EBERHARD KARLS UNIVERSITÄT TÜBINGEN

UNIVERSITÄT BONN

Argelander-Institut für Astronomie

奈良女子大学 Nara Women's University

TNU/SAGI International Summer School of Research and Exploration in Astronomy 2024

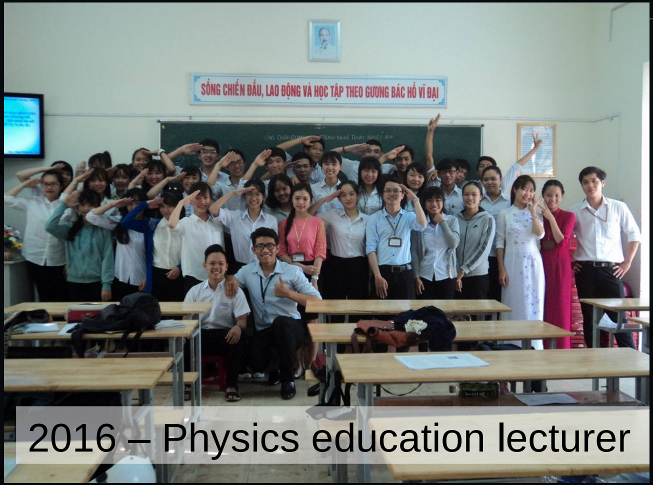
Galaxy clusters

Speaker: Nhàn T. Nguyễn-Đặng (Tübingen, Germany)

Image credit: Volker Springel / Max Planck Institute For Astrophysics

About me

2013 – Bachelor graduation



2016 – Physics education lecturer

2016 – First astronomy activities


2017 – master student

2018 – master student


2023 – PhD candidate

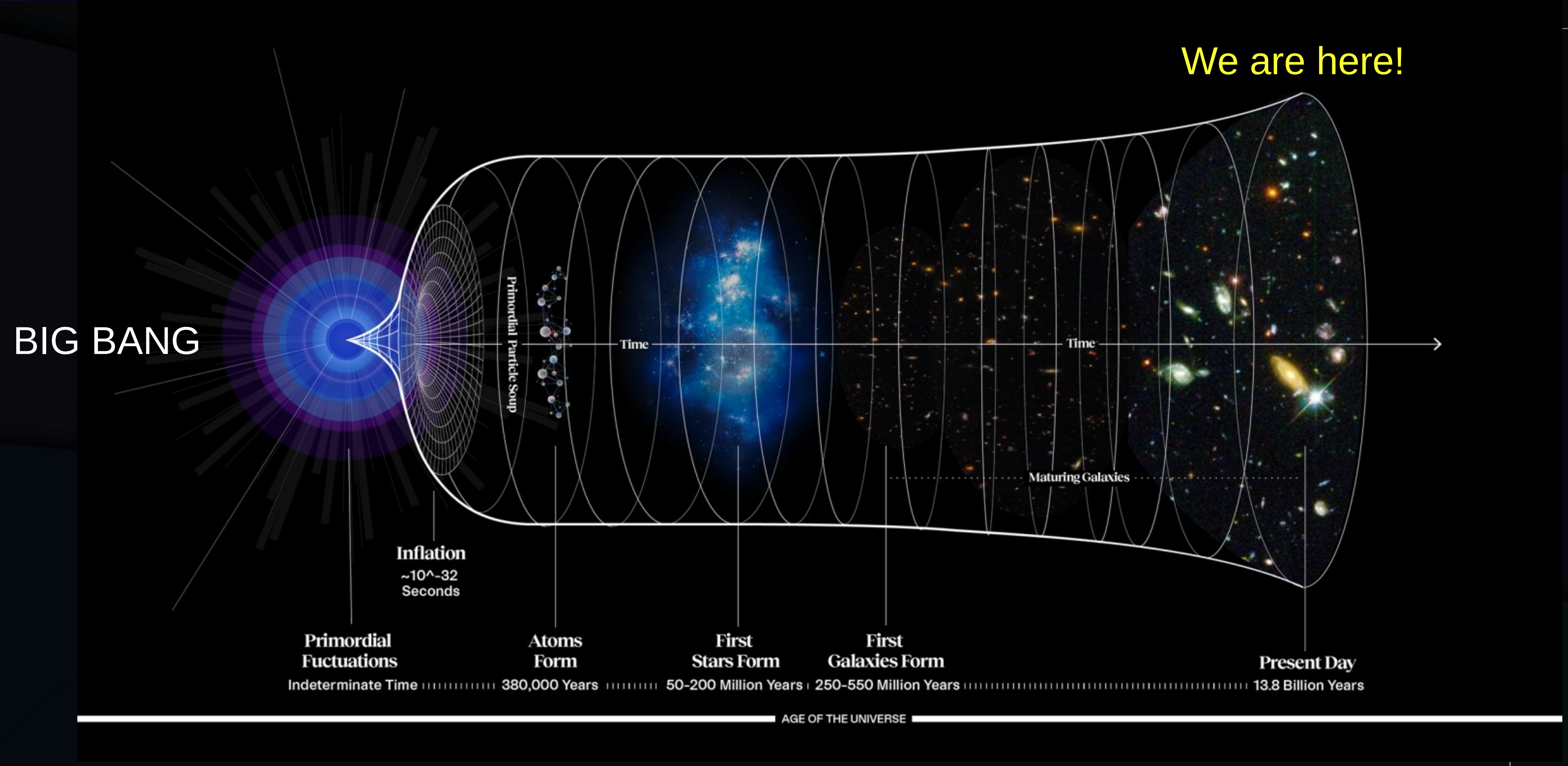


Image credit: Ben Gibson/NASA/Pablo Carlos Budassi/Big Think

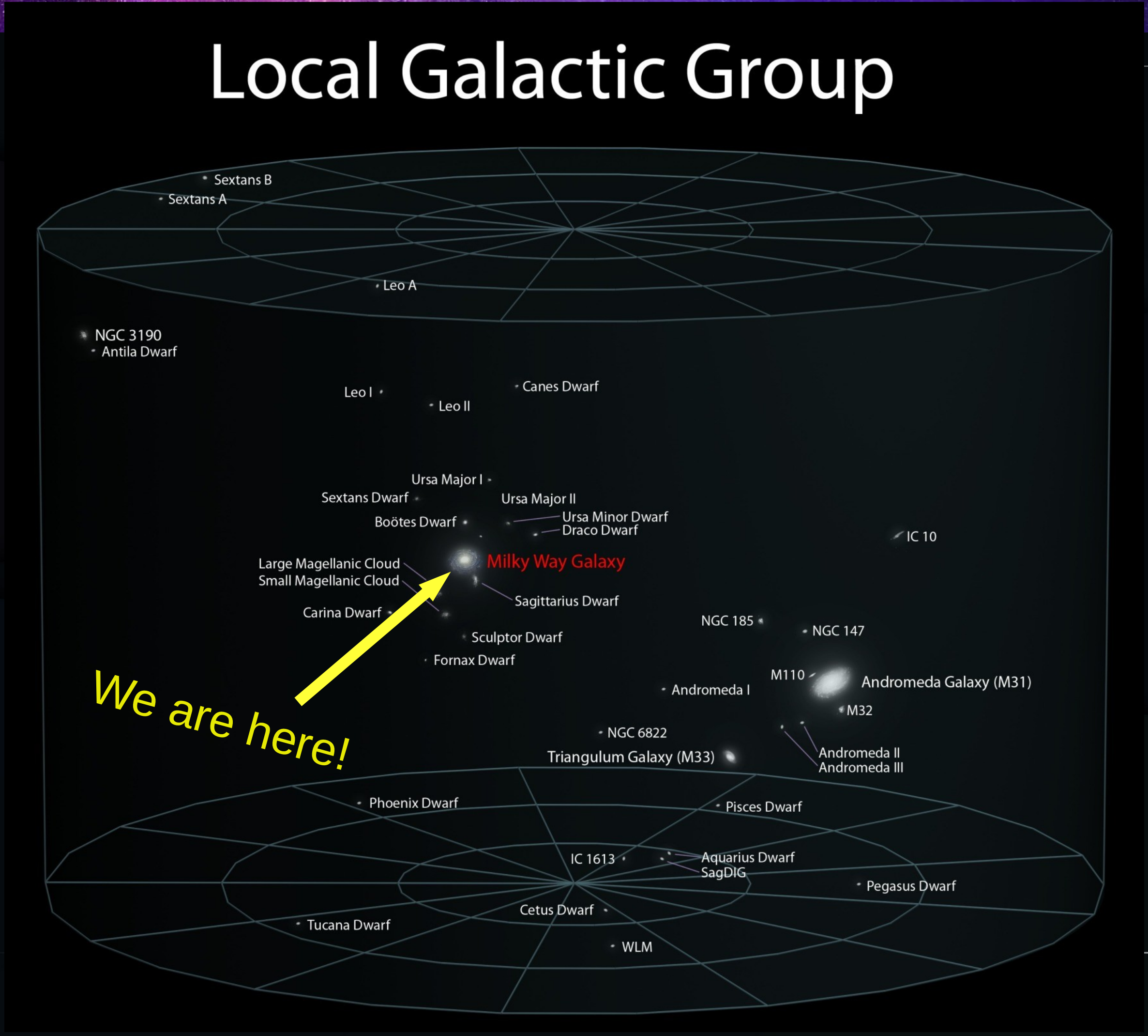
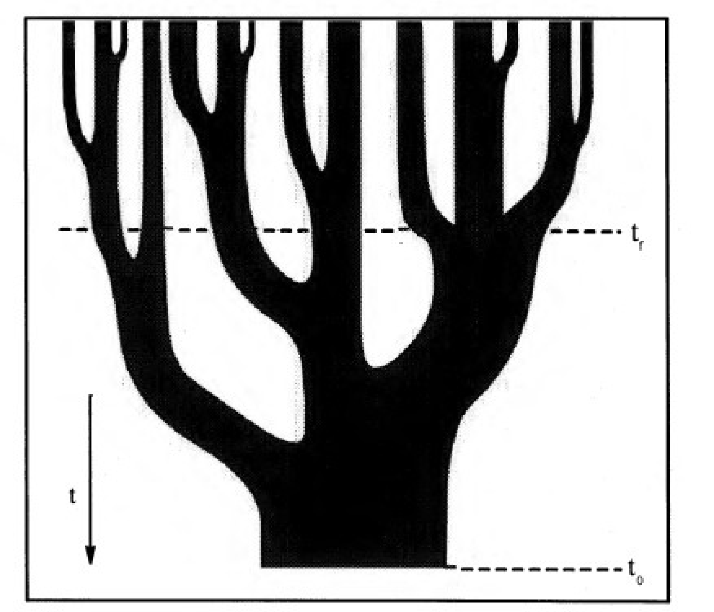


