Star Formation

From Interstellar Gas to Stellar Gas

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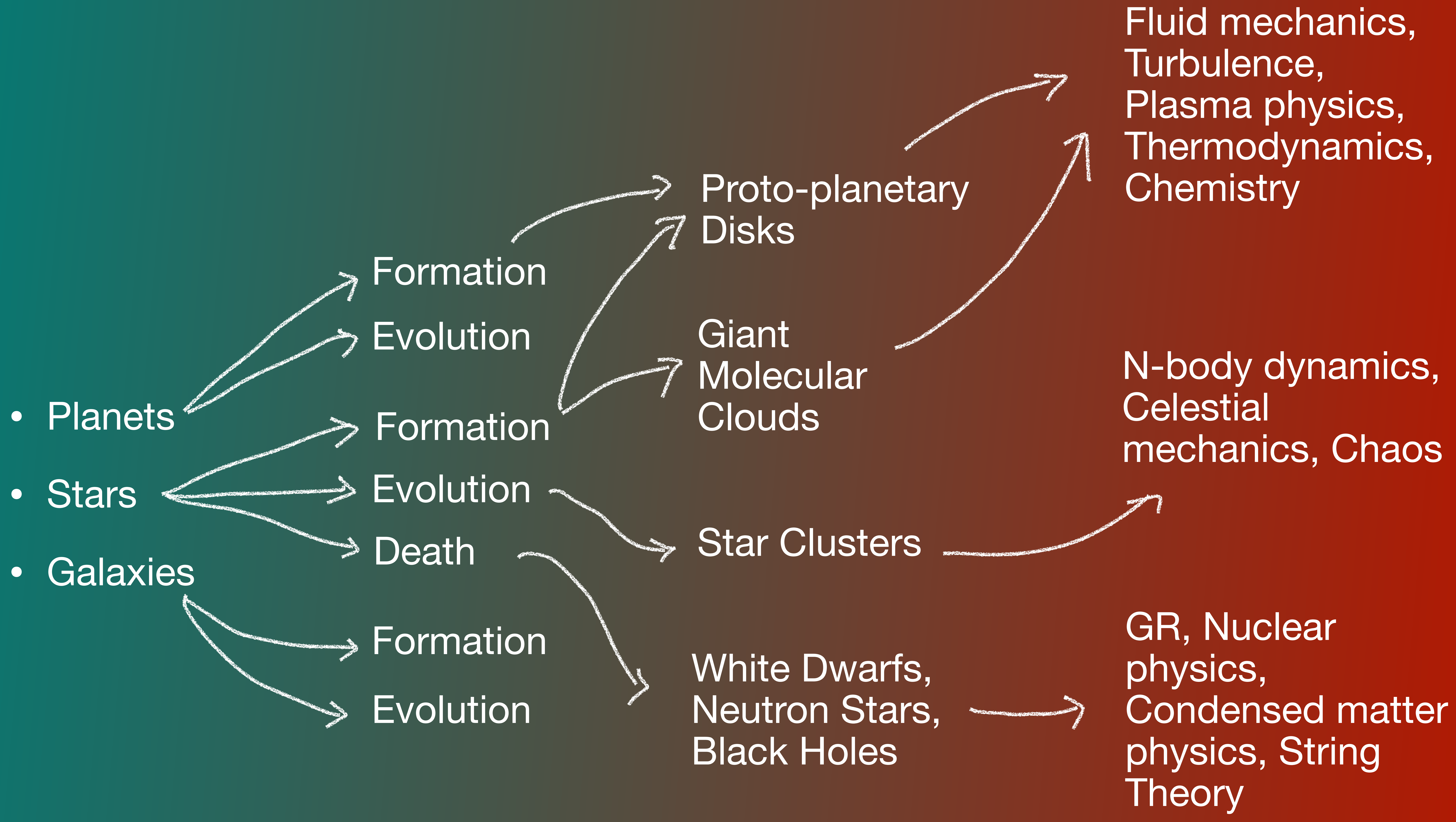

• Planets
• Stars
• Galaxies
Formation
Evolution
Formation
Evolution
Death
Formation
Evolution
Proto-planetary Disks
Giant Molecular Clouds
Star Clusters
White Dwarfs, Neutron Stars, Black Holes
Fluid mechanics, Turbulence, Plasma physics, Thermodynamics, Chemistry
N-body dynamics, Celestial mechanics, Chaos
GR, Nuclear physics, Condensed matter physics, String Theory

Outline

- Circumstances surrounding stellar birth
- How do we systematically study star formation?
- What do we not understand?

Outline

- Circumstances surrounding stellar birth:
  - **Where does star formation occur?**
  - What is the physics that describes these regions?
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Where does star formation occur in the Galaxy?

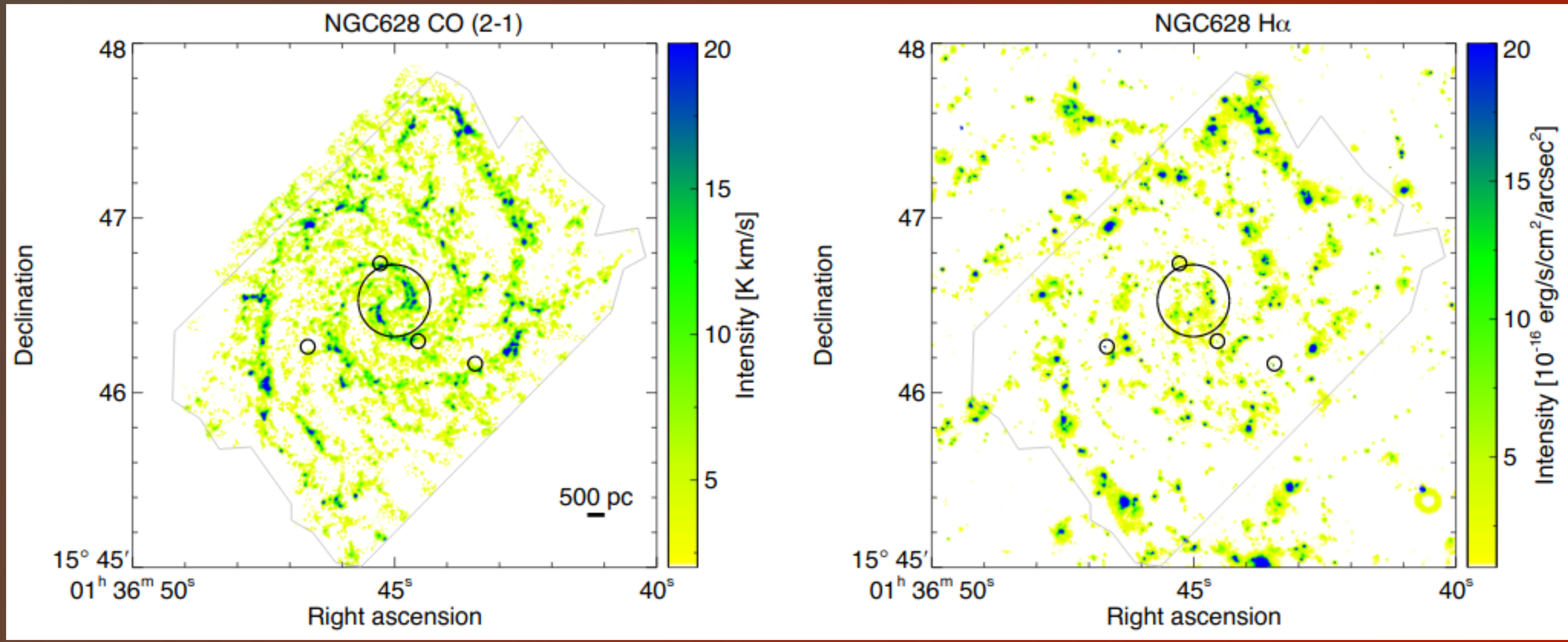
- Giant Molecular Clouds.
- These are huge clumps of molecular hydrogen that span across a few pc to kpc and are roughly 10^4 to 10^8 $M_\odot$.
- T ~ 10K, c_s ~ 0.2 km/s.
- Made of H_2 —> H_2 at 10K, so doesn't have any molecules capable of producing emission.

