Cosmology and astrophysics with galaxy clusters from radio to γ-ray observations

Rémi Adam

CEA seminar — 18/11/2019

Laboratoire Leprince-Ringuet

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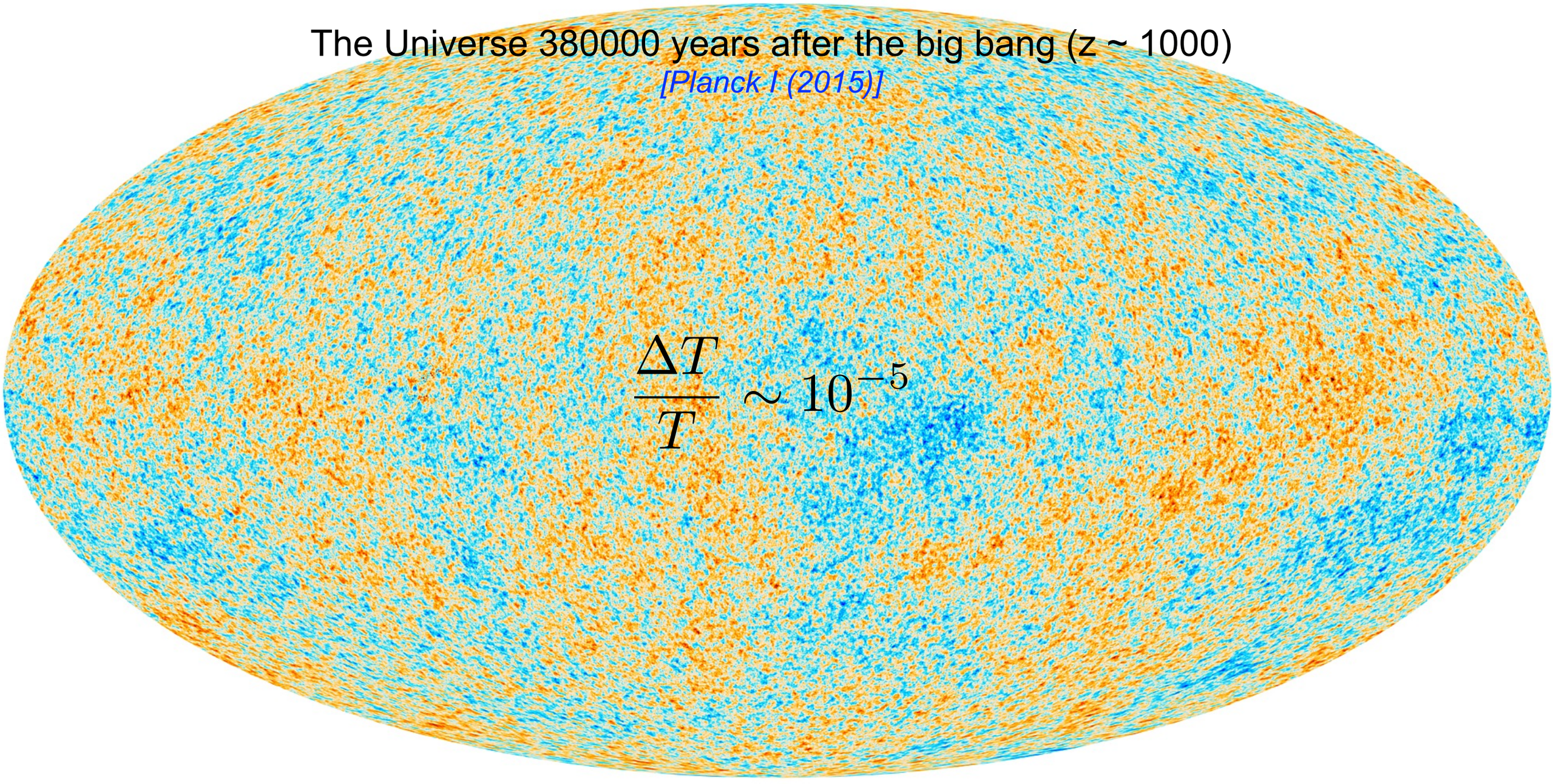
3. The quest for cluster cosmic rays in the γ-rays

Starting from primordial fluctuations

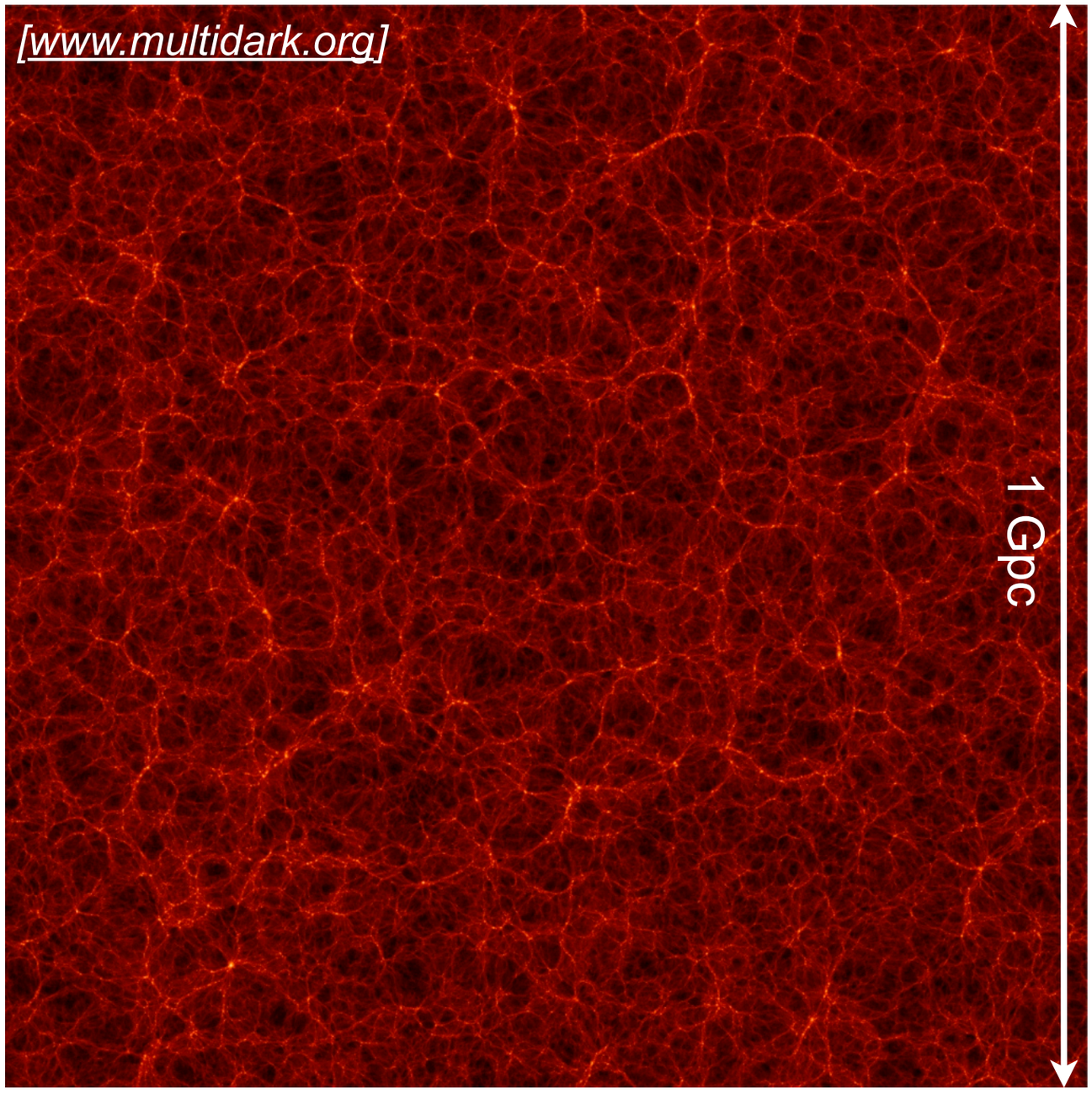
The Universe 380000 years after the big bang (z ~ 1000)

[Planck I (2015)]



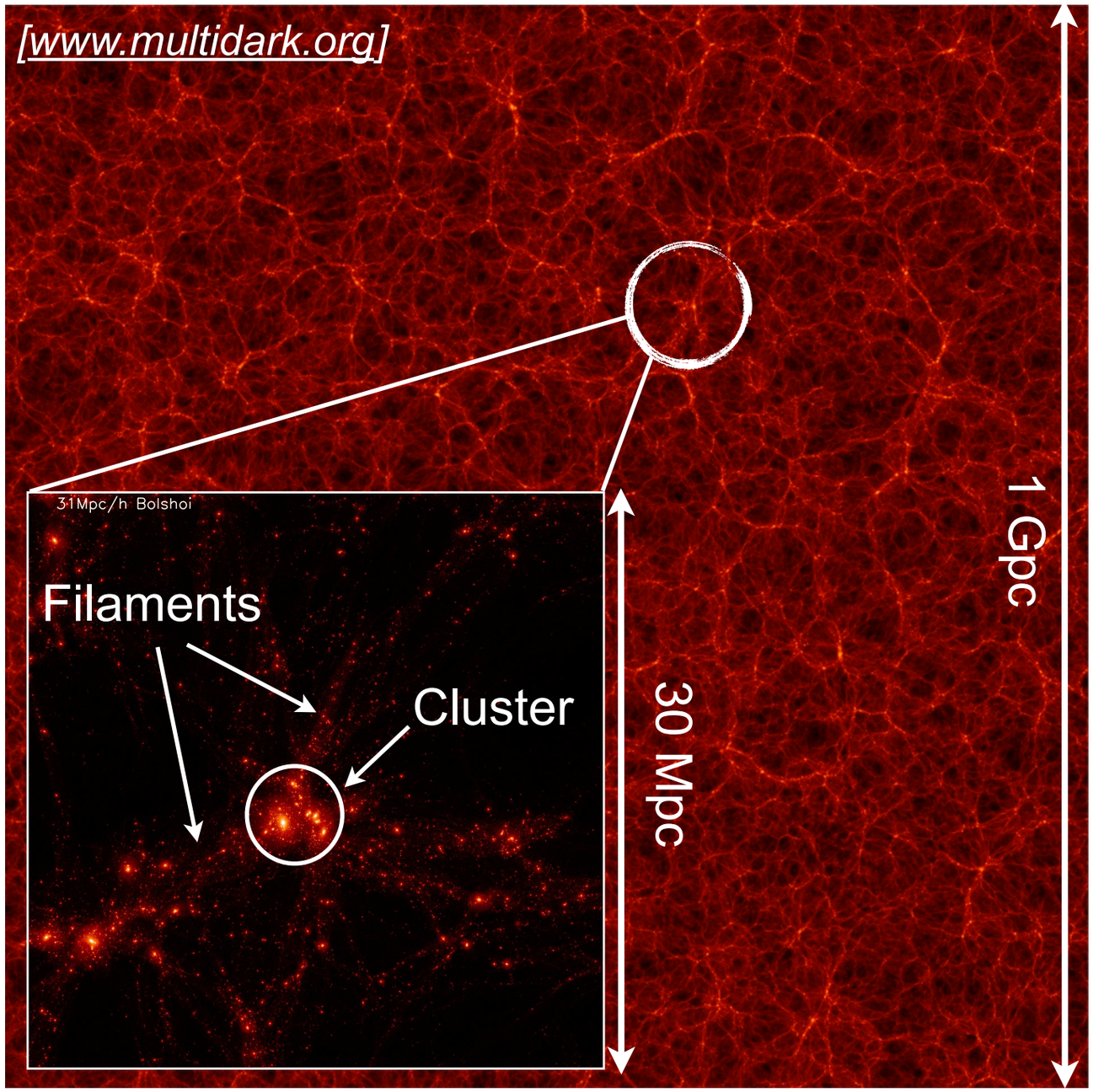
A very homogeneous Universe, with tiny fluctuations

From large scale fluctuations to galaxy clusters



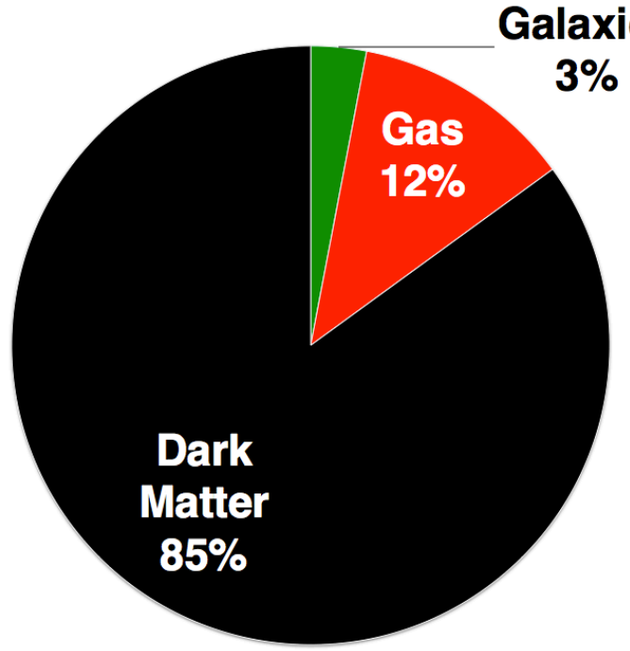
- The primordial fluctuations collapse in the expanding Universe

From large scale fluctuations to galaxy clusters



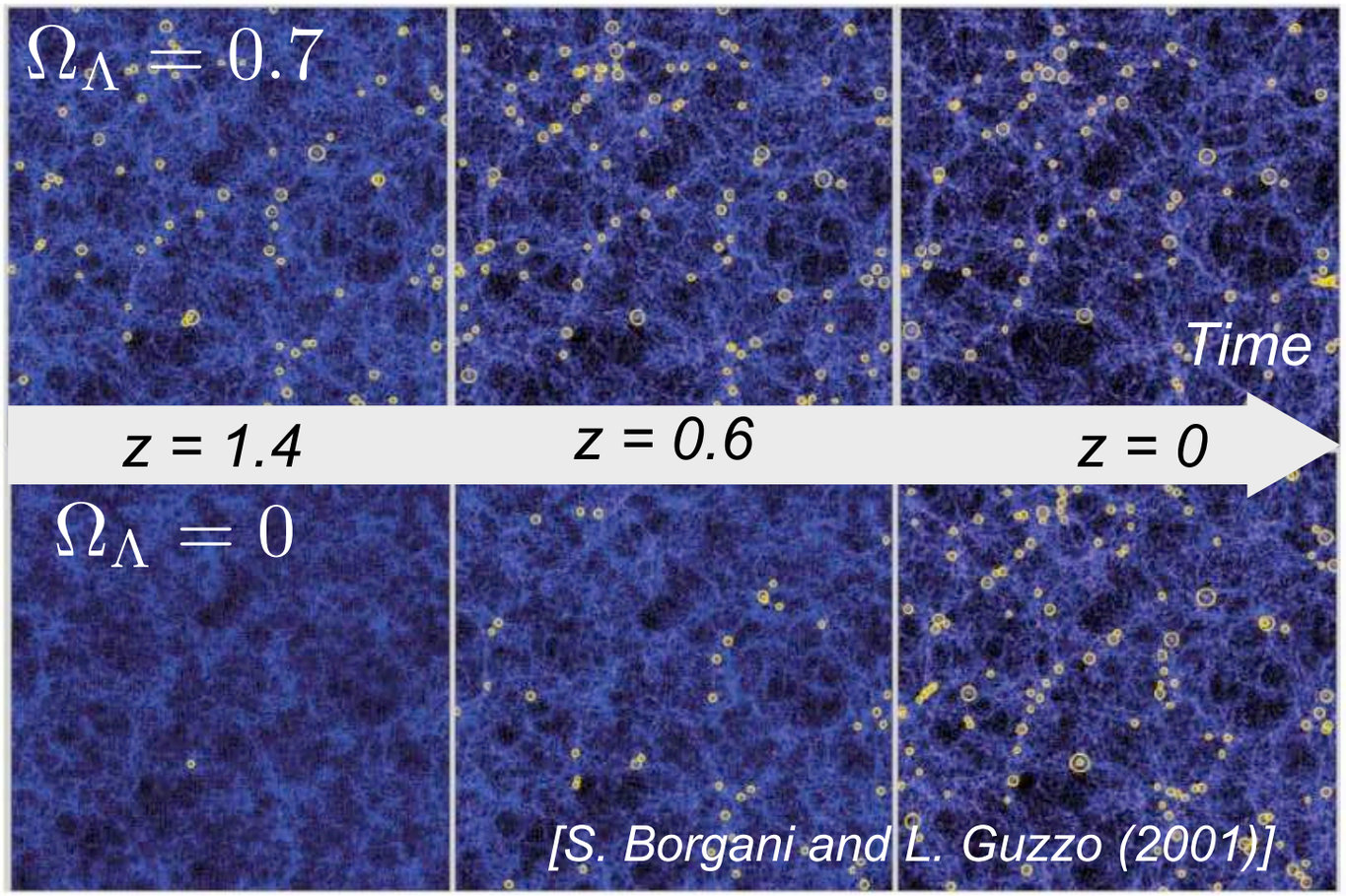
- The primordial fluctuations collapse in the expanding Universe
- To form clusters: the largest gravitationally bound structures

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



Galaxy clusters are peaks in the matter density field

Cosmology with cluster counts

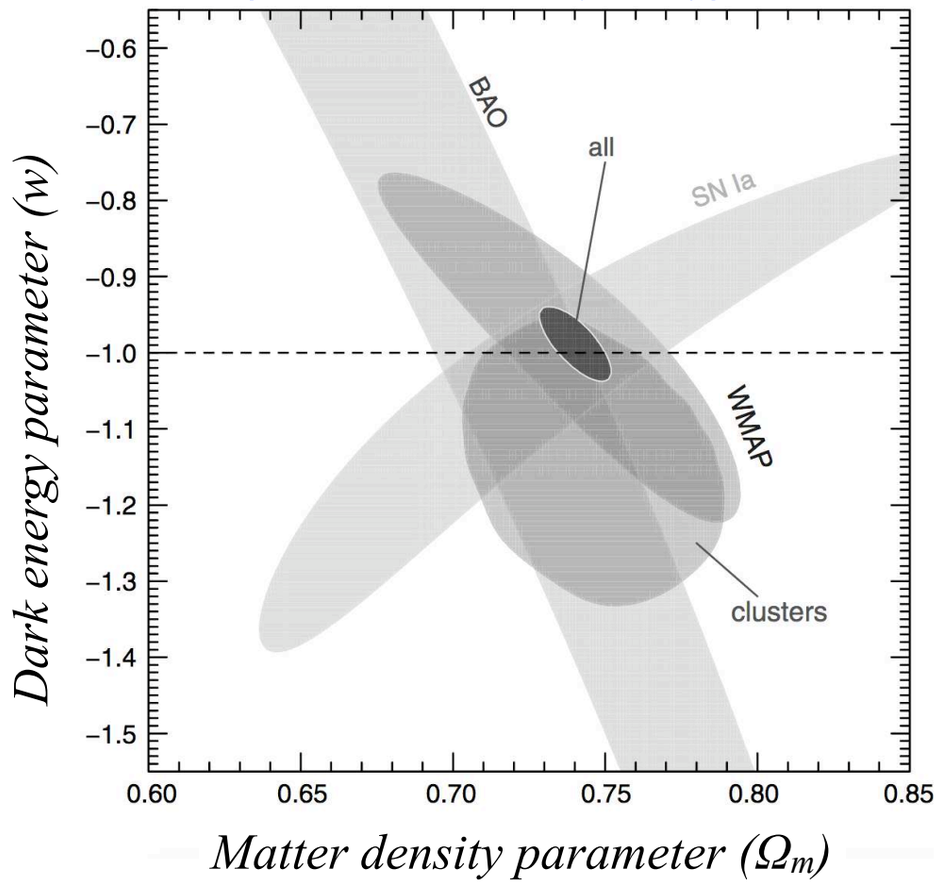


Survey detection ↘ $\frac{dN}{dz} = \int \chi(z, M) \frac{d^2 N}{dz dM} dM$ ↖ *Model*

Selection function — *Mass-obs. relations*

Cosmology with cluster counts

[Vikhlinin et al. (2009)]



