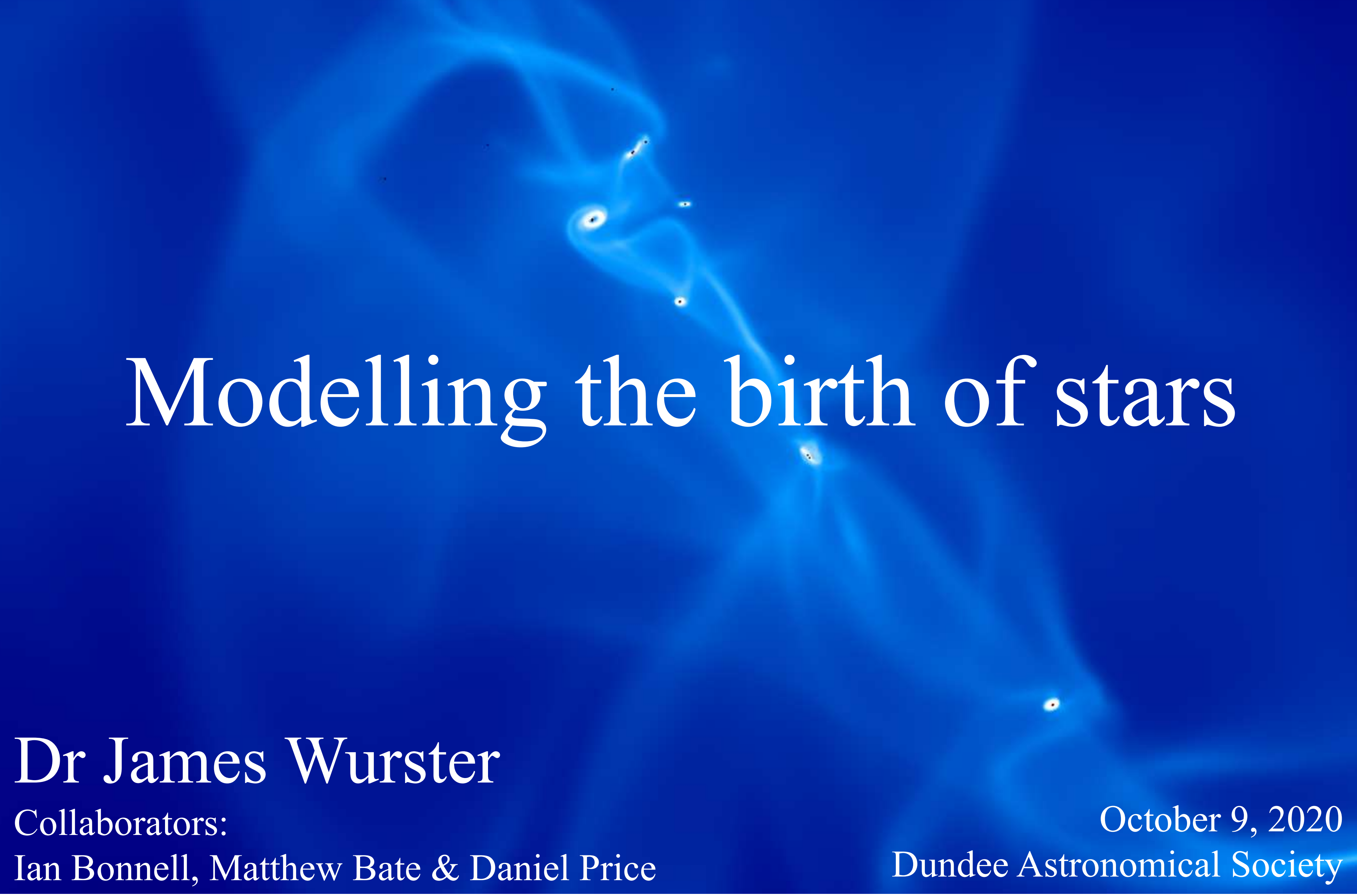


Modelling the birth of stars

Dr James Wurster

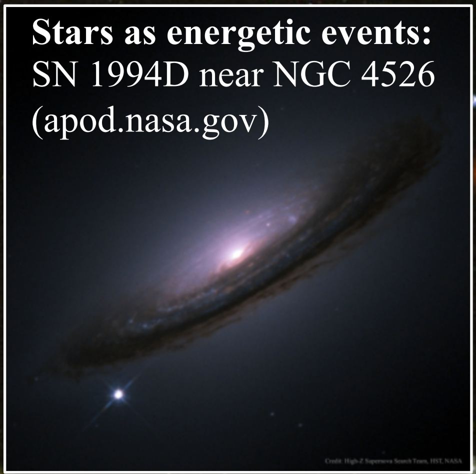
Collaborators:
Ian Bonnell, Matthew Bate & Daniel Price

October 9, 2020
Dundee Astronomical Society

University of St Andrews
University of Exeter
erc
DiRAC
Monash University

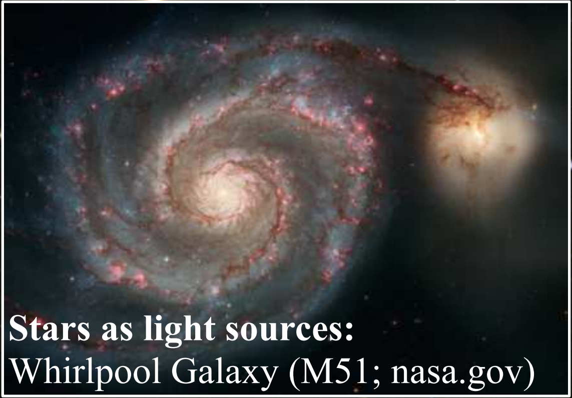
Importance of stars: Our introduction

Importance of stars: The big picture

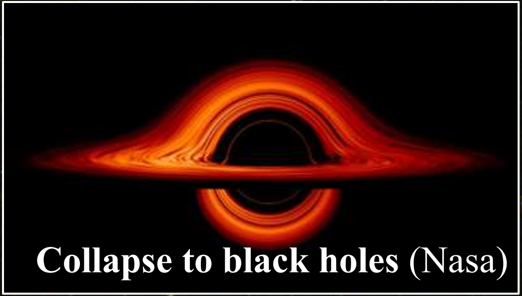


Stars as energetic events: SN 1994D near NGC 4526 (apod.nasa.gov)

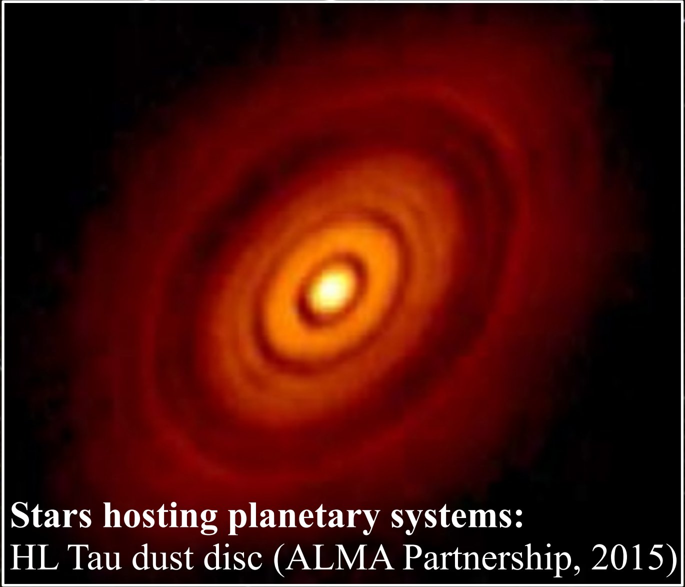
Stars launching jets: Large scale HH jet driven by a proto-brown dwarf (Riaz et. al., 2017)



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

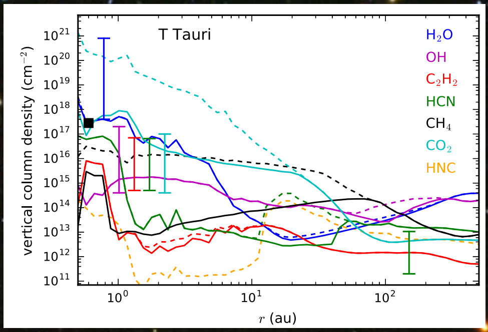


Collapse to black holes (Nasa)



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

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



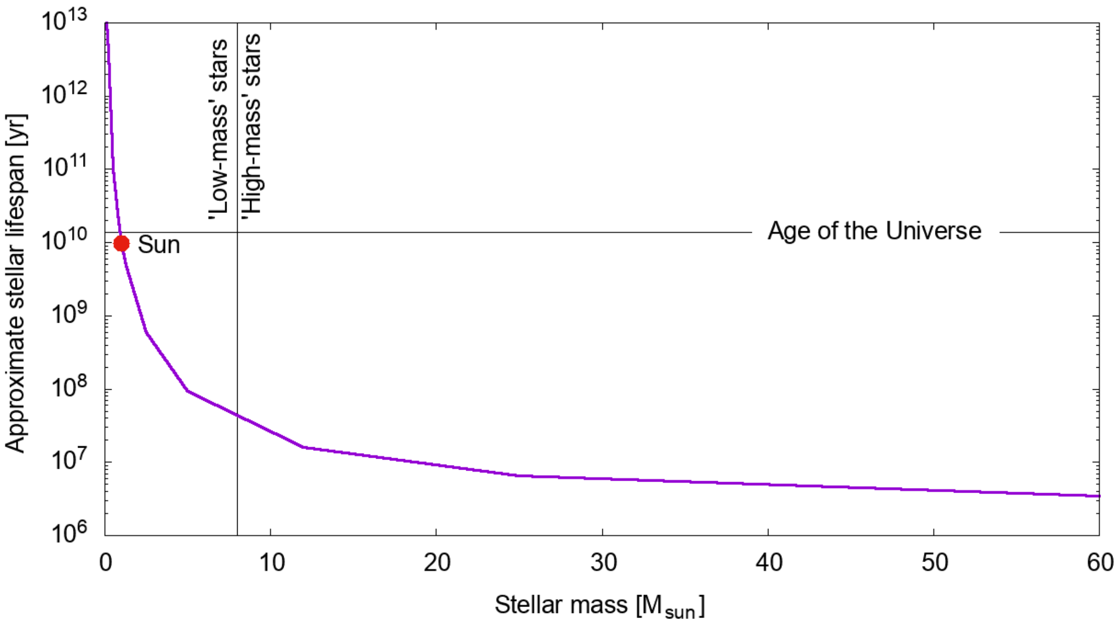
Chemical Evolution (Agundez + 2018)

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

Importance of stars: Masses

- Main classes of stellar masses

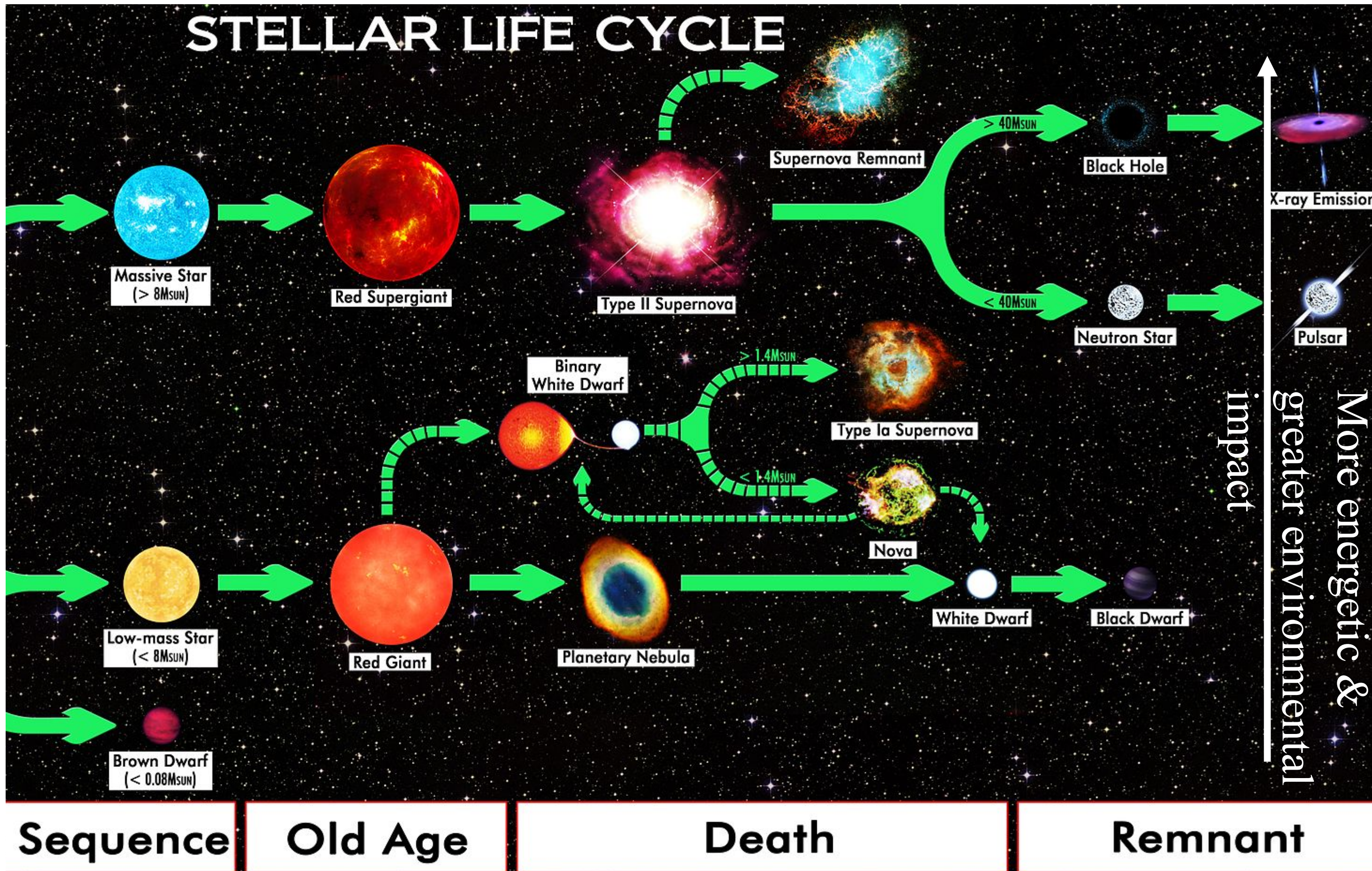
- Massive stars ($M > 8M_{sun}$)
- Low-mass stars ($0.08M_{sun} < M$ & $M < 8M_{sun}$)
- Brown Dwarfs ($M < 0.08M_{sun}$)



Importance of stars: Masses

- Main classes of stellar masses

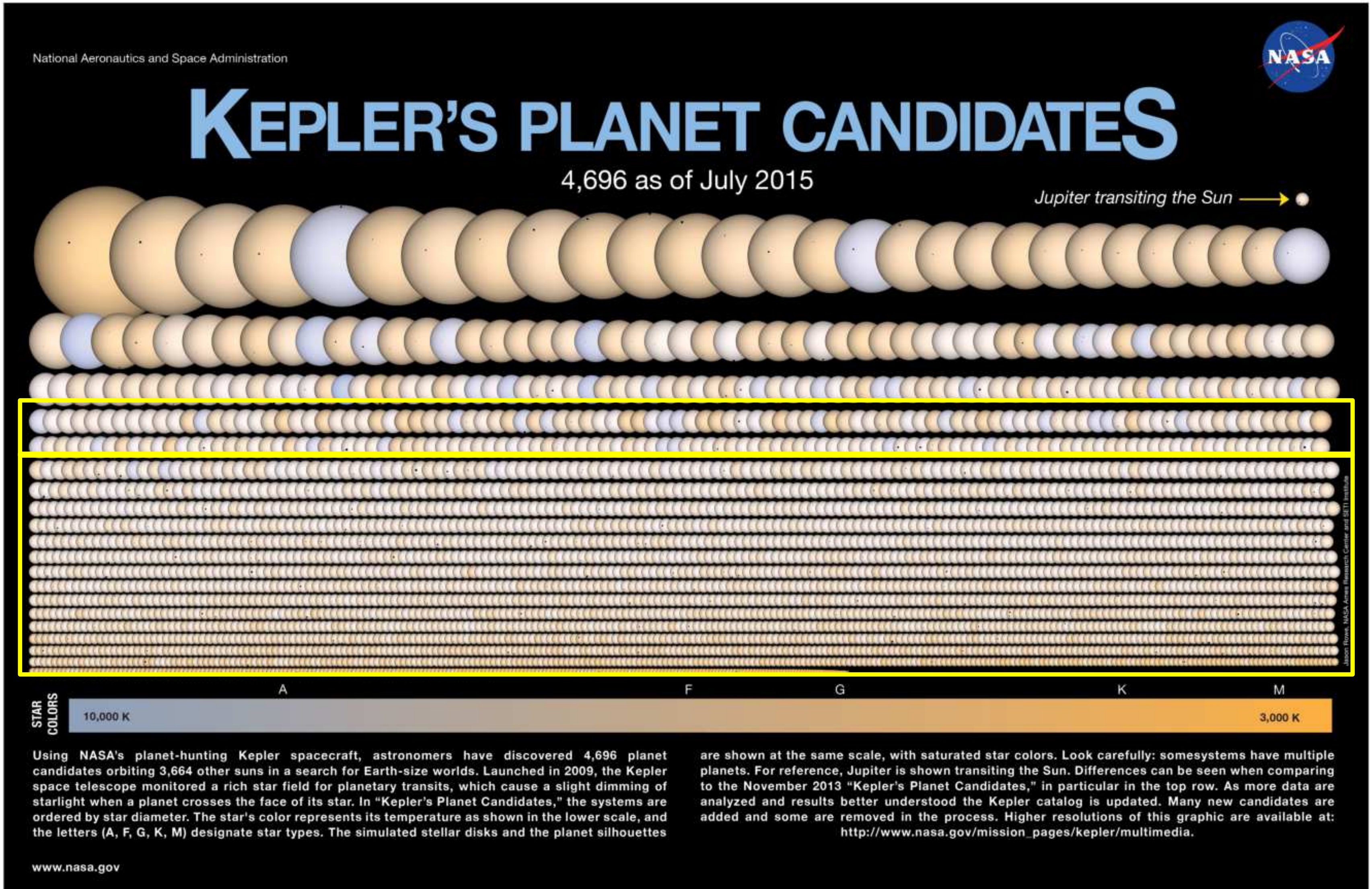
- Massive stars ($M > 8M_{sun}$)
- Low-mass stars ($0.08M_{sun} < M$ & $M < 8M_{sun}$)
- Brown Dwarfs ($M < 0.08M_{sun}$)



- 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)

