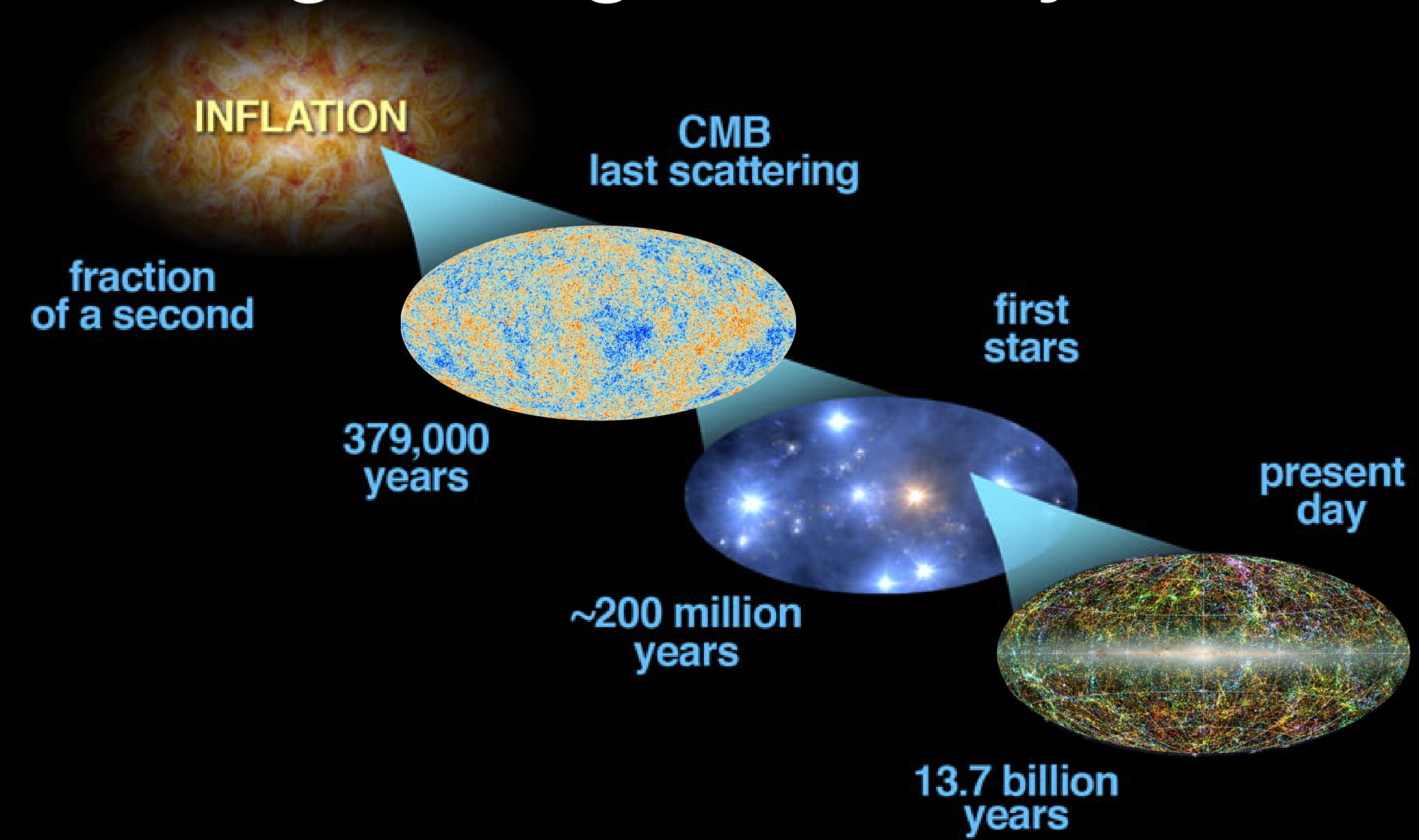
The Magic of Red Galaxies: Tracing Structure Formation with Galaxy Clusters and More

Eli Rykoff
SLAC/KIPAC

KIPMU Seminar

February 27th, 2020

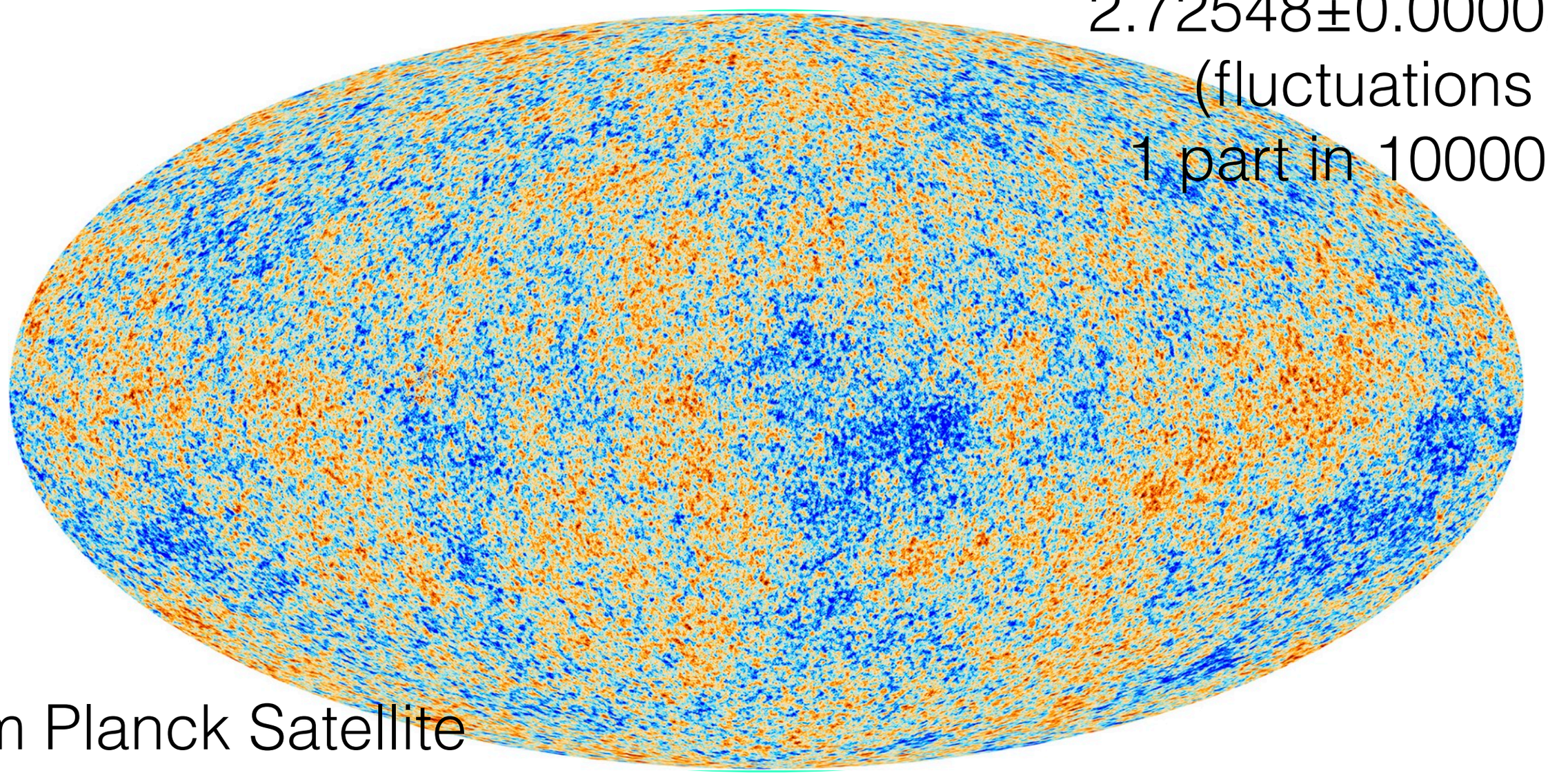
Big Bang and Beyond



Cosmic Microwave Background

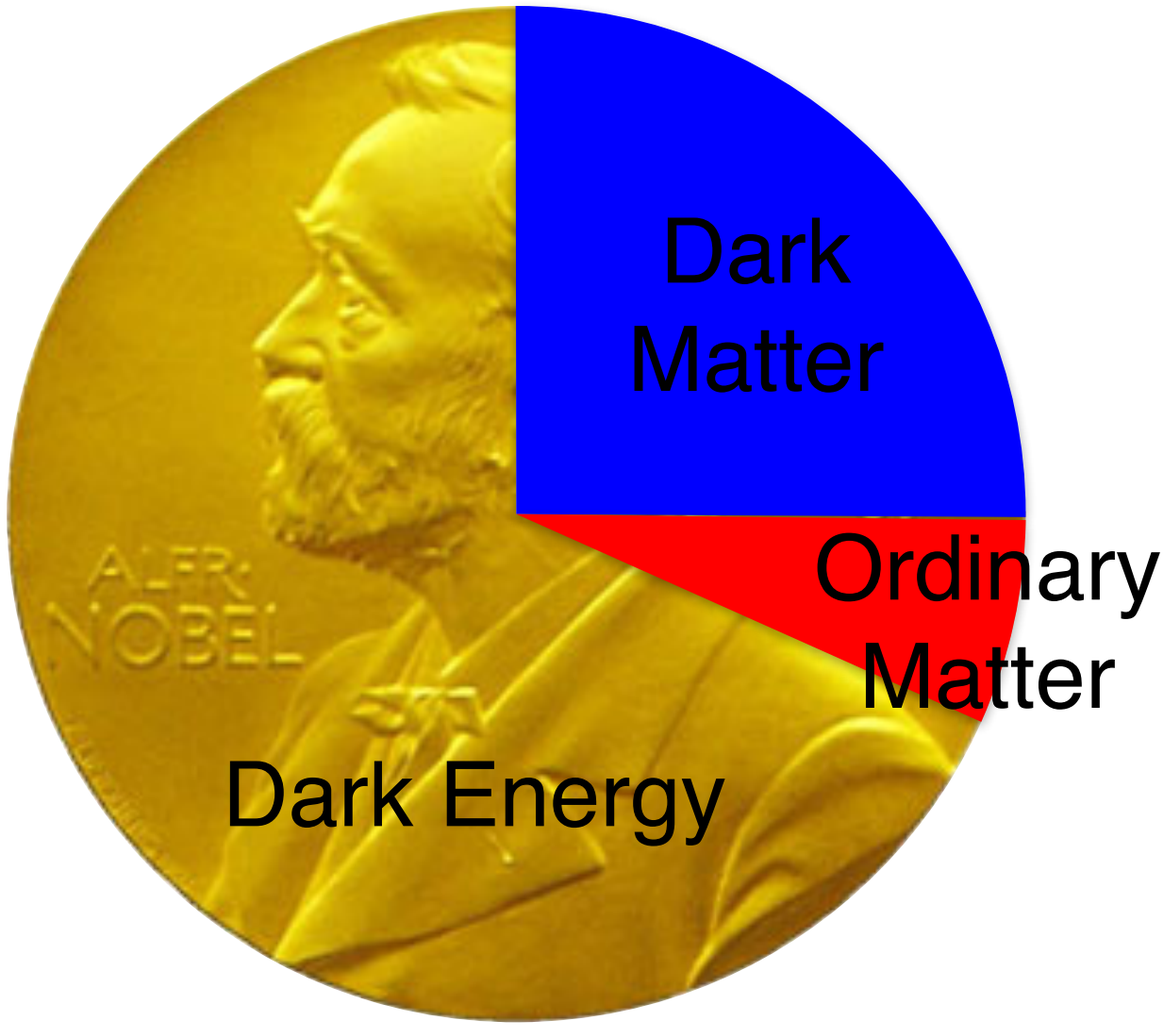
- The Universe is isotropic and homogeneous
  - Same in all directions, and uniform over large scales

2.72548±0.00002 K
(fluctuations
1 part in 100000)



from Planck Satellite

What Makes Up the Universe?



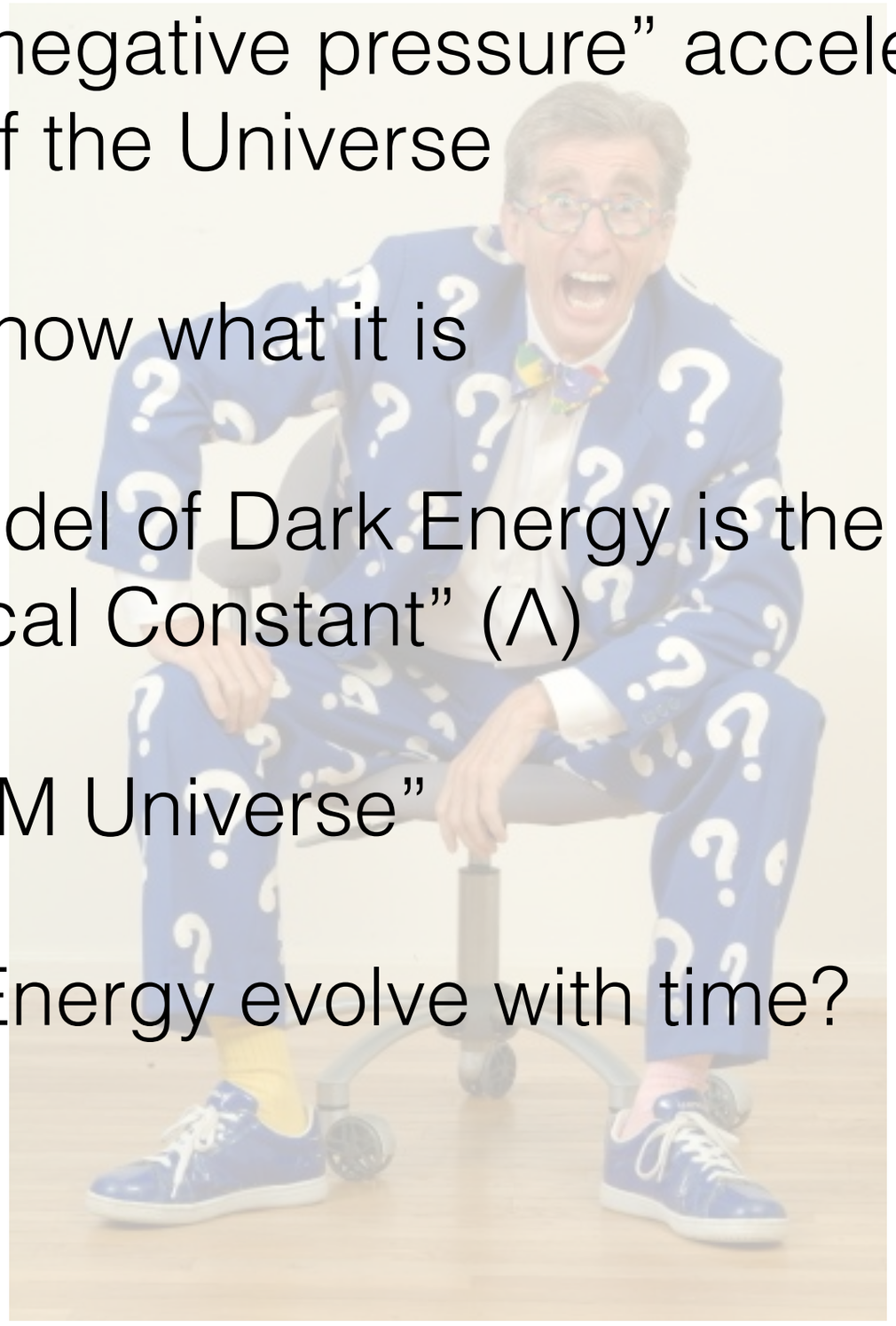
Dark Matter

- “Dark” matter is dark because it neither absorbs nor emits light
- Cosmologically, “cold dark matter” (CDM) behaves as a physicist’s “ideal” substance
- Cold: slow-moving
- Only gravity, no messy gas physics
- Like working in a frictionless vacuum!