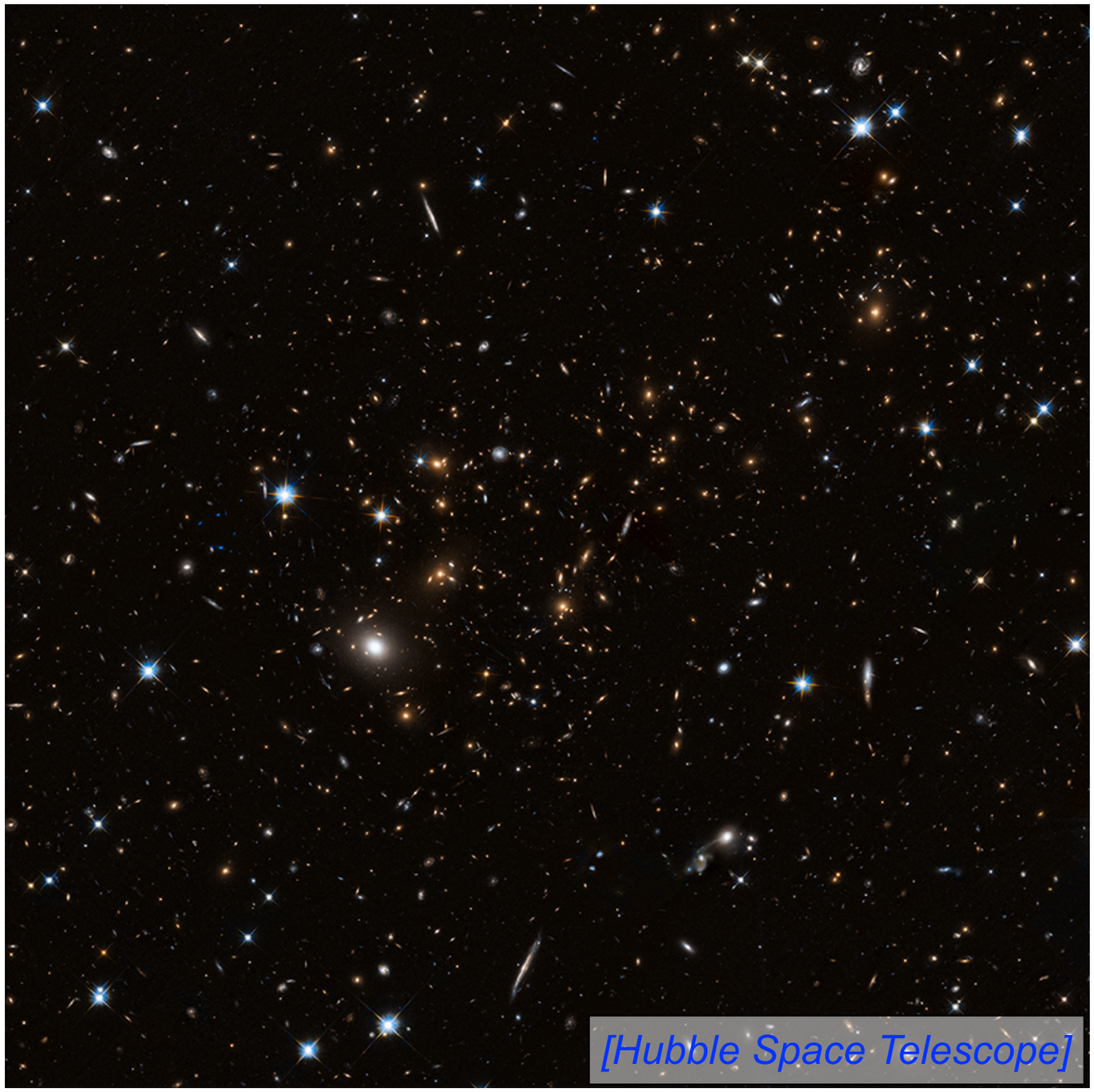
Survey detection → $\frac{dN}{dz} = \int \chi(z, M) \frac{d^2 N}{dz dM} dM$ ← *Model*

Selection function — *Mass-obs. relations*

Sensitive to geometry, dark matter/energy and gravitation

Key ingredients: mass + observational properties

Multi-wavelength view of galaxy clusters



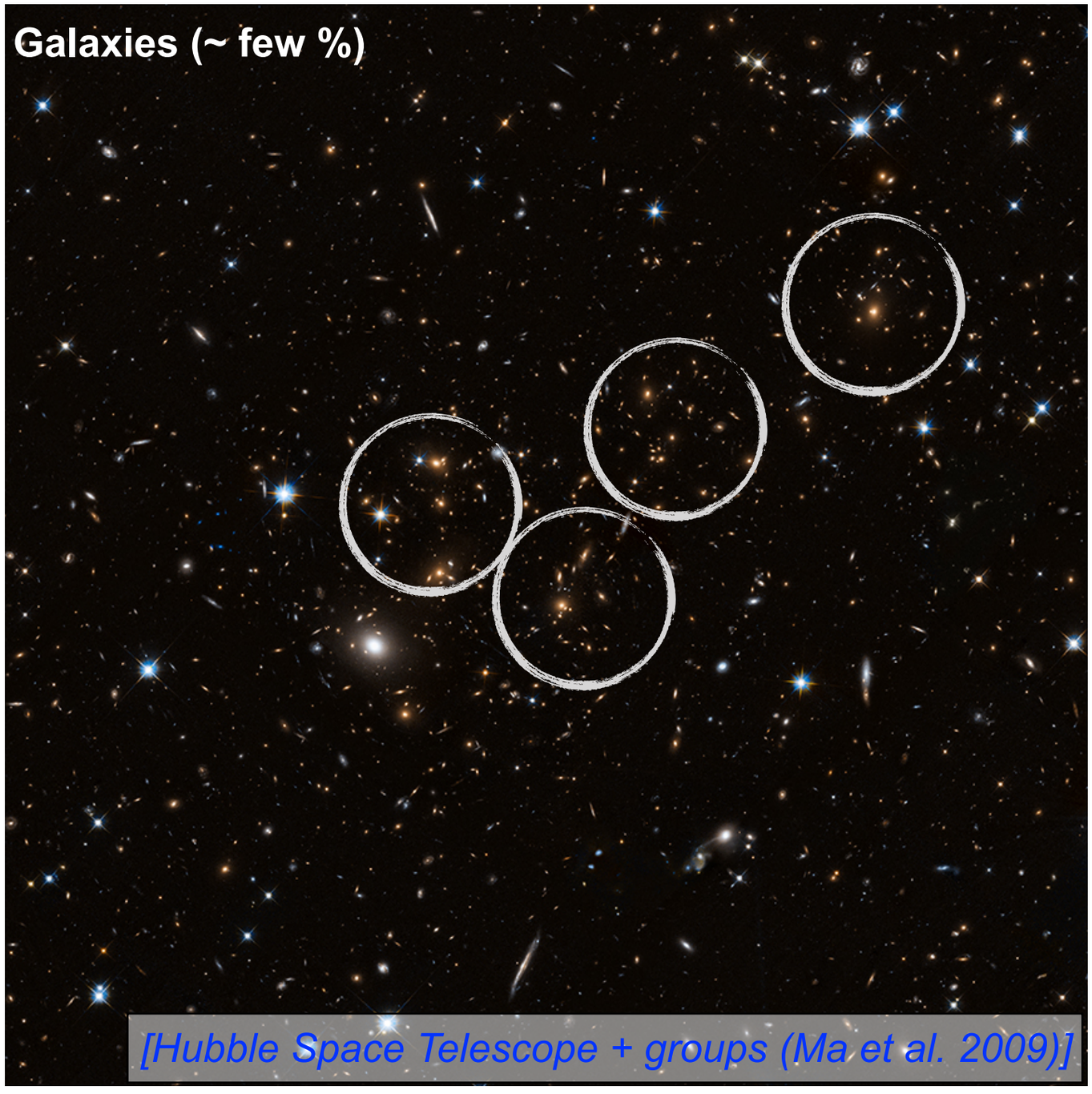
[Hubble Space Telescope]

Multi-wavelength view of galaxy clusters

Optical & infrared:

- Galaxies

➡ **Stellar population**



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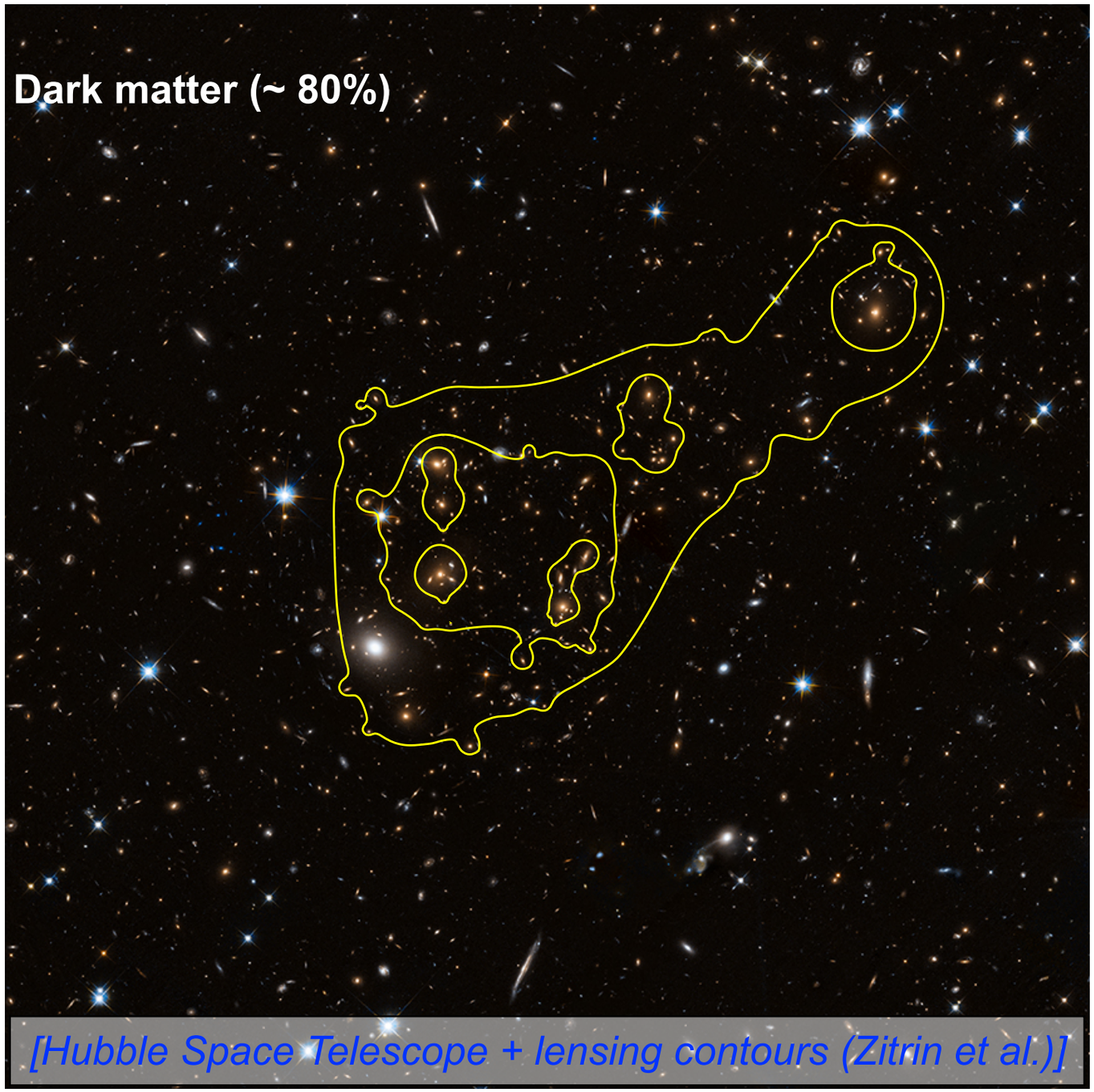
➡ **Stellar population**

➡ **Lensing mass**



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

Multi-wavelength view of galaxy clusters

Optical & infrared:

- Galaxies

➡ **Stellar population**

➡ **Lensing mass**

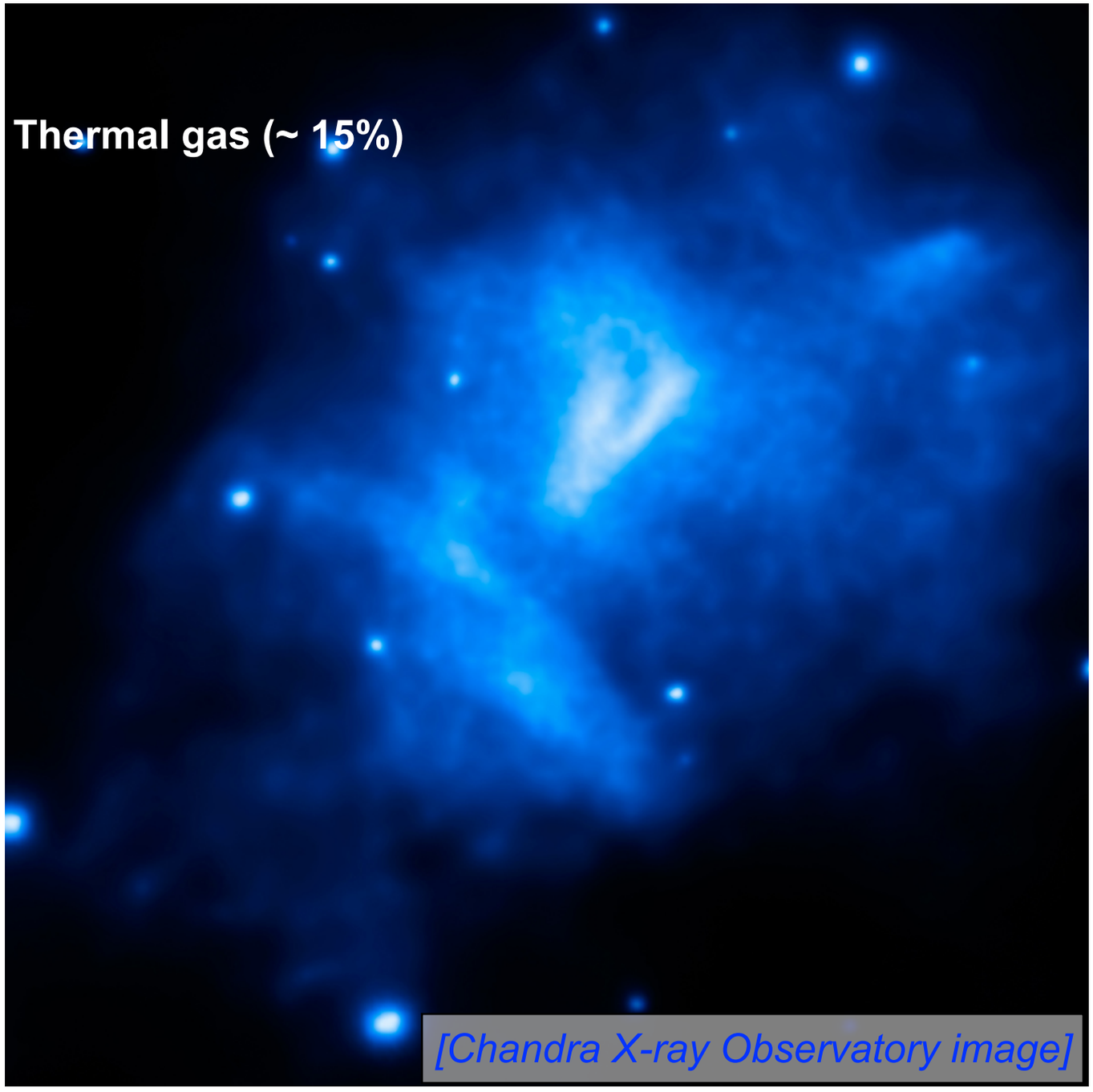
X-ray:

- Bremsstrahlung thermal gas emission

➡ **Gas density**

➡ Spectroscopic temperature (~10^8 K)

➡ Mass from hydrostatic equilibrium



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Sunyaev-Zel'dovich effect:

- Inverse Compton (e^- + CMB)

➡ **Thermal gas pressure**

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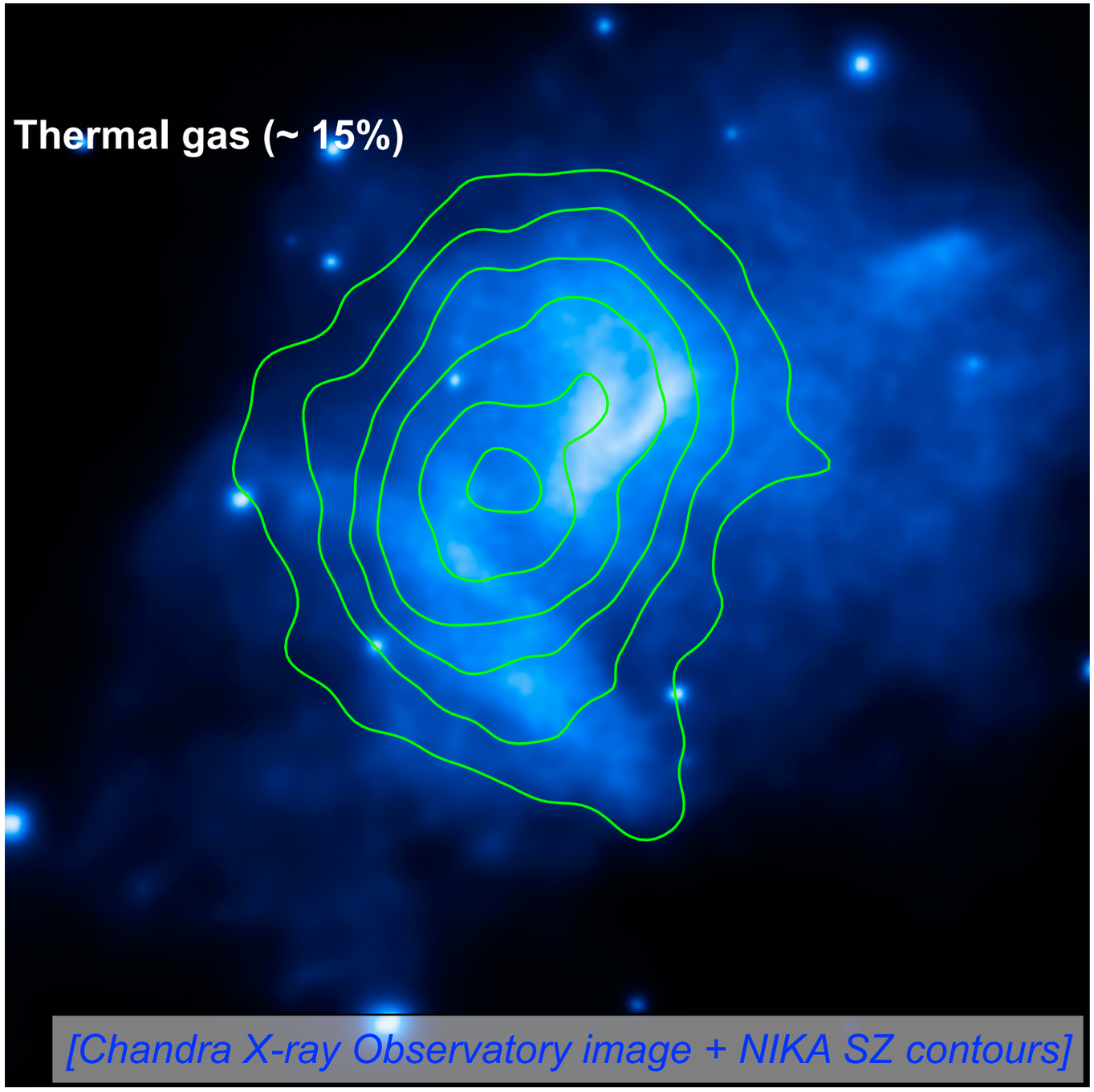

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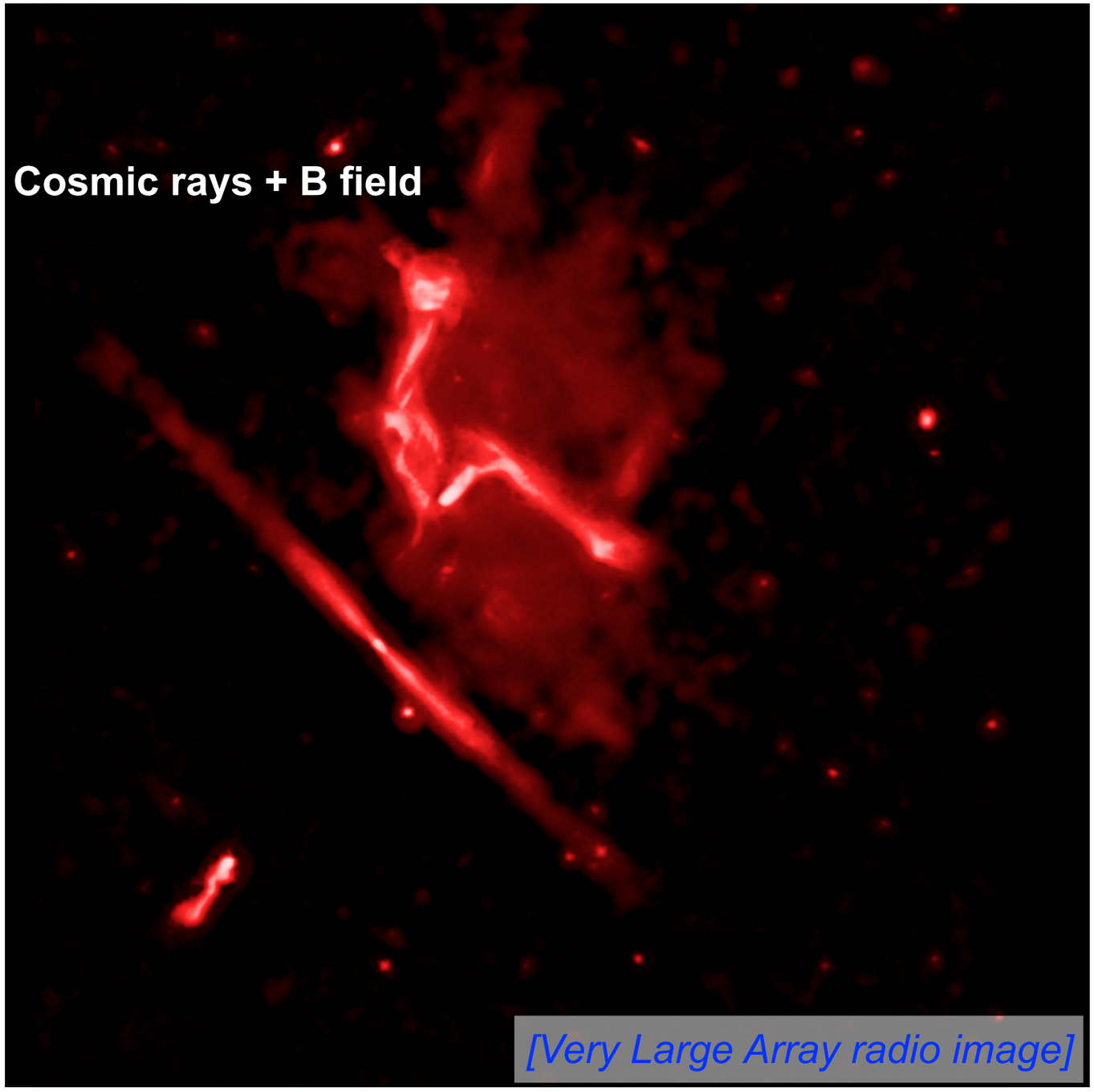
- Non-thermal emission (+DM?)