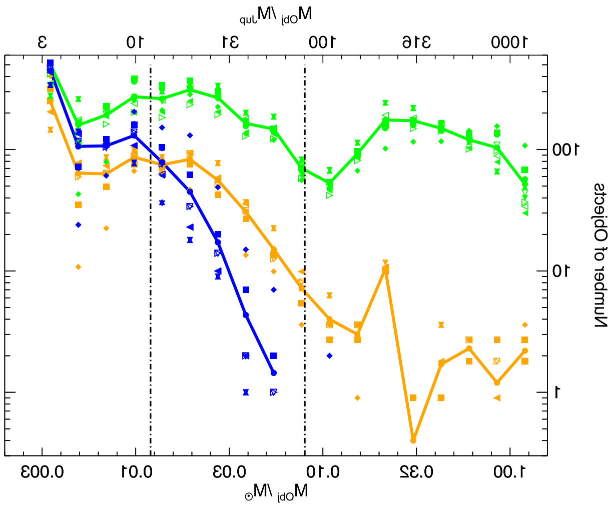
Importance of stars: Numbers



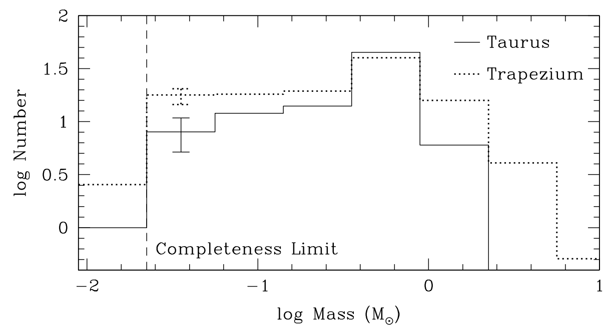
- Low mass stars are much more plentiful than high-mass stars

Importance of stars: Numbers

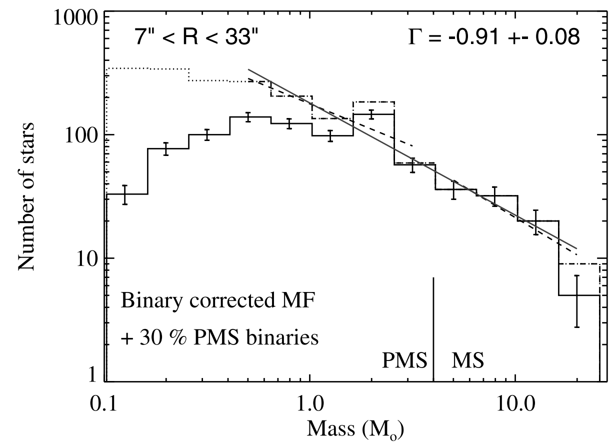
- Number of stars, by mass, for different regions



Orion (Drass+2016)



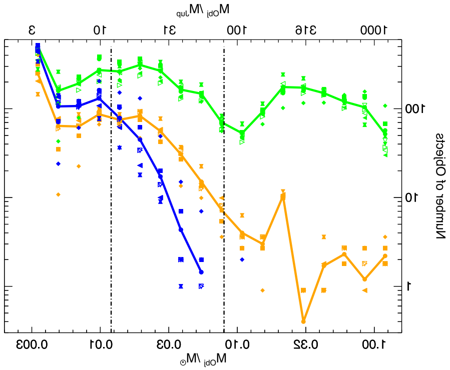
Taurus (Briceno+2002)

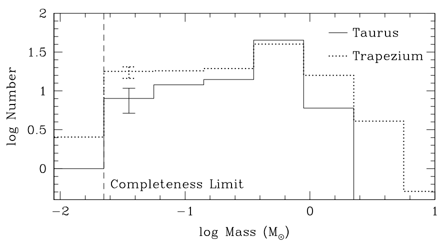


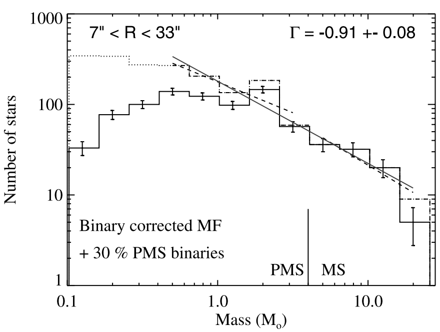
NCG 3603 (Stolte+ 2006)

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

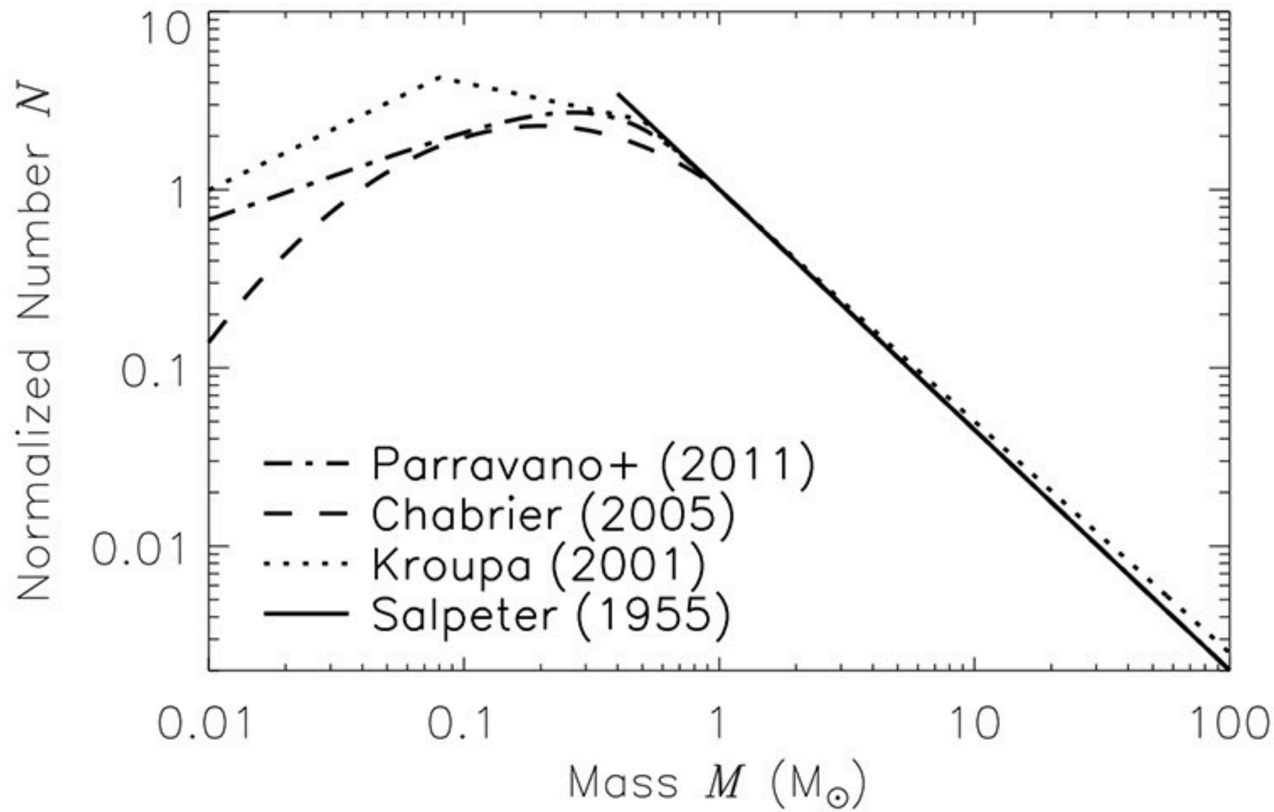
Importance of stars: Numbers







- Initial mass function



Drass+(2016)
Briceno+(2002)
Stolte+(2006

Krumholz & Federrath (2019)

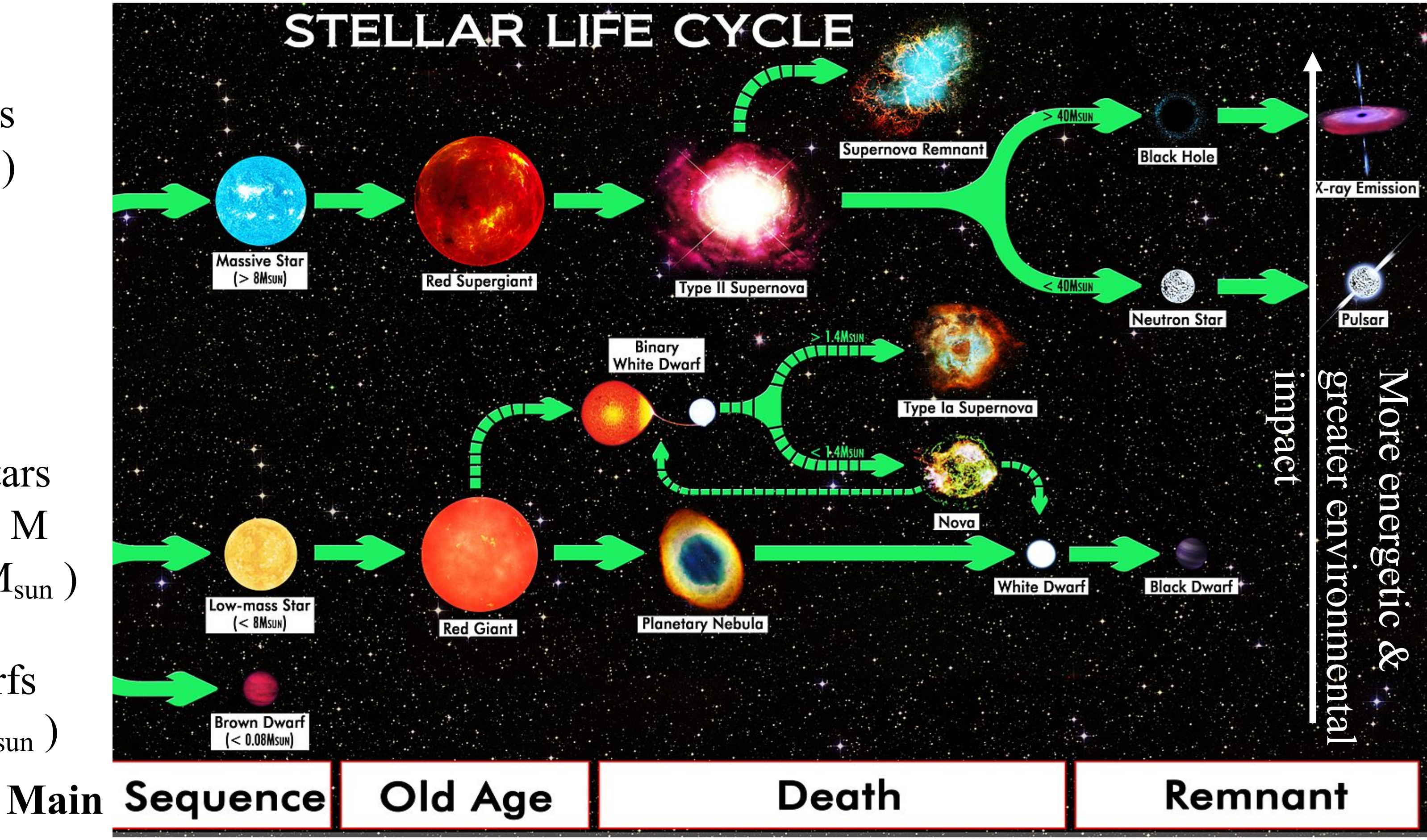
Importance of stars: Masses

➢ Main classes of stellar masses

❖ Massive stars
($M > 8M_{sun}$)

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

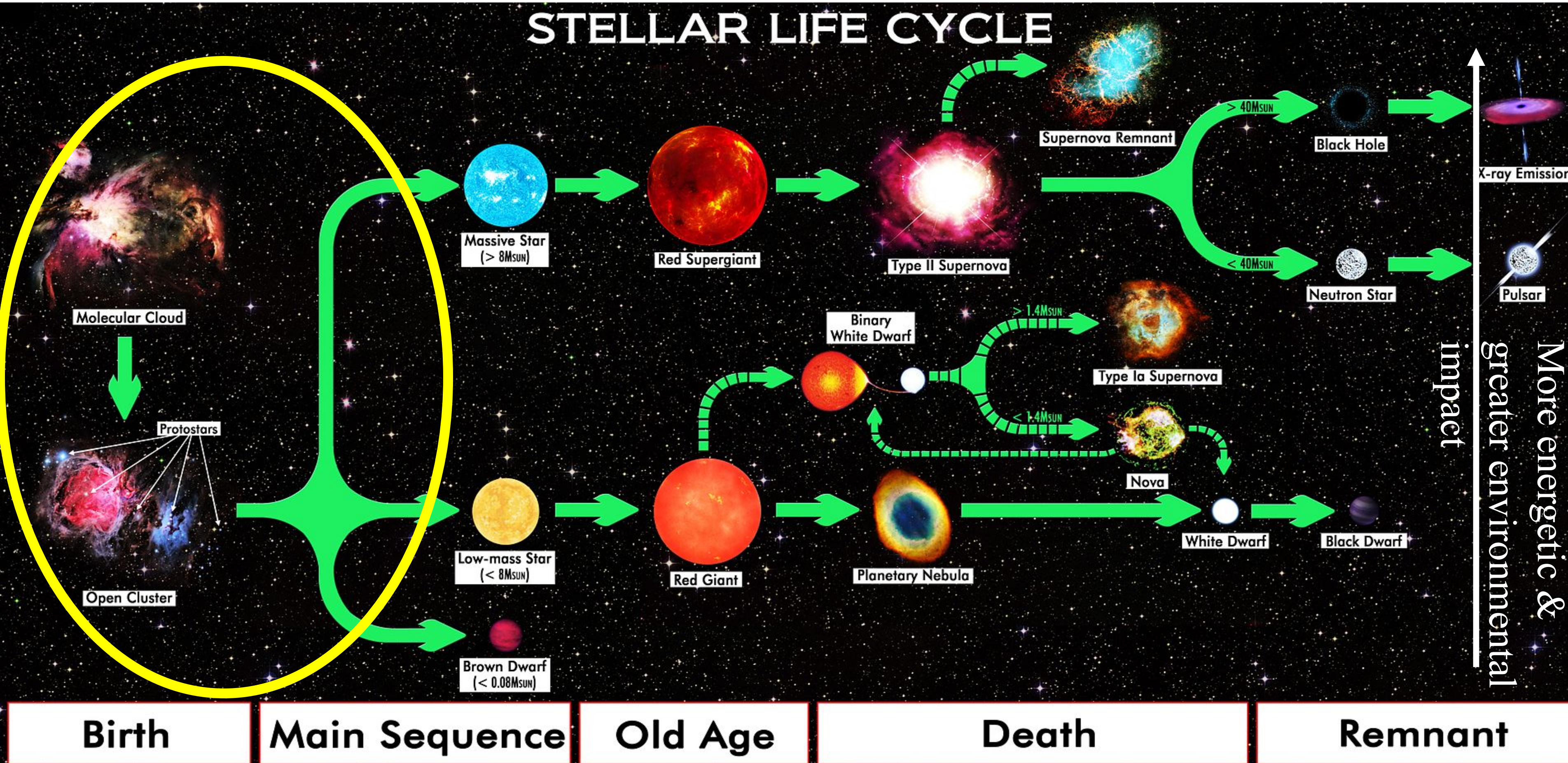
❖ Brown Dwarfs
($M < 0.08M_{sun}$)



➢ Evolutionary path is determined by its mass

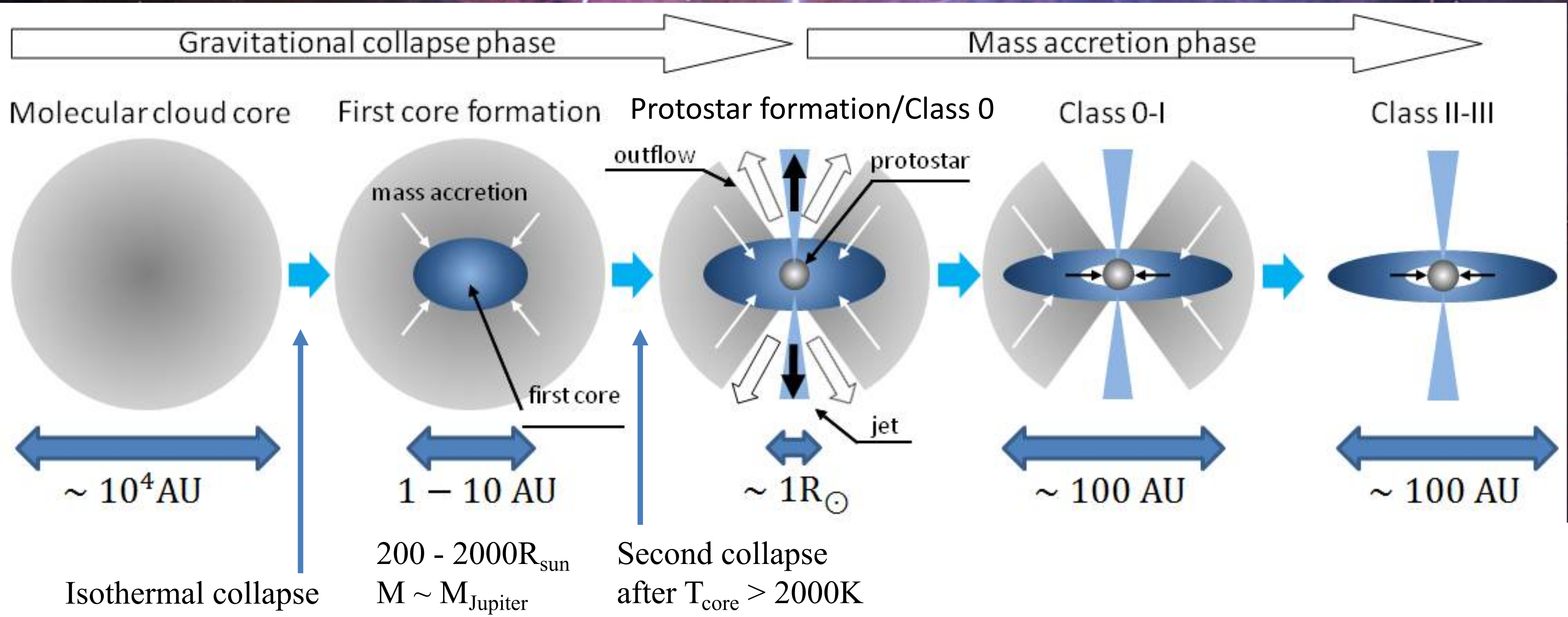
Image: R.N. Bailey (Own work, CC BY 4.0, https://commons.wikimedia.org/w/index.php?curid=59672008)

