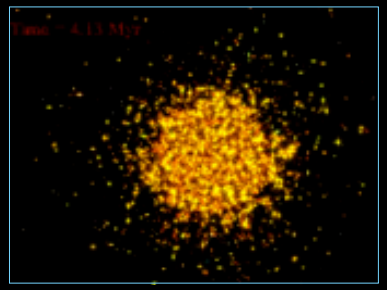
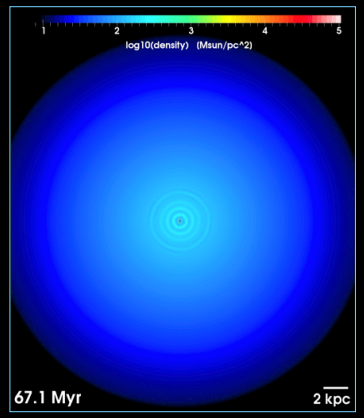
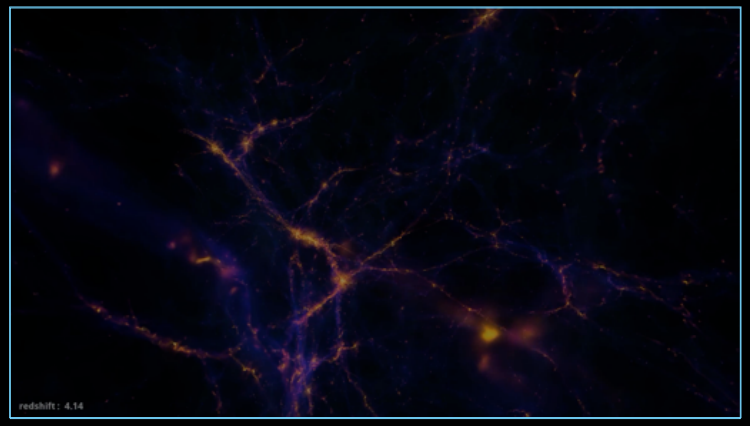
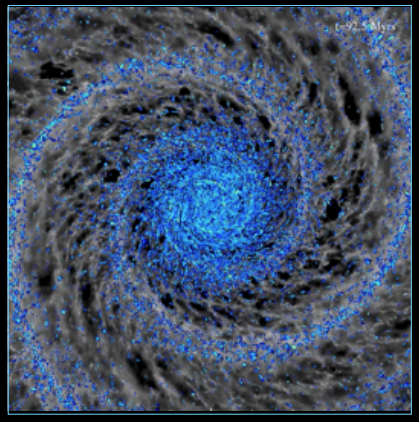
Simulating our Universe

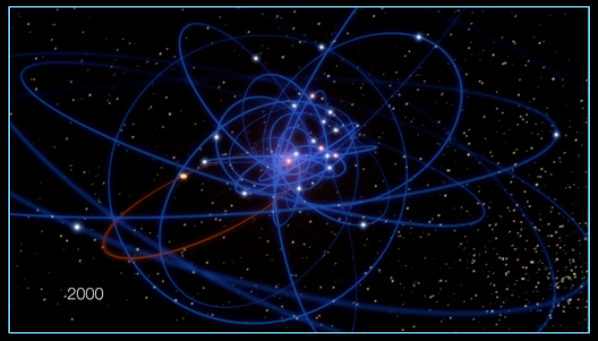
Andreas Burkert (Munich)

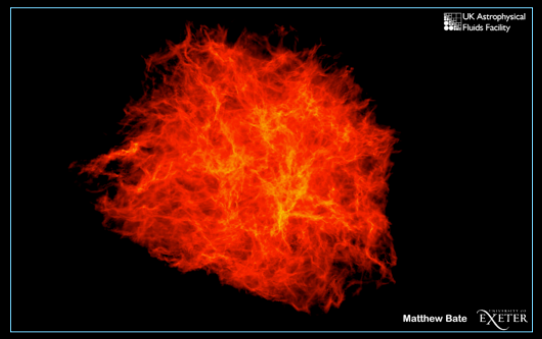




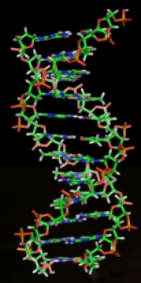








The Golden Age of Astrophysics



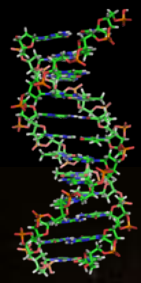
What is the structure of the Universe?

How did it form and how does it evolve?

How did life form in the Universe?

Are we alone in the Universe?

The Golden Age of Computational Astrophysics



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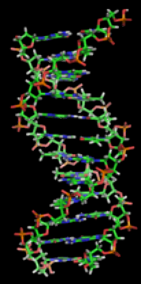


What is the structure of the Universe?

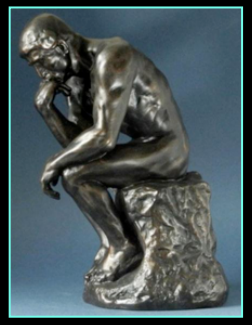
How did it form and how does it evolve?

How did life form in the Universe?

Are we alone in the Universe?

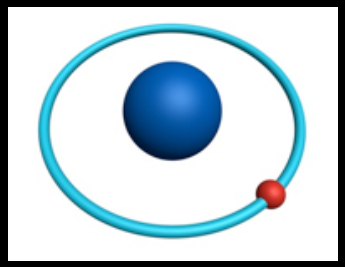
- The Universe is **far from equilibrium**, non-linear and self-organized
- The Universe itself and its ingredients are **emergent structures** that connect processes on very different spatial scales and cannot be understood in isolation

Self consciousness



The Energy of Life

H



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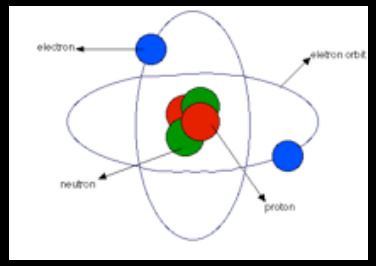
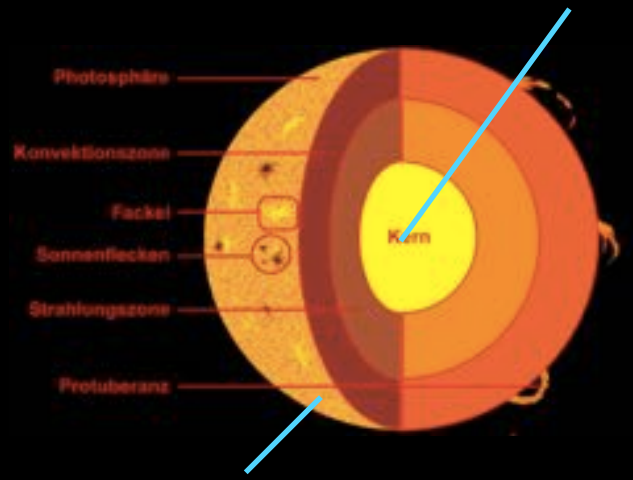
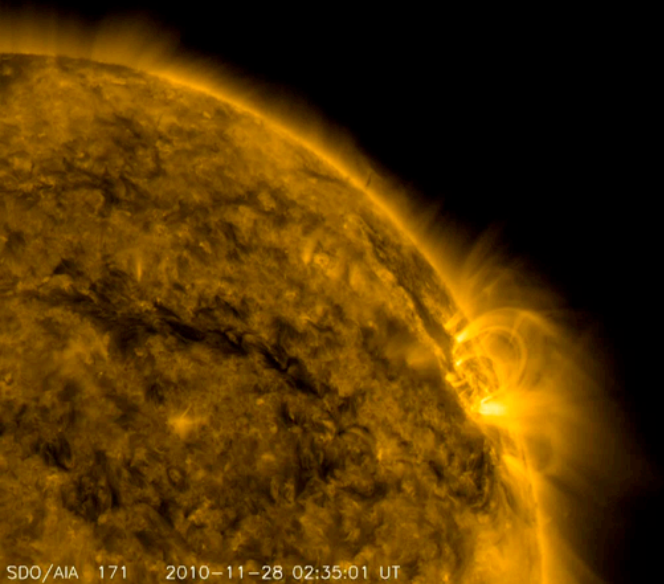
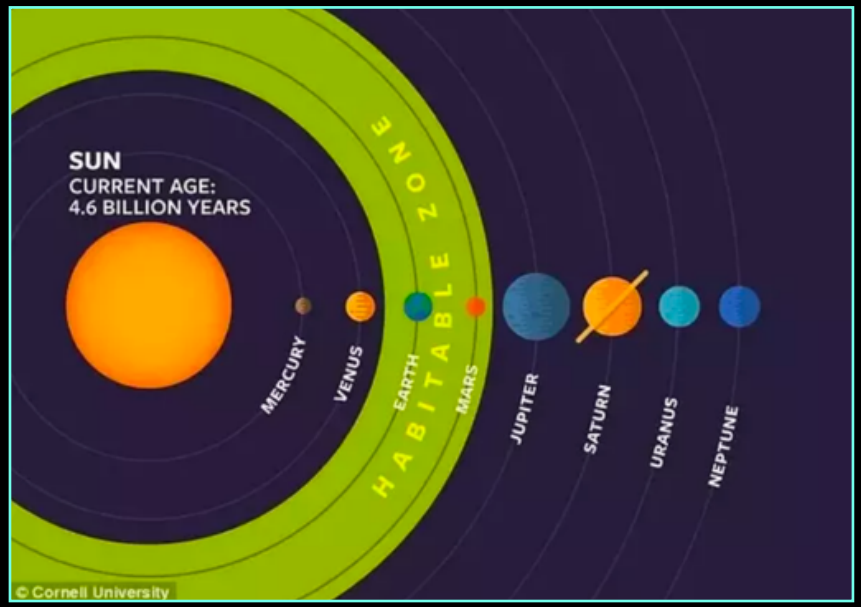


15 million degrees



6400 degrees



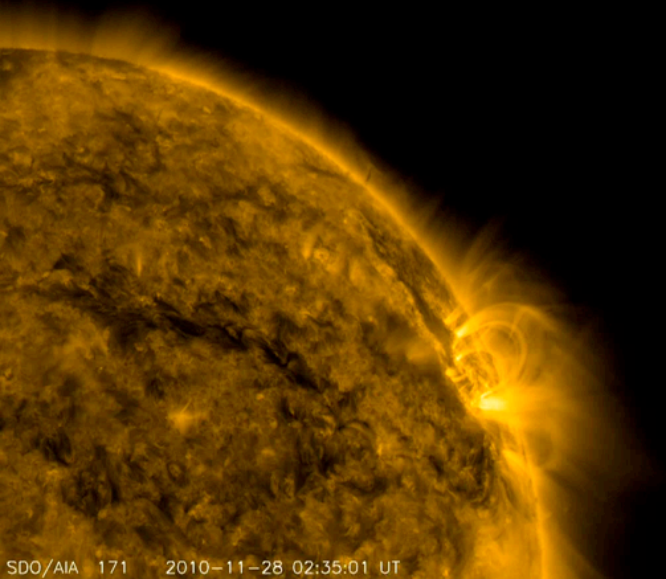


Simulating Stellar Structure and Evolution

(Hayashi, Nishida, Hoshi&Sugimoto 1962; Hofmeister, Kippenhahn&Weigert 1964)

- **Costs:** 3 million $, corresponding today to 20 million $
- **Processing speed:** 100 Kflops
- **RAM**: 32 kB
- **Punching cards**

IBM 7090



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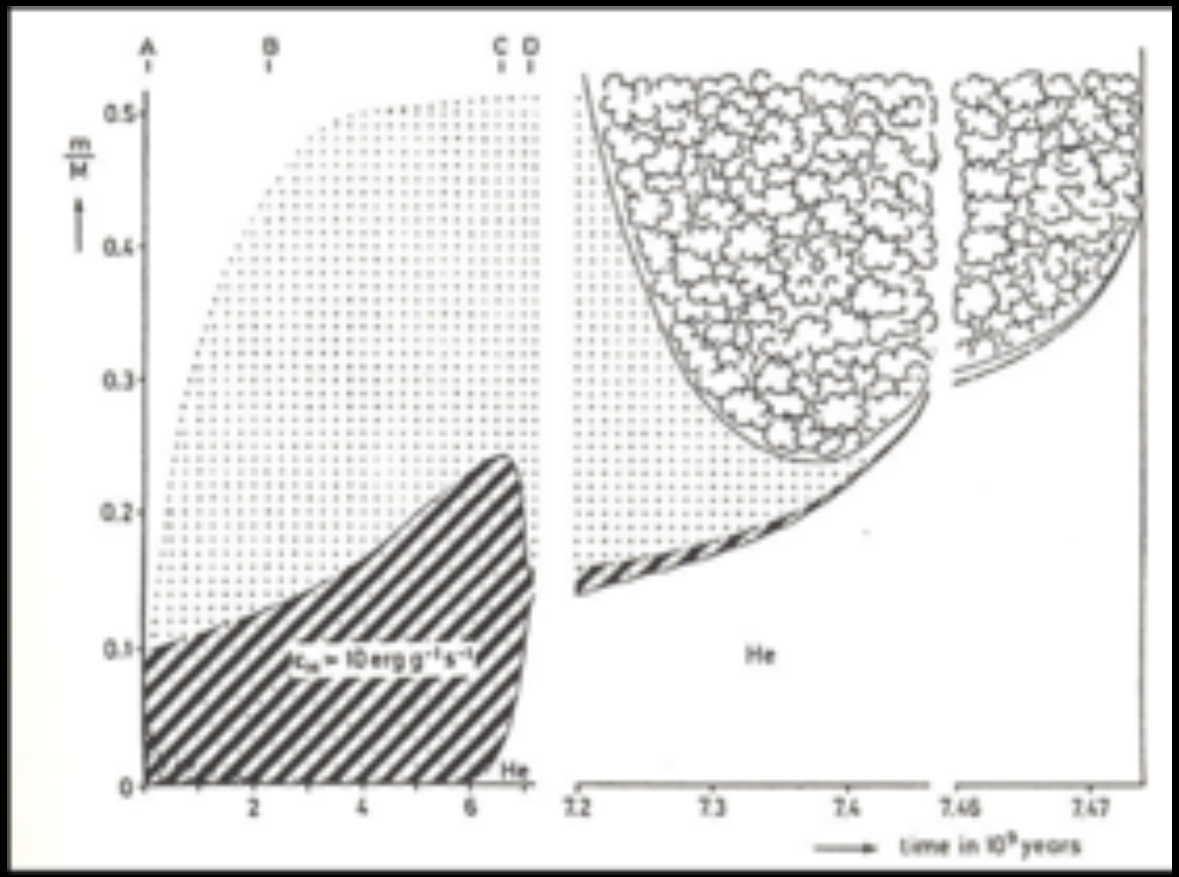
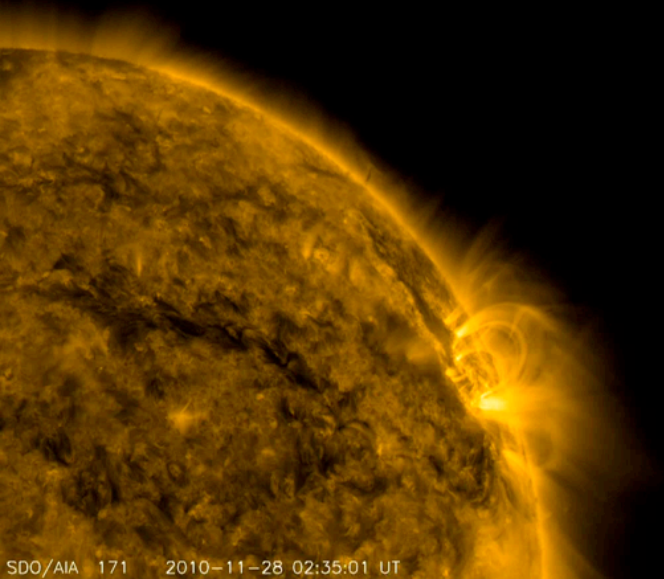
Thomas, 1967





