Star formation with magnetohydrodynamics: What we learn from computer simulations

Dr James Wurster

Primary collaborators: Matthew Bate, Daniel Price & Ian Bonnell

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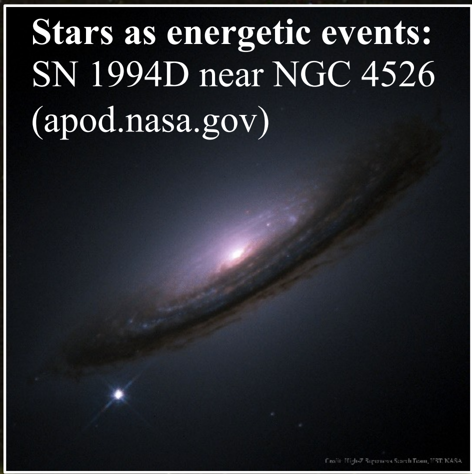
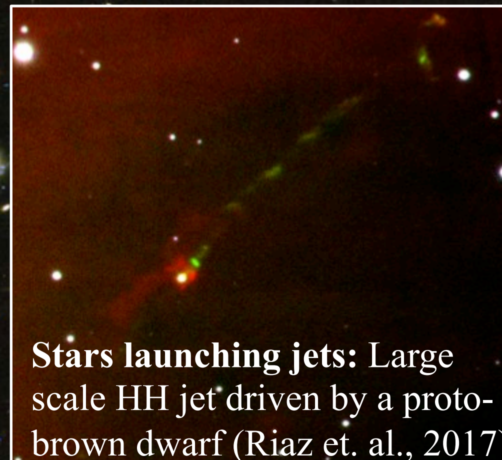
February 6, 2022

Importance of stars: The big picture

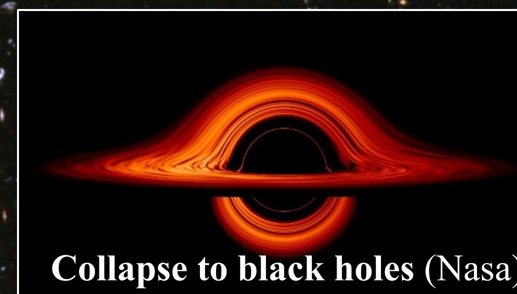


Stars as energetic events: SN 1994D near NGC 4526 (apod.nasa.gov)



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

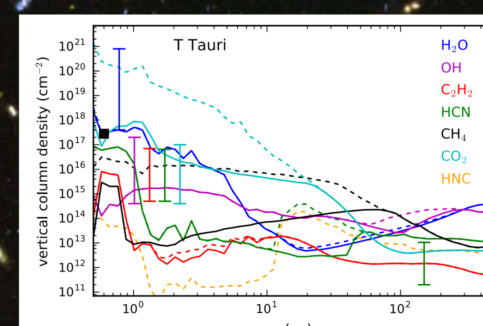
Stars as light sources: Whirlpool Galaxy (M51; nasa.gov)



Collapse to black holes (Nasa)

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

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



Chemical Evolution (Agundez + 2018)

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

Importance of stars: Masses

- Main classes of stellar masses

- Massive stars
  ($M > 8M_{sun}$)
- Low-mass stars
  ($0.08M_{sun} < M$
  & $M < 8M_{sun}$)
- Brown Dwarfs
  ($M < 0.08M_{sun}$)

Importance of stars: Masses

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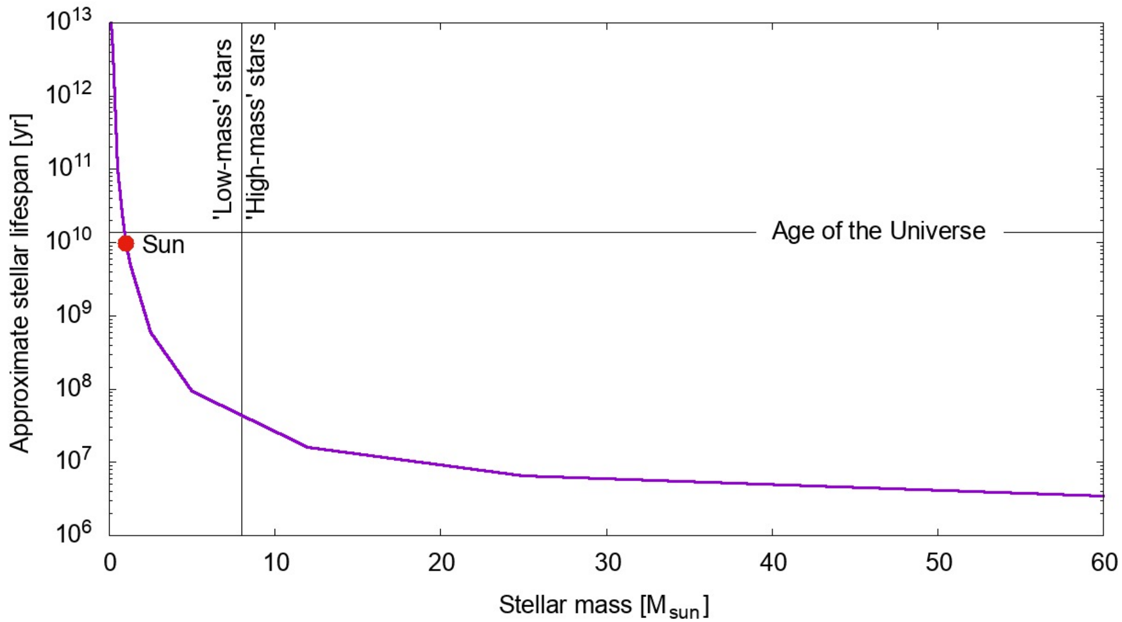

Image: R.N. Bailey (Own work, CC BY 4.0, https://commons.wikimedia.org/w/index.php?curid=59672008)

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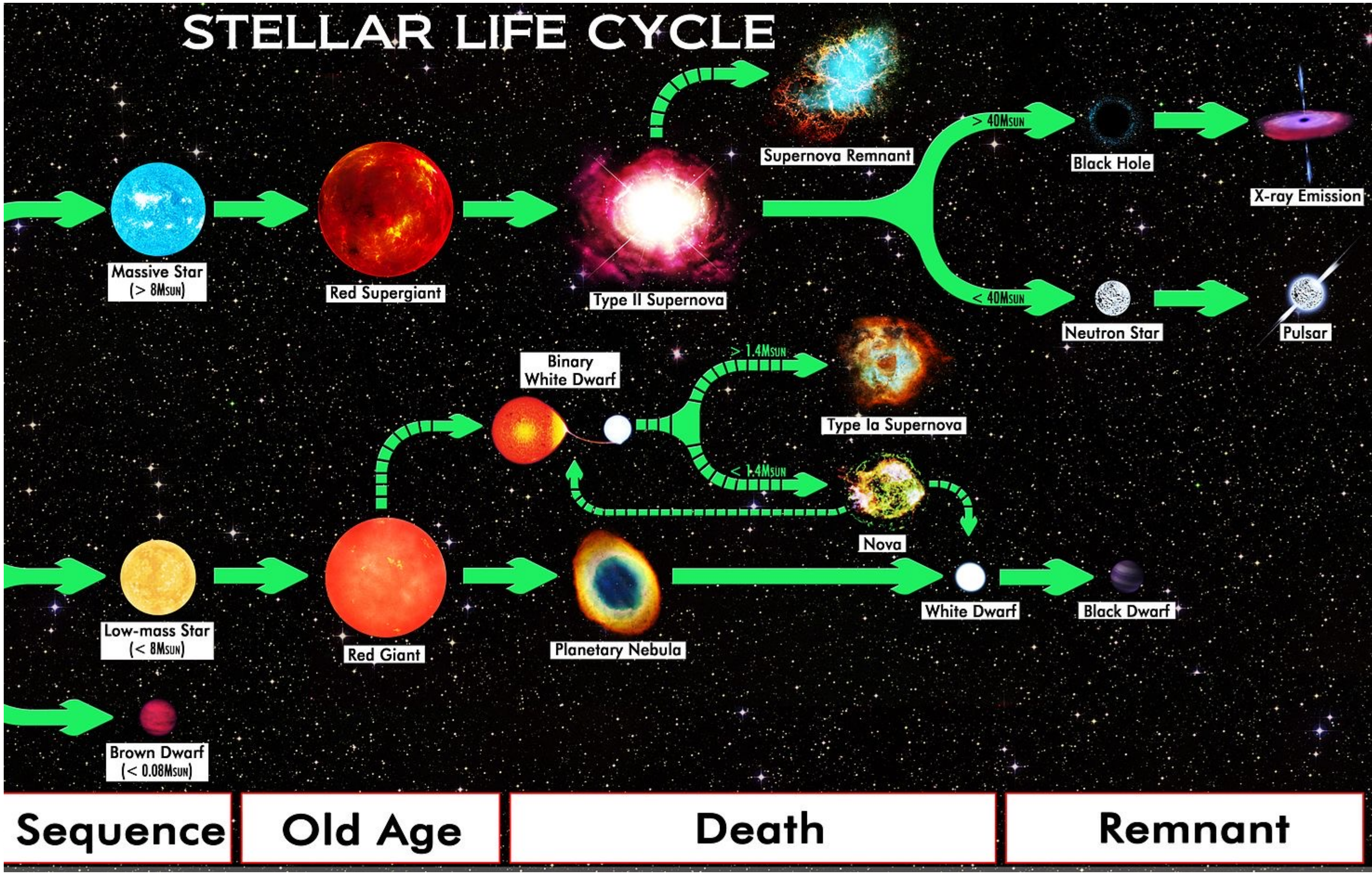

- Evolutionary path is determined by its mass

Importance of stars: Masses

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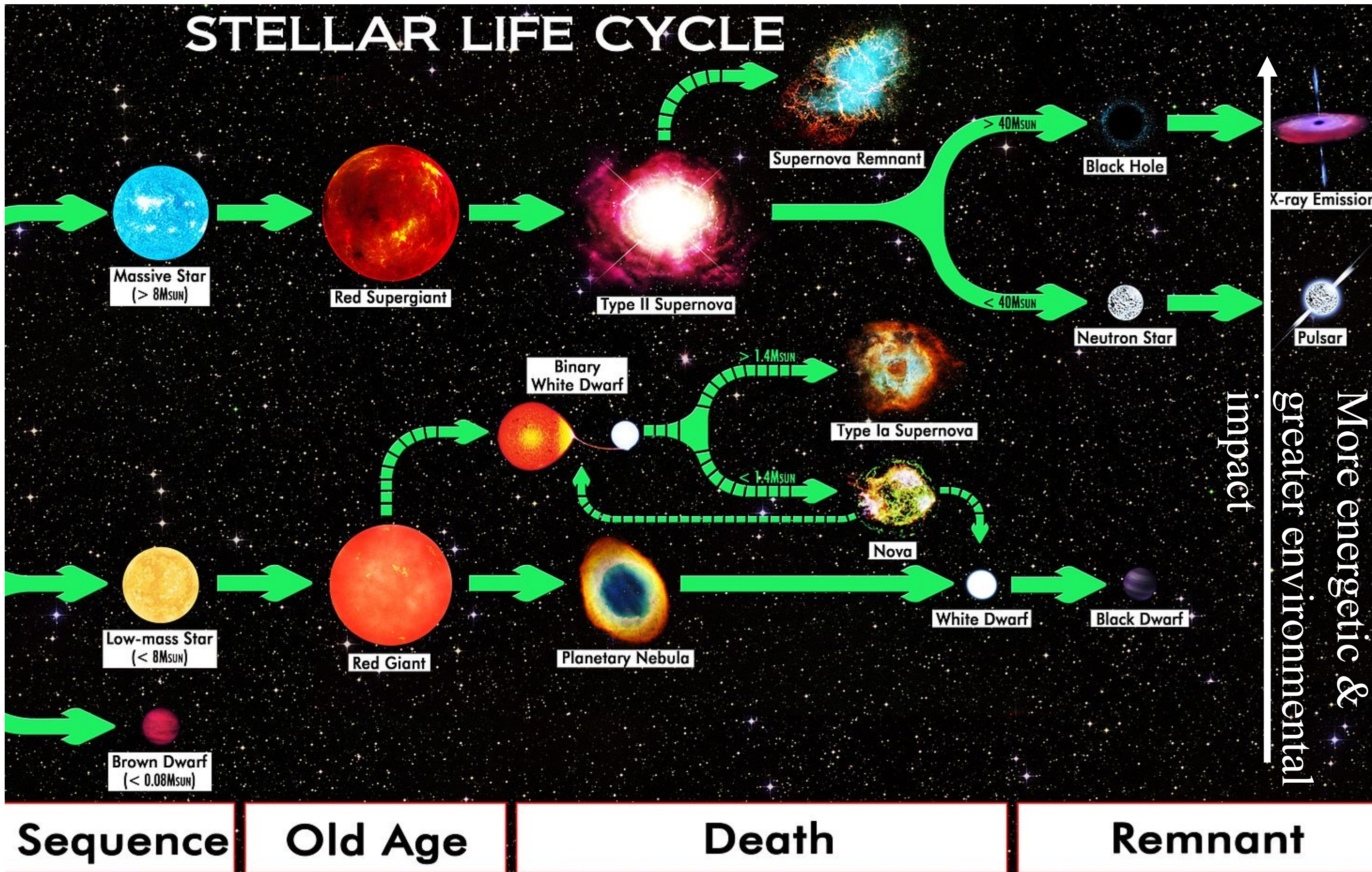
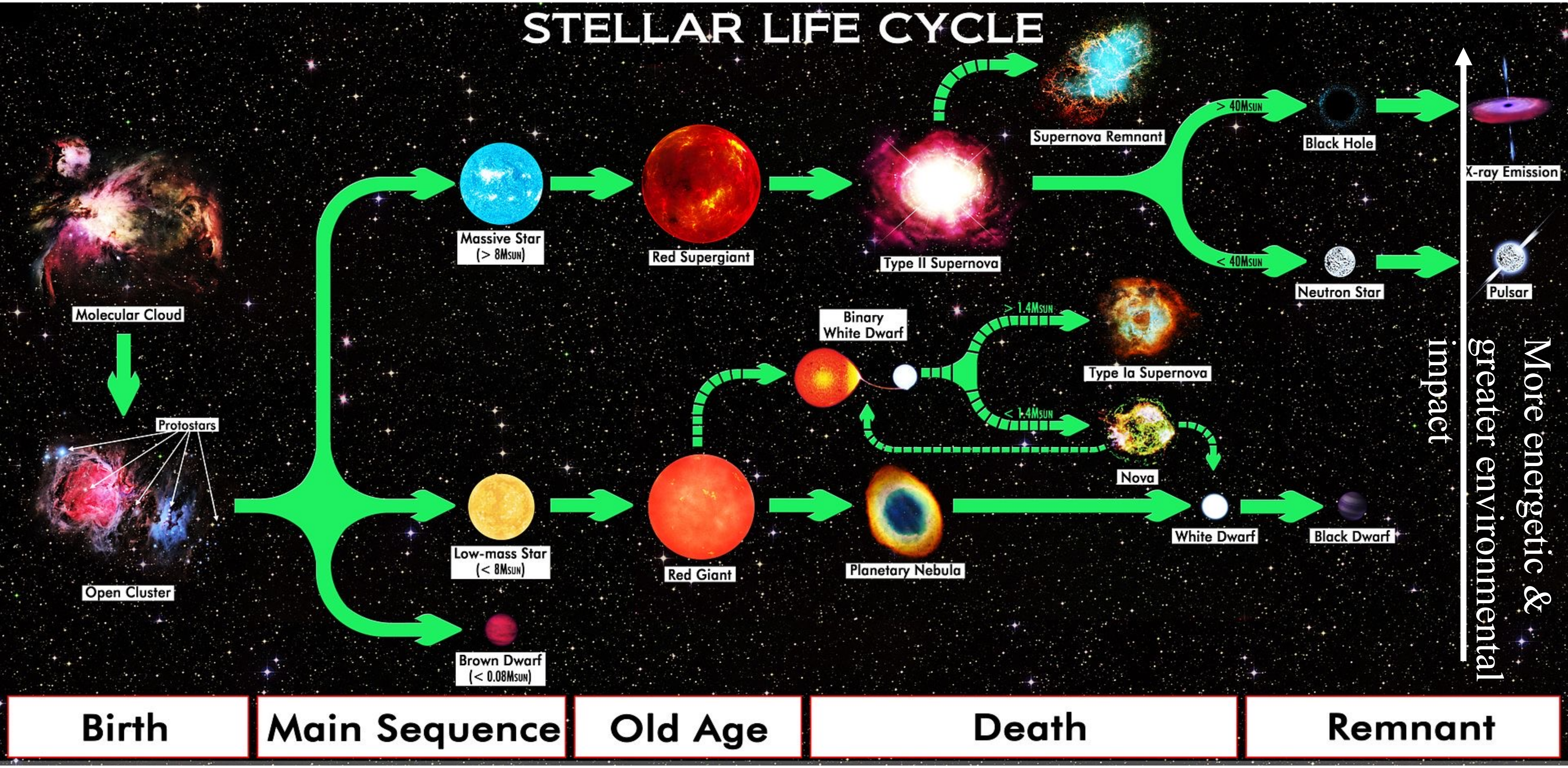


