



IPS Winter Chat

星系團中的黑洞噴流

林彥興 | 2023.02.12

大綱

➤ 背景介紹

- 星系團 Galaxy Clusters：宇宙的最大的重力束縛天體
- 星系團內介質 ICM：目不可視的炙熱氣體
- 冷卻流問題 Cooling flow problem
- 黑洞與星系的共同演化：活躍星系核回饋 AGN Feedback
- 方法：磁流體力學模擬 MHD Simulations
- 研究：奇異電波圈 Odd Radio Circles, ORCs

背景

星系團與 AGN 回饋

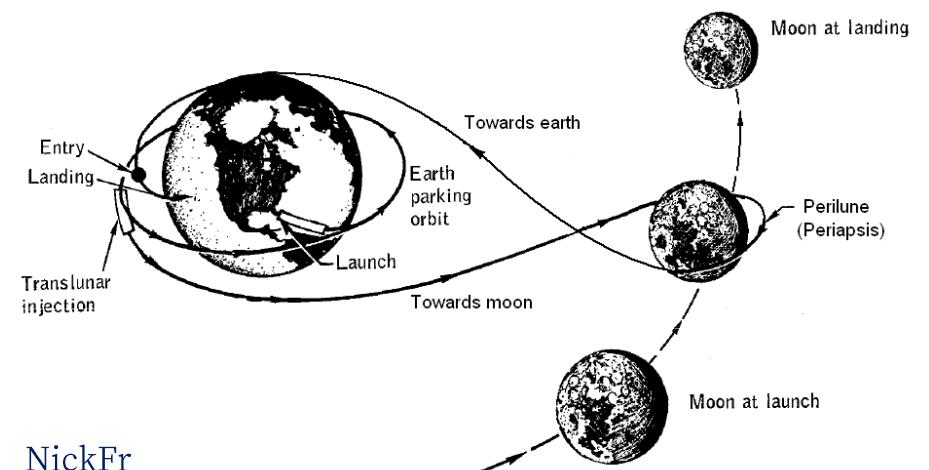
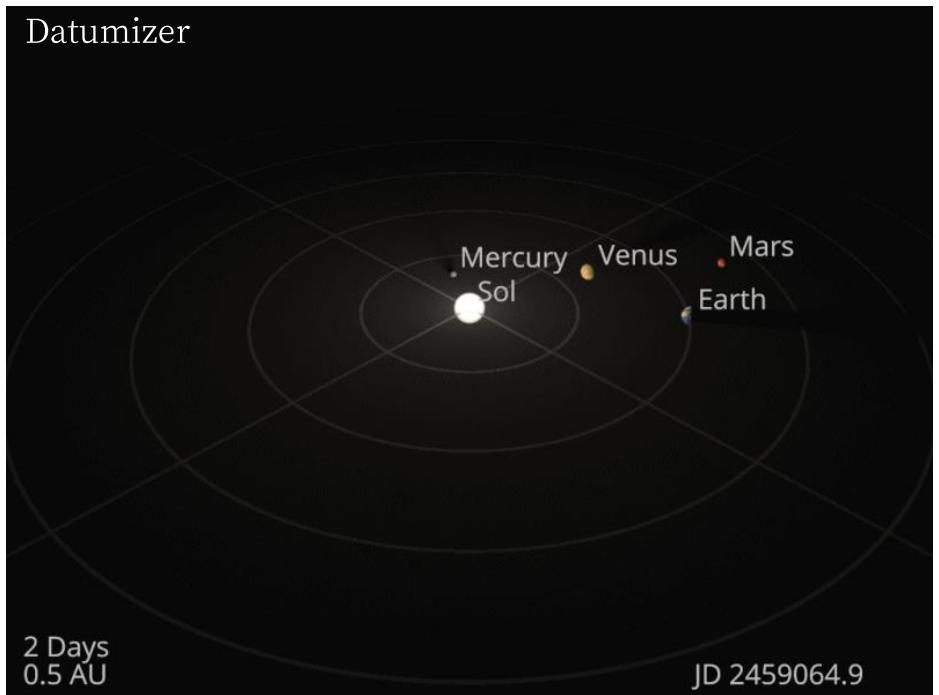
回顧：宇宙的階層

高中地科：

行星 → 恒星 → 星系 → 星系團 → 宇宙網



Datumizer



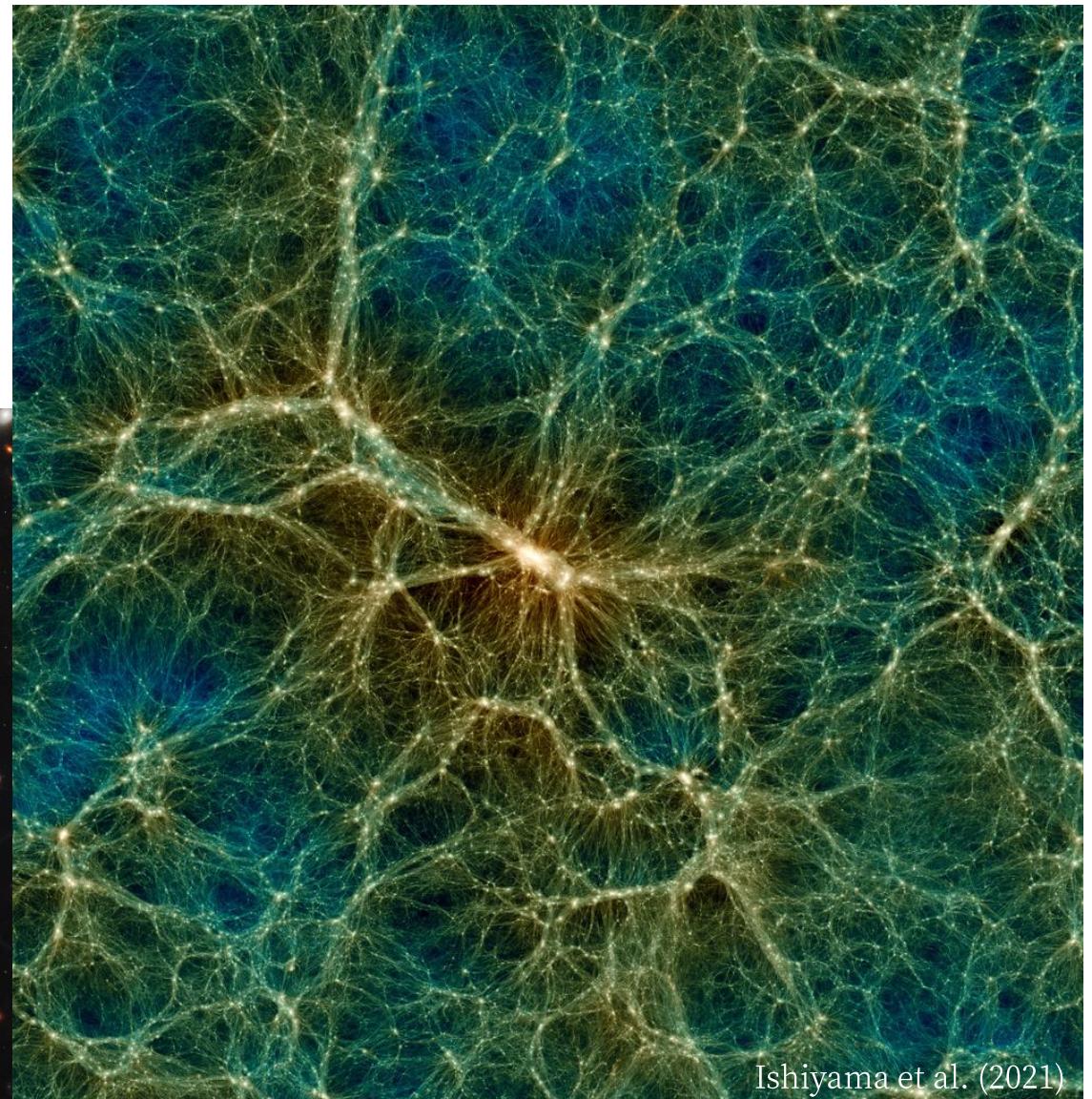
回顧：宇宙的階層

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NASA, ESA, CSA, STScI



Ishiyama et al. (2021)

可見光影像



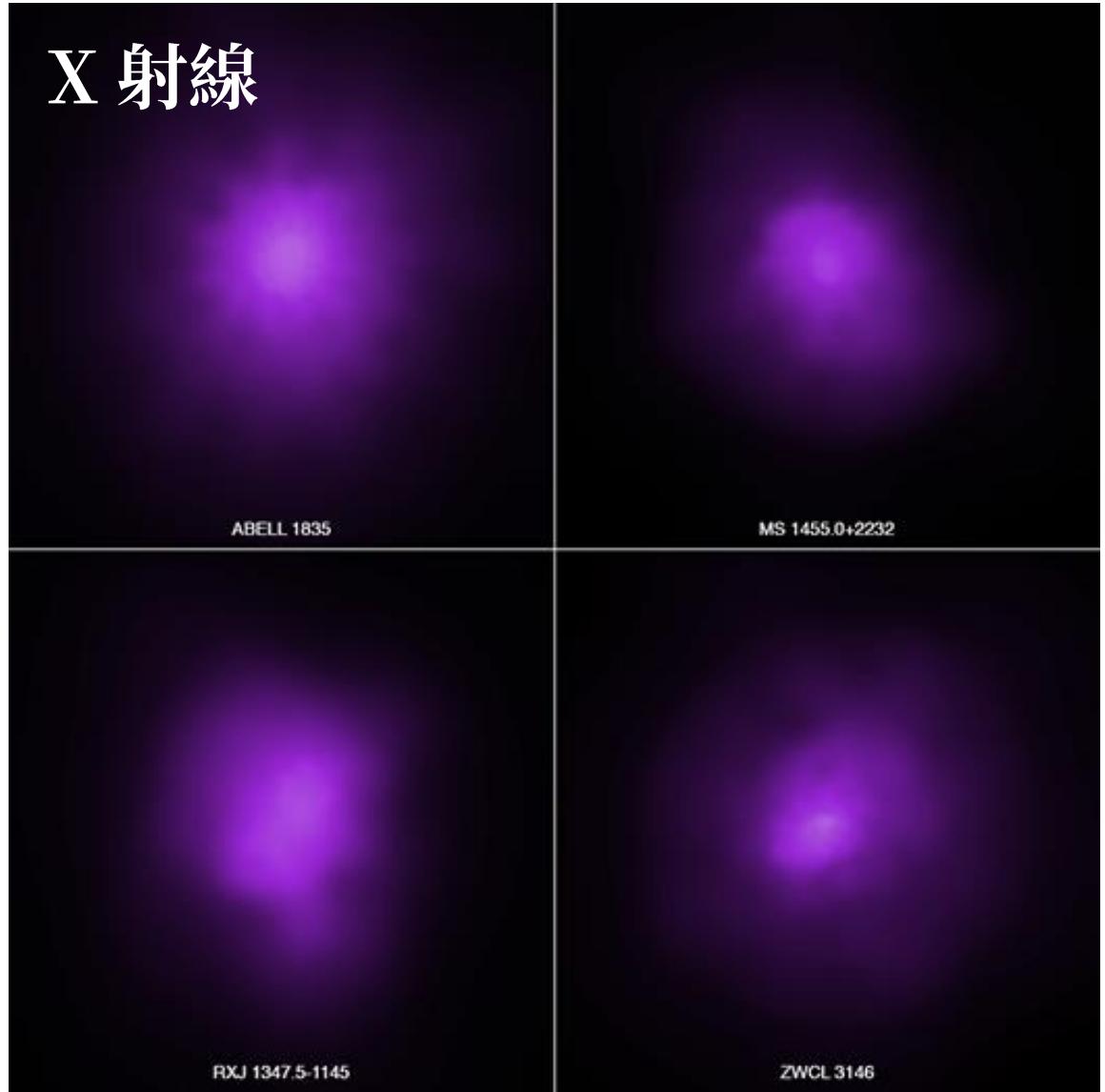
Fabian et al 2011
Abell 1147.5-1145

星系團 Galaxy Clusters

宇宙中最大的重力束縛系統

- 質量： $\sim 10^{14-15}$ 太陽質量
85% 暗物質、15% 一般物質
- 大小：數百萬光年
- 組成：約 1000 個星系
 - 星系一般較大、較紅
 - 中心：星系團最亮星系 BCG
 - 週圍：衛星星系 Satellites