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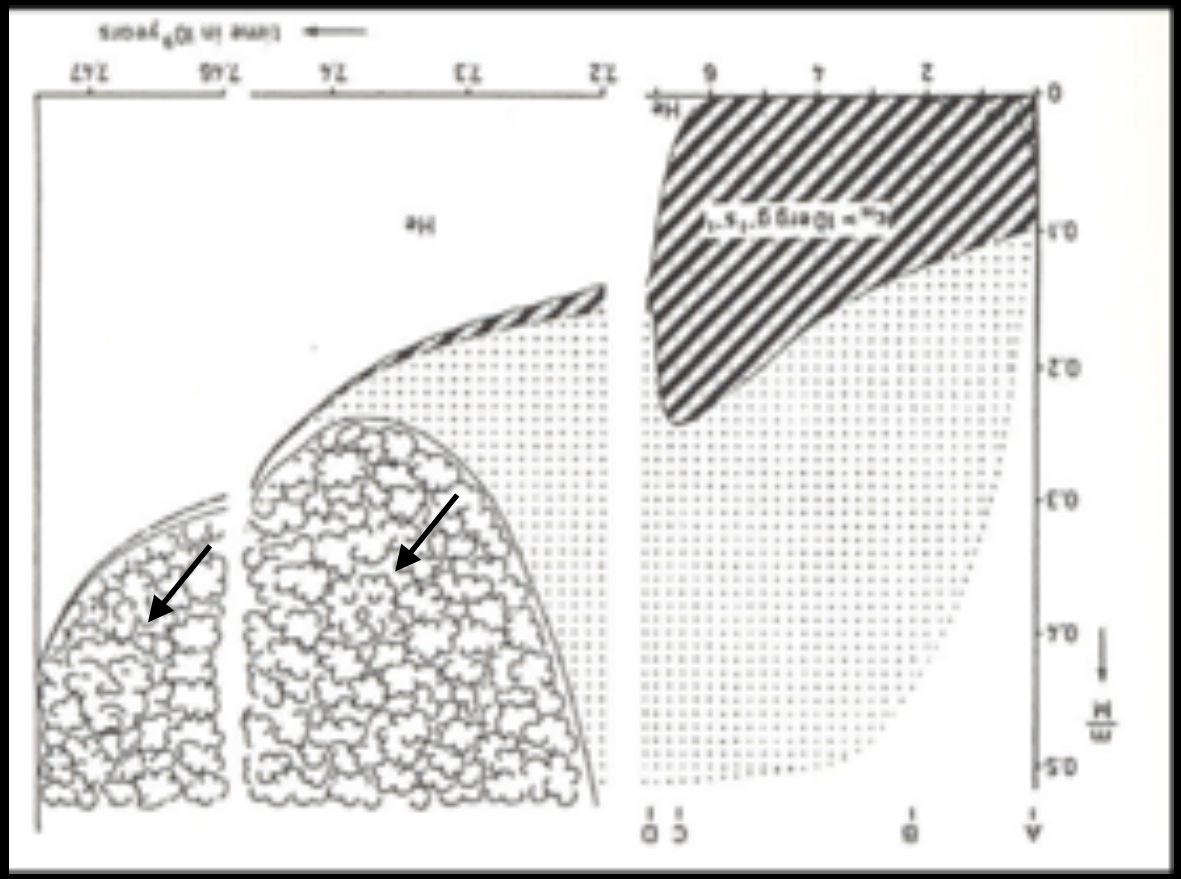
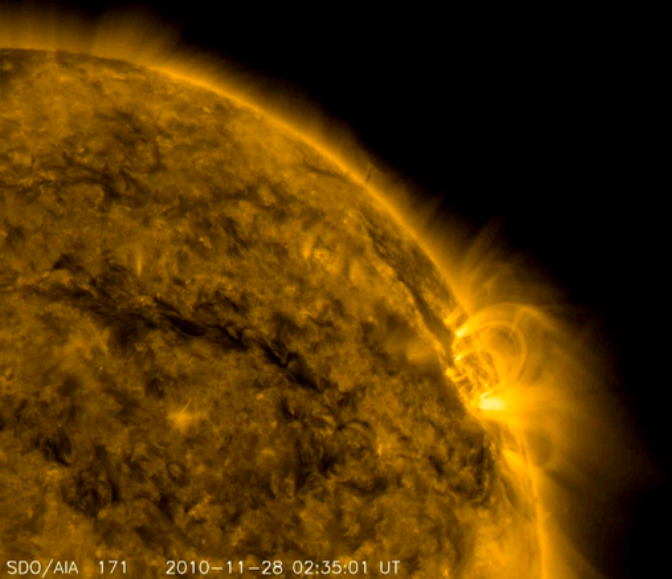
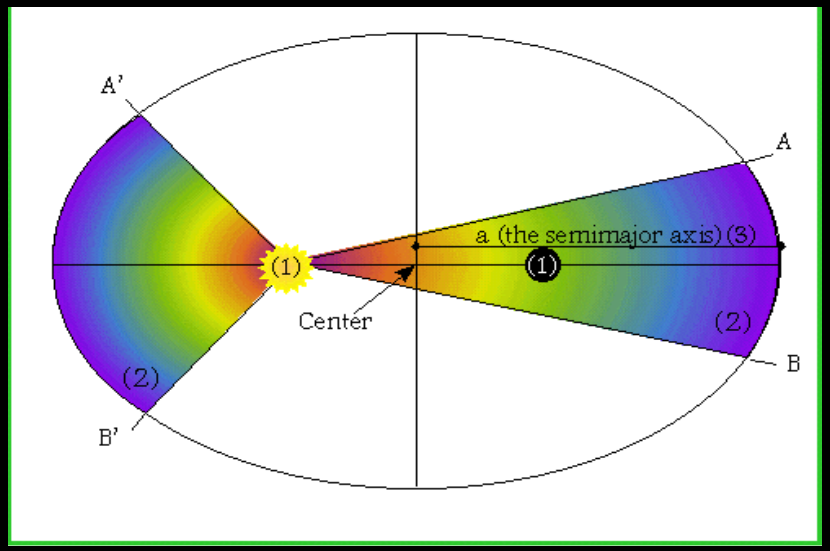




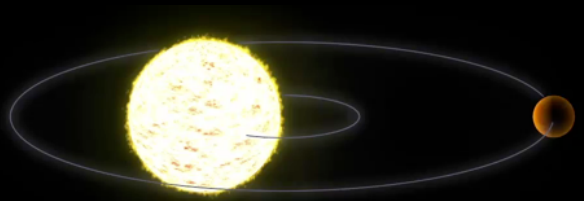
Simulating our Solar System

Simulating our Solar System

Kepler's laws



2 is order

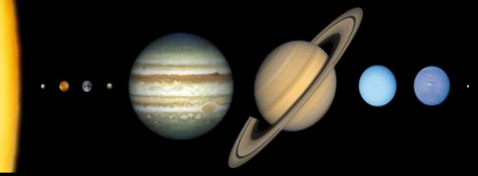


What determines a ?

$$r = \frac{p}{1 + e\cos\phi}$$

$$\left(\frac{T}{yrs}\right)^2 = \left(\frac{a}{AU}\right)^3$$

J. Kepler
1571-1630



Simulating our Solar System

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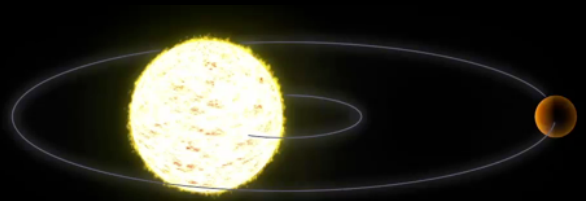
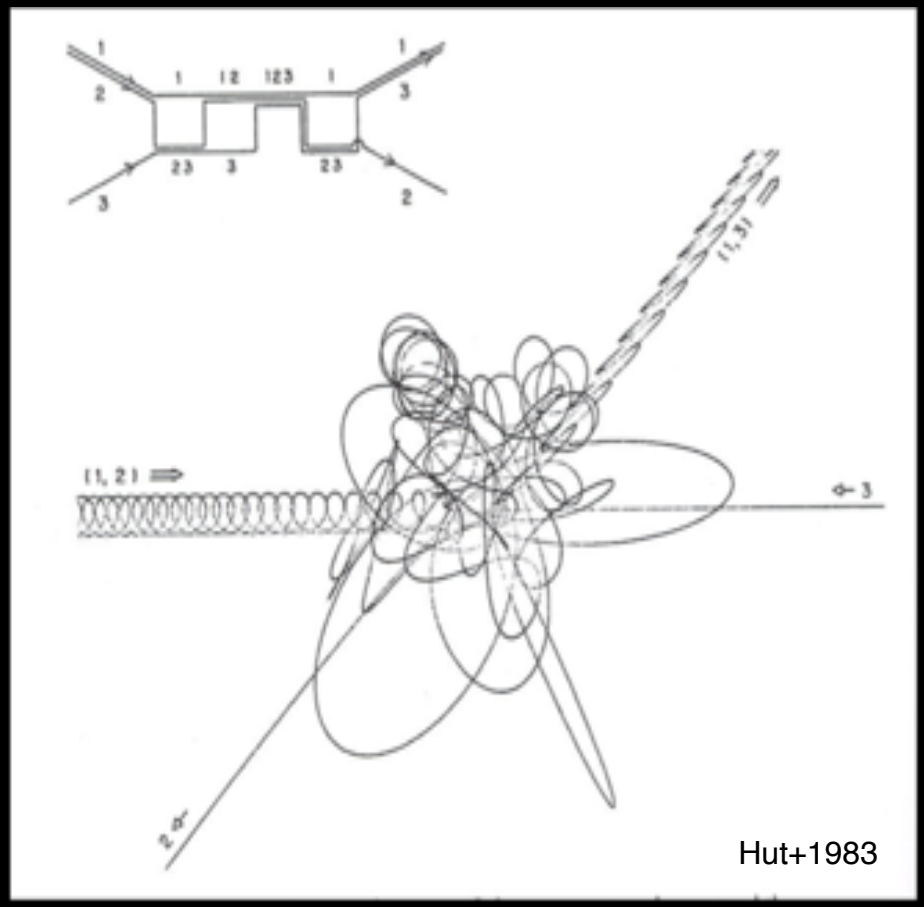
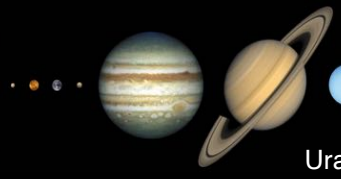


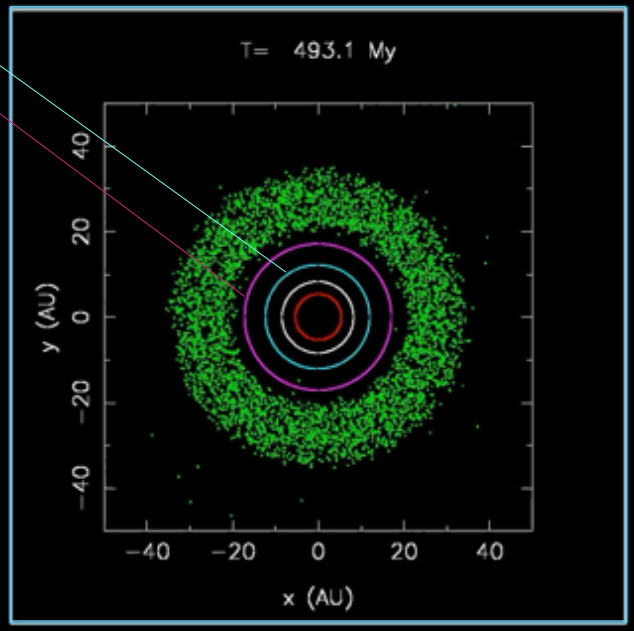
J. Kepler
1571-1630

3 is complexity



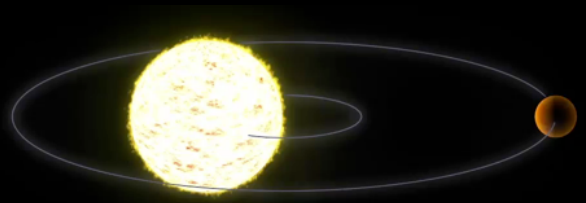
Simulating our Solar System





The Nice model (Morbidelli+05)

2 is order



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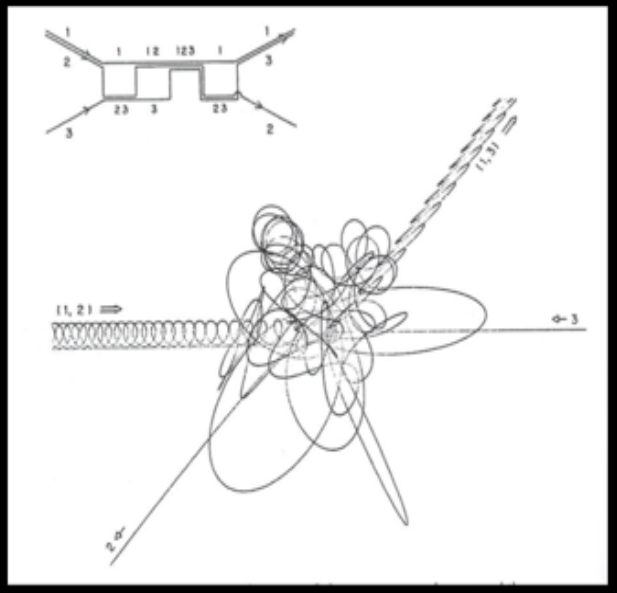
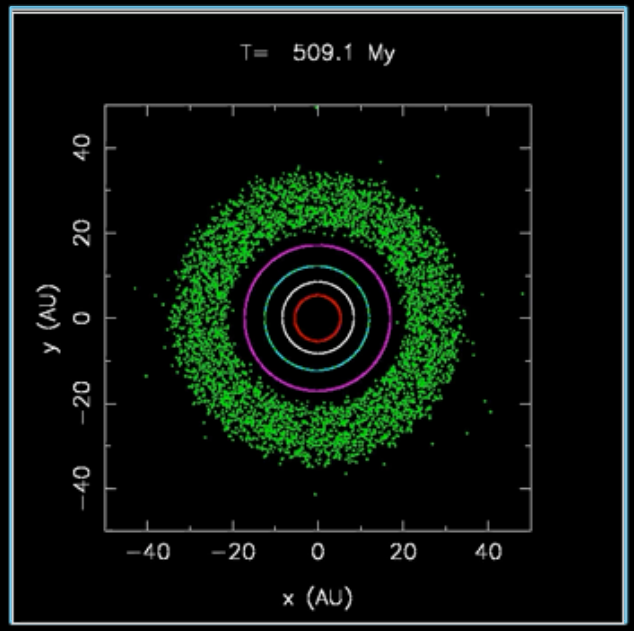


