Diffuse gas in galaxy clusters

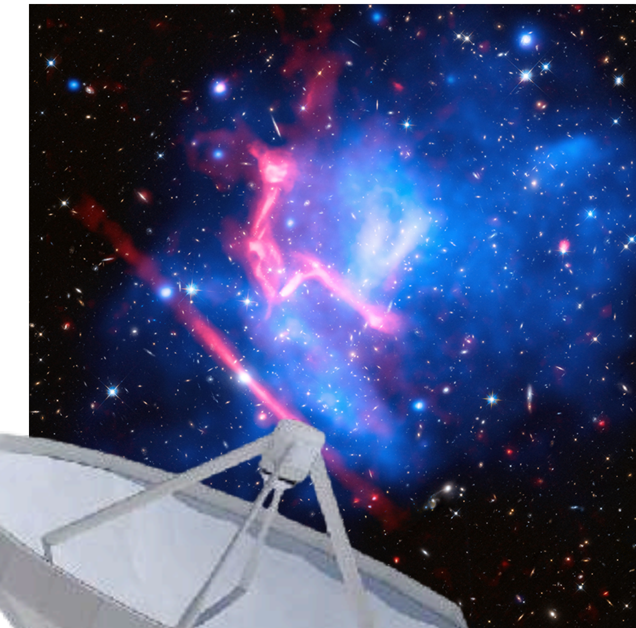
On the thermal and non-thermal components

Rémi Adam

INPA seminar — 24/04/2020

Laboratoire Leprince-Ringuet

Outline

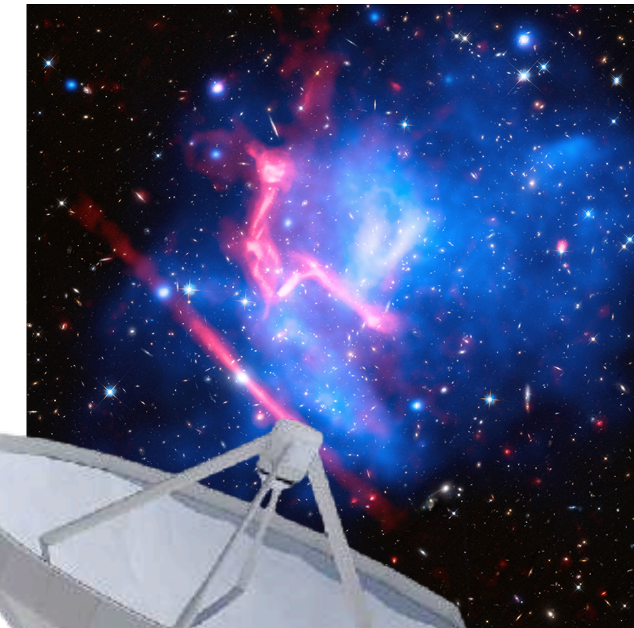


1. **Clusters of galaxies as cosmic laboratories**

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

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

Outline



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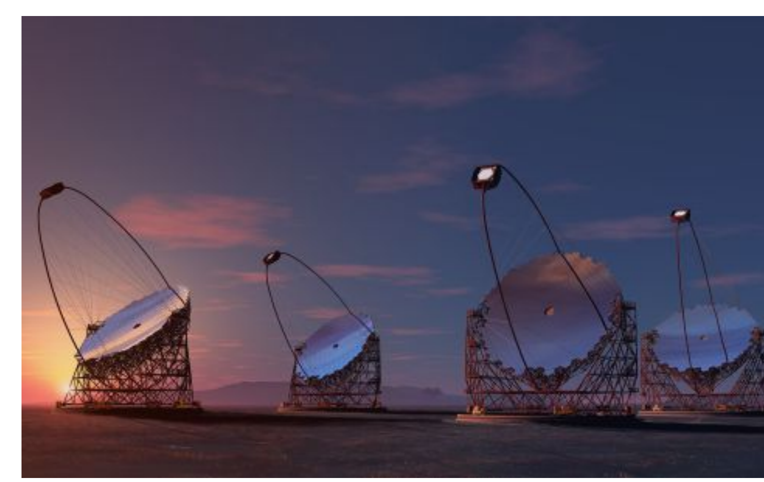
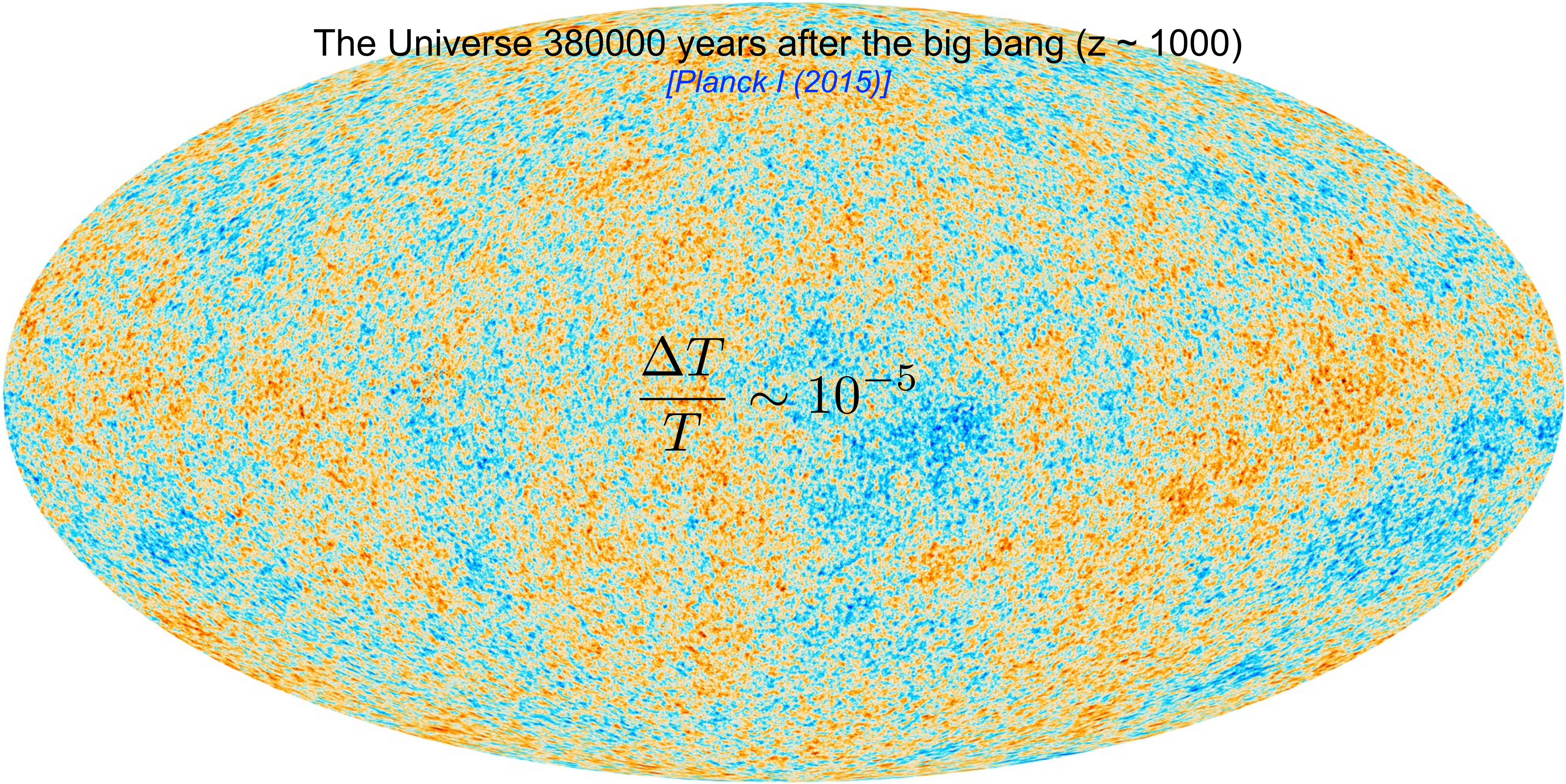
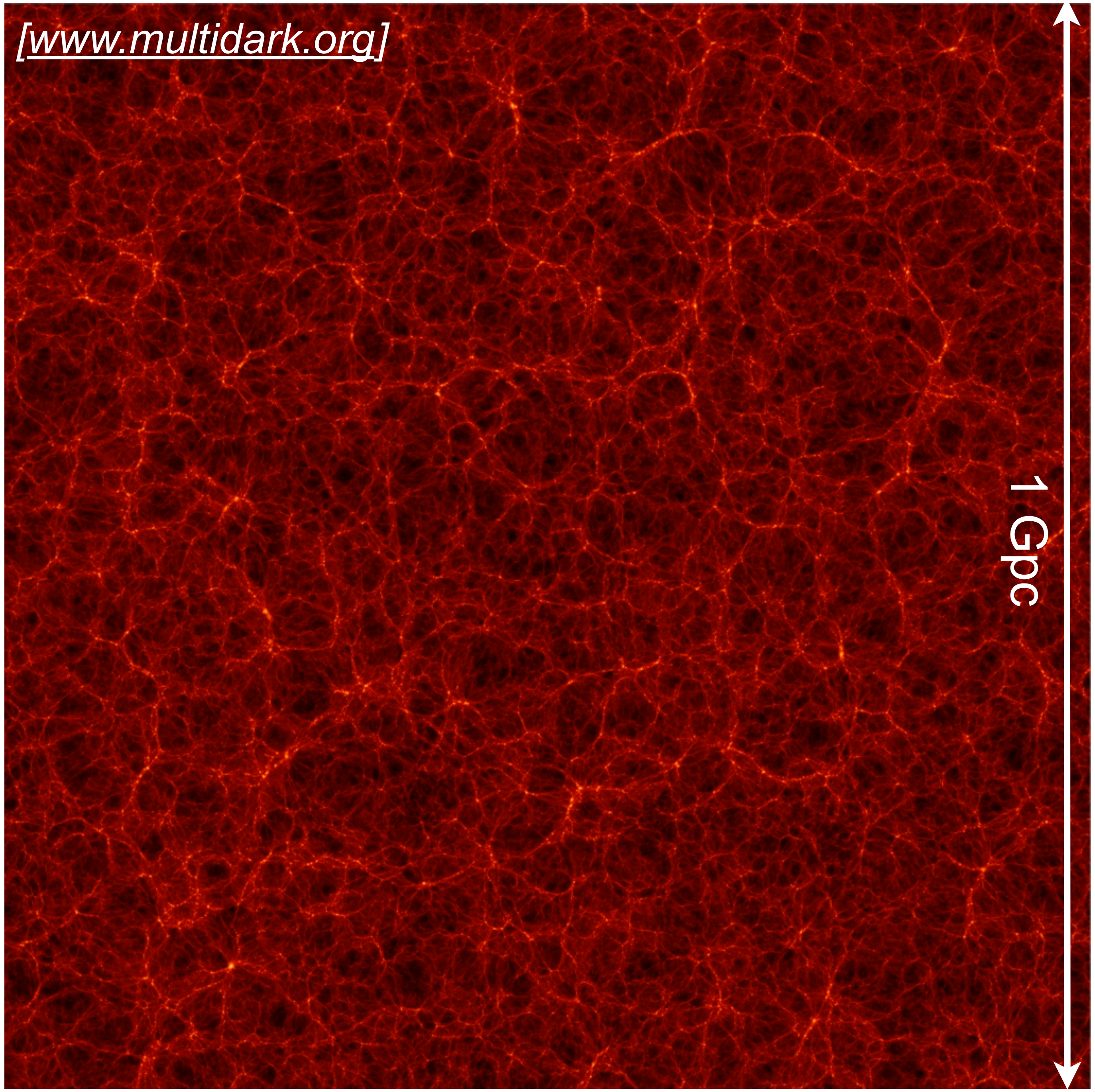


Starting from primordial fluctuations



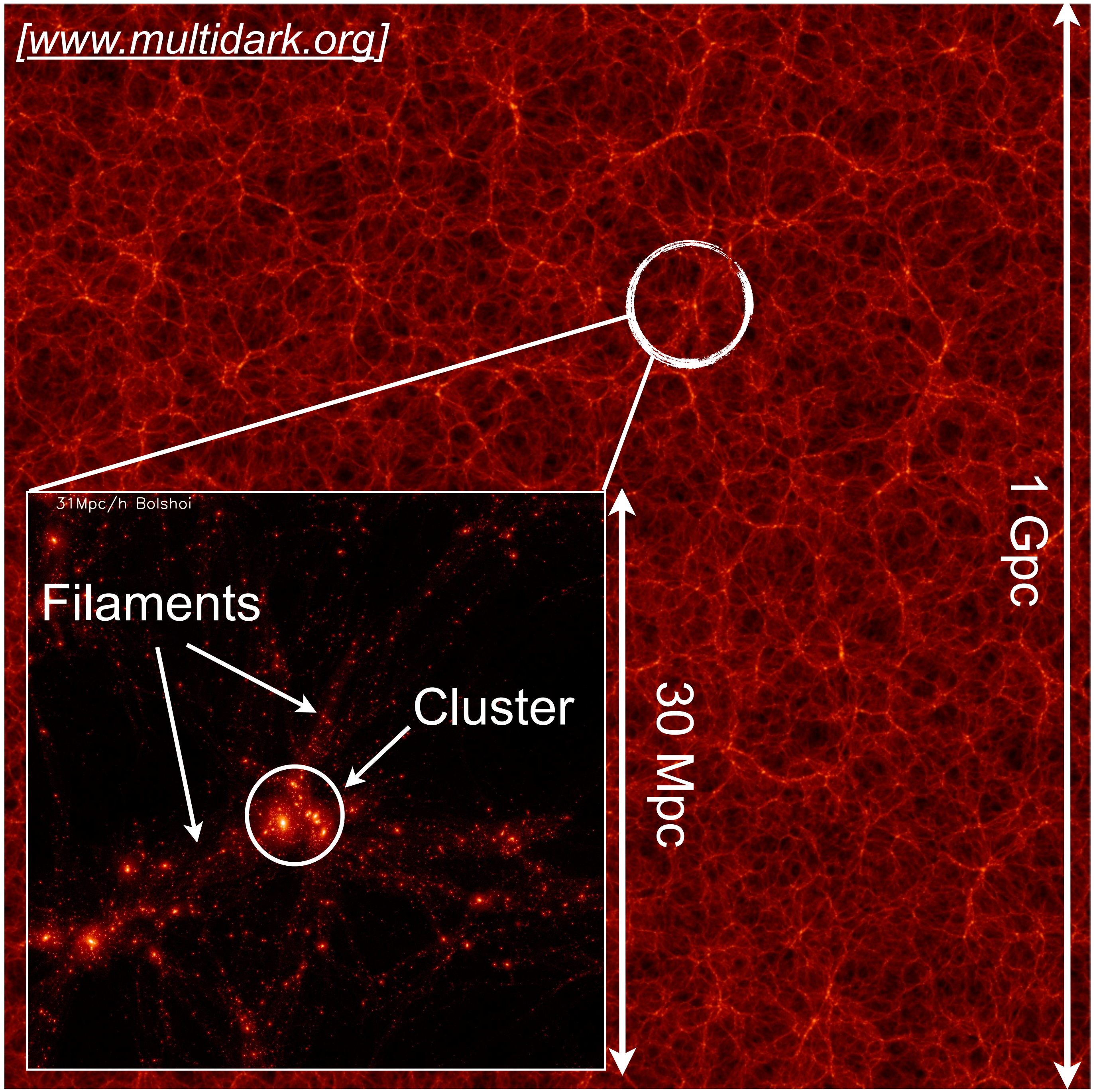
A very homogeneous Universe, with tiny fluctuations

From large scale fluctuations to galaxy clusters



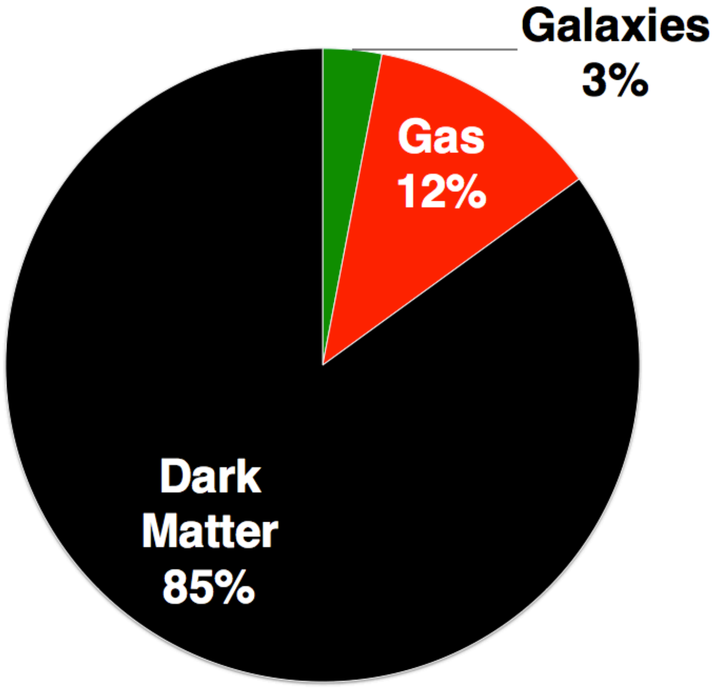
- The primordial fluctuations collapse in the expanding Universe

From large scale fluctuations to galaxy clusters



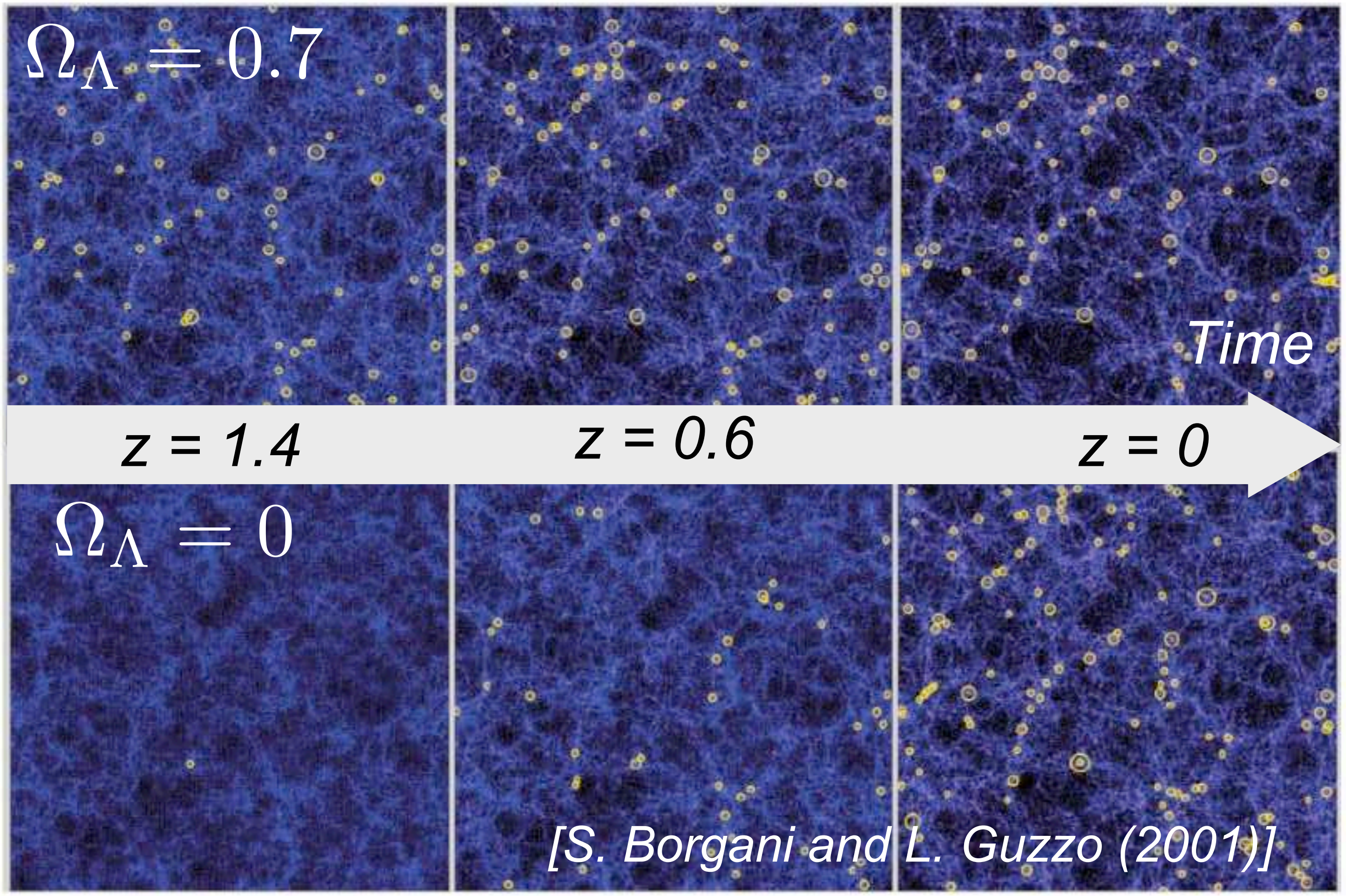
- The primordial fluctuations collapse in the expanding Universe
- To form clusters: the largest gravitationally bound structures

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



Galaxy clusters are peaks in the matter density field

Cosmology with cluster counts



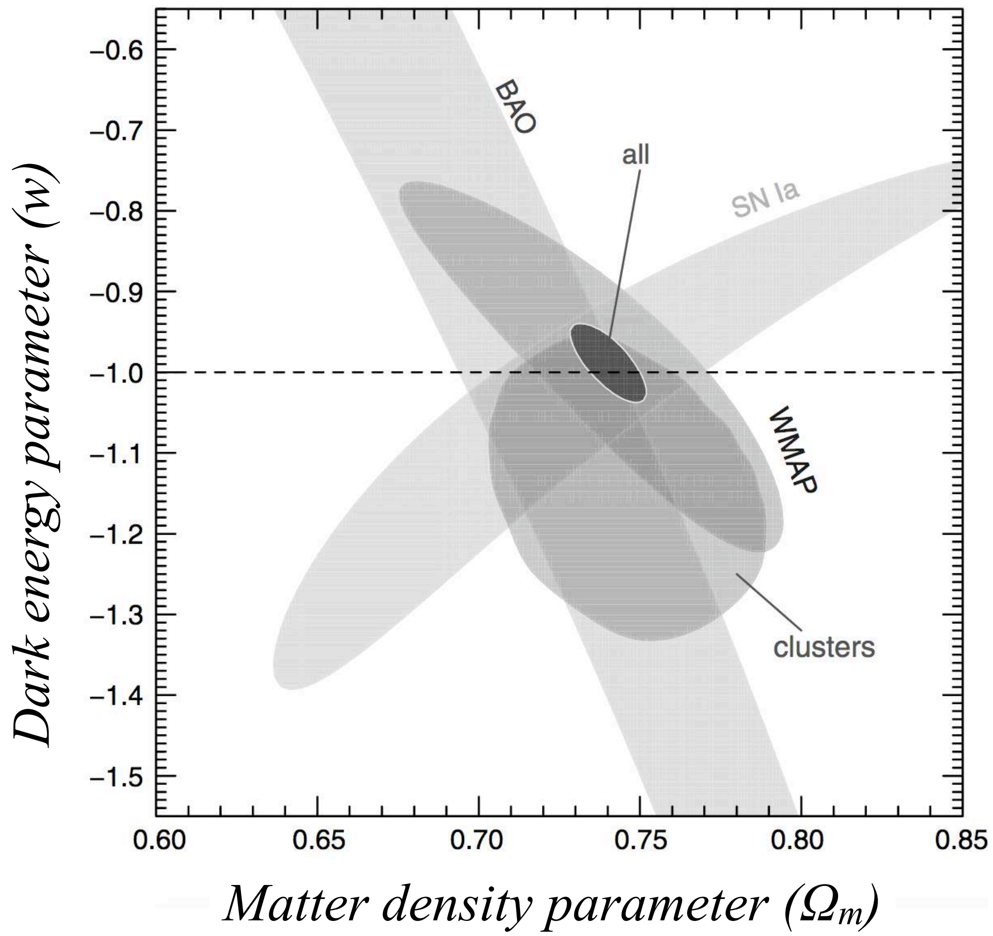
Survey detection *Model*

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

Selection function *Mass-obs. relations*

Cosmology with cluster counts

[Vikhlinin et al. (2009)]



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

Selection function *Mass-obs. relations*

Sensitive to geometry, dark matter/energy and gravitation

Key ingredients: mass + observational properties

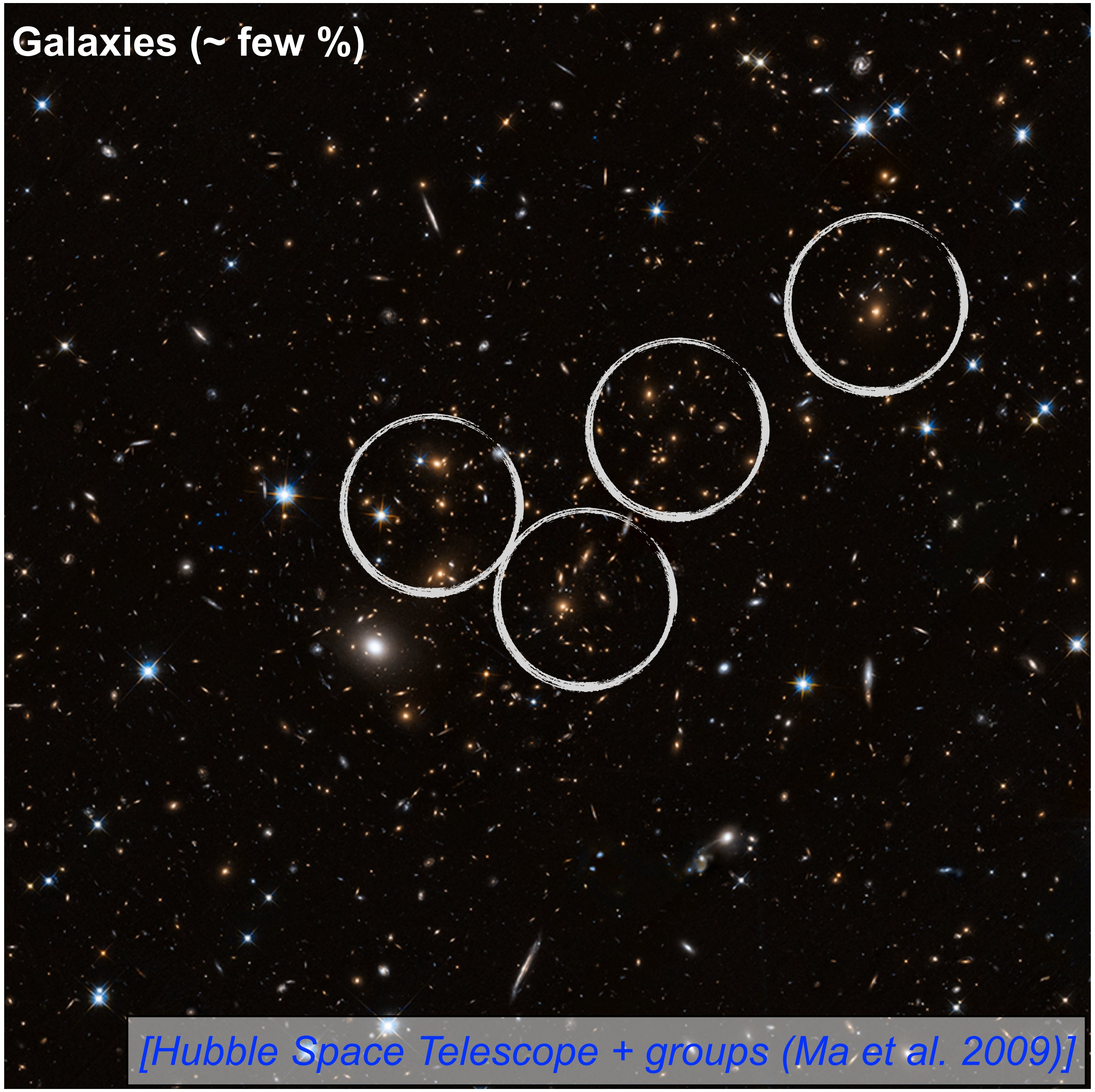
Multi-wavelength view of galaxy clusters

