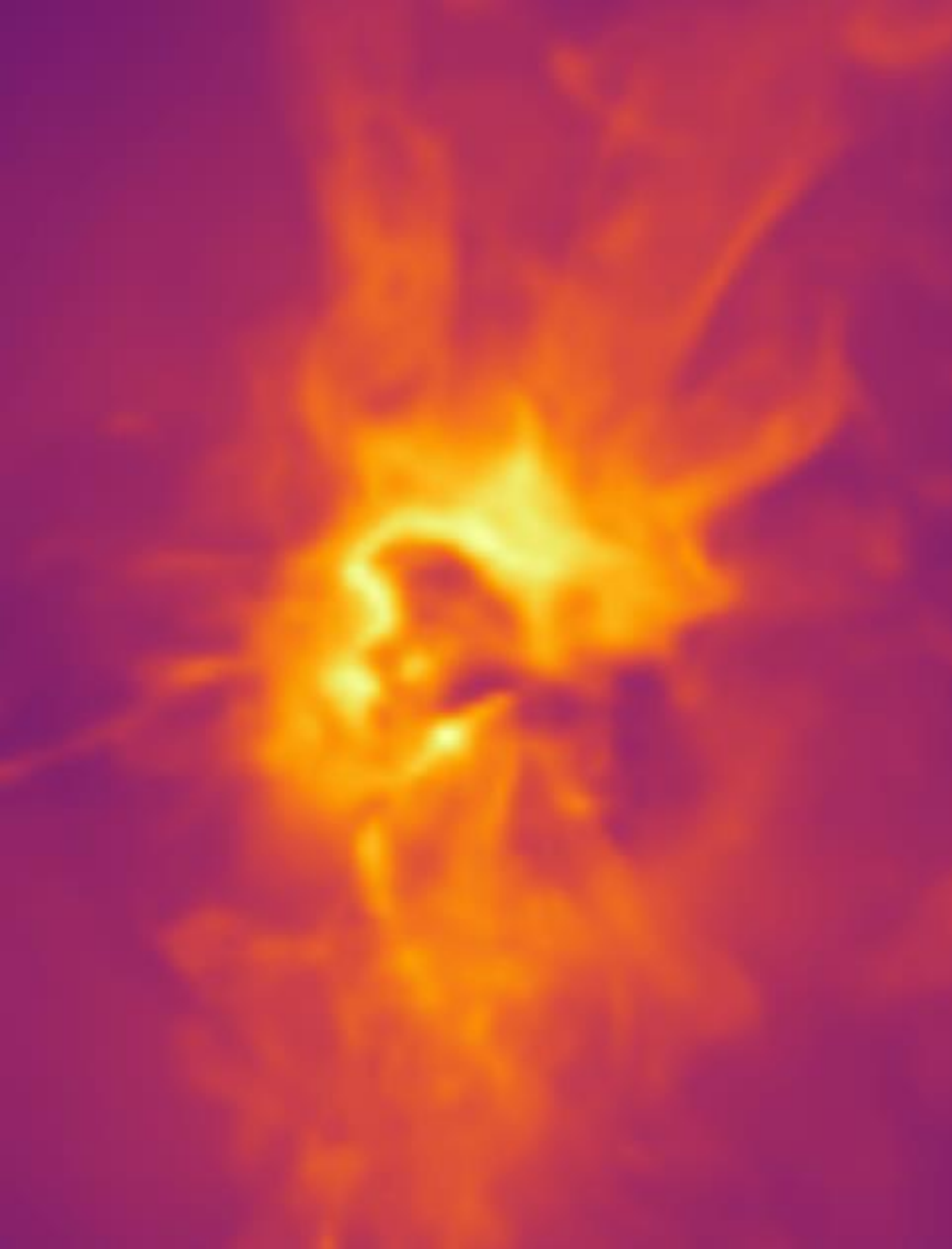


NTHUAC AstroRead

Introduction to Astrophysical Fluid Dynamics

Lin Yen-Hsing (NTHU IoA) | 2023.05.02

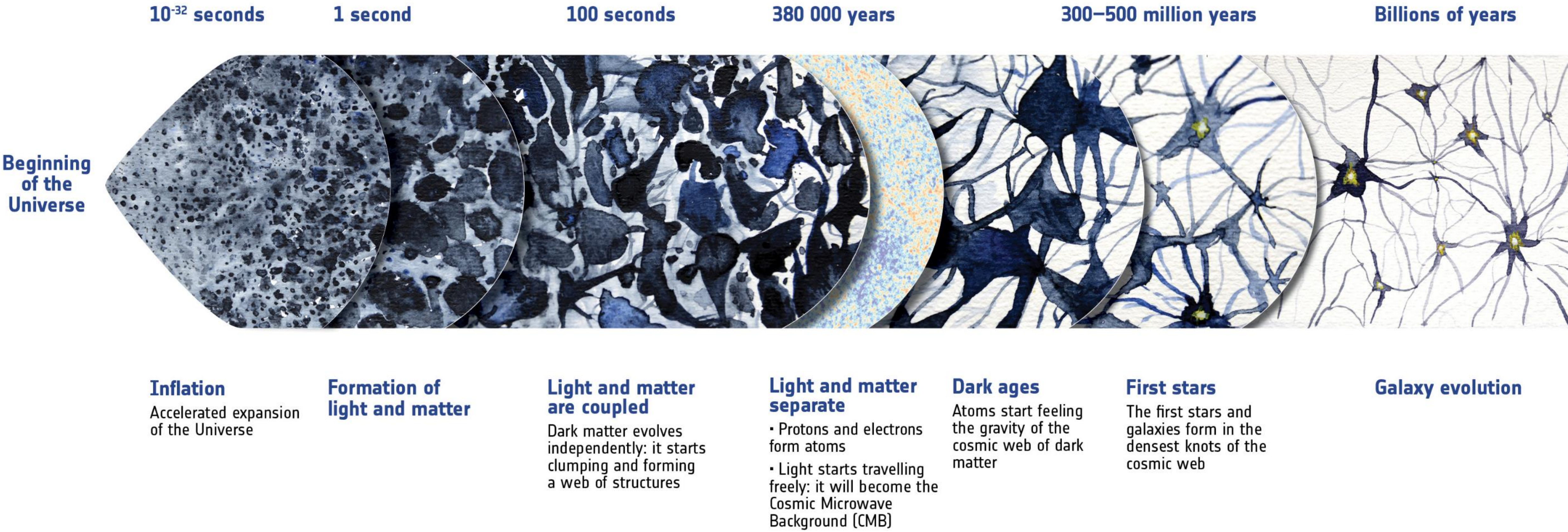
Outline

- **Role of gas in the universe**
  - Cosmology
  - Galaxy formation
  - Star and planet formation
- What physics does gas follows → Fluid Dynamics
  - Euler Equations and when is fluid approx. vaild
  - How to include more physics
- Gallery

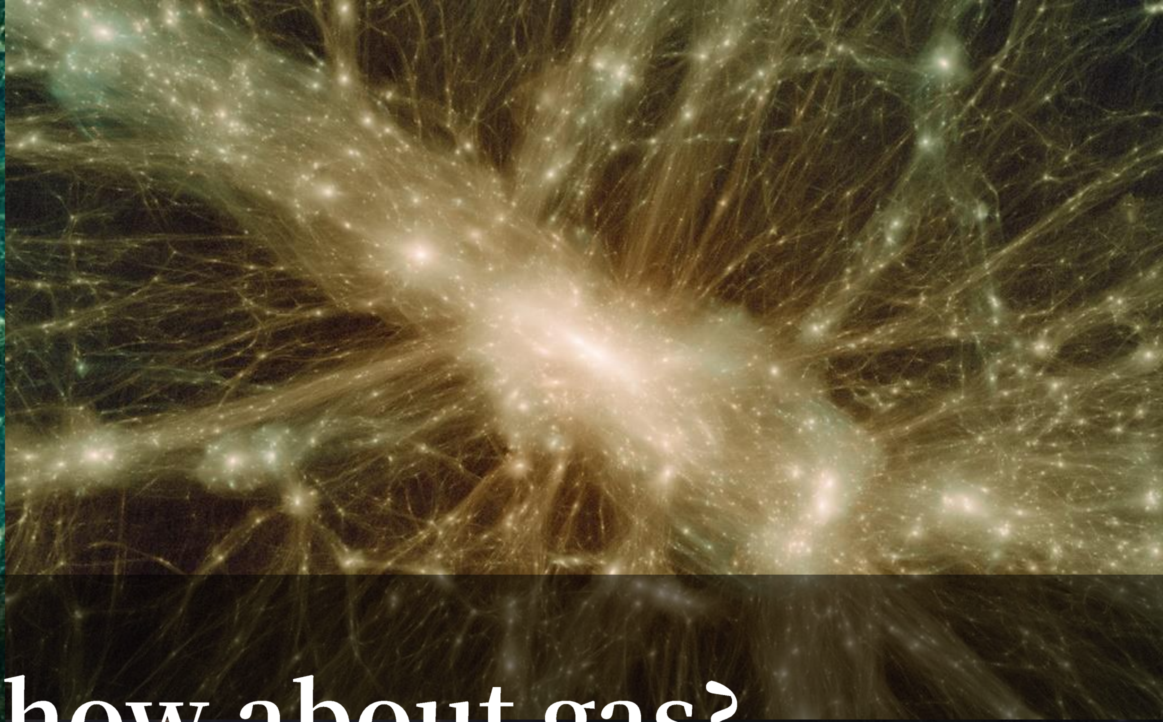
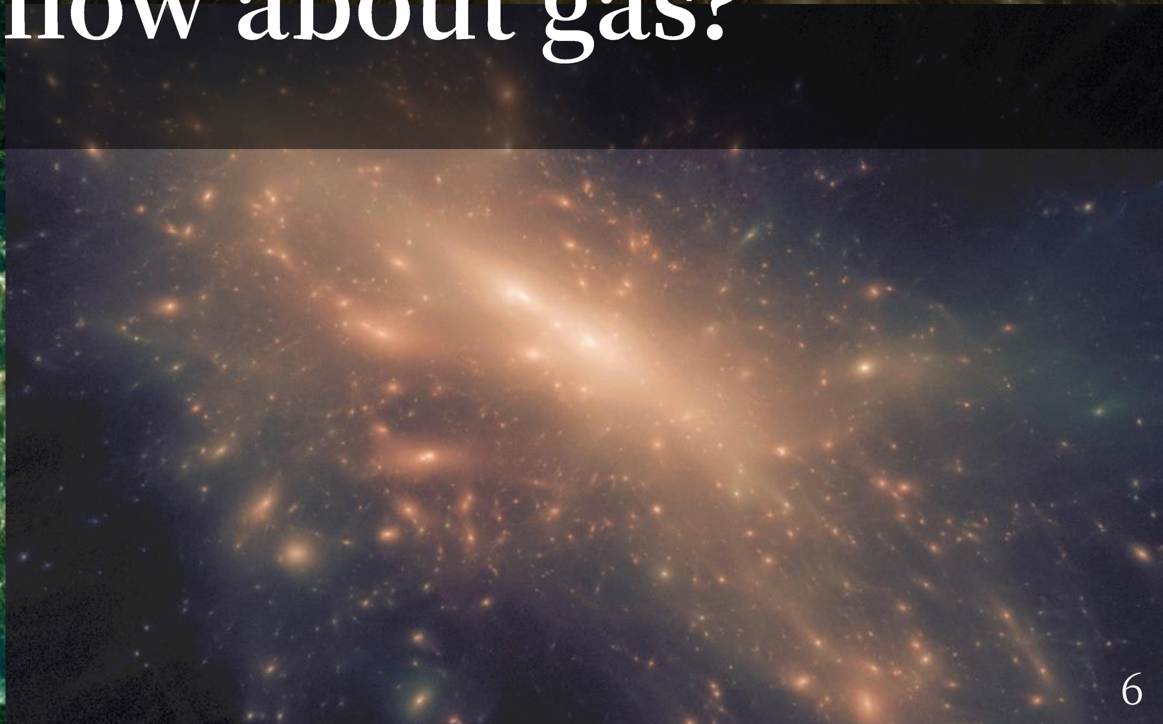
Introduction