➡ **Particle acceleration**



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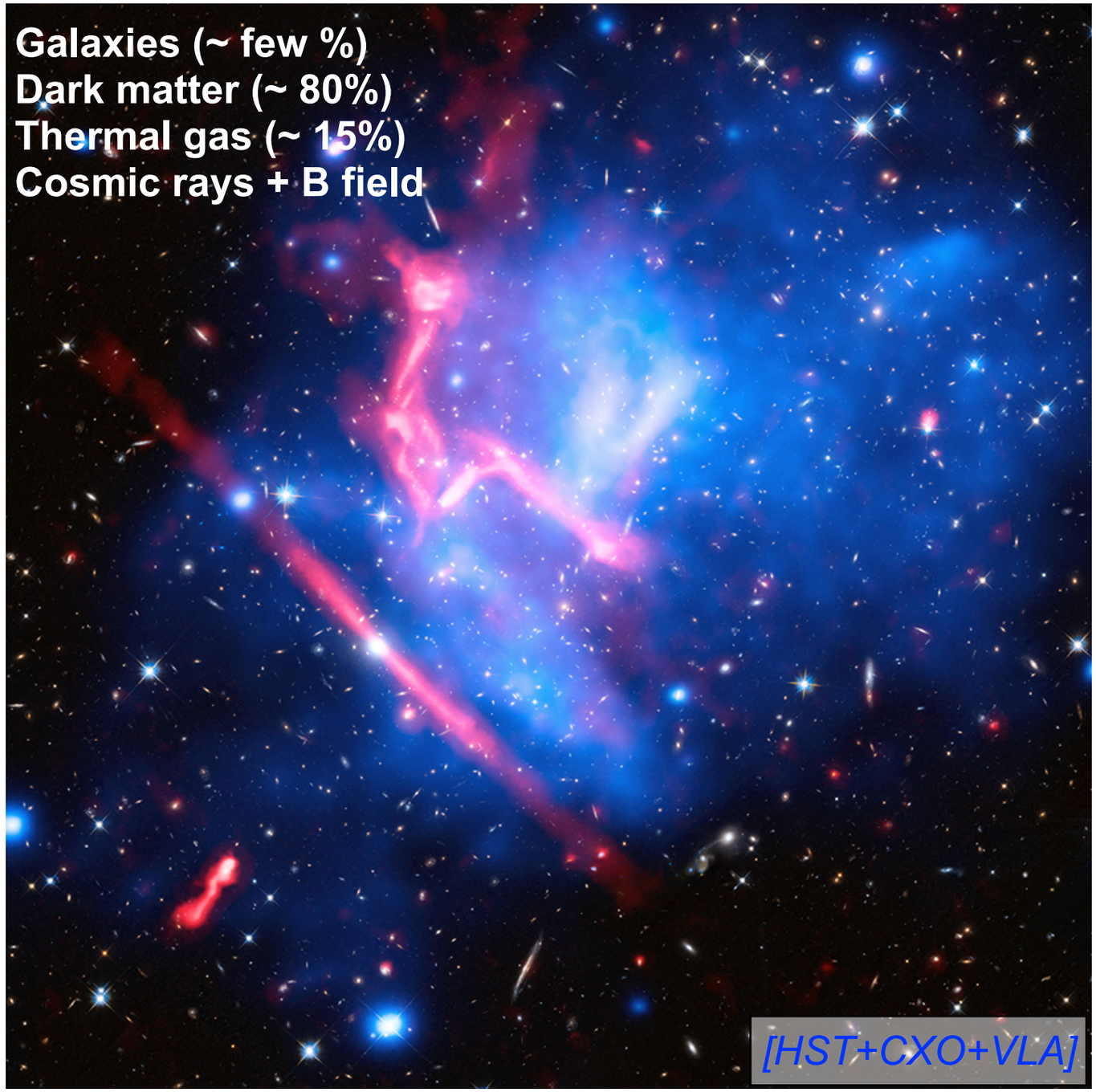

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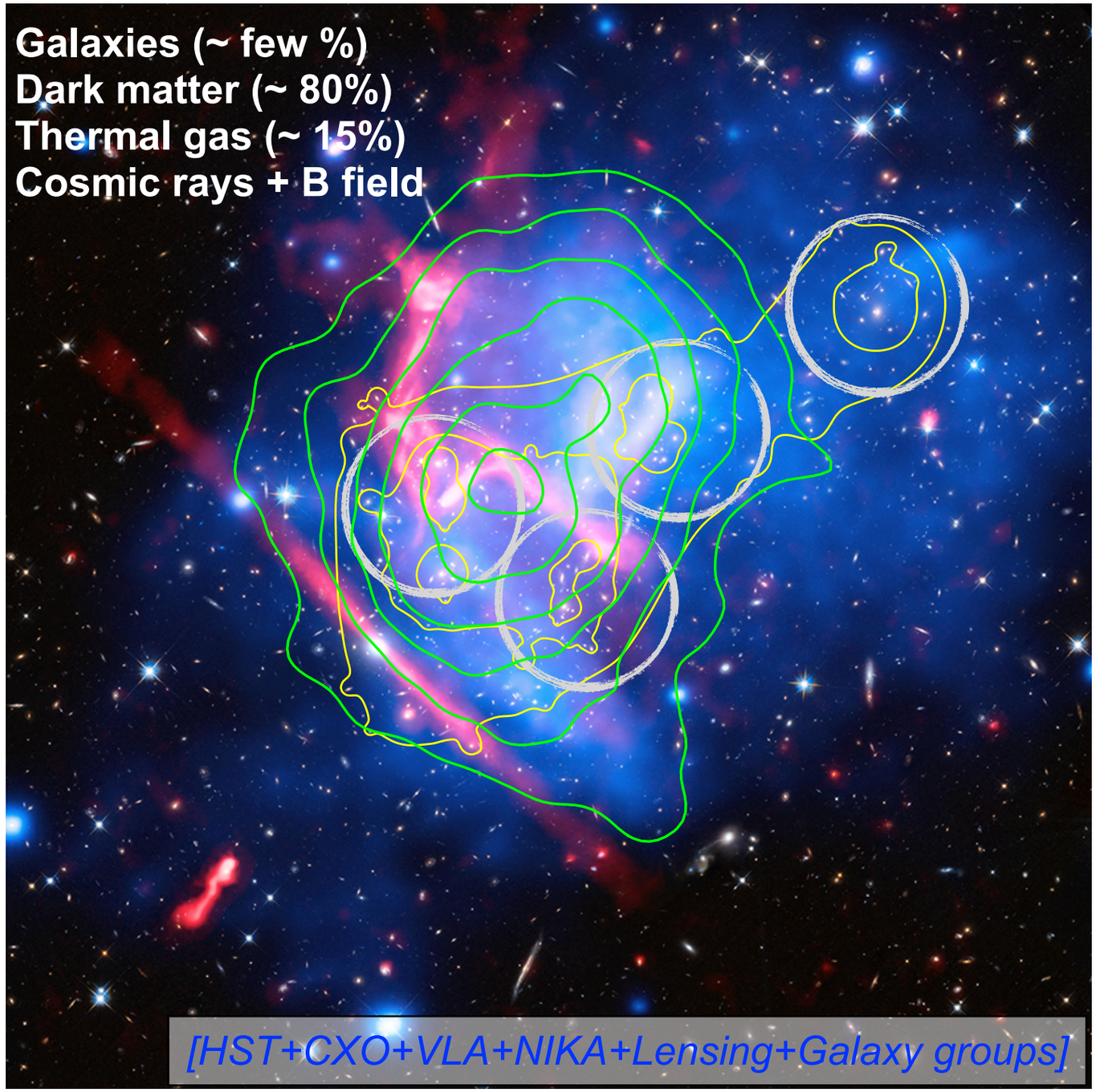
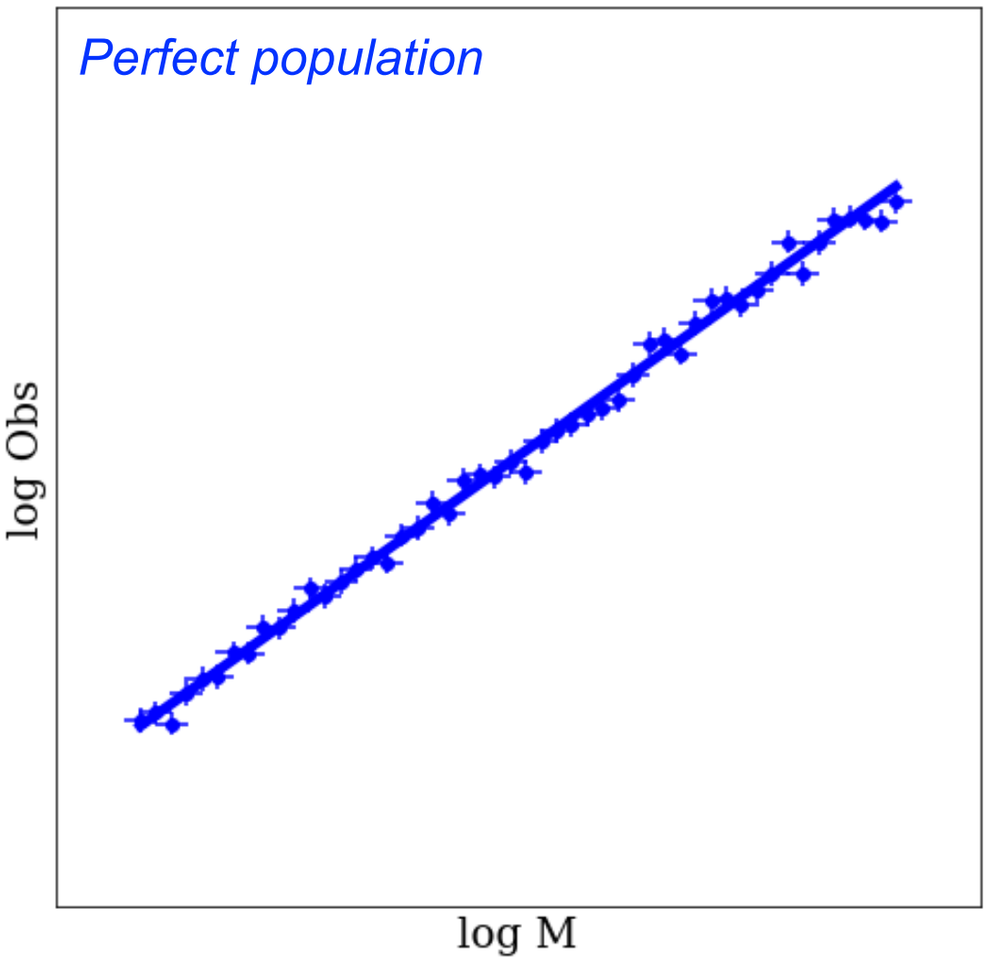


Huge complementarity from different wavelengths

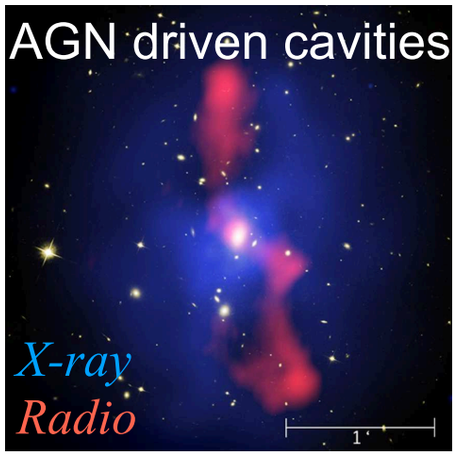
Shaping clusters observables with astrophysics



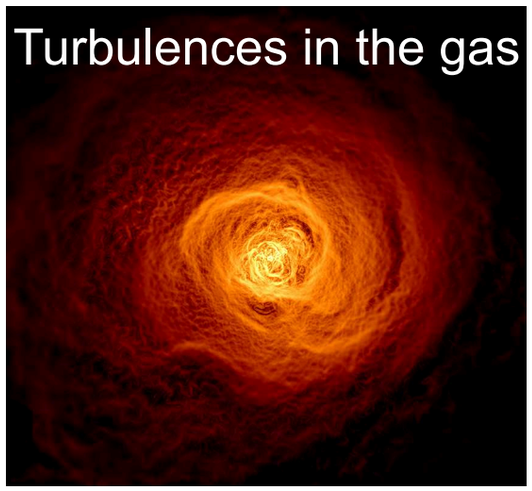
In surveys, observables are used as mass proxies
At 1st order, they are fully determined by M and z

Shaping clusters observables with astrophysics

[Sun et al. (2006)]



[CXO press release]



[Walker, et al. (2017)]

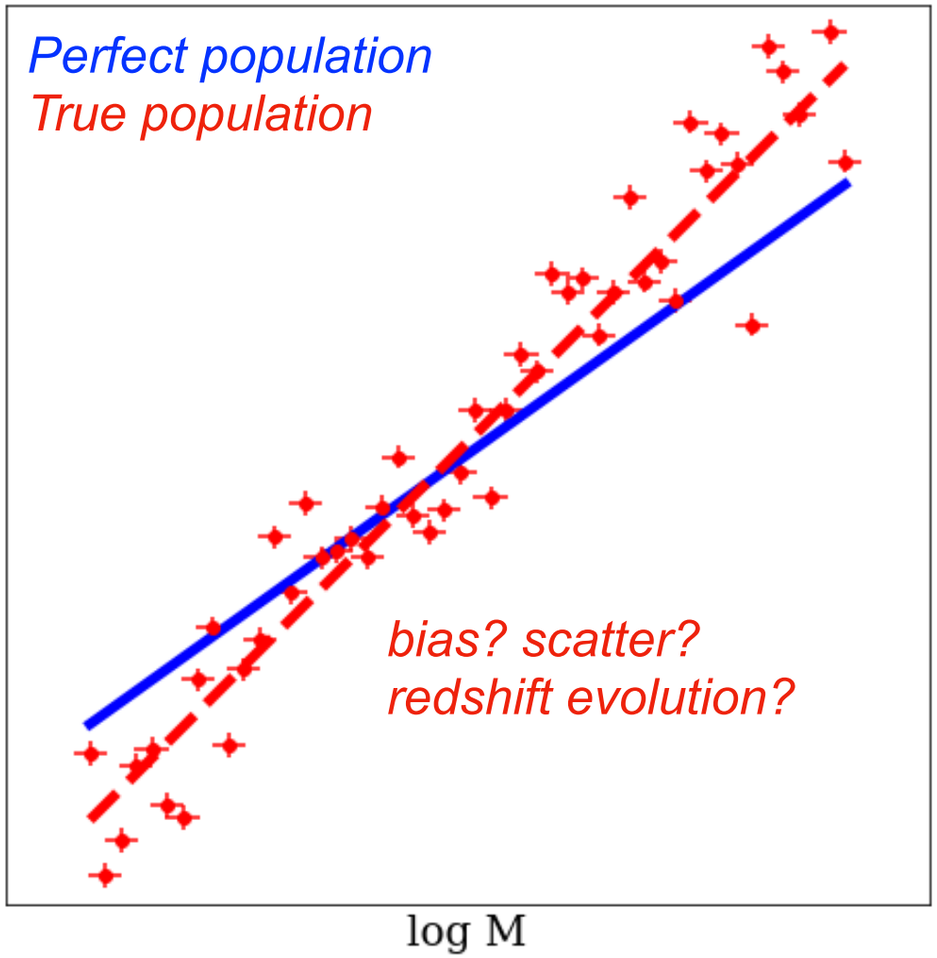
[Markevitch (2010)]

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

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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1. Clusters of galaxies as cosmic laboratories

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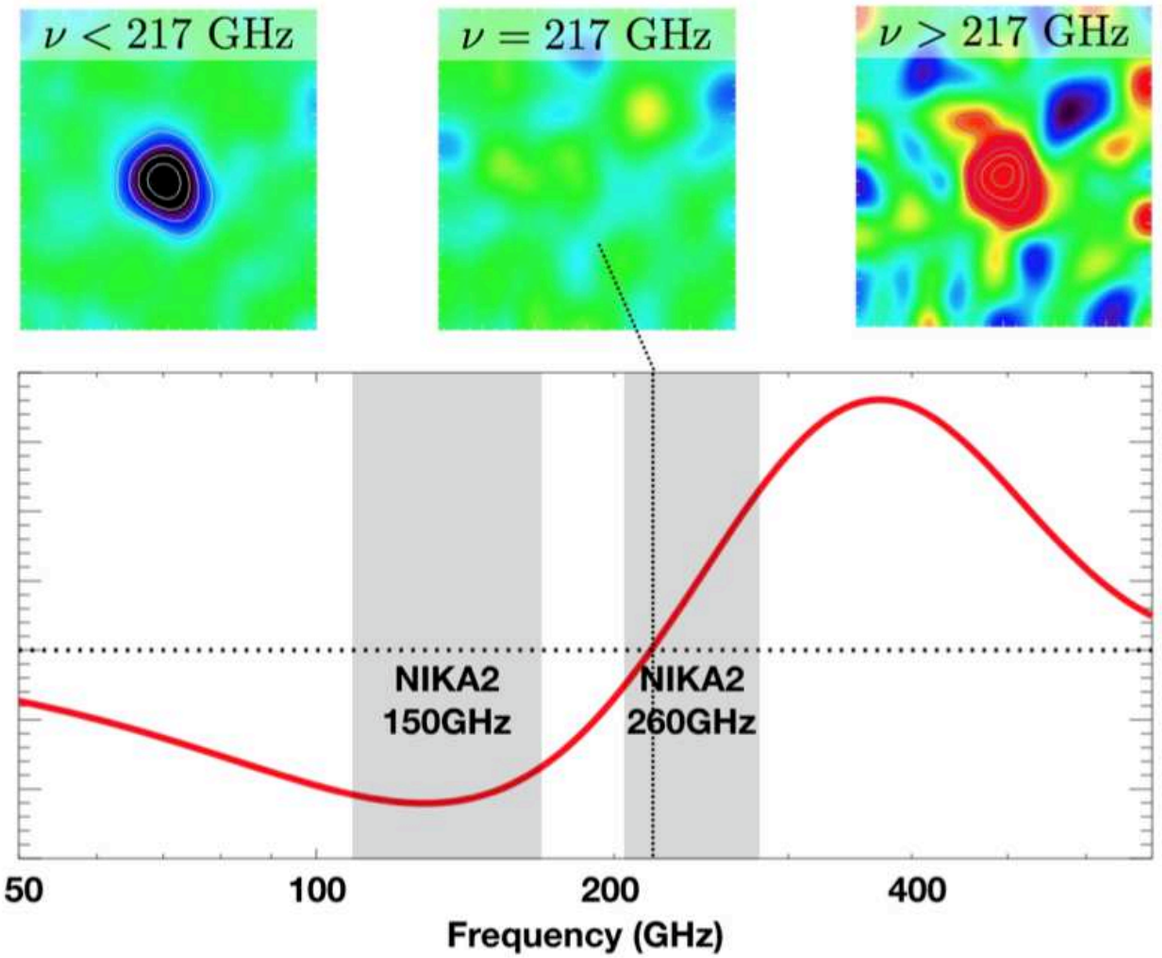
A key observable, the Sunyaev-Zel'dovich effect