Simulating our Solar System



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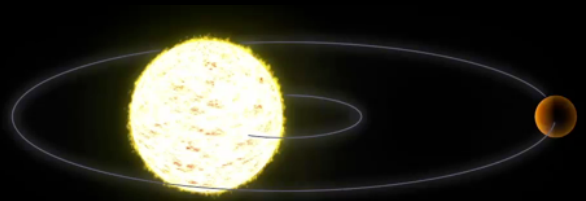

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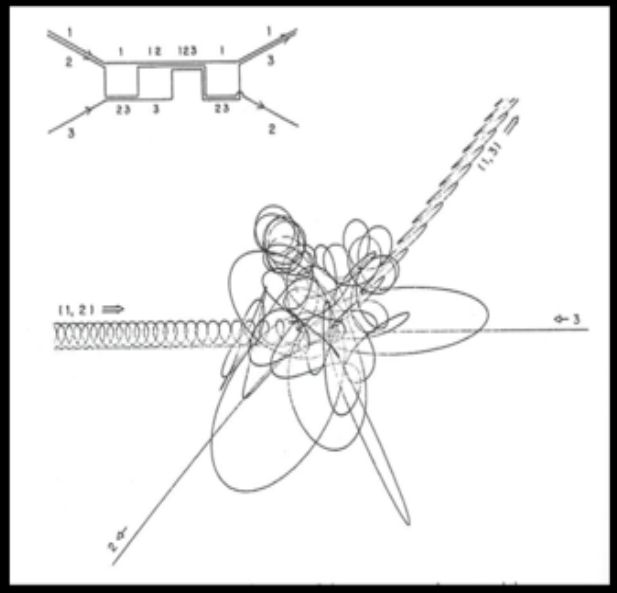
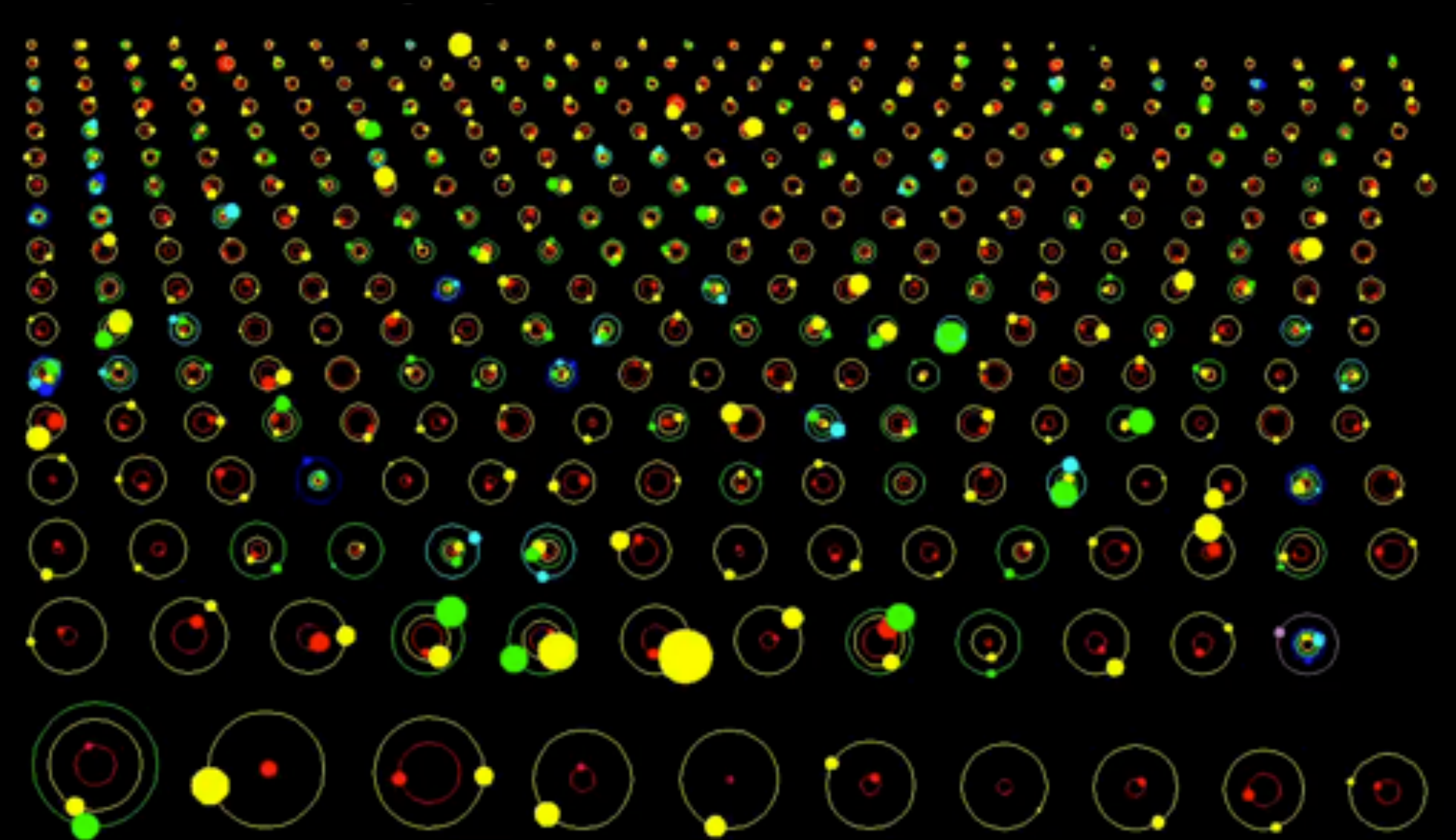


Simulating the diversity of planetary systems



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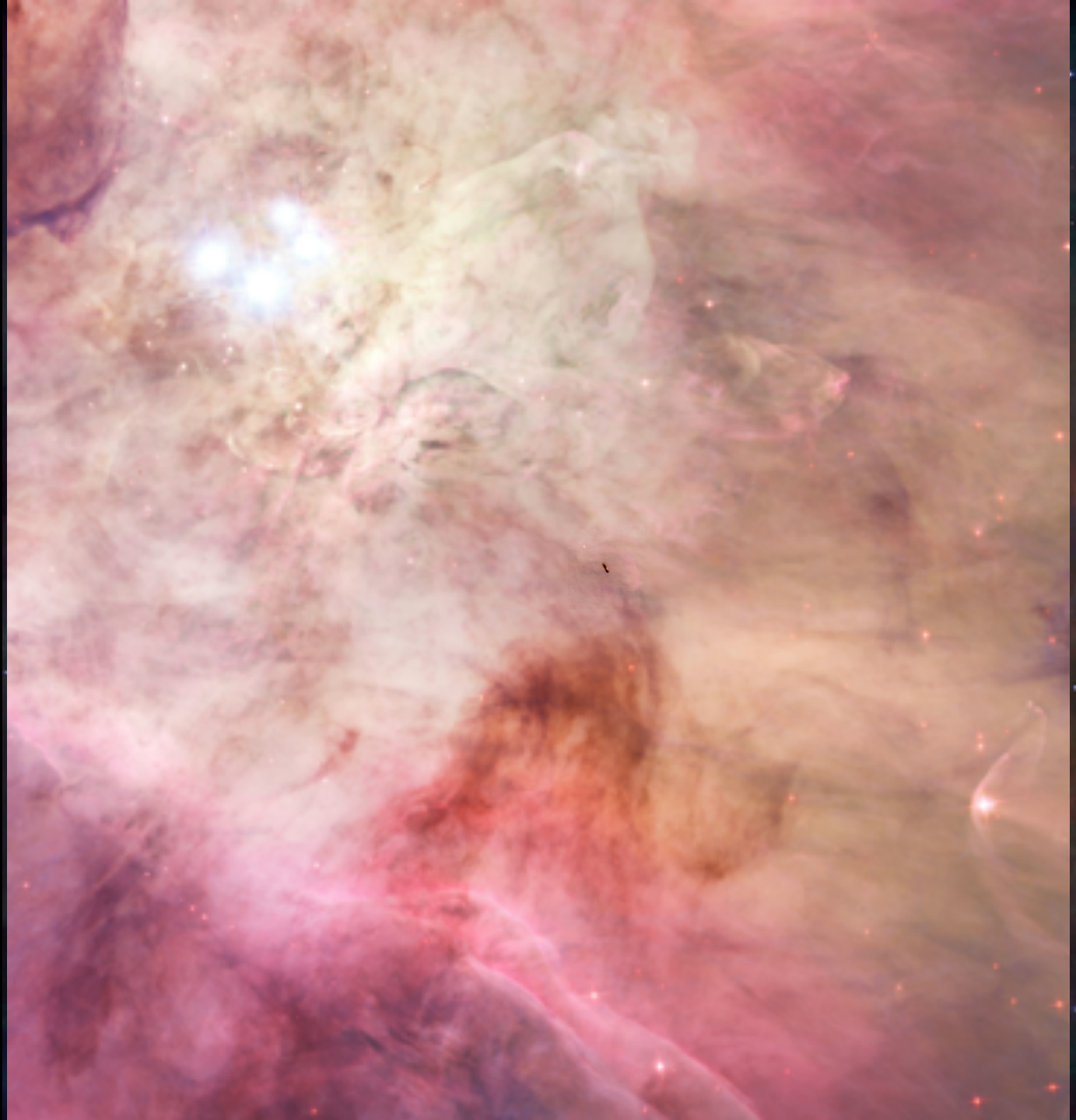

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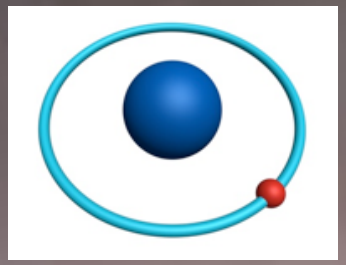

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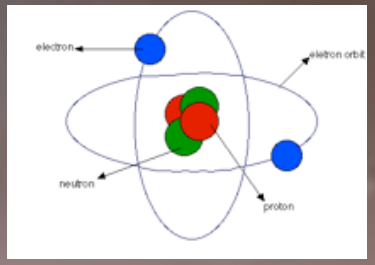

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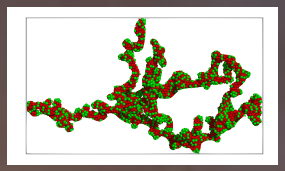
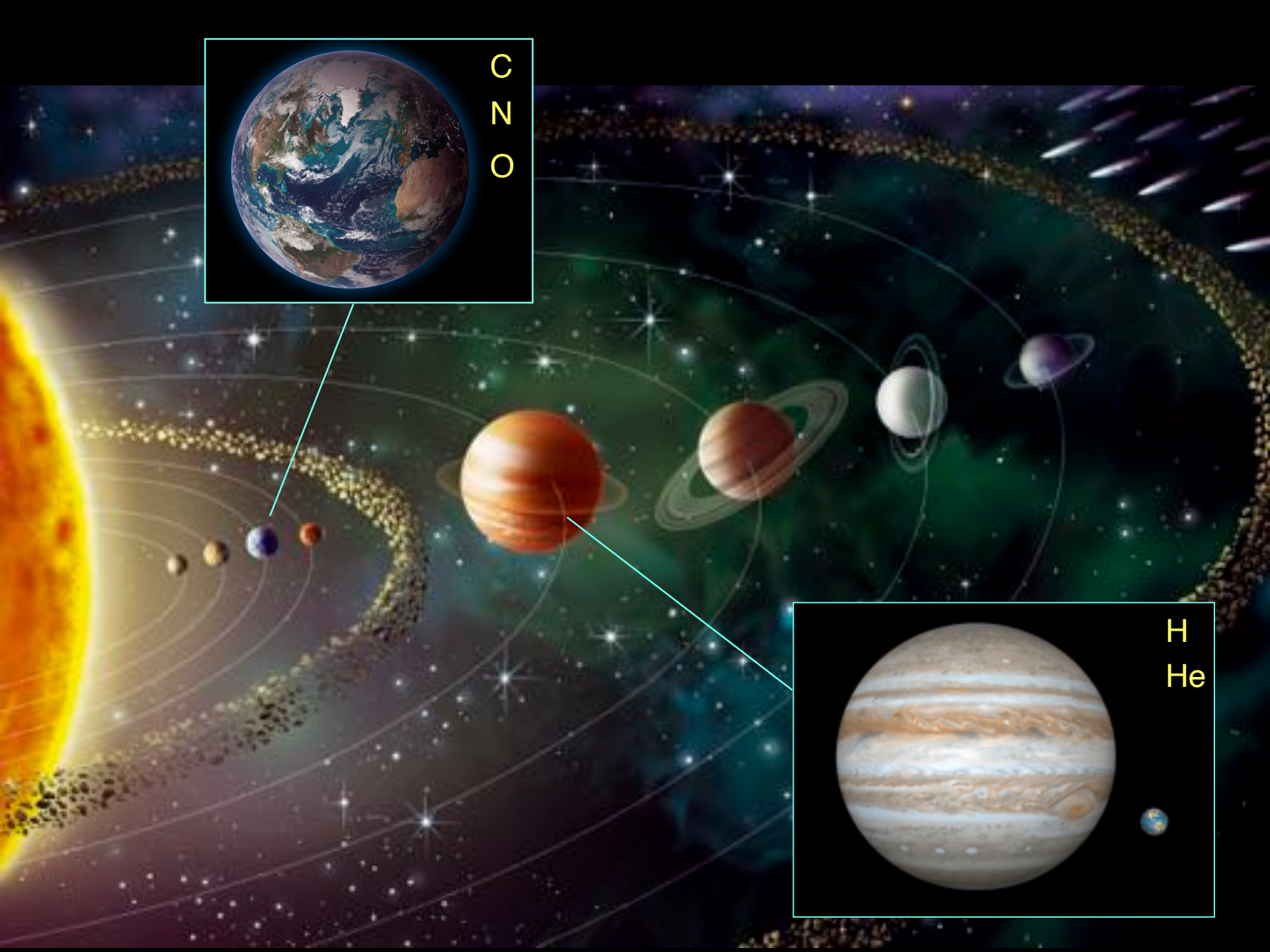
Dust