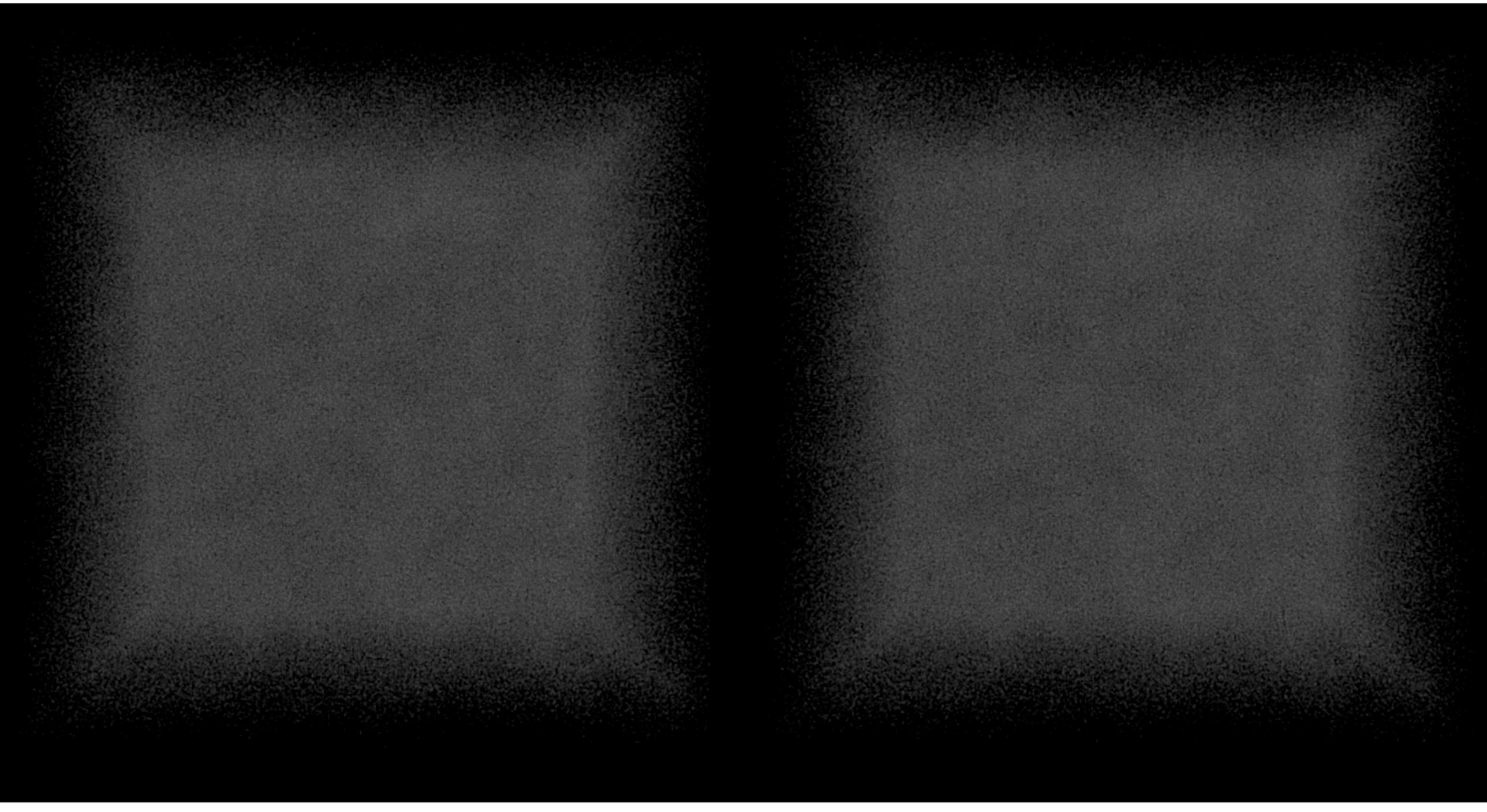
Kaeler (SLAC)

Dark Energy

- Acts like a “negative pressure” accelerating the expansion of the Universe
- We do not know what it is
- Simplest model of Dark Energy is the “Cosmological Constant” (Λ)
  - The “ΛCDM Universe”
- Does Dark Energy evolve with time?



Two Universes

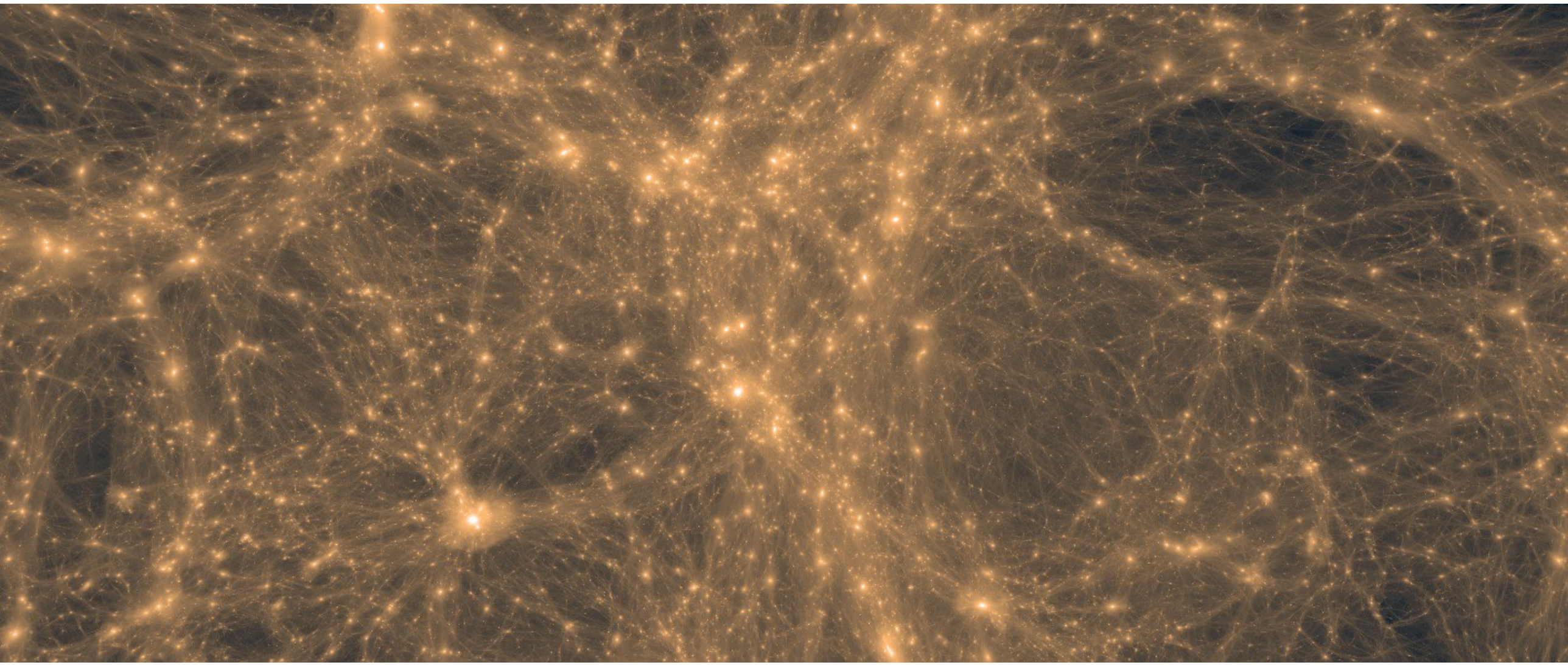


Same start, different cosmologies

movie, simulation: Ralf Kaehler, Yao-Yuan Mao, Risa Wechsler (Stanford/SLAC)

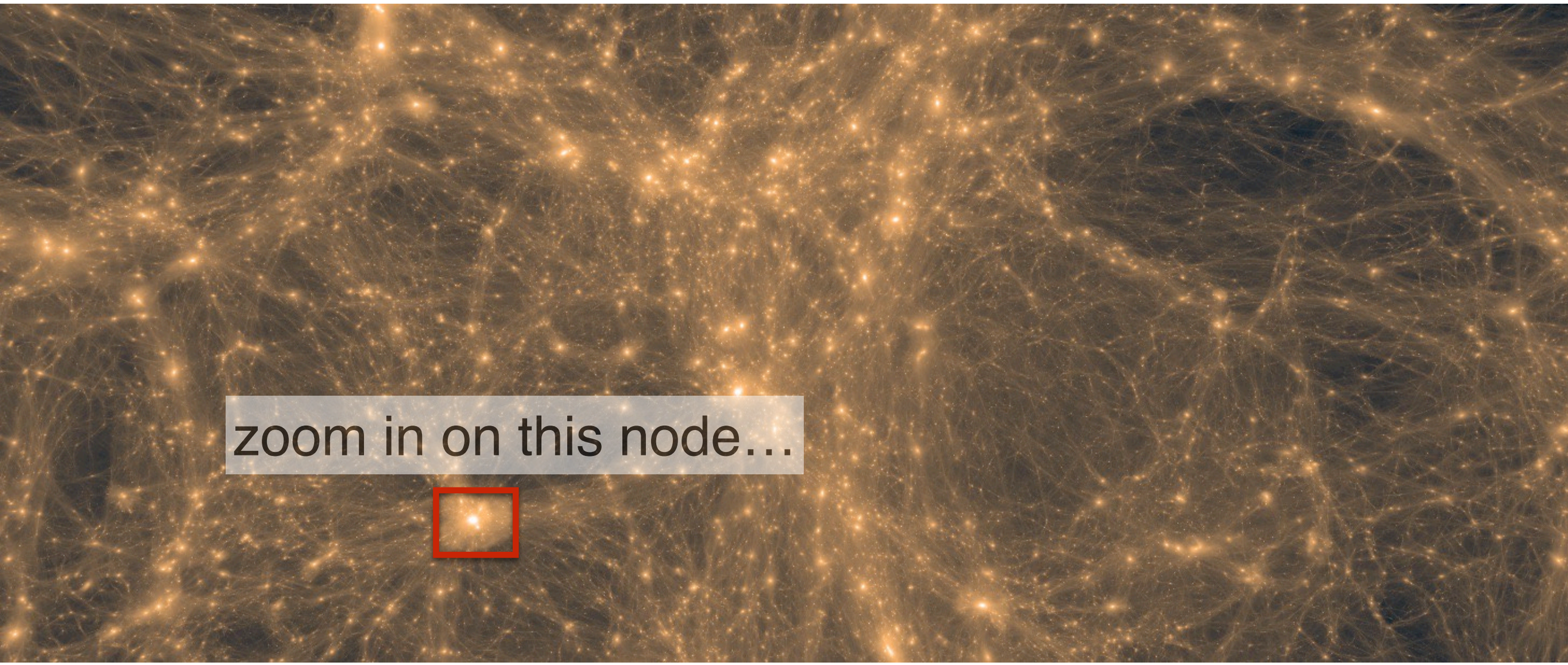
The Cosmic Web

- Nodes, filaments, and voids … at all scales
- Depends on amount of Dark Matter (Ω_M), Dark Energy (Ω_Λ), and “clumpiness” (σ_8)