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



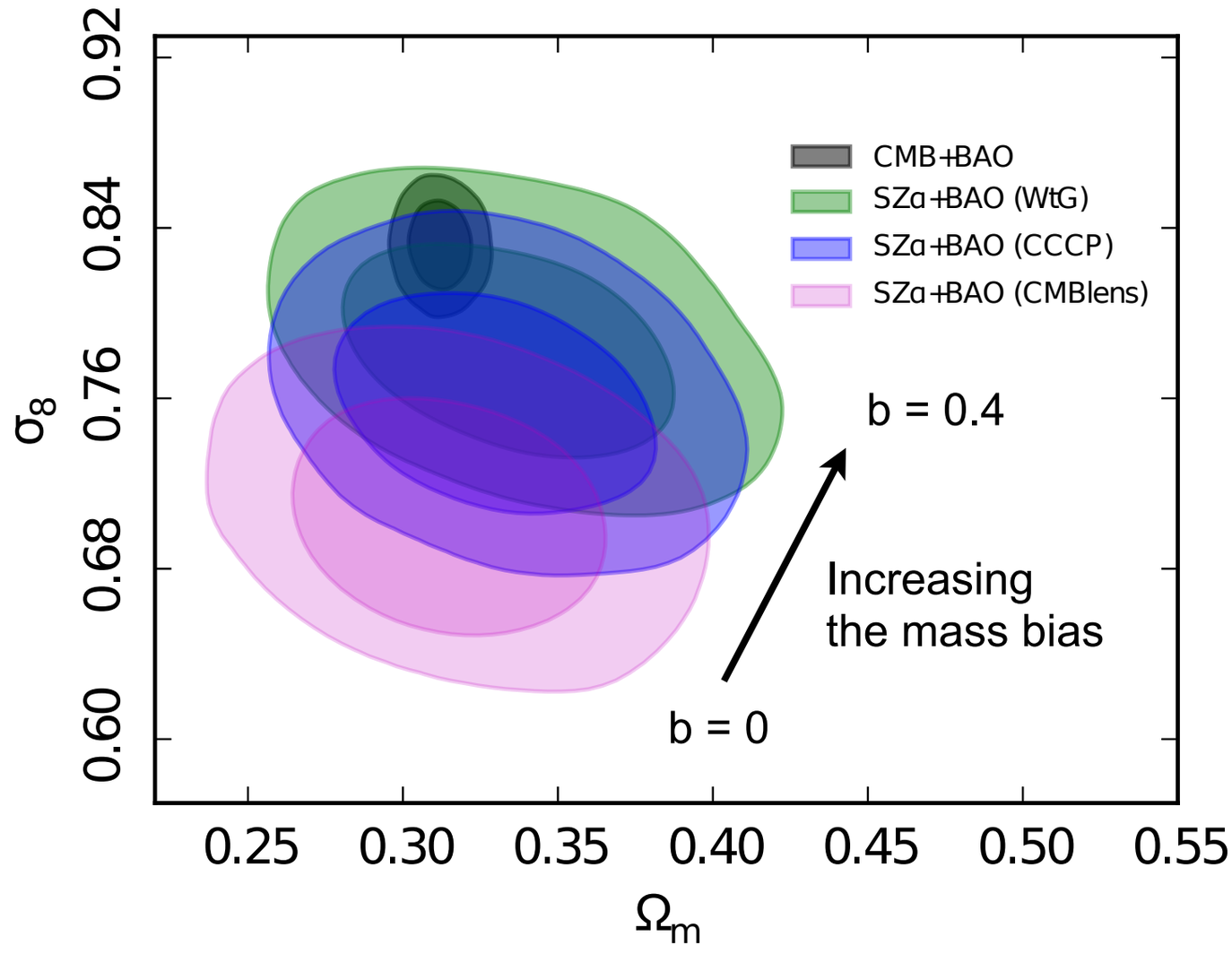
Excellent probe for the hot gas in distant clusters

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)]

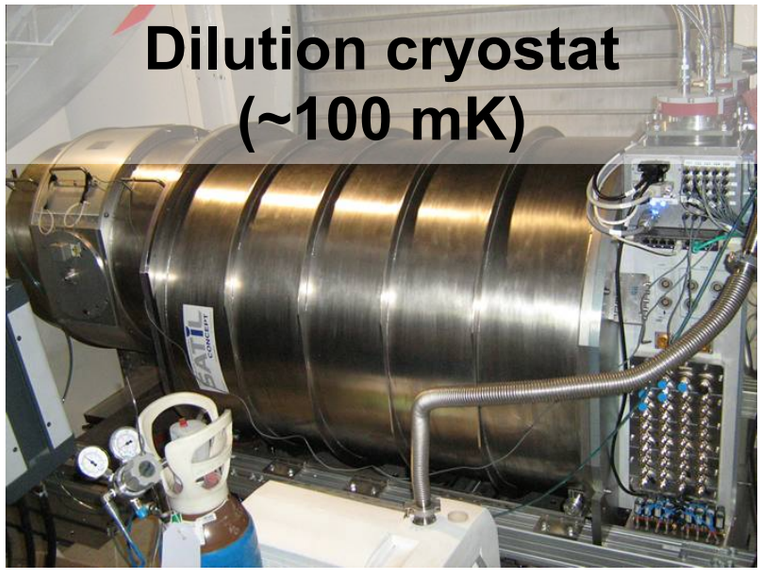
CMB & clusters & hydro sim in tension

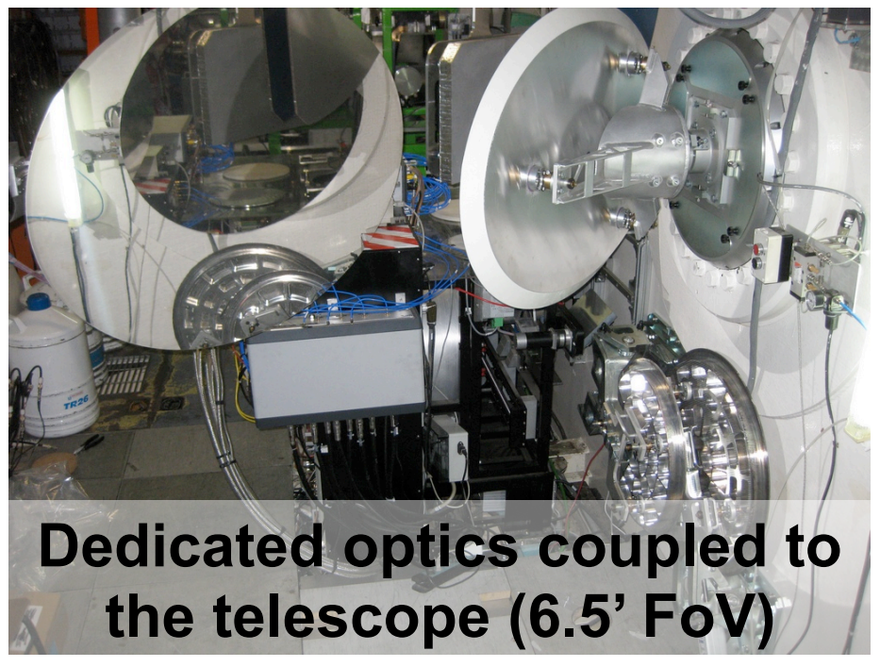
Astrophysical mismodeling?
Missing physics in simulations? In ΛCDM?
Statistical fluctuation?

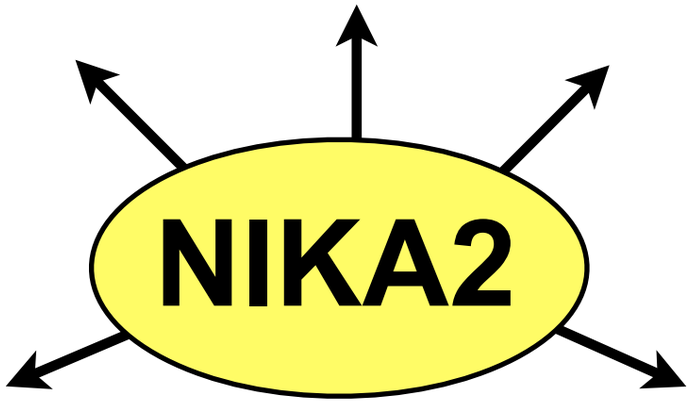


Need for resolved observations up to high redshift

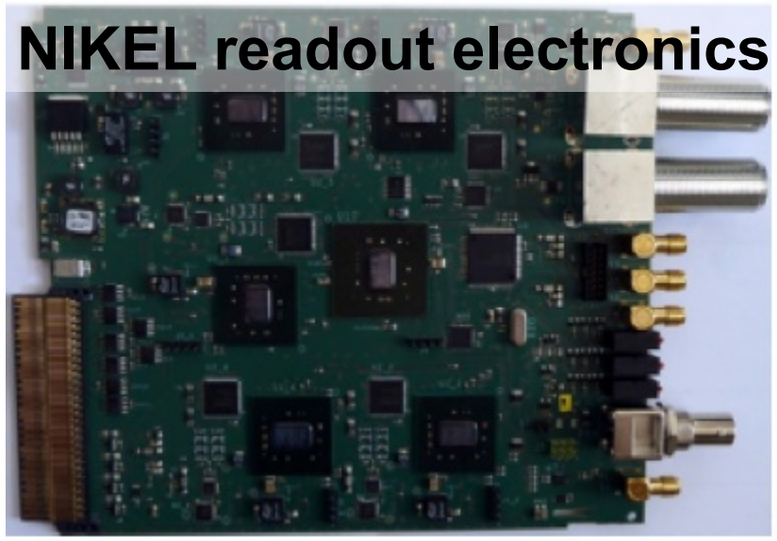
NIKA2: the New IRAM KIDs Array 2





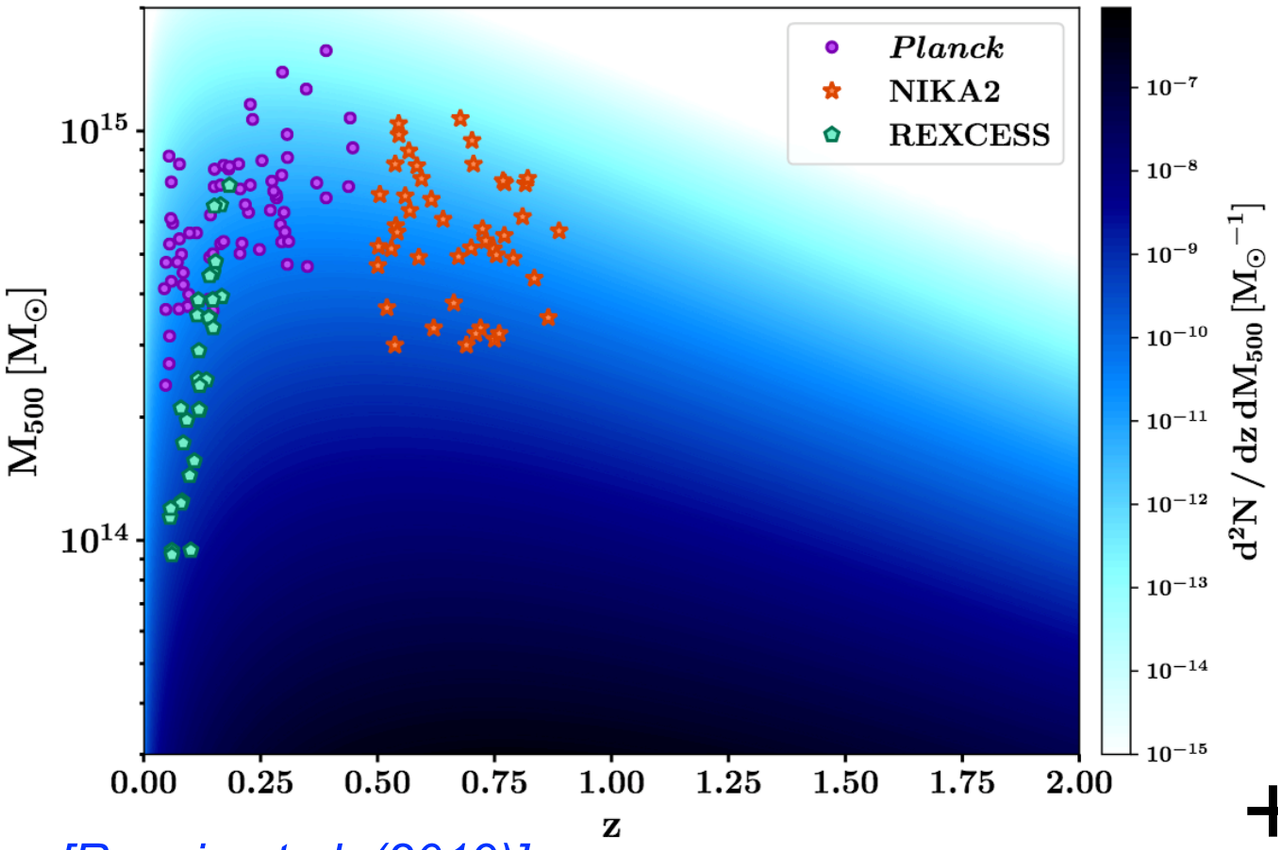


[NIKA collaboration (2018)]



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

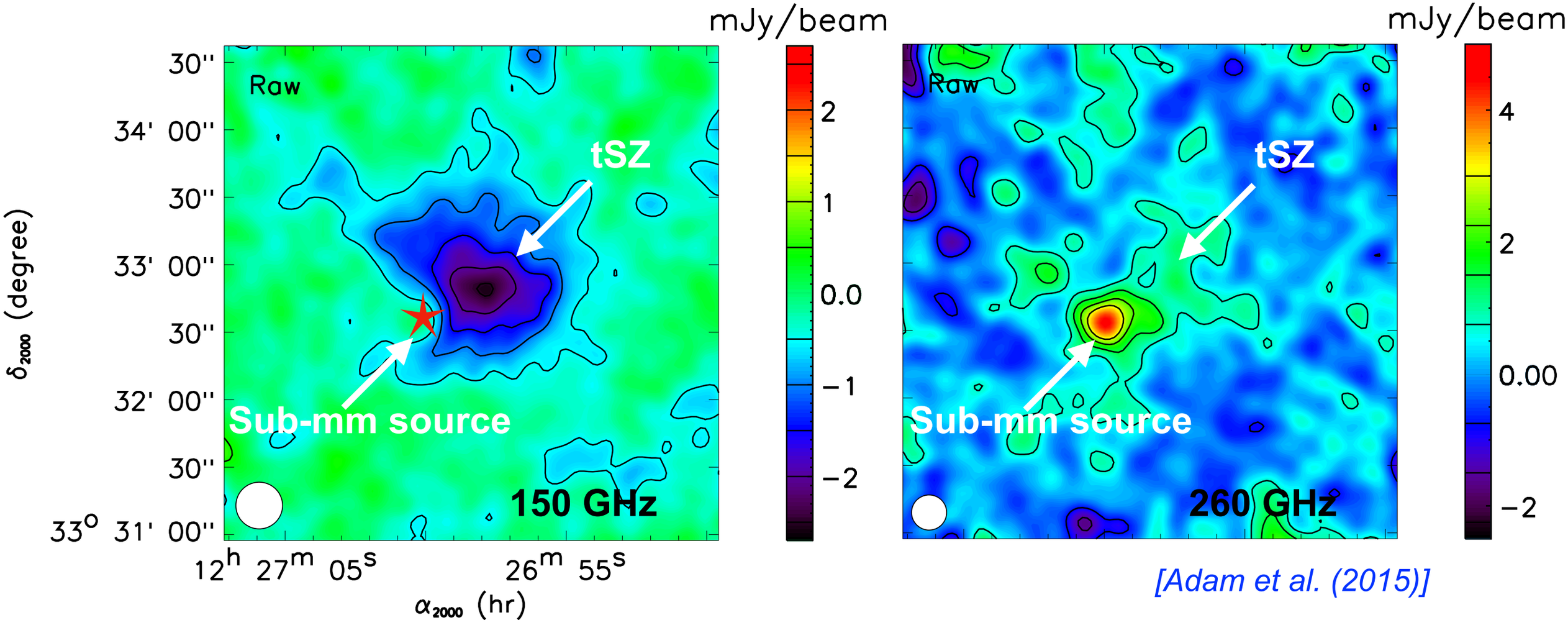
- NIKA pathfinder validation program
  - 6 clusters in various configurations

➡

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

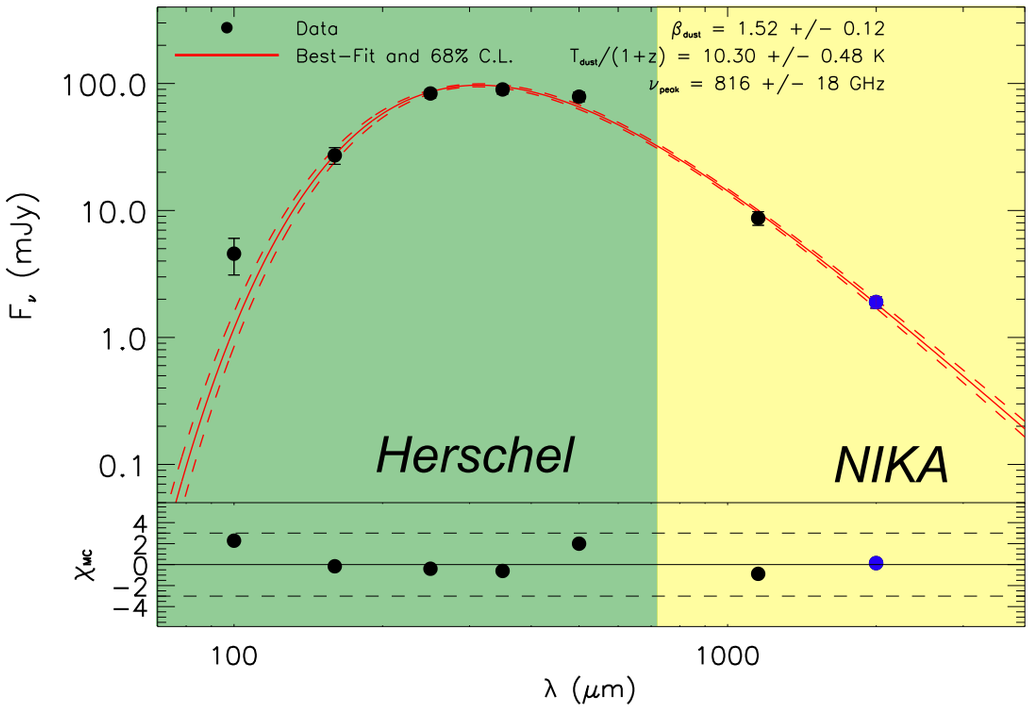


[Adam et al. (2015)]