Multi-wavelength view of galaxy clusters

Optical & infrared:

- Galaxies

➡ **Stellar population**



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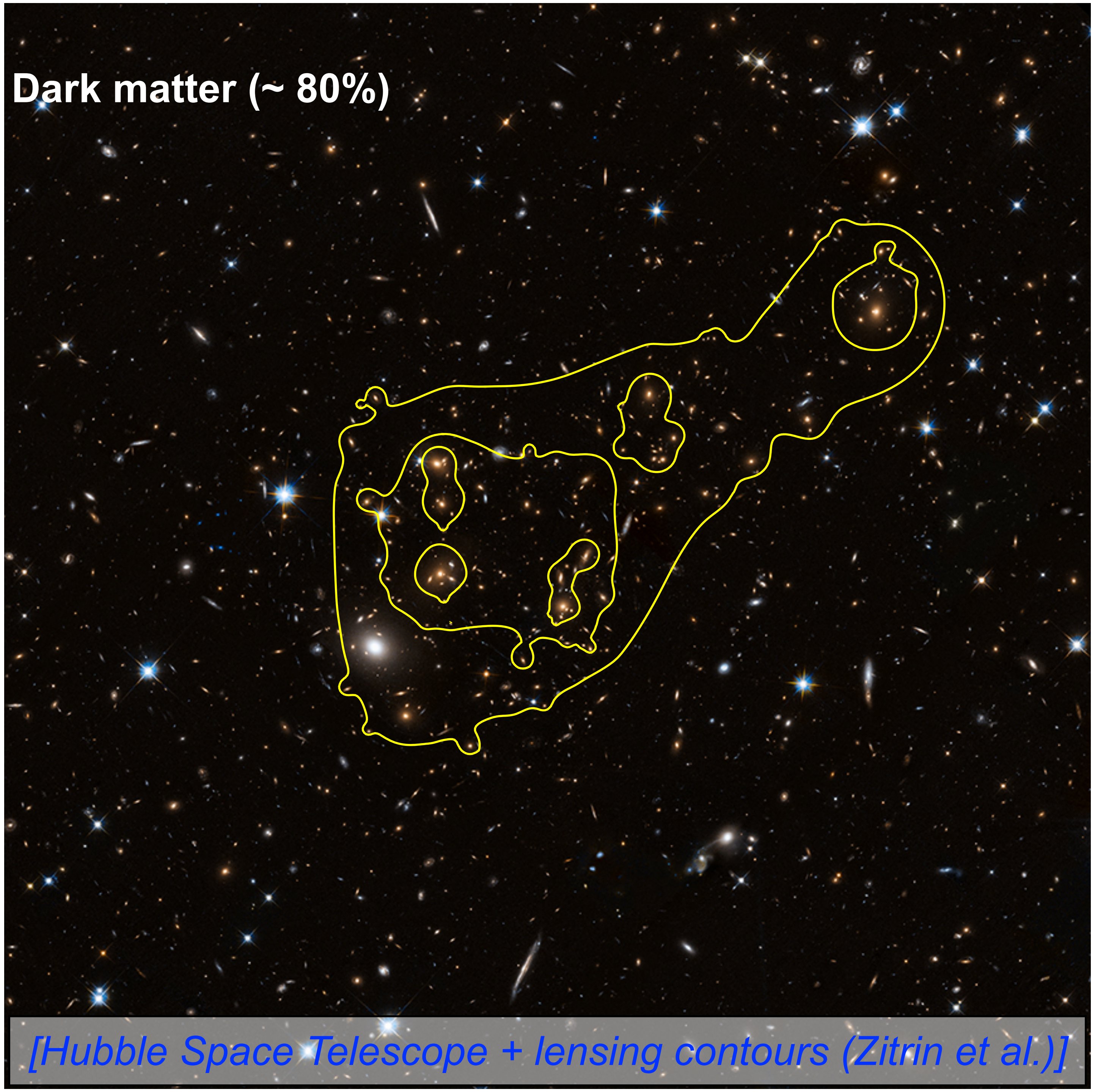
➡ **Lensing mass**



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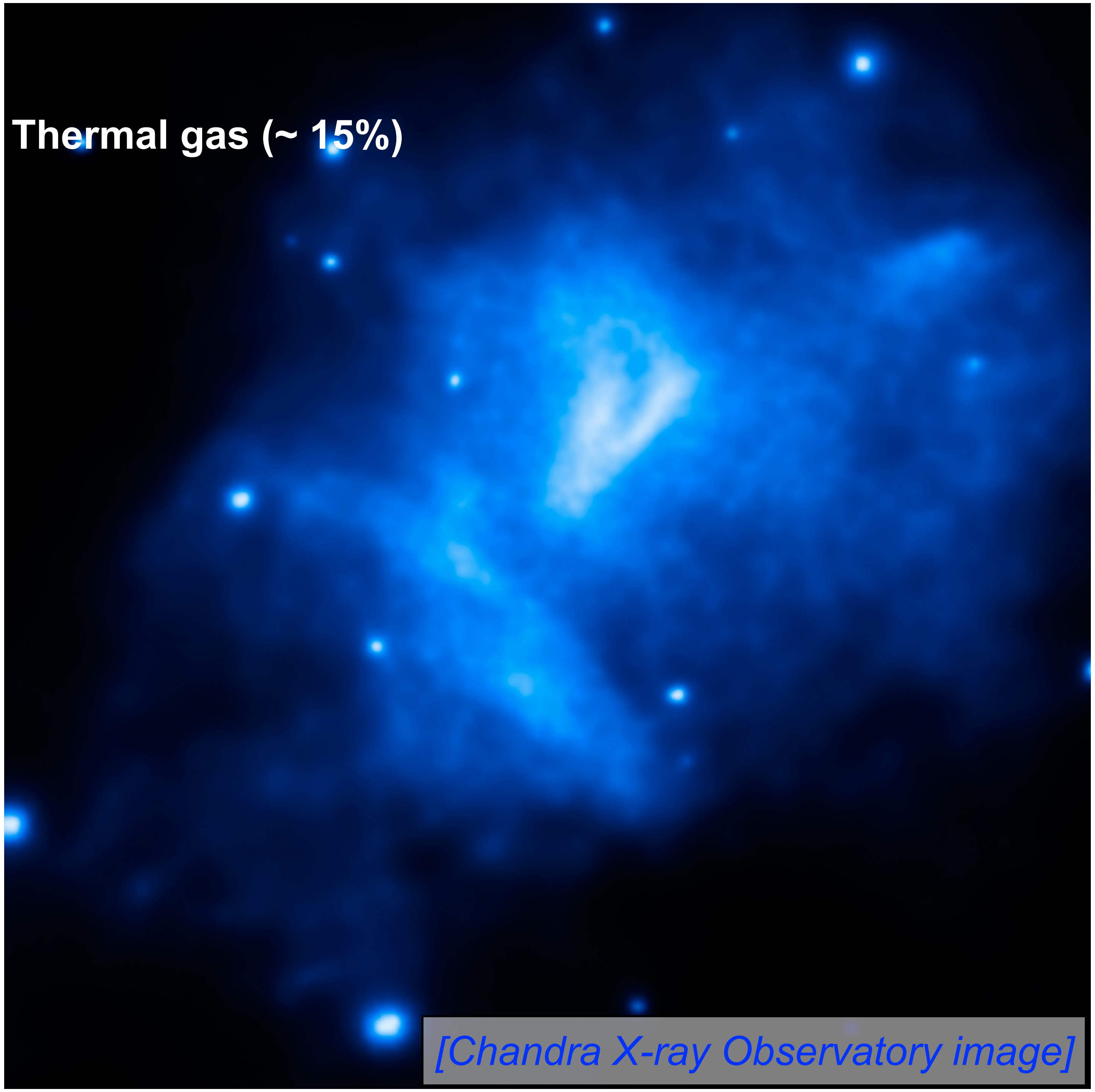
X-ray:

- Bremsstrahlung thermal gas emission

➡ **Gas density**

➡ Spectroscopic temperature (~10^8 K)

➡ Mass from hydrostatic equilibrium



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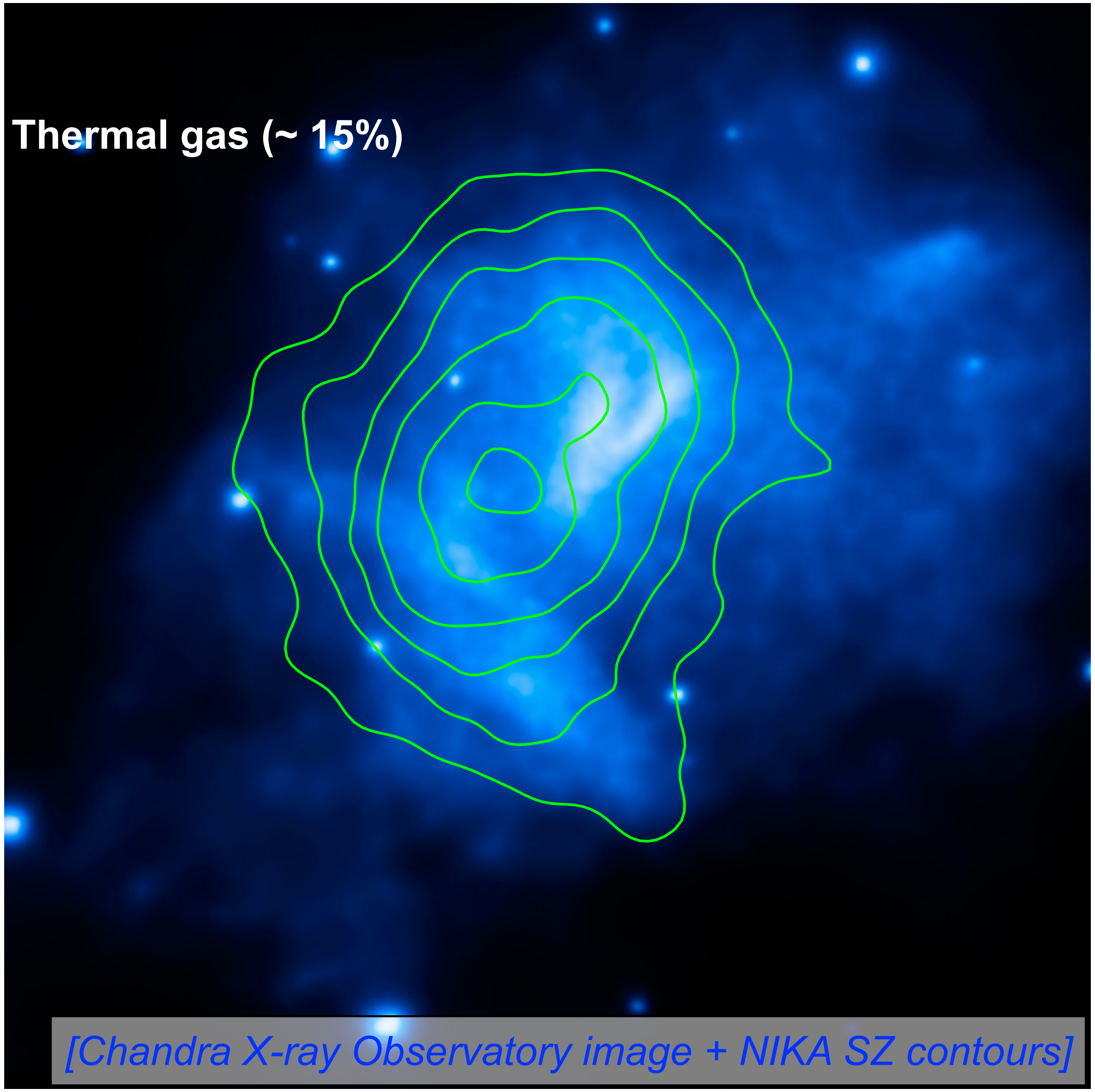

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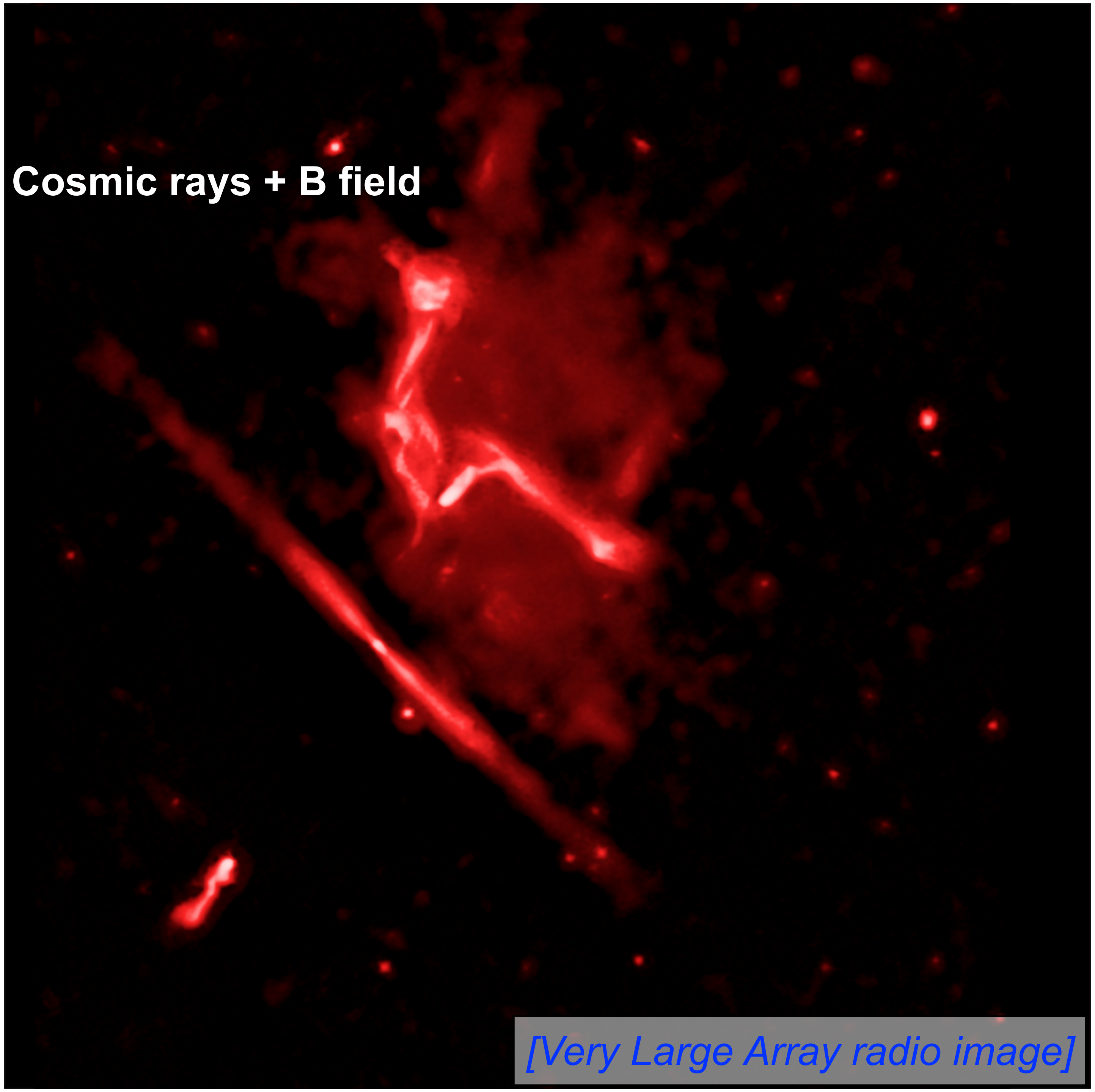
Radio (+ γ-rays):
- Non-thermal emission (+DM?)

➡ **Particle acceleration**



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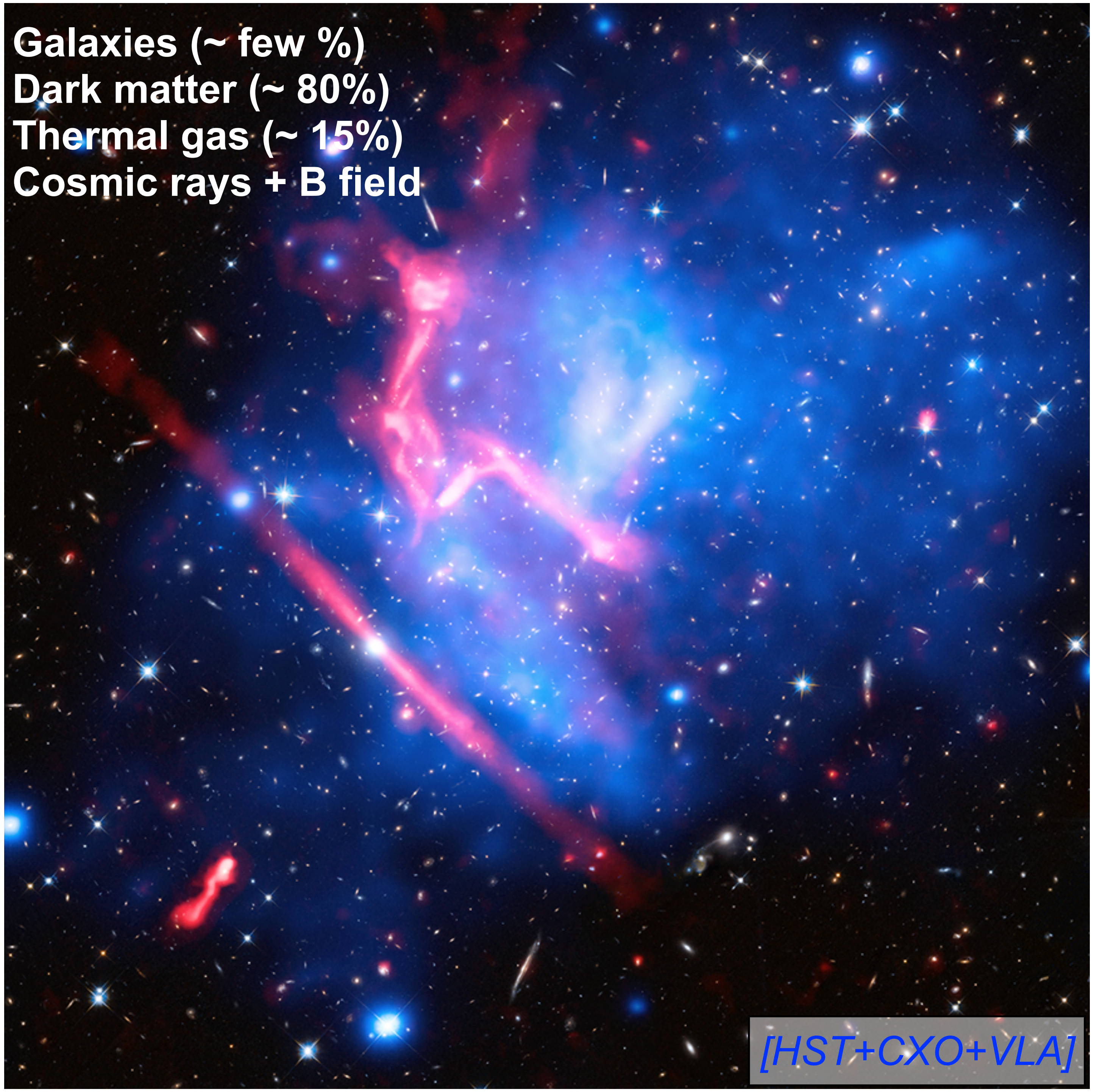

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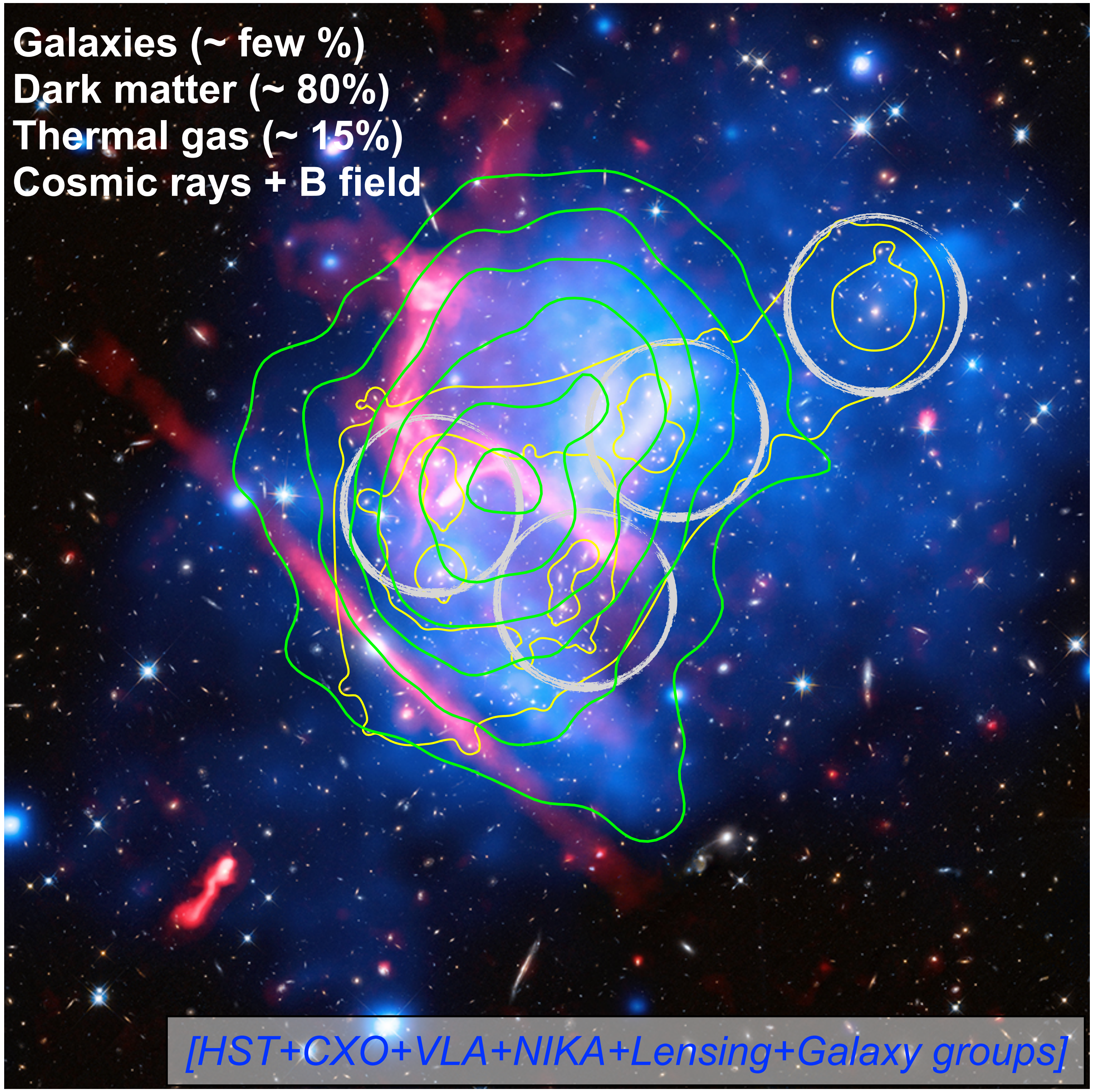
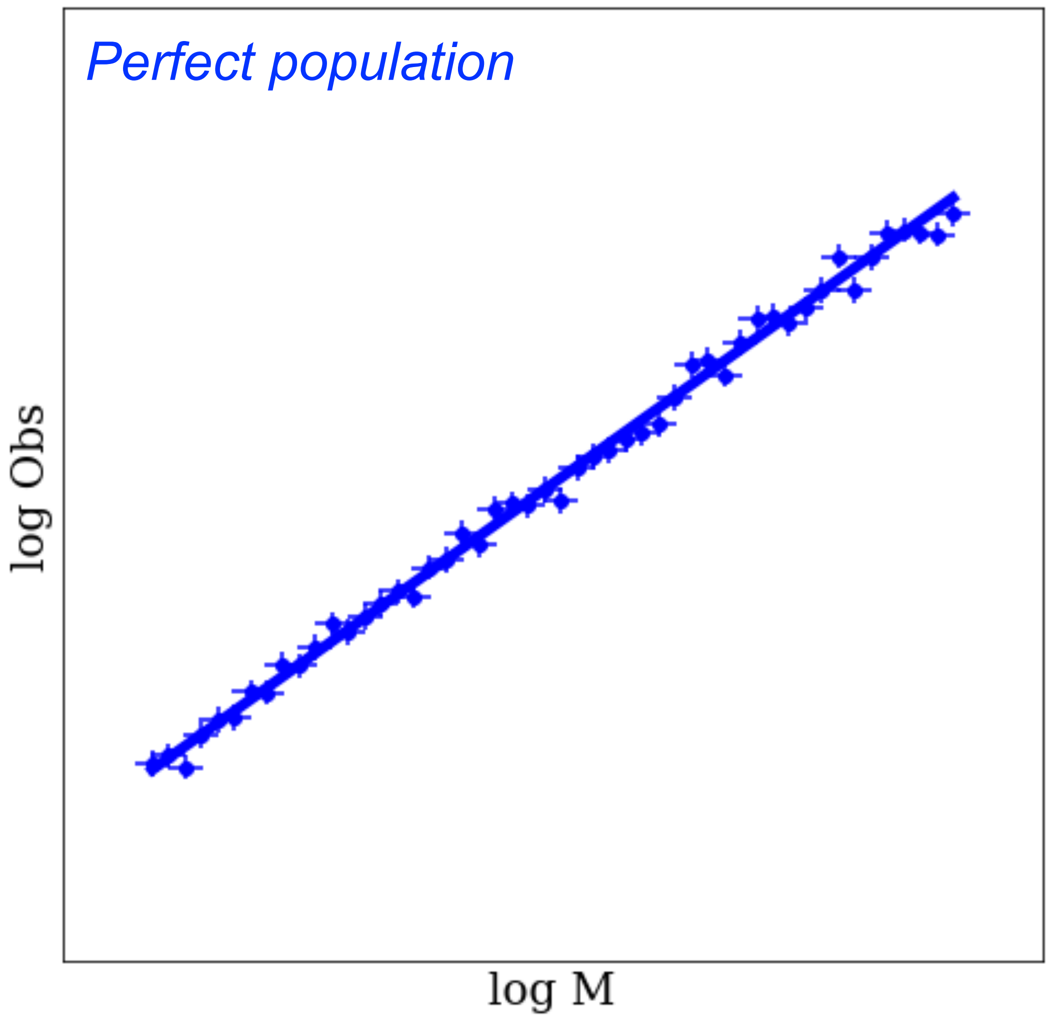


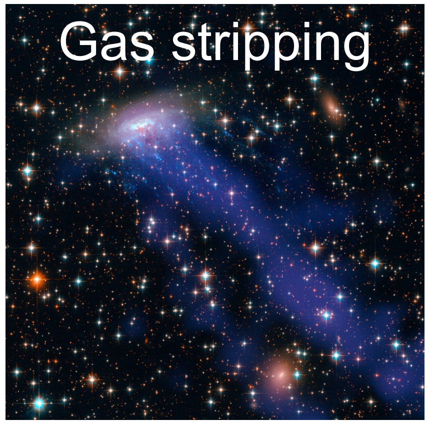
Huge complementarity from different wavelengths

Shaping clusters observables with astrophysics

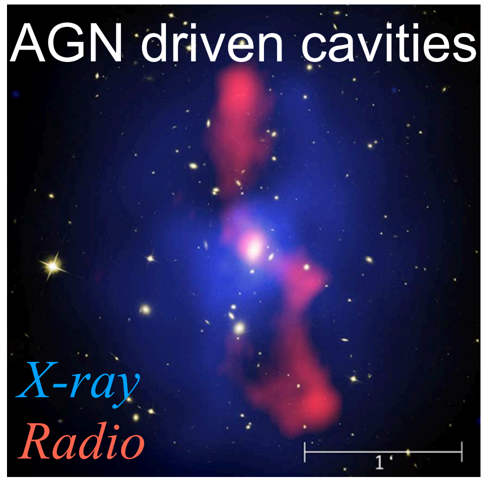


In surveys, observables are used as mass proxies
At 1st order, they are fully determined by M and z