Visualization: Ralf Kaehler, Tom Abel; Simulation: Oliver Hahn, Tom Abel

The Cosmic Web



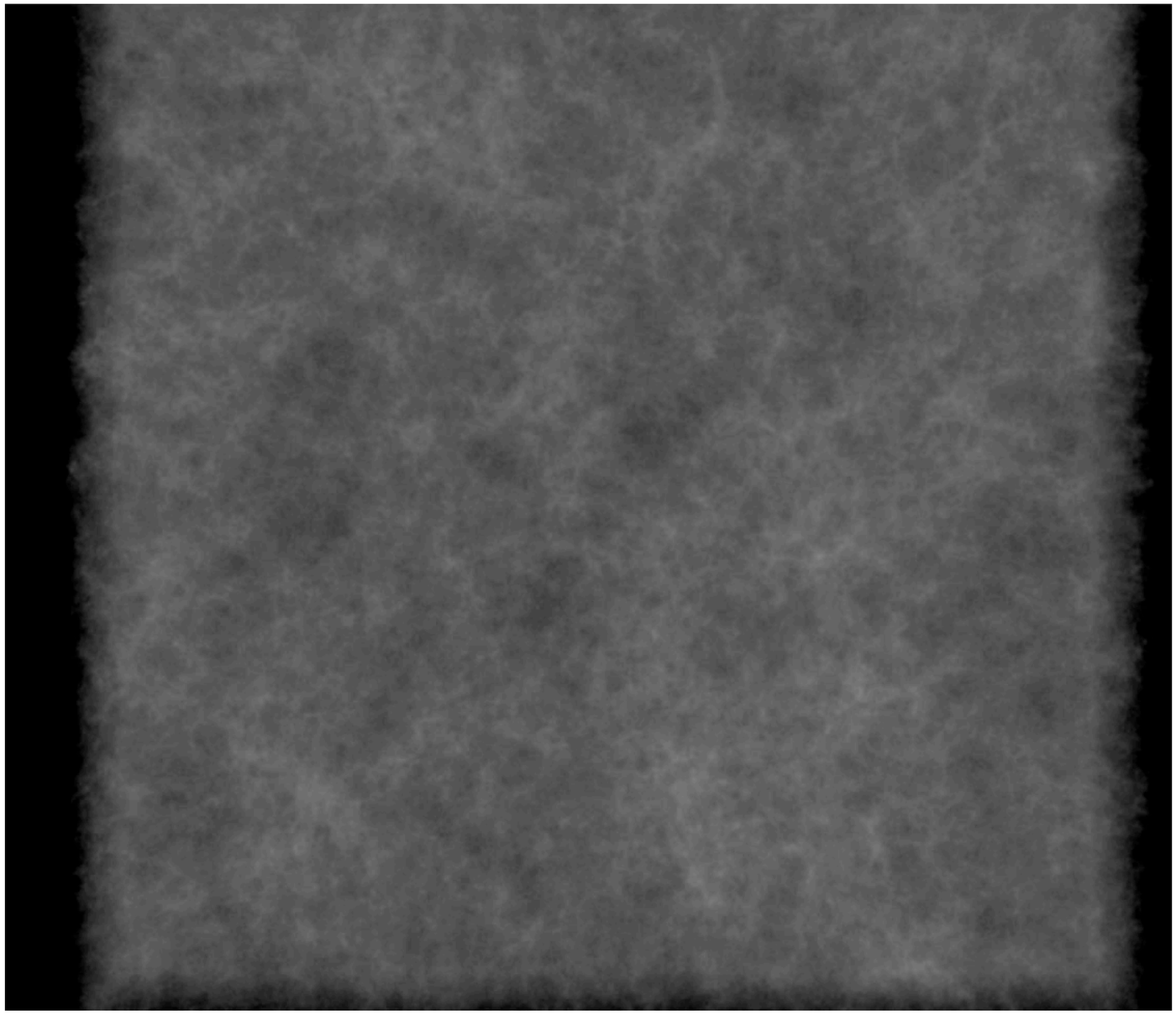
Visualization: Ralf Kaehler, Tom Abel; Simulation: Oliver Hahn, Tom Abel

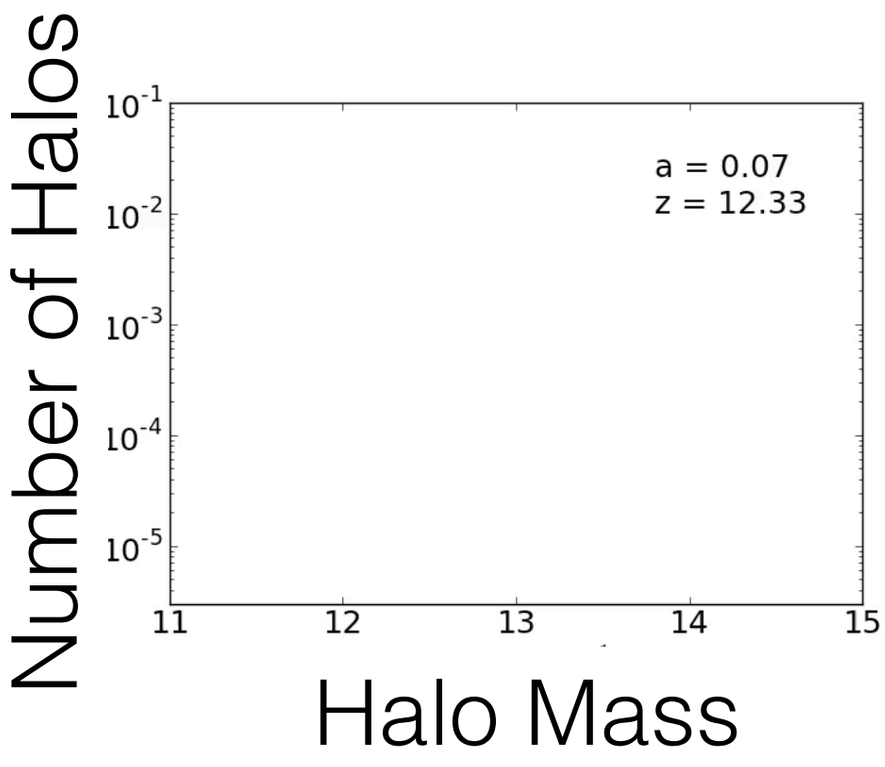
Dark Matter Halo

- A big puffy ball of dark matter

The “Halo Mass Function”

- Count and Weigh these dark matter halos as a function of cosmic time





movie, simulation, statistics: Matt Becker, Ralf Kaehler, Yao-Yuan Mao, Rachel Reddick, Risa Wechsler (Stanford/SLAC)

“Red,” Elliptical Galaxies

- “Happy families are all alike; every unhappy family is unhappy in its own way.” - Leo Tolstoy

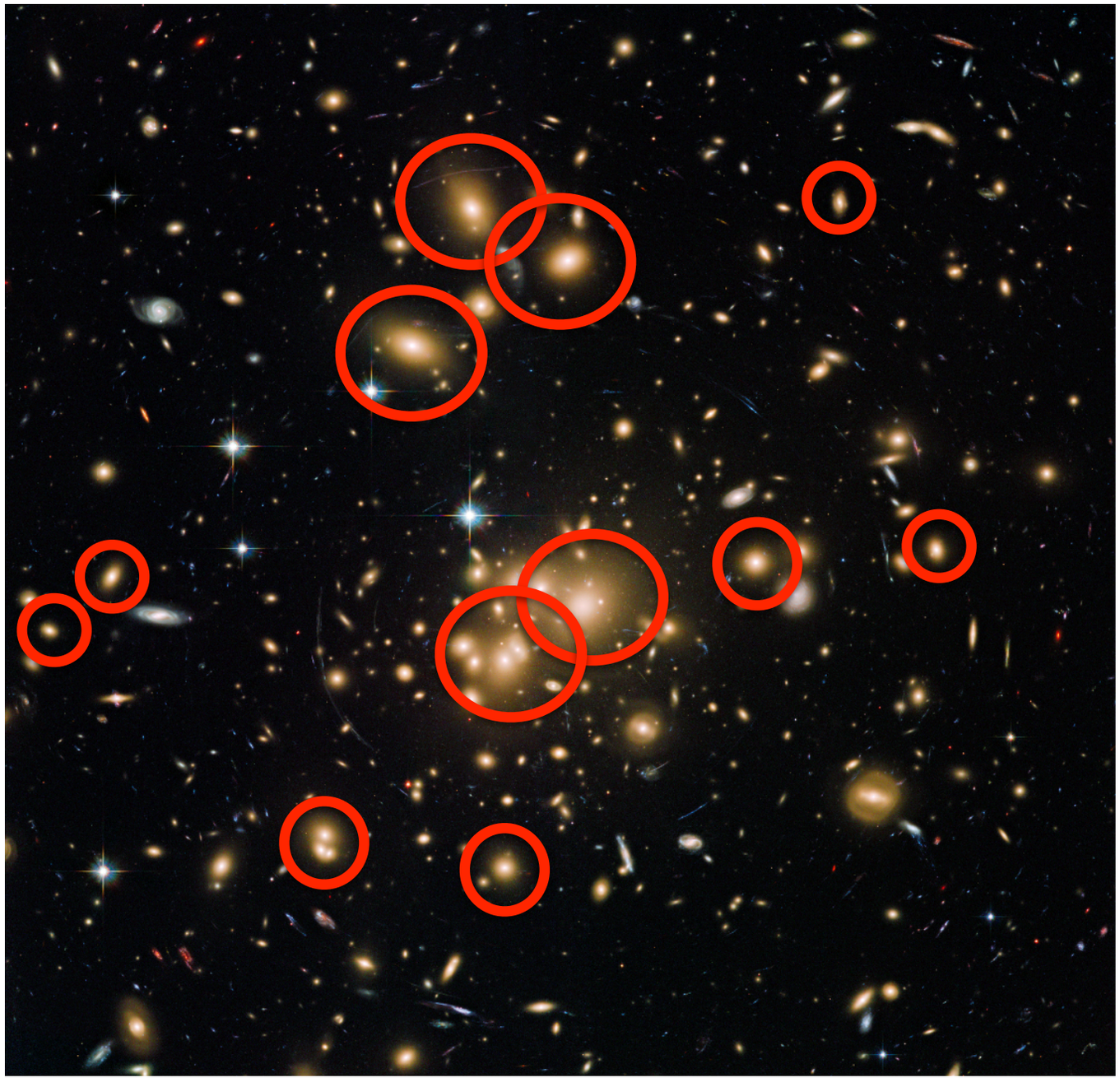
- The galaxies in clusters are happy families of elliptical galaxies

- Star formation ended billions of years ago

- Old stars, fading away

Galaxy Clusters

- Galaxy Clusters are… clusters of galaxies
- Bigger clusters are bigger (in all respects)
- Can count members to compute “richness”
- Richness is a “proxy” for mass



Hubble image of Abell 1689

“The largest bound objects in the Universe”

Clusters of galaxies are the largest bound objects in the Universe, and are uniquely powerful cosmological probes (e.g., Henry et al. 2009; Vikhlinin et al. 2009;

(Peebles 1980). The galaxy clusters are the most massive of these bound structures and act as signposts for the extrema of the cosmological density field on the relevant scales. The

to their high masses. Galaxy clusters represent the most massive gravitationally bound structures in the universe

Galaxy clusters, as the largest gravitationally-bound structures in the Universe, are important probes of cosmology and astrophysics.

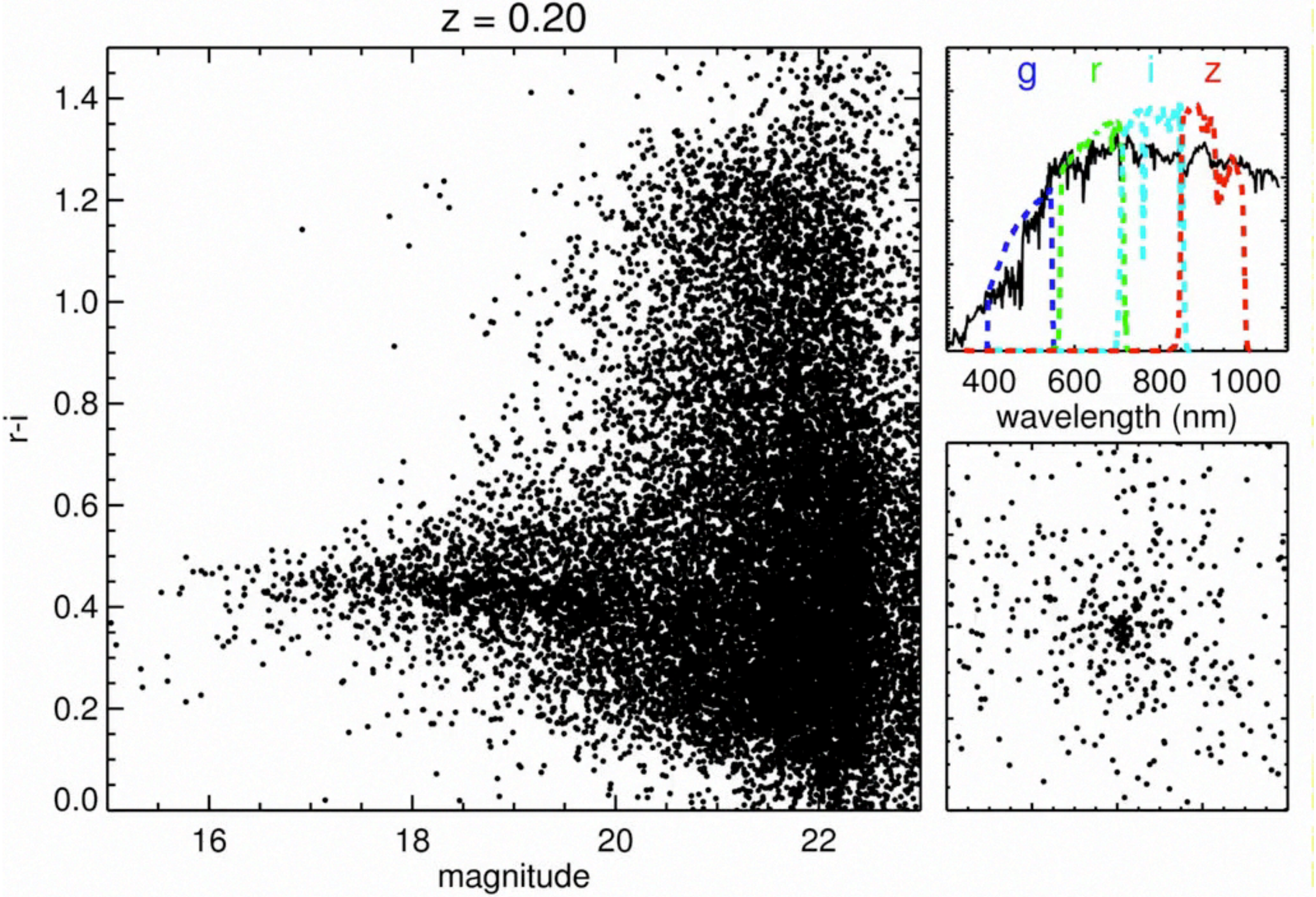
matter and dark energy. Galaxy clusters are the most massive gravitationally bound structures, sitting at the largest nodes of the cosmic