The Horsehead Nebula [*Image Credit: NASA,ESA, and The Hubble Heritage Team (STScI/AURA)*]

So how do we see these invisible clouds?

- You can't see the gas, dust absorbs optical light from the stars.
- We can use other molecules, e.g. - CO, NH_3, HCN.
- What do we do about the stars? Look at stuff in NIR (protostars), $H\alpha$ (HII regions)
- There are limitations to each of these tracers.

The Spider Nebula [*Image Credit: NASA, JPL-Caltech, Spitzer Space Telescope, 2MASS]*



Chevance et al. (2020)

The Carina Nebula [*Image Credit: NASA, EA, N. Smith (U. California, Berkeley) et al., and The Hubble Heritage Team (STScI/AURA)*]

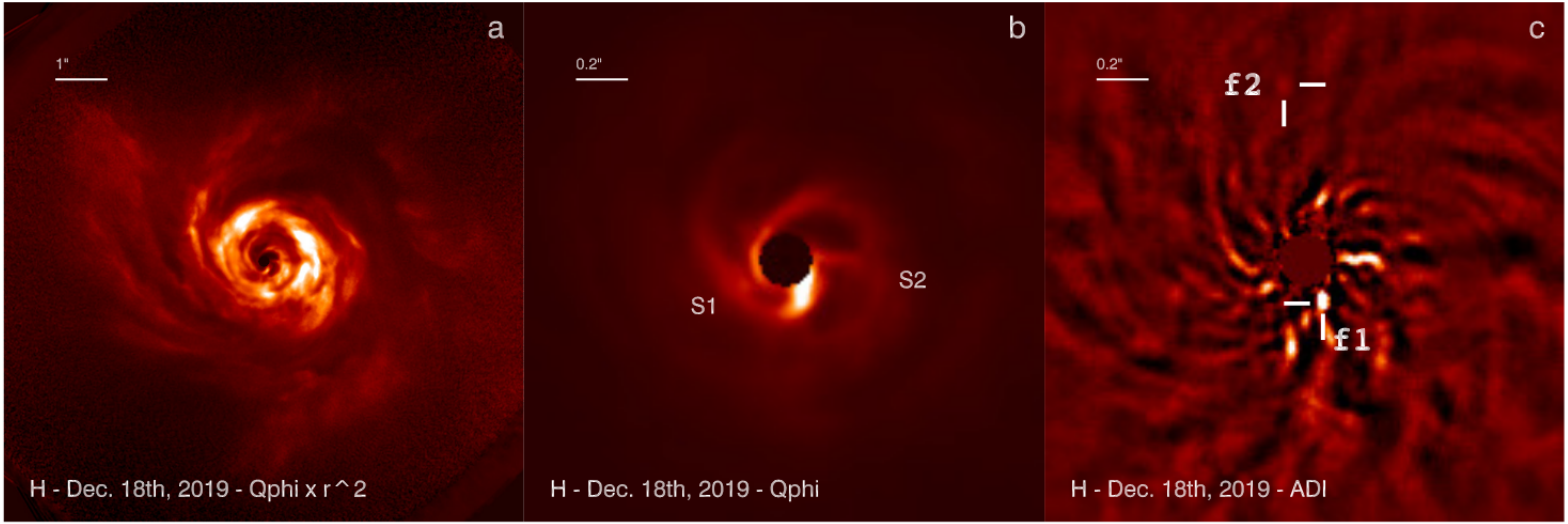


Fig. 1. Images of the AB Aur system obtained with SPHERE in polarized light (*a*, *b*) and unpolarized light (*c*). A large field of view (10″) is shown in *panel a*, where the polarized intensity has been multiplied with the square of the stellocentric distance ($Q_\phi \times r^2$) to visually enhance the outer part of the disk. A narrower field of view (2″) of the Q_ϕ map is displayed in *panel b*, in which the inner spirals are labelled S1 and S2. Comparable ADI-processed image is shown in *panel c* for total intensity in the *H* band filter. Features `f1` and `f2` are discussed in Sect. 4. North is up, east is left.

Boccaletti et al. (2020)

Why do we care about how stars form? - Part I

- Important to understand galaxy and planet formation.
- The initial mass function (IMF) tells us how many of what type of stars do there exist at their birth. IMF is important to study stellar cluster and galaxy evolution.
- Merger rates, supernovae events depend on how many massive stars there are.