➢ Evolutionary path is determined by its mass

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

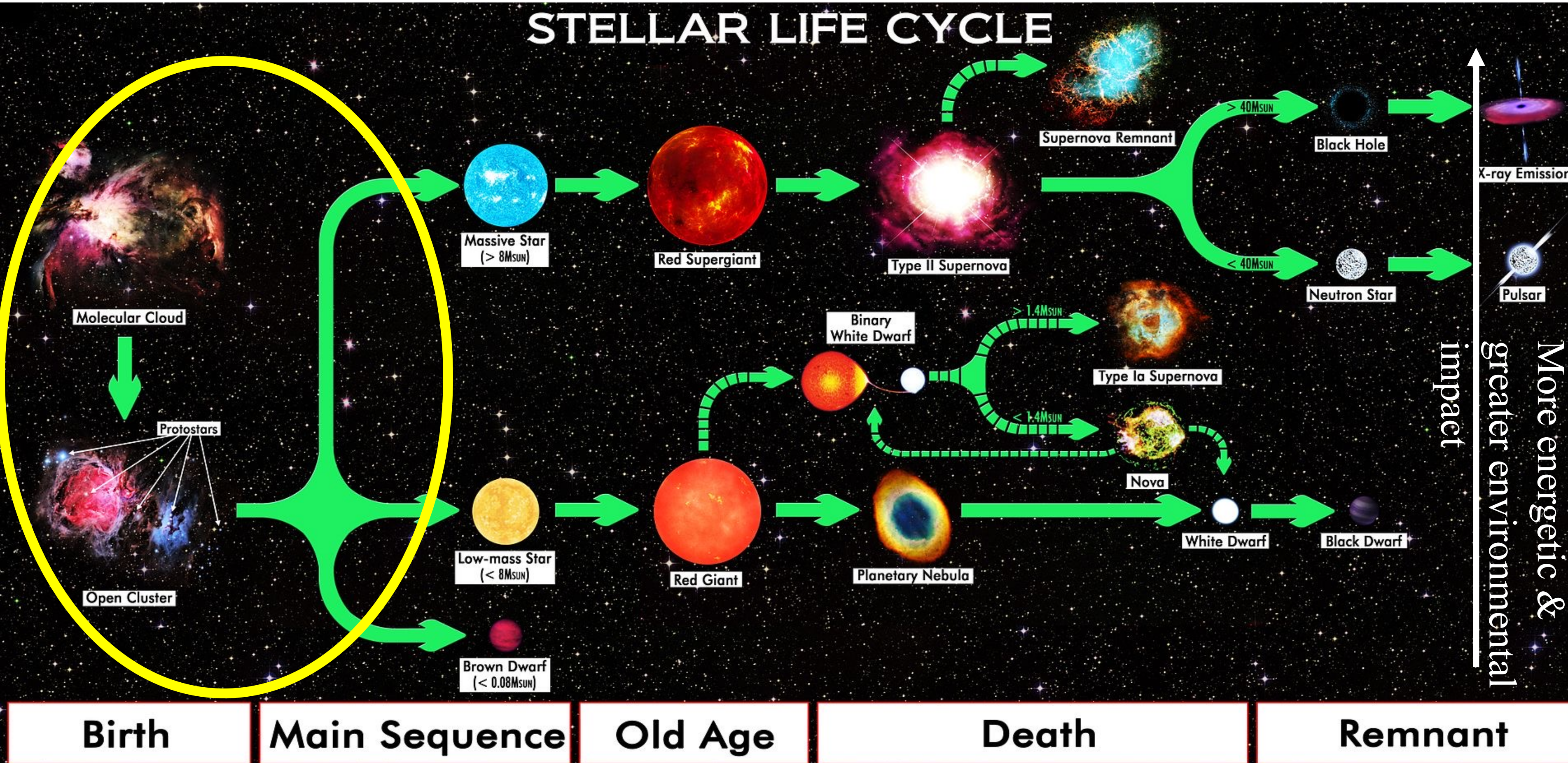
Importance of stars: Masses



- 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



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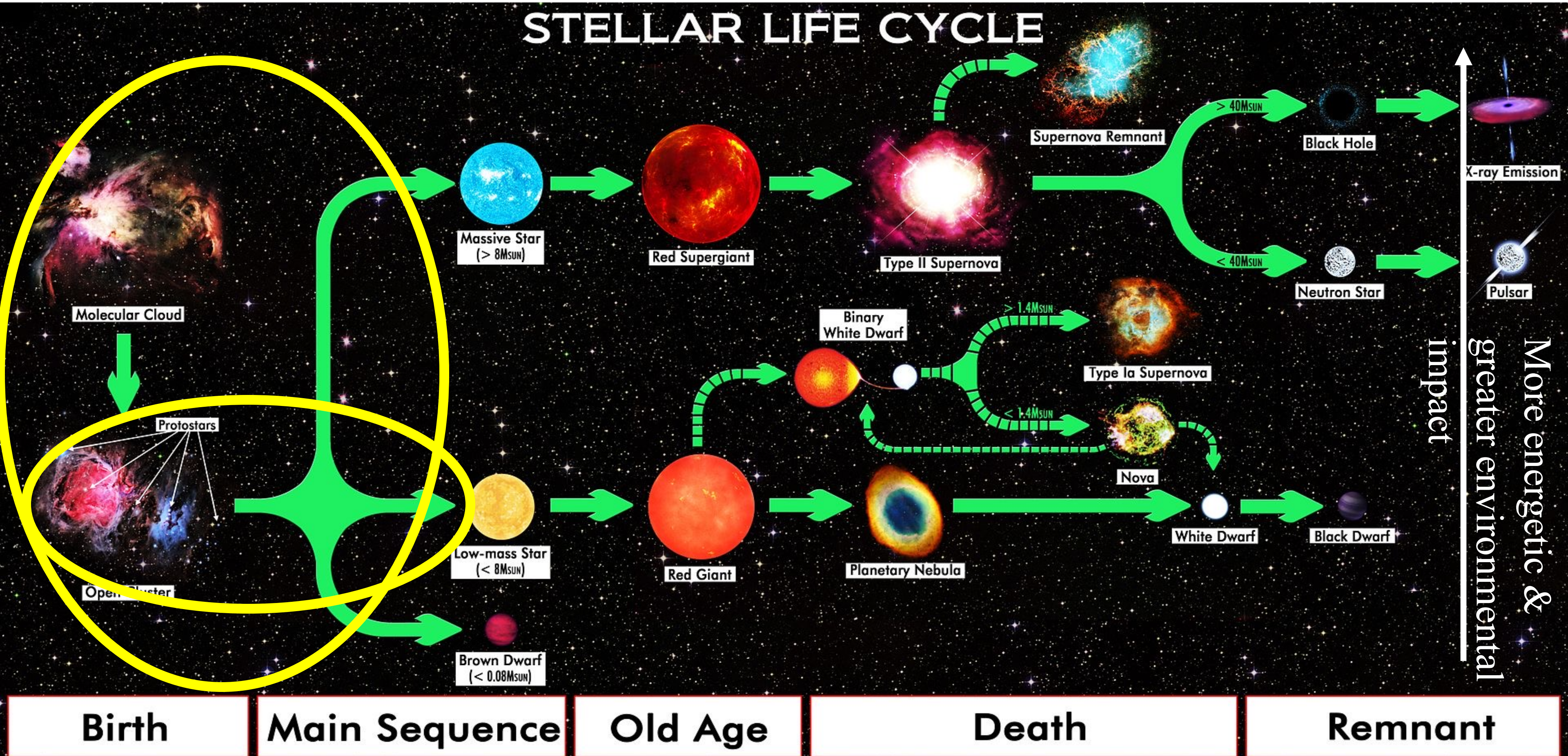
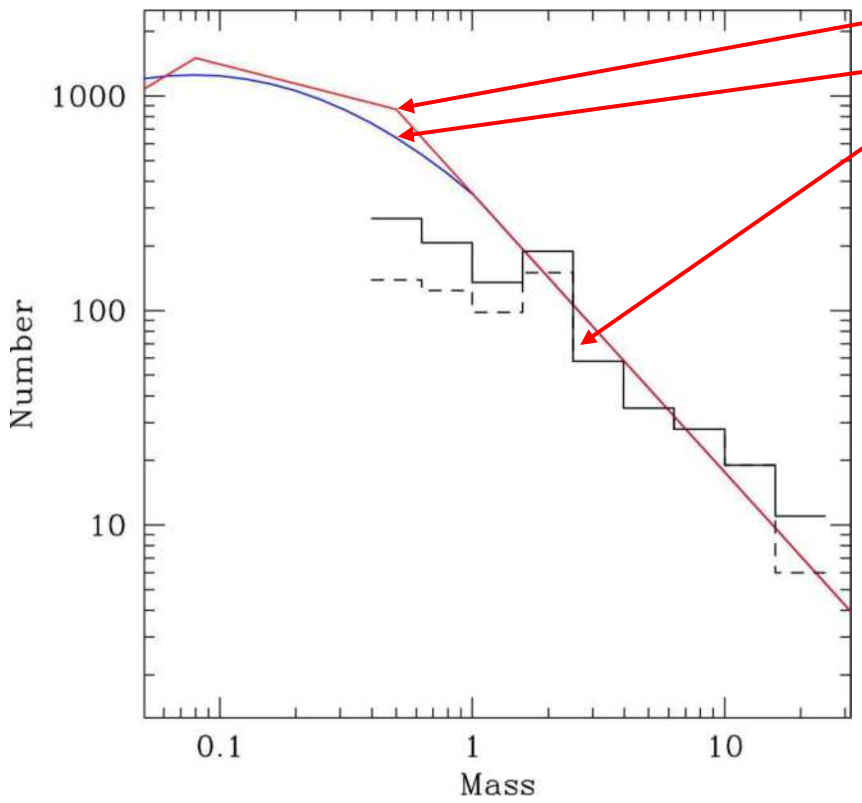


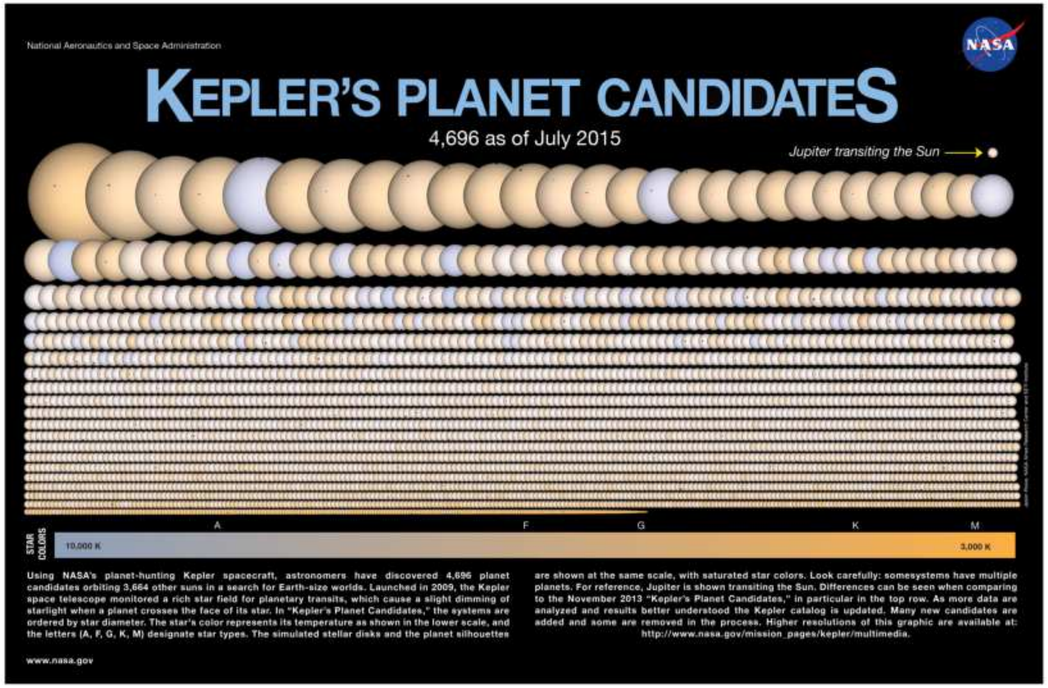
- Evolutionary path is determined by its *birth* mass

Importance of stars: Masses

- Initial mass function (IMF) of NCG 3603



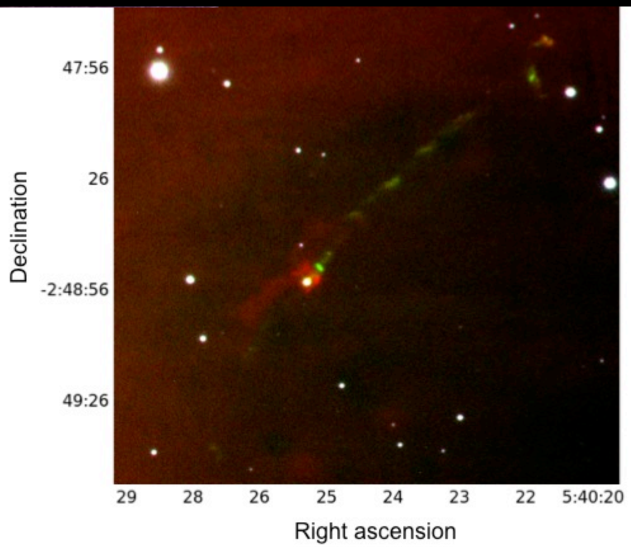
Kroupa IMF (2001)
Chabrier IMF (2003)
NCG 3603 (Stolte+ 2006)

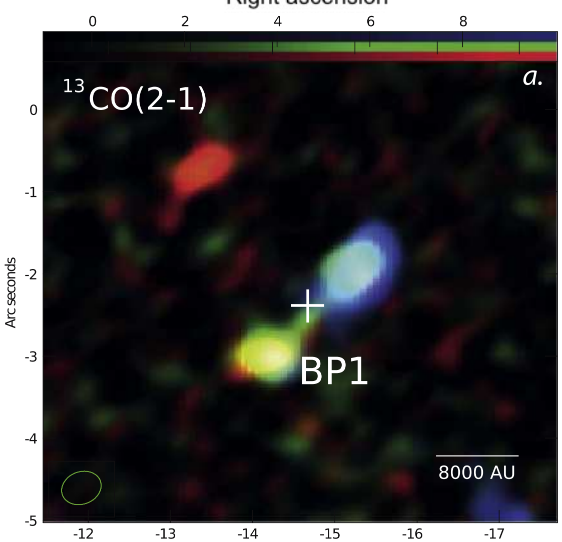


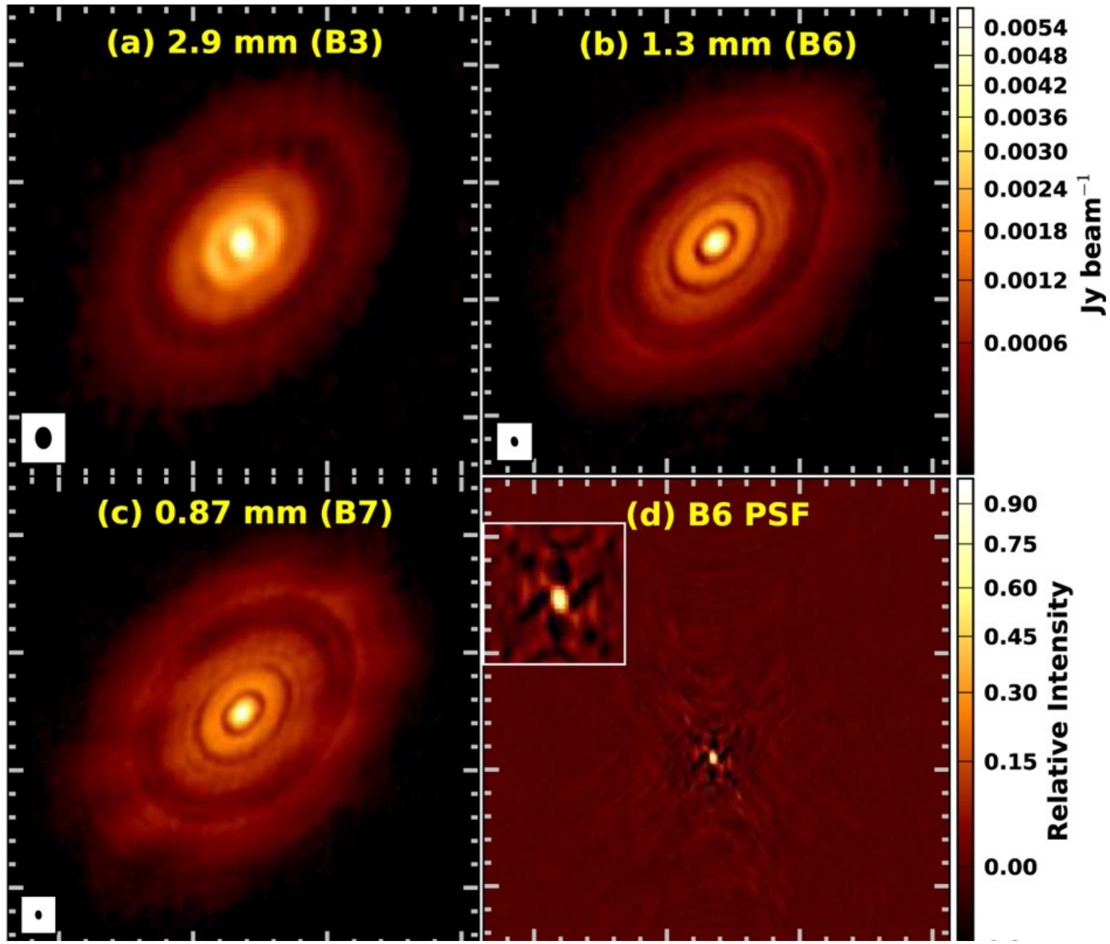
- Low mass stars are much more plentiful than high-mass stars

Left: Bonnell, Larson, Zinnecker (2007)

Importance of Low-stars: Outflows & Discs

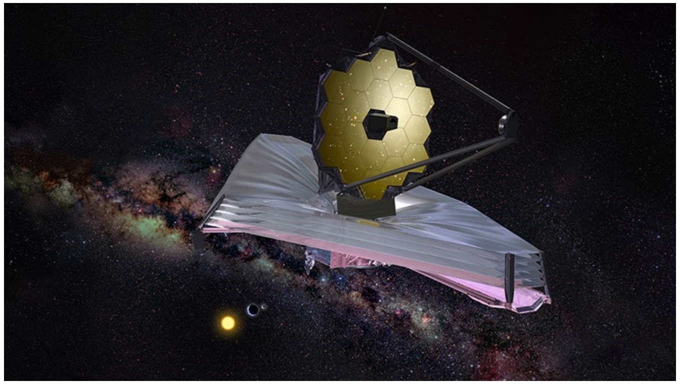


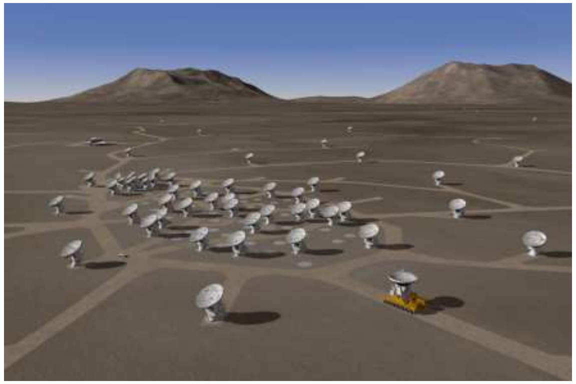




Top left: Large scale Herbig-Haro jet driven by a proto-brown dwarf (Riaz et. al., 2017)
Bottom left: CO outflows from low-mass stars with 1pc of Sgr A* (Yusef-Zadeh et. al., 2017)
Right: HL Tau dust disc (ALMA Partnership, 2015)

Observational vs. theoretical astronomy

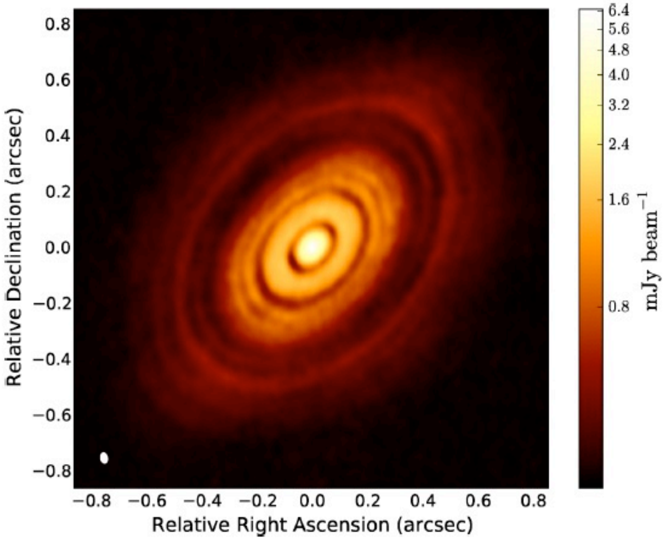


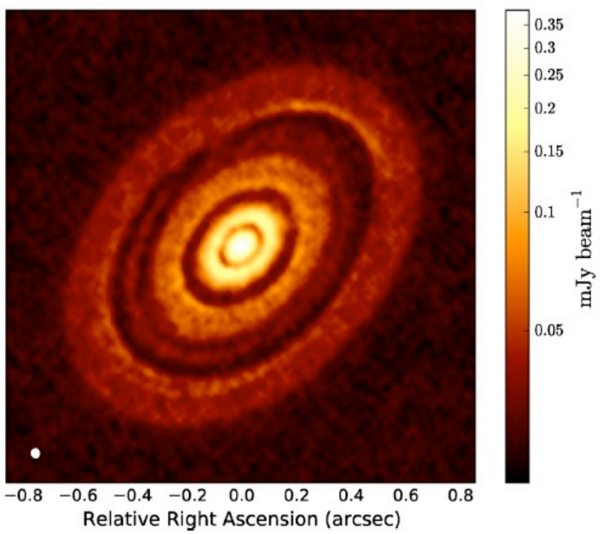


vs.