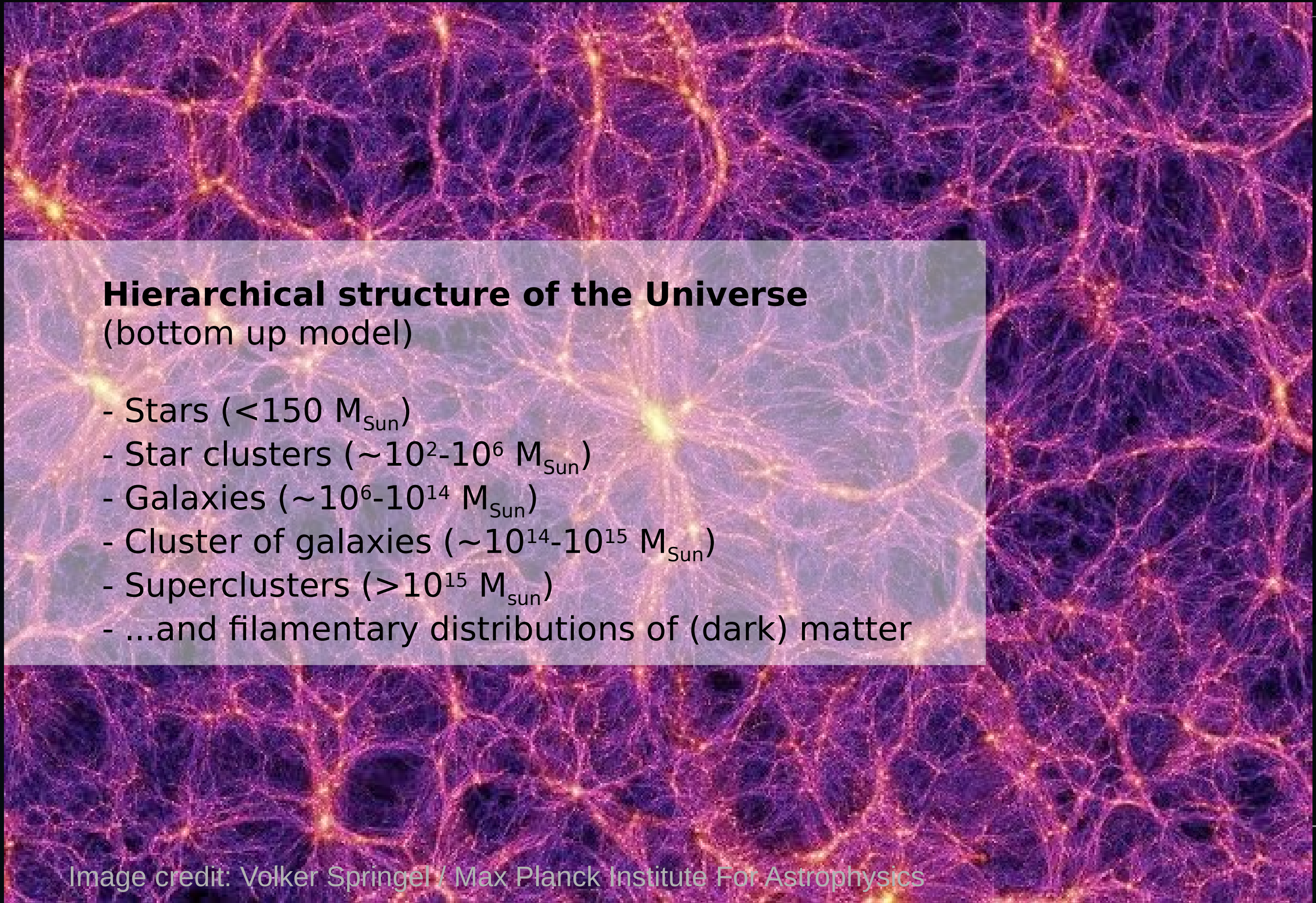
Image credit: By Azcolvin429, via Wikimedia Commons



Lacey & Cole (1993)

Hierarchical structure of the Universe
(bottom up model)

- Stars (<150 M_{Sun})
- Star clusters (~10^2-10^6 M_{Sun})
- Galaxies (~10^6-10^{14} M_{Sun})
- Cluster of galaxies (~10^{14}-10^{15} M_{Sun})
- Superclusters (>10^{15} M_{sun})
- … and?



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- Superclusters (>10^{15} M_{sun})
- ...and filamentary distributions of (dark) matter

Image credit: Volker Springel / Max Planck Institute For Astrophysics

GALAXIES MERGING

Image credit: B. Whitmore & NASA

The Antennae

Image credit: NASA, ESA, CSA, STScI

The Cartwheel

GALAXY CLUSTERS MERGING

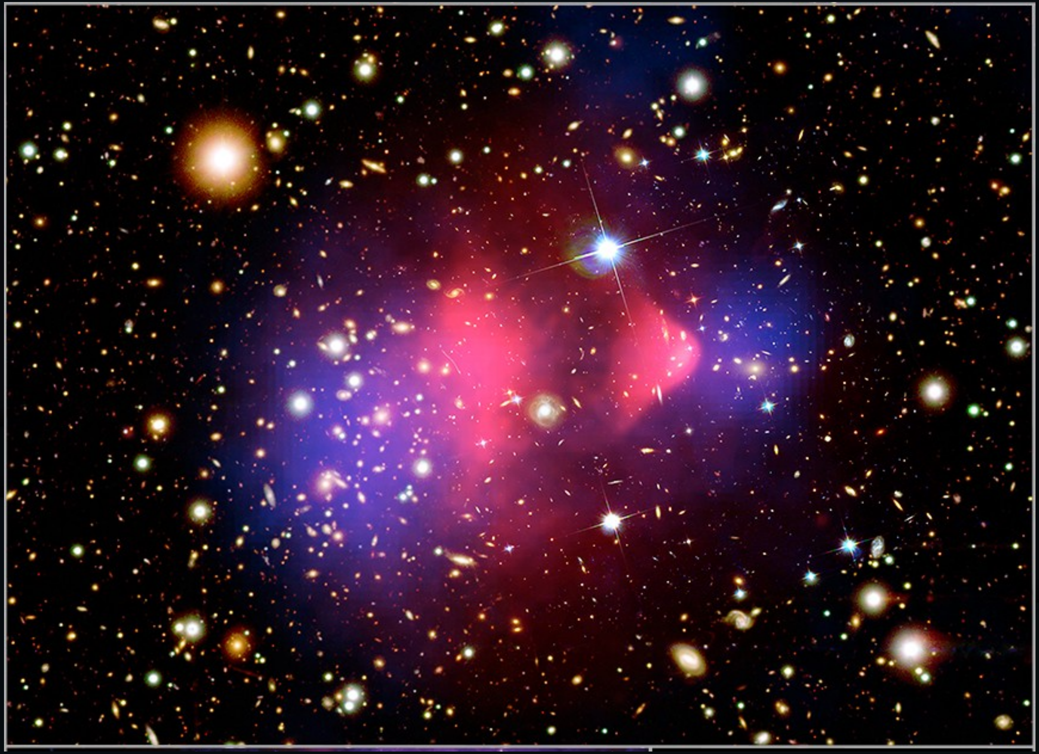


Image credit: X-ray: NASA/CXC/CfA/M.Markevitch, Optical and lensing map: NASA/STScI, Magellan/U.Arizona/D.Clowe, Lensing map: ESO WFI

The Bullet

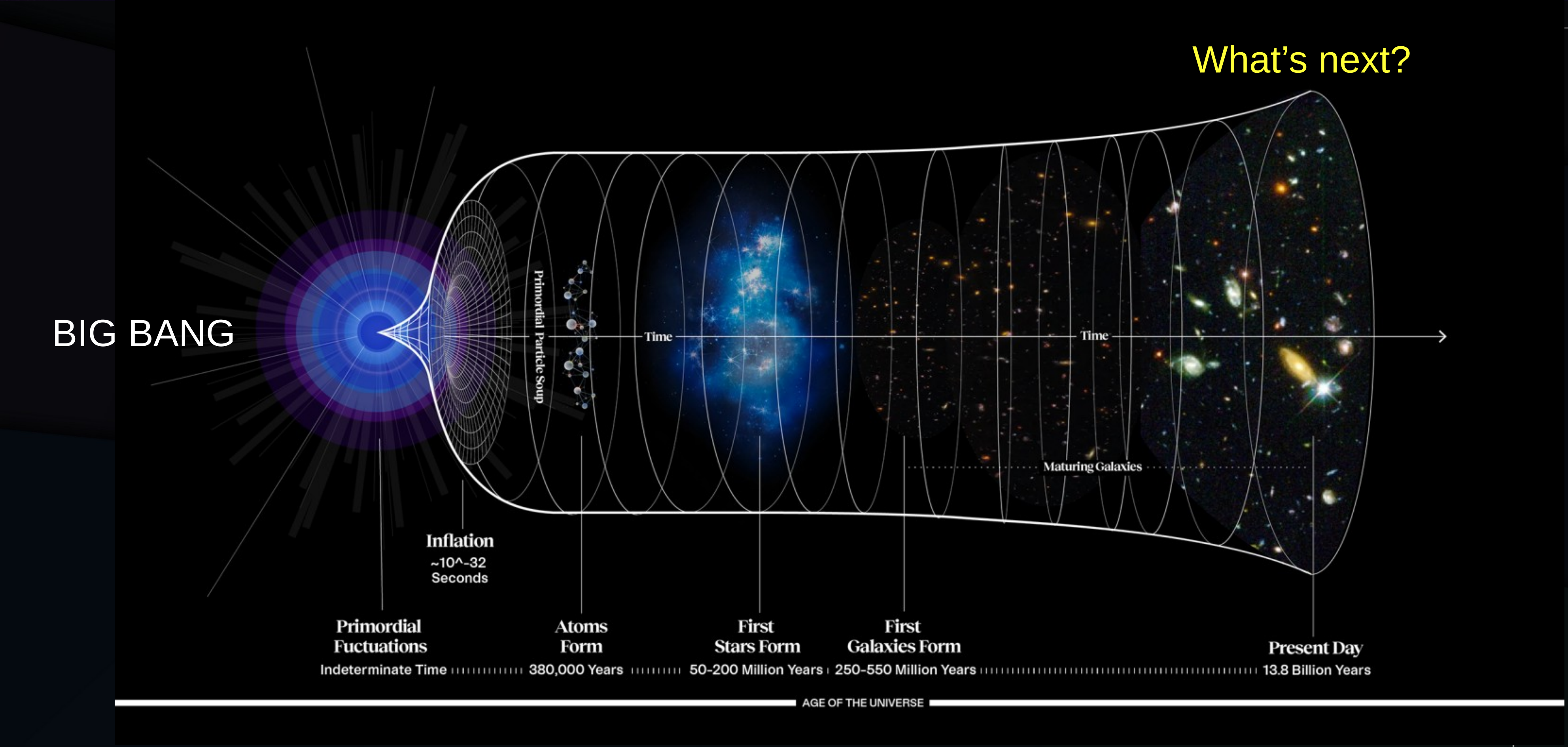


Image credit: Ben Gibson/NASA/Pablo Carlos Budassi/Big Think

HUBBLE EXPANSION

Image credit: https://www.nature.com/articles/nature.2013.13379

- The observed galaxies are redshifted.
=> Almost all galaxies are moving away from each other!