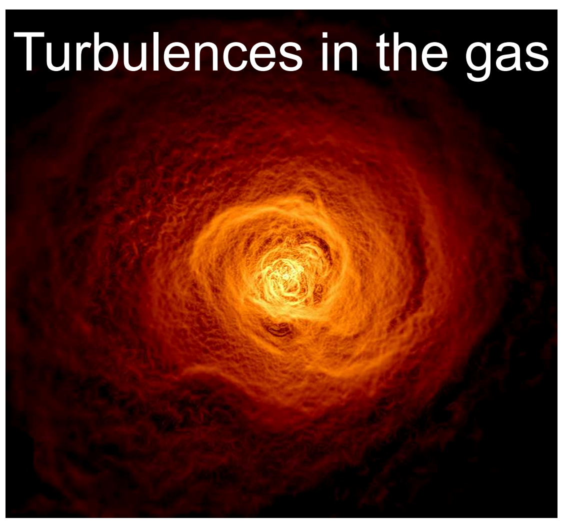
Shaping clusters observables with astrophysics



[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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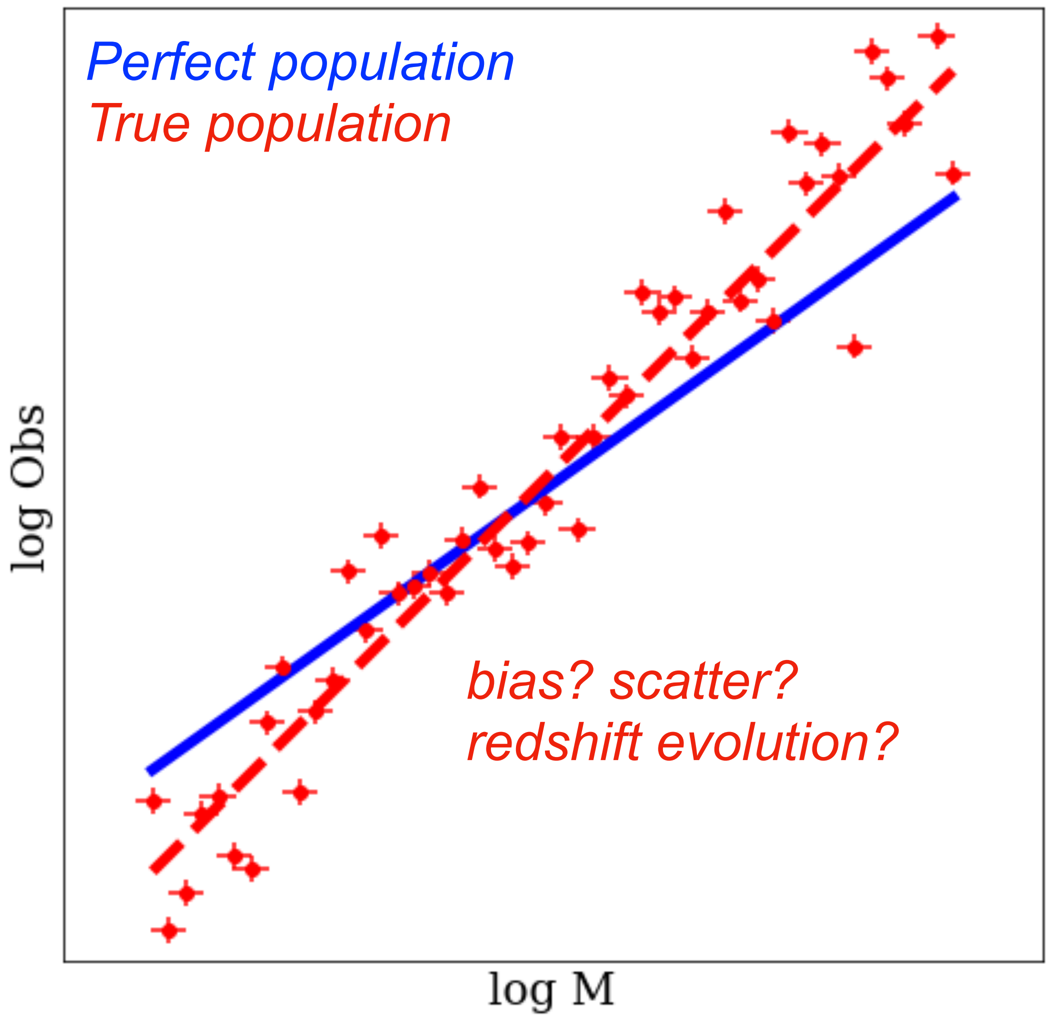
But rich astrophysical processes are at play

- *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]

Outline

1. Clusters of galaxies as cosmic laboratories

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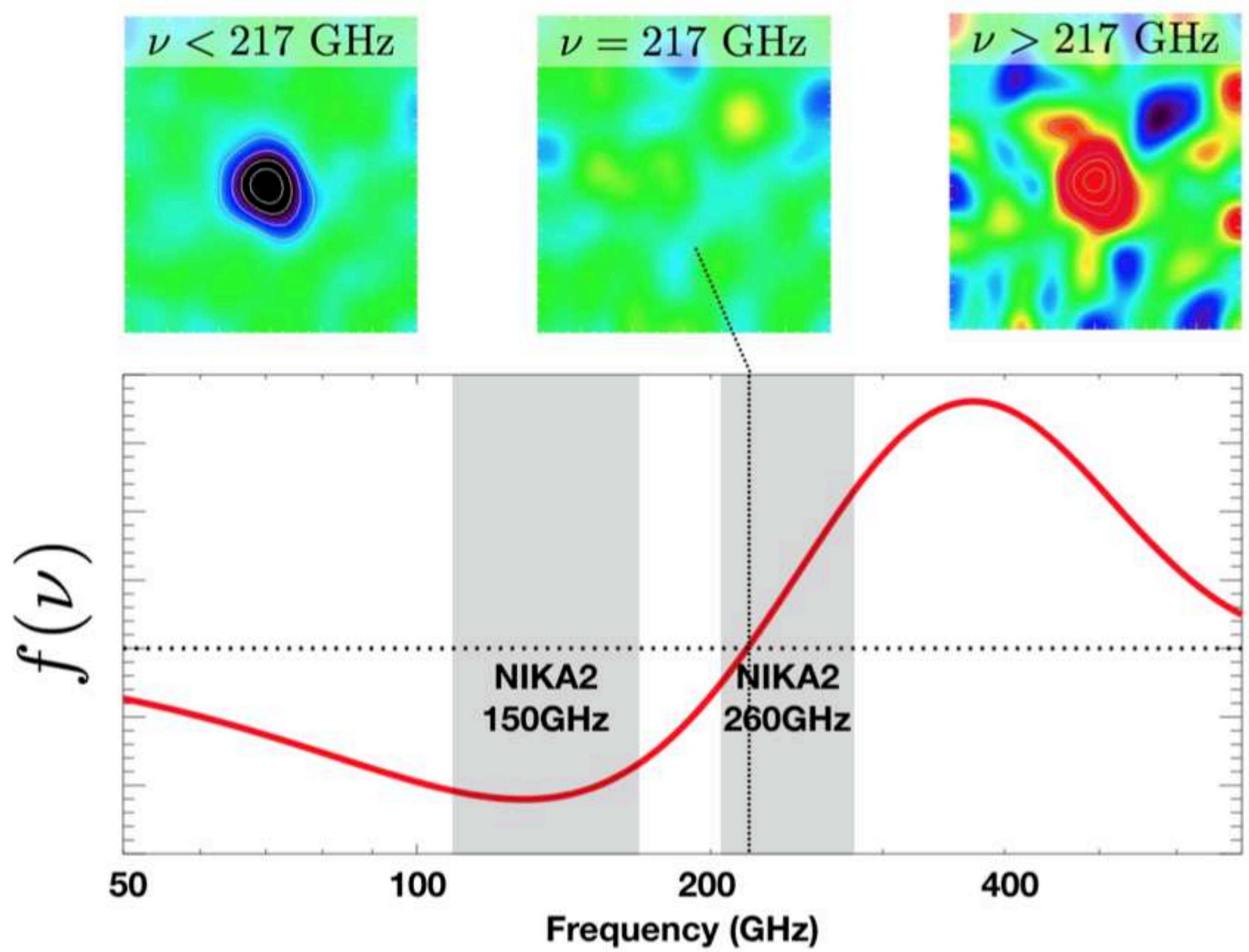
3. The quest for cluster cosmic rays in the γ-rays

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



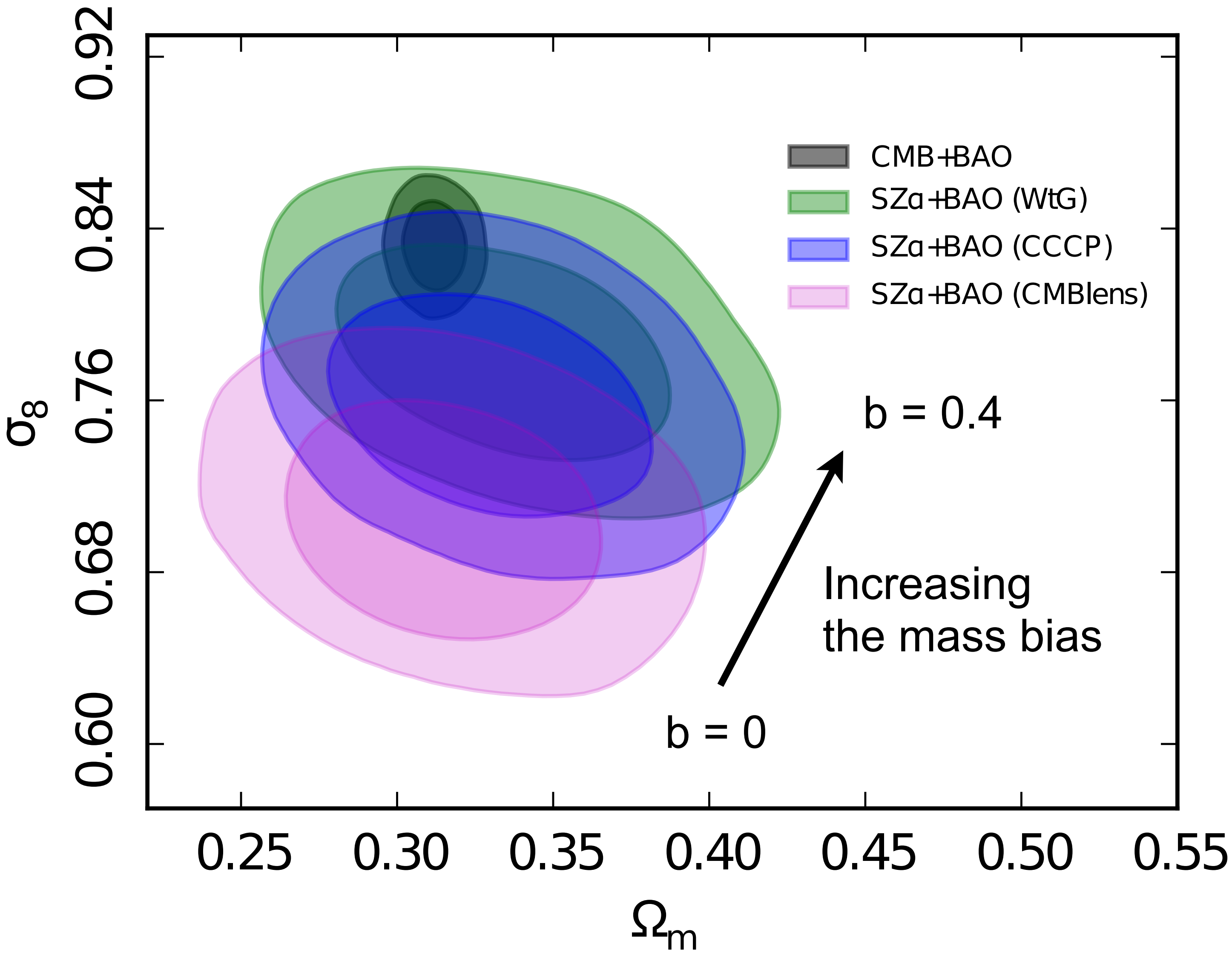
Excellent probe for the hot gas in distant clusters

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)]

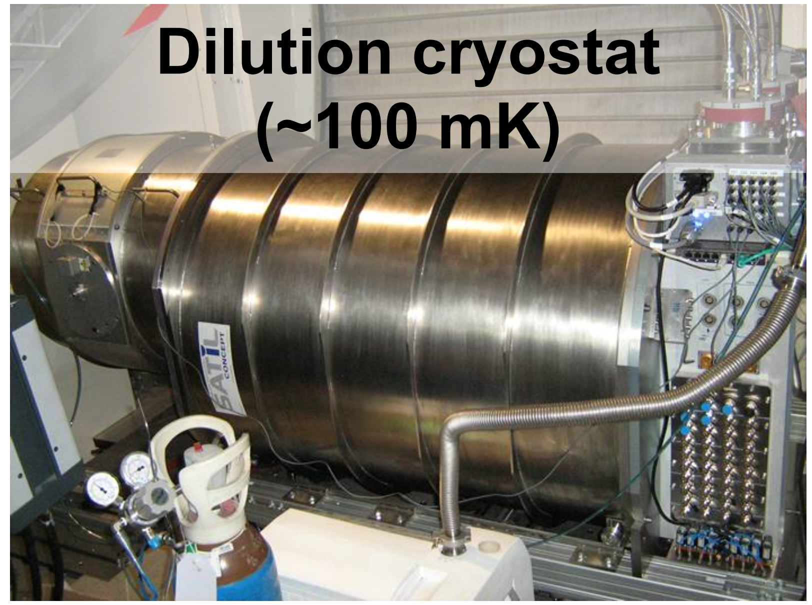
CMB & clusters & hydro sim in tension

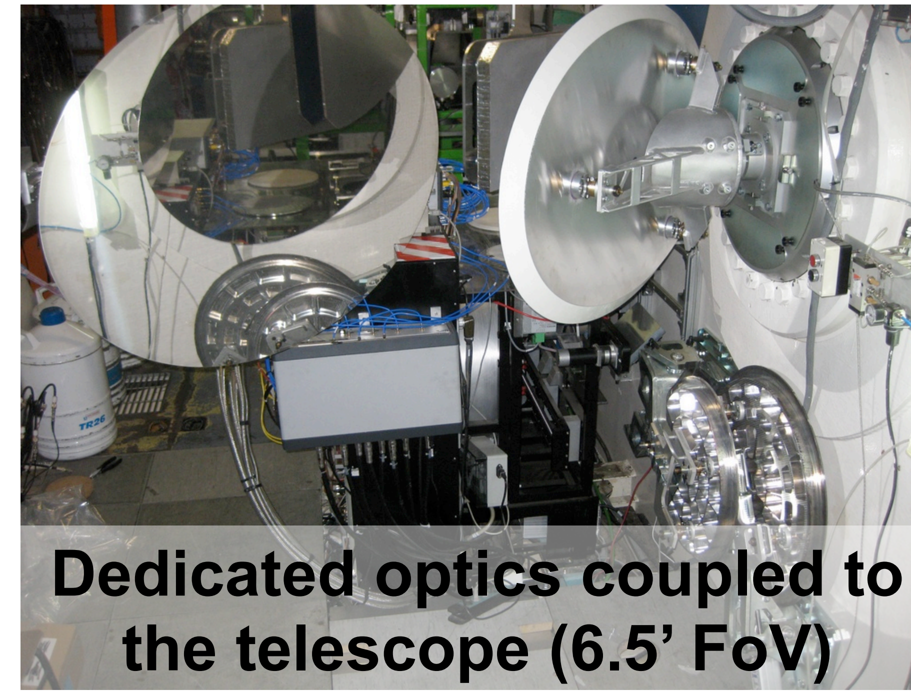
Astrophysical mismodeling?
Missing physics in simulations? In ΛCDM?
Statistical fluctuation?

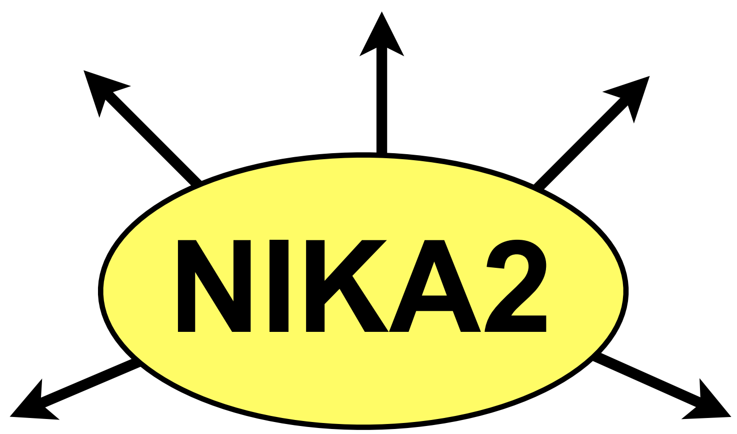


Need for resolved observations up to high redshift

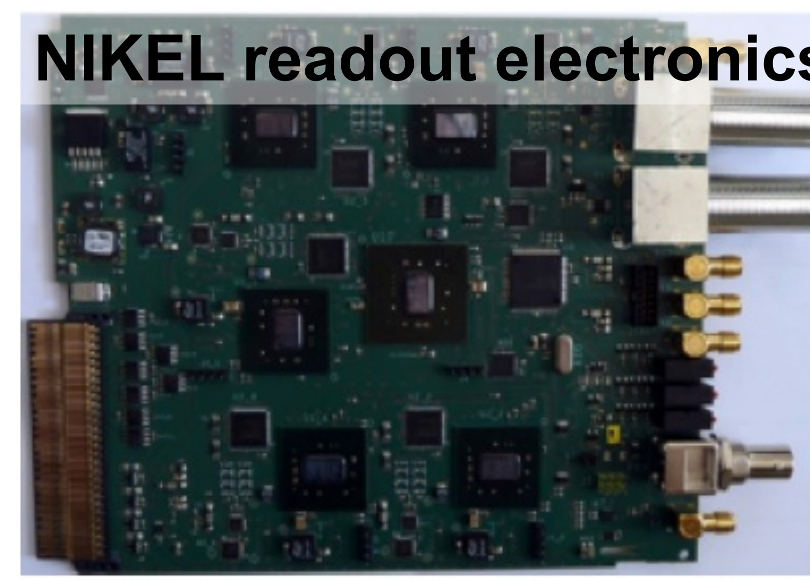
NIKA2: the New IRAM KIDs Array 2







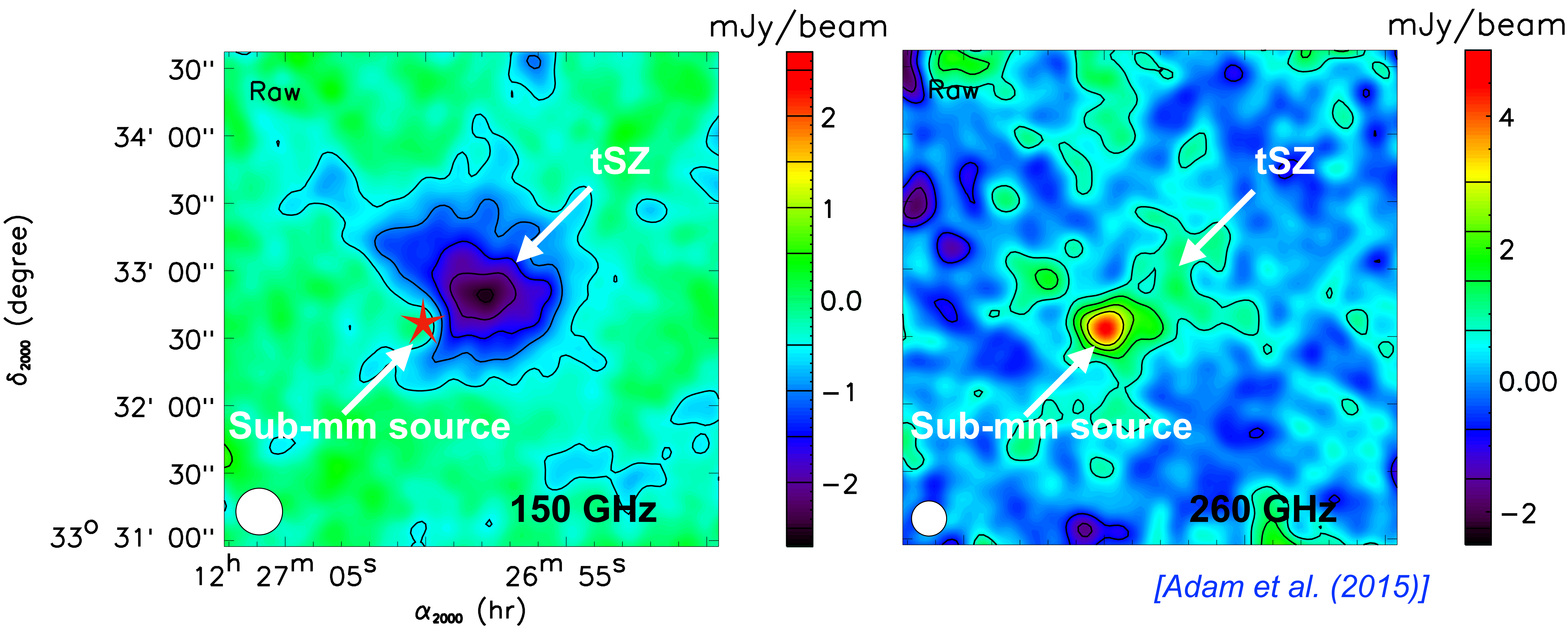
[NIKA collaboration (2018)]



Excellent for resolving distant clusters

A first look at the data

CLJ1227 at z=0.89

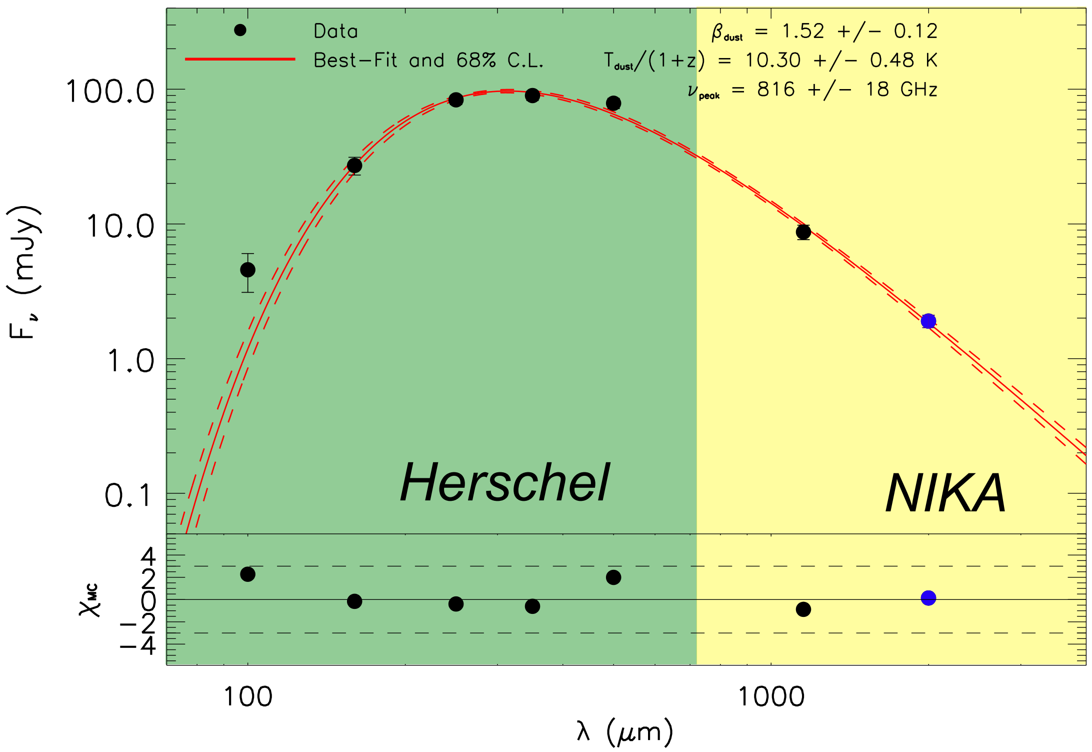


[Adam et al. (2015)]

Sub-mm and radio galaxies can bias the SZ signal

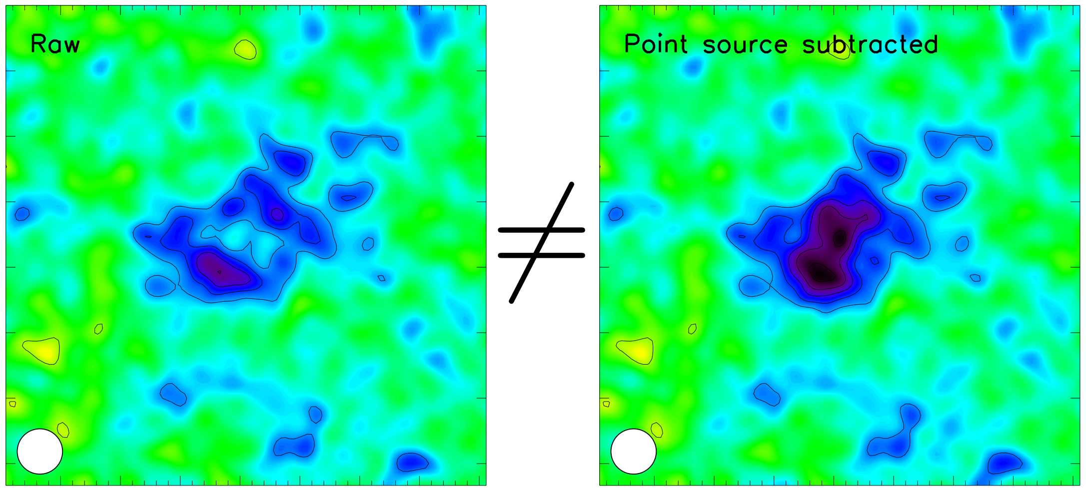
Cleaning the ‘contaminant’ galaxies

Dust + radio synchrotron fitting

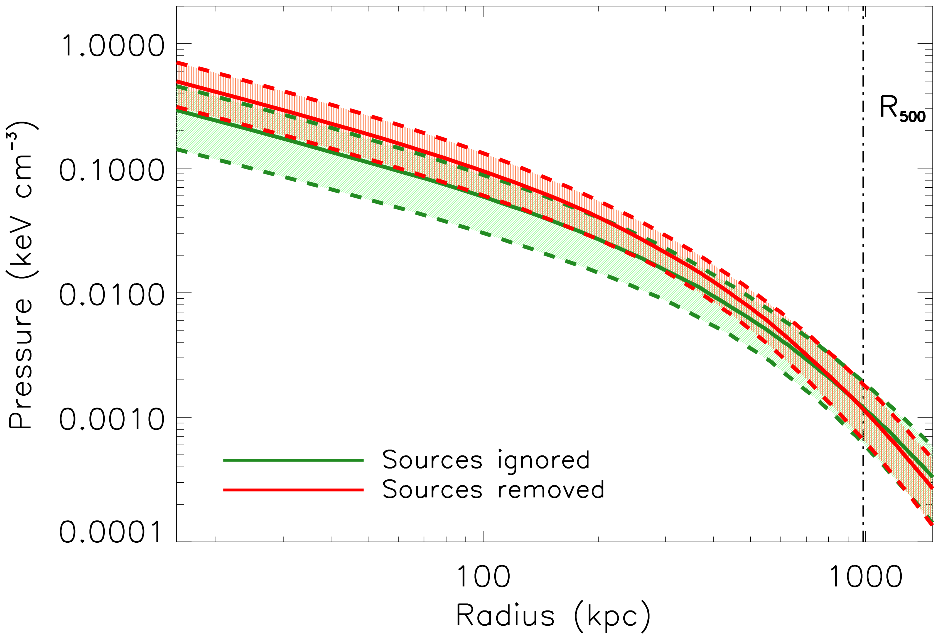


[Adam et al. (2016)]

