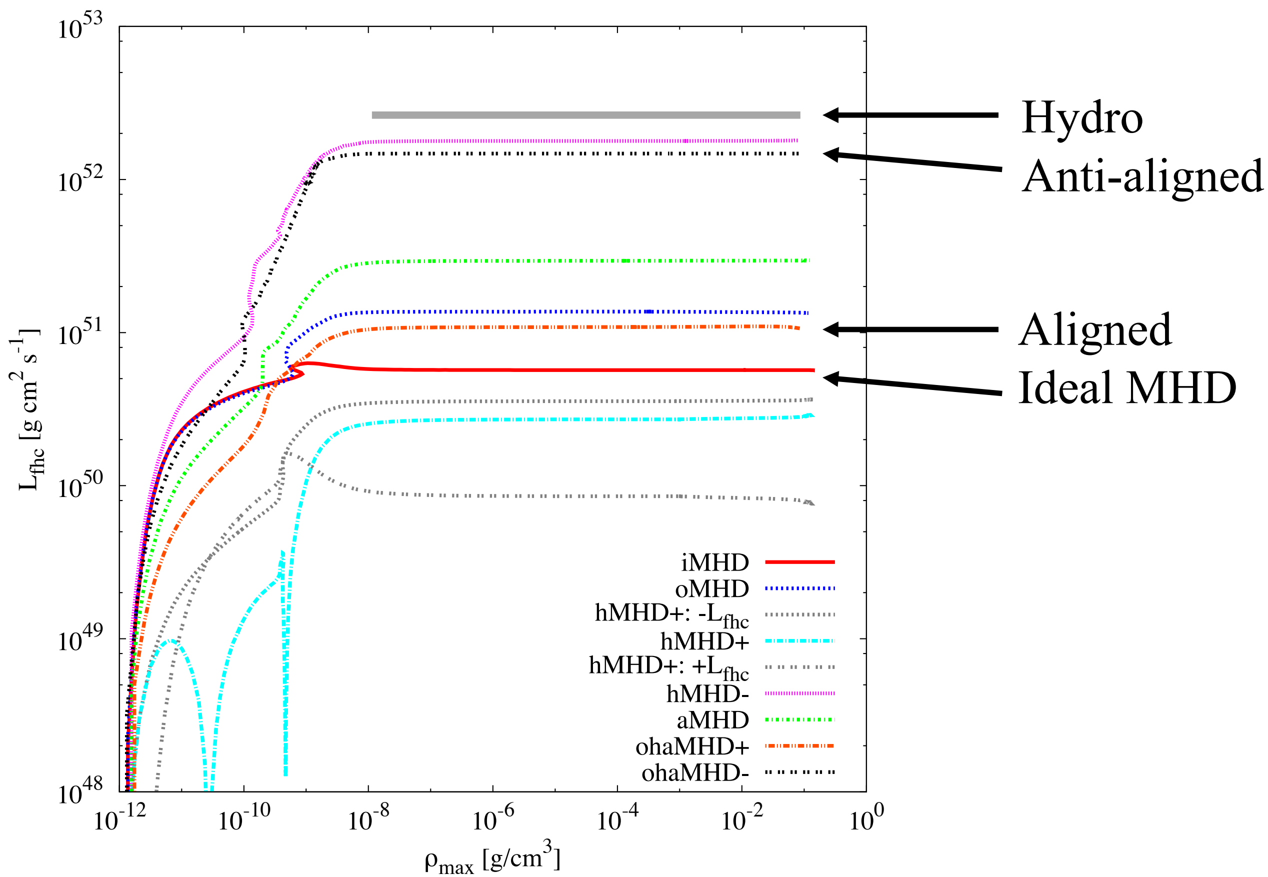


- The Hall effect with $-B_z$ is primarily responsible for forming large discs early
- Ohmic resistivity & ambiploar diffusion will form small discs later

Wurster, Bate & Bonnell (2021); Wurster, Bate & Price (2018a,c); see also Wurster, Price & Bate (2016)