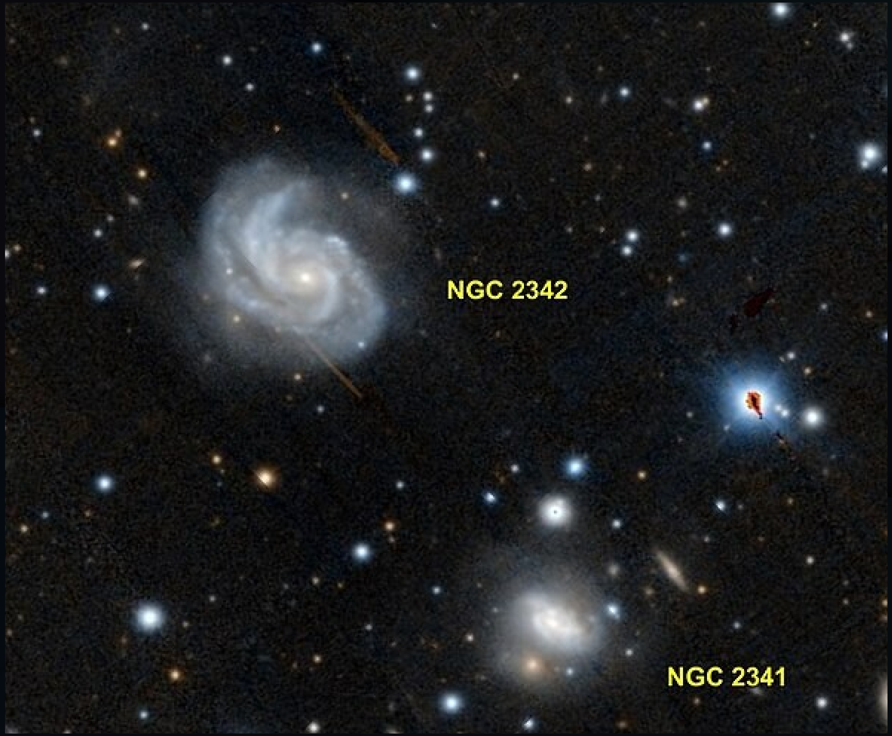
- Recession velocity increases with distance.
=> The further galaxies are moving away from us more quickly!

- Hubble law: $v = H_0\, D$

Recession velocity (km/s)
Hubble constant ~ 70 ($\mathrm{kms^{-1}Mpc^{-1}}$)
Proper distance to us (Mpc)

HUBBLE EXPANSION

$$v = H_0 \, D$$

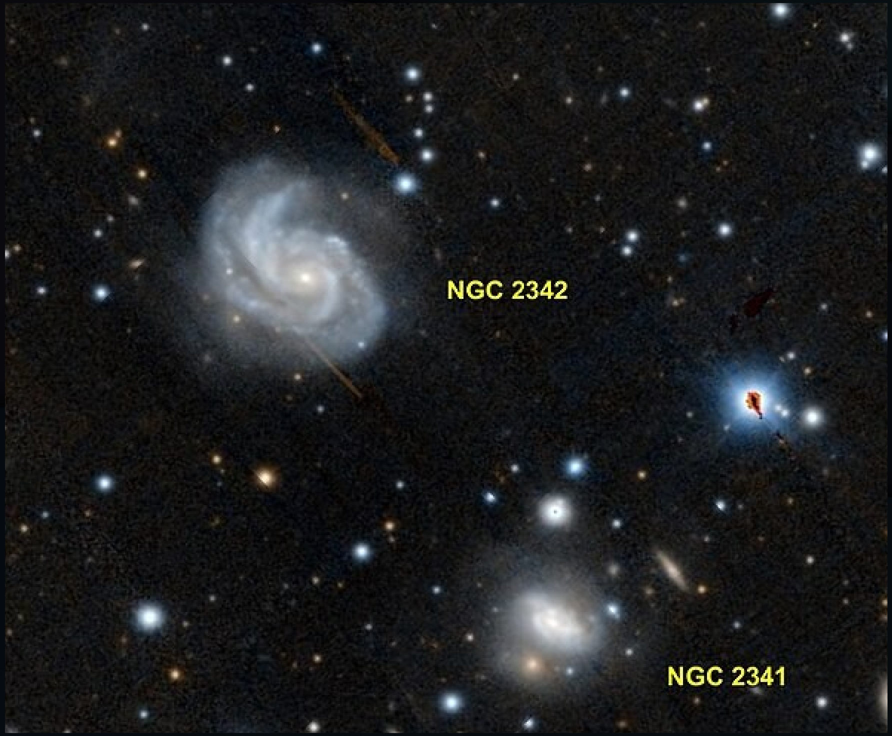


Exercise:

NGC 2342 is a galaxy at redshift z = 0.017. Assume the Hubble constant to be H_0 = [68, 70, 72] km/s/Mpc, please estimate the distance from this galaxy to Earth according to Hubble's law.

HUBBLE EXPANSION

$$v = H_0\, D$$



Exercise:

NGC 2342 is a galaxy at redshift z = 0.017. Assume the Hubble constant to be H_0 = [68, 70, 72] km/s/Mpc, please estimate the distance from this galaxy to Earth according to Hubble's law.

Solution:

+ Redshift formula: $z = v/c$
+ Hubble's law: $v = H_0.D$

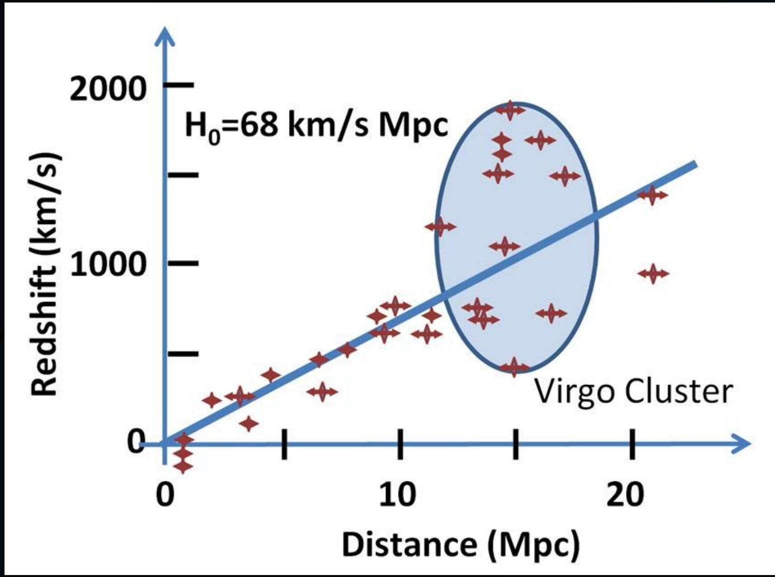
=> $D = (z.c)/H_0$

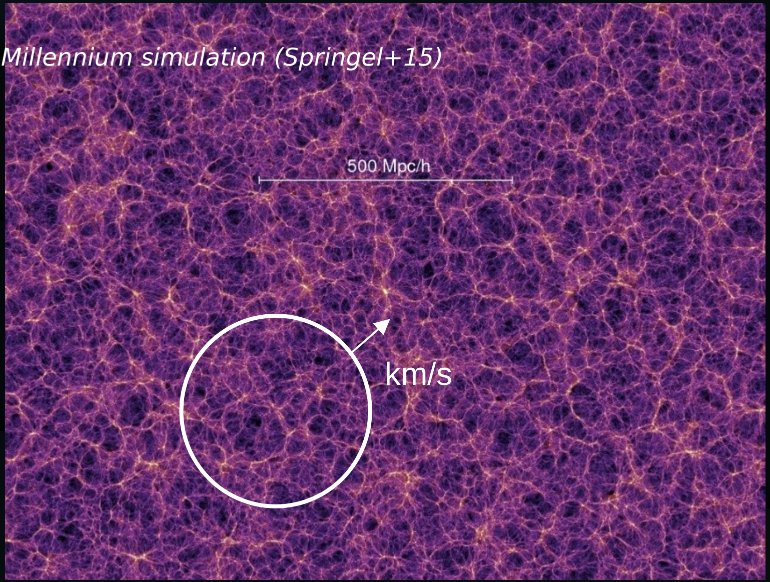
H_0 (km/s/Mpc)	D (Mpc)
68	75
70	73
72	71

BULK MOTION

Local matter inhomogeneties → Stronger gravitational pull towards a direction

Image credit: Brews ohare, via Wikipedia





$$z_{\mathrm{meas}} \approx z_{\mathrm{cosm}} + z_{\mathrm{pec}}$$

COSMOLOGICAL PRINCIPALS

The Universe is isotropic and homogeneous

Same cosmic properties in every sky direction on large scales

Similar amount of matter averaged over large scales, everywhere

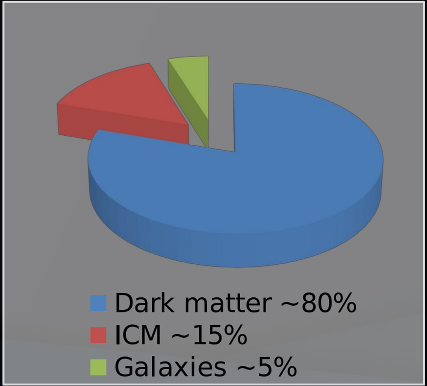
Same **expansion rate** towards every direction!