Strong impact on the morphology…

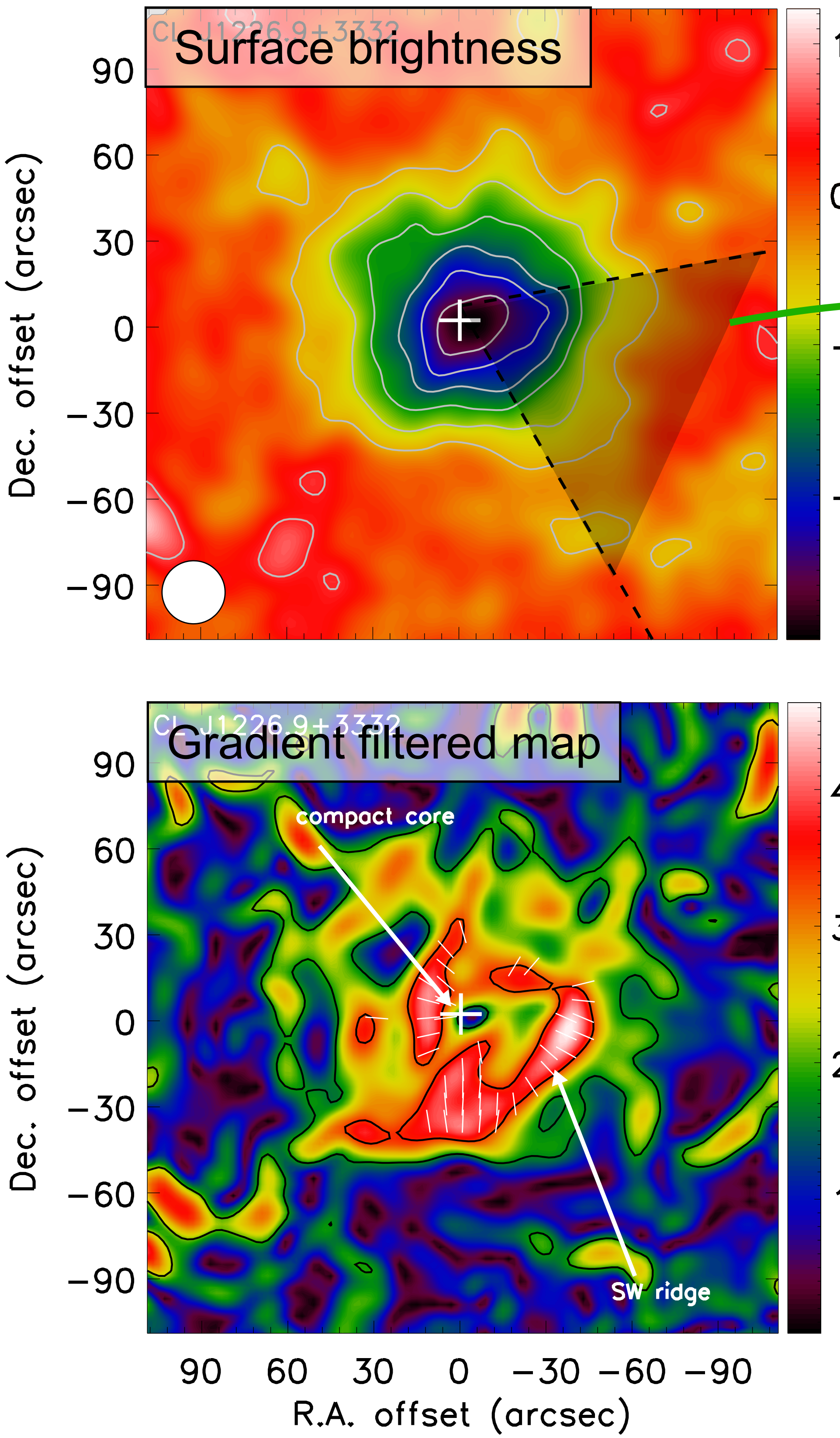


… and the pressure profile



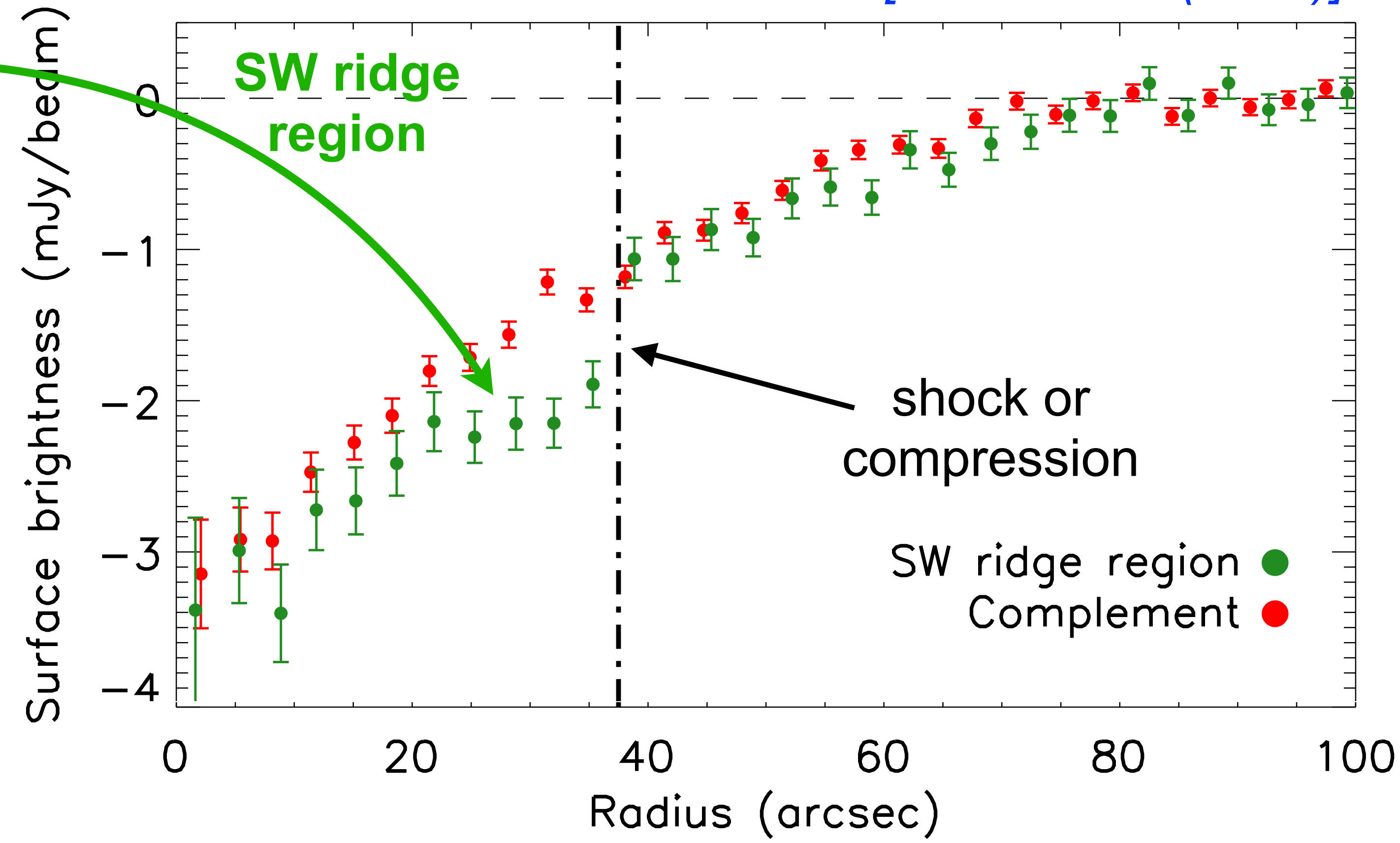
It is crucial to account for contaminant sources

Substructure and merger detection



The case of CL J1226.9+3332 at $z = 0.89$

[Adam et al. (2018)]



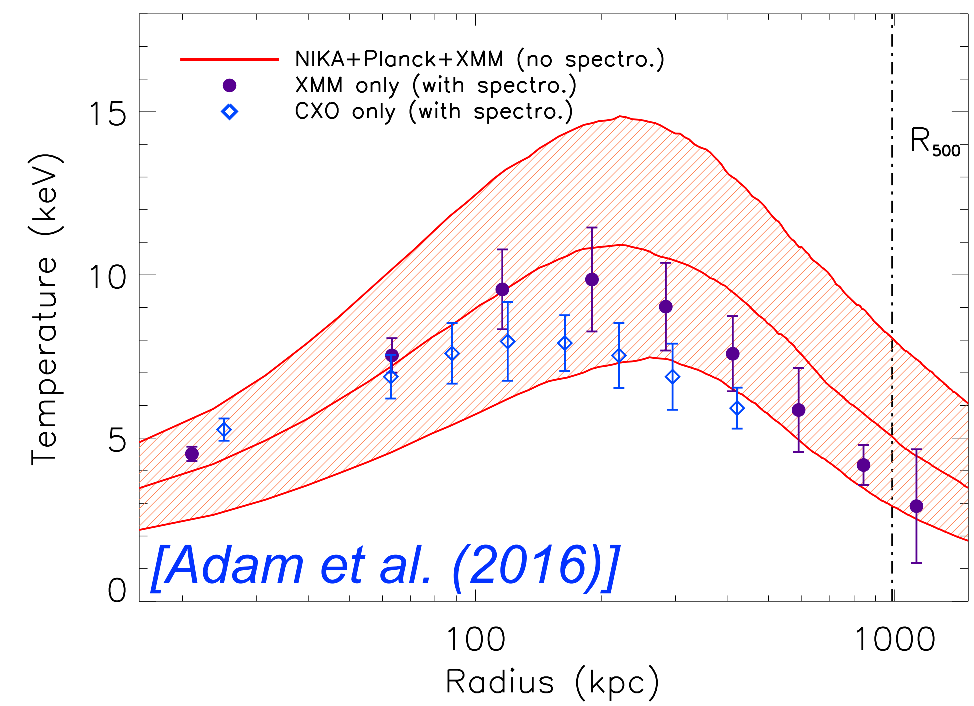
Identification of a merging event in the south-west

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

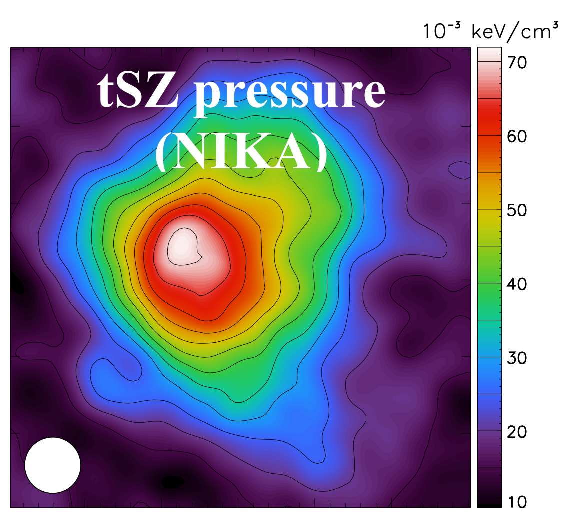
$$\Rightarrow k_{\mathrm{B}}T = P_e / n_e$$

tSZ ↗ ↖ *X-ray*



- Independent cross-check of X-ray spectro.

➡ Done in 1D and 2D



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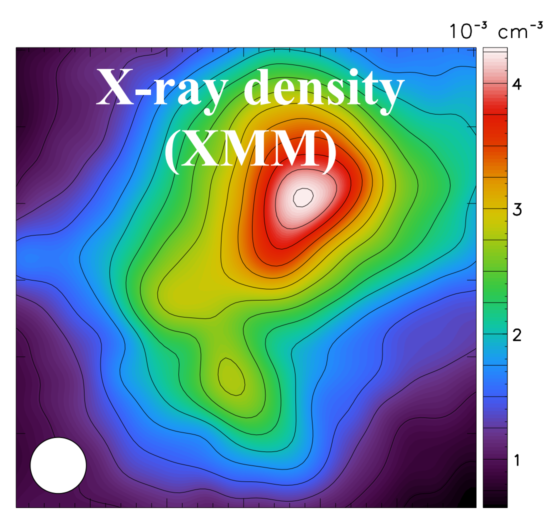

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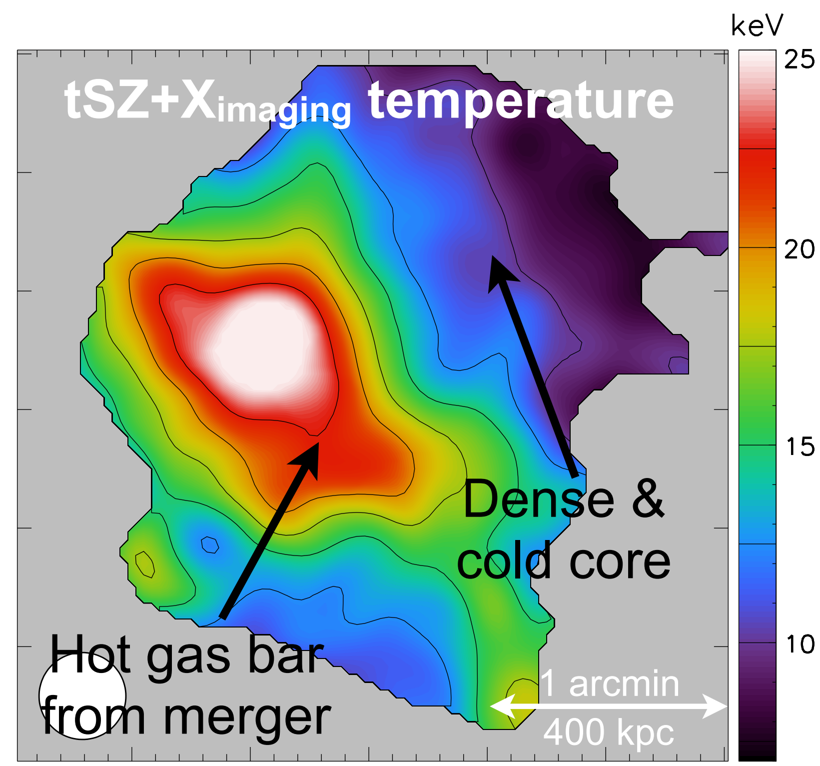


[Adam et al. (2017)]

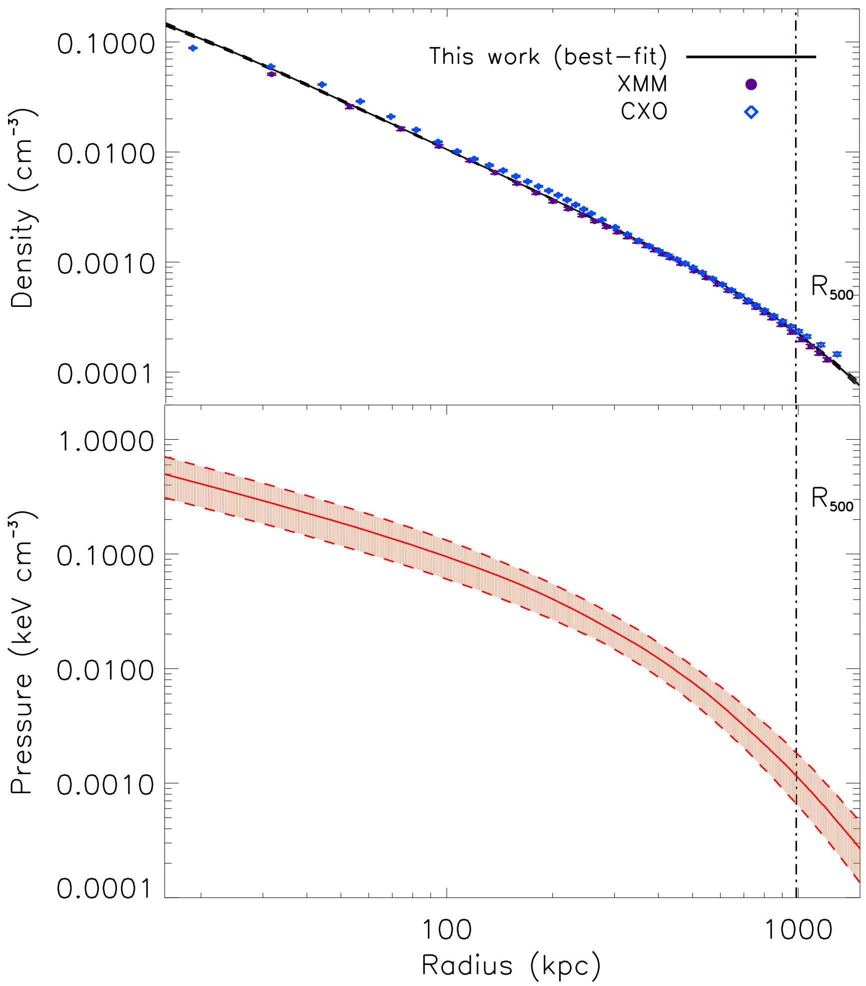
Excellent to obtain the temperature at high z

Direct mass measurement from X-ray+SZ

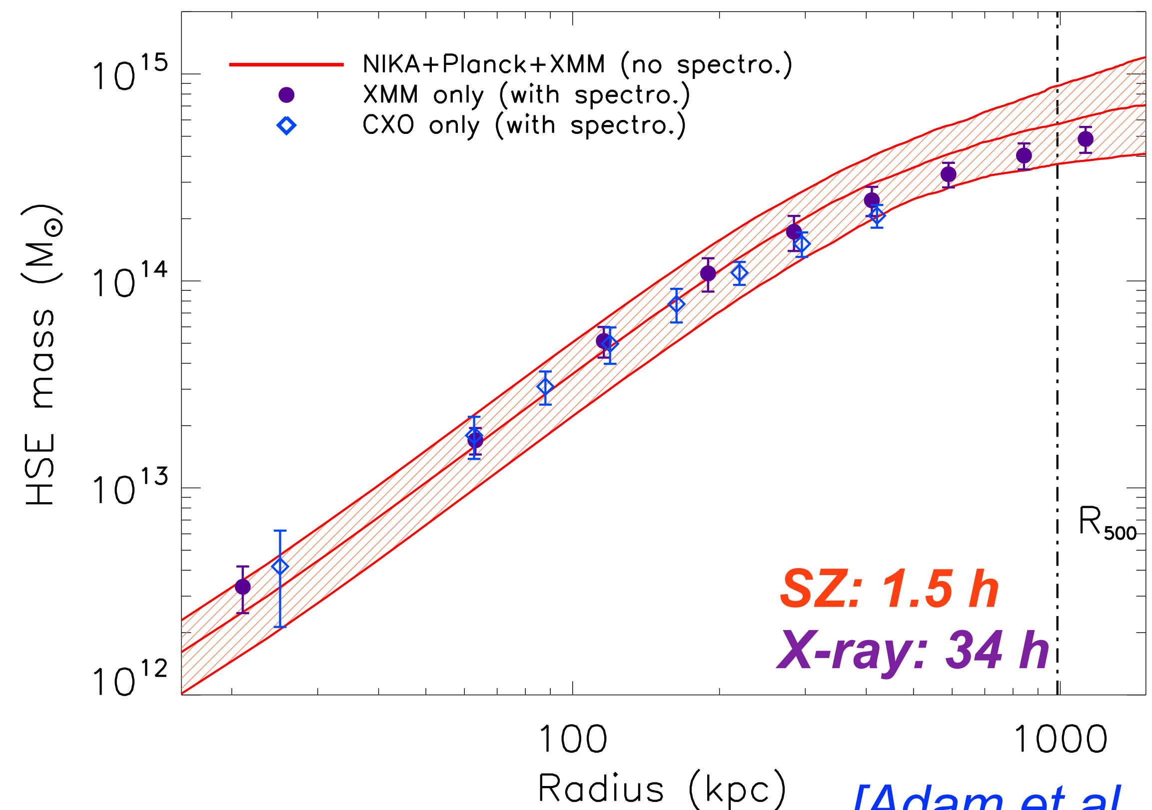
$$M_{\mathrm{HSE}}(r) = -\frac{r^2}{\mu_{\mathrm{gas}} m_{\mathrm{p}} n_{\mathrm{e}}(r) G} \frac{\mathrm{d}P_{\mathrm{e}}(r)}{\mathrm{d}r}$$

SZ measurement

Easy from X-ray



X-ray + SZ

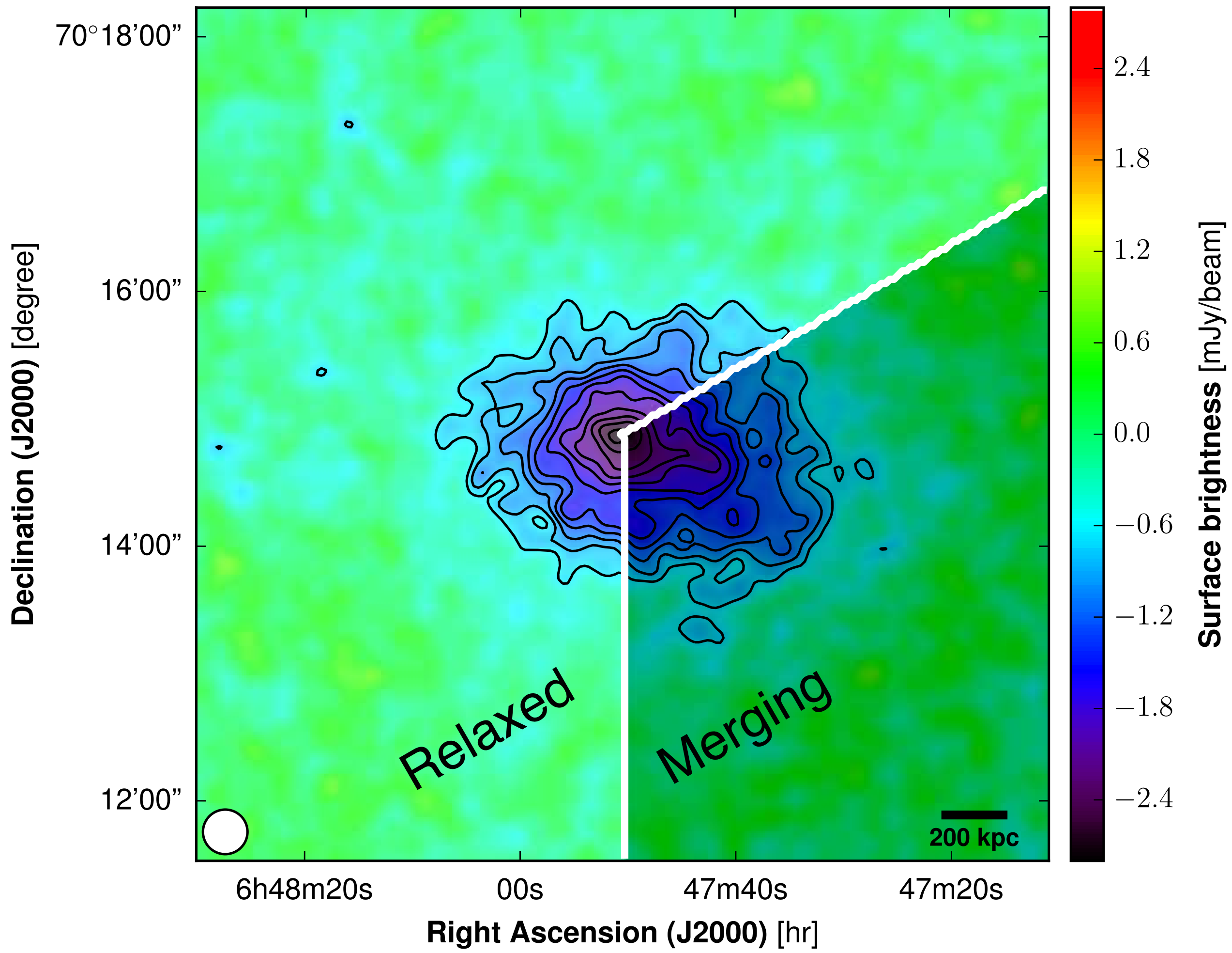


[Adam et al. (2016)]

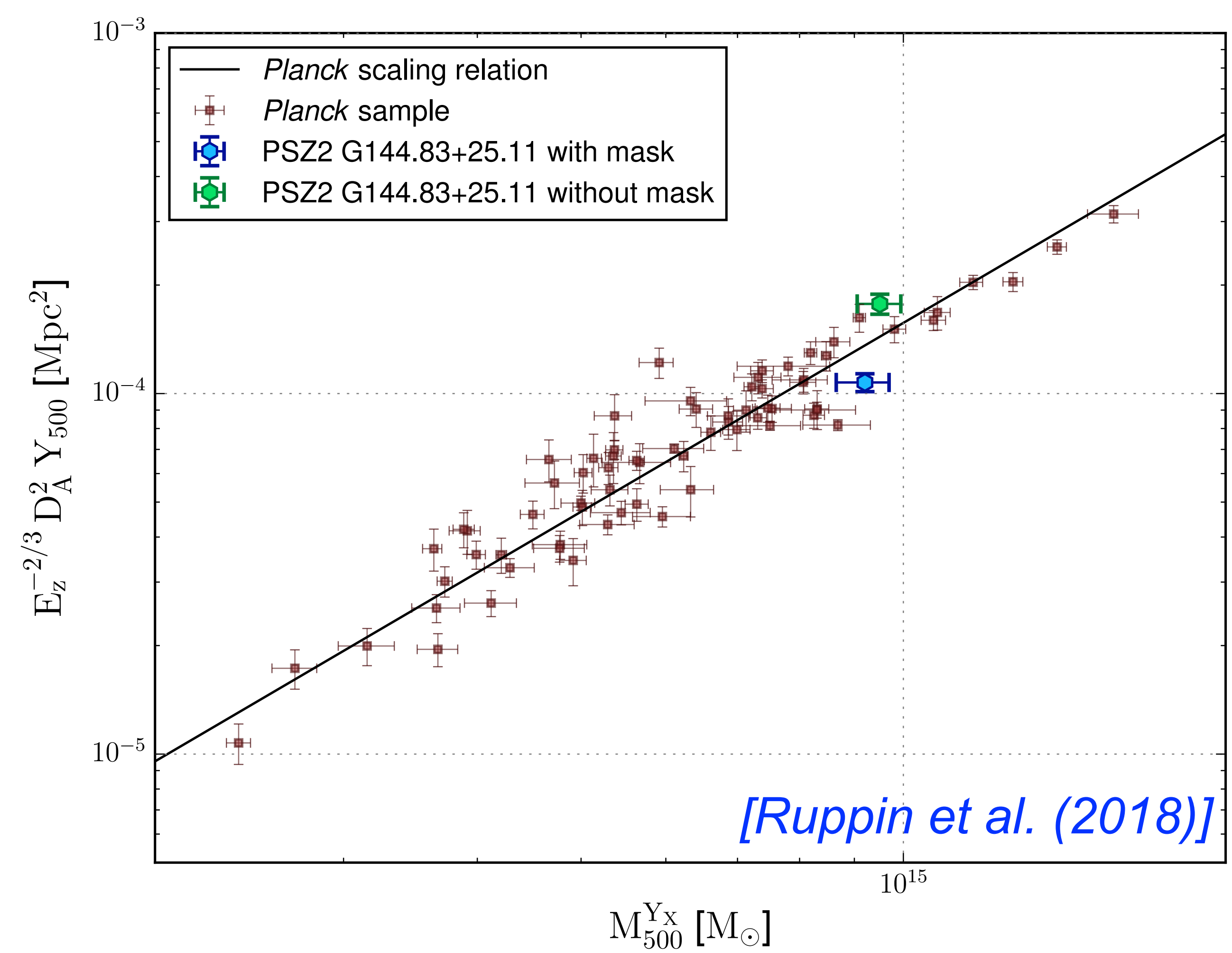
➡ Access to the mass, the SZ flux, and the cluster dynamics (morphology)

