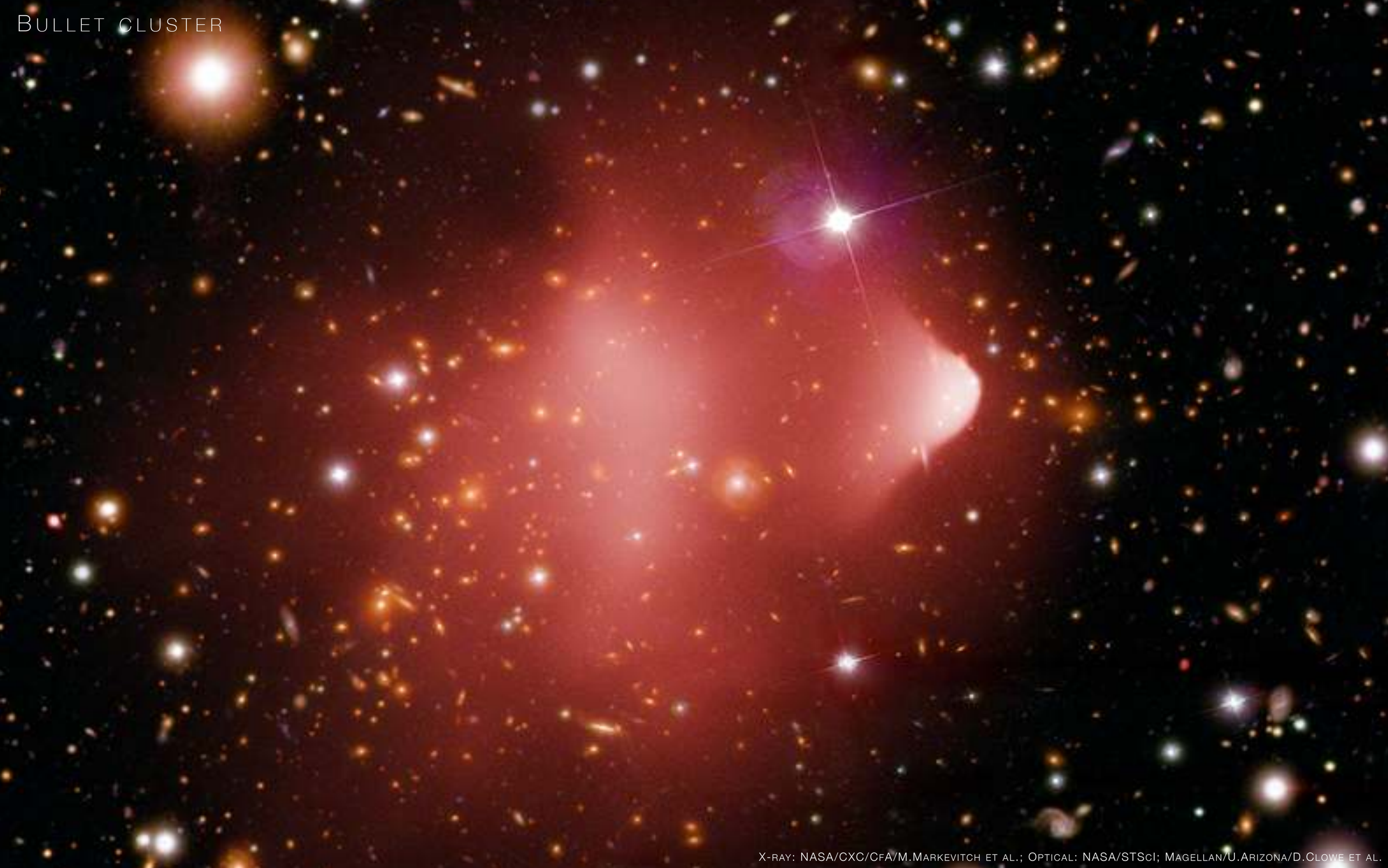
Sunyaev-Zeldovich effect at high angular resolution

Radiative processes in Astrophysics - 05.06.2023

Luca Di Mascolo | Università degli Studi di Trieste
Osservatorio Astronomico di Trieste
Institute for Fundamental Physics of the Universe

Bullet cluster



X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.

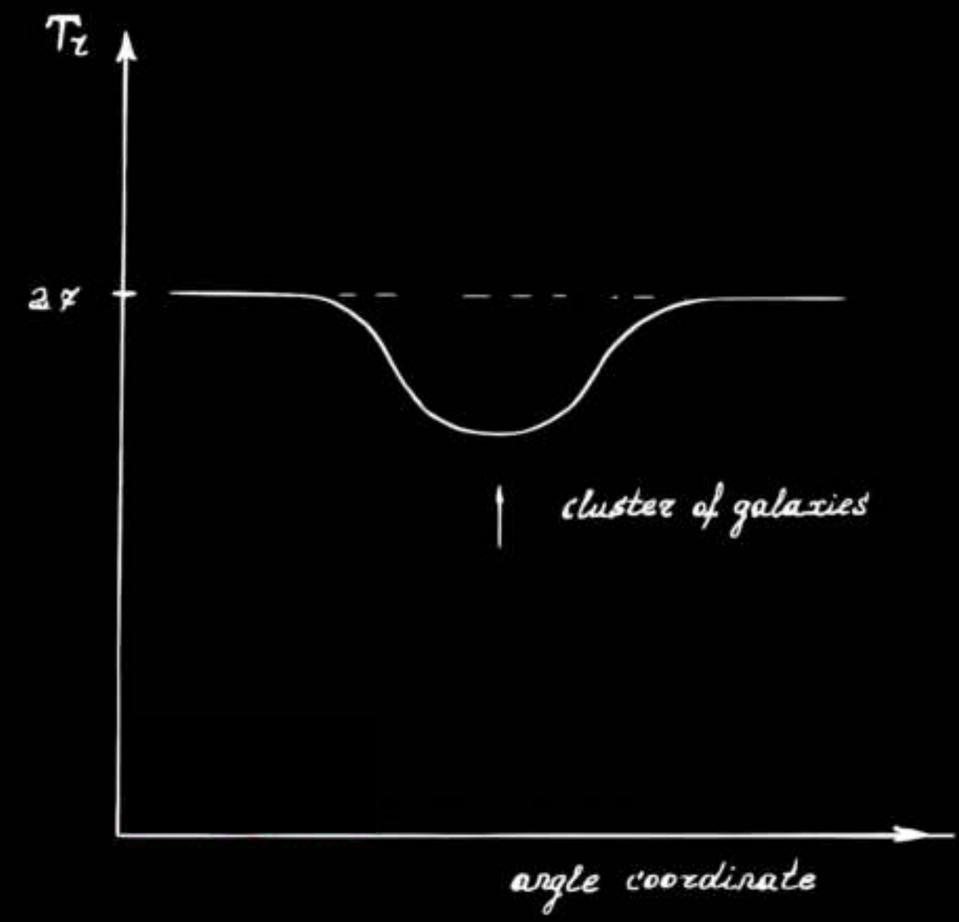
RASHID SUNYAEV

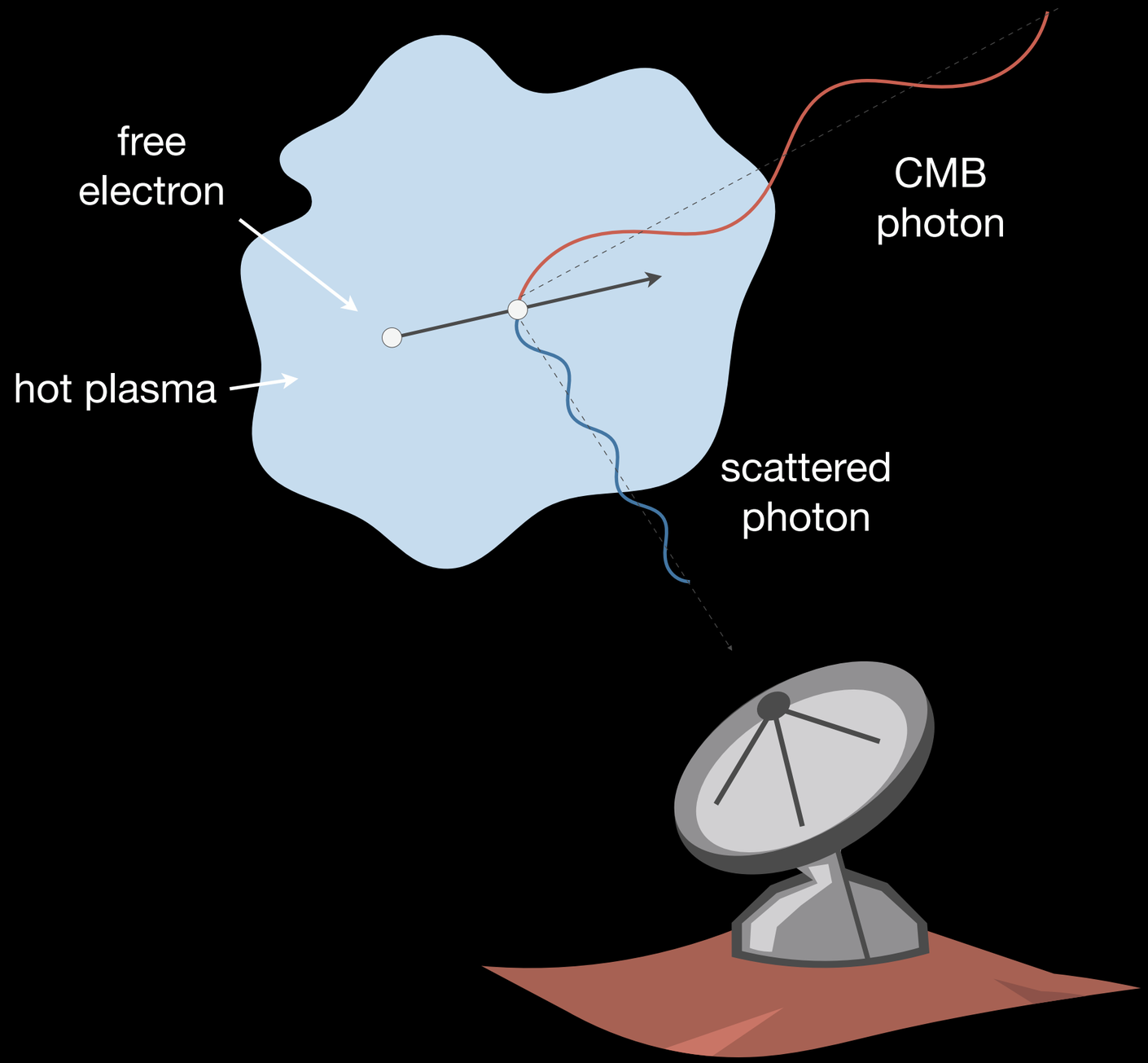
YAKOV ZELDOVICH

The Observation of Relic Radiation as a Test of the Nature of X-Ray Radiation from the Clusters of Galaxies

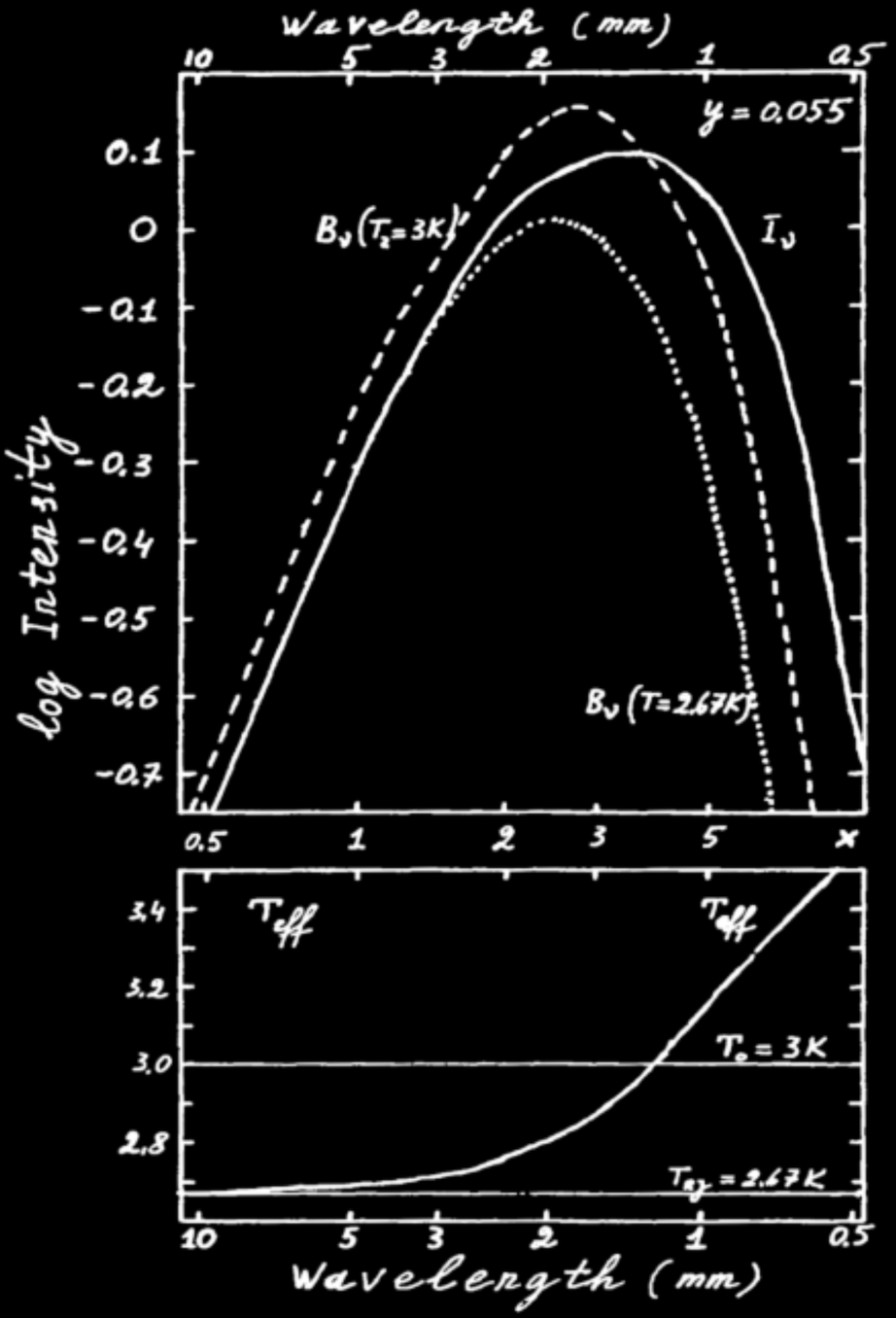
Introduction

The x-ray radiation from a number of clusters of galaxies (Coma, Virgo, Perseus) was discovered recently.[1] It is assumed that clusters of galaxies form an important class of powerful x-ray sources, possibly giving the main contribution to the x-ray background radiation of the Universe.[2] What is the nature of these sources? What physical mechanisms give the observed x-ray radiation?