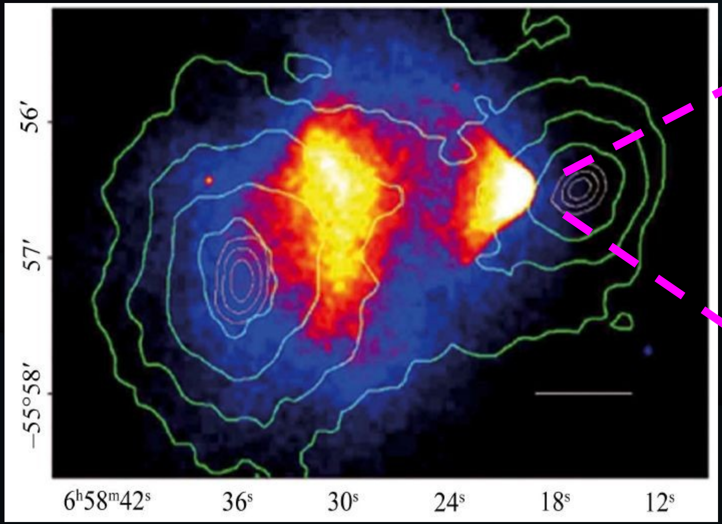
No > 150 km/s **bulk flows** at scales of > 300 Mpc!

GALAXY CLUSTERS

- Most massive bound objects in the Universe.

$M_{tot} \sim 10^{14} - 10^{15}\ M_{sun}$



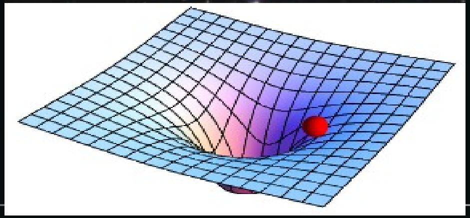


- Consist of:
  + **Galaxies**
  + **Gas** (T_{gas} ~ 1-10keV)
  + **Dark matter**
  + **Relativistic particles**
- Strong constraints on cosmological models, large scale structure study, AGN activities.

Image credit: ned.ipac.caltech.edu, NASA-ESA, www.gregegan.net

THE BCG

- Brightest galaxy of a cluster, most massive
- Normally located near the cluster center



- Search for the BCGs for galaxy clusters in a cluster sample.

- Criteria: brightest in optical – near infrared (NIR) bands, extended envelope, closer to the cluster's center.

- Make use of all-sky surveys.

- Calculate the optical – NIR **luminosities** of the BCGs.

cosmology-dependent!

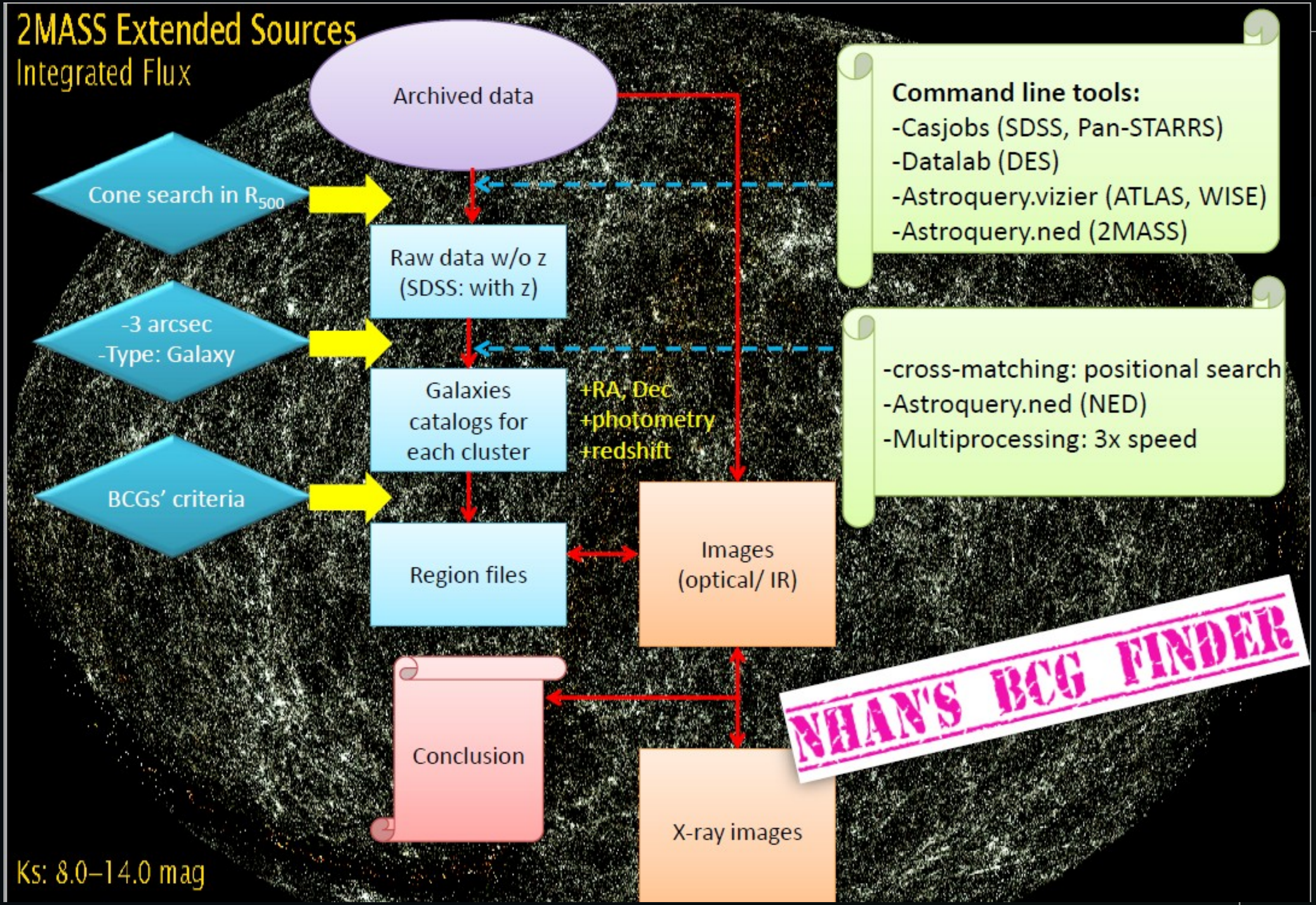
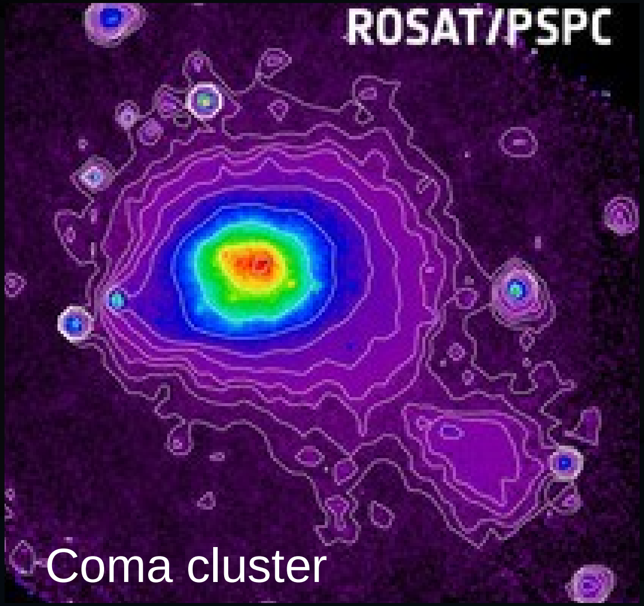
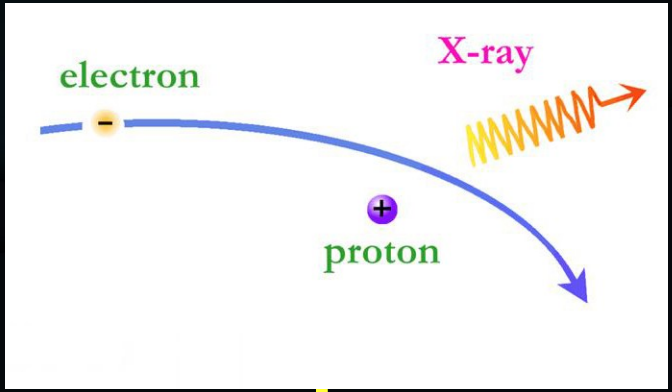


Image credit: http://https://sci.esa.int/web/planck



Bremsstrahlung
(free – free emission)

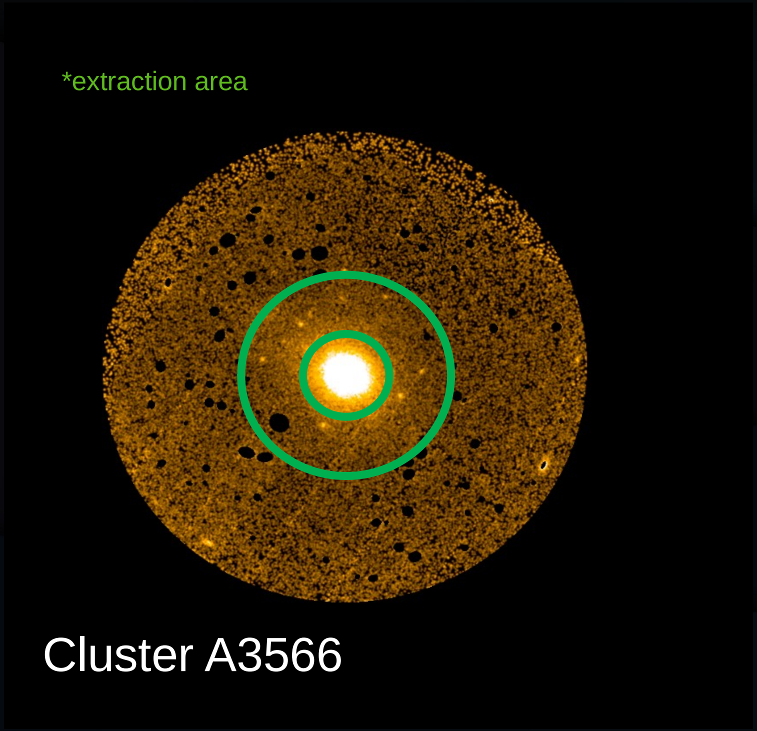


X-ray photons with $E \sim 0.1 - 10$ keV

Flux + redshift ➜ assume H_0, etc. to get distance ➜ **Get X-ray luminosity L_x**

cosmology-dependent!