Sub-mm and radio galaxies can bias the SZ signal

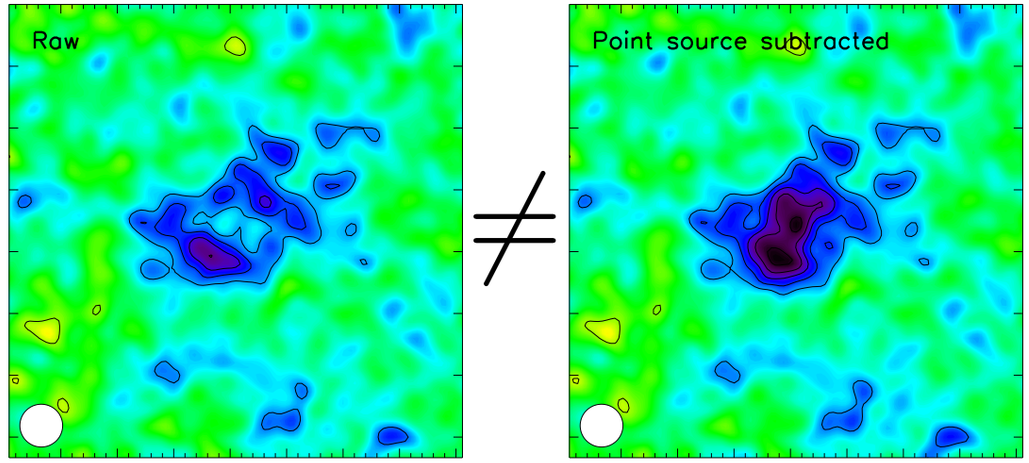
Cleaning the ‘contaminant’ galaxies

Dust + radio synchrotron fitting

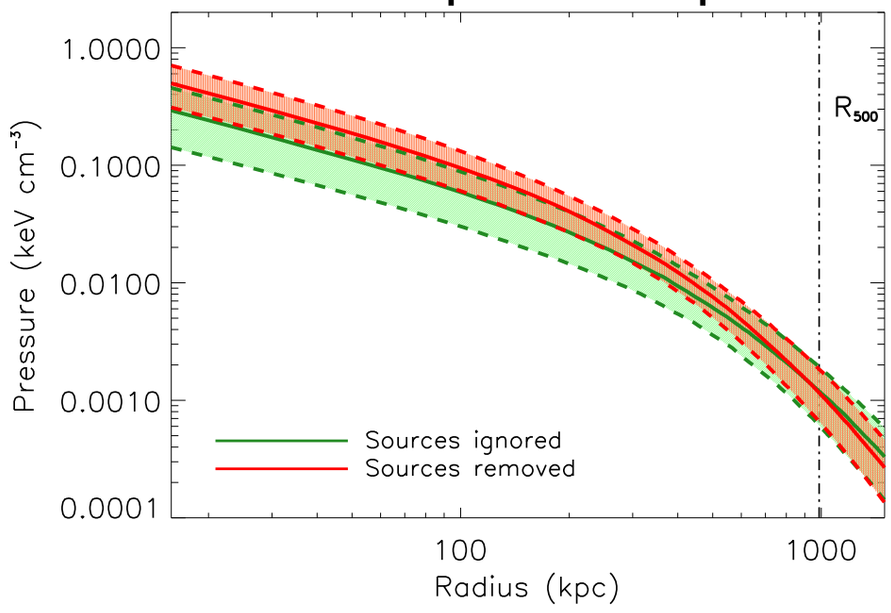


[Adam et al. (2016)]

Strong impact on the morphology…



… and the pressure profile



It is crucial to account for contaminant sources

Gas temperature from X-ray+SZ imaging

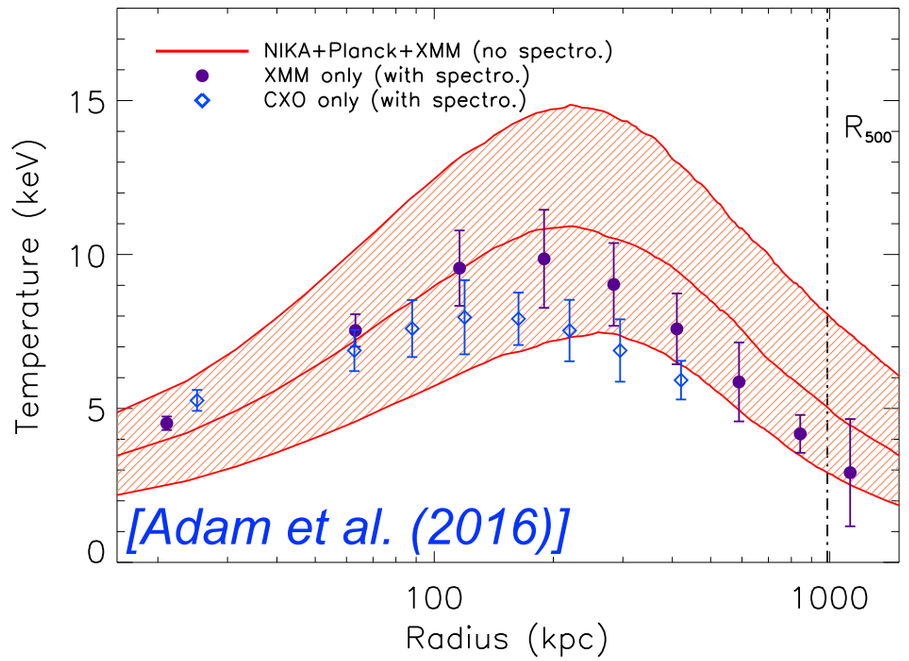
- Temperature fundamental for astro & cosmo
  - Mass calibration
  - Cluster dynamical state
- Systematics in X-ray spectro. + challenging at high z

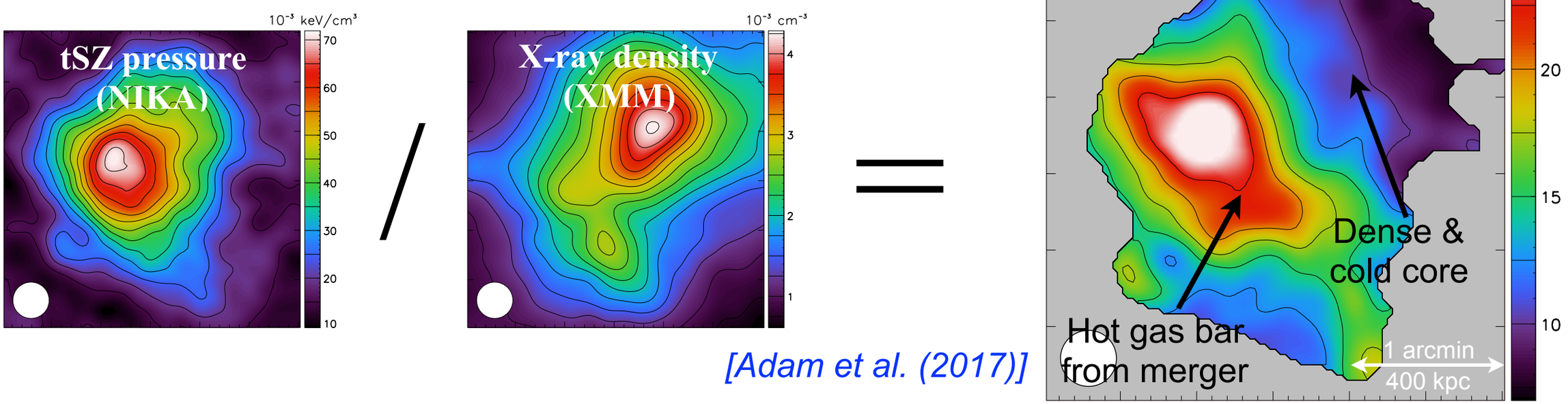
$$\Rightarrow k_{\rm B}T = P_e/n_e$$

tSZ ↗ ↖ *X-ray*

- Independent cross-check of X-ray spectro.

➡ Done in 1D and 2D





[Adam et al. (2017)]

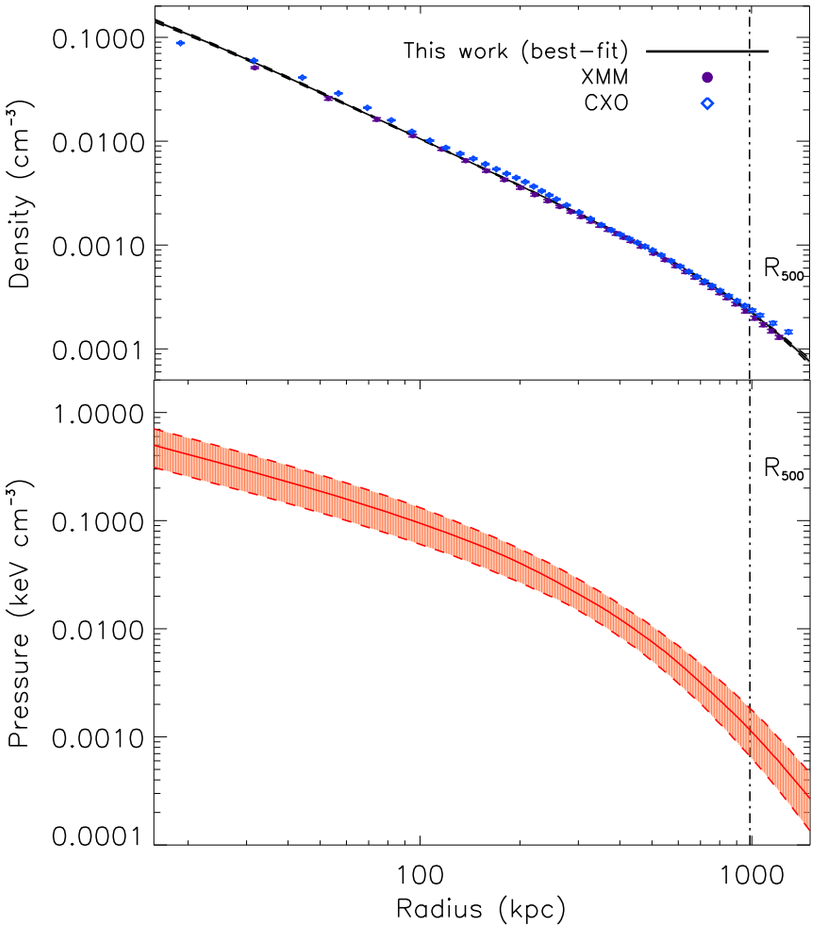
Excellent to obtain the temperature at high z

Direct mass measurement from X-ray+SZ

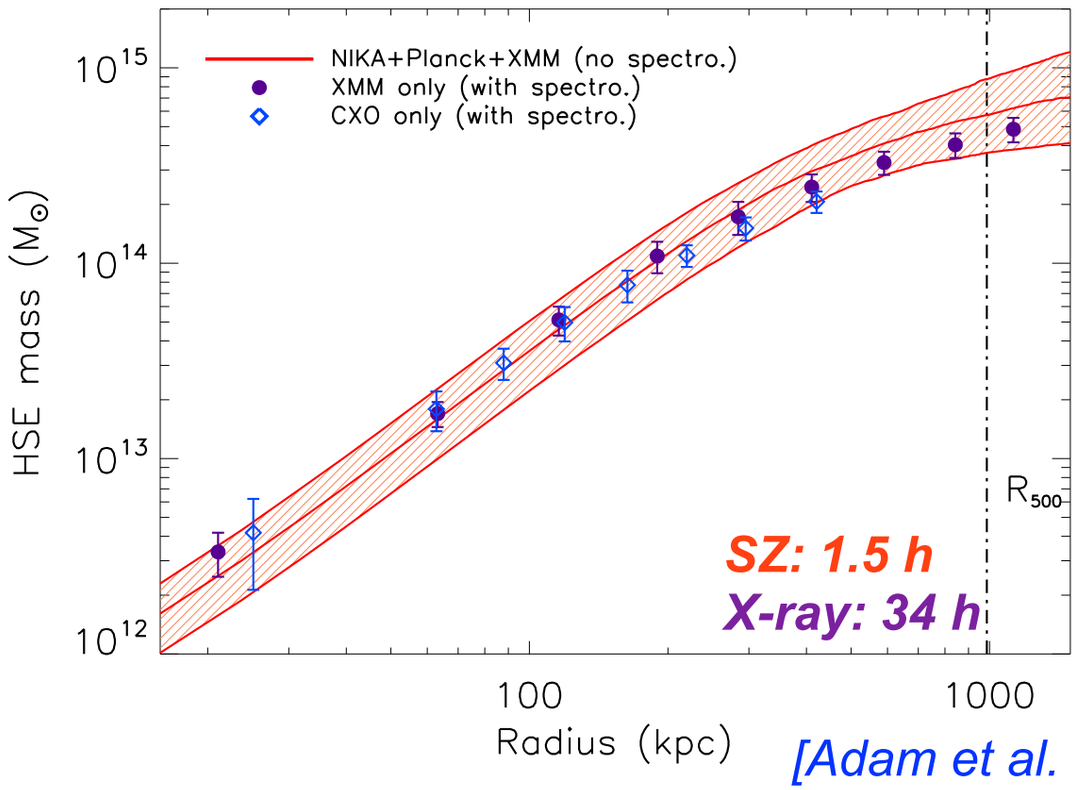
$$M_{\rm HSE}(r) = -\frac{r^2}{\mu_{\rm gas} m_{\rm p} n_{\rm e}(r) G} \frac{{\rm d}P_{\rm e}(r)}{{\rm d}r}$$

← SZ measurement

Easy from X-ray →



X-ray + SZ

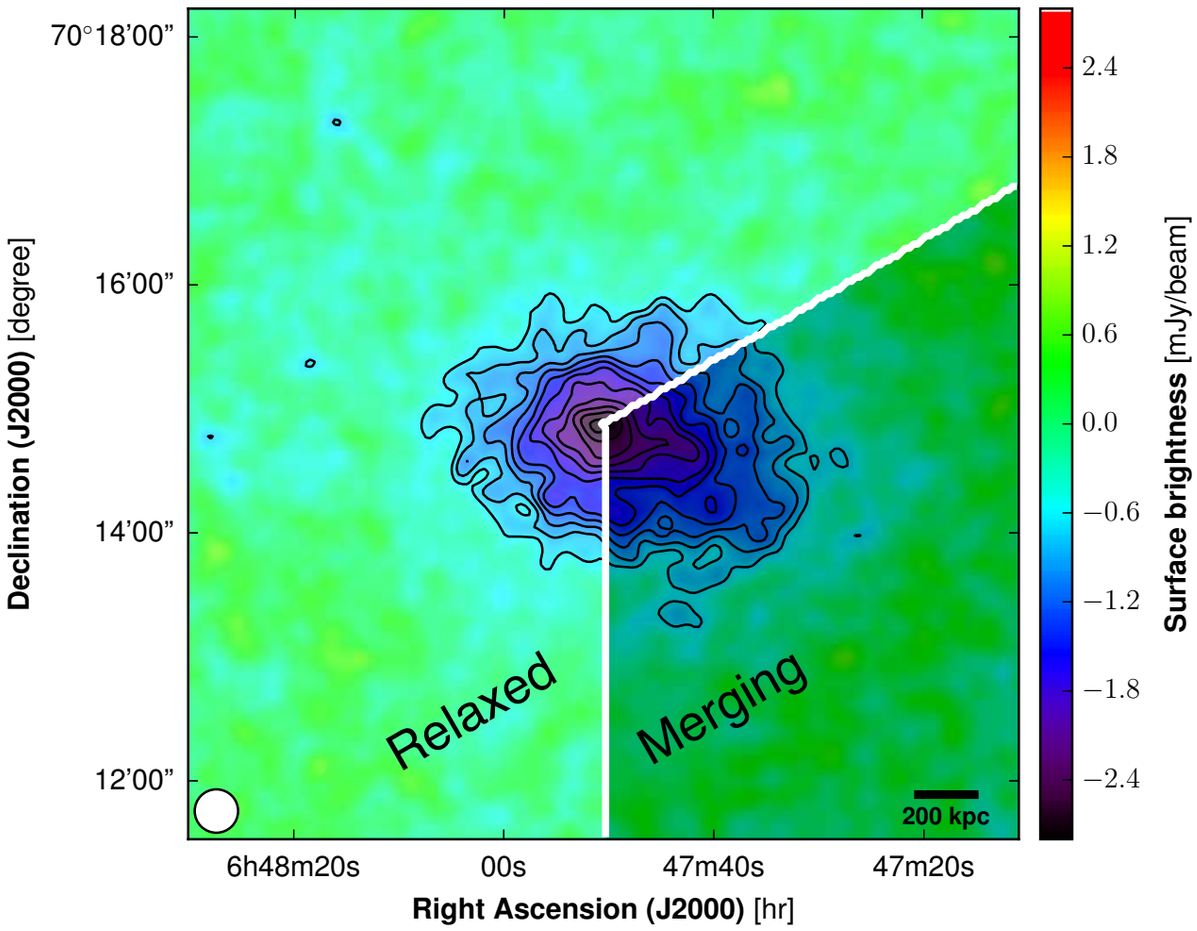


[Adam et al. (2016)]

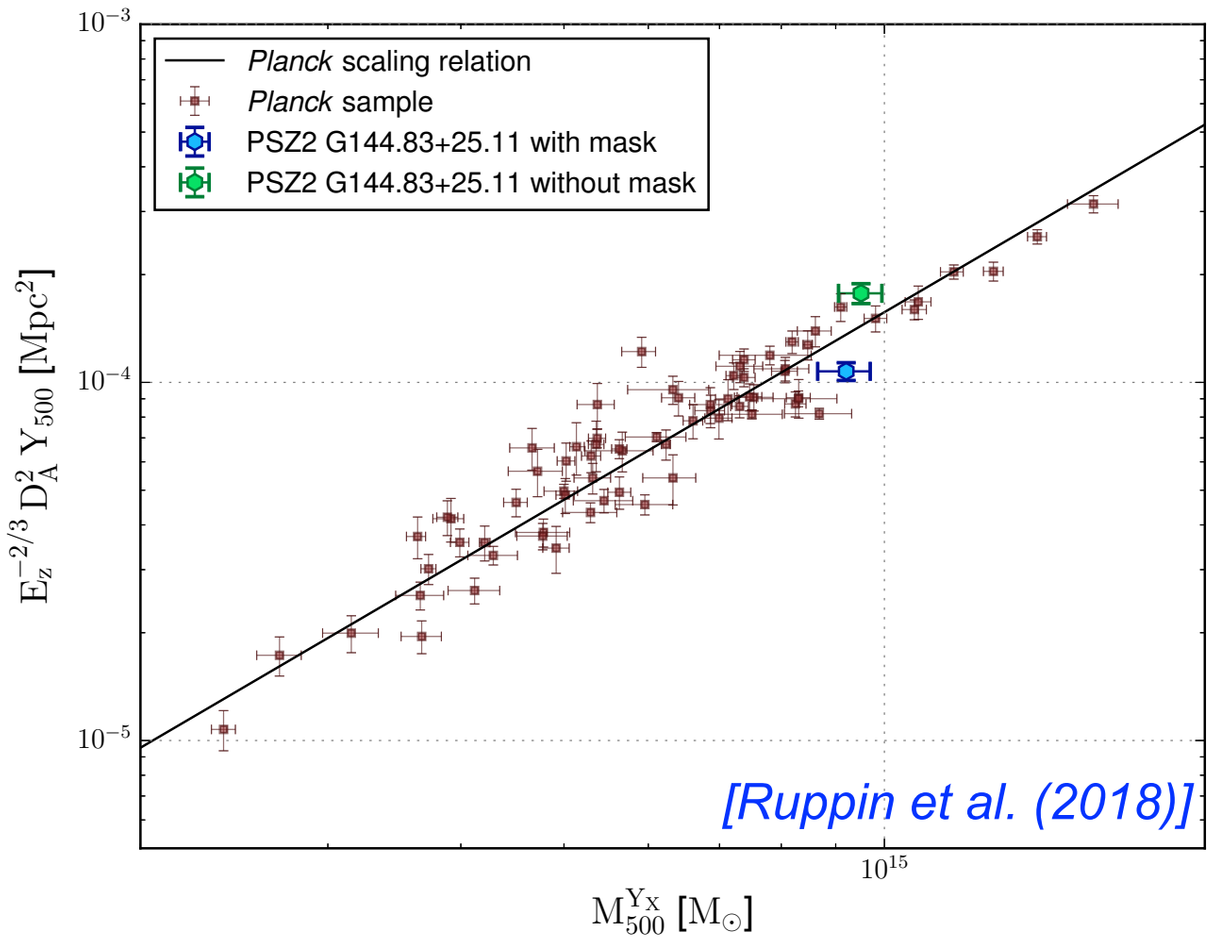
➡ Access to the mass, the SZ flux, and the cluster dynamics (morphology)

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%



[Ruppin et al. (2018)]