free
electron
hot plasma
CMB
photon
scattered
photon

CMB spectral distortion

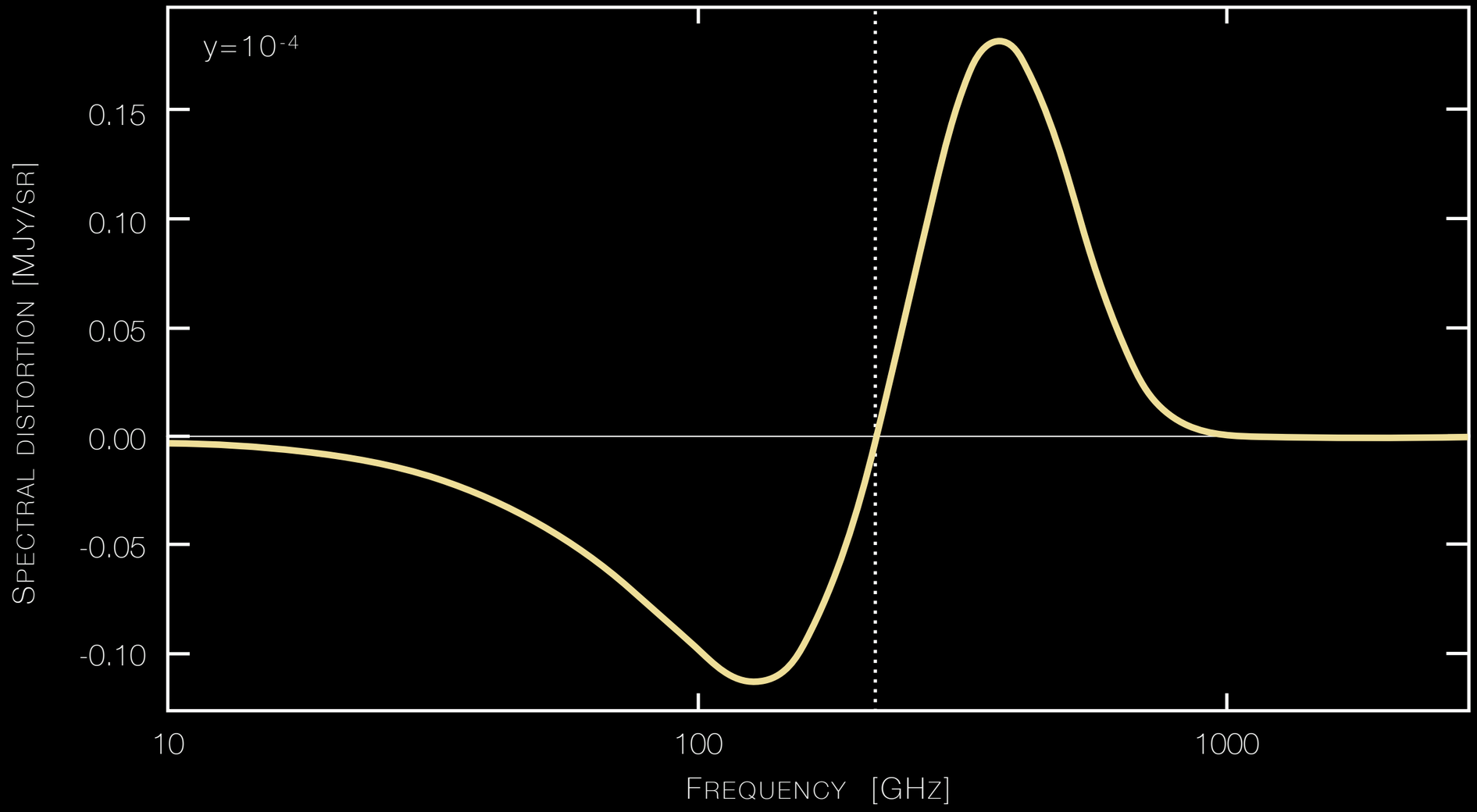


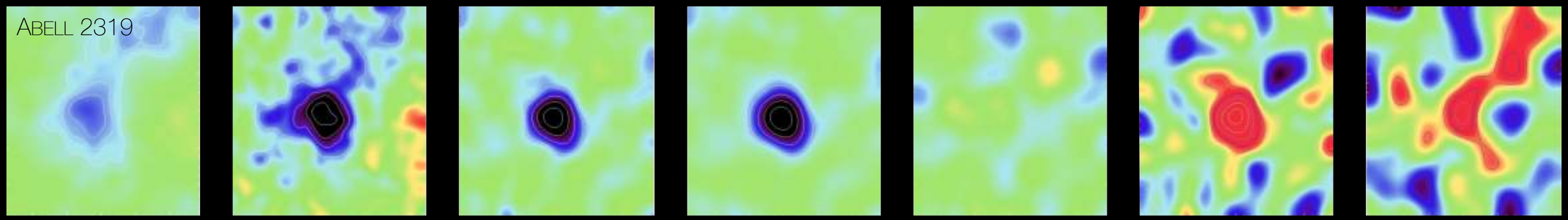
Sunyaev & Zeldovich, ARA&A, 18, 1980

Some useful equations

$$\delta I_\nu \approx \frac{2(k_\mathrm{B}T_\mathrm{CMB})^3}{(h\nu)^2}\frac{x^4e^x}{(e^x-1)^2}\left[x\frac{e^x+1}{e^x-1}-4\right]y \qquad x=\frac{h\nu}{k_\mathrm{B}T_\mathrm{CMB}}$$

$$\delta T \approx T_\mathrm{CMB}\underbrace{\left[x\frac{e^x+1}{e^x-1}-4\right]}_{\text{peculiar spectral signature}}y \qquad y=\frac{\sigma_\mathrm{T}}{m_ec^2}\int n_eT_e\mathrm{d}l$$





ESA/Planck LFI & HFI Consortia

Some useful equations

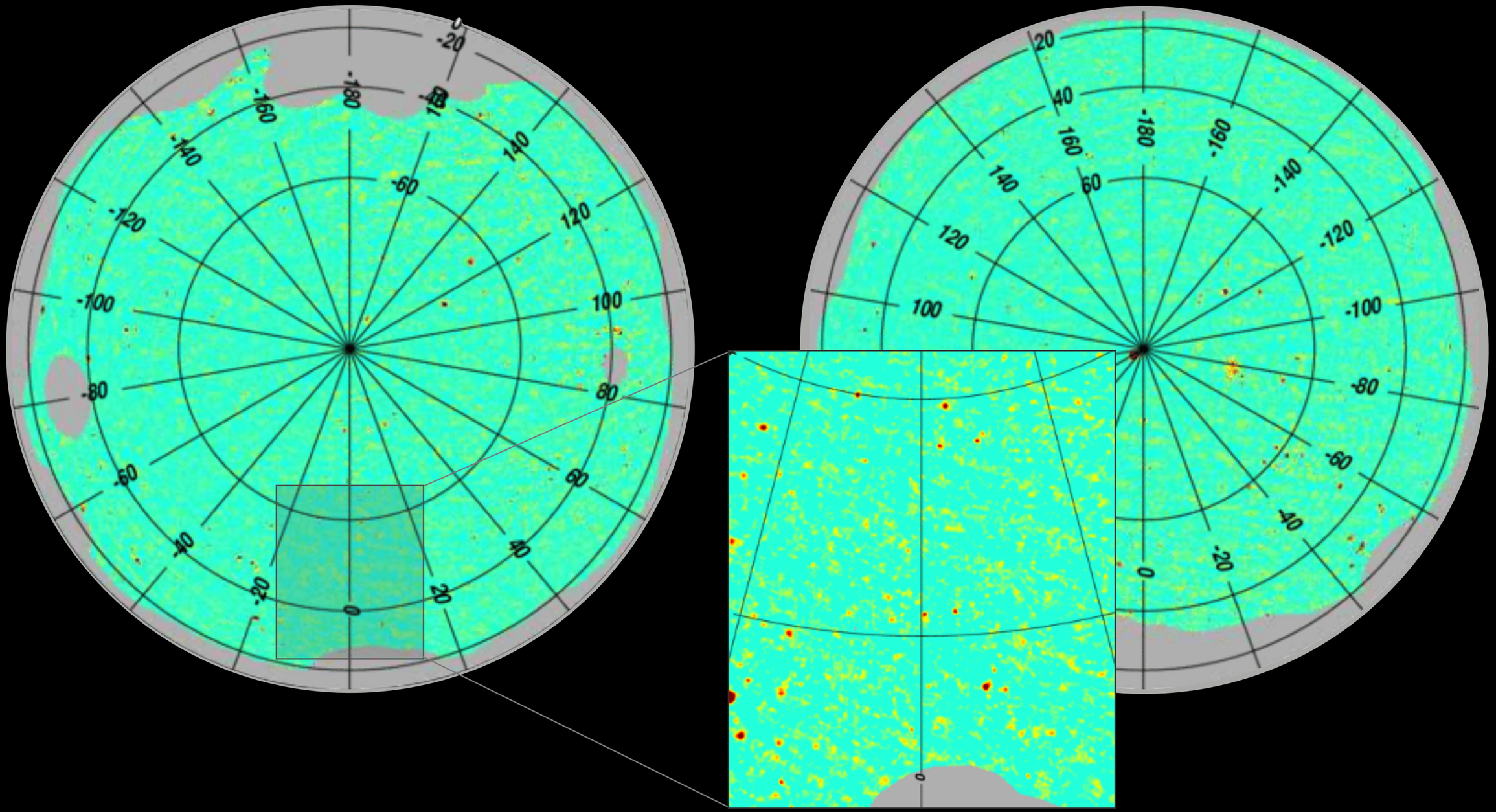
$$\delta I_\nu \approx \frac{2(k_\mathrm{B}T_\mathrm{CMB})^3}{(h\nu)^2}\frac{x^4e^x}{(e^x-1)^2}\left[x\frac{e^x+1}{e^x-1}-4\right]y \qquad x=\frac{h\nu}{k_\mathrm{B}T_\mathrm{CMB}}$$

$$\delta T \approx T_\mathrm{CMB}\underbrace{\left[x\frac{e^x+1}{e^x-1}-4\right]}_{\text{peculiar spectral signature}\\ \text{no redshift dependence}}y \qquad y=\underbrace{\frac{\sigma_\mathrm{T}}{m_ec^2}\int n_eT_e\mathrm{d}l}_{\text{no redshift dependence}}$$

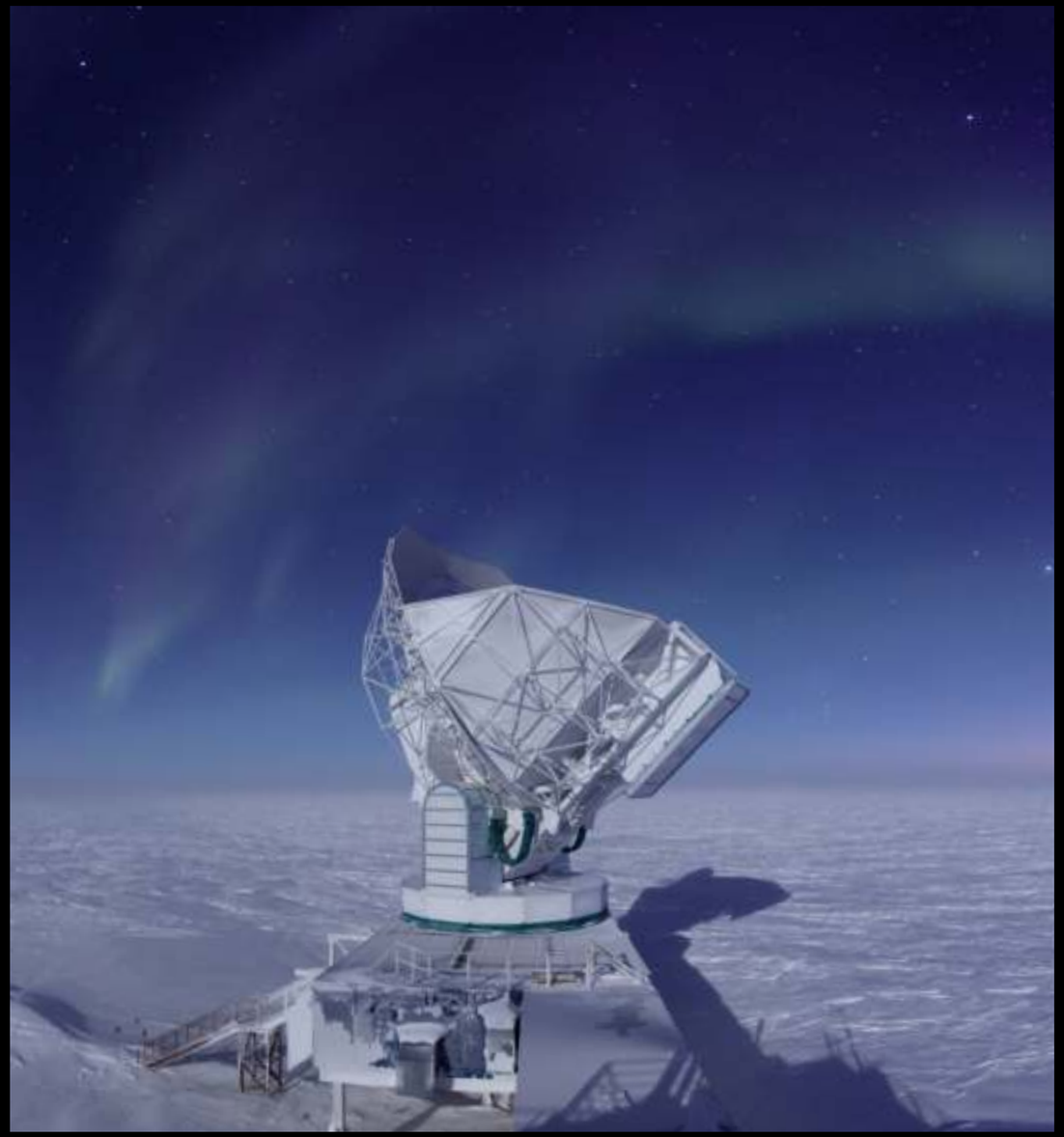
Planck satellite

ESA mission
full operation during 2009-2011, extended till 2013
1.5m primary mirror (10arcmin resolution @ 100GHz)
3 LFI (27-77 GHz) and 6 HFI (83-1000 GHz) bands

Planck's view of galaxy clusters



Planck collaboration XXII, A&A, 594, A22, 2016

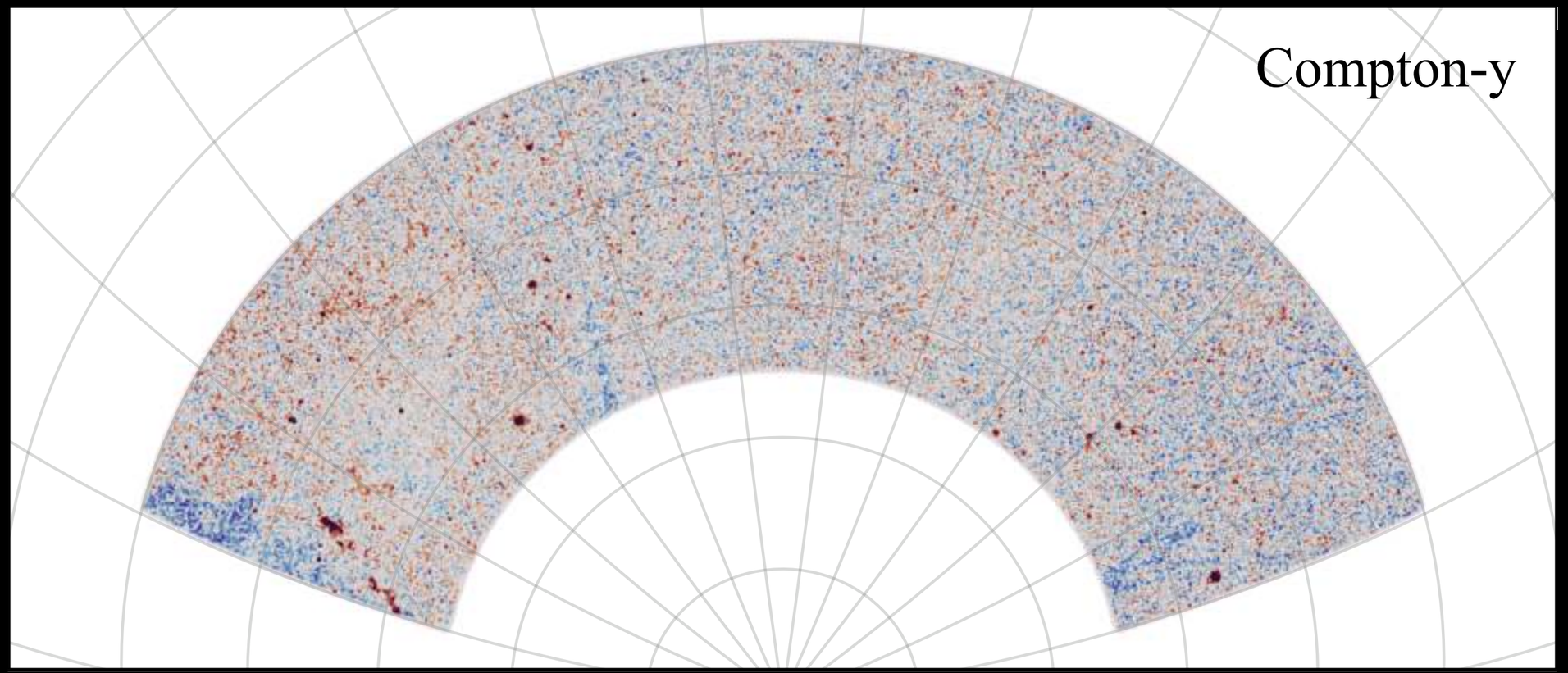


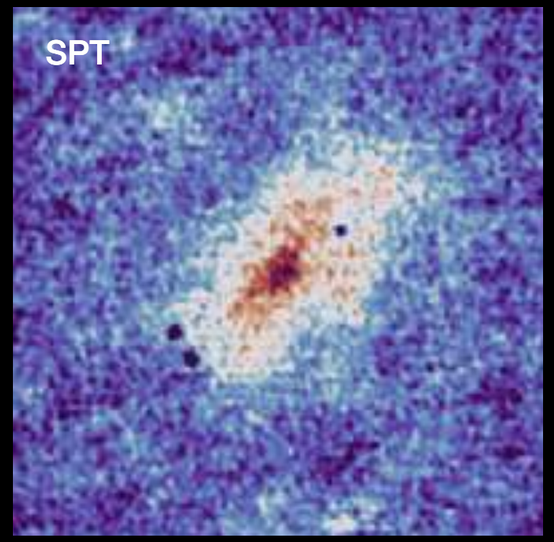
South Pole Telescope

10m primary mirror (1.6 arcmin resolution @ 100GHz)
3 bands (100-150-220 GHz)