Image credit: http://https://sci.esa.int/web/planck



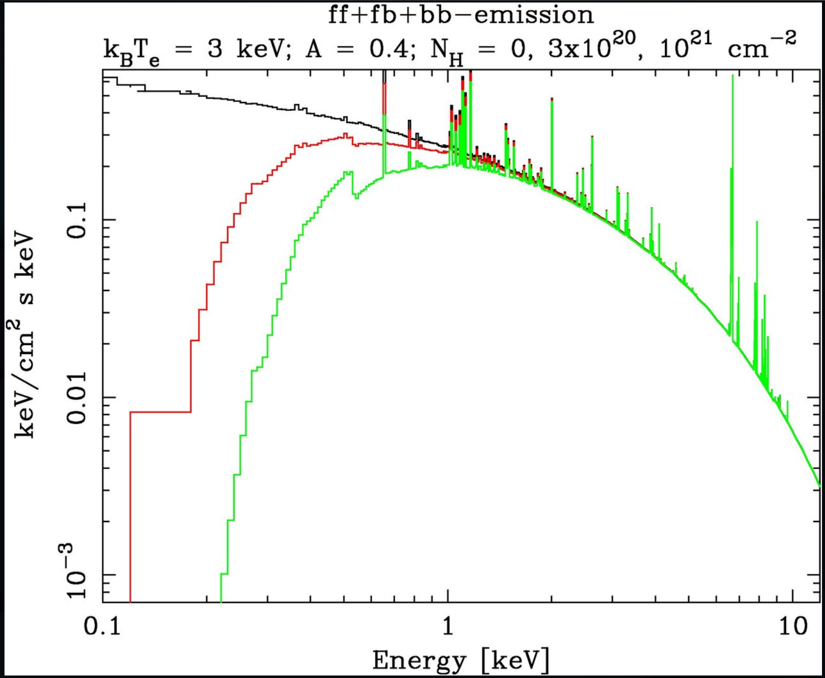
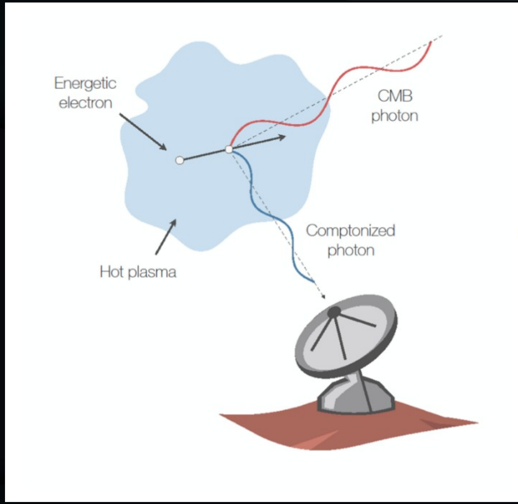


Image credit: *Reiprich et al. (2013), SSR, 177, 195*

From X-ray spectra fitting → **Get gas temperature T**

cosmology-independent!

Sunyaev-Zeldovich effect:
Inverse Compton of the CMB



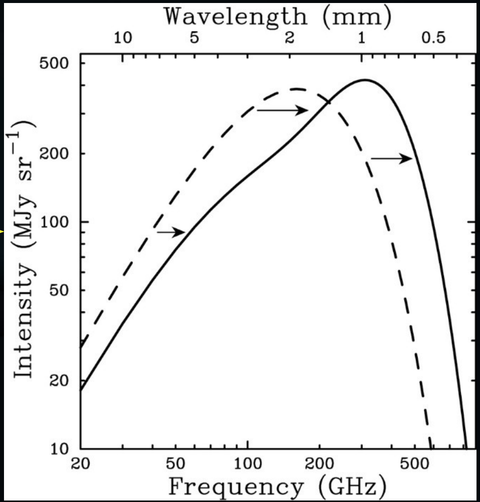


Image credit: https://astro.uni-bonn.de/, Carlstrom+02

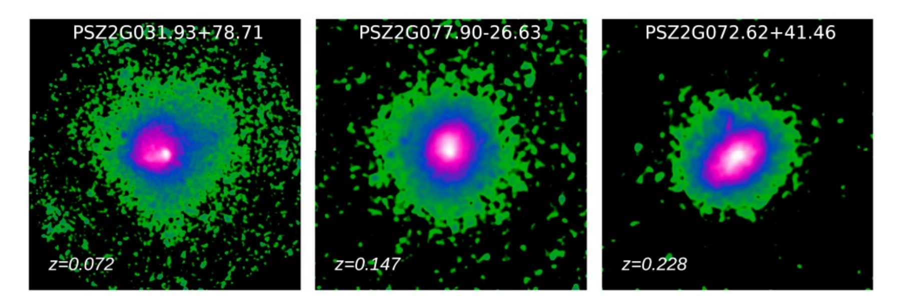
- Traces thermal state of ICM gas
- Intrinsic cluster property ($\mathbf{Y_{sz}}$ in kpc^2) depends on cluster's physical size
- Measure SZ distortion ➜ assume H_0, etc. to get distance ➜ **Get Y_{sz}**

cosmology-dependent!

"All galaxy clusters are scale-down or scale-up versions of each other."

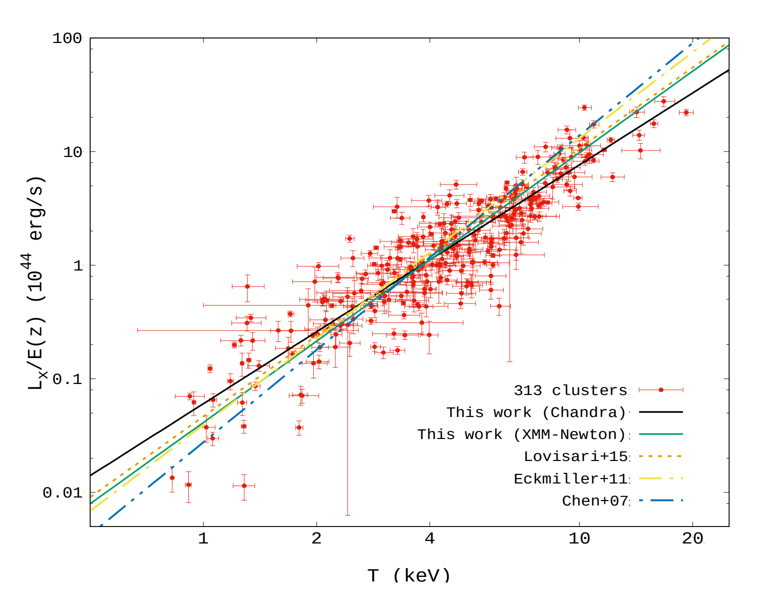
Image credit: ubuy.co.id

=> Scaling relations between observable parameters



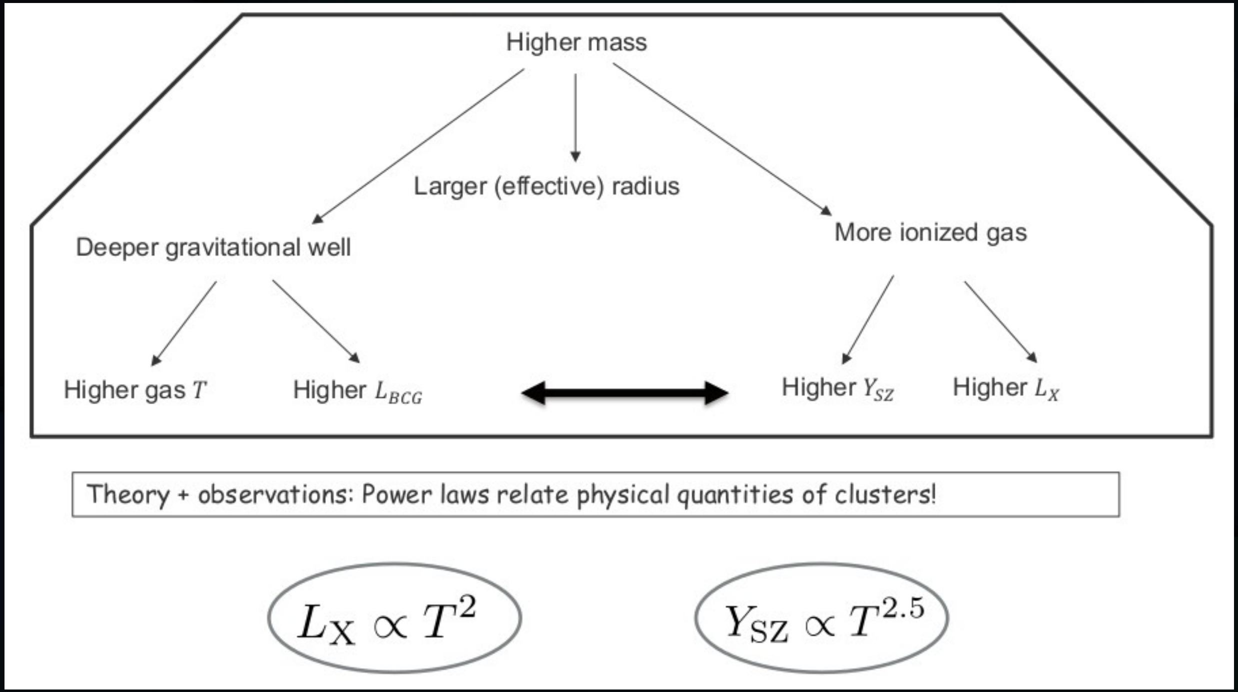
Smoothed XMM-Newton images of clusters of **different mass**. *Credit: CHEX-MATE Collaboration et al. (2021)*