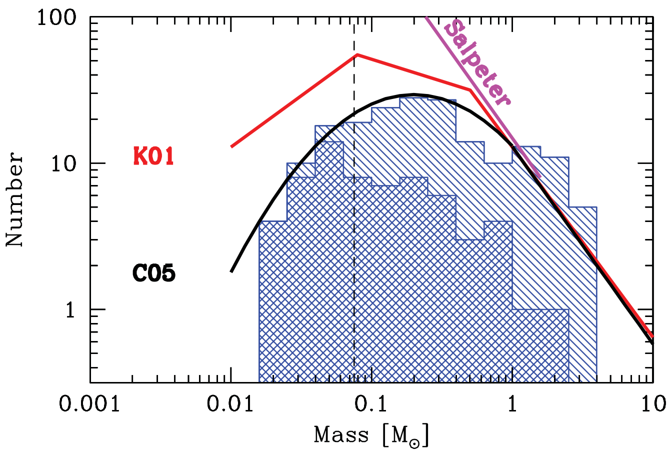
Observational vs. theoretical astronomy

- HL Tau: Observed with ALMA vs numerically produced





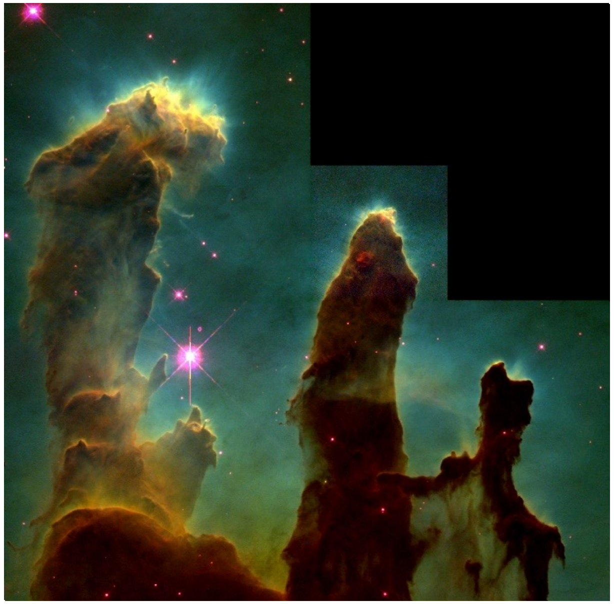
- Initial Mass Function: Observed (lines) vs numerical models



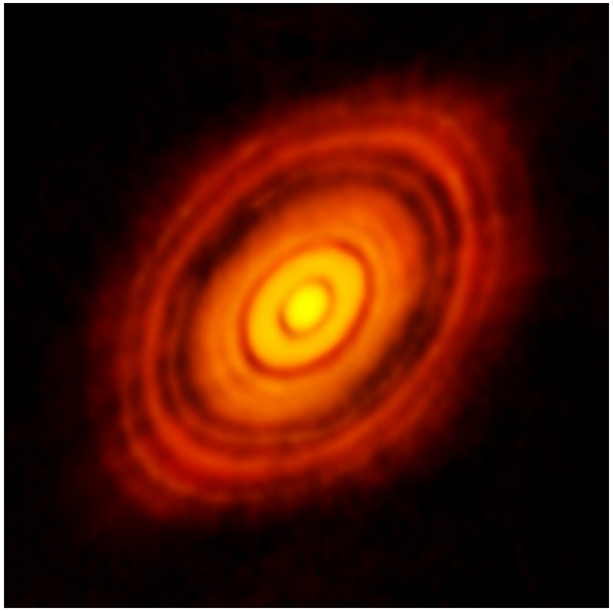
Top: Alma Partnership (2015), Dipierro+2015
Bottom: Bate (2012)

Observational vs. theoretical astronomy

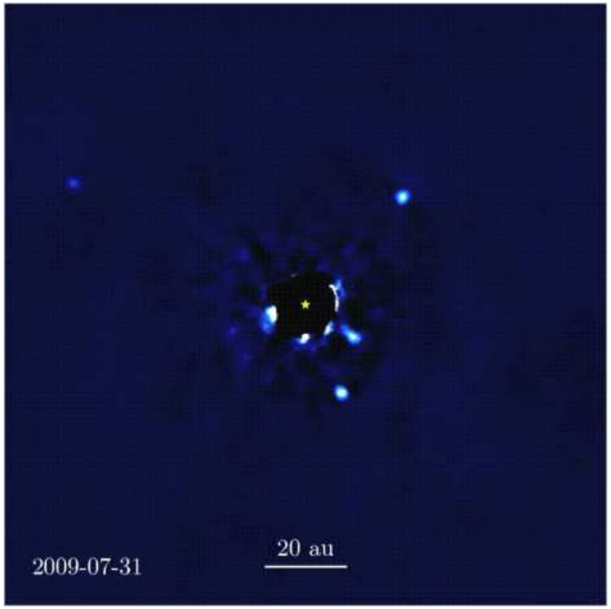
- Star formation is a long process, lasting millions of years
- Observationally, we take 'snap-shots' in time,
  and piece them together to form a star formation theory



Star forming region
Pillars of Creation
(Hubble Space Telescope)



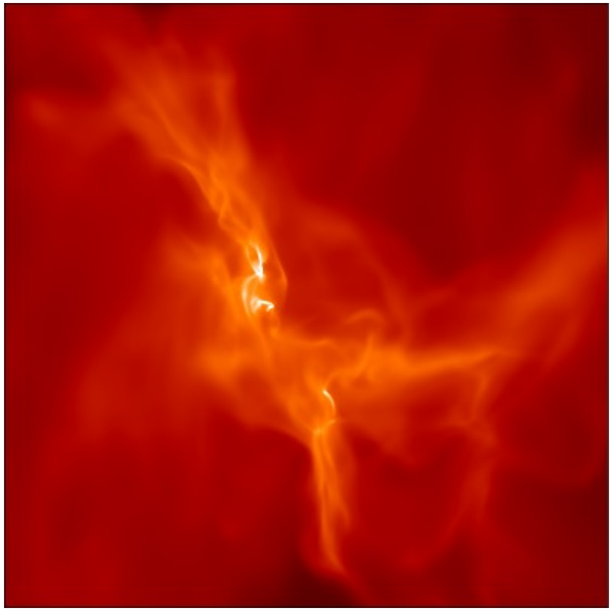
Protoplanetary disc
HL Tau
(ALMA Partnership 2015)



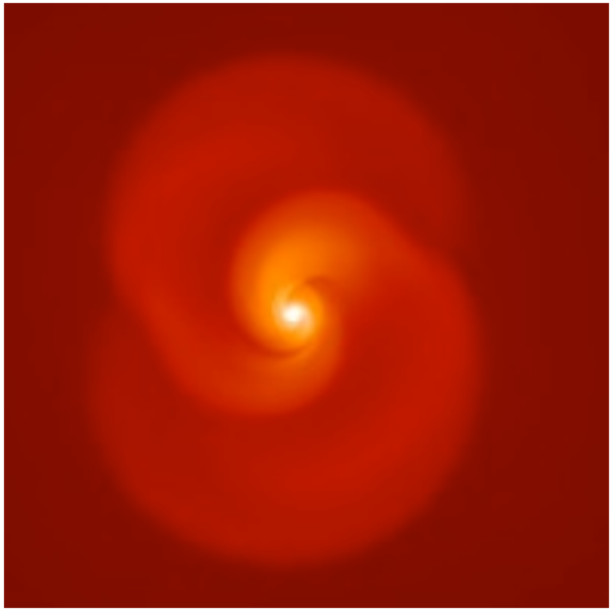
Planetary system
HR 8799
(Jason Wang & Christian Marois)

Observational vs. theoretical astronomy

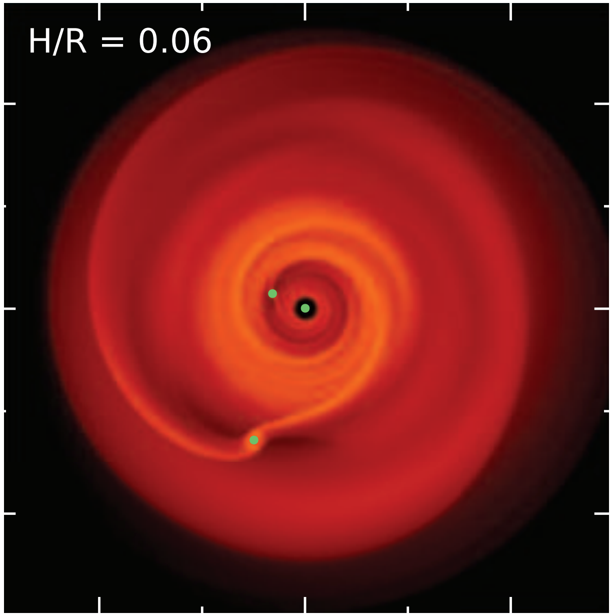
- Star formation is a long process, lasting millions of years
- Observationally, we take ‘snap-shots’ in time,
  and piece them together to form a star formation theory
- Numerical simulations can self-consistently model long periods of time to follow the evolution of a single system



Star forming region
(Wurster+2019)



Protoplanetary disc
(Wurster+2018)



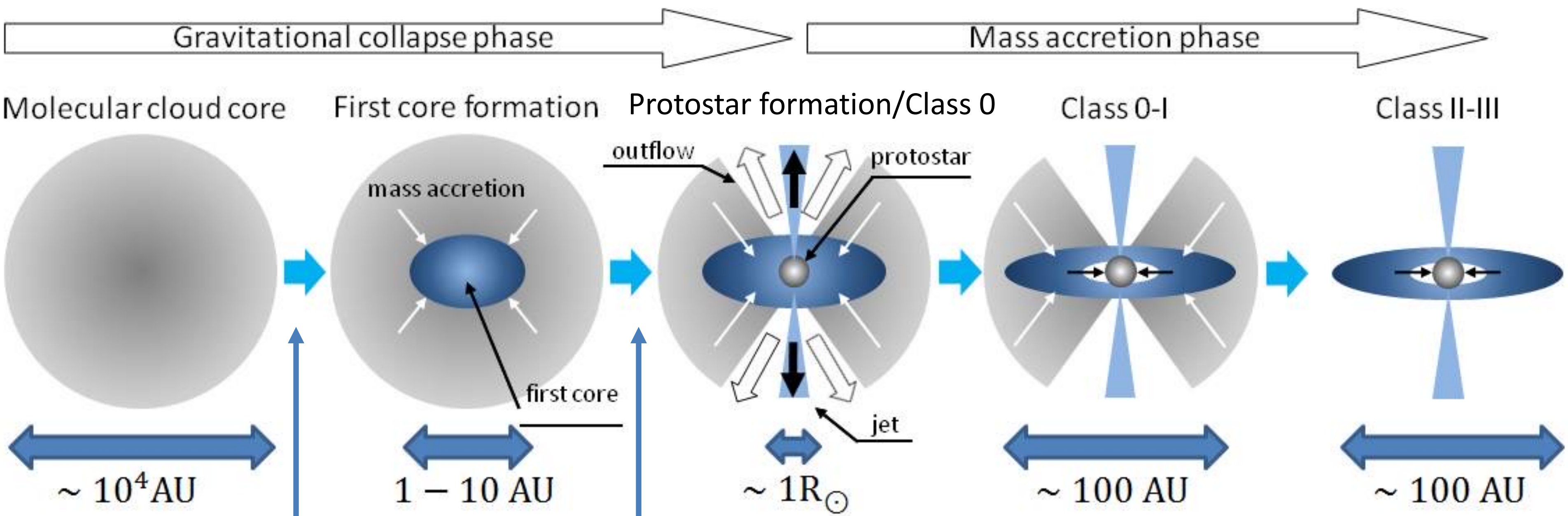
Planetary system
(Veronesi+2019)

Star formation: From the beginning

How is a star formed?

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

Star formation: From the beginning



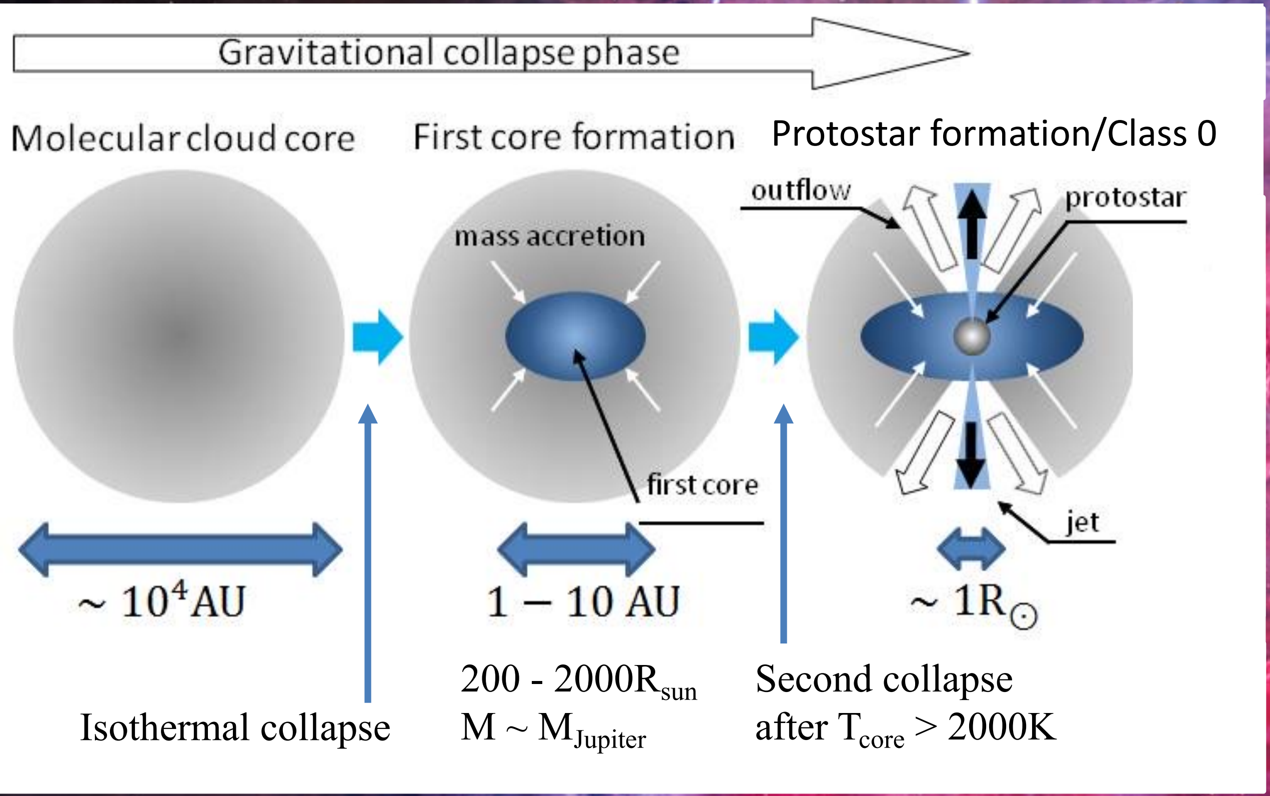
Isothermal collapse

200 - 2000R_{sun}
M ~ $M_{Jupiter}$

Second collapse
after T_{core} > 2000K

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

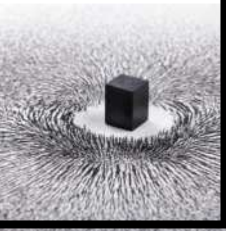
Star formation: From the beginning



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

Larson (1969); Illustration by Y. Tsukamoto

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



Continuum Magnetohydrodynamic Equations

- Continuum equations to be solved:

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = -\rho\nabla\cdot\boldsymbol{v},$$

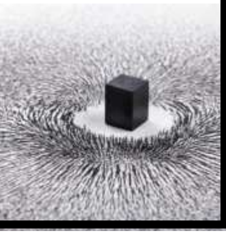
$$\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} = -\frac{1}{\rho}\nabla\cdot\left[\left(p+\frac{B^2}{2}\right)I-\boldsymbol{B}\boldsymbol{B}\right]-\nabla\Phi+\frac{\kappa F}{c},$$

$$\rho\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\boldsymbol{B}}{\rho}\right) = (\boldsymbol{B}\cdot\nabla)\,\boldsymbol{v}+\left.\frac{\mathrm{d}\boldsymbol{B}}{\mathrm{d}t}\right|_{\text{non-ideal}},$$

$$\rho\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{E}{\rho}\right) = -\nabla\cdot\boldsymbol{F}-\nabla\boldsymbol{v}{:}\boldsymbol{P}+4\pi\kappa\rho B_{\mathrm{P}}-c\kappa\rho E,$$

$$\rho\frac{\mathrm{d}u}{\mathrm{d}t} = -p\nabla\cdot\boldsymbol{v}-4\pi\kappa\rho B_{\mathrm{P}}+c\kappa\rho E+\rho\left.\frac{\mathrm{d}u}{\mathrm{d}t}\right|_{\text{non-ideal}},$$

$$\nabla^2\Phi = 4\pi G\rho,$$



Continuum Magnetohydrodynamic Equations

- Simplified Continuum Equations:
  - Continuity Equation

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = -\rho\nabla\cdot\boldsymbol{v}$$

  - Equation of Motion

$$\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} = -\frac{1}{\rho}\nabla\left[\left(P+\frac{B^2}{2\mu_0}\right)I-\frac{1}{\mu_0}\boldsymbol{B}\boldsymbol{B}\right]$$

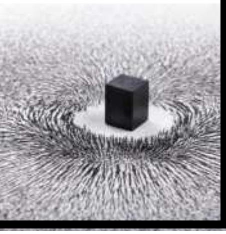
  - Induction Equation

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\boldsymbol{B}}{\rho}\right) = \left(\frac{\boldsymbol{B}}{\rho}\cdot\nabla\right)\boldsymbol{v}$$

  - Energy Equation

$$\frac{\mathrm{d}u}{\mathrm{d}t} = -\frac{P}{\rho}\nabla\cdot\boldsymbol{v}$$

  - Equation of state (e.g.) $P = (\gamma-1)\,\rho u$



Discrete Magnetohydrodynamic Equations

- Discrete Equations:
  - Density Equation

$$\rho_a = \sum_b m_b W_{ab}(h_a); \quad h_a = \eta \left(\frac{m_a}{\rho_a}\right)^{1/3}$$

  - Equation of Motion

$$\frac{\mathrm{d}v_a^i}{\mathrm{d}t} = \sum_b m_b \left[\frac{S_a^{ij}}{\Omega_a \rho_a^2} \nabla_a^j W_{ab}(h_a) + \frac{S_b^{ij}}{\Omega_b \rho_b^2} \nabla_a^j W_{ab}(h_b)\right]$$

  - Induction Equation

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{B_a^i}{\rho_a}\right) = -\frac{1}{\Omega_a \rho_a^2} \sum_b m_b v_{ab}^i B_a^j \nabla_a^j W_{ab}(h_a)$$

  - Energy Equation

$$\frac{\mathrm{d}u_a}{\mathrm{d}t} = \frac{P_a}{\Omega_a \rho_a^2} \sum_b m_b v_{ab}^j \nabla_a^j W_{ab}(h_a)$$

  - MHD stress tensor

$$S_a^{ij} \equiv -\left(P_a + \frac{1}{2\mu_0} B_a^2\right) \delta^{ij} + \frac{1}{\mu_0} B_a^i B_a^j$$

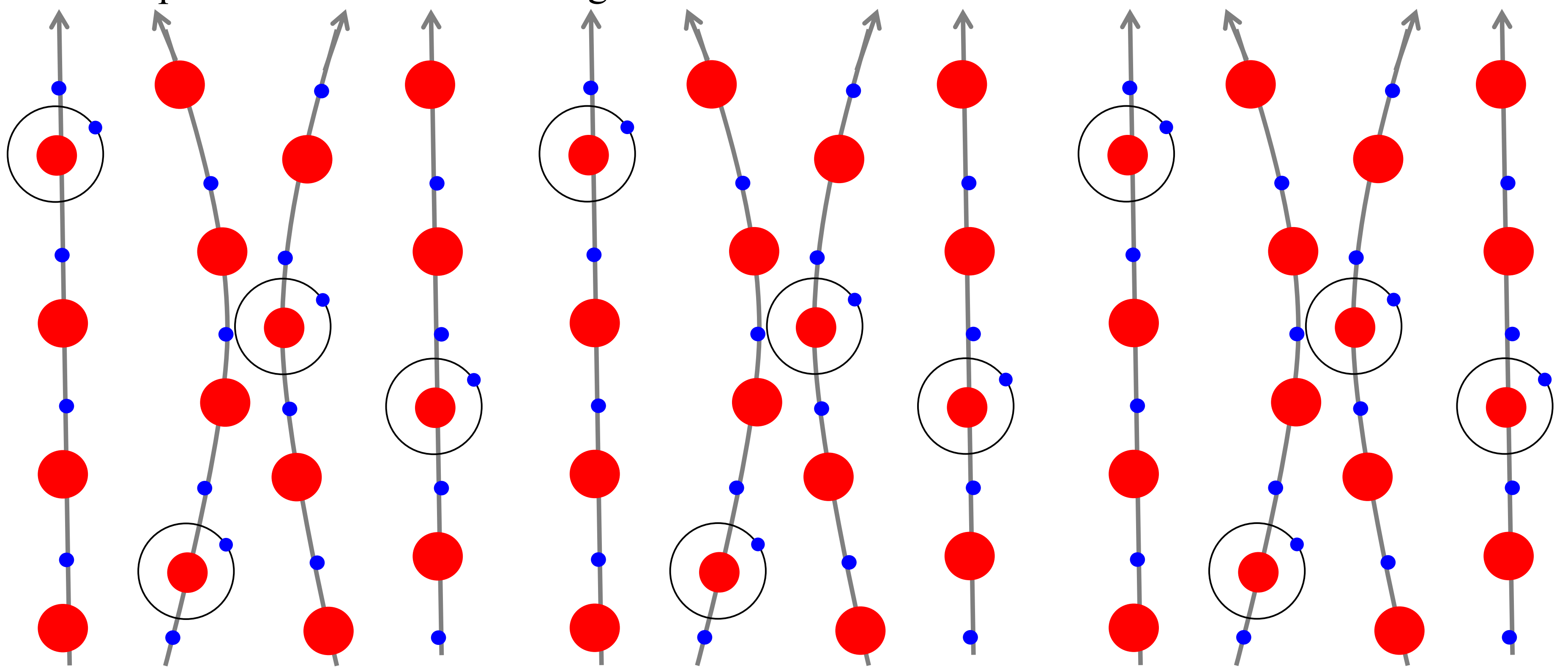
  - Note: In all SPMHD equations, ***B*** has been normalised such that $\boldsymbol{B} = \boldsymbol{B}/\sqrt{\mu_0}$