The inter-connected universe

Review: History of the universe

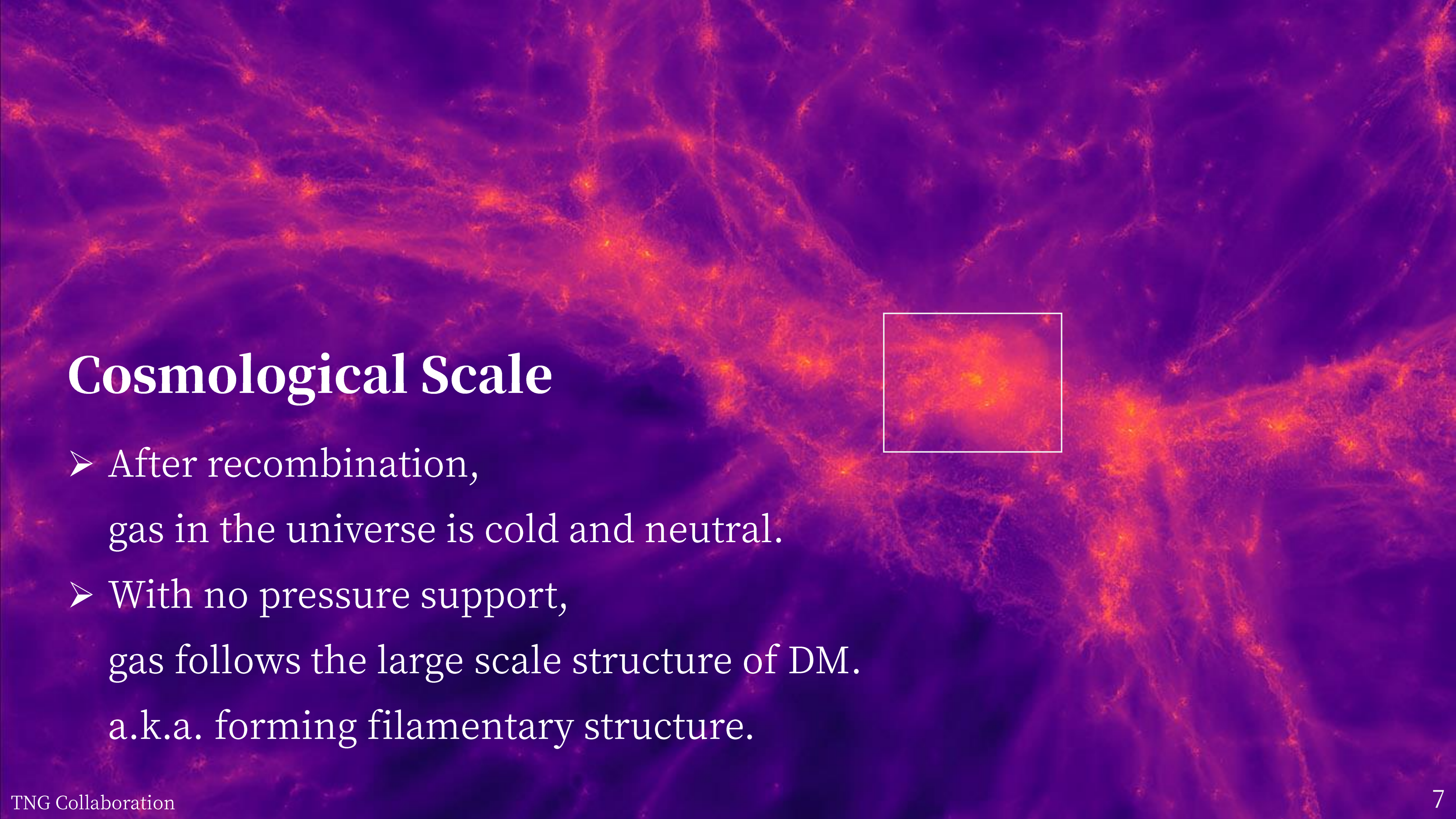


ESA

This is Dark Matter, how about gas?

Ishiyama et al. (2021)



Cosmological Scale

- After recombination,
  gas in the universe is cold and neutral.
- With no pressure support,
  gas follows the large scale structure of DM.
  a.k.a. forming filamentary structure.

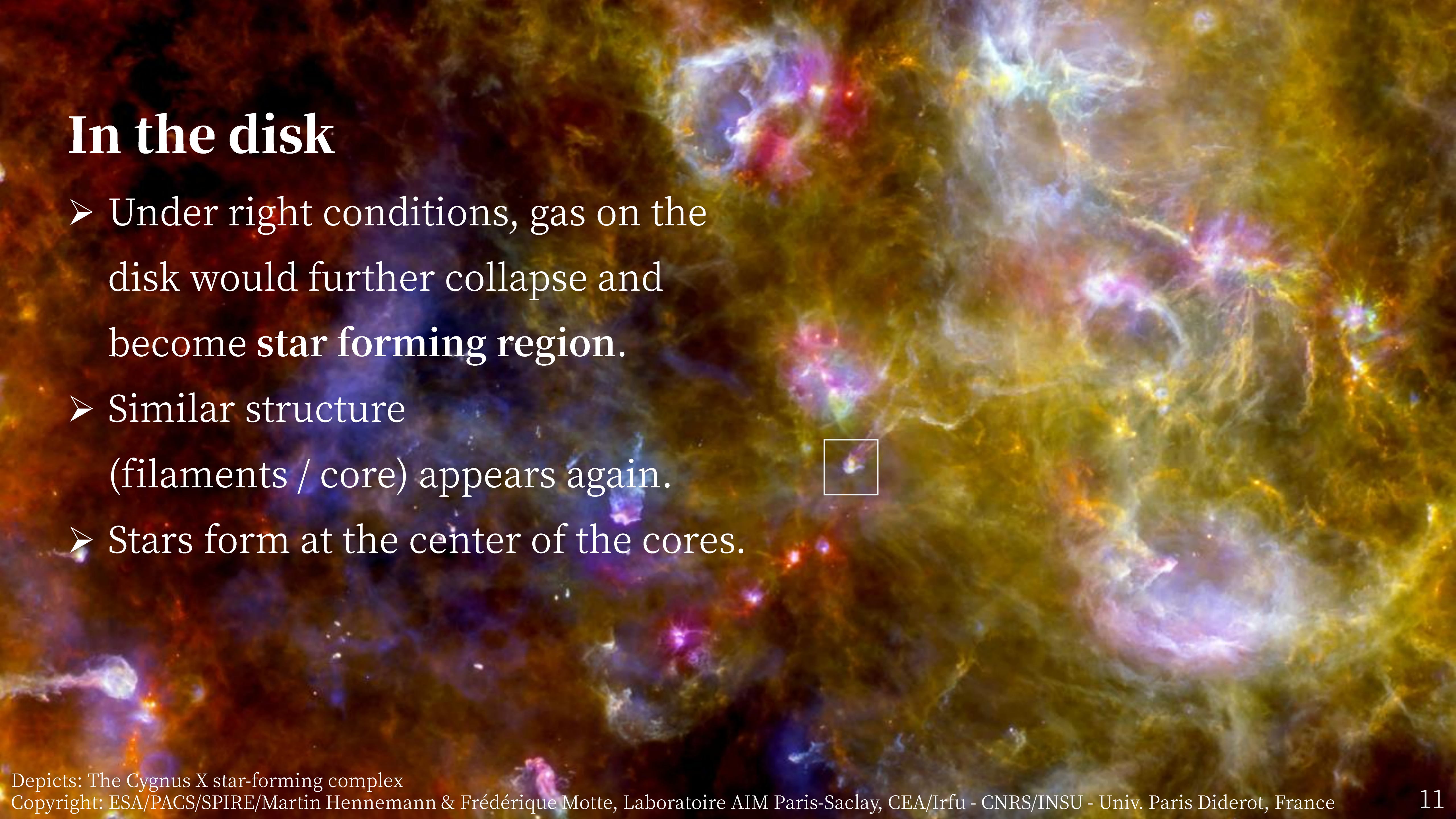
TNG Collaboration

Gas in DM halo

- In DM halos, gas would fall into the center of the potential well.
- Angular momentum conservation requires gas to speed up and form a rotationally supported disk.
- The disk eventually form stars and becomes so called galaxy.

In the disk

- Under right conditions, gas on the disk would further collapse and become **star forming region**.
- Similar structure (filaments / core) appears again.
- Stars form at the center of the cores.



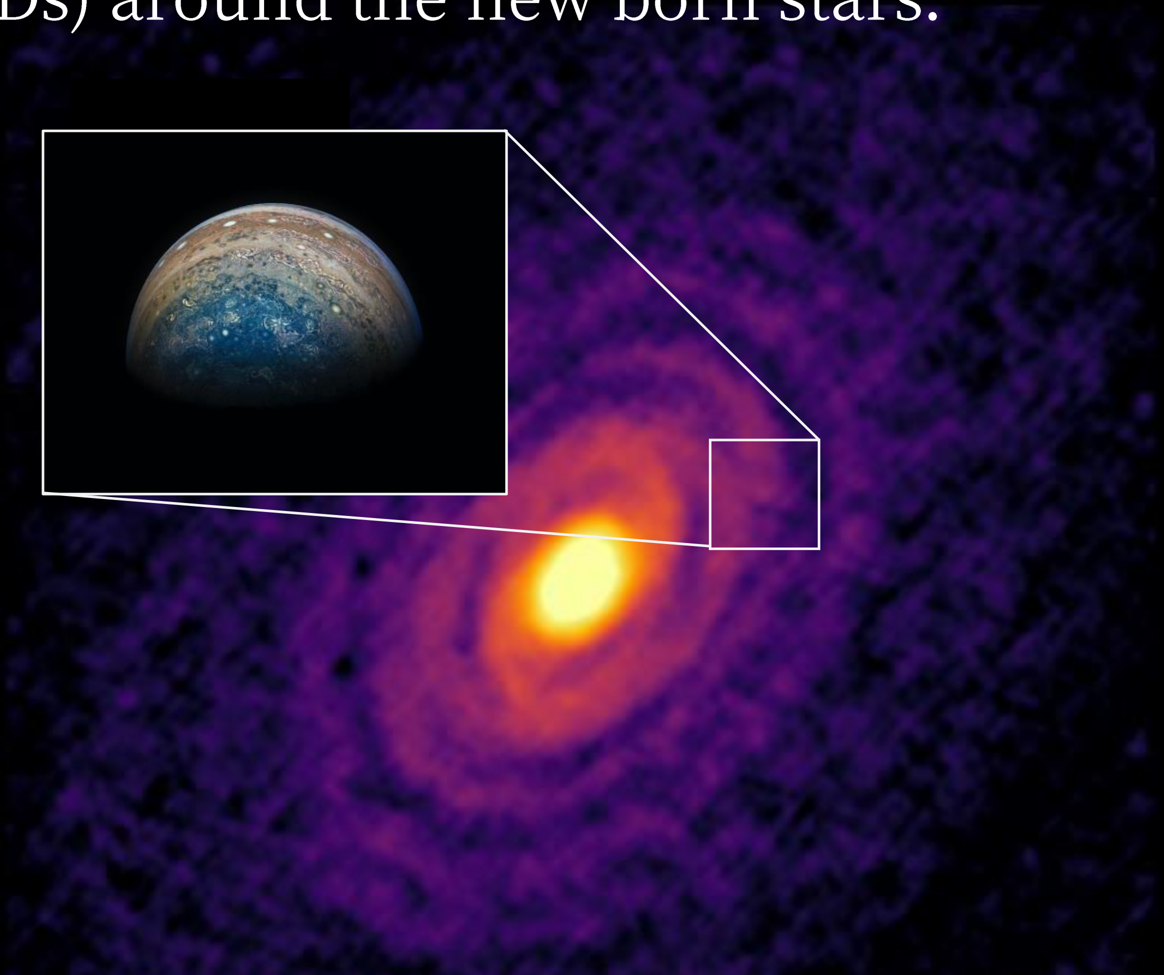
Depicts: The Cygnus X star-forming complex

Star and planet formation

- Gas forms protoplanetary disks (PPDs) around the new born stars.
- Planets form within the PPDs.