Image credit: ubuy.co.id

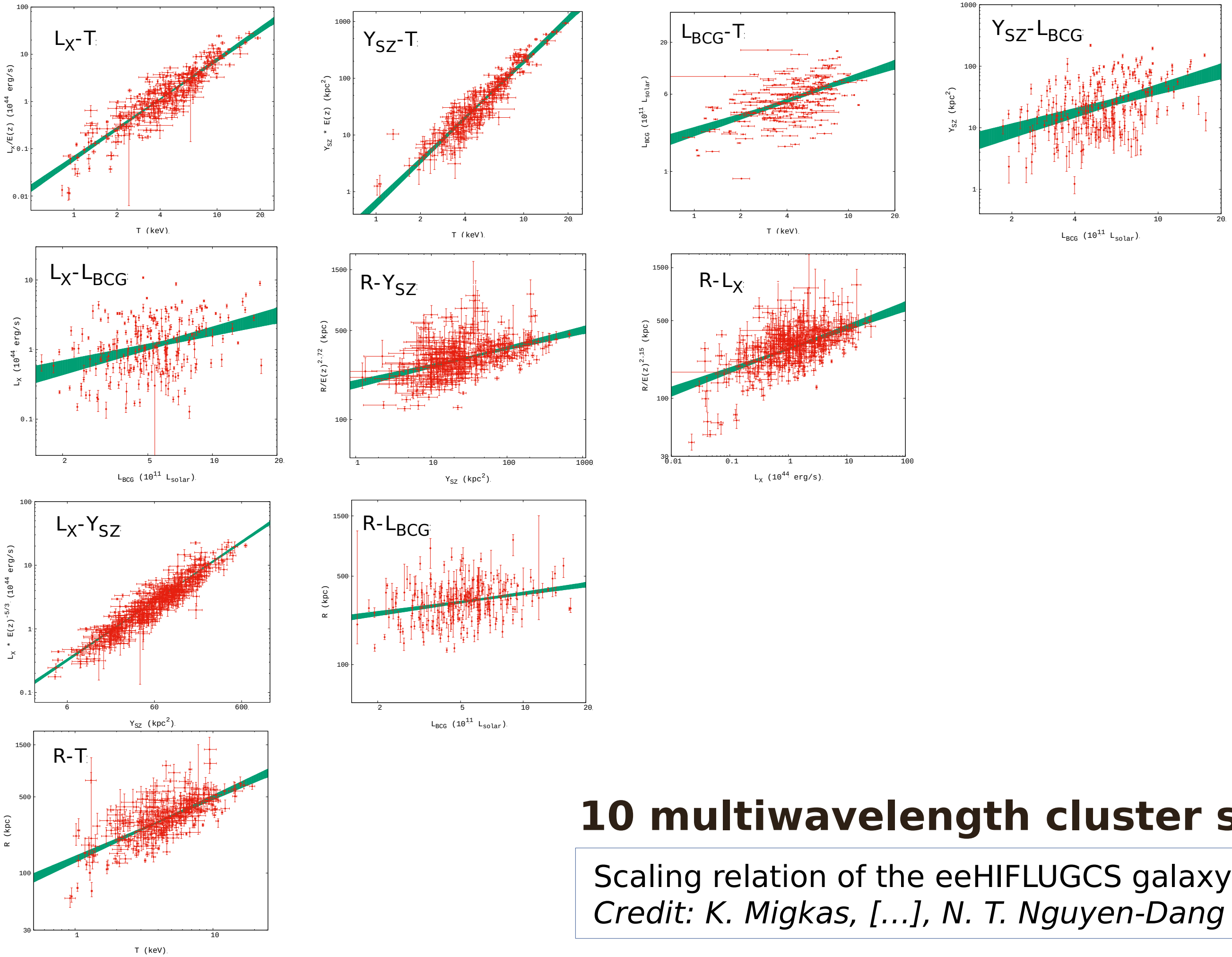


The X-ray luminosity – temperature scaling relation of the eeHIFLUGCS galaxy cluster sample.
Credit: K. Migkas, [...], N. T. Nguyen-Dang et al. (2021)

=> Scaling relations between observable parameters



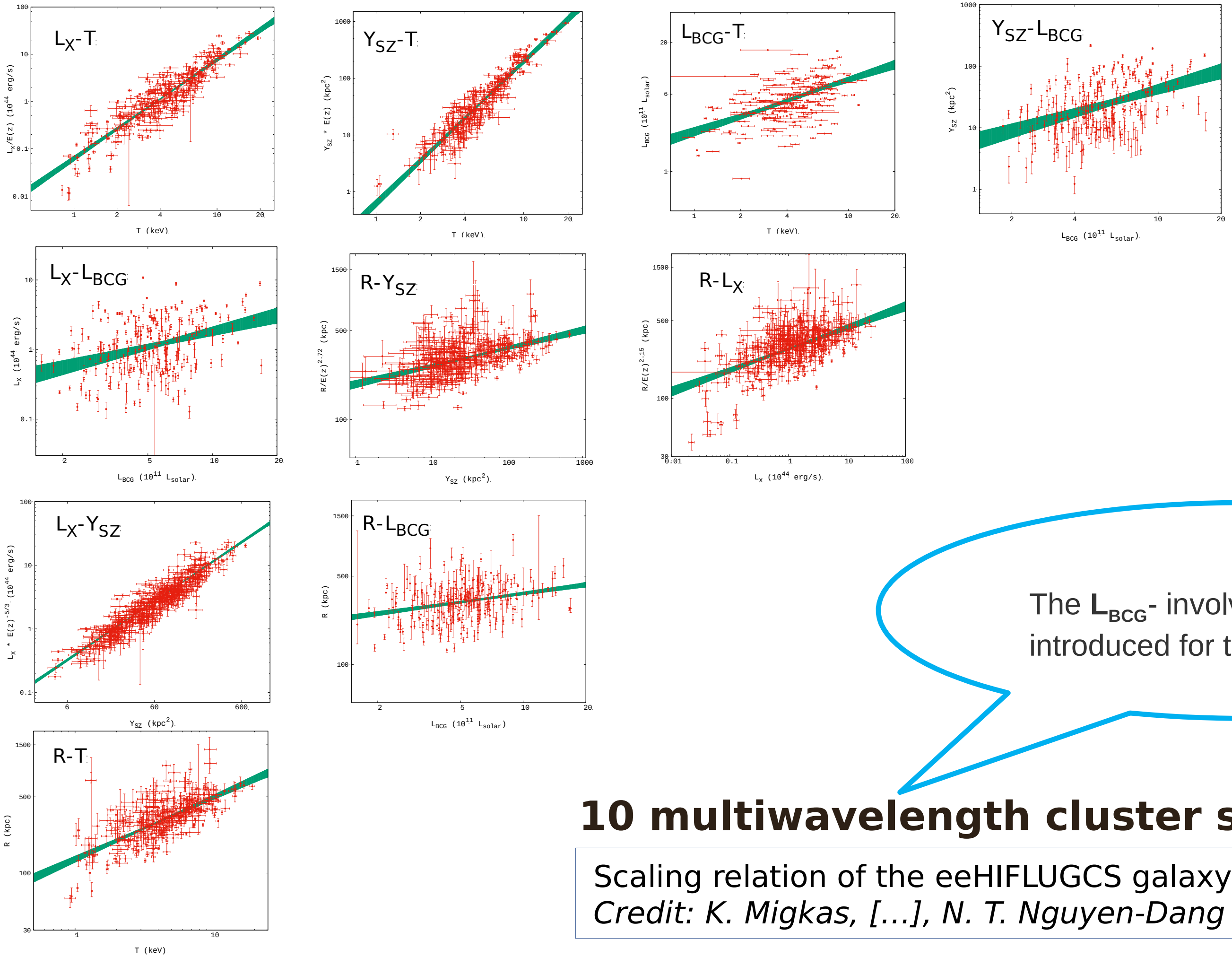
2. Galaxy clusters
2.5. The self-similar model



Parameters:
- L_X
- T
- L_{BCG}
- Y_{SZ}
- R

10 multiwavelength cluster scaling relations!

Scaling relation of the eeHIFLUGCS galaxy cluster sample.
Credit: K. Migkas, [...], N. T. Nguyen-Dang et al. (2021)



Parameters:
- L_X
- T
- L_{BCG}
- Y_{SZ}
- R

The $\mathbf{L_{BCG}}$- involved relations were introduced for the first time!

10 multiwavelength cluster scaling relations!

Scaling relation of the eeHIFLUGCS galaxy cluster sample.
Credit: K. Migkas, […], N. T. Nguyen-Dang et al. (2021)

Constrain isotropy with scaling relations

$$L_X E(z)^{-1} \propto T^{B_{LT}}$$

$$Y_{SZ} E(z) \propto T^{B_{YT}}$$

$\propto \mathrm{distance}(H_0, z)^2$

Strong cosmology and bulk flow dependence!

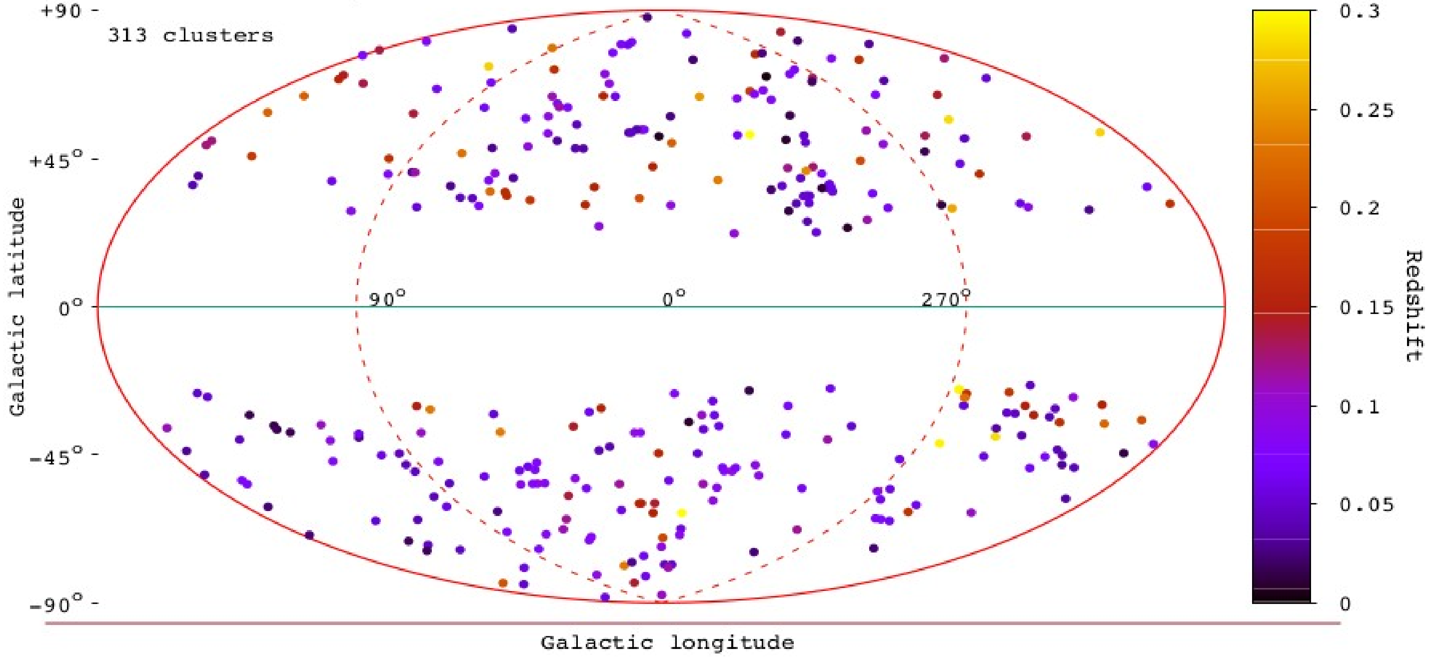
Measure ➜ Predict left part

cosmology-independent!