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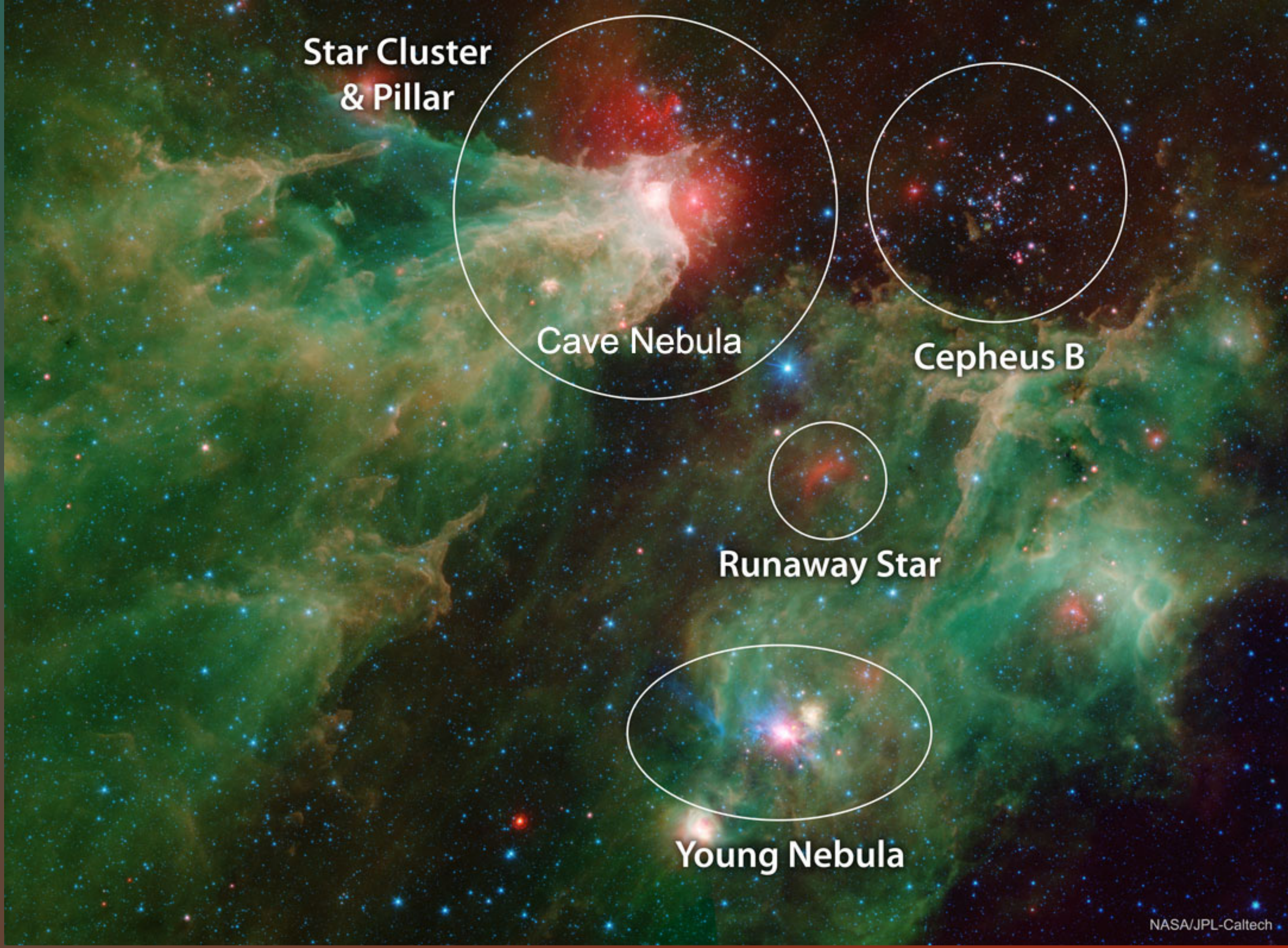
Setting the stage

(for interstellar drama)

- Typical stellar density ~ 1 g/cm^{-3}.
- Typical ISM density - 10^{-24} g/cm^{-3}.
- So maybe things just... you know... sort of... clump together and... you eventually get stars?



The Cave Nebula in IR *[Image Credit: NASA, JPL-Caltach, Spitzer Space Telescope]*

Setting the stage
(for interstellar drama)

- If only it were that simple. Here's what complicates things -
  - IT'S A FLUID.
  - Something can be treated as a fluid when $l_{\mathrm{mfp}} \ll L_{\mathrm{sys}}$
  - Mean free path in the ISM ~ 10^{14} cm.
  - System size L ~ 10^{20} cm.

Fluid Mechanics

- Conservation of Mass:

  - $$\frac{\partial \rho}{\partial t} + \overrightarrow{\nabla} \cdot (\rho \overrightarrow{v}) = 0$$

- Conservation of Momentum:

  - $$\frac{\partial}{\partial t}(\rho \mathbf{v}) = -\nabla \cdot (\rho \mathbf{v}\mathbf{v}) - \nabla P - \rho \nabla \phi + \rho \nu \nabla^2 \mathbf{v}$$

Navier-Stokes Equations
Millennium Prize $1M

- Conservation of Energy:

  - $$\frac{\partial E}{\partial t} + \nabla \cdot (E + P)\mathbf{v} = \rho \mathbf{v} \cdot \nabla \phi$$

Fluid Mechanics

- Fluids —> Navier-Stokes equations, PDEs.
- PDEs —> Hard to do much analytically, self similar solutions.
- Need to solve PDEs numerically on a computer —> Computational Hydrodynamics.