PPD IM Lupi in NIR by SPHERE

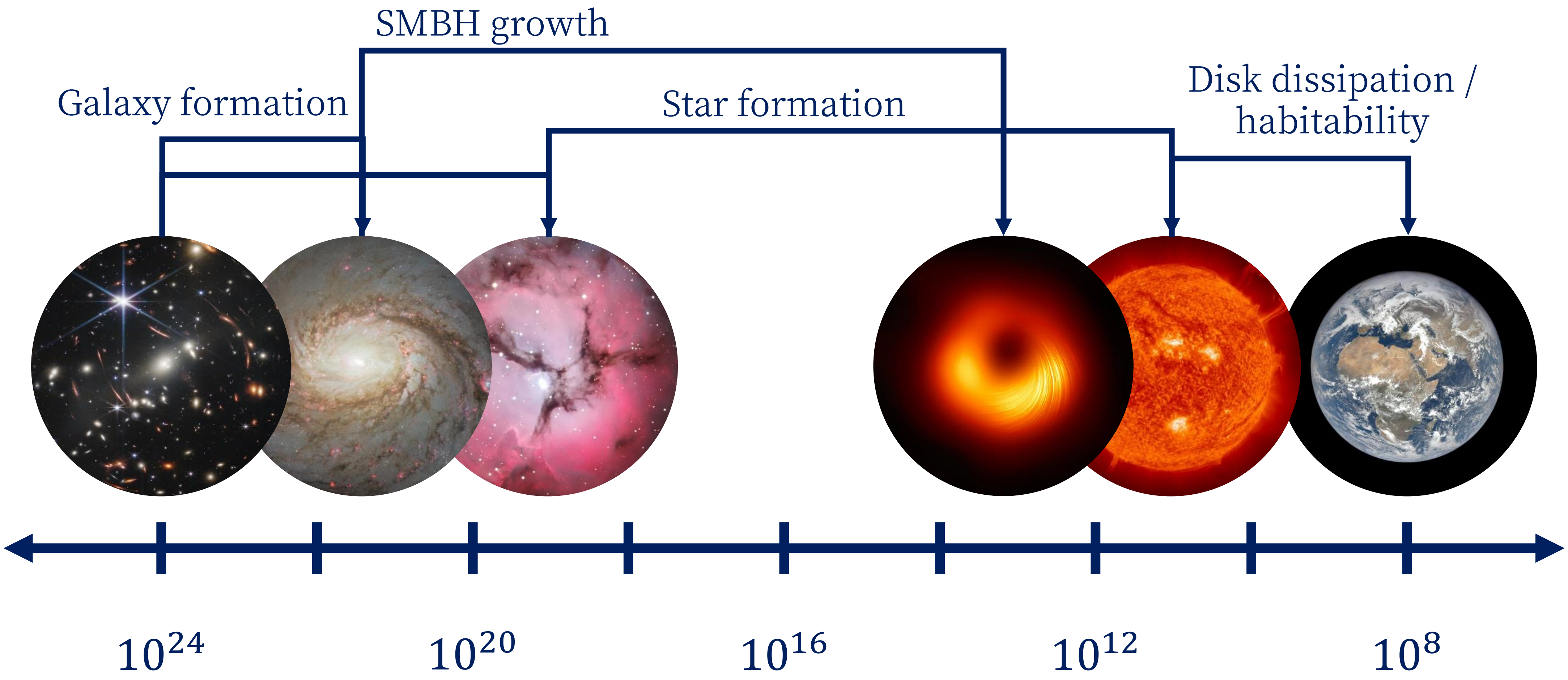
ESO/H. Avenhaus et al./DARTT-S collaboration



PPD IM Lupi in Submm by ALMA

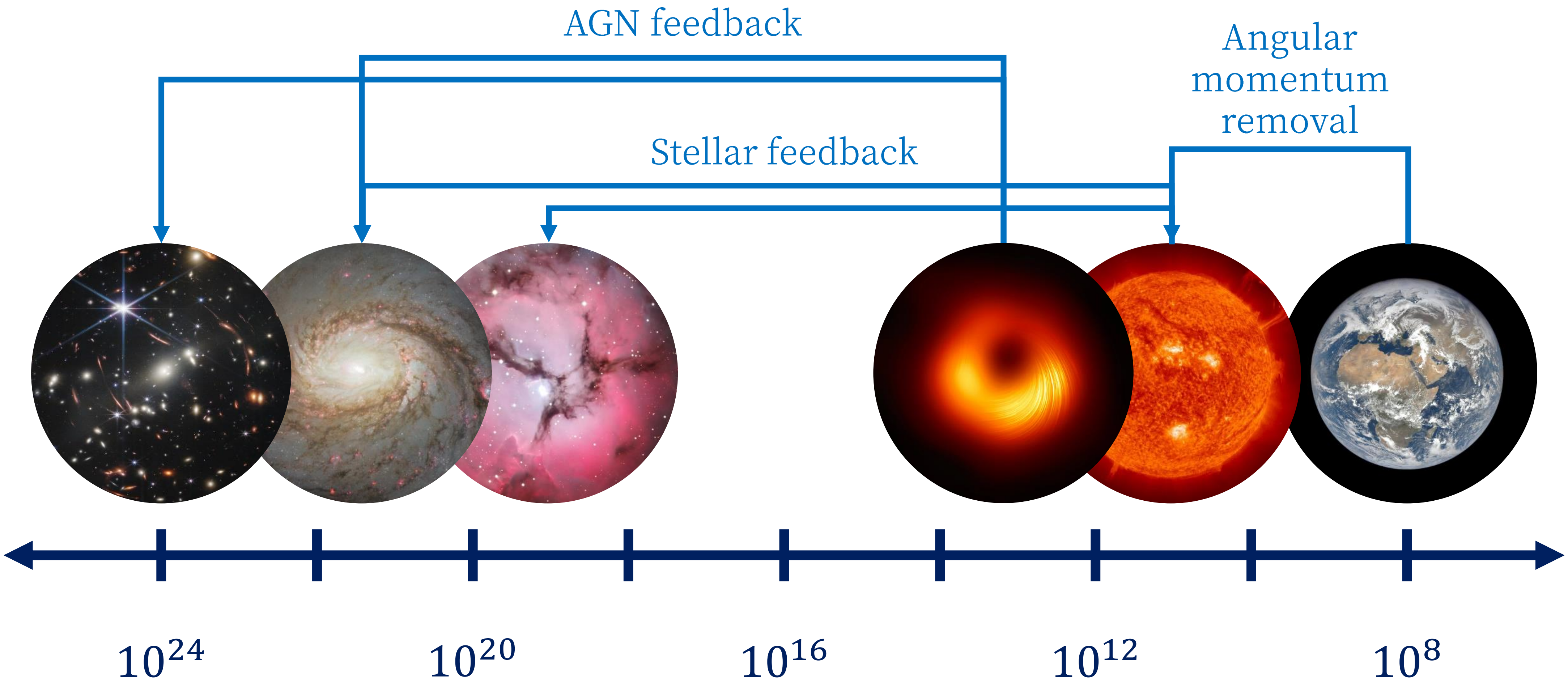
Verrios et al. 2022 | NASA/SwRI/MSSS/Gerald Eichstädt/Seán Doran

Story of gas spans more than 16 orders in spatial scale!



NASA, ESA, CSA, STScI | NASA, ESA & A. van der Hoeven | SOHO | DSCOVR EPIC

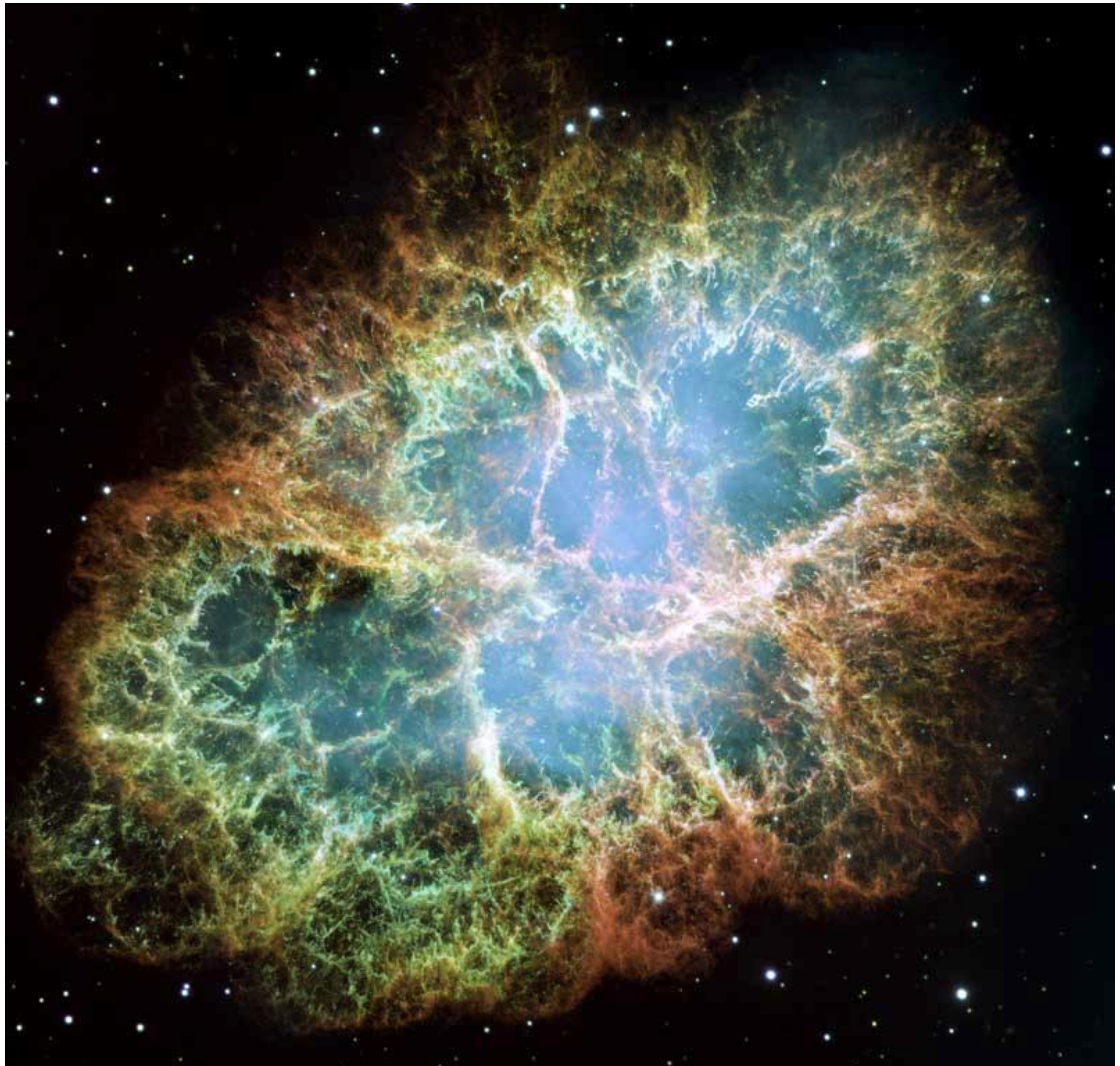
Feedback from small to large scale!



NASA, ESA, CSA, STScI | NASA, ESA & A. van der Hoeven | SOHO | DSCOVR EPIC

Stellar feedback

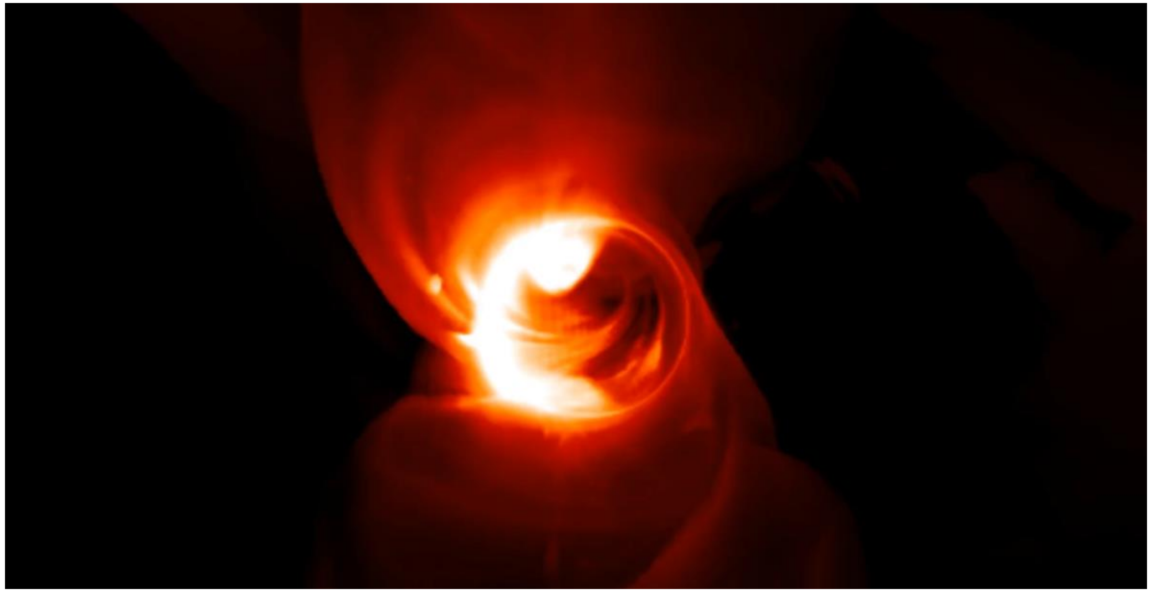
- Young stars forms wind and jets (HH objects).
- Massive stars produce:
  - Ionizing radiation.
  - Stellar wind.
  - Supernova explosion.
- Energy returned from stars can affect evolution of galaxies.