The basis: eeHIFLUGCS sample

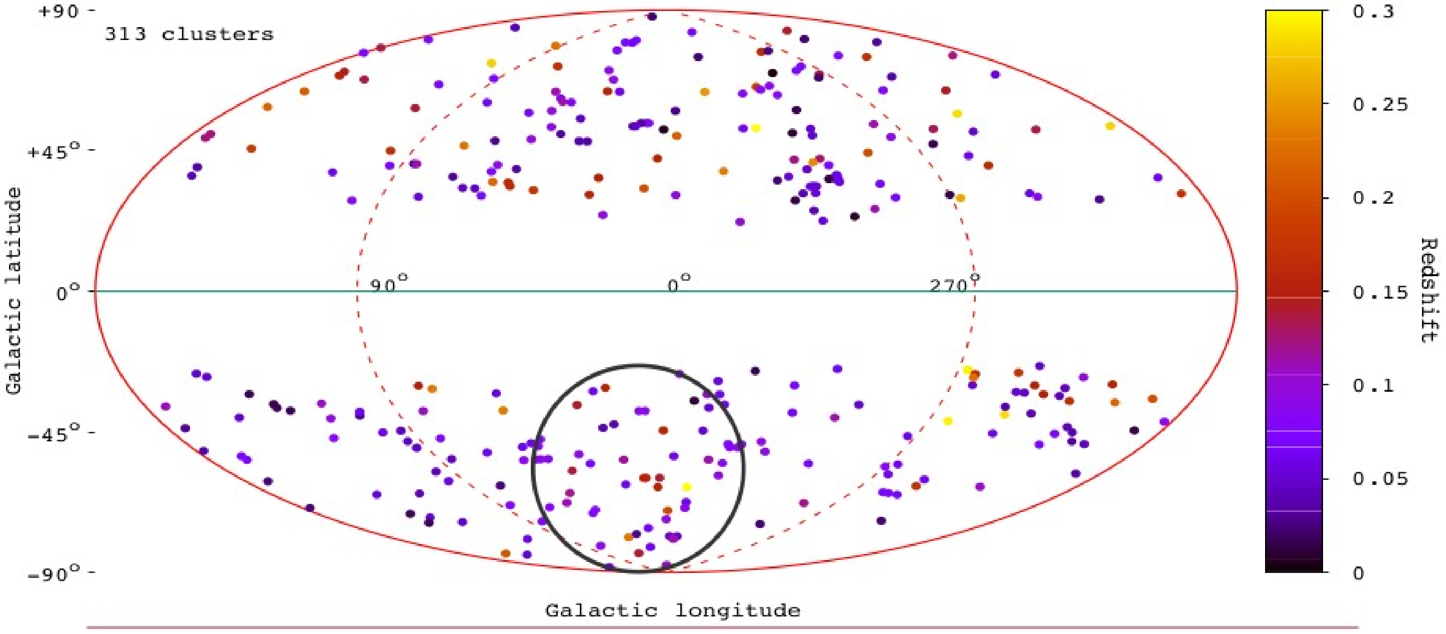
extremely expanded HIghest X-ray FLUx Galaxy Cluster Sample (Reiprich et al. 2017)

- X-ray selected: ROSAT All Sky Survey, Chandra & XMM-Newton follow-up.
- Homogeneously selected, covers sky uniformly, mostly $z < 0.25$
- Brightest X-ray clusters in the sky
- Precise temperature measurements for 313 of them

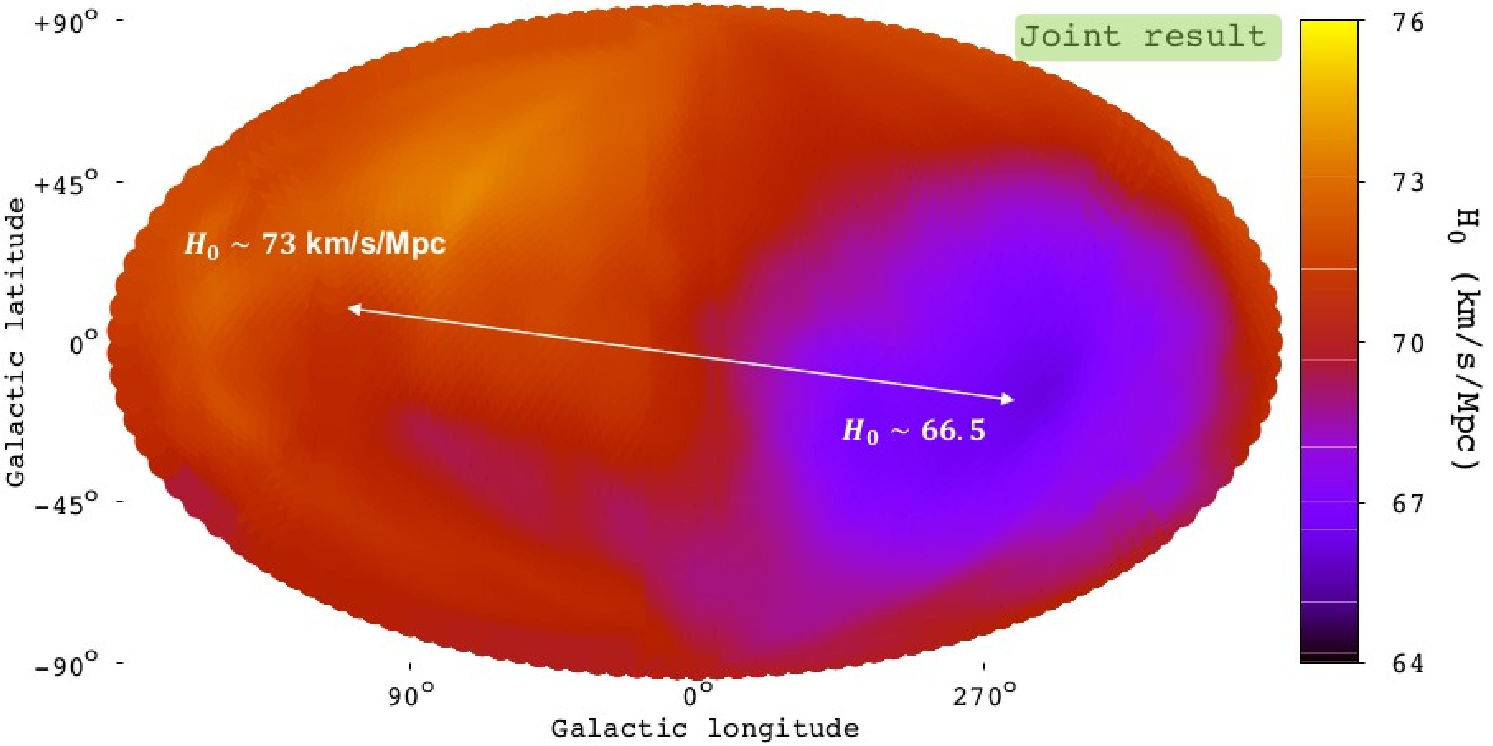


Constrain isotropy with scaling relation

- Point cone towards every direction in the sky
- Only clusters within cone radius (usually $60^{o} - 75^{o}$)
- Fit the scaling relation to constrain H_0 relative change
- Create color map with the value of H_0 for every direction



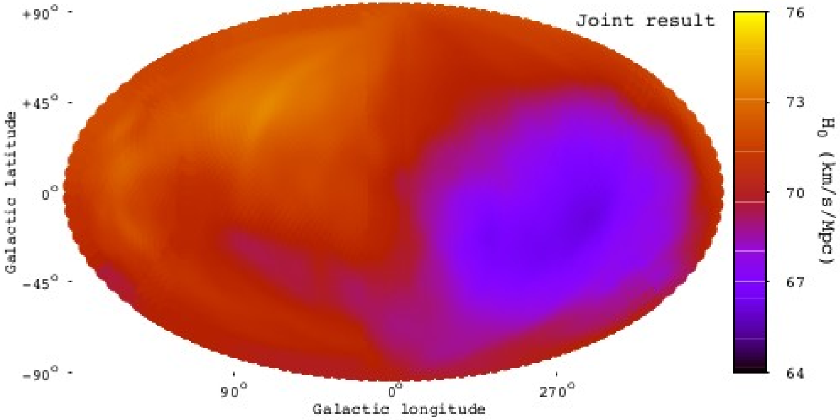
Overall result: 5.9σ! *(from Monte Carlo)*



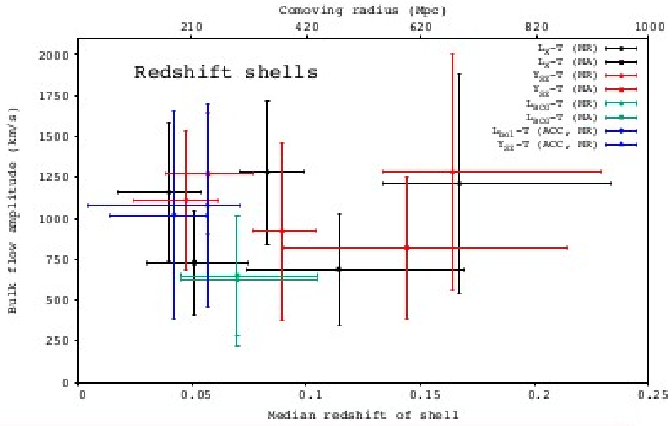
Most robust detection of late-Universe anisotropy ever!

$$(l, b) = (273^{\circ}{}^{+42^{\circ}}_{-38^{\circ}}, -11^{\circ}{}^{+27^{\circ}}_{-27^{\circ}})$$

It looks like H_0 anisotropy or bulk flow...



Contradicts isotropy!



Contradicts homogeneity!

CONCLUSION

- Cosmic isotropy is too important to not be continuously tested with new independent methods.

- Developed powerful method to scrutinize isotropy with galaxy clusters.

- Clusters show strong local anisotropies: local anisotropy or large bulk flow?

- Both contradicting concordance cosmology.

- Keep pushing to improve data, statistics and methodology.

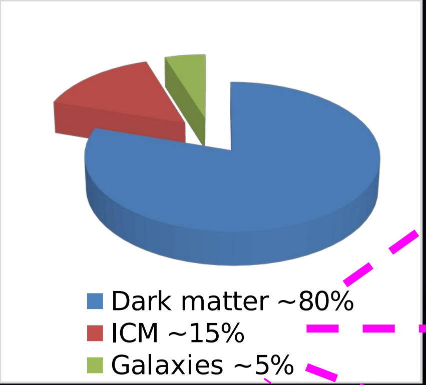
FUTURE PERSPECTIVE

- Reducing the scatter of scaling relations (core excised LX, morphology param. in the fit, gass mass vs T, etc.)

