



NTHUAC AstroRead

AGN Feedback in Galaxy Clusters

Yen-Hsing Lin | 2023.05.18

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

➤ 一些結果：如果有時間談的話……

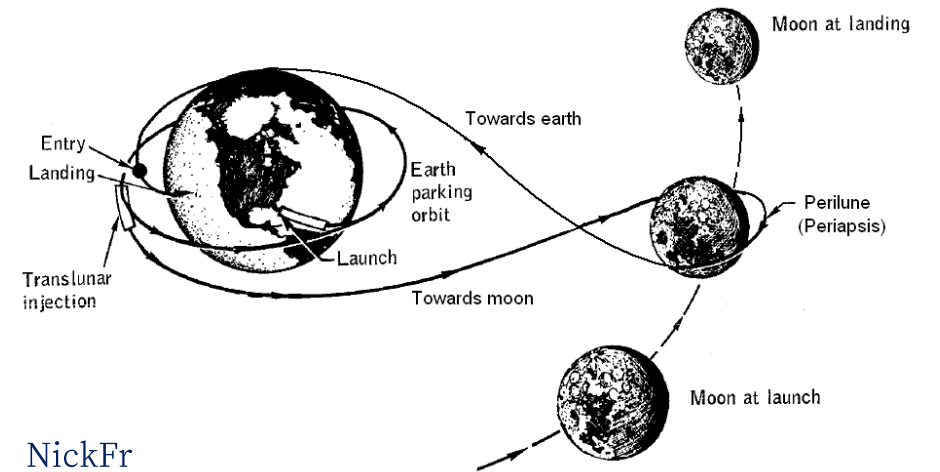
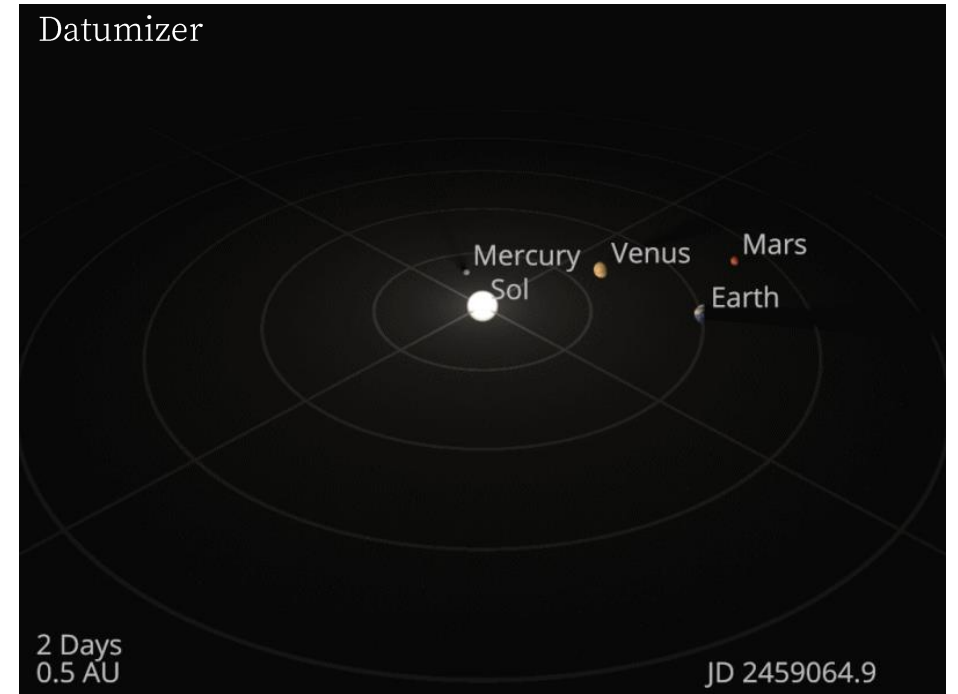
背景