Ideal magnetohydrodynamics

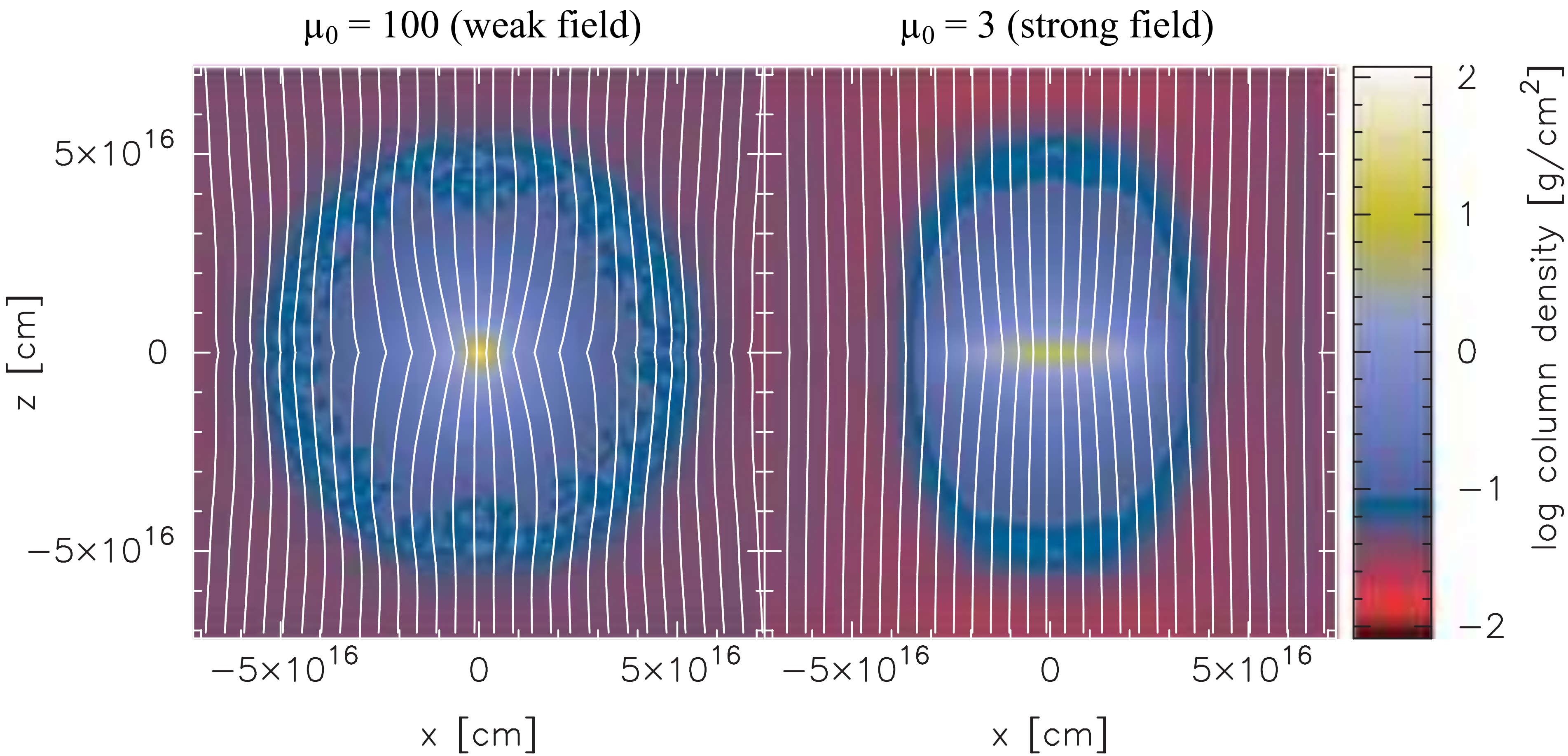
- Highly ionised plasma:

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

- 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)

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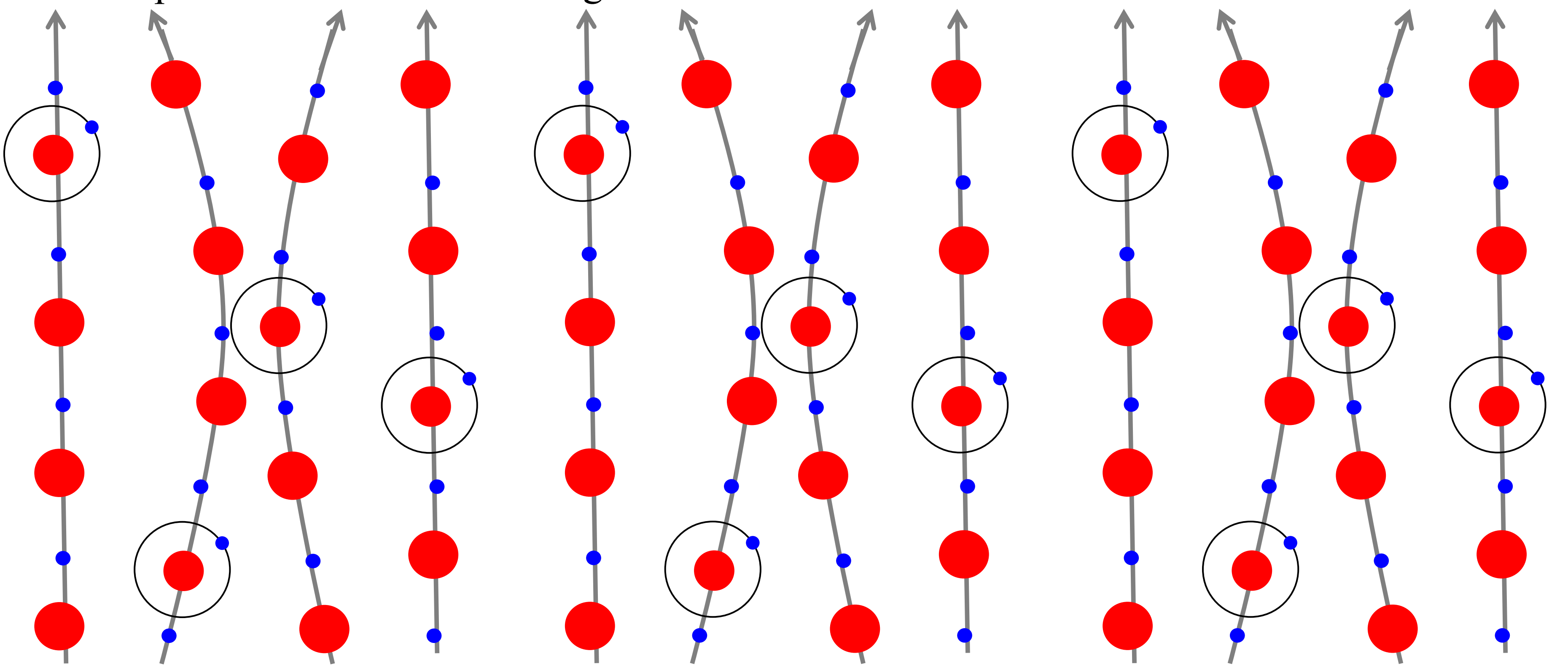

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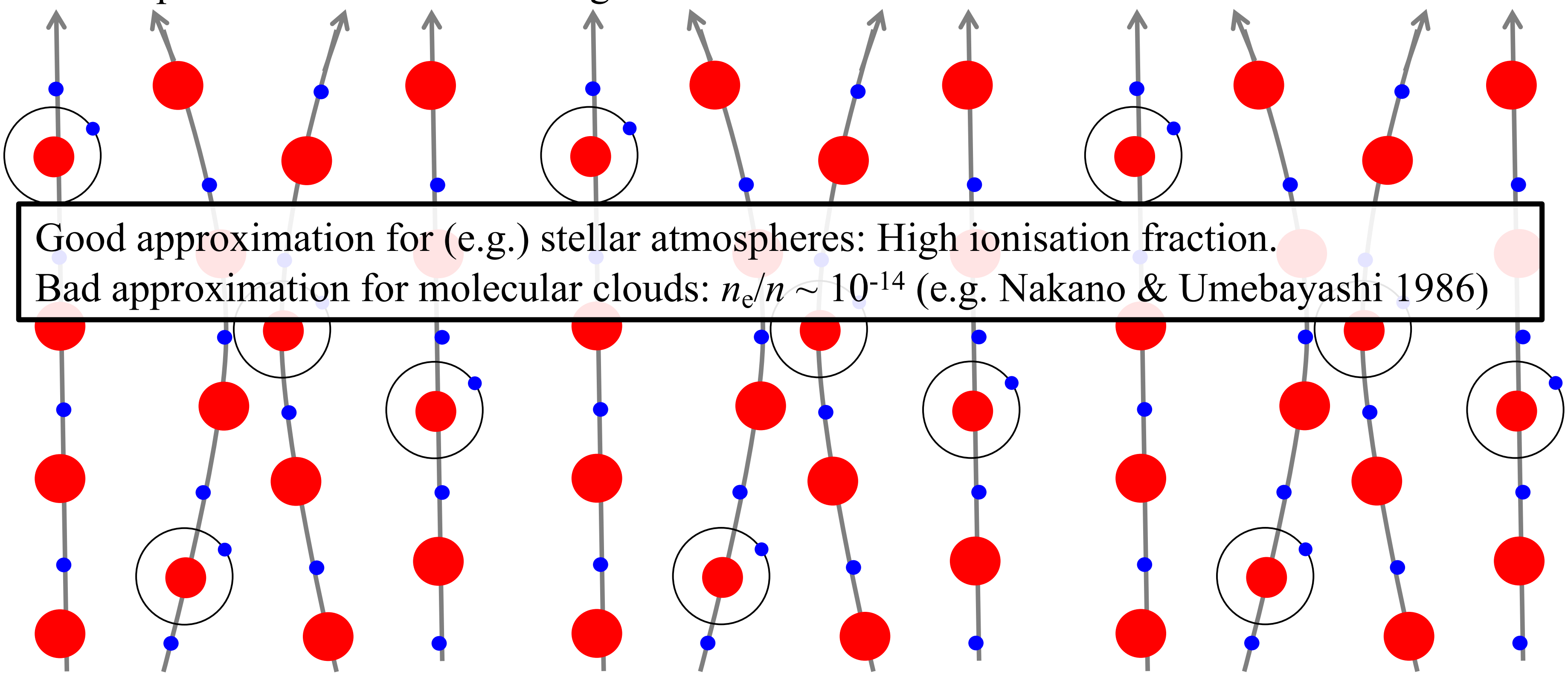
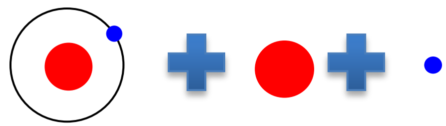
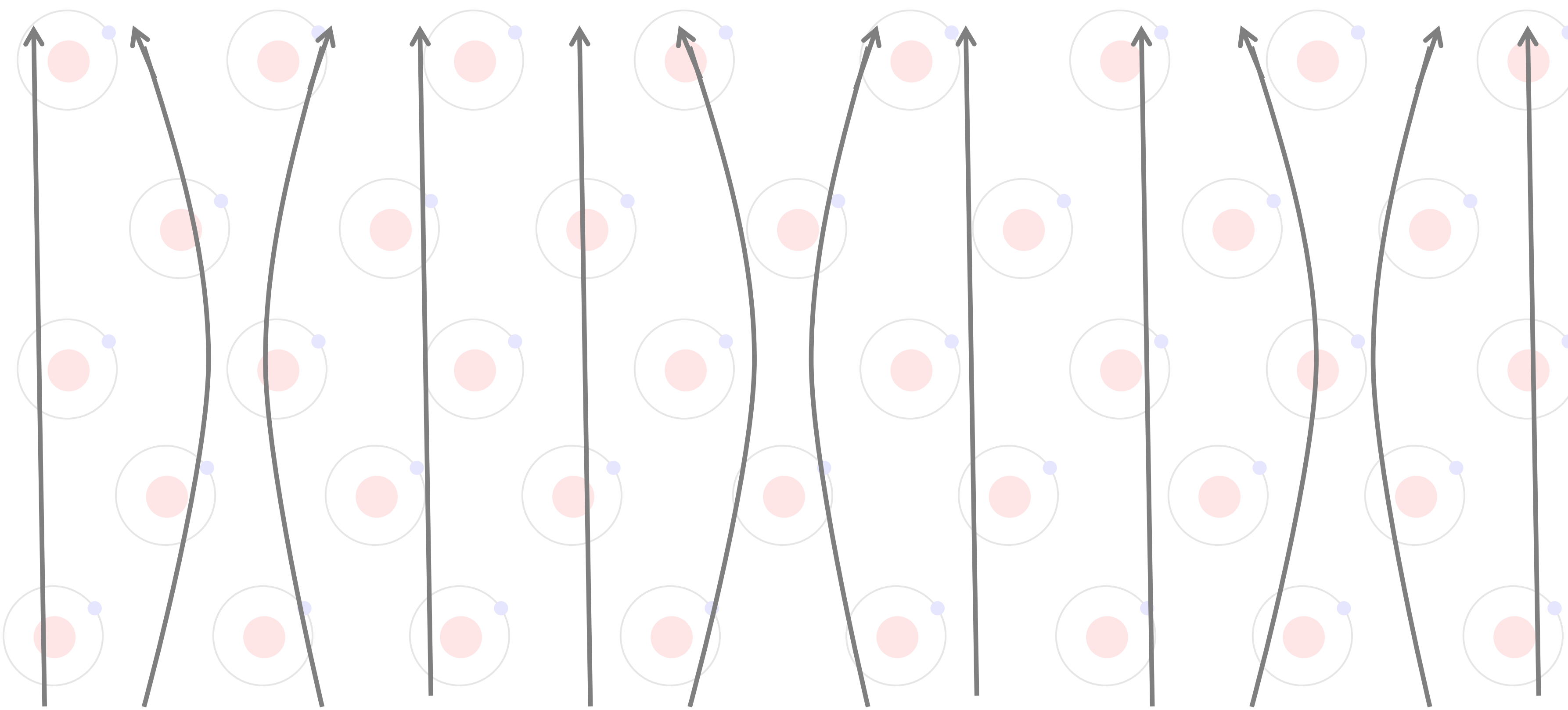


Good approximation for (e.g.) stellar atmospheres: High ionisation fraction.
Bad approximation for molecular clouds: $n_e/n \sim 10^{-14}$ (e.g. Nakano & Umebayashi 1986)

Non-ideal magnetohydrodynamics

- Partially ionised plasma: 

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



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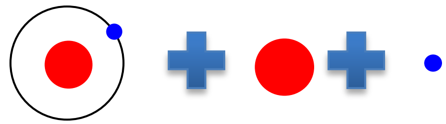
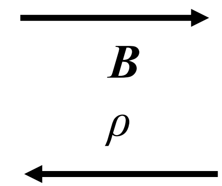
- ➢Partially ionised plasma: 



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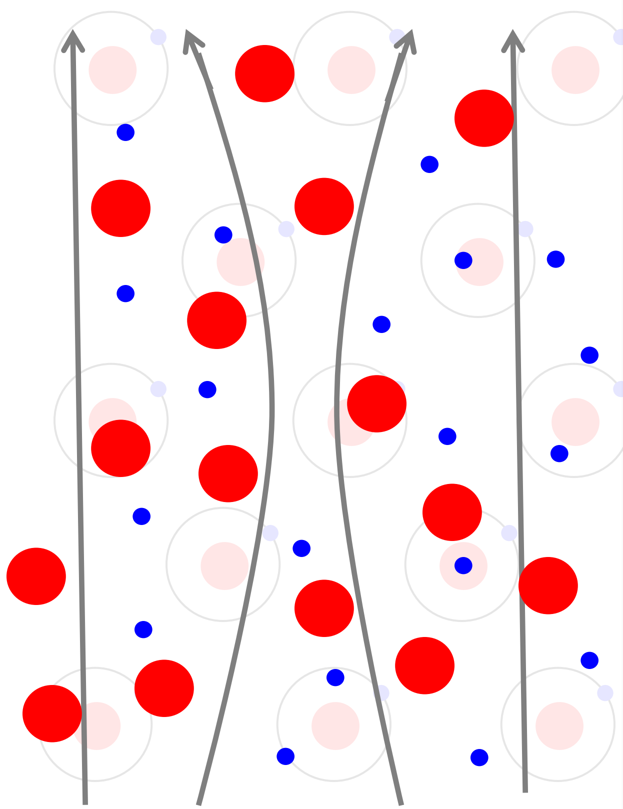
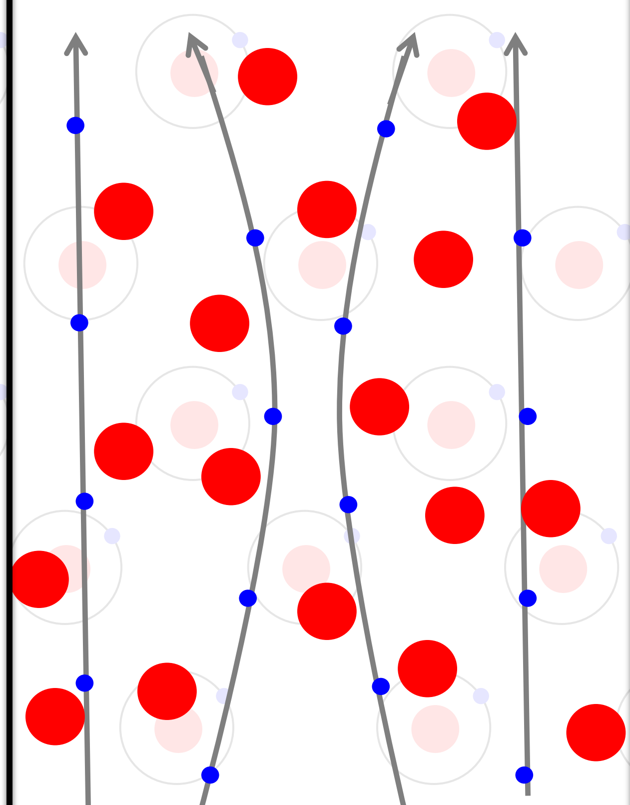
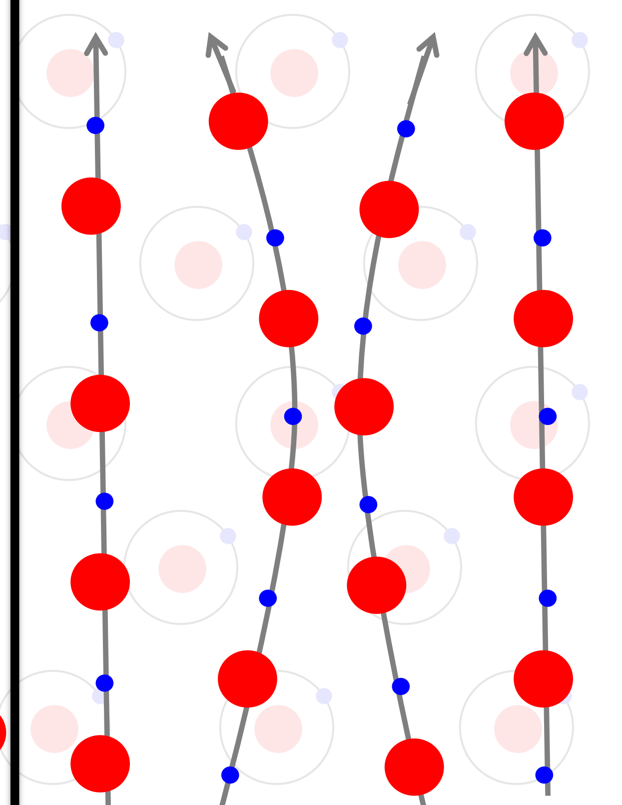


Ohmic Resistivity
(diffusive)

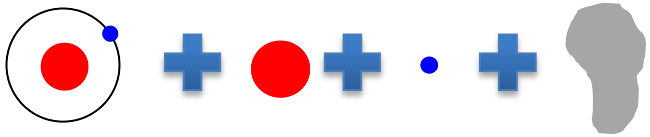


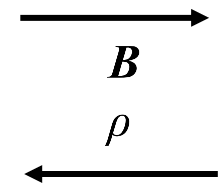
Hall Effect
(dispersive)