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Magnetic Fields

- Faraday Rotation
- Zeeman Effect
- Synchrotron Emission
- B ~ 5-10 μG

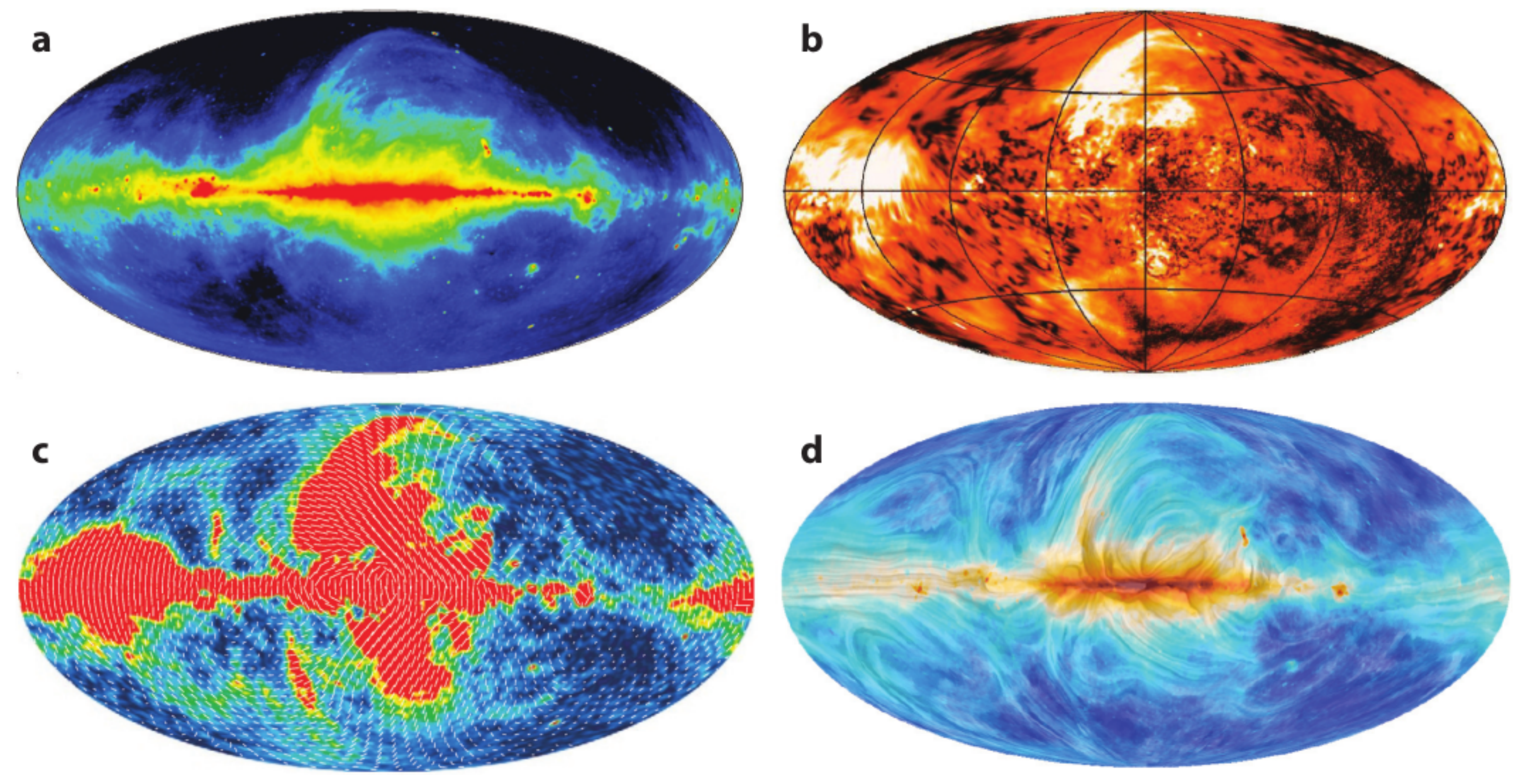

Figure 2

All-sky maps of (*a*) synchrotron emission and (*b*) the polarization emission at 1,400 MHz, and of the synchrotron emission (*c*) at 23 GHz with *E*-vectors observed by WMAP and (*d*) at 30 GHz observed by *Planck* combined with the 90°-rotated polarization angles for the fingerprints of the Galactic magnetic fields. Adapted with permission from (*a*,*b*) Reich & Reich (2009), (*c*) Bennett et al. (2013) by the AAS, and (*d*) Planck Collab. et al. (2016a) ©ESO.

Han (2016)

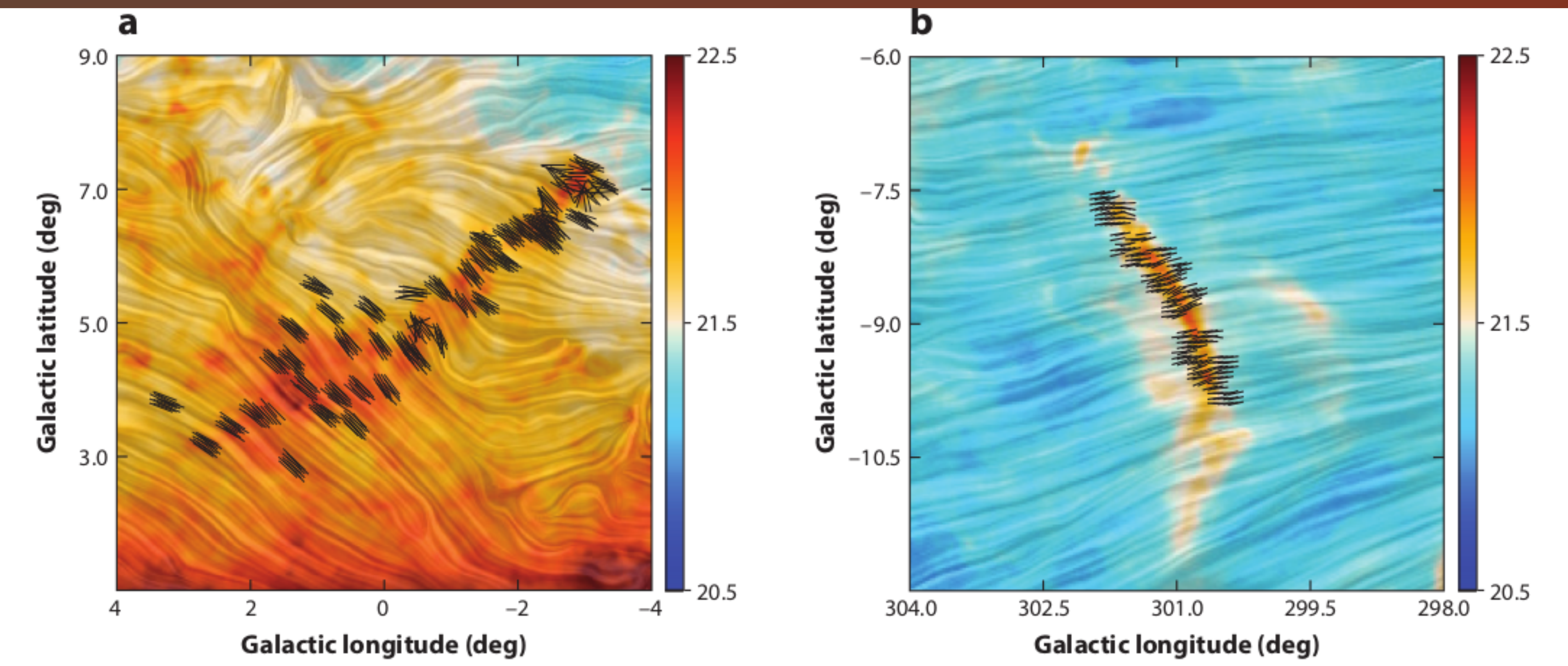

Figure 4

Magnetic field orientations in the (*a*) Pipe and (*b*) Musca molecular clouds inferred from the polarized thermal dust emission by *Planck* images (same color scheme as **Figure 1**) and starlight polarization (*black bars*). The colors represent the total gas column density, and the "drapery" pattern indicates the magnetic field orientation. Adapted with permission from Soler et al. (2016) ©ESO.

Magnetic Fields

- Magneto-hydrodynamics
- Extra terms, extra equations, complicates things.
- $\dfrac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times (\vec{v} \times \vec{B}); \quad \vec{\nabla} \cdot \vec{B} = 0$
- $\vec{\nabla} \cdot \vec{B} = 0$ is very difficult to solve numerically.