星系團與 AGN 回饋

回顧：宇宙的階層

高中地科：

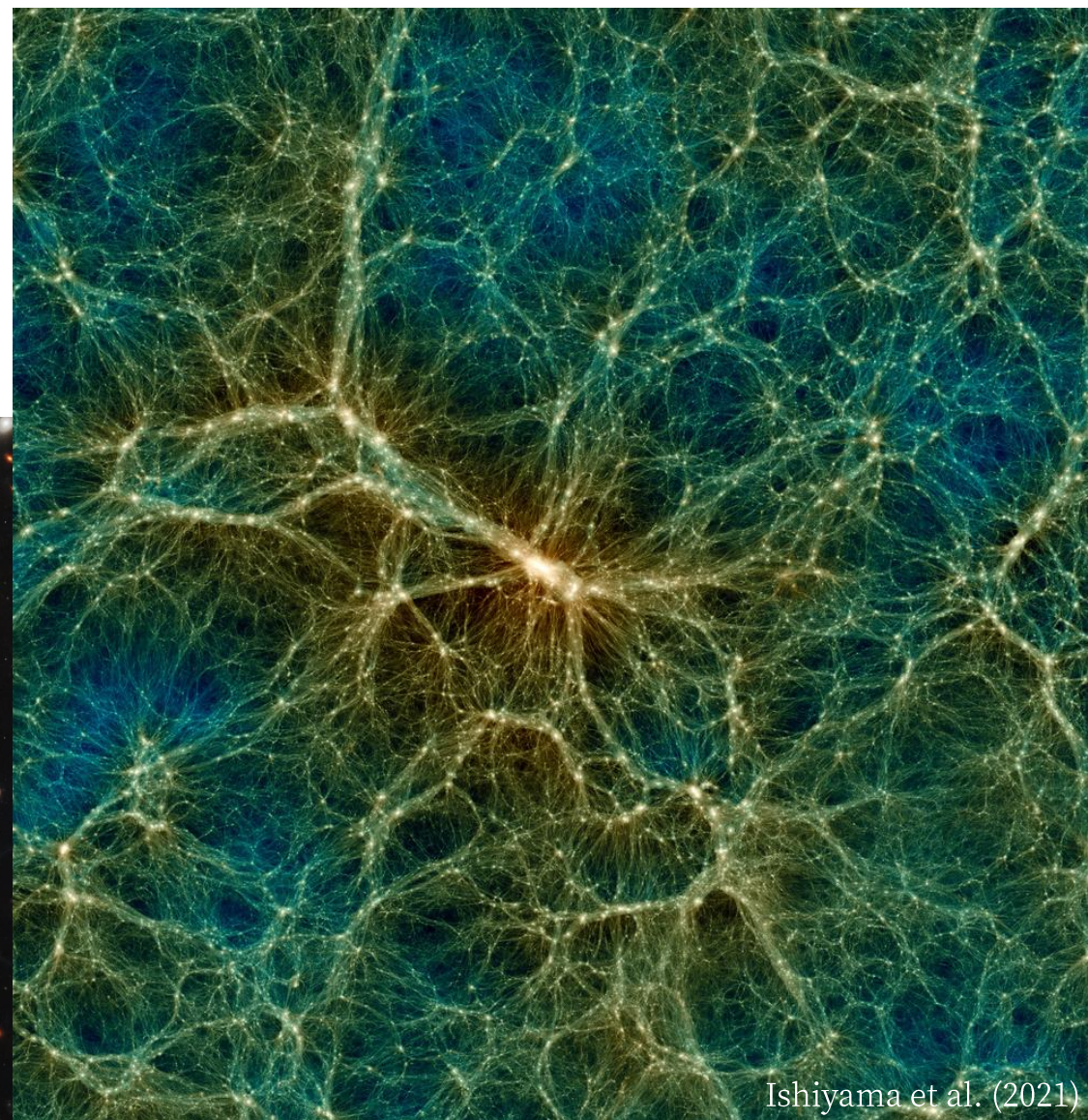
行星 → 恆星 → 星系 → 星系團 → 宇宙網



回顧：宇宙的階層

高中地科：

行星 → 恆星 → 星系 → 星系團 → 宇宙網



註：不是一堆星系在一起就是星系團



場星系 Field Galaxies

單獨存在，不受其他星系重力束縛

NGC 1313 | ESO, Henri Boffin



星系群 Galaxy Groups

約 50 個星系

Stephans Quintet | NASA/ESA/STScI

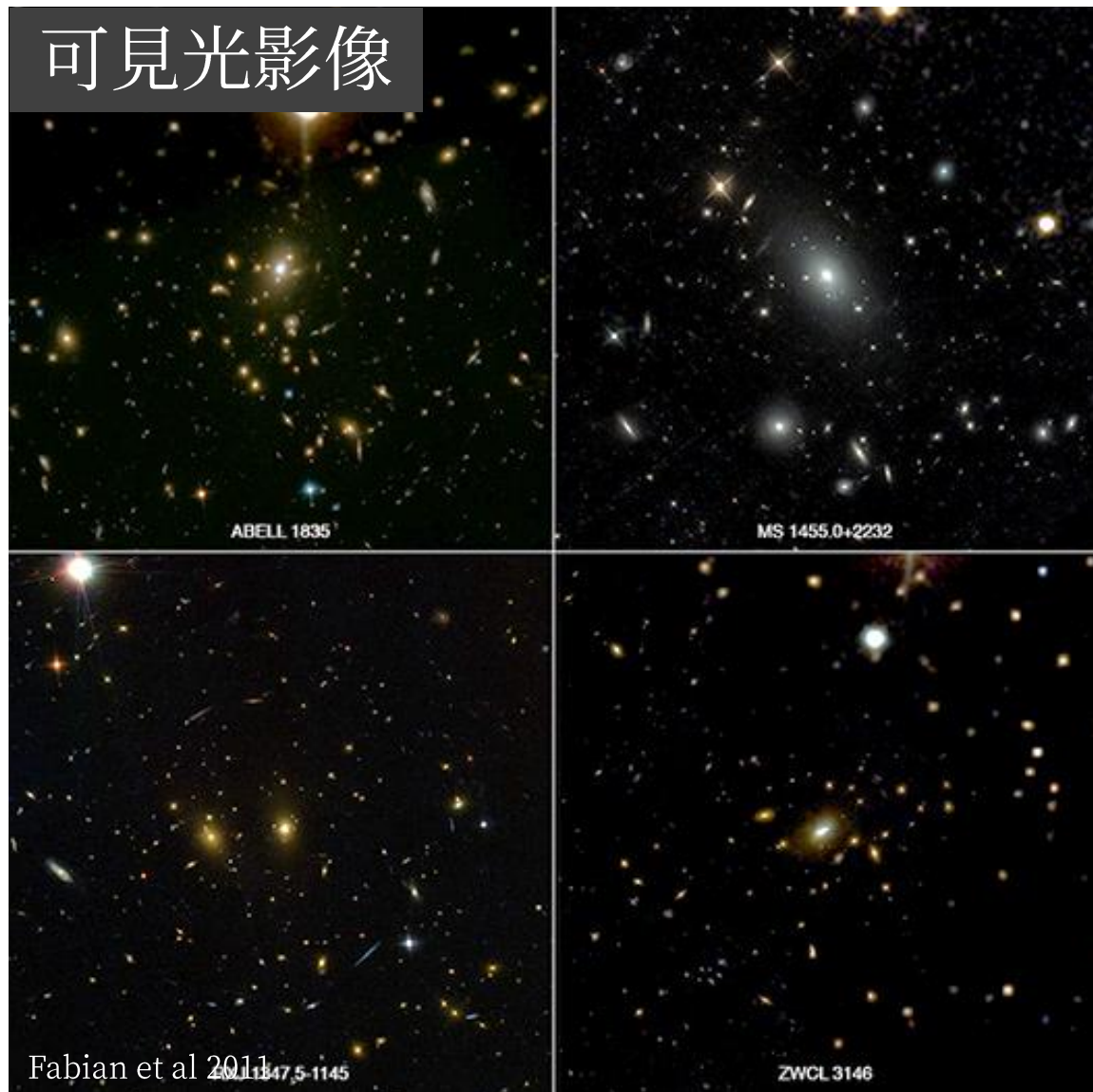


星系團 Galaxy Clusters

約 1000 個星系

SMACS 0723 | NASA, ESA, CSA, STScI

可見光影像

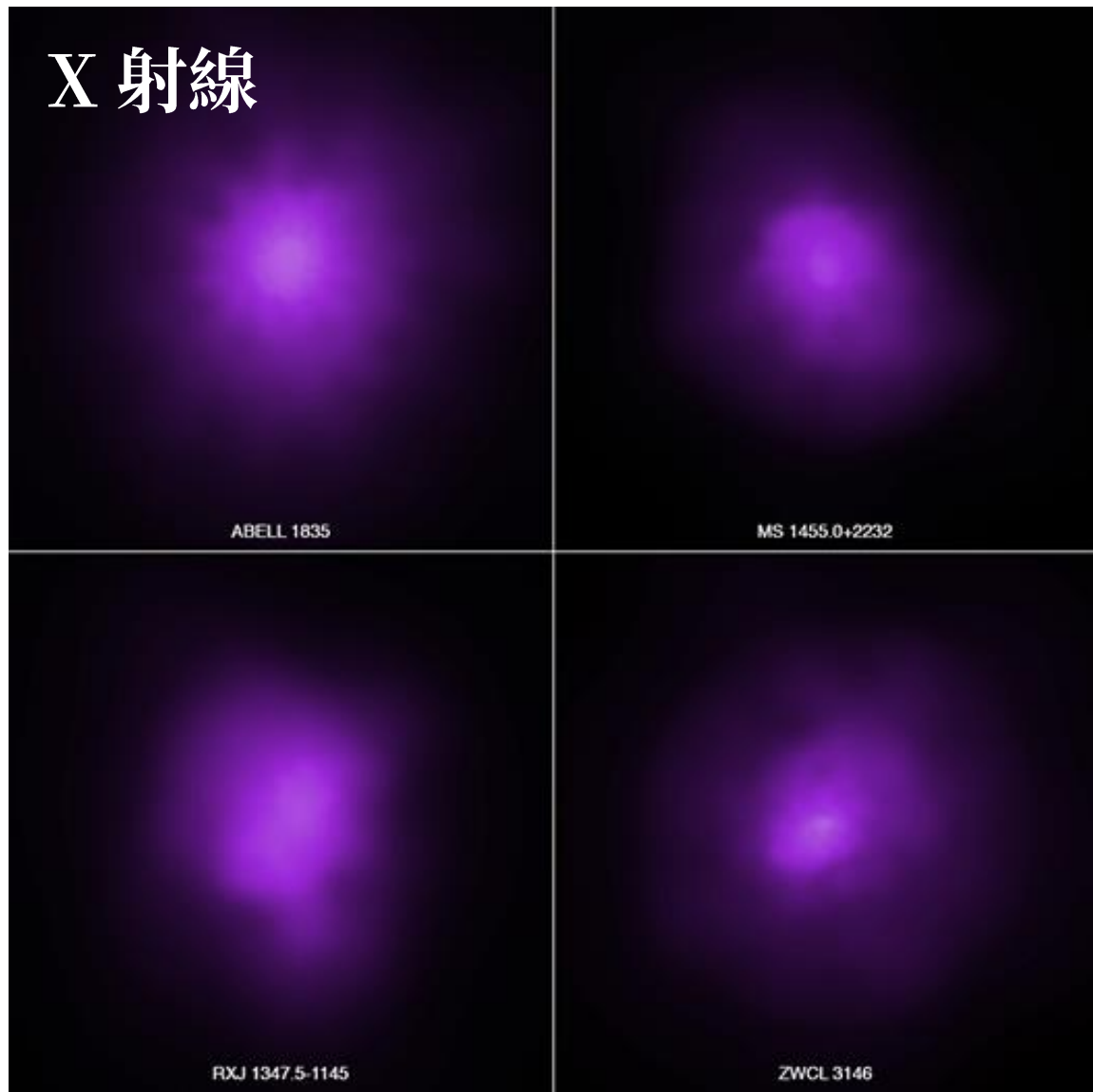


星系團 Galaxy Clusters

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

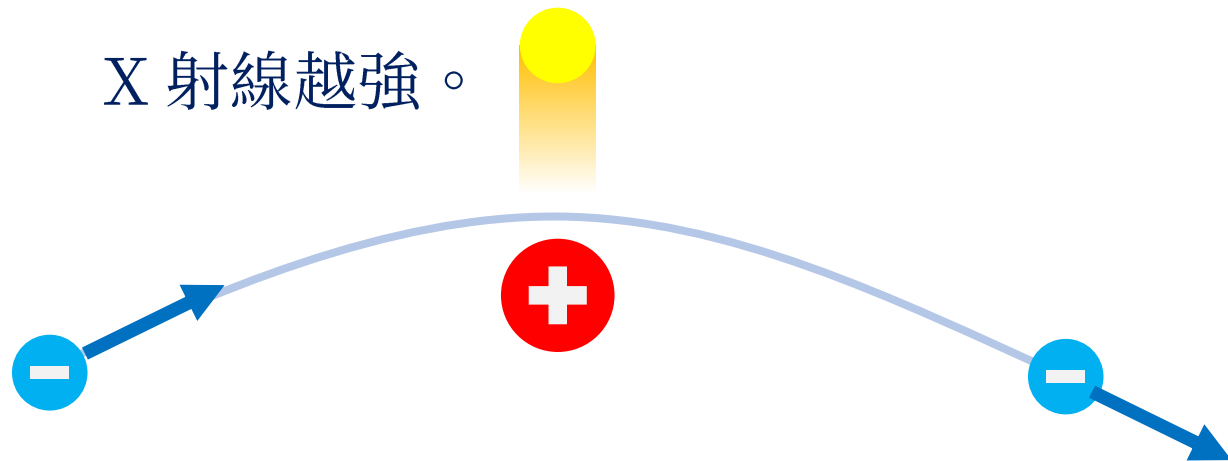
X 射線



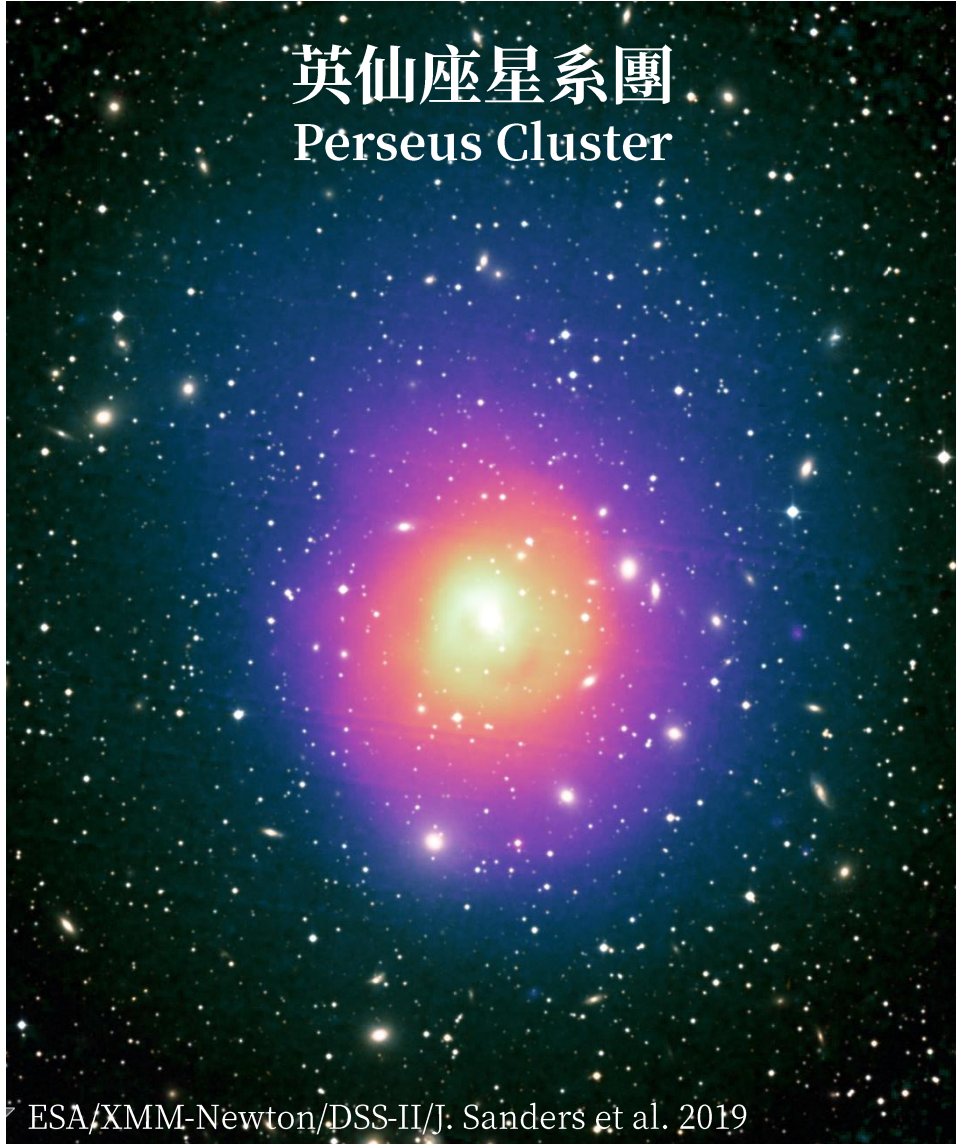
星系團內介質 ICM

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



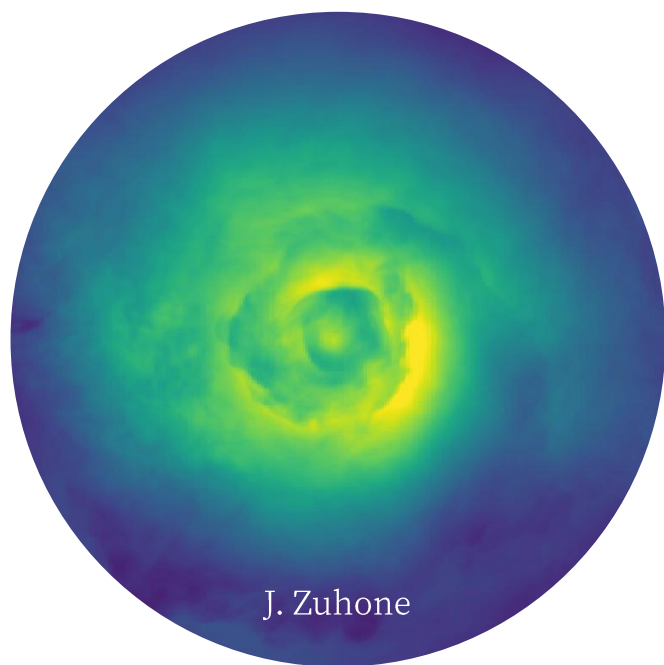
ESA/XMM-Newton/DSS-II/J. Sanders et al. 2019

冷卻流問題 Cooling Flow Problem

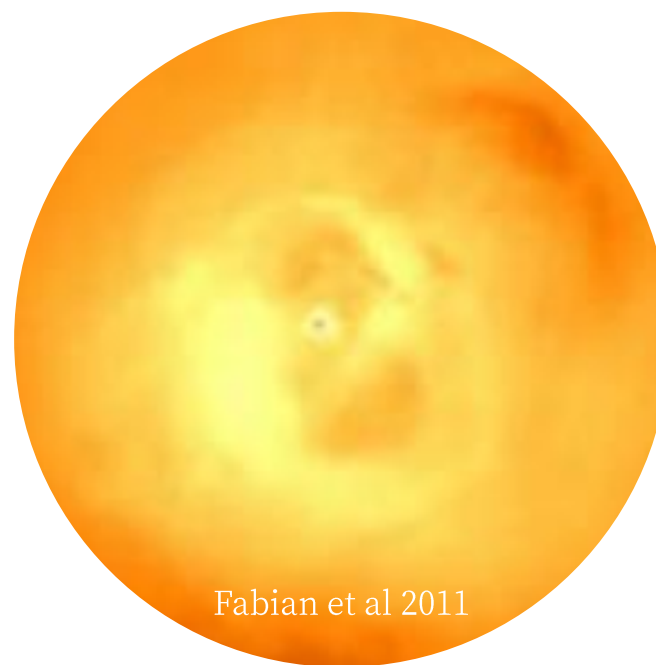
- 有些星系團在 X 射線波段「太亮了」。
- 從 X 射線觀測：
發出 X 射線 → 失去能量 → 壓力降低 →
冷卻的氣體落入中心 BCG → 大量恆星形成
- 從可見光觀測：
BCG 恆星形成率比預期低一個數量級
- 為甚麼會這樣呢？
這被稱為冷卻流問題 Cooling Flow Problem