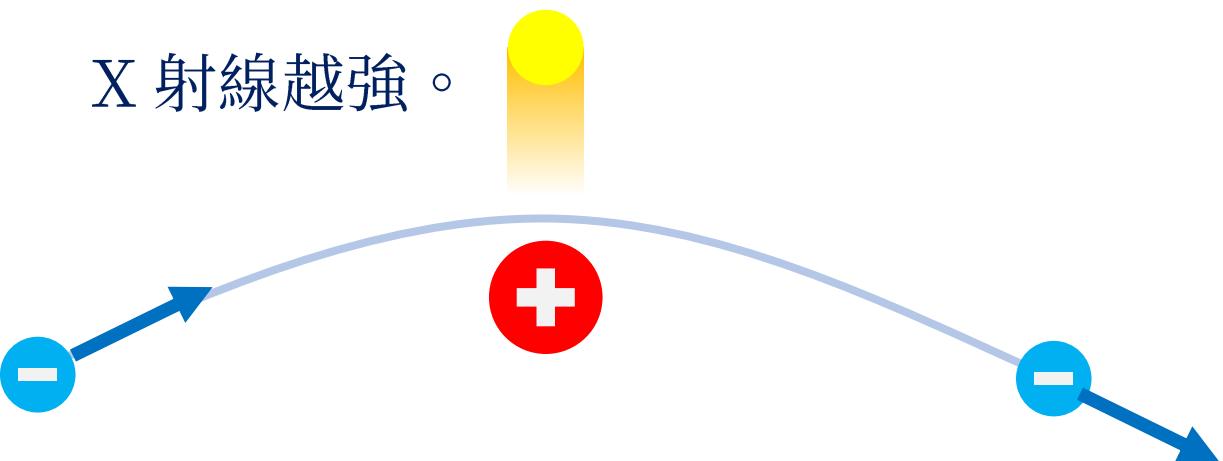
X 射線



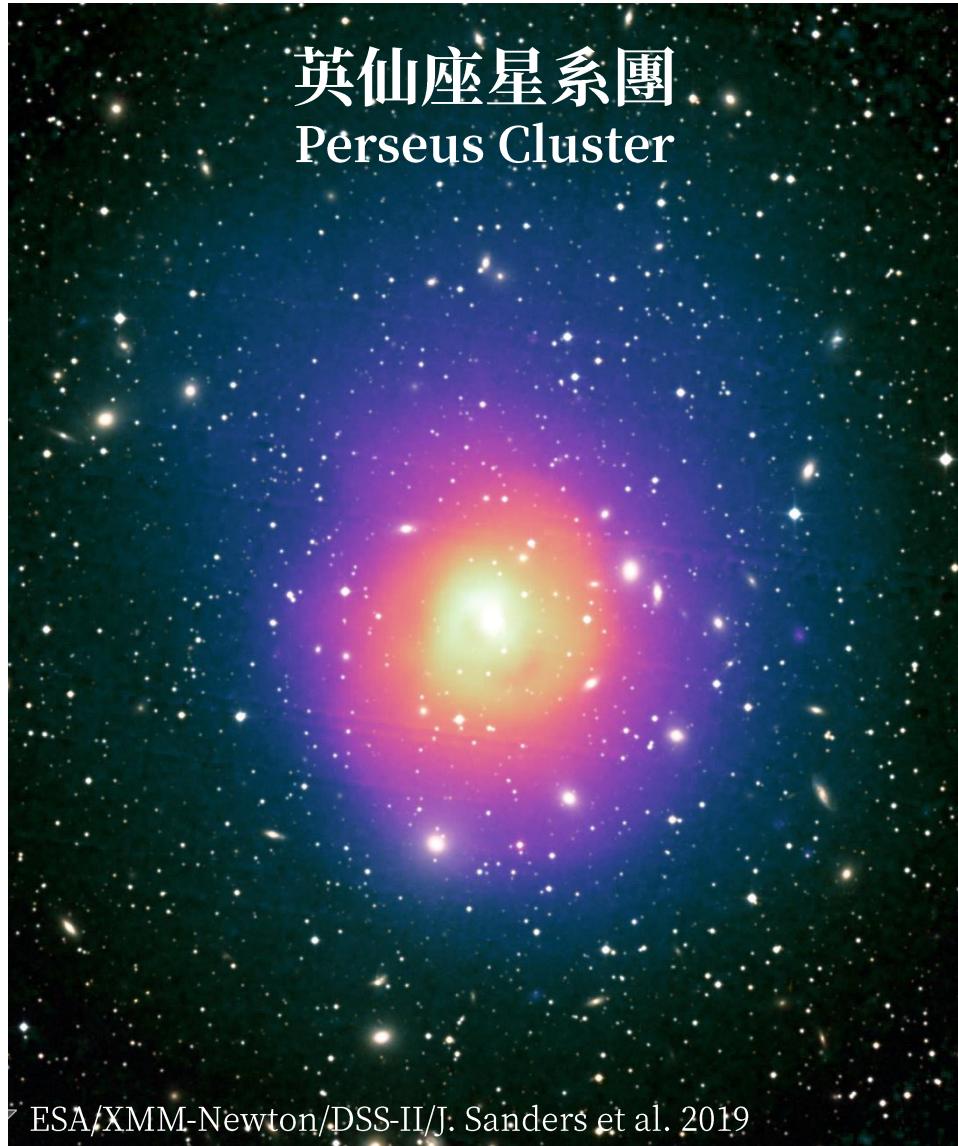
星系團內介質 ICM

充斥星系團內的高溫稀薄氣體

- 質量：星系團中一般物質的 90%
- 溫度： 10^7 - 10^8 K
- 輻射機制：煞車輻射 Bremsstrahlung
- 越靠近中心，ICM 密度越高、發出的 X 射線越強。



英仙座星系團
Perseus Cluster



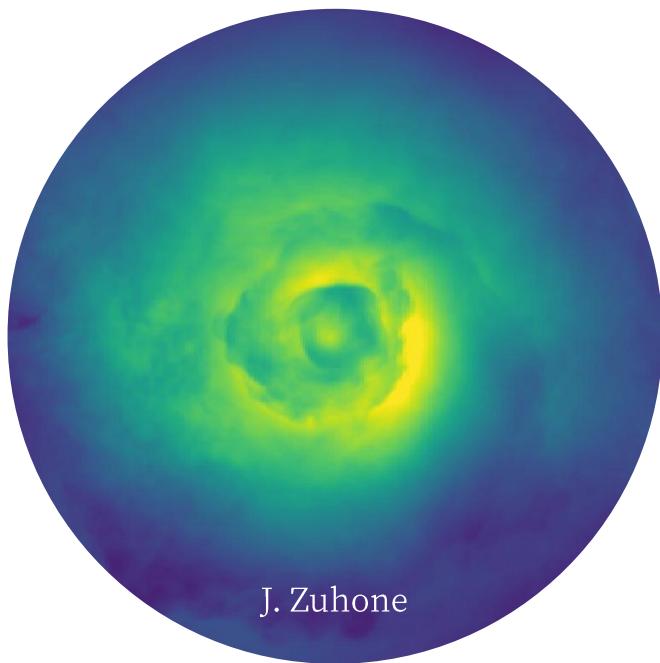
ESA/XMM-Newton/DSS-II/J. Sanders et al. 2019

冷卻流問題 Cooling Flow Problem

- 有些星系團在 X 射線波段「太亮了」。
- 從 X 射線觀測：
 發出 X 射線 → 失去能量 → 壓力降低 →
 冷卻的氣體落入中心 BCG → 大量恆星形成
- 從可見光觀測：
 BCG 恒星形成率比預期低一個數量級
- 為甚麼會這樣呢？
 這被稱為冷卻流問題 Cooling Flow Problem