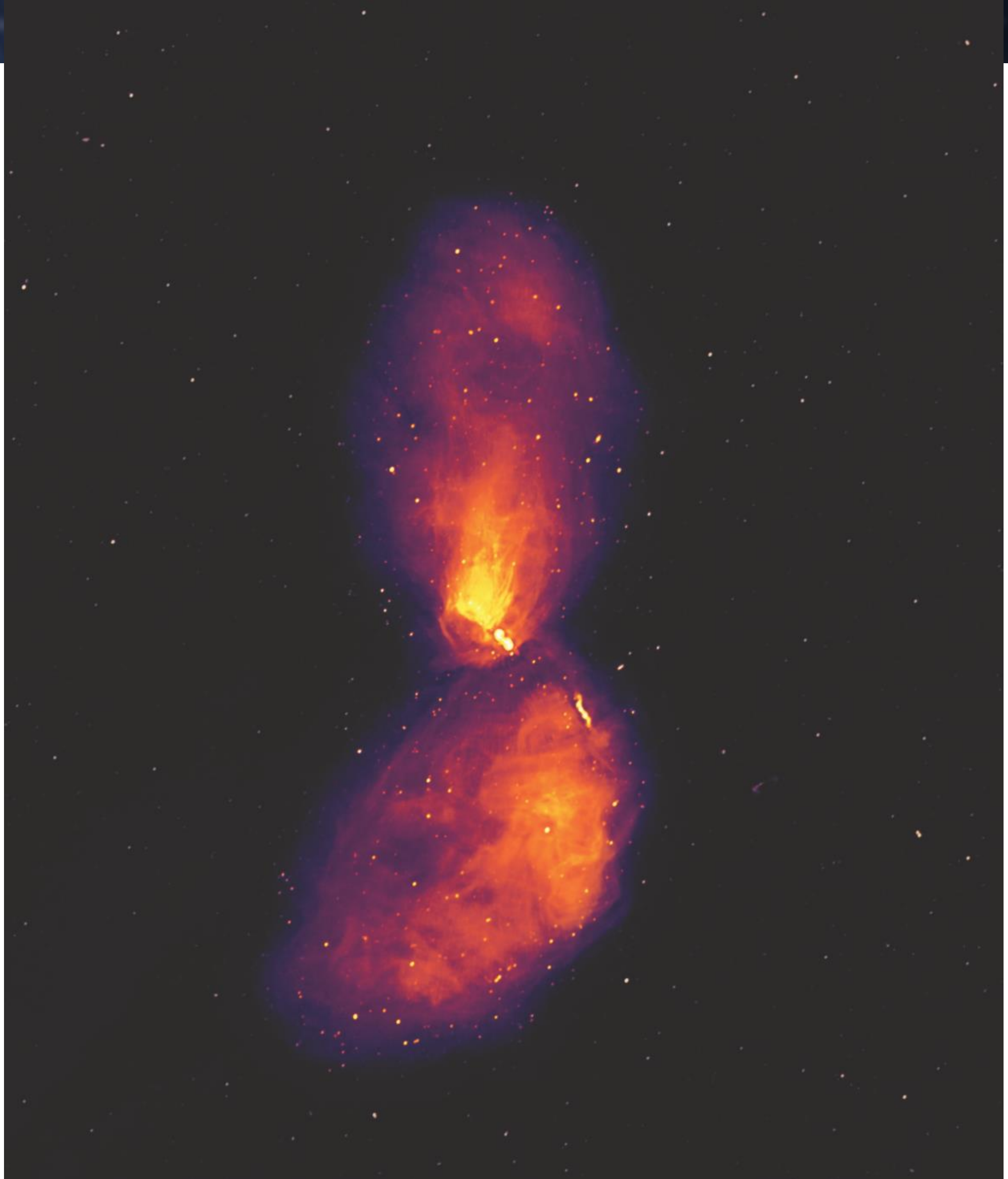
Crab Nebula. NASA, ESA, J. Hester and A. Loll (Arizona State University)

AGN feedback

- Gas accretion on SMBHs.
- Jet launching: AU scale.
  Jet affects: Mpc scale.



Credit: Lia Medeiros, Chi-Kwan Chan, Feryal Özel, Dimitrios Psaltis



Credit: Ben McKinley, ICRAR/Curtin and Connor Matherne, Louisiana State University.

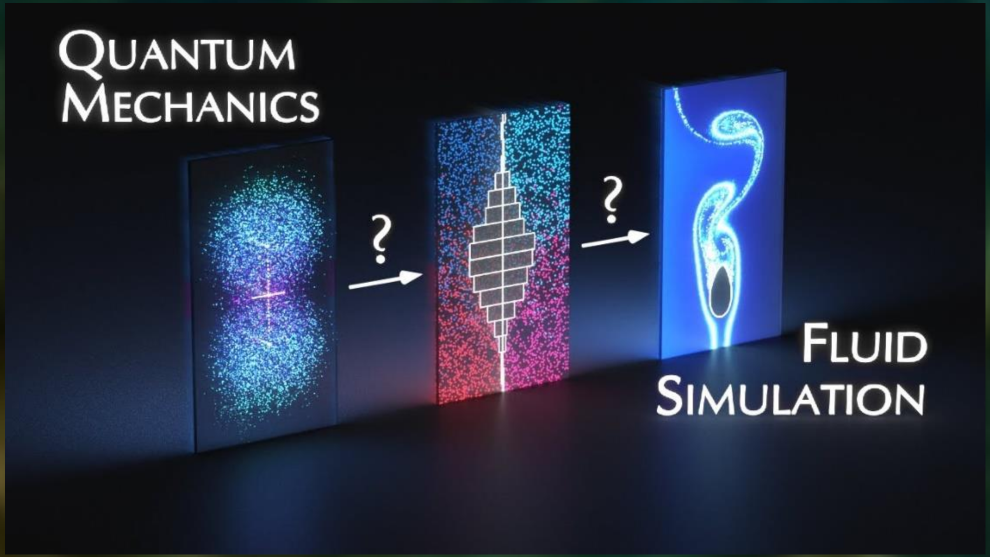
Gas in the universe

- Gas is involved in almost all astrophysical system we are interested in.
- Multi-scale and multi-physics nature of gas:
  - Spatial scale: Mpc (structure formation) to km (X-ray binary accretion disk).
  - Timescale: Gyr (structure formation) to ms (supernova explosion).
  - Physics involved: gravity (Newtonian/GR), hydrodynamics, magnetic field, radiative processes, nuclear physics, neutrino transport, etc.
- We need a **framework** that can (in principle) handle all the physical processes together with reasonable resources.

Hydrodynamic Simulations

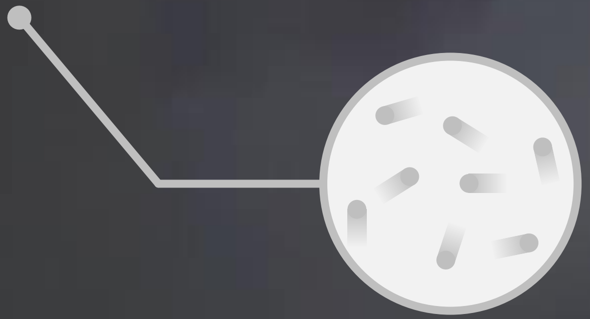
流體力學與天文物理

- 任何理論模型都是對真實世界的有效近似
- 天文物理考慮的尺度：
  - 恆星：10^{30} 公斤 → 10^{57} 顆原子
    光是儲存就需要 10^{45} TB 的儲存空間
  - 可觀測宇宙：> 10^{48} 太陽質量
  - 光子、重力場、波函數、量子場……
- 勢必需要以宏觀統計性質簡化系統
- 流體近似是最常見、最強大的作法之一



Quantum mechanics to fluid simulation
- the story of everything | braintruffle

觀察系統 → 建立模型 → 寫下方程式 → 解方程式 → 詮釋結果



$\rho, \vec{v}, T, P,$ etc

Treat the system of interest as multiple continuous fields.

What equations should fluid follows?

Let us start from density: what is the relation between density and velocity?

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0 \quad \text{Mass Conservation}$$

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot (\rho \boldsymbol{v} \otimes \boldsymbol{v}) + \nabla p_{\text{tot}} = 0 \quad \text{Momentum Conservation}$$

$$\frac{\partial e}{\partial t} + \nabla \cdot [(e + p_{\text{tot}})\boldsymbol{v}] = 0 \quad \text{Energy Conservation}$$

These are called **Euler Equations** for fluid dynamics.

One can put **source terms** on the right hand side to add in physics.

Example: Gravity and blast

Place a bomb in the atmosphere that would explode and release energy at t = 0.

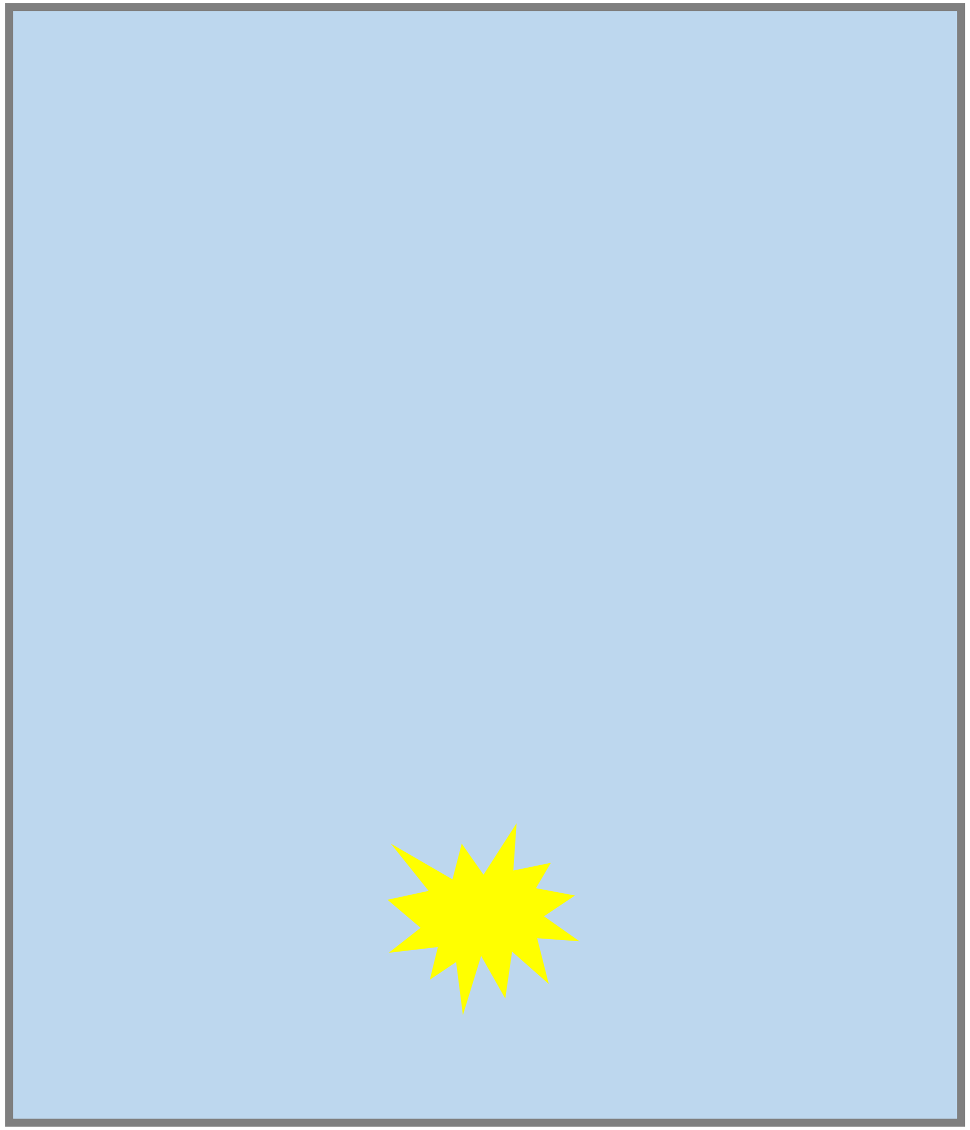
$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0$$