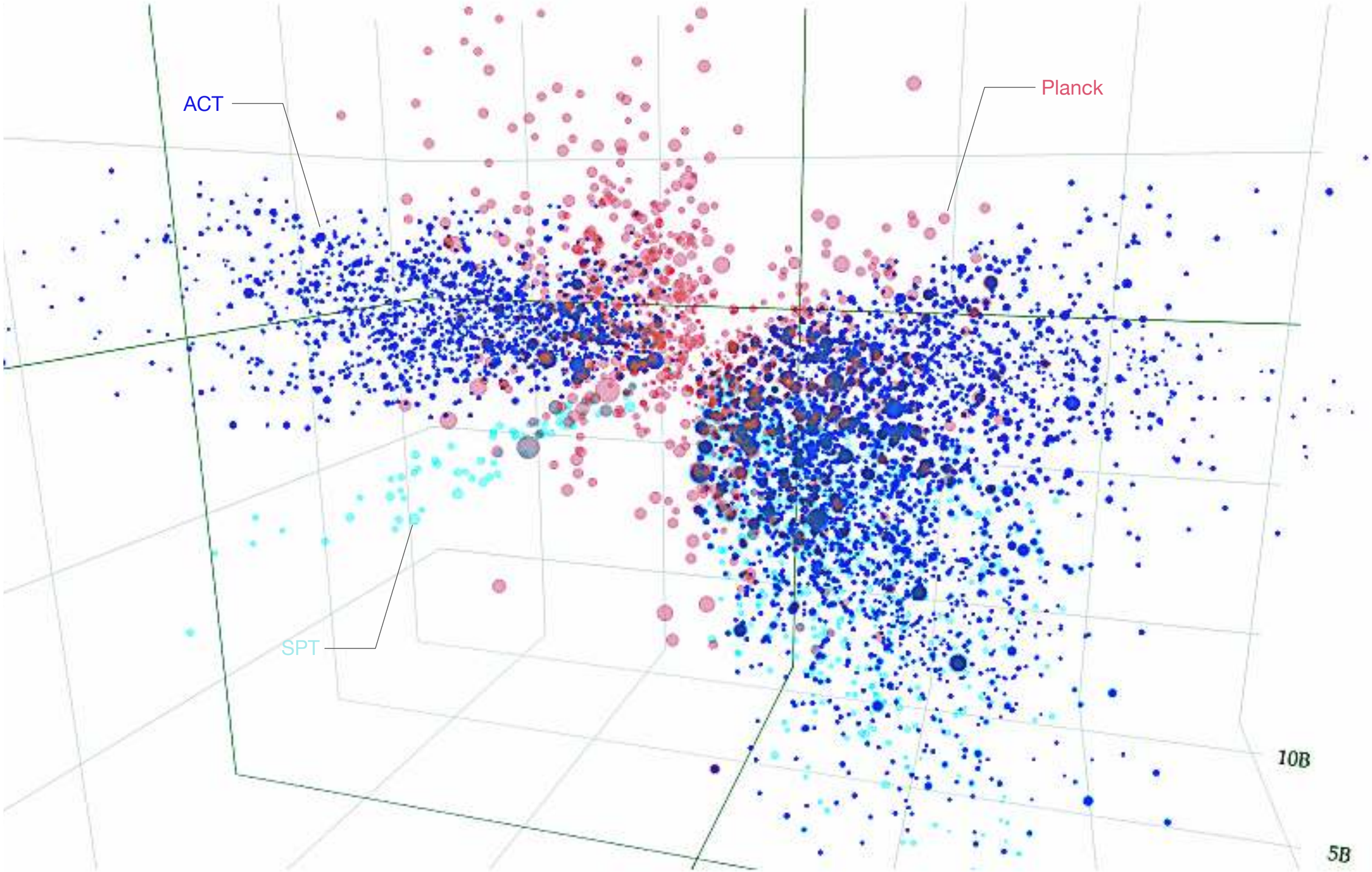
Atacama Cosmology Telescope

6m primary mirror (1.3 arcmin resolution @ 150GHz)
3 bands (90-150-220 GHz)





L. Bleem et al., ApJ, 258, 2, 36, 2022



ACT COLLABORATION (PRIVATE)

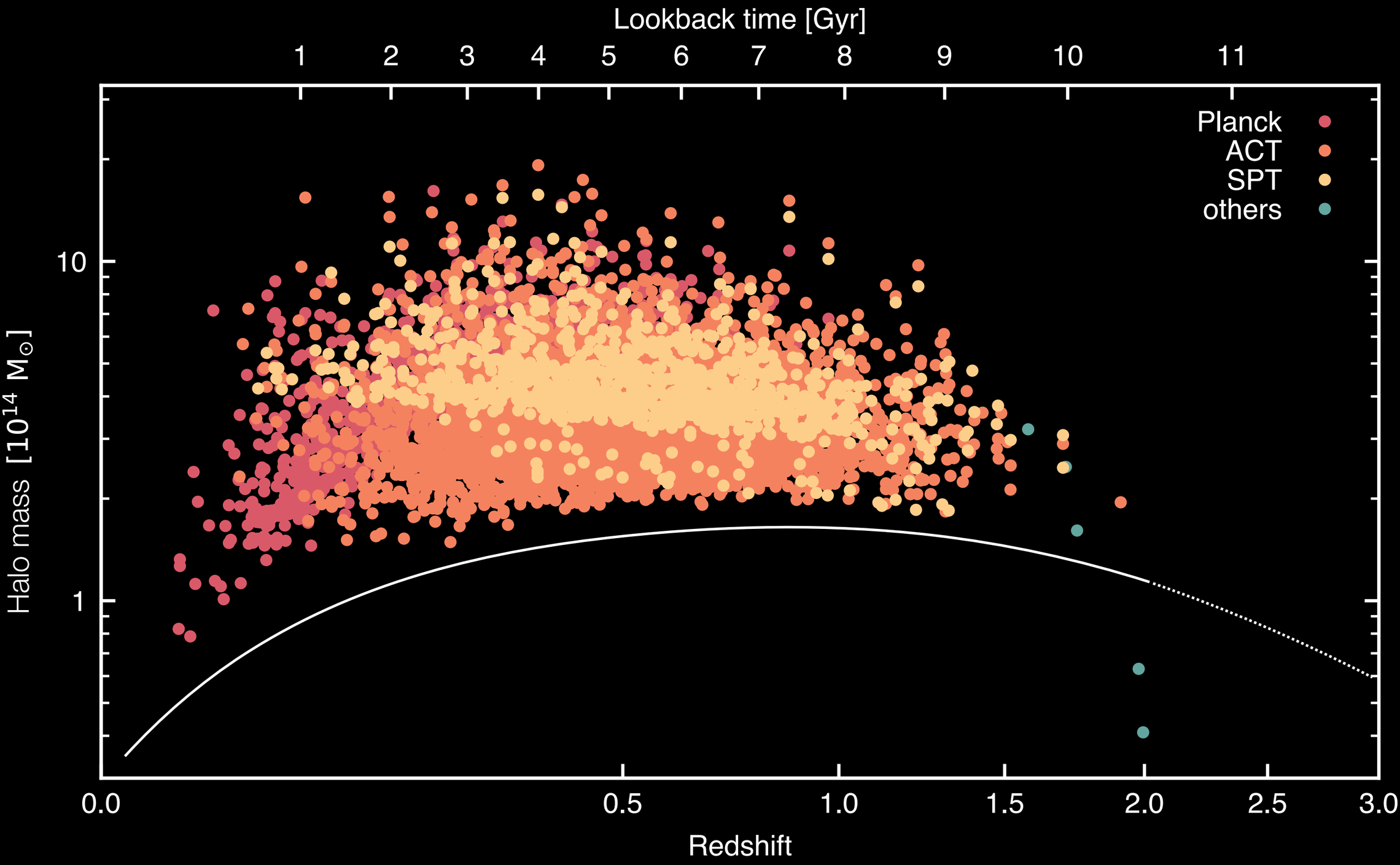
Some useful equations

$$\delta I_\nu \approx \frac{2(k_\mathrm{B}T_\mathrm{CMB})^3}{(h\nu)^2}\frac{x^4e^x}{(e^x-1)^2}\left[x\frac{e^x+1}{e^x-1}-4\right]y \qquad x=\frac{h\nu}{k_\mathrm{B}T_\mathrm{CMB}}$$

$$\delta T \approx T_\mathrm{CMB}\left[x\frac{e^x+1}{e^x-1}-4\right]y \qquad y=\frac{\sigma_\mathrm{T}}{m_ec^2}\int n_eT_e\mathrm{d}l$$

$$Y_\mathrm{sph}(<r)=\frac{\sigma_\mathrm{T}}{m_ec^2}\int_0^r n_eT_e4\pi\eta^2\mathrm{d}\eta \propto E_\mathrm{th} \propto M(<r)$$

clusters across cosmic time



PlanckXXVII 2016, Hilton+2021, Bocquet+2019, Huang+2020, Bleem+2020

ENVIRONMENT FOR GALAXY EVOLUTION

impact galaxy morphology,
star formation, AGN activity, …

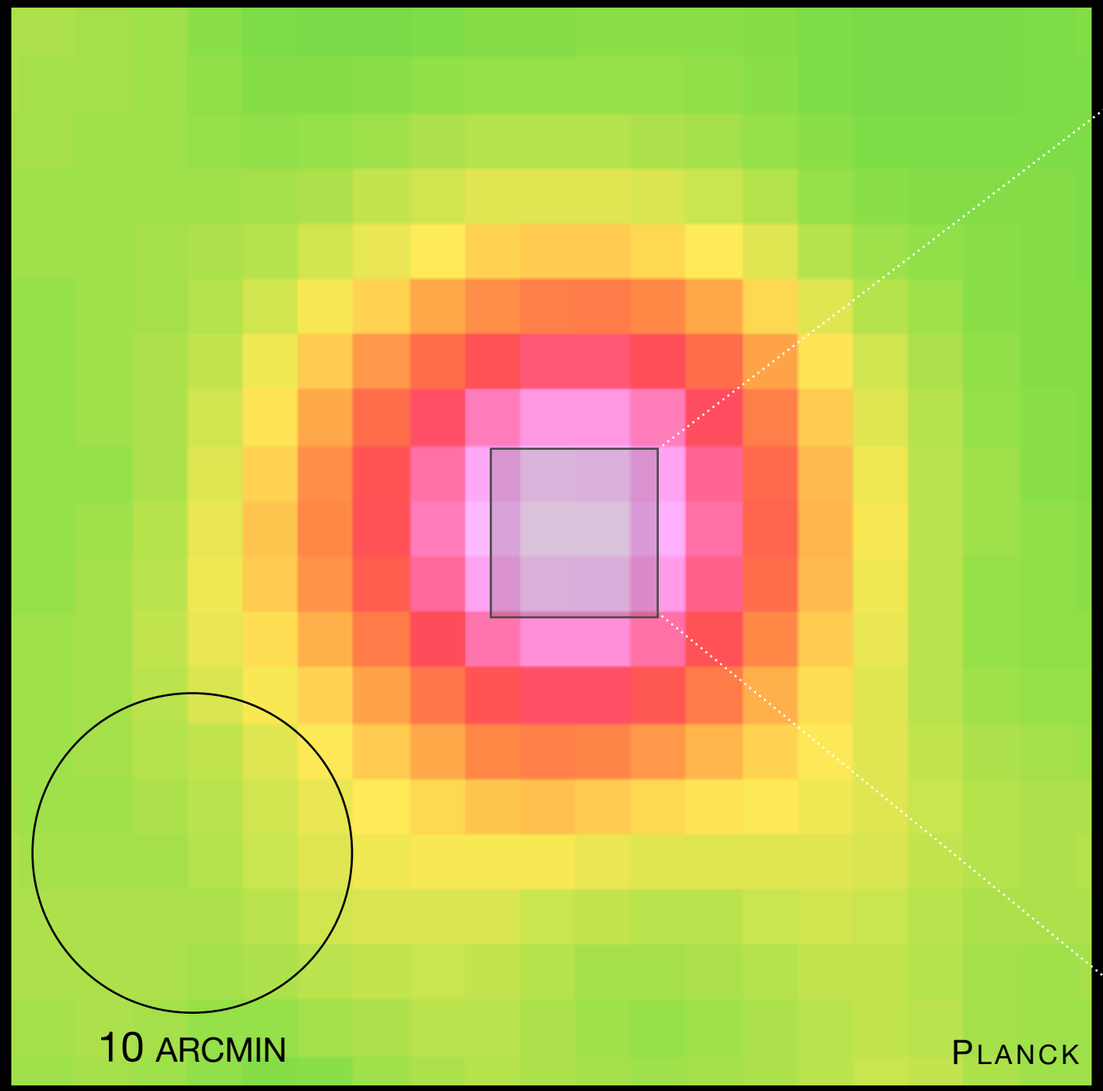
LARGEST STRUCTURES IN THE UNIVERSE

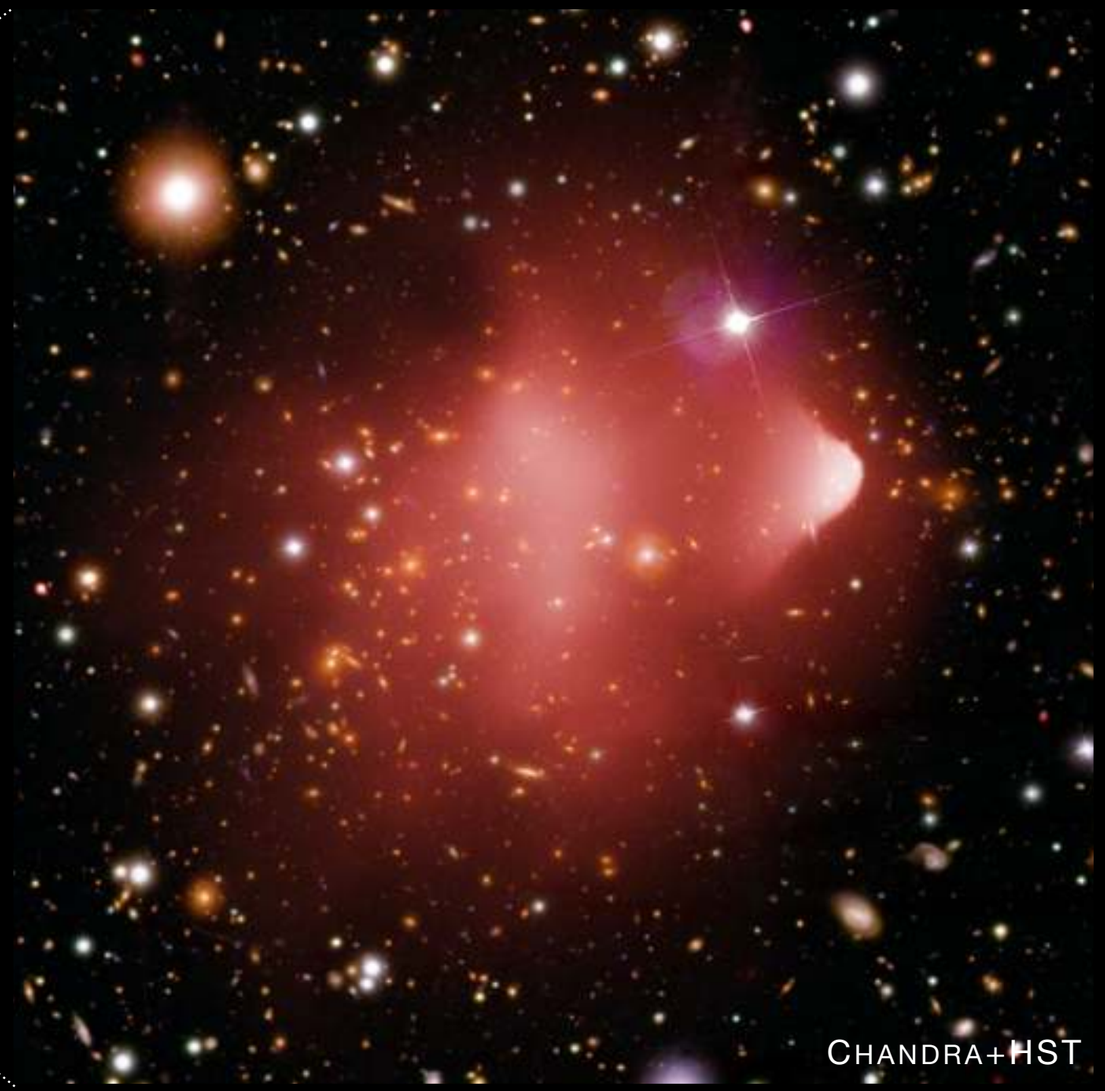
tracers of large-scale structure formation
and mass content of the Universe
window on dark matter properties