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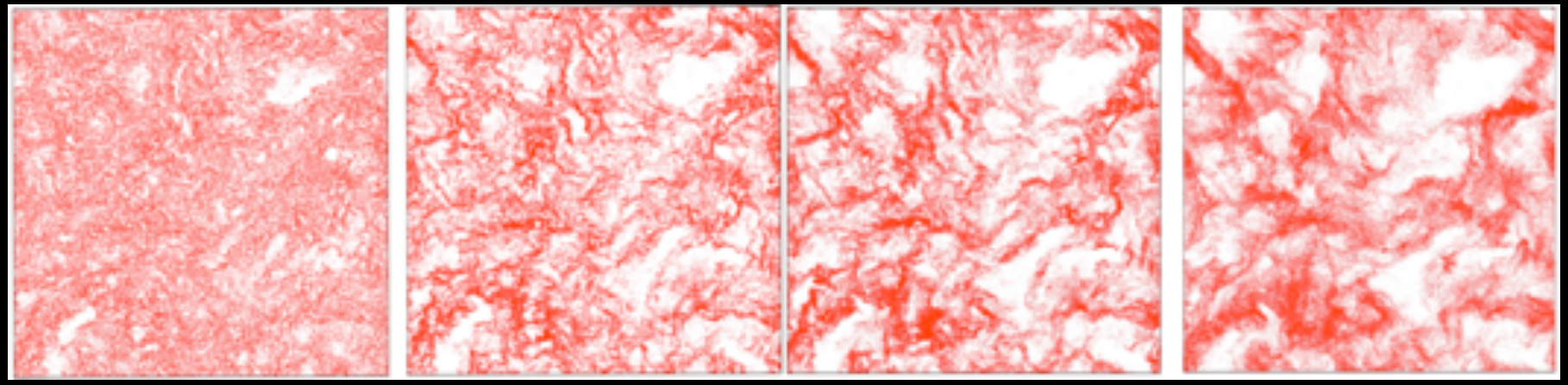
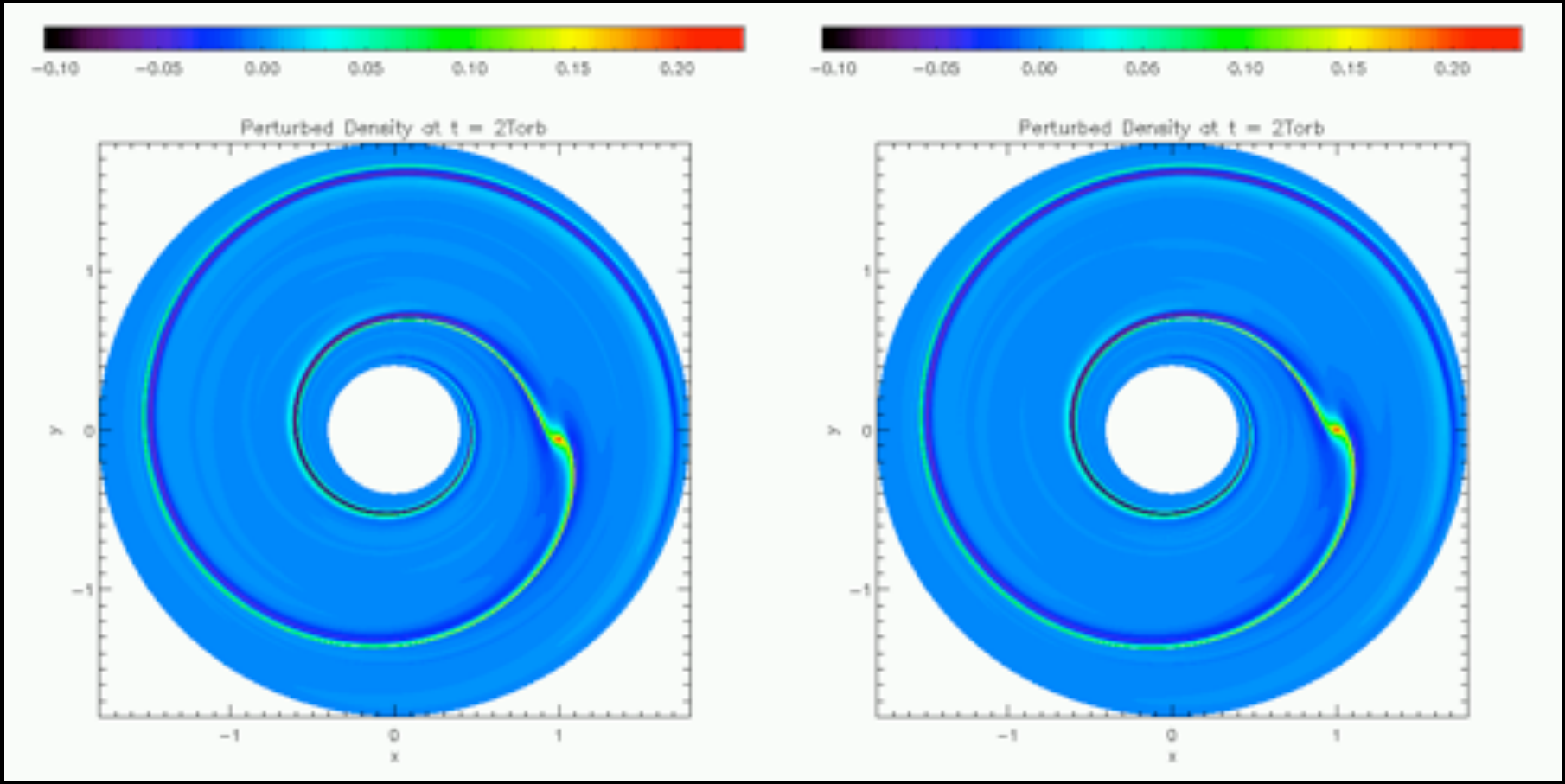
Simulating dust coagulation in turbulent protoplanetary disks

(Umemura, M.; Ishihara, T.)

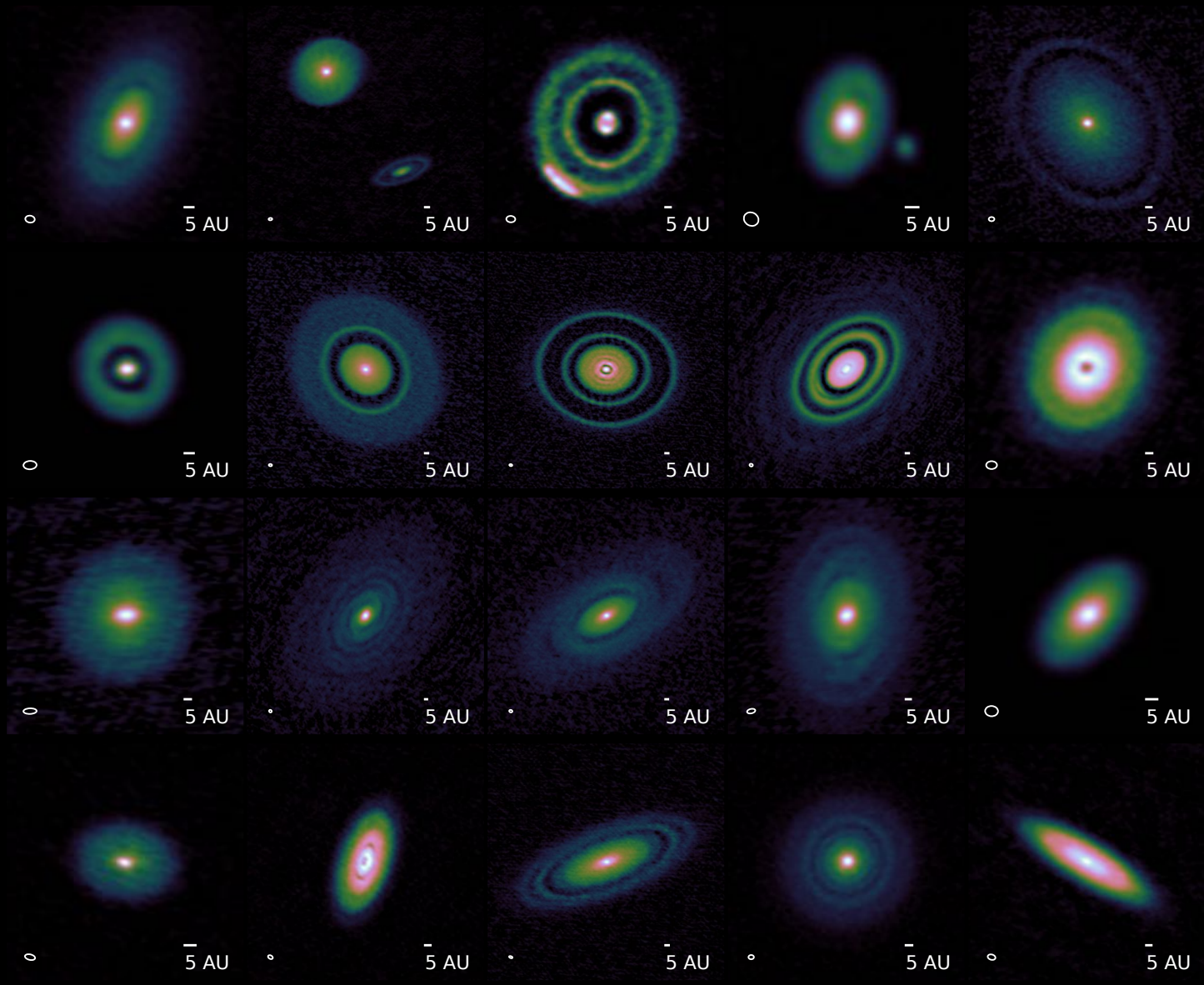


(Ishihara+ 2018)

Simulating the growth and migration of giant gas planets



(e.g. Kley+)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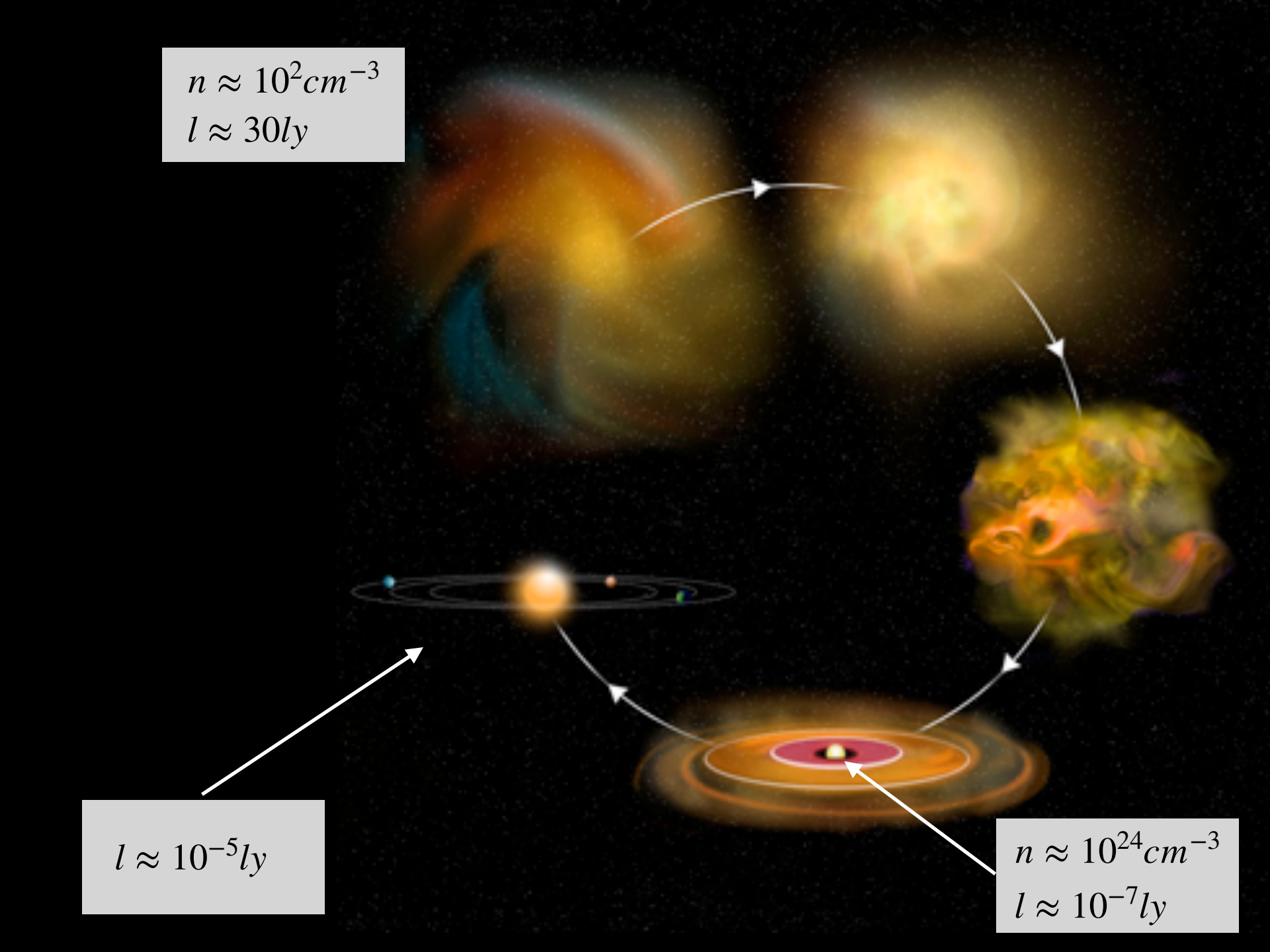
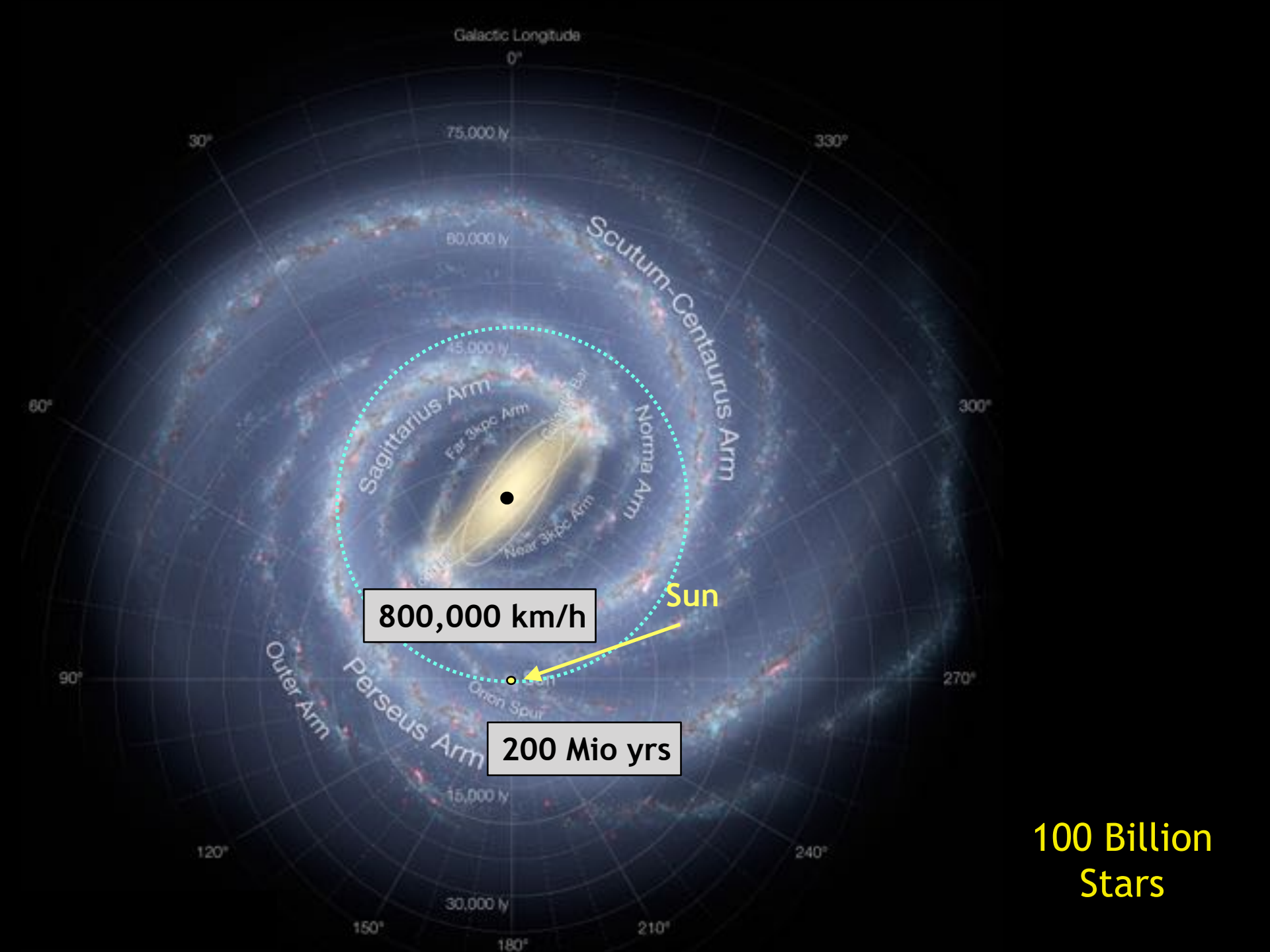