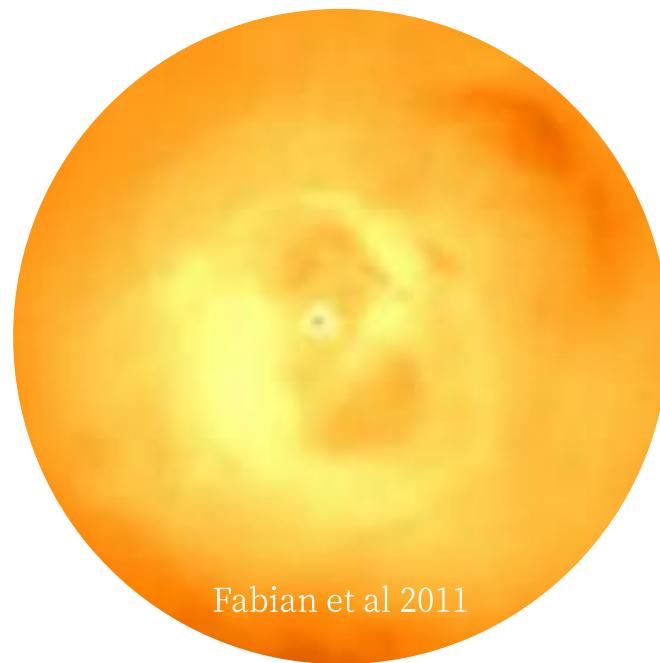
如何解決冷卻流問題？

想避免冷卻流的出現，就需要能夠加熱 ICM 的機制



J. Zuhone

氣體晃盪 Gas Sloshing

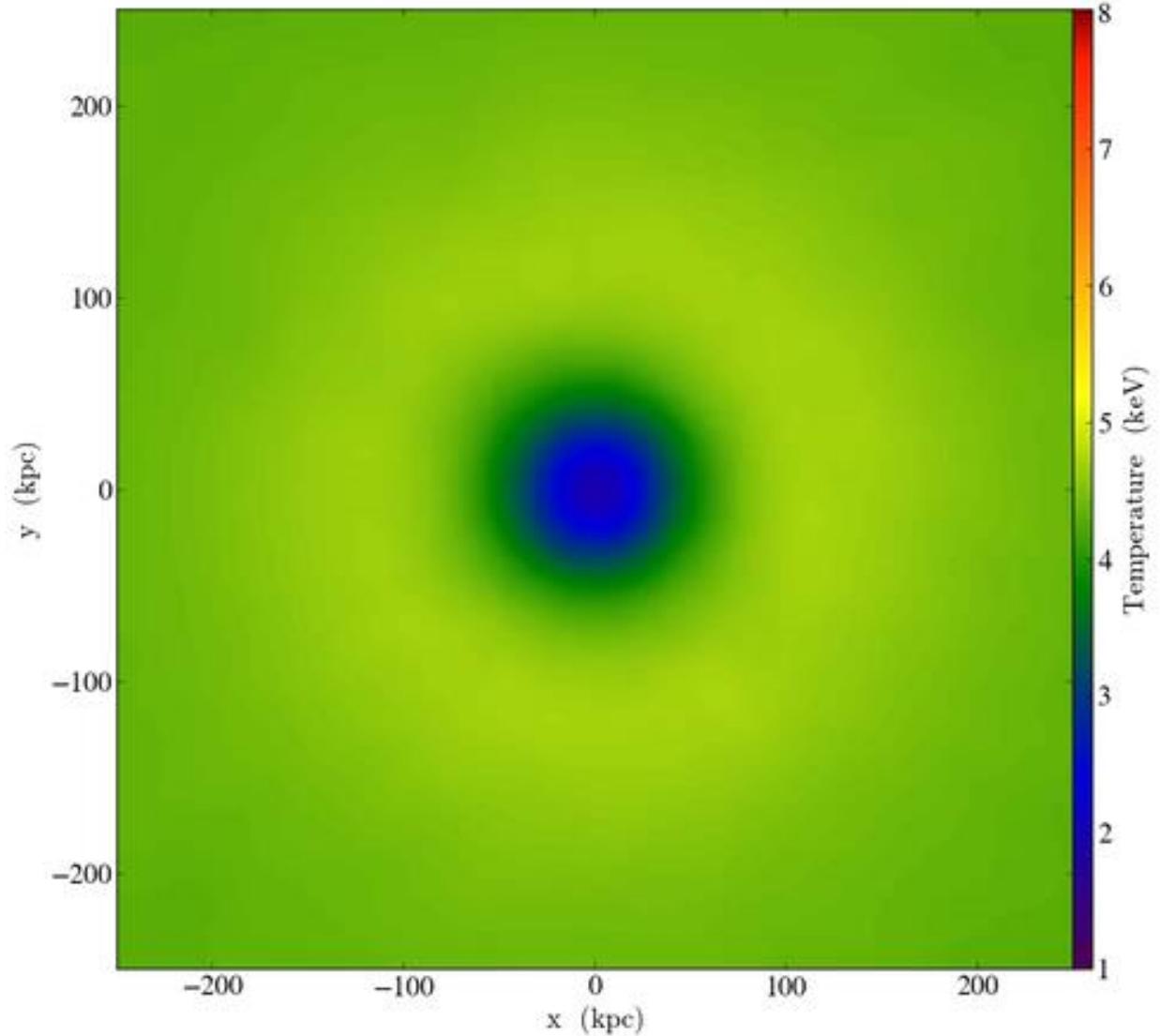


Fabian et al 2011

黑洞噴流 AGN Jets

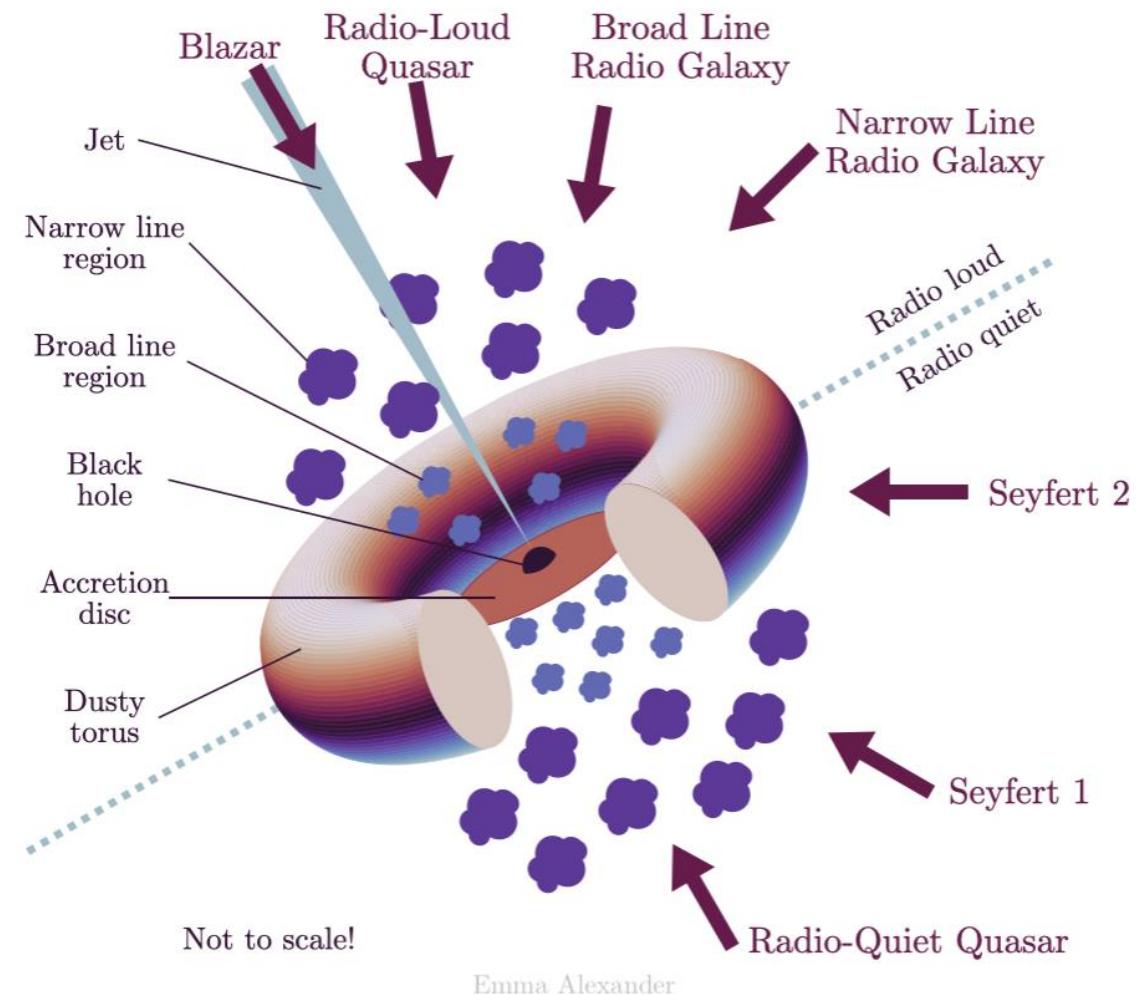
氣體晃蕩 Gas sloshing

- 星系團的一生中會經歷多次大大小的「合併 merger」事件。
- 質量相當的合併：Major Merger
一大一小的合併：Minor Merger
- 當小星系掉入星系團中，
小星系的重力場會攪動並加熱 ICM。
- 問題：晃蕩的發生取決於星系合併
並不是一個「負回饋」的機制



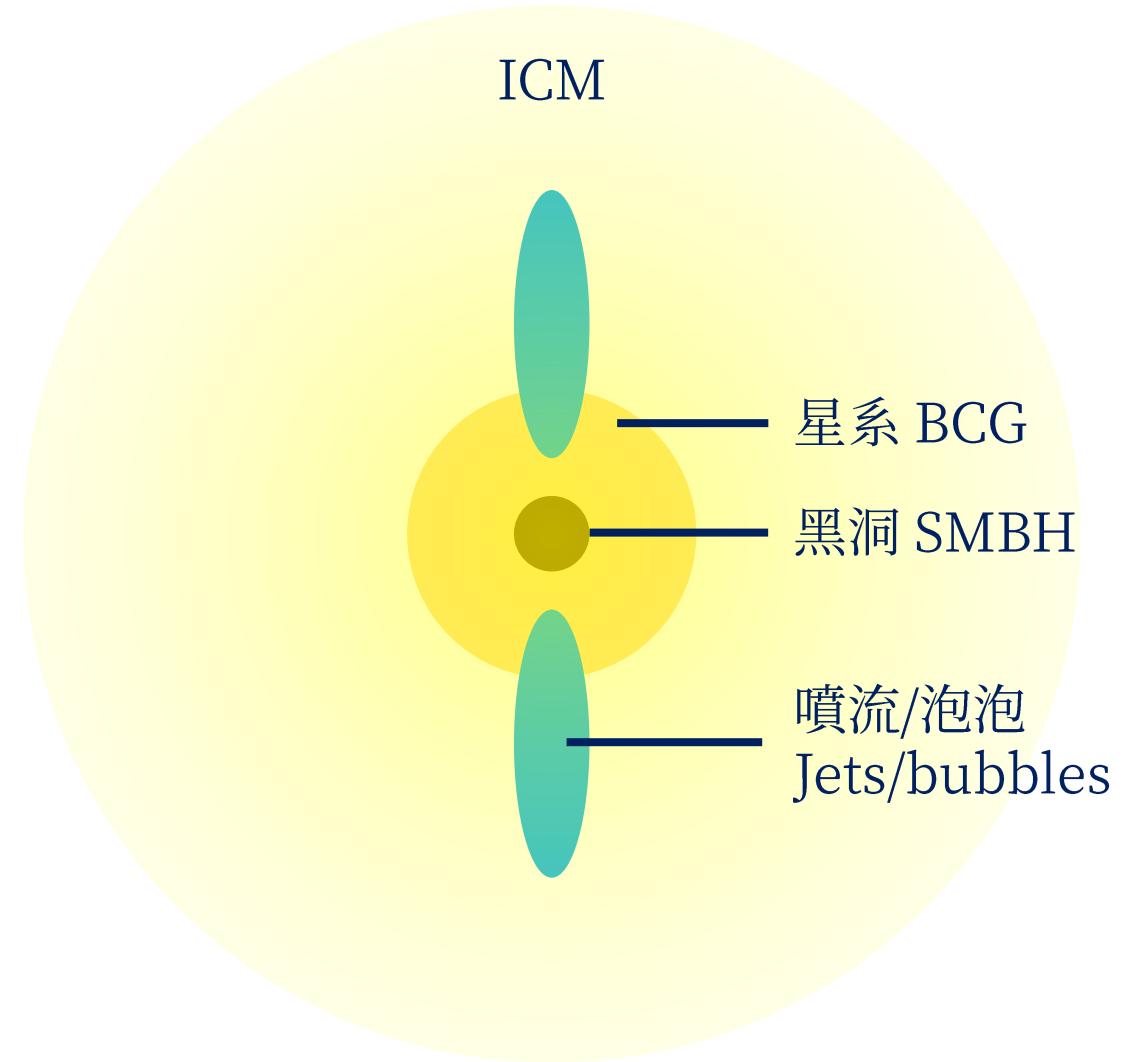
活躍星系核回饋 AGN Feedback

- 星系中心都有「超大質量黑洞 SMBH」
- 當氣體被黑洞吸積，將釋放巨大的能量，成為「活躍星系核 AGN」。
- AGN 釋放的能量將影響星系演化，稱為活躍星系核回饋 AGN Feedback
- 活躍星系核的功率可以達到 10^{42} W 約是銀河系的數十萬倍
- 適當條件下，AGN 會以噴流釋放能量



星系團中的黑洞噴流

- 動力學過程 Dynamics：
 - 氣體冷卻後被 BCG 的黑洞吸積
 - 黑洞從 BCG 中心發射噴流
 - 噴流穿過星系，進入 ICM 產生震波
 - 噴流在 ICM 中形成「泡泡 Bubbles」
 - 泡泡因浮力上浮並最終破碎消散
- 噴流的能量逐漸轉移給 ICM，阻止冷卻流的形成，形成負回饋循環
- 此機制被稱為 Jet mode feedback

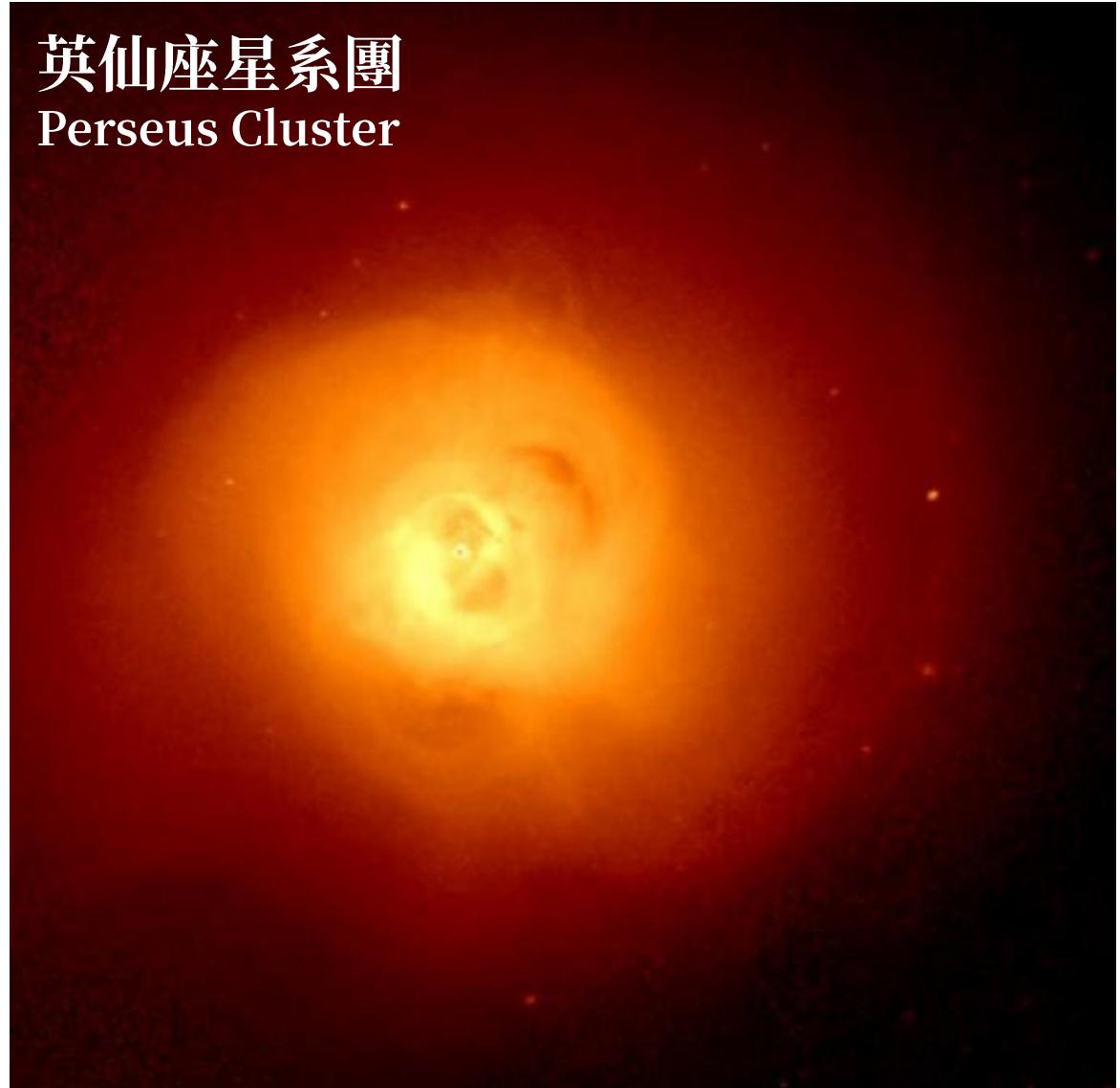


非實際比例

觀測星系團中的黑洞噴流

- Jet mode feedback
擁有多觀測證據支持
- X 射線「空洞 Cavity」
- 為什麼會有空洞？
 - X 射線來自煞車輻射
 - 煞車輻射 $\propto \rho^2 T^{\frac{1}{2}}$
 - 低密度的泡泡亮度較低