LARGE RESERVOIRS OF PLASMA

host most energetic events in the universe
unique laboratories for plasma physics

IllustrisTNG team


10 ARCMIN
PLANCK


CHANDRA+HST

dish diameter

ACT/SPT
~1.5 arcmin

Planck
9 arcmin

resolution

Green Bank Telescope

dish diameter

Planck
9 arcmin

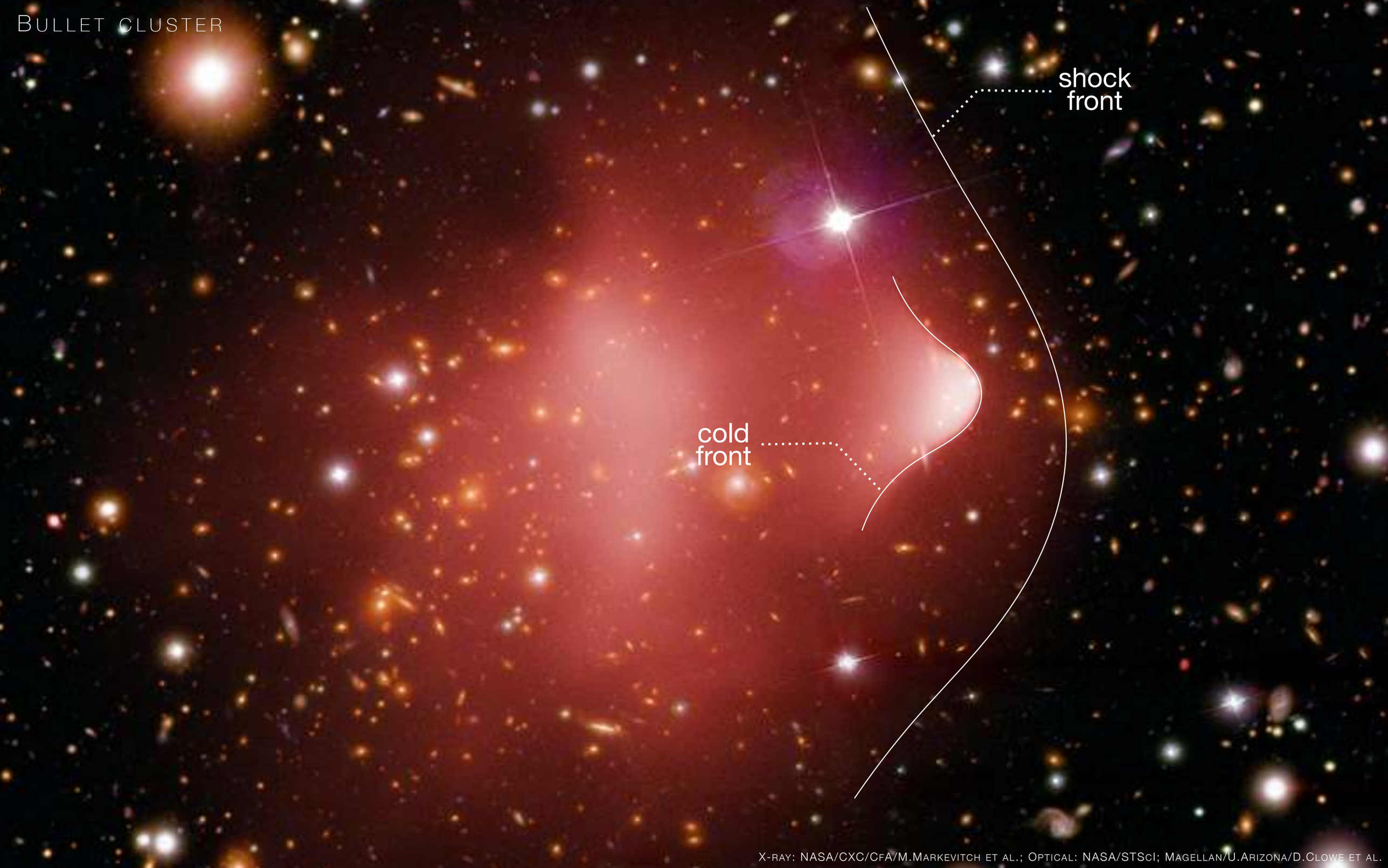
ACT/SPT
~1.5 arcmin

IRAM+NIKA2
~15 arcsec

GBT+MUSTANG2
LMT+TolTEC
~9 arcsec

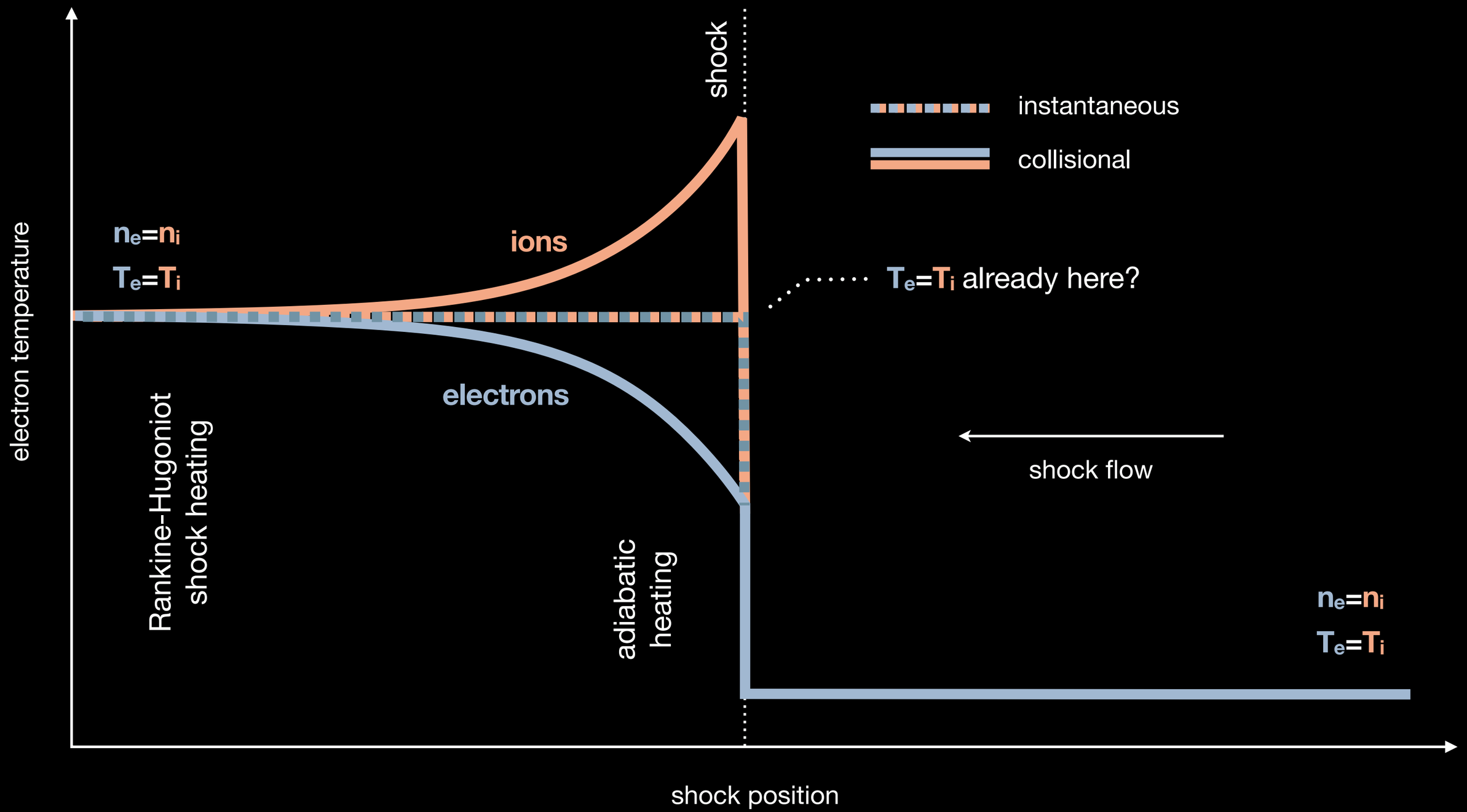
resolution

Bullet cluster

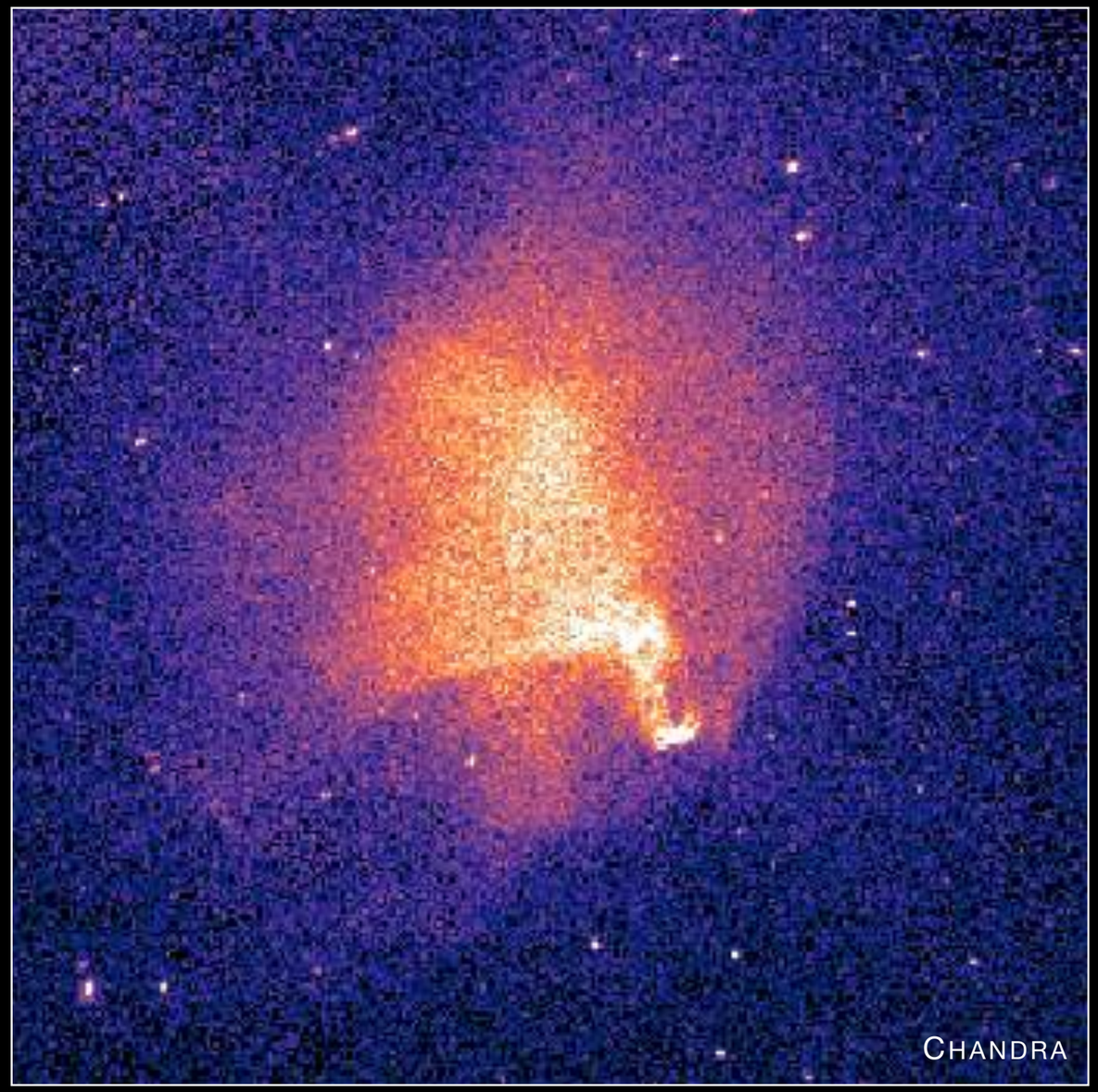


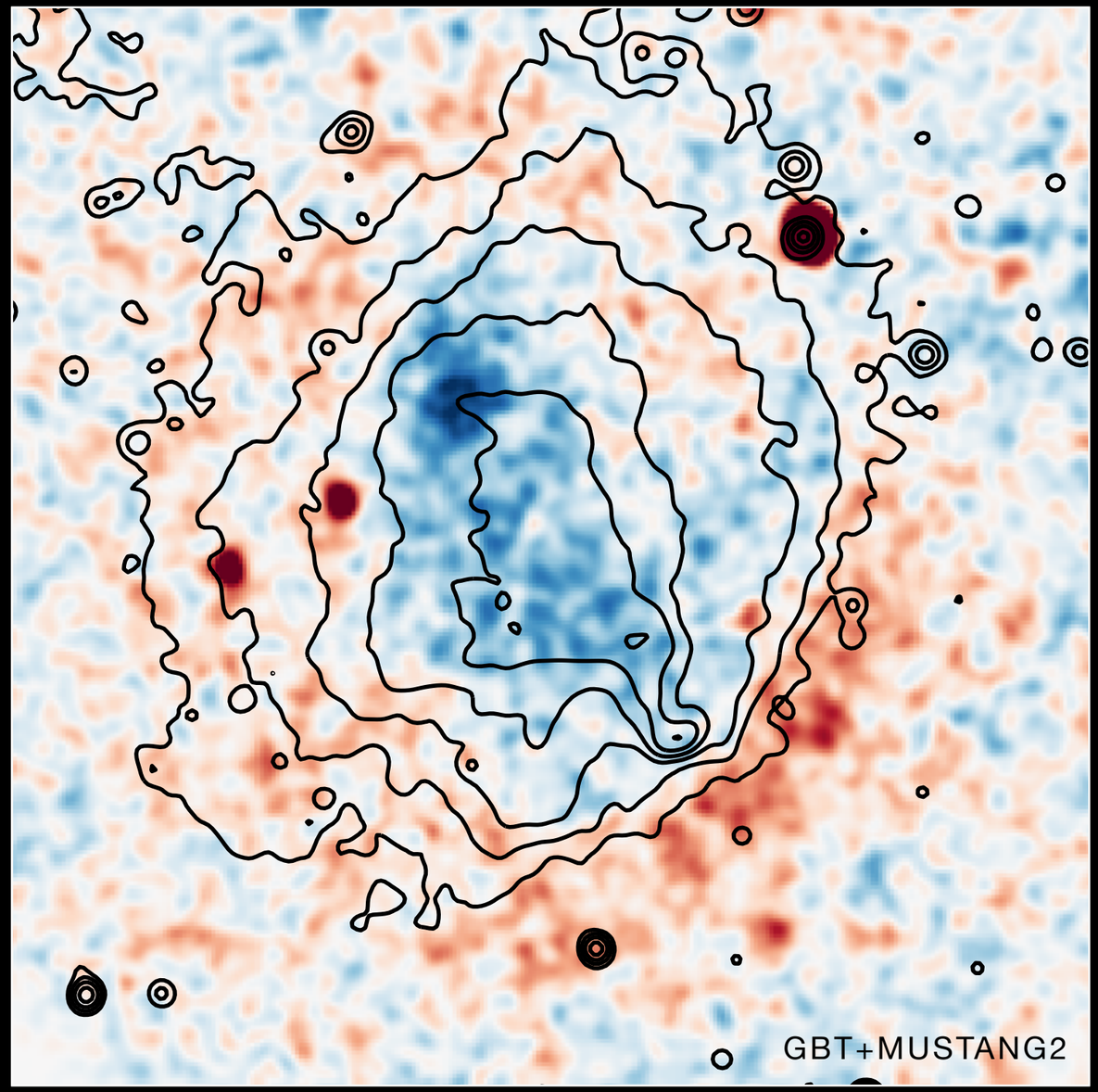
X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.