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    - Fluid Mechanics
    - **Magnetic Fields**
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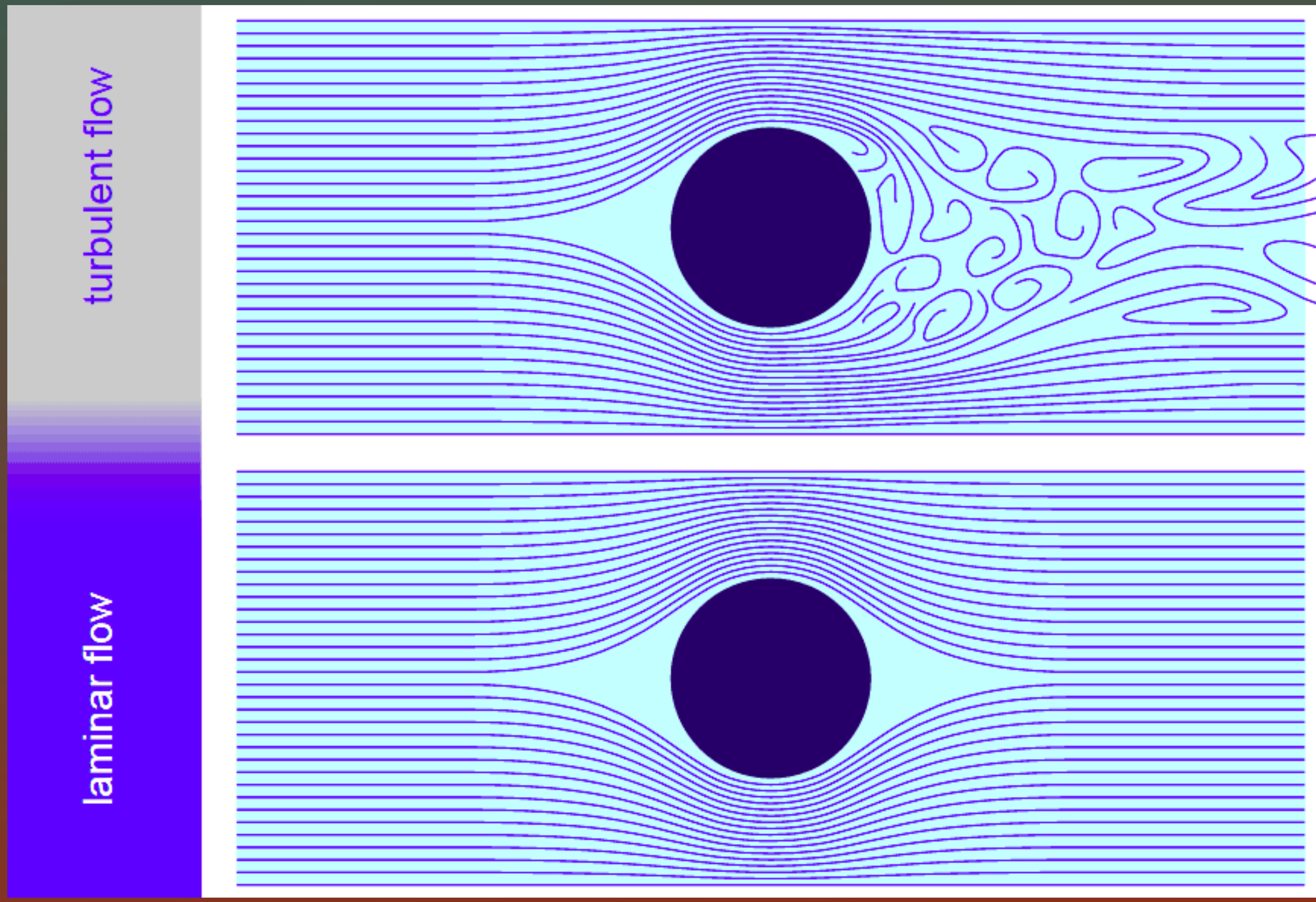
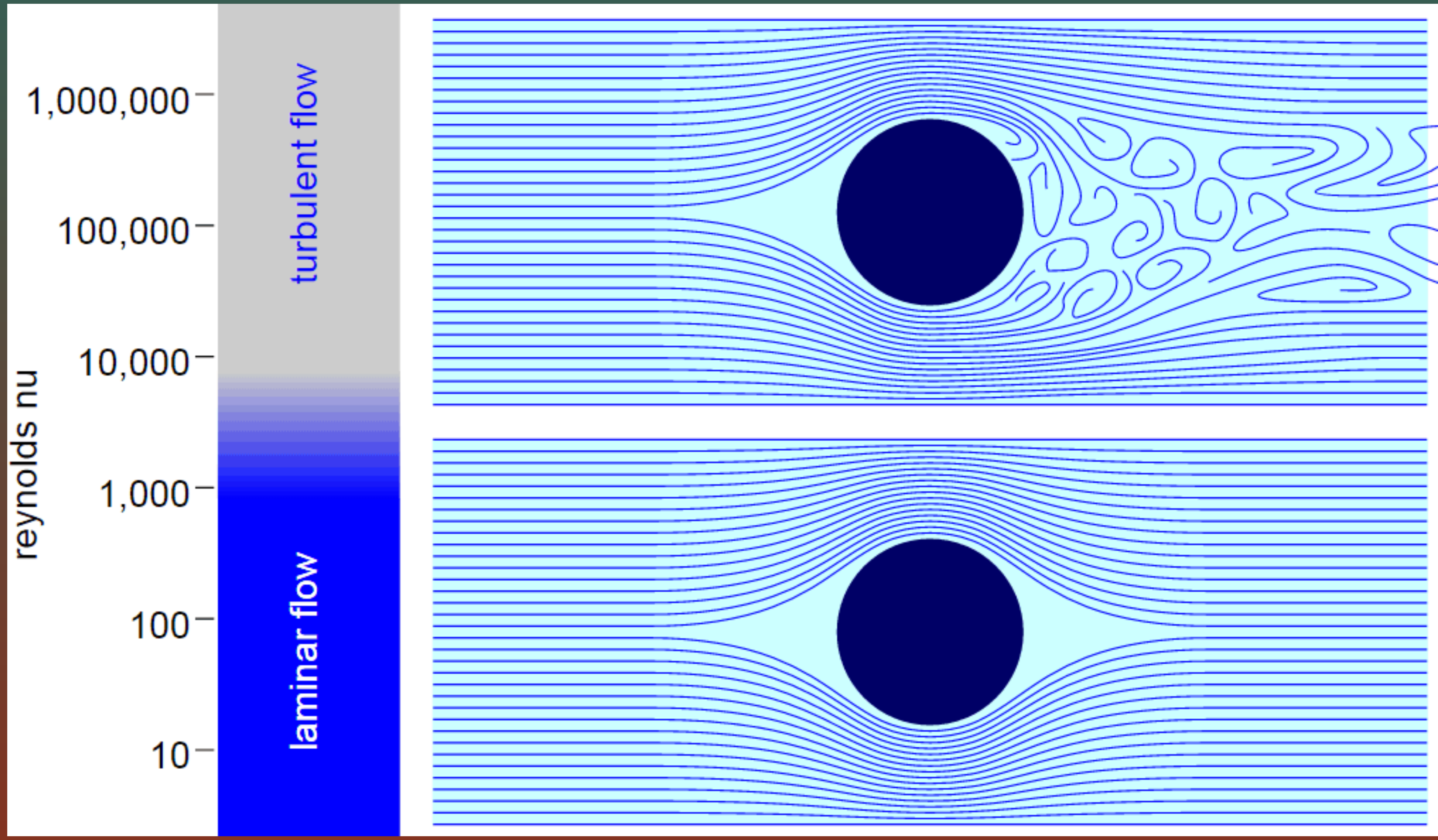
Turbulence

- When do we consider a fluid to be turbulent?