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



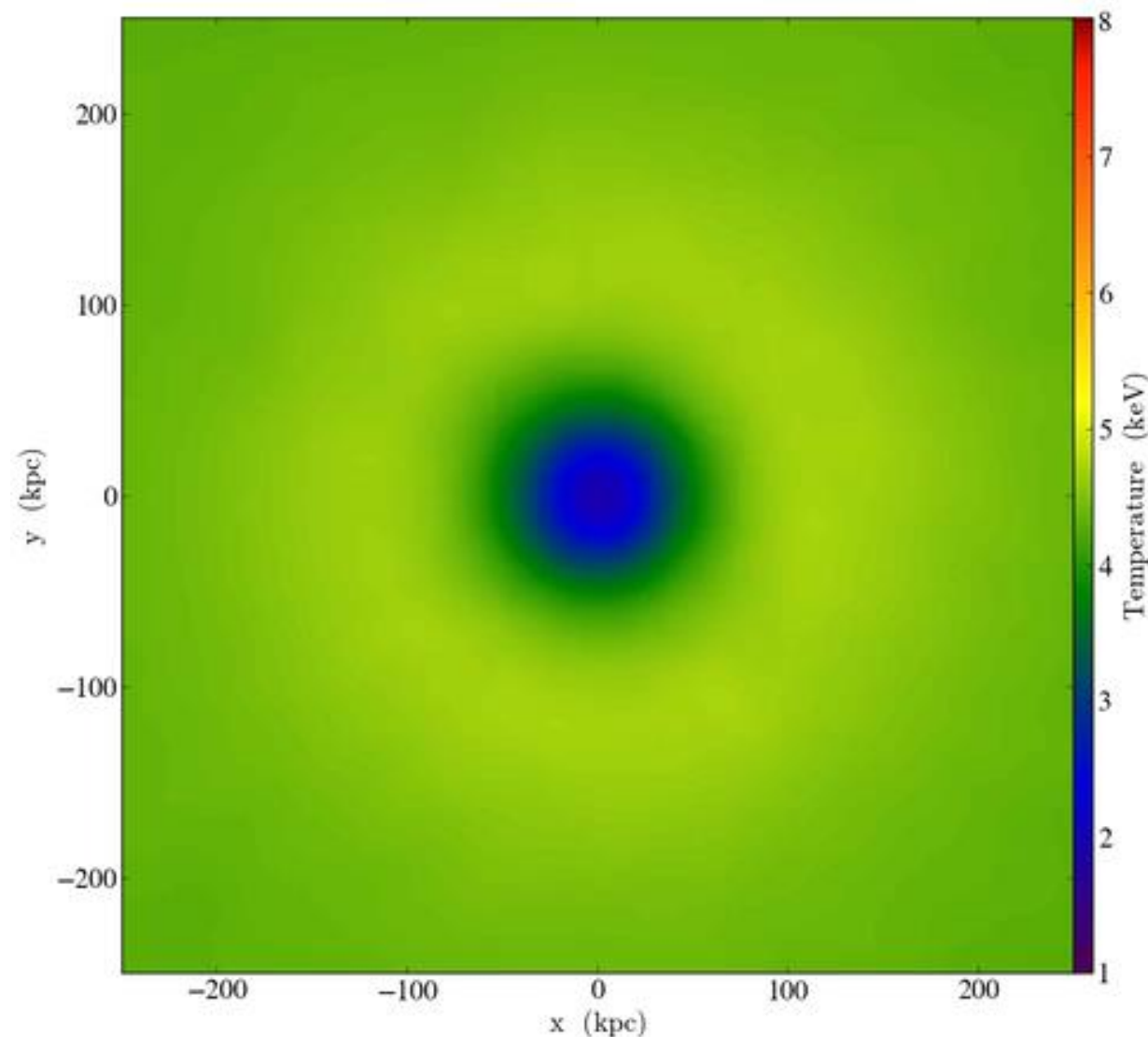
氣體晃盪 Gas Sloshing



黑洞噴流 AGN Jets

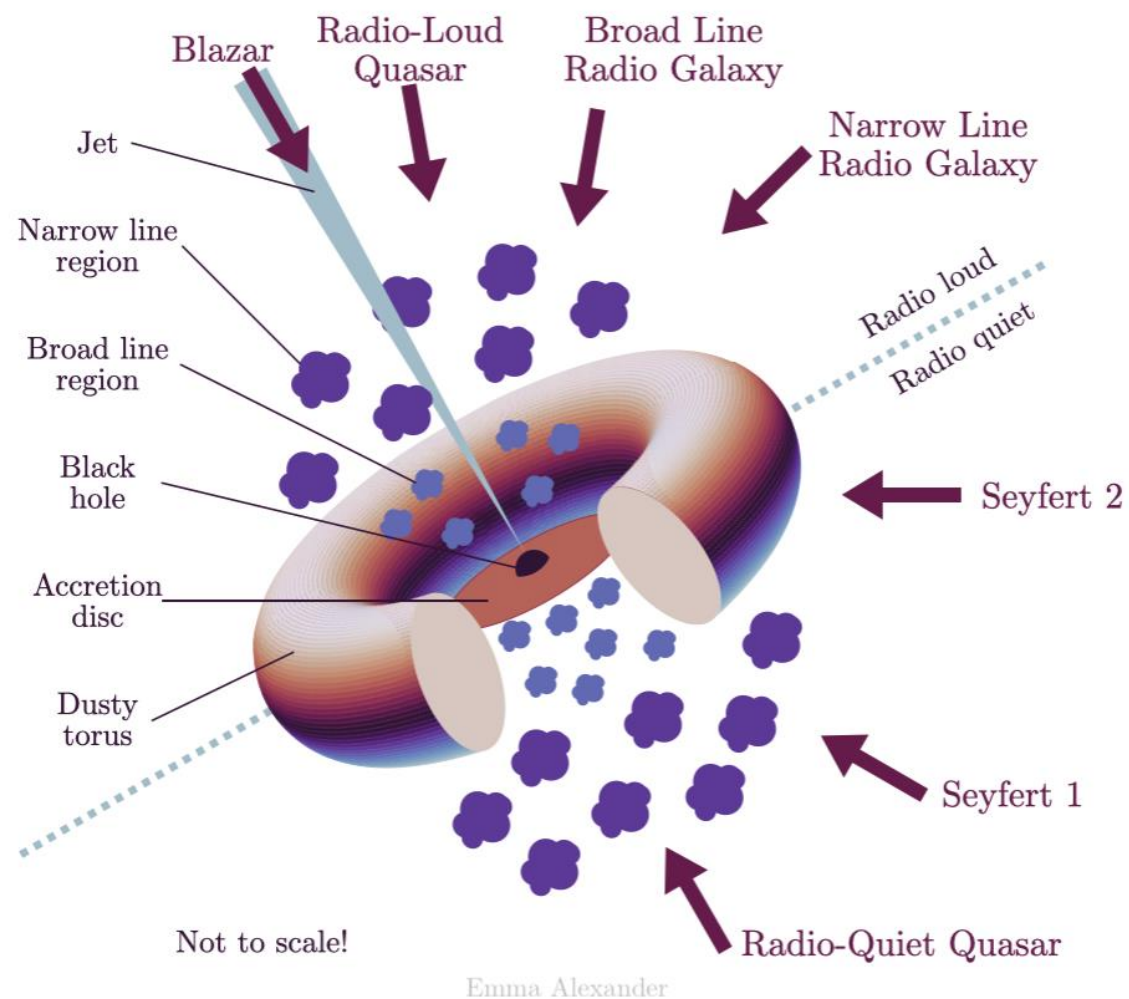
氣體晃蕩 Gas sloshing

- 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



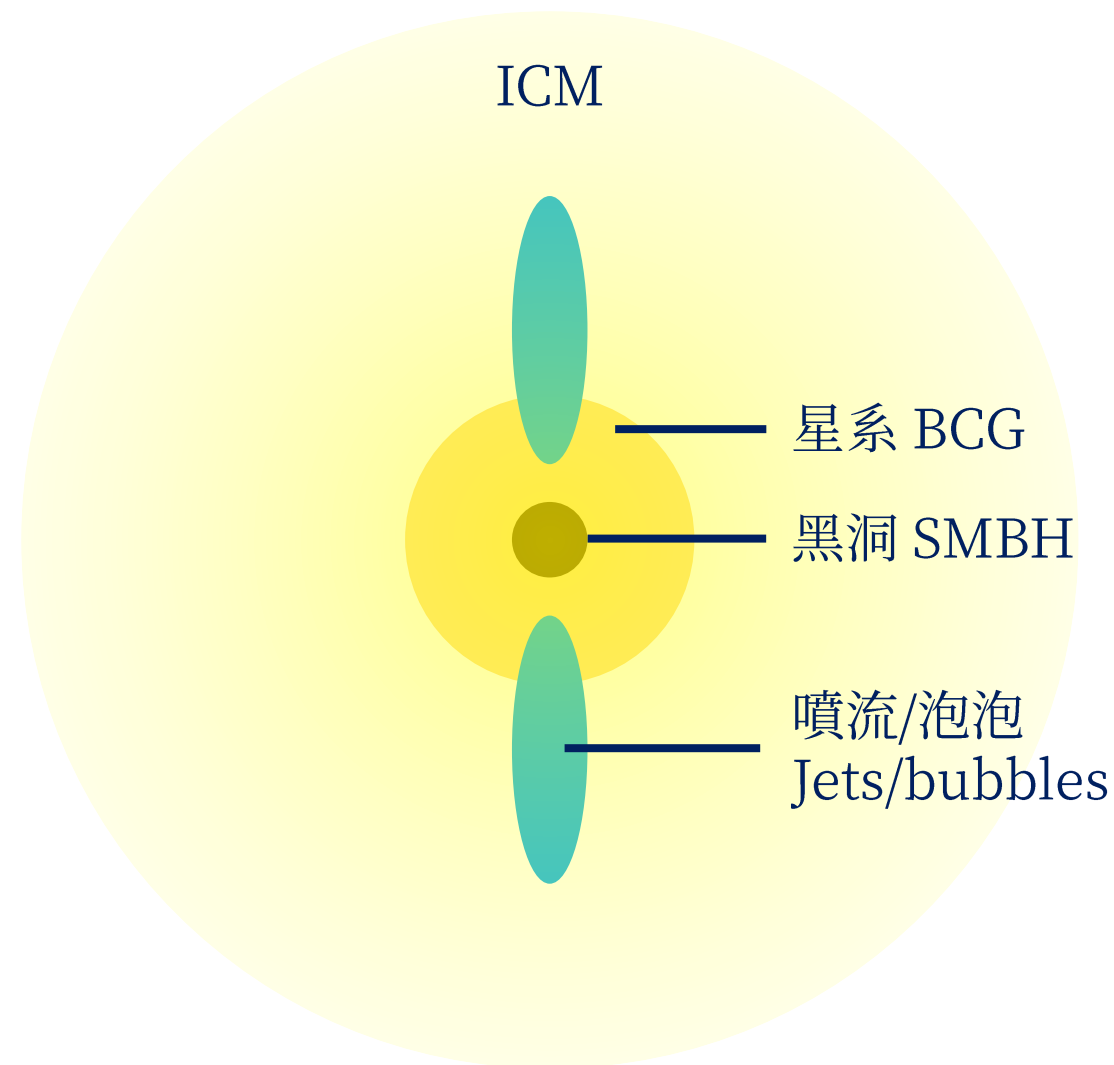
活躍星系核回饋 AGN Feedback

- 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