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%



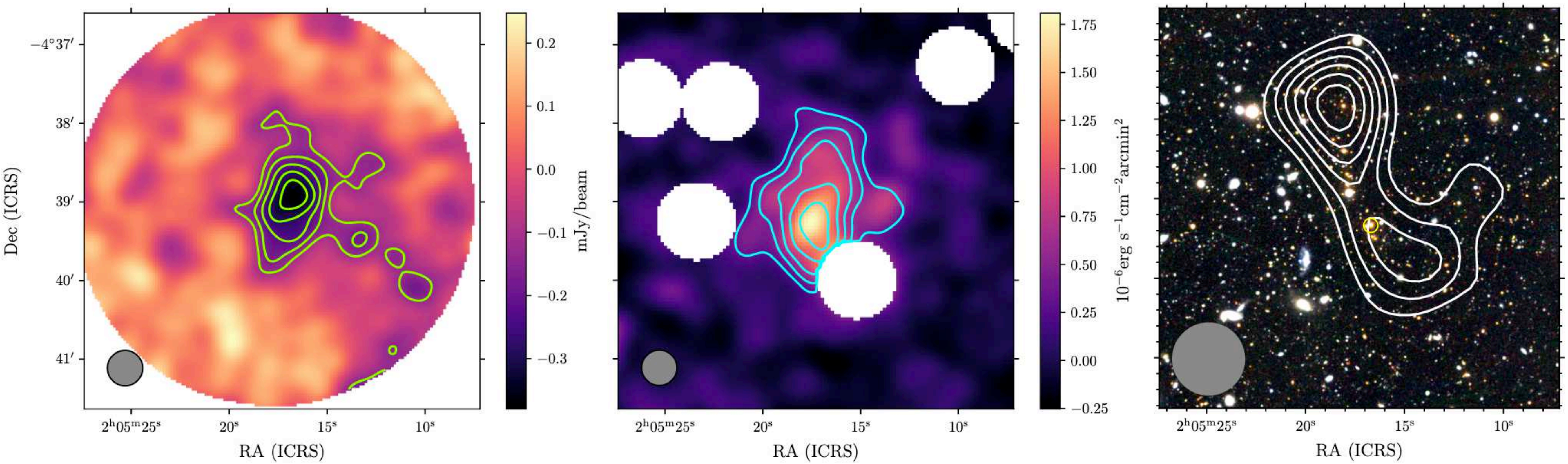
Strong impact of inner structure on SZ-M relation

SZ imaging at low mass and high redshift

Follow-up of XXL-survey clusters in unexplored regime from resolved SZ data

(*$z=1$, $M_{500}<3\times10^{14}$* M_{sun}, *[Ricci et al. (2020)]*)

Preliminary results on the first target:



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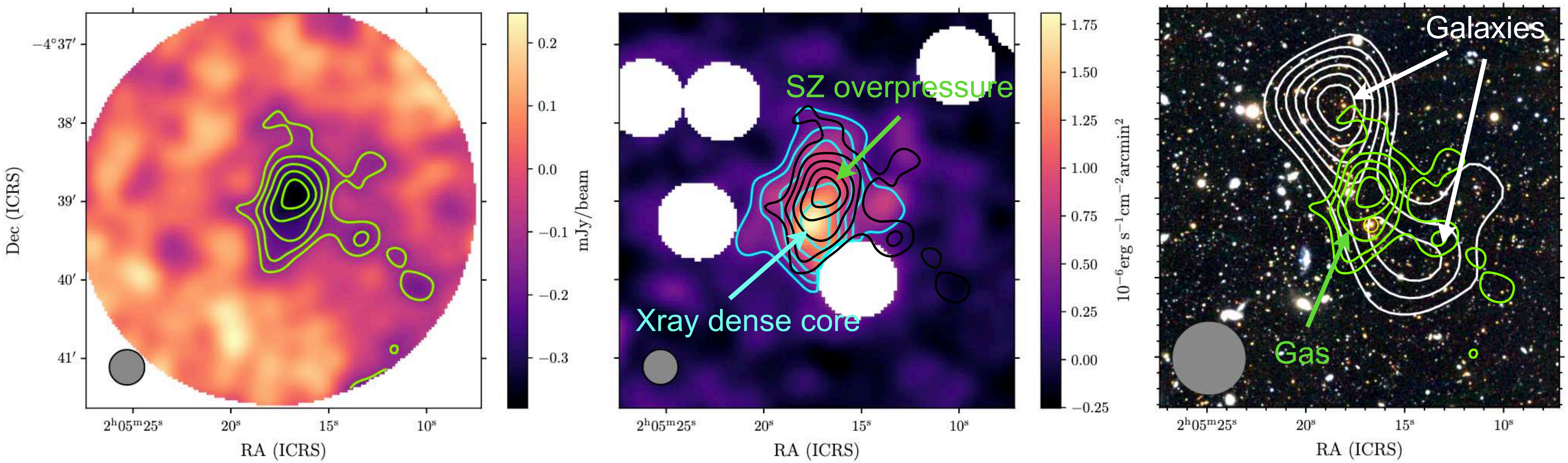

- Large scale X/SZ agreement, but local deviations due to substructures
- Huge ICM/galaxies offset

A new low mass bullet cluster at z~1

SZ imaging at low mass and high redshift

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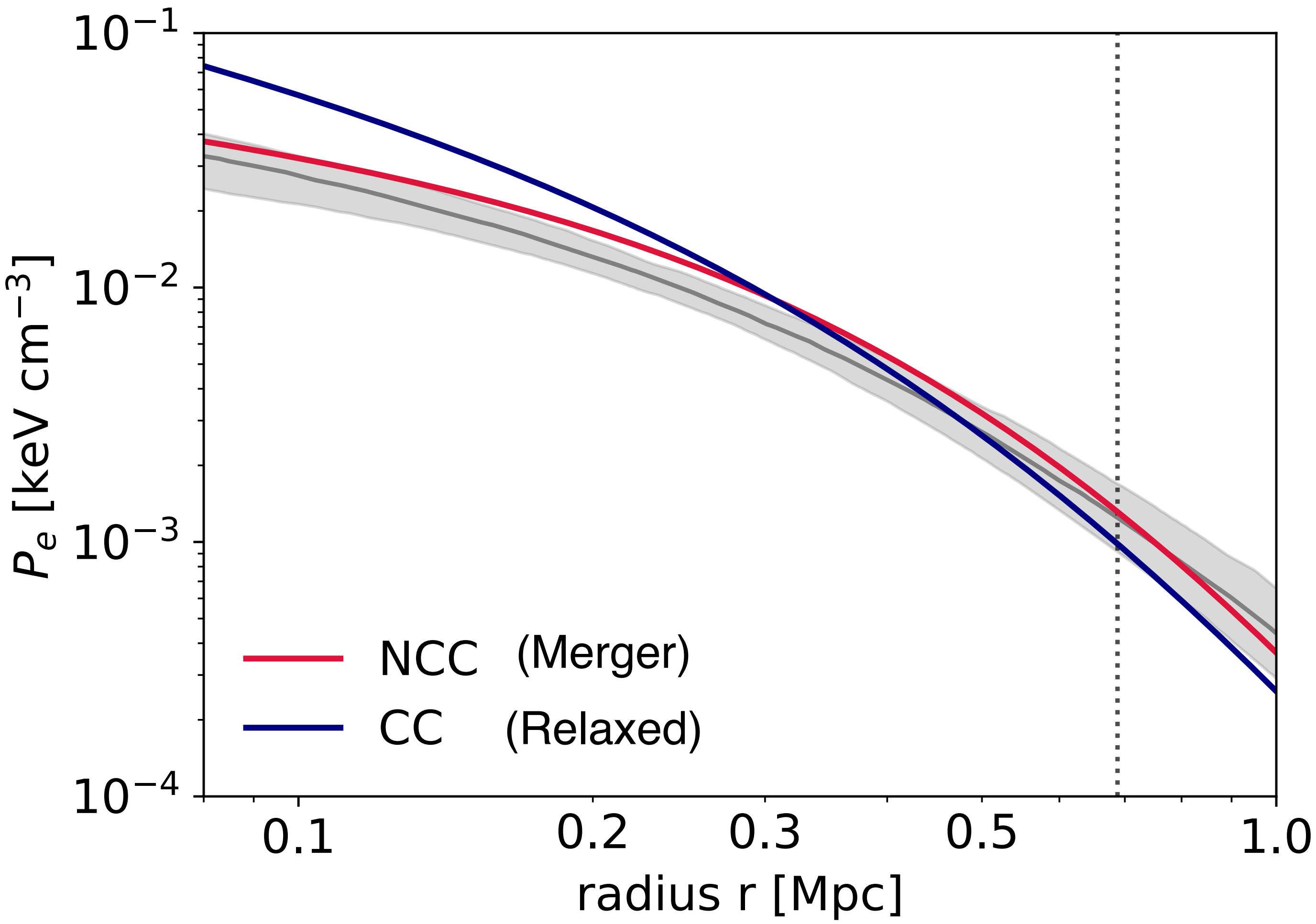
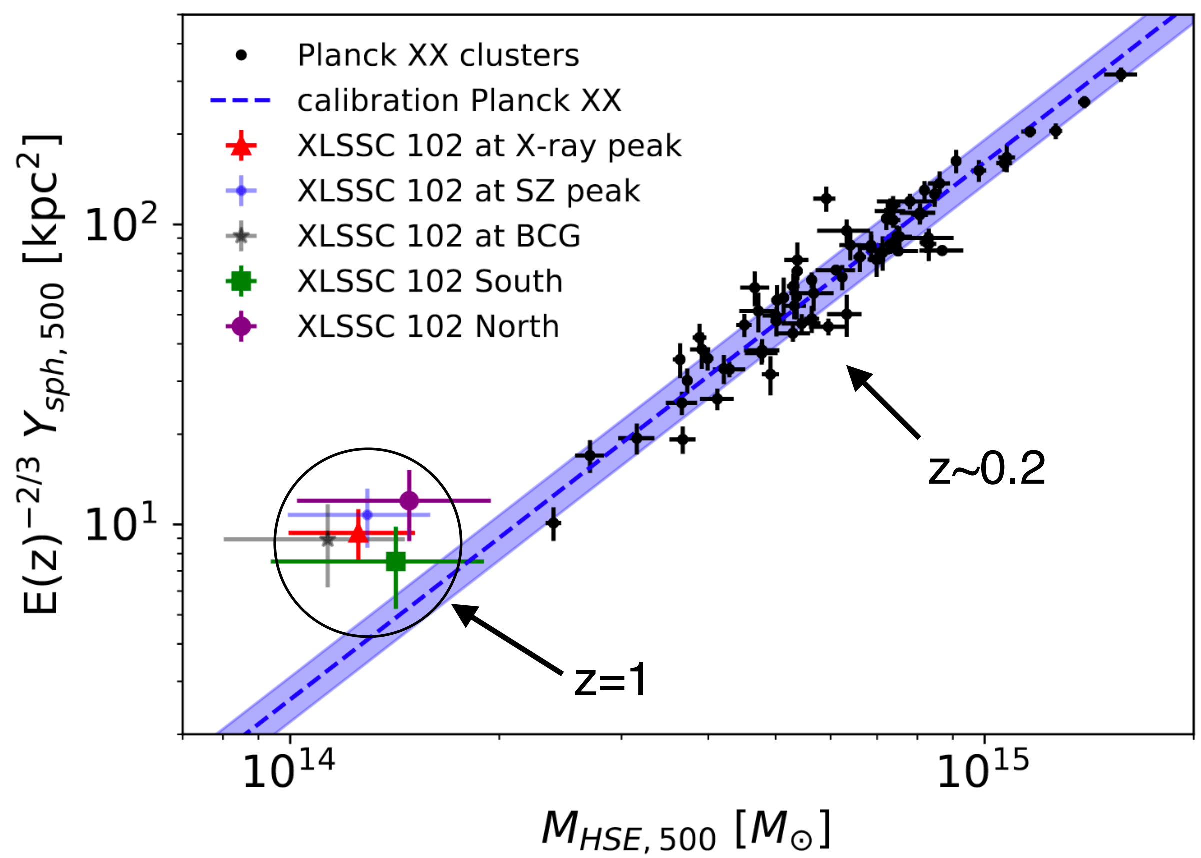
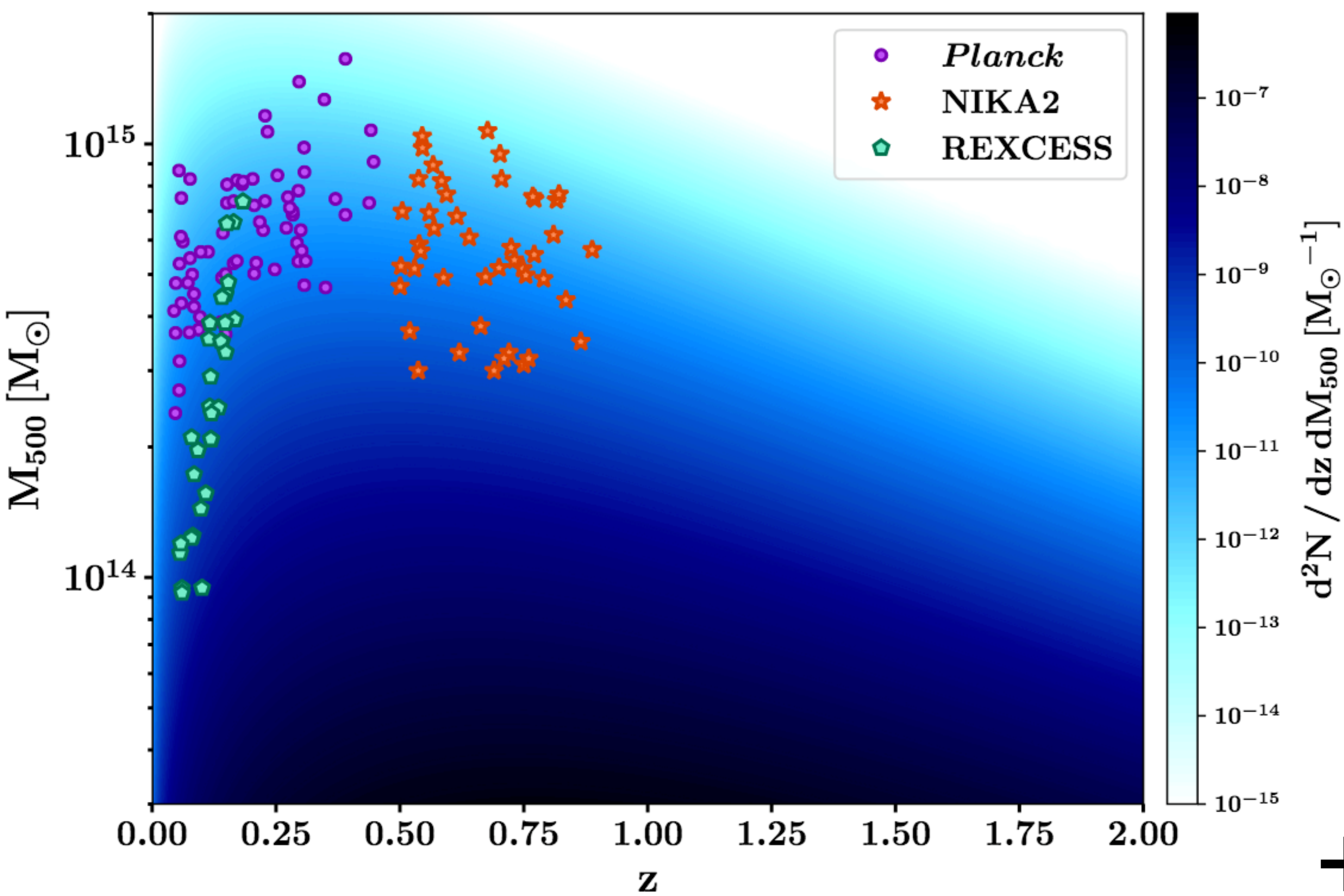




Pressure profile and scaling consistent with expectations from local sample

The NIKA2 guaranteed time SZ large program



[Ruppin et al. (2019)]

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

\+

- NIKA pathfinder validation program
  - 6 clusters in various configurations

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

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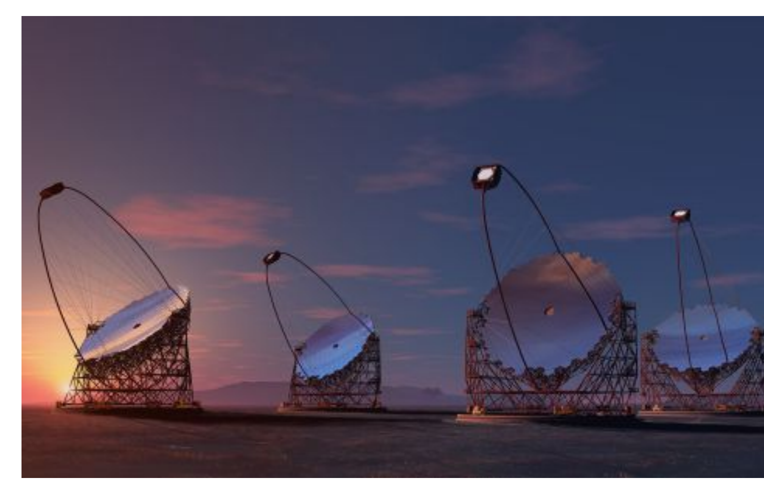
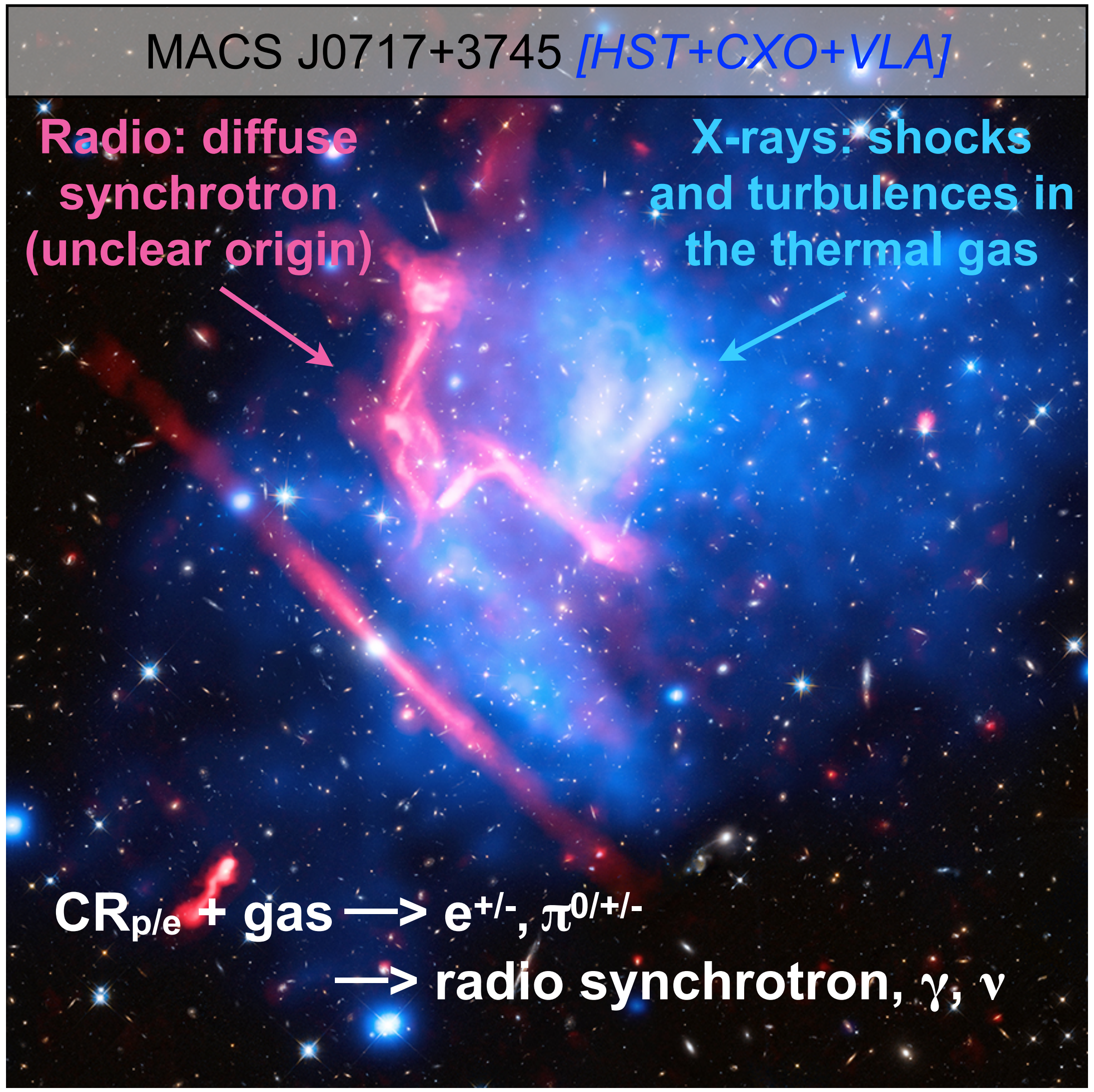


Cosmic ray and dark matter in galaxy clusters



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

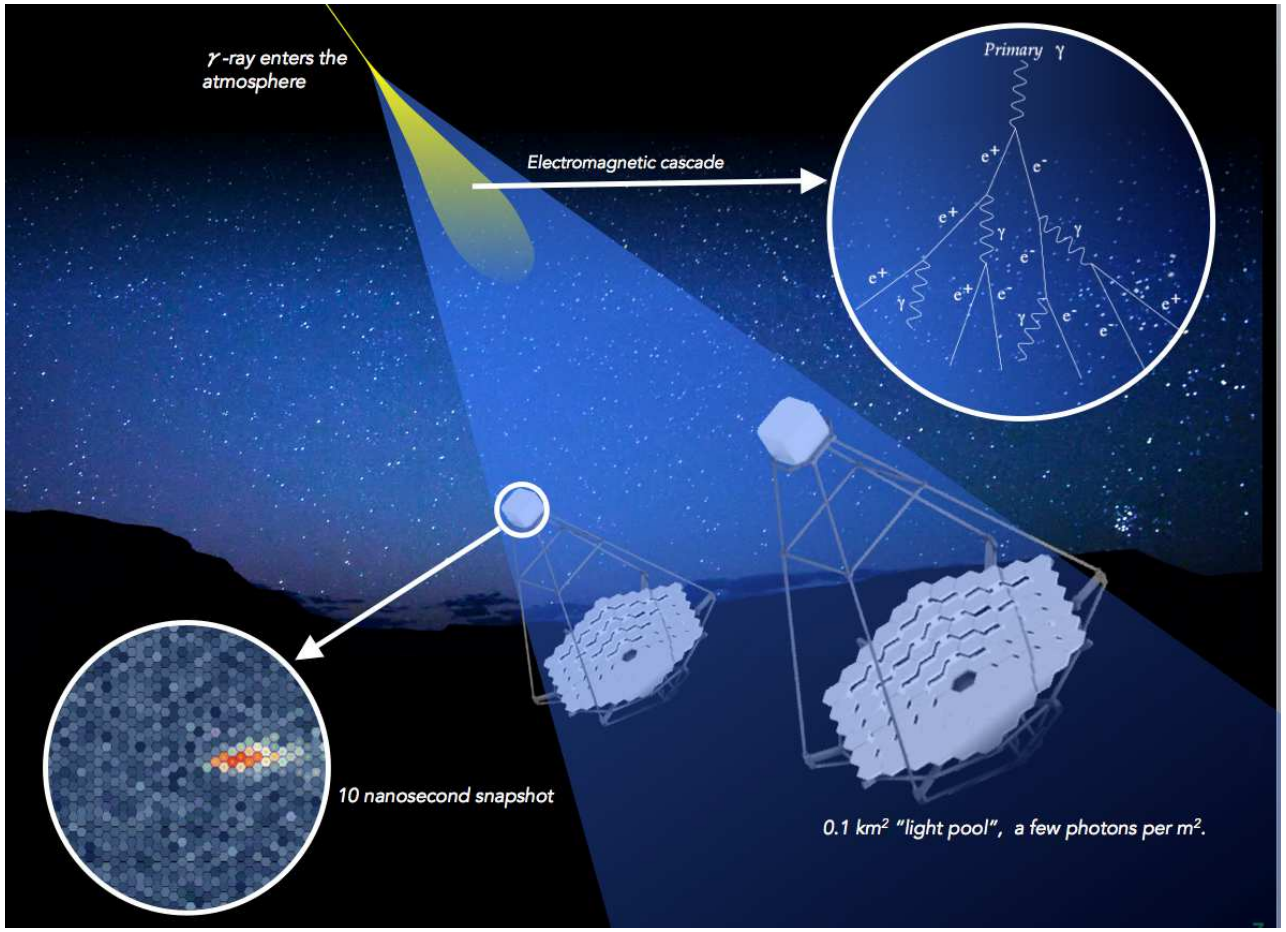
➡ **Test the nature of dark matter**

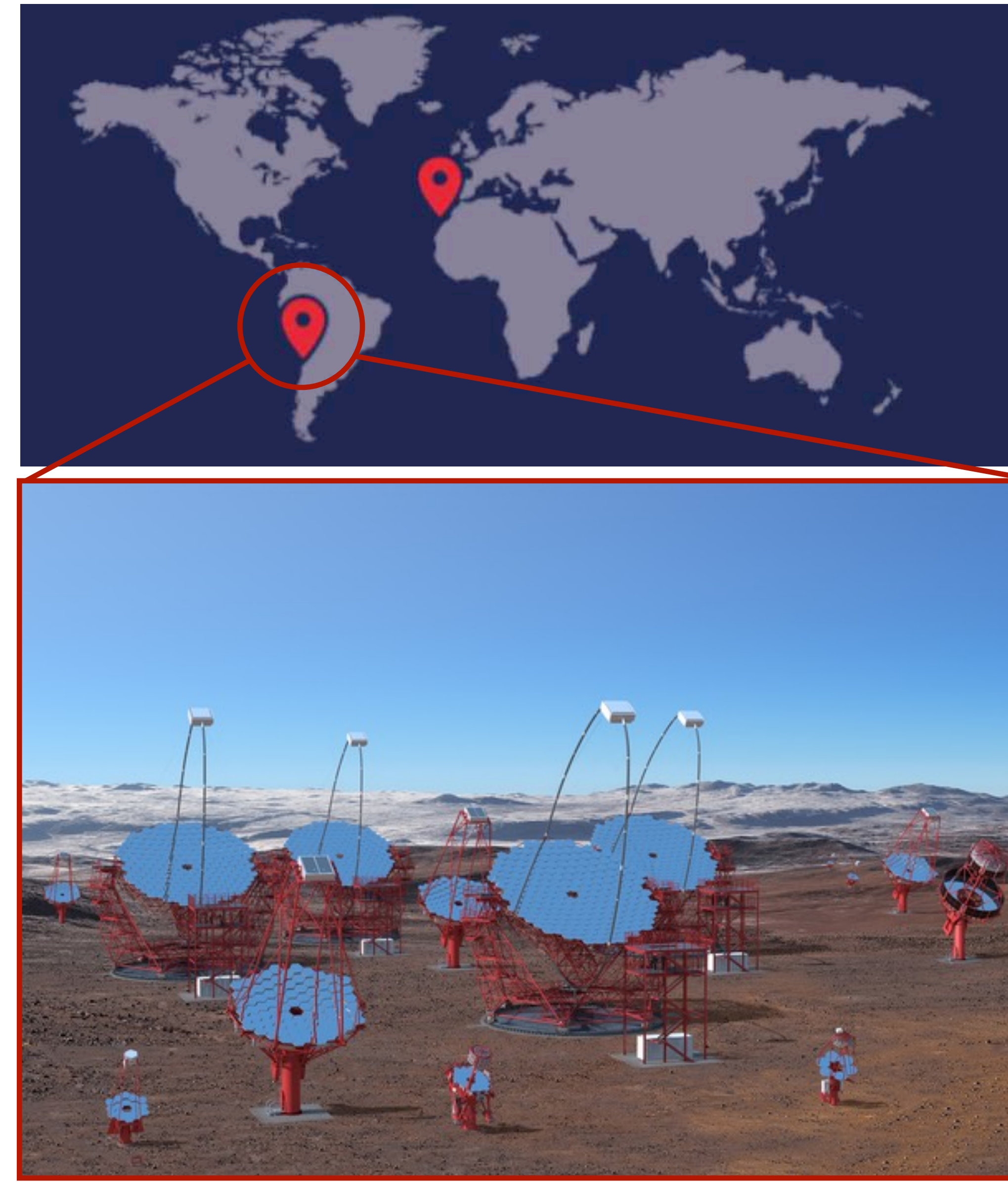
- Galaxies (~few %) + thermal ionized gas (~15%)
  - γ-ray from particle acceleration