Importance of stars: Masses



- Evolutionary path is determined by its *birth* mass

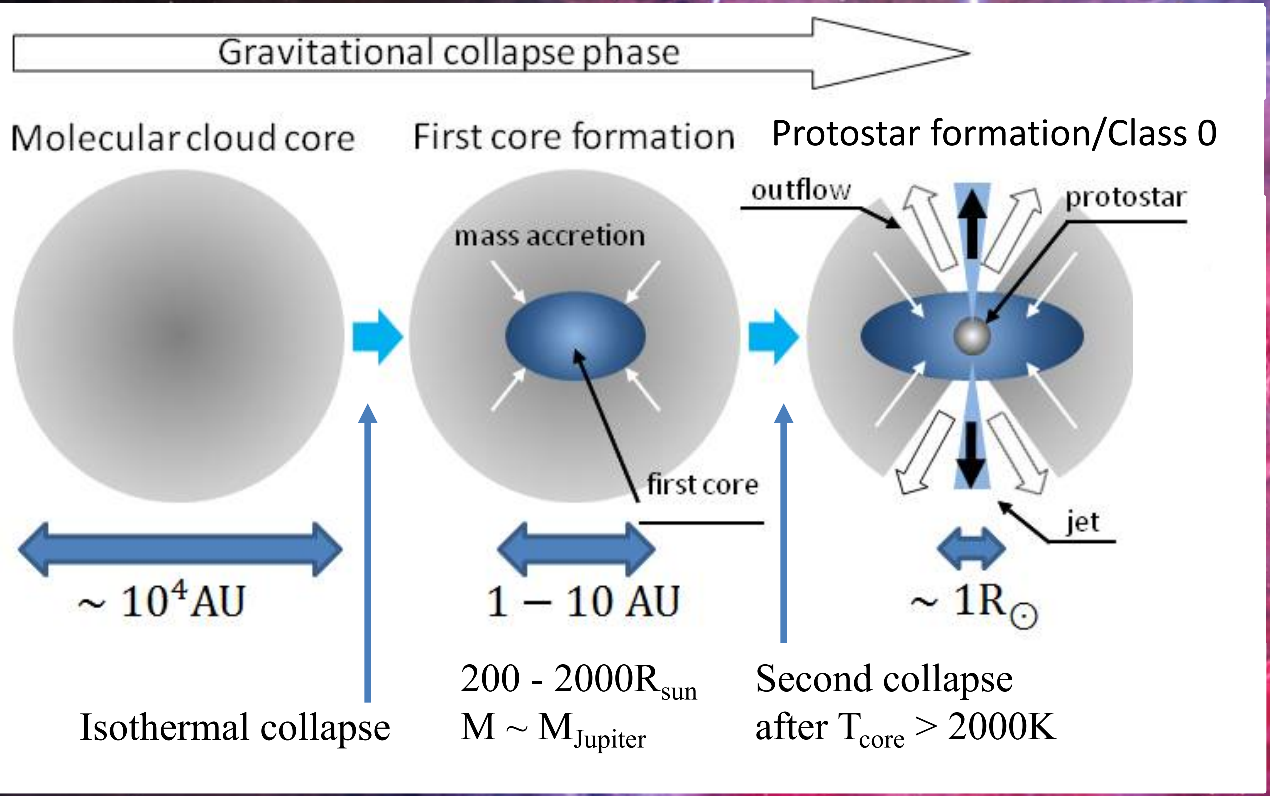
Star formation: From the beginning



- Cannot discuss star formation without discussing disc formation and outflows

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

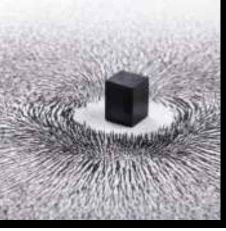
Star formation: From the beginning

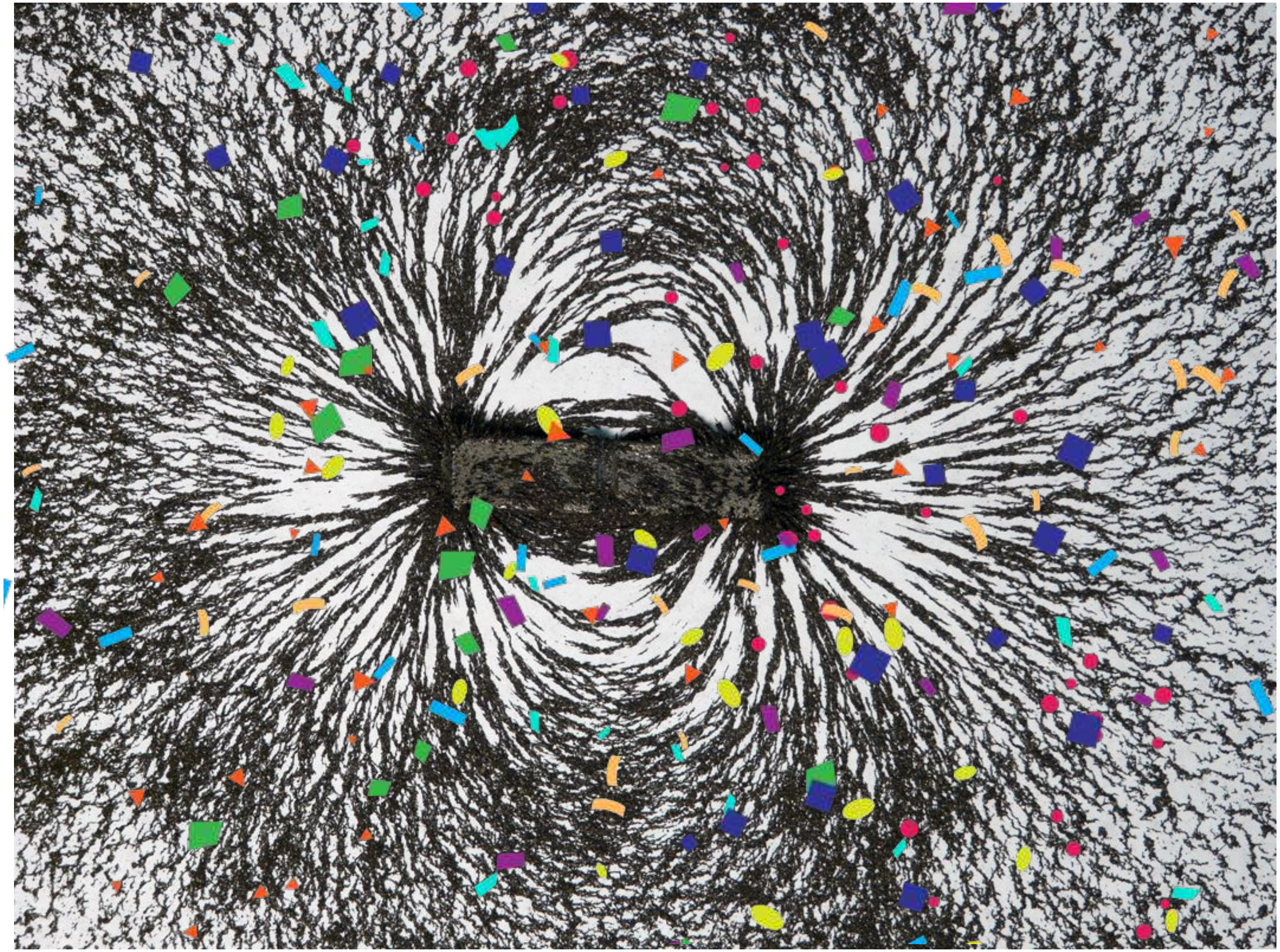


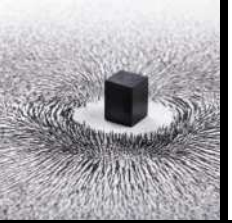
- Relevant processes include
  - Gas
  - Dust
  - Radiation
  - Rotation & Turbulence
  - Magnetic fields

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

Magnetic fields







Magnetic fields

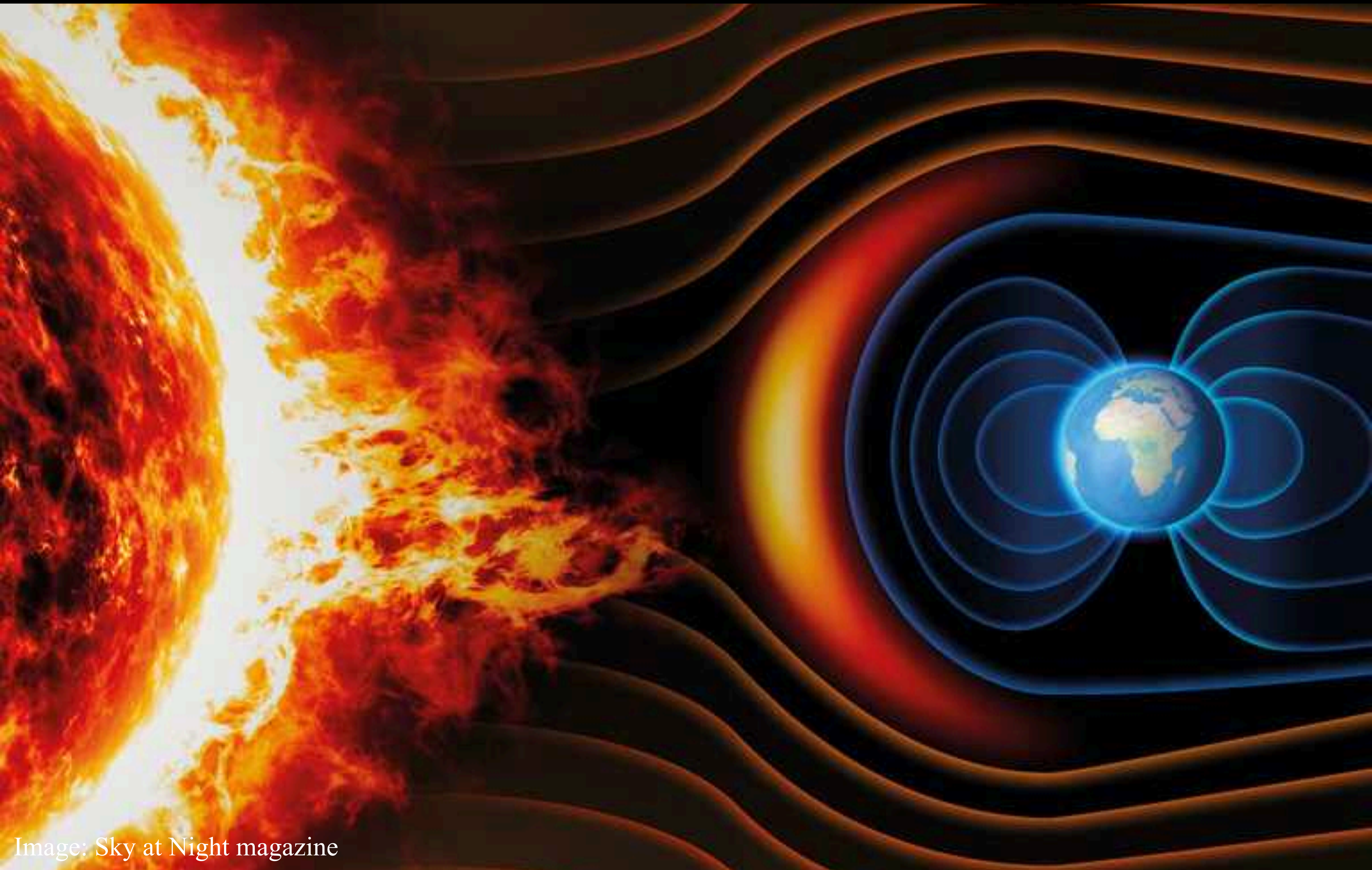
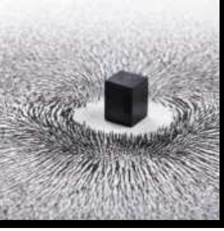
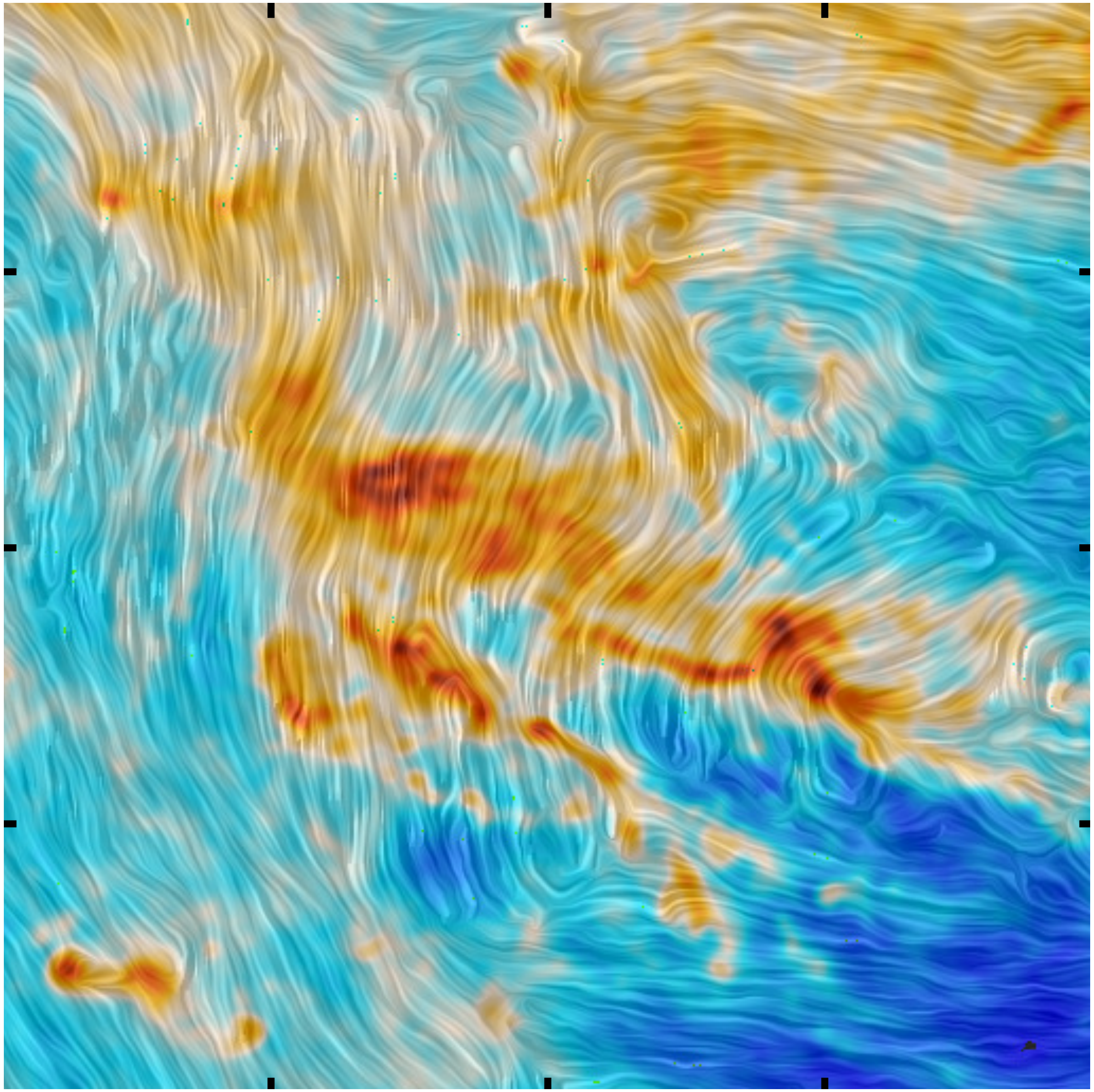


Image: Sky at Night magazine

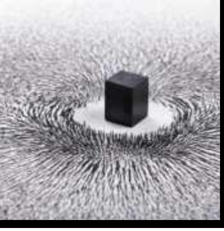


Magnetic fields

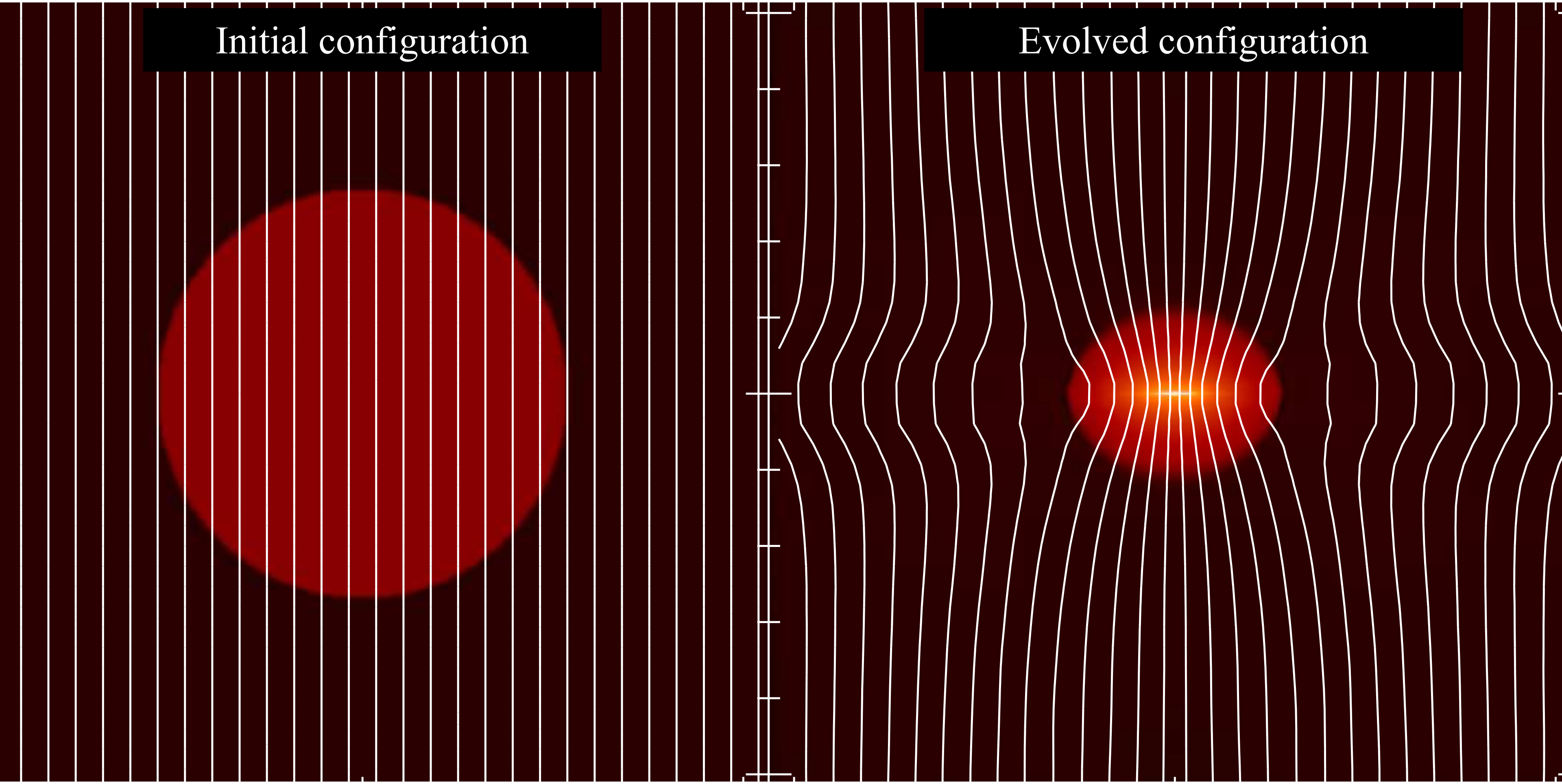


Magnetic field and column density towards Taurus; Planck Collaboration (2016)