Galaxy clusters are the most massive gravitationally self-bound objects in the Universe. These clusters form at the

Cluster “Red Sequence”

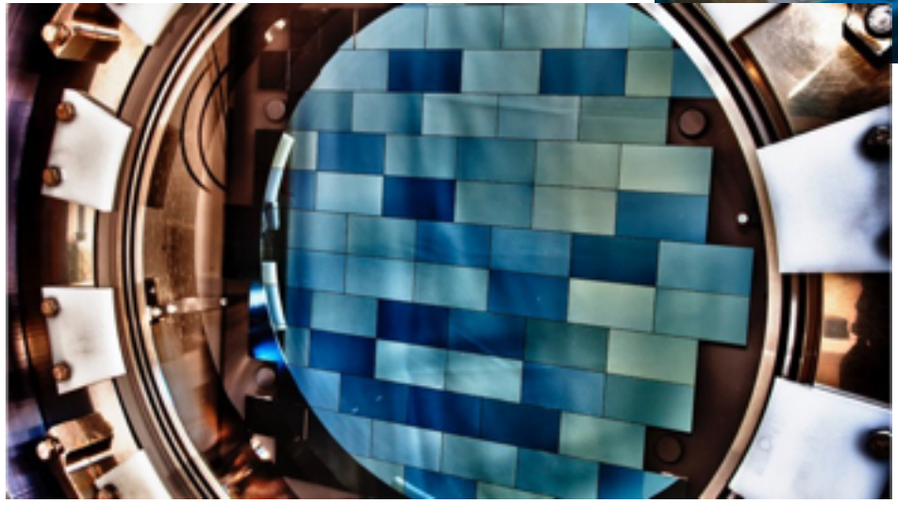
Animation by Josh Meyers

Cluster Red Sequence

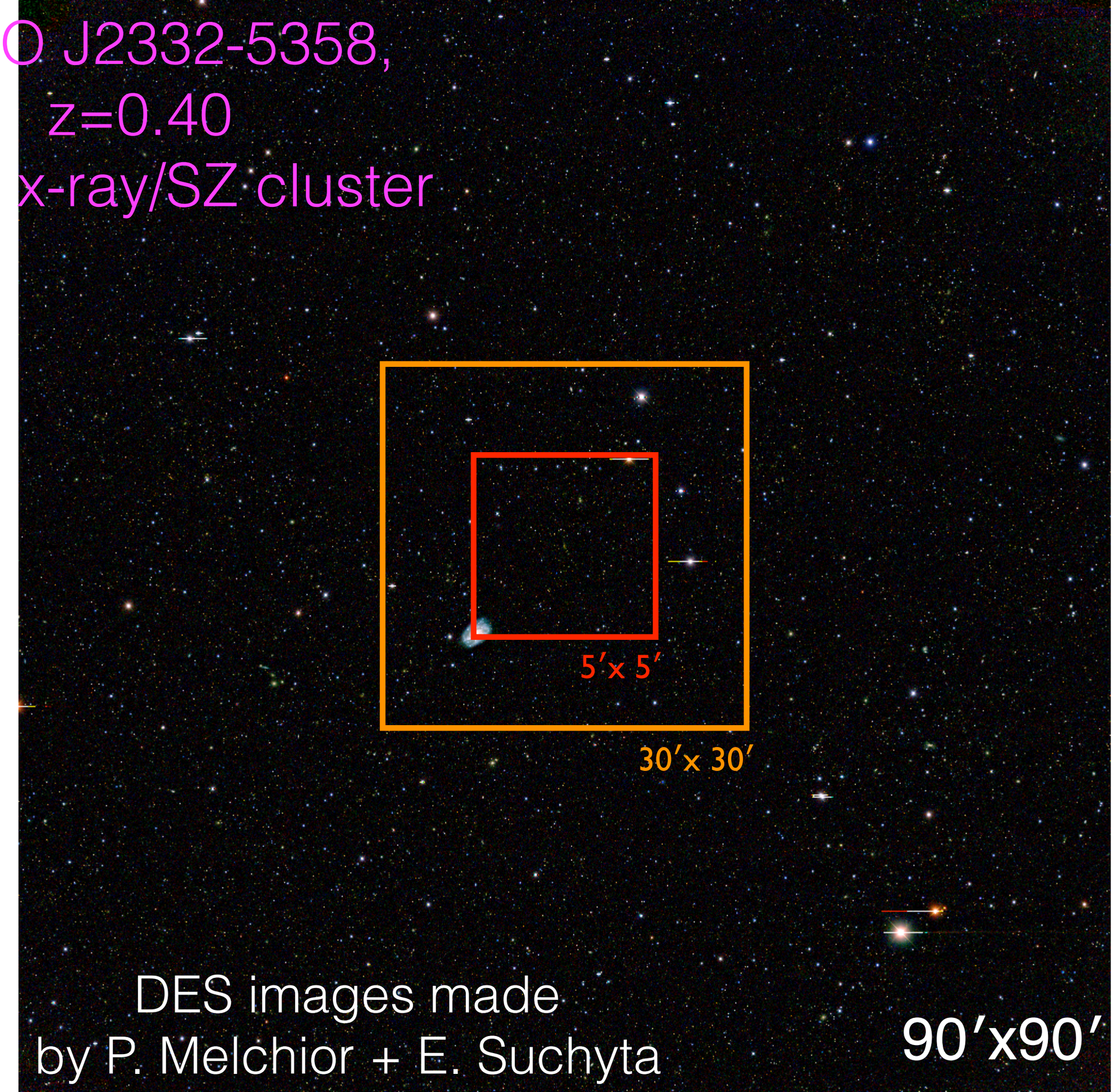


Dark Energy Survey

- "Dark Energy Camera" on the Blanco telescope in Chile
  - 570 megapixel camera
- International collaboration of 100s of astrophysicists in US, UK, Spain, Germany, Australia, Brazil, Switzerland
- Completed 6th year of 5 year mission



SCSO J2332-5358,
z=0.40
bright x-ray/SZ cluster



Vera Rubin Observatory
Legacy Survey of Space and Time

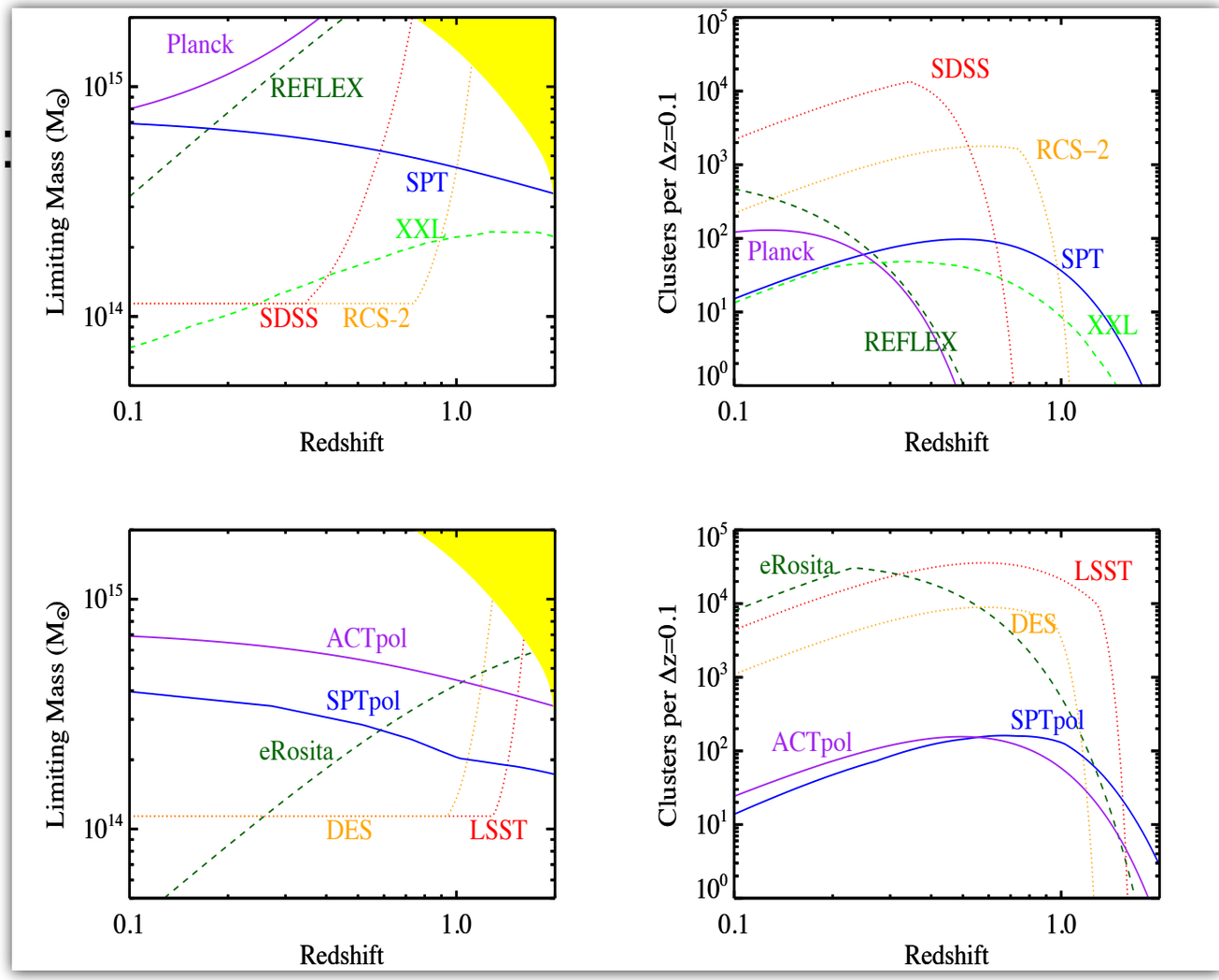
- 8.4 meter primary mirror
- 10 deg^2 field of view
- 3.2 gigapixel camera

- Image entire visible sky in 3-4 days
- DES-equivalent every couple of months 😯
- 20 terabytes of data per night for 10 years

LSST Simulated Image

LSST vs DES

- From my perspective, LSST is a super-DES:
  - Deeper! More area! More galaxies!
- LSST is of course much more:
  - Time domain in the "wide-fast-deep" survey
  - Galactic plane survey



