Cosmology and astrophysics with galaxy clusters

from radio to γ-ray observations

Rémi Adam (LLR)

LPNHE seminar — July 8th 2019

Outline

1. Clusters of galaxies as cosmic laboratories

2. Mapping the hot gas in the millimeter & X-ray

3. The quest for cluster cosmic rays in the γ-rays

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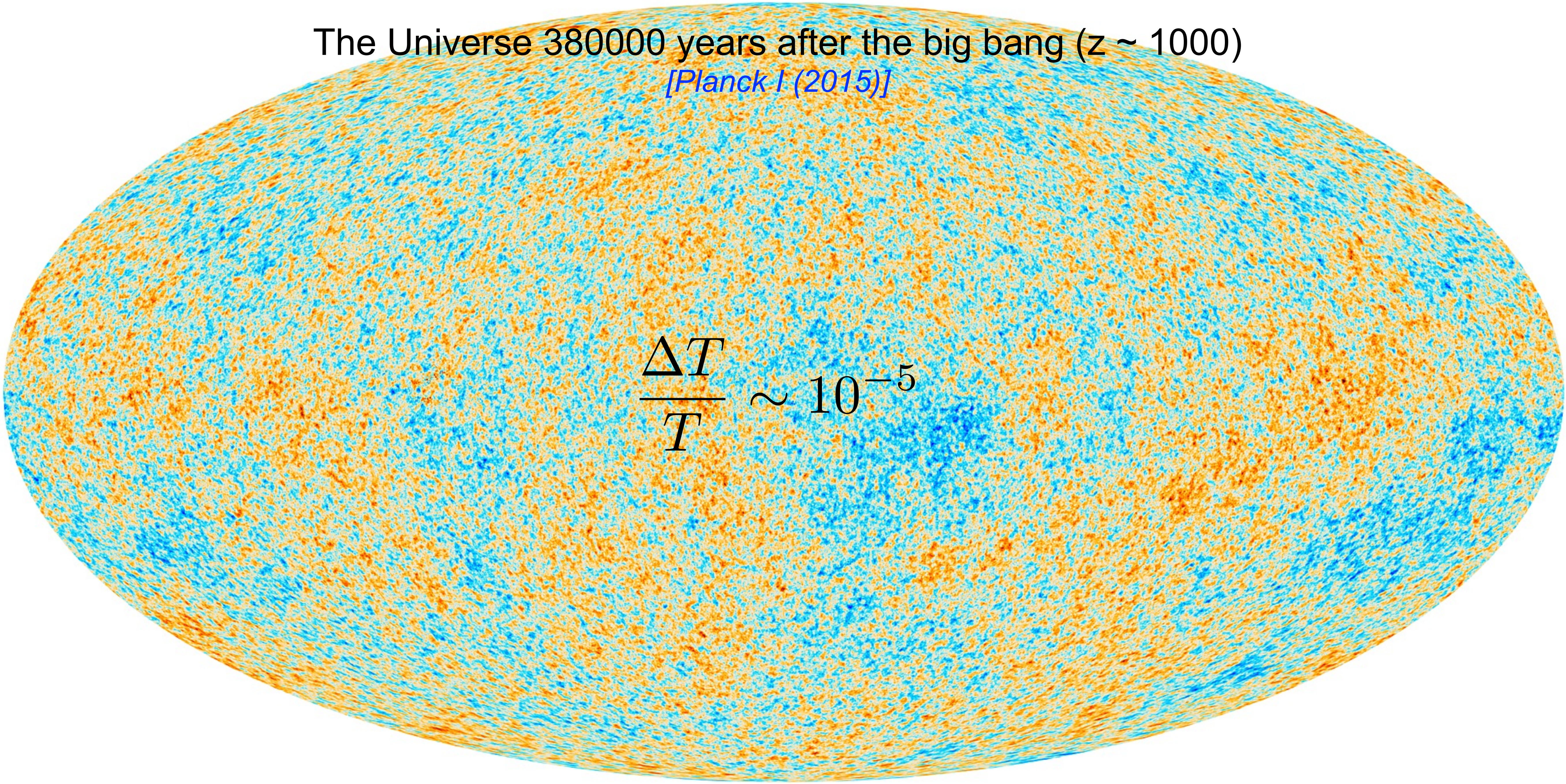
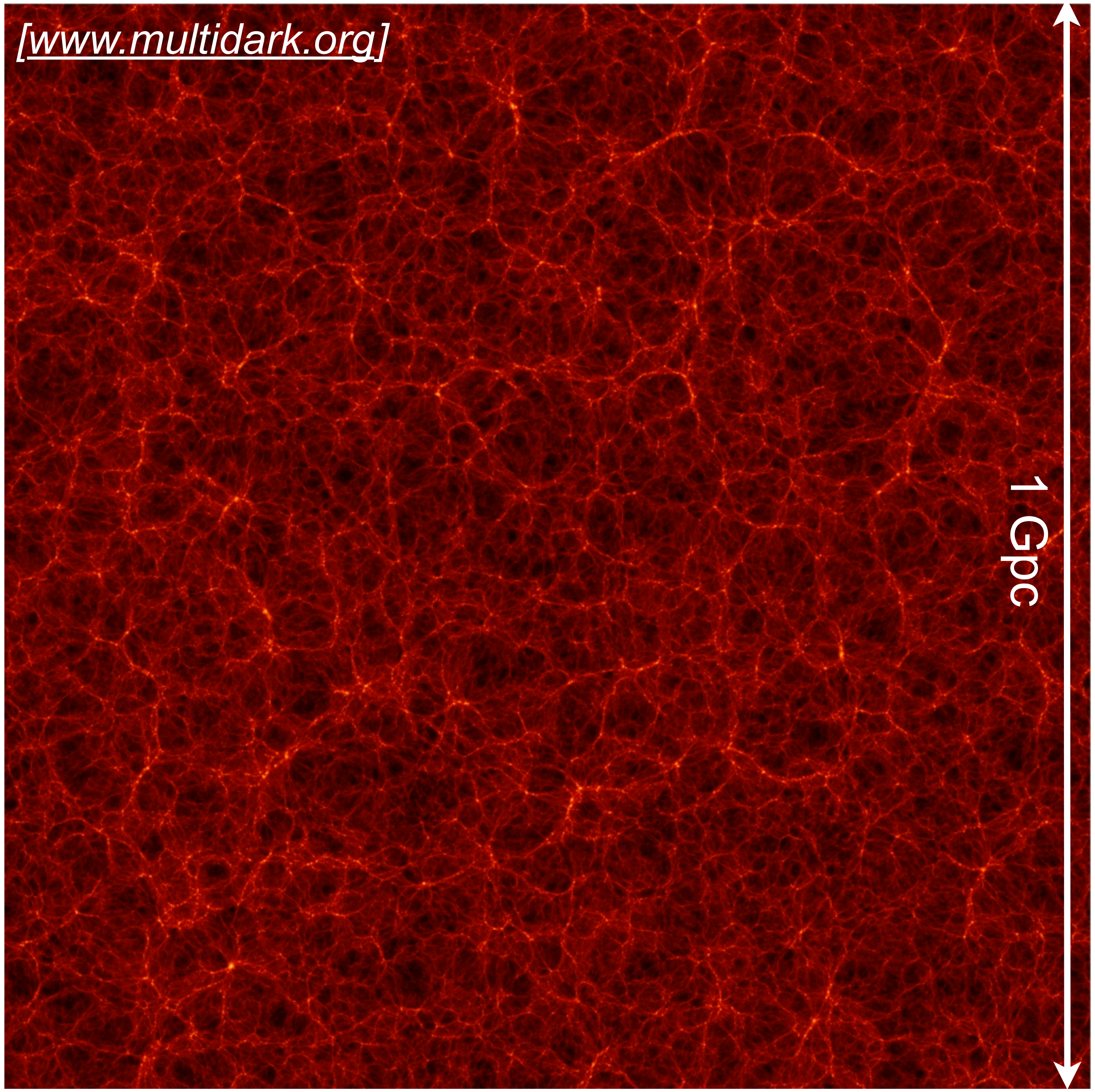
Starting from primordial fluctuations



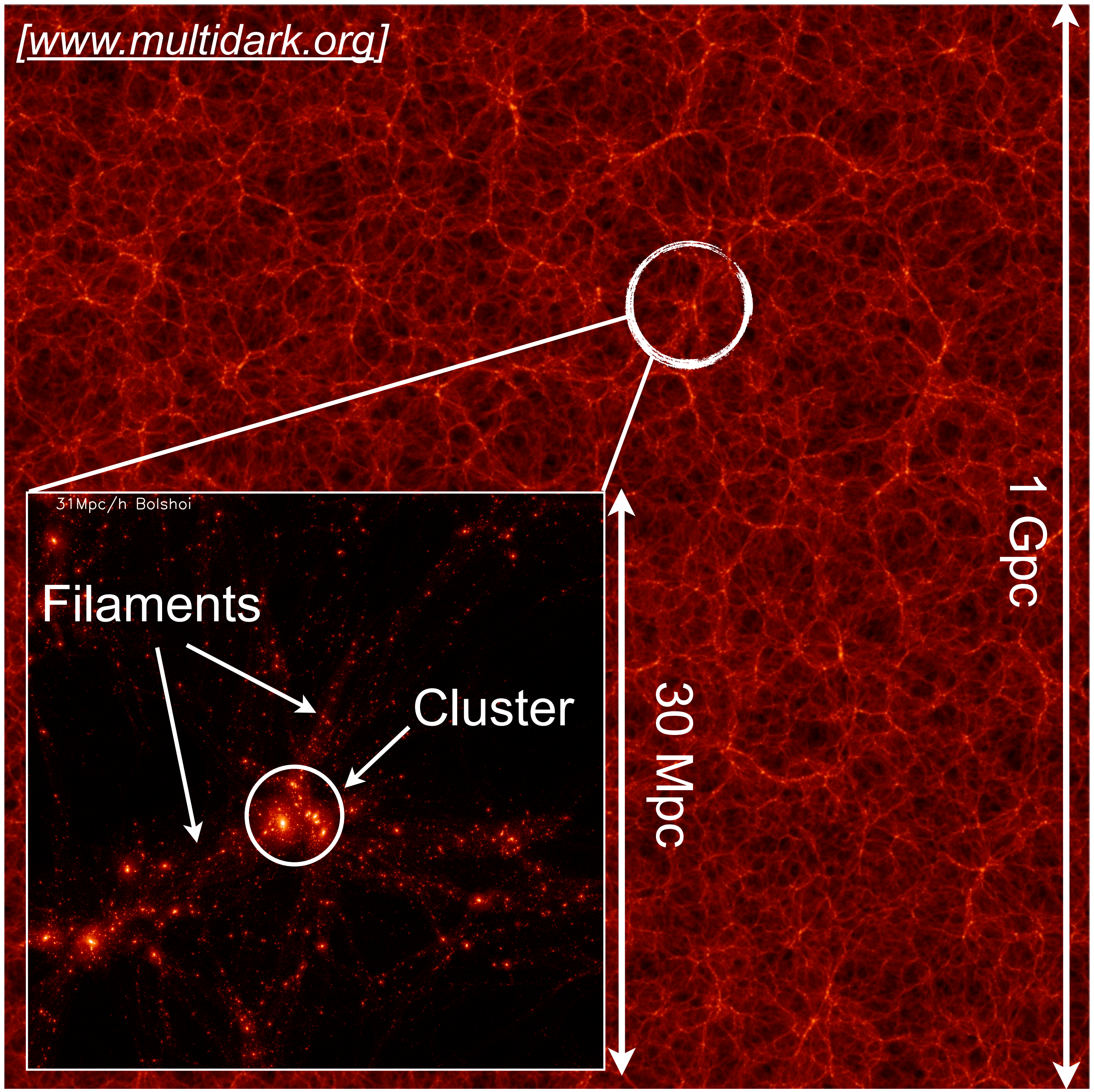
A very homogeneous Universe, with tiny fluctuations

From large scale fluctuations to galaxy clusters



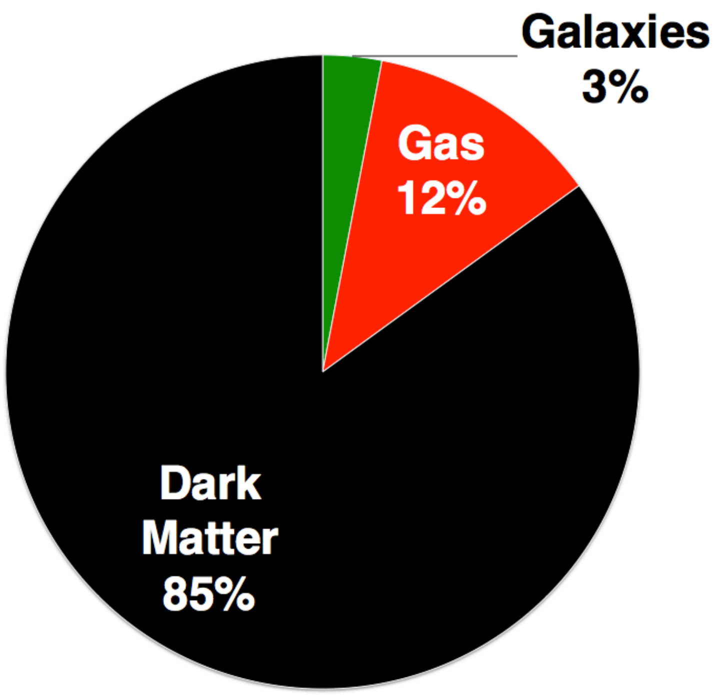
- The primordial fluctuations collapse in the expanding Universe

From large scale fluctuations to galaxy clusters



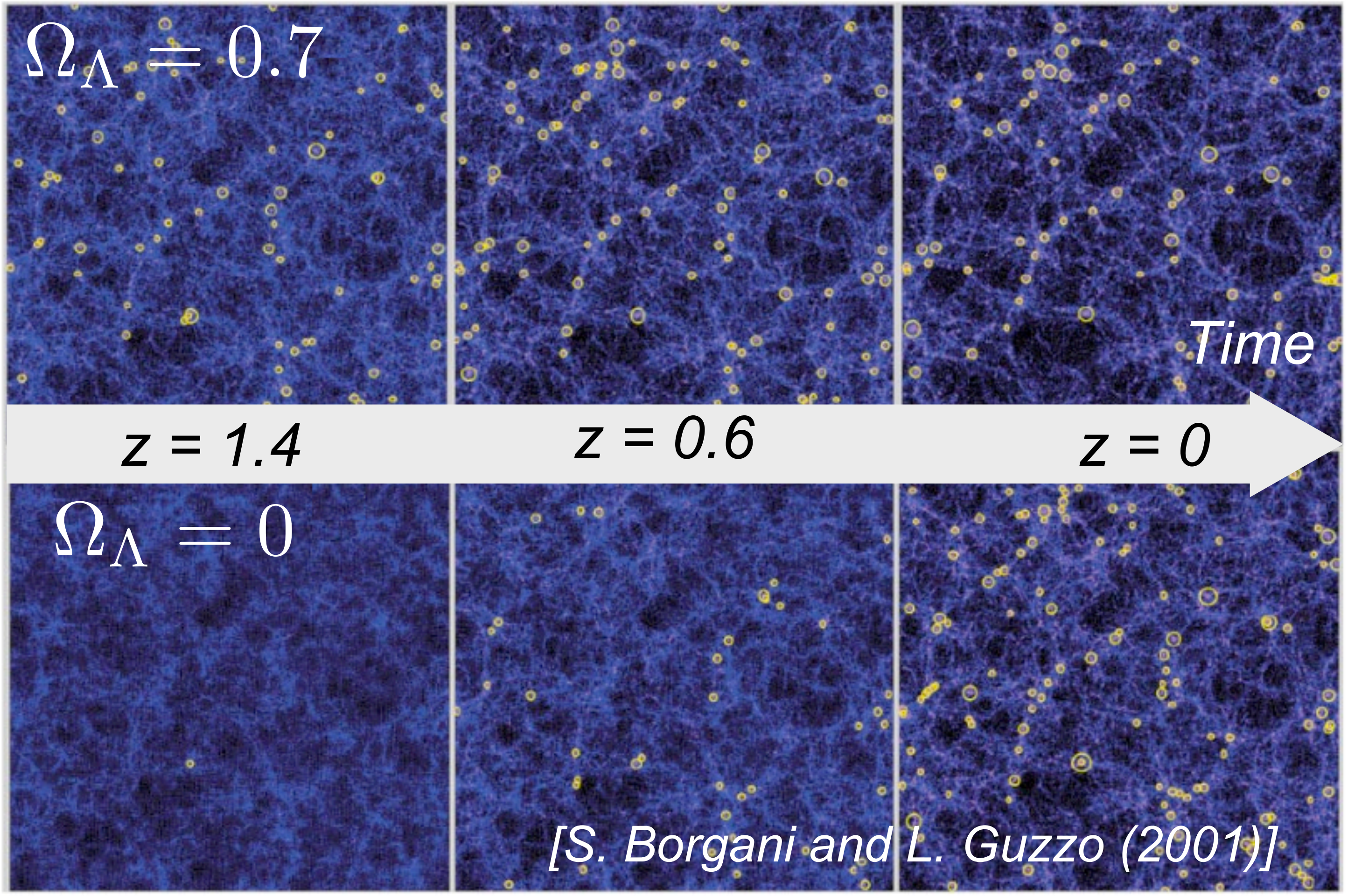
- The primordial fluctuations collapse in the expanding Universe
- To form clusters: the largest gravitationally bound structures

$$N_{\rm galaxy} \sim 50 - 1000$$
$$M_{\rm tot} \sim 10^{14} - 10^{15} M_{\odot}$$
$$l \sim 1 \text{ Mpc}$$



Galaxy clusters are peaks in the matter density field

Cosmology with cluster counts



Survey detection

Model

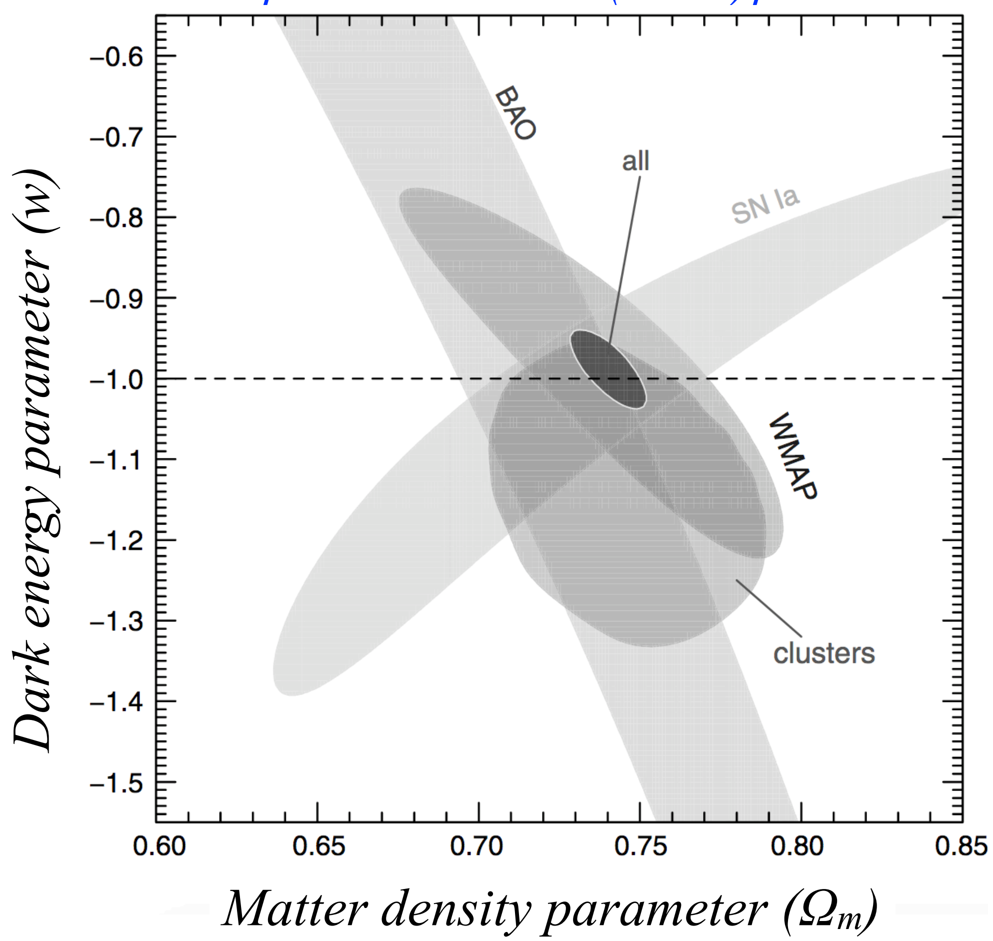
$$\frac{dN}{dz} = \int \chi(z, M) \frac{d^2 N}{dz dM} dM$$

Selection function

Mass-obs. relations

Cosmology with cluster counts

[Vikhlinin et al. (2009)]



Survey detection *Model*

$$\frac{dN}{dz} = \int \chi(z,M) \frac{d^2N}{dz\,dM} dM$$

Selection function *Mass-obs. relations*

Sensitive to geometry, dark matter/energy and gravitation

Key ingredients: mass + observational properties

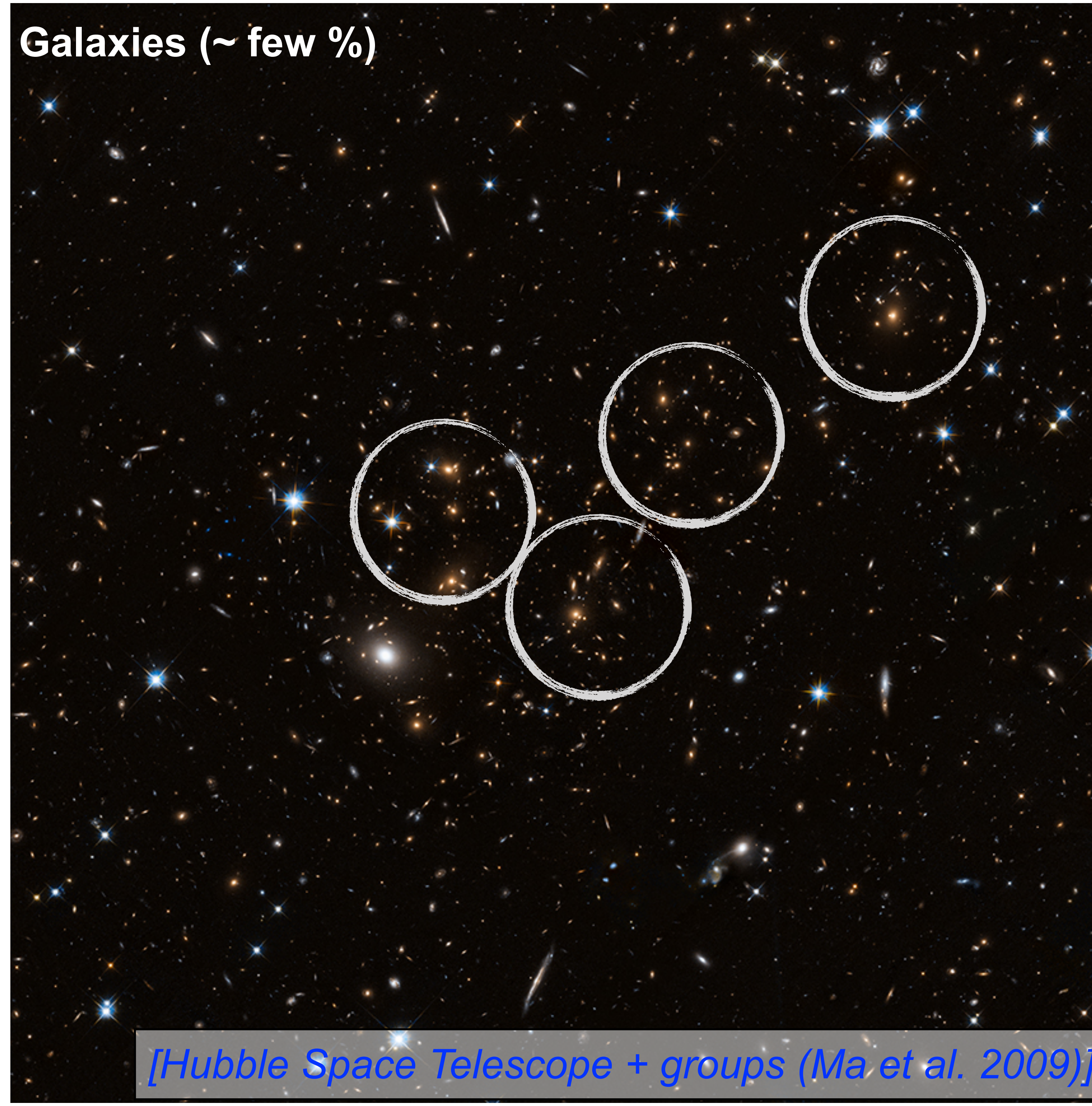
Multi-wavelength view of galaxy clusters