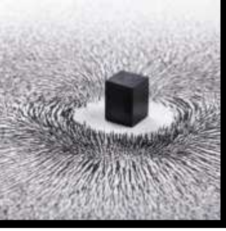
Magnetic fields



- Strong field; large-scale structure

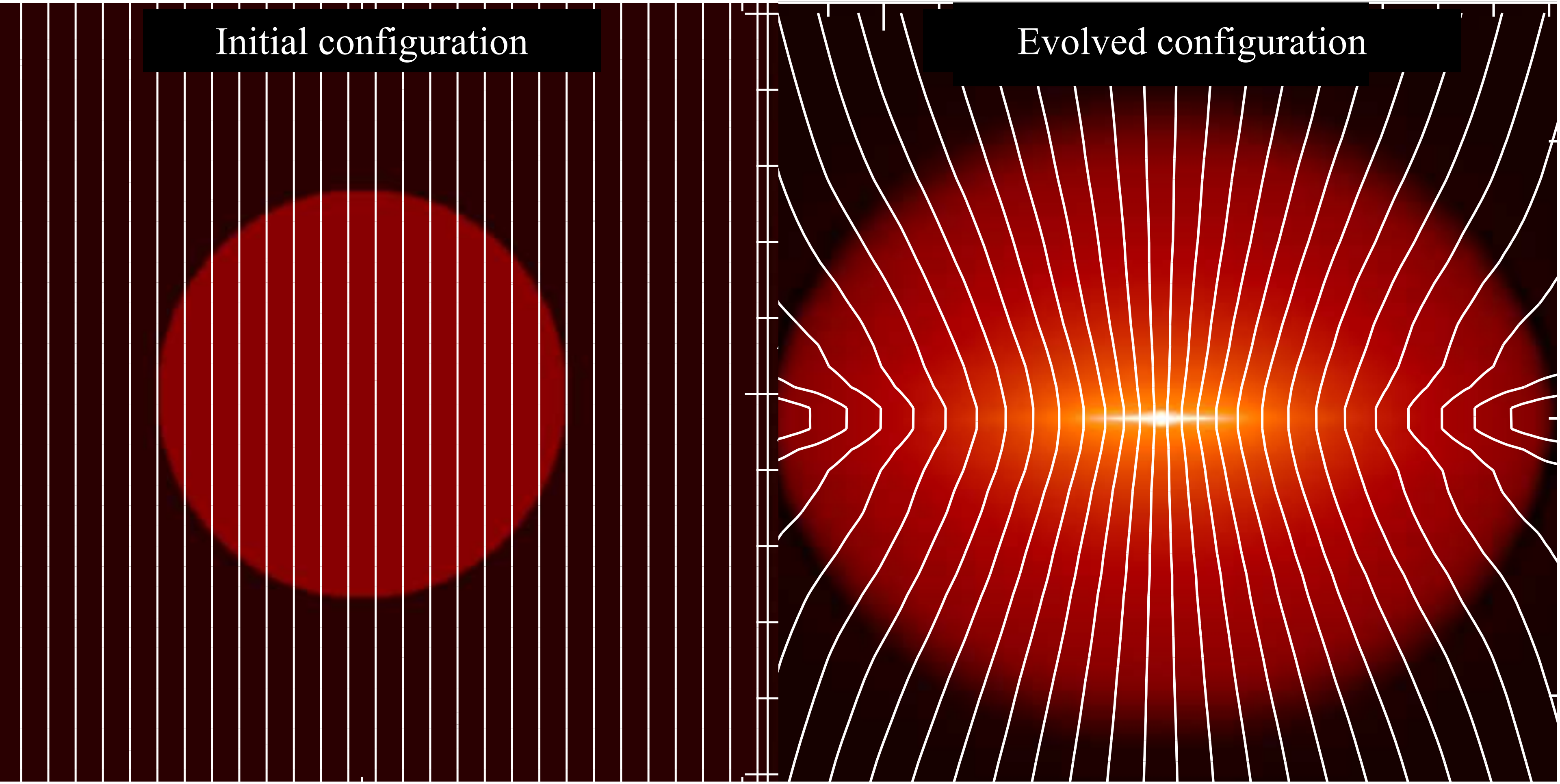


- Background represents gas column density

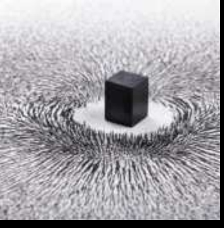


Magnetic fields

- Strong field; large-scale structure

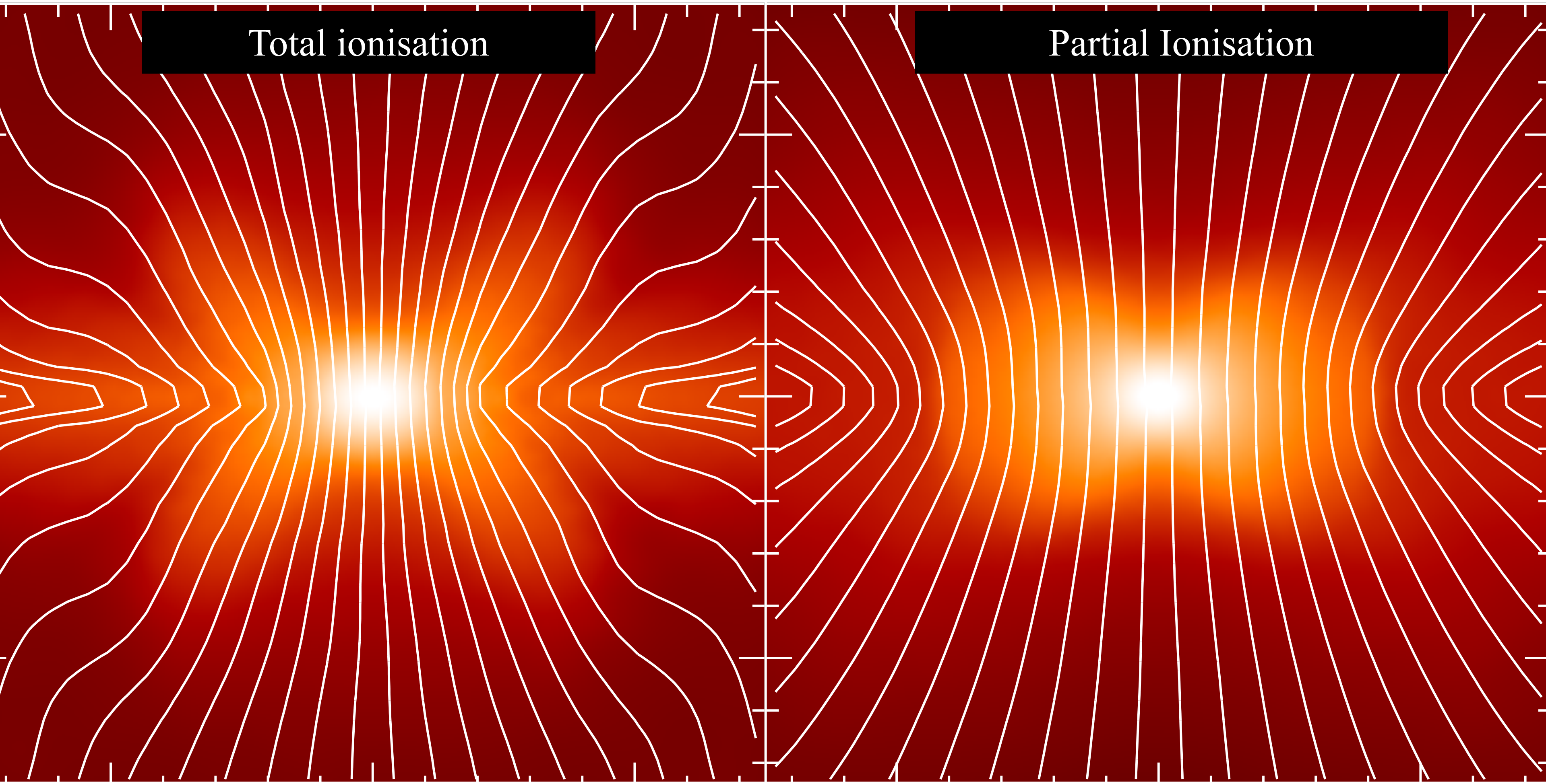


- Background represents gas column density

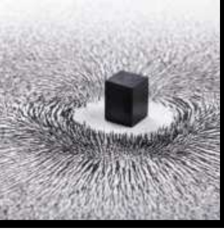


Magnetic fields

- Strong field; small scale structure

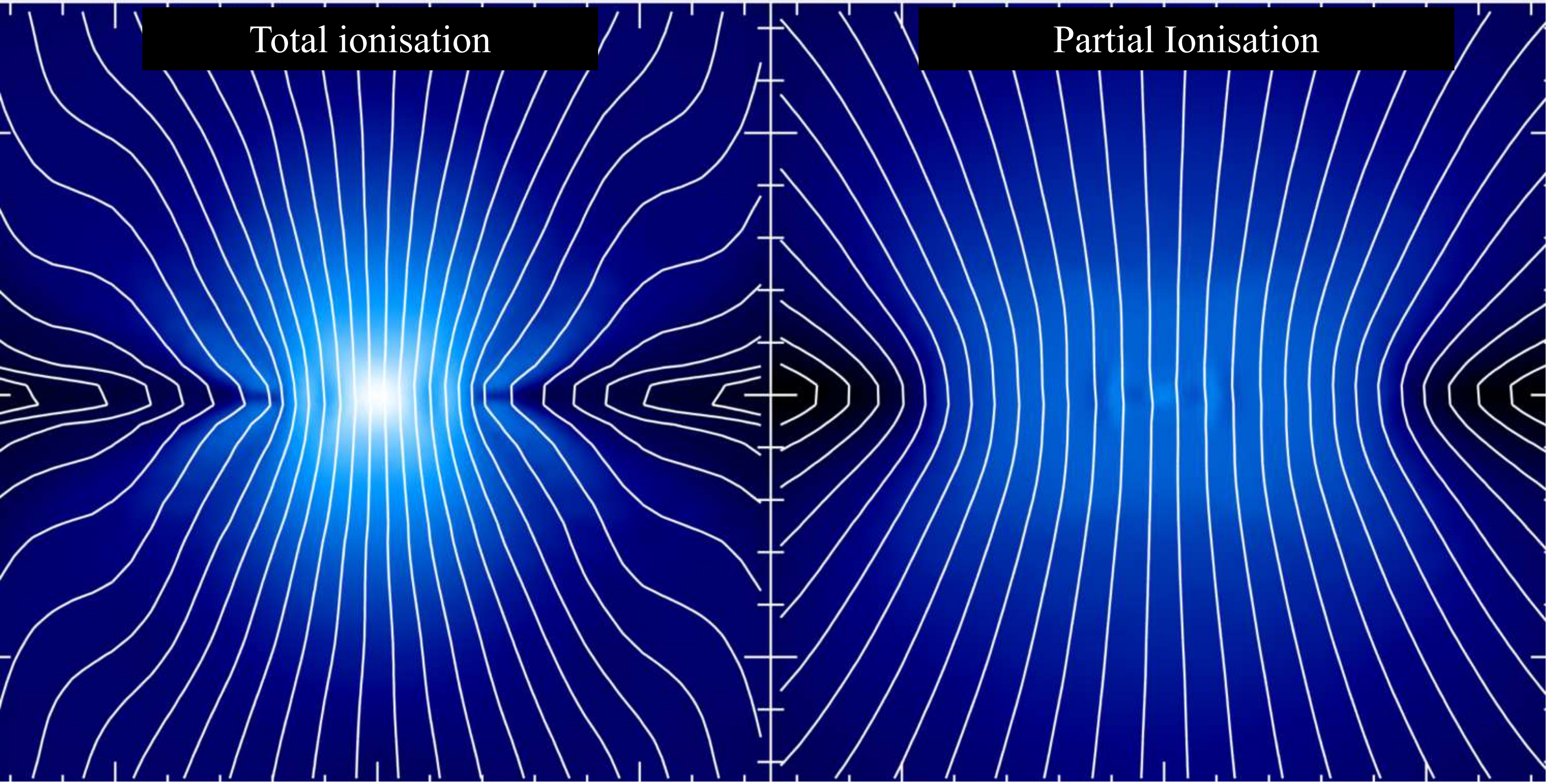


- Background represents gas column density



Magnetic fields

- Strong field; small scale structure



- Background represents magnetic field strength
  - Both models have similar central gas density, but different magnetic field strengths

Theoretical (numerical) astronomy

- Requirements
  - A problem to solve:
    How is a star born?

Theoretical (numerical) astronomy

- Requirements
  - A problem to solve:
    How is a star born?
  - A description of the physics:
    radiation non-ideal magnetohydrodynamic

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

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

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

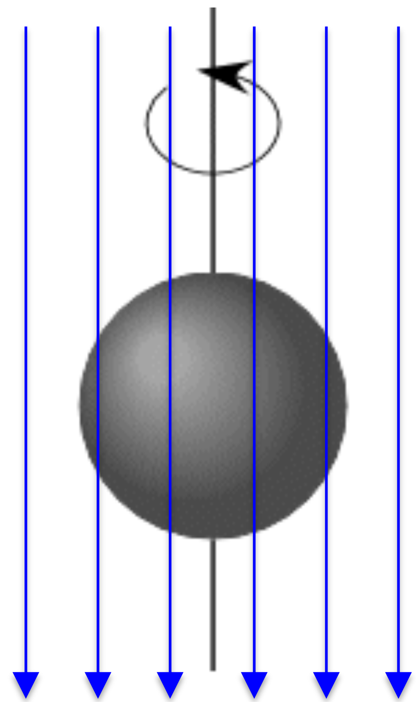
$$\rho\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{E}{\rho}\right) = -\nabla\cdot\boldsymbol{F} - \nabla\boldsymbol{v}{:}\boldsymbol{P} + 4\pi\kappa\rho B_{\mathrm{P}} - c\kappa\rho E,$$

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

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

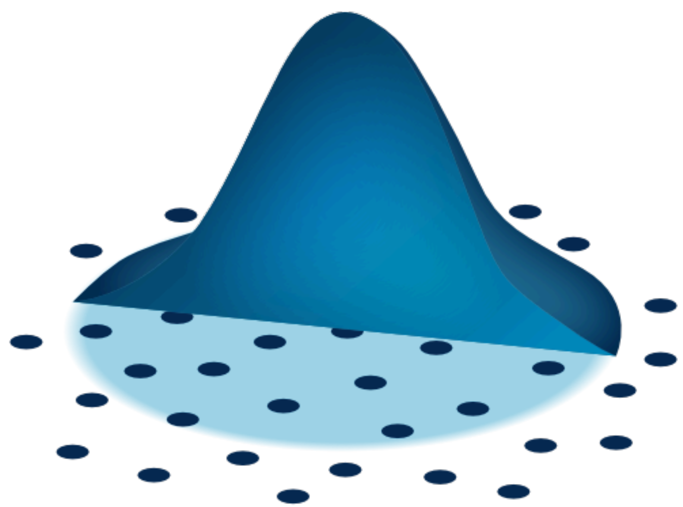
Theoretical (numerical) astronomy

- Requirements
  - A problem to solve:
    How is a star born?
  - A description of the physics:
    radiation non-ideal magnetohydrodynamic
  - Initial configuration:
    rotating sphere of gas, threaded with a magnetic field



Theoretical (numerical) astronomy

- Requirements
  - A problem to solve:
    How is a star born?
  - A description of the physics:
    radiation non-ideal magnetohydrodynamic
  - Initial configuration:
    rotating sphere of gas, threaded with a magnetic field
  - A numerical method:
    smoothed particle magnetohydrodynamic



Theoretical (numerical) astronomy

- Requirements
  - A problem to solve:
    How is a star born?
  - A description of the physics:
    radiation non-ideal magnetohydrodynamic
  - Initial configuration:
    rotating sphere of gas, threaded with a magnetic field
  - A numerical method:
    smoothed particle magnetohydrodynamic
  - A High Performance Computing cluster

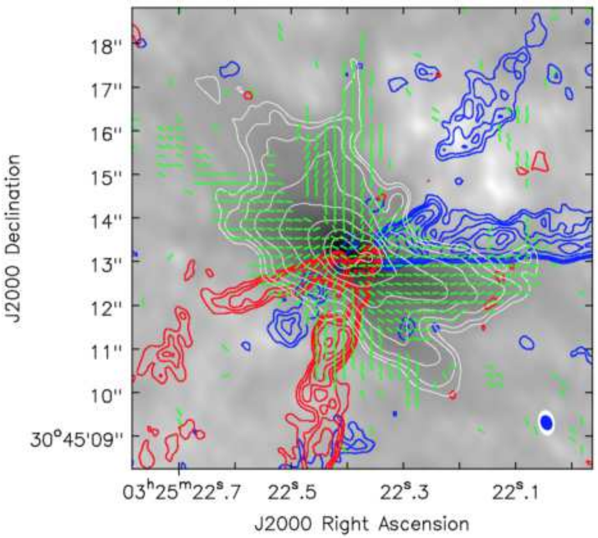
Theoretical (numerical) astronomy

- Requirements
  - A problem to solve:
    How is a star born?
  - A description of the physics:
    radiation non-ideal magnetohydrodynamic
  - Initial configuration:
    rotating sphere of gas, threaded with a magnetic field
  - A numerical method:
    smoothed particle magnetohydrodynamic
  - A High Performance Computing cluster
  - Patience

Formation of a low-mass star: Expectations

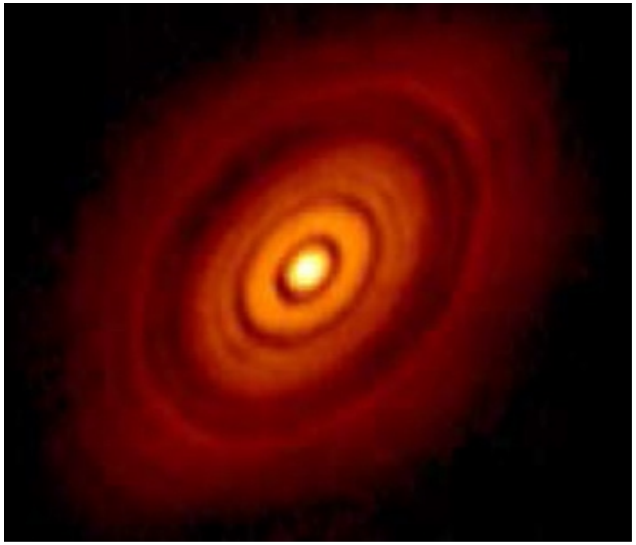
➢What we expect to form in addition to a low-mass star:

‘Hour-glass’
magnetic field morphology



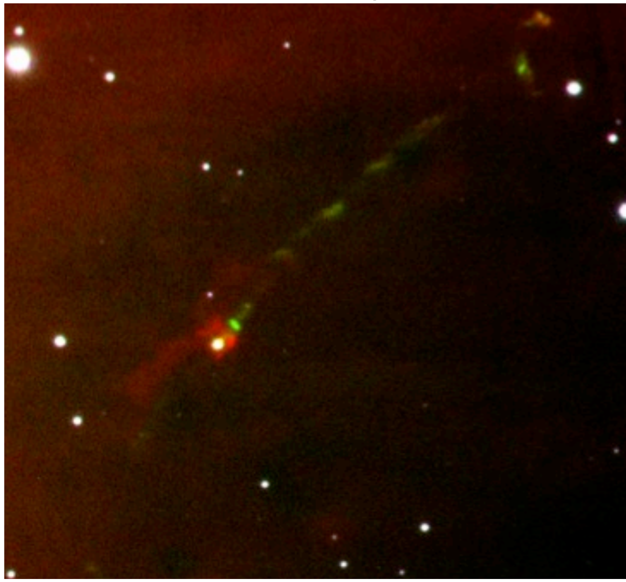
(Kwon+ 2019)

Protoplanetary disc



(ALMA Partnership, 2015)