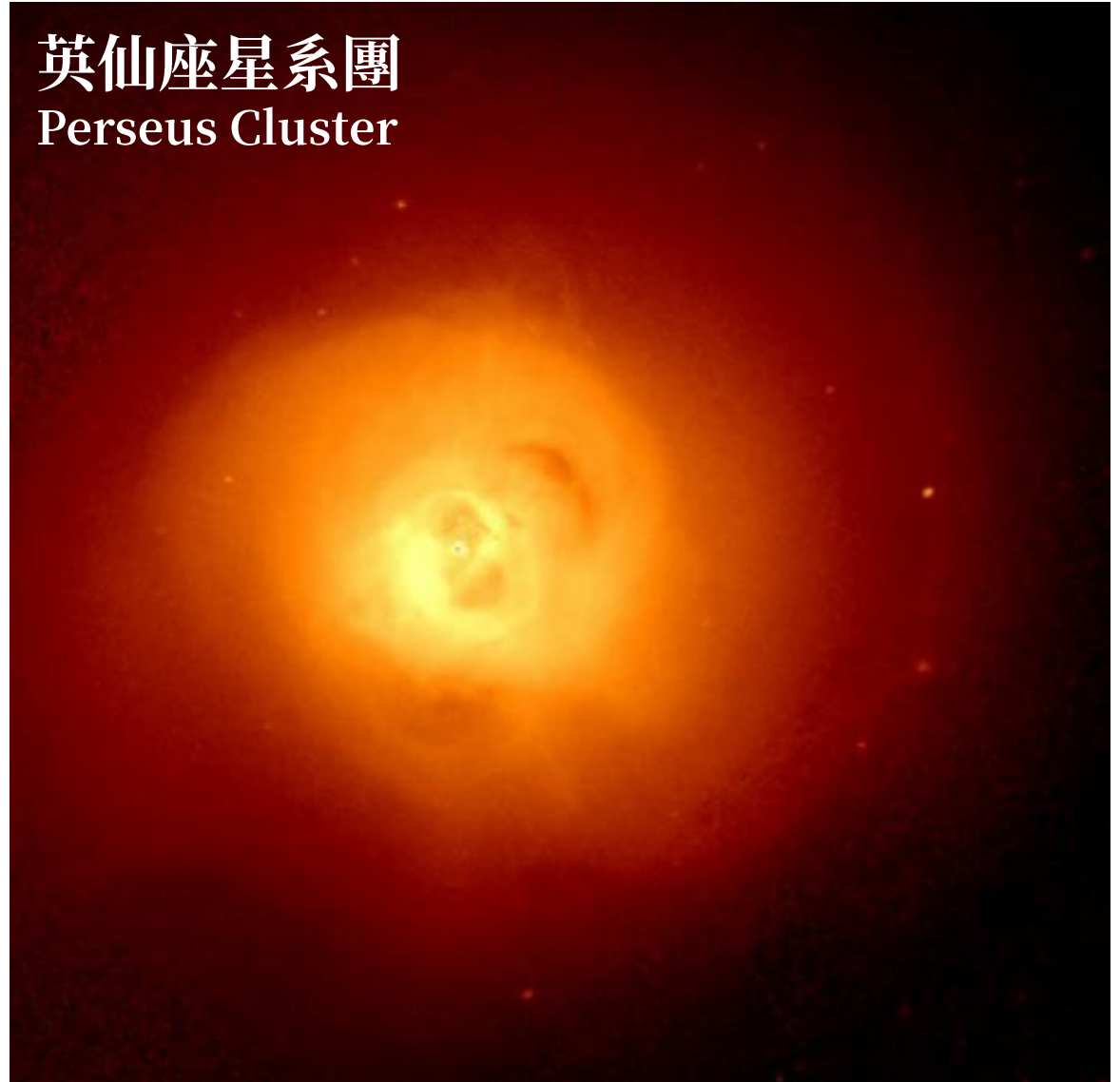


非實際比例

觀測星系團中的黑洞噴流

- Jet mode feedback
 - 擁有眾多觀測證據支持
- 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

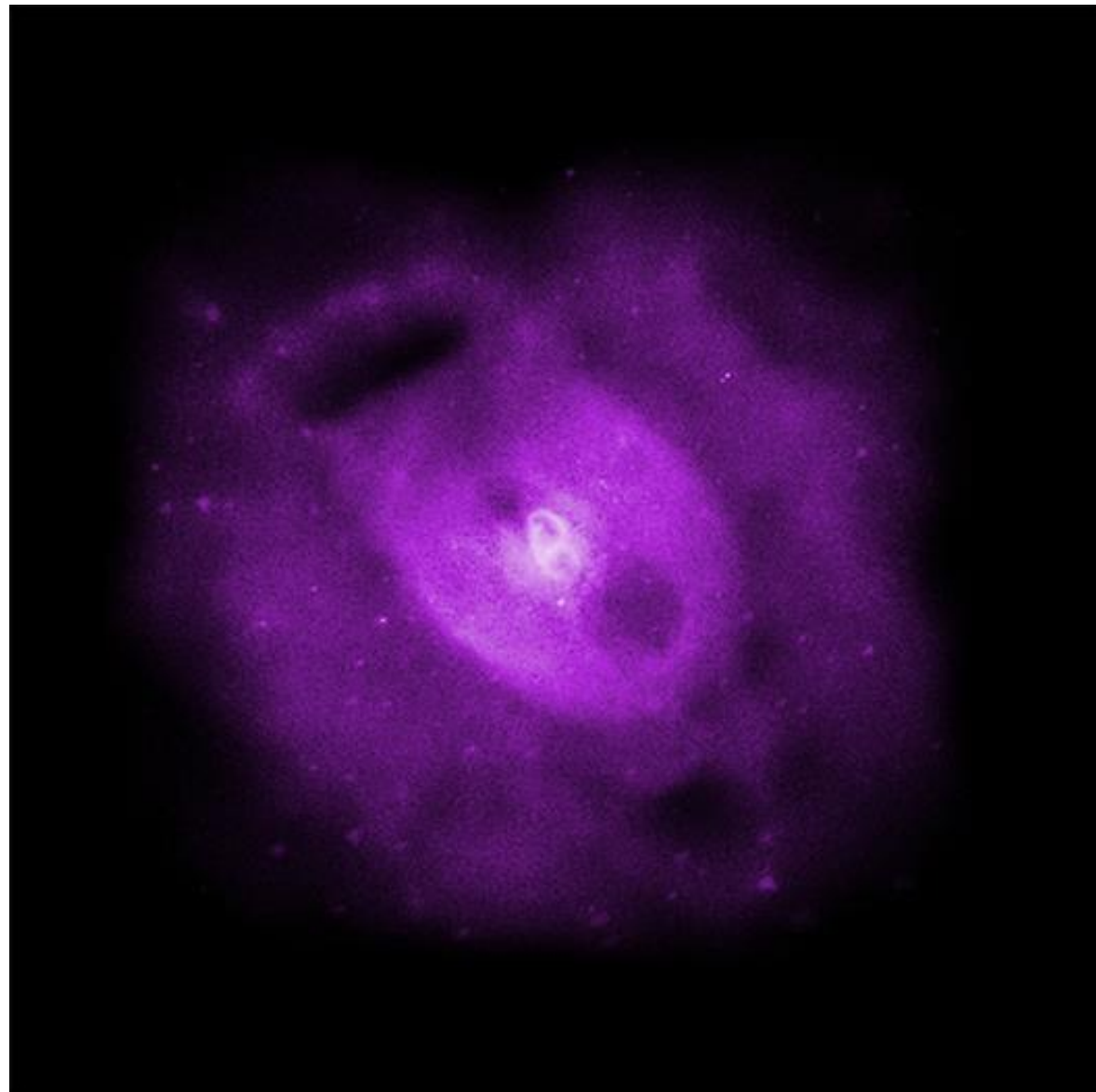
英仙座星系團
Perseus Cluster



NGC 5813 星系群



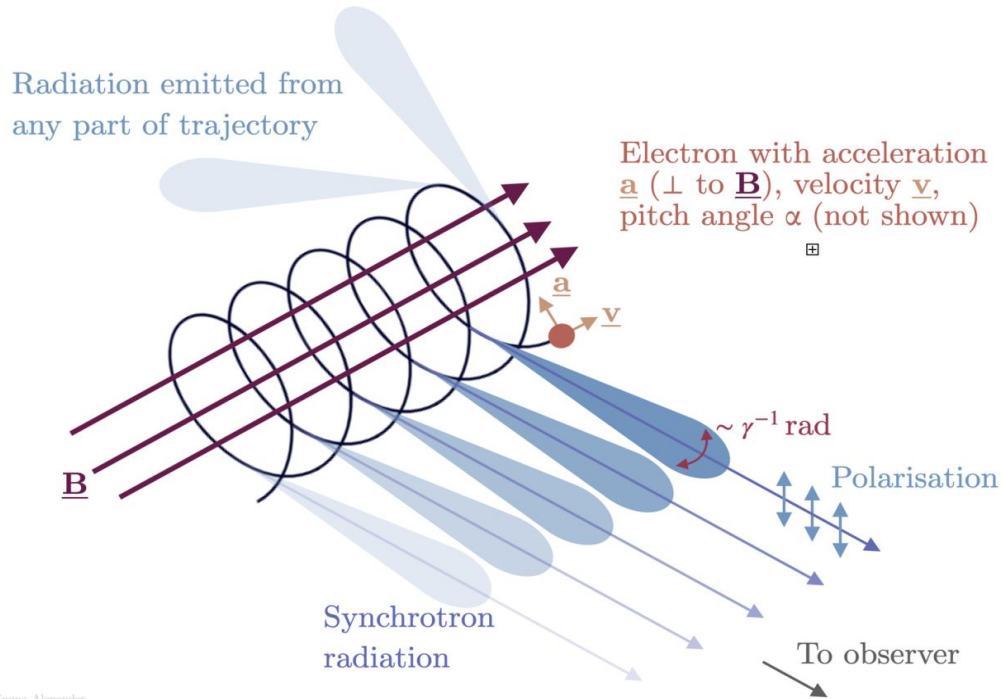
X-ray: NASA/CXC/SAO/S.Randall et al., Optical: SDSS