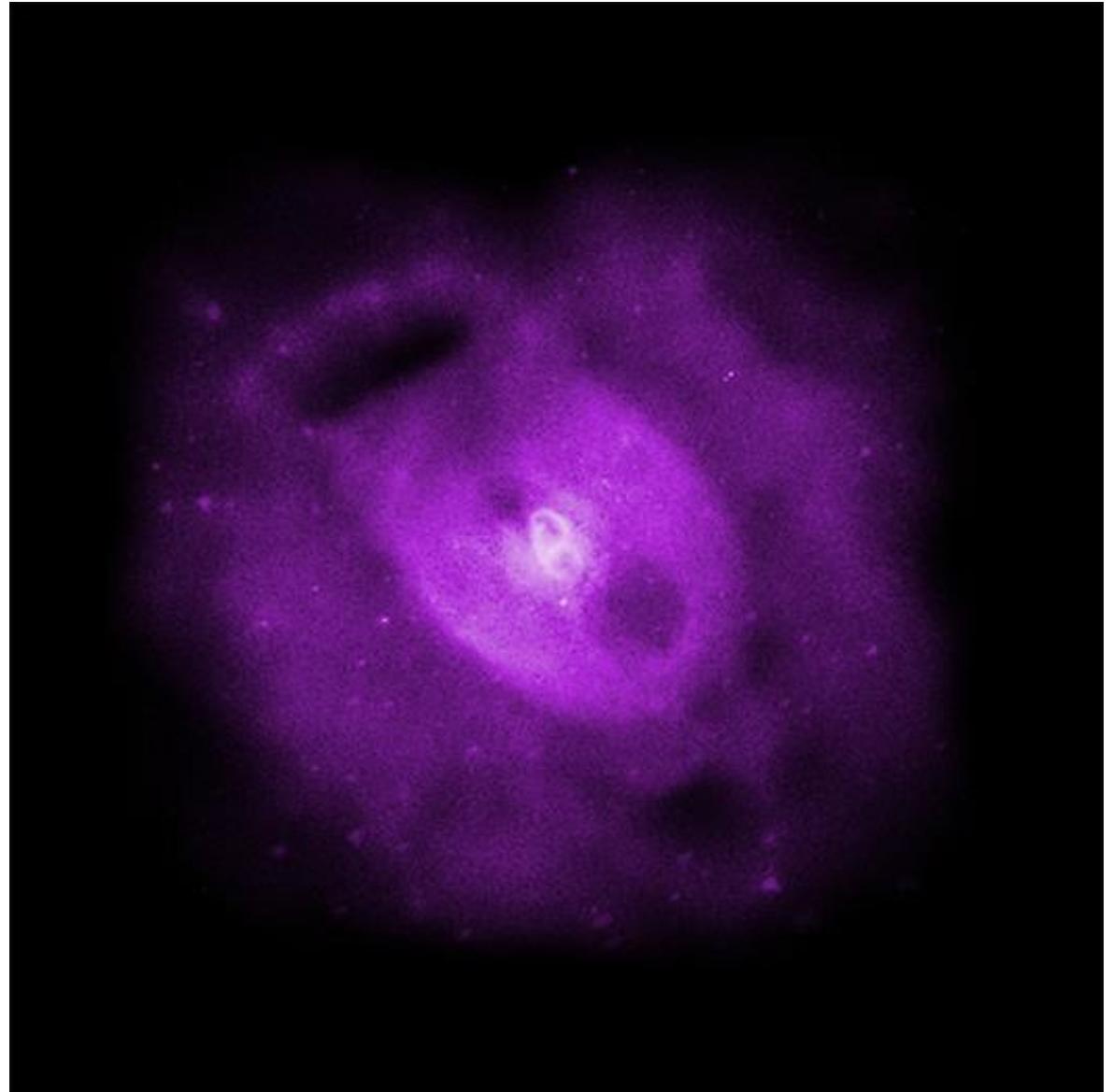
英仙座星系團
Perseus Cluster



NGC 5813 星系群

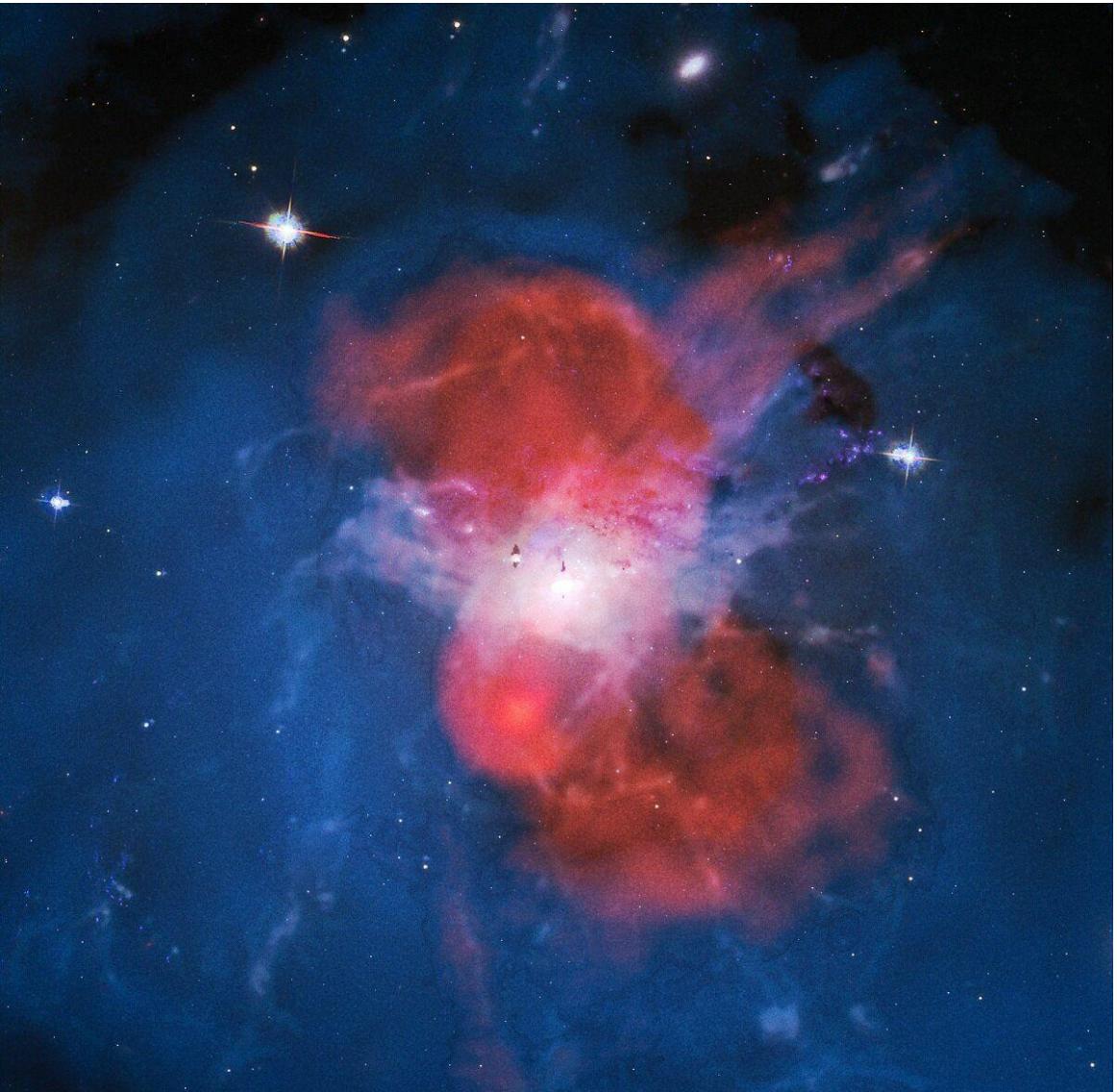
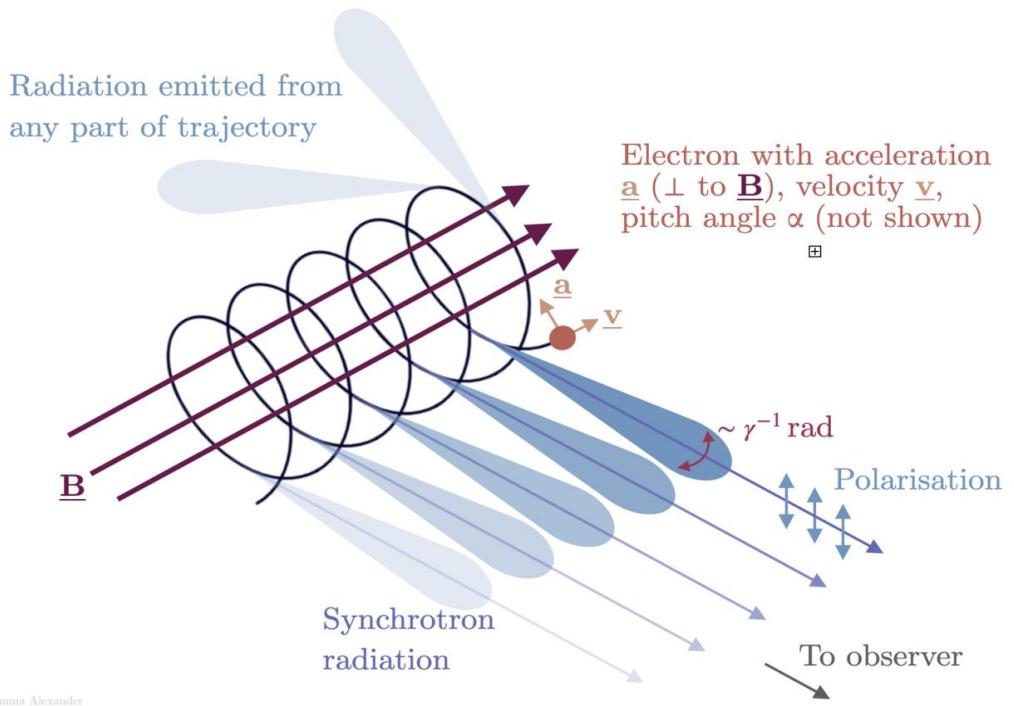


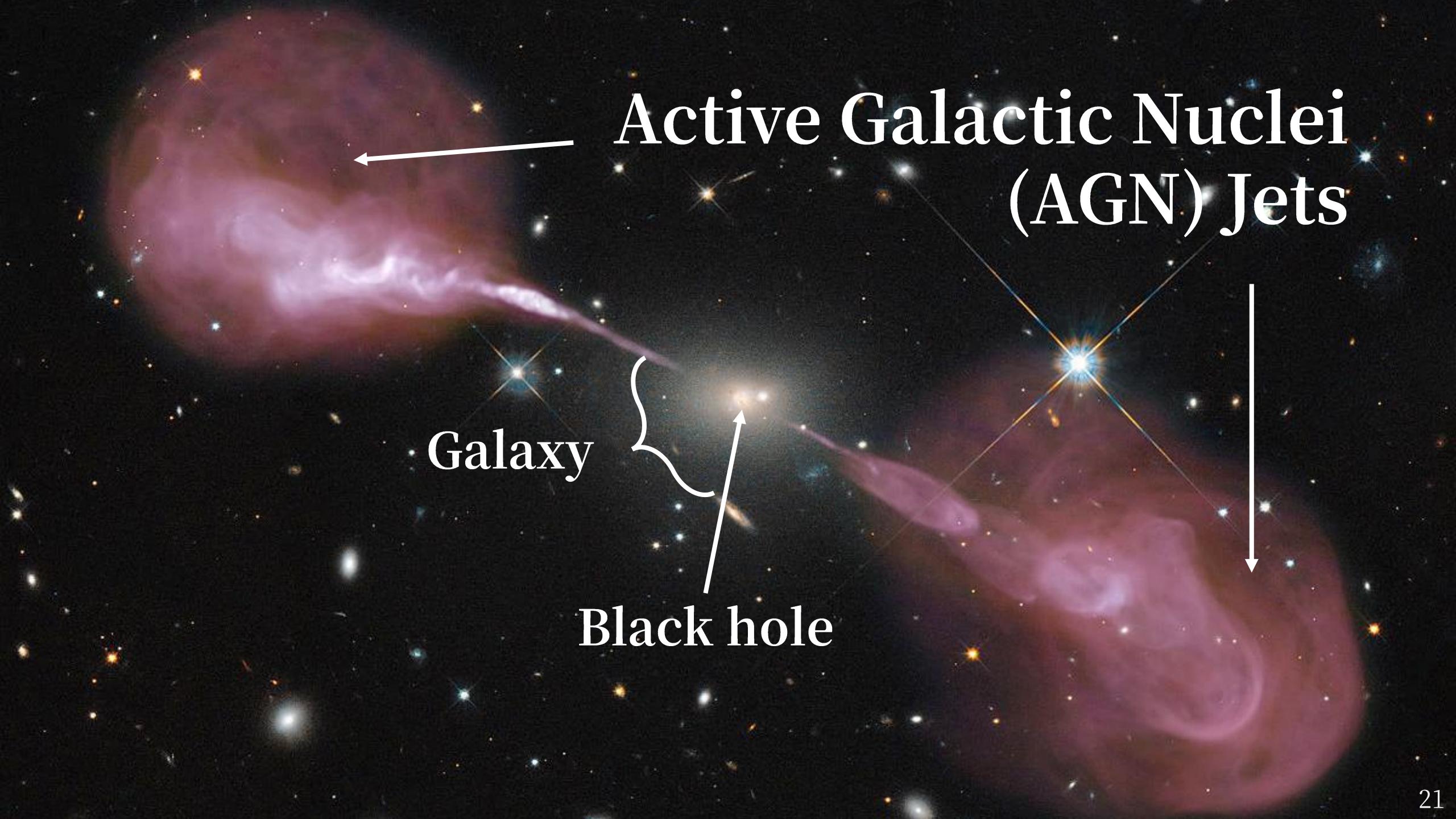
X-ray: NASA/CXC/SAO/S.Randall et al., Optical: SDSS



觀測星系團中的黑洞噴流

- 電波瓣 Radio Lobe
- 同步輻射 Synchrotron



A composite image showing two galaxies against a dark background of stars. The galaxy on the left has a large, diffuse, reddish-pink nebula-like structure extending from its center. The galaxy on the right is smaller and more compact, with a bright central region and a prominent, long, blue/purple jet extending towards the bottom right. Arrows point from the text labels to these features.