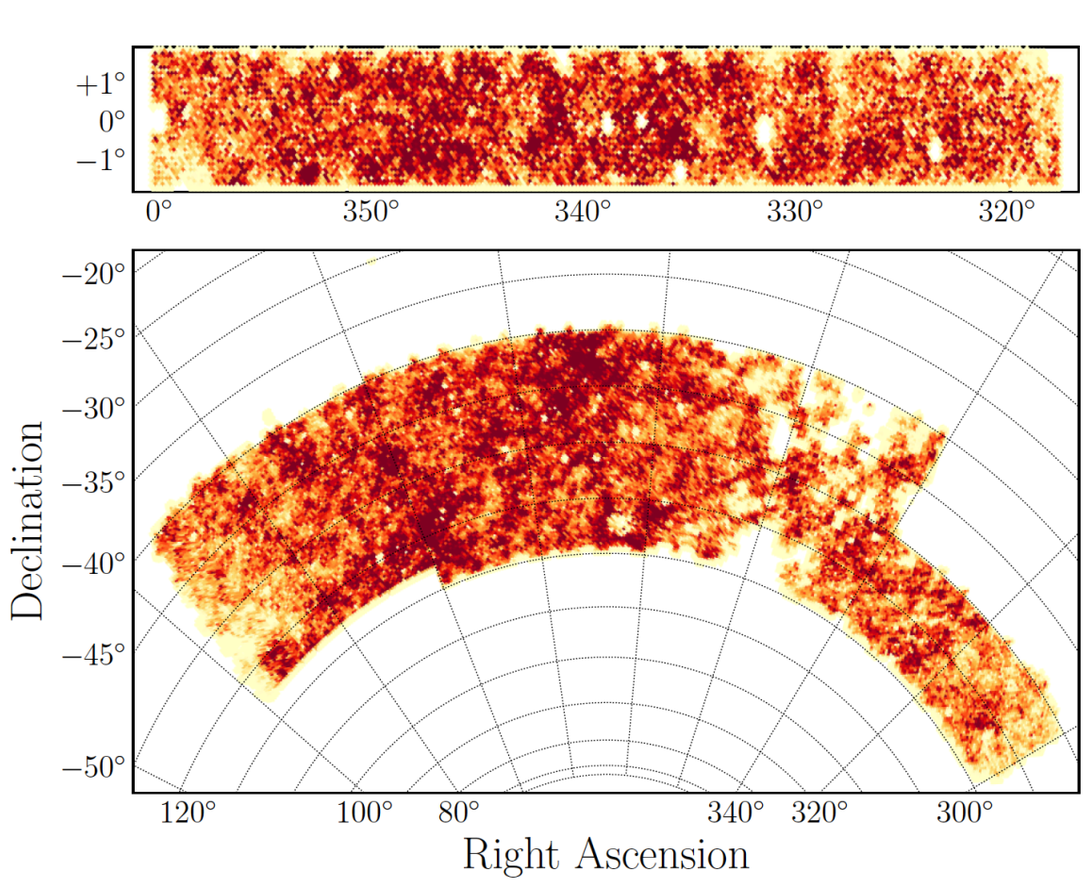
Weinberg+13

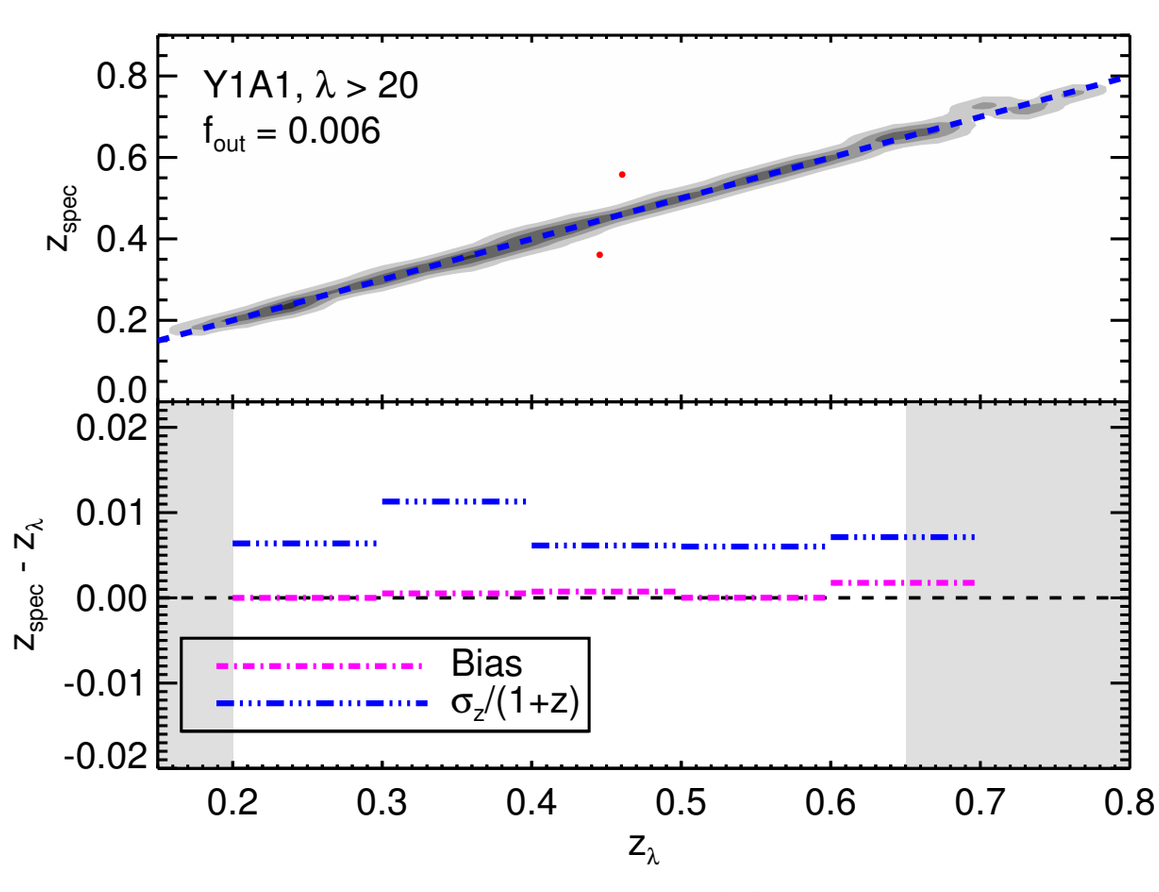
redMaPPer

- The red-sequence Matched-filter Probabilistic Percolation algorithm and catalogs (Rykoff+14, Rykoff+16)
  - Red-sequence cluster finder based on optimized richness estimator λ (Rozo, Rykoff+09, Rykoff+12)
- Every galaxy (in the survey!) gets a membership probability
- High precision photometric redshifts by fitting all members to the red sequence simultaneously
- Probabilistic centering algorithm
- Primary cluster finder for DES and (so far) in LSST DESC

redMaPPer on DES Y1

- Approximately 1500 deg^2, out of total 5000 deg^2 survey
- Overlapping the South Pole Telescope (SPT) region + equatorial “Stripe 82”
- Much work to get good photometry and uniformity (see Drlica-Wagner, Sevilla, Rykoff+2018)

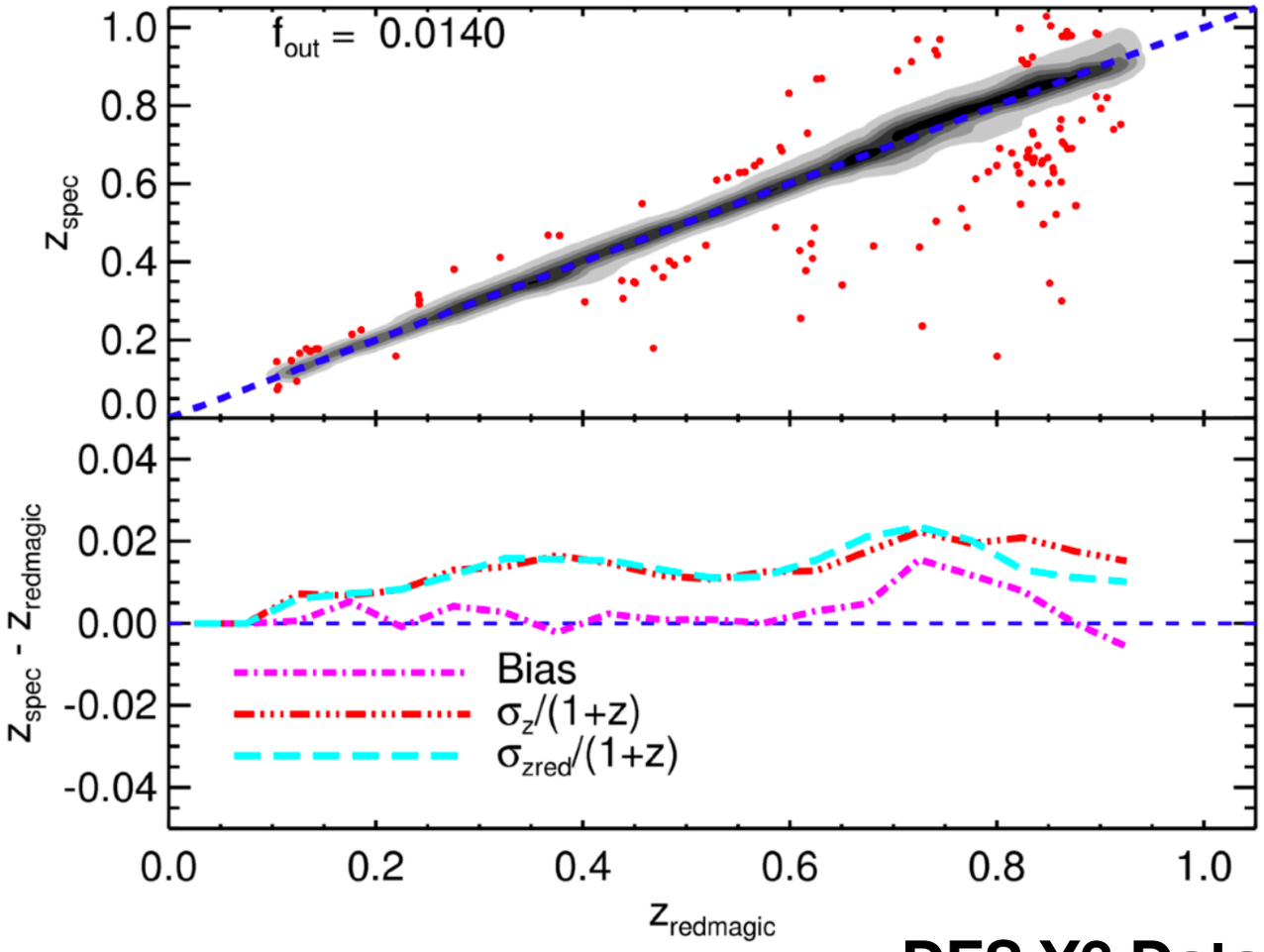




McClintock+2018

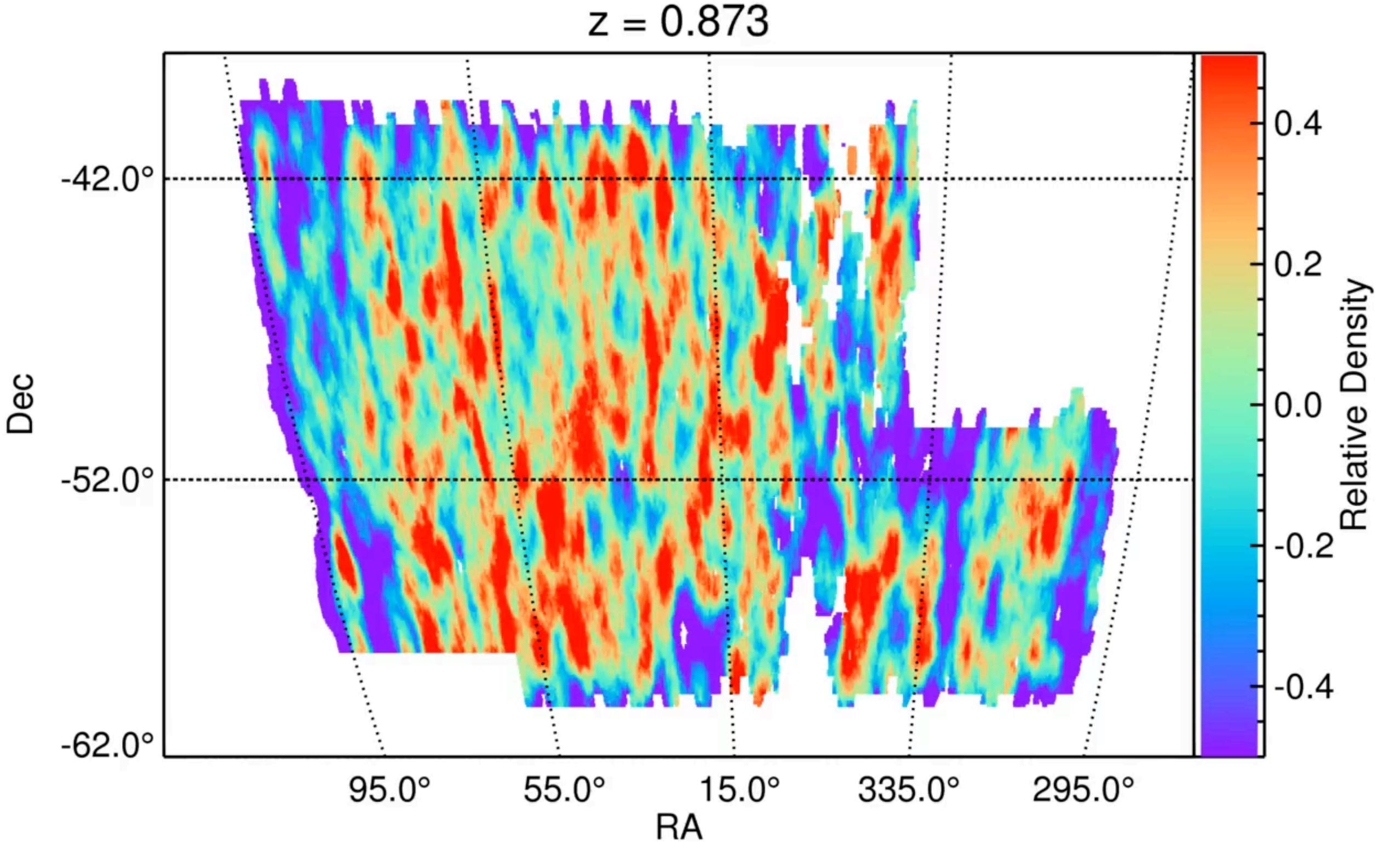
redMaGiC

- Use the redMaPPer red-sequence model to select high confidence red galaxies: the red-sequence Matched-filter Galaxies Catalog (redMaGiC)
  - Choose galaxies specifically to have high precision photometric redshifts
  - Low outlier fraction
  - Constant comoving density (arbitrary)
  - High luminosity, high mass red galaxies
  - Efficient tracers of structure formation
- See Rozo, Rykoff++ 2016