Strong impact of inner structure on SZ-M relation

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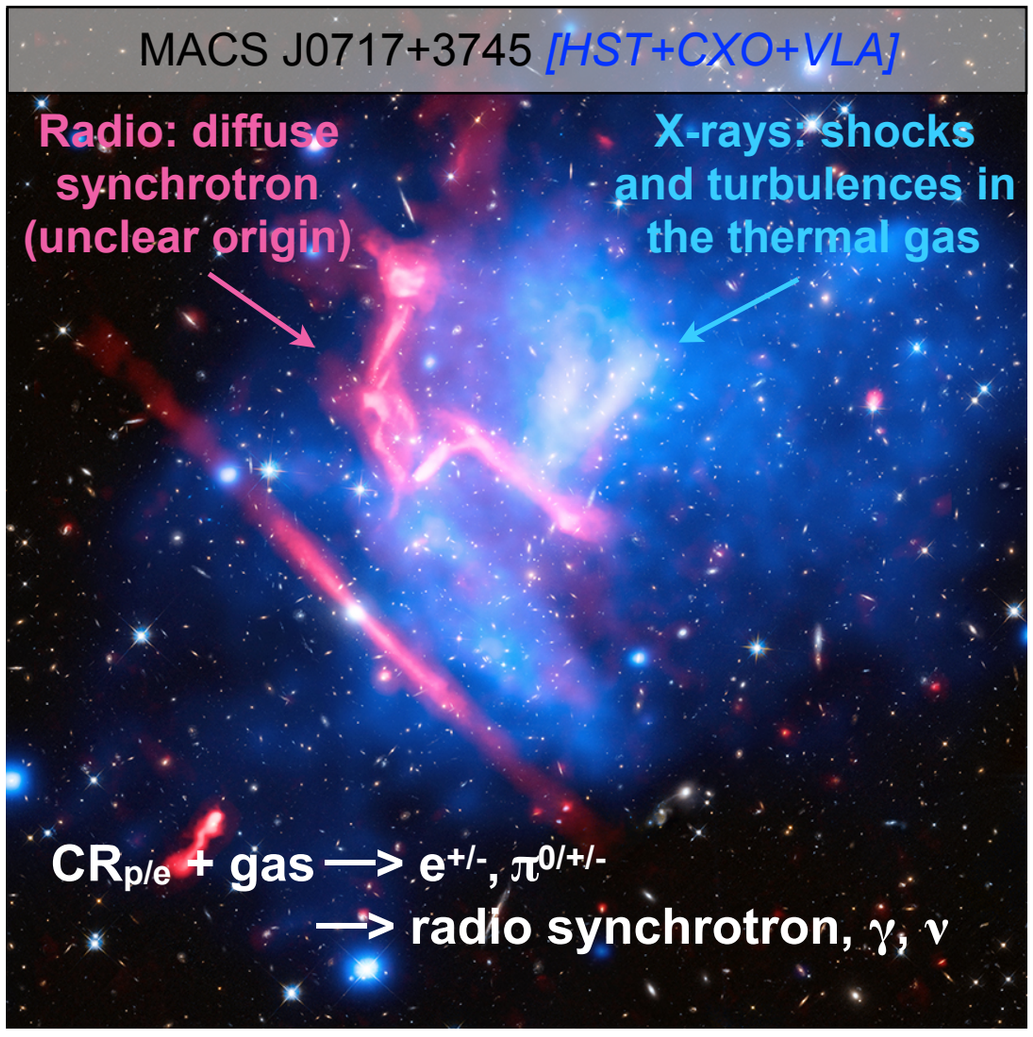
Cosmic ray and dark matter in galaxy clusters



- A lot of dark matter (~80%)
  - γ-ray from annihilation/decay

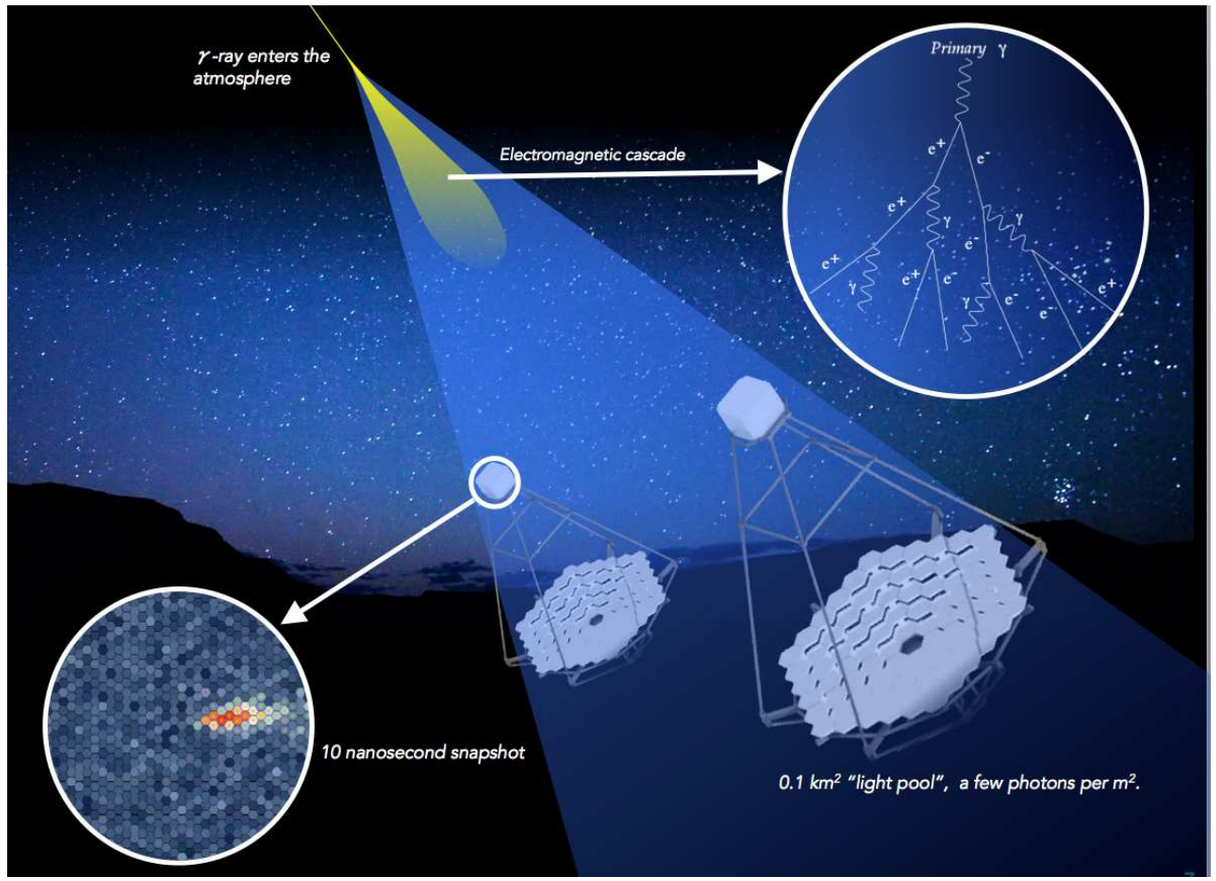
Test the nature of dark matter

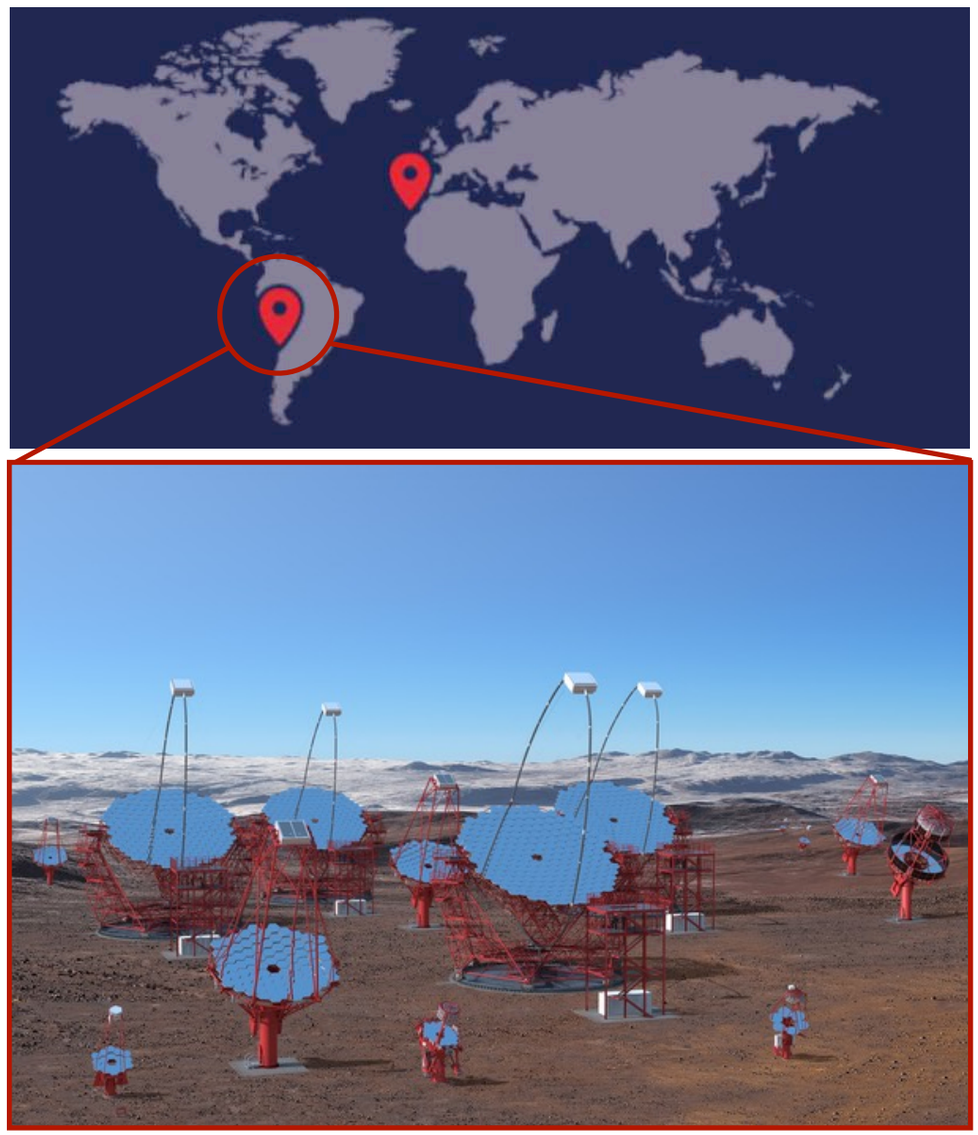
- Galaxies (~few %) + thermal ionized gas (~15%)
  - γ-ray from particle acceleration

Understand CR physics at the clusters scale

Cosmic ray physics can be constrained from γ-rays

The Cherenkov Telescope Array

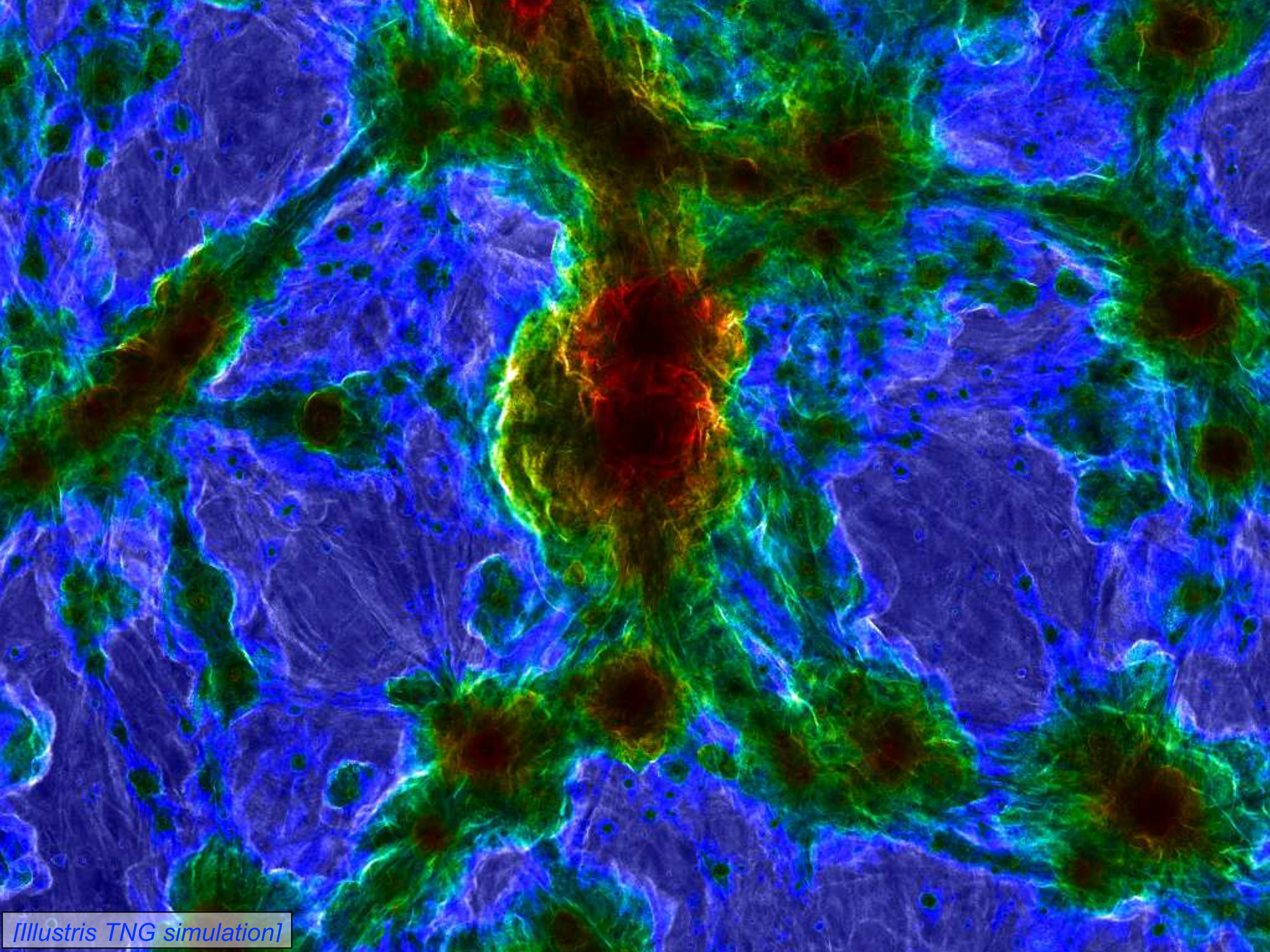


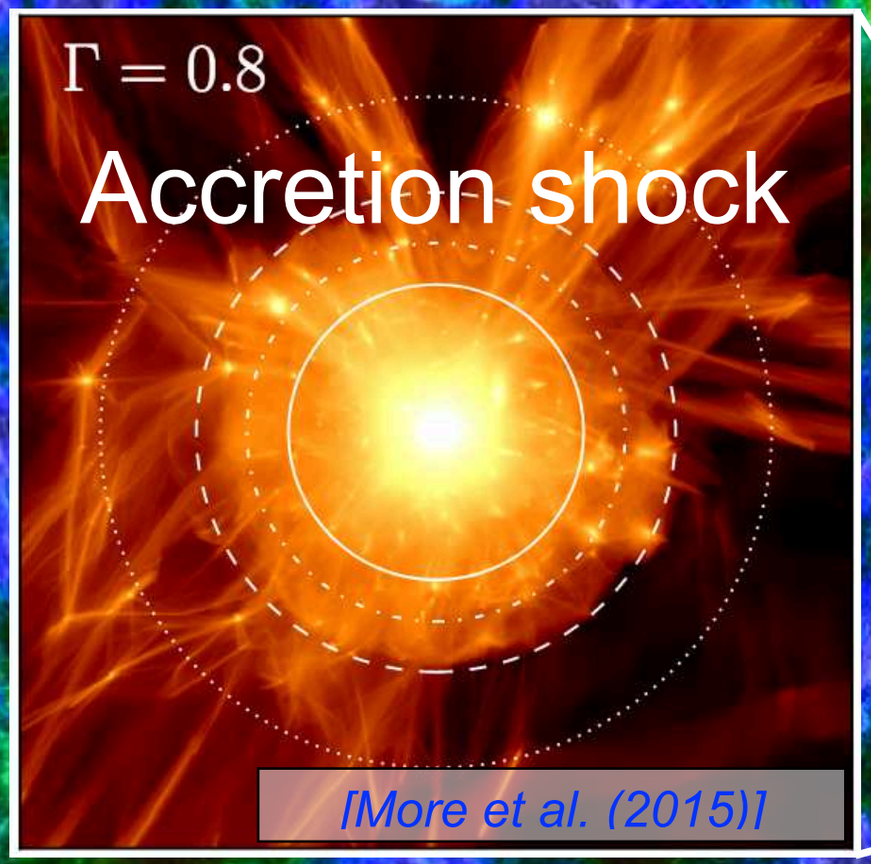


From ~20 GeV to 200 TeV γ rays
Sensitivity down to ~10^{-12} erg/cm²/s in few hours
~3 arcmin angular resolution above 1 TeV
Expected to start observations in ~2022

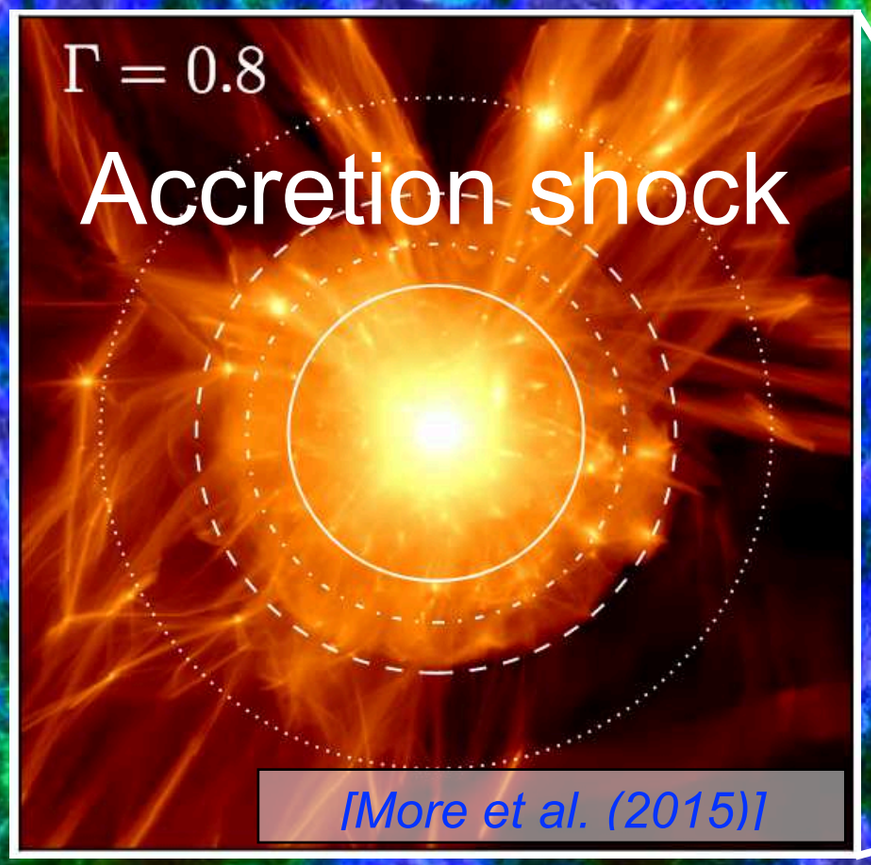
[https://www.cta-observatory.org/]

CTA Key Science Project: Perseus cluster to be observed for 300h


[Illustris TNG simulation]



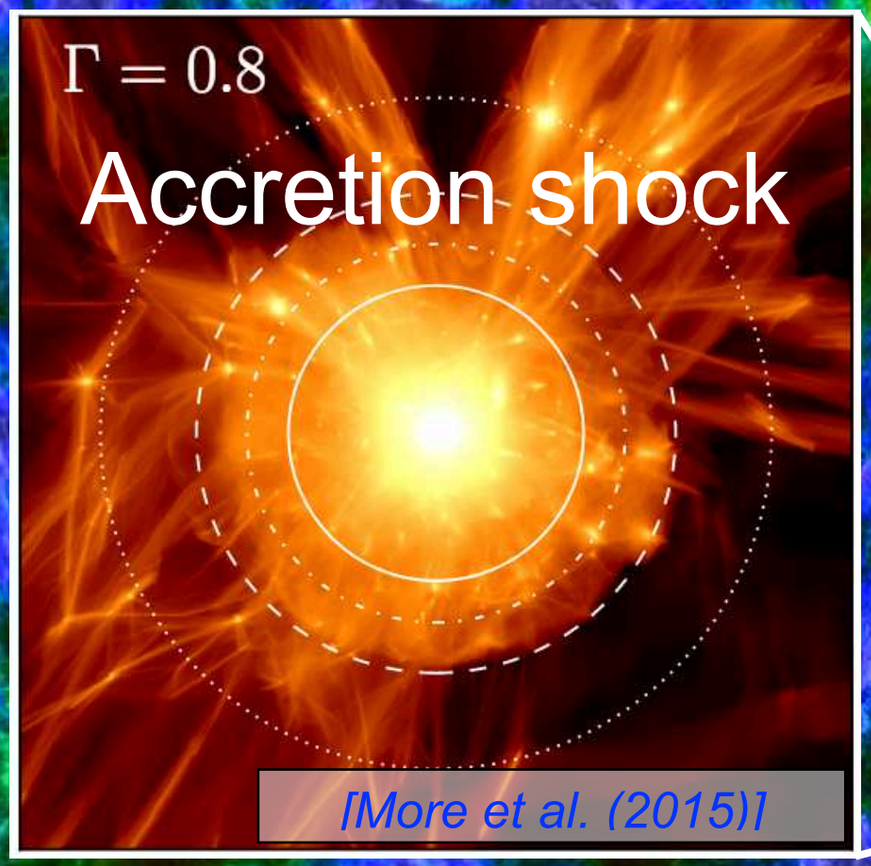
[Illustris TNG simulation]