Turbulence

- When do we consider a fluid to be turbulent?
- Re ~ $\dfrac{LV}{\nu}$, $\nu = 2\bar{u}l_{\rm mfp}$, $\bar{u} \sim c_s$



Turbulence

- Random motions.
- Can only be studied statistically.
- Kolmogorov theory
- We’re concerned with supersonic turbulence.

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Stellar Feedback

Jets and Outflows

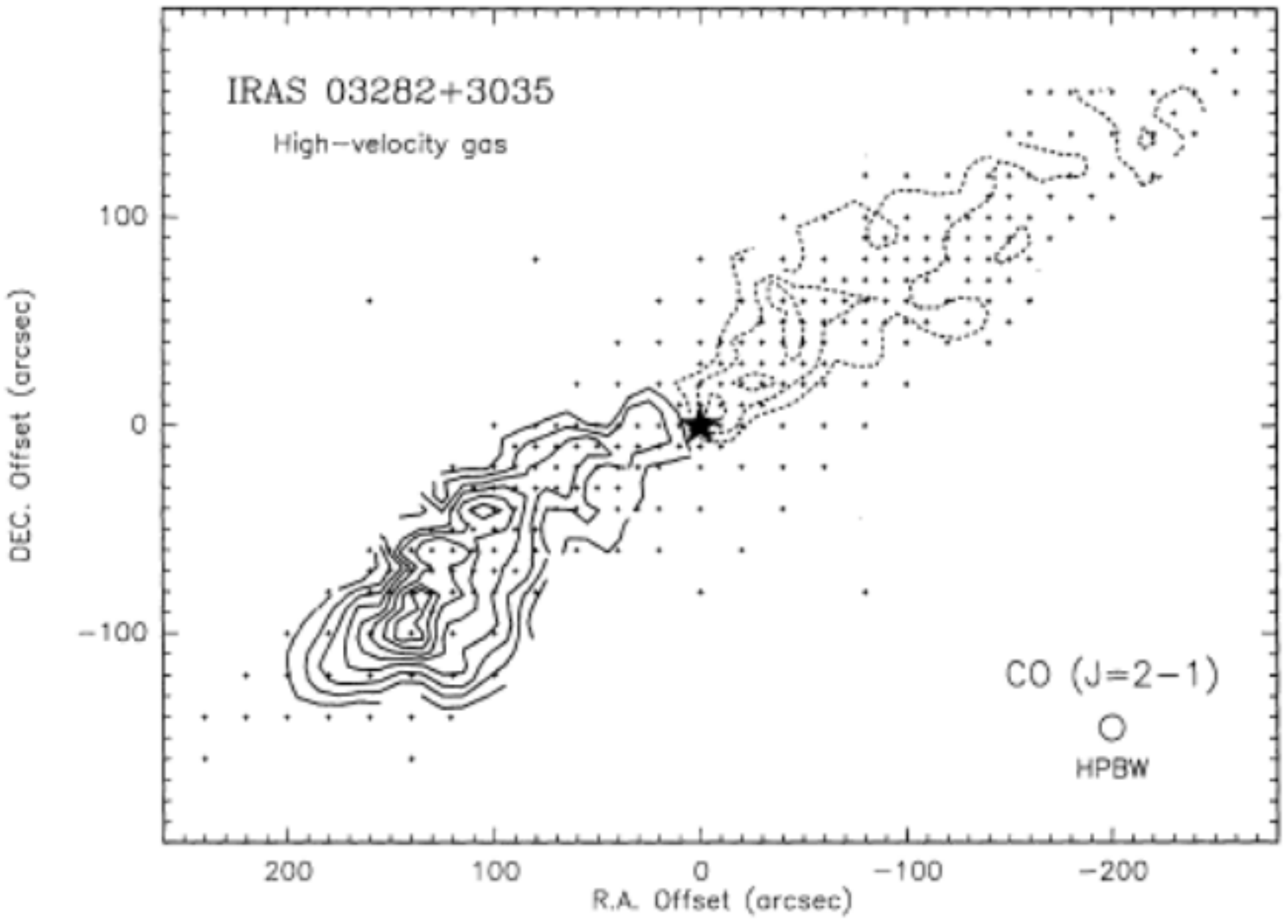

Fig. 6. Map of CO J=2→1 intensity integrated in the line wings around IRAS 3282. The central position is that given by IRAS (see Table 1). The solid thin contours represent the blueshifted emission (from -60 km s^{-1} to 0 km s^{-1}), while the dashed contours are for the redshifted emission (integrated from 14 km s^{-1} to 74 km s^{-1}). First contour and contour interval are 6 K km s^{-1}. The crosses represent the observed positions. The CO contours reveal the presence of a bipolar outflow centered on the IRAS source

Bachiller+ (1991)

Image Credits: NASA, ESA, and M. Livio and the Hubble 20th Anniversary Team (STScI)

Stellar Feedback

- Proto-stellar Jets
- Stellar Winds
- Stellar Heating
- Supernovae
- Radiation pressure