Ion-electron post-shock equilibration



A cosmic train wreck

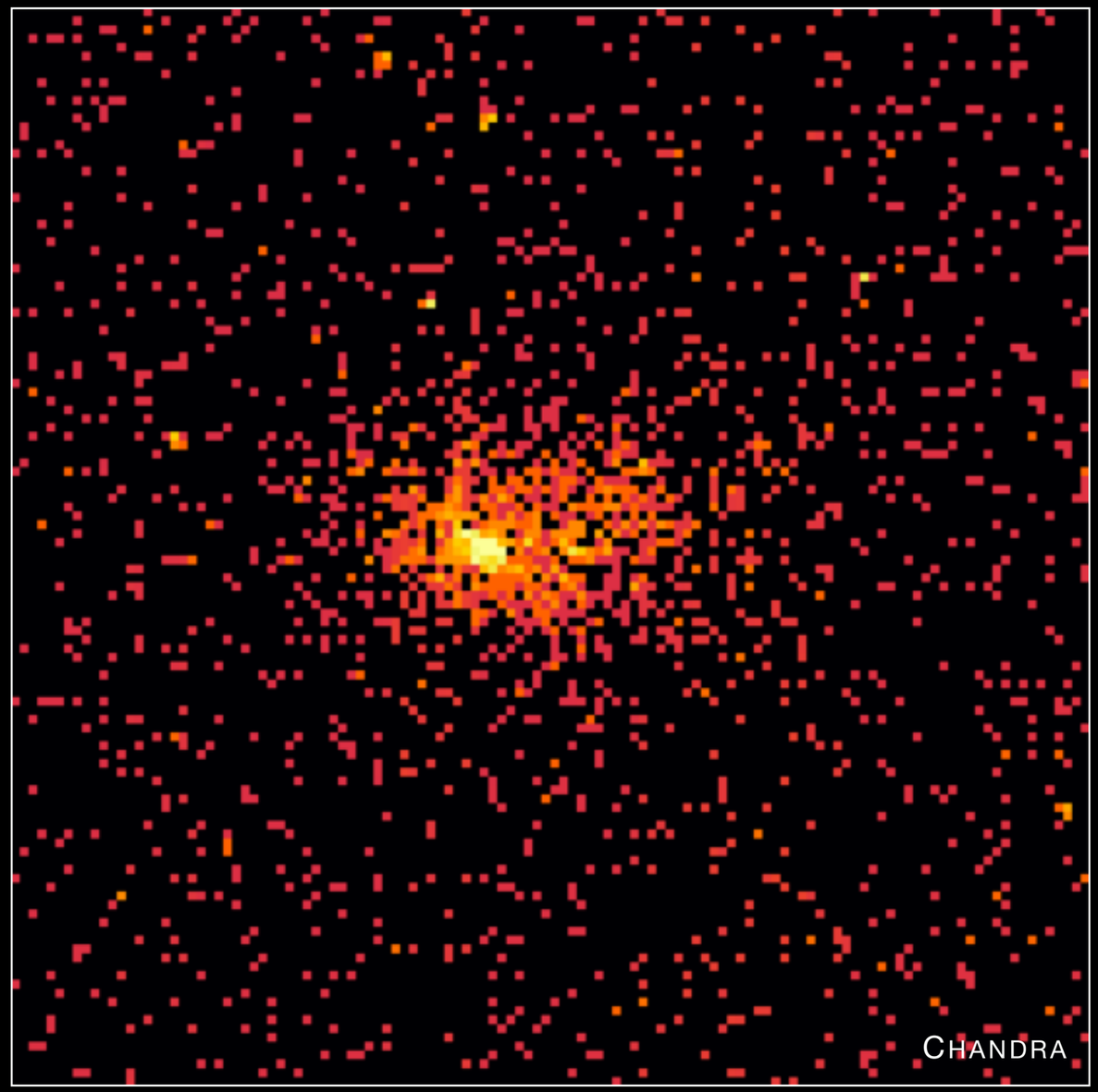


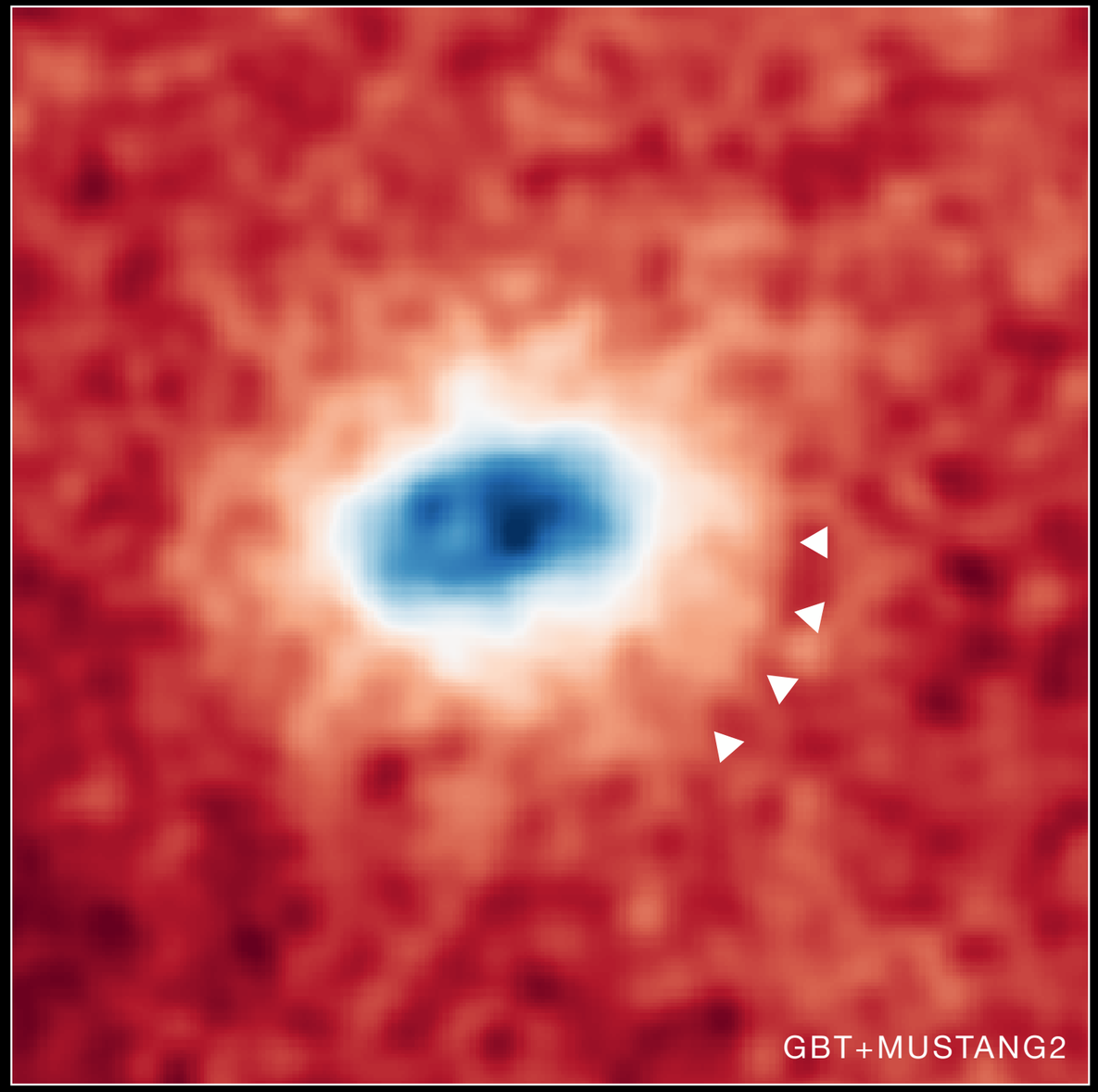


TRAIN WRECK CLUSTER

ADAPTED FROM WANG ET AL., 2018, APJ, 856, 2, 162

High-redshift mergers





MOO J1142+1527

RUPPIN ET AL., 2019, APJ, 893, 1, 74
ADAPTED FROM DICKER ET AL., 2020, APJ, 902, 2, 144

A WORLDWIDE COLLABORATION

22 countries involved

2816 papers

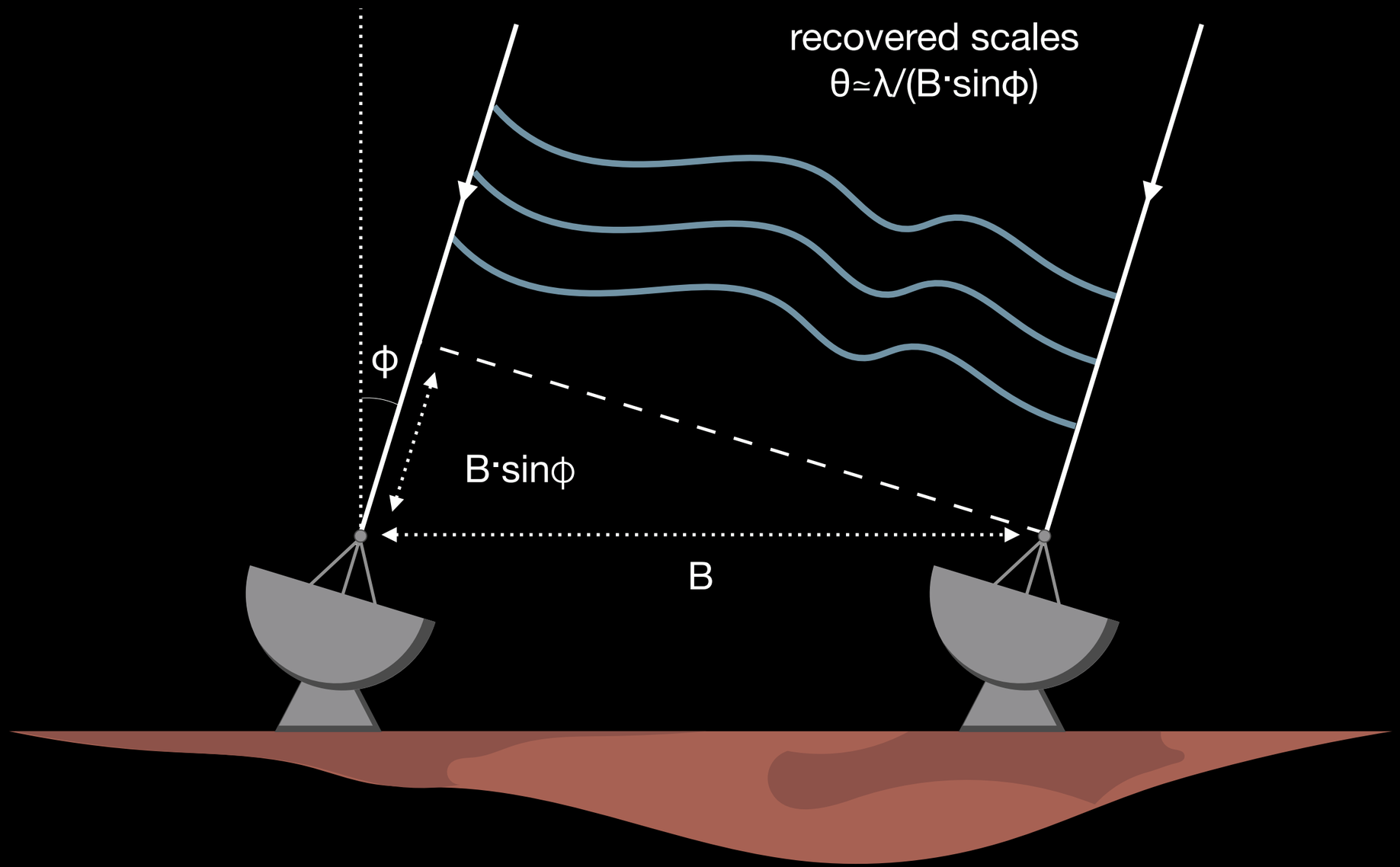
>1000/year new projects

ONE TELESCOPE, MANY ANTENNAE

x54 12-meter (ALMA)

x12 7-meter (ACA)