Multi-wavelength view of galaxy clusters

Optical & infrared:

- Galaxies

➡ **Stellar population**



Multi-wavelength view of galaxy clusters

Optical & infrared:

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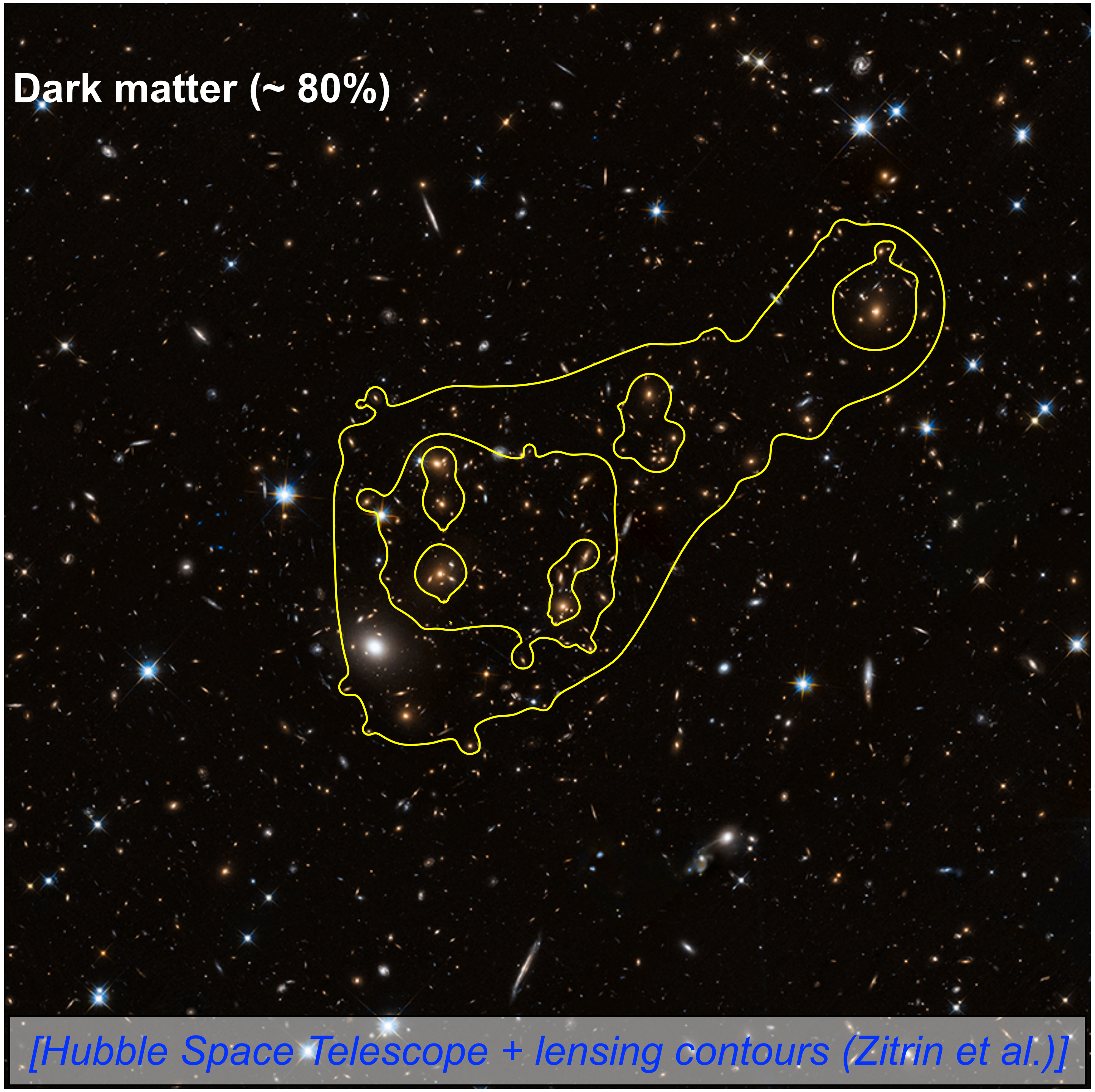
➡ **Stellar population**

➡ **Lensing mass**



[Hubble Space Telescope + lensing contours (Zitrin et al.)]

Multi-wavelength view of galaxy clusters

Optical & infrared:

- Galaxies

➡ **Stellar population**

➡ **Lensing mass**

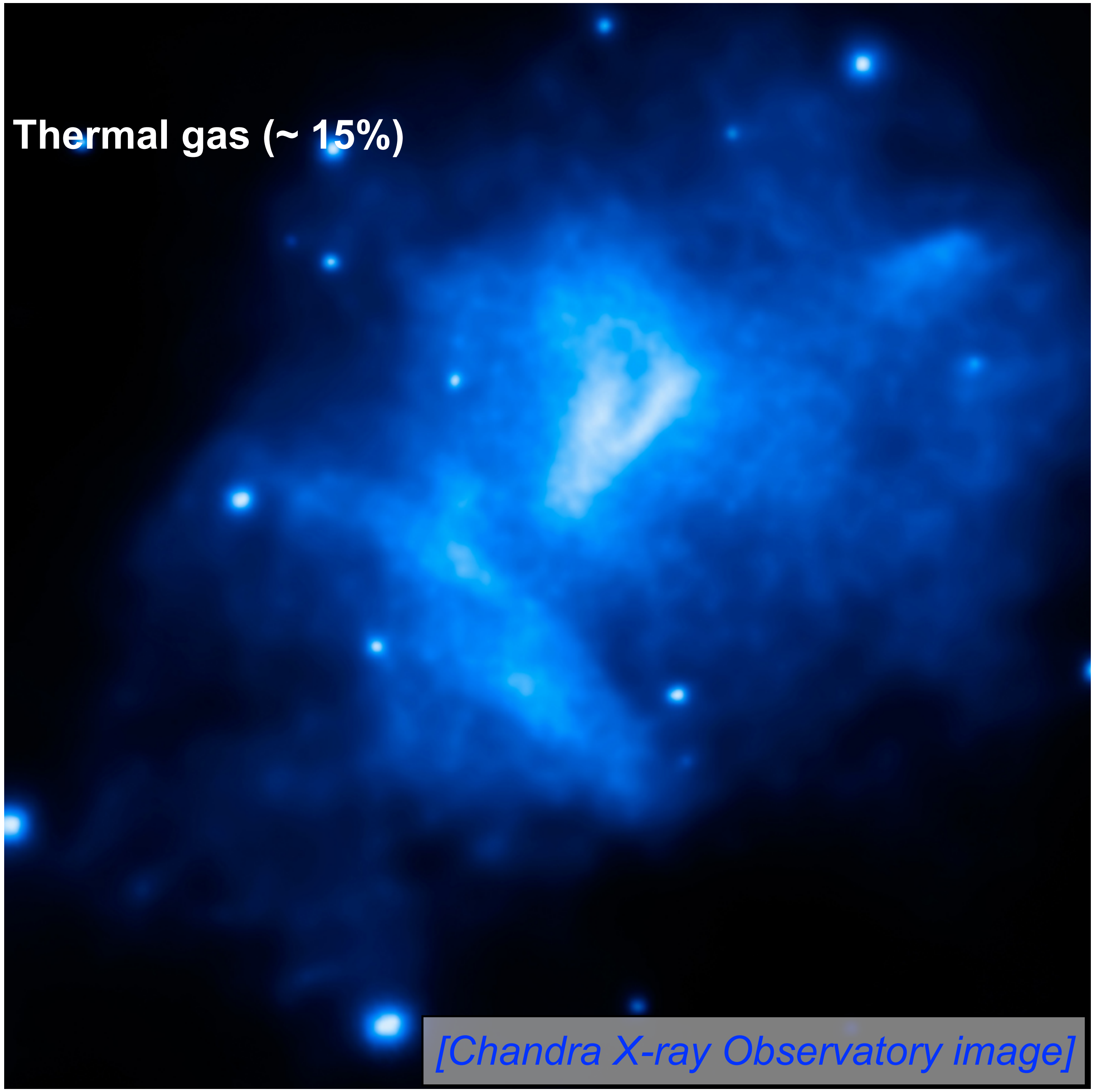
X-ray:

- Bremsstrahlung thermal gas emission

➡ **Gas density**

➡ Spectroscopic temperature (~10^8 K)

➡ Mass from hydrostatic equilibrium



[Chandra X-ray Observatory image]

Multi-wavelength view of galaxy clusters

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Sunyaev-Zel'dovich effect:
- Inverse Compton (e^- + CMB)
➡ Thermal gas pressure
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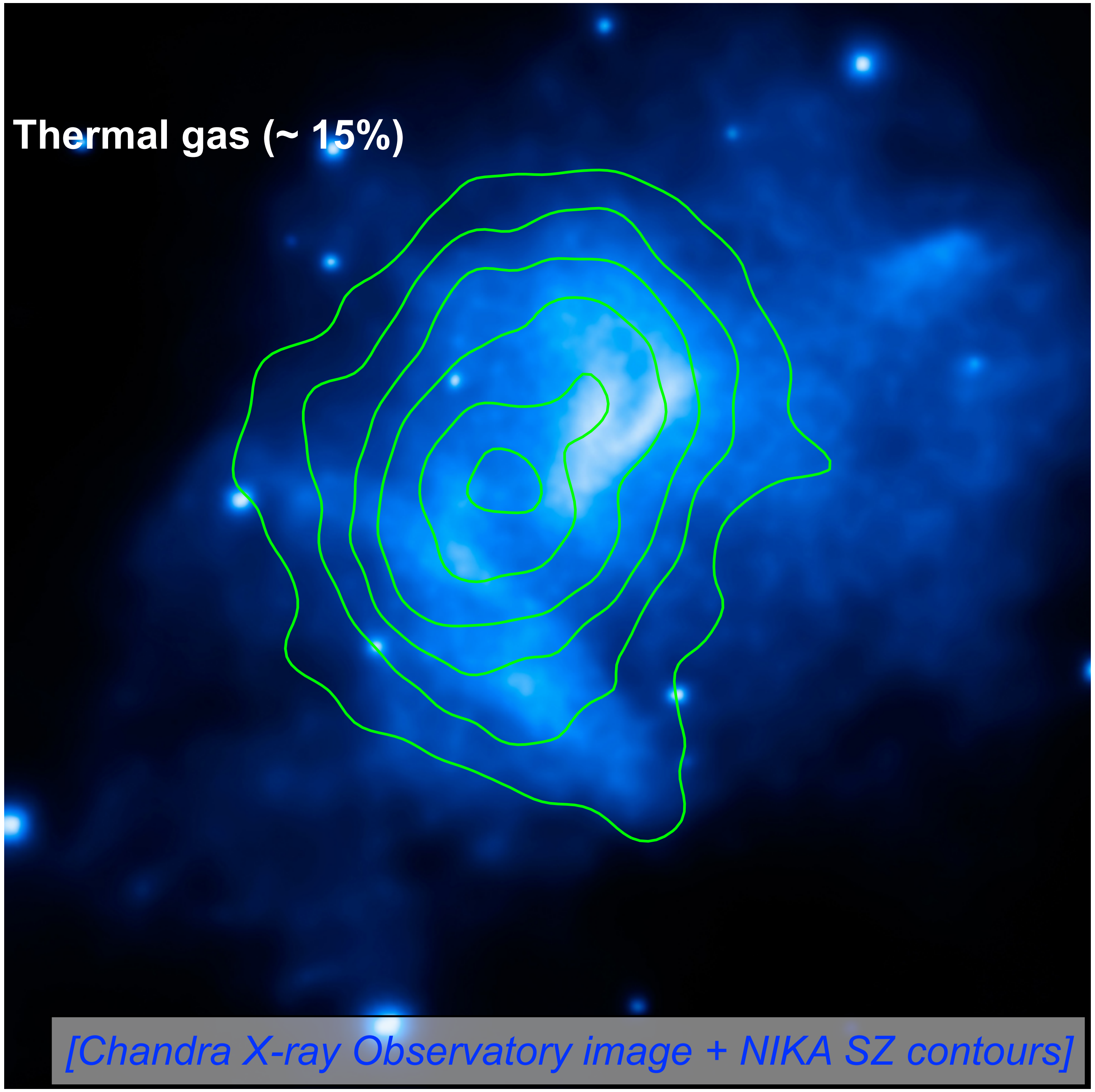

[Chandra X-ray Observatory image + NIKA SZ contours]

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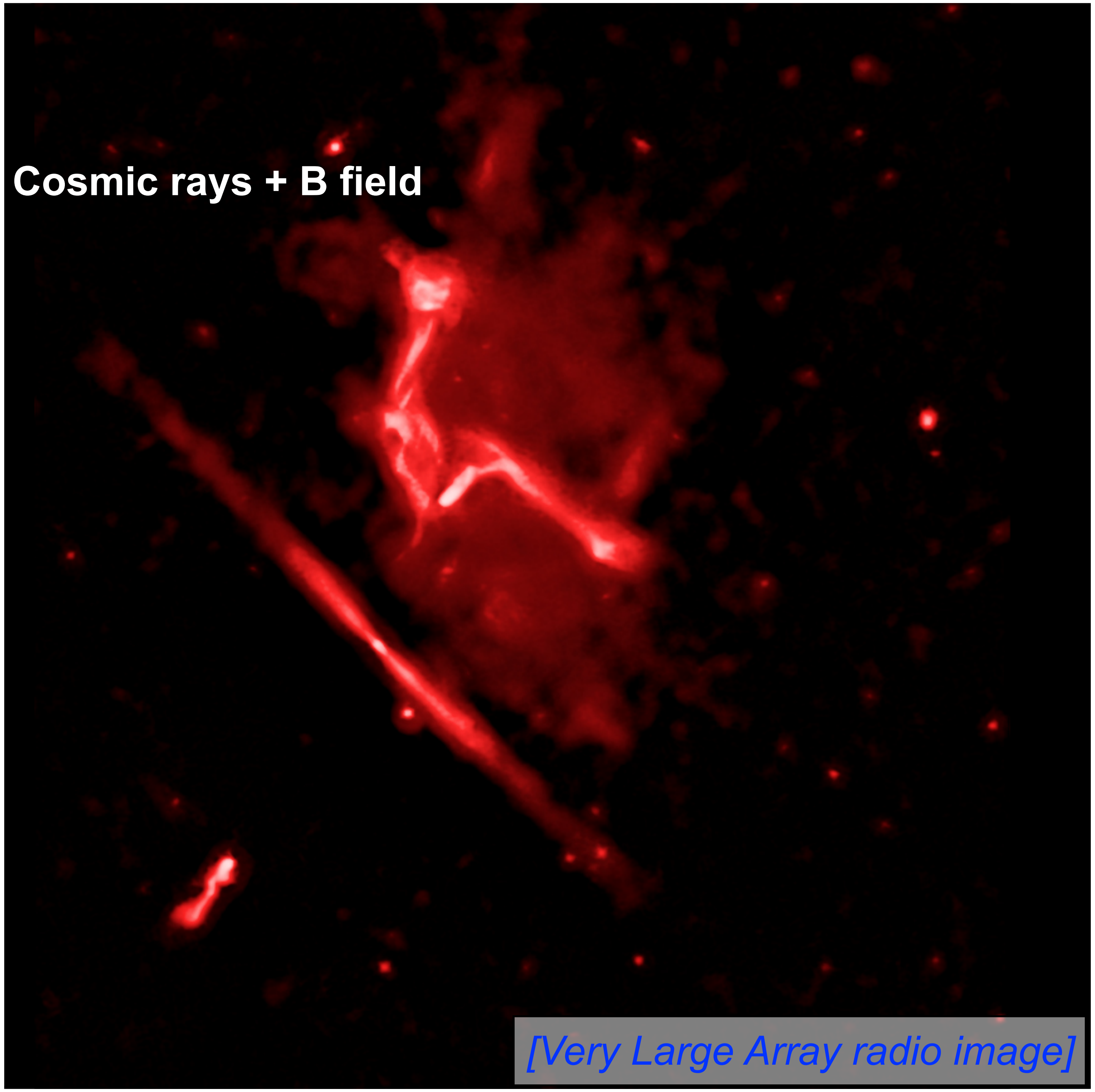
<u>Radio (+ γ-rays)</u>:
- Non-thermal emission (+DM?)

➡ **Particle acceleration**



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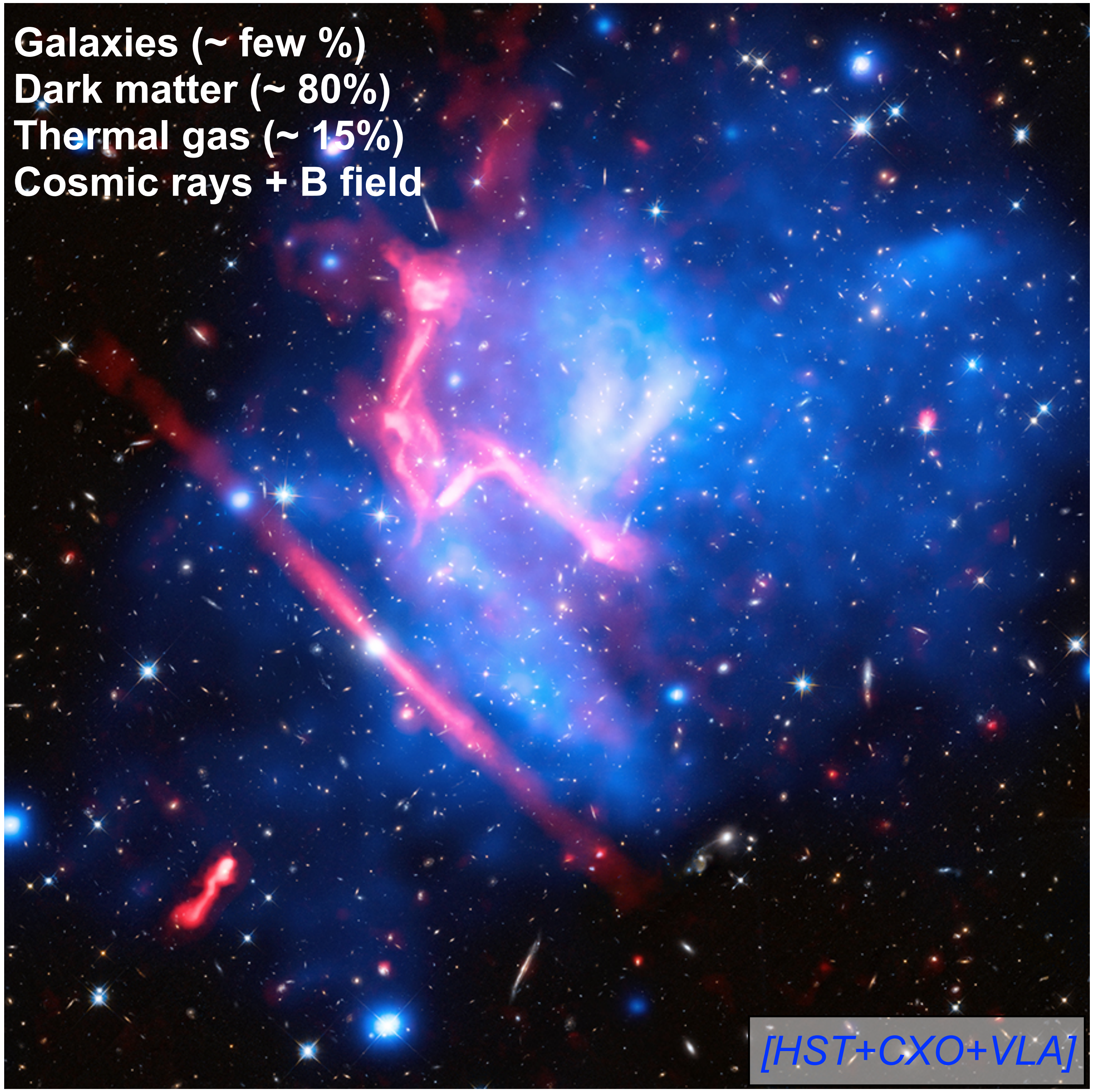