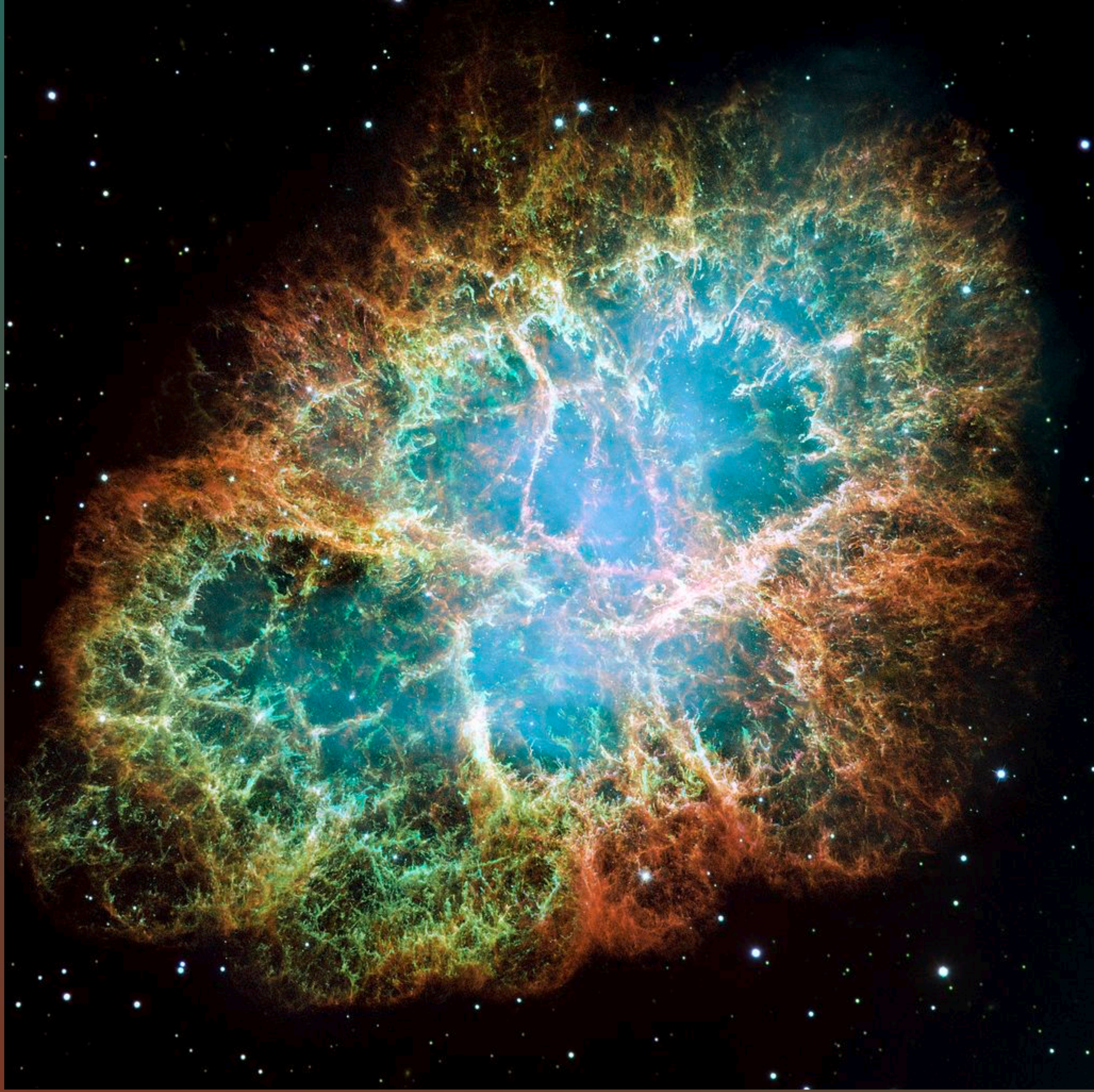

Image Credits: NASA, ESA, J. Hester and A. Loll (Arizona State University)

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    - Turbulence
    - **Feedback**
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But photons...

- Radiative Transfer Equation:

- $$\frac{1}{c}\frac{\partial}{\partial t}I_\nu + \vec{\Omega}\cdot\vec{\nabla}I_\nu + (k_{\nu,s} + k_{\nu,a})I_\nu = j_\nu + \frac{1}{4\pi}k_{\nu,s}\int_\Omega I_\nu d\Omega$$

- Integro-differential equation. Difficult to solve. Timescales are so different for these physical processes.

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Setting the stage

(for interstellar drama)

- Life with fluids is not easy.
- There’s also radiation
- The ISM is turbulent
- The ISM has magnetic fields
- Stars are cry babies

Why do we care about how stars form? - Part II

- Important to understand galaxy and planet formation.
- The initial mass function (IMF) tells us how many of what type of stars do there exist at their birth. IMF is important to study stellar cluster and galaxy evolution.
- Merger rates, supernovae events depend on how many massive stars there are.
- Understand how astrophysical systems behave and evolve.
- Understand how magnetized fluids work.
- Understand how supersonic turbulence works.