Non-ideal MHD Components: Angular momentum

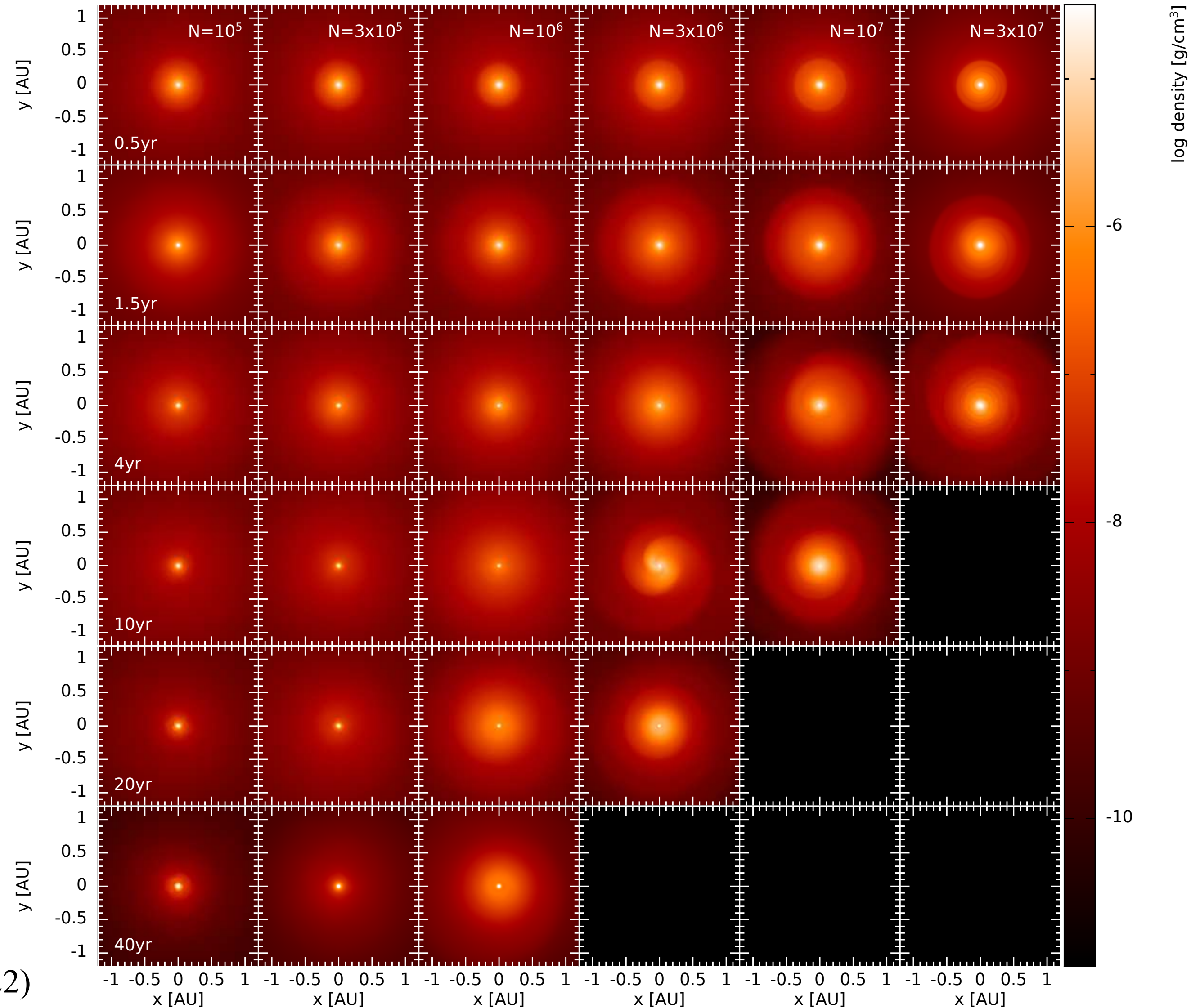
➢All non-ideal components, except the Hall effect with $+B_z$ increase the angular momentum of the first core, thus promote disc formation



Wurster, Bate & Bonnell (2021)

Rotationally supported discs: Numerical resolution

➢Numerical resolution is important on the formation of the discs, especially the small discs in our aligned simulations:



Wurster, Bate, Price & Bonnell (2022)

Star formation: From the beginning

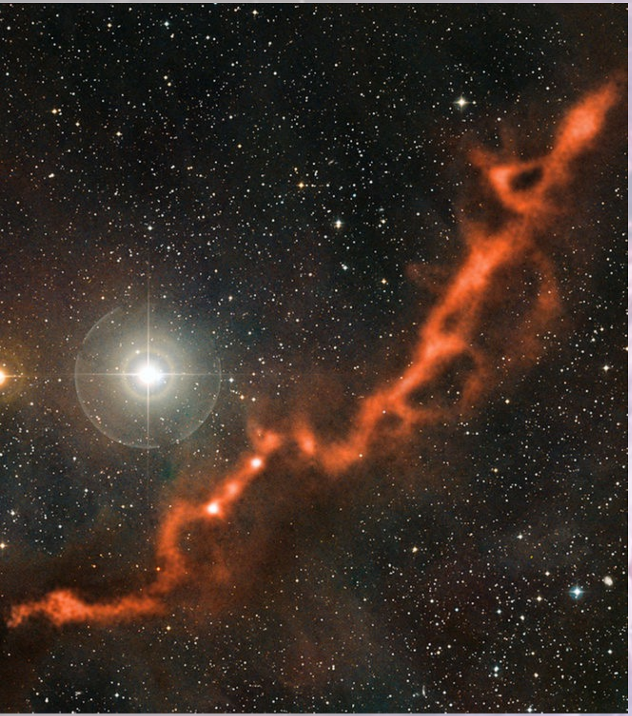
- Stars do not form in isolation
- Star forming environments, on the large scale, are turbulent

Orion Molecular Cloud. (image credit: Drudis & Goldman via APOD)

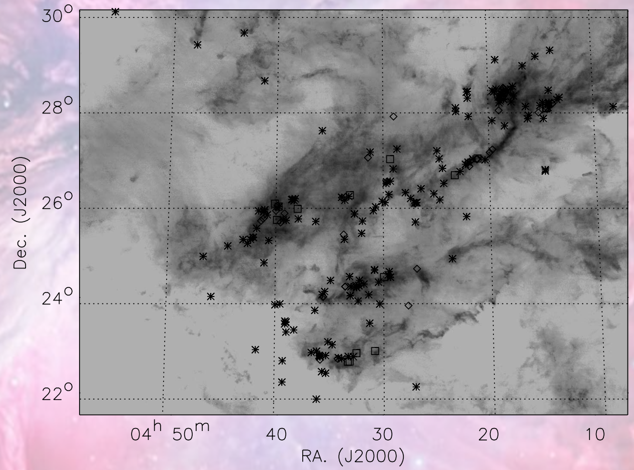
Star formation: From the beginning

Pillars of Creation: Hubble Space Telescope [visible] vs JWST [near IR] vs JWST [mid-IR].
(image credit: webbtelescope.org)