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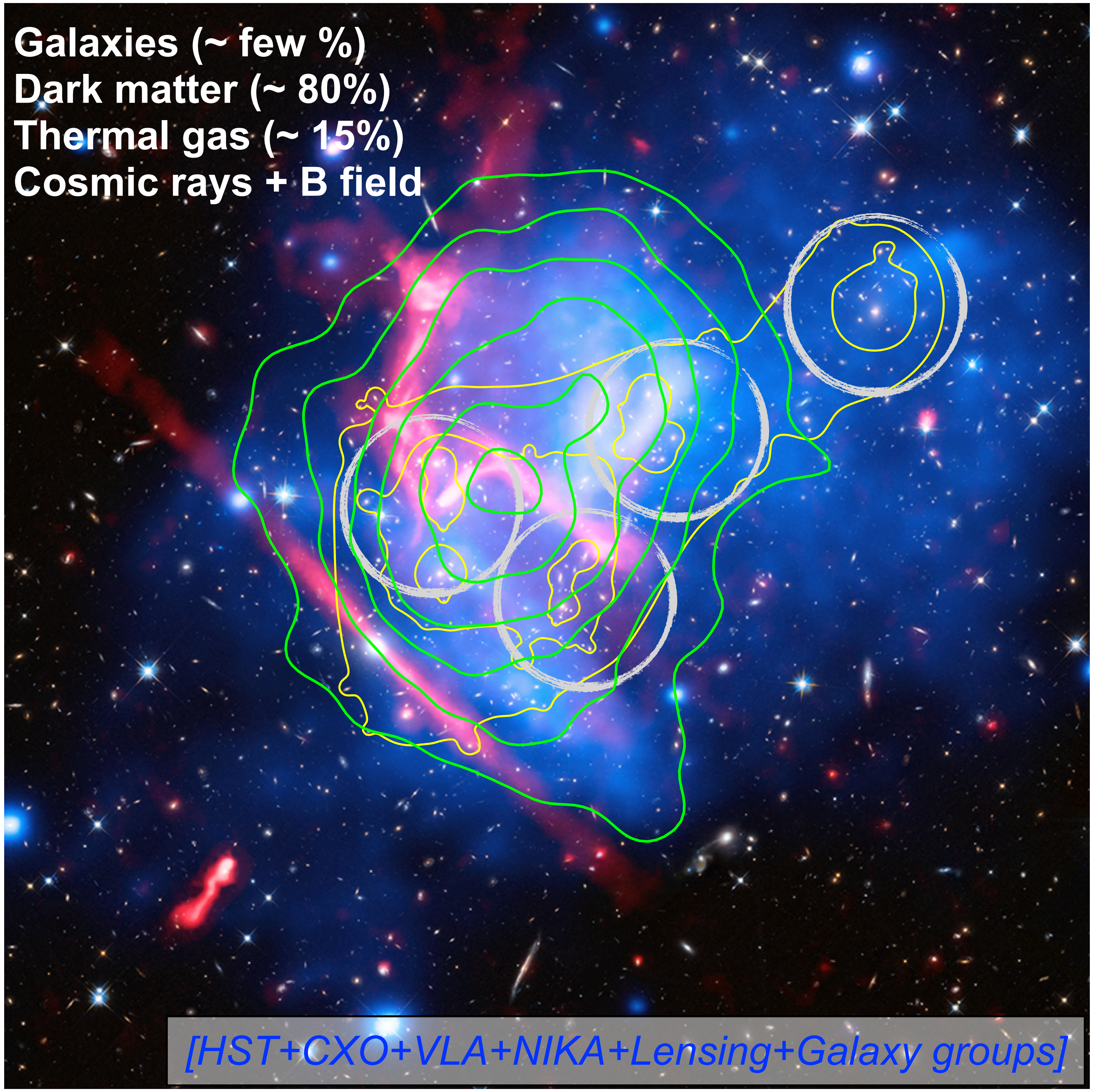
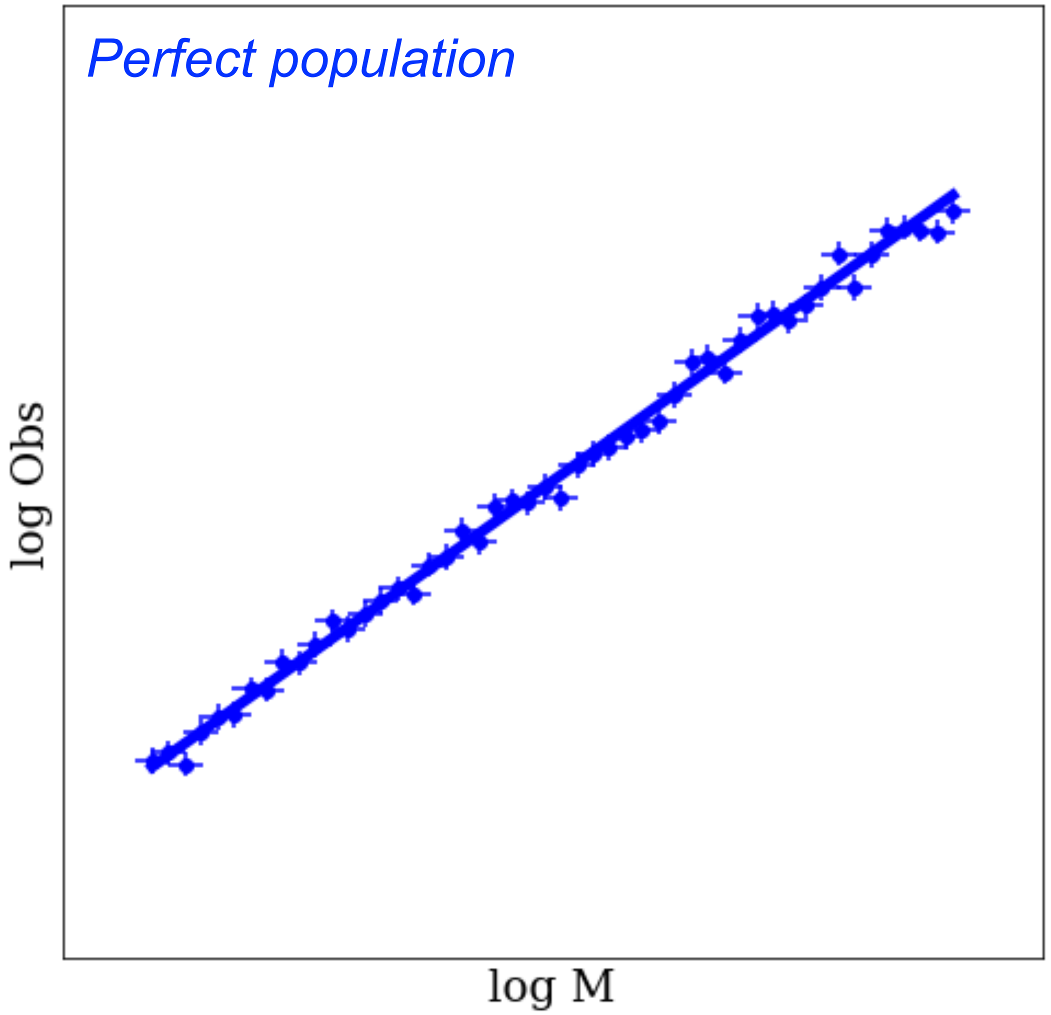


Huge complementarity from different wavelengths

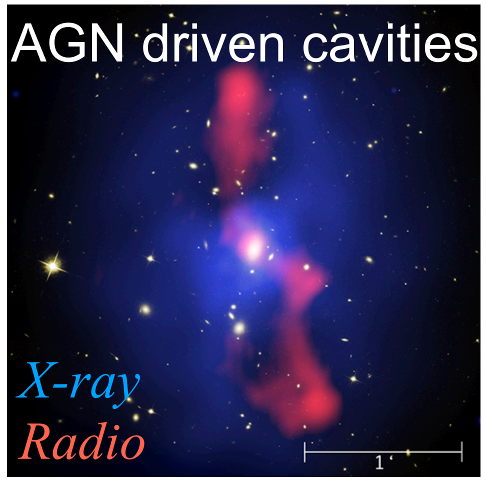
Shaping clusters observables with astrophysics



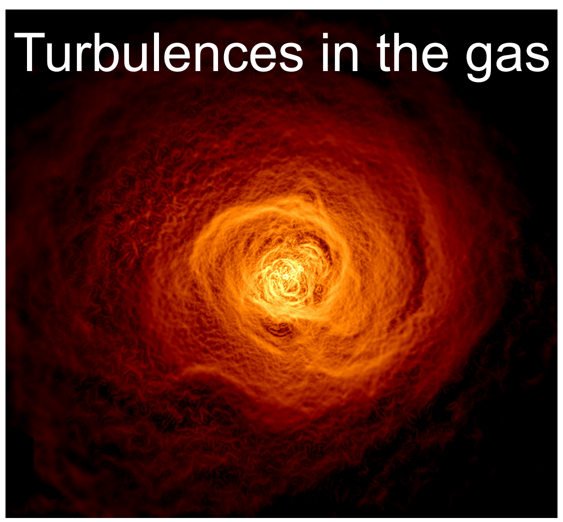
In surveys, observables are used as mass proxies
At 1st order, they are fully determined by M and z

Shaping clusters observables with astrophysics

[Sun et al. (2006)]



[CXO press release]



[Walker, et al. (2017)]

[Markevitch (2010)]

In surveys, observables are used as mass proxies
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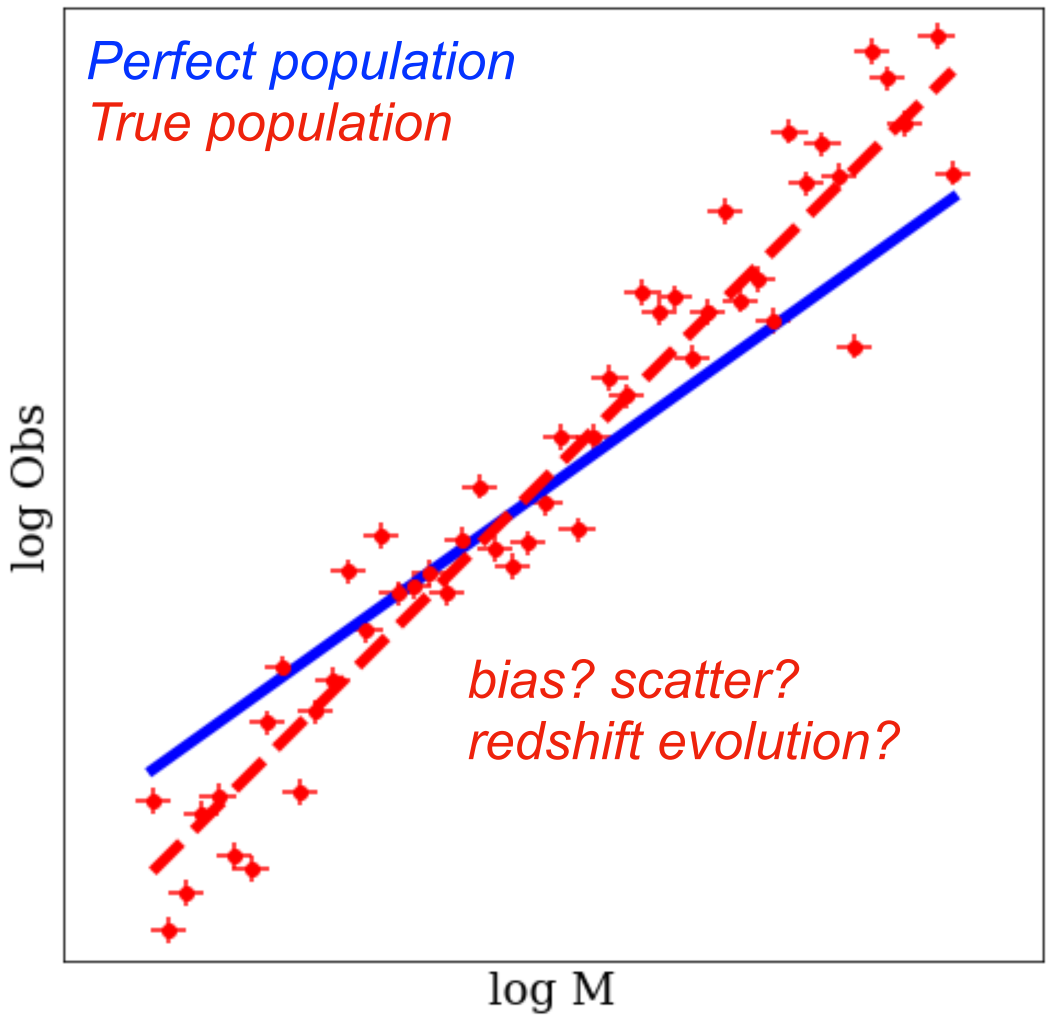
But rich astrophysical processes are at play

- *Mergers / Shocks / turbulences*
- *Dark matter / hot gas / galaxies interactions*
- *Feedback from compact sources (AGN, SN)*
- *Particle acceleration*
- *…*

Shaping clusters observables with astrophysics



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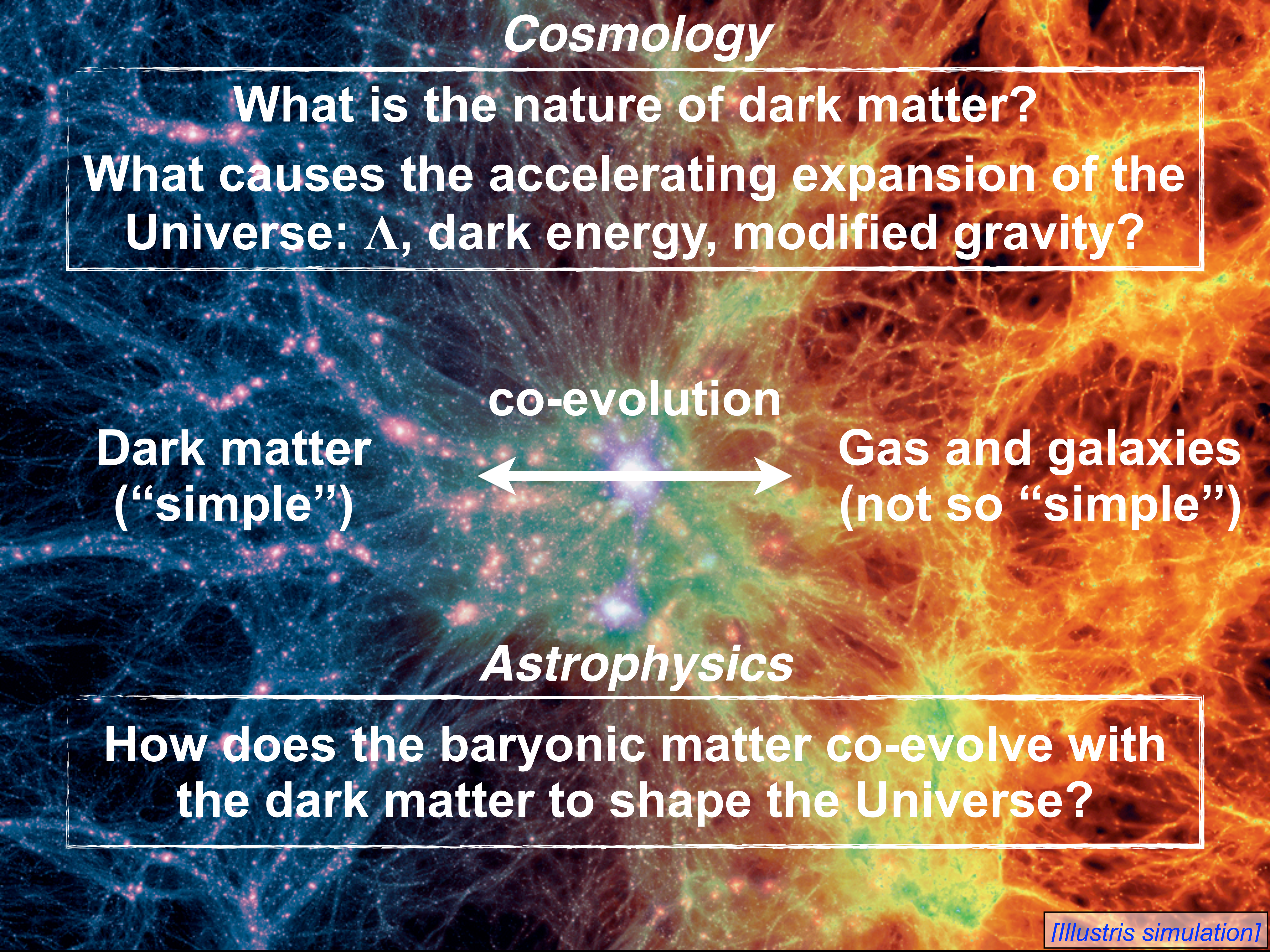
- *…*

Affecting the observables

- *Morphology, substructure*
- *Gas thermodynamics (pressure, density, …)*
- *Non-thermal pressure from cosmic rays*
- *Galaxy colors*
- *…*

Very rich physics, to be controlled for cosmology



Cosmology

What is the nature of dark matter?

What causes the accelerating expansion of the Universe: Λ, dark energy, modified gravity?

co-evolution

Dark matter ("simple") ⟷ **Gas and galaxies (not so "simple")**

Astrophysics

How does the baryonic matter co-evolve with the dark matter to shape the Universe?

[Illustris simulation]

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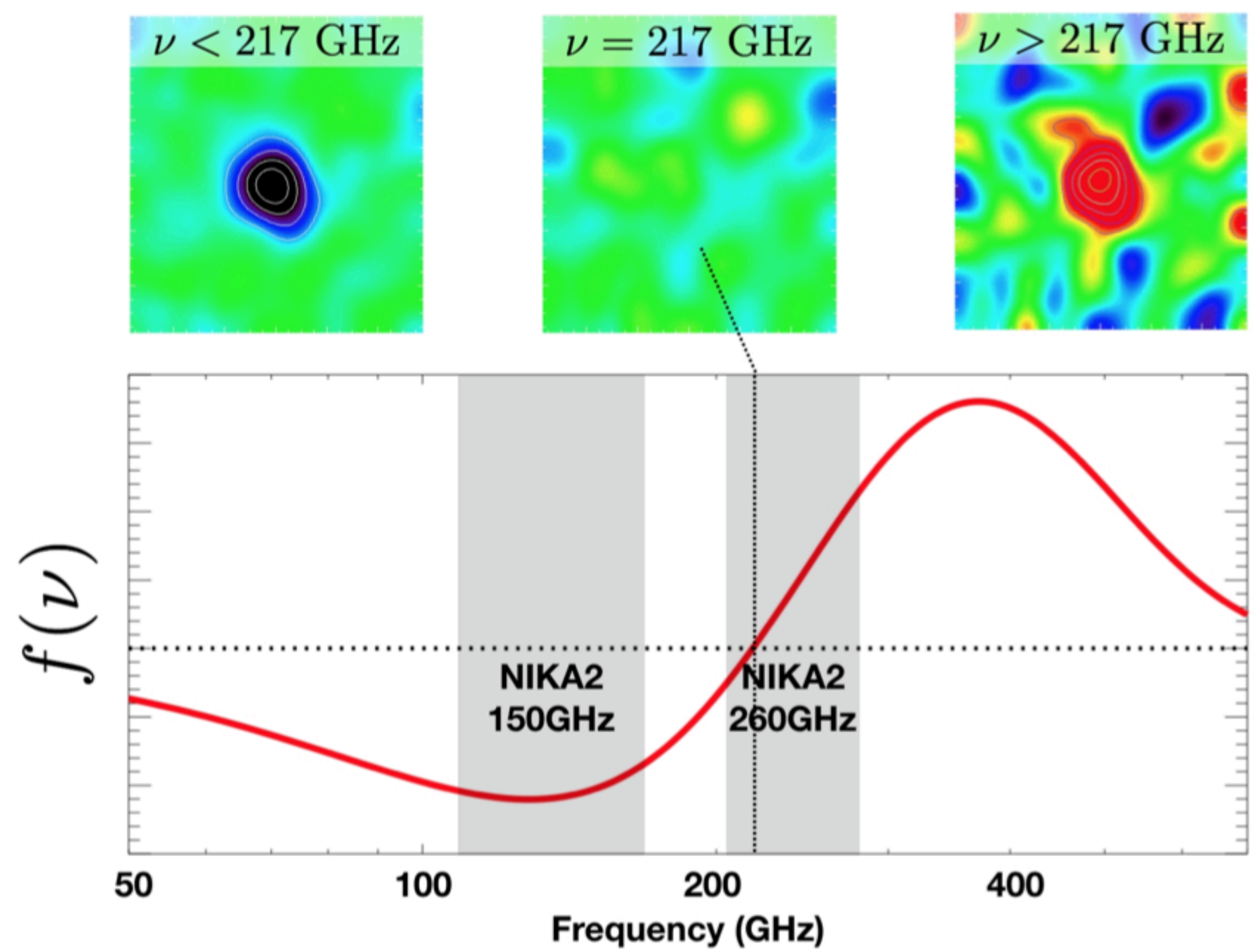
A key observable, the Sunyaev-Zel'dovich effect

The SZ effect is the inverse Compton scattering of γ_{CMB} + $e^-_{cluster}$

$$\Delta I_{\mathrm{tSZ}} \propto f(\nu) \int P_e d\ell$$

- Brightness independent of redshift
- Sensitive to thermal pressure
- Closely tracks the total mass



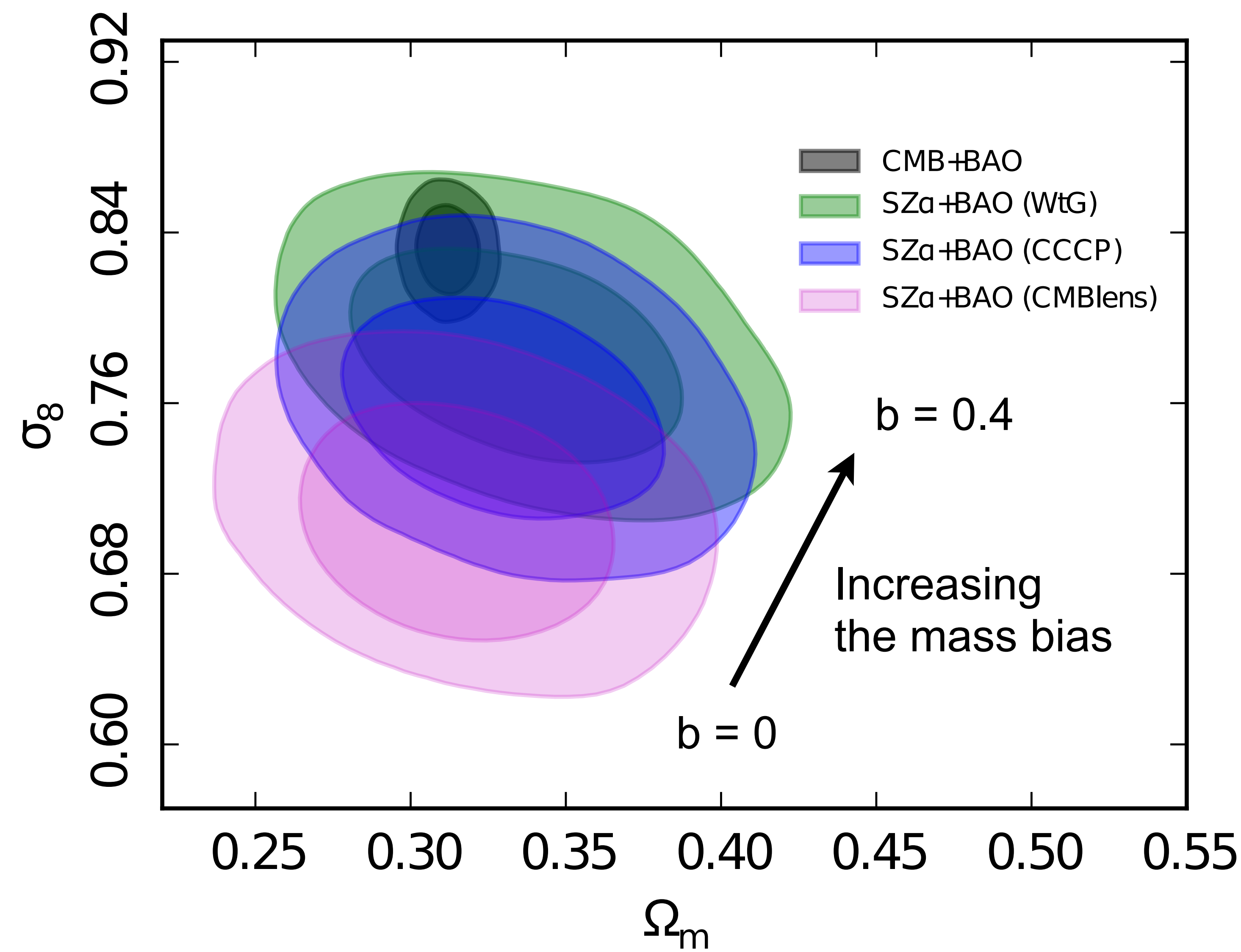
Excellent probe for the hot gas in distant clusters

Cluster cosmology after Planck

- Detailed study of nearby clusters
[Planck V, VIII, X (2013)]
- All-sky catalog (1653 objects) & map
[Planck XXIX (2013), XXVII & XXII (2015)]
- Number count constraints
[Planck XX (2013), Planck XXIV (2015)]

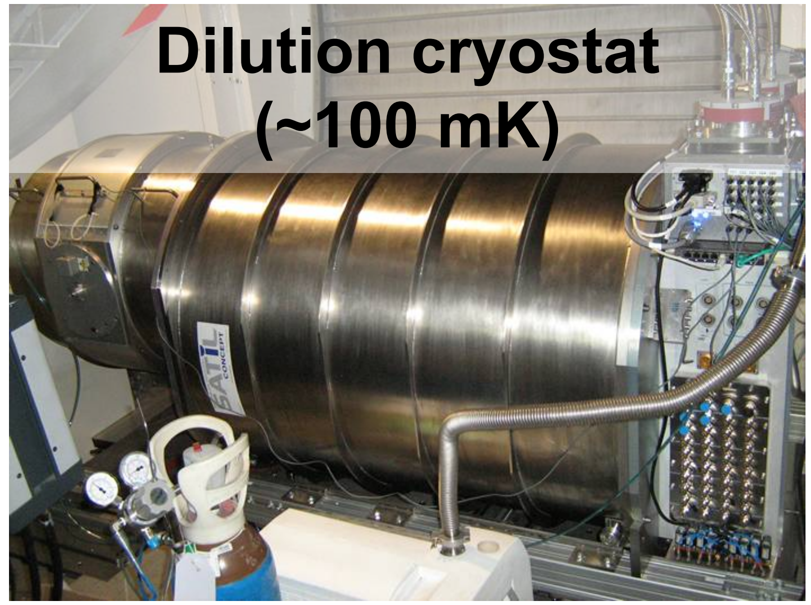
CMB & clusters & hydro sim in tension

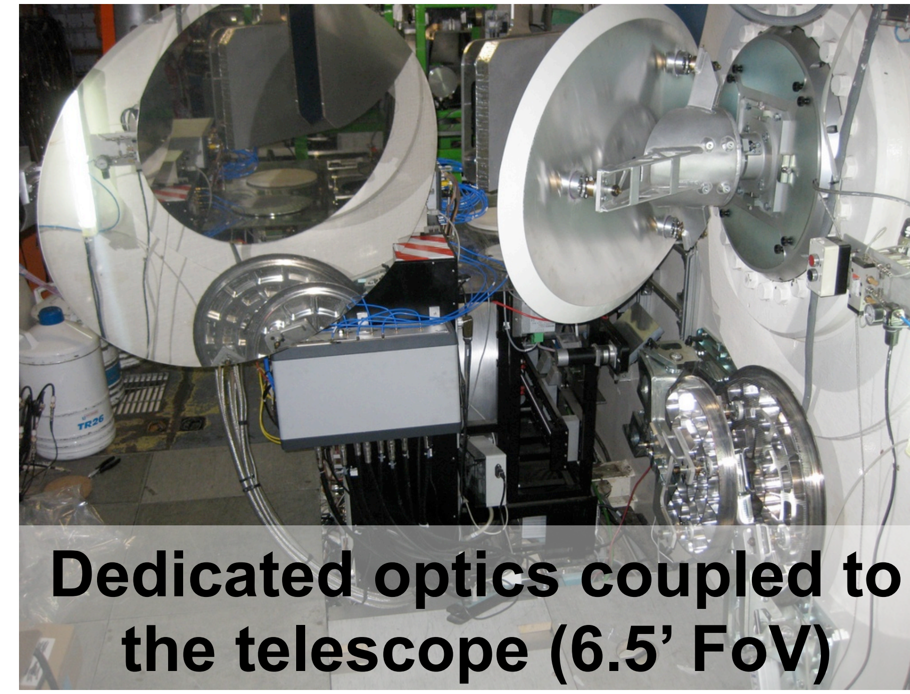
Astrophysical mismodeling?
Missing physics in simulations? In ΛCDM?
Statistical fluctuation?