Active Galactic Nuclei (AGN) Jets

Galaxy

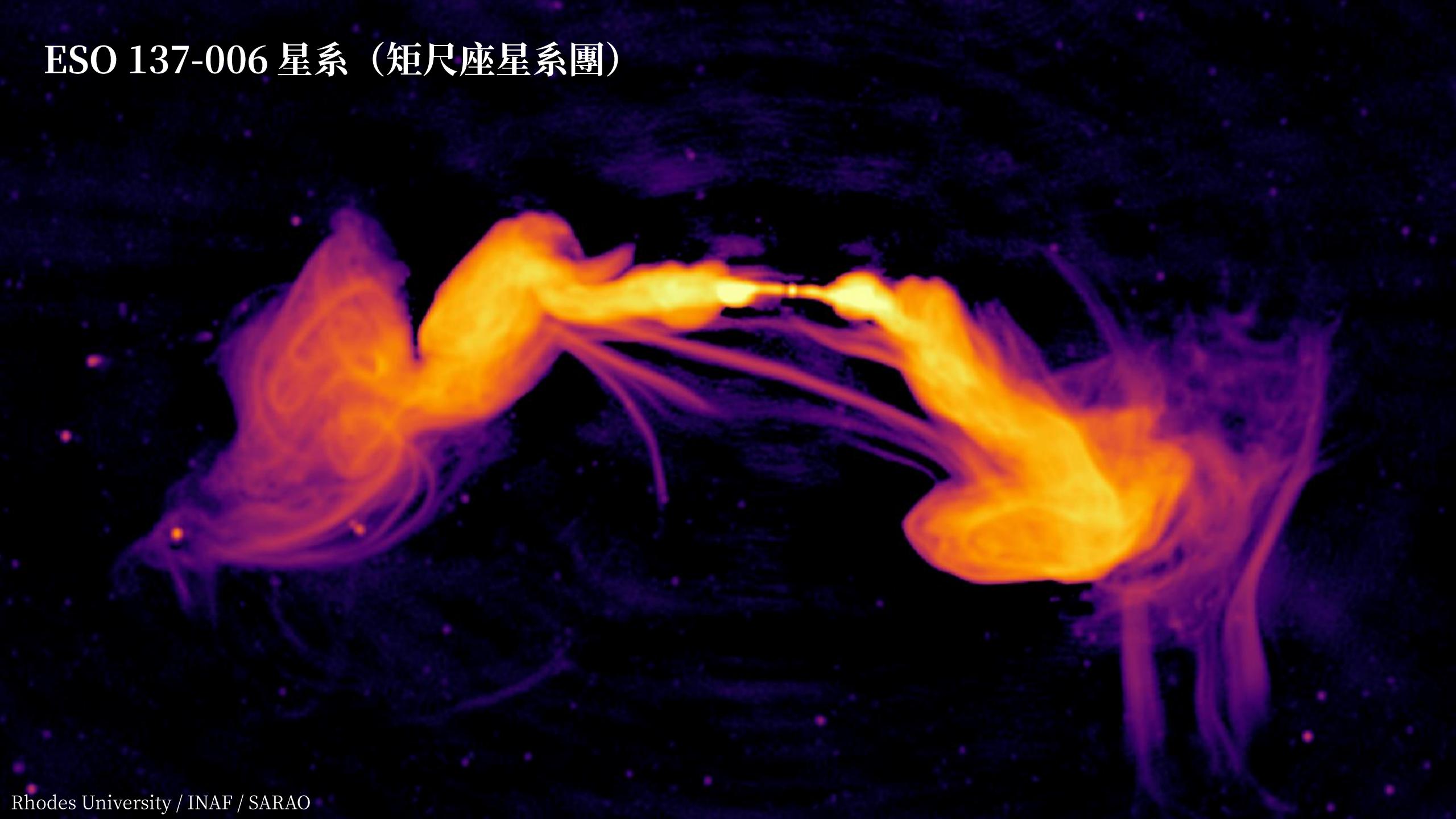
Black hole

半人馬座 A 星系



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

ESO 137-006 星系 (矩尺座星系團)



觀測泡泡的性質

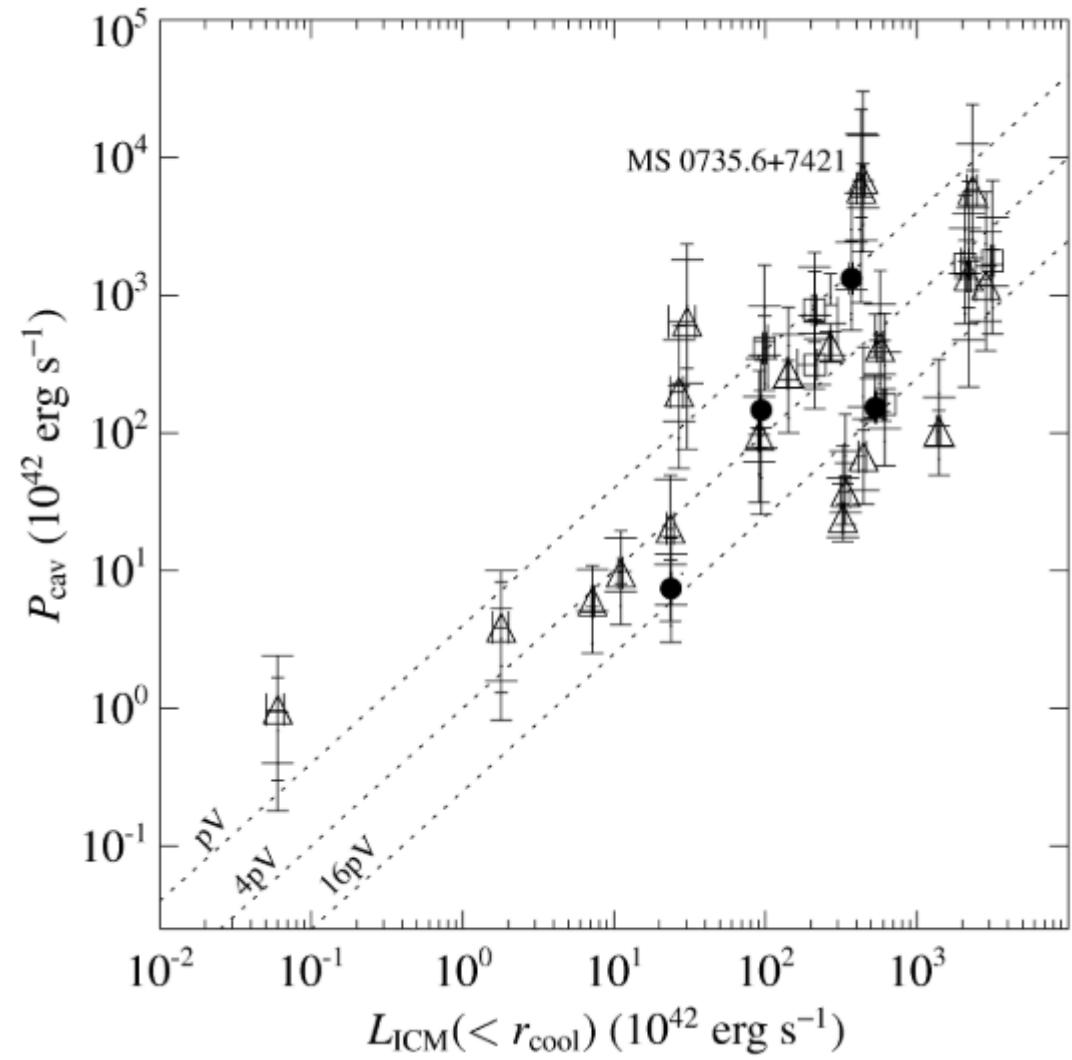


LOFAR/Chandra/WIYN/Hubble/Frits Sweijen

- X-ray : ICM 的溫度與壓力
 - 泡泡的總能量
 - 泡泡的年齡
 - 泡泡的功率 (Cavity Power)
- Radio : 泡泡的磁場和宇宙射線
 - 無線電光度 Radio luminosity
 - 磁場與相對論性電子能量密度

AGN 回饋的觀測證據

- 泡泡功率（加熱）
X 射線光度（冷卻）
有橫跨多個數量級的正相關
- 無線電光度 – X 射線光度
黑洞質量 – 星系質量 (M-sigma relation)
等特性也有類似關係
- 佐證 AGN 回饋確實存在
是影響星系演化的重要推手



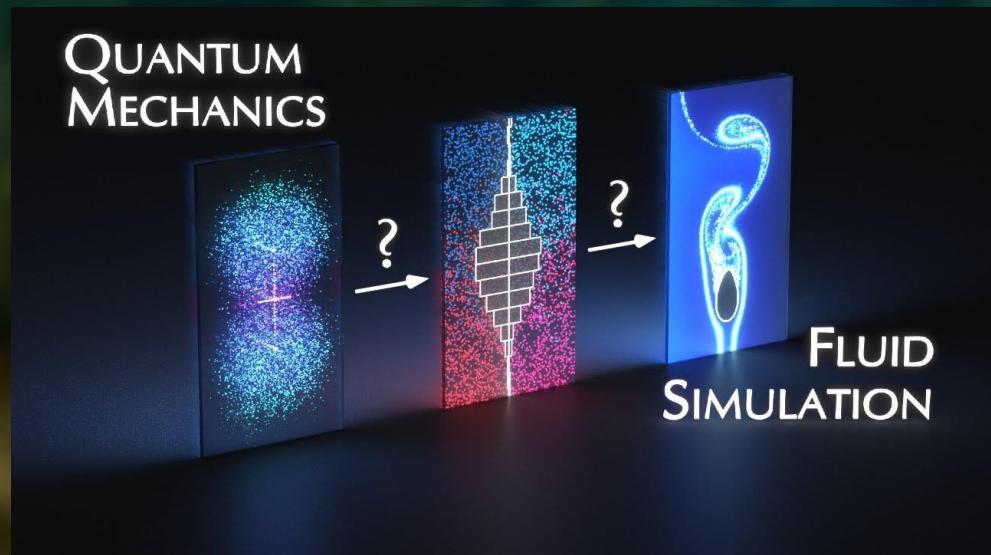
Rafferty et al. 2006

方法

磁流體力學模擬 MHD 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：
 - 恒星： 10^{30} 公斤 $\rightarrow 10^{57}$ 顆原子
光是儲存就需要 10^{45} TB 的儲存空間
 - 大型宇宙學模擬： $> 10^{18}$ 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

流體力學與天文物理

➤ 物理學家的思考方式：

觀察系統 → 建立模型 → 寫下方程式 → 解方程式 → 詮釋結果

➤ 當氣體的「平均自由徑 mfp」遠小於系統的大小，氣體的行為可以用流體近似，並以溫度、密度、壓力等宏觀性質進行描述。

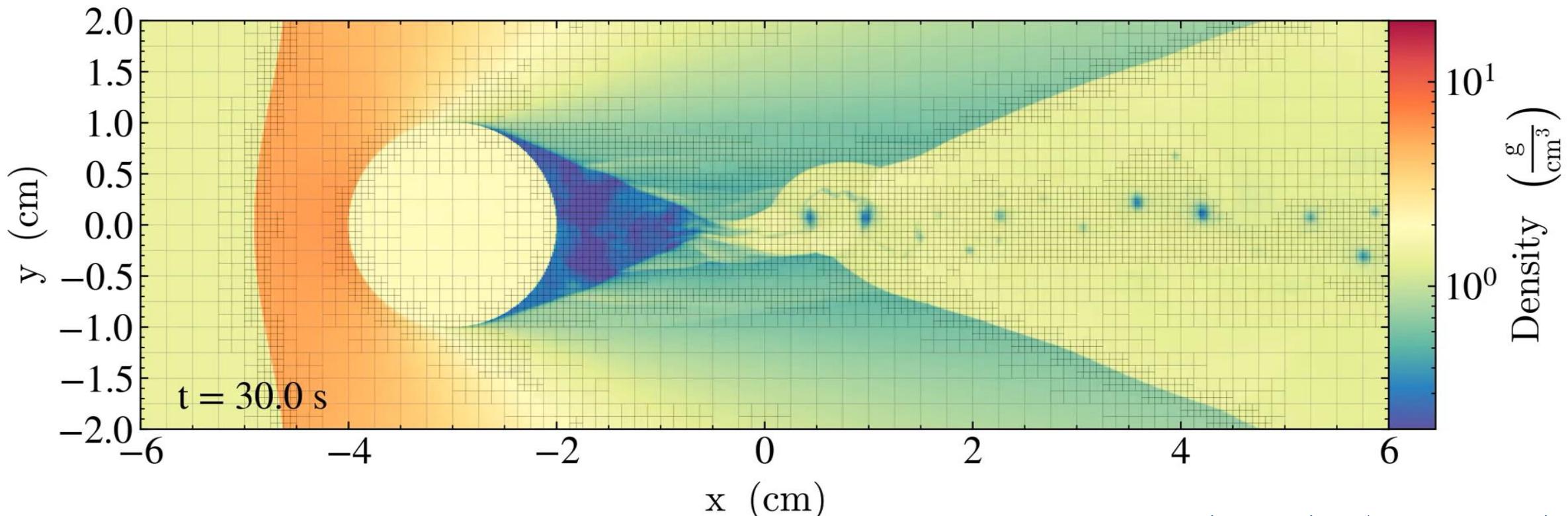
$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \quad \text{質量守恆 Mass Conservation}$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v} \otimes \mathbf{v}) + \nabla p_{\text{tot}} = \rho \mathbf{g} \quad \text{動量守恆 Momentum Conservation}$$

$$\frac{\partial e}{\partial t} + \nabla \cdot [(e + p_{\text{tot}}) \mathbf{v}] = \rho \mathbf{v} \cdot \mathbf{g} \quad \text{能量守恆 Energy Conservation}$$