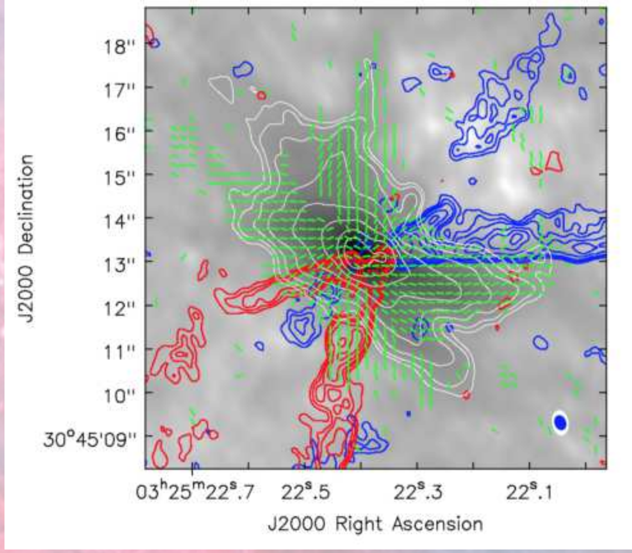
Star formation: Stellar nurseries



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

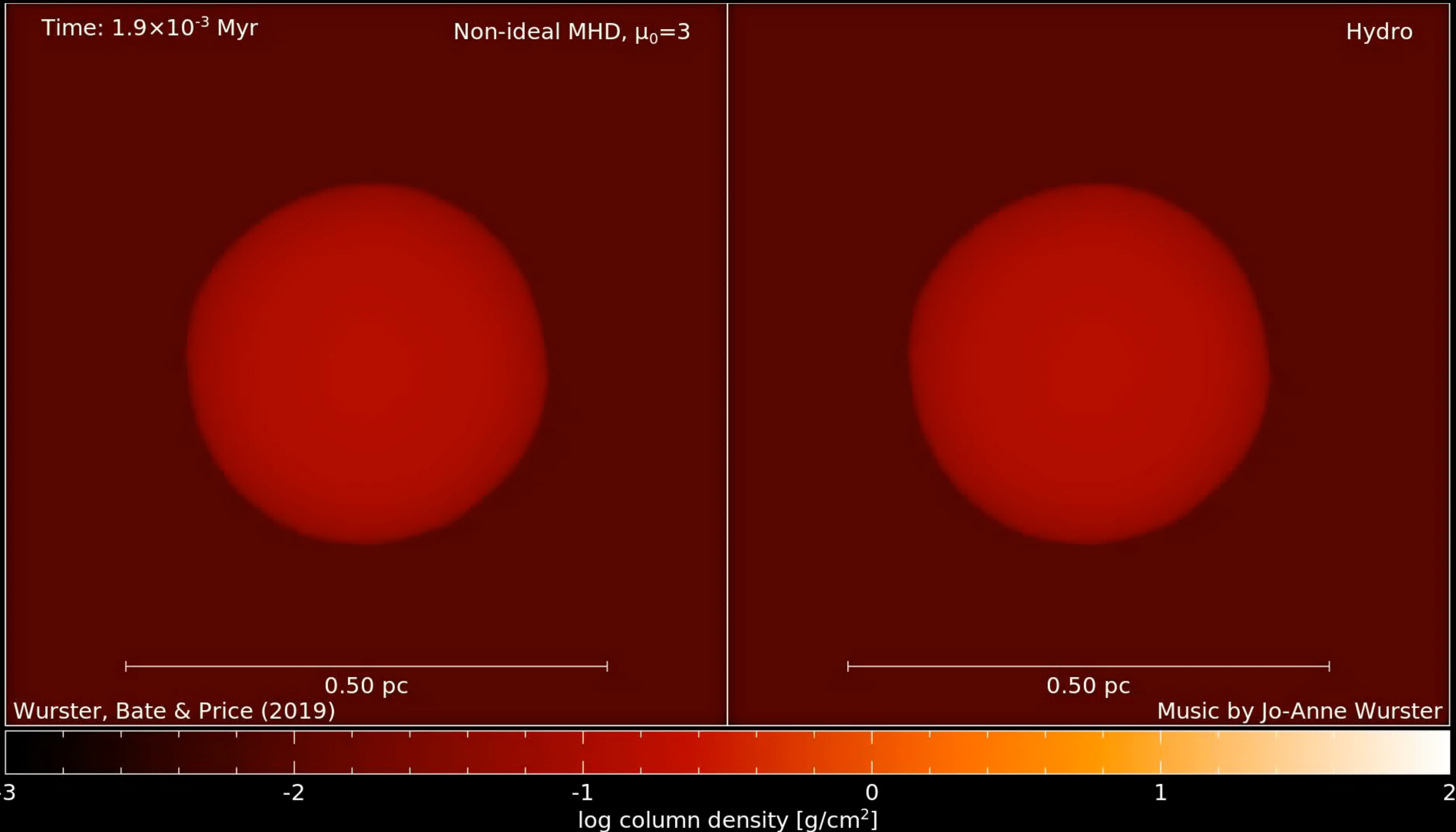


Taurus Molecular Cloud: H_2 column density map with positions of young stars (Goldsmith et. al., 2008)



Magnetic field morphology around L1448 IRS 2 (Kwon+ 2019)

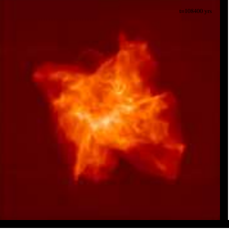
Cluster Formation: Effect of non-ideal MHD