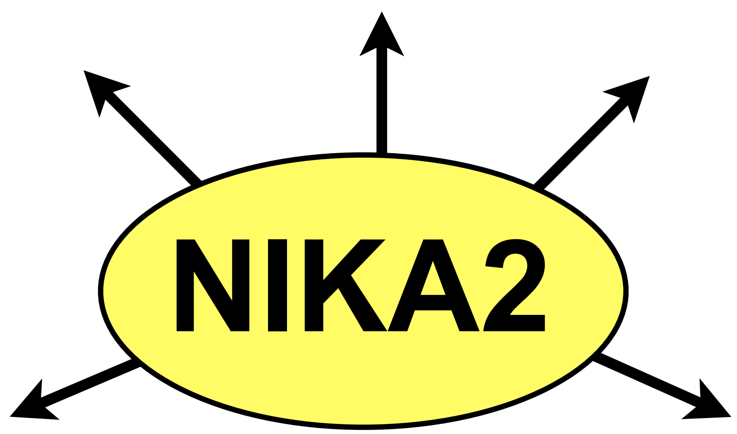


Need for resolved observations up to high redshift

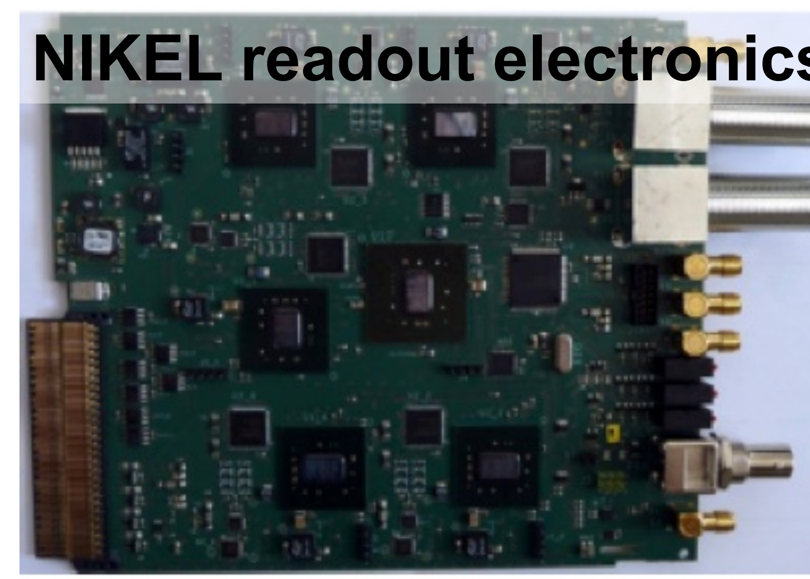
NIKA2: the New IRAM KIDs Array 2





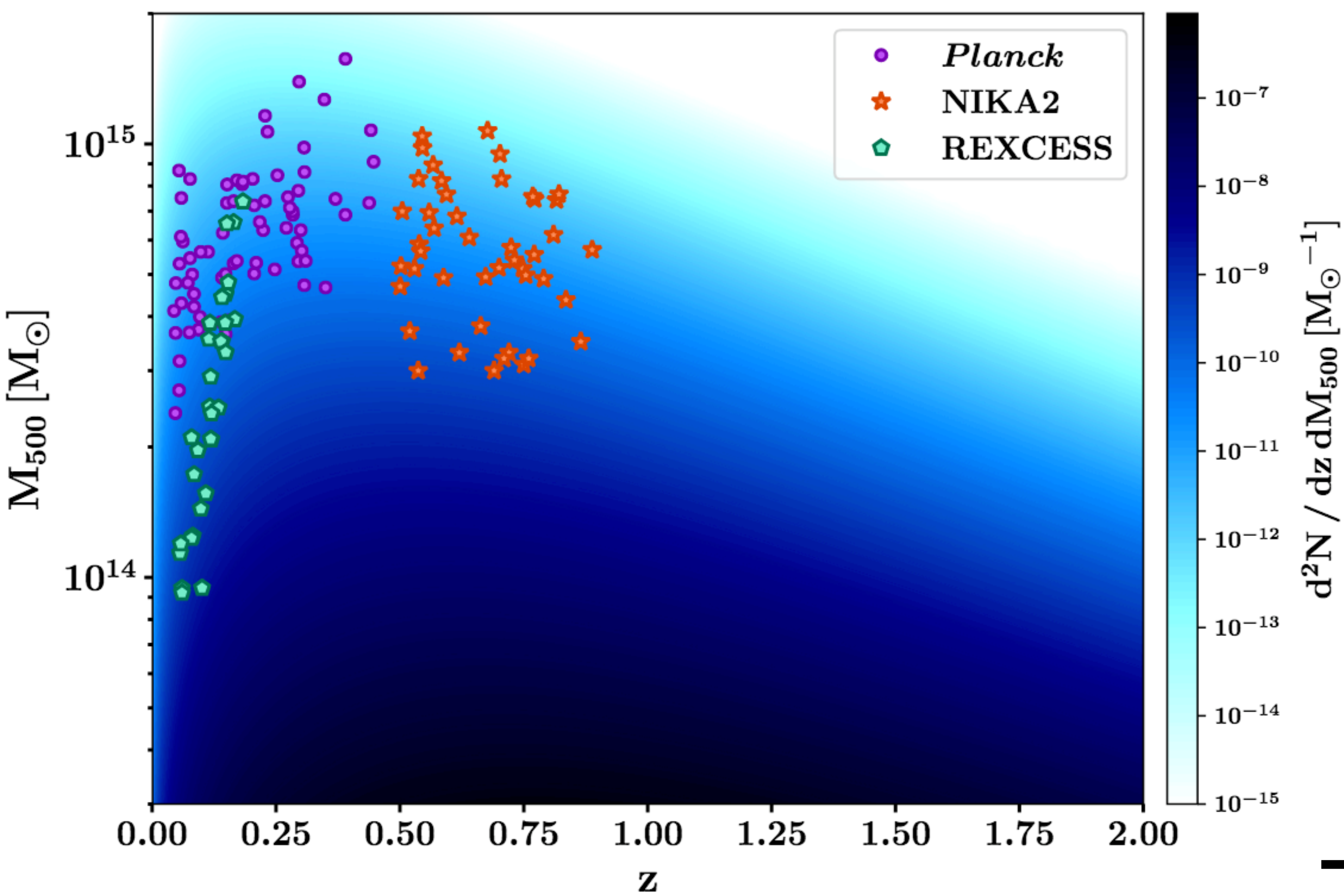


[NIKA collaboration (2018)]



Excellent for resolving distant clusters

The NIKA2 guaranteed time SZ large program



[Ruppin et al. (2019)]

- High resolution observations of 50 clusters
  - *$0.5 < z < 0.9$, $M_{500} > 3x10^{14}$* M_{sun}
- Planck/ACT tSZ selected
  - representativity
- Combinaison to XMM data
  - Full thermodynamics
- 300 hours of guaranteed time
  - ~10 clusters observed so far

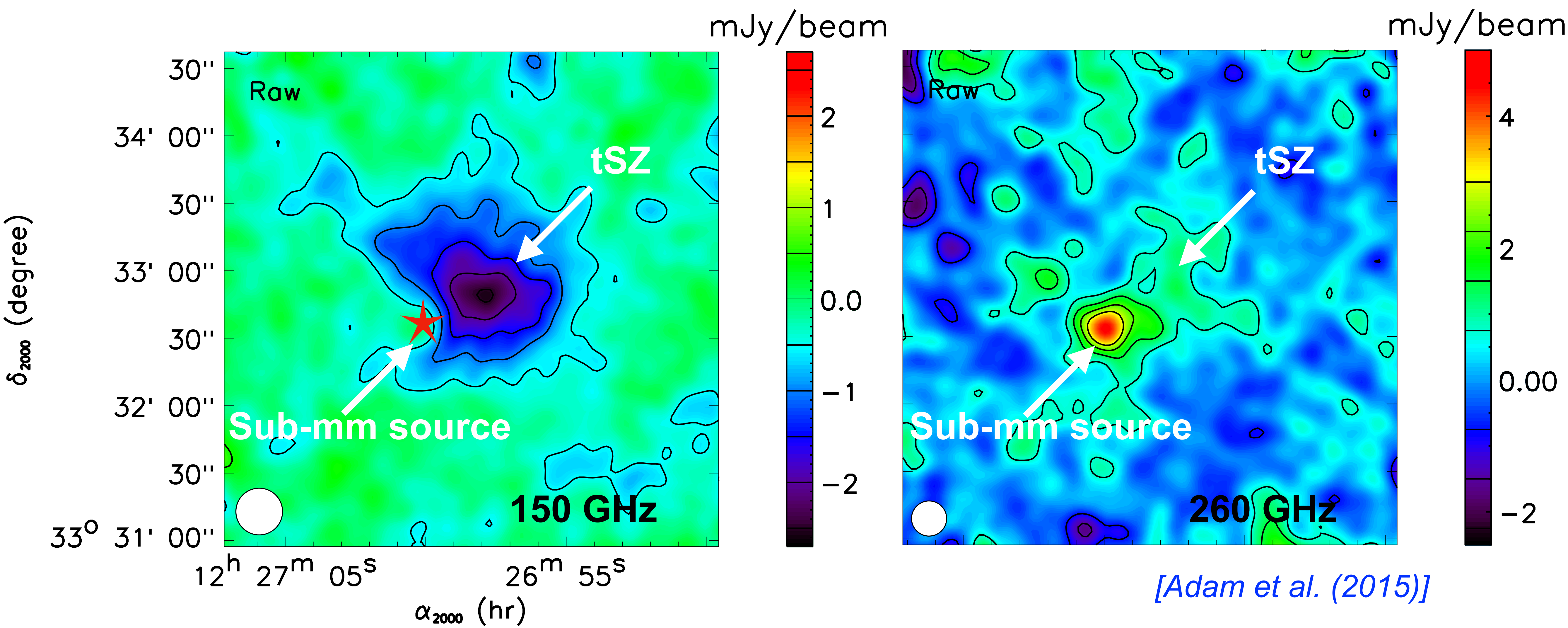
+

- NIKA pathfinder validation program
  - 6 clusters in various configurations

In depth population study of the ICM:
- Redshift evolution of the ICM properties and scaling relations
- Dependence on cluster dynamical state

A first look at the data

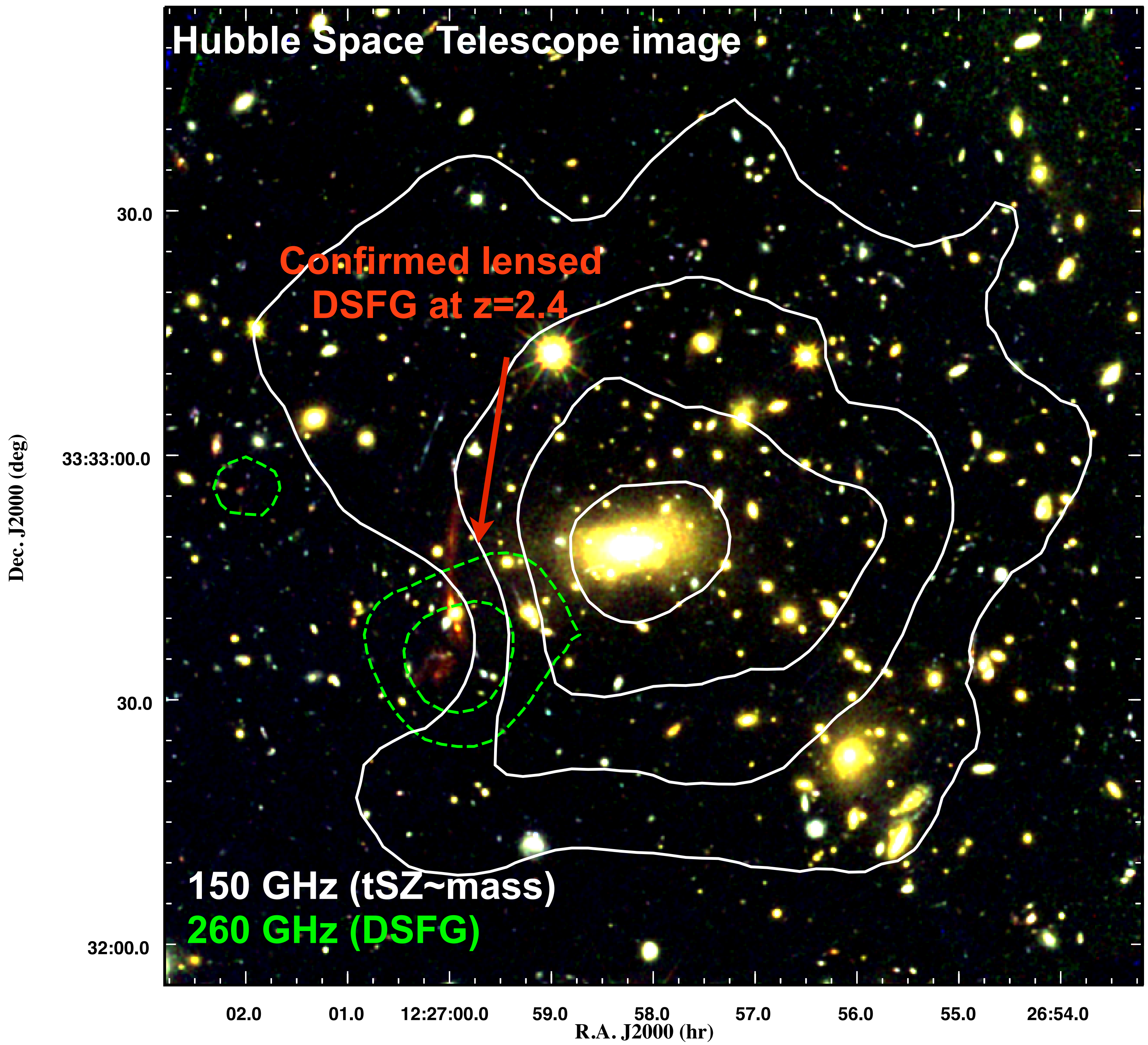
CLJ1227 at z=0.89



[Adam et al. (2015)]

Sub-mm and radio galaxies can bias the SZ signal

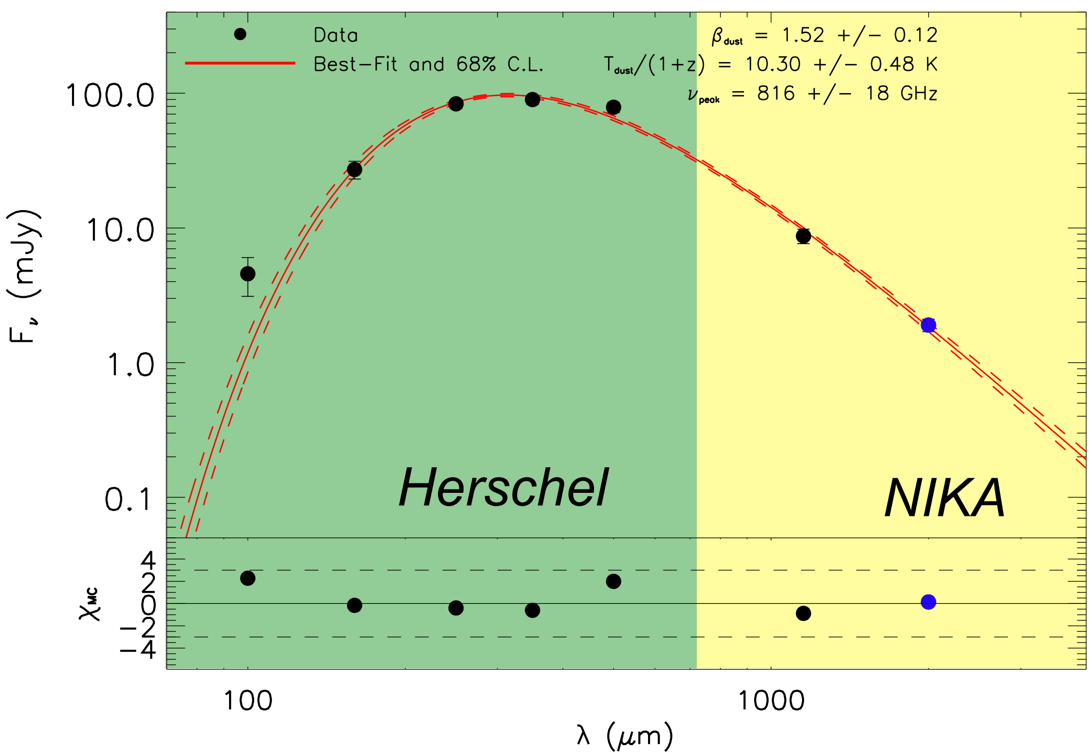
Lensed galaxies behind clusters



Clusters allow us to find distant galaxies

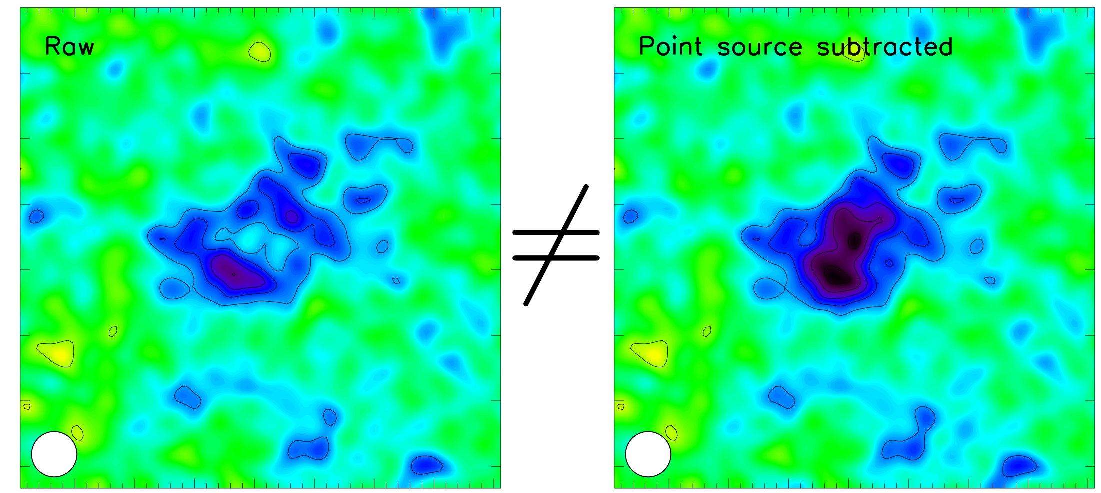
Cleaning the ‘contaminant’ galaxies

Dust + radio synchrotron fitting

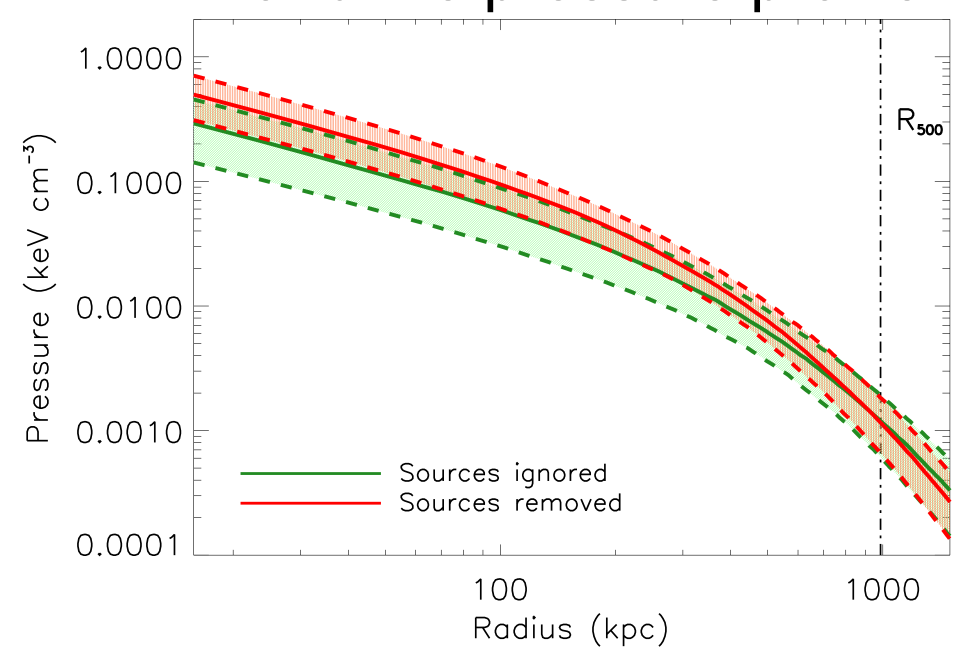


[Adam et al. (2016)]