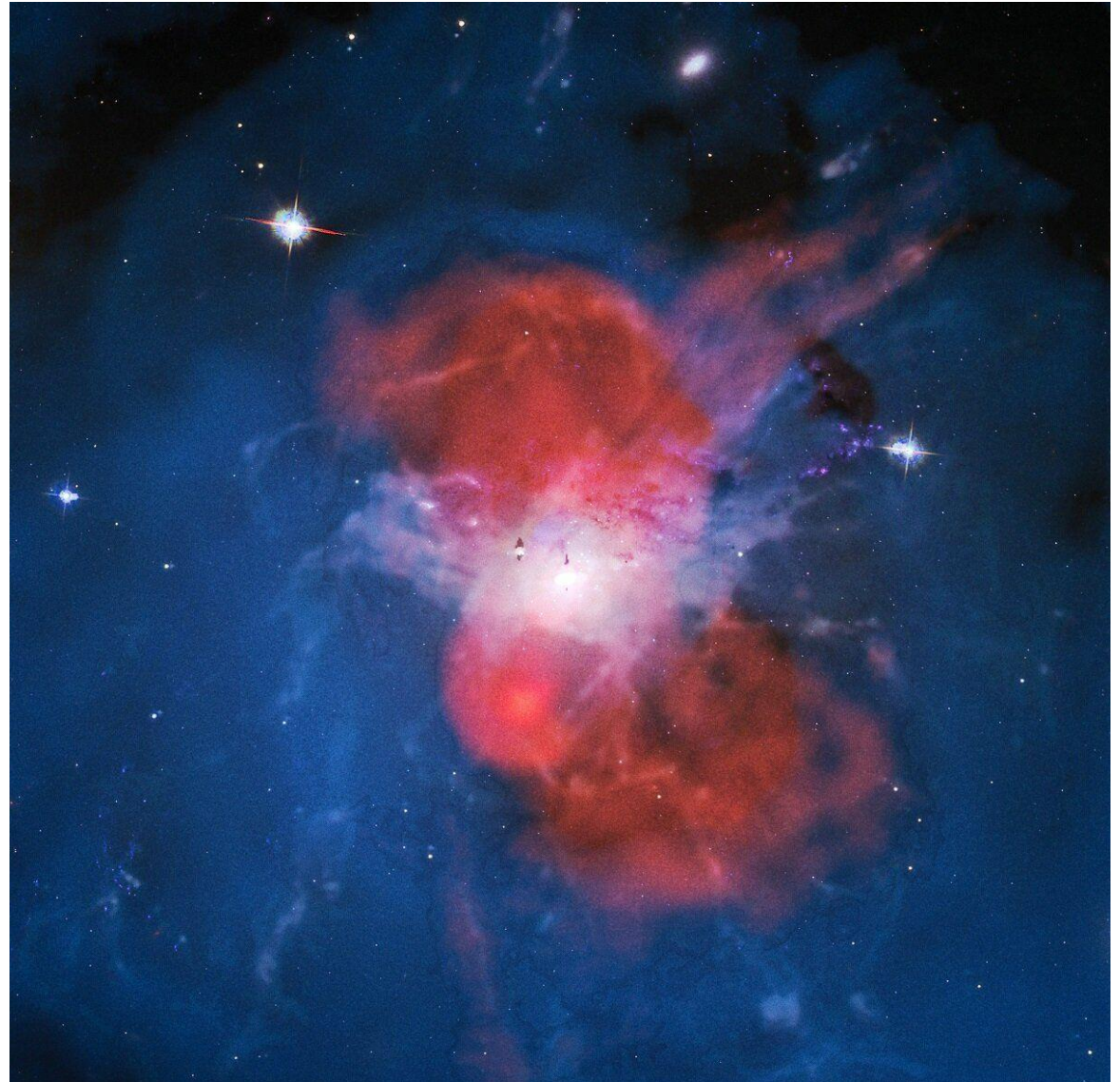
觀測星系團中的黑洞噴流

➤ 電波瓣 Radio Lobe

同步輻射 Synchrotron



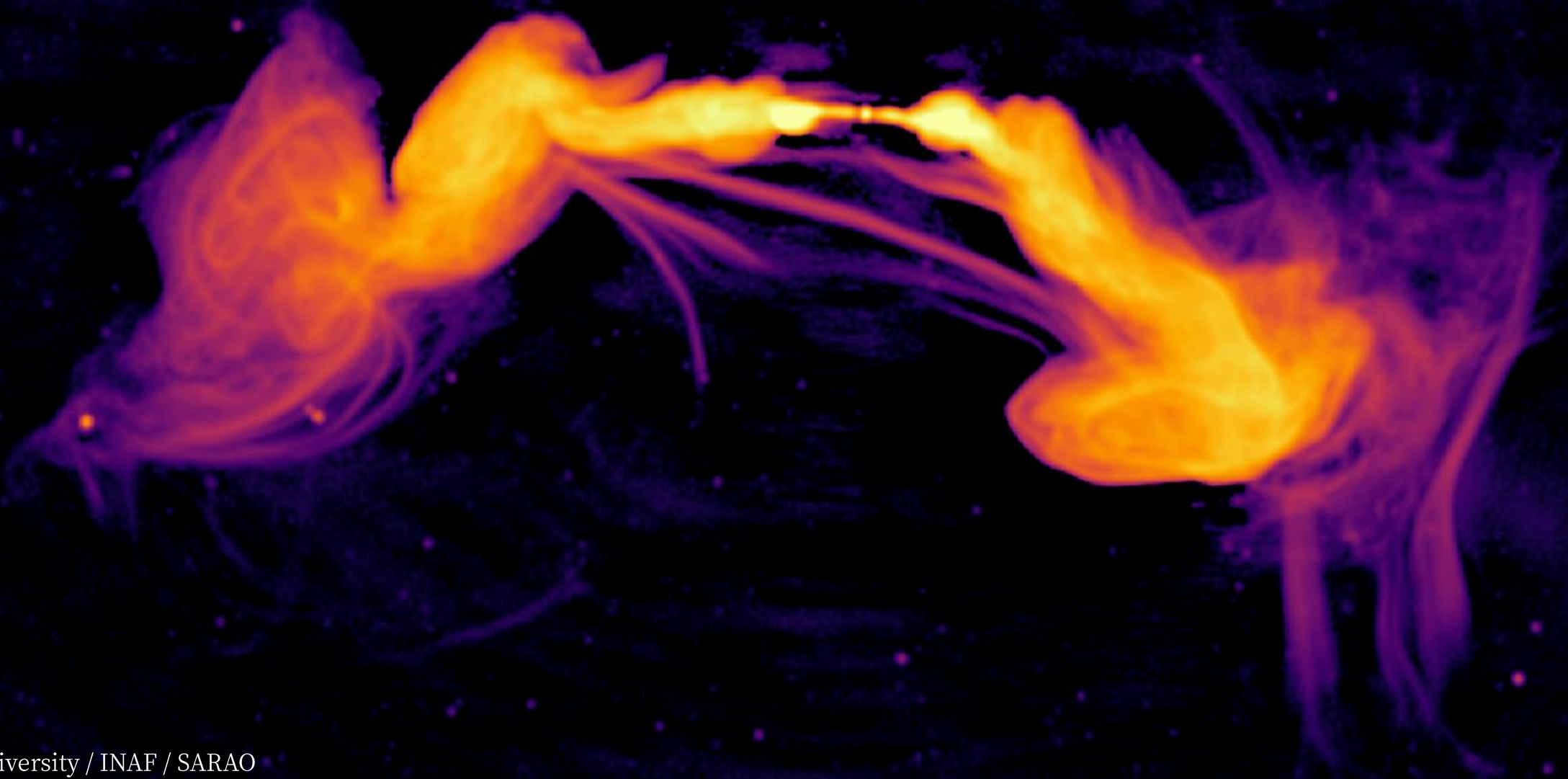
Emma Alexander



半人馬座 A 星系



ESO 137-006 星系 (矩尺座星系團)



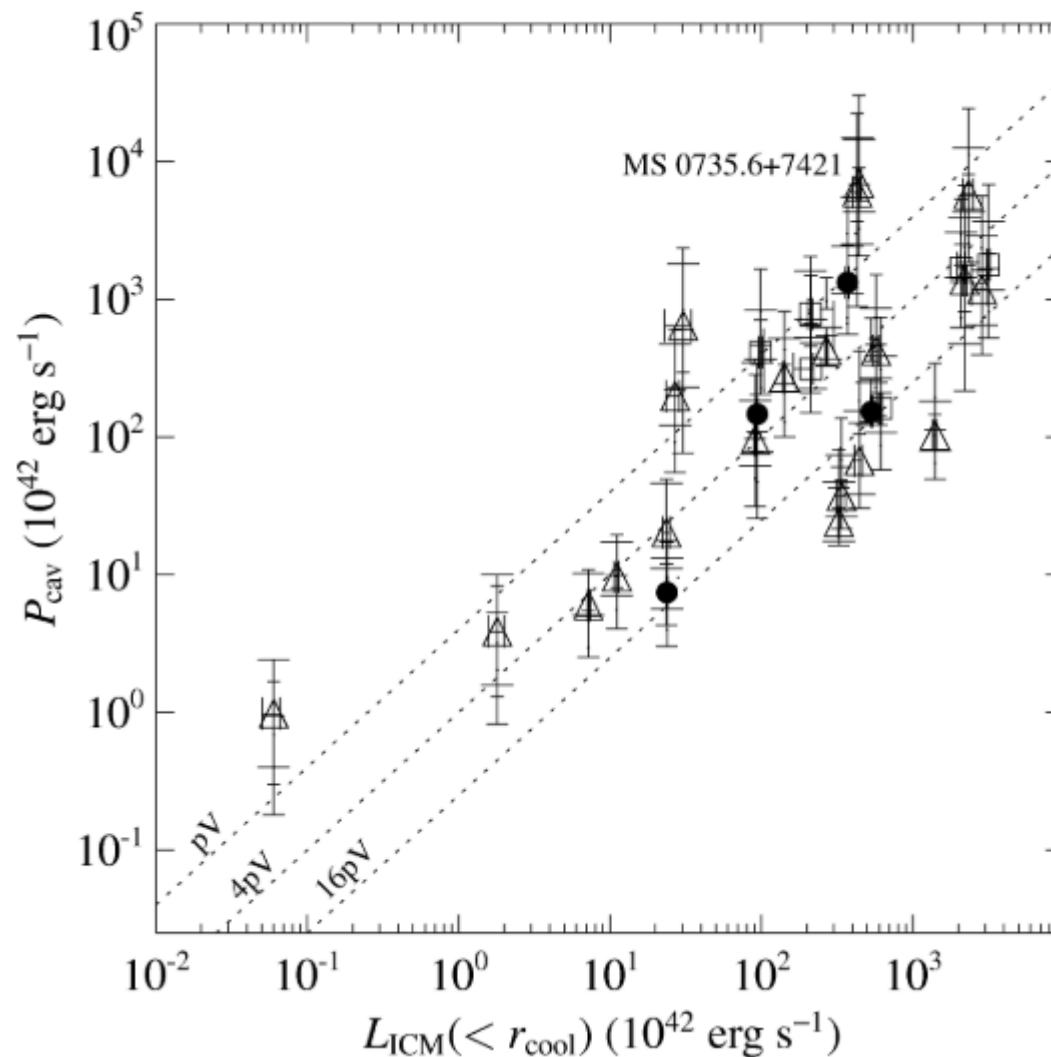
觀測泡泡的性質



- 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

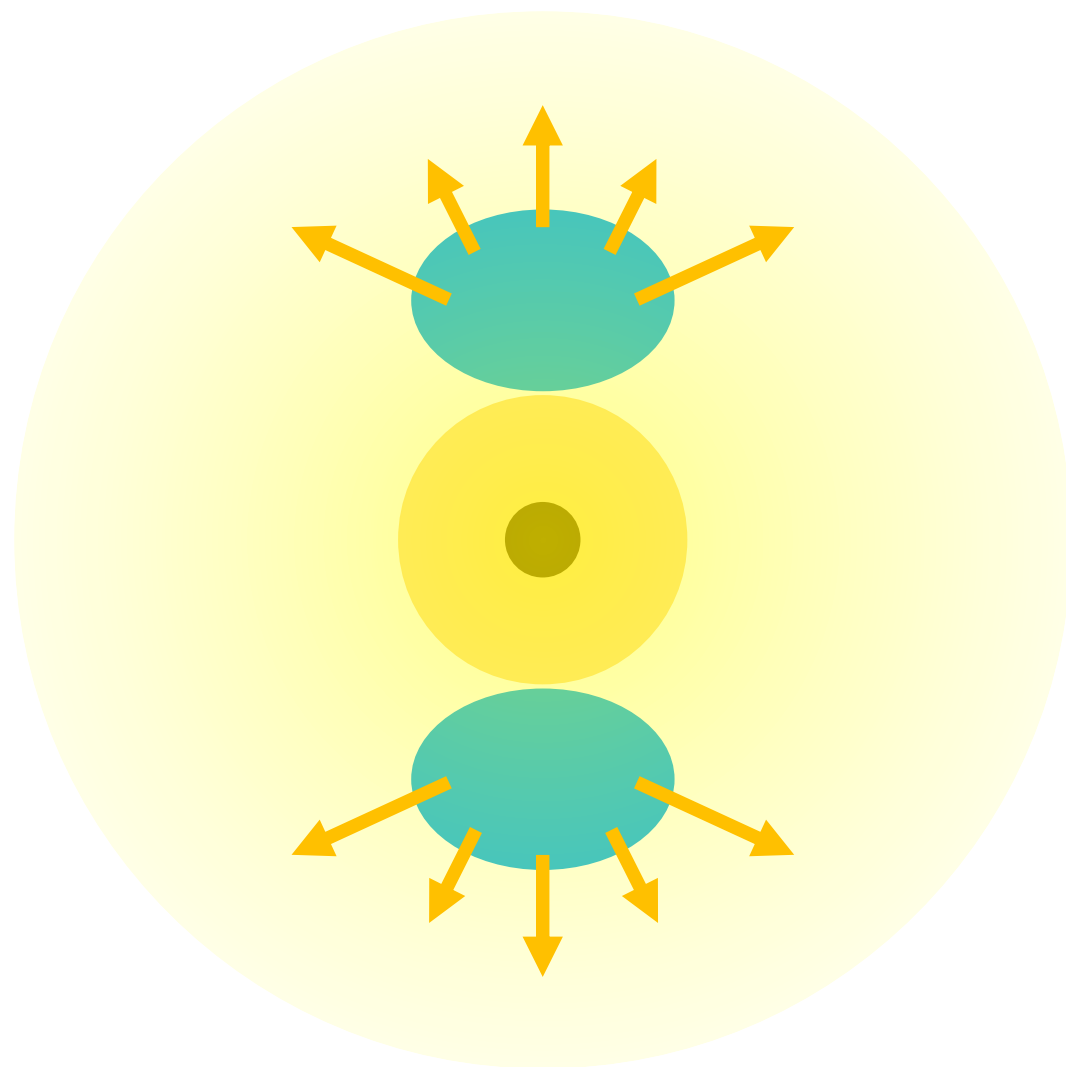
- 泡泡功率 (加熱)
X 射線光度 (冷卻)
有橫跨多個數量級的正相關
- 無線電光度—X 射線光度
黑洞質量—星系質量 (M-sigma relation)
等特性也有類似關係
- 佐證 AGN 回饋確實存在
是影響星系演化的重要推手