Available at https://youtu.be/VZixbkDMZO8

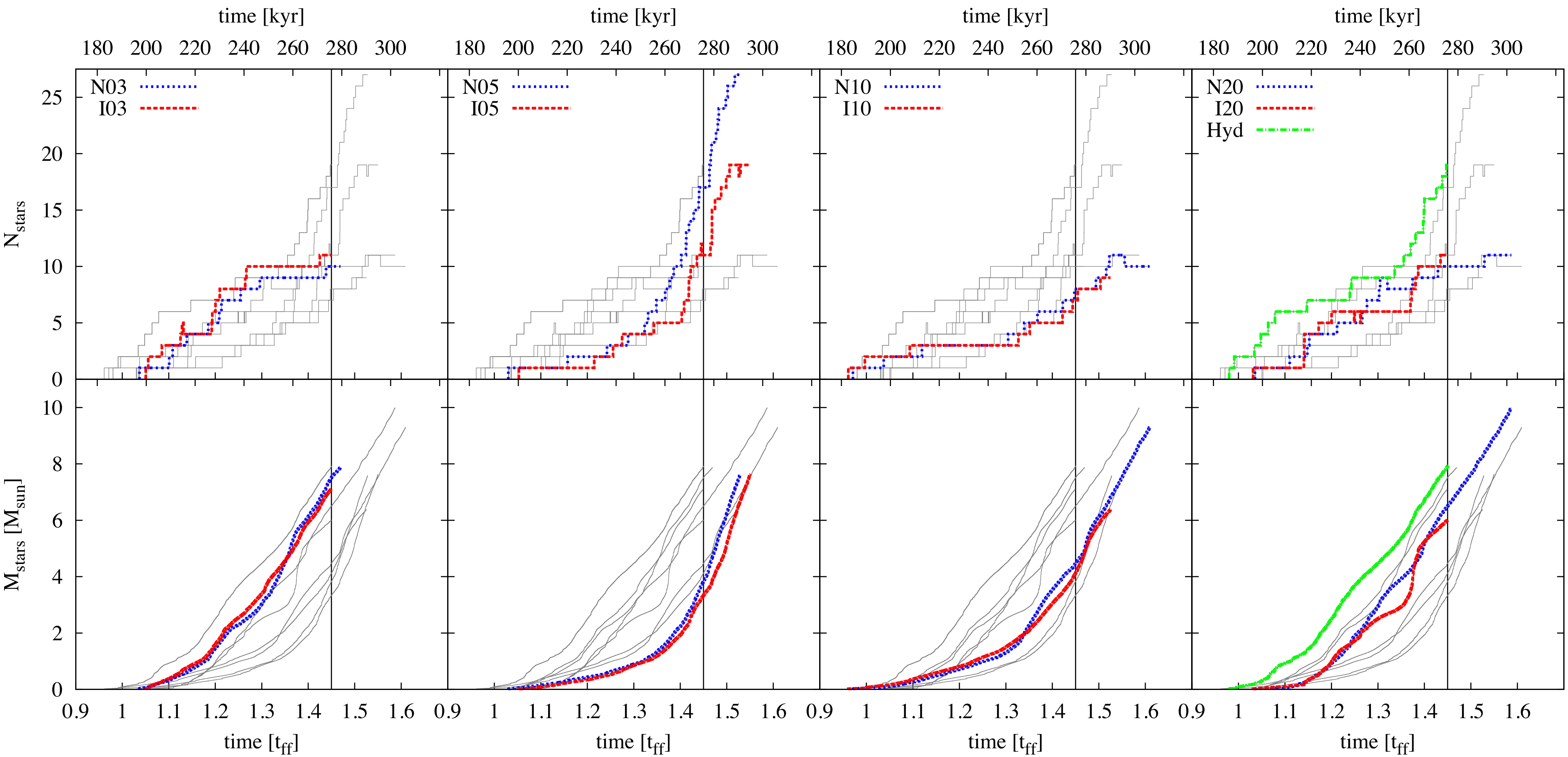
Wurster, Bate & Price (2019)