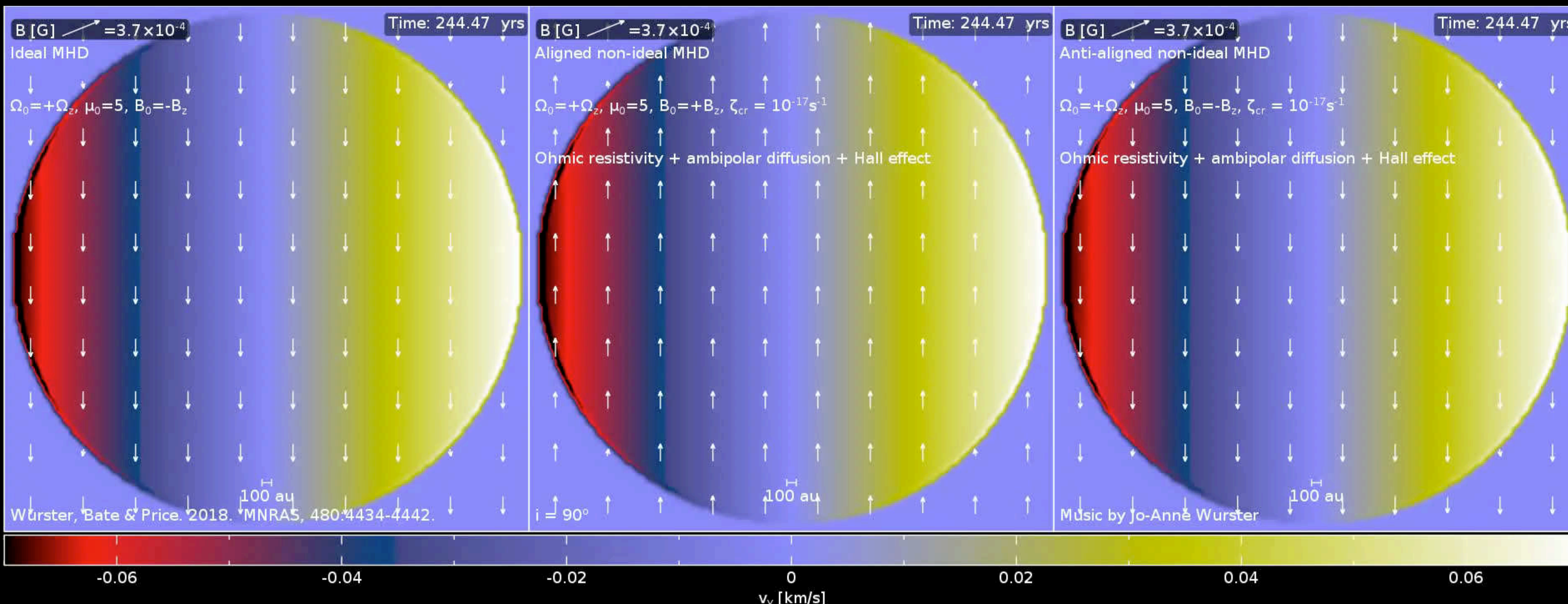
Outflows and/or jets



(Riaz+2017)

Formation of a low-mass star

Total ionisation | Partial ionisation (aligned) | Partial ionisation (anti-aligned)

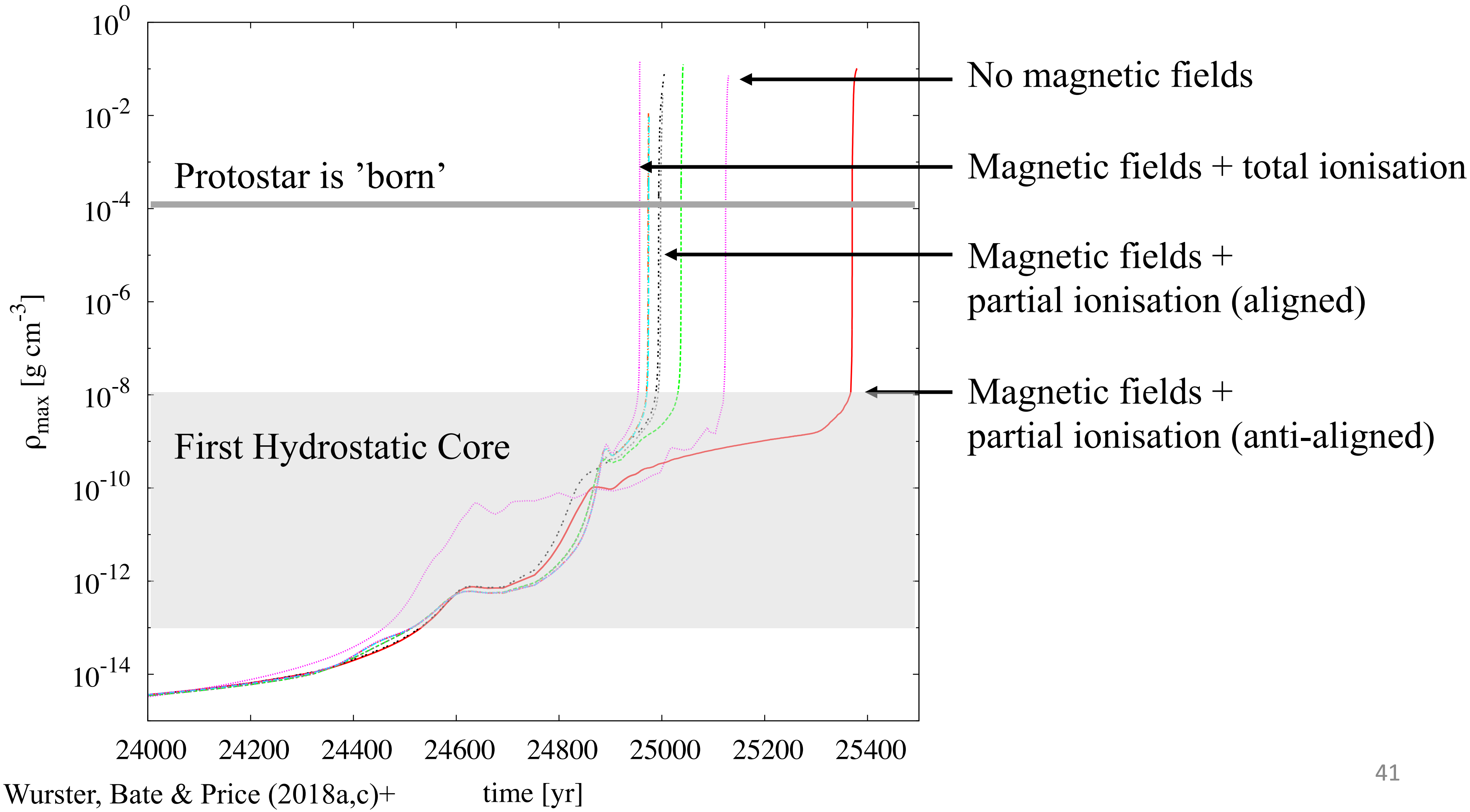


Wurster, Bate & Price (2018c): https://www.youtube.com/watch?v=2SQxgXbdJyg&t=17s

Music: Jo-Anne Wurster

Formation of a low-mass star

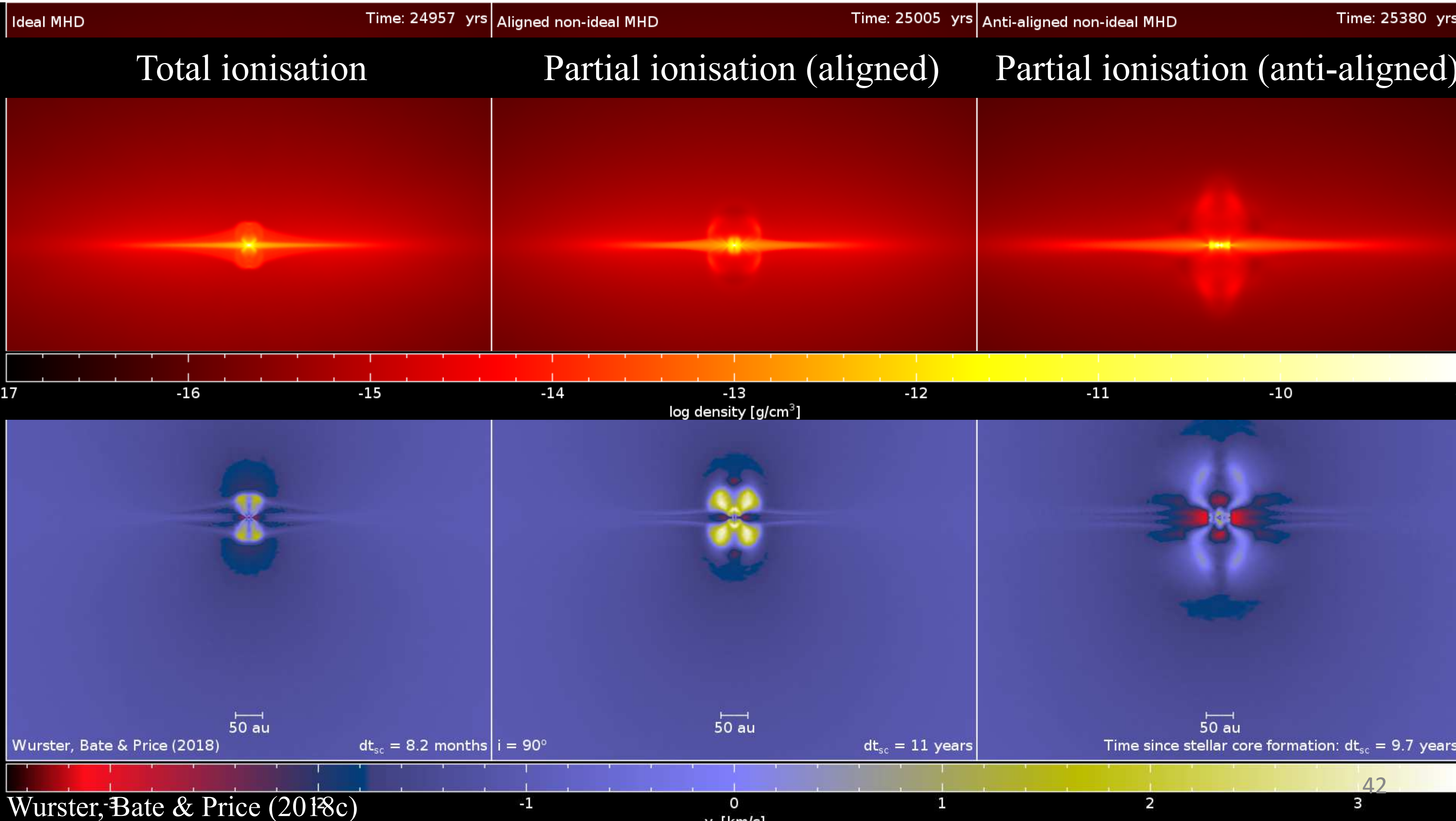
- Magnetic fields clearly play an important role in the evolution of the star
  - Evolution occurs at a different rate



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

Formation of a low-mass star

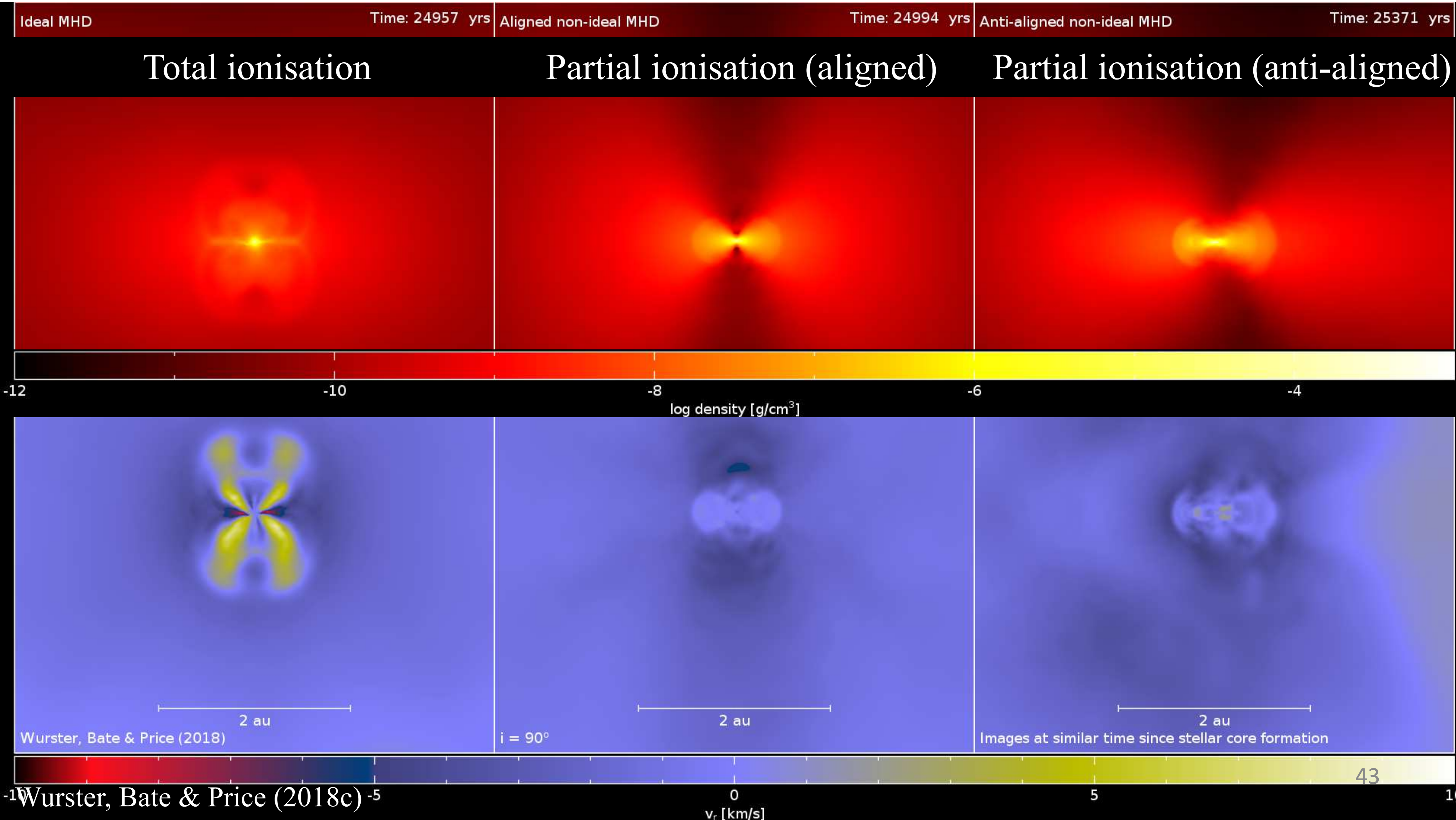
- Magnetic fields clearly play an important role in the evolution of the star
  - Size & structure of first core outflows



Wurster, Bate & Price (2018c)

Formation of a low-mass star

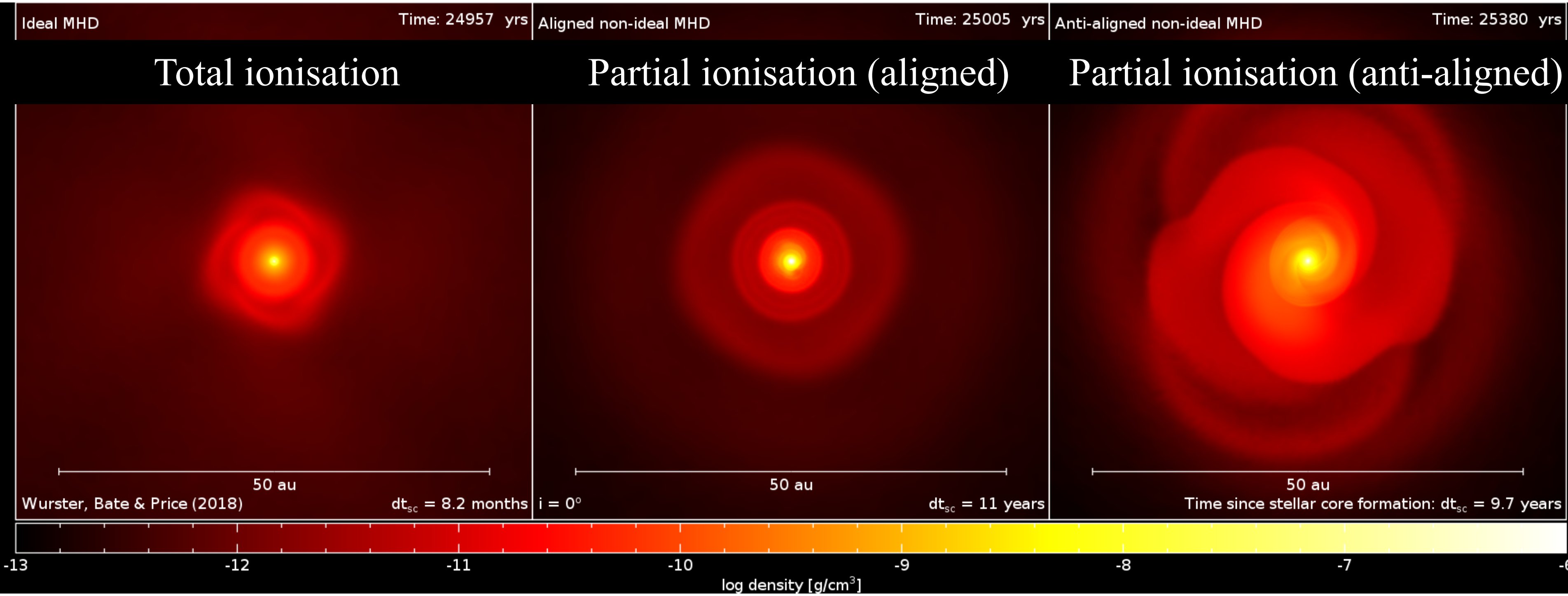
- Magnetic fields clearly play an important role in the evolution of the star
  - Size & structure of second core outflows



Wurster, Bate & Price (2018c)

Formation of a low-mass star

- Magnetic fields clearly play an important role in the evolution of the star
    - Formation of a disc

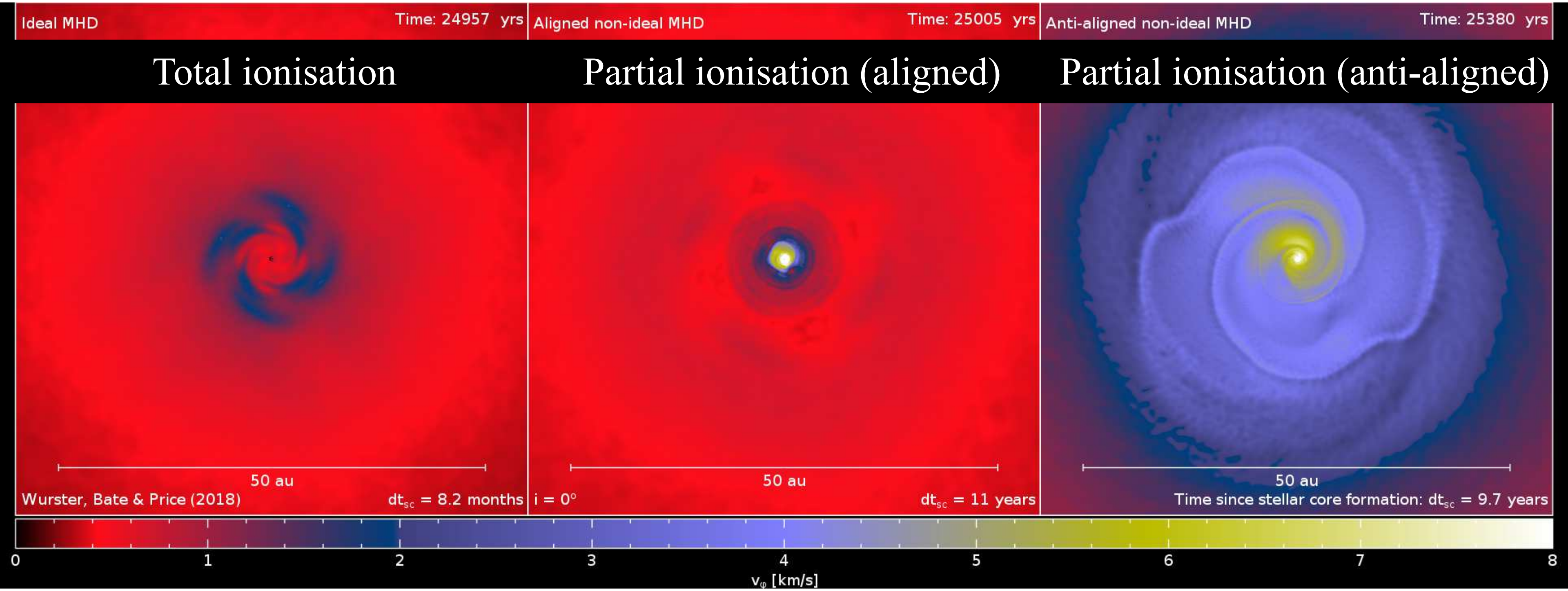


Clear ~25au disc

Wurster, Bate & Price (2018c)