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」。

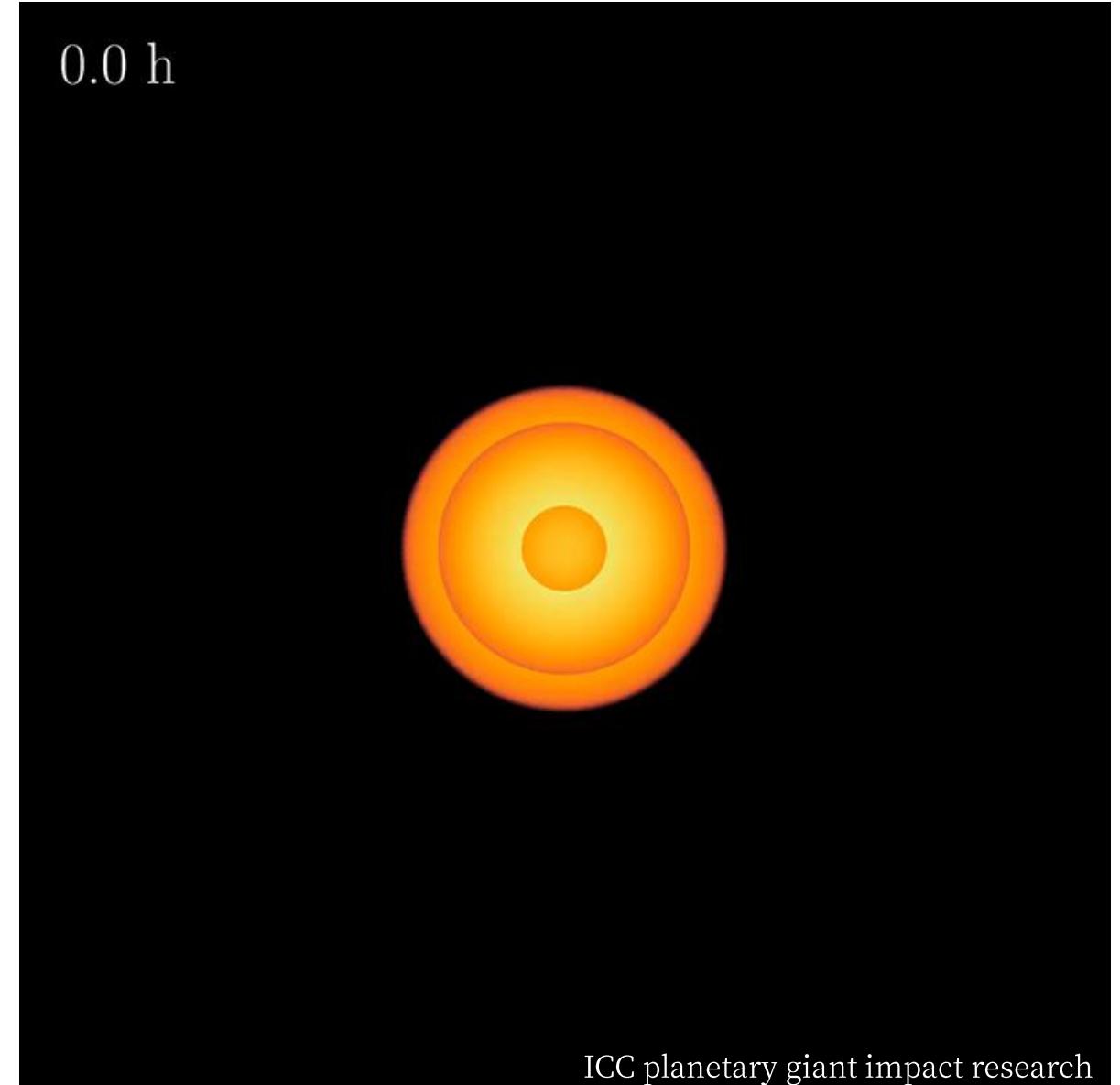


Γ Ζ

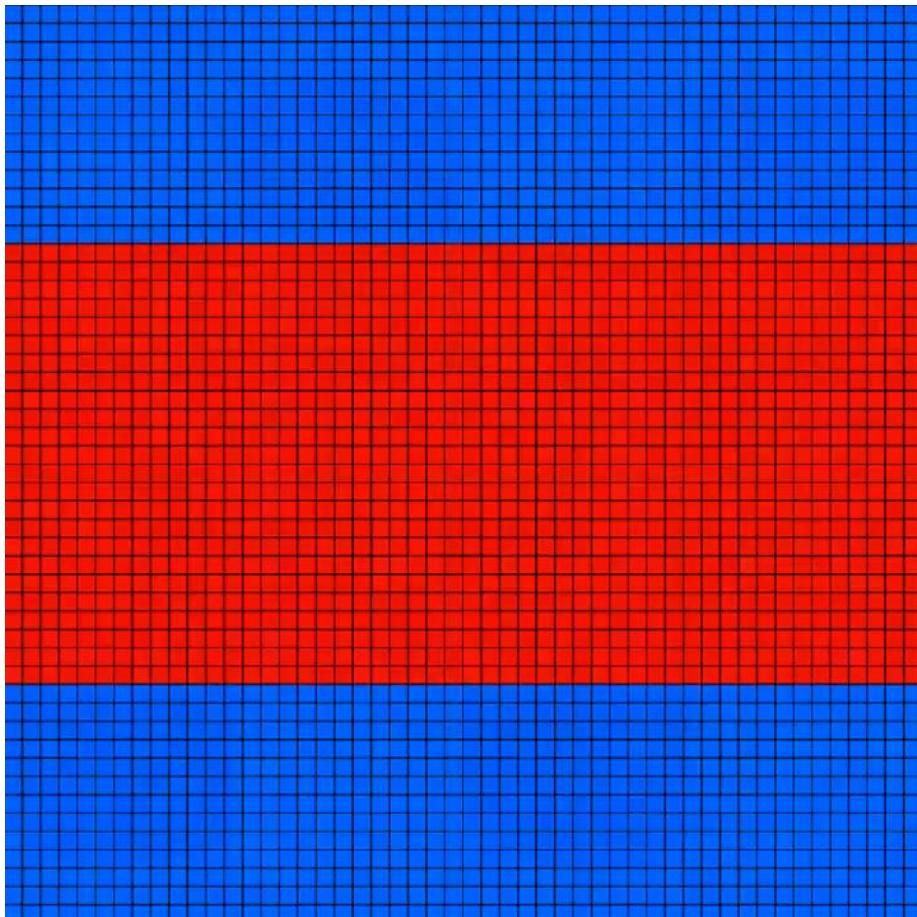
Λ Ζ

解算方程組：SPH Method

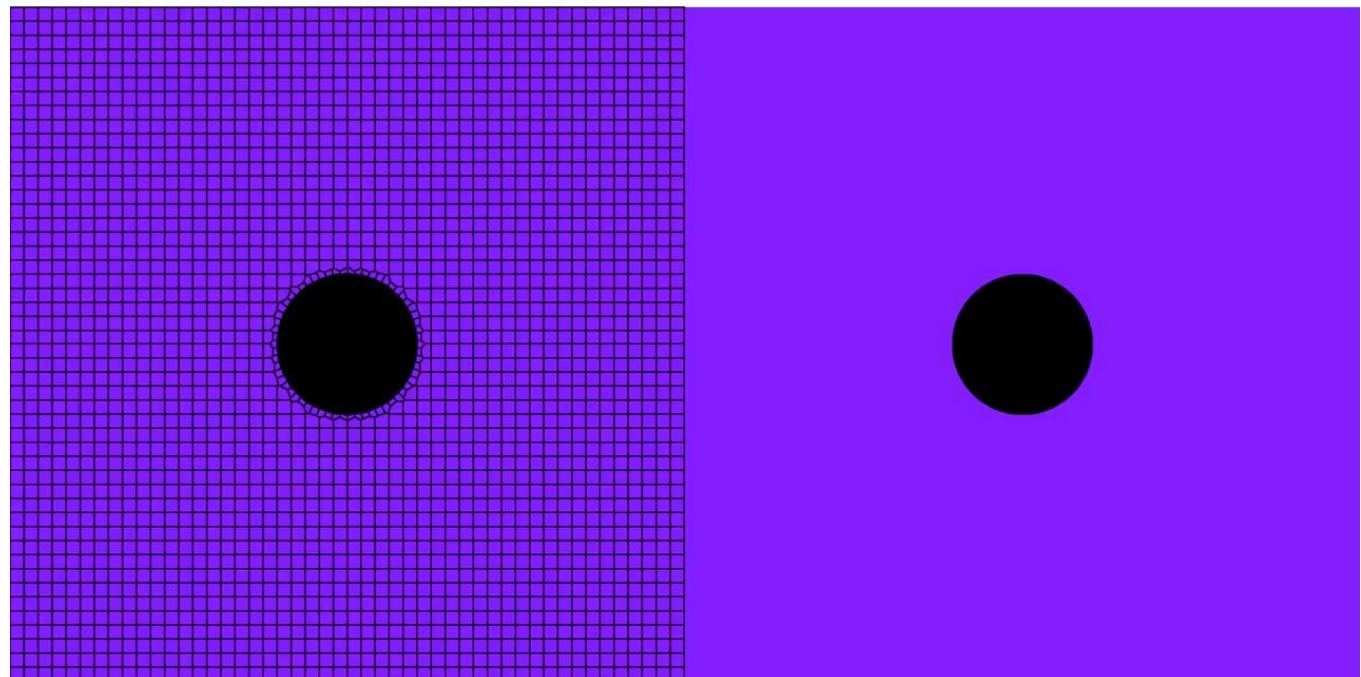
- 另一種常見的方法稱為
光滑粒子流體動力學法
Smoothed Particle Hydrodynamics
- 用一顆一顆的粒子代表流體



解算方程組：Hybrid / Moving Mesh Method



- 結合 FVM 和 SPH 各自的優勢



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：

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

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

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

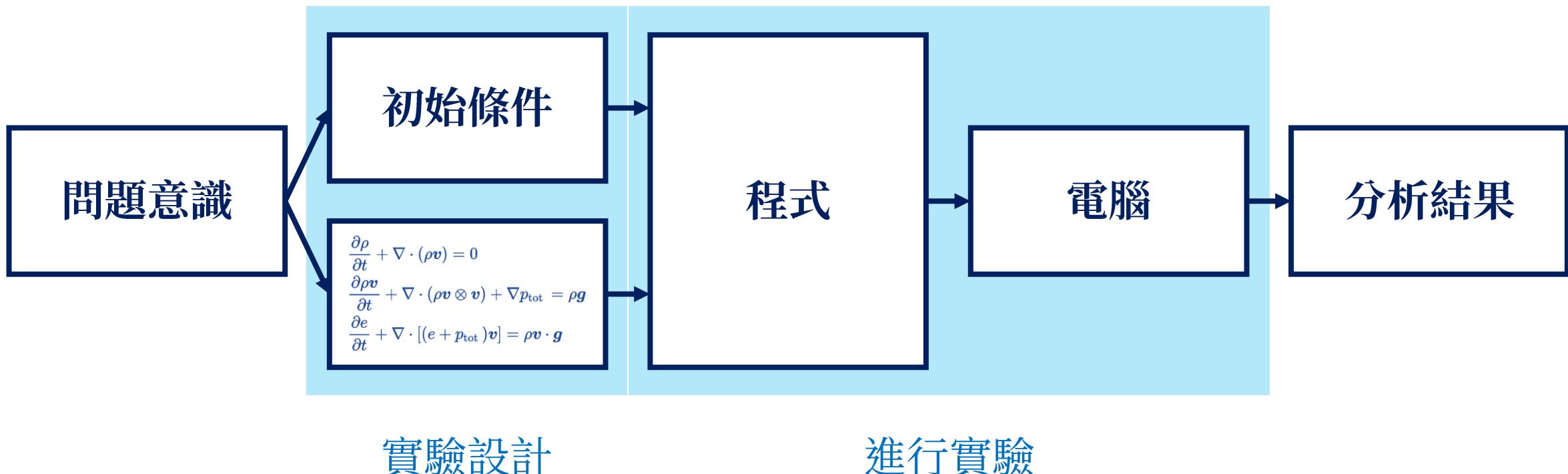
$$\frac{\partial e}{\partial t} + \nabla \cdot \left[(e + p_{\text{tot}}) \mathbf{v} - \frac{\mathbf{B}(\mathbf{B} \cdot \mathbf{v})}{4\pi} \right] = \rho \mathbf{v} \cdot \mathbf{g}$$

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

流體力學與天文物理

- 計算天文物理模擬的基本流程



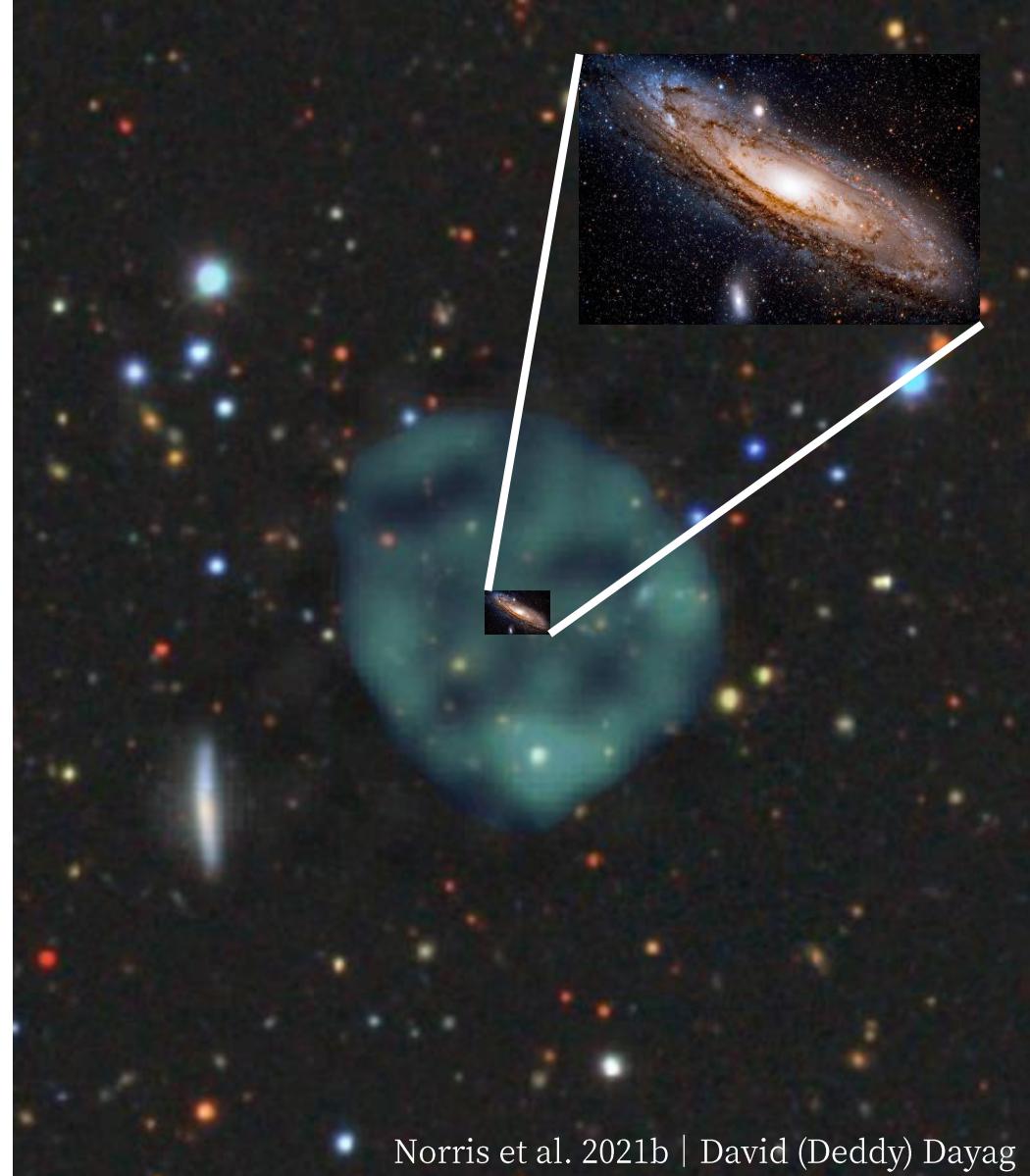
- 計算天文物理是理論工作，但是研究流程其實類似實驗

研究

Odd Radio Circles as Cosmic-Ray dominated AGN jets

怪異電波圈 ORCs

- ORCs: Odd Radio Circles.
- Discovered: 2021 by ASKAP telescope.
- Important properties: (Norris+ 2022)
 - Low surface brightness
(faint, hard to see)
 - Edge brightening
 - Large ($R \sim 250$ kpc)
- Origin unknown.