Music by Jo-Anne Wurster

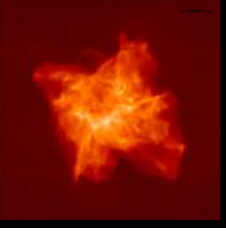


Cluster Formation: Stellar Mass

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

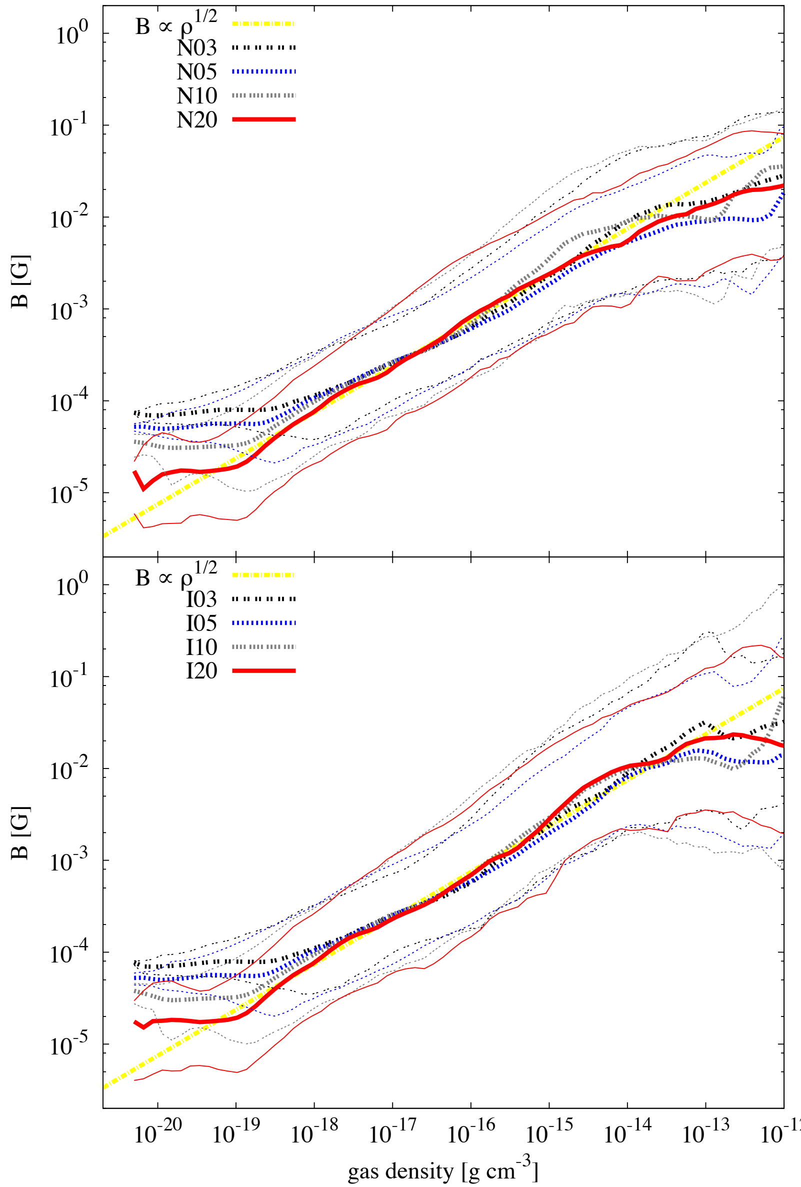


Wurster, Bate & Price (2019)

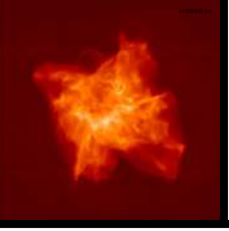


Cluster Formation: Star forming regions

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

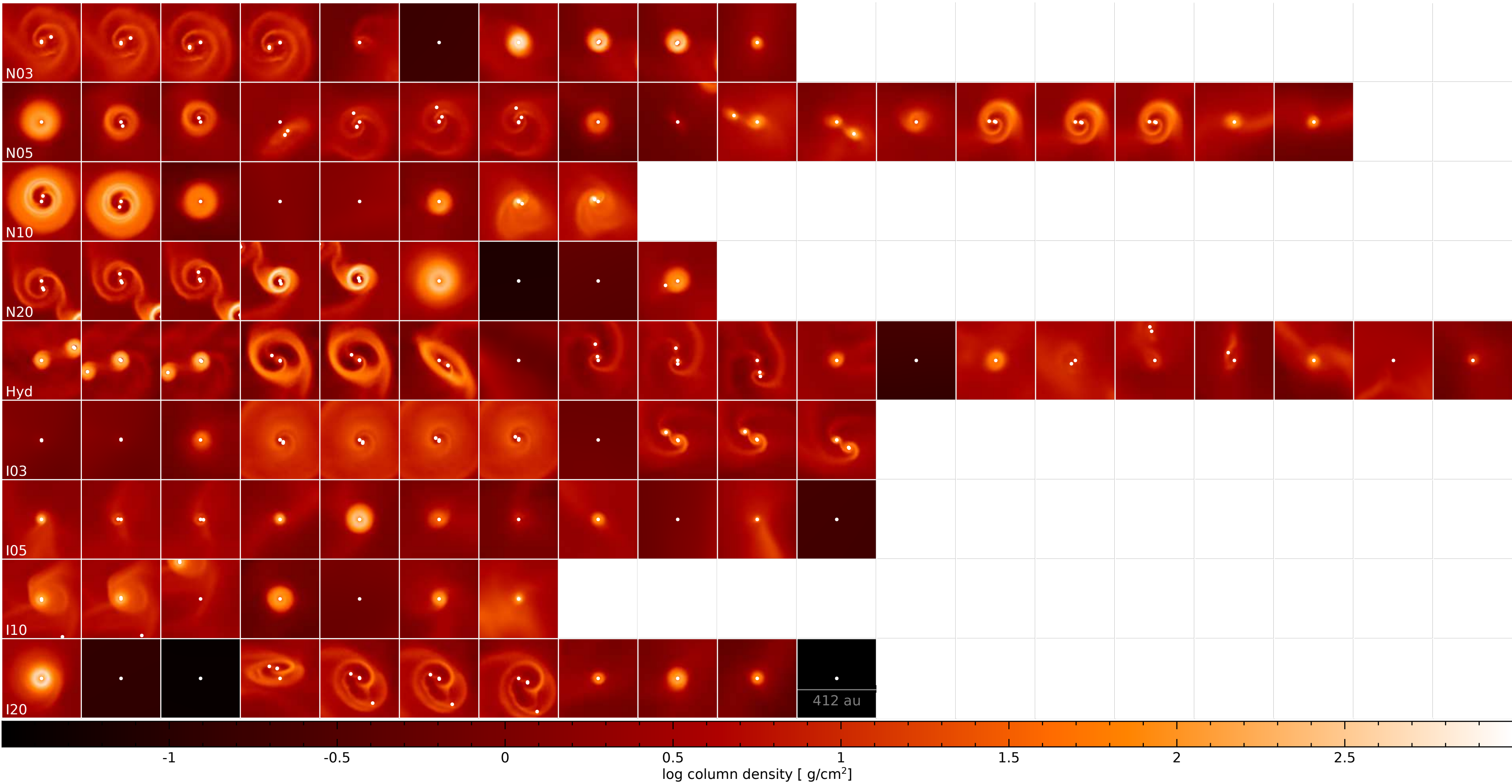


Wurster, Bate & Price (2019)

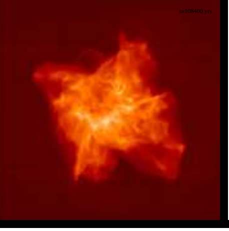


Cluster Formation: Protostellar discs

➢Large protostellar discs form in *all* our models



Wurster, Bate & Price (2019)