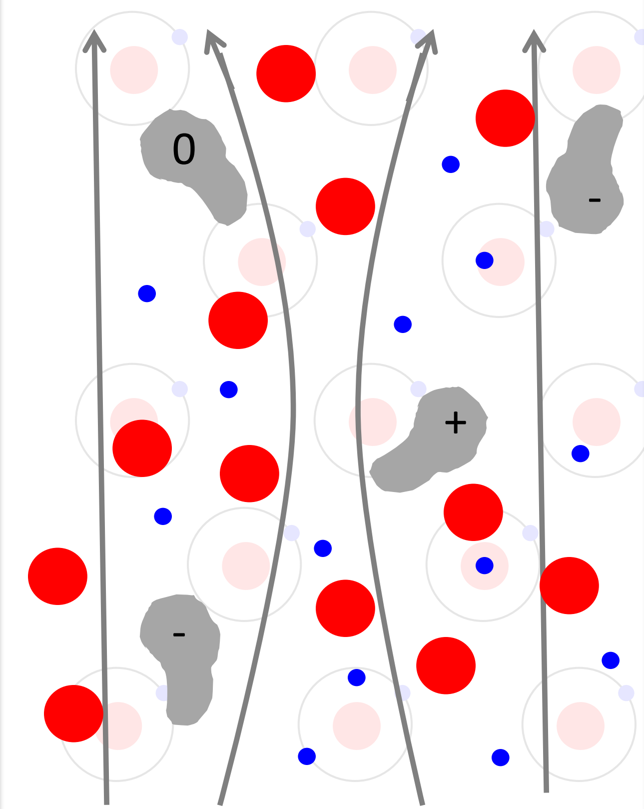
Ambipolar Diffusion
(diffusive)

Non-ideal magnetohydrodynamics

- Partially ionised plasma and dust: 



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



Ohmic Resistivity
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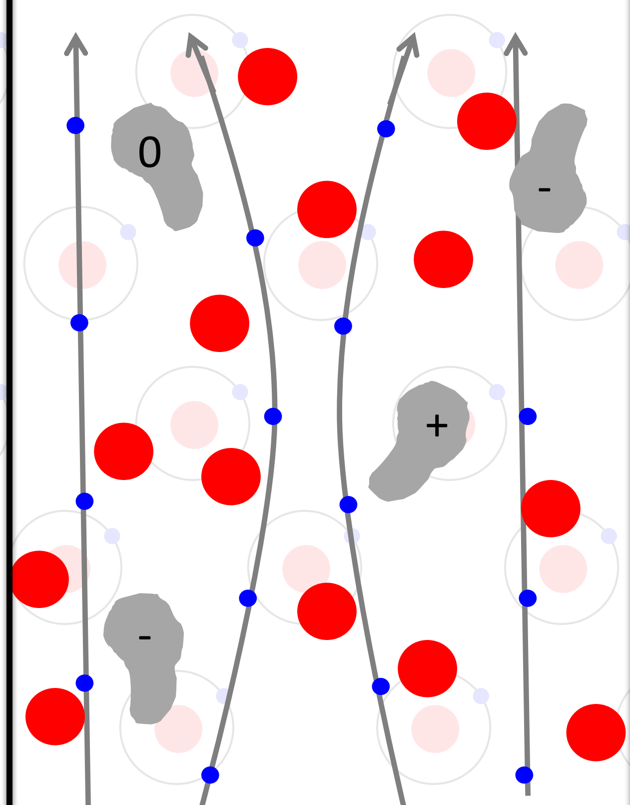

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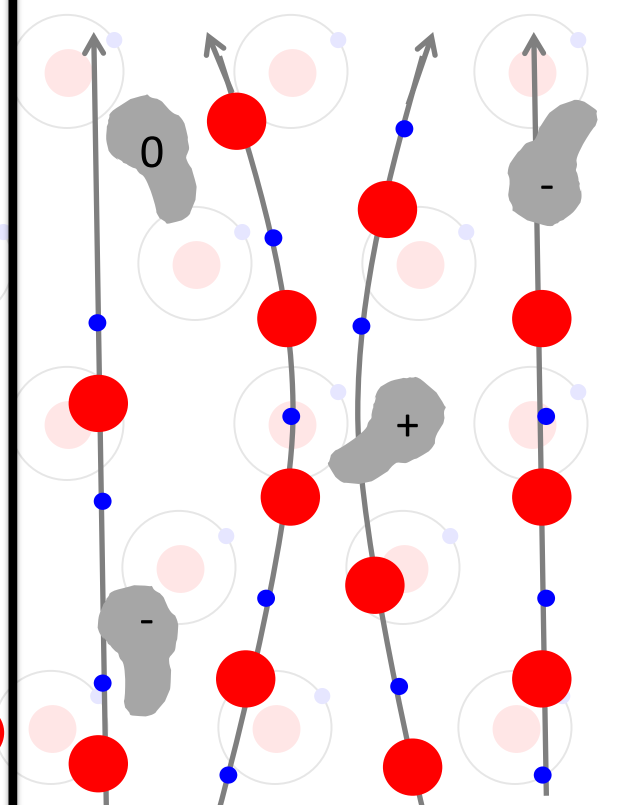

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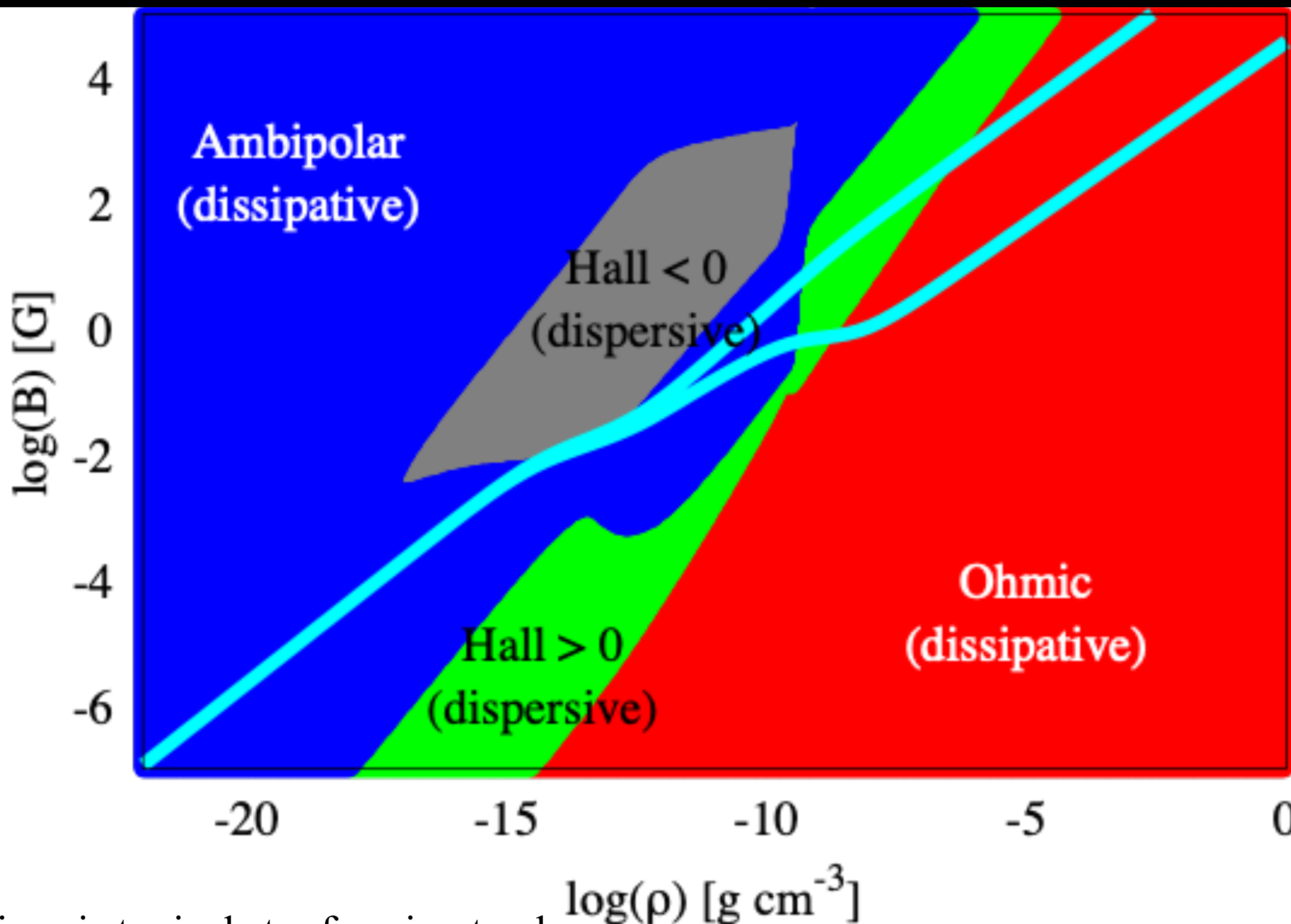
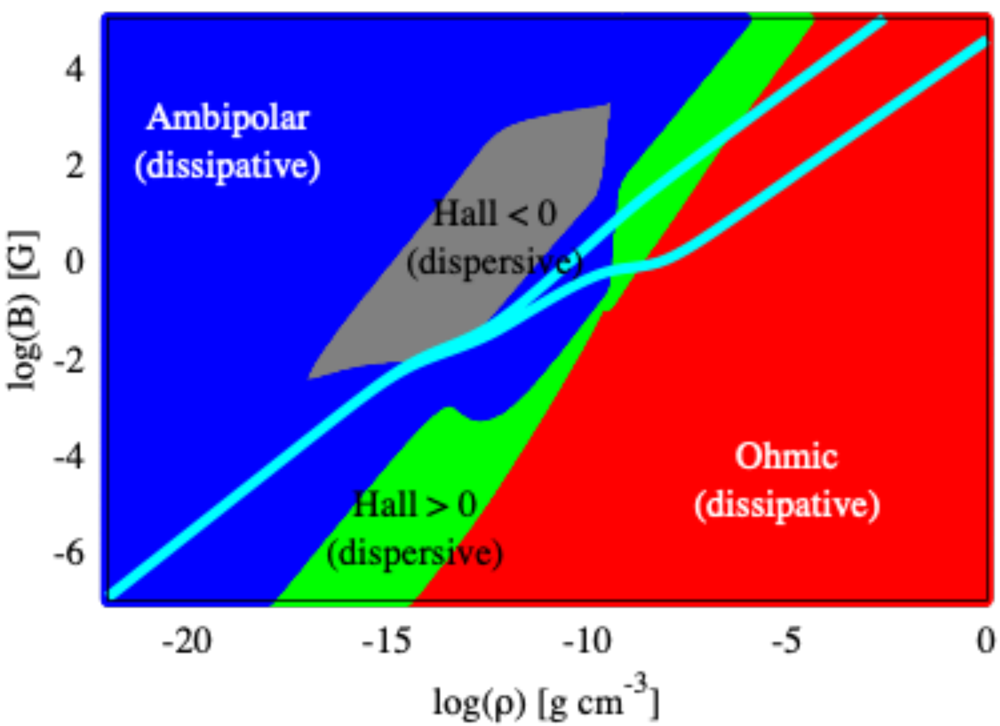
Non-ideal magnetohydrodynamics

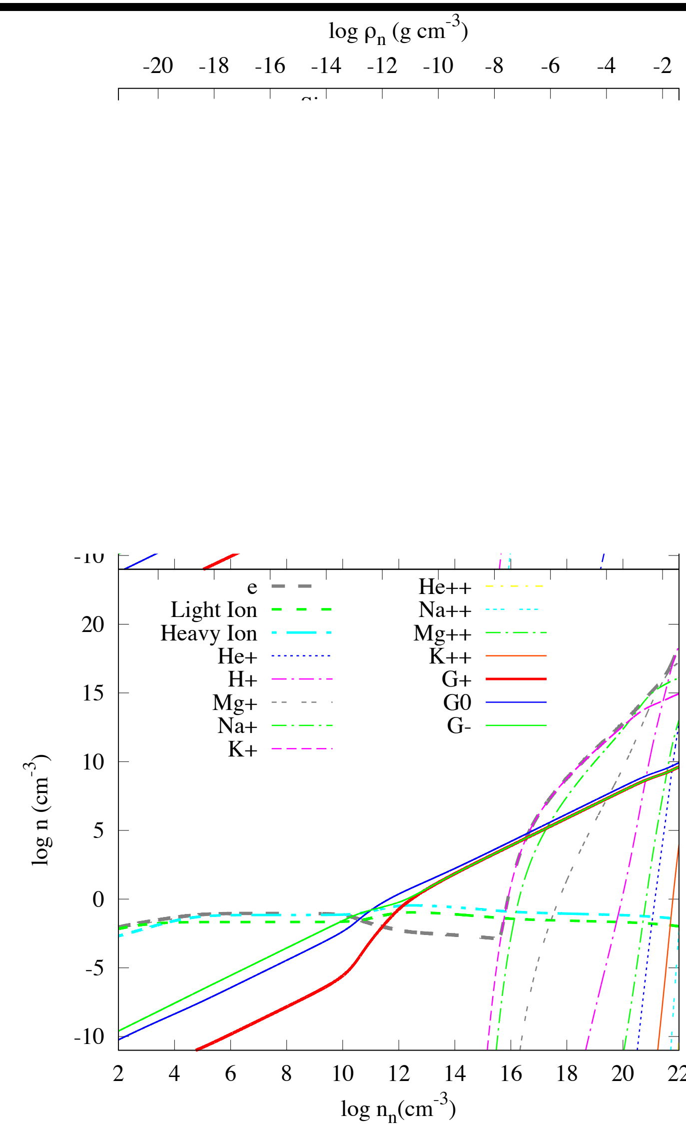


- Cyan lines is typical star forming tracks
- Values dependent on microphysics: Grain size, ionised species, cosmic ray ionisation rate

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

Non-ideal magnetohydrodynamics: Components





Adapted from Wardle (2007);
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Bottom: Abundances using proxy chemical species (Wurster 2016)

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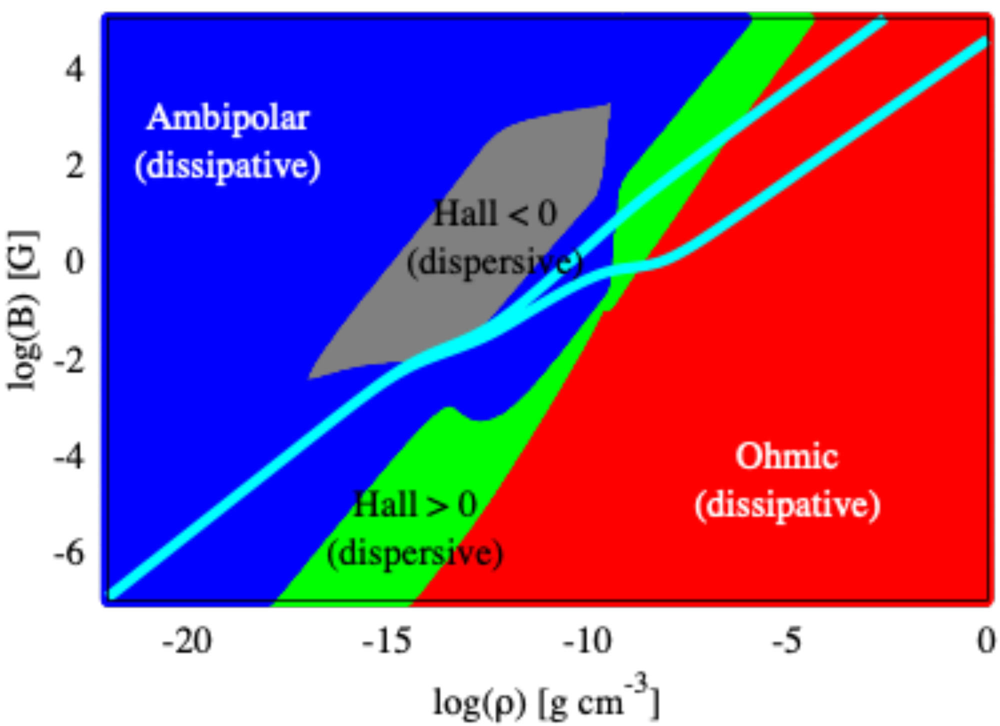
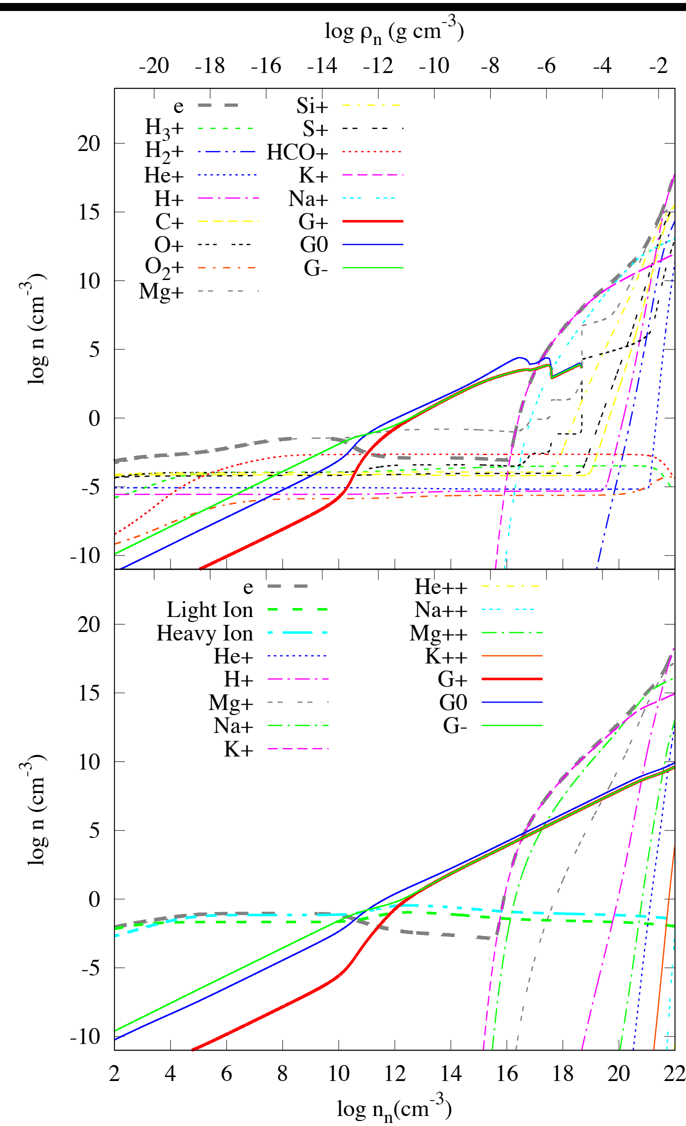
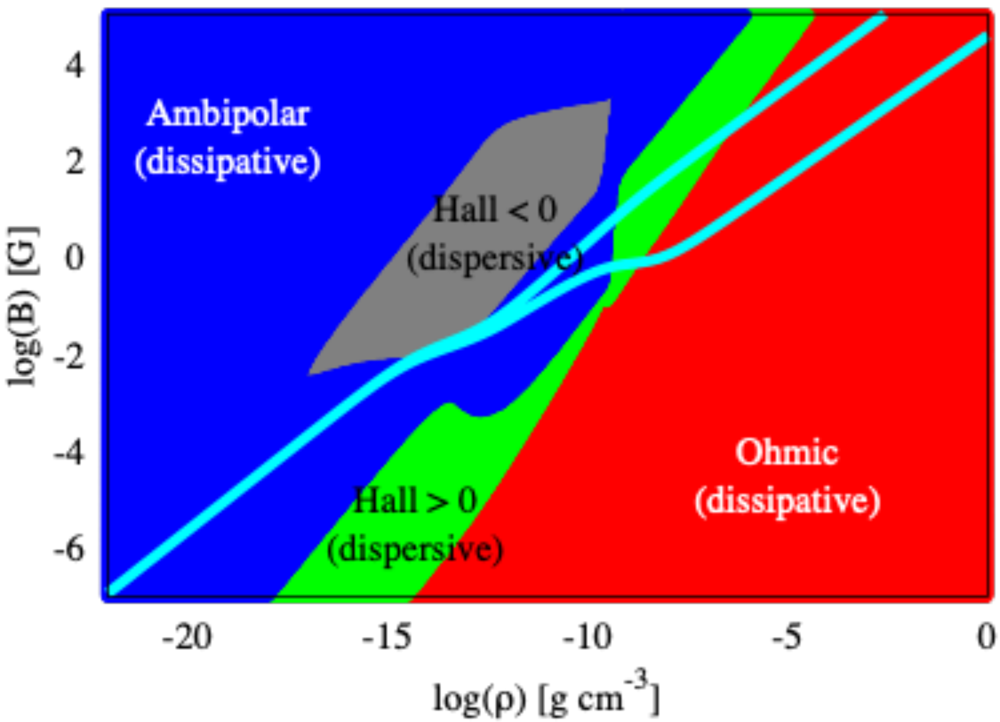