$n \approx 10^2 cm^{-3}$
$l \approx 30ly$
$l \approx 10^{-5}ly$
$n \approx 10^{24} cm^{-3}$
$l \approx 10^{-7}ly$

Matthew Bate
UNIVERSITY OF EXETER


Galactic Longitude
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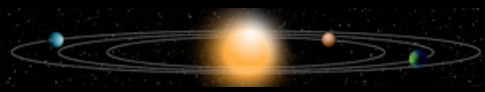
60°
300°
90°
270°
120°
240°
150°
210°
180°
75,000 ly
60,000 ly
45,000 ly
30,000 ly
15,000 ly
Scutum-Centaurus Arm
Sagittarius Arm
Norma Arm
Perseus Arm
Outer Arm
Far 3kpc Arm
Near 3kpc Arm
Orion Spur
800,000 km/h
Sun
200 Mio yrs
100 Billion
Stars

Order out of Self-organised, Turbulent Complexity

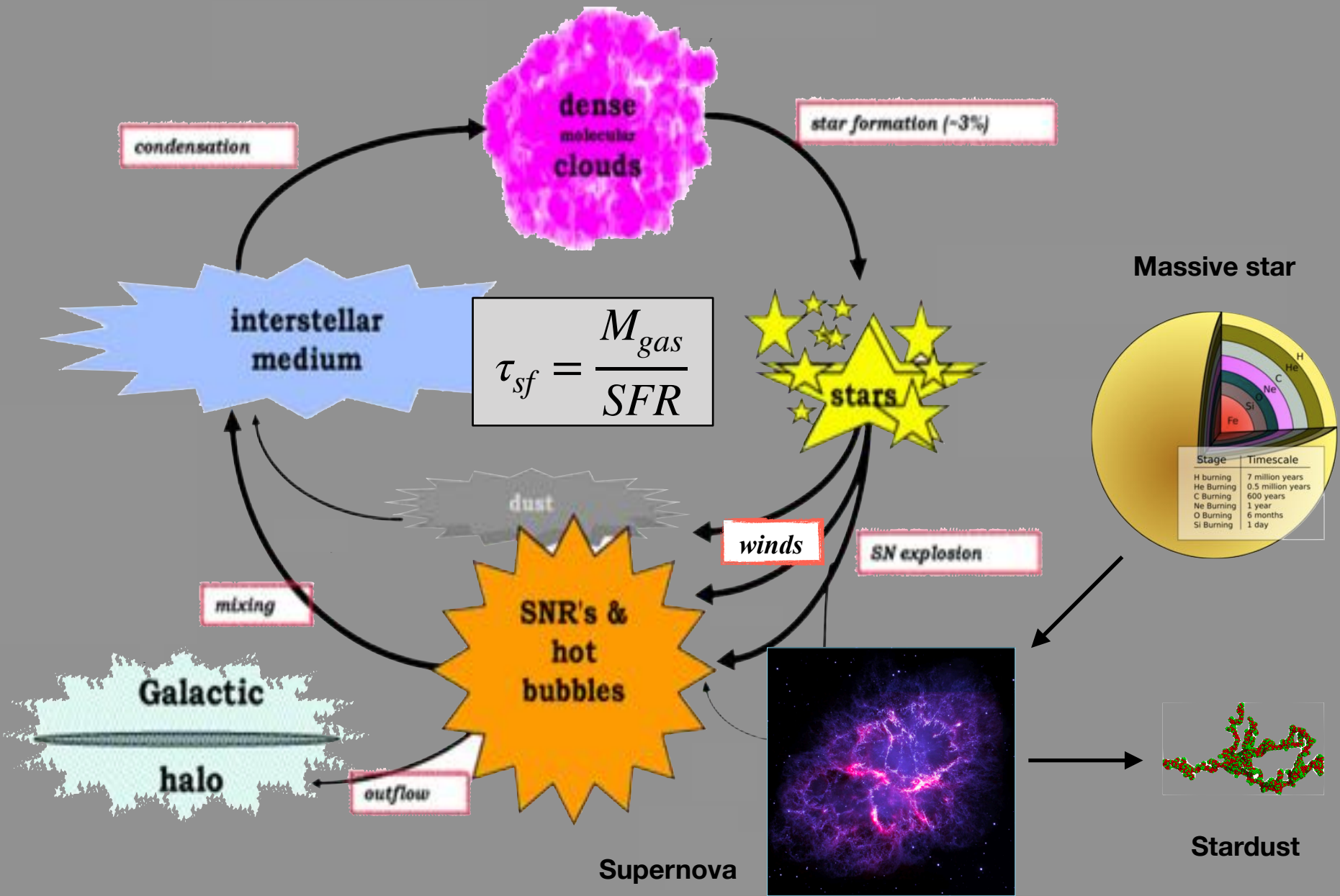
Molecular clouds are not spheroidal and not isolated.

$10^5 ly$

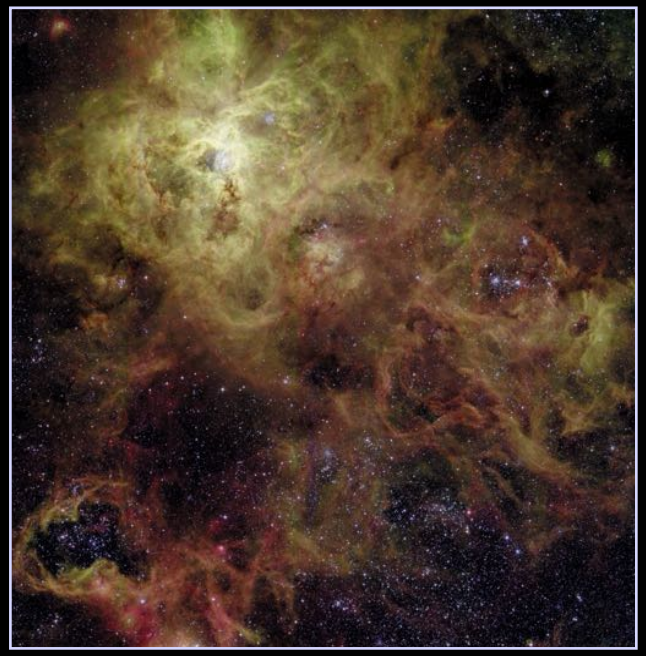
$10^{-5} ly$



The Galactic Cycle of Life



The Puzzle of Star Formation



Gas reservoir: $3 \cdot 10^9 \, M_\odot$

Collapse time: $3 \cdot 10^6 \, yrs$

→ **Expected star formation rate**

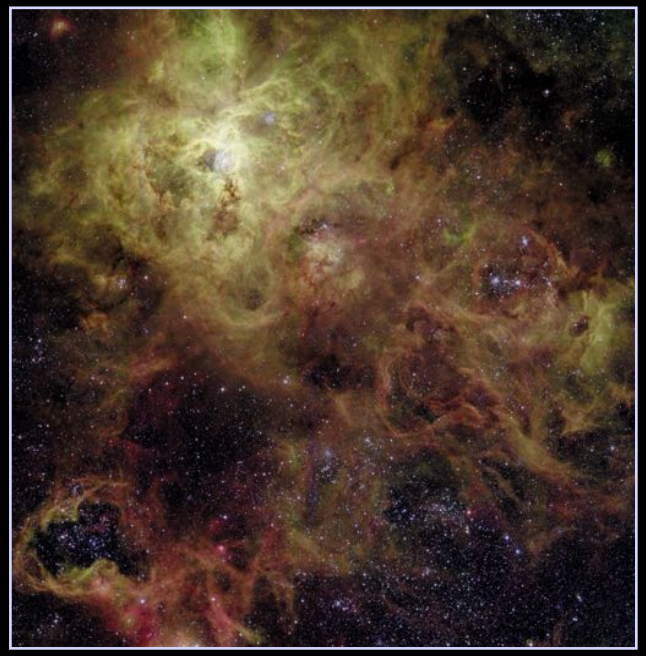
$$1000 \frac{M_\odot}{yr}$$

Observed: $3 \frac{M_\odot}{yr}$

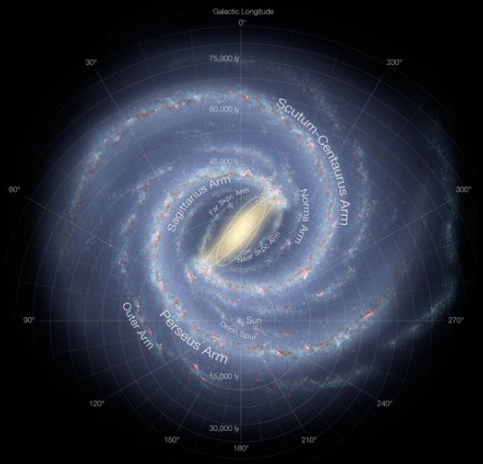
→ **Star formation timescale**

$$10^9 \, yrs$$

The Puzzle of Star Formation



Maybe, our Milky Way is unique!



Gas reservoir: $3 \cdot 10^9 \, M_\odot$

Collapse time: $3 \cdot 10^6 \, yrs$

Expected star formation rate

$$1000 \frac{M_\odot}{yr}$$

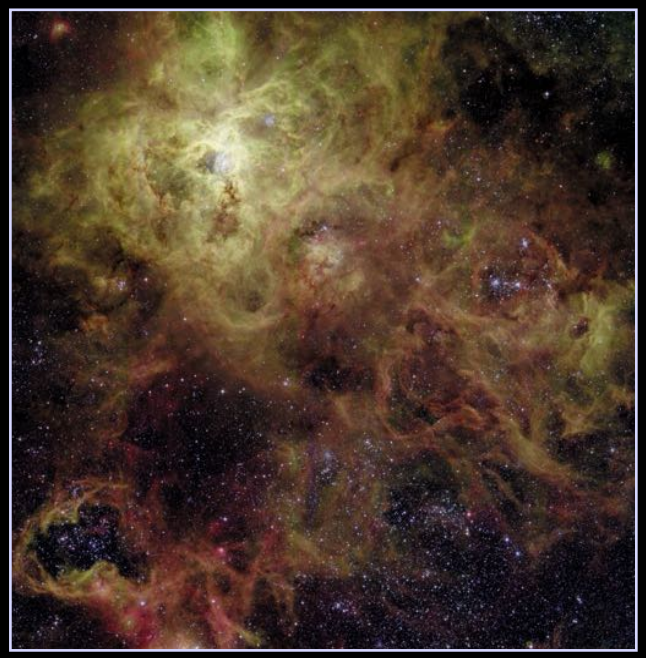
Observed: $3 \frac{M_\odot}{yr}$

Star formation timescale

$10^9 \, yrs$

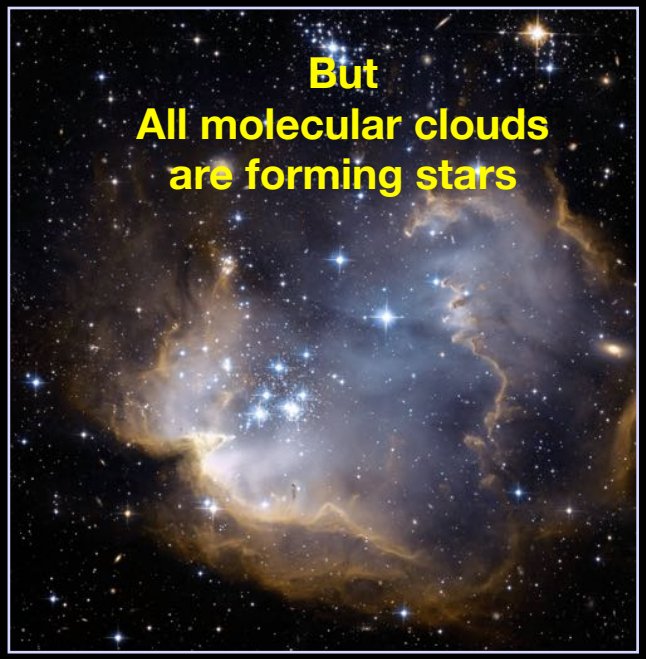
Universal

The Puzzle of Star Formation



0.3% of all clouds form stars?

99.7% of all clouds do not form stars



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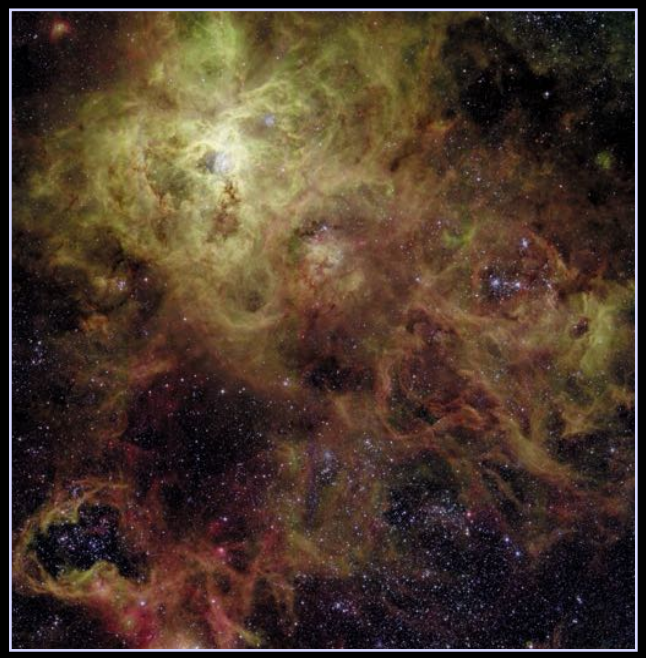