Formation of a low-mass star

- Magnetic fields clearly play an important role in the evolution of the star
  - Formation of a disc

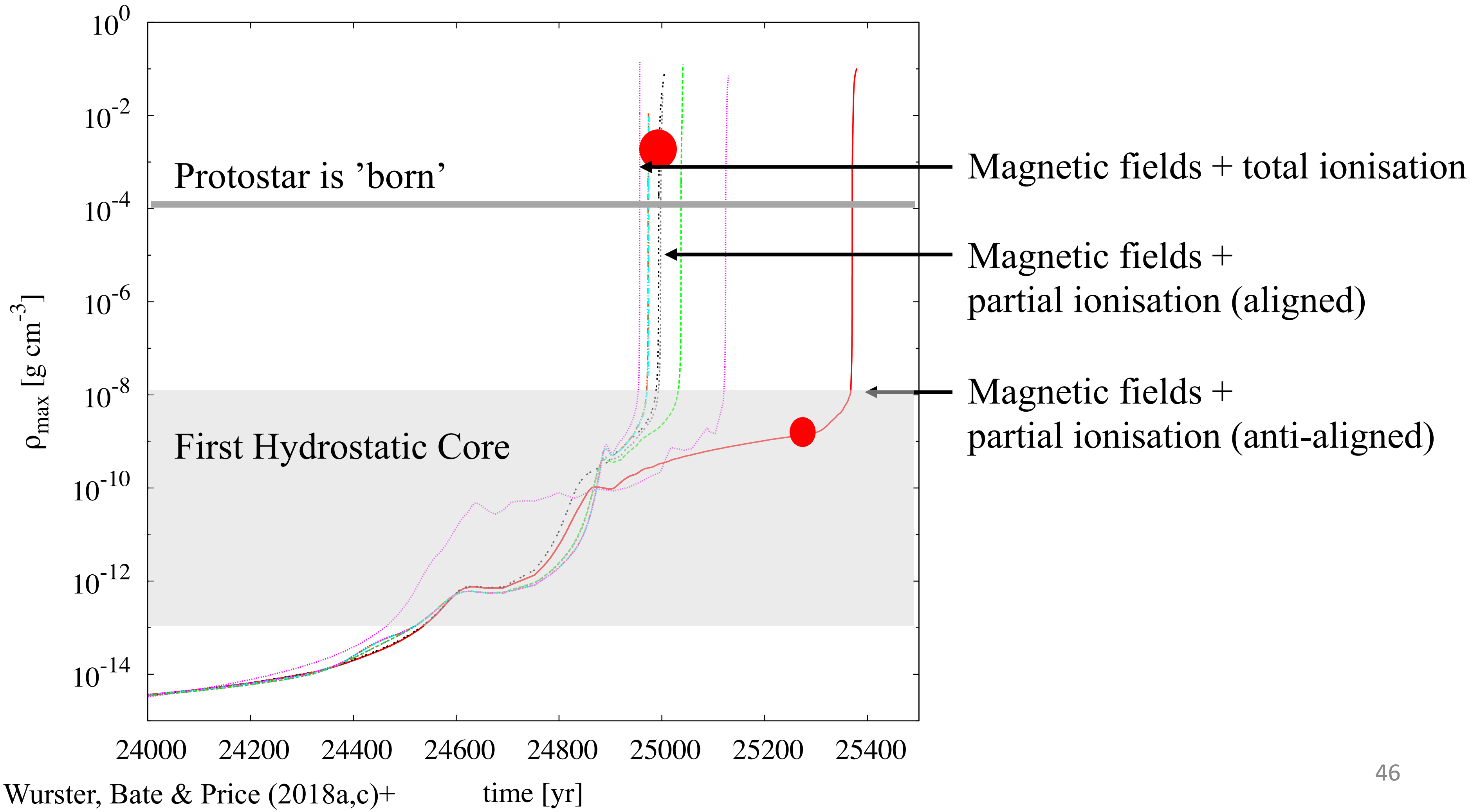


No disc ~2au disc Clear ~25au disc

Wurster, Bate & Price (2018c)

Formation of a low-mass star

- Magnetic fields clearly play an important role in the evolution of the star
  - The two discs form at different times



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

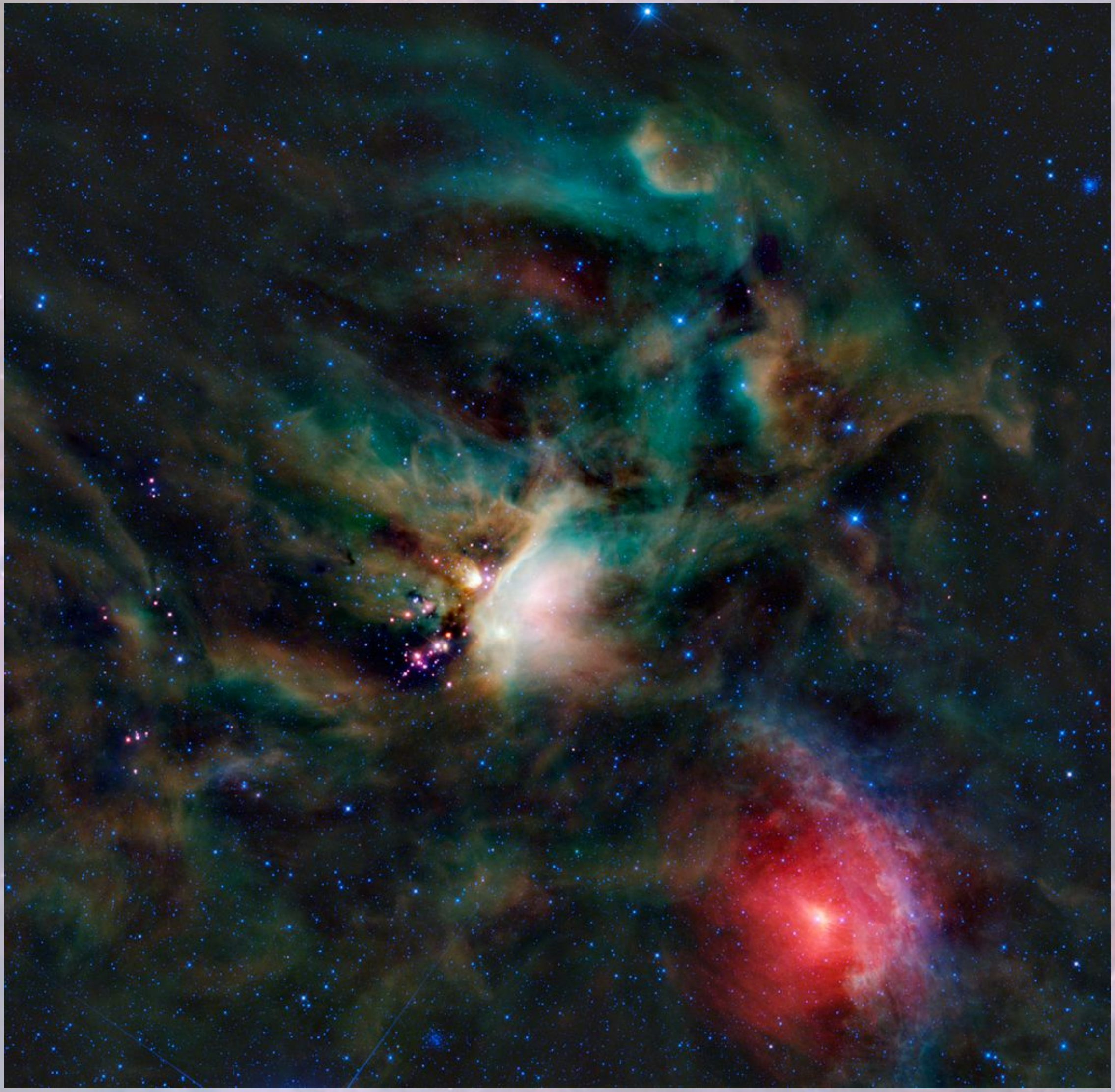
Star formation: From the beginning

- Previous simulations act as controlled 'laboratories' where we can carefully examine and test all various physical processes and characteristics

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

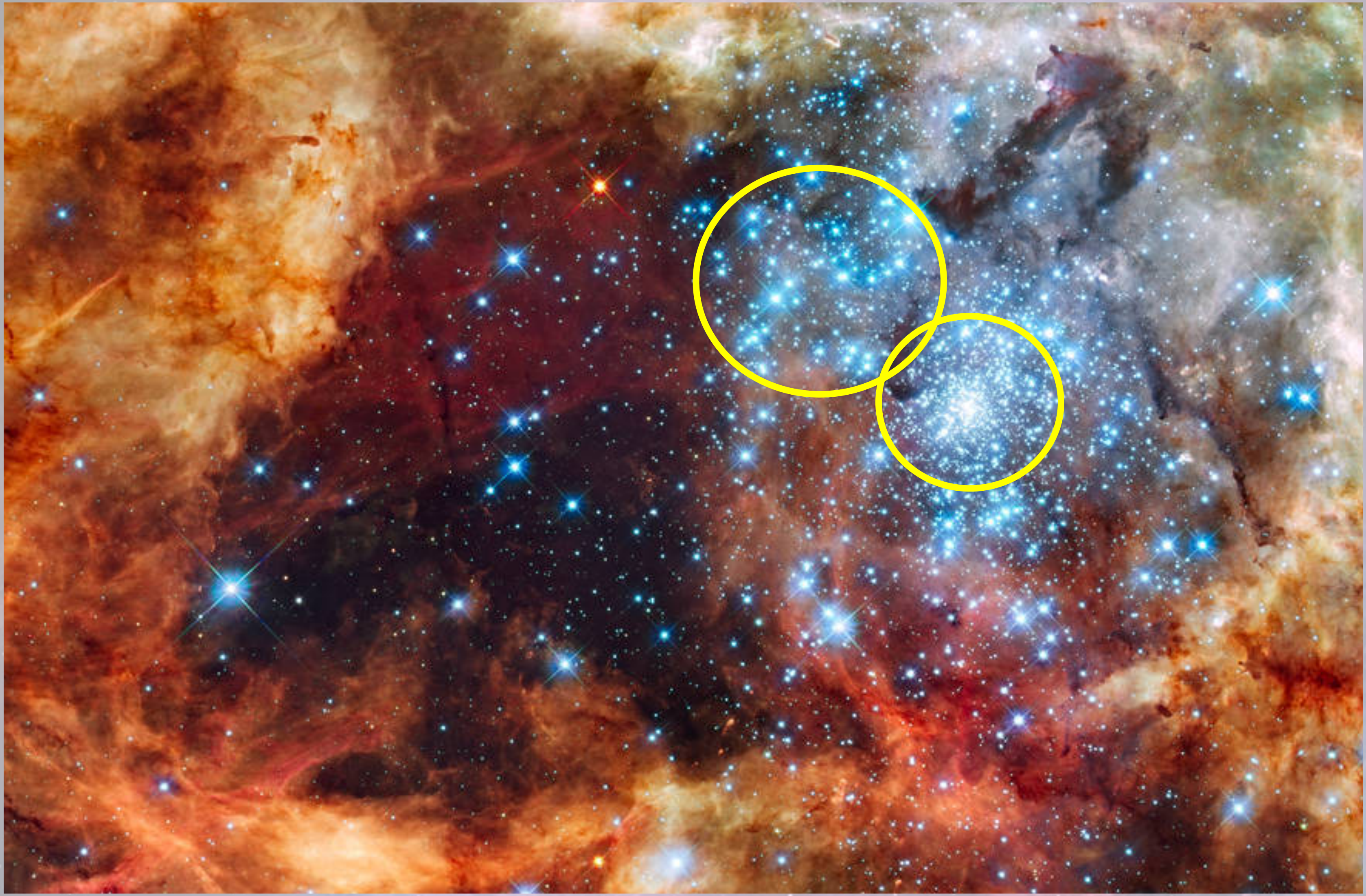
Orion Molecular Cloud. (image credit: Drudis & Goldman via APOD)

Star formation: Stellar nurseries



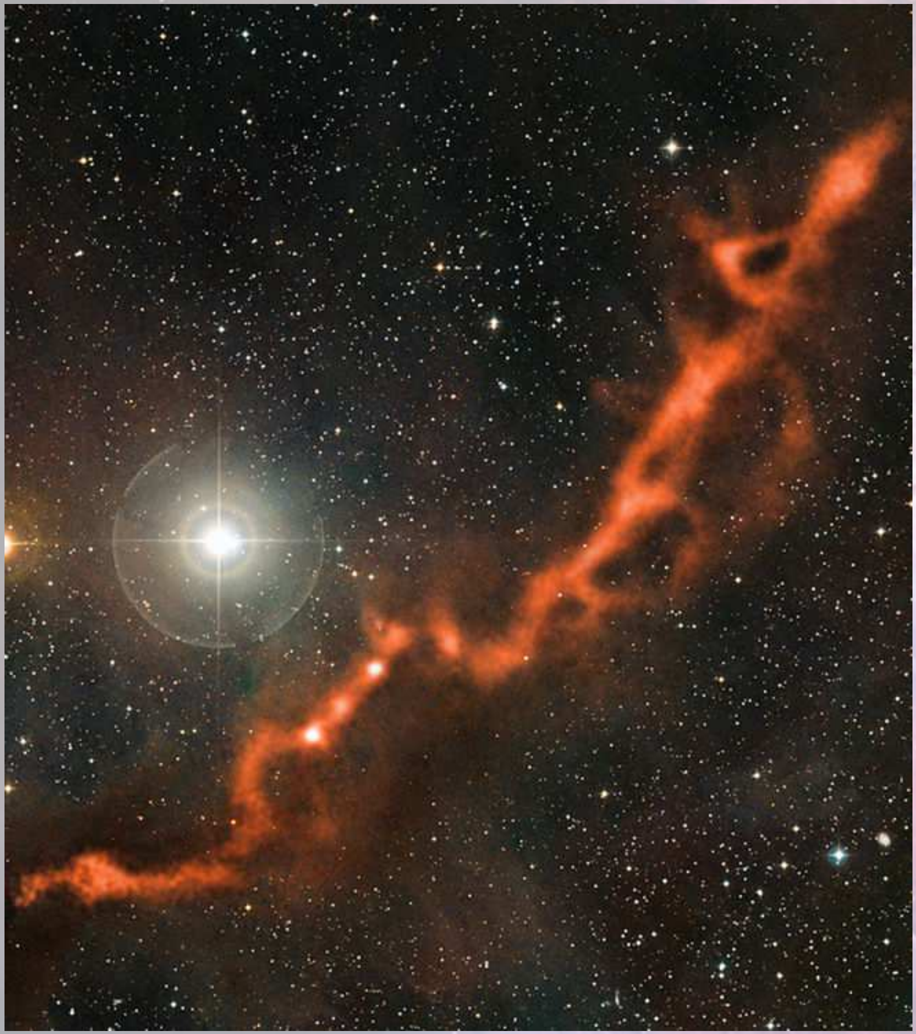
Rho Ophiuchi Cloud Complex
(image credit: By NASA/JPL-Caltech/WISE Team - WISE)

Star formation: Stellar nurseries

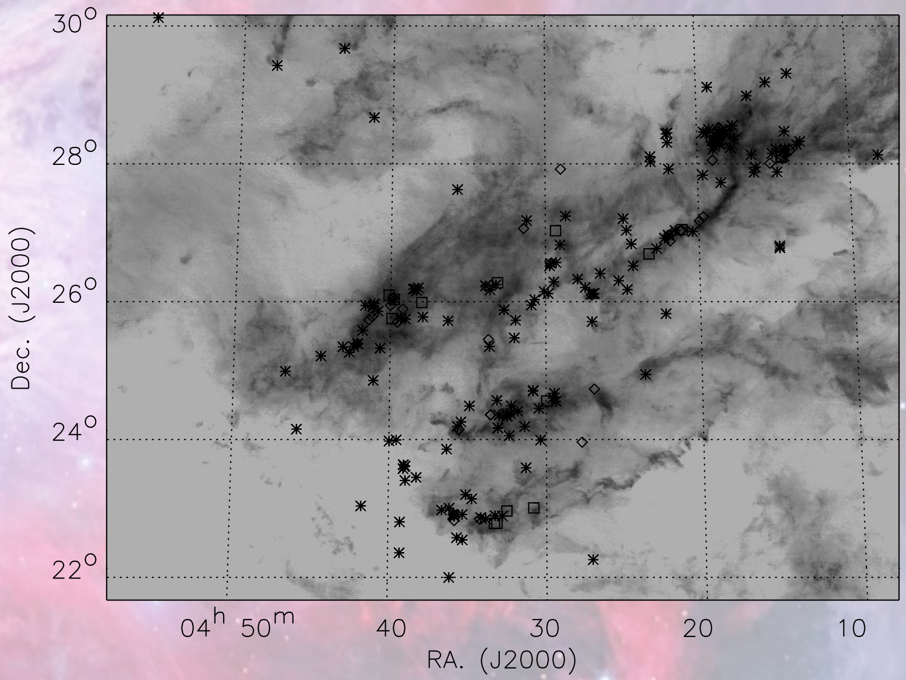


30 Doradus (aka Trantula Nebula)
(image by HST. credit: NASA, ESA, F. paresce)

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)