Strong impact on the morphology…



… and the pressure profile



It is crucial to account for contaminant sources

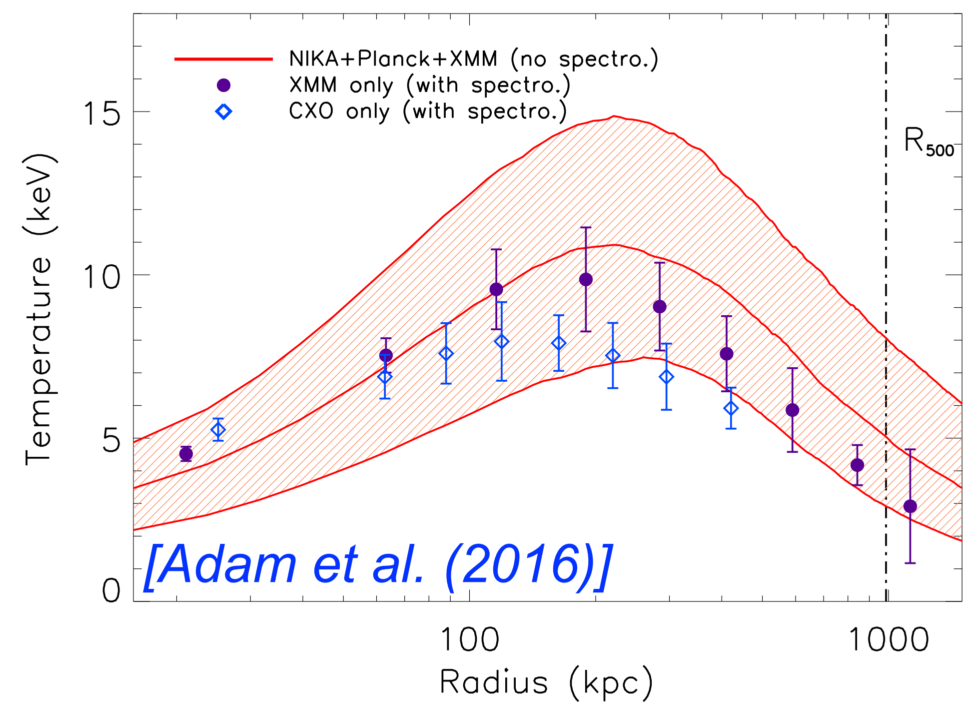
Gas temperature from X-ray+SZ imaging

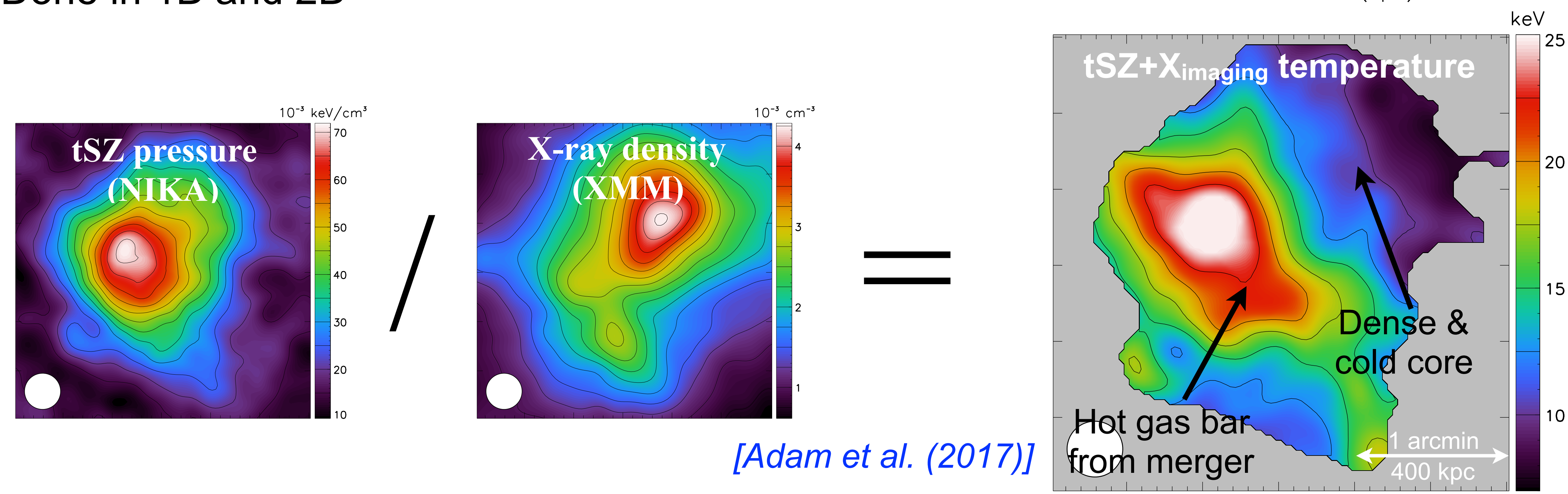
- Temperature fundamental for astro & cosmo
  - Mass calibration
  - Cluster dynamical state
- Systematics in X-ray spectro. + challenging at high z

$$\Rightarrow k_{\mathrm{B}}T = \underbrace{P_e}_{tSZ} / \underbrace{n_e}_{X\text{-}ray}$$

- Independent cross-check of X-ray spectro.

➡ Done in 1D and 2D





[Adam et al. (2017)]

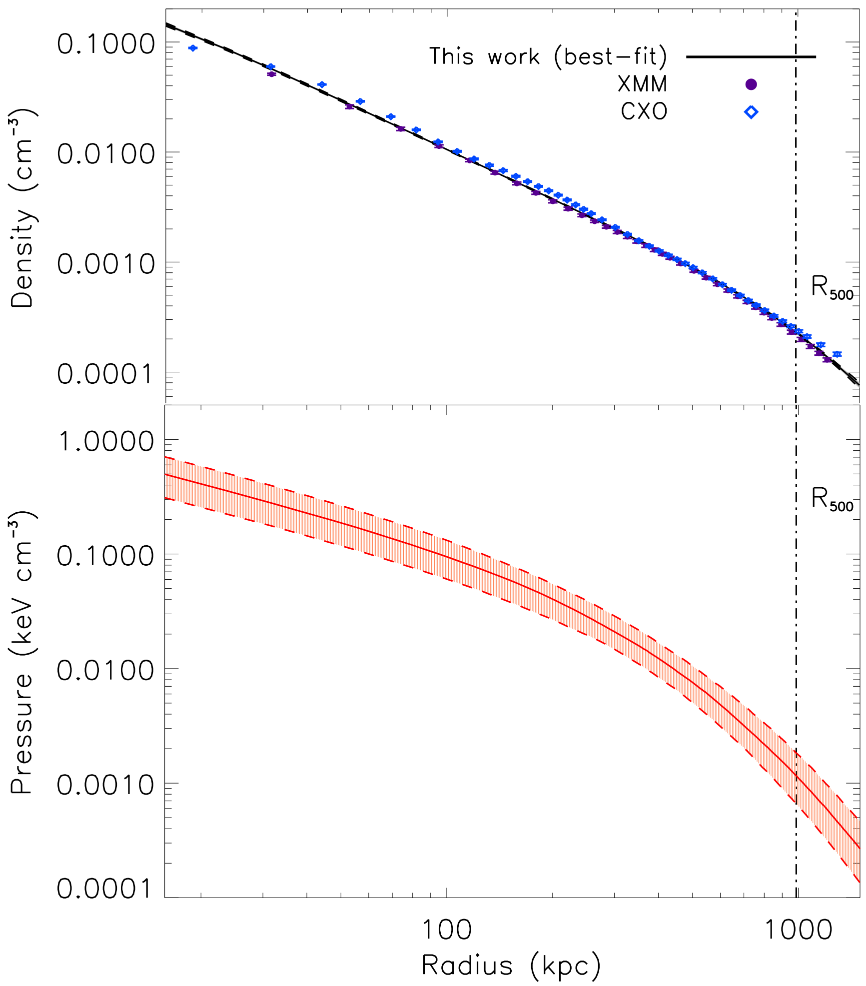
Excellent to obtain the temperature at high z

Direct mass measurement from X-ray+SZ

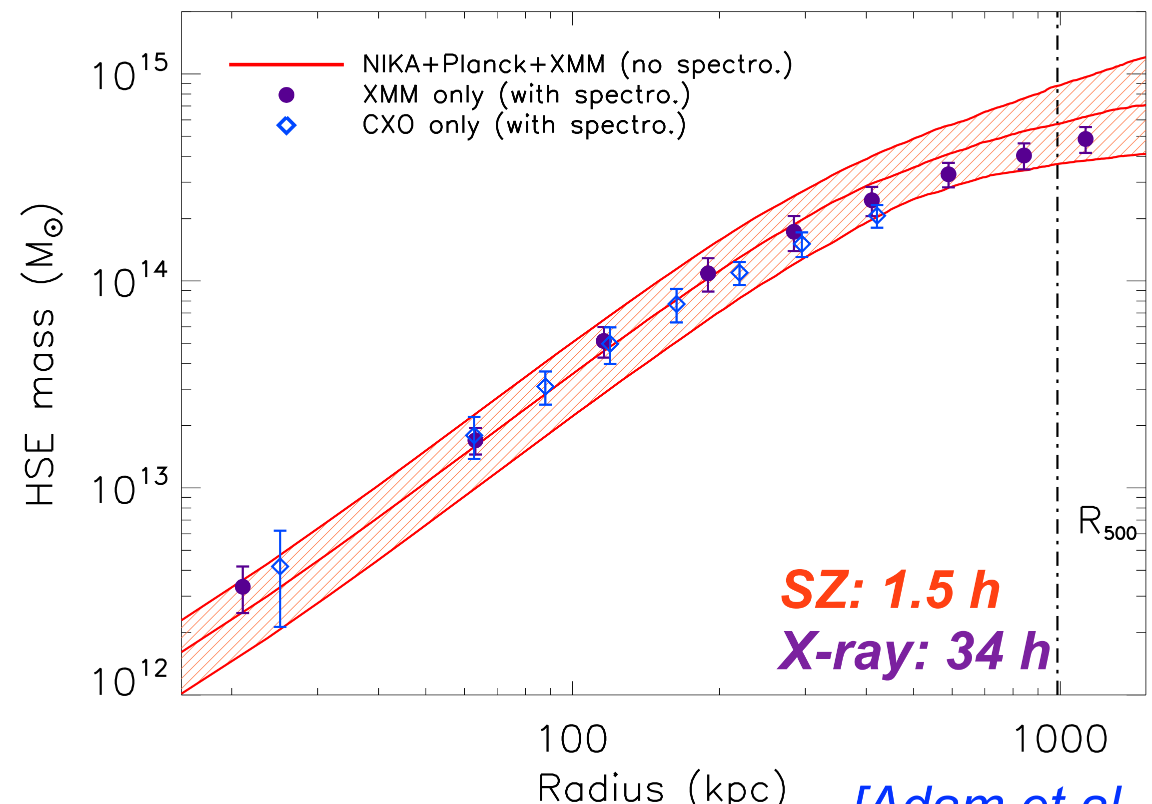
$$M_{\rm HSE}(r) = -\frac{r^2}{\mu_{\rm gas} m_{\rm p} n_{\rm e}(r) G} \frac{{\rm d}P_{\rm e}(r)}{{\rm d}r}$$

SZ measurement

Easy from X-ray



X-ray
+
SZ

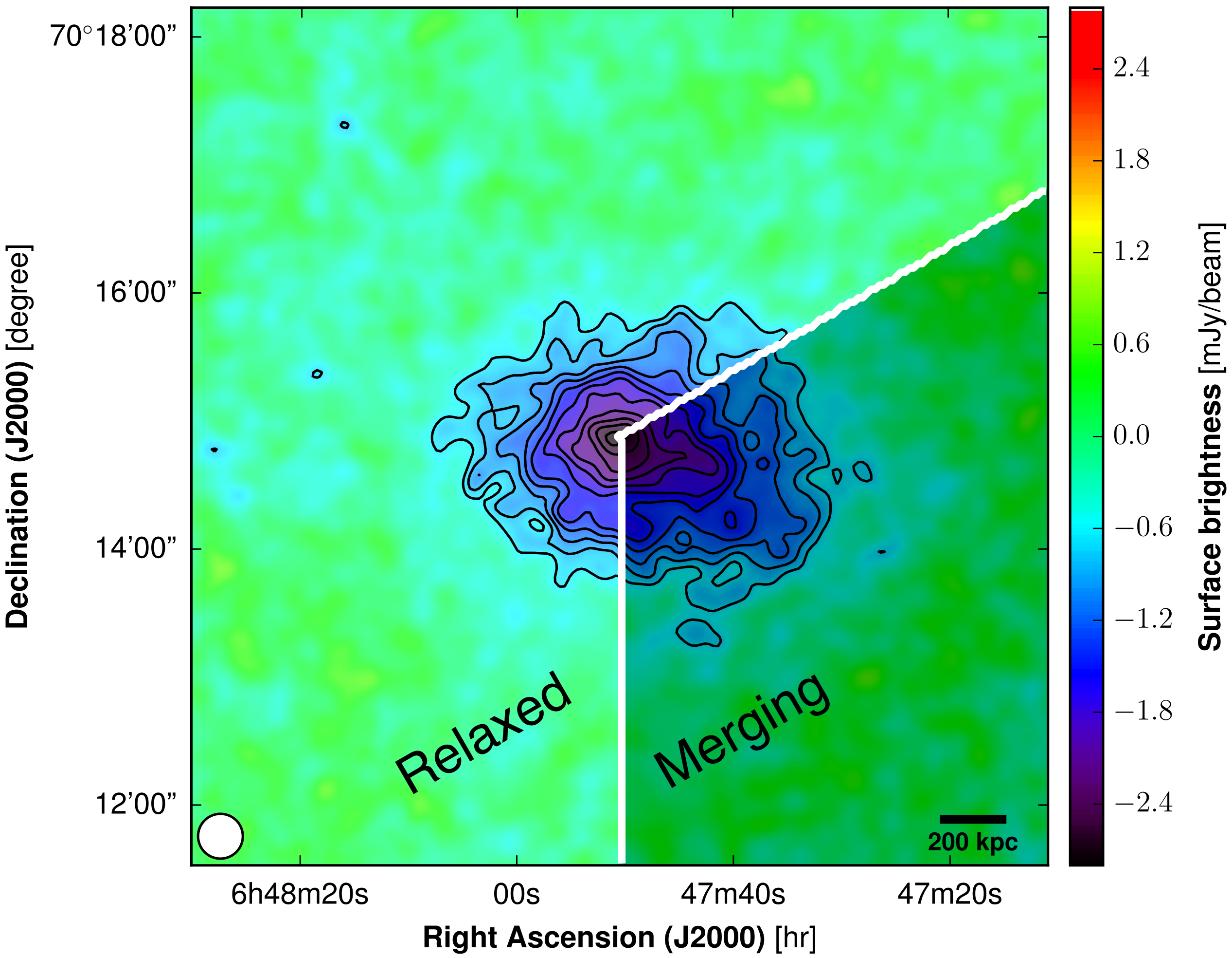


[Adam et al. (2016)]

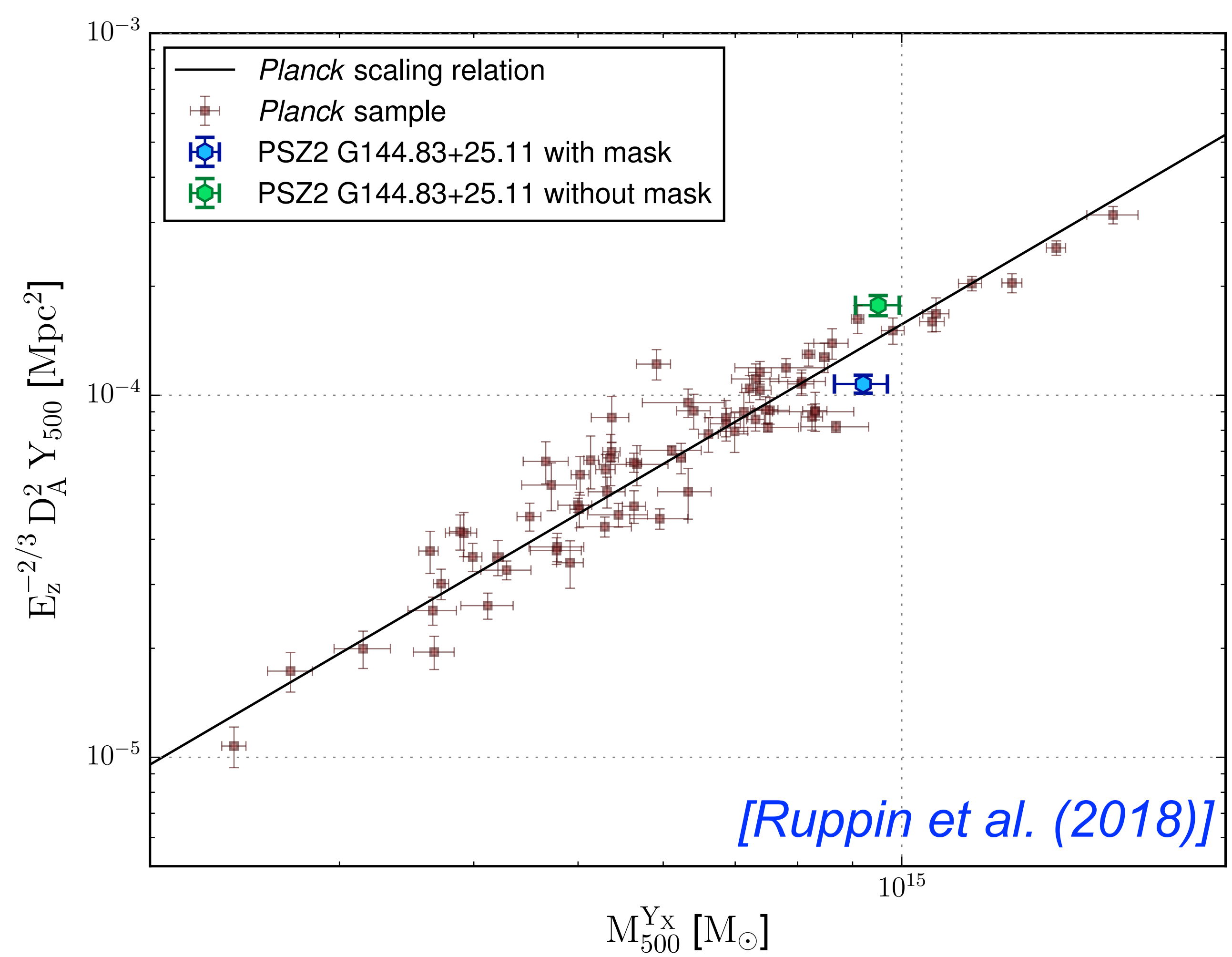
➡ Access to the mass, the SZ flux, and the cluster dynamics (morphology)

In depth study of SZ-mass calibration available

Implication of substructures on the SZ - mass scaling relation



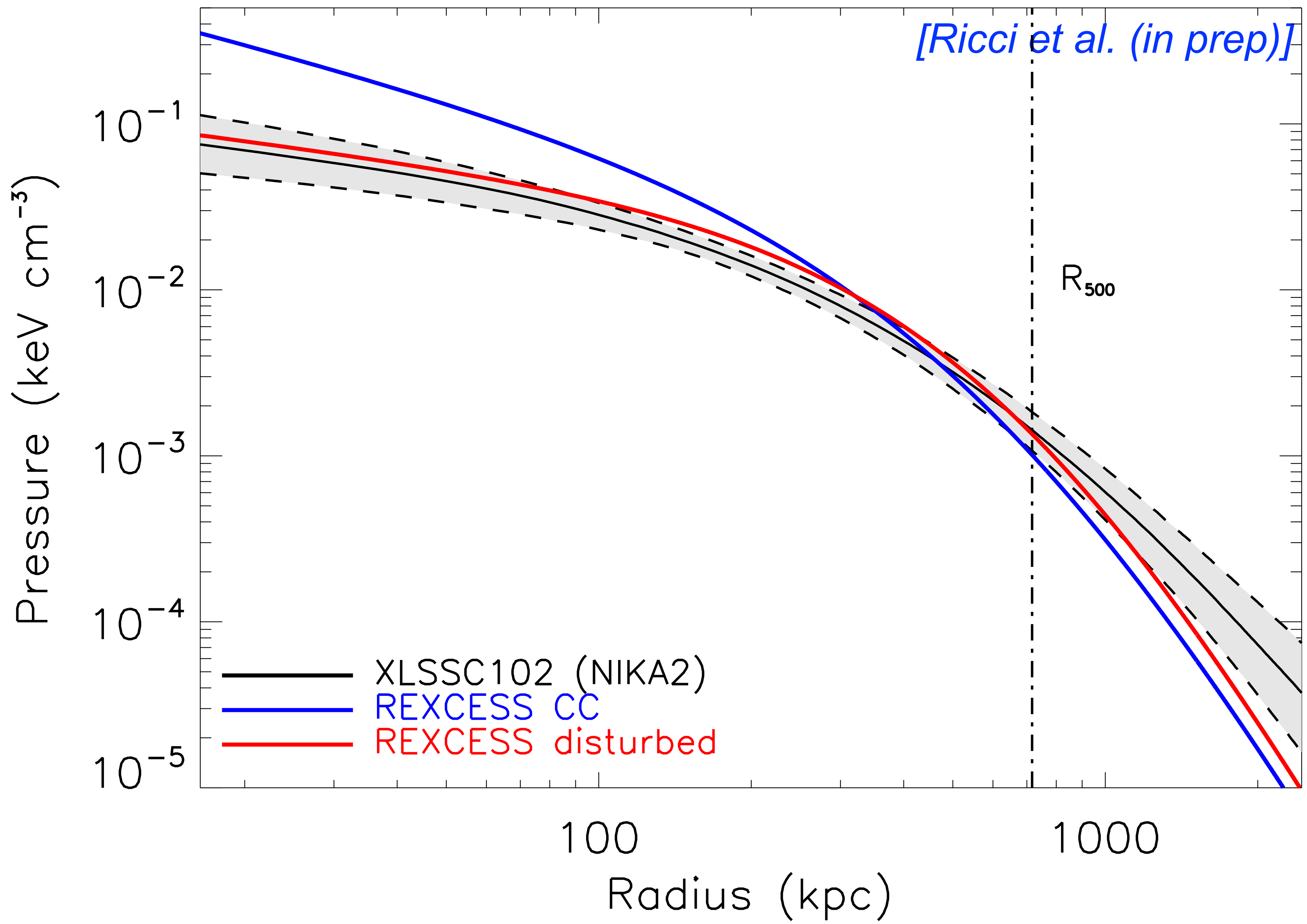
- Identification of disturbed region
  - induces significant deviations from the 'universal profile'
  - boost of the SZ flux by >60%