Feedback

0.3% of a cloud turns into stars

99.7% of a cloud is blown away

Gas reservoir: $3 \cdot 10^9 \, M_\odot$

Collapse time: $3 \cdot 10^6 \, yrs$

Expected star formation rate

$$1000 \frac{M_\odot}{yr}$$

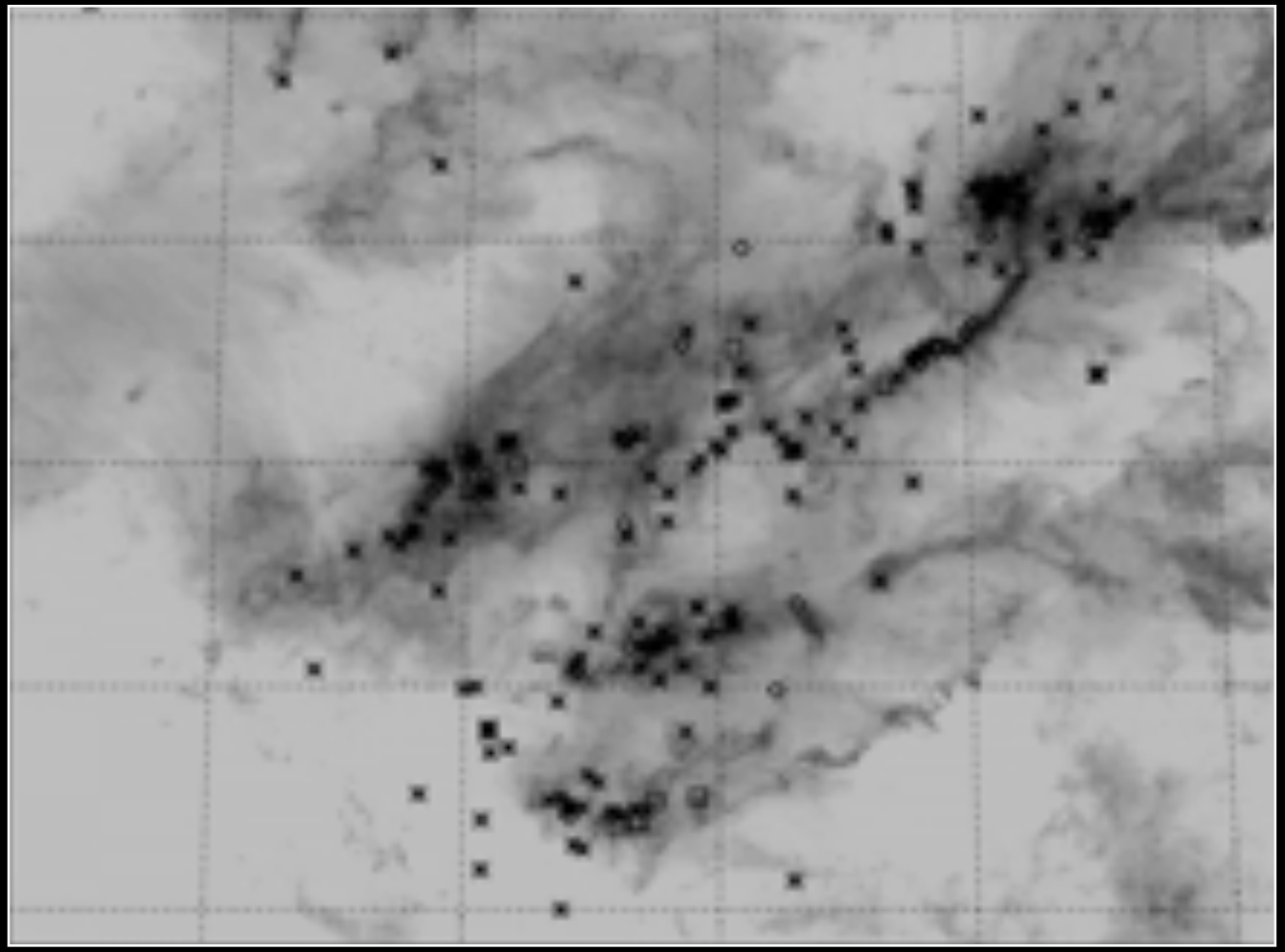
Observed: $3 \frac{M_\odot}{yr}$

Star formation timescale

$10^9 \, yrs$

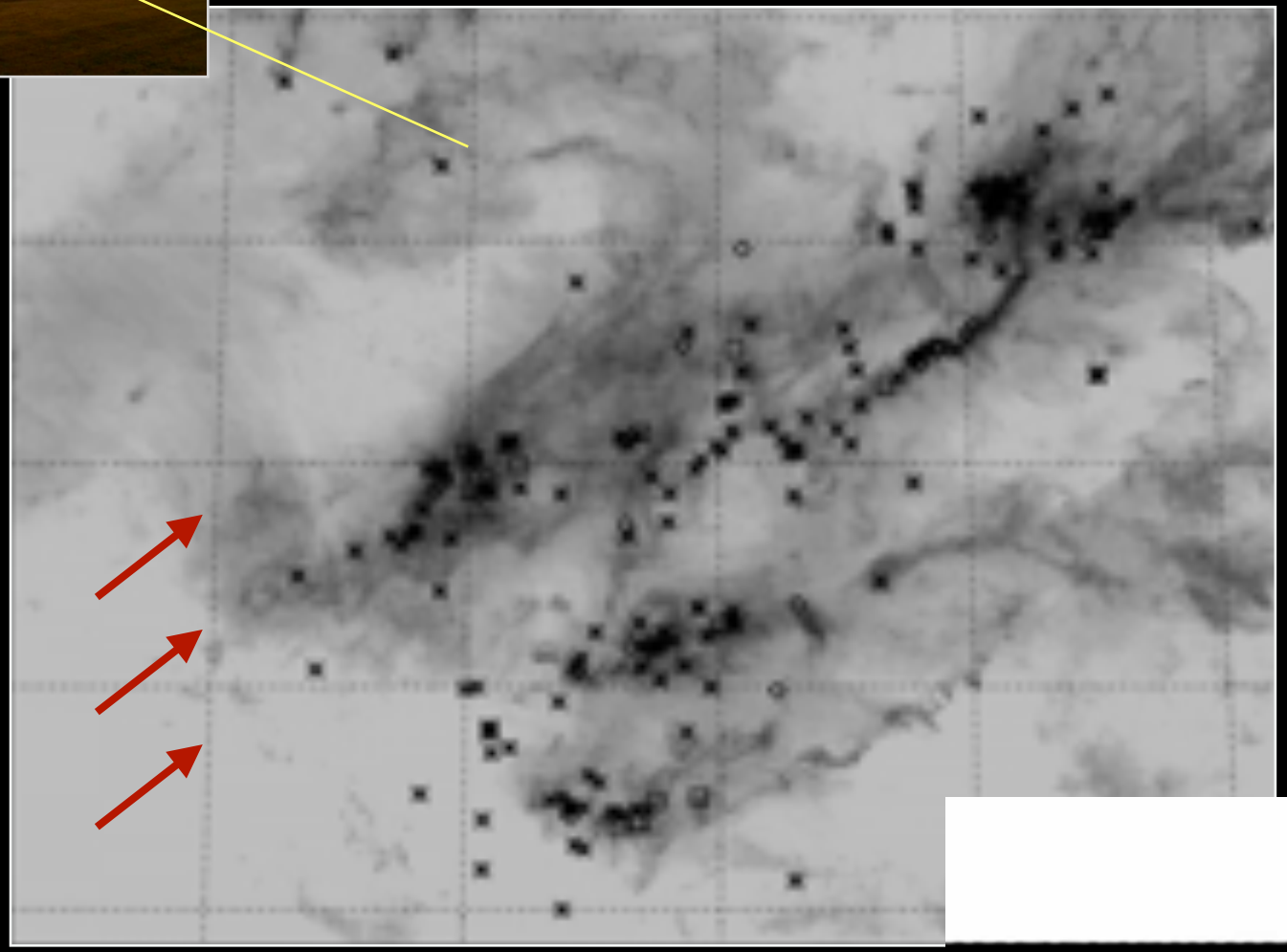
Universal

Star-Forming Filaments



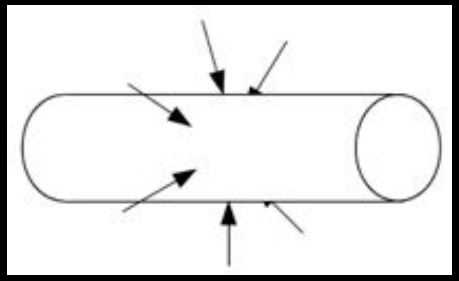
Taurus

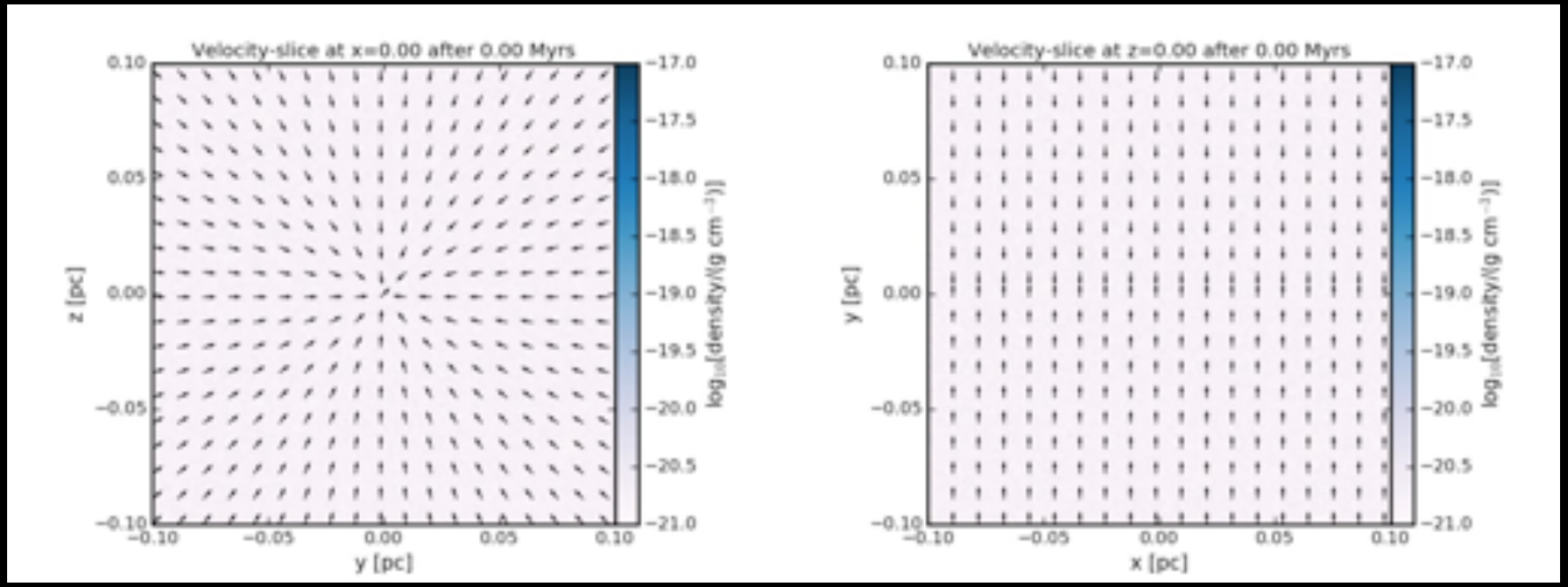
Turbulence and Filaments



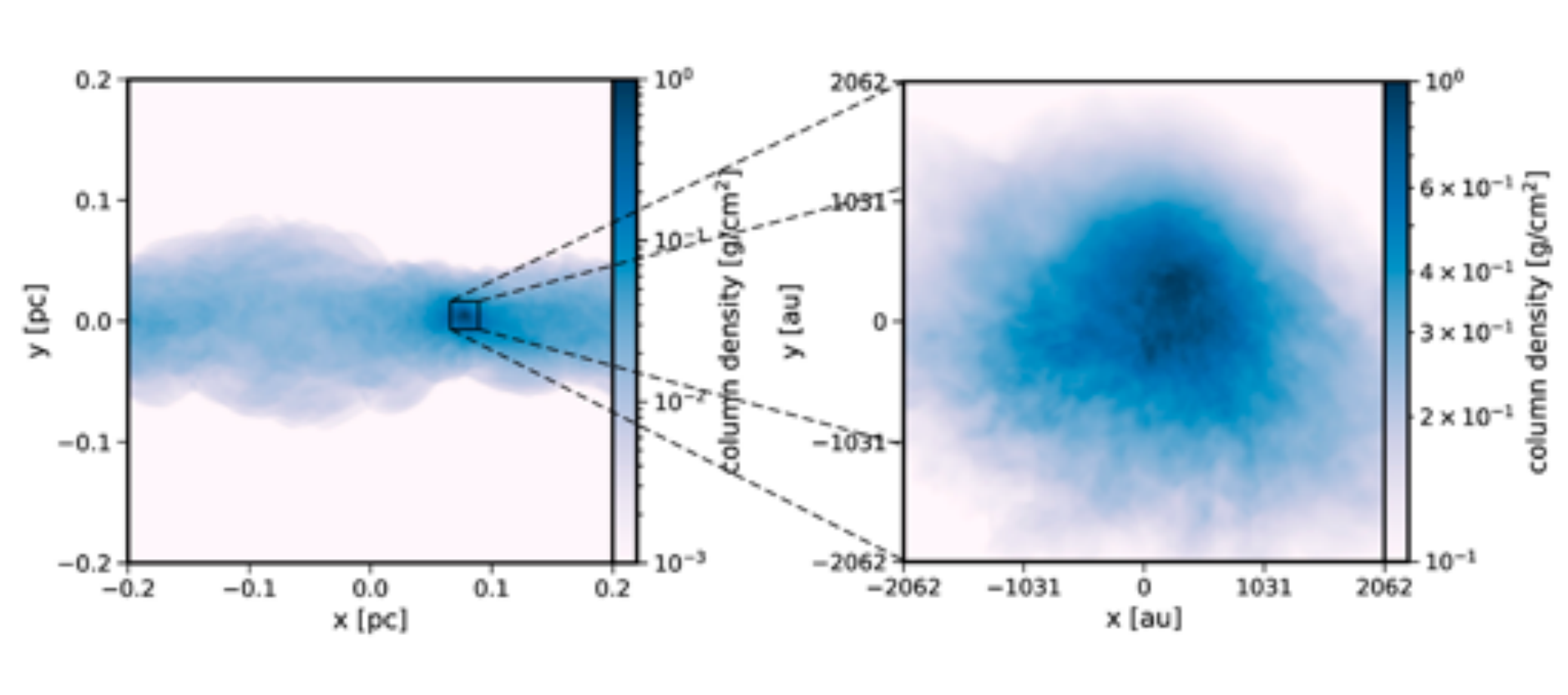
Star Formation in Filaments

(Heigl+ 17, 21, 22)