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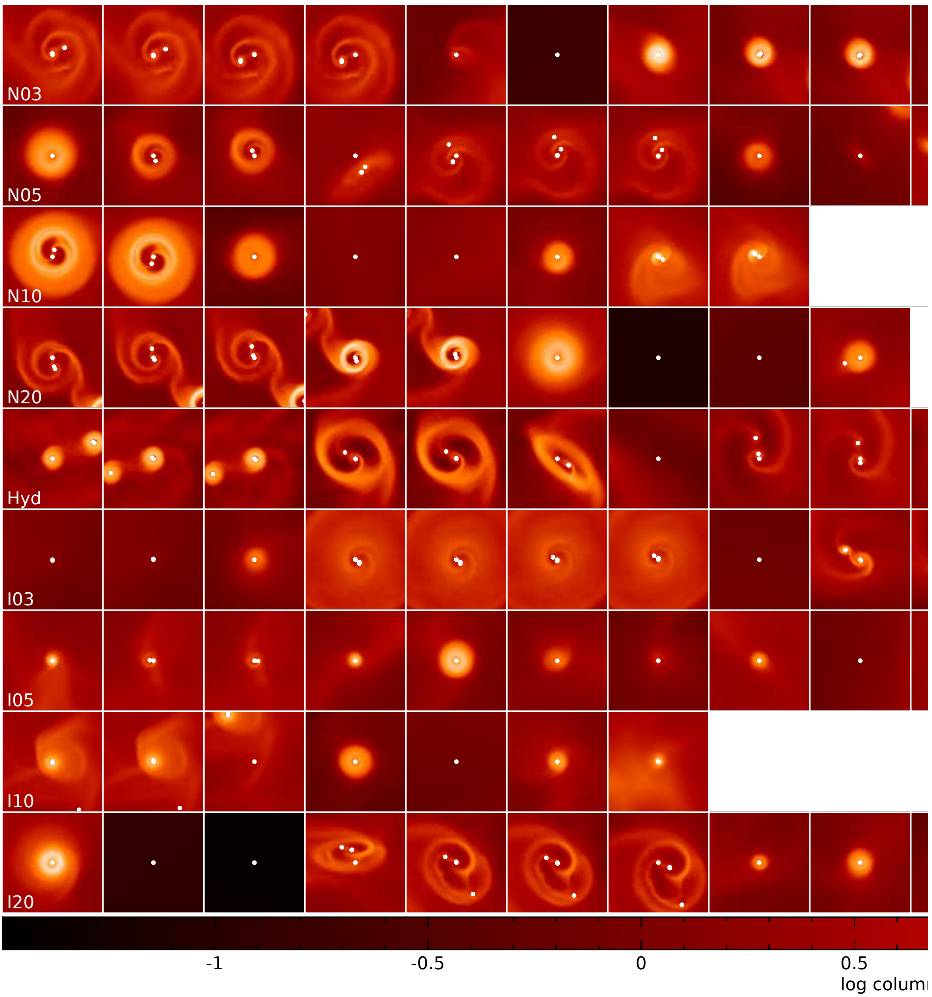
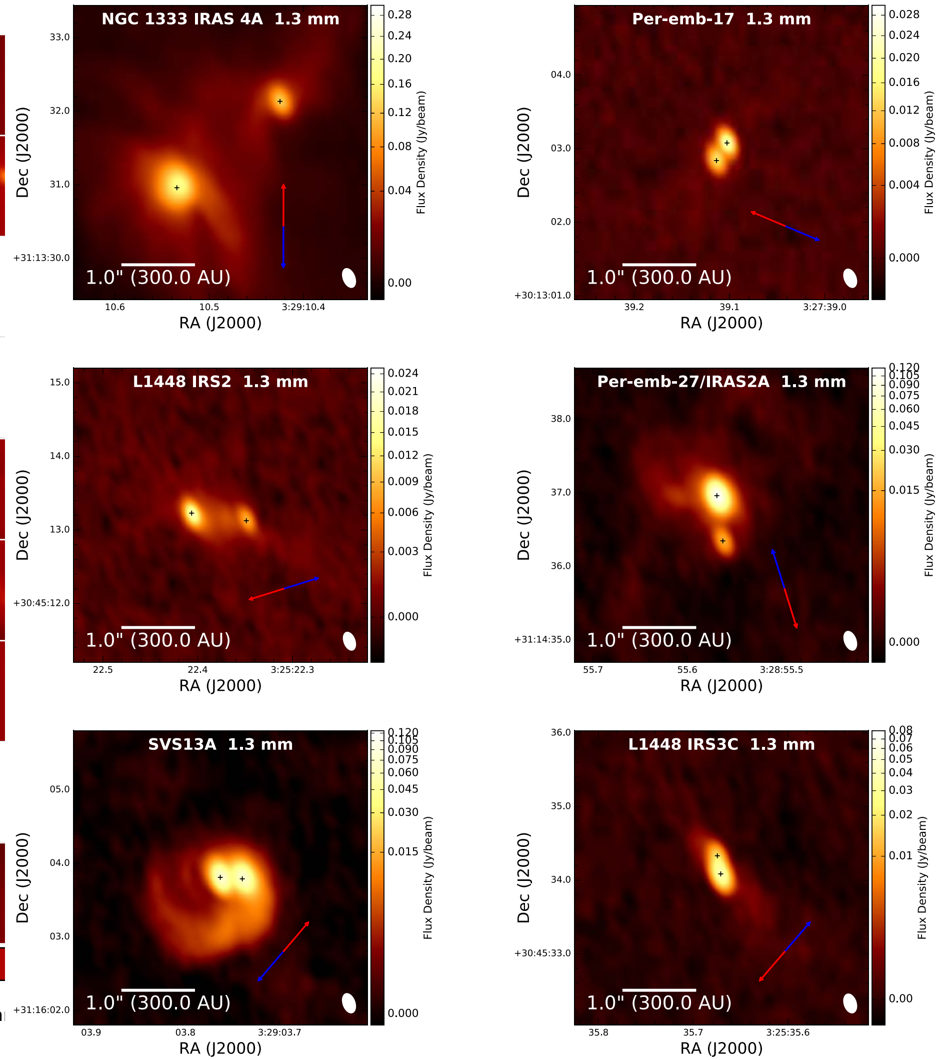
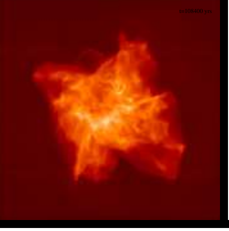