- New local cluster samples for further confirmation of anisotropies.

- More distant clusters to tell apart anisotropy and bulk flows.

GALAXY CLUSTERS OBSERVATION



Optical (gravitational lensing – tracing dark matter)

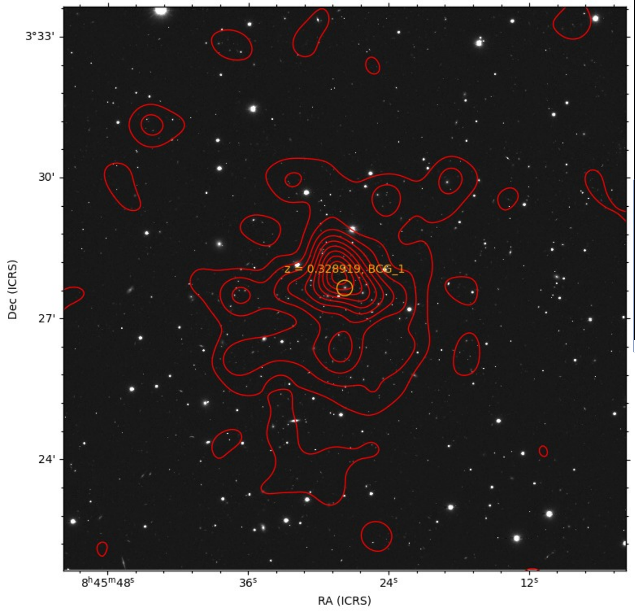
X-ray (tracing hot gas)

Optical (tracing normal matter)

Submilimeter (relativistic particles)

- Galaxy clusters are the largest scale structures in the universe => good laboratories for testing cosmological models.
- Cluster sample's characteristics a.k.a the evaluations of selection method are important instruction before use. E.g: sample with disturbed clusters deviates from equilibrium.
- Cluster sample selection methods and caveats: optical (projection effect), X-ray (cool-core bias), Sunyaev-Zeldovich (massive clusters)...

DYNAMICAL STATE/ MORPHOLOGY

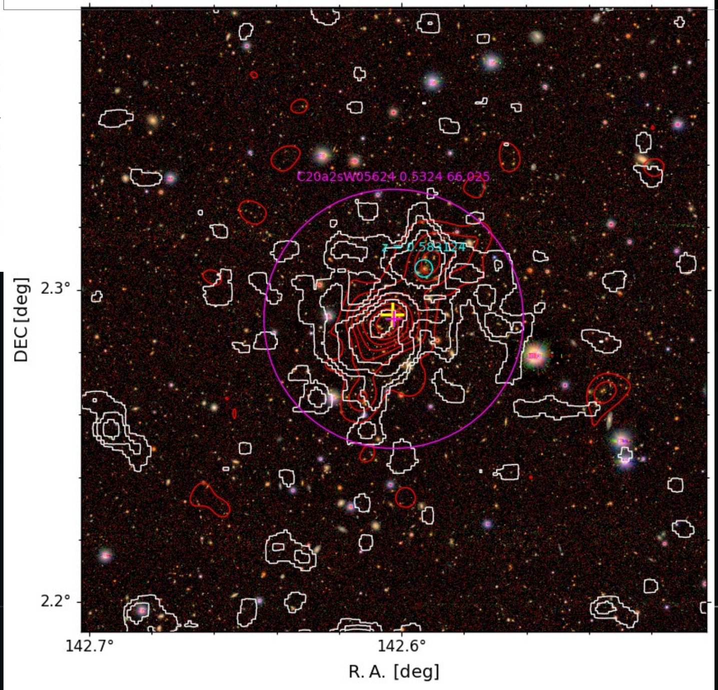


Relaxed

Various cluster morphology (optical image, X-ray contour)
Credit: N. Ota, N. T. Nguyen-Dang et al. (2023)

CAMIRA optical cluster sample

Disturbed

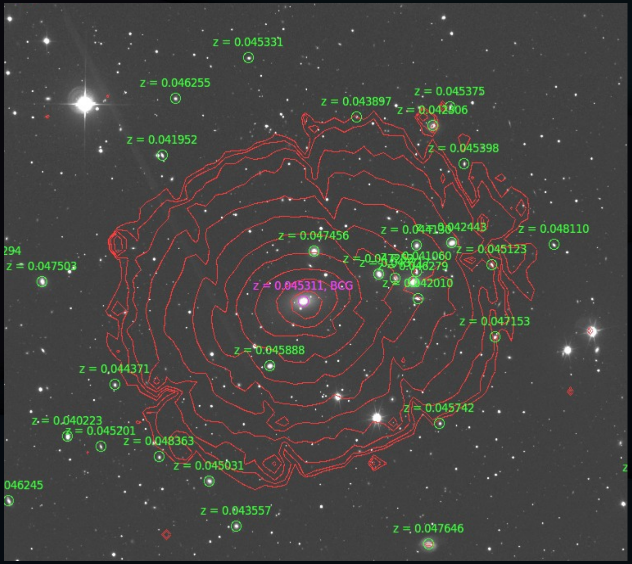


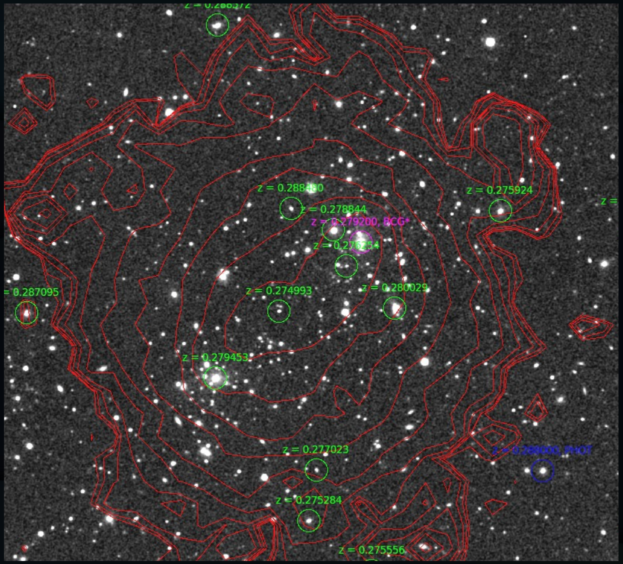
Credit: http://www.youtube.com/watch?v=F0AJxmfAFH0

Different appearances of a same object via different cameras.

BCG – X-ray center offset as a morphology indicator:
small offset => relaxed, large offset => merger

Relaxed





Disturbed

Various cluster morphology found in the X-ray eeHIFLUGCS sample (optical image, X-ray contour).
Credit: M. E. Ramos-Ceja, S. Park, N. T. Nguyen-Dang et al. (2024 in prep.)

Result of the CAMIRA optical sample

- Study the dynamical states of the cluster sample, using the BCG – X-ray peak offsets, X-ray gas concentration, optical galaxy multi-peak number.

=> relaxed fraction = 2 (< 39%).

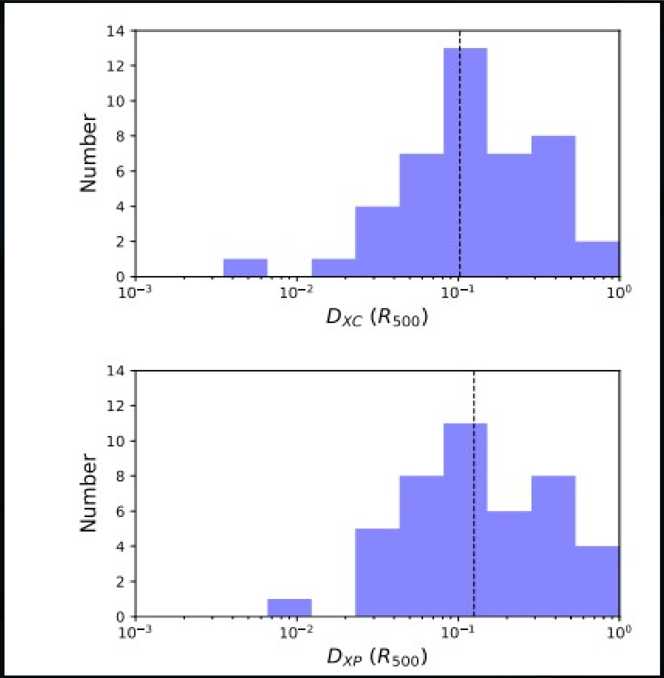
=> Optical sample presents a wider range of morphology.

Compare to other samples

- Rossetti et al. 2016: (Sunyaev-Zeldovich) 52 ± 4% relaxed; HIFLUGCS 74 ± 5%, MACS 73 ± 4% and REXCESS (X-ray) 77 ± 7%.

- Migkas et al. 2021: eeHIFLUGCS (X-ray) ~ 44% relaxed

- Ota et al. 2020: (optical) 29 ± 11(±13)%



The BCG – X-ray centroid/peak offset of the high-richness CAMIRA clusters.
Credit: N. Ota, N. T. Nguyen-Dang et al. (2023)

1. Where are we (time, space) in this Universe?

2. How are structures formed in the Universe?

3. What is Hubble expansion?

4. What is bulk motion?

5. What are the cosmological principals?

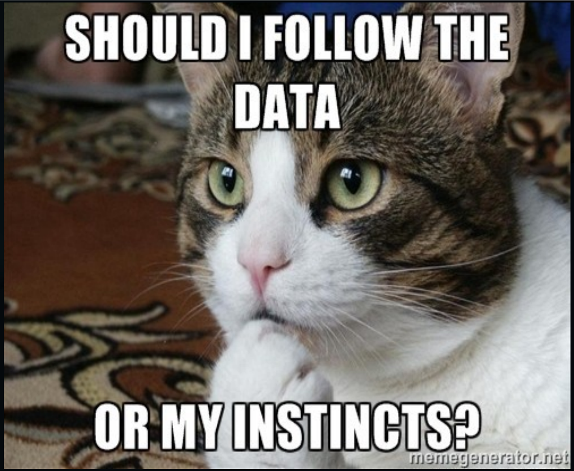
6. What are galaxy clusters? What are their components? What makes them such important probes for cosmology research?

7. What are clusters scaling relations? Provide an example of testing cosmological principals using scaling relations.

8. Why do we need to investigate the dynamical state/morphology of galaxy clusters?

9. Why can we use the BCG – X-ray center offset to indicate clusters’ dynamical state?

10. Did you enjoy the lecture? :D



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- nguyen@astro.uni-tuebingen.de