Rafferty et al. 2006

AGN 回饋的未解問題之一

- 泡泡究竟是怎麼加熱 ICM 的？
 - 震波加熱 Shock Wave
 - 音波 Sound Wave
 - 紊流 Turbulence
 - 熱傳導 Thermal Conduction
 - 混合 Direct Mixing
 - 宇宙射線 Cosmic-ray
- 如何研究這些加熱機制？



方法

磁流體力學模擬 MHD Simulations

流體力學 Hydrodynamics

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

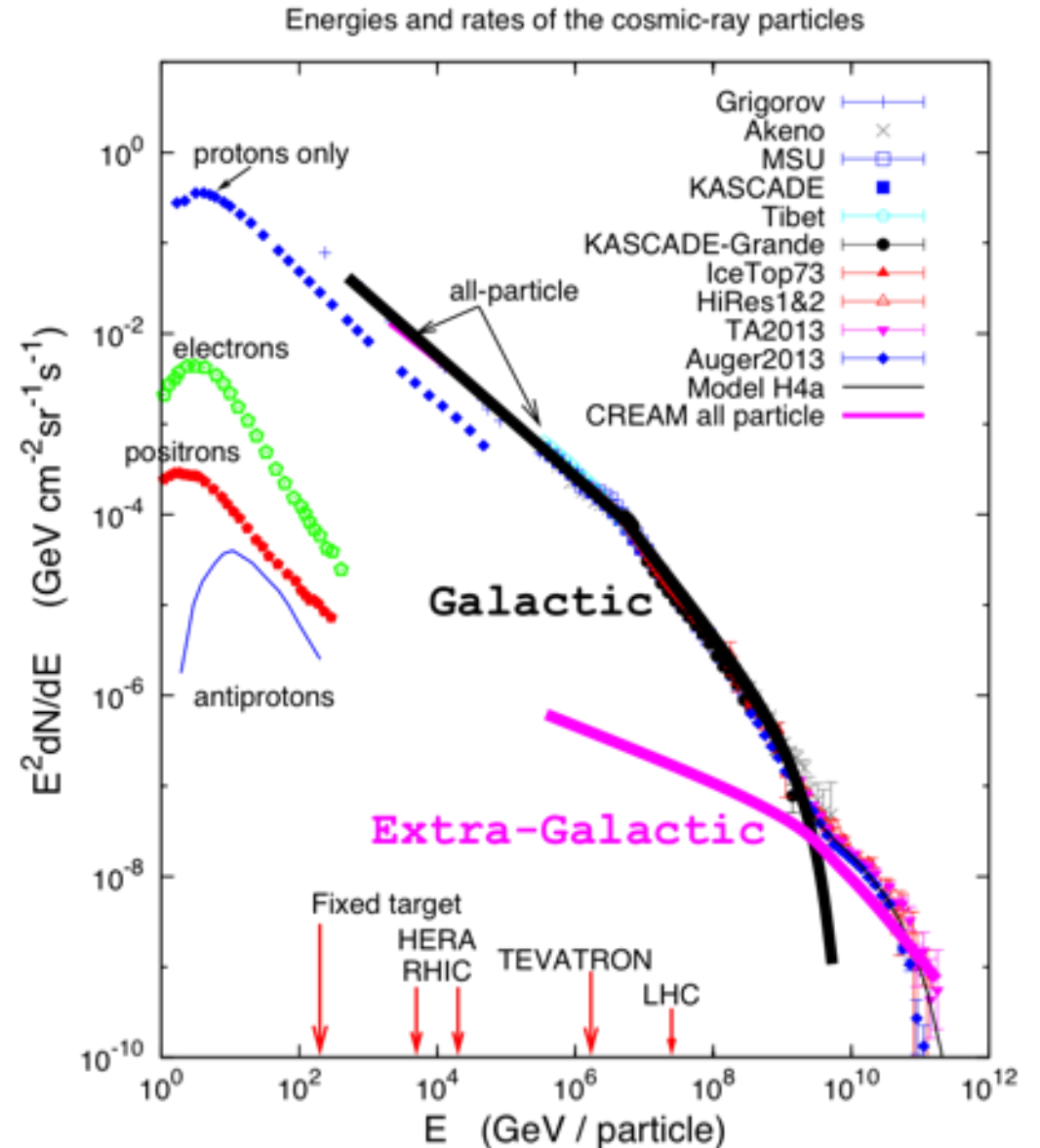
$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v} \otimes \mathbf{v}) + \nabla p_{\text{tot}} = \rho \mathbf{g} \quad \text{動量守恆 Momentum Conservation}$$

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

Hydrodynamics provides a general framework to efficiently include complicated physics.

Cosmic-rays (CR)

- Relativistic particles. Mainly protons (CRp) and electrons (CRe).
- Energy spectrum: power-law from $1 - 10^{12}$ GeV with slope ~ -2.5
- Well scattered by magnetic field
=> CR moves along with gas to the first order
- What is CR doing in galaxy clusters?
Provide pressure, heating, emit radiation.



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

CR diffusion
CR effects on total energy



Cosmic-ray interaction

➤ Hadronic (proton) processes

$$p + p \rightarrow p + p + \pi^0$$

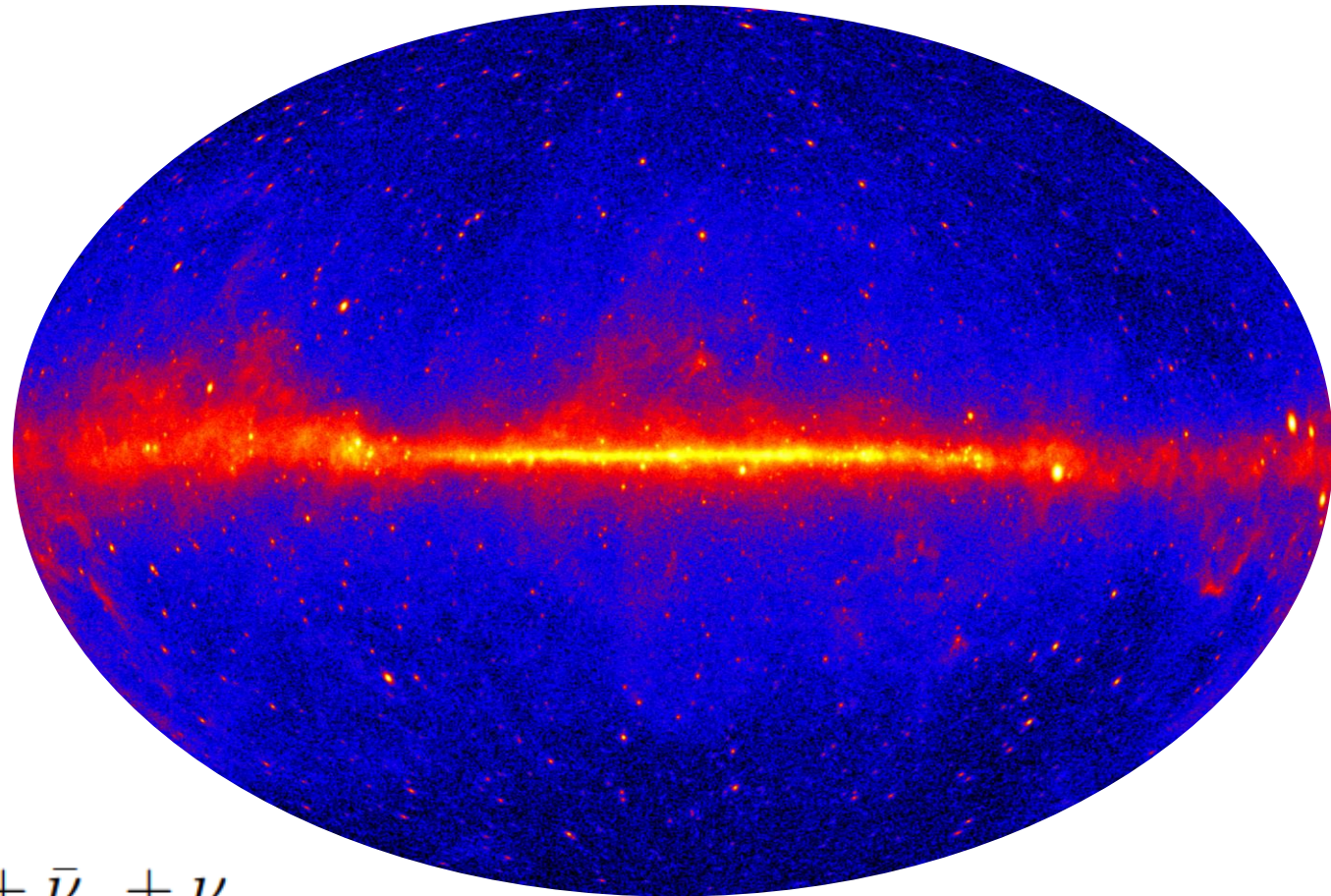
$$p + p \rightarrow p + n + \pi^+$$

$$p + p \rightarrow p + p + \pi^+ + \pi^- \dots$$

$$\pi^0 \rightarrow \gamma + \gamma$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad \text{and} \quad \mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \quad \text{and} \quad \mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$$



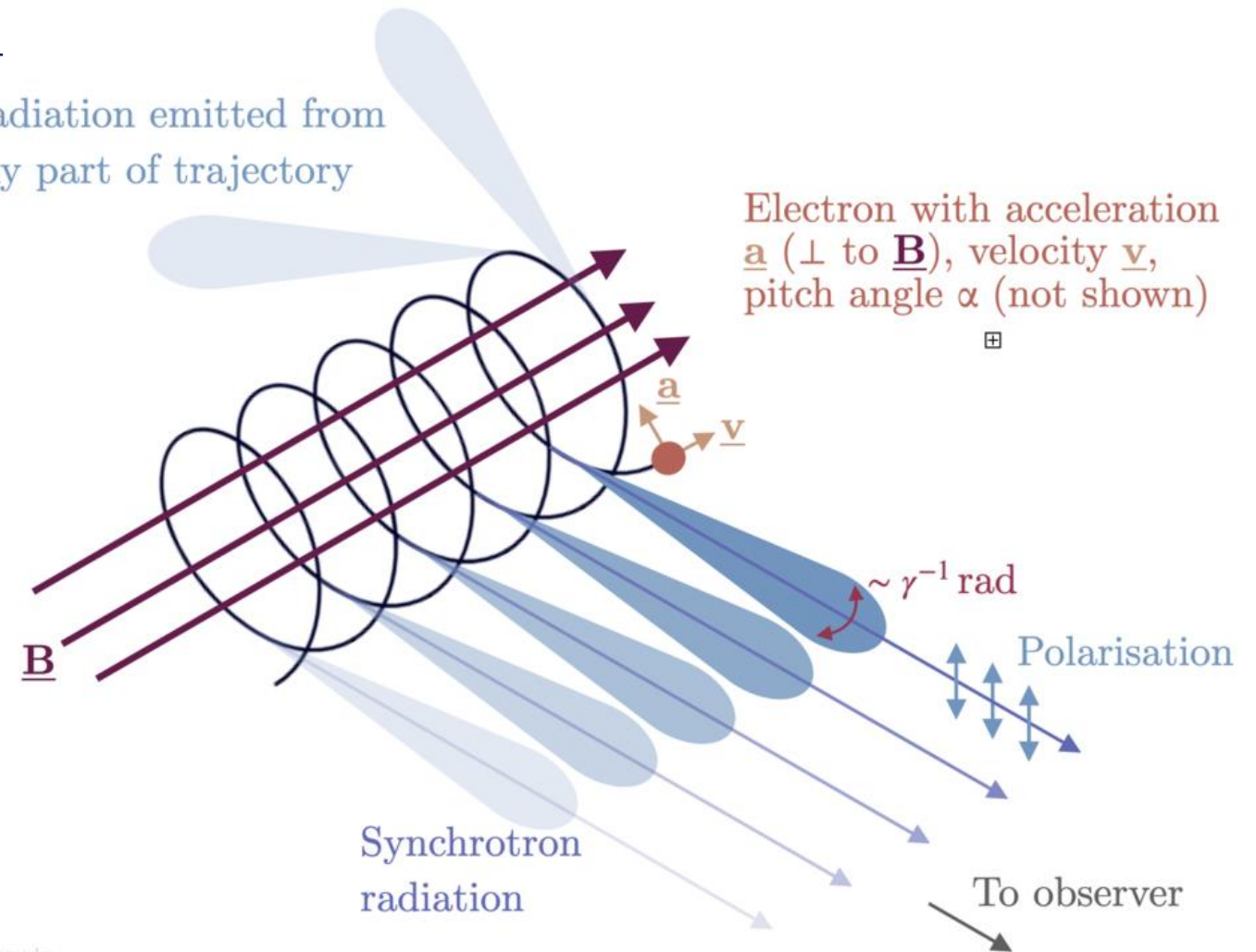
Cosmic-ray interaction

➤ Synchrotron emission

Electron/positron gyrates around magnetic field.
Efficient way of losing energy for CRe.