Wurster, Bate & Price (2019)

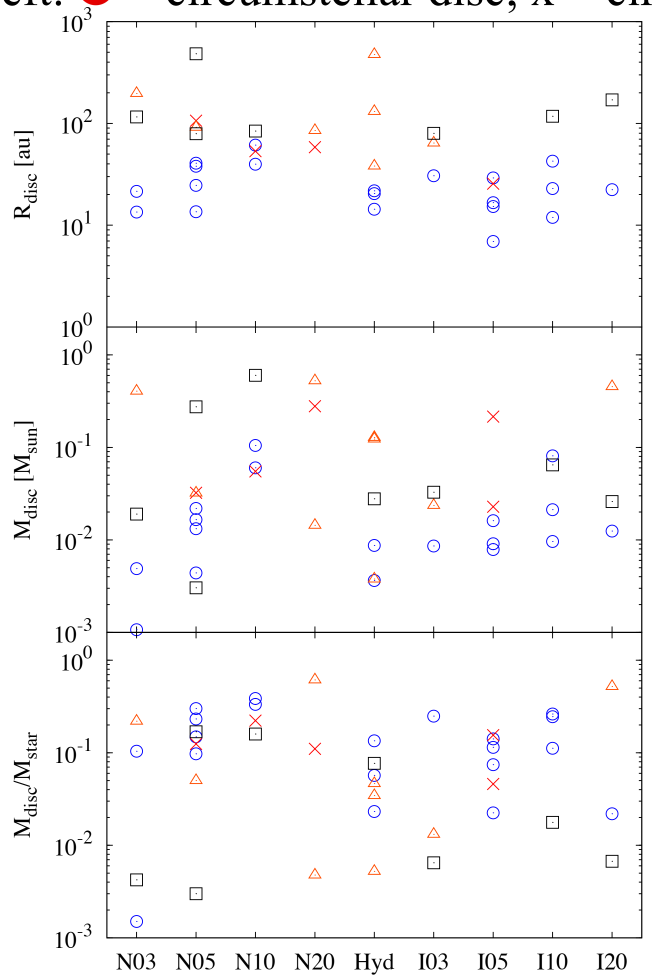


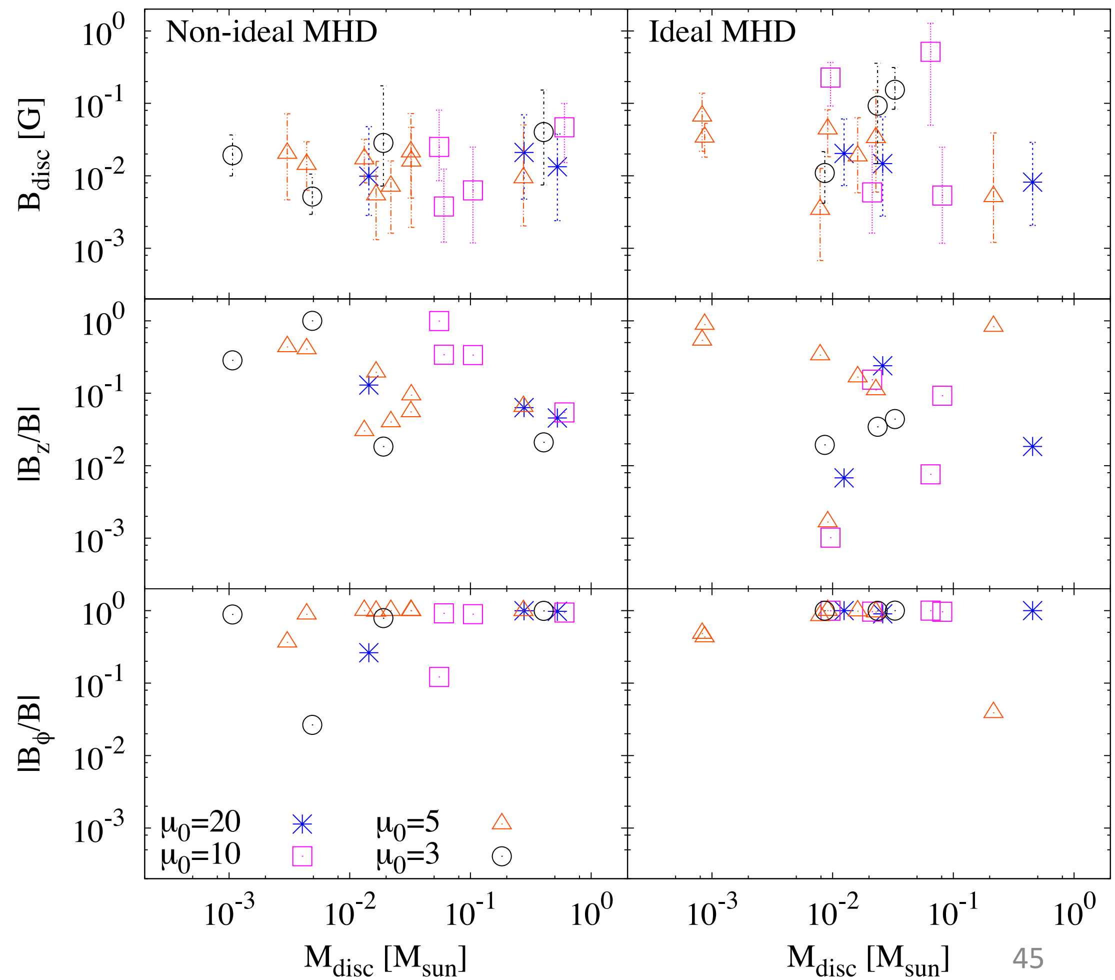
Discs in Perseus (Tobin+2018)