[More et al. (2015)]

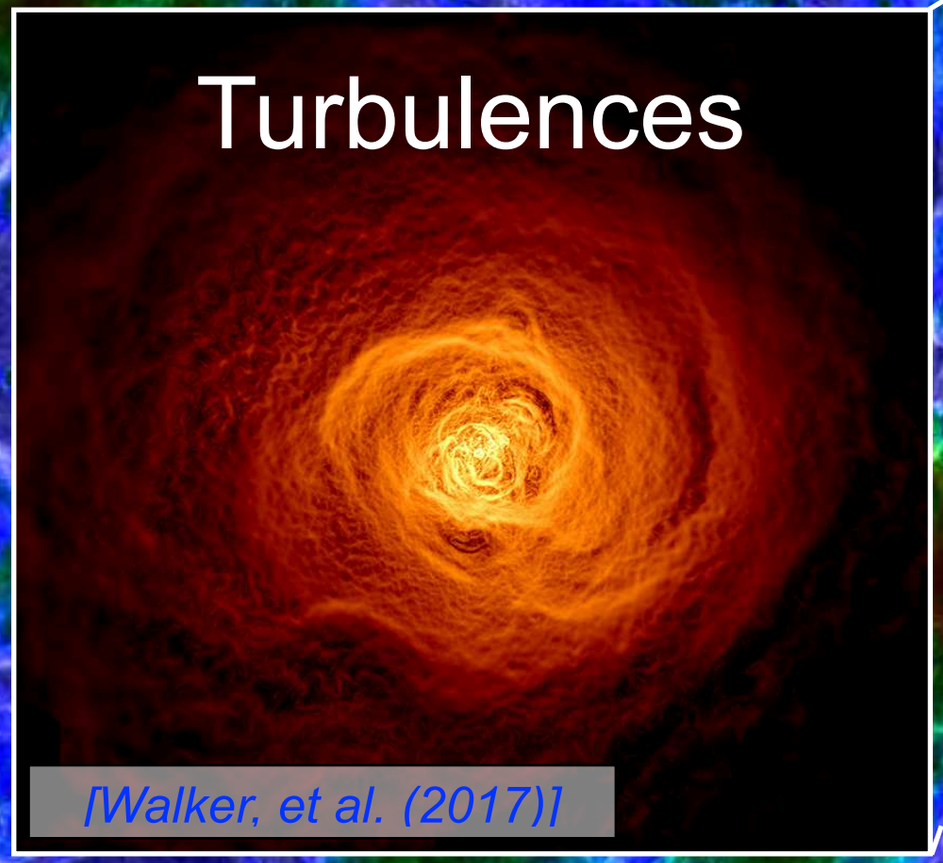
[Markevitch & Vikhlinin (2007)]

[Illustris TNG simulation]



[More et al. (2015)]

[Markevitch & Vikhlinin (2007)]



[Walker, et al. (2017)]

[Illustris TNG simulation]

$\Gamma = 0.8$

Accretion shock

[More et al. (2015)]

Major merger shock

[Markevitch & Vikhlinin (2007)]

Turbulences

[Walker, et al. (2017)]

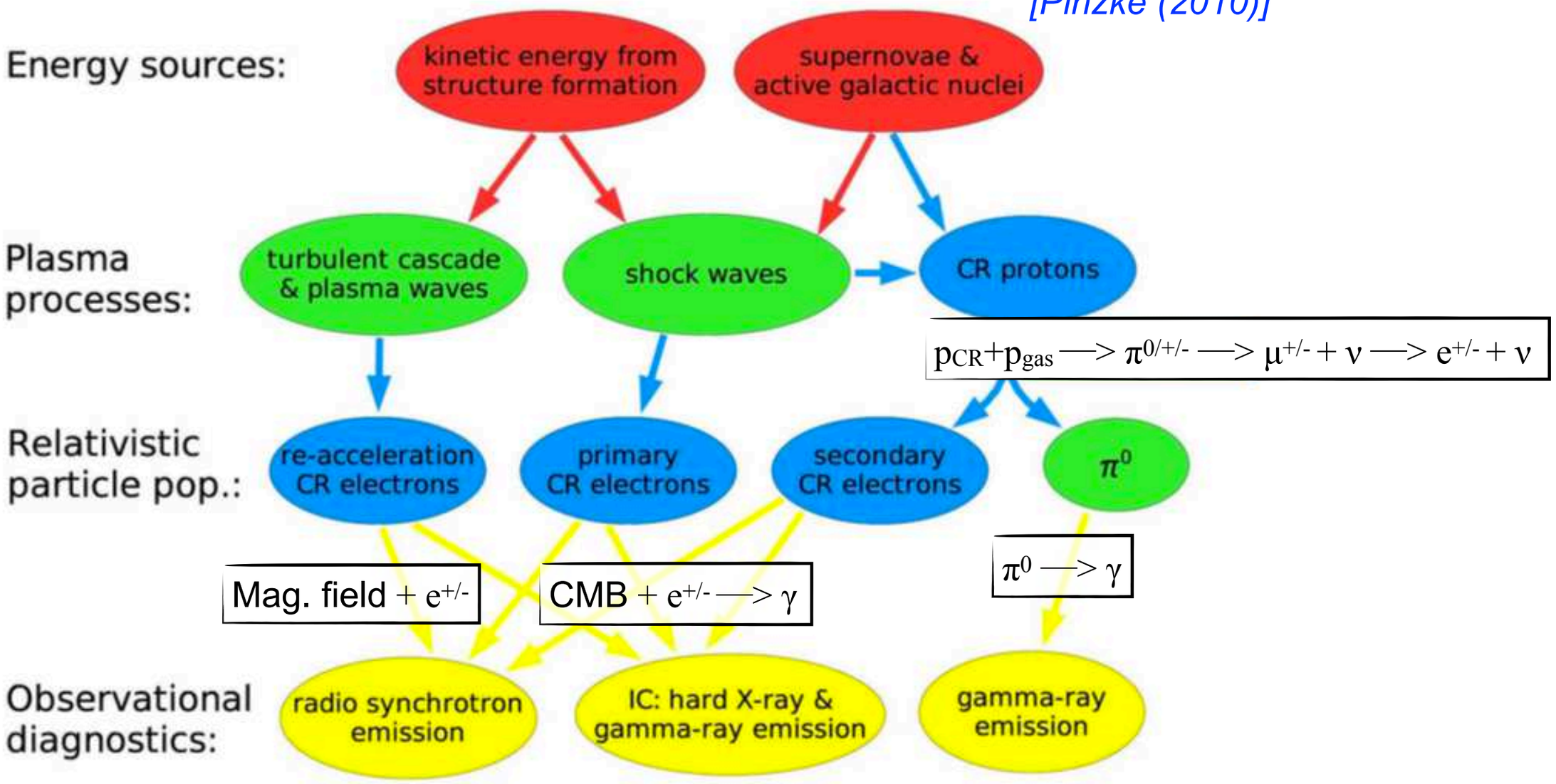
[Illustris TNG simulation]

Energy injection from AGN & SN

[Chandra press release]

From energy injection to γ-ray emission

[Pinzke (2010)]



Particle acceleration, and γ-ray signal, is expected

Modeling the gamma ray signal

Target thermal gas
- Gas density and pressure profile from external data

+

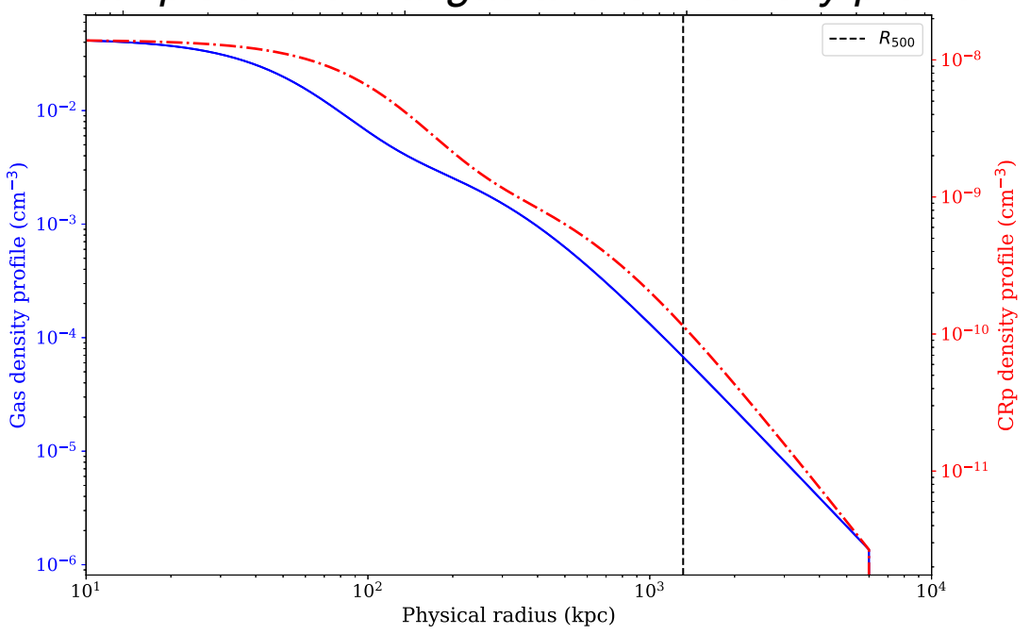
CR protons
- Power law spectrum (slope ~2.3)
- Radial density profile including possible diffusion
- Normalization using CR to thermal energy ratio

+

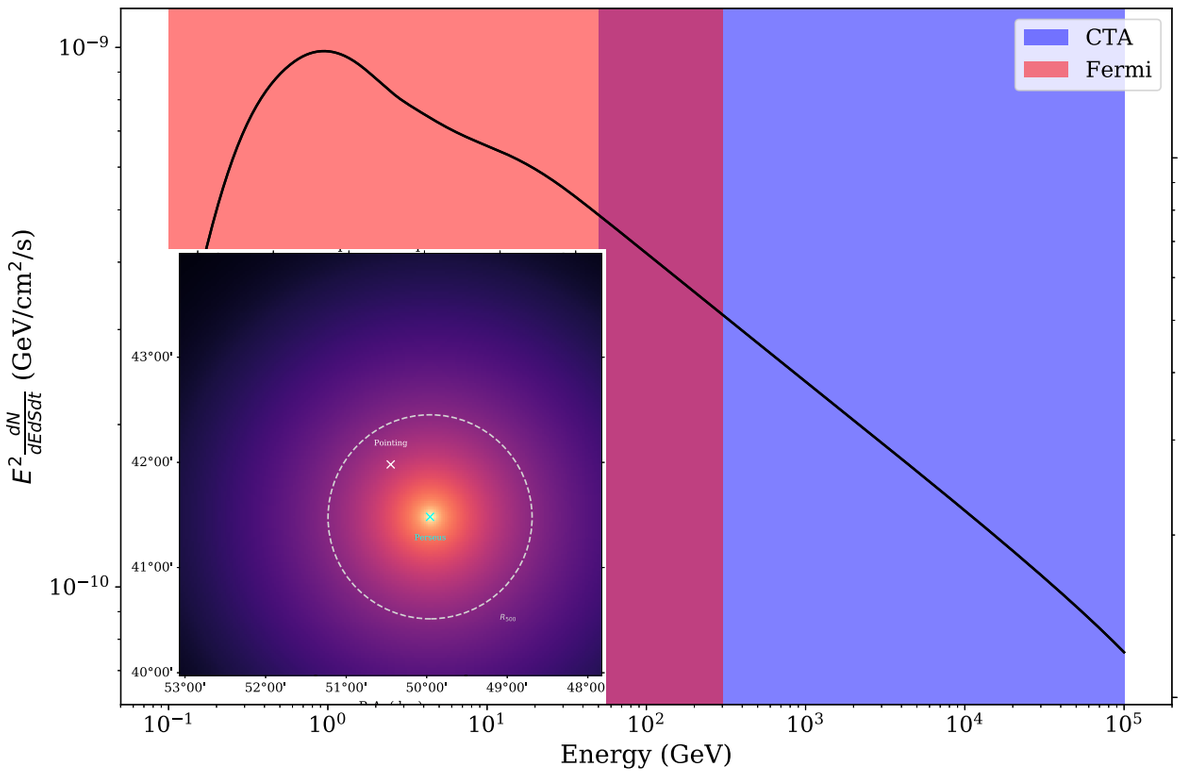
CR/gas interactions
- π^0, $e^{+/-}$, and γ production rate using
- Volume integration and normalization

Computing gamma ray observable
- Spatial template
- Spectral template

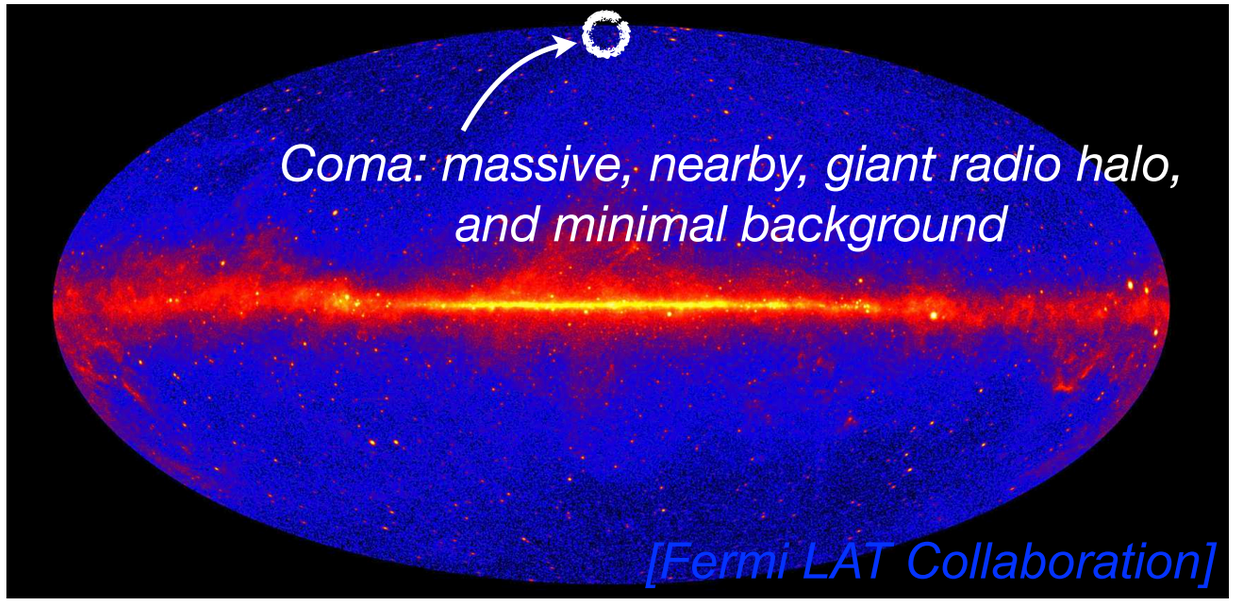
Example of thermal gas and CR density profile

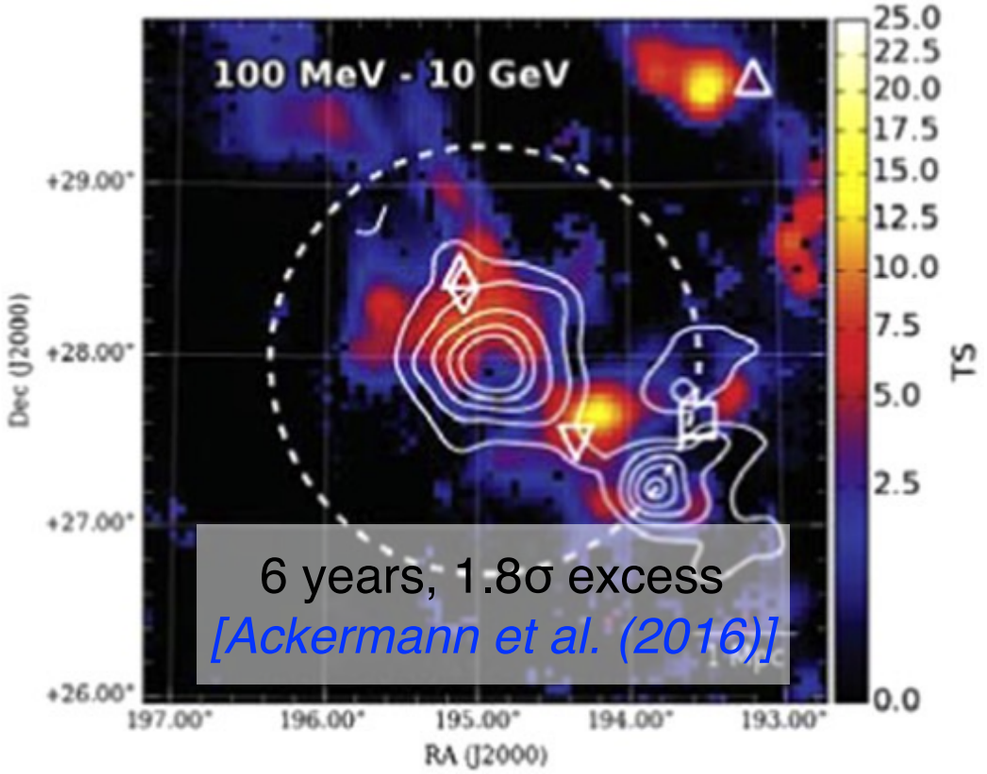


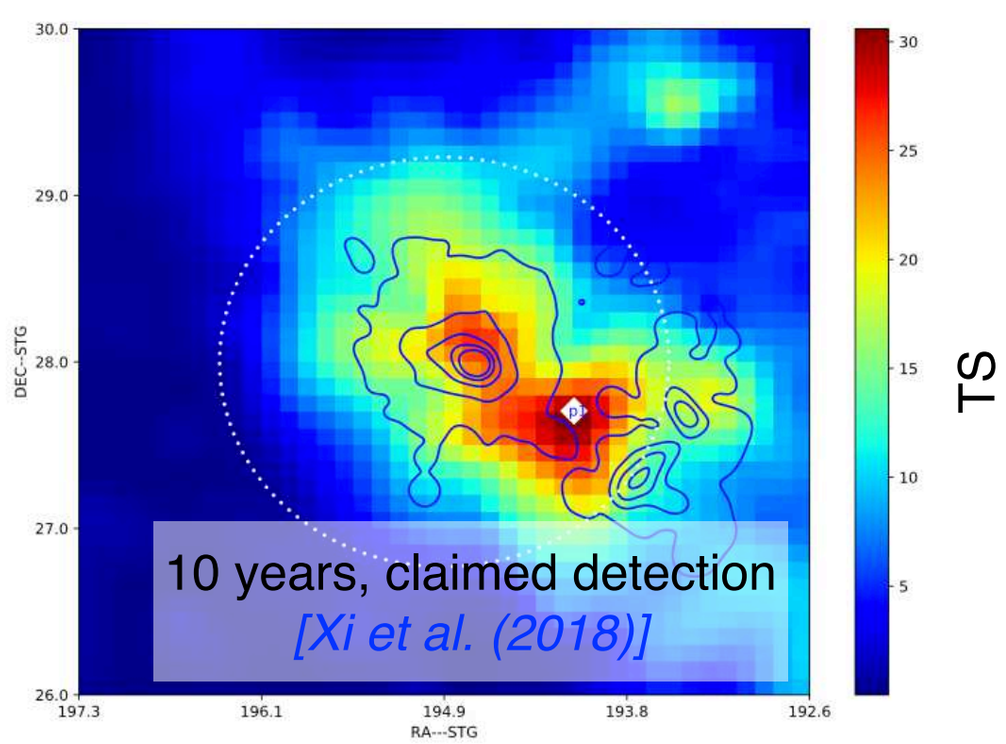
Example of spatial and spectral templates