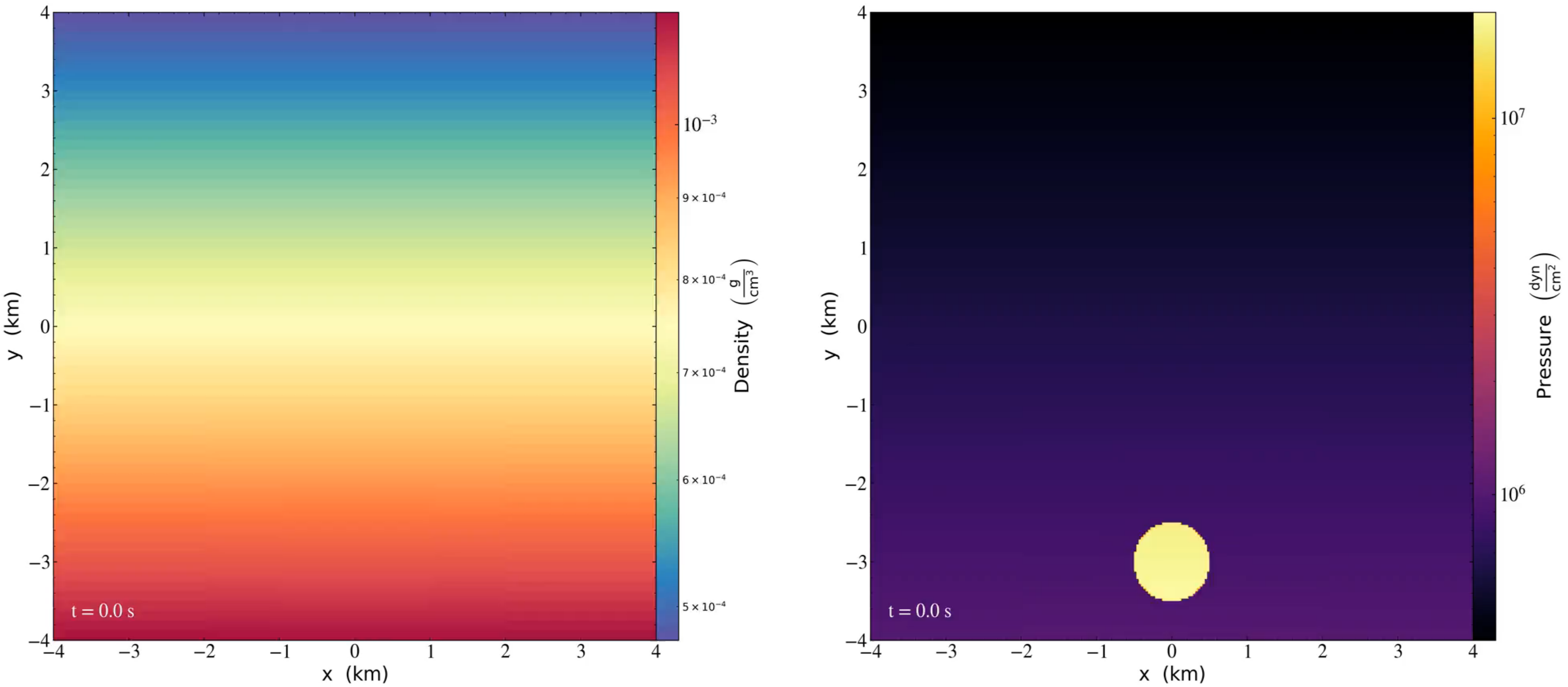
$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot (\rho \boldsymbol{v} \otimes \boldsymbol{v}) + \nabla p_{\mathrm{tot}} = \underline{\rho \boldsymbol{g}}$$

$$\frac{\partial e}{\partial t} + \nabla \cdot [(e + p_{\mathrm{tot}})\boldsymbol{v}] = \underline{\rho \boldsymbol{v} \cdot \boldsymbol{g}} + \underline{e_{\mathrm{blast}}(x, y, t_0)}$$

Source term: gravity

Source term: bomb energy




t = 0.0 s
y (km)
x (km)
Density $\left(\frac{g}{cm^3}\right)$
10^{-3}
9×10^{-4}
8×10^{-4}
7×10^{-4}
6×10^{-4}
5×10^{-4}
t = 0.0 s
y (km)
x (km)
Pressure $\left(\frac{dyn}{cm^2}\right)$
10^7
10^6

Equation of states (EoS)

If you count the number of variables and equations:

- Variable: $\rho, \vec{v}, e, P$. 6 fields
- Equation: 5 independent ones.

One need another equation to solve the system. This is the EoS.

ρ, P, T → ?

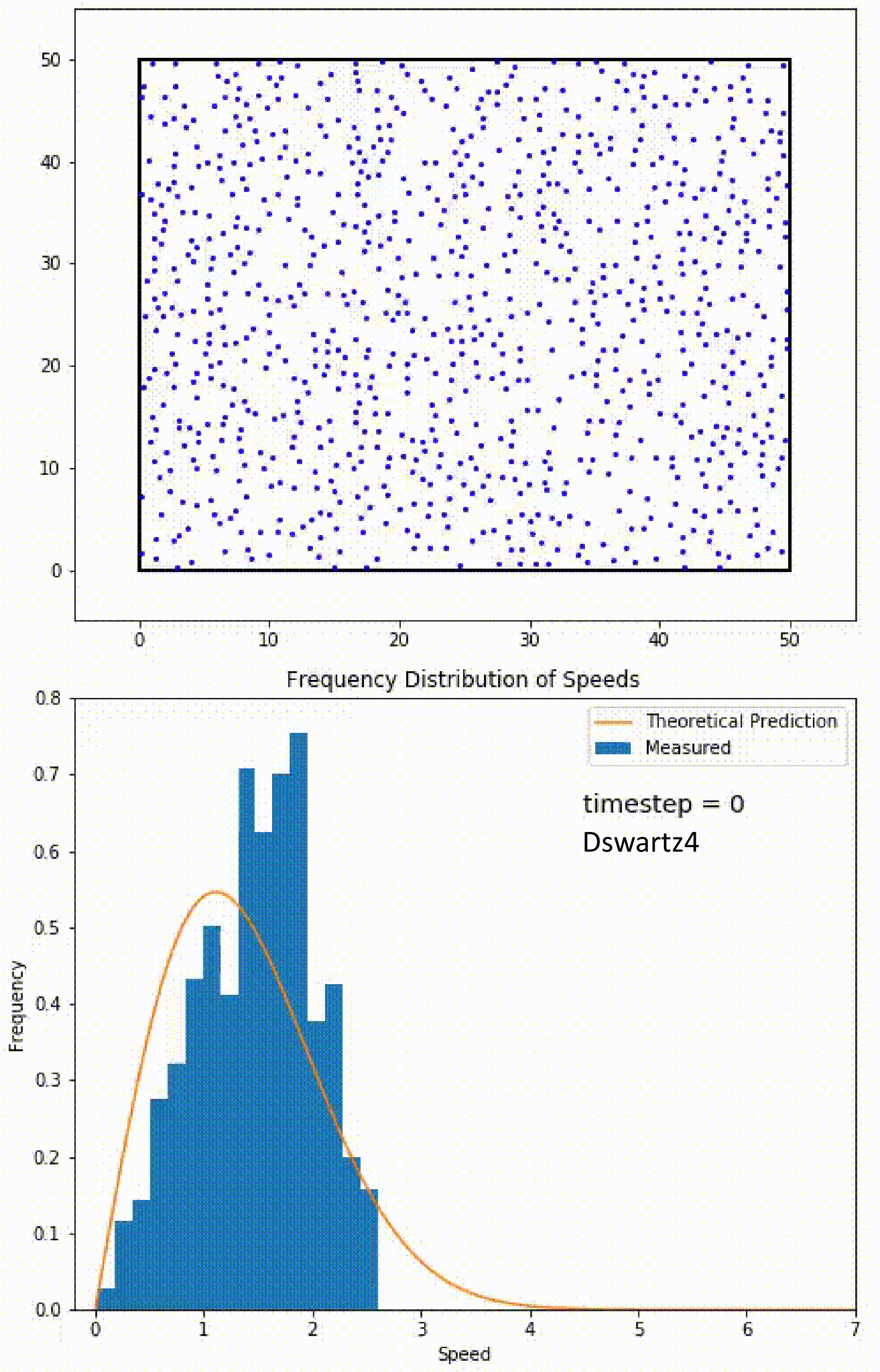
$4\rho, ?, T$

EoS links the thermal dynamics properties of the fluid.

Effectively captures the properties of the materials.

When can we use fluid approx. ?

- Fluid dynamics simplifies particle motion into macroscopic properties (e.g. temperature).
  Is that valid for all systems?
- No. That only works if there are sufficient collision between particles.
- Fluid approximation only works if:
  - Mean free path << System scale
  - Collision timescale << Timescale of interest



磁流體力學 MHD

➢ 宇宙中磁場幾乎無處不在，且在許多系統中皆扮演著重要的角色。

➢ 在流體力學的基礎上，可以進一步加入磁場的影響：

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

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot \left(\rho \boldsymbol{v}\boldsymbol{v} - \frac{\boldsymbol{B}\boldsymbol{B}}{4\pi} \right) + \nabla p_{\mathrm{tot}} = \rho \boldsymbol{g}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} - \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) = 0$$

$$\frac{\partial e}{\partial t} + \nabla \cdot \left[(e + p_{\mathrm{tot}})\boldsymbol{v} - \frac{\boldsymbol{B}(\boldsymbol{B} \cdot \boldsymbol{v})}{4\pi} \right] = \rho \boldsymbol{v} \cdot \boldsymbol{g}$$