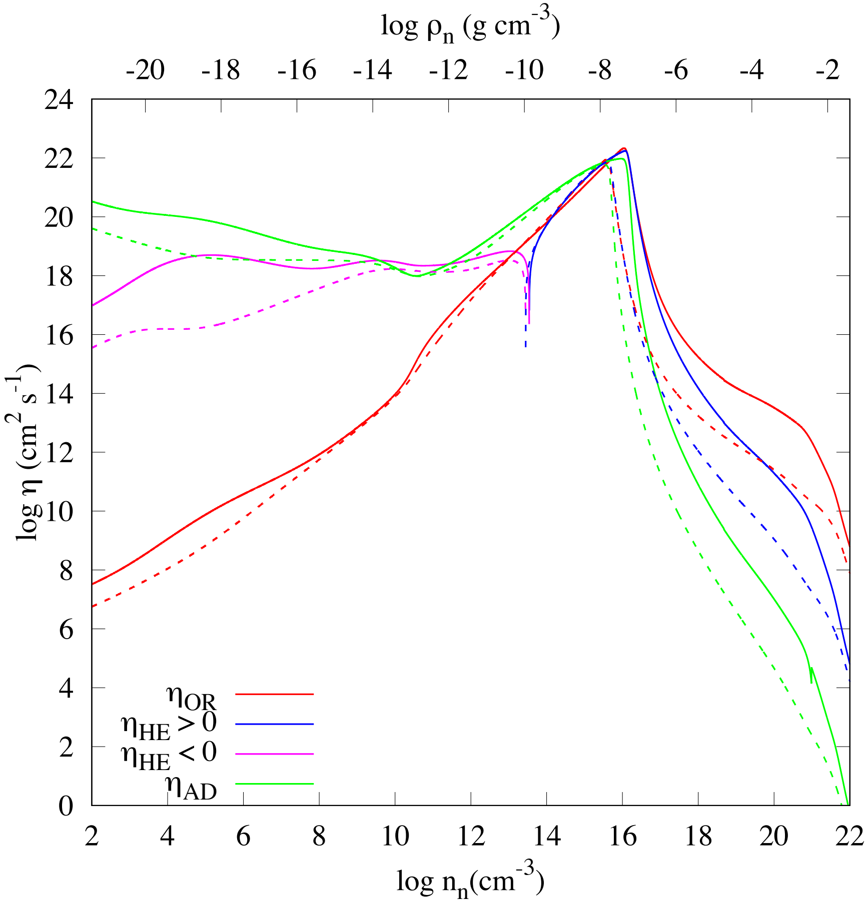


Adapted from Wardle (2007); constructed using NICIL v2.0 (Wurster 2016)

Bottom: Abundances using proxy chemical species (Wurster 2016)
Top: Abundances using a simplified chemical network (Wurster 2021)

Non-ideal magnetohydrodynamics: Components



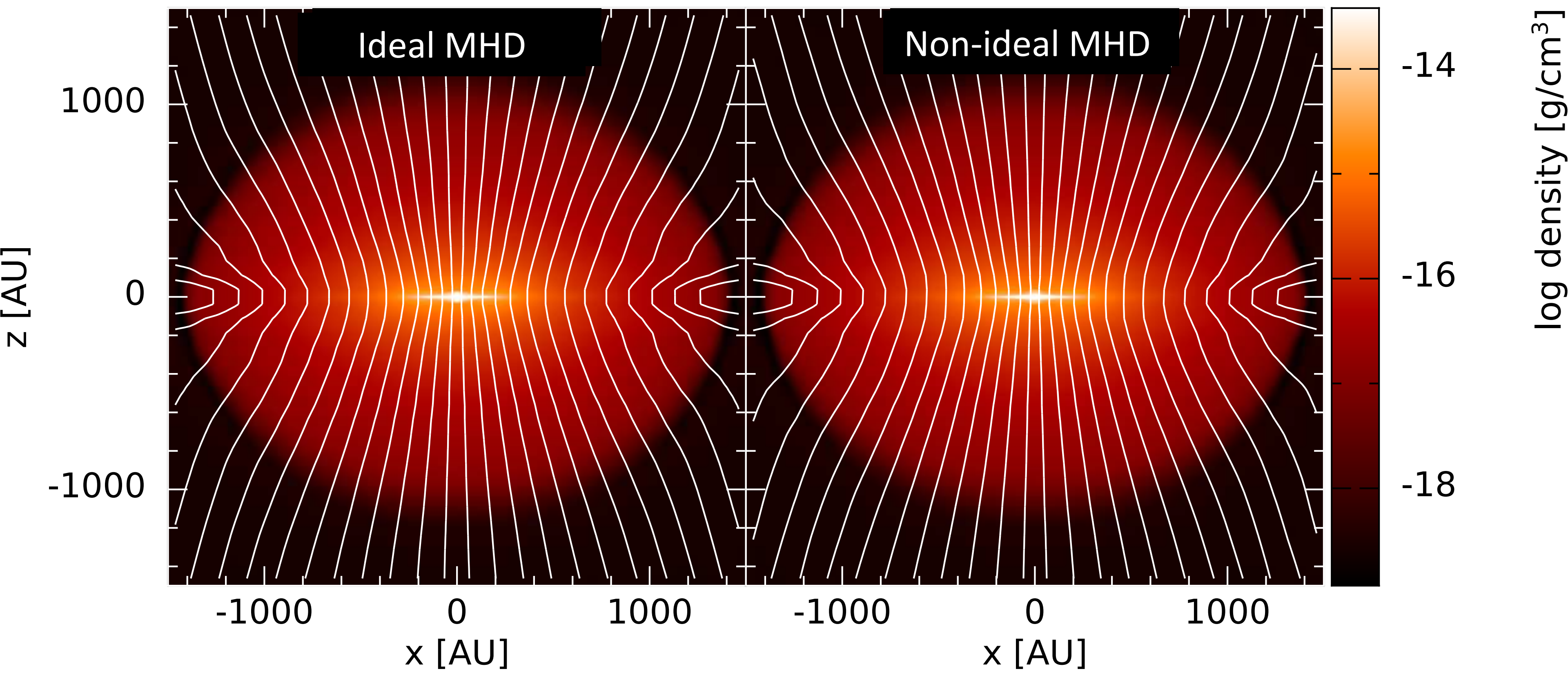


Adapted from Wardle (2007);
constructed using NICIL v2.0 (Wurster 2016)

Non-ideal MHD coefficients using simplified vs reduced chemical network (Wurster 2021)

Non-ideal magnetohydrodynamics

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



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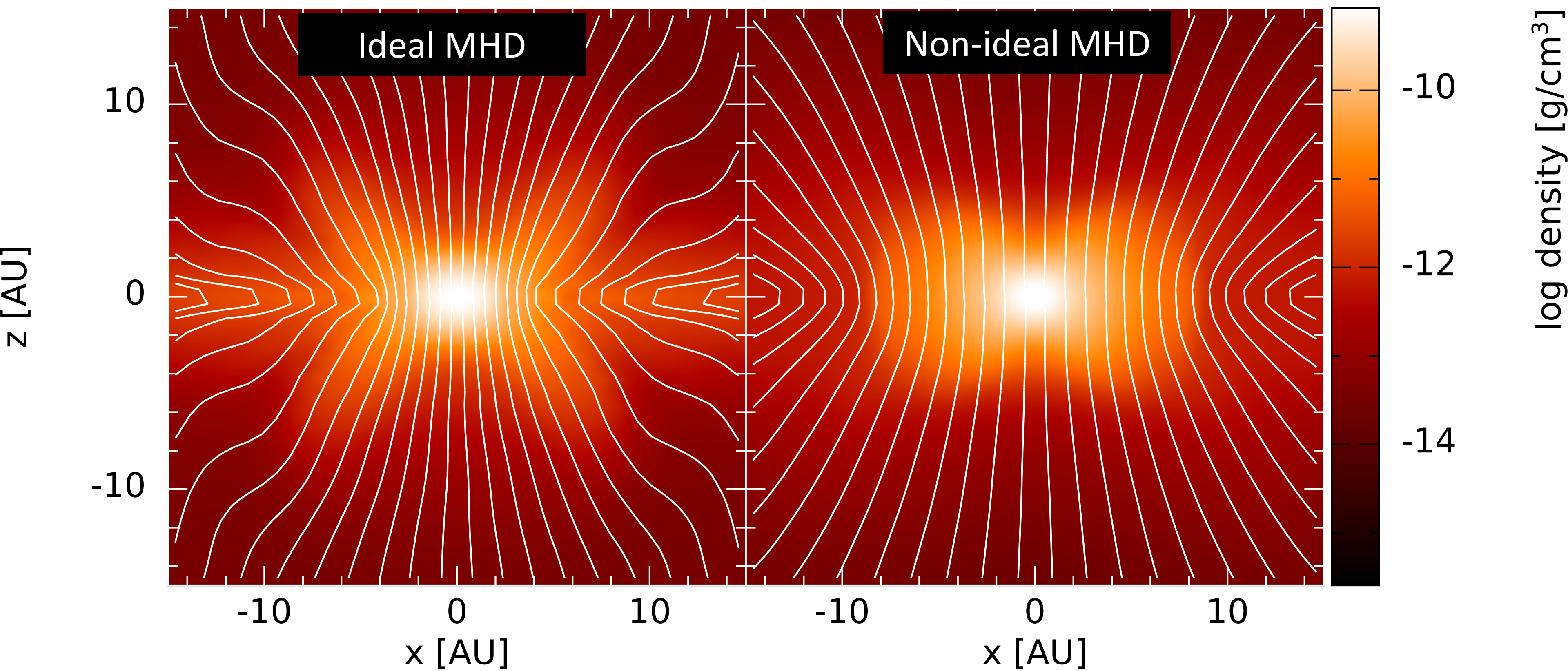

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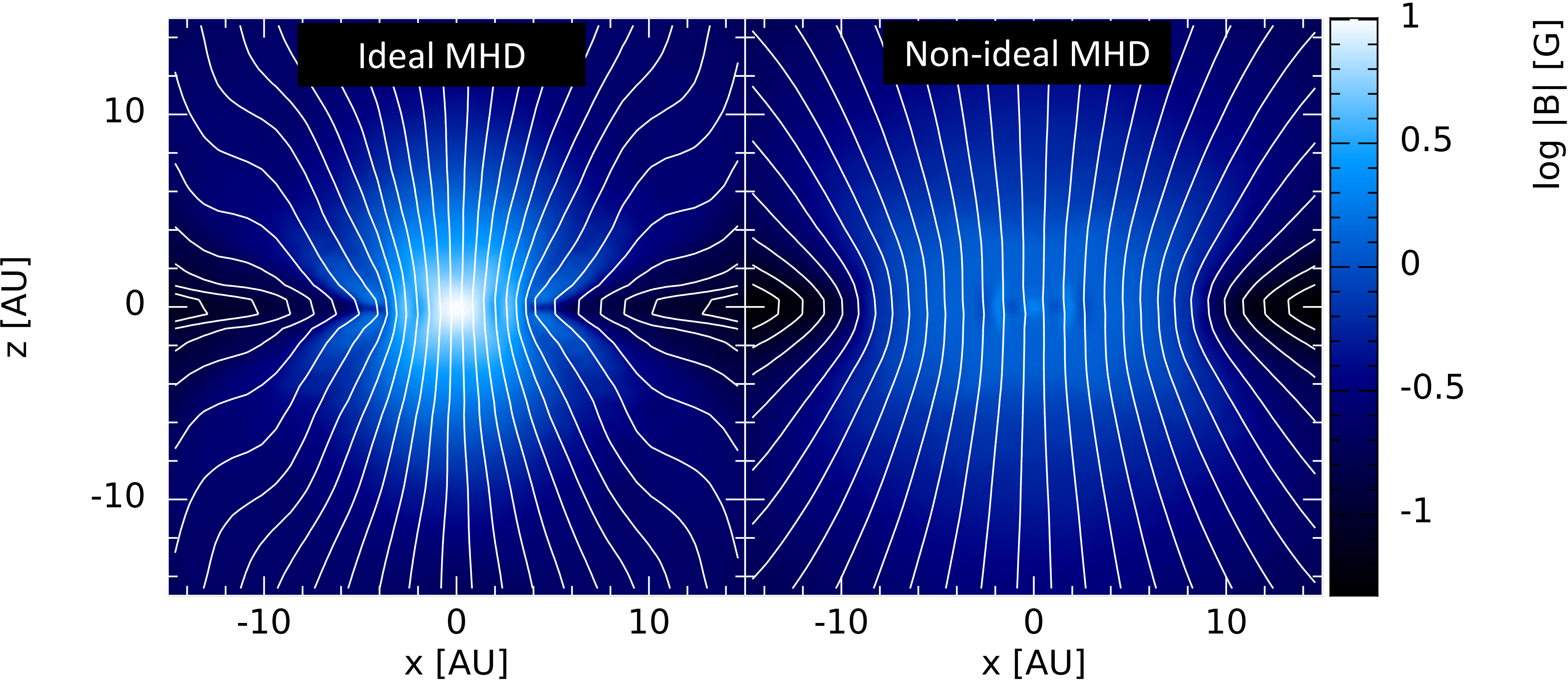
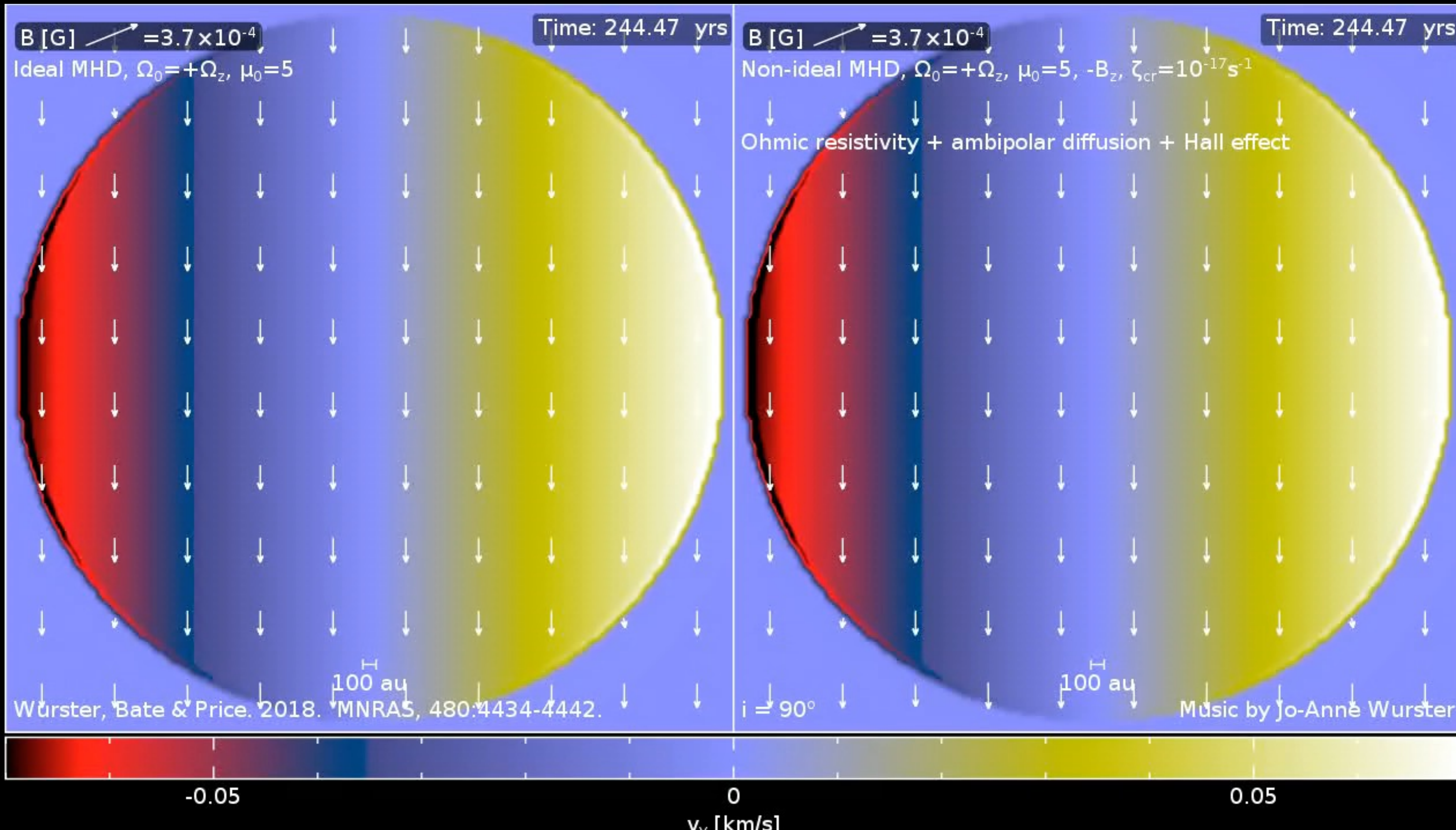


Formation of a low-mass star

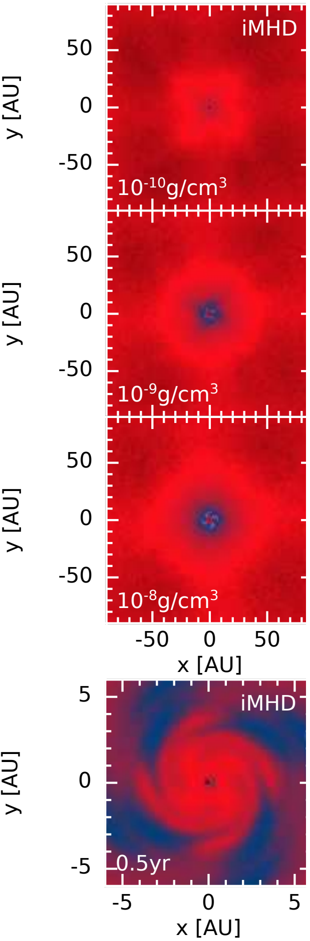


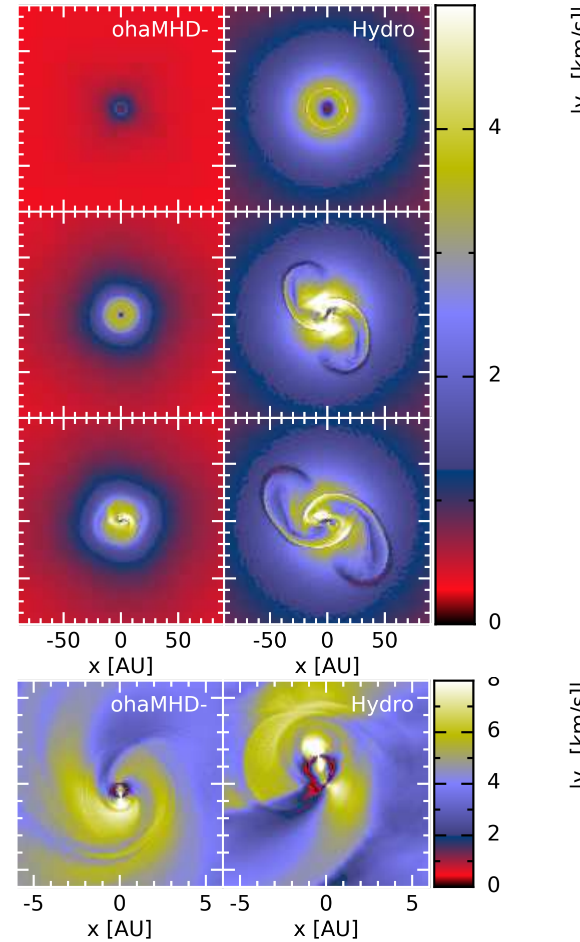
Wurster, Bate & Price (2018c): https://youtu.be/czdixAn6VNs