DES Y3 Data

DES Structure



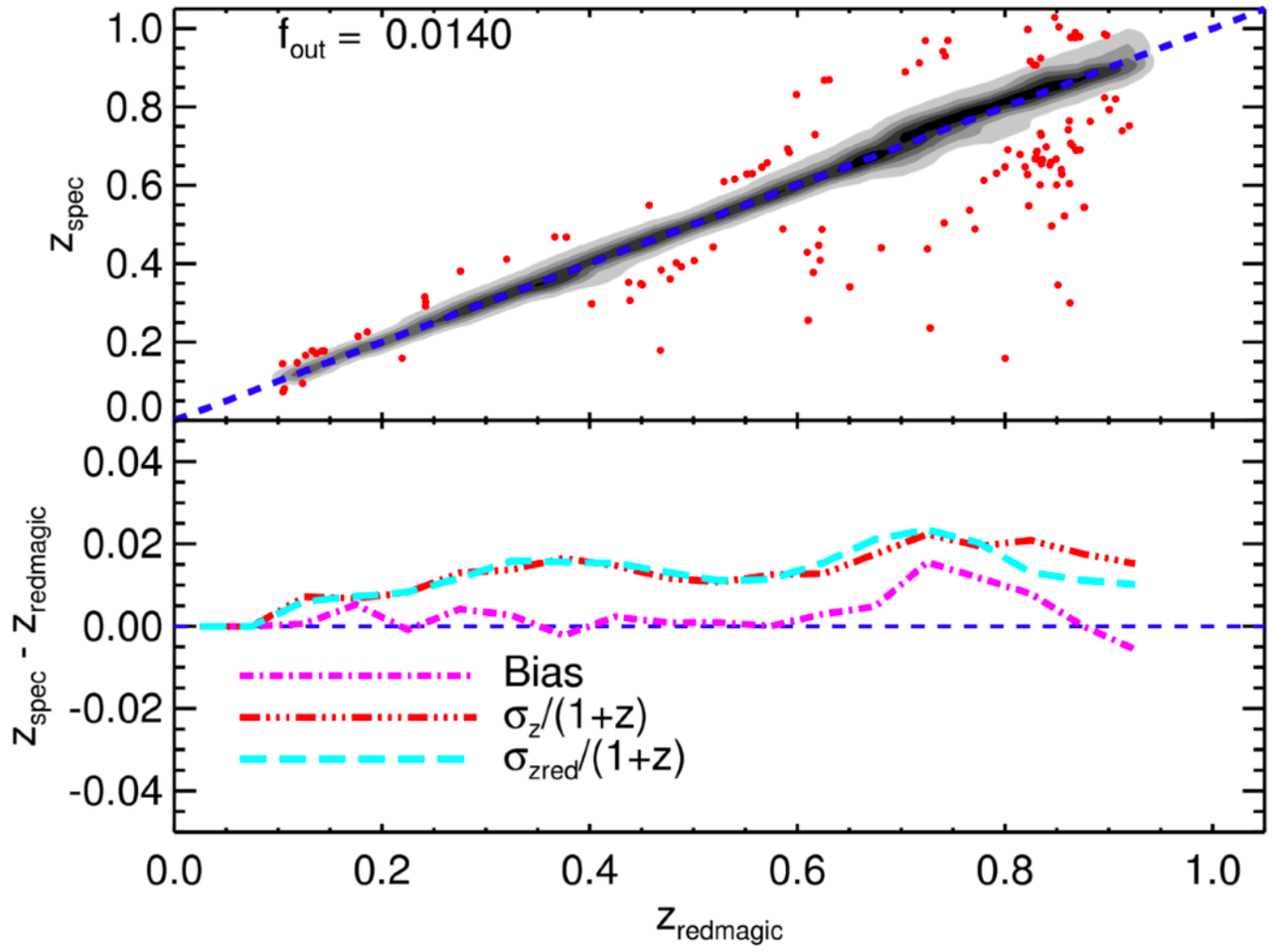
redMaGiC Isn't Perfect…

- Around filter transitions the 4000Å break is hard to resolve

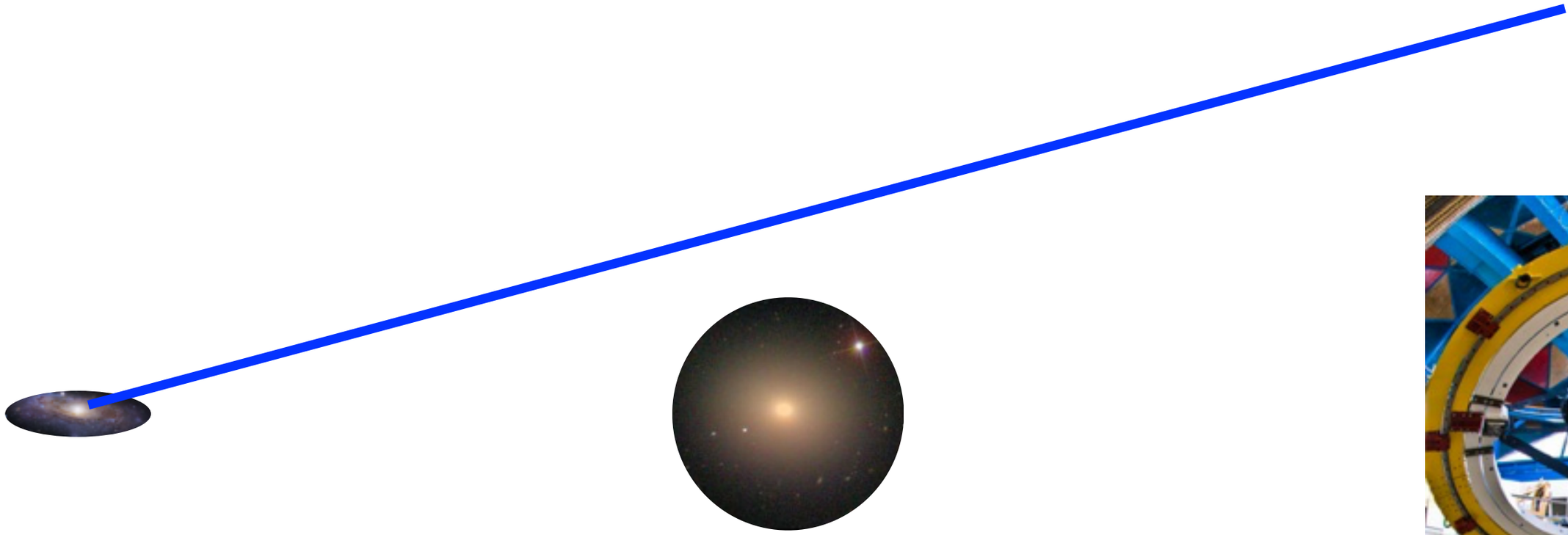
- Red galaxies are mostly dust-free … but not 100%
  - Host reddening is parallel to red-sequence shift

- Errors in photometry, etc.

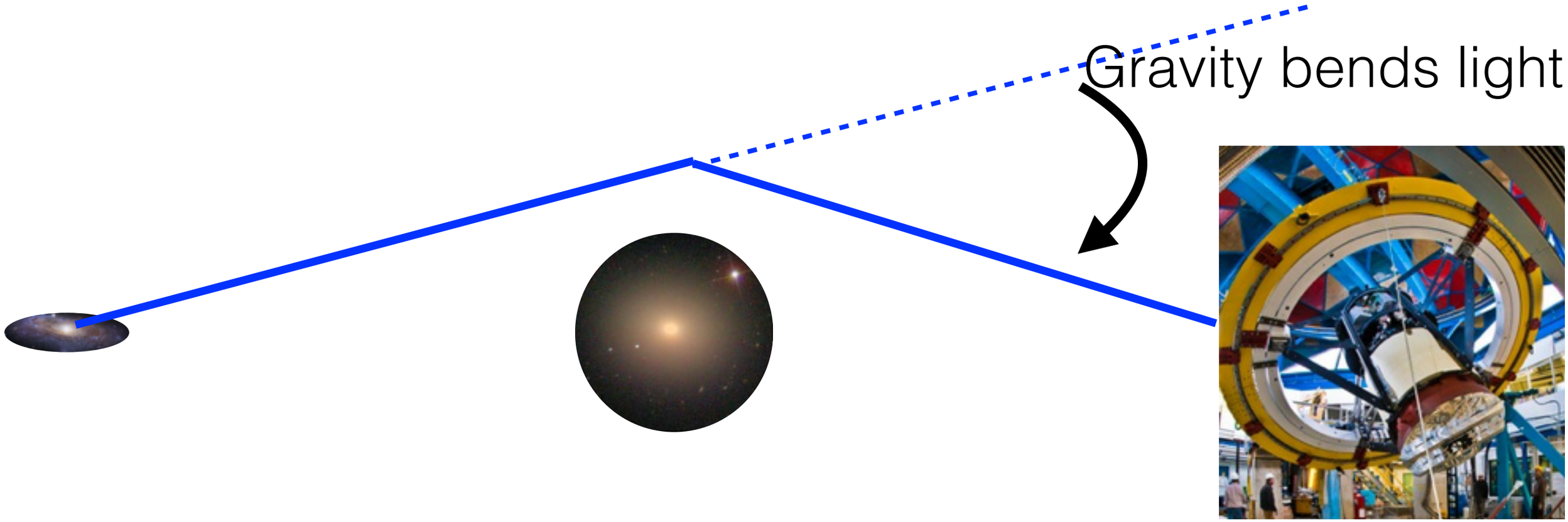
- Double stars



Gravitational Lensing



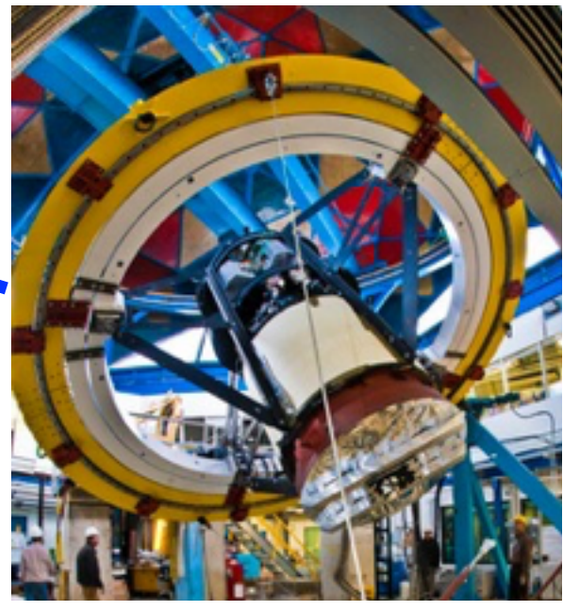
Gravitational Lensing



Gravitational Lensing

And it looks like the background galaxy is here!