根據模擬的系統，這套方程組可以再加入

➢ 宇宙射線 Cosmic-Ray

➢ 輻射 Radiation

➢ 黏滯性 Viscosity

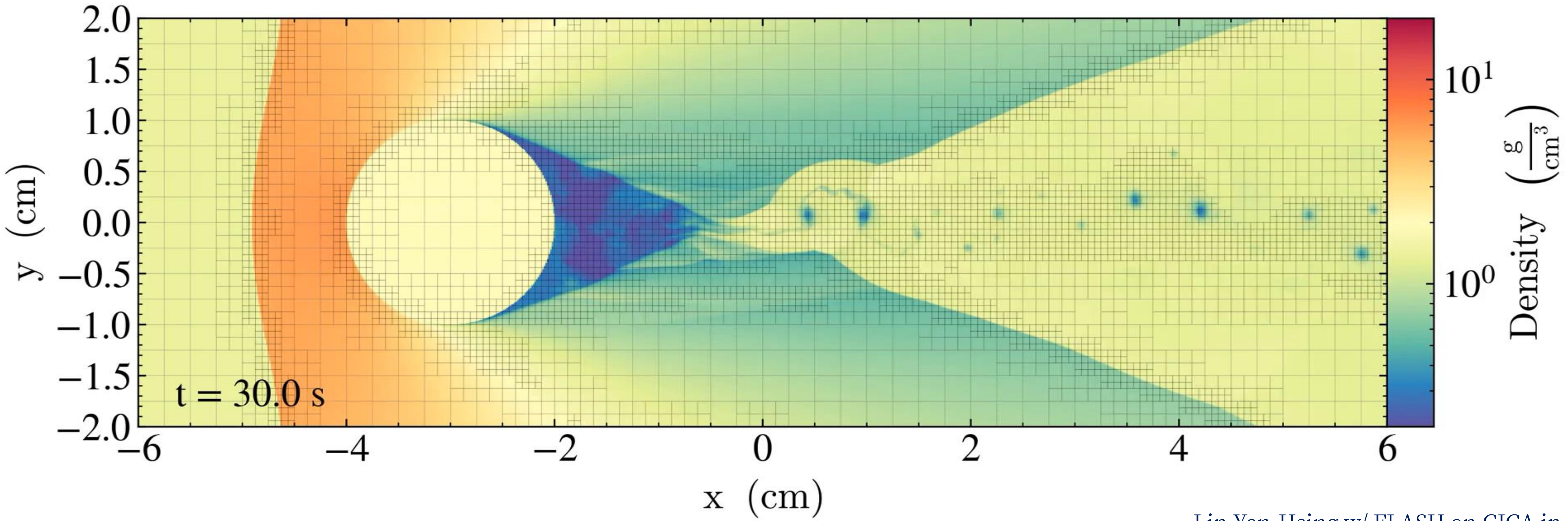
➢ 電阻 Resistance

➢ 相對論效應 Relativity

➢ 恆星與 AGN 回饋……等

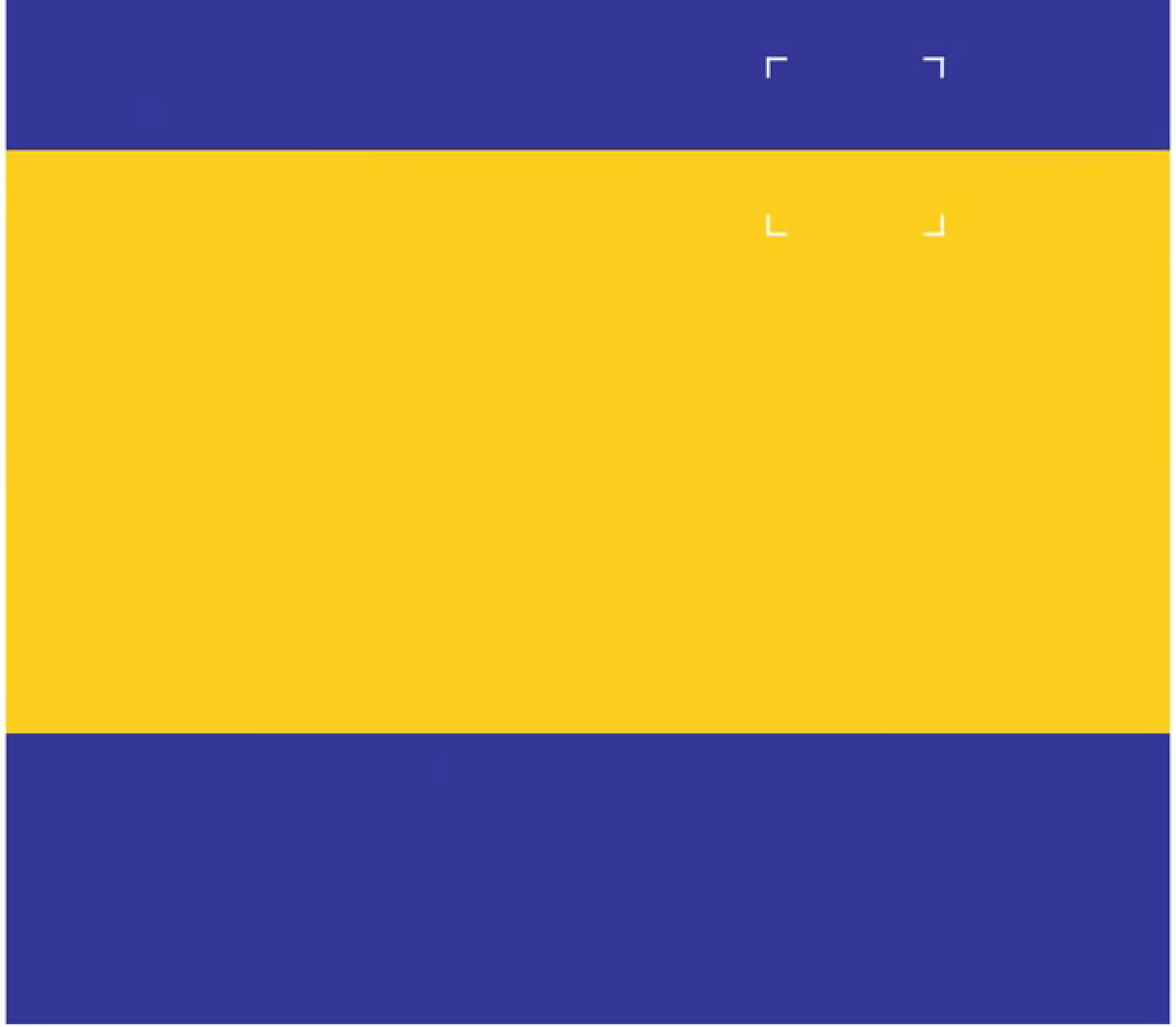
解算方程組：Grid Based Method

- 有了方程式，接下來就是用電腦幫我們解開它們。
- 一種常用方法是「**有限體積法 Finite Volume Method, FVM**」加上「**自適應網格 Adaptive Mesh Refinement, AMR**」。



Lin Yen-Hsing w/ FLASH on CICA in NTHU

Kelvin–Helmholtz instability



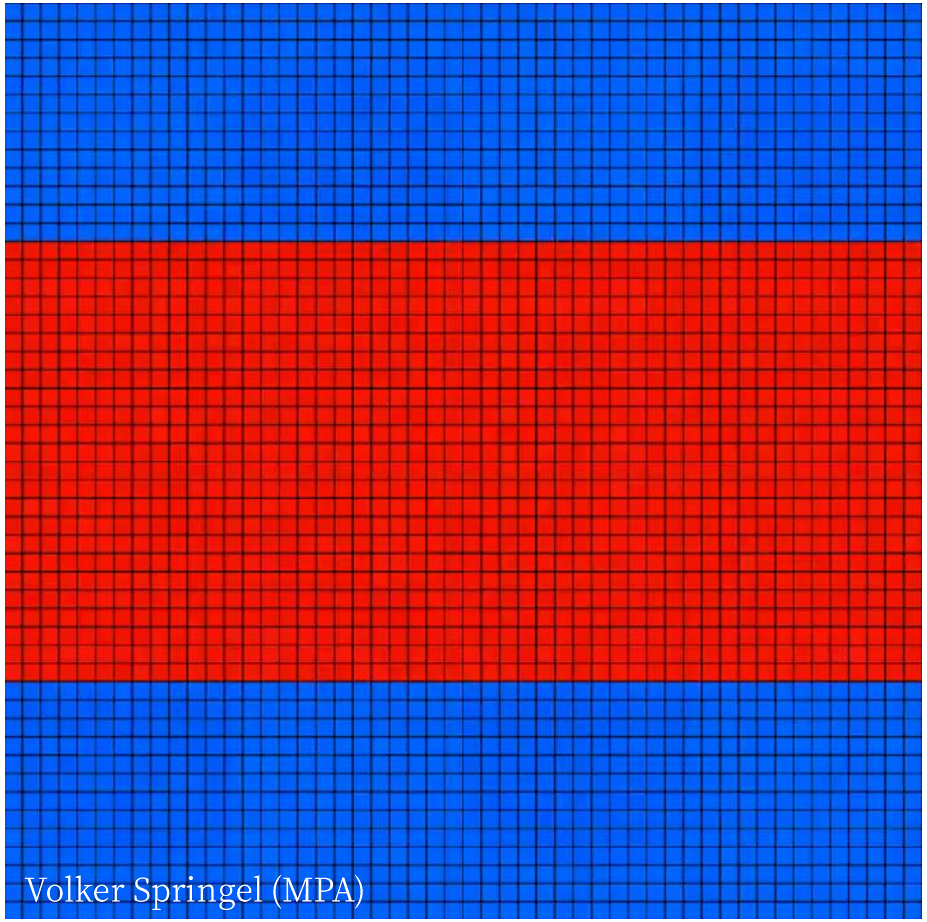
Kevin Schaal

Credit: NASA/Ames Research Center/Timothy Sandstrom, Francois Cadieux, Michael Barad, Cetin Kiris

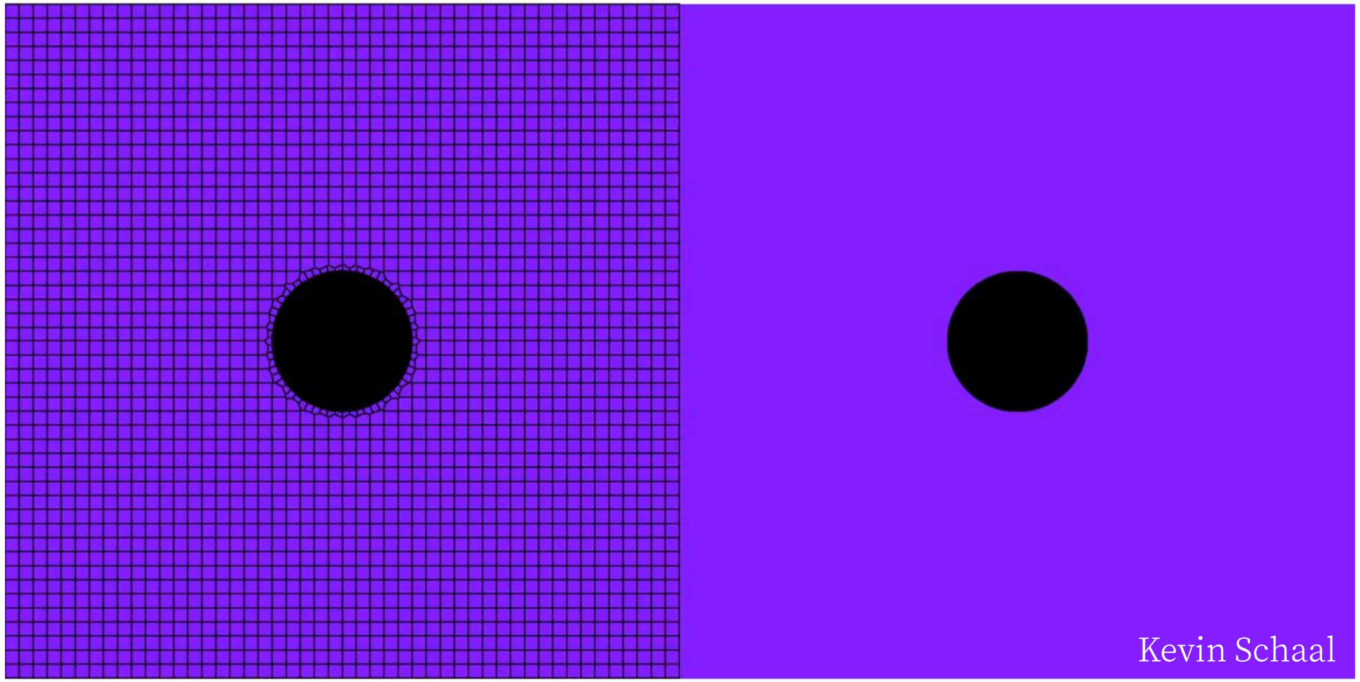
解算方程組：SPH Method

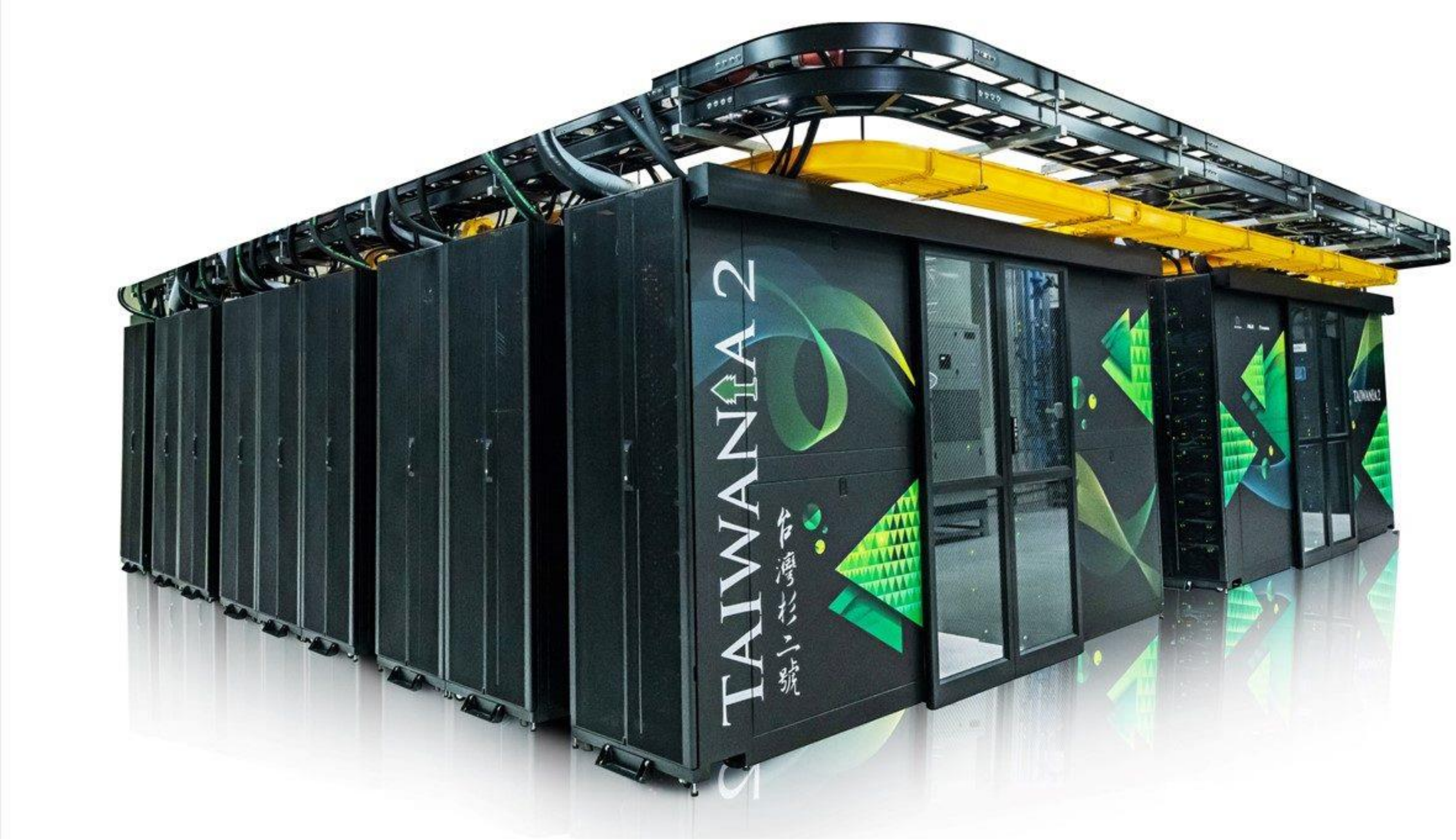
另一種常見的方法是**光滑粒子流體動力學法 Smoothed Particle Hydrodynamics**