Music: Jo-Anne Wurster

Rotationally supported discs

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



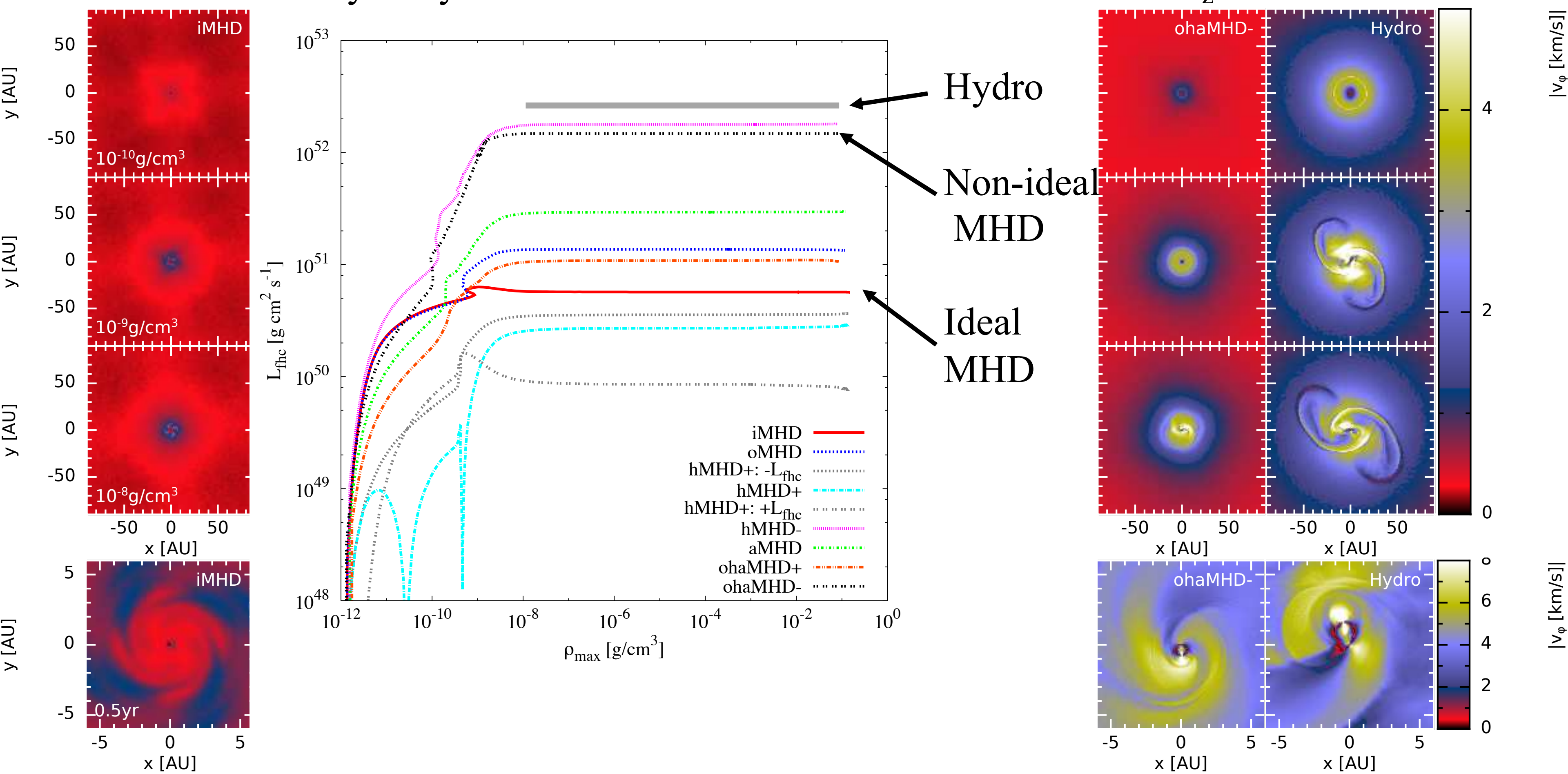


- ➢Discs form during the first hydrostatic core phase in the non-ideal & Hydro models

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

Rotationally supported discs

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

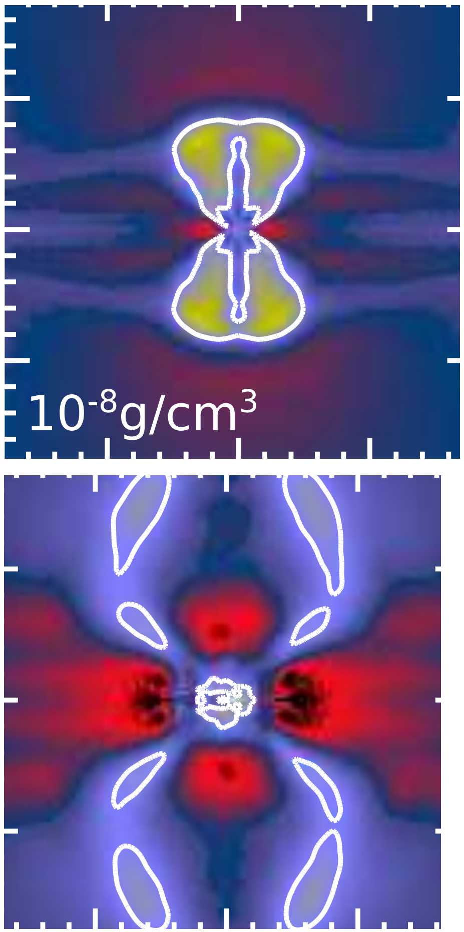


Wurster, Bate & Bonnell (2021); Wurster, Bate & Price (2018a,c)

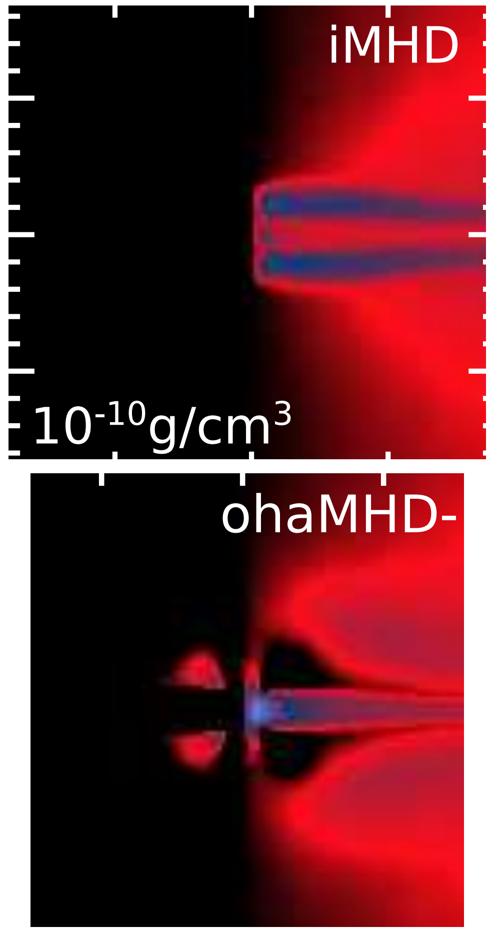
Other characteristics

➢Forming discs was the motivation, however, many other aspects of star formation can be investigated from these simulations, including

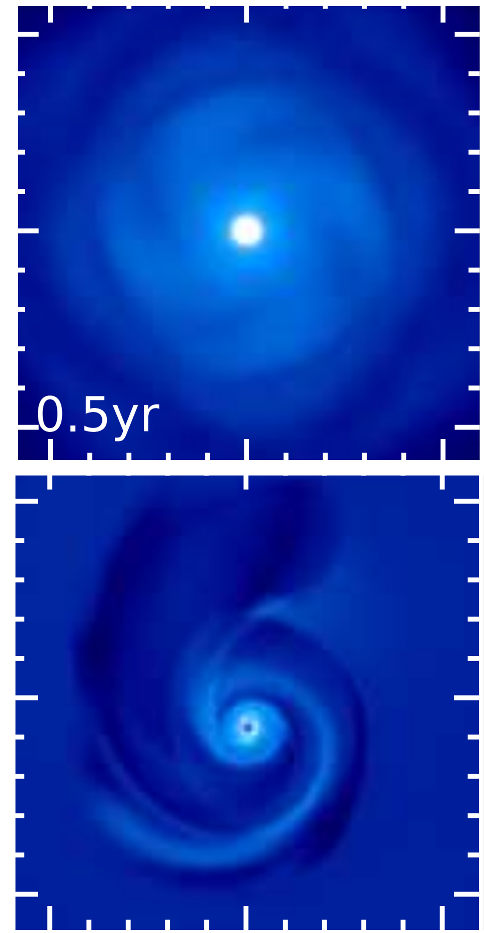
Outflows (winds/jets)



Counter-rotating envelopes



magnetic field geometry



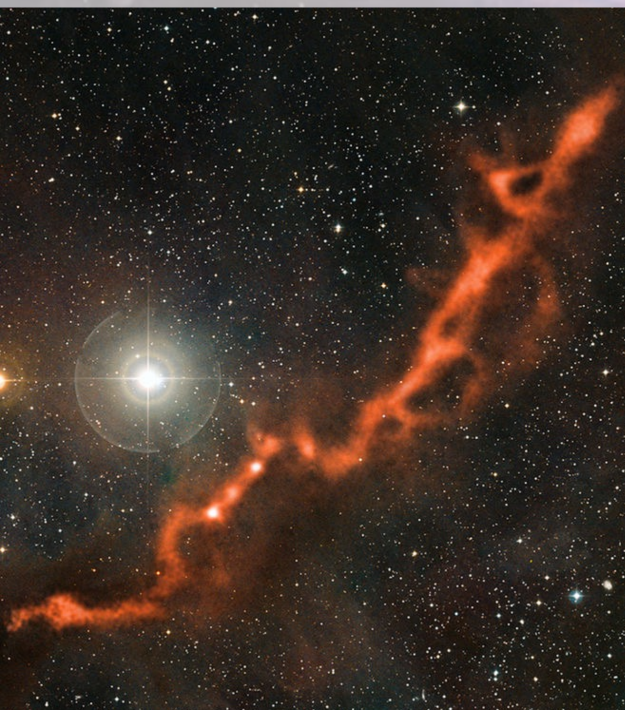
Wurster, Bate & Bonnell (2021); Wurster, Bate & Price (2018c)

Star formation: From the beginning

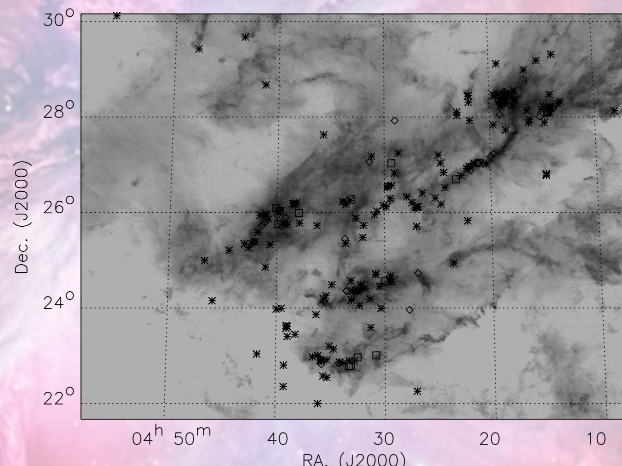
Stars do not form in isolation

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

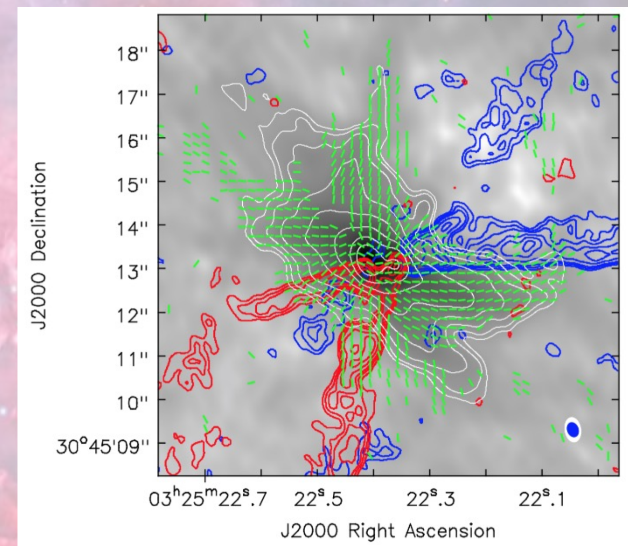
Star formation: Stellar nurseries



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

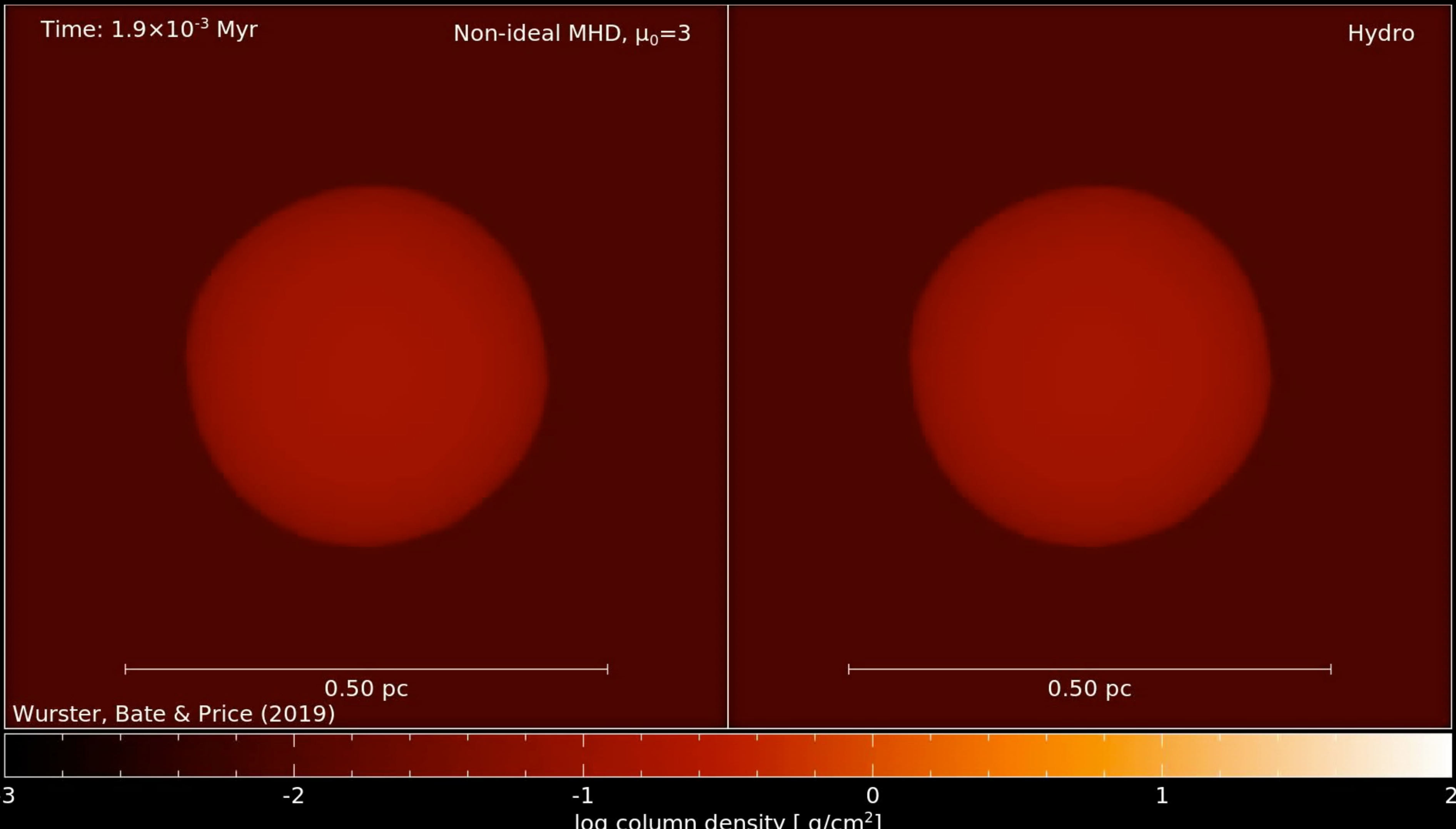


Taurus Molecular Cloud: H_2 column density map with positions of young stars (Goldsmith et. al., 2008)



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

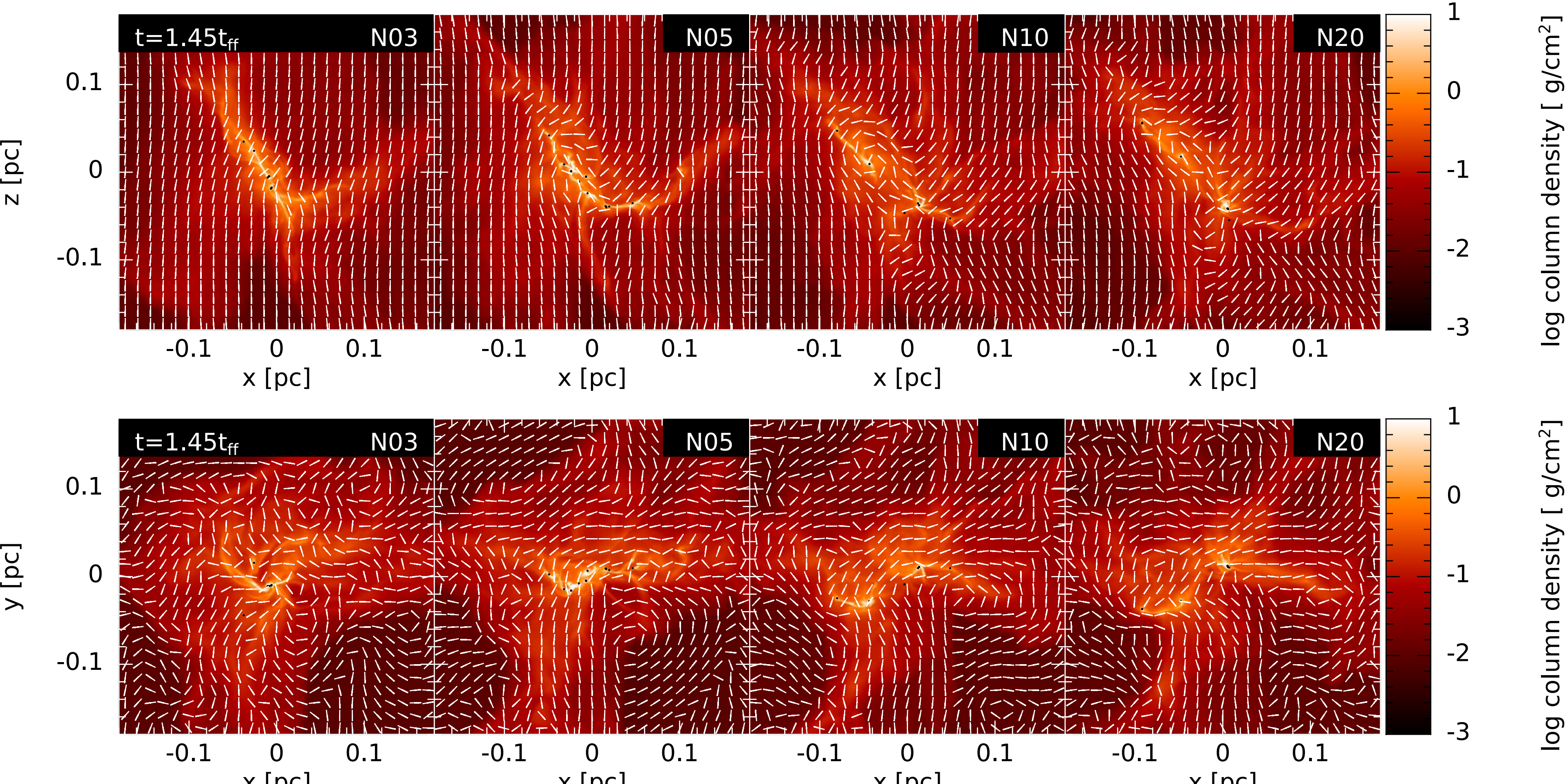
Cluster Formation: Effect of non-ideal MHD



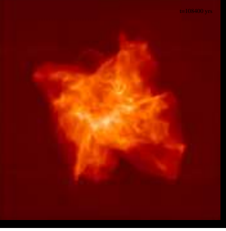
Wurster, Bate & Price (2019): https://youtu.be/CLhmaOhj5RU

Cluster Formation: Magnetic field lines

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



Wurster, Bate & Price (2019)