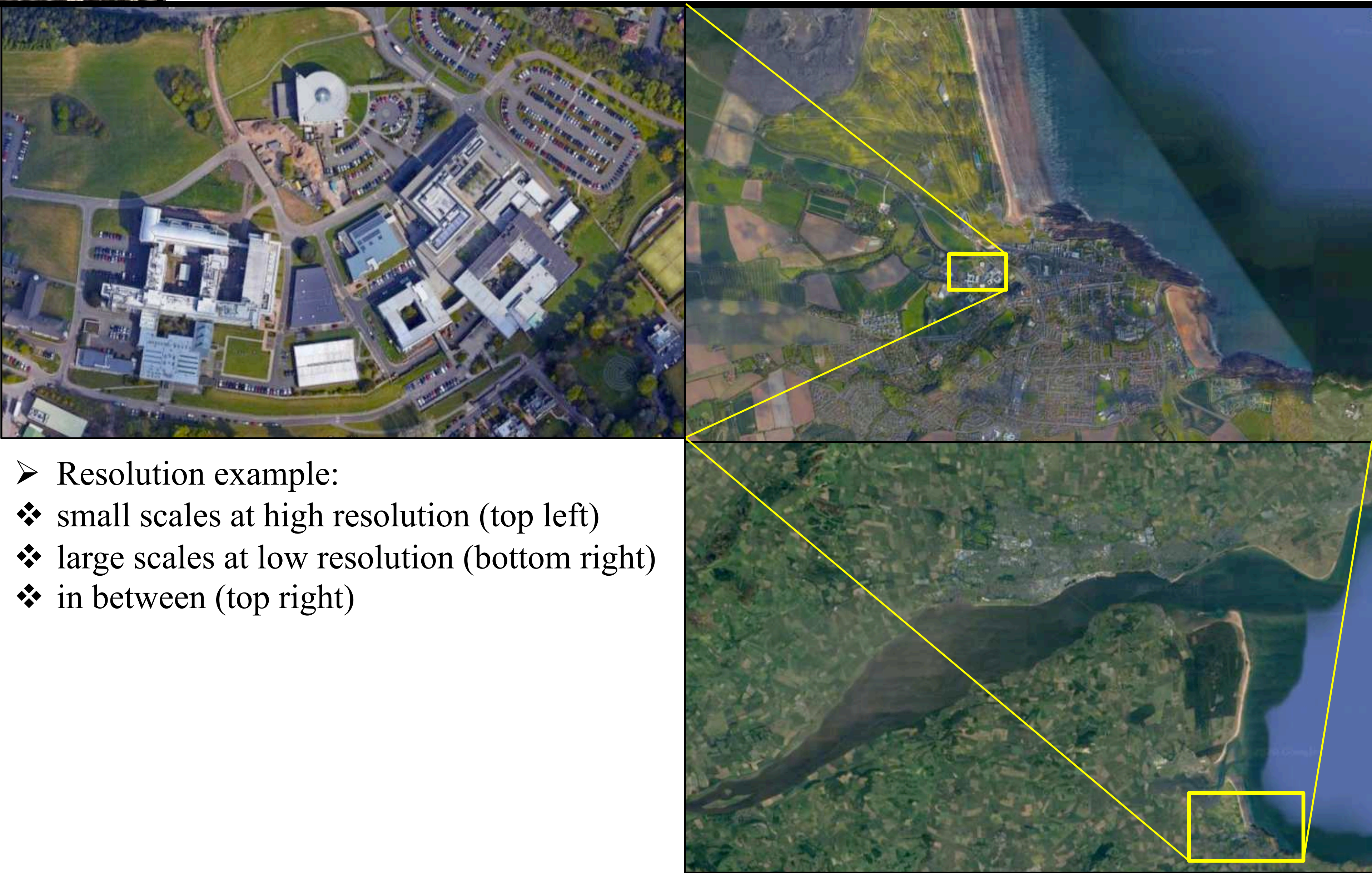
Theoretical (numerical) astronomy

- Requirements
  - A problem to solve:
    How is a star *cluster* born & *how does it evolve*?
  - A description of the physics:
    radiation non-ideal magnetohydrodynamic
  - Initial configuration:
    sphere of *turbulent* gas, threaded with a magnetic field
  - A numerical method:
    smoothed particle magnetohydrodynamic
  - A High Performance Computing cluster
  - Patience

Theoretical (numerical) astronomy

- Requirements
  - A problem to solve:
    How is a star *cluster* born & *how does it evolve*?
- Must make a choice:
  - A: investigate small scales at high resolution
  - B: investigate large scales at low resolution

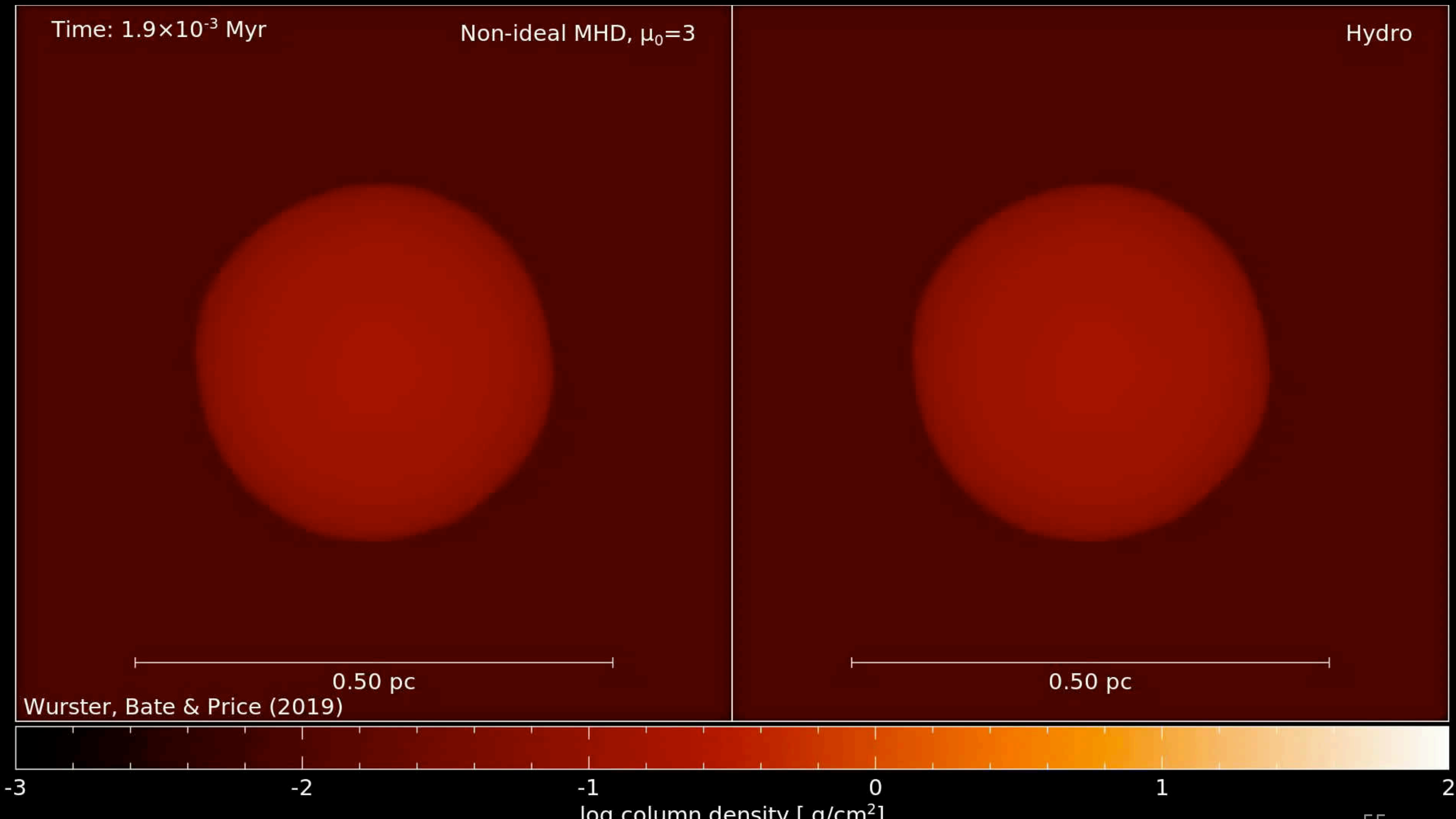
Theoretical (numerical) astronomy



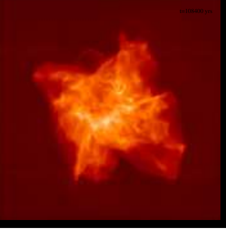
- ➢ Resolution example:
- ❖ small scales at high resolution (top left)
- ❖ large scales at low resolution (bottom right)
- ❖ in between (top right)

Low-mass star cluster formation

Partial ionisation (aligned) | No ionisation (i.e. no magnetic fields)

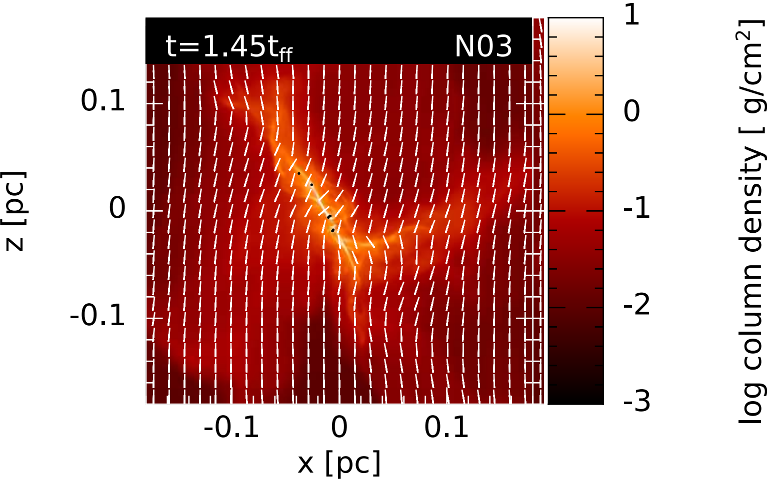


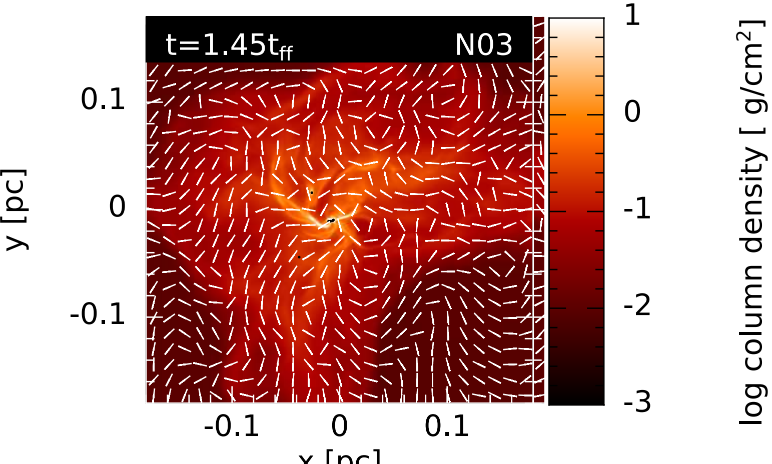
Wurster, Bate & Price (2019): https://www.youtube.com/watch?v=CLhmaOhj5RU



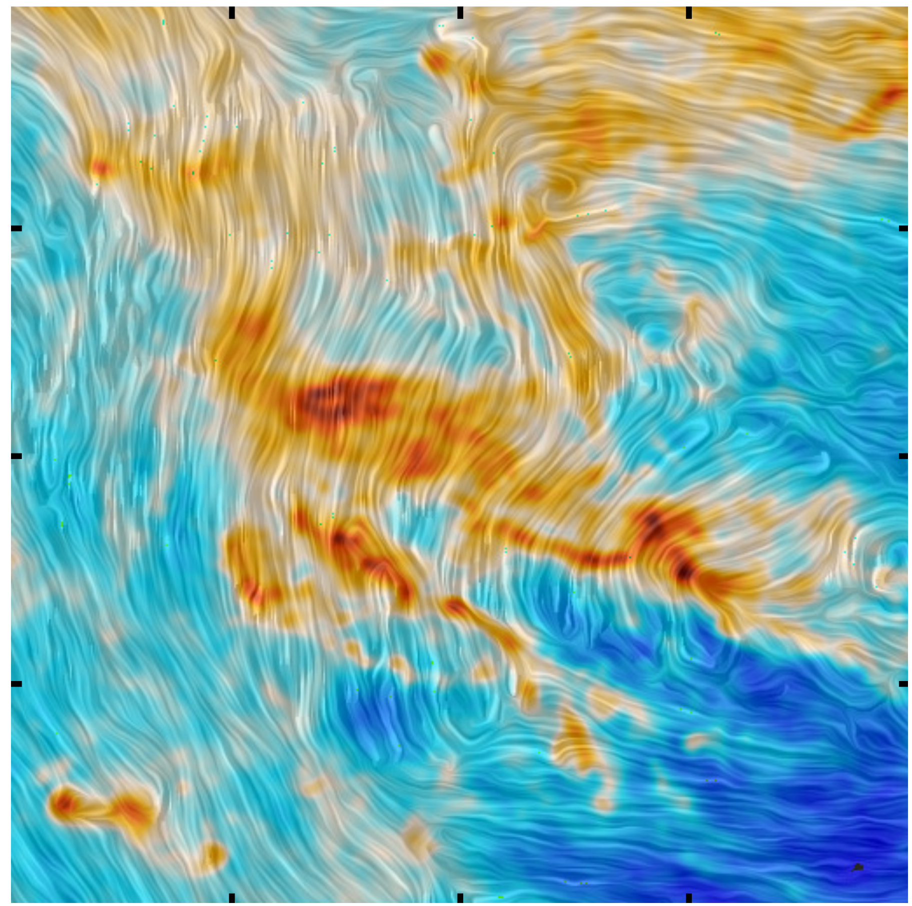
Cluster Formation: Magnetic field lines

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





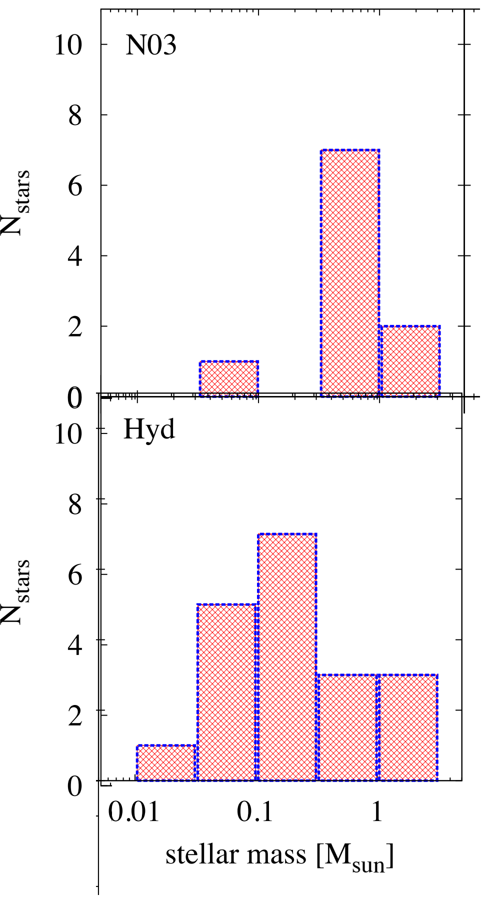
Wurster, Bate & Price (2019)

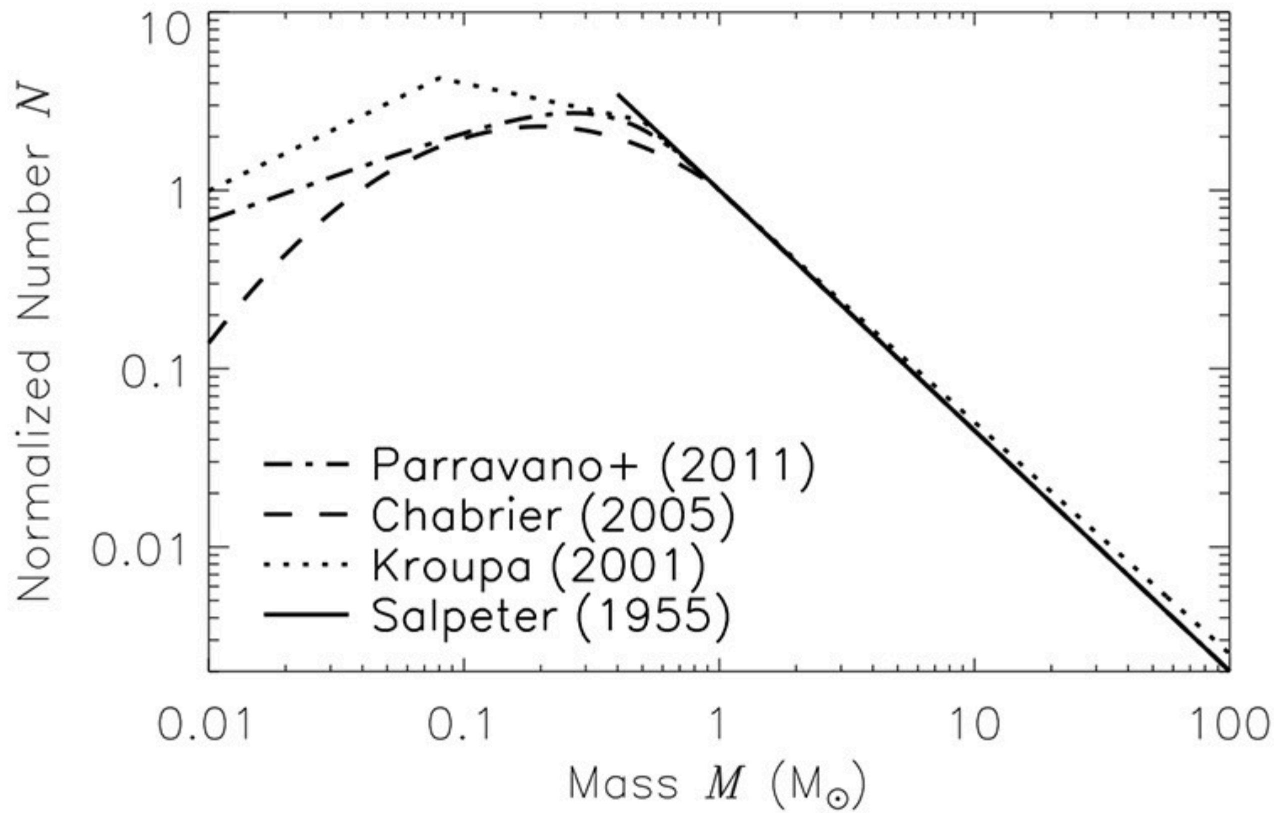


Magnetic field and column density towards Taurus; Planck Collaboration (2016)

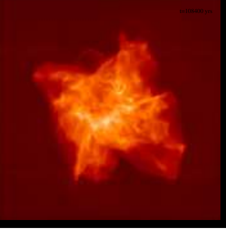
Cluster Formation: Stellar Mass

➢No trend in IMF (although this is low-number statistics)



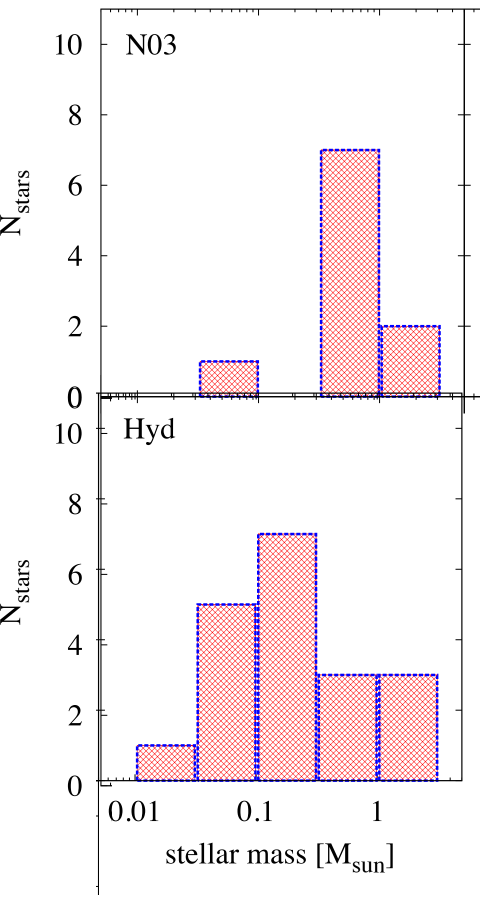


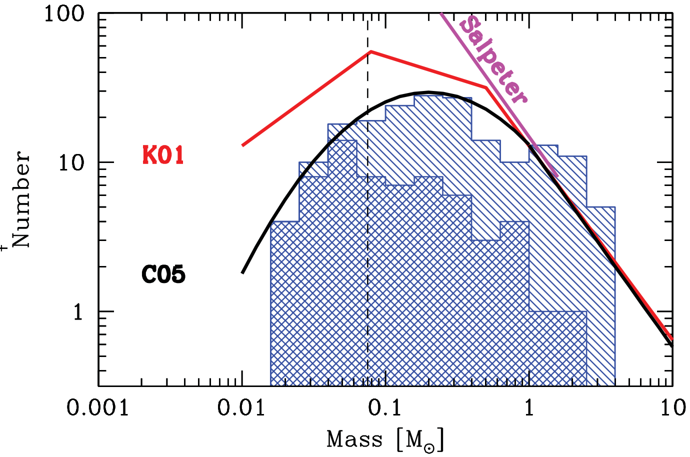
Wurster, Bate & Price (2019); Krumholz & Federrath (2019)