解算方程組：Hybrid / Moving Mesh Method

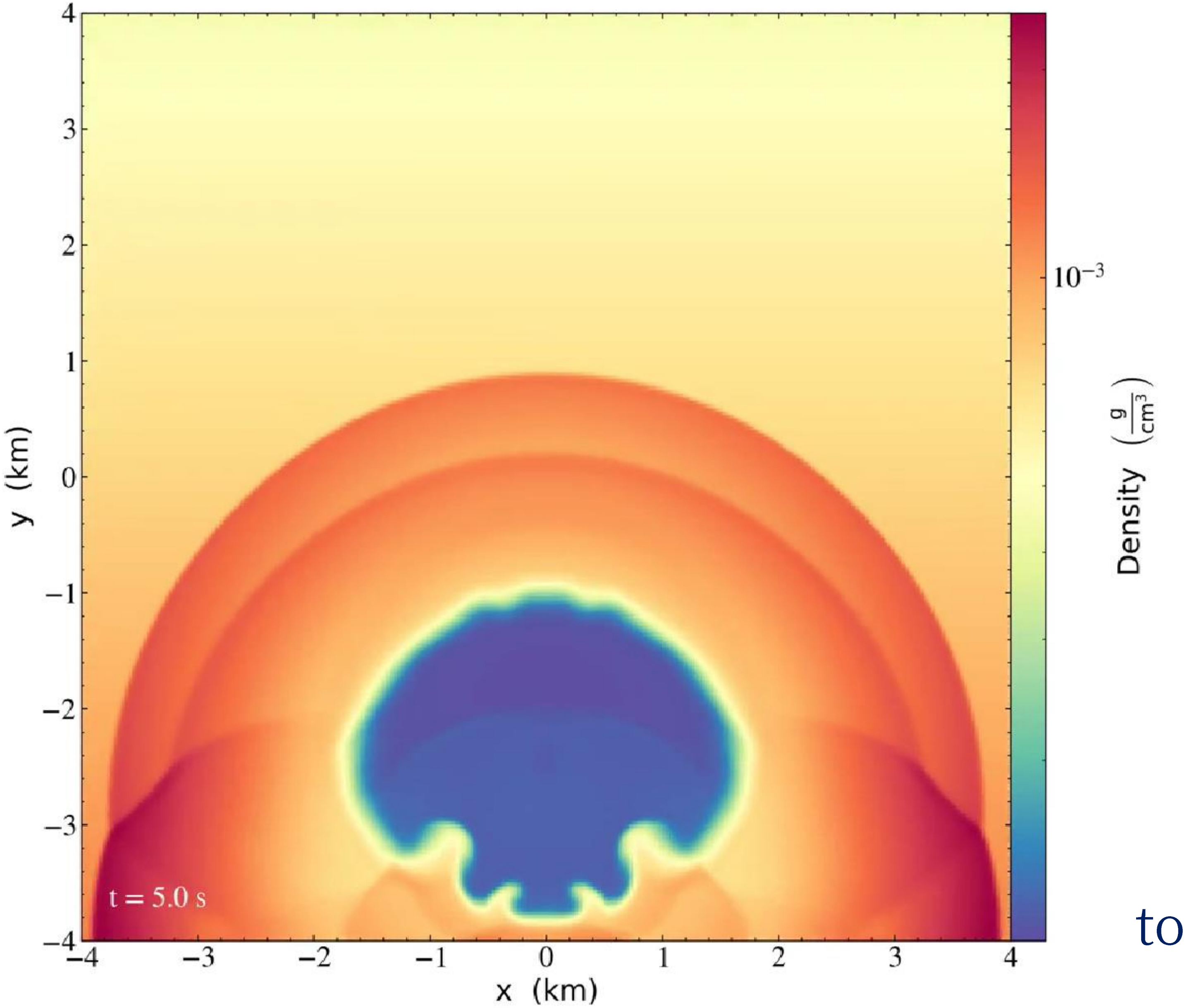


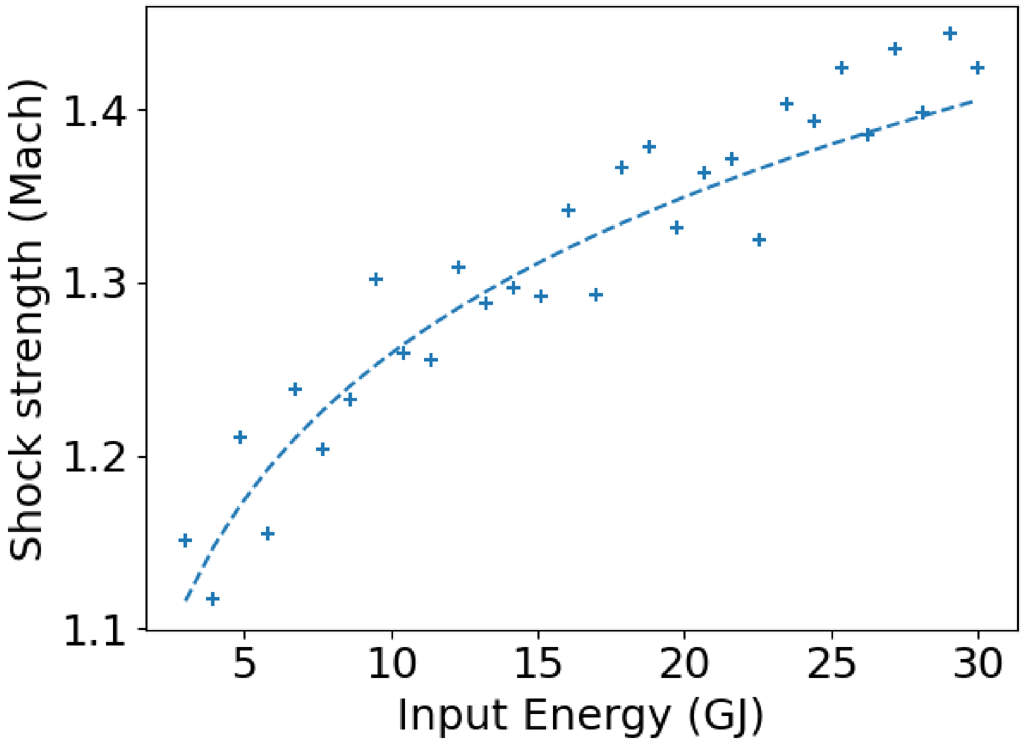
- 結合 FVM 和 SPH 各自的優勢





Computer go BRRRRRRRR

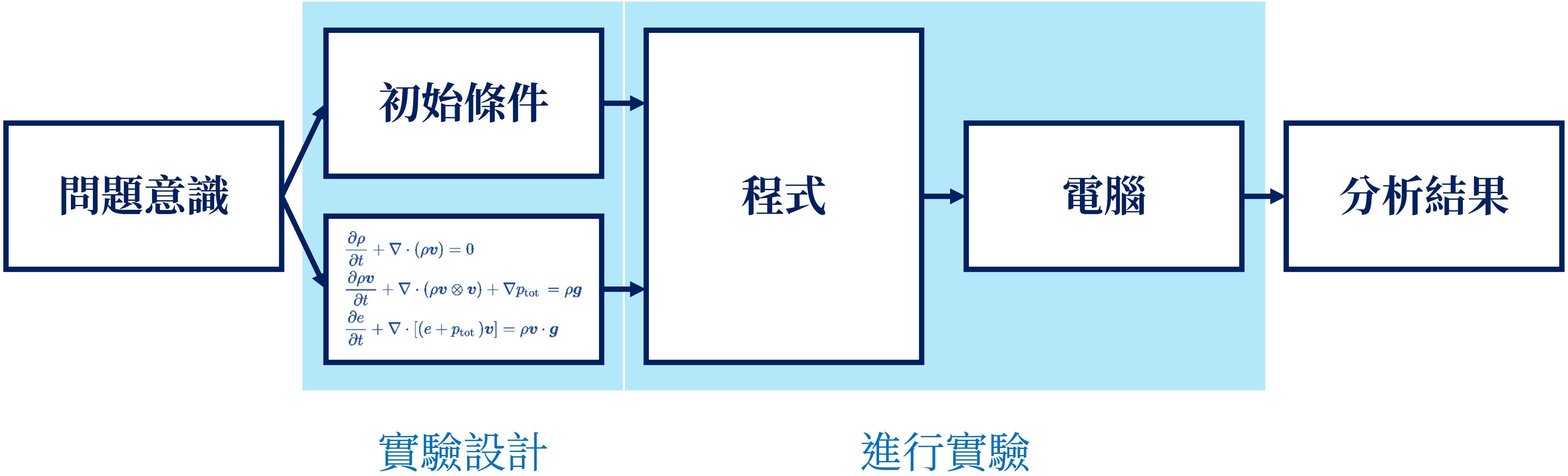




Understand how large
your bomb needs to be
to destroy everything within 3km.