➡ **Understand CR physics at the clusters scale**

Cosmic ray physics can be constrained from γ-rays

The Cherenkov Telescope Array

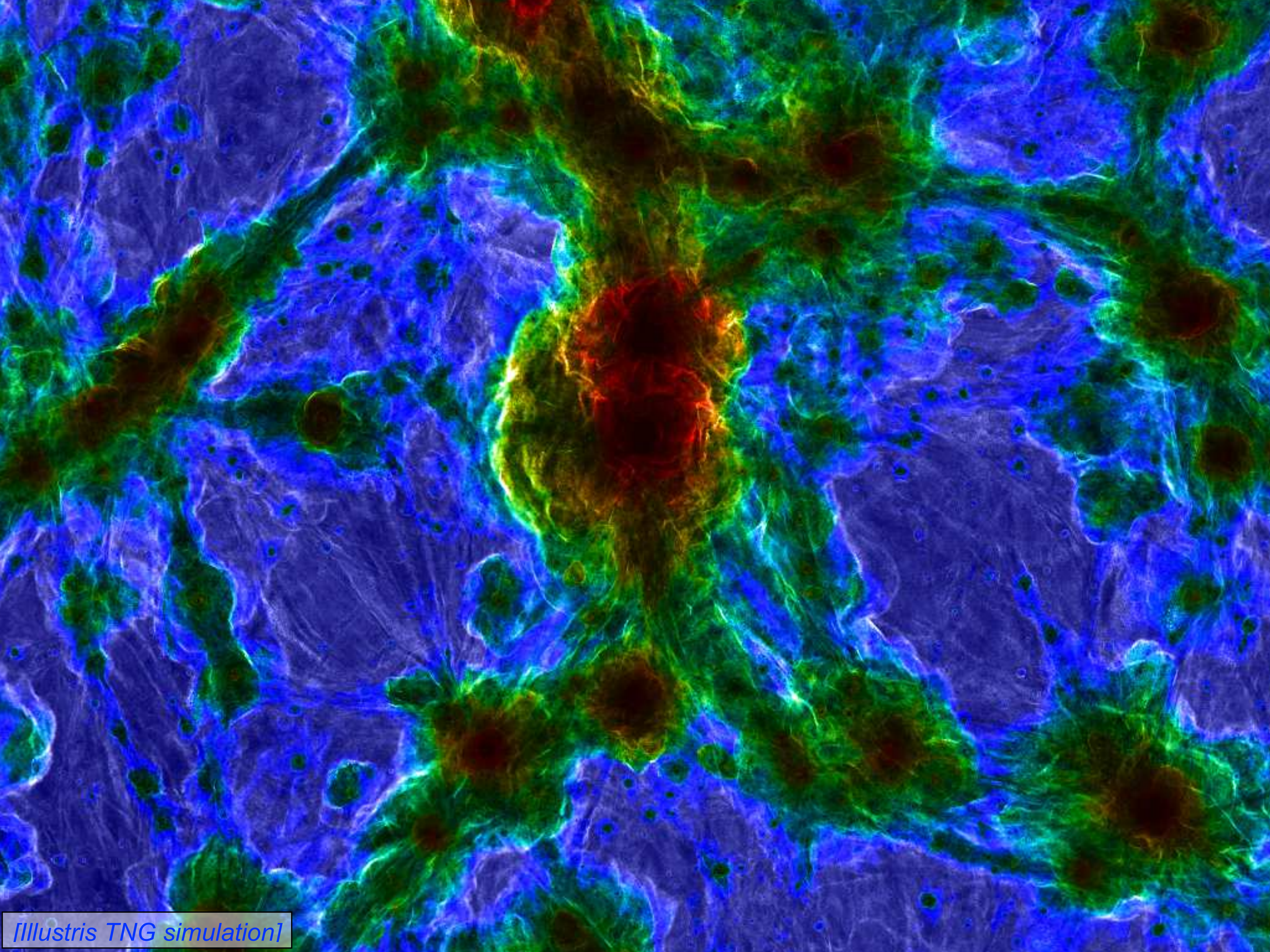


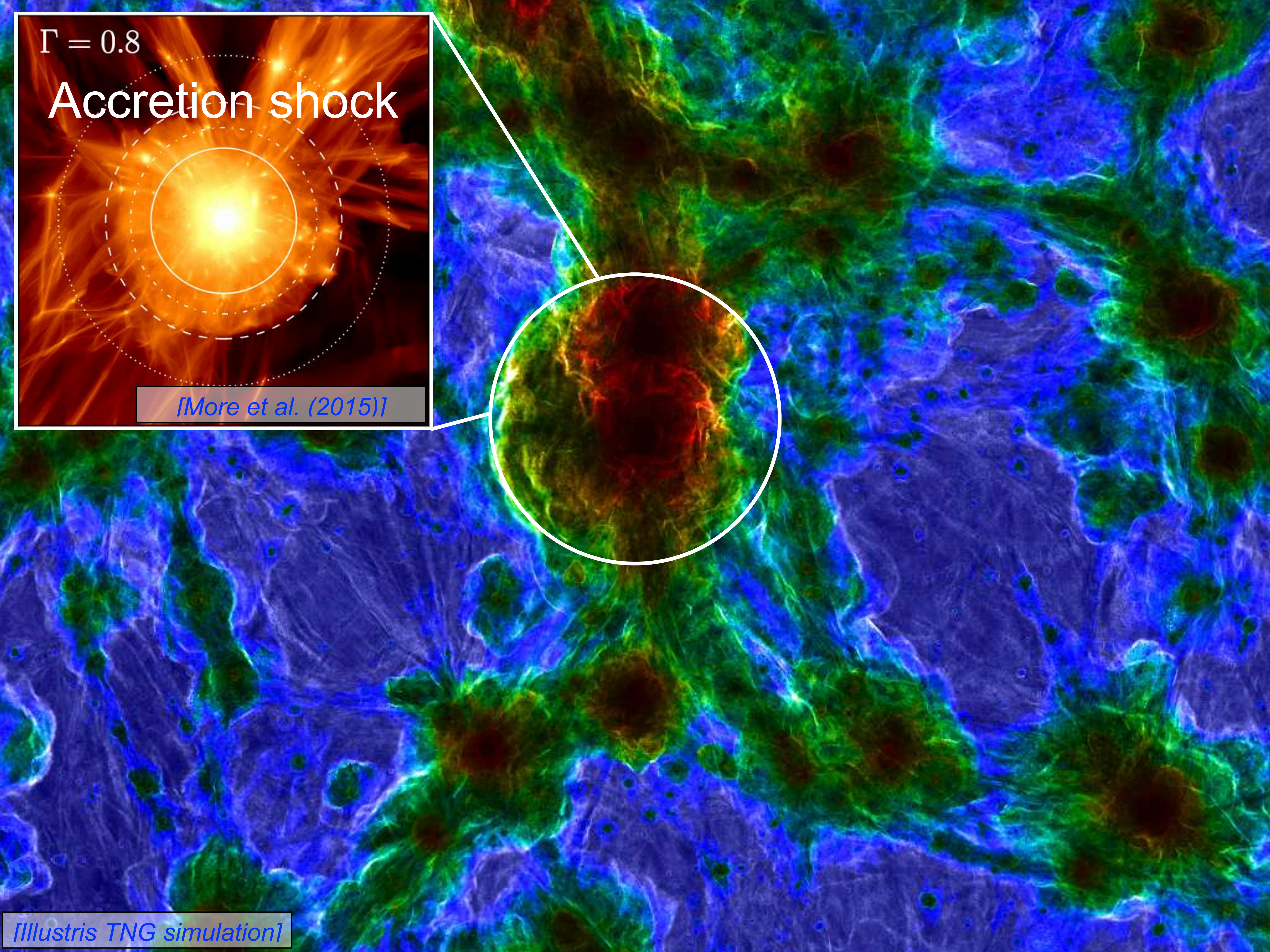


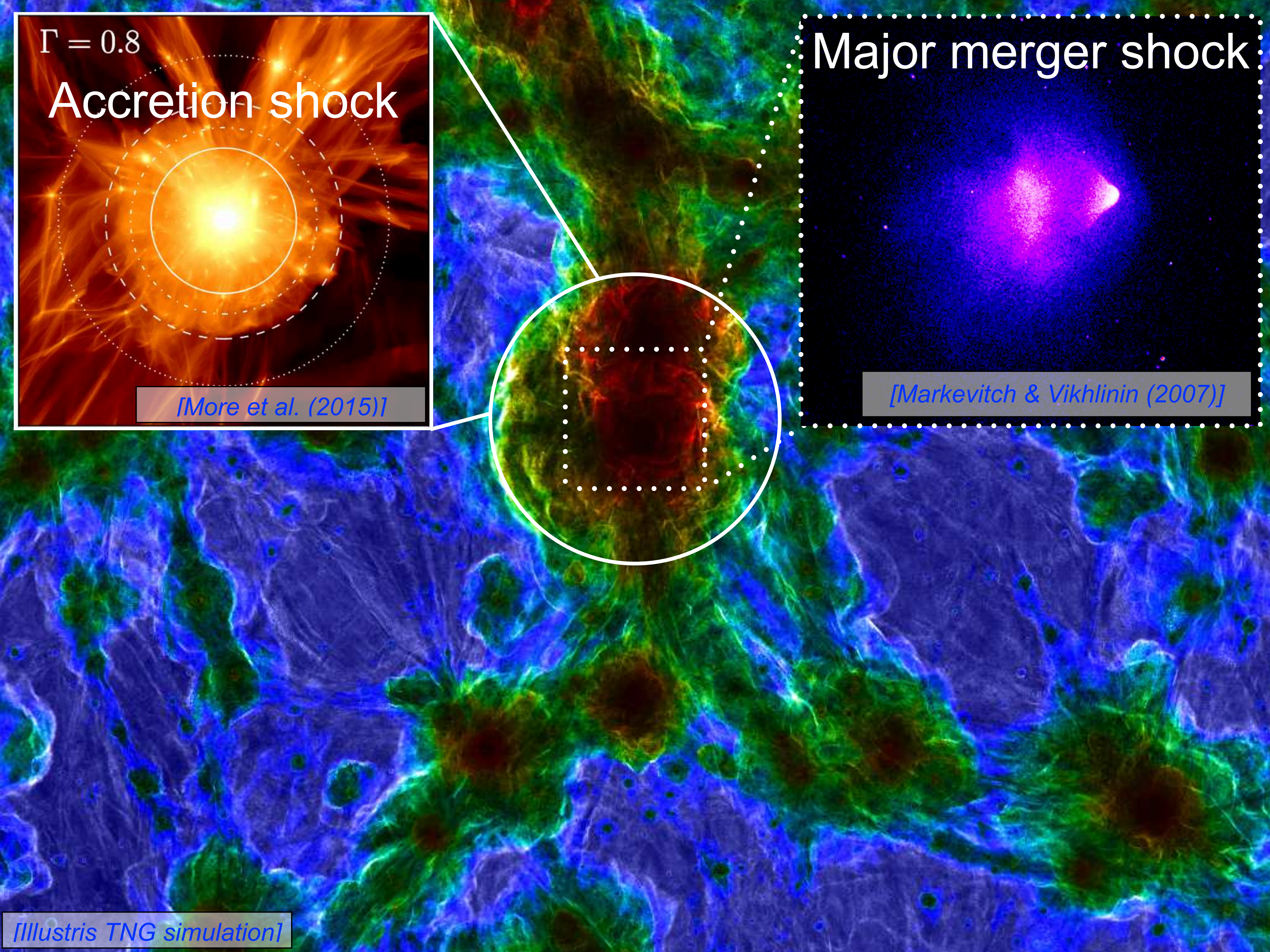
From ~20 GeV to 200 TeV γ rays
Sensitivity down to ~10^{-12} erg/cm^2/s in few hours
~3 arcmin angular resolution above 1 TeV
Expected to start observations in ~2022

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

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


[Illustris TNG simulation]


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



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[More et al. (2015)]
Major merger shock
[Markevitch & Vikhlinin (2007)]
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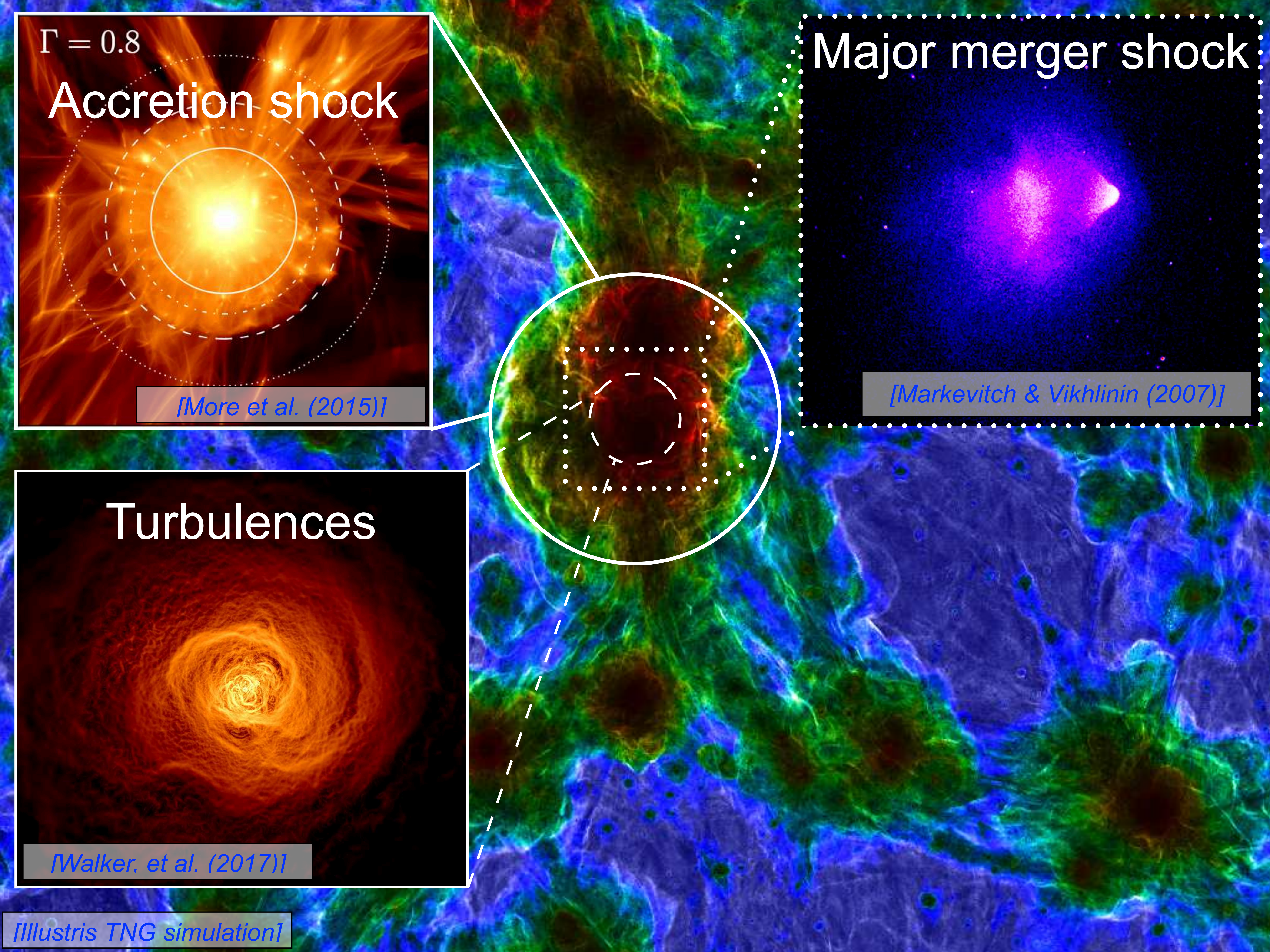

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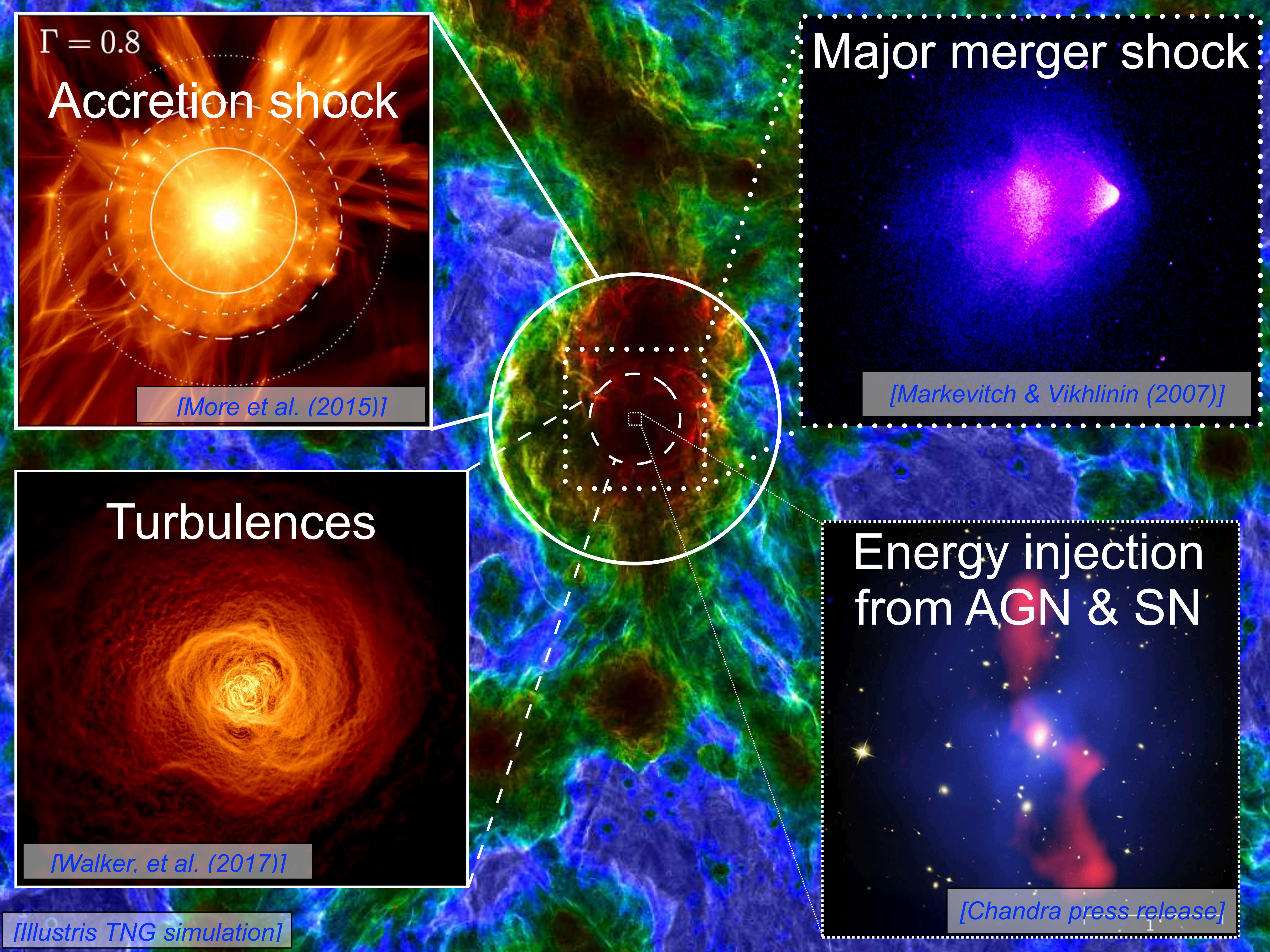
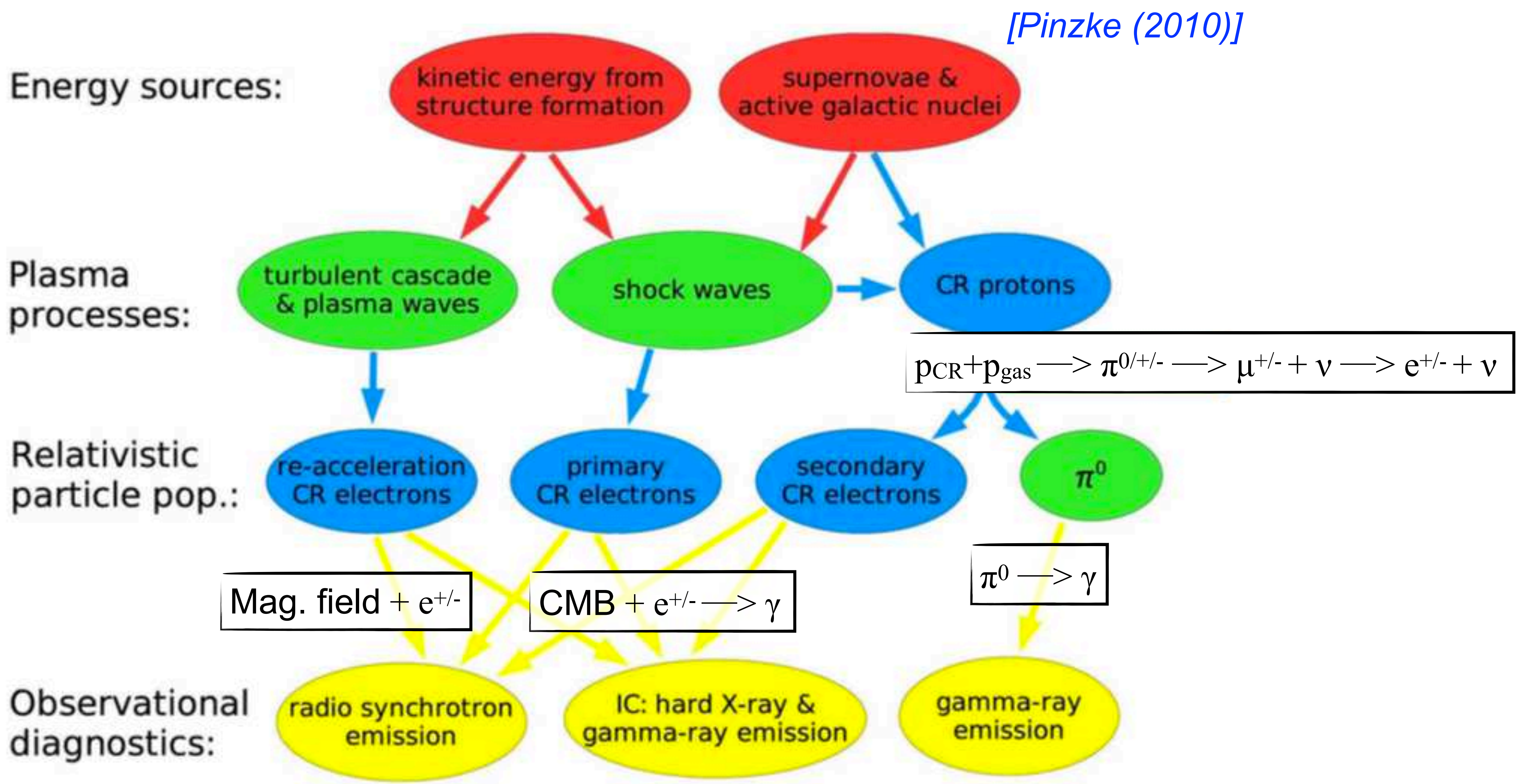

$\Gamma = 0.8$
Accretion shock
[More et al. (2015)]
Major merger shock
[Markevitch & Vikhlinin (2007)]
Turbulences
[Walker, et al. (2017)]
Energy injection
from AGN & SN
[Chandra press release]
[Illustris TNG simulation]

From energy injection to γ-ray emission



Particle acceleration, and γ-ray signal, is expected

Modeling the gamma ray signal

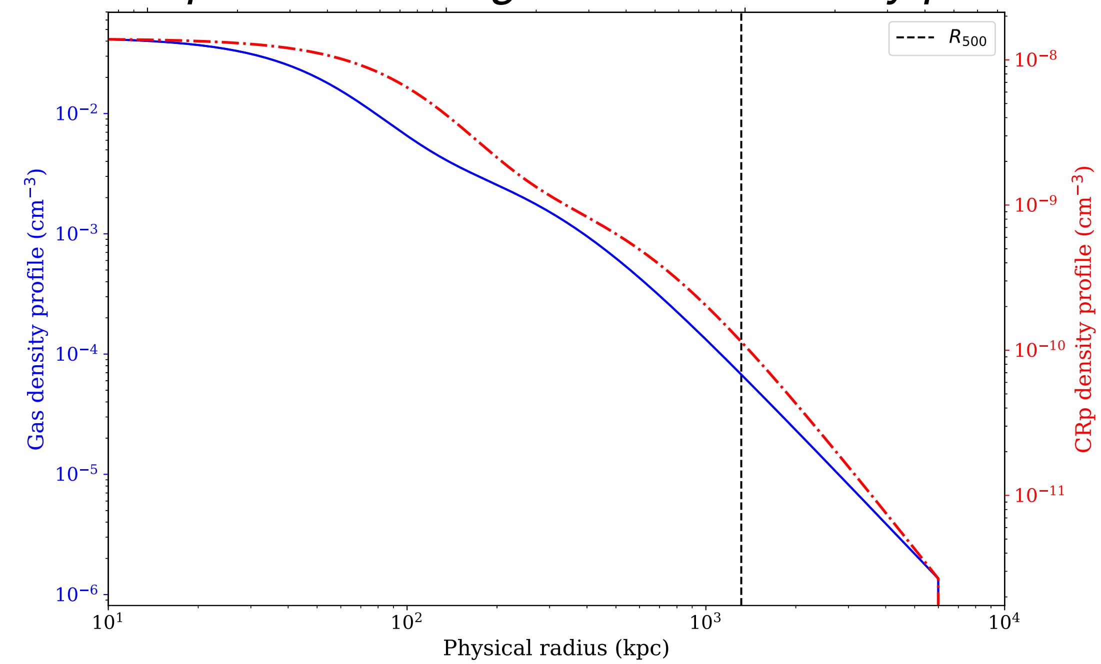
Target thermal gas
- Gas density and pressure profile from external data

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

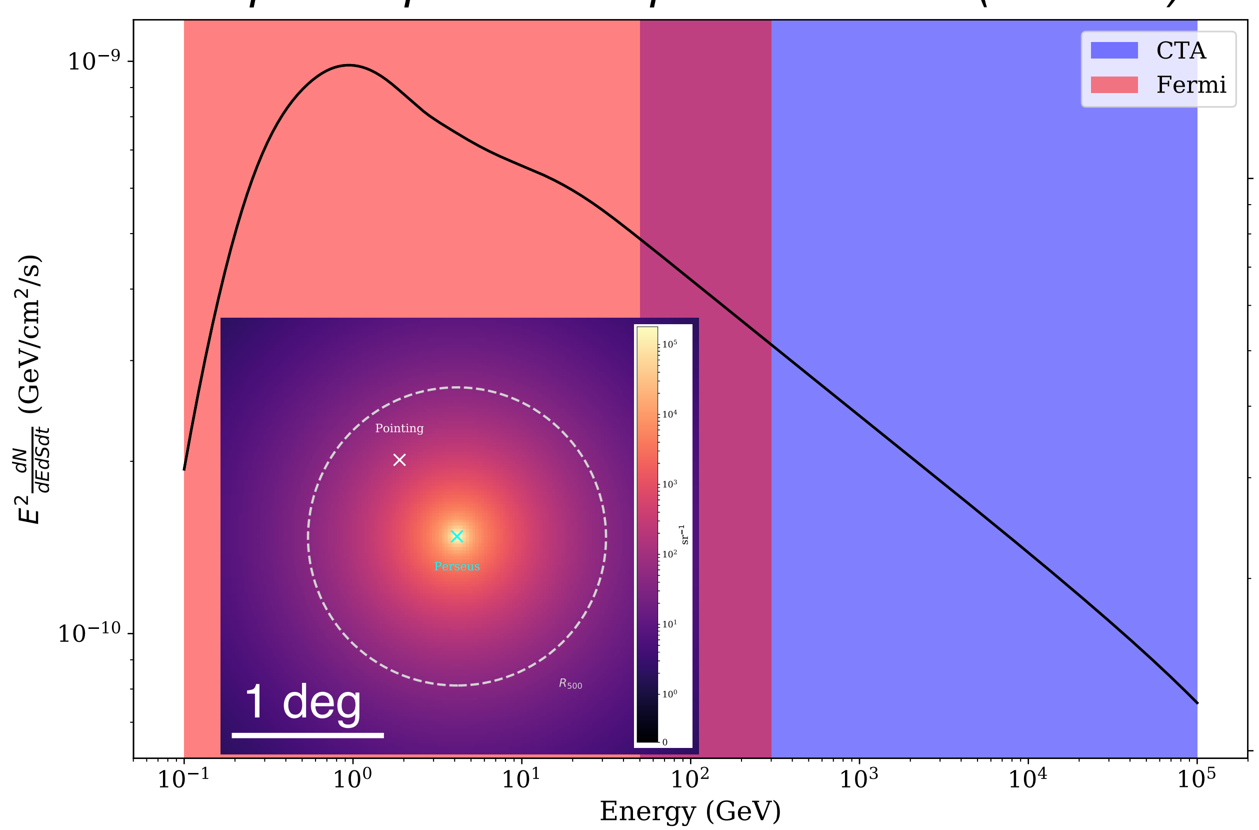
\+ **CR/gas interactions**
- π^0, $e^{+/-}$, and γ production rate (pp interaction)
- Volume integration and normalization