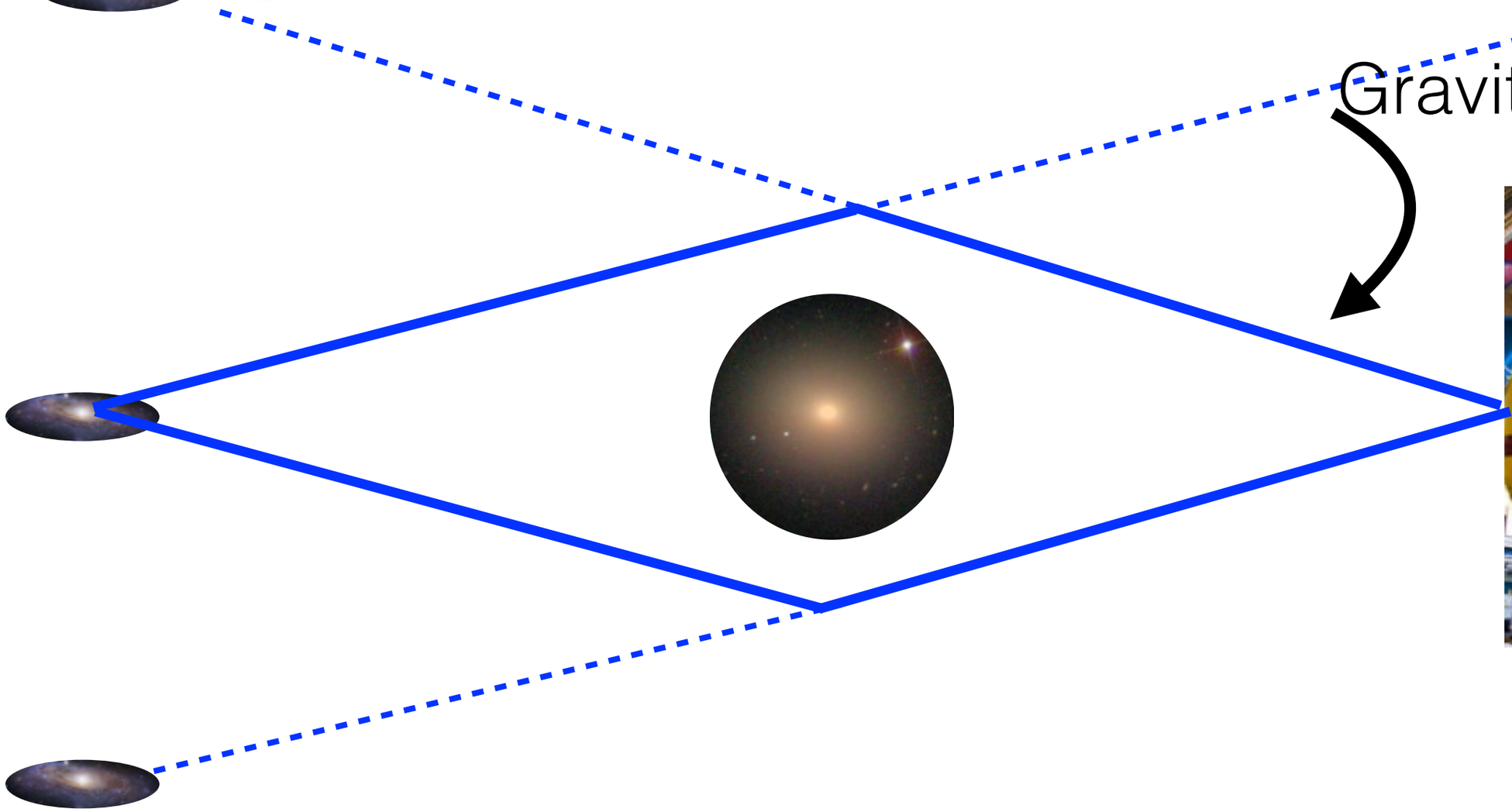
Gravity bends light



Gravitational Lensing

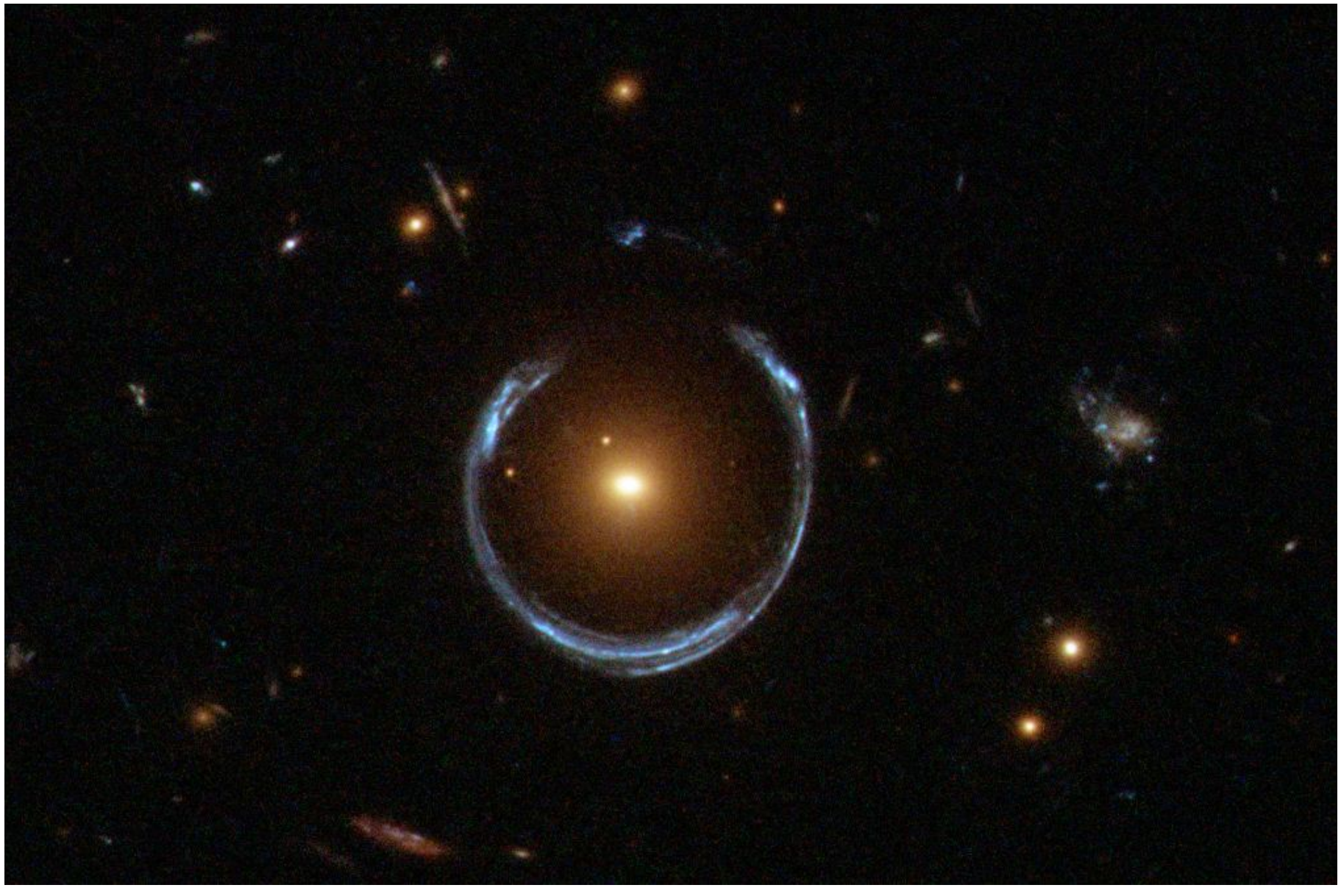
And it looks like the background galaxy is here!

Gravity bends light



… and here

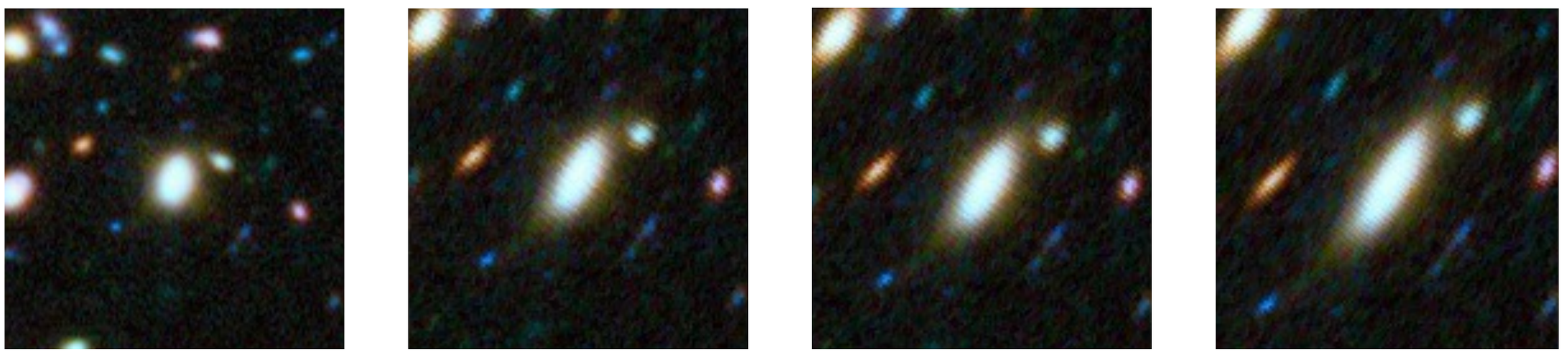
Einstein Rings



"Cosmic Horseshoe"
(imaged by Hubble Space Telescope)

Weighing the Universe

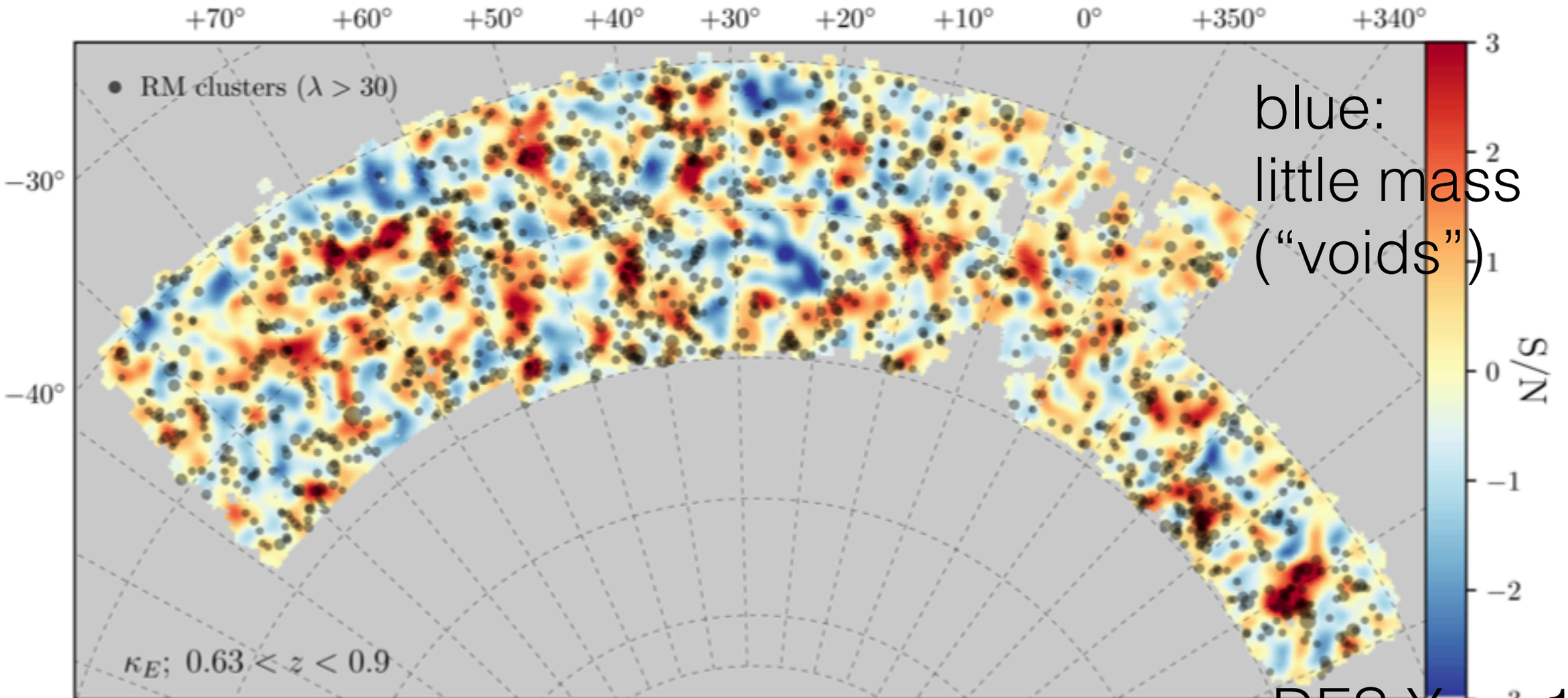
- Weak lensing: the shapes of background galaxies are ever-so-slightly sheared by foreground mass
- These shapes are correlated
- Amount of shearing tells you the mass of the foreground cluster



←low foreground mass high foreground mass→

Mass and Clusters

red:
lots of mass
(“nodes”)

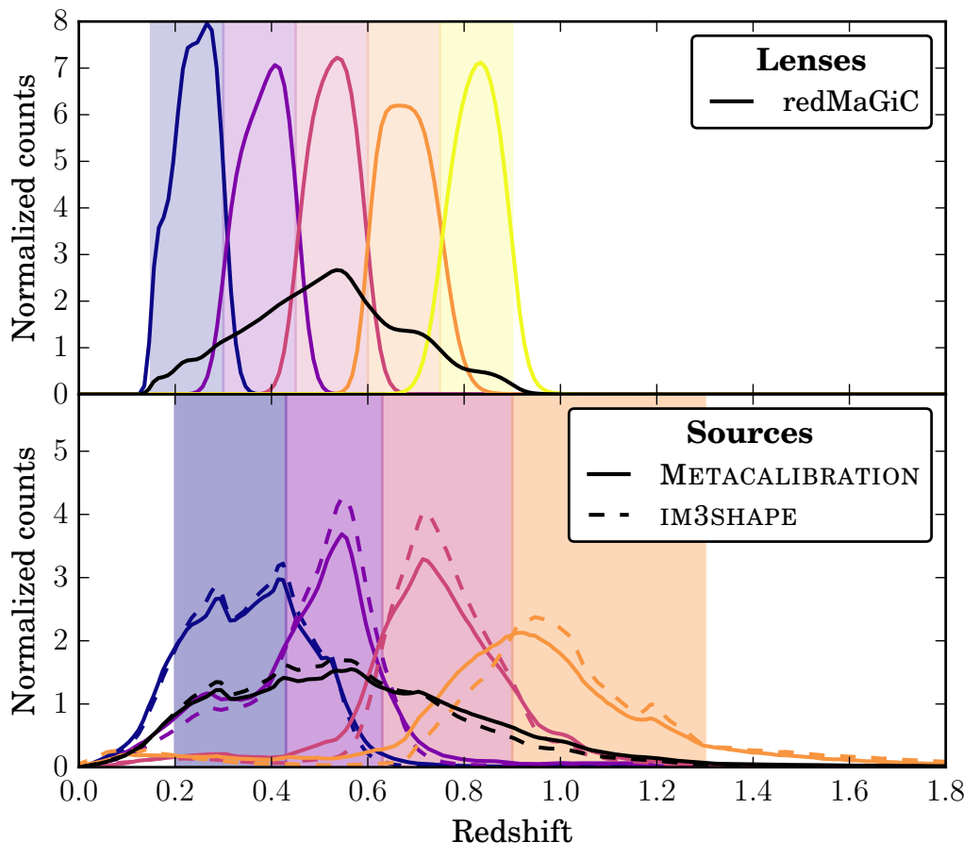


blue:
little mass
(“voids”)

DES Year 1
(Chang++18)

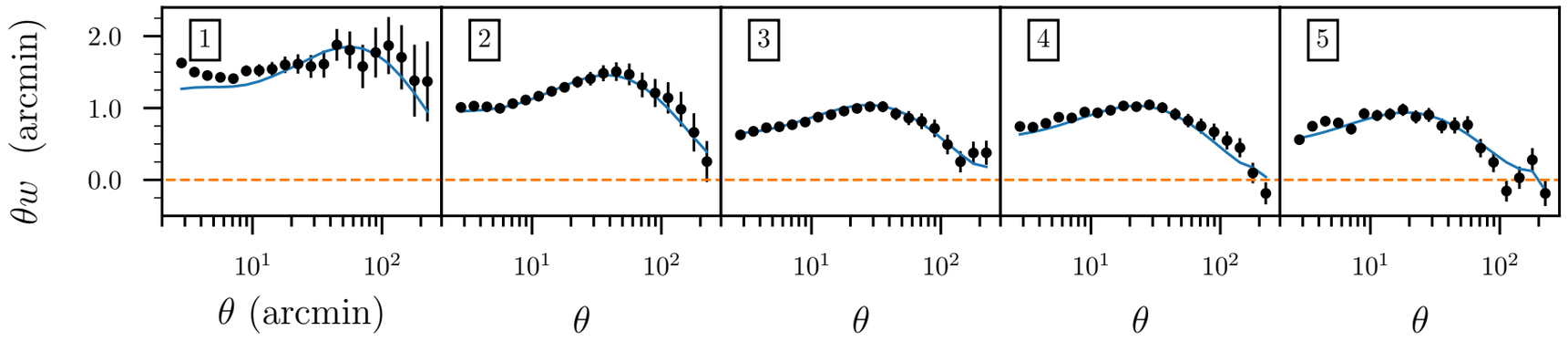
DES “3x2 Point” Cosmology

- Three probes of cosmology
  - Galaxy/galaxy correlation function (“galaxy clustering”)
  - Galaxy/shear correlation function (“galaxy-galaxy lensing”)
  - Shear/shear correlation function (“cosmic shear”)
- Use redMaGiC galaxies as “lenses"
- See Troxel+2018, Elvin-Poole+2018, Prat, Sanchez+2018, Zuntz, Sheldon+2018, Hoyle, Gruen+2018, Drlica-Wagner, Sevilla, ER+2018, Krause, Eifler+2018, DES+2018 (more than one!), and more!