流體力學與天文物理

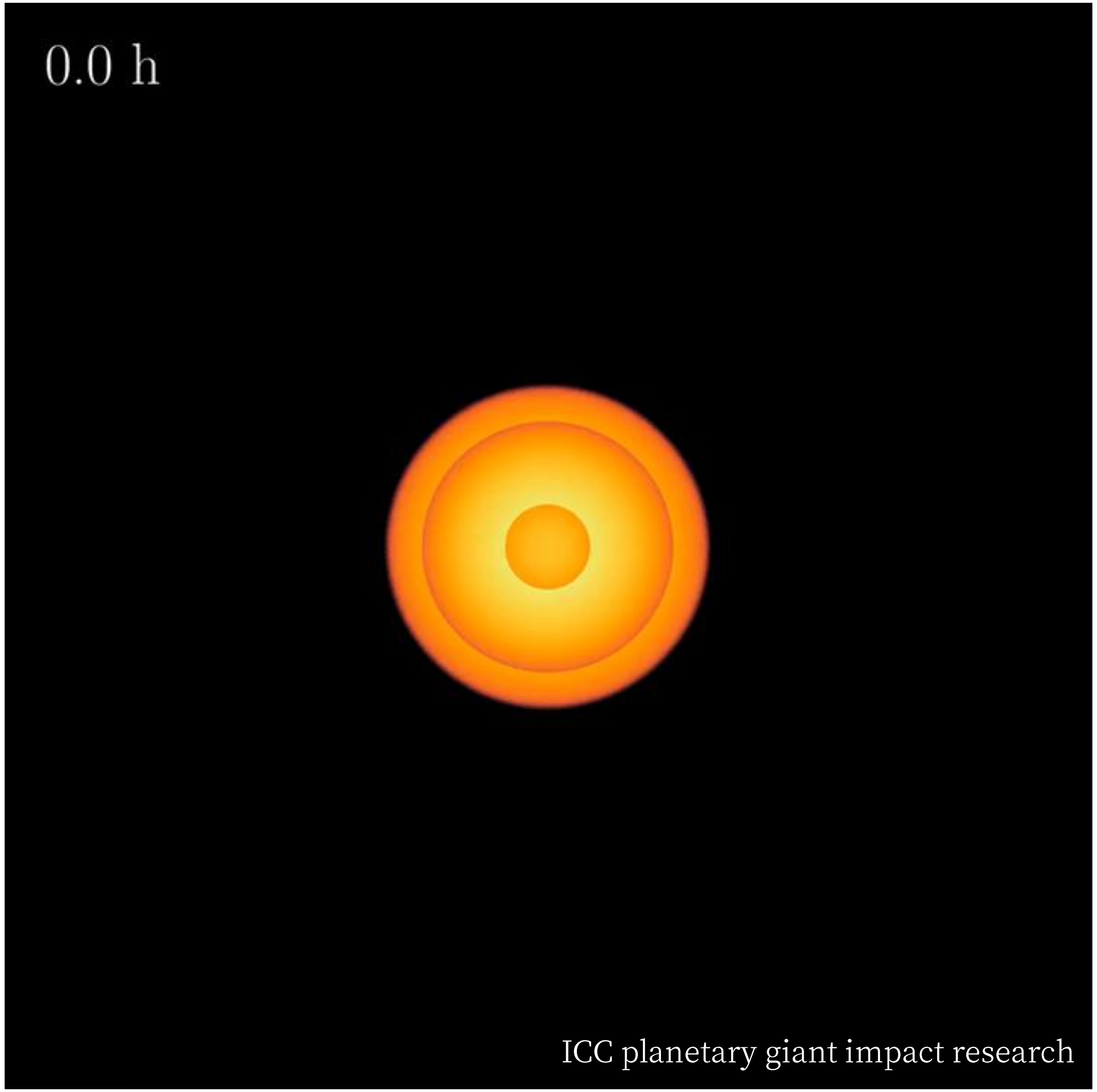
- ➢ 計算天文物理模擬的基本流程

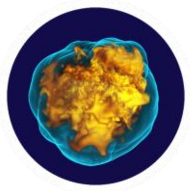


- ➢ 計算天文物理是理論工作，但是研究流程其實類似實驗

Gallery

- Planetary collision.
- Code: Swift (SPH).
- IC: Giant impact that changed the rotation axis of Uranus.
- Physics:
  - EoS for rock (e.g. SiO_2, MgO, FeS)
  - EoS for ice (e.g. H_2O, NH_3, CH_4).



Gallery 

- Supernova explosion.
- Code: FLASH (FVM).
- IC: Center of massive stars.
- Physics:
  - GR & Self-gravity
  - Neutrino transport
  - Nuclear EoS

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

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}\boldsymbol{v}) + \nabla P = -\rho \nabla \Phi$$

$$\frac{\partial \rho E}{\partial t} + \nabla \cdot [(\rho E + P)\boldsymbol{v}] = -\rho \boldsymbol{v} \cdot \nabla \Phi$$

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

$$\frac{\partial \rho Y_l^t}{\partial t} + \nabla \cdot (\rho \boldsymbol{v} Y_l^t) = 0$$

$$\frac{\partial \left(\rho Z_l^t\right)^{3/4}}{\partial t} + \nabla \cdot \left(\boldsymbol{v} \left(\rho \mathbf{Z}_l^t\right)^{3/4}\right) = 0$$

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Ministry of Science and Technology

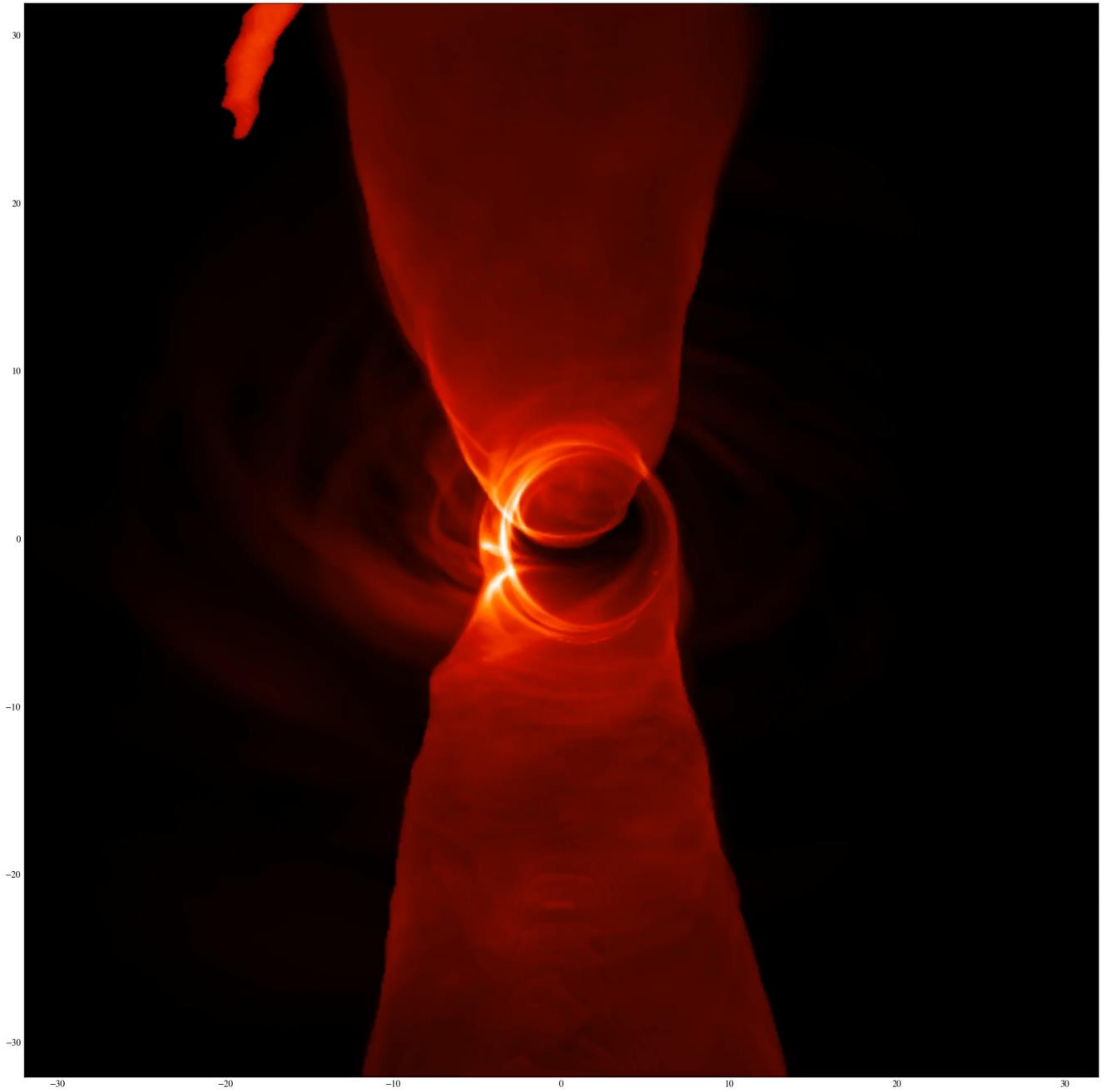
NCHC
NARLabs 財團法人國家實驗研究院
國家高速網路與計算中心
National Center for High-performance Computing

Core-Collapse Supernova Simulation

Visualization: Kuo-Chuan Pan (潘國全)
Department of Physics
Institue of Astronomy
National Tsing Hua University, Taiwan

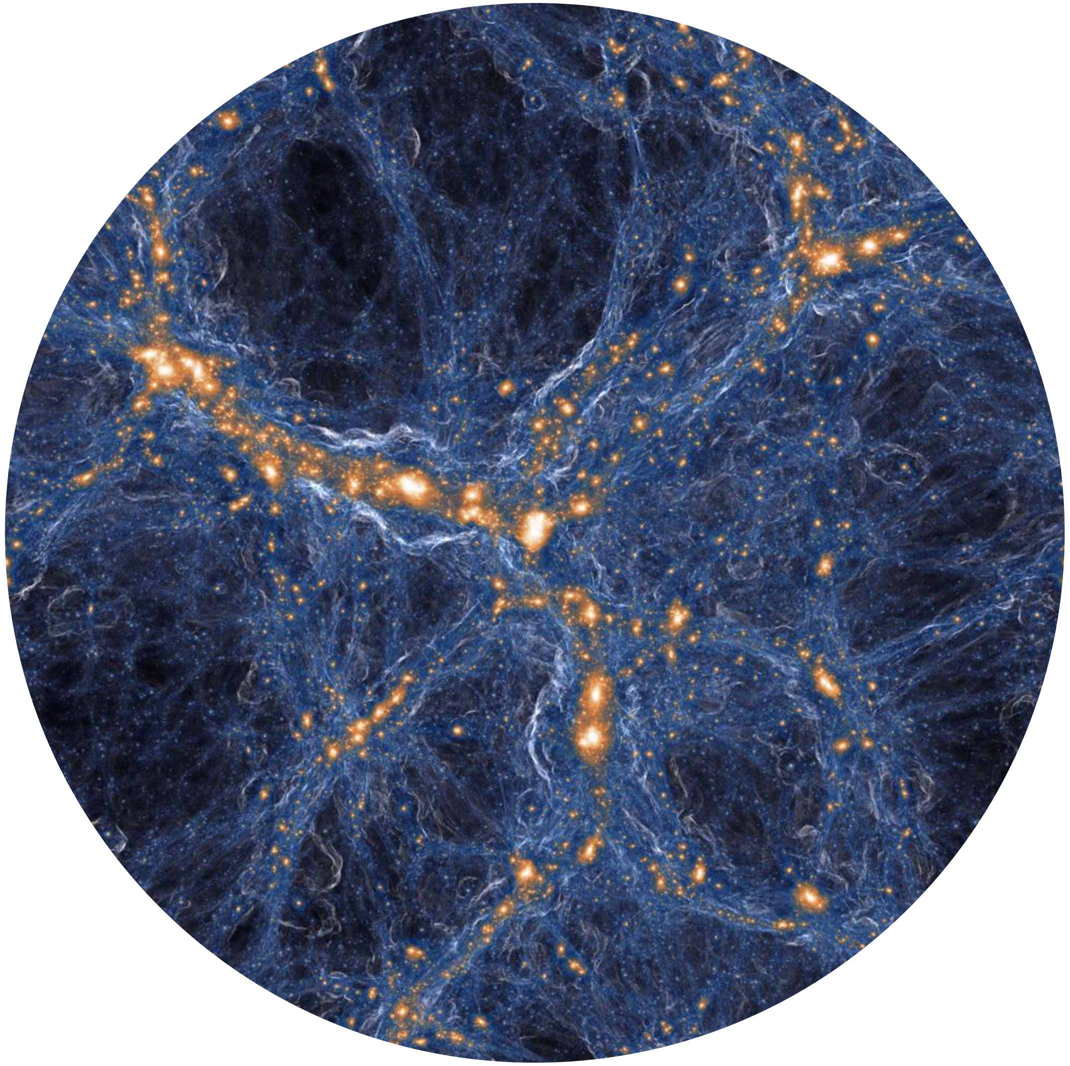
Gallery

- SMBH accretion
- Code: HARM (FVM).
- IC: SMBH and accretion disk.
- Physics:
  - General relativity
  - MHD Plasma physics
  - GR radiative transfer



Gallery

- Cosmological Simulation (TNG).
- Code: Arepo (Hybrid).
- IC: Primordial density perturbation
- Physics:
  - Self-gravity (N body)
  - MHD in expanding universe
  - Star formation
  - Stellar / AGN feedback



Summary

- Gas is important in most of the astrophysics.
- Fluid dynamics provides a good framework to describe the multi-physics, multi-scale behavior of gas.
  MHD, gravity (Newton/GR), radiative processes, astrophysical feedbacks, etc.
- Hydro equations can be solved by different numerical methods.
- Hydrodynamic simulations is now widely used to understand complicated astrophysical systems in details.

Trailer: Seminar on Thursday

歐柏昇－Post Main Sequence Stellar Evolution

- 學歷
  - 2012 – 2016 台大物理、歷史雙主修
  - 2016 – 2018 台大物理碩士
  - 2018 – 2023 台大物理／中研院天文所博士班
- 天文圈重要資歷
  - 2013 – 2014 台大天文社社長
  - 2014 – 2019 聯盟立案核心推動者
  - 2019 – 2023 全國大學天文社聯盟理事長
- 合作學者：朱有花、陳科榮