Search for γ-rays towards Coma with Fermi-LAT







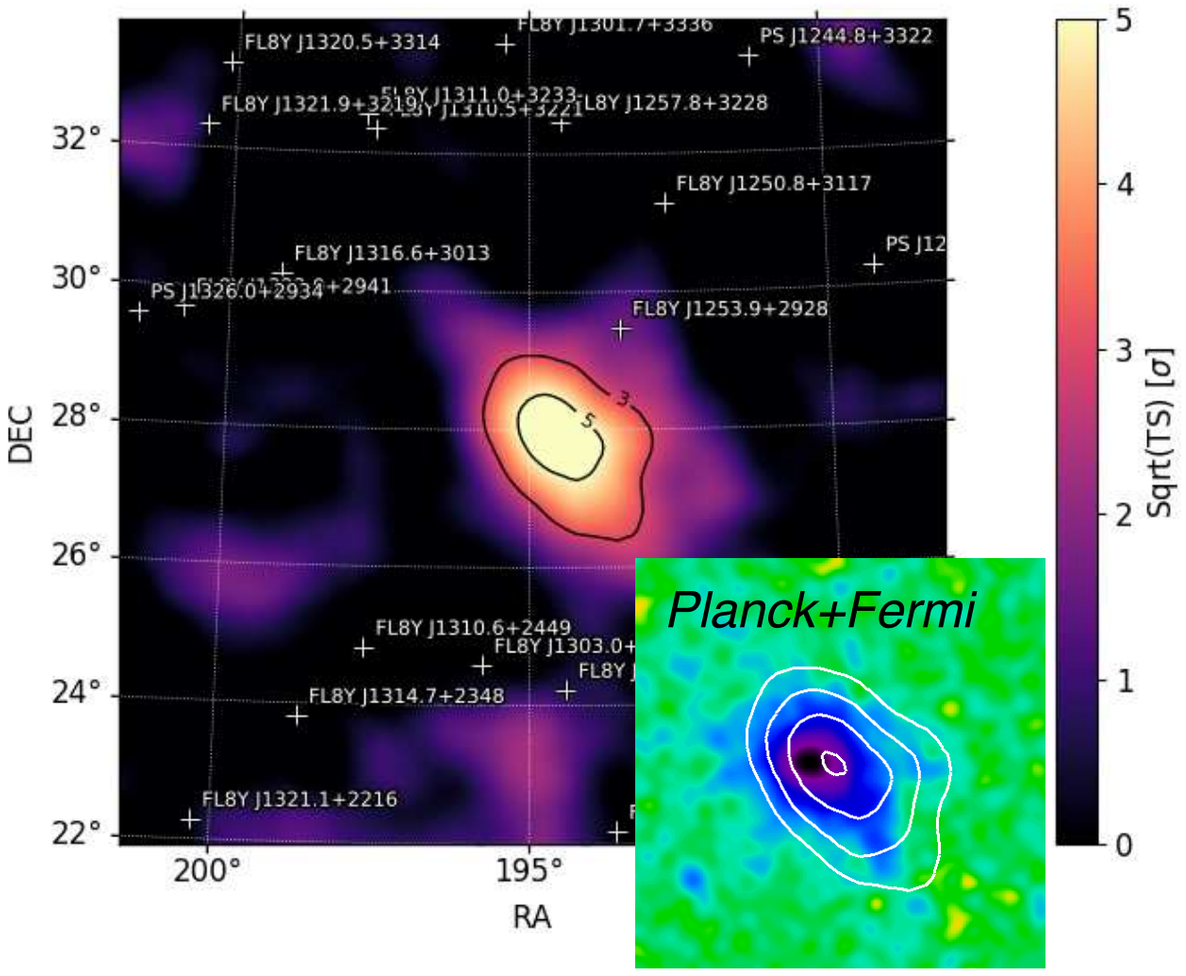
Claimed detection in the direction of Coma

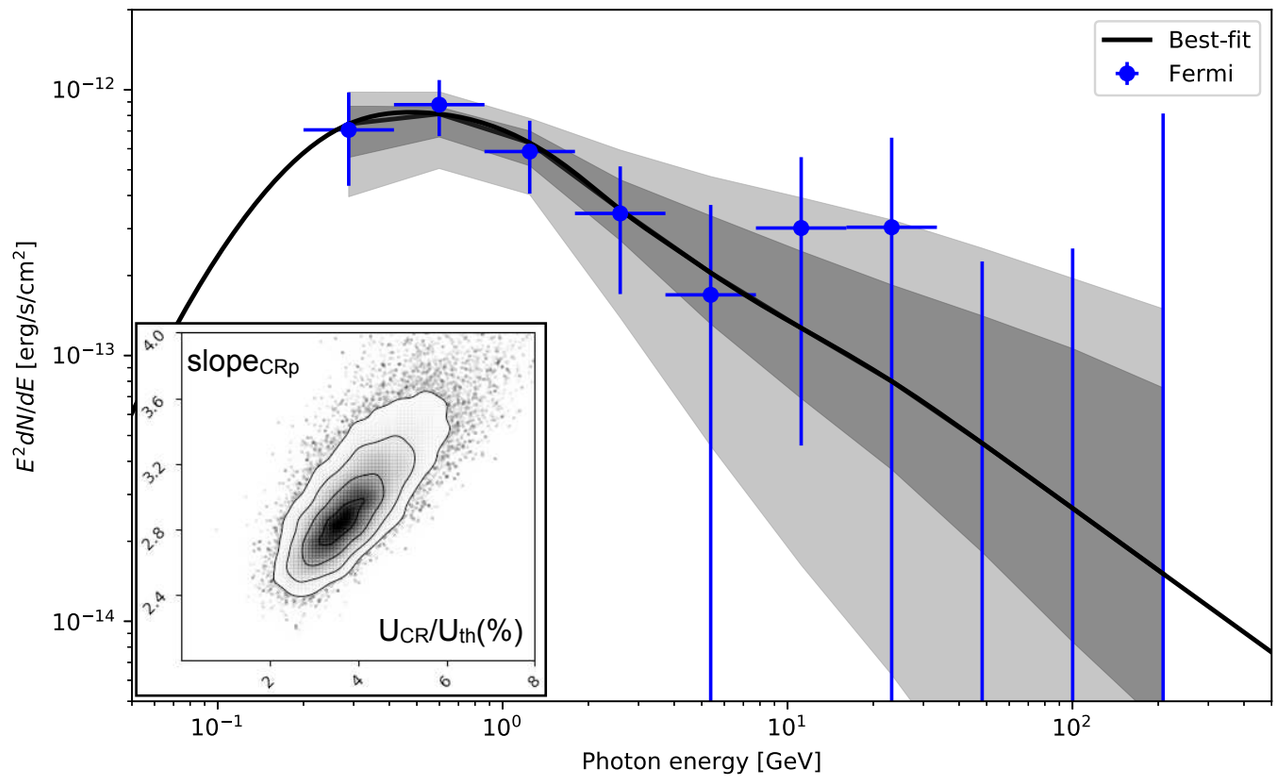
Search for γ-rays towards Coma with Fermi-LAT

(work in progress)

The signal would imply a CR to thermal pressure of few%

- fine with model expectations
- consistent with the multi-wavelength morphology





Search for γ-rays towards Coma with Fermi-LAT

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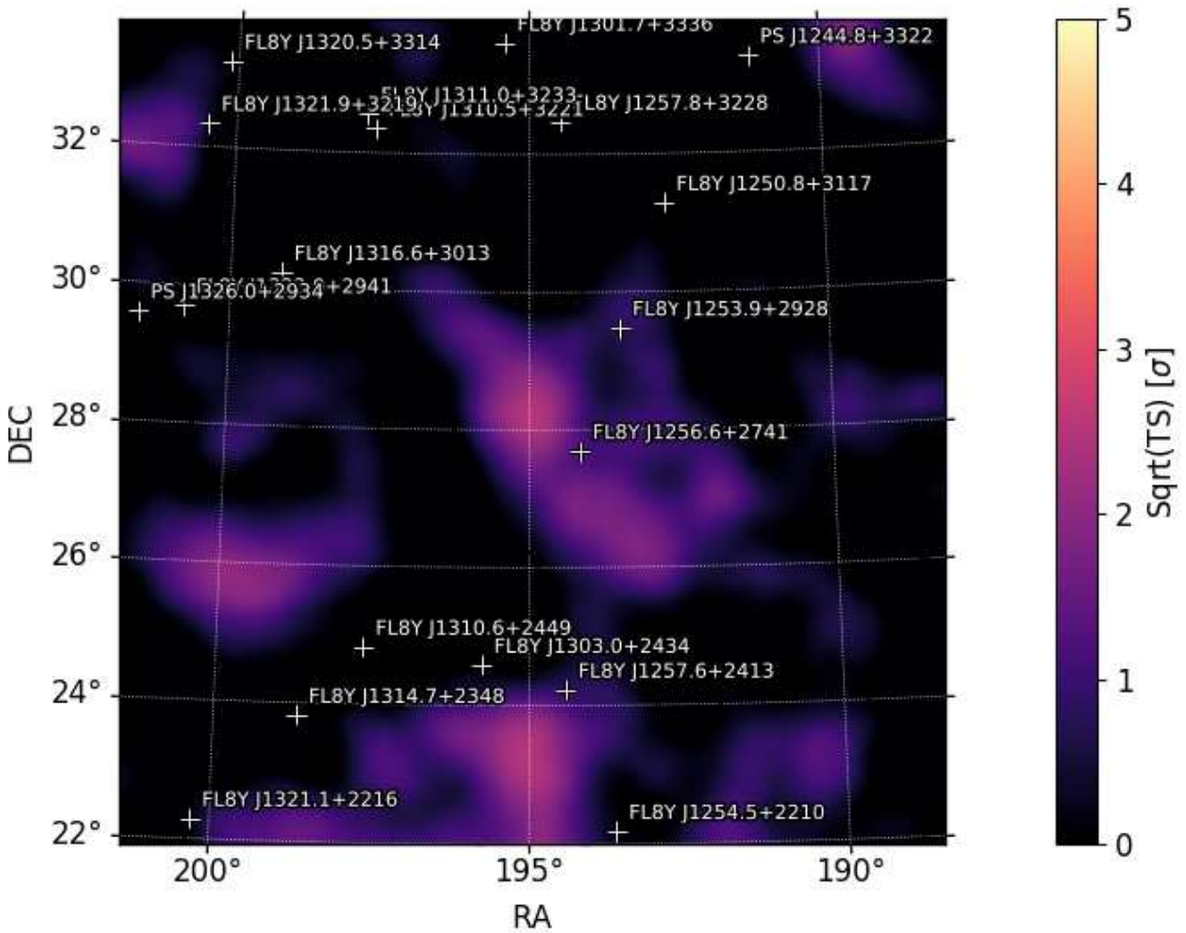
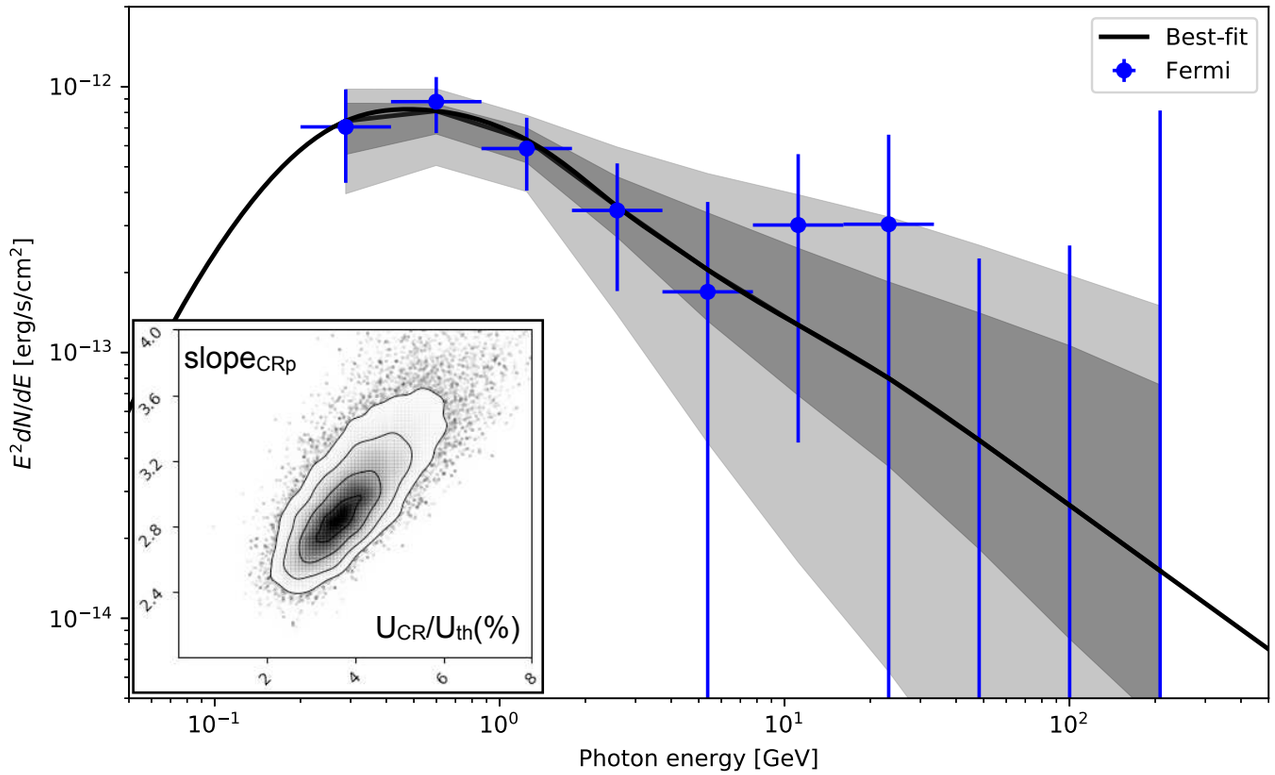




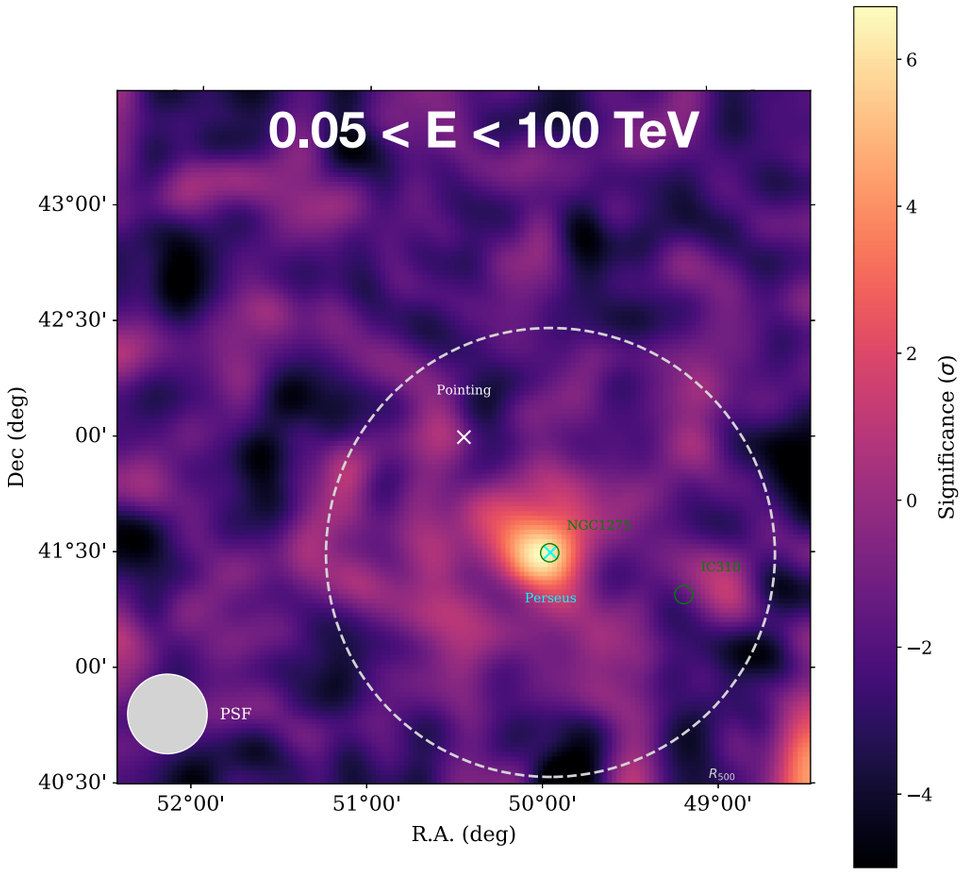
But accounting for a potential point source drastically reduces the significance

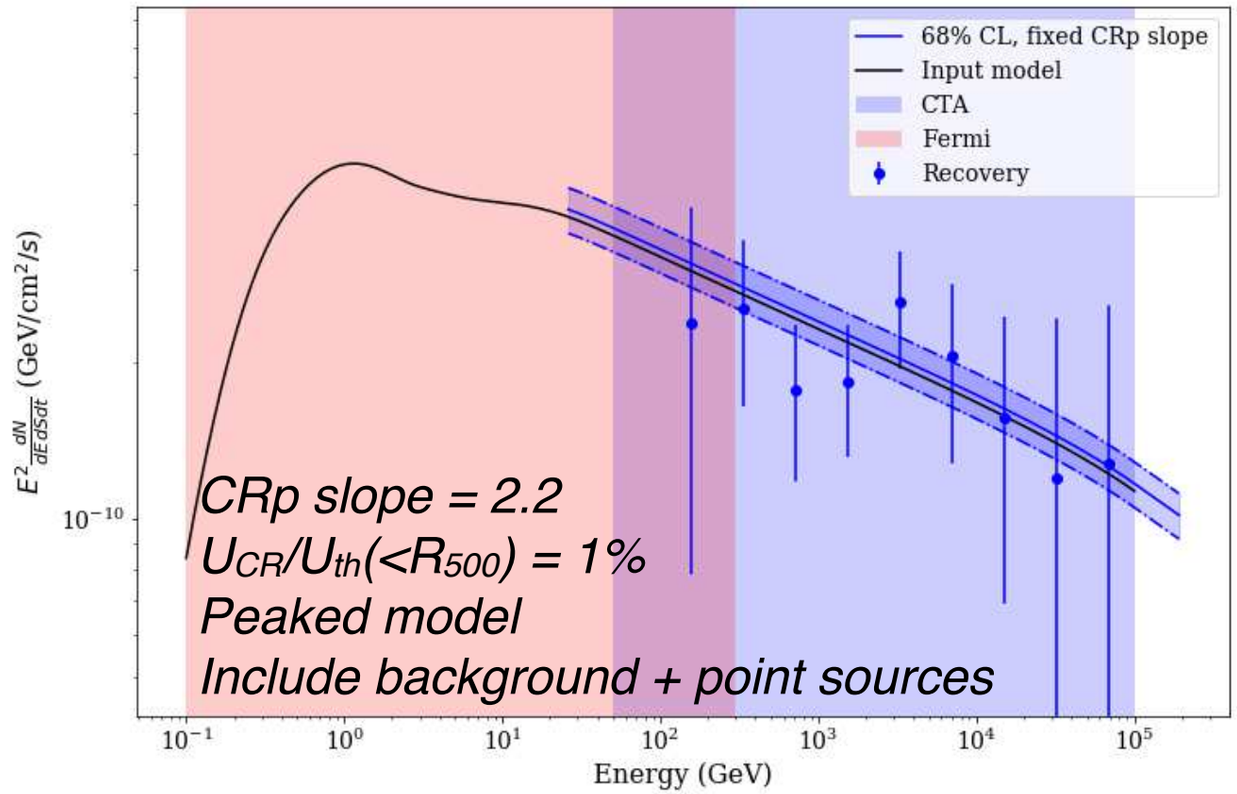
Fake detection due to point source contaminant?

Simulating the expected signal with CTA

(work in progress)

- VHE γ-rays from atmospheric Cherenkov imaging
- Great angular resolution + wide energy range: key to disentangle cluster from AGN
- Perseus to be observed 300h as a key science project *[CTA consortium (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

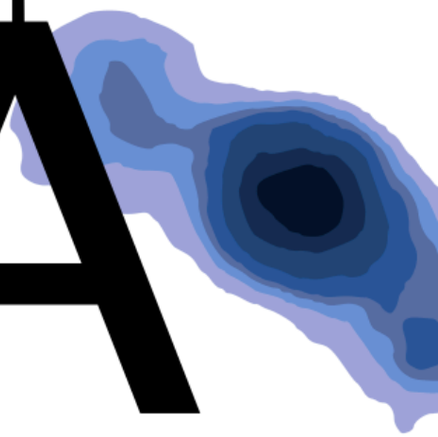
- Resolved observations of the SZ signal
  - Many results from test case demonstration
  - Multi-wavelength analysis proved powerful
- Ongoing observations of 50 clusters
  - In depth study of the gas physics
  - High z SZ-mass calibration will be available

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