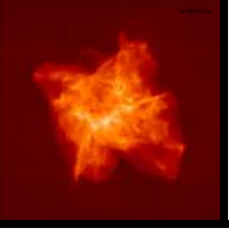
Cluster Formation: Protostellar discs

- Stellar & disc hierarchy is continuously evolving
- There exist circumstellar discs, circumbinary discs, and circumsystem discs
- Left: ⭕ = circumstellar disc; x = circumbinary disc; △ (□)= circumsystem discs about 3 (4) stars





Wurster, Bate & Price (2019)



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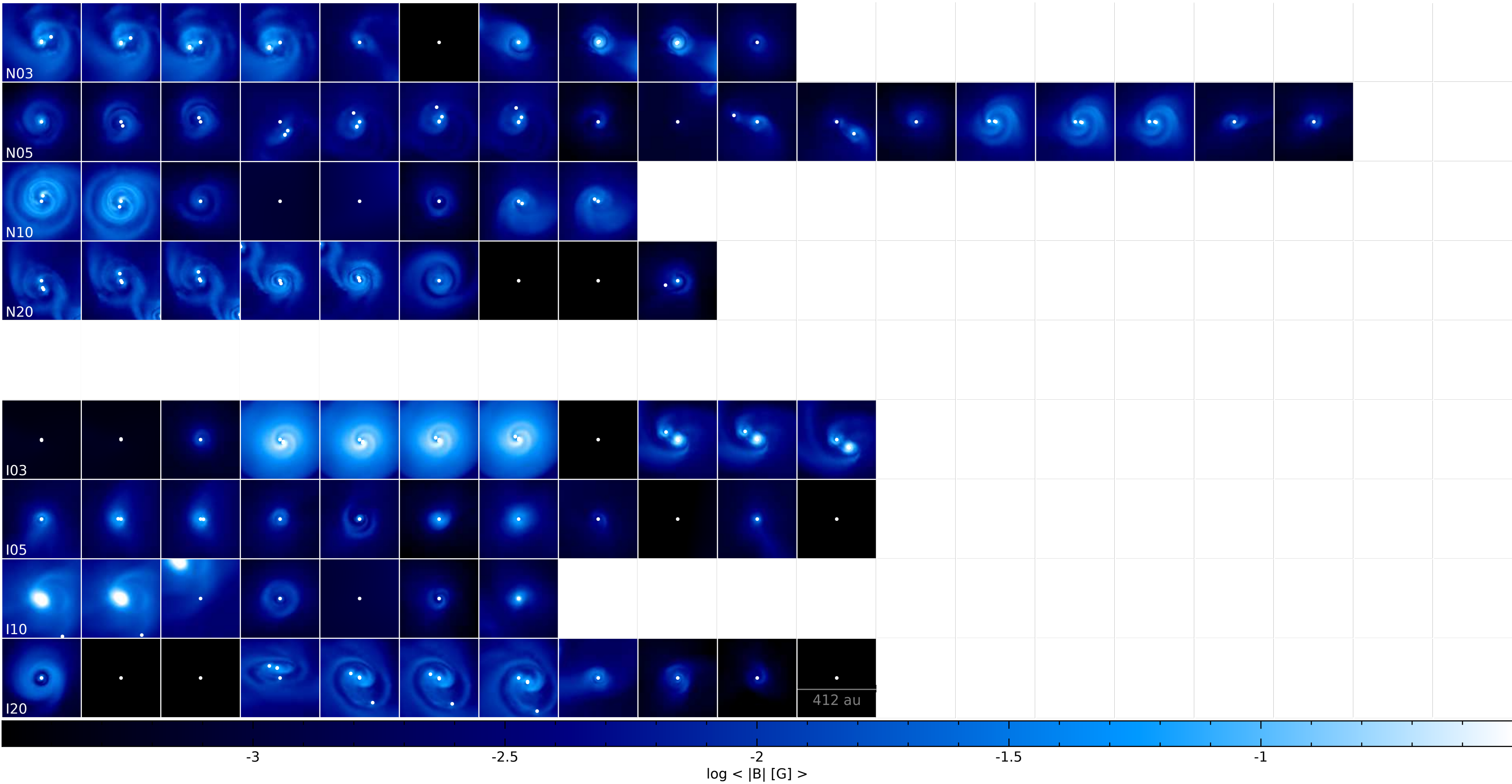

Wurster, Bate & Price (2019)

Conclusions

- Star forming molecular clouds are only weakly ionised
  - Ideal MHD is a poor description

- 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*
  - The Hall effect can cause counter rotating envelopes to form
  - When using non-ideal MHD, the maximum magnetic field strength is not coincident with the central magnetic field strength

- 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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