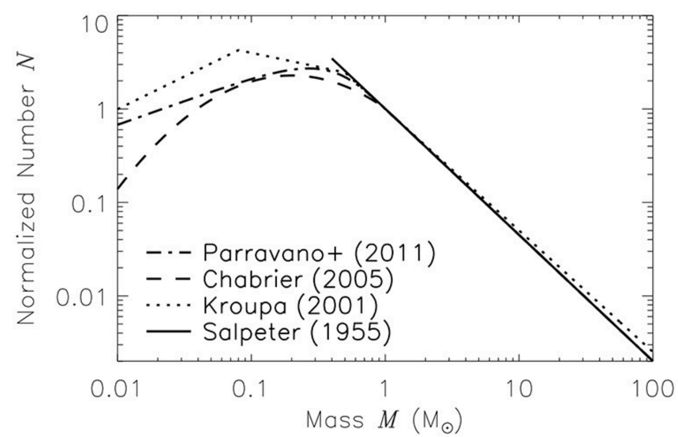


Cluster Formation: Stellar Mass

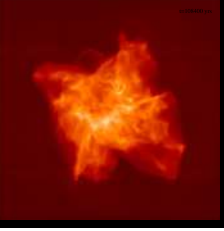
- No trend in IMF (although this is low-number statistics)





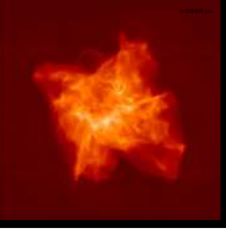


Wurster, Bate & Price (2019); Bate (2012); Krumholz & Federrath (2019)



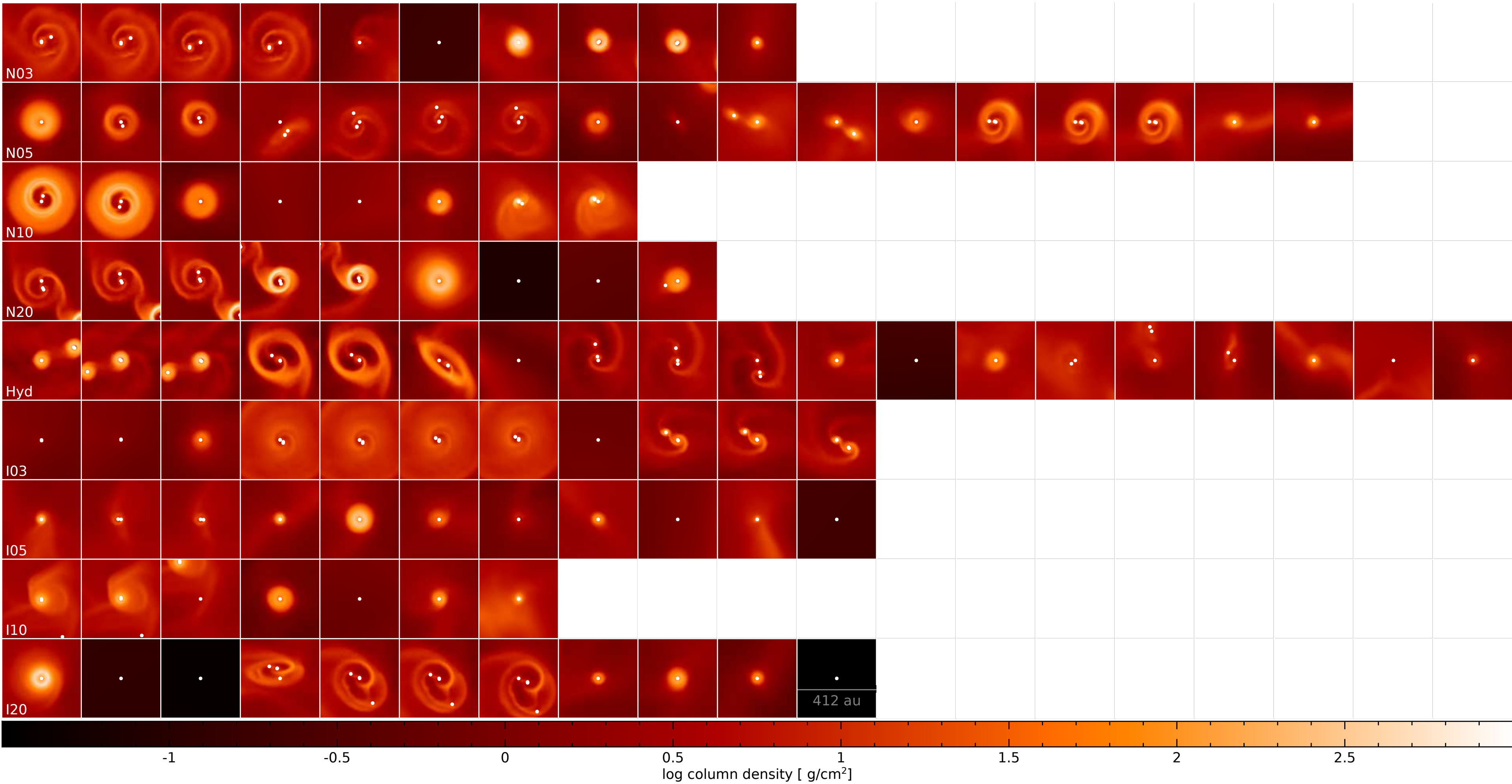
Cluster Formation: Outflows

- None (most likely due to low resolution)

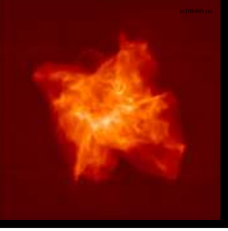


Cluster Formation: Protostellar discs

➢Large protostellar discs form in *all* nine our models

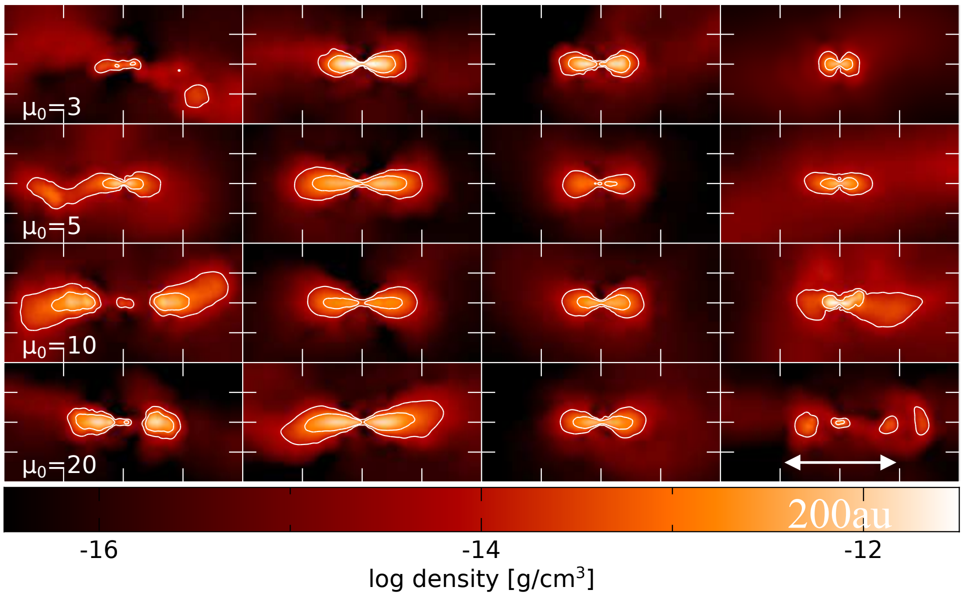


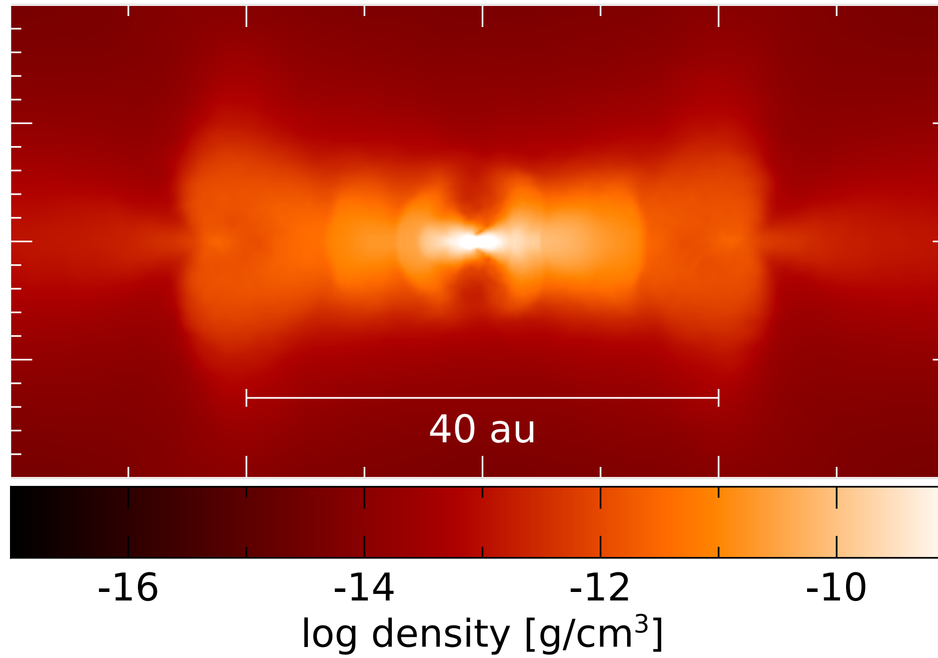
Wurster, Bate & Price (2019)



Cluster Formation: Protostellar discs

- Discs are larger & more varied in these cluster simulations than the isolated simulations

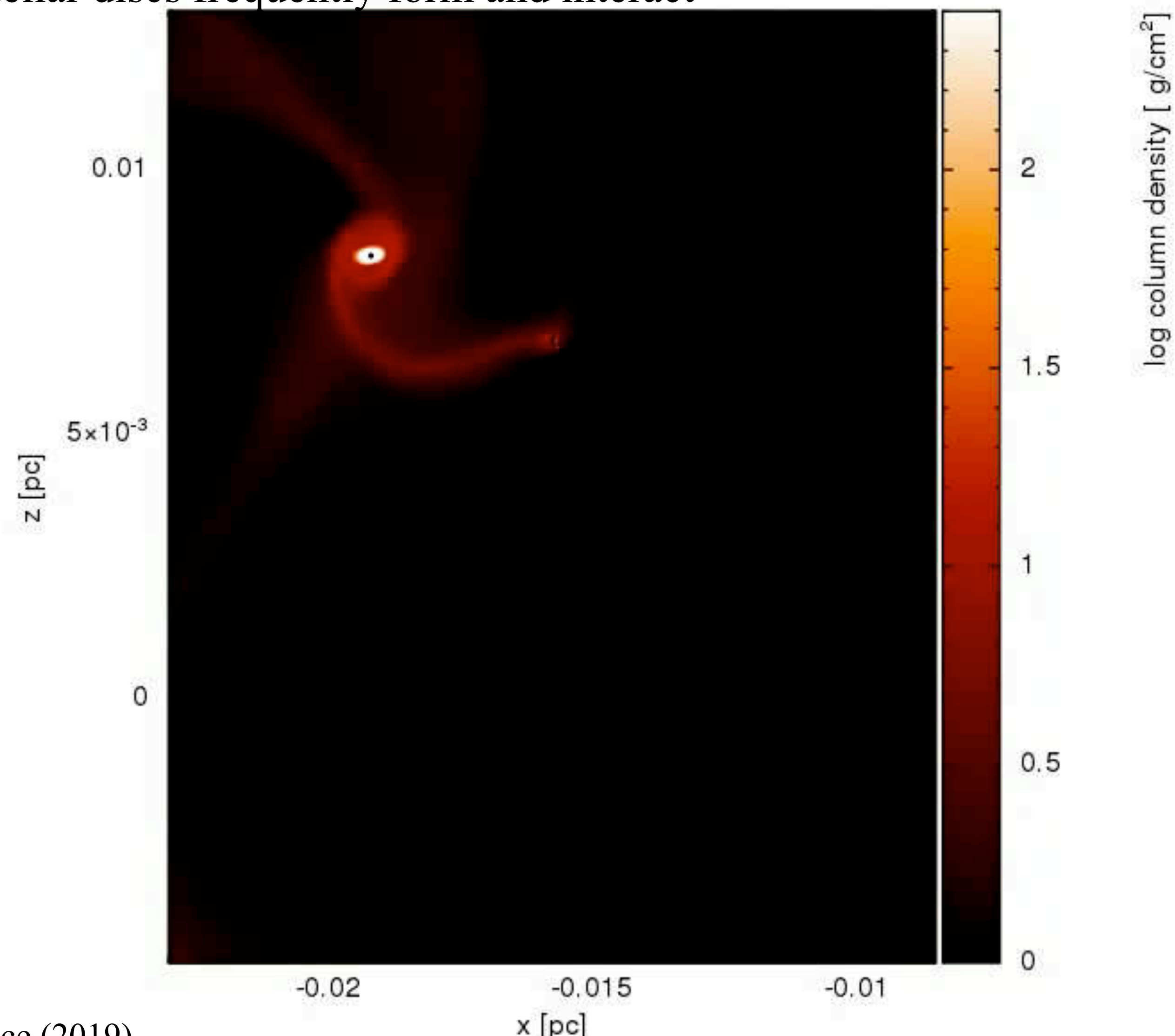




Wurster, Bate & Price (2018c, 2019); Wurster (submitted)

Cluster Formation: Protostellar discs

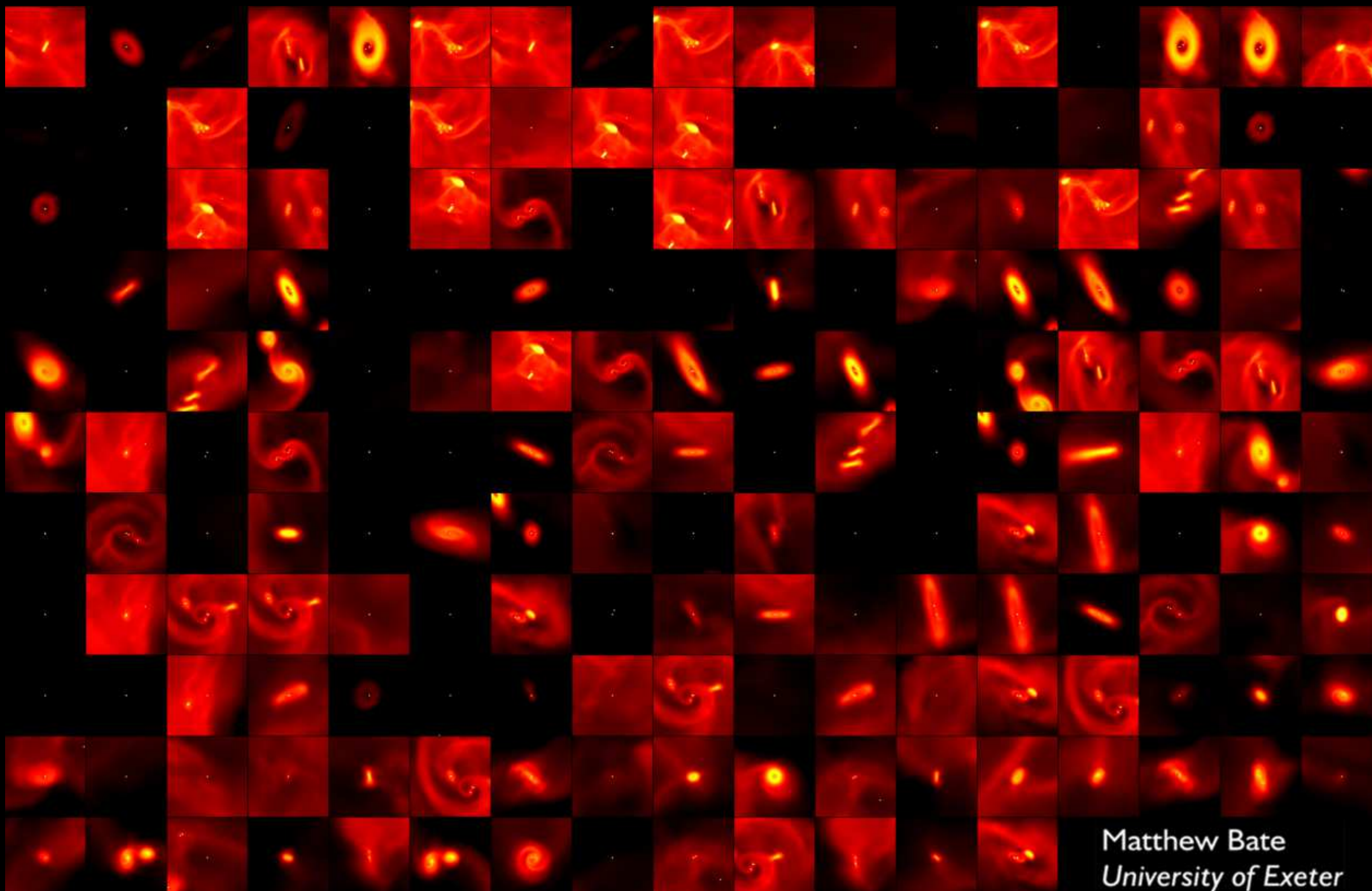
➢Large protostellar discs frequently form and interact



Wurster, Bate & Price (2019)

Cluster Formation: Protostellar discs: Hydro

- Large protostellar discs frequently form and interact



Bate (2018): https://www.astro.ex.ac.uk/people/mbate/Animations/discdiversity.html

Conclusions

- A star's entire life is predetermined by its initial mass
    - Understanding star formation is necessary to understand all aspects of astronomy
- Studying star formation necessarily includes studying disc formation and stellar outflows
- High-mass stars live shorter than low-mass stars, but have a greater affect on their environment
- There are more low-mass stars than high-mass stars (initial mass function)
- Star forming regions contain gas & dust and are permeated by strong magnetic fields
- Magnetic fields strongly affect star formation
- Stars seldom form in isolation
- Stars can be modelled
    - In isolation with high resolution
    - In cluster environments at lower resolution

University of St Andrews
University of Exeter
erc
DiRAC
Monash University

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