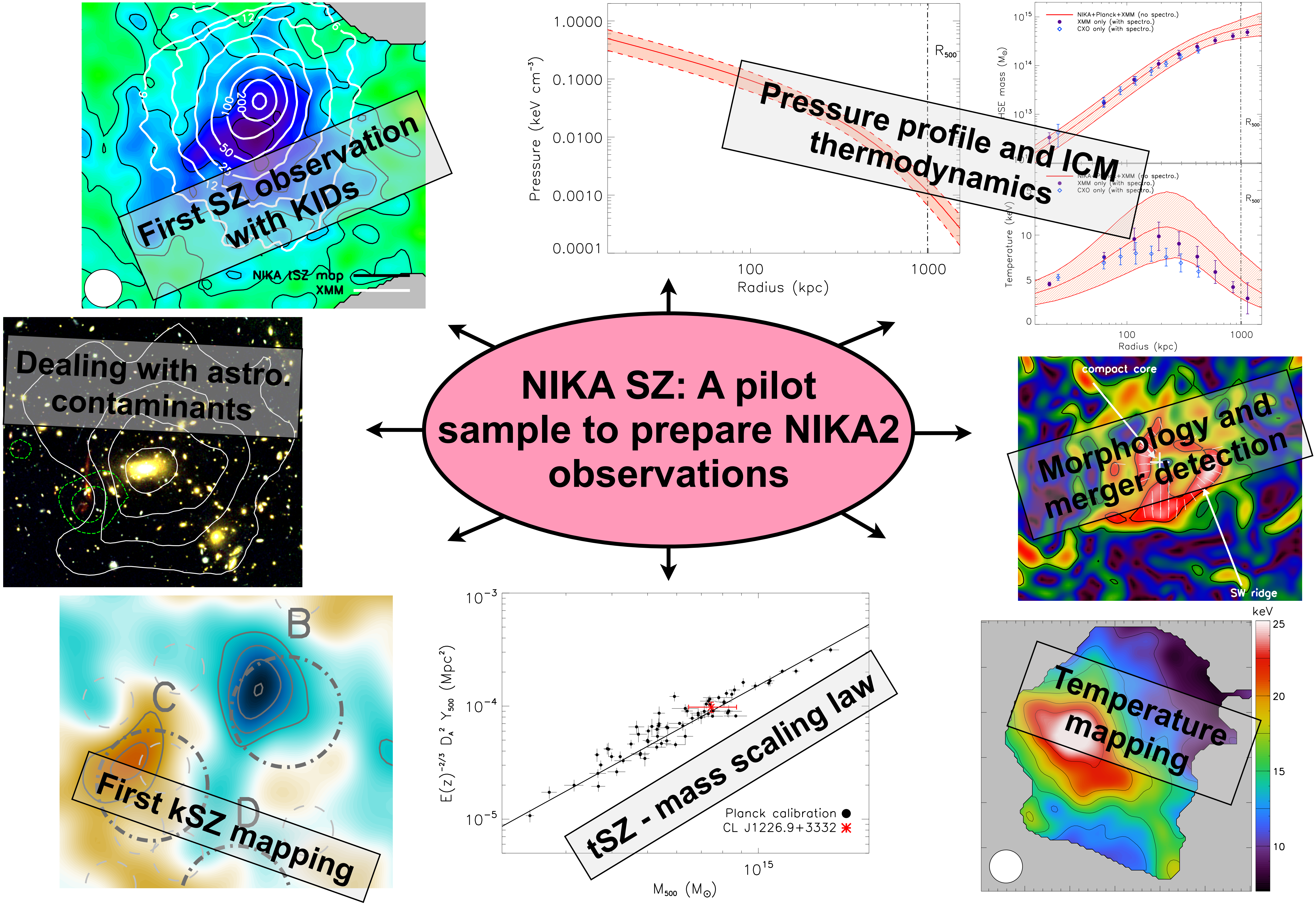
Strong impact of inner structure on SZ-M relation

SZ imaging at low mass and high redshift

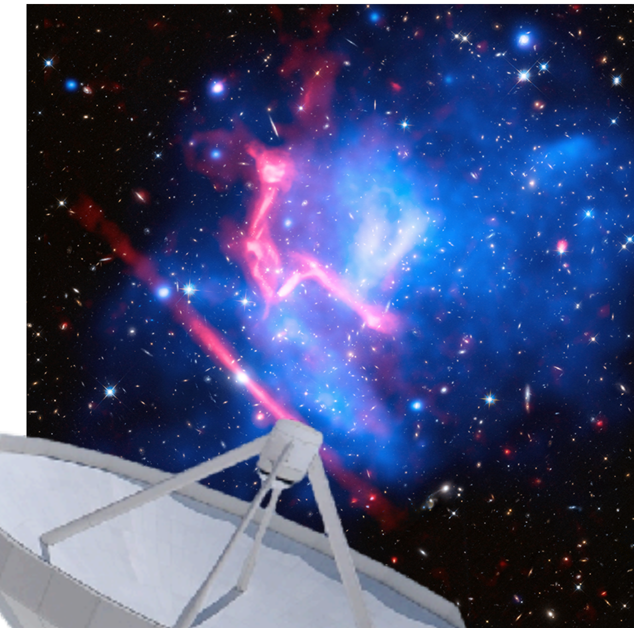
Follow-up of XXL-survey clusters in unexplored regime from resolved SZ data
(z=1, M_{500}<$3x10^{14}$ M_{sun})



Pressure profile consistent with expectations from local sample


NIKA SZ: A pilot sample to prepare NIKA2 observations
First SZ observation with KIDs
NIKA tSZ map
XMM
Pressure profile and ICM thermodynamics
Pressure (keV cm^-3)
Radius (kpc)
R500
HSE mass (M☉)
Temperature (keV)
NIKA+Planck+XMM (no spectro.)
XMM only (with spectro.)
CXO only (with spectro.)
Dealing with astro. contaminants
Morphology and merger detection
compact core
SW ridge
First kSZ mapping
B
C
D
tSZ - mass scaling law
E(z)^-2/3 D_A^2 Y500 (Mpc^2)
M500 (M☉)
Planck calibration
CL J1226.9+3332
Temperature mapping
keV

Outline



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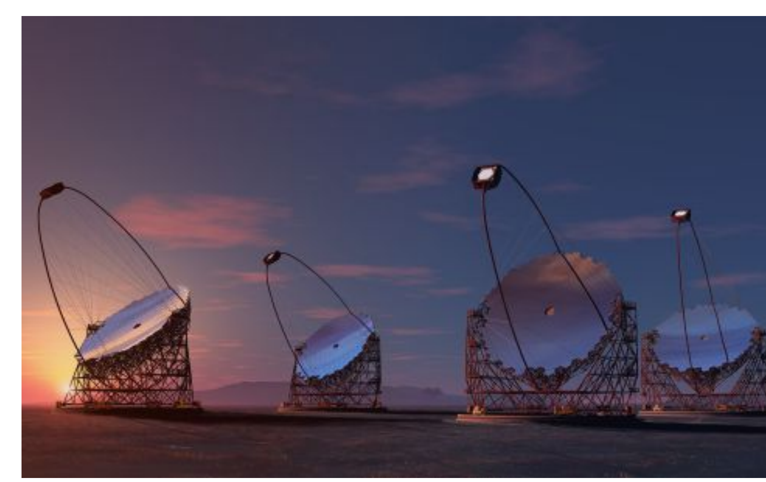
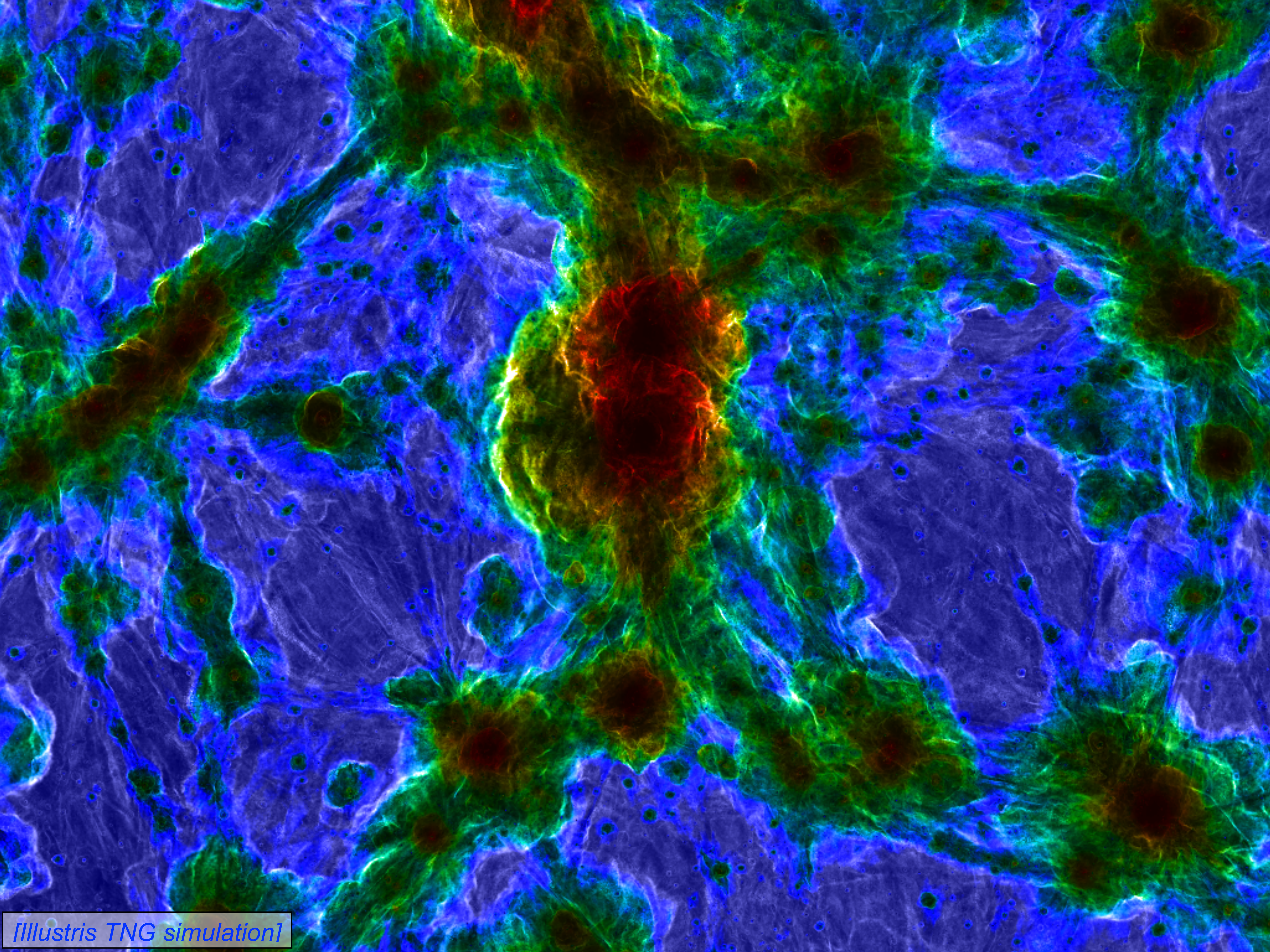
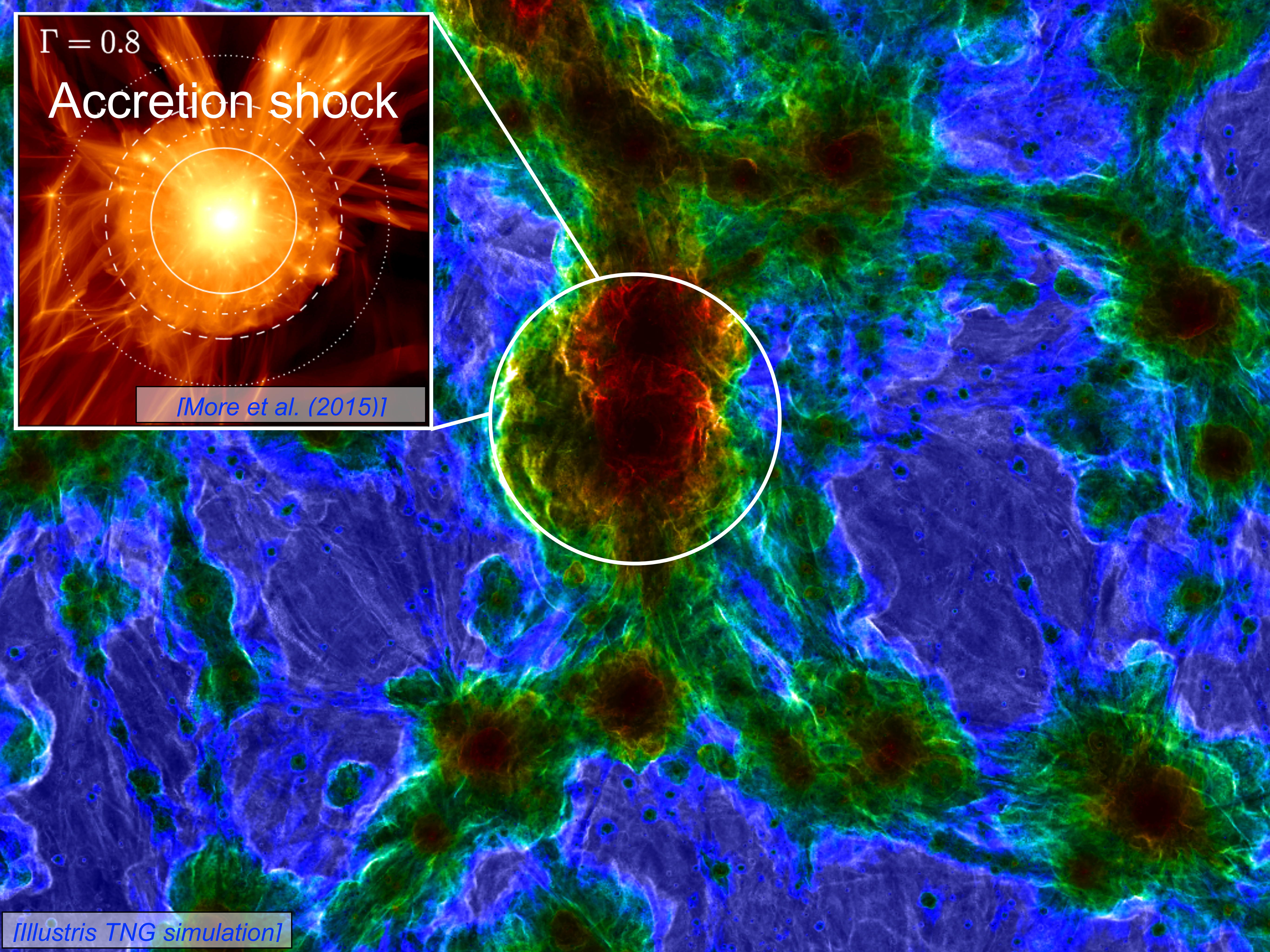
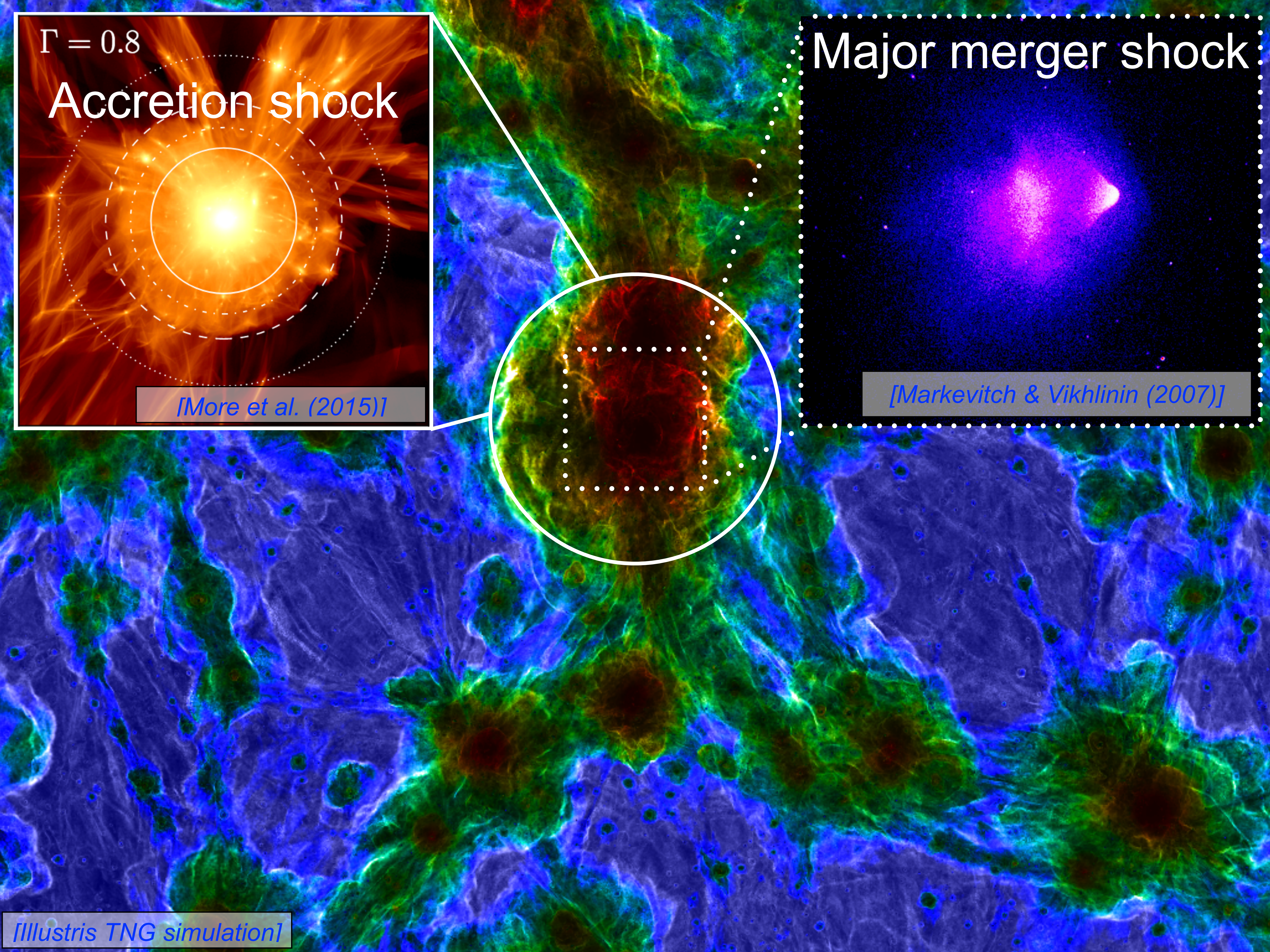



[Illustris TNG simulation]


$\Gamma = 0.8$
Accretion shock
[More et al. (2015)]
[Illustris TNG simulation]



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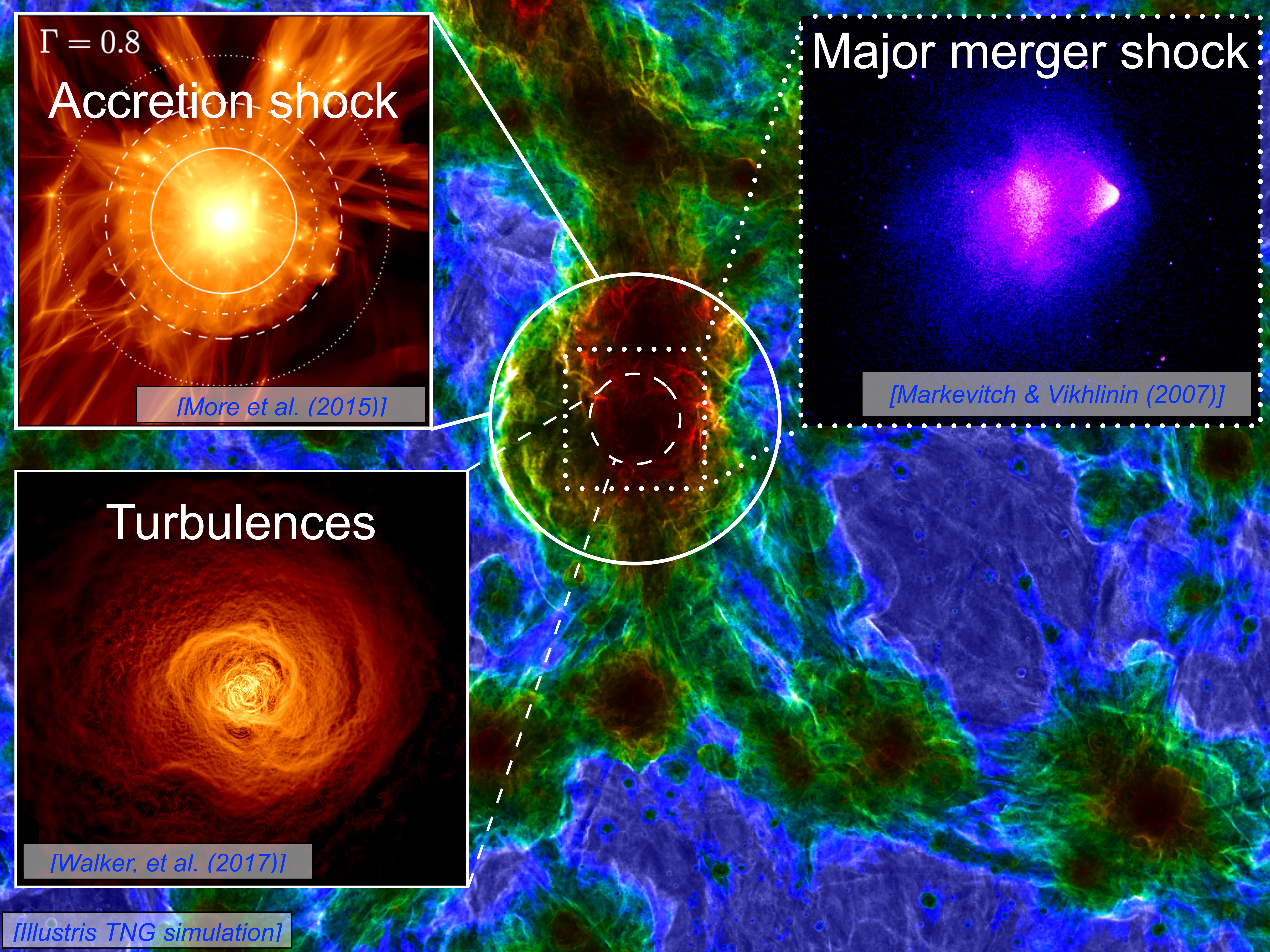

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Turbulences
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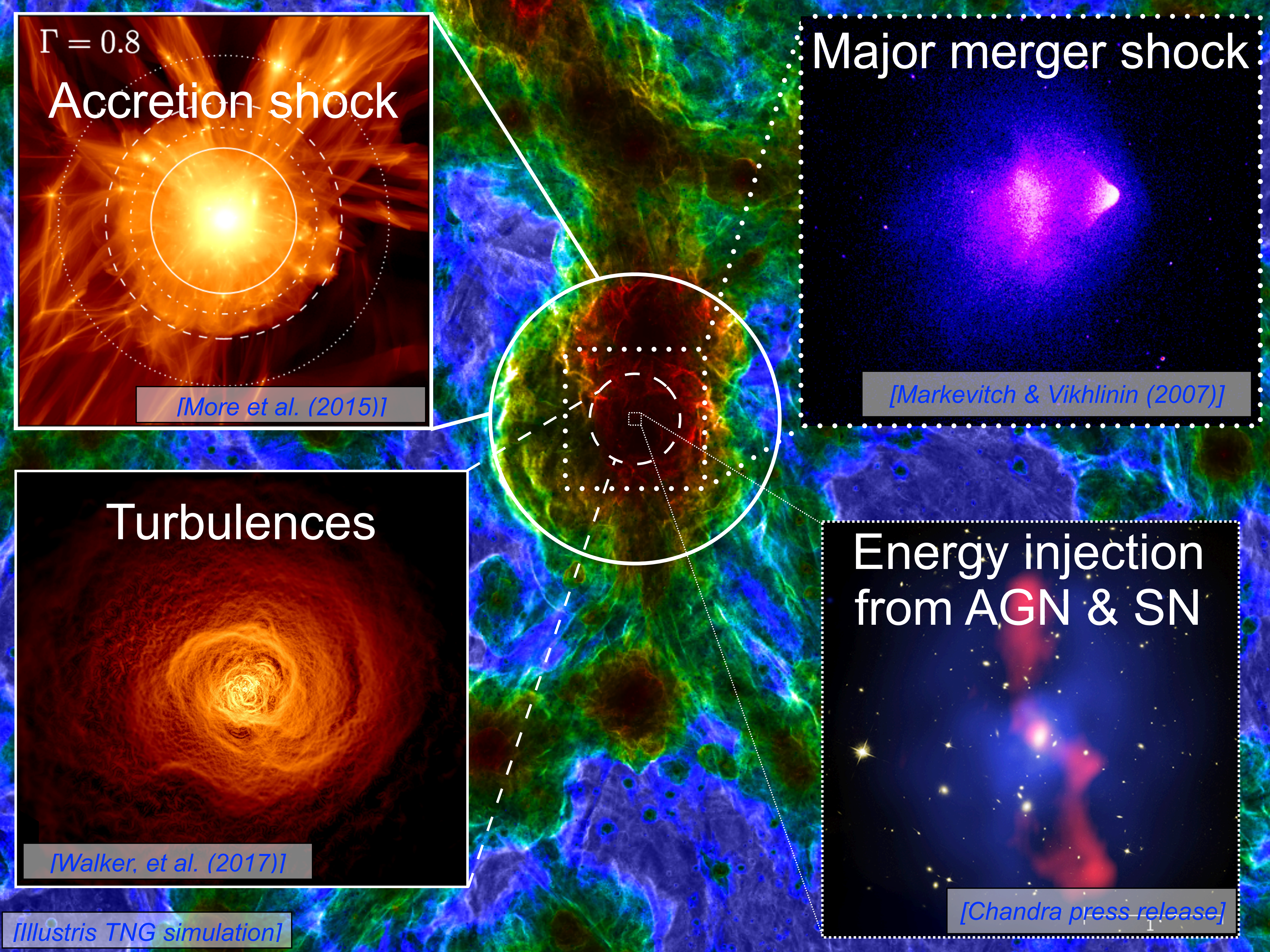