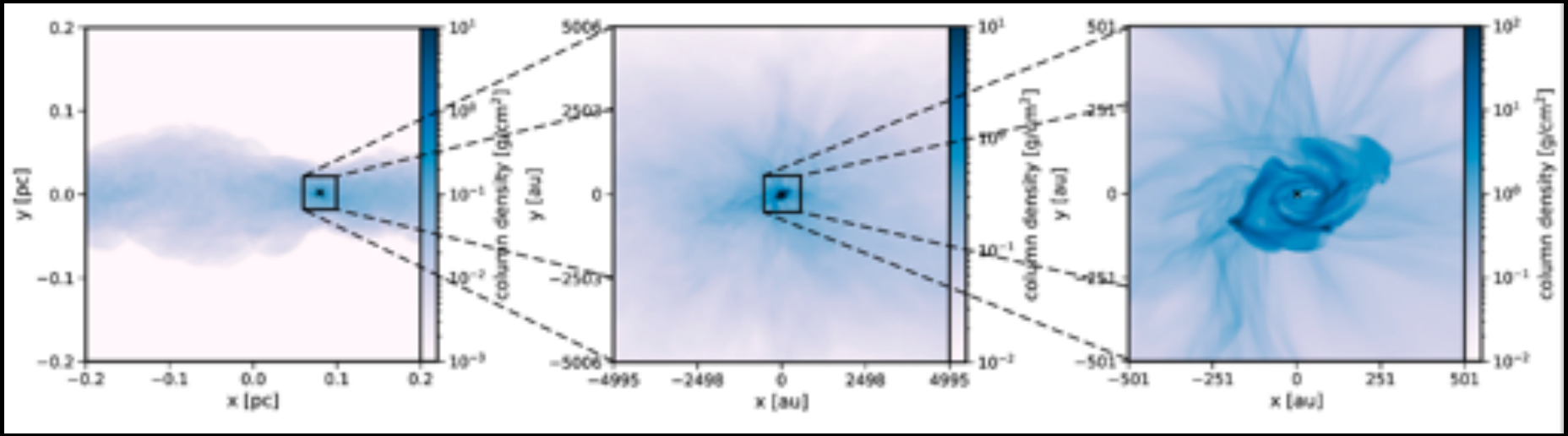


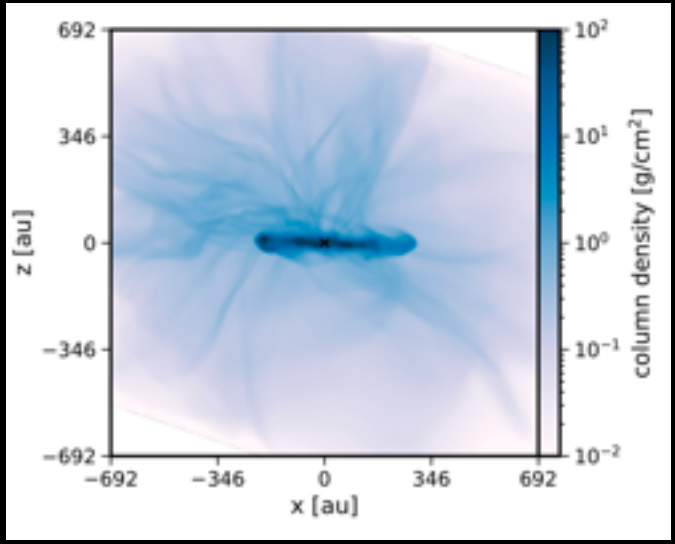


High-resolution zoom-in simulation of a collapsing, turbulent core

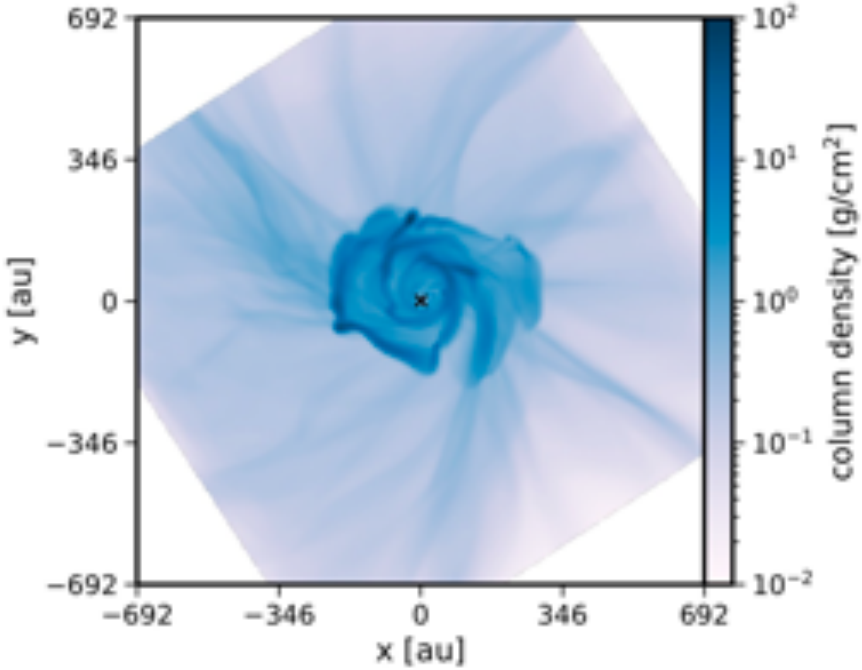


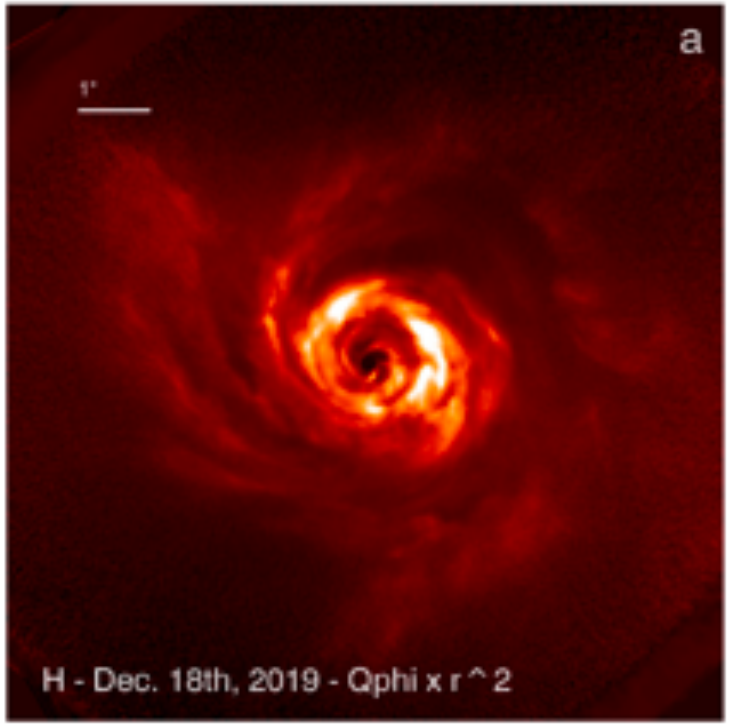
Disk Formation in the Center of the Core





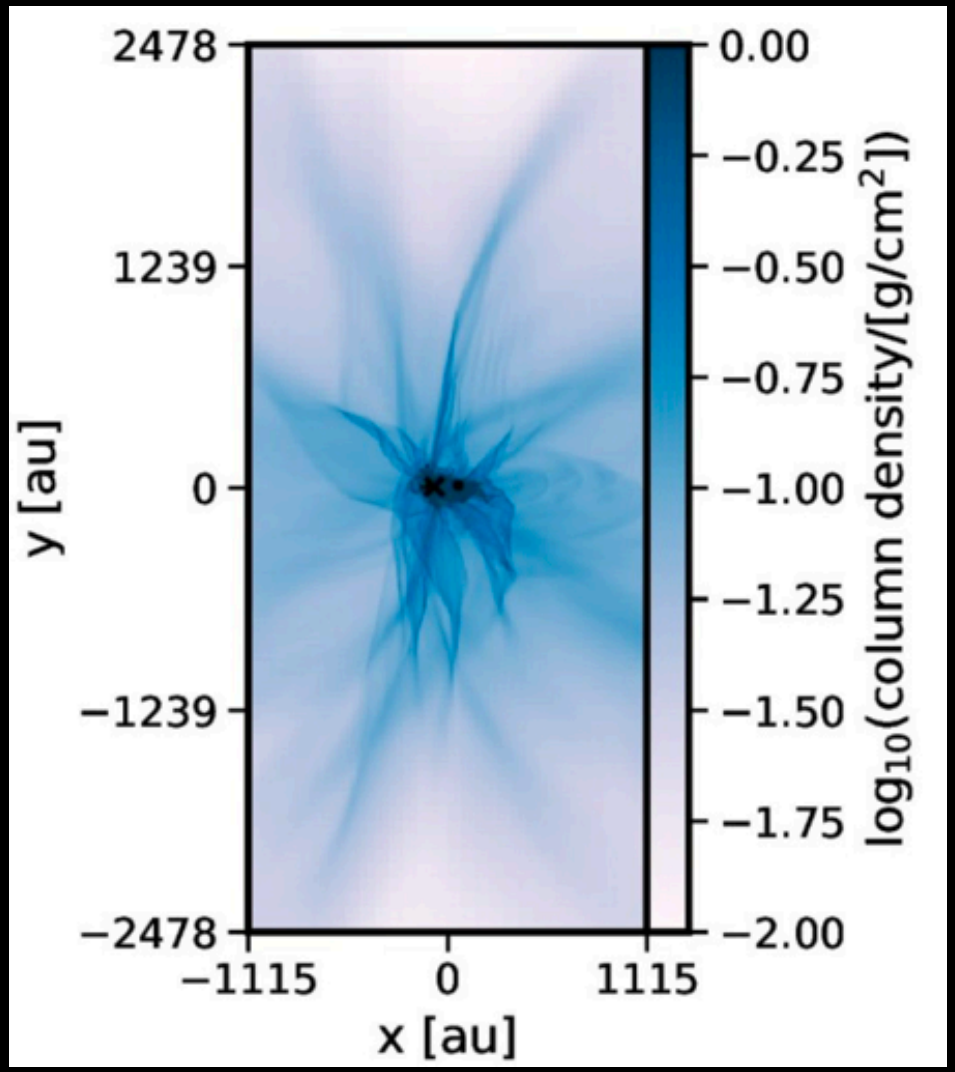
Disk looks very similar to observations

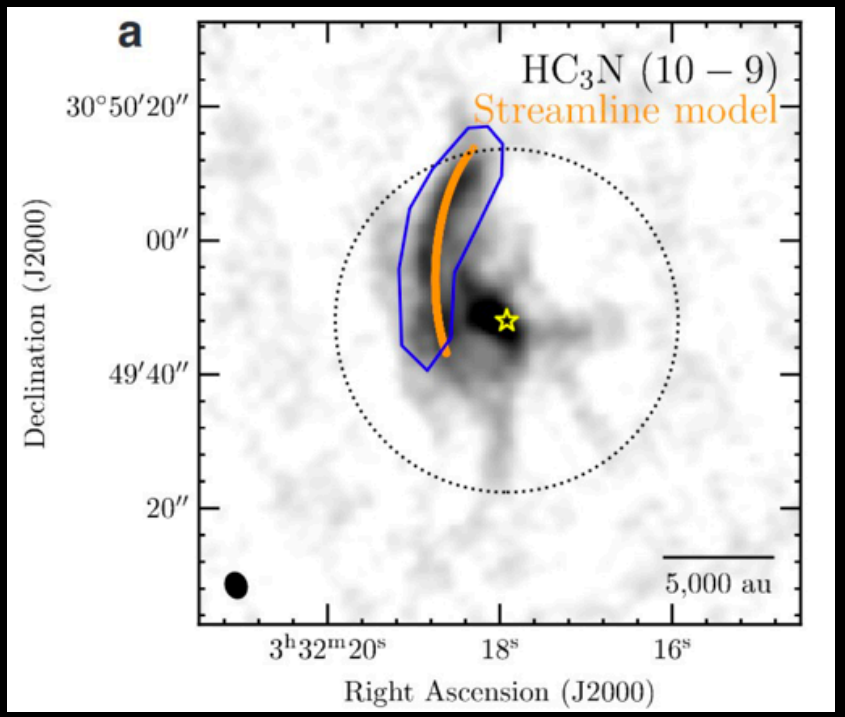




AB Aurigae
in polarized light
(Boccaletti+20)

Multi-Scale Disk Feeding





Per-emb-2
(Pineda+20)

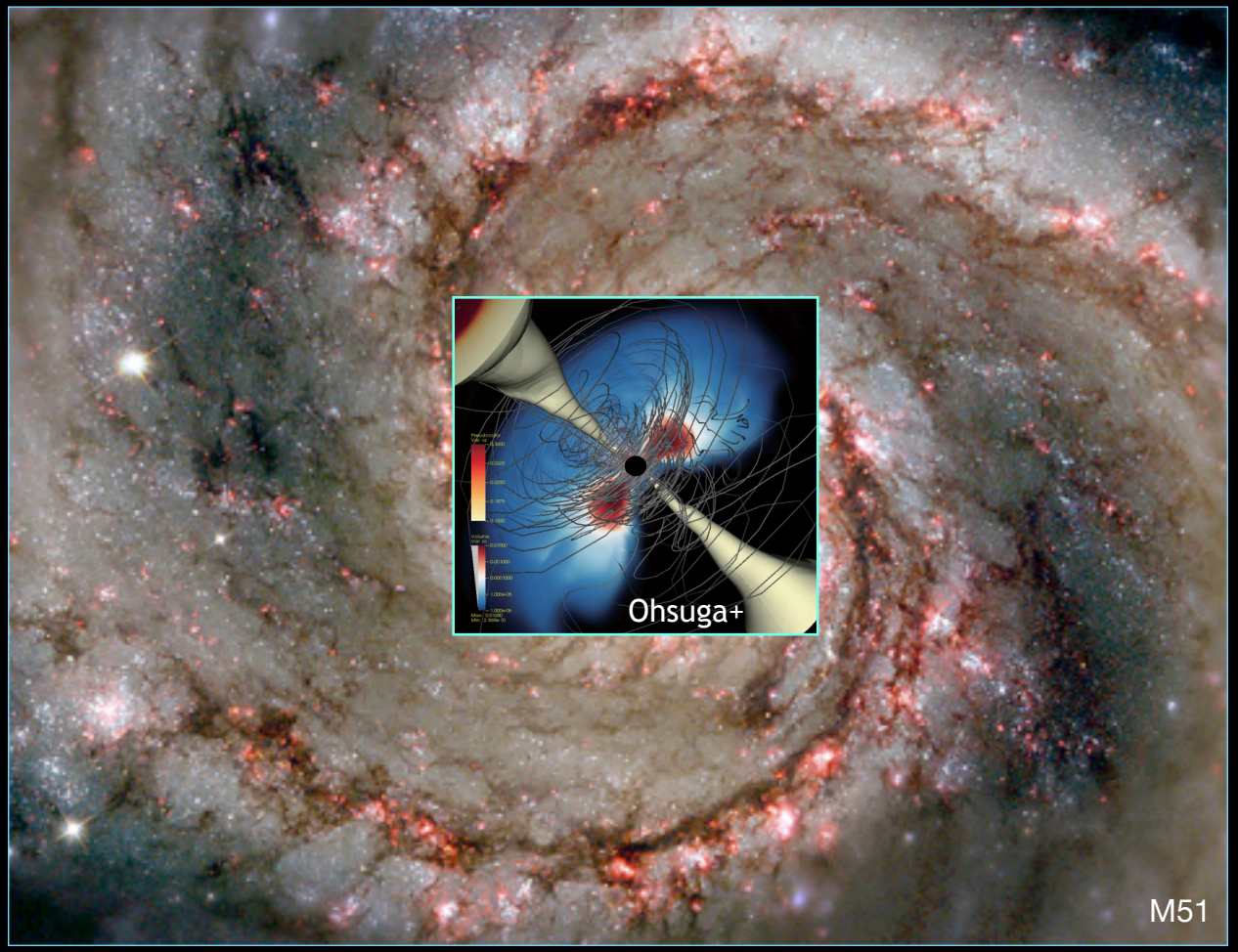
Galaxy Evolution and Supermassive Black Holes (AGNs)

(Ohsuga, K.; Umemura, M.; Wagner, A.; Yajima, H.; Asahina, Y; Ogawa, T.)

Galaxy Evolution and Supermassive Black Holes (AGNs)

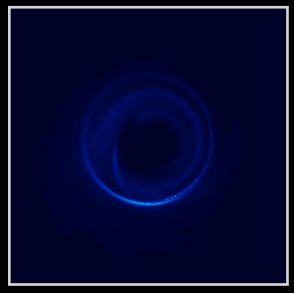
(Ohsuga, K.; Umemura, M.; Wagner, A.; Yajima, H.; Asahina, Y; Ogawa, T.)