➤ $\epsilon \propto e_{\text{cr}} B^2$

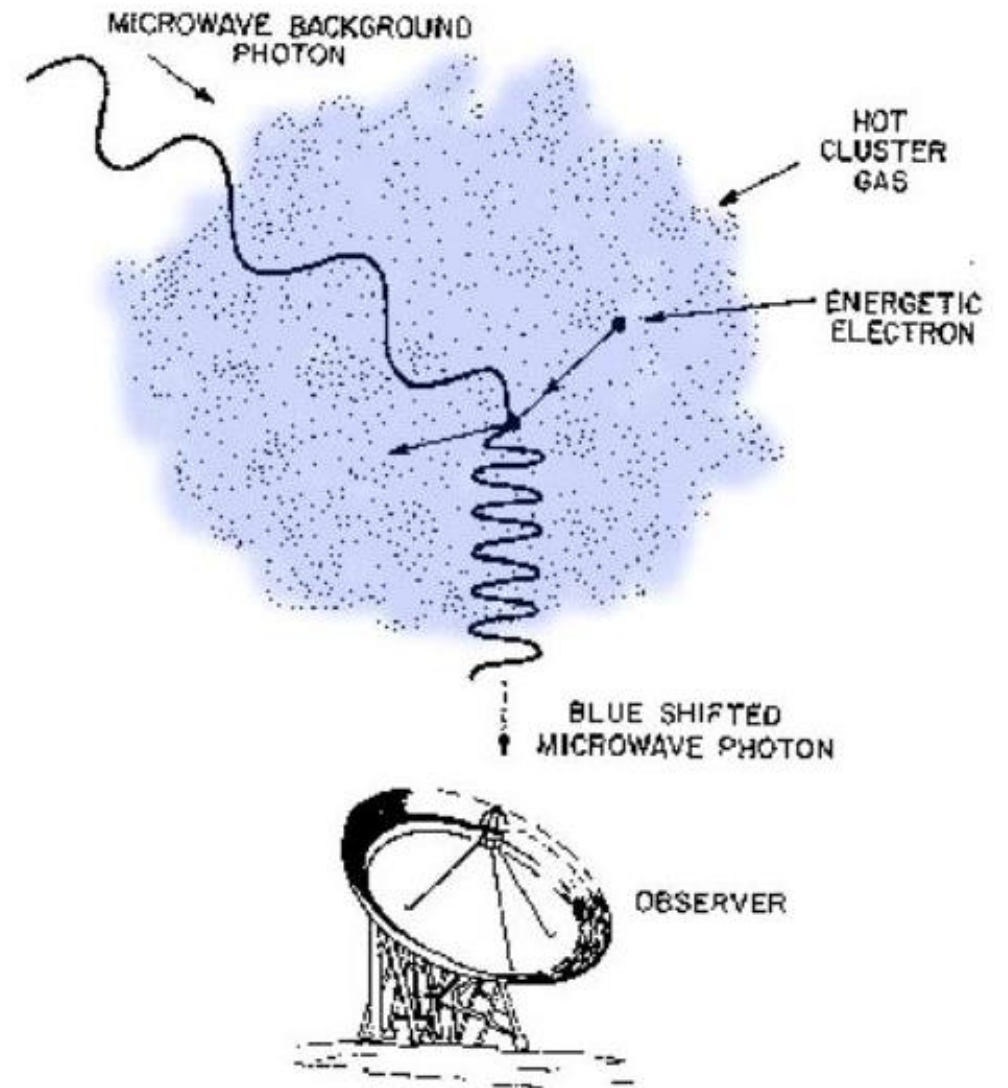
Radiation emitted from any part of trajectory



Emma Alexander

Cosmic-ray interaction

- **Inverse Compton scattering**
Electron/positron collide with CMB photons.
Efficient way of losing energy for CRe.
- $\epsilon \propto e_{\text{cr}} e_{\text{CMB}}$

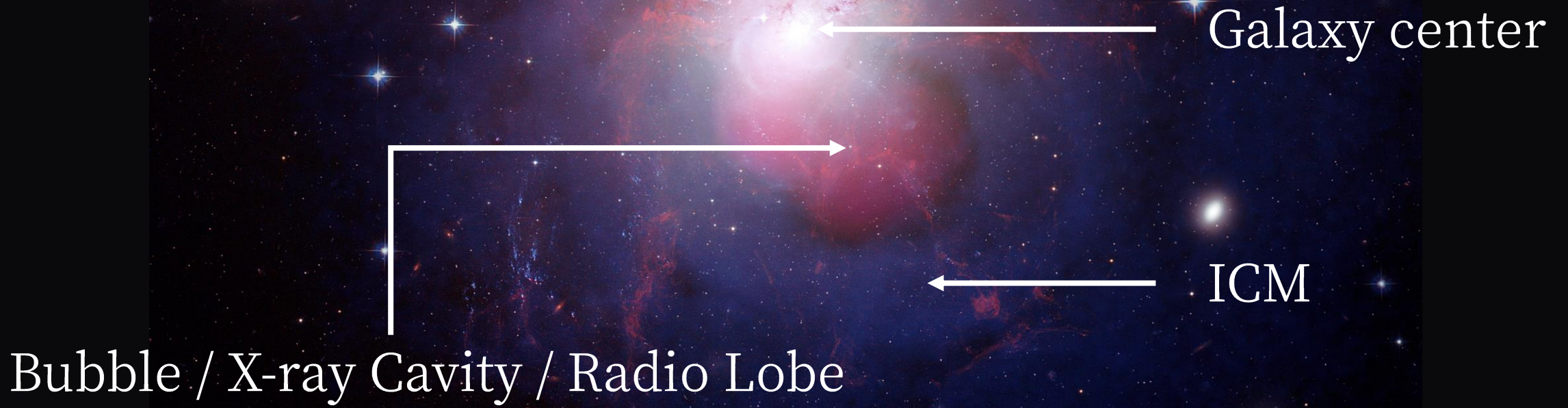


Lin et al. (2023)

Evolution and feedback of AGN jets of different cosmic ray composition

Perseus cluster

HST image overlap with X-ray (blue) and radio (red).



Unsolved problem

- 目前仍不清楚 AGN 噴流具體是怎樣加熱 ICM 的？

可能的機制包括：

震波、聲波、紊流、熱傳導、宇宙射線……等等。

- 噴流的能量組成是什麼？

$$e = e_{\text{th}} + e_{\text{kin}} + e_{\text{B}} + e_{\text{CRp}} + e_{\text{CRe}}$$

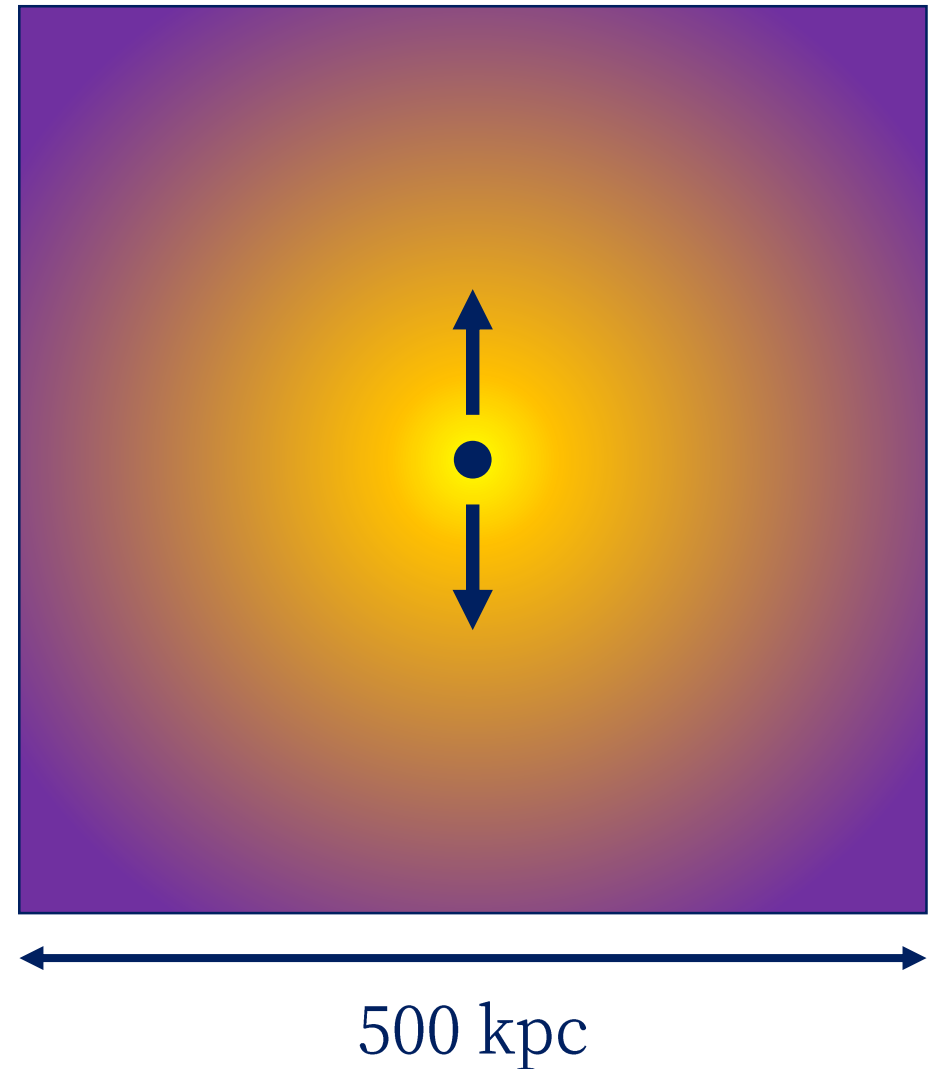
- 觀測證據顯示: [Dunn et al. (2004), Birzan et al. (2008), Croston et al. (2018)]

可能存在 **CRp** 或 **CRe** 主導的噴流。

- 以宇宙射線 + 磁流體力學模擬探討 CRp 與 CRe 噴流與它們形成的泡泡會如何演化並加熱 ICM。

Simulation Setup

- Code: FLASH 4.2.2 (modified)
- Similar to Perseus Cluster
- Box size: 500 kpc
- NFW Profile of gravitational potential
- Gas profile from Perseus
- Eject bipolar jet at the center
- Jet power: 5×10^{45} erg/s
- Jet duration: 10 Myr