Computing gamma ray observable
- Spatial model
- Spectral model

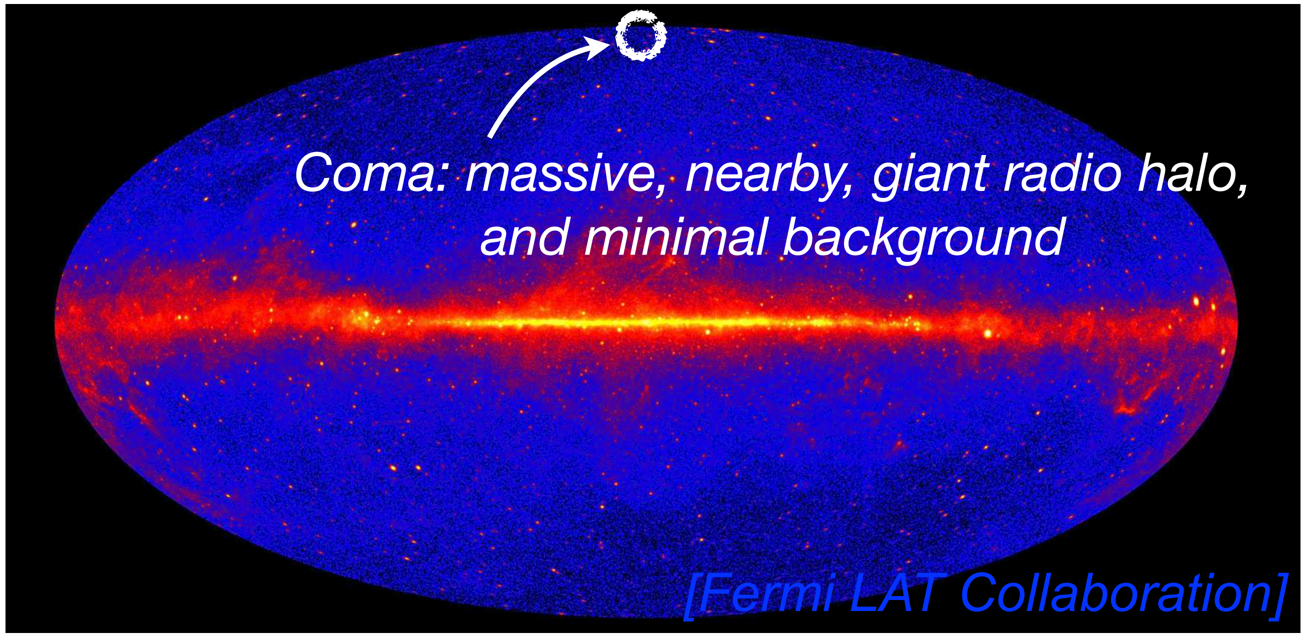
Example of thermal gas and CR density profile

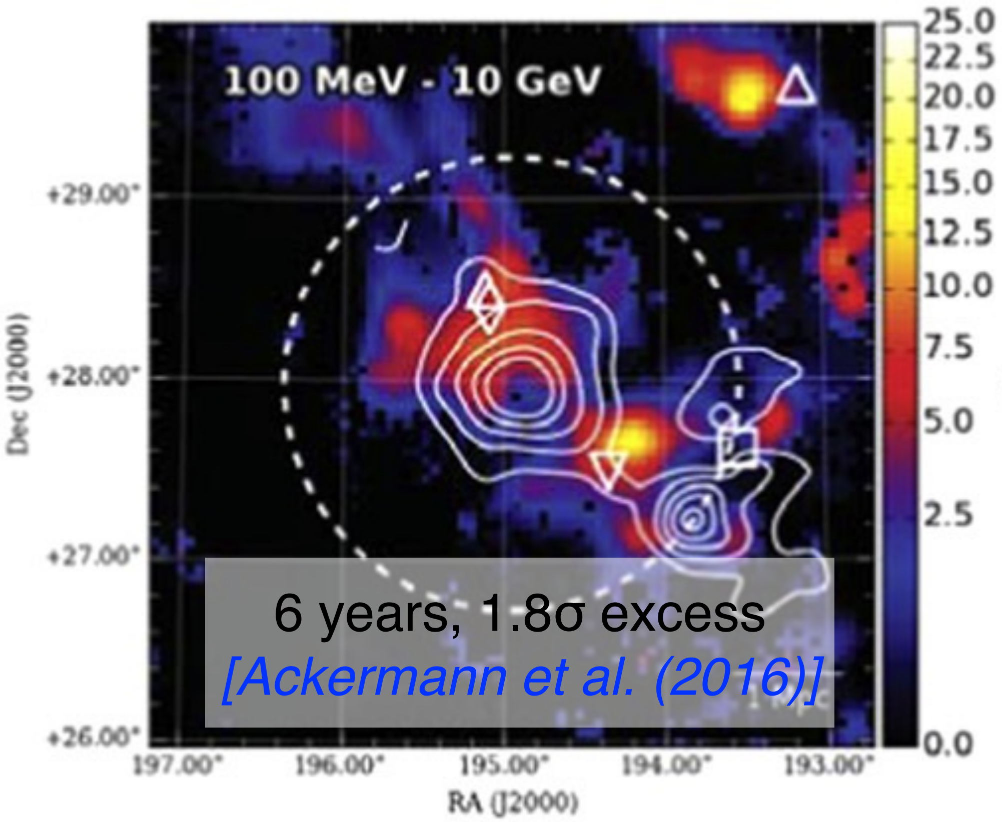


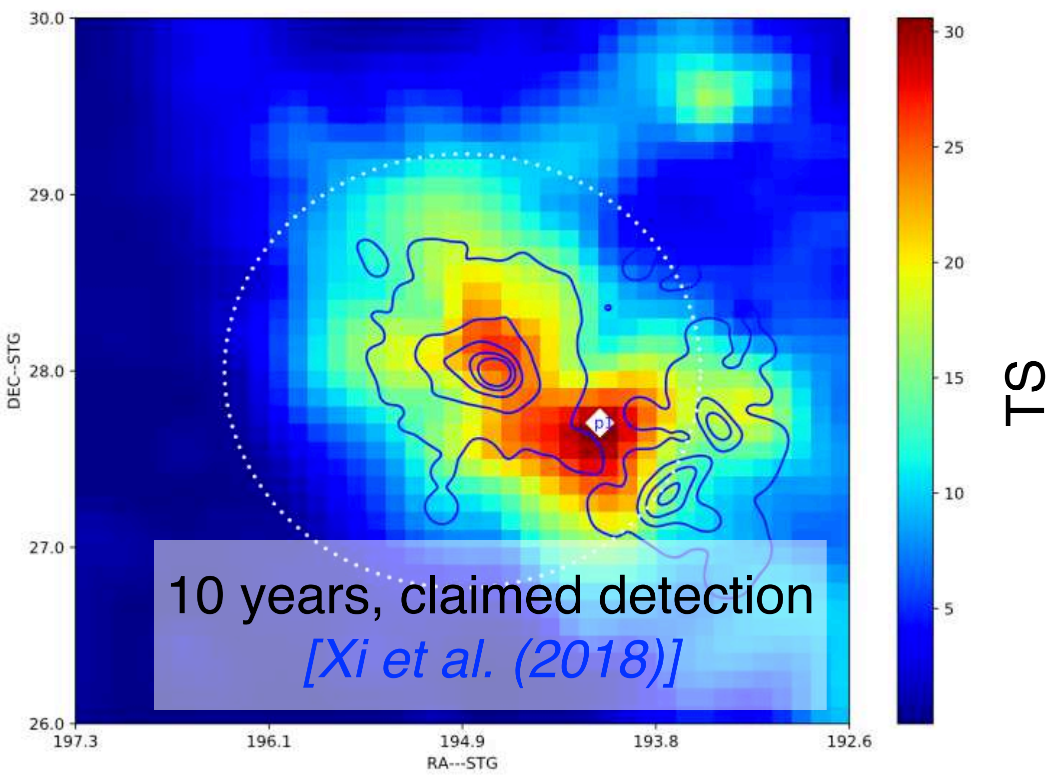
Example of spatial and spectral models (Perseus)



Search for γ-rays towards Coma with Fermi-LAT







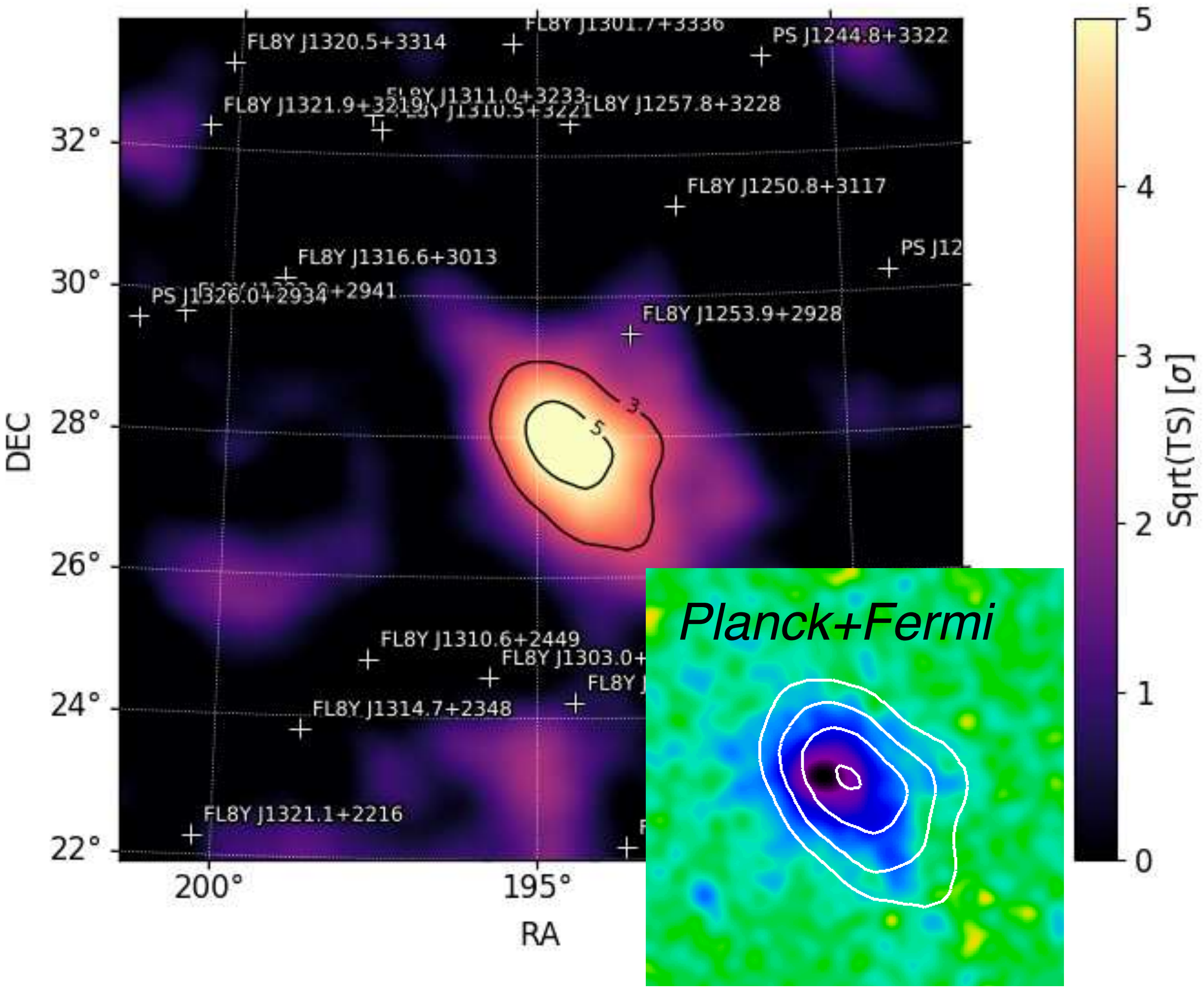
Claimed detection in the direction of Coma

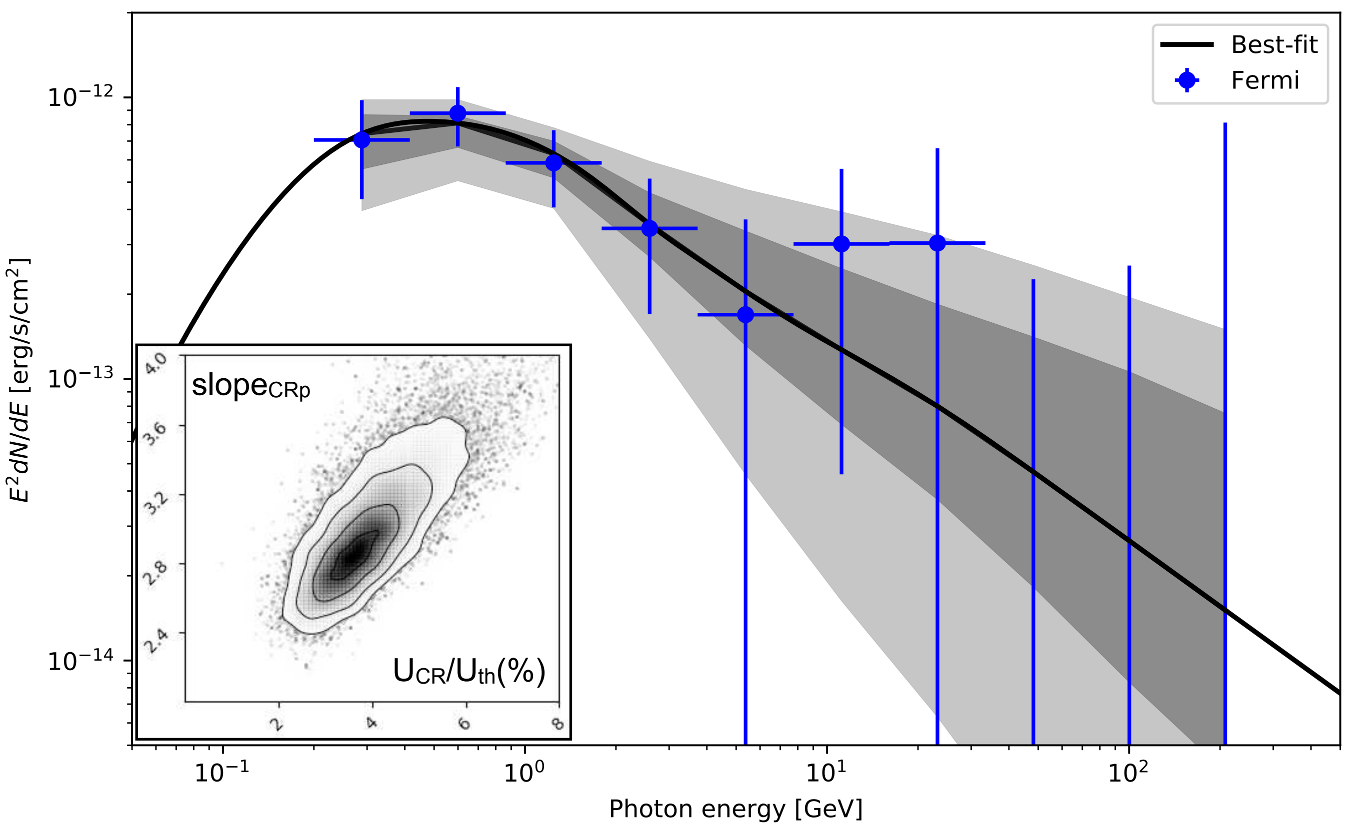
Search for γ-rays towards Coma with Fermi-LAT

(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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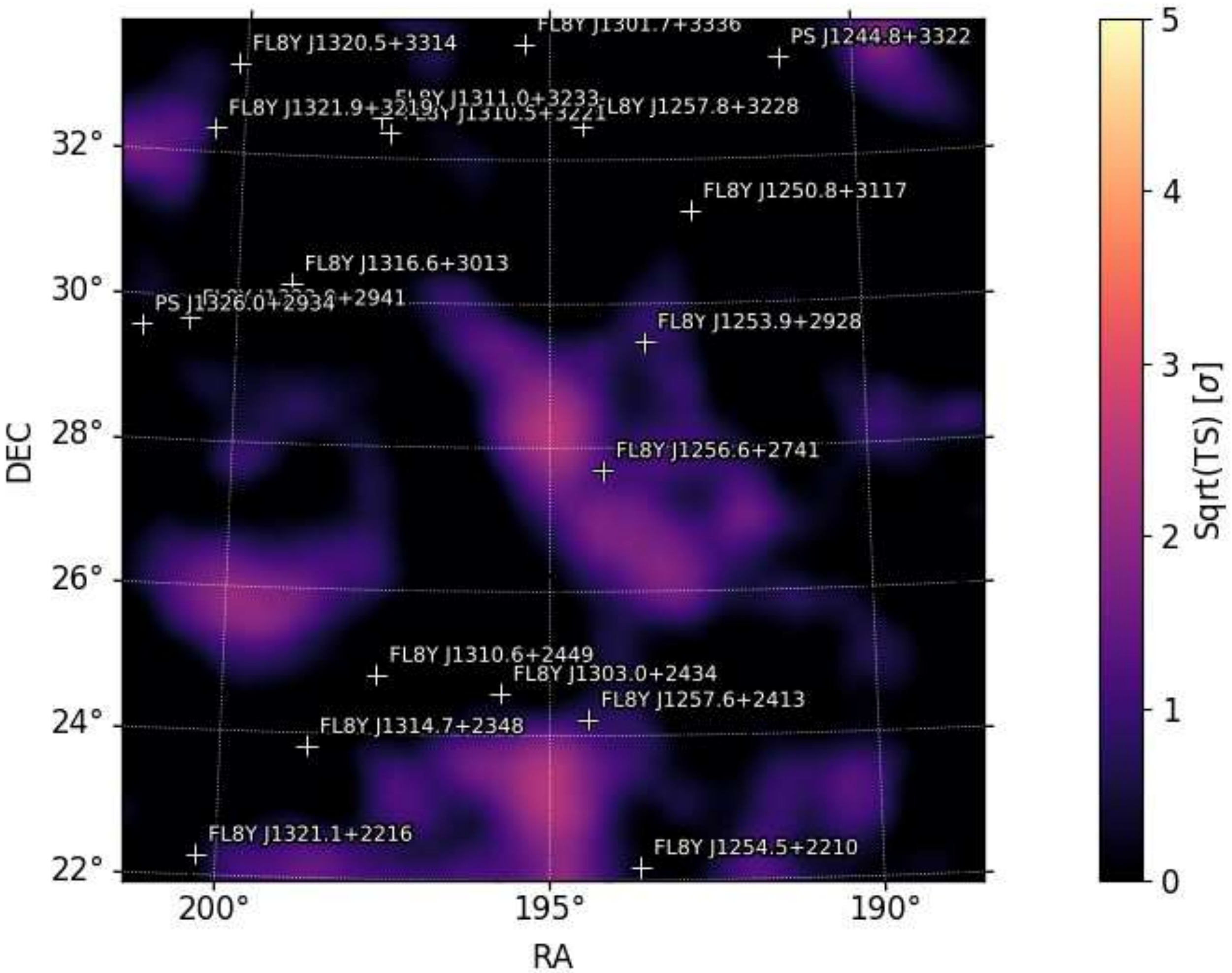
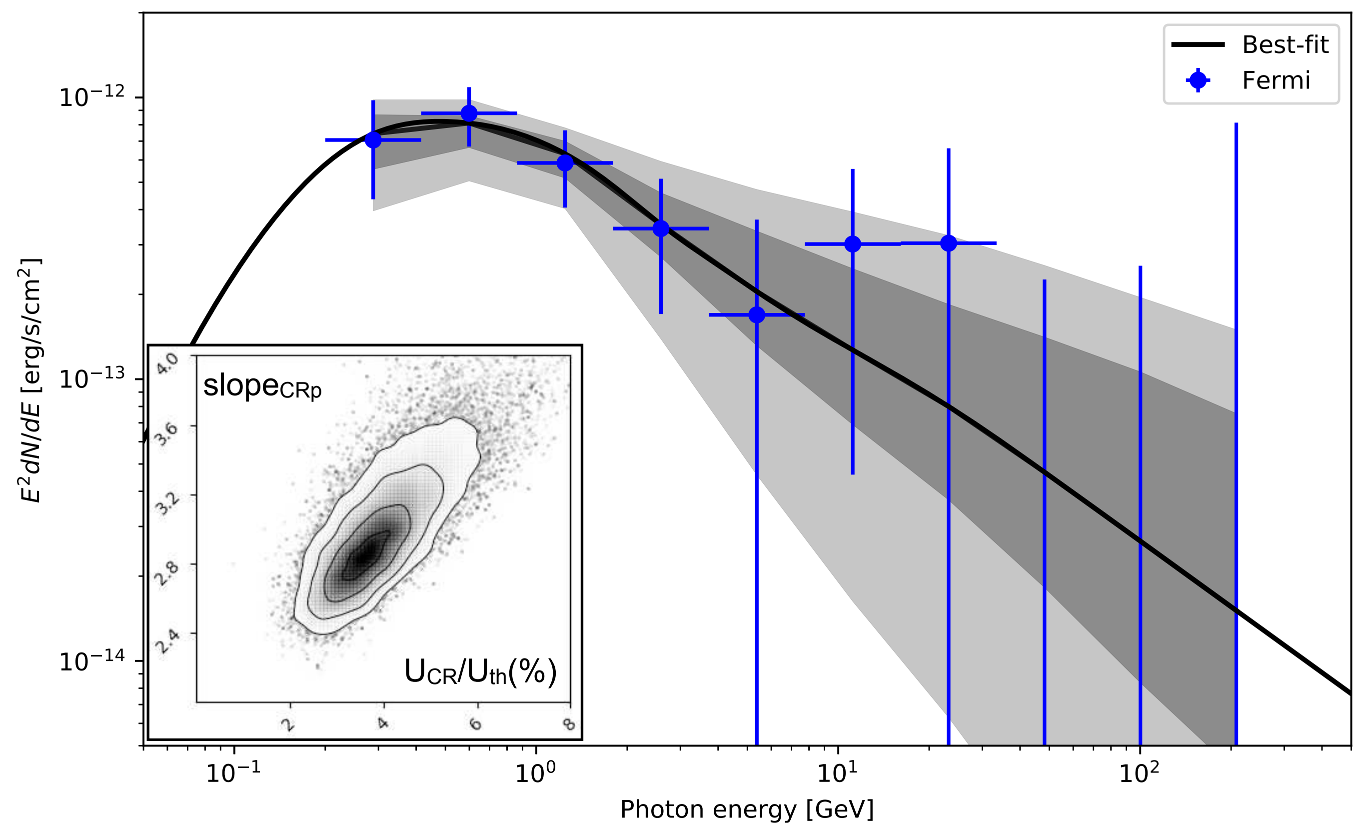




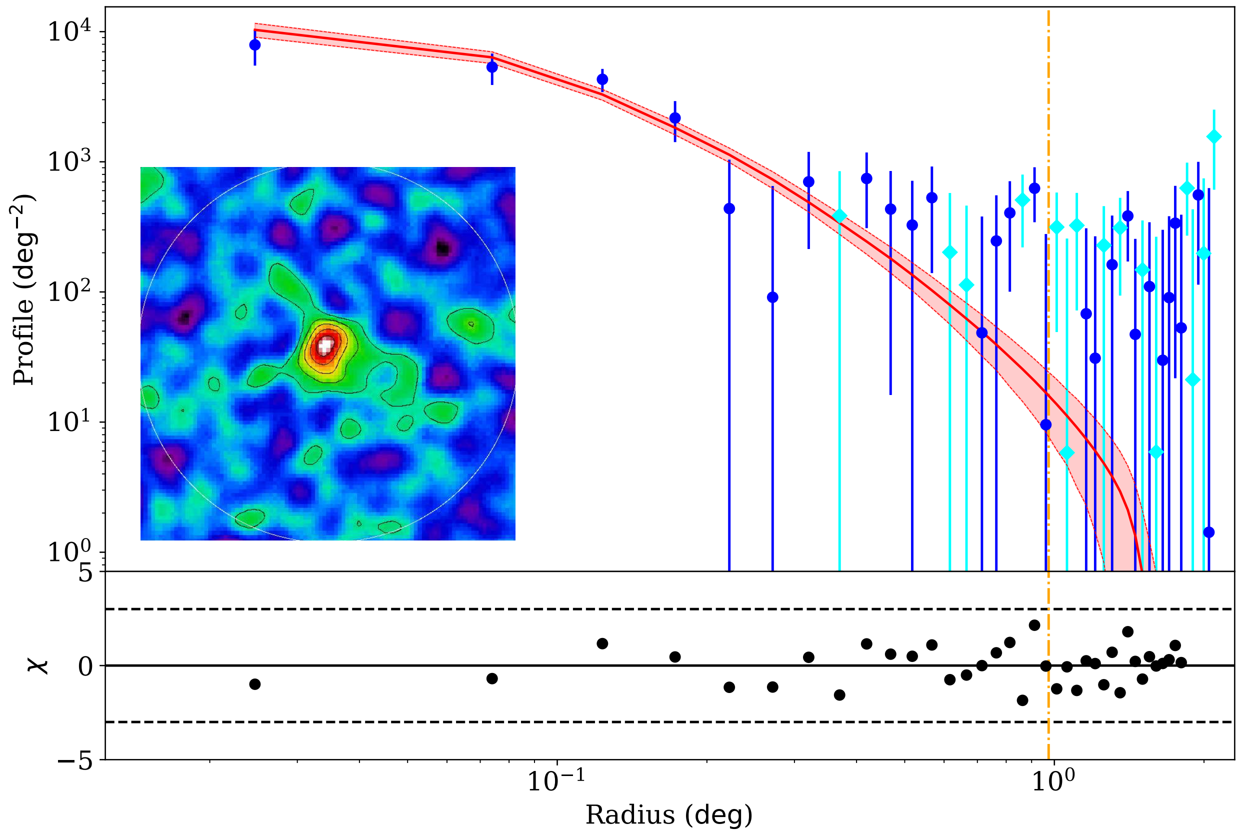
But accounting for a potential point source drastically reduces the significance

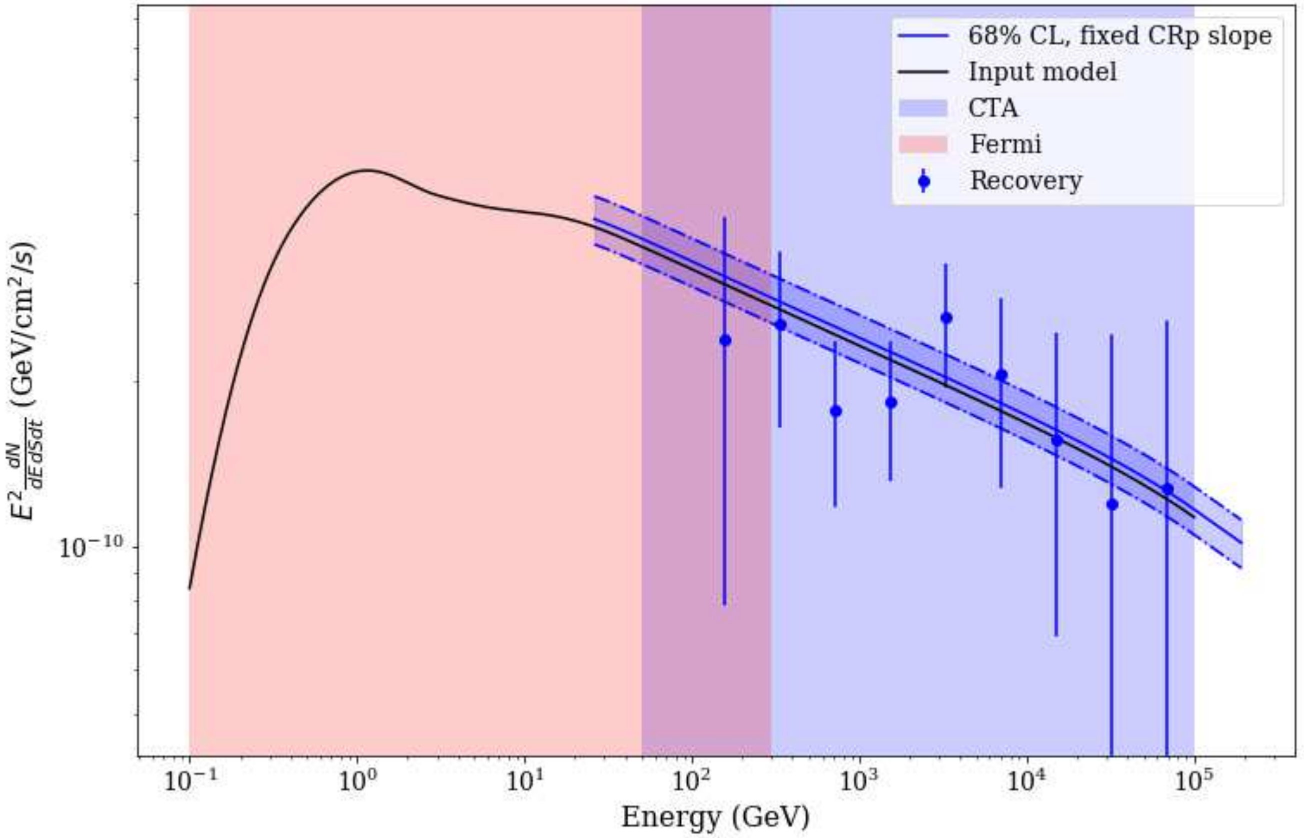
Fake detection due to point source contaminant?