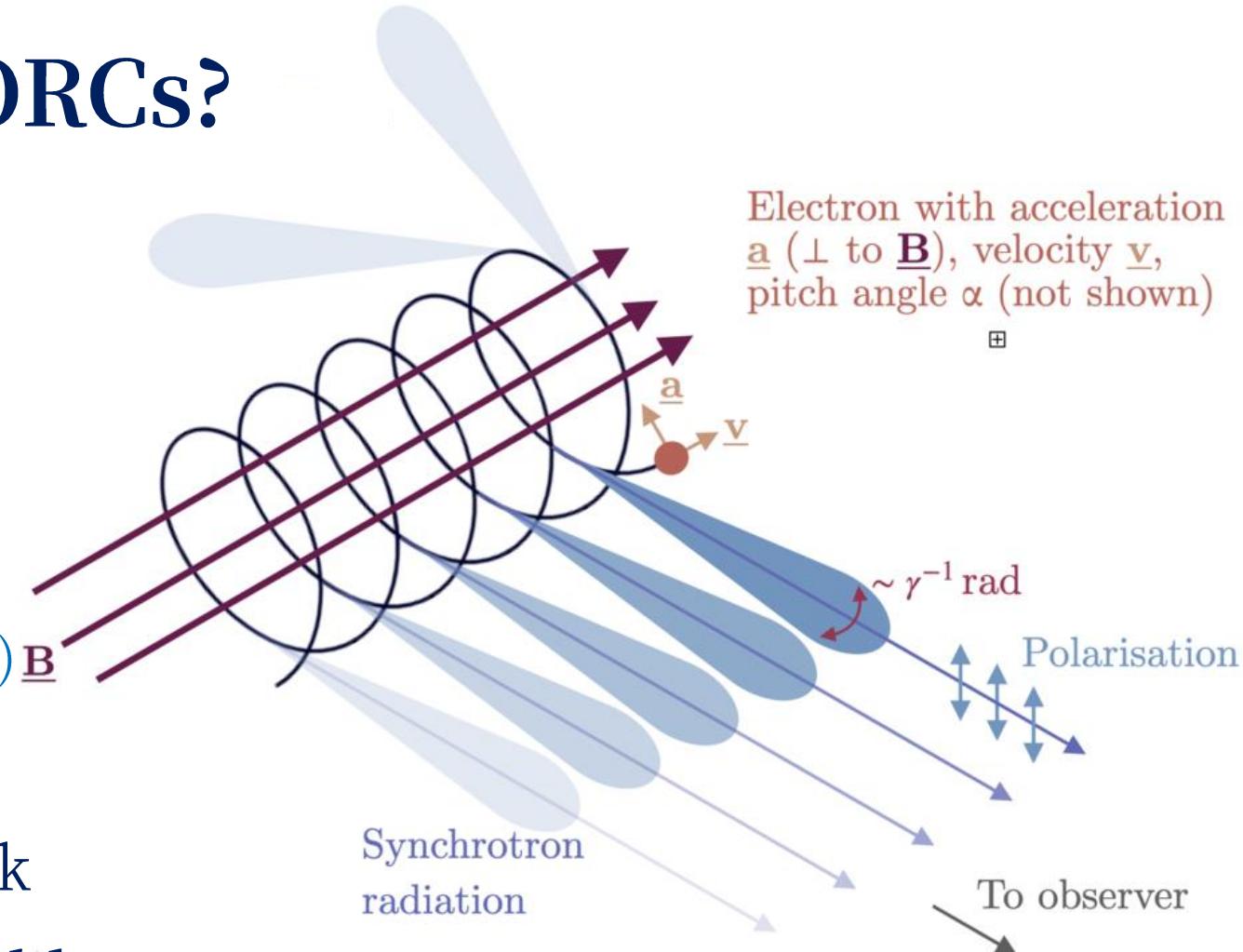


Norris et al. 2021b | David (Deddy) Dayag

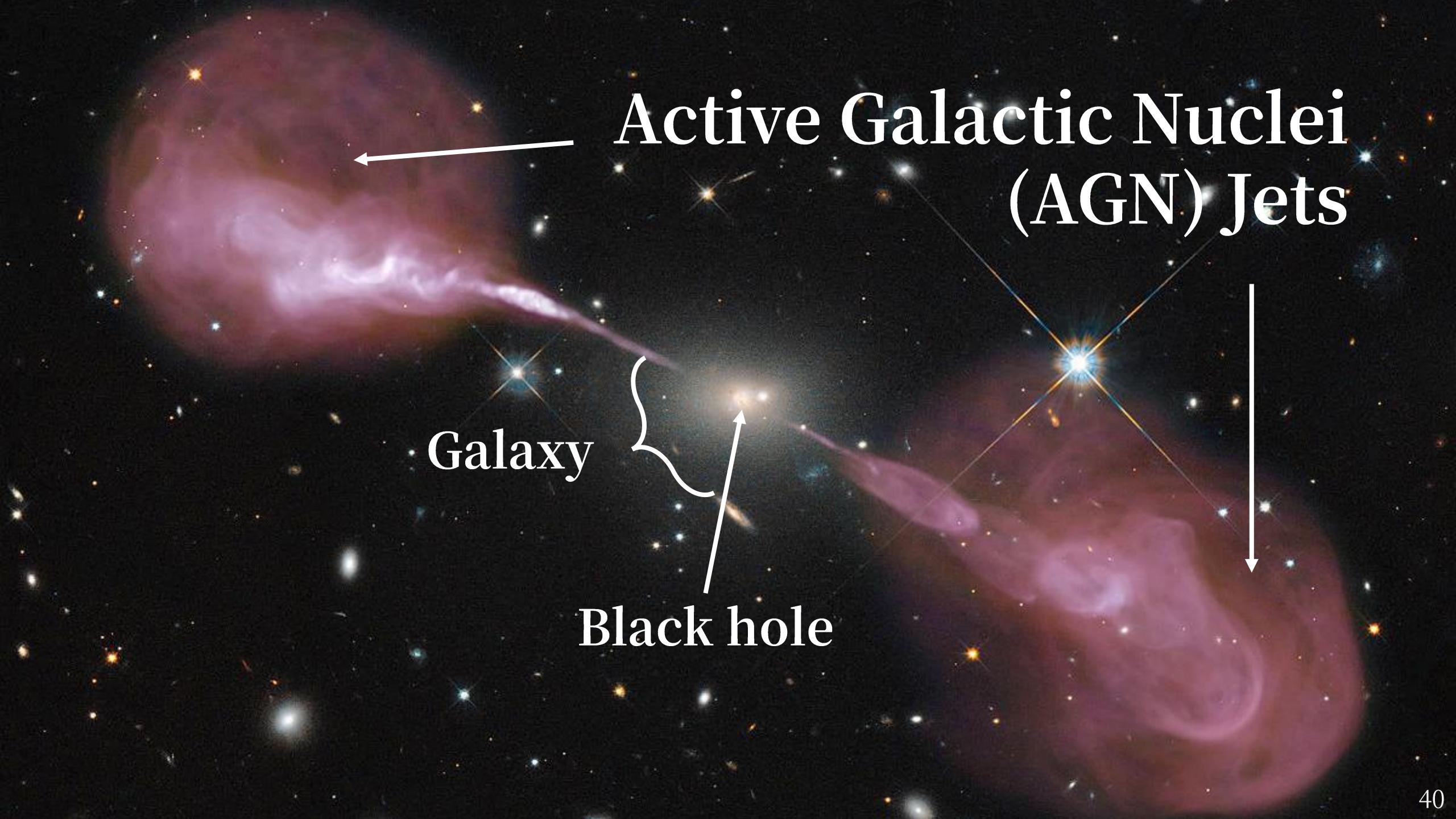
Introduction

What is the origin of ORCs?

- Emission mechanism:
Synchrotron radiation.
- How to create synchrotron?
B field and cosmic-rays (CR).
- Possible explanation: (Norris+ 2022)
 1. Explosion in the host galaxy
 2. Star formation terminal shock
 3. End-on AGN jet inflated bubbles.



Emma Alexander

A composite image showing two galaxies against a dark background of stars. The galaxy on the left has a large, diffuse, reddish-pink nebula-like structure extending from its center. The galaxy on the right is smaller and more compact, with a bright central region and a shorter, more concentrated jet of light extending towards the bottom right. Both galaxies appear to have supermassive black holes at their centers.

Active Galactic Nuclei (AGN) Jets

Galaxy

Black hole

Three white arrows point to specific features in the image: one arrow points to the left galaxy's nebula; another points to the central bright region of the right galaxy; and a third points to the right edge of the right galaxy's nebula.

CR-MHD: Treating CR as a second fluid

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

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

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

$$\frac{\partial e}{\partial t} + \nabla \cdot \left[(e + p_{\text{tot}}) \mathbf{v} - \frac{\mathbf{B}(\mathbf{B} \cdot \mathbf{v})}{4\pi} \right] = \rho \mathbf{v} \cdot \mathbf{g} + \nabla \cdot (\boldsymbol{\kappa} \cdot \nabla e_{\text{cr}}) + \mathcal{H}_{\text{cr}} + n_e^2 \Lambda(T)$$

$$\frac{\partial e_{\text{cr}}}{\partial t} + \nabla \cdot (e_{\text{cr}} \mathbf{v}) = -p_{\text{cr}} \nabla \cdot \mathbf{v} + \nabla \cdot (\boldsymbol{\kappa} \cdot \nabla e_{\text{cr}}) + \mathcal{C}_{\text{cr}}$$

↑ ↑ ↑ ↑
 CR Adiabatic CR CR cooling
 advection term diffusion (Hadronic, Sync, IC, etc)