Let’s talk radio-interferometry



dish diameter

Planck
9 arcmin

ACT/SPT
~1.5 arcmin

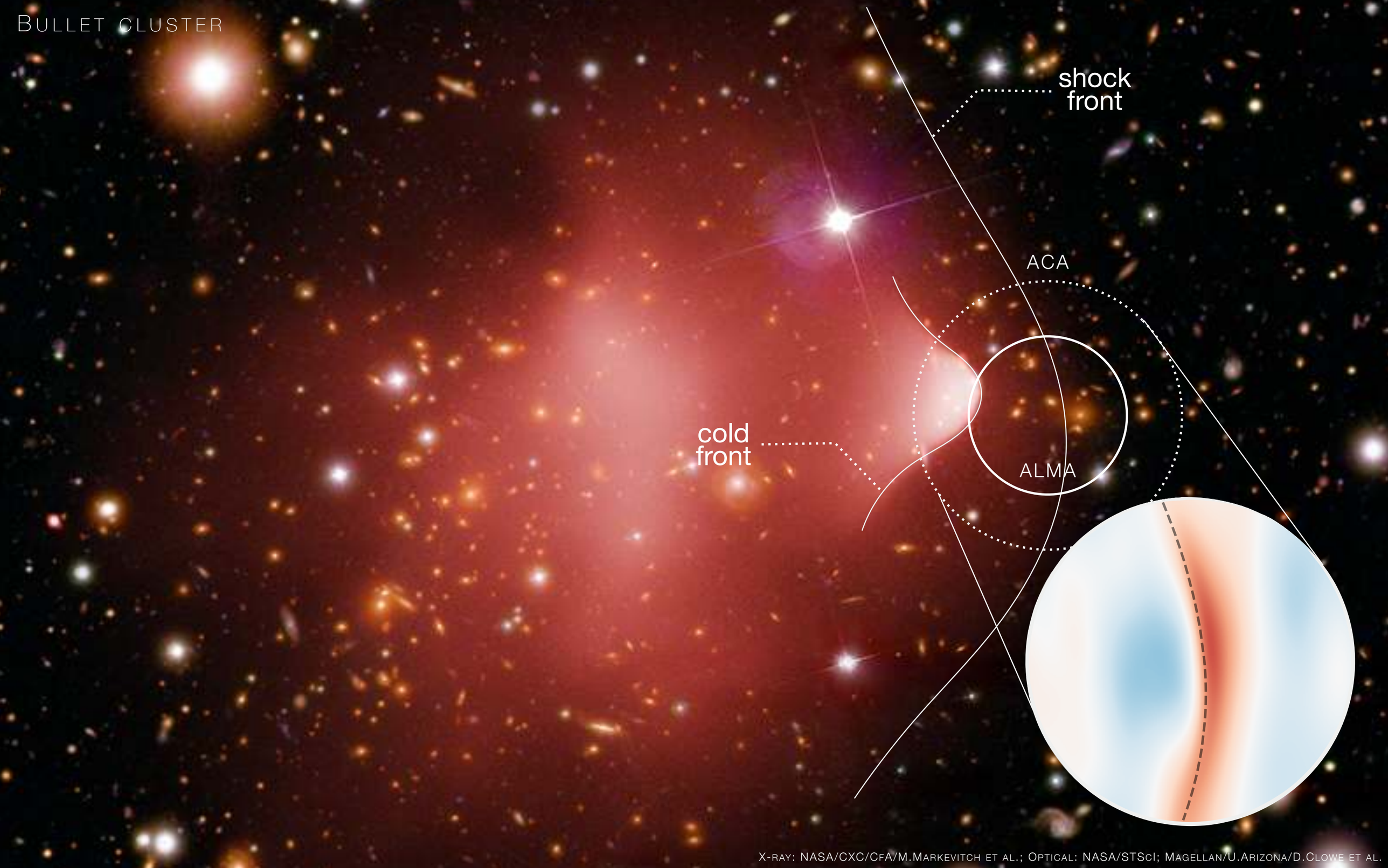
IRAM+NIKA2
~15 arcsec

GBT+MUSTANG2
LMT+TolTEC
~9 arcsec

ALMA
<5 arcsec

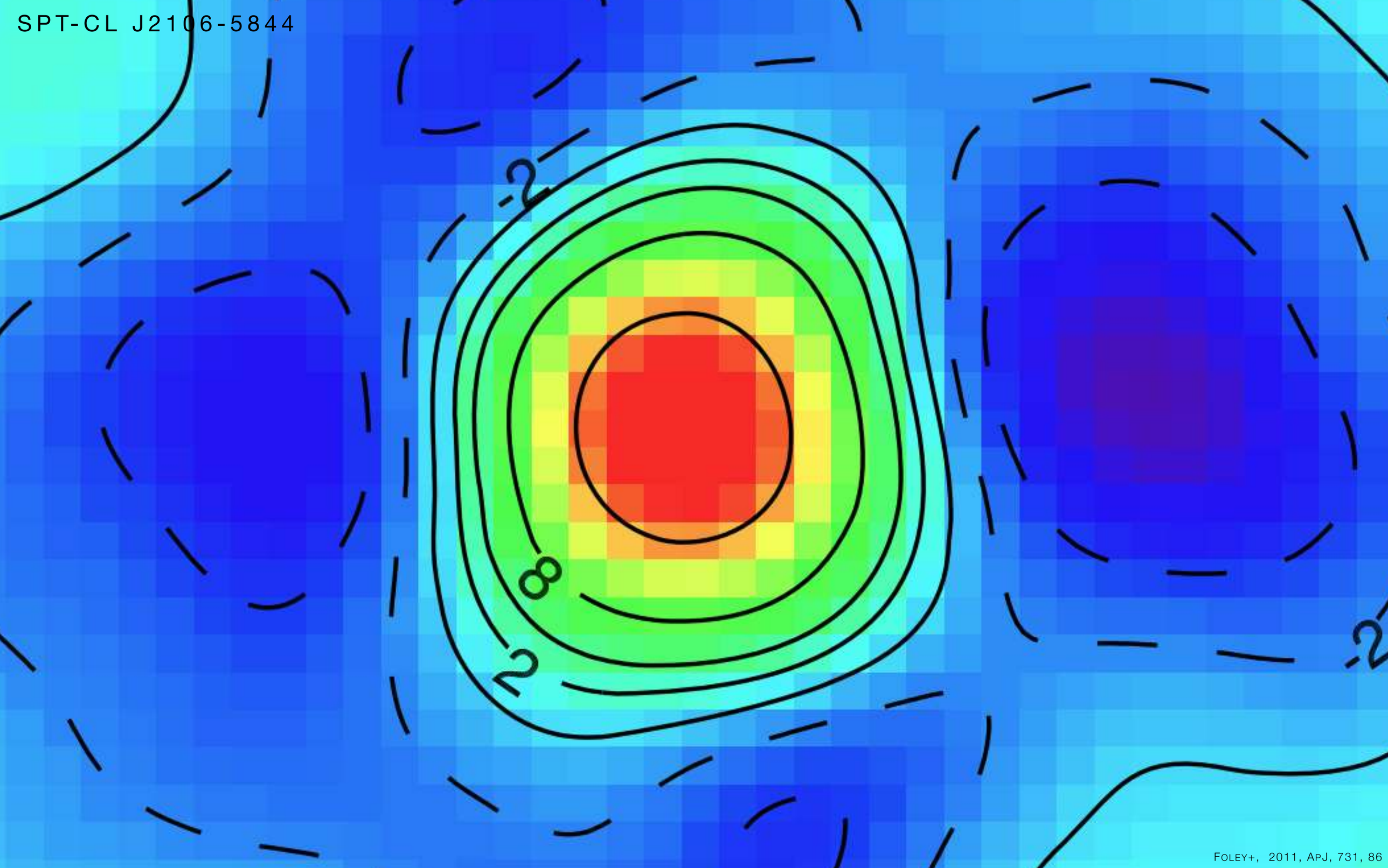
resolution

BULLET CLUSTER



X-RAY: NASA/CXC/CFA/M.MARKEVITCH ET AL.; OPTICAL: NASA/STSCI; MAGELLAN/U.ARIZONA/D.CLOWE ET AL.

SPT-CL J2106-5844

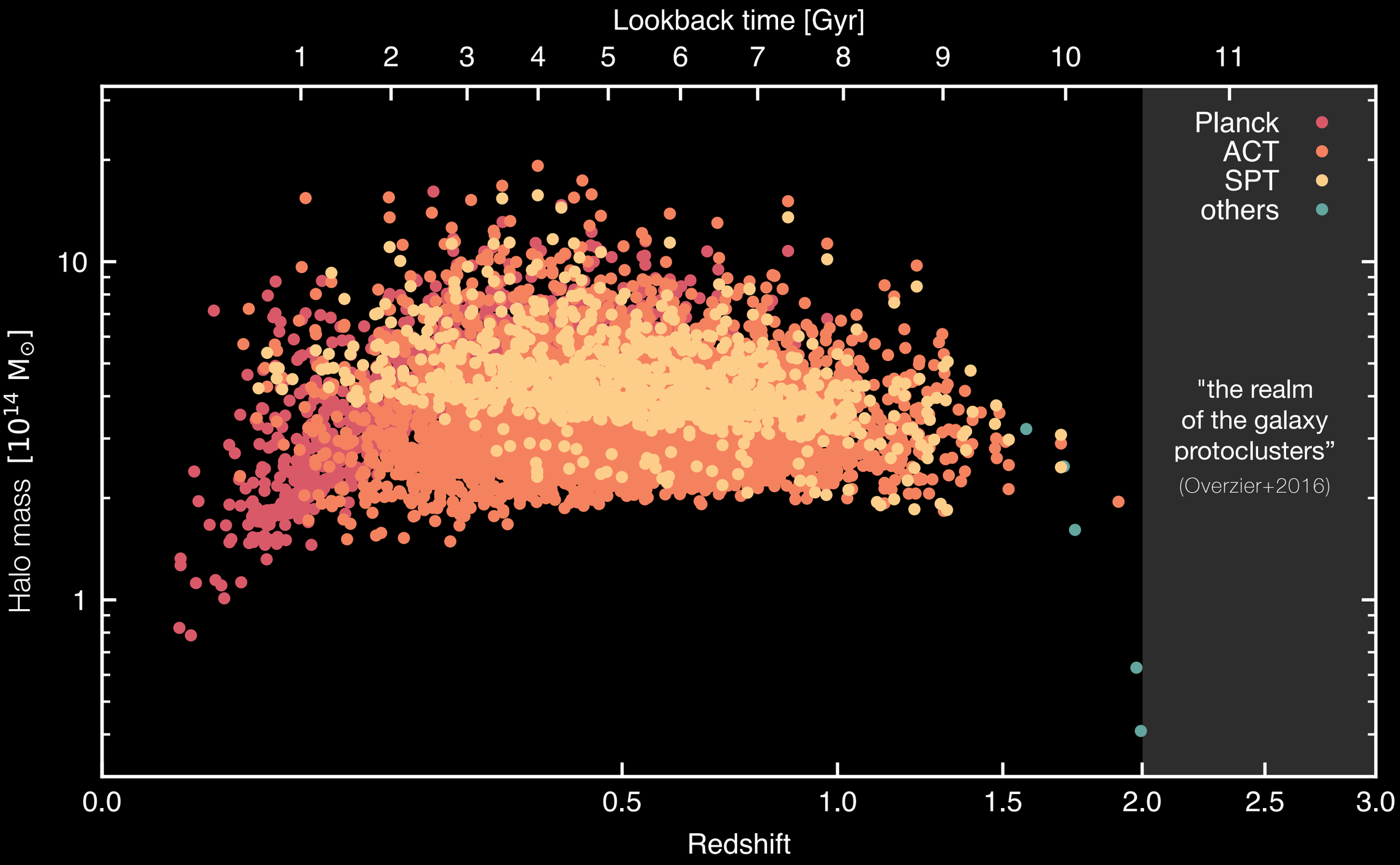


FOLEY+, 2011, APJ, 731, 86

SPT-CL J2106-5844

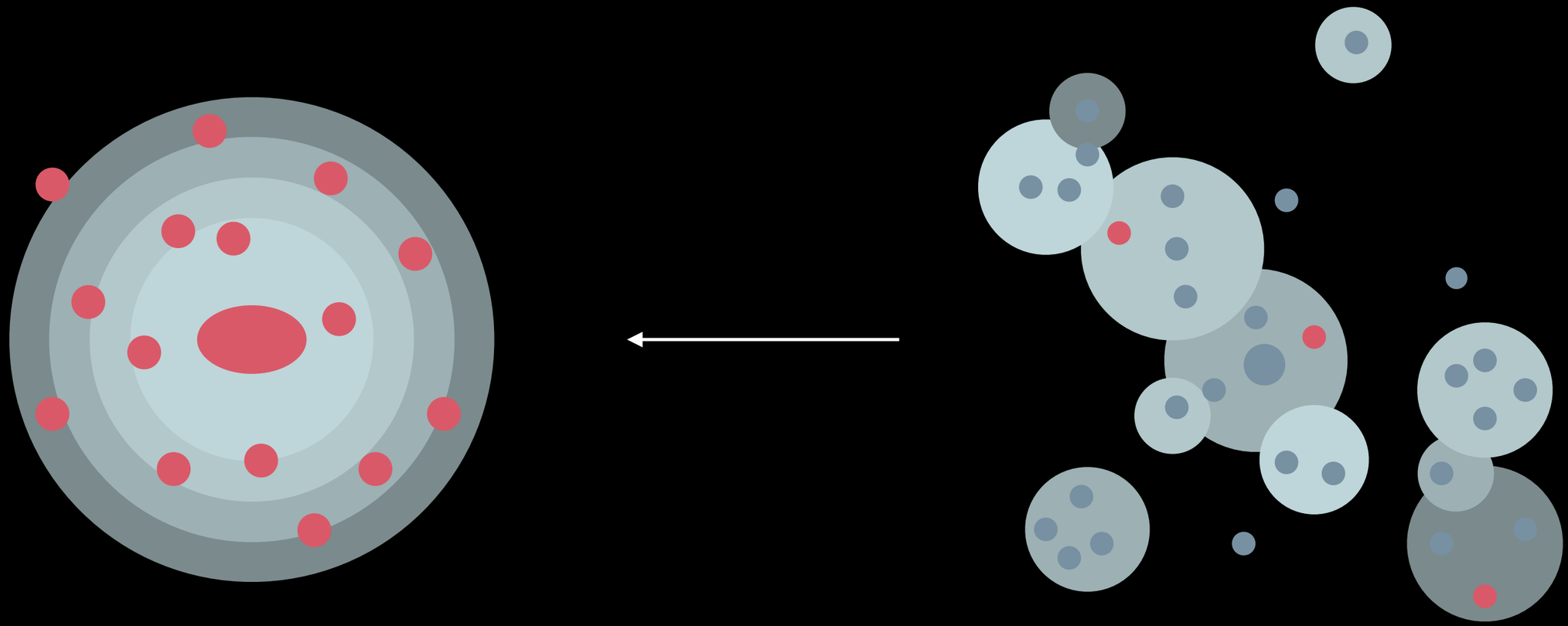
L. Di Mascolo et al., A&A, 650, A153, 2021

clusters across cosmic time



PlanckXXVII 2016, Hilton+2021, Bocquet+2019, Huang+2020, Bleem+2020

a turning point in cosmic history



mature clusters

environmental quenching
extended, thermalised haloes
of intracluster medium

protocluster overdensities

energetic AGN feedback
sustained star formation

adapted from Chiang+2017 & Shimakawa+2018

SPIDERWEB PROTOCLUSTER

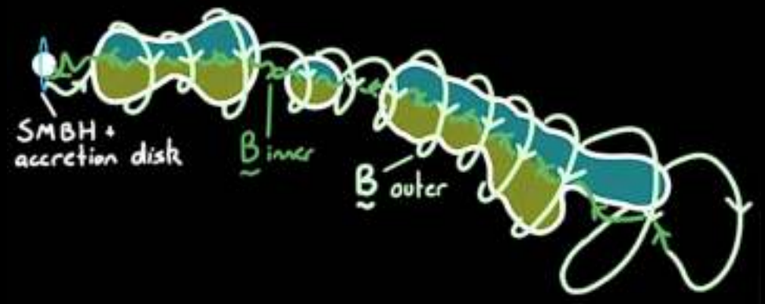
proto-ICM

central galaxy

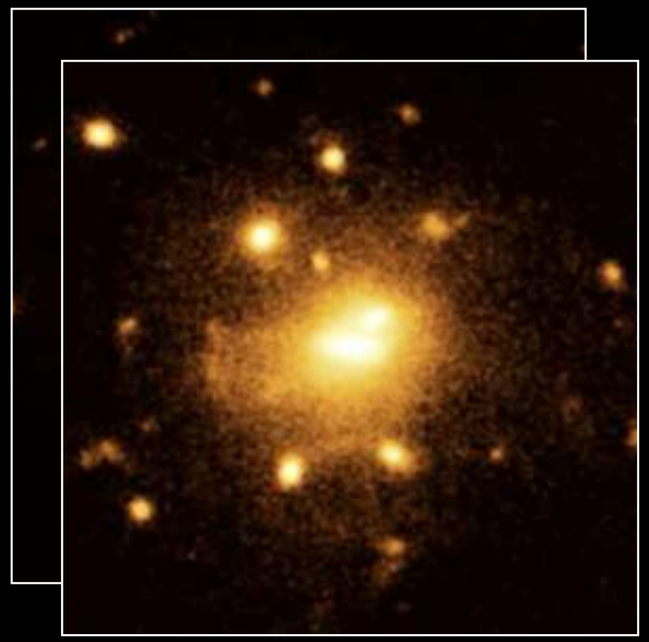
radio jets

confirmation of long-standing predictions

Pentericci+1997, Hatch+2009
Star-bursting proto-BCG fed by “cooling flow”-like precipitation (but not the only scenario)