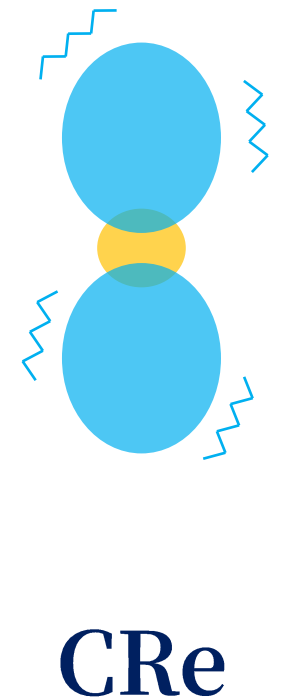
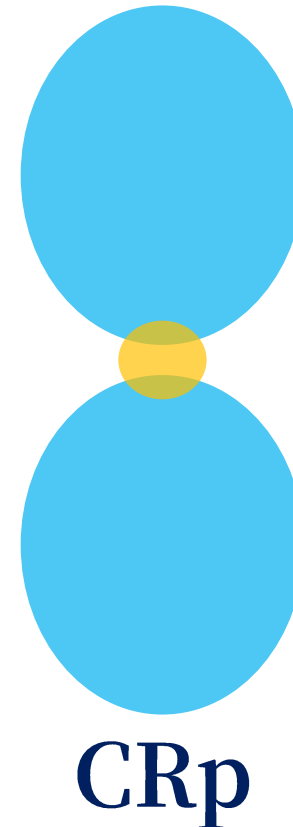
Key difference between CRp and CRe

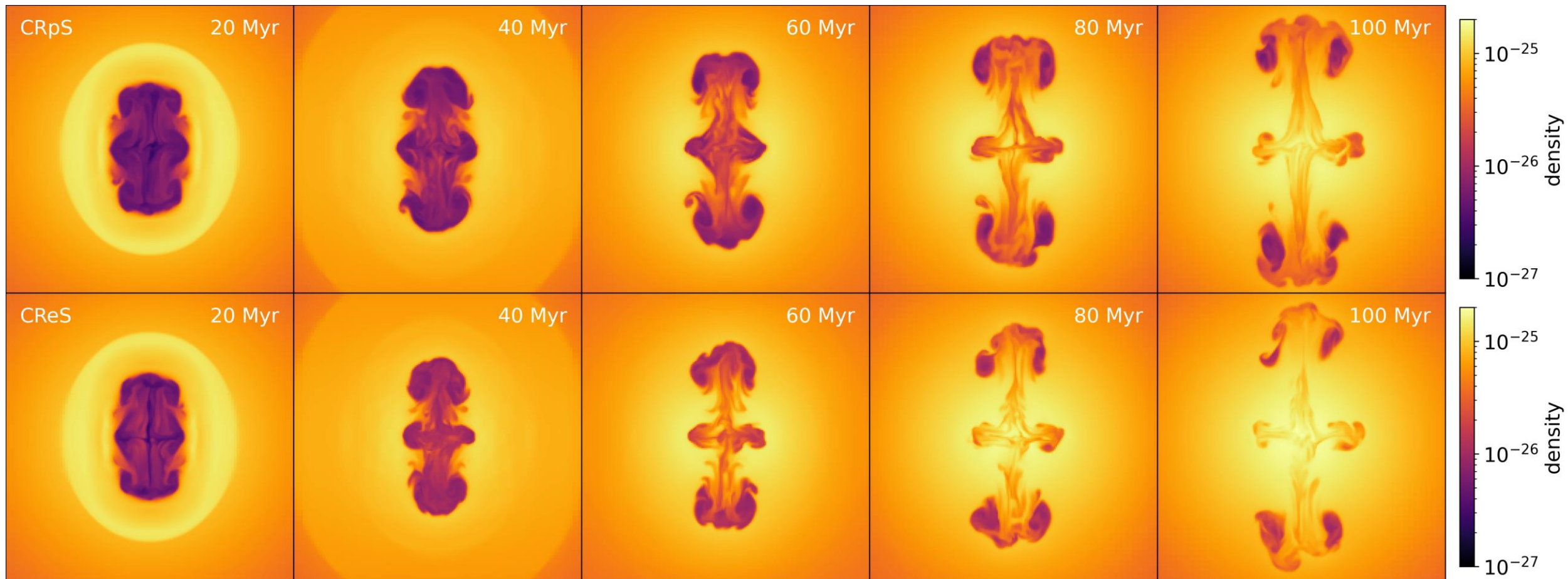
Cooling: $CRe \gg CRp$ (Synchrotron + inverse Compton scattering with CMB)

Heating: $CRp > CRe$ (Coulomb + Hadronic collision)

Expectation:

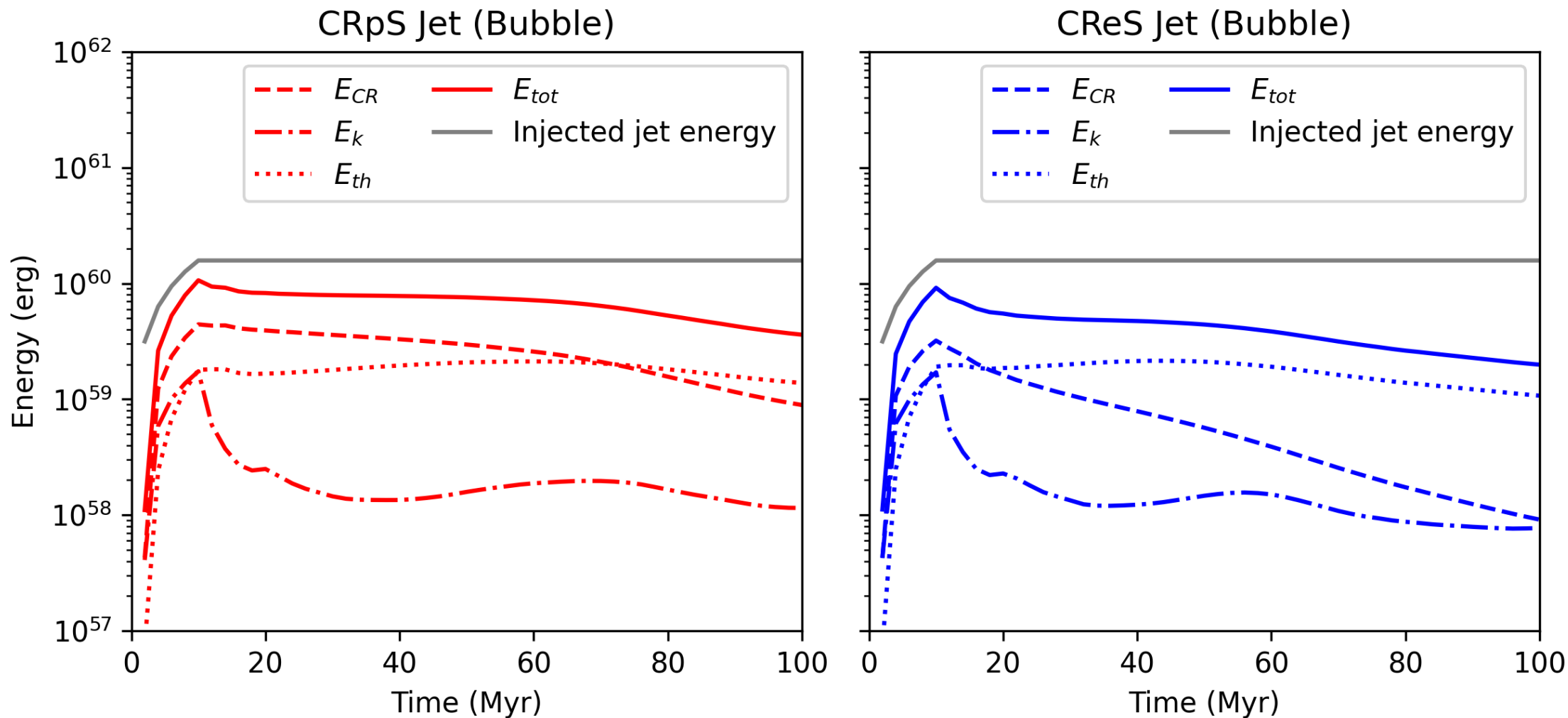
- Dynamics: Blowing a balloon with holes.
 - CRe jets might fail to inflate bubble.
 - CRe bubbles might deflates.
- Heating: Can not heatup ICM
 - A failed AGN feedback?



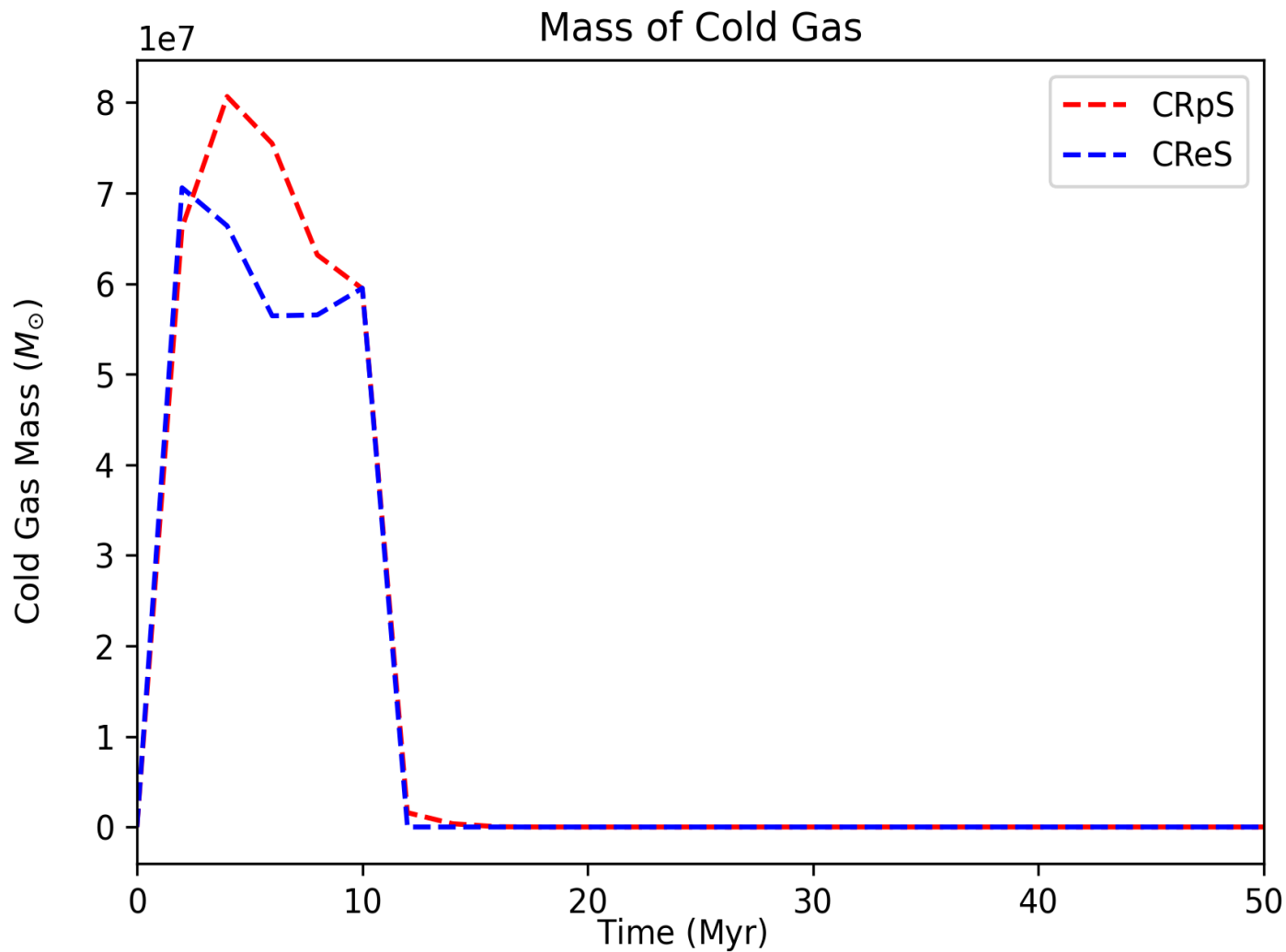


Result

CRp and CRe bubbles are quite similar! Why?



Evolution of different energy component in the bubbles



Heating to ICM

- Mass of cold ($T < 5 \times 10^5$ K) gas is usually used to measure heating efficiency.
- Initial rise due to rapid expansion induced local thermal instability.
- Quickly heat up by the bubbles within 10 Myr.

CRpS

60Myr

CReS

60Myr



Key results

1. Despite difference in cooling, CRe and CRp bubbles have similar dynamical evolution.
2. CRe bubbles quickly become thermal bubbles within ~ 20 Myr.
3. CRp/CRe jets/bubbles can provide similar heating/feedback to the ICM.