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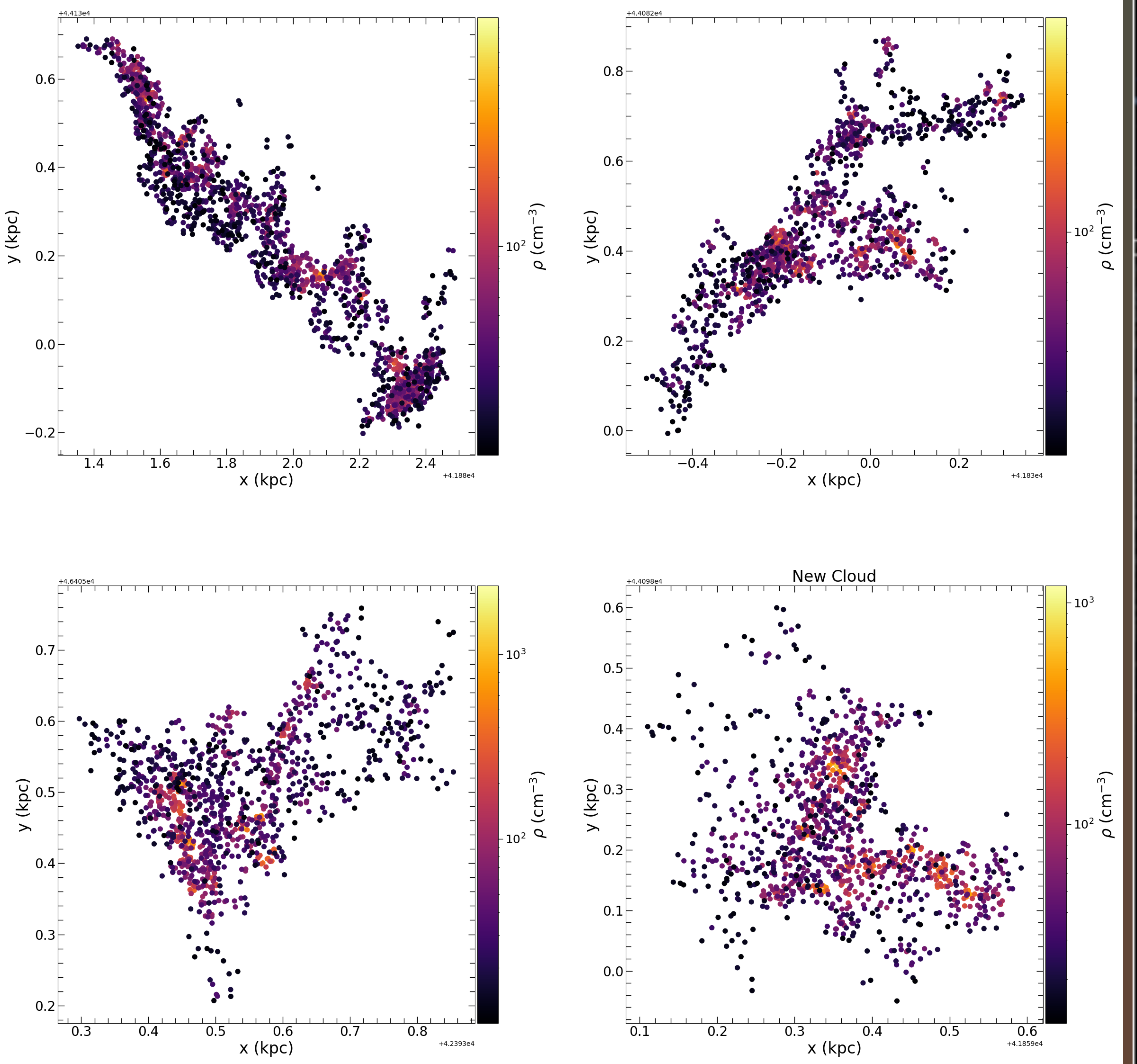
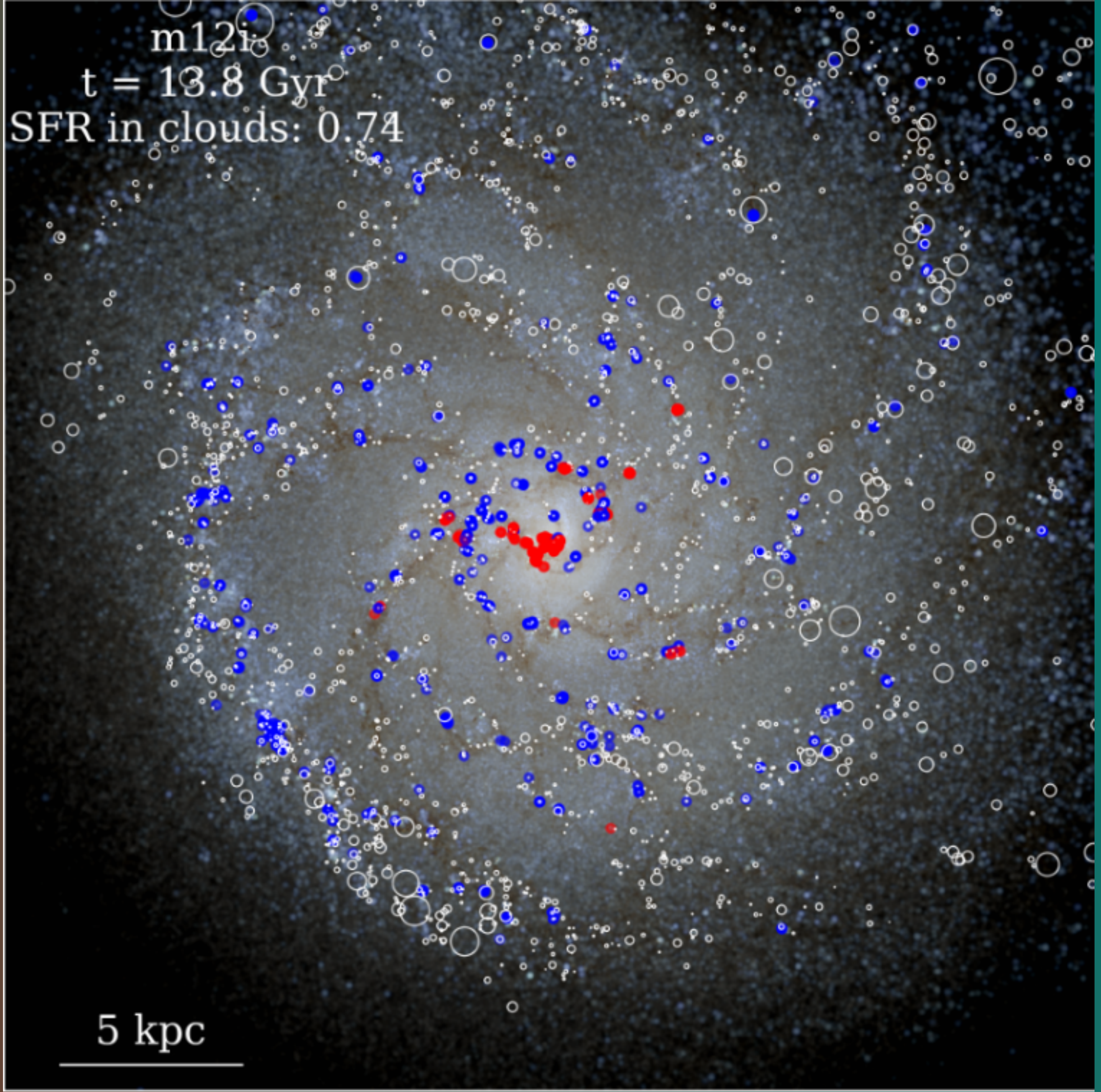
Simulations

- Discretize the equations, and put them on a grid.
- Use some hydrodynamics solvers to solve the fluid equations. Publicly available codes that do this - FLASH, RAMSES, PLUTO, GADGET, GIZMO, AREPO.
- Radiation in post-processing / approximate radiation.
- Initial conditions, prescriptions for stellar feedback, how to drive turbulence?
- Computationally expensive - so need to be run on supercomputers.

Simulations

- Movie Time!





Guszejnov et al. (2020)

Important Questions

- The SFR in the Galaxy and in other galaxies is seen to be very low. Why is the SFR so low?
- The star formation efficiency is very low. Why? Is it low for all star forming regions? How much does the galactic environment matter?
- How long do GMCs live for? Do their properties determine the SFR/IMF?

Important Questions

- How do we find which analytical models are the best?
- What is the IMF and is it universal? Star formation dictates galaxy evolution.
- How many companions does the average star have? Is the Sun very rare or is it the norm?

Open Questions

- Why do some GMCs tend to be stragglers and others form stars more efficiently?
- Does the IMF actually vary with the environment?
- What set of physics determines the IMF?
- How can we study supersonic turbulence analytically?
- Simulations - coming up with better methods to solve equations, more accurate simulations.

Thank You!

Resources

- "Star Formation", book by Mark Krumholz (2015).
- "The Physics of Fluids and Plasmas", book by Arnab Rai Choudhuri.
- "Astrophysics for Physicists", book by Arnab Rai Choudhuri.
- "The big problems in star formation", review article by Mark Krumholz (2014).
- "The Molecular Cloud Lifecycle", review article by Chevance et al (2020).