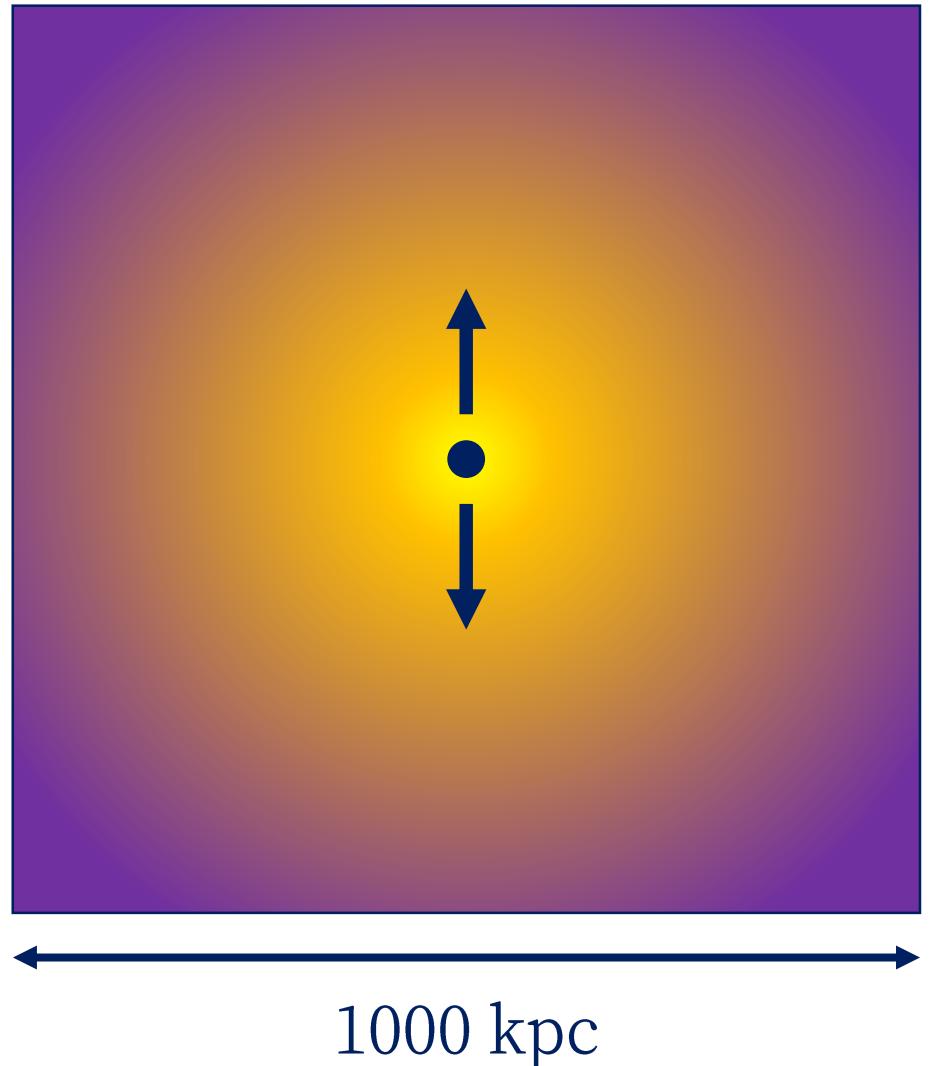
CR
diffusion

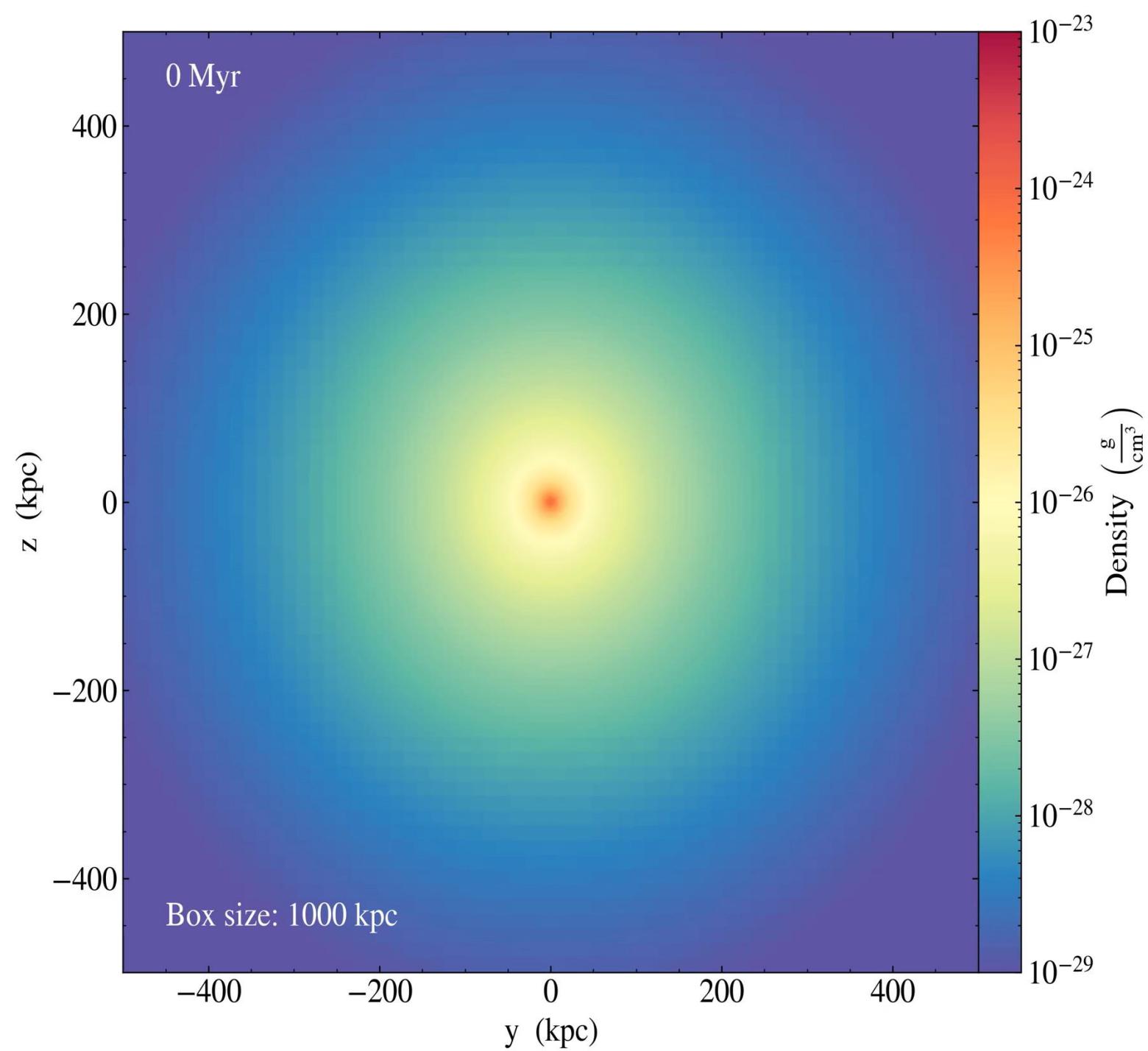
CR effects on
total energy

Method

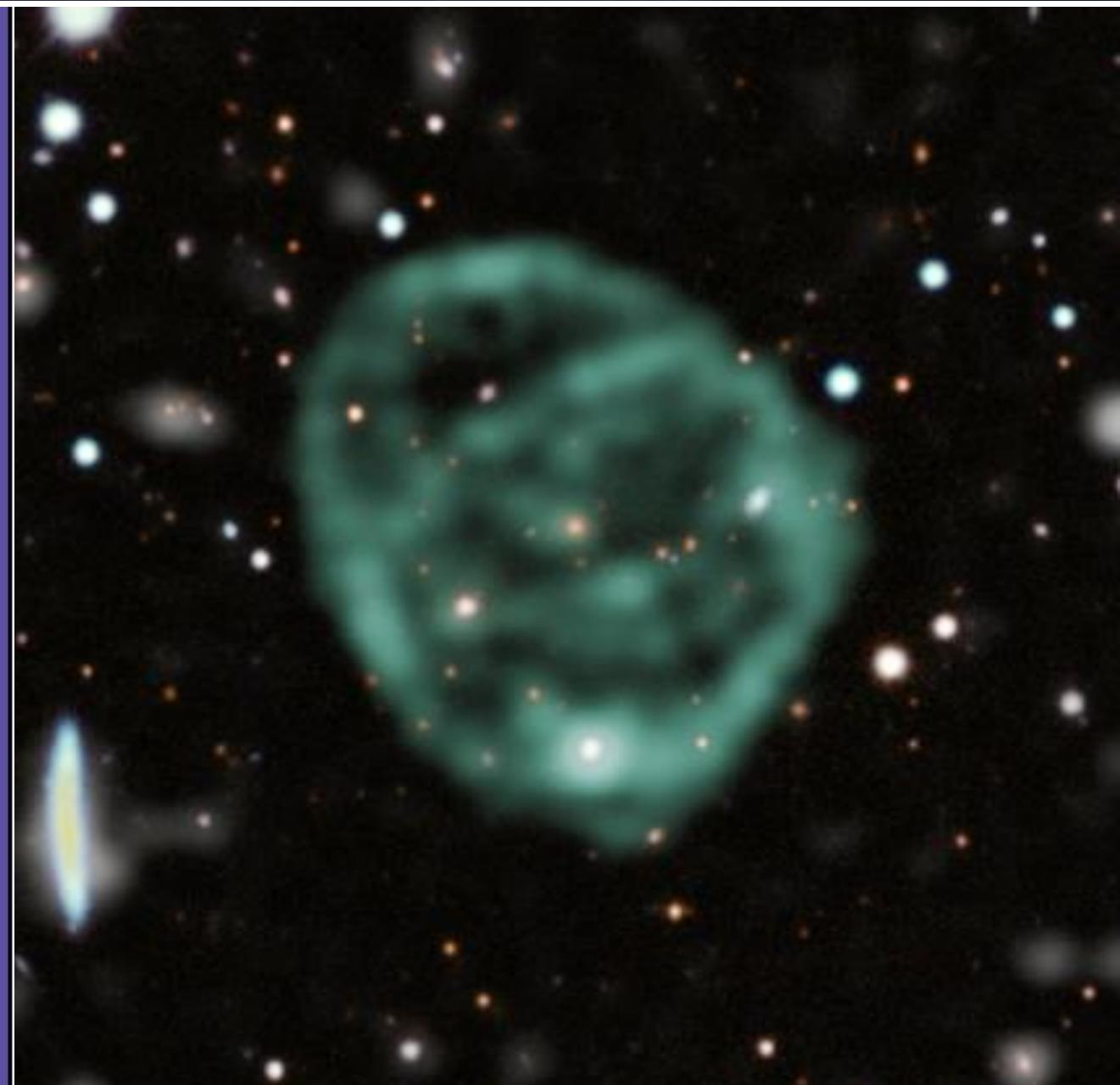
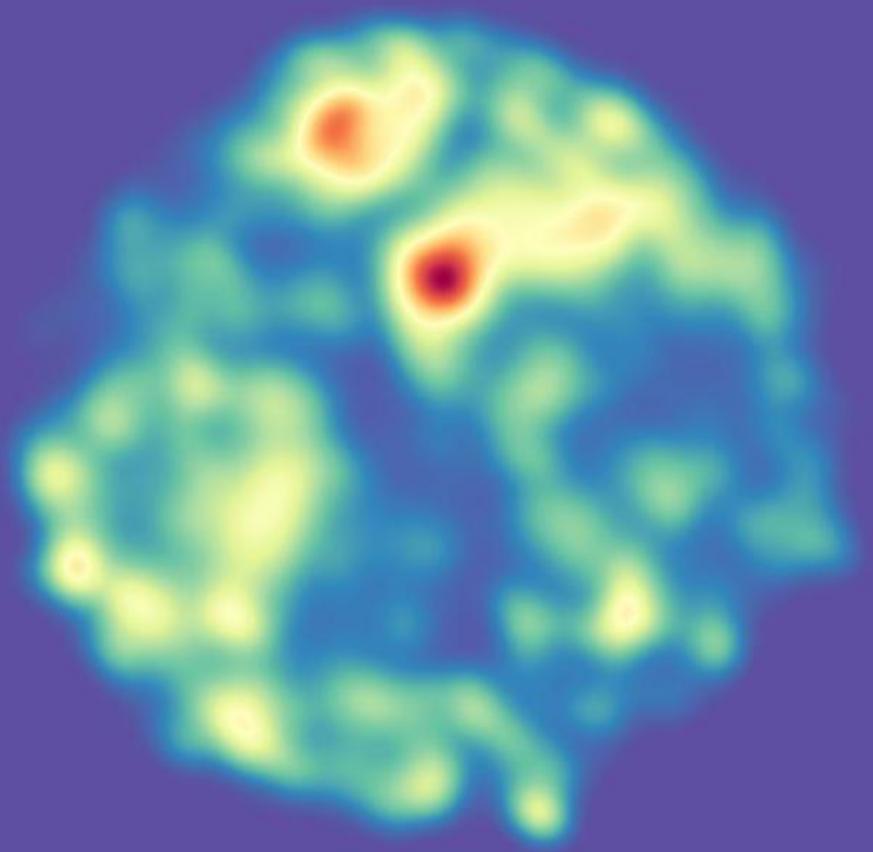
Simulation setup

- Code: FLASH, modified to include CR.
- Box size: 1 Mpc; Resolution: 1 kpc.
- Initial condition: Mimic galaxy cluster.
- Jet: bipolar injection of energy and momentum from the center.
- Mock observation:
yt package ([python](#), widely used). Integrate Sync. emissivity to get radio morphology





198 Myr



Summary

ORCs as AGN jet inflated bubbles

- ORCs: New mysterious extragalactic radio objects
- Possible explanation: End on AGN jet inflated bubbles.
- Goal: Try to reproduce them with numerical simulations.
- Method: FLASH code with a galaxy cluster environment.
- Result: Circular, edge brightened radio object reproduced.

$$\frac{v^2}{2} + gz + \frac{p}{\rho} = \text{ constant}$$



$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} - \nu \nabla^2 \mathbf{u} = -\nabla \left(\frac{p}{\rho_0} \right) + \mathbf{g}$$



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

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v} \otimes \mathbf{v}) + \nabla p_{\text{tot}} = \rho \mathbf{g}$$

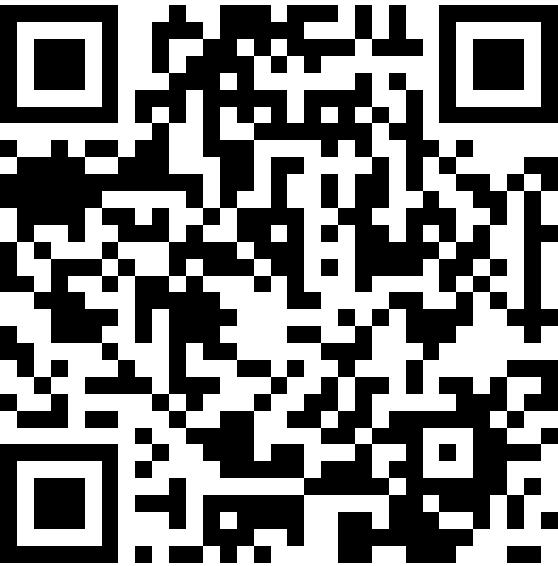
$$\frac{\partial e}{\partial t} + \nabla \cdot [(e + p_{\text{tot}}) \mathbf{v}] = \rho \mathbf{v} \cdot \mathbf{g}$$

$$\partial_\nu T^{i\nu} = 0$$

$$\partial_0 T^{i0} + \partial_j T^{ij} = 0$$

$$\partial_t \left(\frac{1}{c^2} (\rho c^2 + p) v^i \gamma^2 \right)$$

$$+ \partial_j \left(\left(\rho + \frac{p}{c^2} \right) v^i v^j \gamma^2 + p \delta^{ij} \right) = 0$$



NTHU IoA
Feedback in
Galaxies and Clusters
PI: Hsiang-Yi Karen Yang