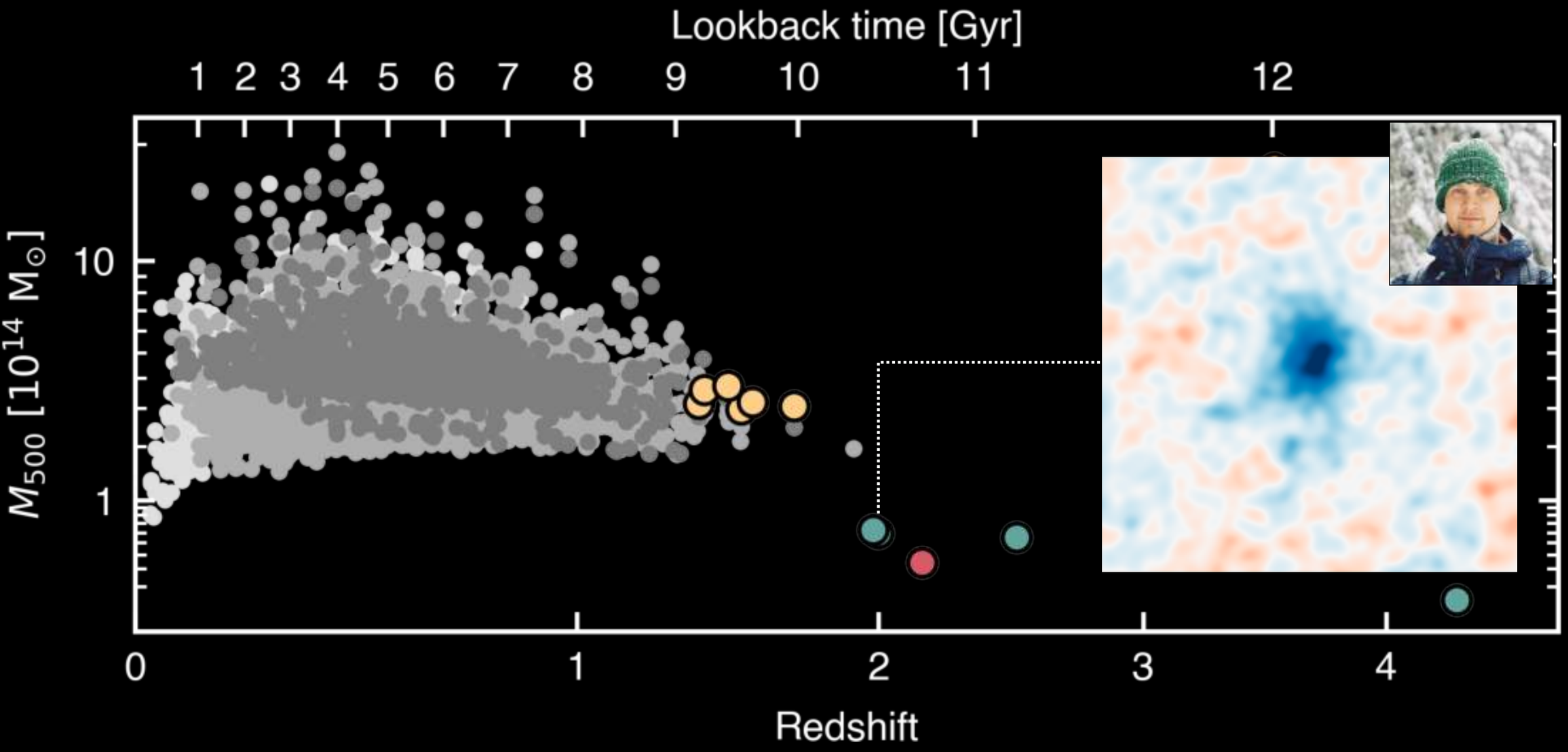


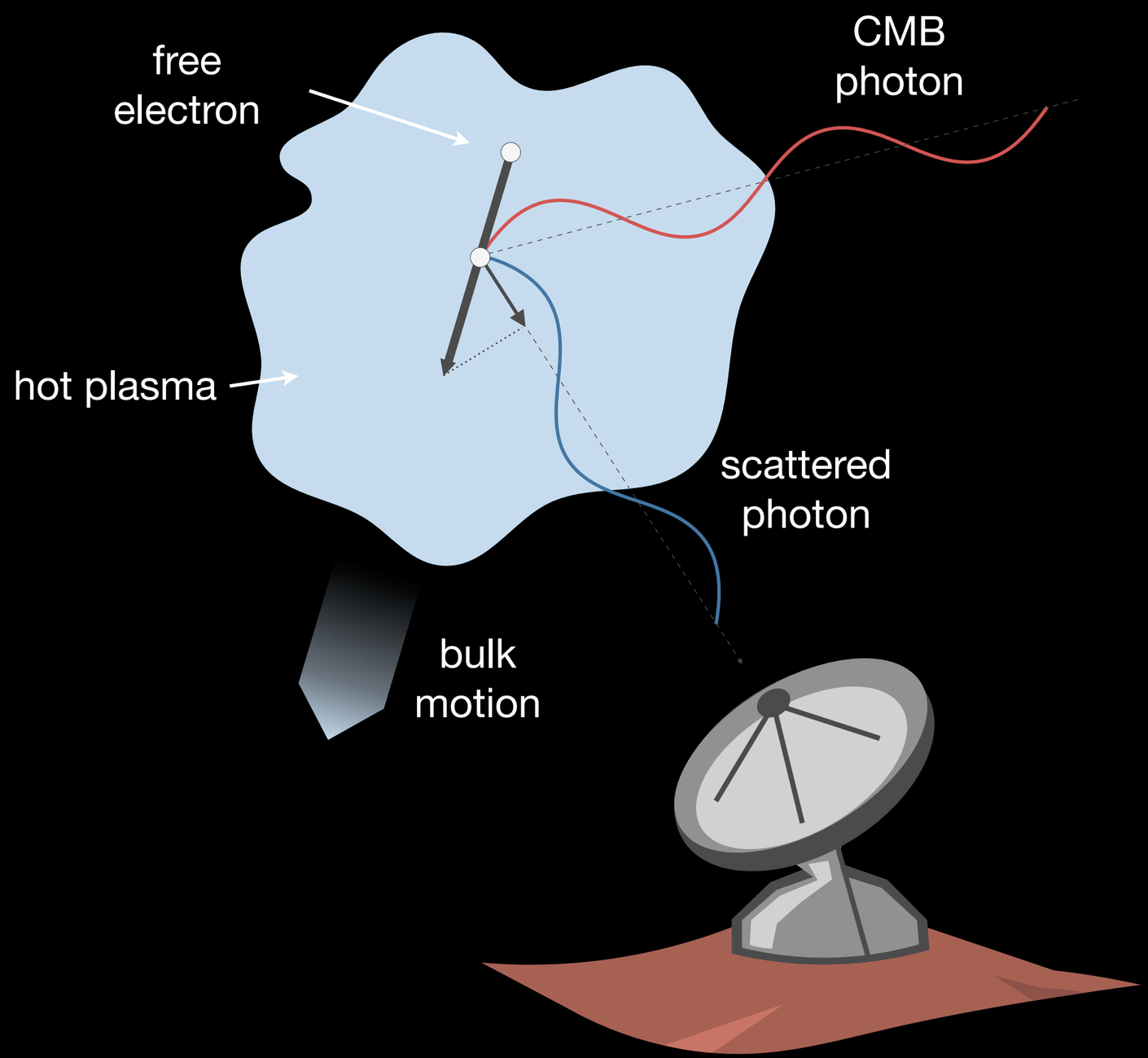
Carilli+1997, Anderson+2022
RMs generate in thin sheath of hot gas around the radio jet



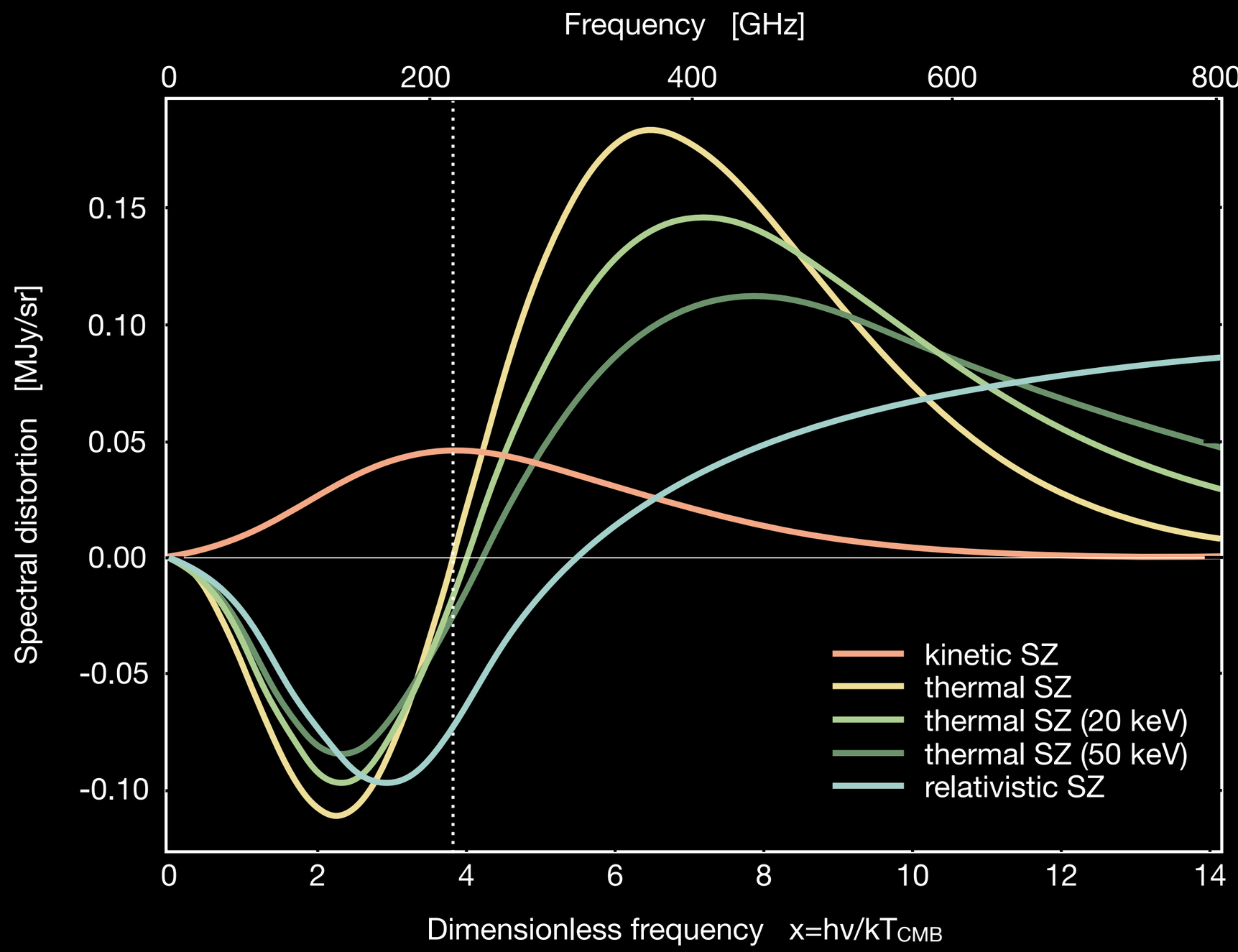
Saro+2009
simulated protoclusters with gravitational potential permeated by ICM at 2-5 keV

extending our observational horizon

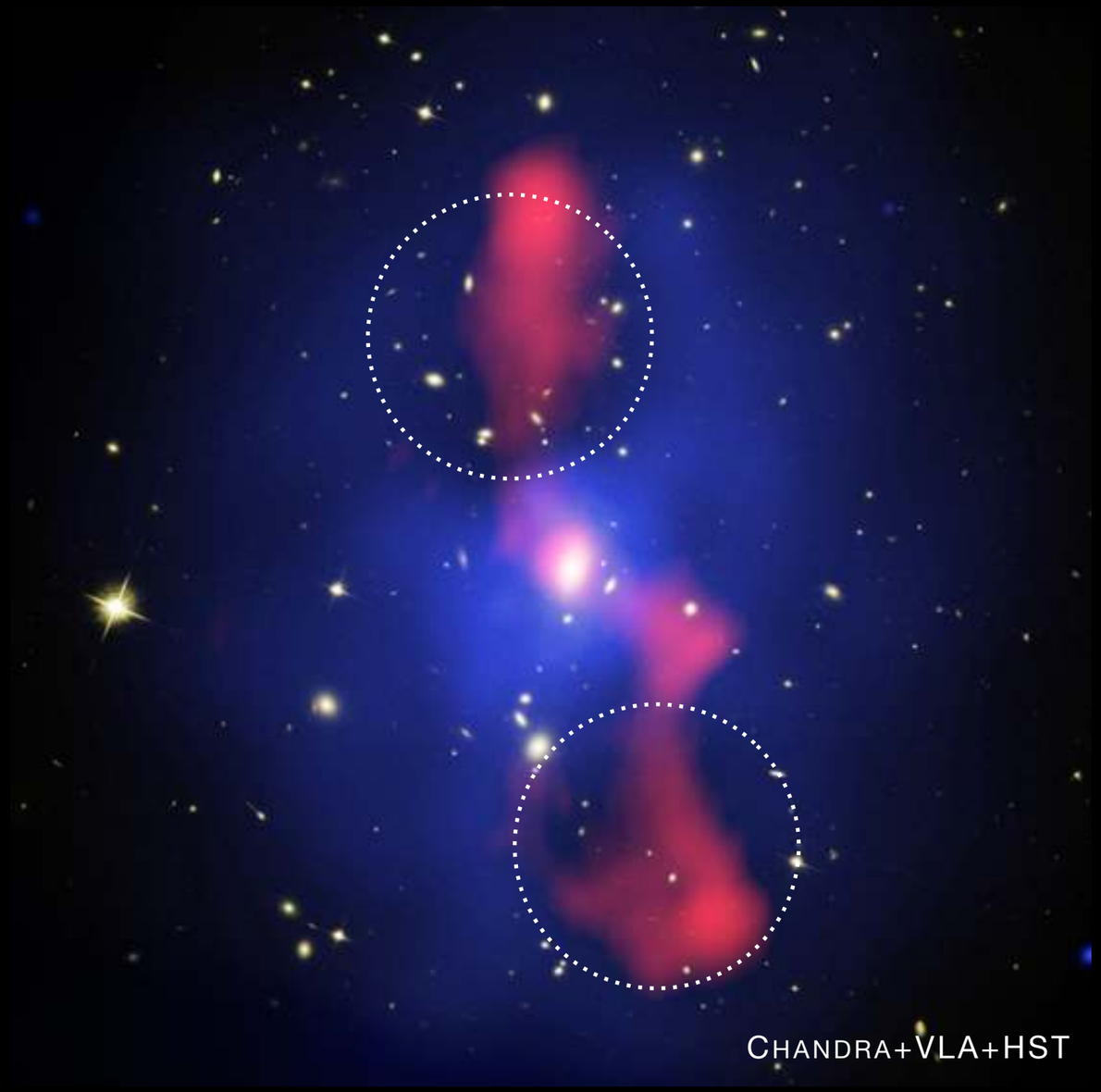


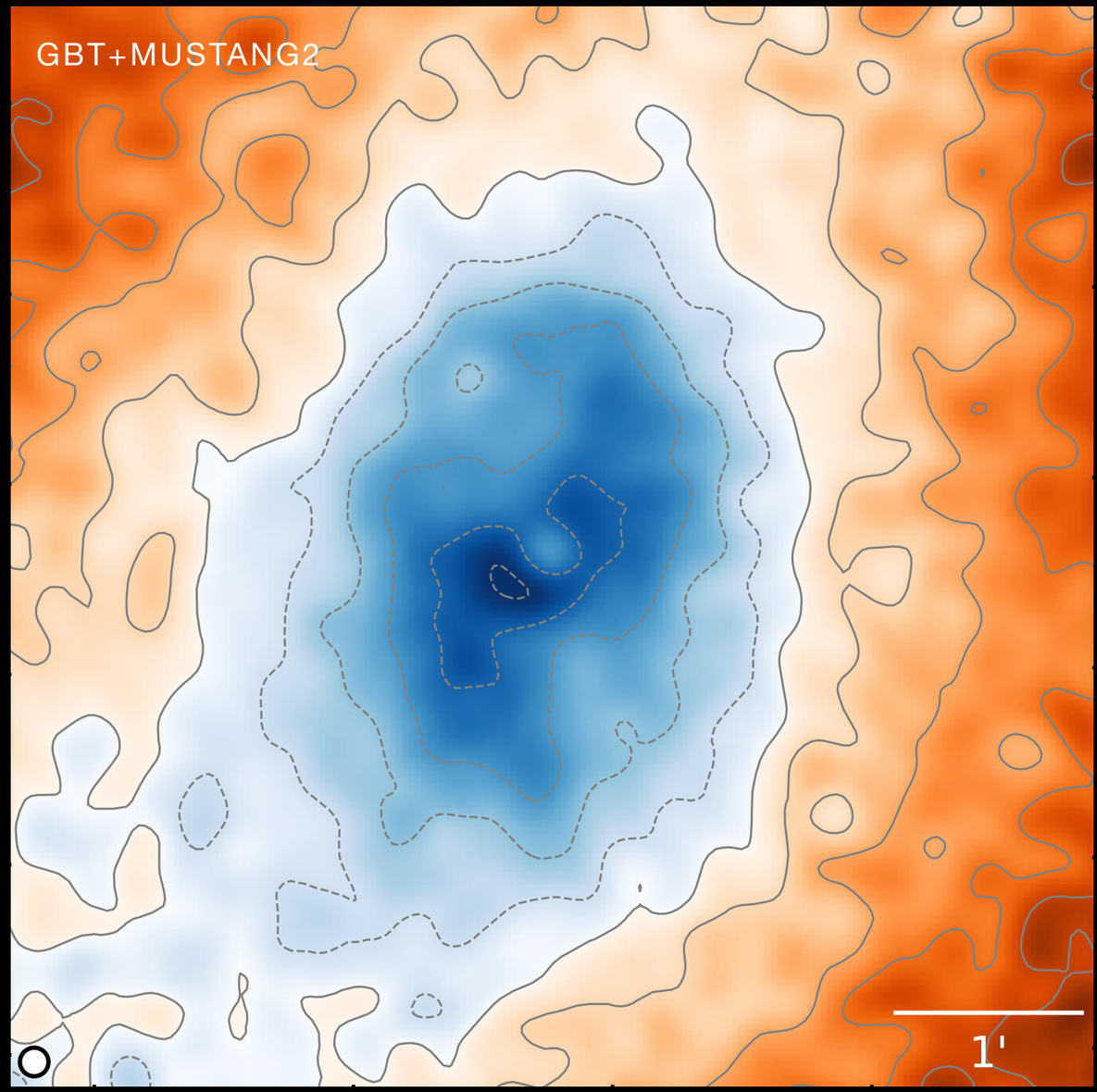

free
electron
CMB
photon
hot plasma
scattered
photon
bulk
motion

The SZ effect(s)