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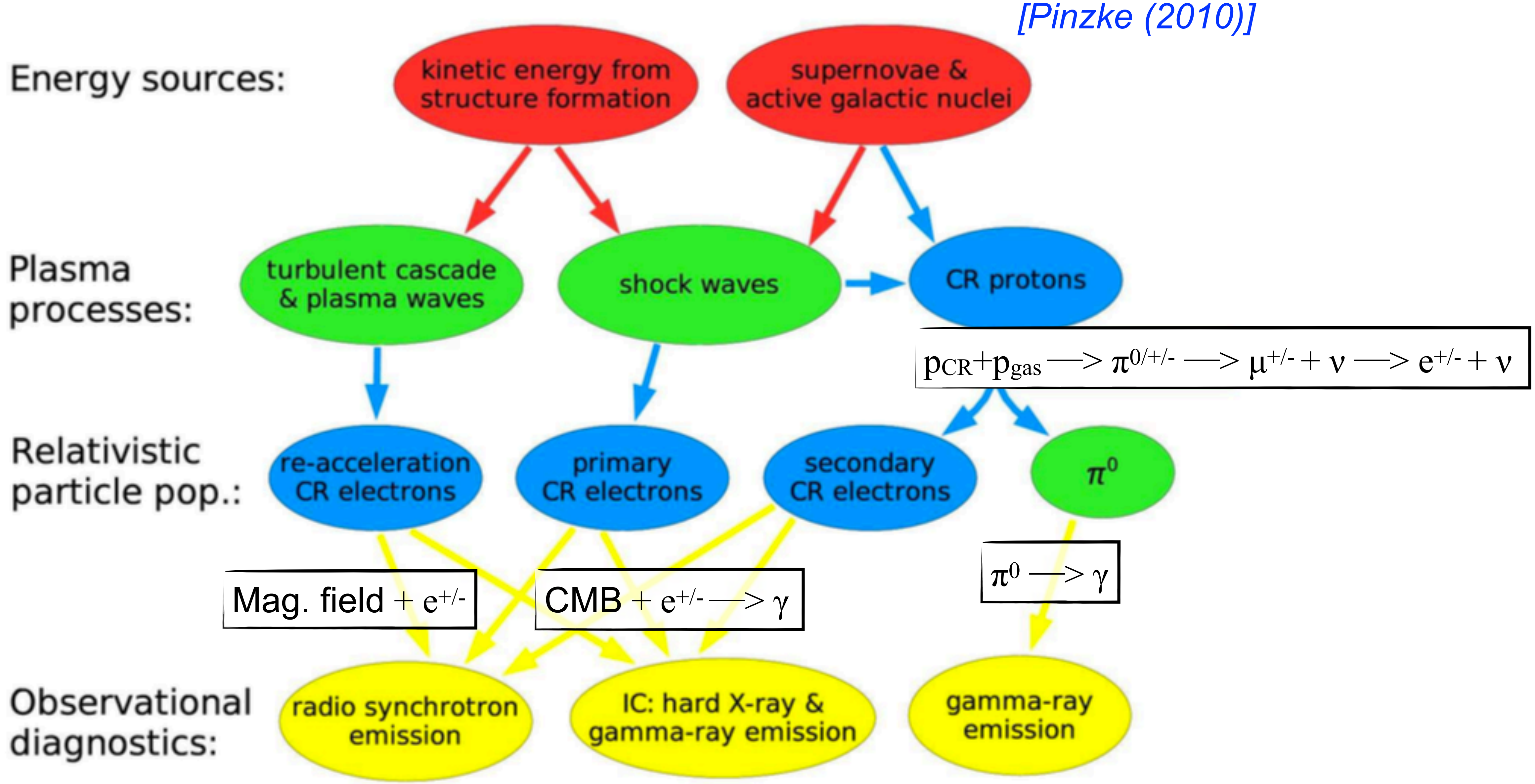
Major merger shock
[Markevitch & Vikhlinin (2007)]
Turbulences
[Walker, et al. (2017)]
Energy injection from AGN & SN
[Chandra press release]
[Illustris TNG simulation]

From energy injection to γ-ray emission

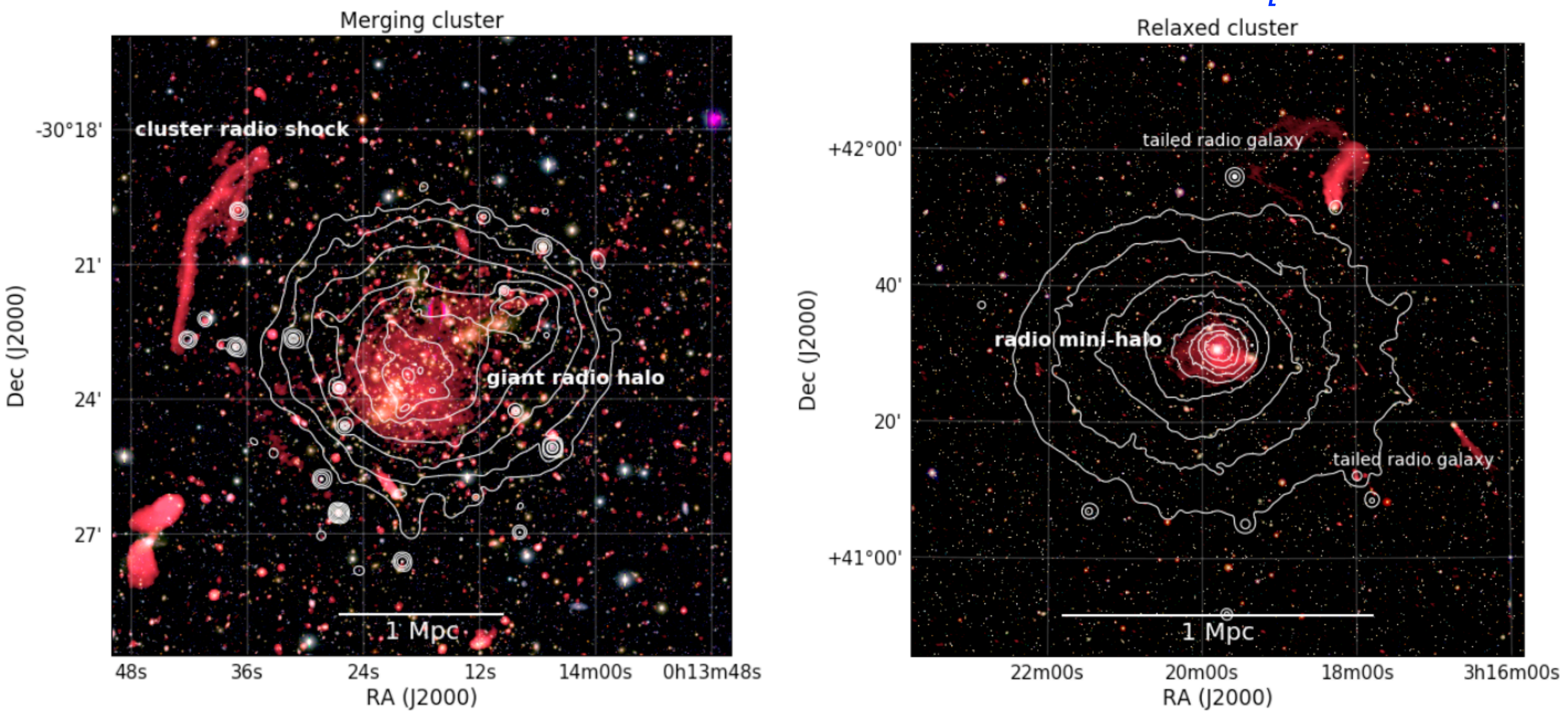
[Pinzke (2010)]



Particle acceleration, and γ-ray signal, is expected

Diffuse radio emission in galaxy clusters

[Van Weeren et al. (2019)]

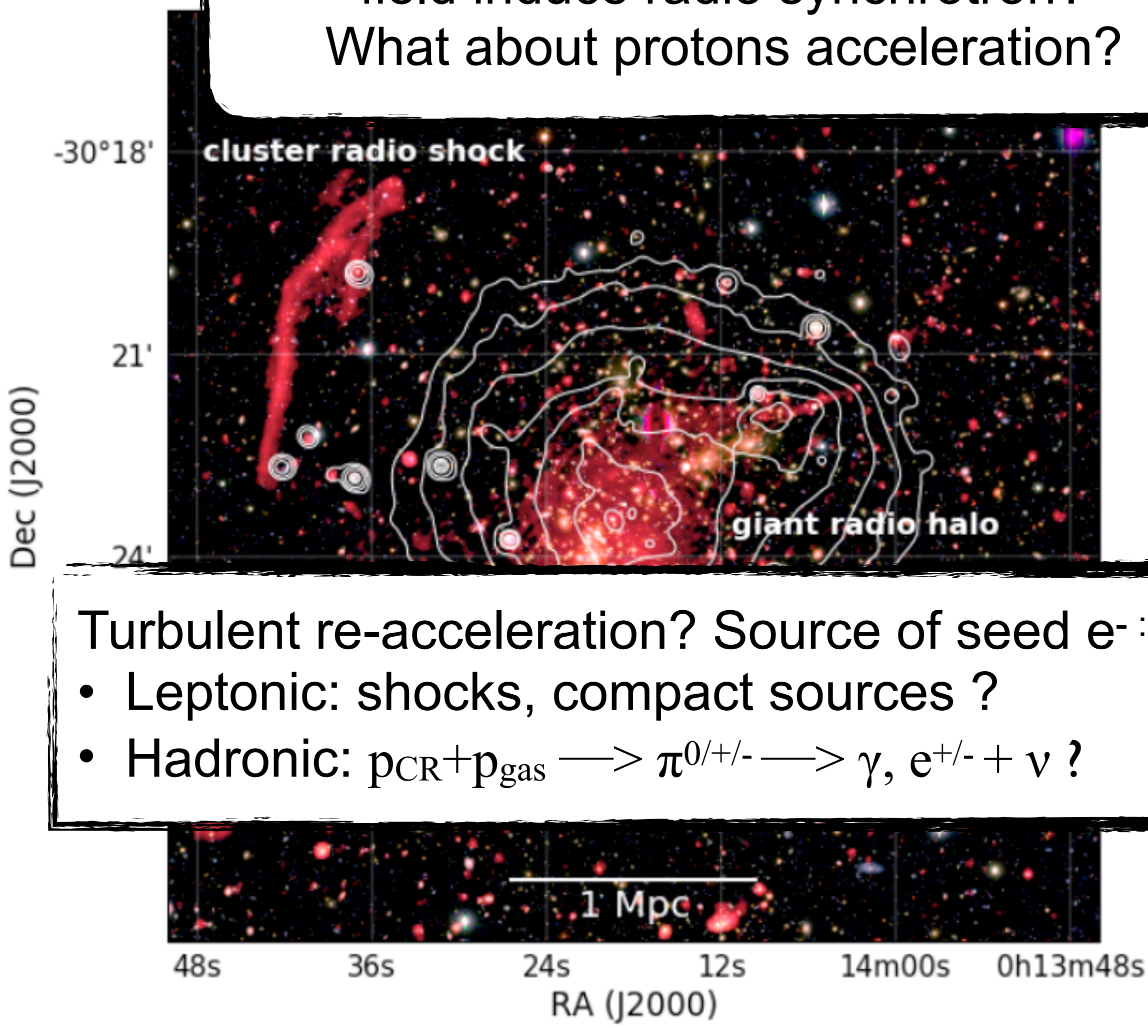


- Presence of relativistic e^- and B field from radio synchrotron, but unclear origin
- CR protons should accumulate over cosmic time, with $U_{CR} \sim 10^{-2}\ U_{therm}$ [Brunetti et al. (2014)]

Diffuse radio emission in galaxy clusters

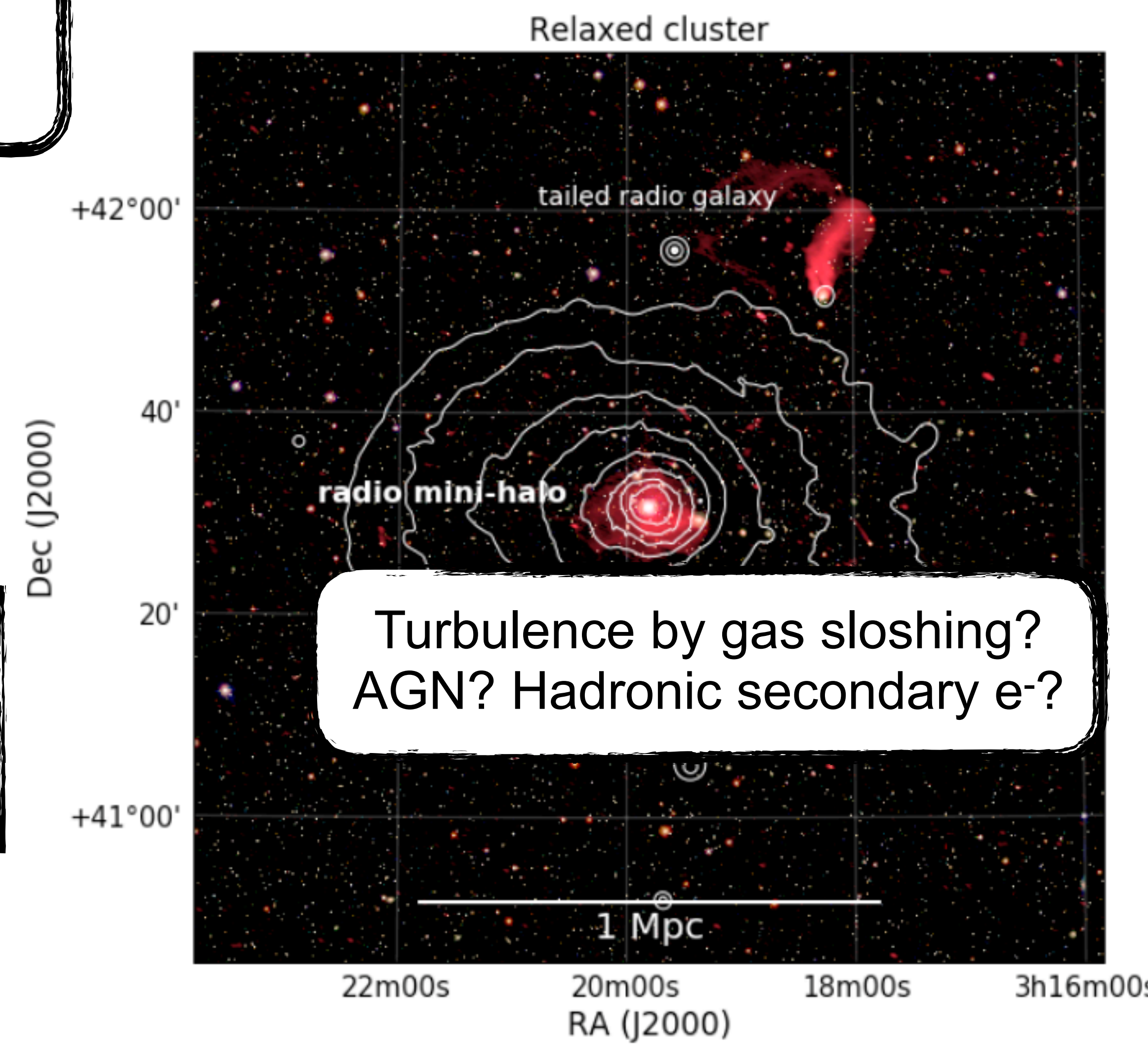
[Van Weeren et al. (2019)]

Merger shock e^- acceleration + magnetic field induce radio synchrotron?
What about protons acceleration?



Turbulent re-acceleration? Source of seed e^- :

- Leptonic: shocks, compact sources ?
- Hadronic: $p_{CR} + p_{gas} \longrightarrow \pi^{0/+/-} \longrightarrow \gamma,\ e^{+/-} + \nu$?



Turbulence by gas sloshing?
AGN? Hadronic secondary e^-?

- Presence of relativistic e^- and B field from radio synchrotron, but unclear origin
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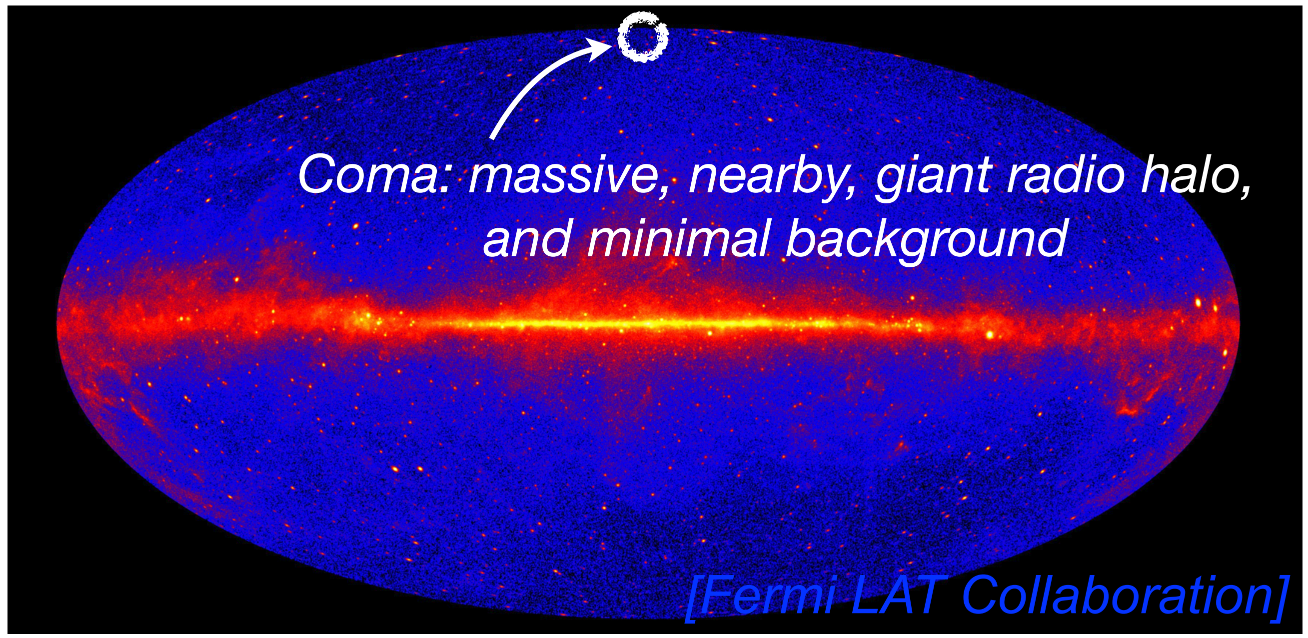
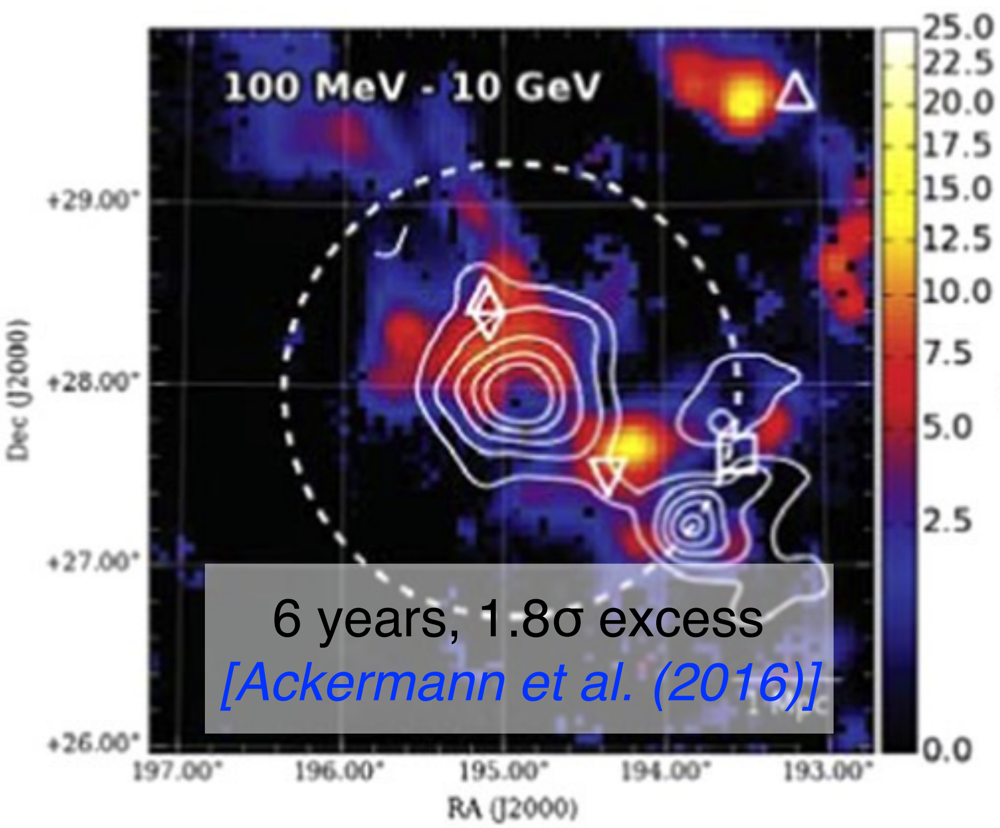
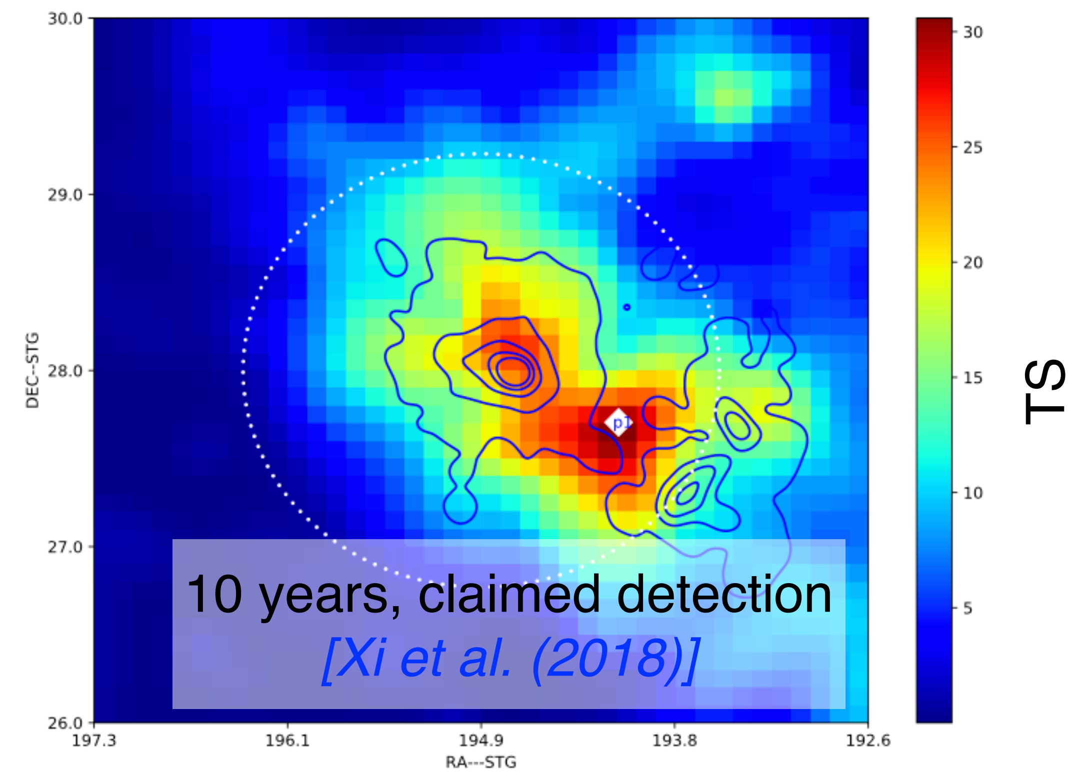
γ-rays would provide unambiguous diagnostics for cosmic ray protons