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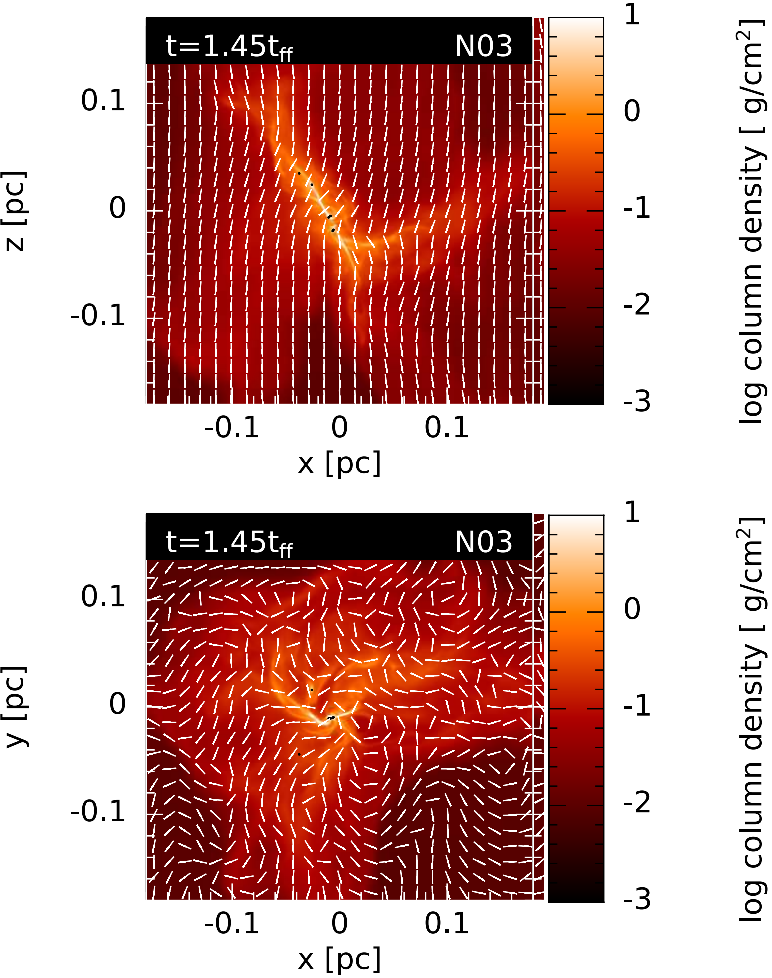
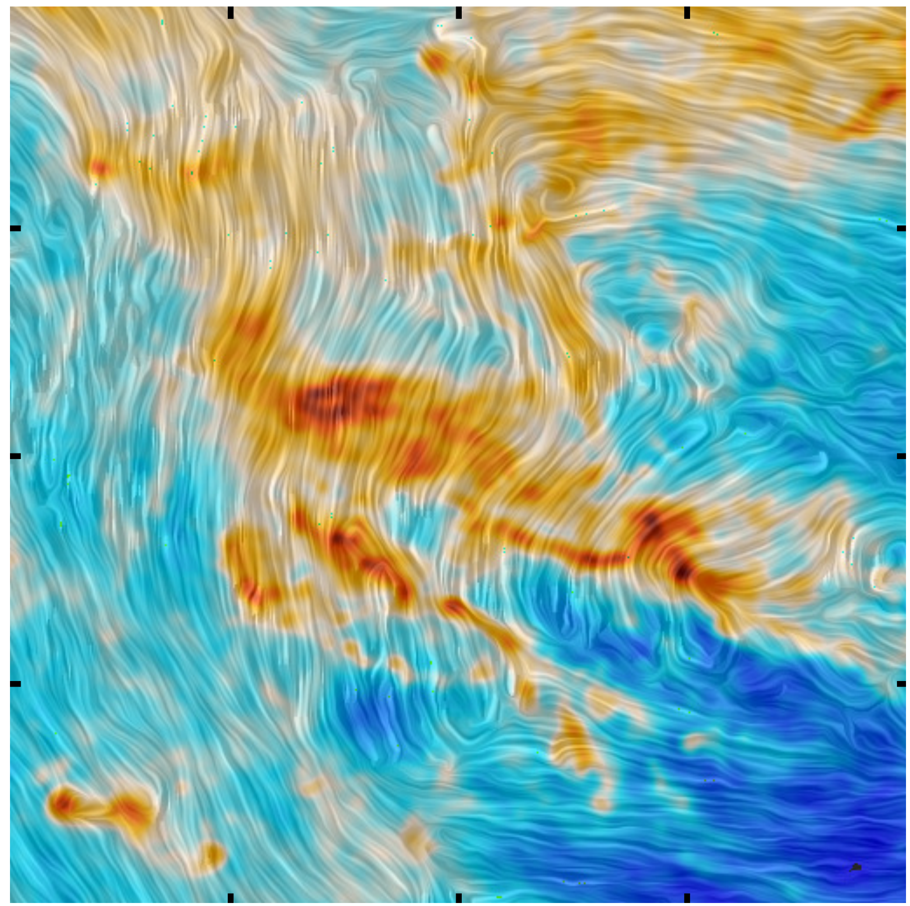
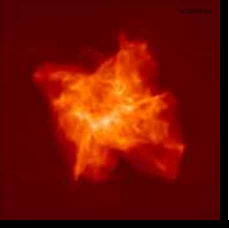


Wurster, Bate & Price (2019)

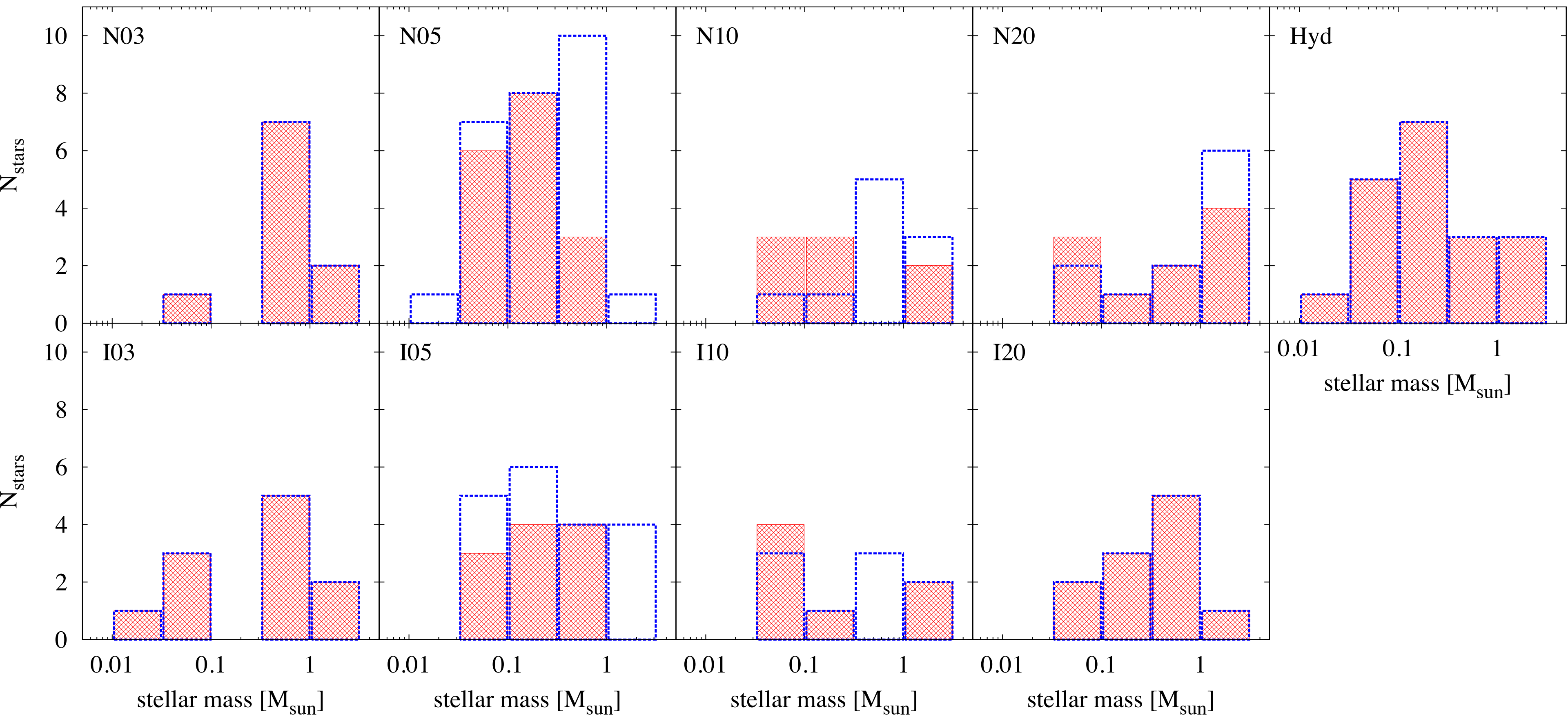


Magnetic field and column density towards Taurus; Planck Collaboration (2016)

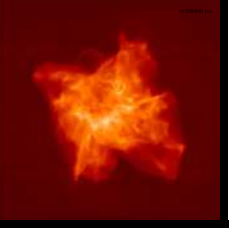


Cluster Formation: Stellar Mass

- 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 (2019)



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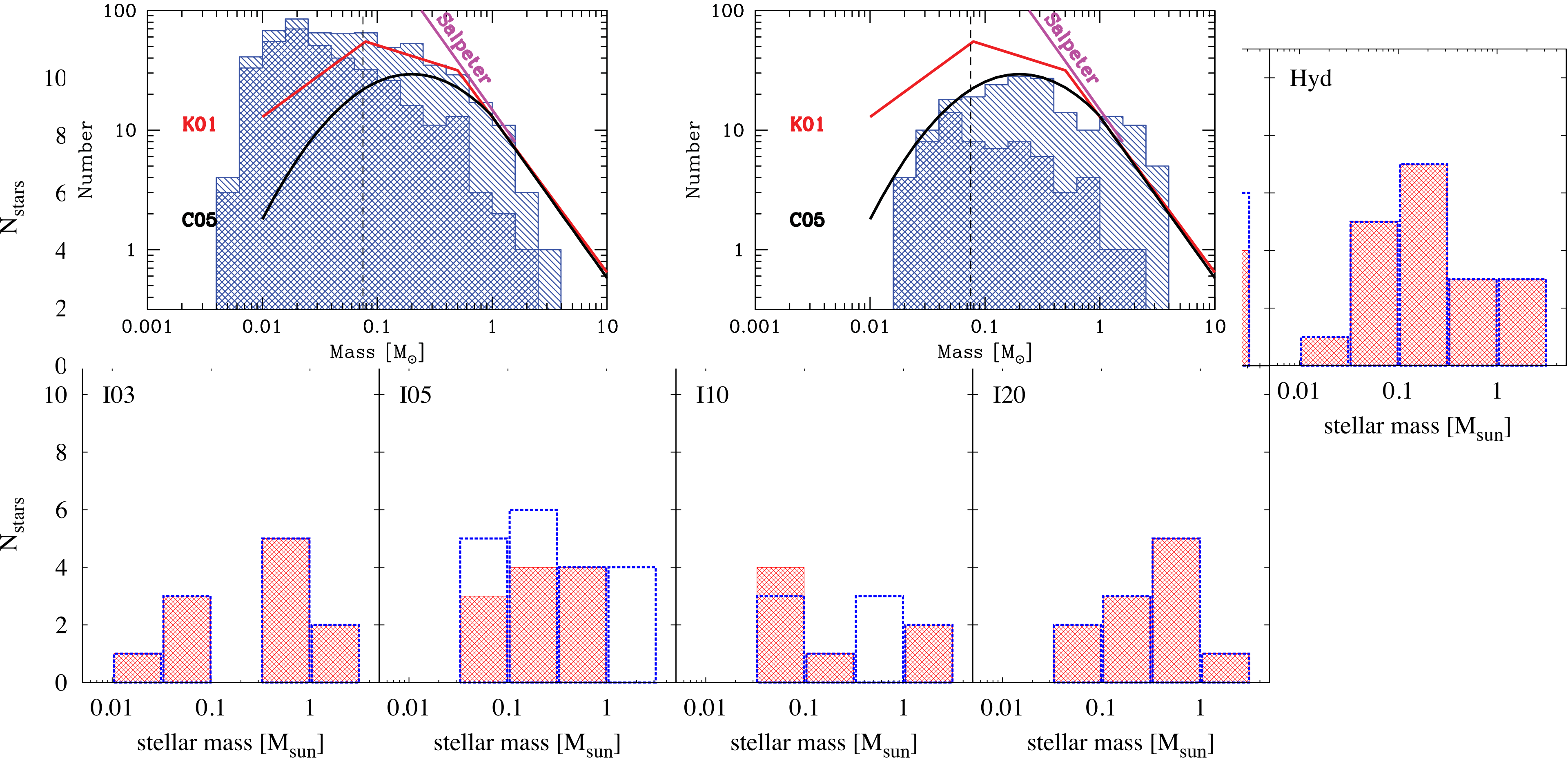
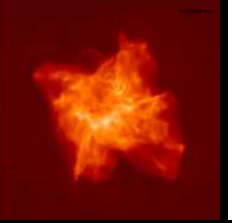


Wurster, Bate & Price (2019); inset from Bate (2012)

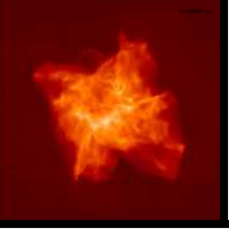


Cluster Formation: Protostellar discs: Hydro

- Large protostellar discs frequently form and interact

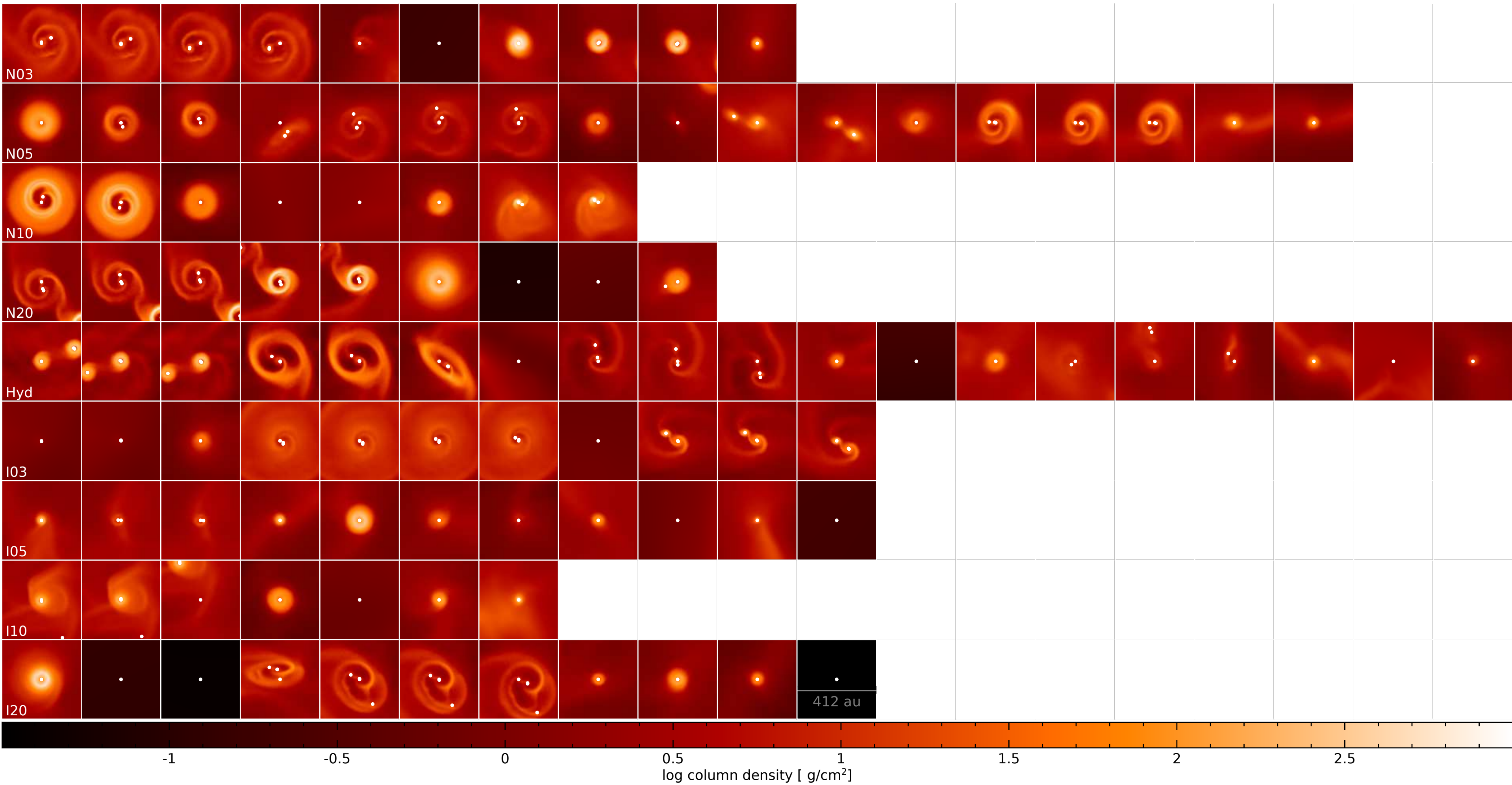
Matthew Bate
University of Exeter

Bate (2018): http://www.astro.ex.ac.uk/people/mbate/Animations/Bate2018_Movie.mov

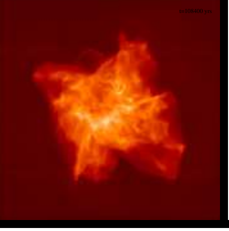


Cluster Formation: Protostellar discs

➢Large protostellar discs form in *all* our models



Wurster, Bate & Price (2019)



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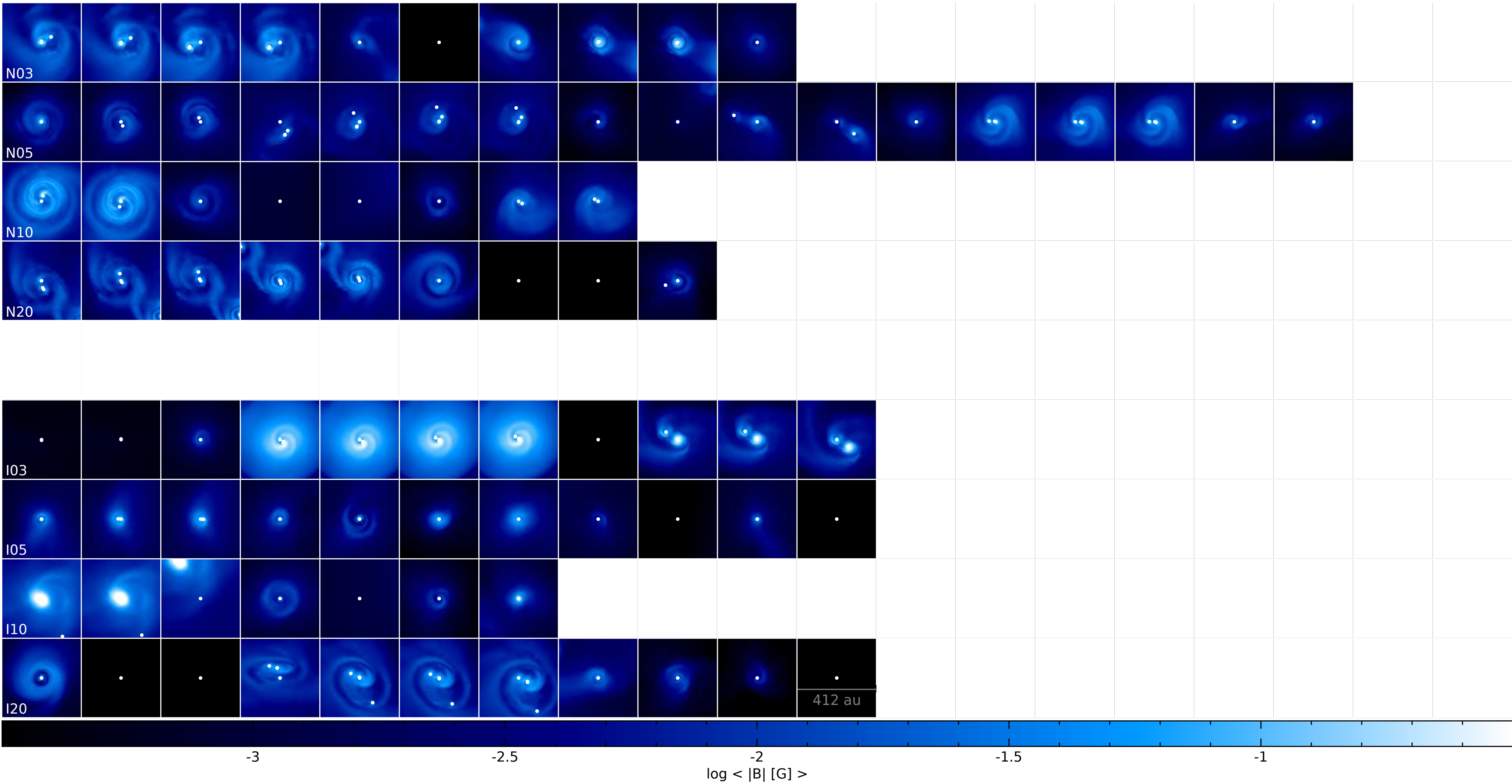

Wurster, Bate & Price (2019)

Conclusions

- Astronomy is a synergy between observation and theory
- Much astronomical theory is performed using numerical simulations
- Star formation simulations requires a synergy between astrophysics, physics, mathematics, chemistry, and computer science

- Star forming molecular clouds are only weakly ionised
    - Ideal MHD is a poor description
    - Non-ideal MHD is a reasonable description and can better reproduce observations

- Stars form in clusters and generally group and form discs

University of St Andrews · University of Exeter · erc · DiRAC · Monash University

James Wurster jhw5@st-andrews.ac.uk https://jameswurster.bitbucket.io/