SZ view of AGN feedback

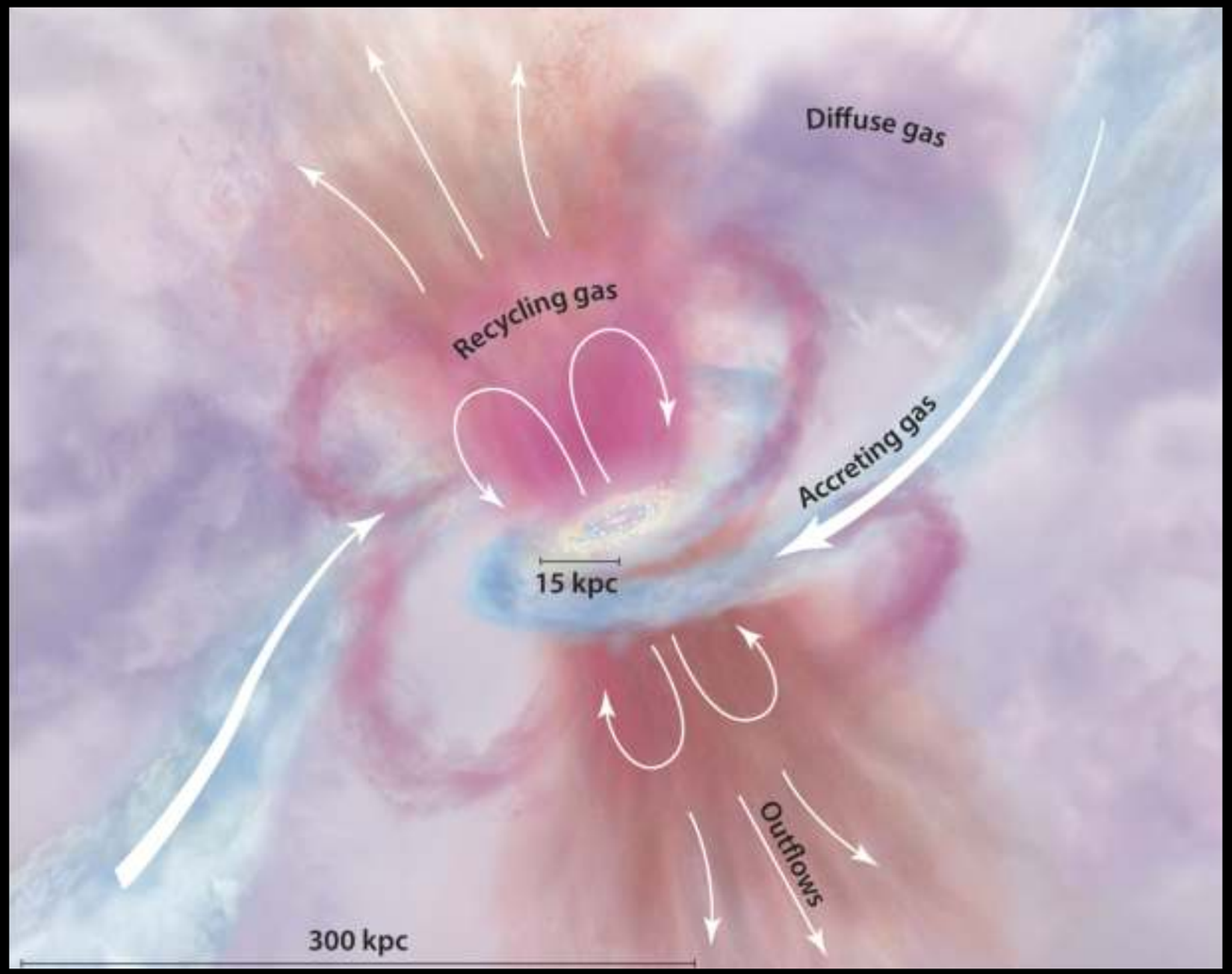


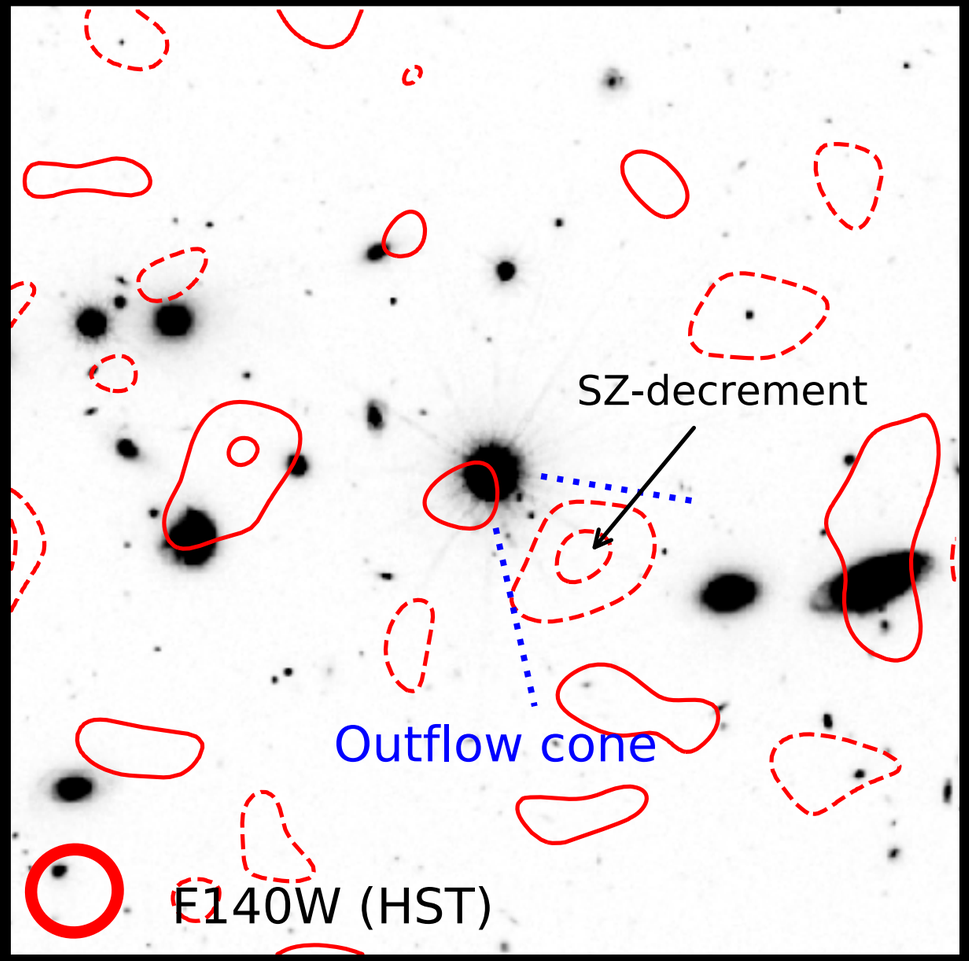


MS 0735.6+7421

NASA/CXC, NASA/ESA/STScI, B. McNamara (University Waterloo) / NRAO, L. Birzan et al. (Ohio University) / T. Mroczkowski (ESO)

Detecting quasar outflows





J. Tumlinson et al., ARA&A, 55, 1, 207 / M. Lacy et al., MNRAS, 483, 2019

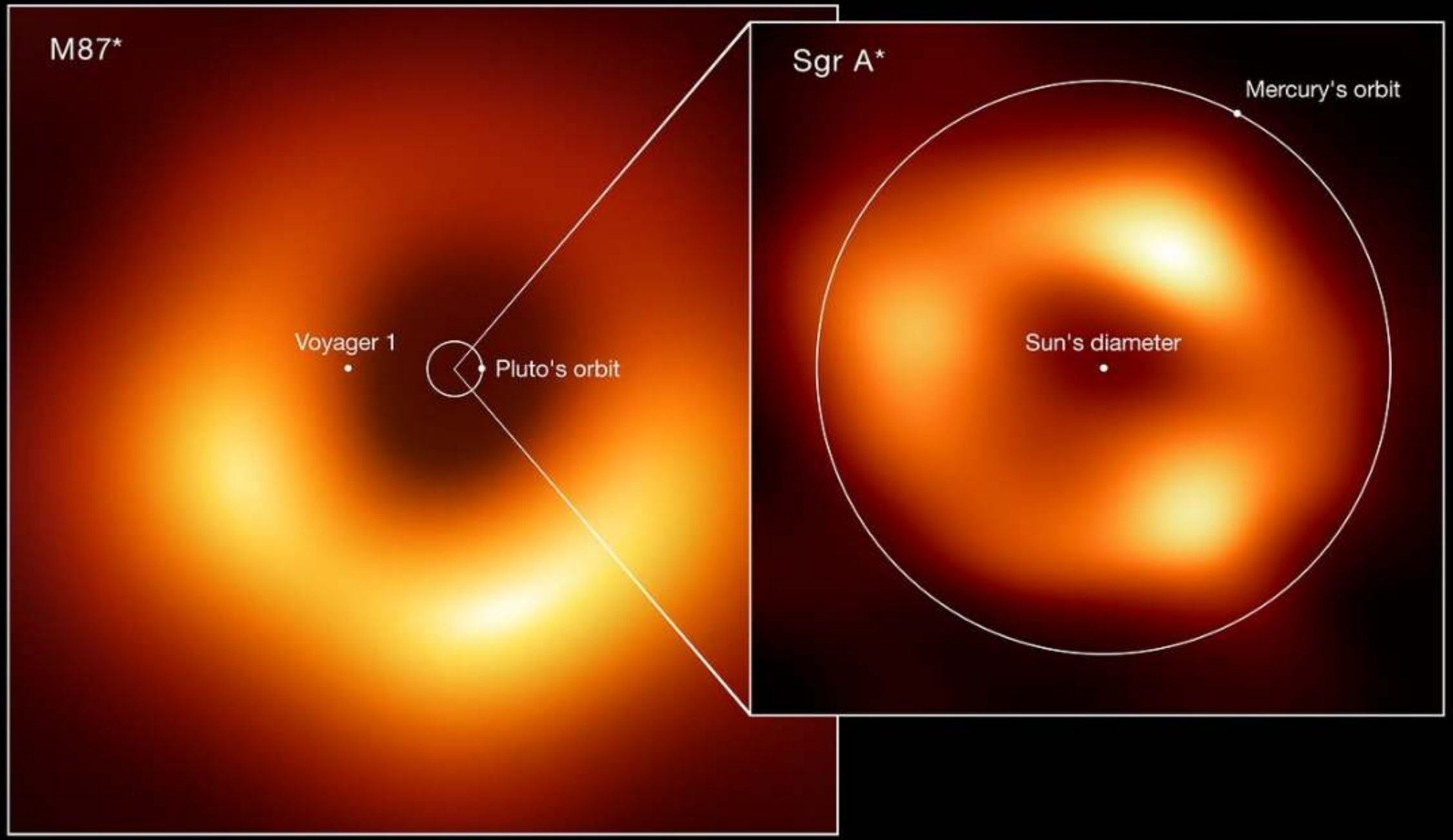
A new window on the millimetre Universe

Large Millimeter telescope
TolTEC

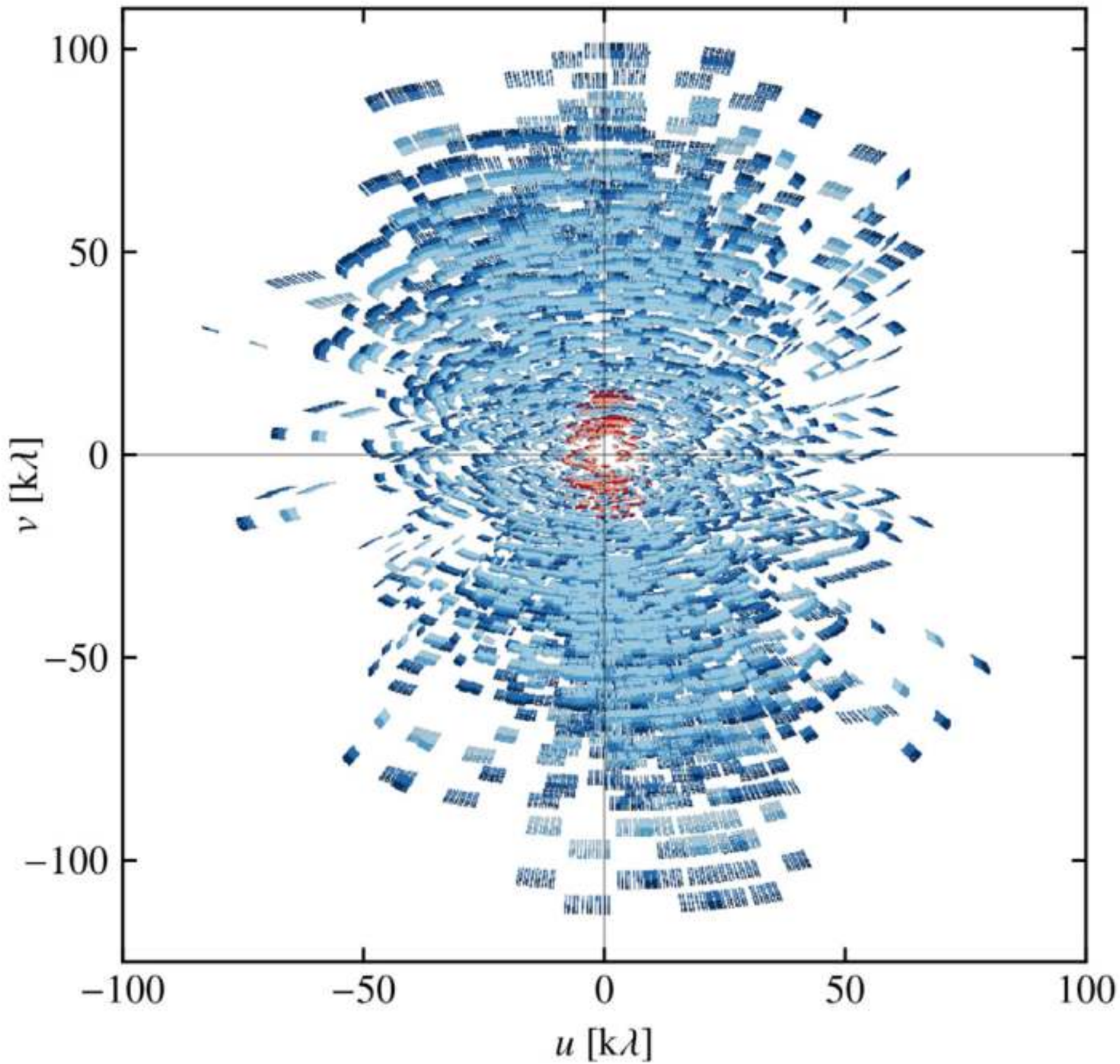
Sardinia Radio Telescope
MISTRAL

Atacama Large Aperture
Submillimeter Array

Hope to see you soon!


M87*
Voyager 1
Pluto's orbit
Sgr A*
Mercury's orbit
Sun's diameter

Let's talk radio-interferometry



April 5

April 6

April 10

April 11

DIFMAP

eht-imaging

SMILI

50 μas

Brightness Temperature (10^9 K)

0

2

4

6

0

2

4

6

8

10

0.0

2.5

5.0

7.5