$10^5 ly$



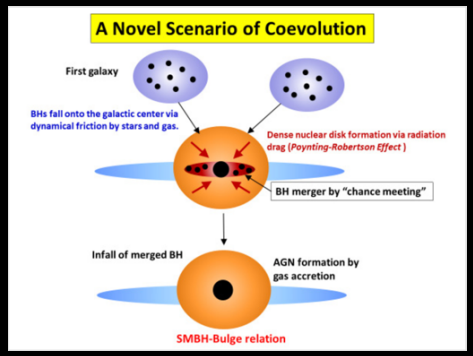
Black hole shadow

$10^{-3} ly$



(Kawashima; Ohsuga+)

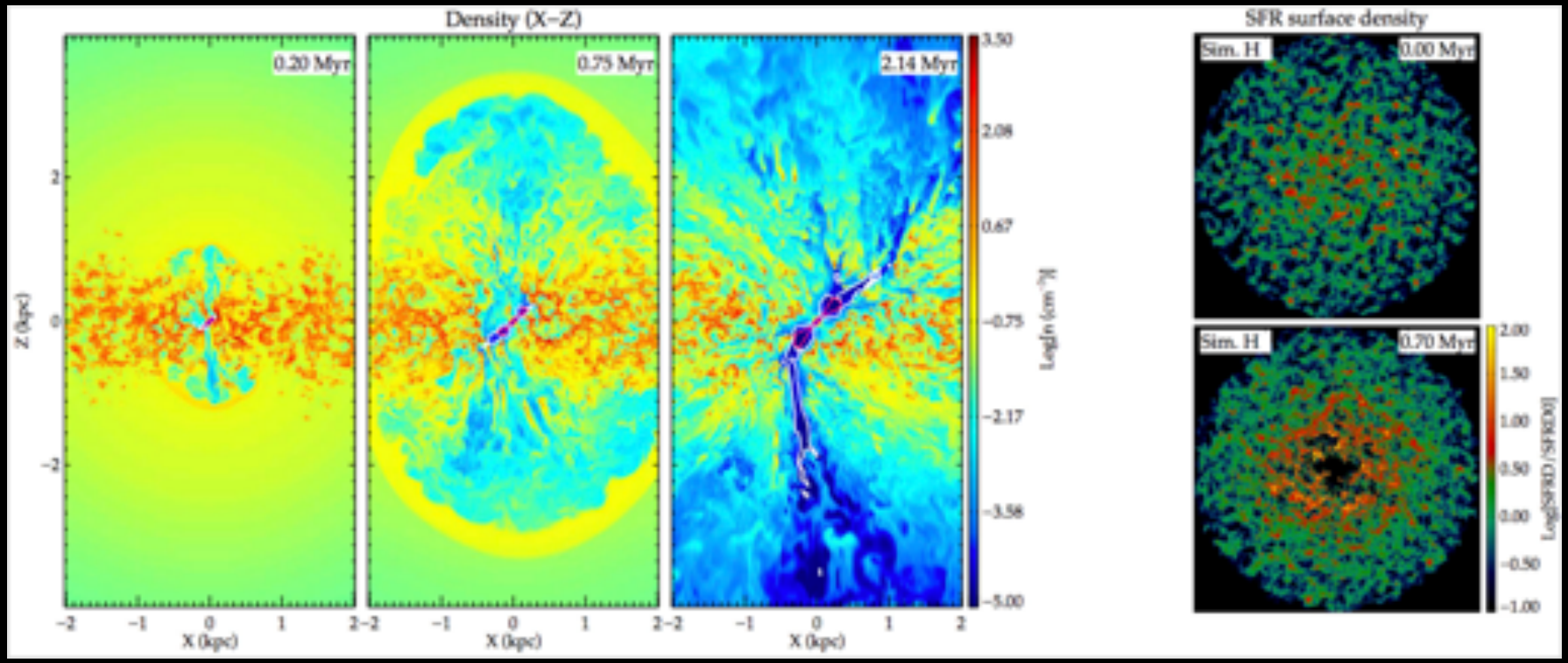
BH mergers and gravitational waves



(Umemura+)

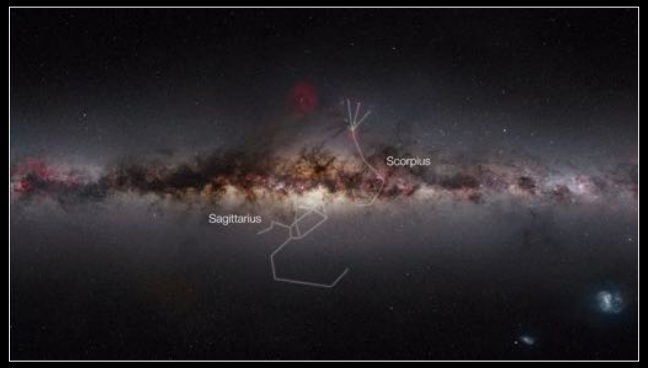
Interstellar Turbulence Driven by AGN Feedback

(Wagner, A.+)



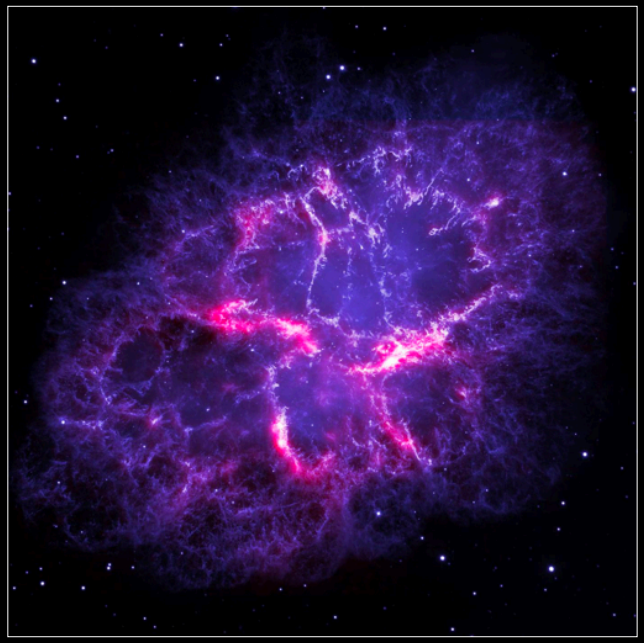
The Puzzle of Star Formation

Age: 10 Gyrs



Stellar mass loss

50% returned to the ISM



Current star formation rate:

$$3\frac{M_\odot}{yr}$$

$$3 \times 10^9 M_\odot$$

Gas depletion timescale

$$10^9\ yrs$$

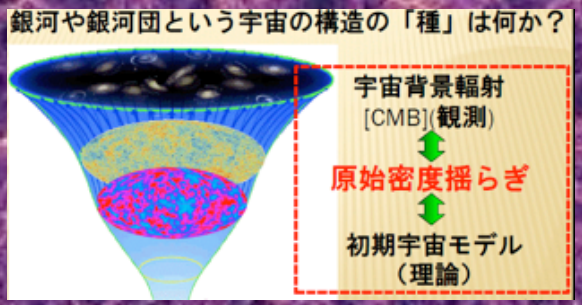
Gas depletion rate:

$$1.5\frac{M_\odot}{yr}$$

Depletion timescale

$$2 \cdot 10^9\ yrs$$

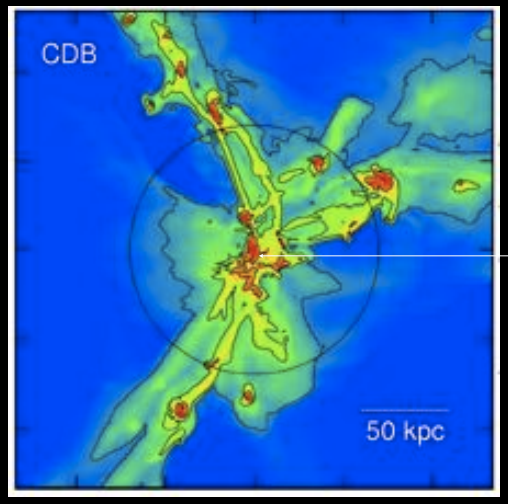
500 Mpc/h



Takamizu, Y.

Credit: V. Springel,MPA

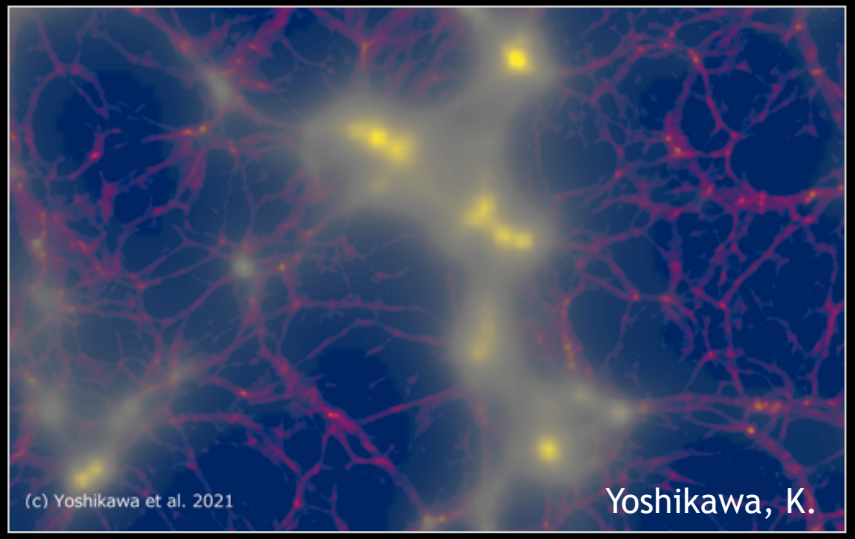
Cosmic web



Galaxies

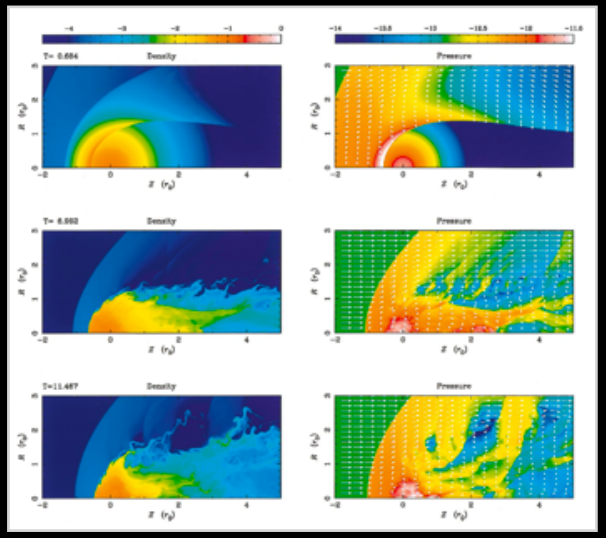
Galaxy Formation and Evolution within the Cosmic Web

High-resolution cosmic structure formation



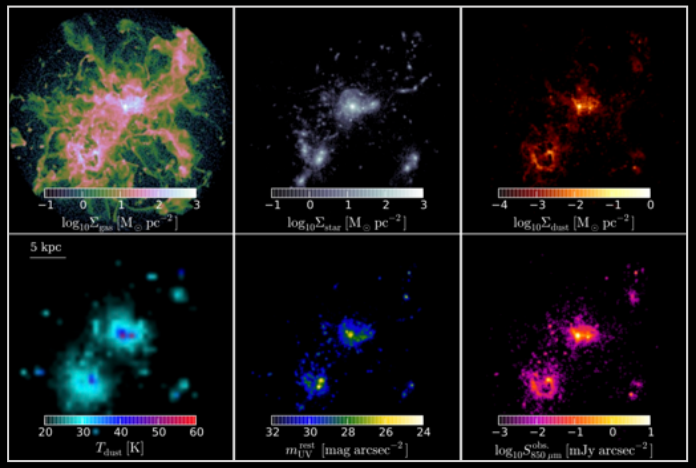
Yoshikawa, K.

Galaxy interaction and stripping



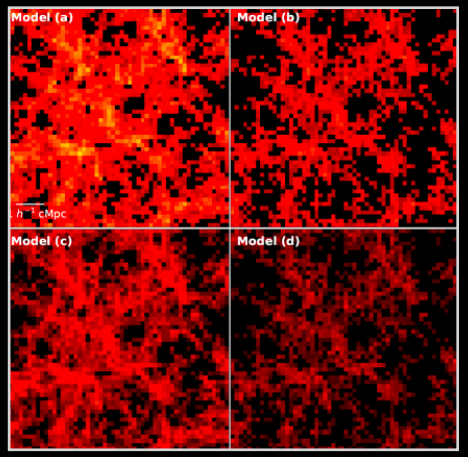
Mori,M.

High-resolution simulation of large-scale structure formation



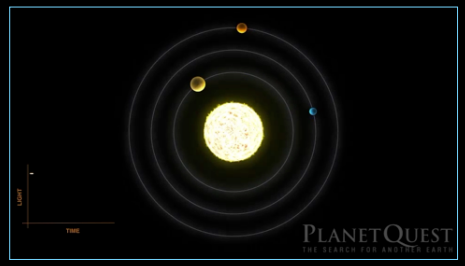
Yajima,H.; Abe, M.; Inoue, S.; Fukushima, H.

Early Chemical Enrichment

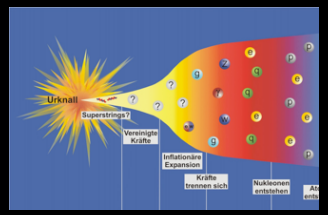


Kirihara, Hasegawa, Umemura, Mori, Tomoaki

The Cosmic Flow of Life



$10^{-7}ly$

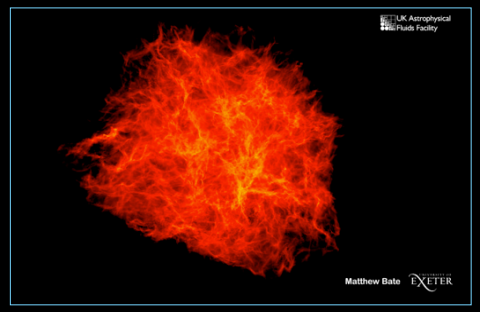


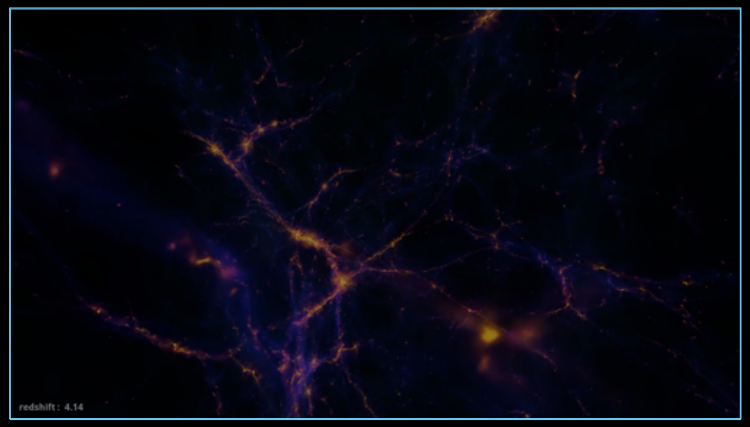
$10^{-7}ly$

$10^{-5}ly$

$10^{7}ly$

$10^{-5}ly$

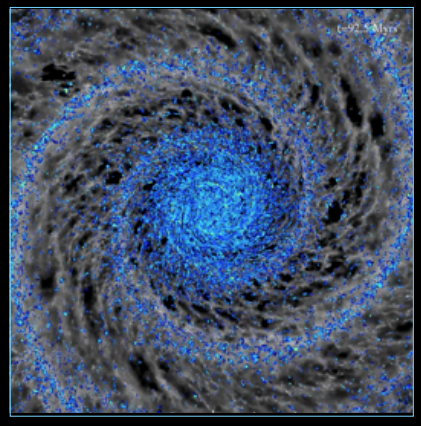




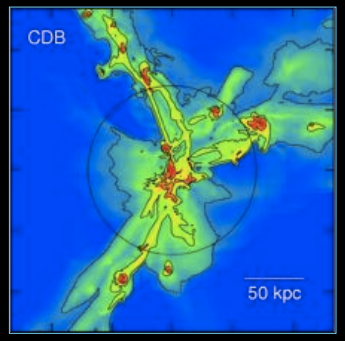
$10^{2}ly$

$10^{6}ly$

$10^{2}ly$



$10^{5}ly$



$10^{5}ly$