Search for γ-rays towards Coma with Fermi-LAT



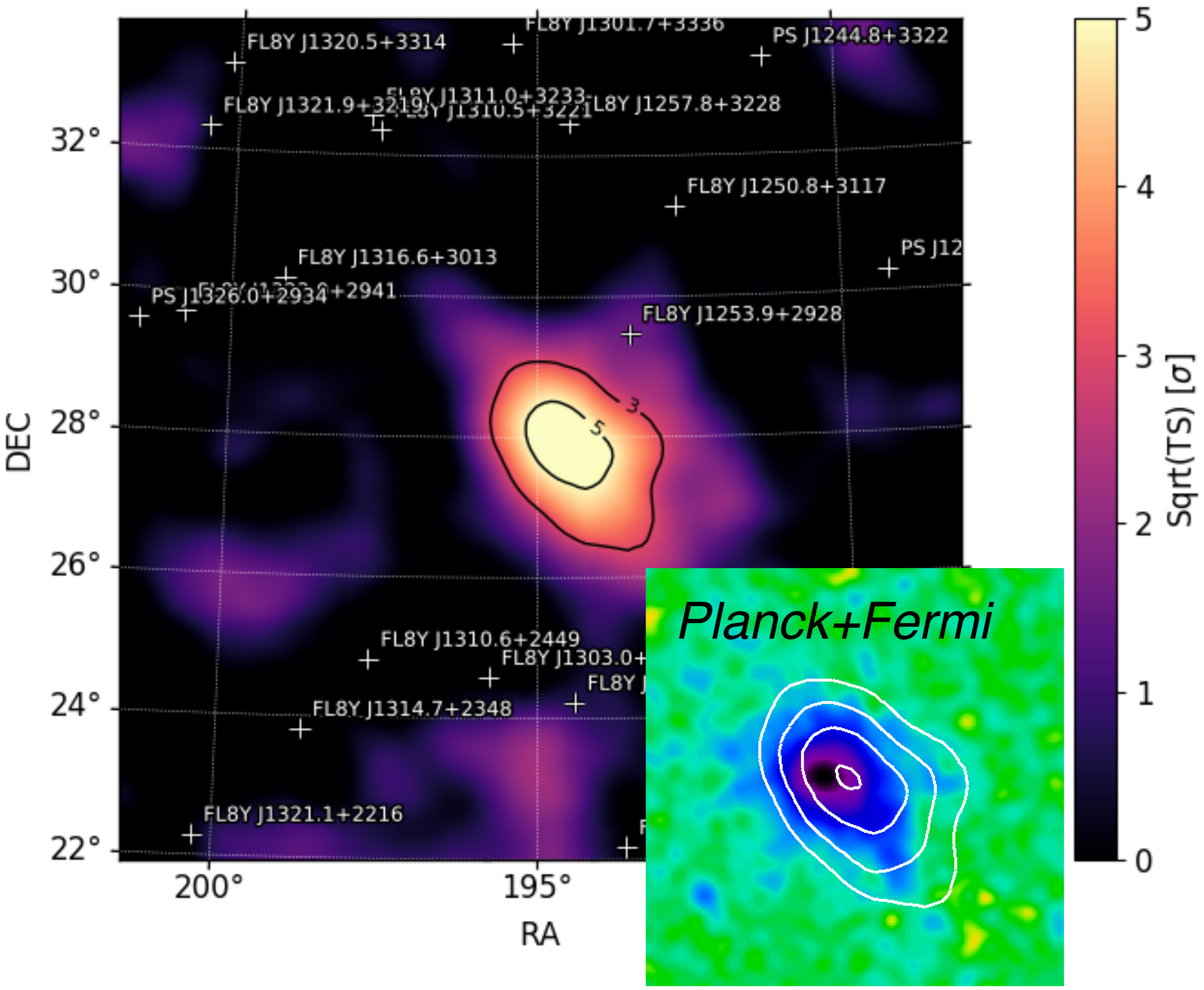


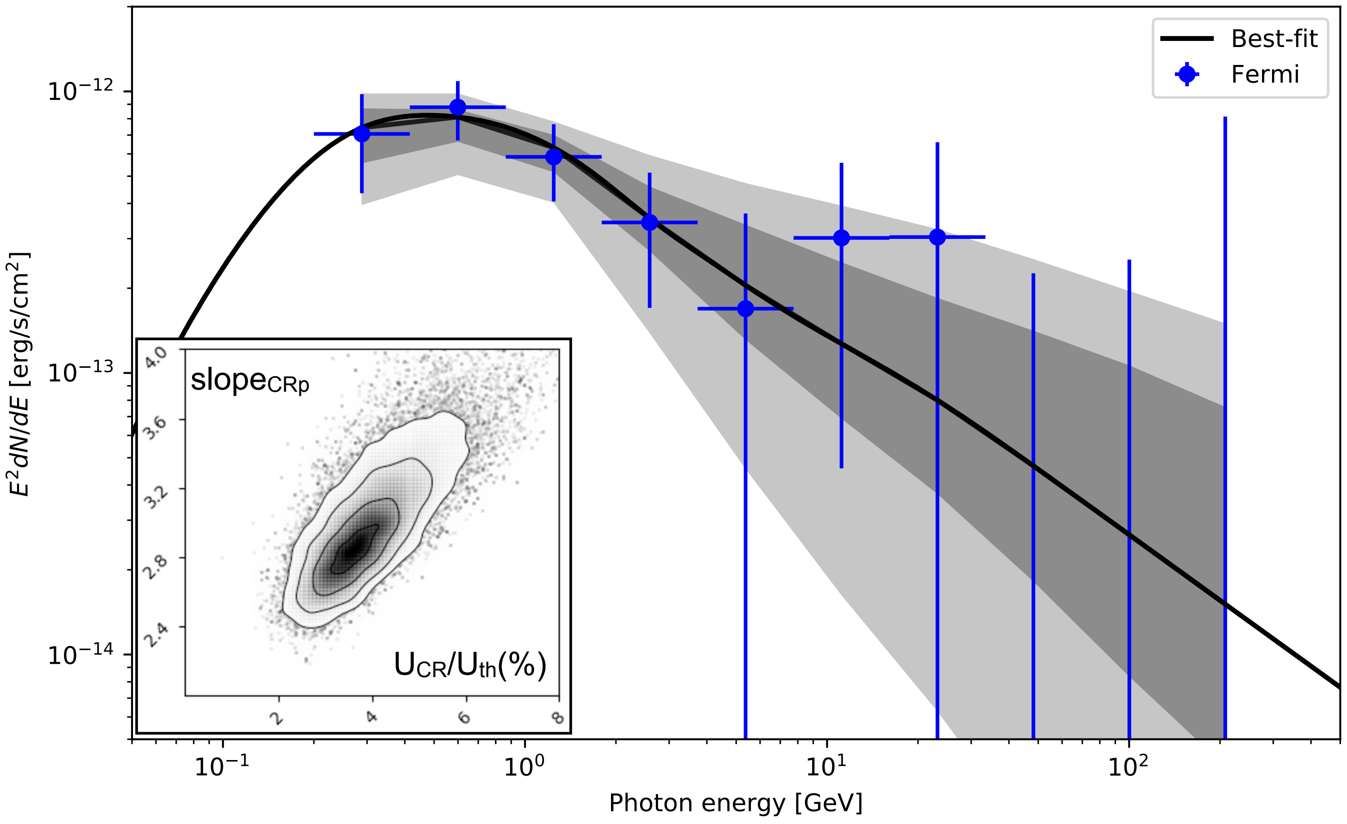


Claimed detection in the direction of Coma

Search for γ-rays towards Coma with Fermi-LAT
(work in progress)

The signal would imply a CR to thermal pressure of few%
- fine with model expectations
- consistent with the multi-wavelength morphology





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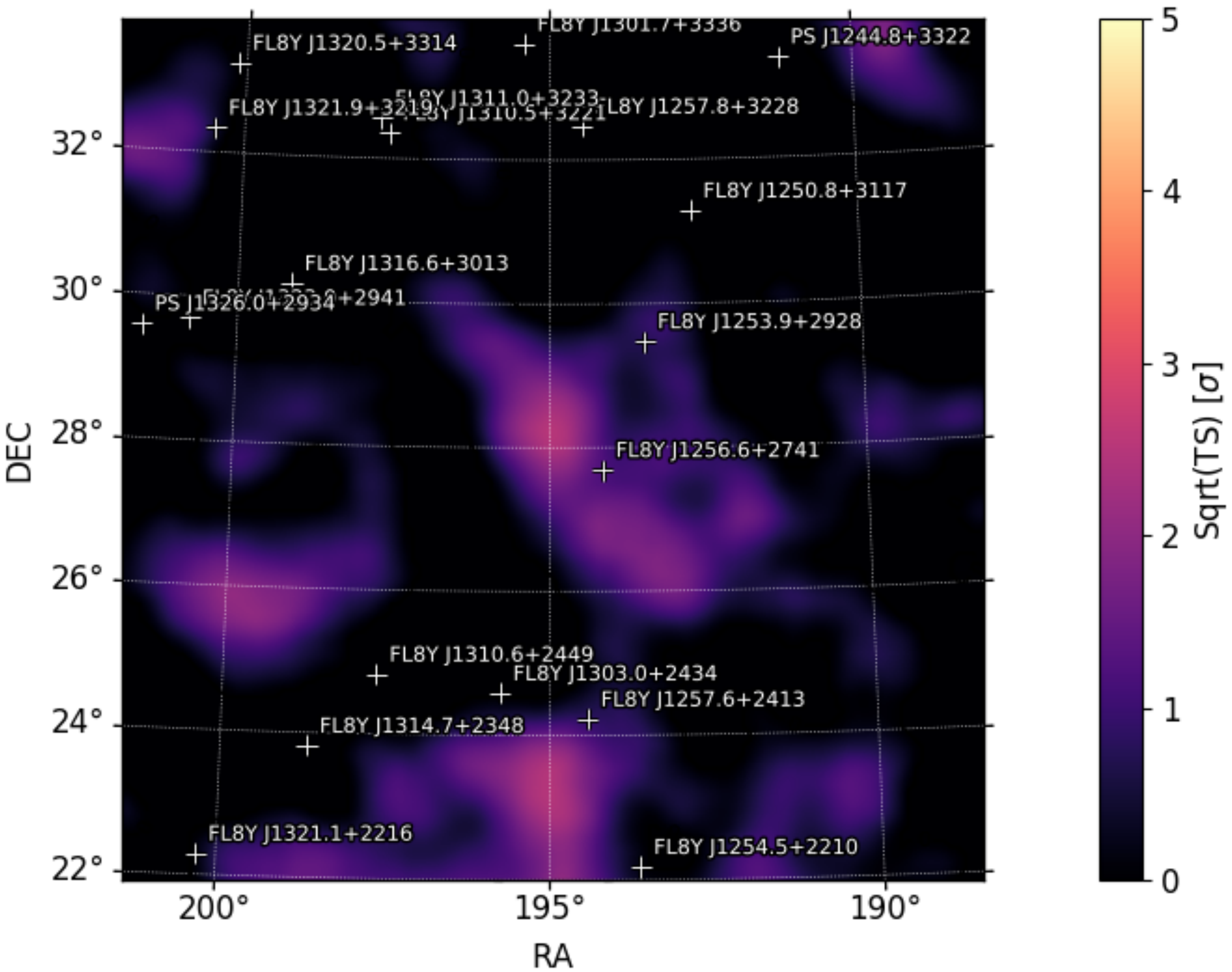
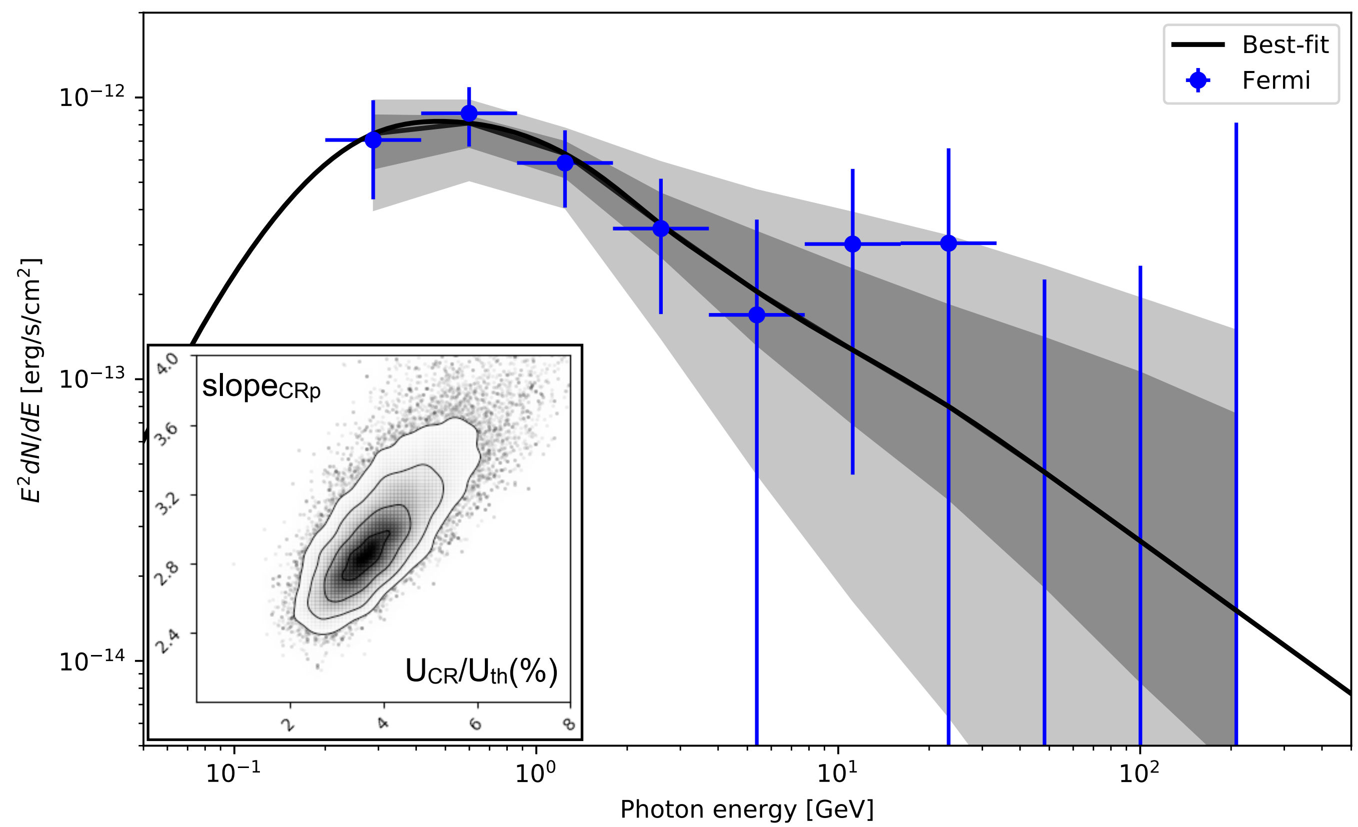




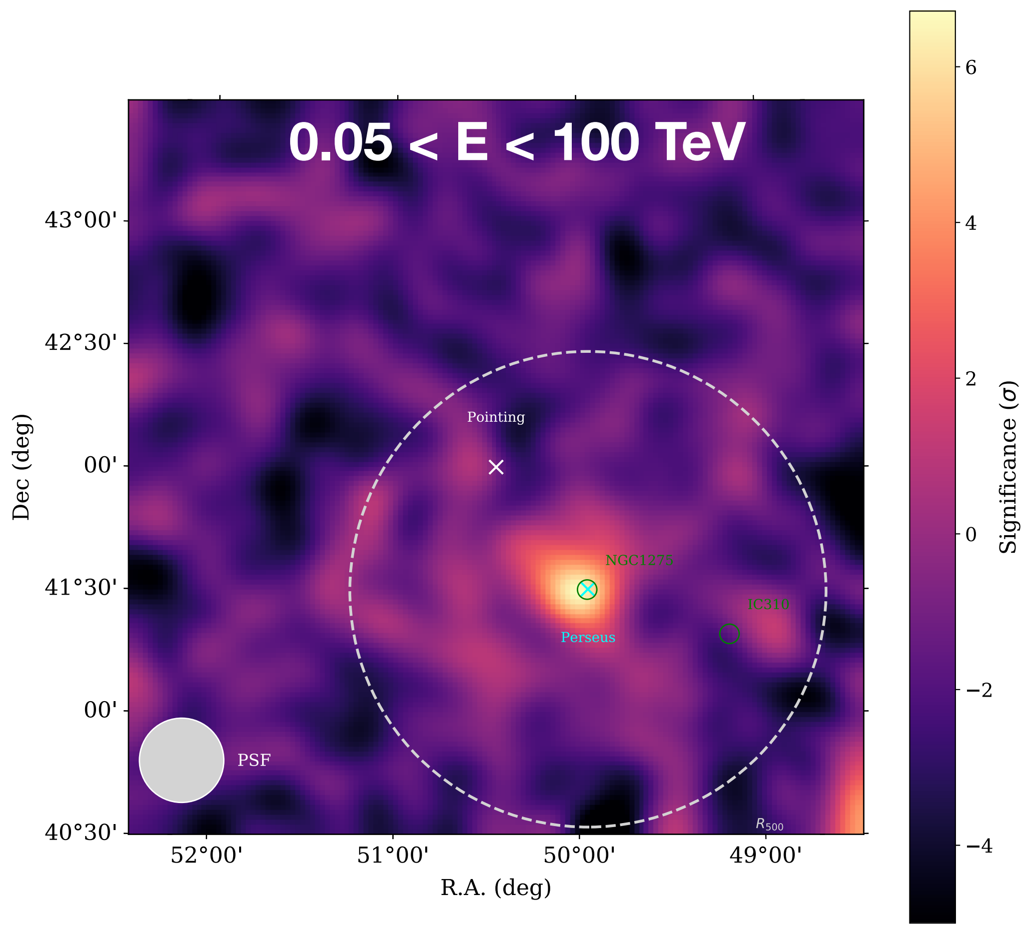
But accounting for a potential point source drastically reduces the significance

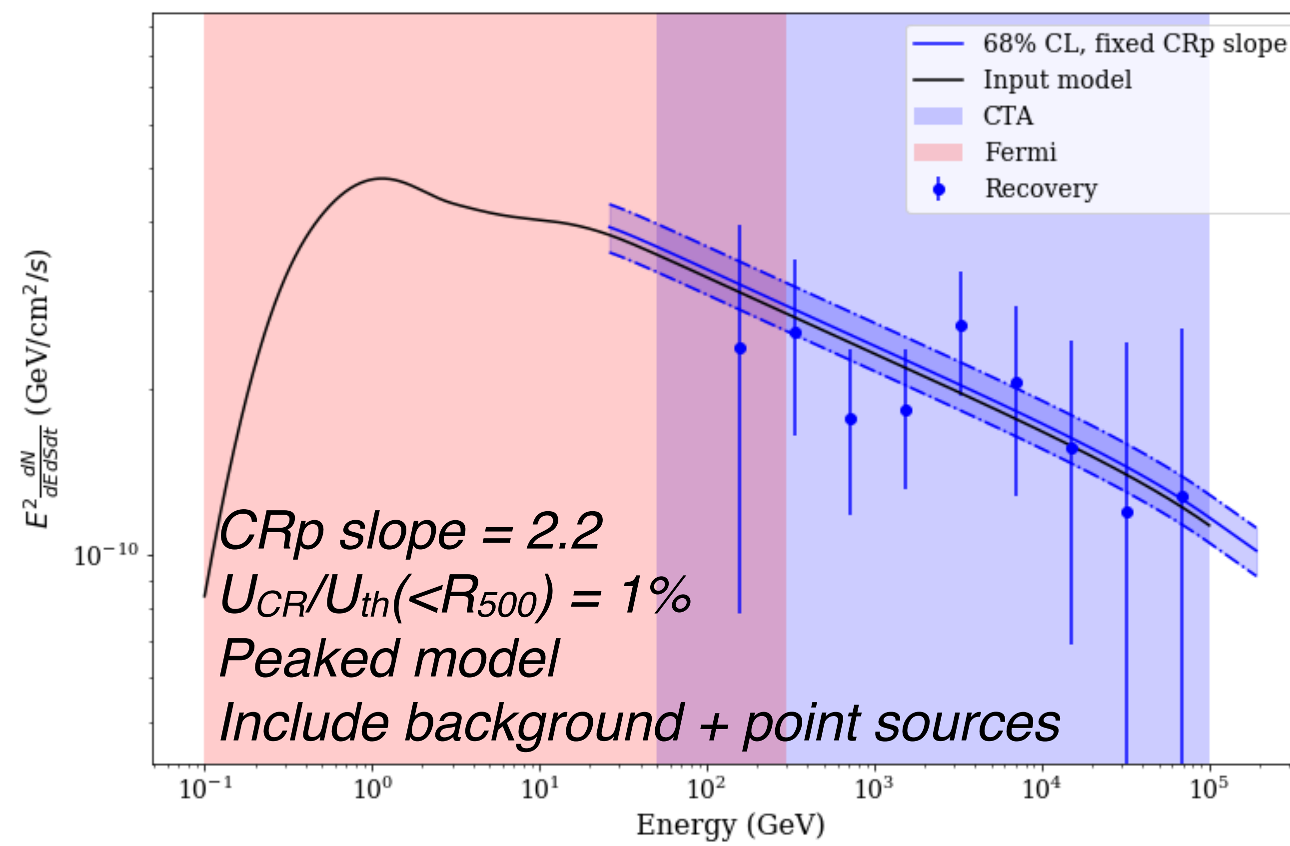
Fake detection due to point source contaminant?

Simulating the expected signal with CTA

(work in progress)

- VHE γ-rays from atmospheric Cherenkov imaging
- Great angular resolution + wide energy range will be key to disentangle cluster emission from point sources
- Perseus to be observed 300h as a key science project *[CTA collaboration (2018)]*





Major step in understanding CRp & non-thermal physics expected with CTA

Outline

1. Clusters of galaxies as cosmic laboratories

2. Mapping the hot gas in the millimeter & X-ray

3. The quest for cluster cosmic rays in the γ-rays

Summary

Clusters as cosmic laboratories

- Clusters are very rich environment
  - Cosmology & astrophysics
- Astrophysical processes to be modeled for cosmology
  - The CMB/cluster tension remains unclear
  - Unique environment to study the DM-baryons co-evolution

NIKA2 SZ observations

- Resolved observations of the SZ signal
  - Many results from test case demonstration
  - Multi-wavelength analysis proved powerful
- Ongoing observations of 50 clusters
  - In depth study of the gas physics
  - High z SZ-mass calibration will be available

Cluster physics in the γ-rays

- Unique view on non-thermal physics
  - Clusters are cosmic calorimeters
  - Possible Fermi detection, but still unclear
- Observations with CTA
  - CTA is now under construction
  - Perseus will be the prime target

planck

NIKA

euclid
consortium

cta
cherenkov telescope array