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)]*

CRp slope = 2.2, $U_{CR}/U_{th}(<R_{500})$ = 1%, Peaked model, Include background + point sources





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

- Cosmology with galaxy clusters
  - Clusters can be used to test cosmological models
  - Mass estimates are key for cluster cosmology
  - The CMB/cluster tension remains unclear
- Cluster astrophysics (to be controlled for cosmology)
  - Unique environment to study the DM-baryons co-evolution
  - Thermal properties of cluster to be tested versus M and z
  - Cosmic rays at play, but details remains poorly understood

Evolution of the thermal gas properties

- NIKA2 resolved SZ observations
  - 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

Cosmic rays: the quest for γ-rays

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

planck

NIKA

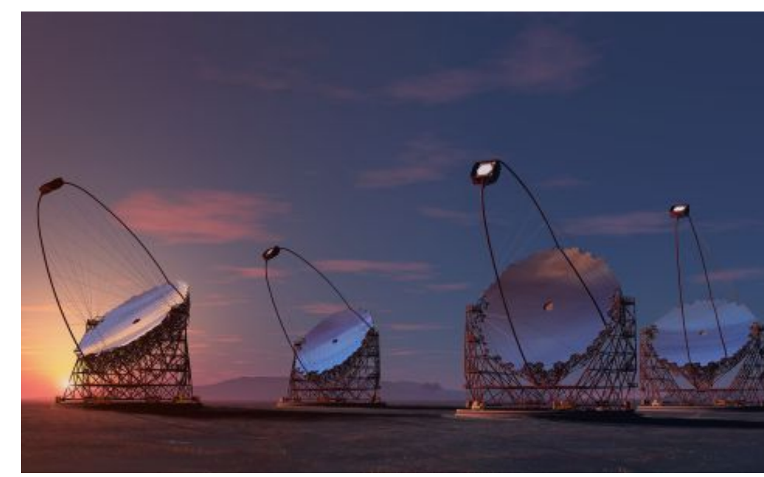
euclid
consortium

cta
cherenkov telescope array

Outline

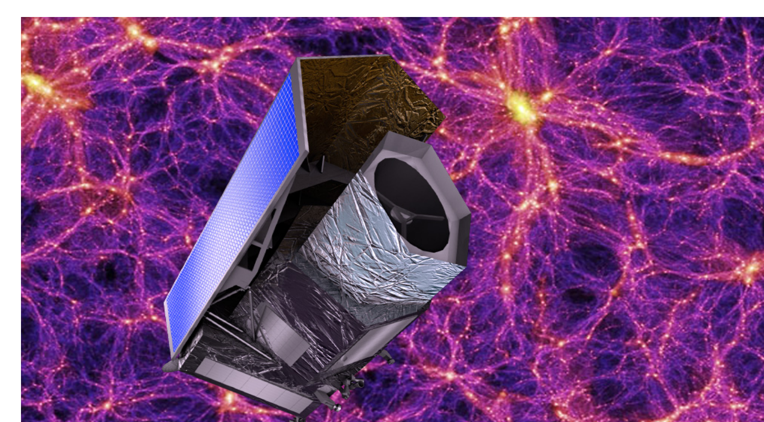
1. Clusters of galaxies as cosmic laboratories

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

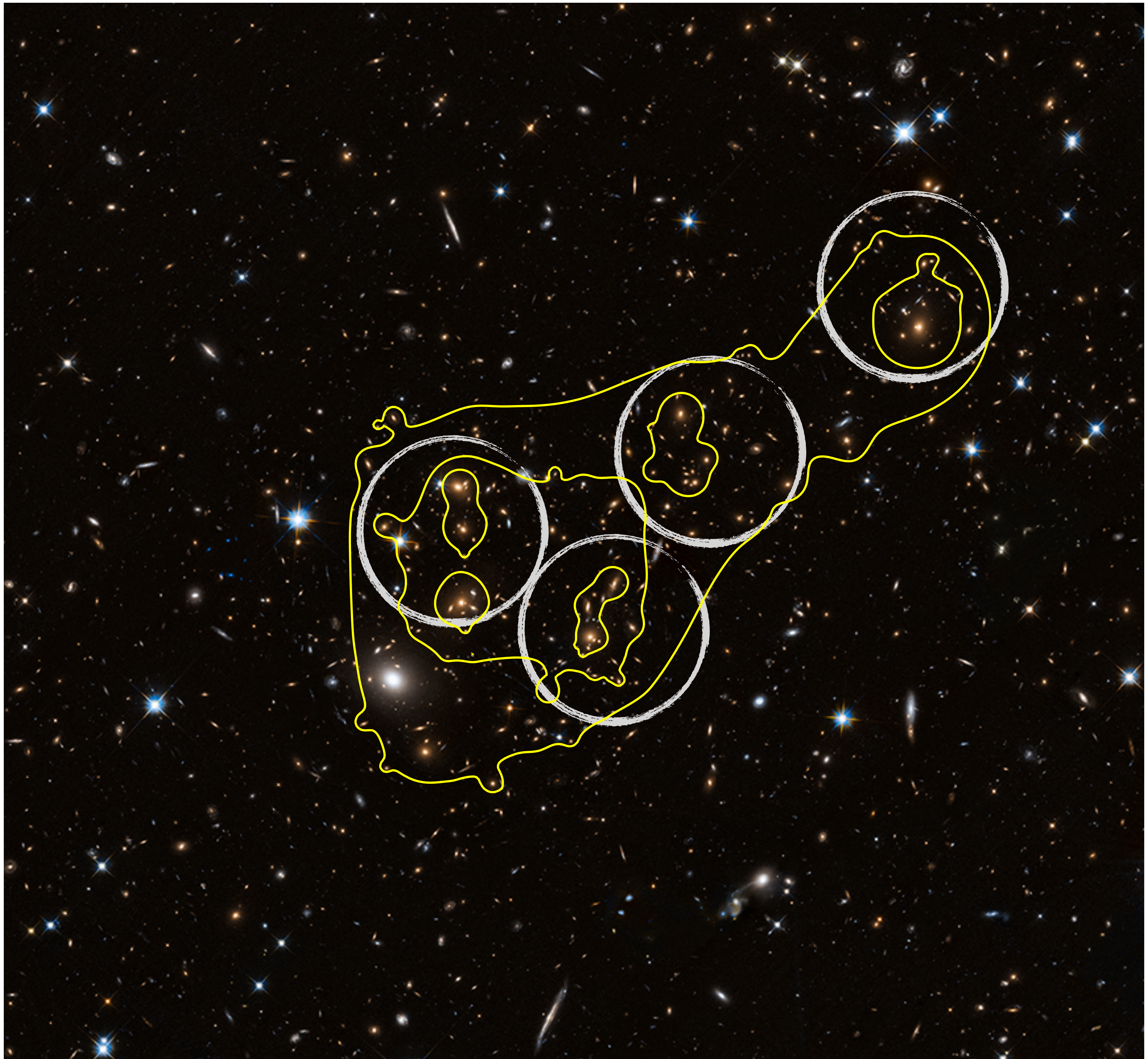


3. The quest for cluster cosmic rays in the γ-rays

4. **Detecting clusters in the optical/near-IR**



Detecting clusters in the optical / near IR



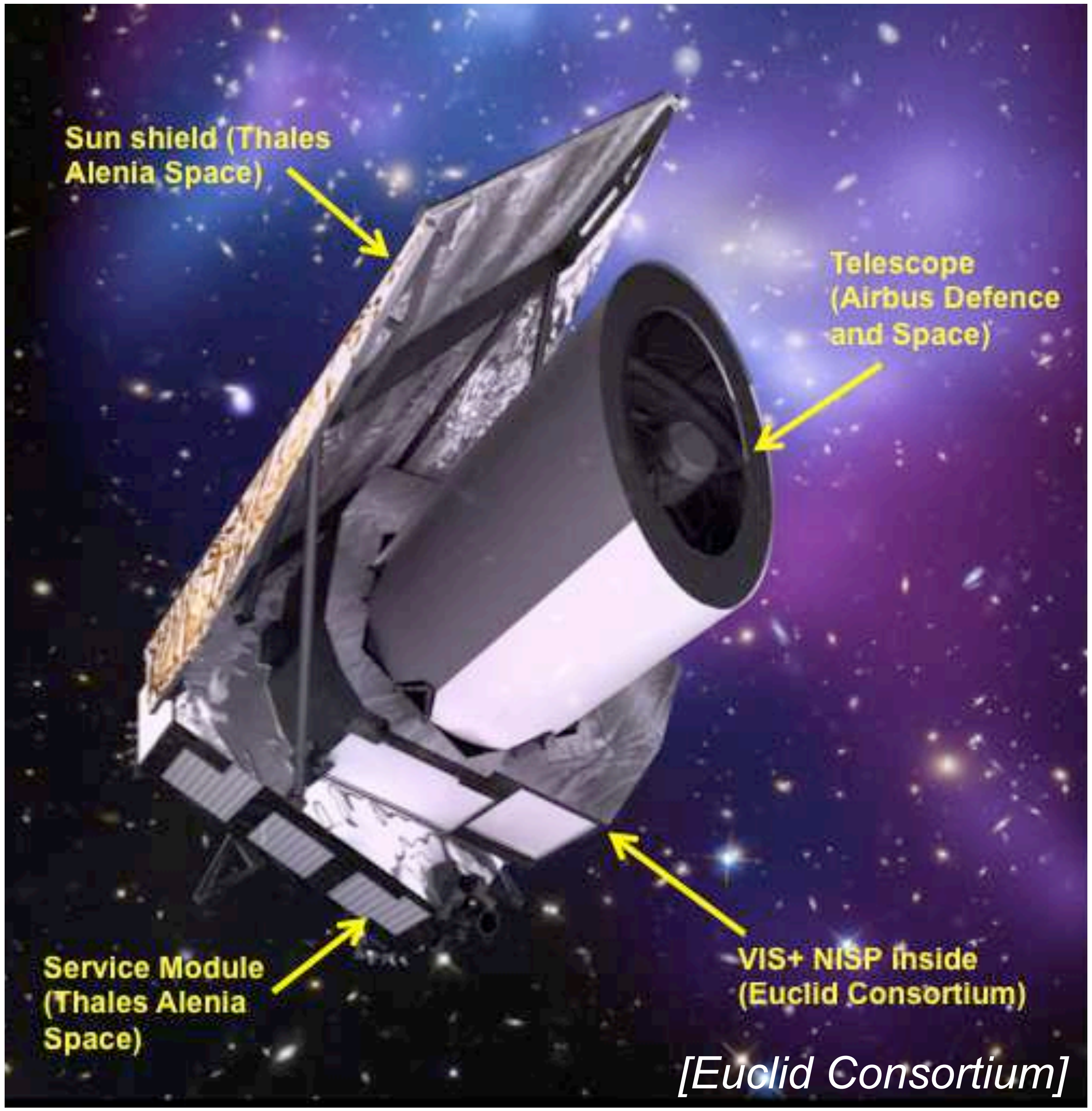
[Hubble Space Telescope image + Ma et al. (2009) groups]

- Cluster masses from lensing
  - ➡ Only most massive clusters
  - ➡ Not available at high z
- Galaxies trace the total mass
  - ➡ Optical richness ~ mass

Detect galaxy over-densities in 2d+1 space

Next steps for cluster cosmology: Looking at distant clusters with Euclid

Euclid satellite: 2200 kg, 4.5x3m



ESA mission dedicated to map the geometry of the Universe and structure formation

Large and deep galaxy survey

- 15 000 deg^2 (wide) + 40 deg^2 (deep)
- 6 years of survey, starting in 2021

Visible imaging + near IR spectro/photometer

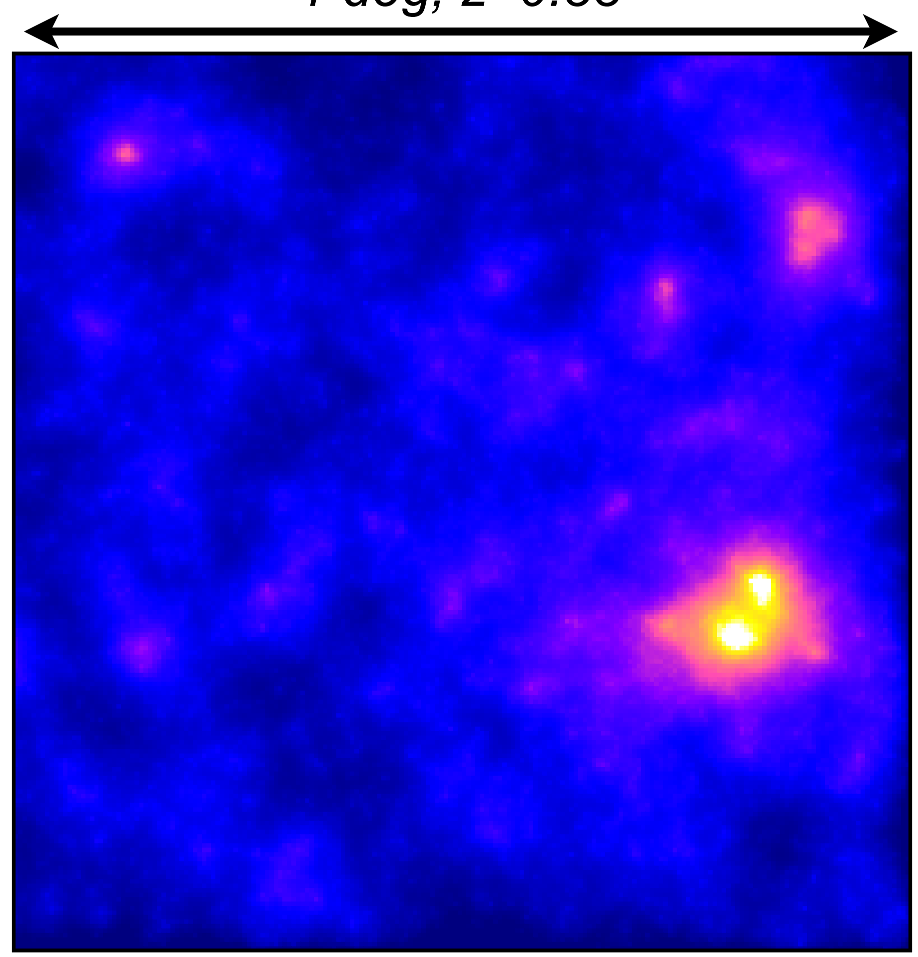
- Galaxies shapes: lensing masses
- High redshift clusters, out to z~2

New window for cluster cosmology at high z

Baseline detection algorithm of galaxy clusters with Euclid

Algorithm selection among 6 main competitors within the Euclid Cluster Challenge *[Euclid collaboration et al. (2019)]*

- Winner: AMICO (Adaptive Matched filter) *[Bellagamba et al. (2018)]*



Modeling the data:

$$D(\vec{\theta}, m, z) = \underbrace{A}_{\text{Amplitude}} \times \underbrace{M(\vec{\theta} - \vec{\theta}_c, m, z)}_{\text{Cluster galaxies: spherical profile+luminosity function}} + \underbrace{N(m, z)}_{\text{Noise: field galaxies}}$$

Extracting the signal from matched filter:

$$A(\vec{\theta}_c, z) = \int \underbrace{\phi_z(\vec{\theta} - \vec{\theta}_c, m)}_{\text{Filter: model/noise}} D(\vec{\theta}, m, z) dm dz d^2\theta - \underbrace{B}_{\text{Background}}$$

Match filtering: very efficient, but assumptions

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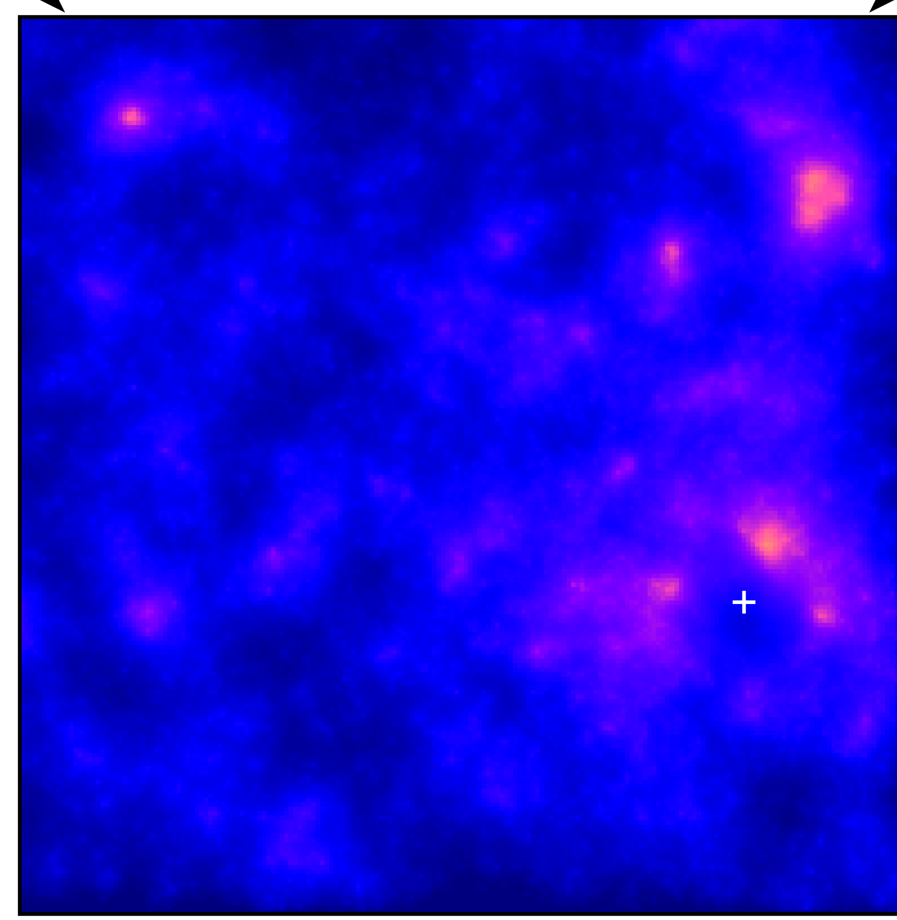
1 deg, z=0.33



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Amplitude — *Cluster galaxies: spherical profile+luminosity function* — *Noise: field galaxies*

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Filter: model/noise — *Background*

Match filtering: very efficient, but assumptions

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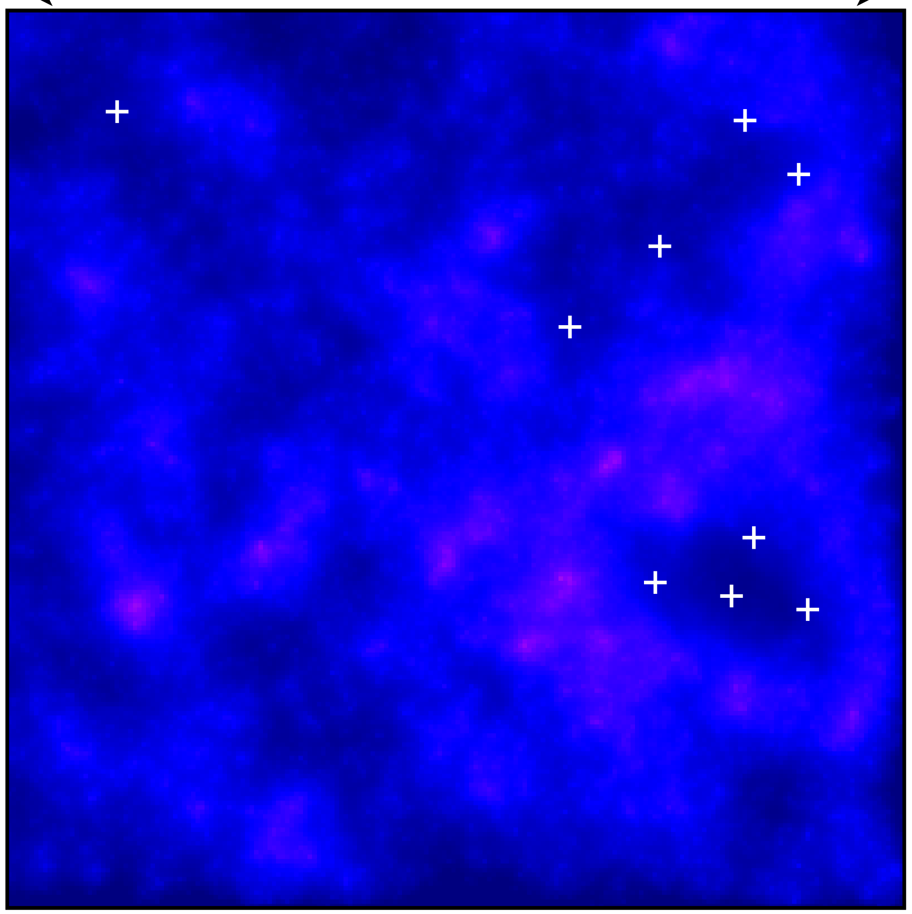

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Match filtering: very efficient, but assumptions

Towards the selection function of the cluster survey

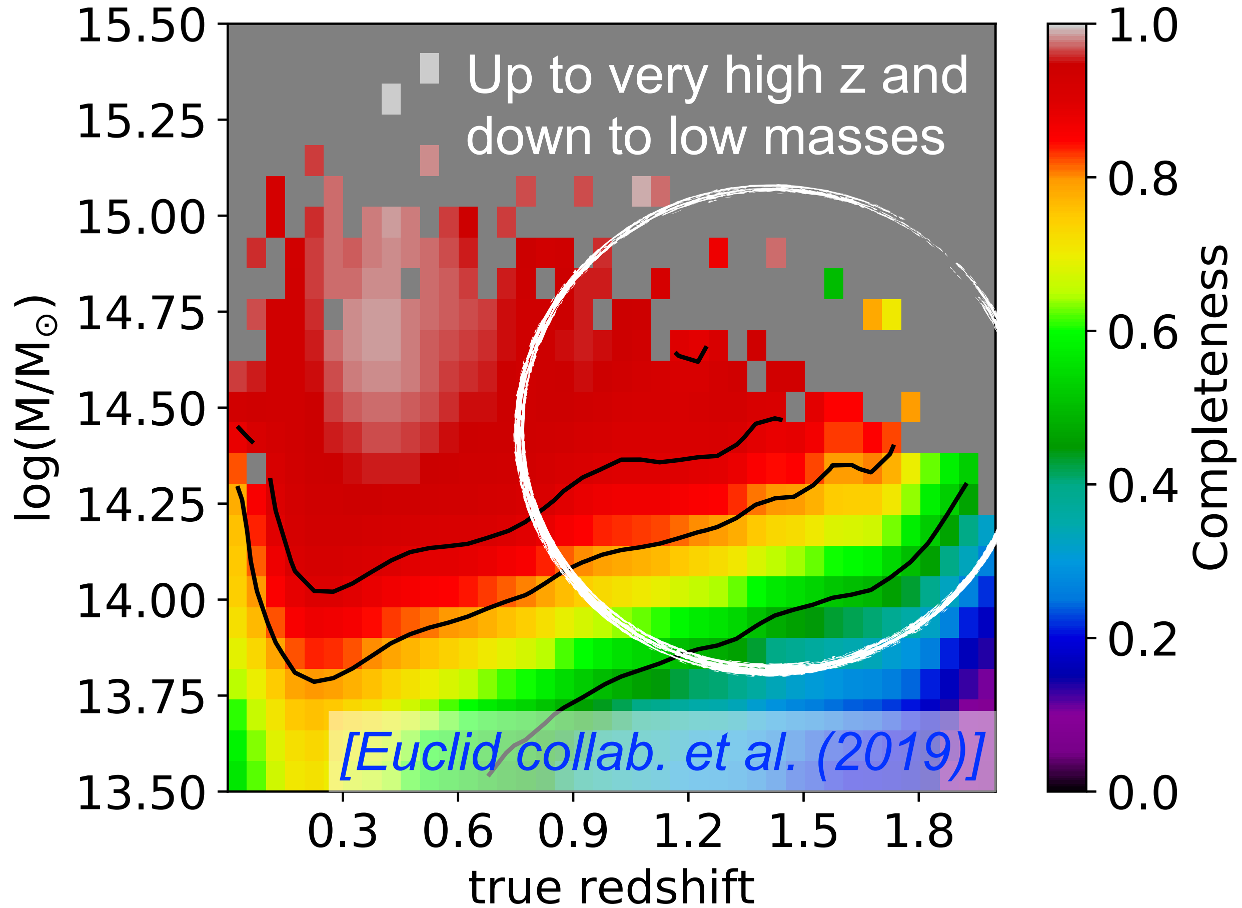
Selection function : link between theoretical predictions & observations

➡ Need a pure & complete sample, and **well characterized** (~ %)

a) Apply cluster finders to mock galaxy samples

b) Compare input and recovered clusters:

- Purity: #true detections / #detections
- Completeness: #true detections / #true clusters
- Test detection versus cluster properties



Unprecedented redshift range with Euclid

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
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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

Future surveys in the optical/near-IR

- LSST & Euclid in preparation
- Cluster detection with Euclid
  - Unprecedented mass/redshift range
  - Selection of the AMICO code
- Cluster cosmology with Euclid
  - A new stage is to be expected
  - Robust, % level, mass calibration up to high redshift will be crucial