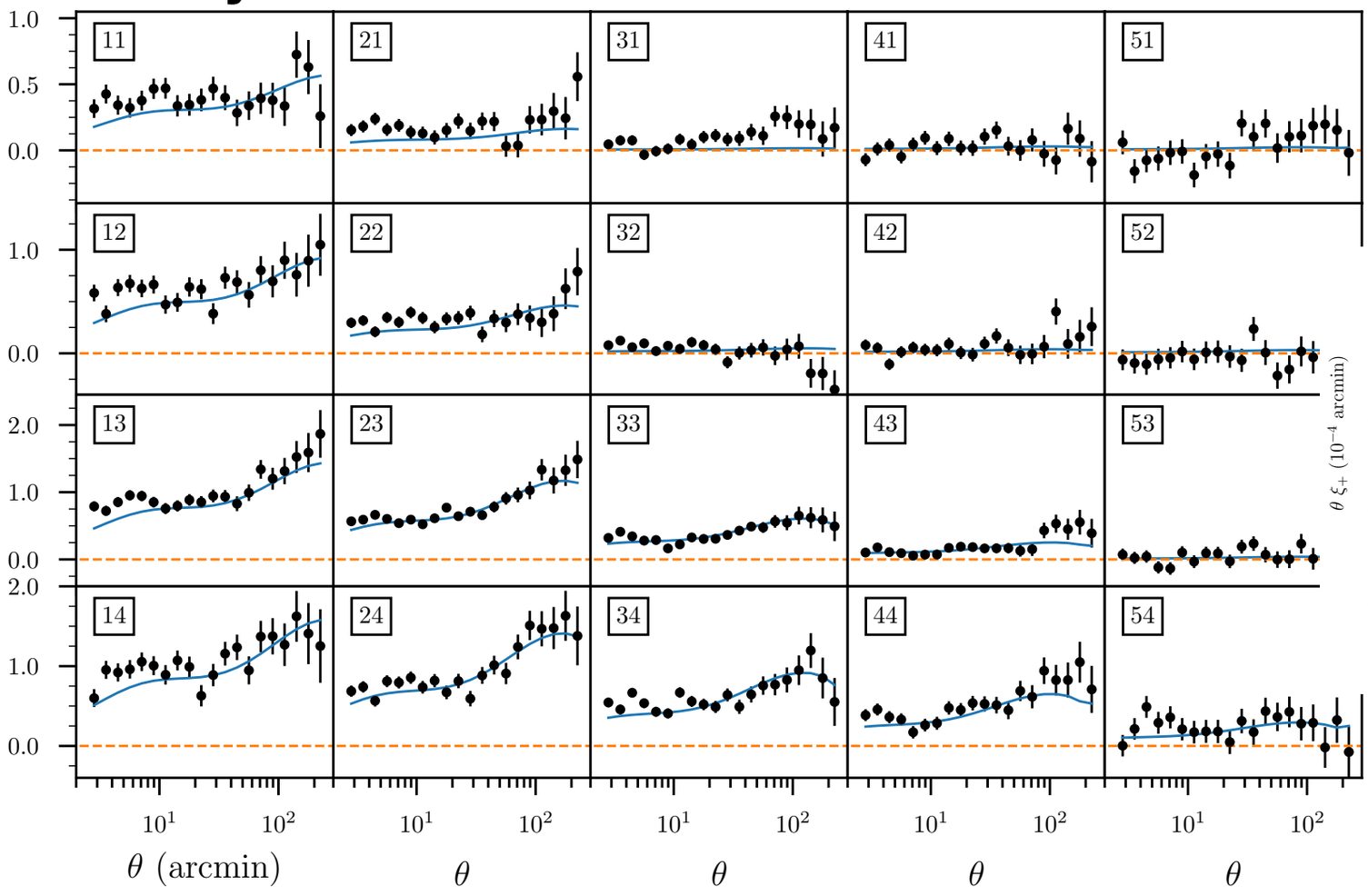


DES 3x2 Year 1 Cosmology

Galaxy/Galaxy

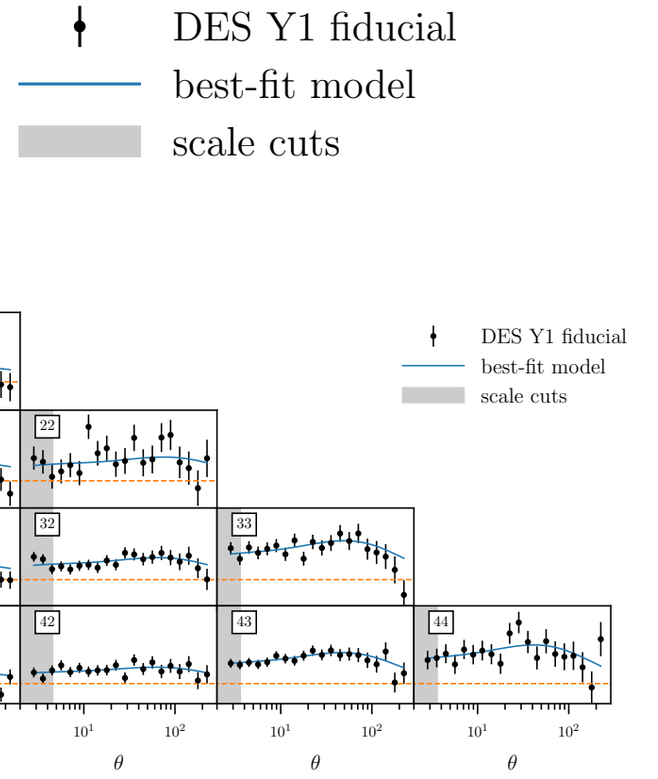


Galaxy/Shear



<- Source redshift

Lens redshift ->

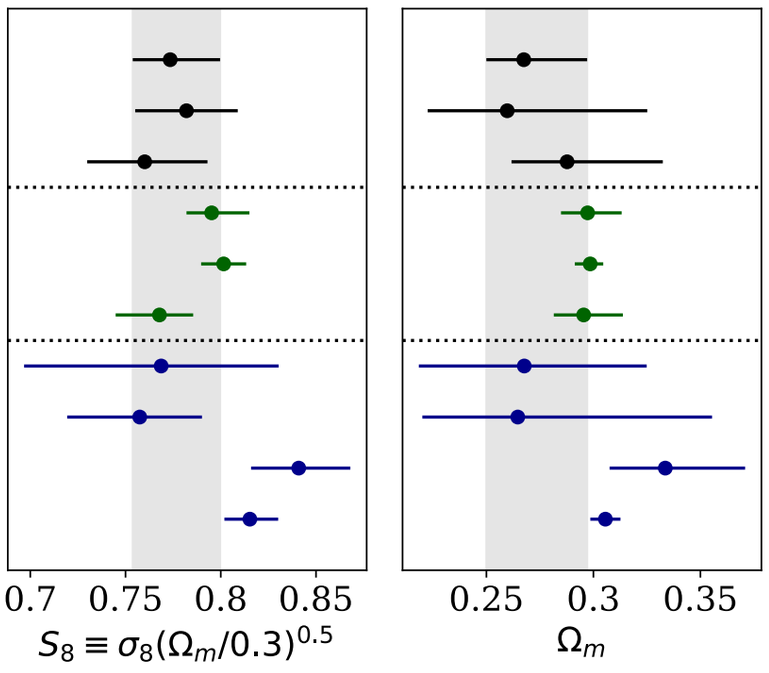


Shear/Shear

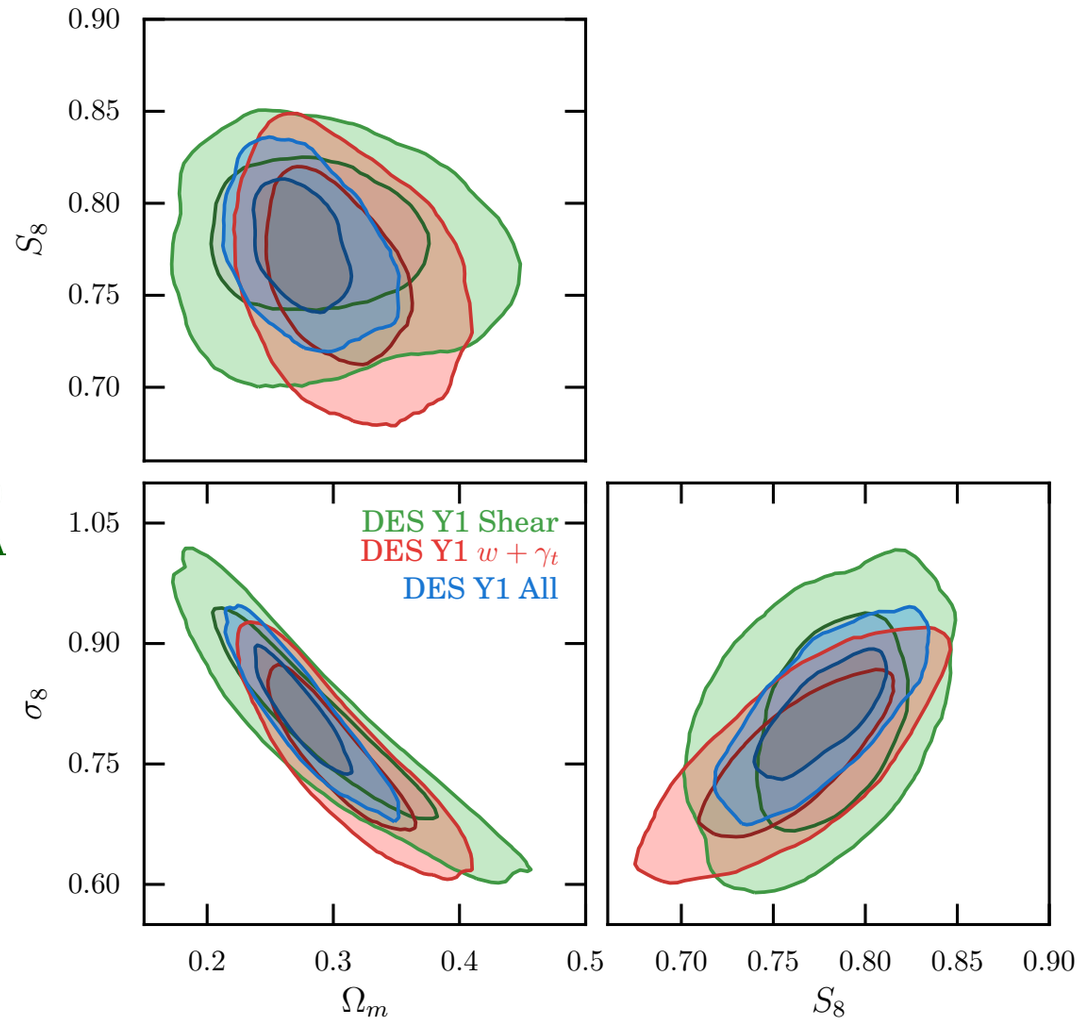
DES+2018

DES 3x2 Year 1 Cosmology

- Combining these 3 probes gives exceptional constraints on Ω_M and σ_8
- Possible tensions between low-z (DES) and high-z (Planck & CMB)



DES Y1 All
DES Y1 Shear
DES Y1 $w + \gamma_t$
DES Y1 All + Planck (No Lensing)
DES Y1 All + Planck + BAO + JLA
DES Y1 All + BAO + JLA
DES SV
KiDS-450
Planck (No Lensing)
Planck + BAO + JLA



DES+2018

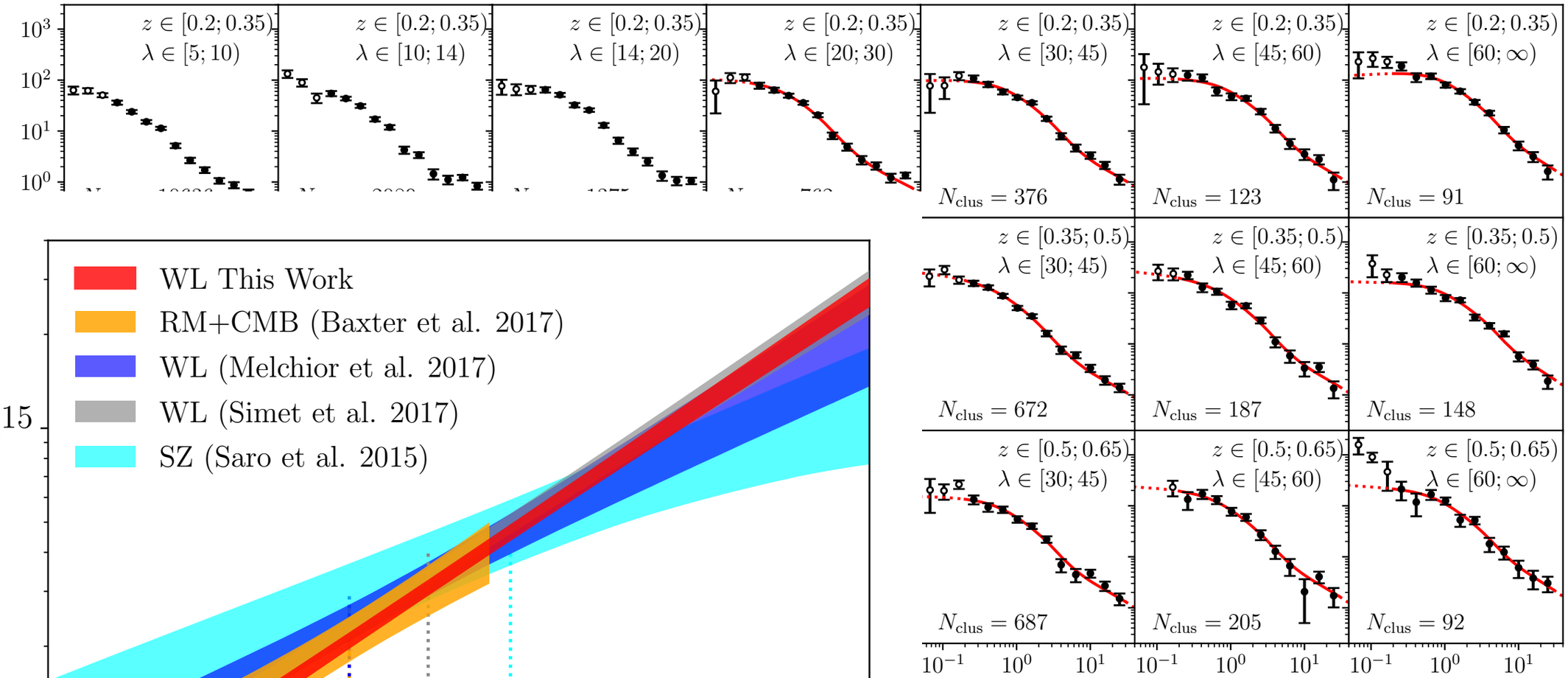
And the Clusters

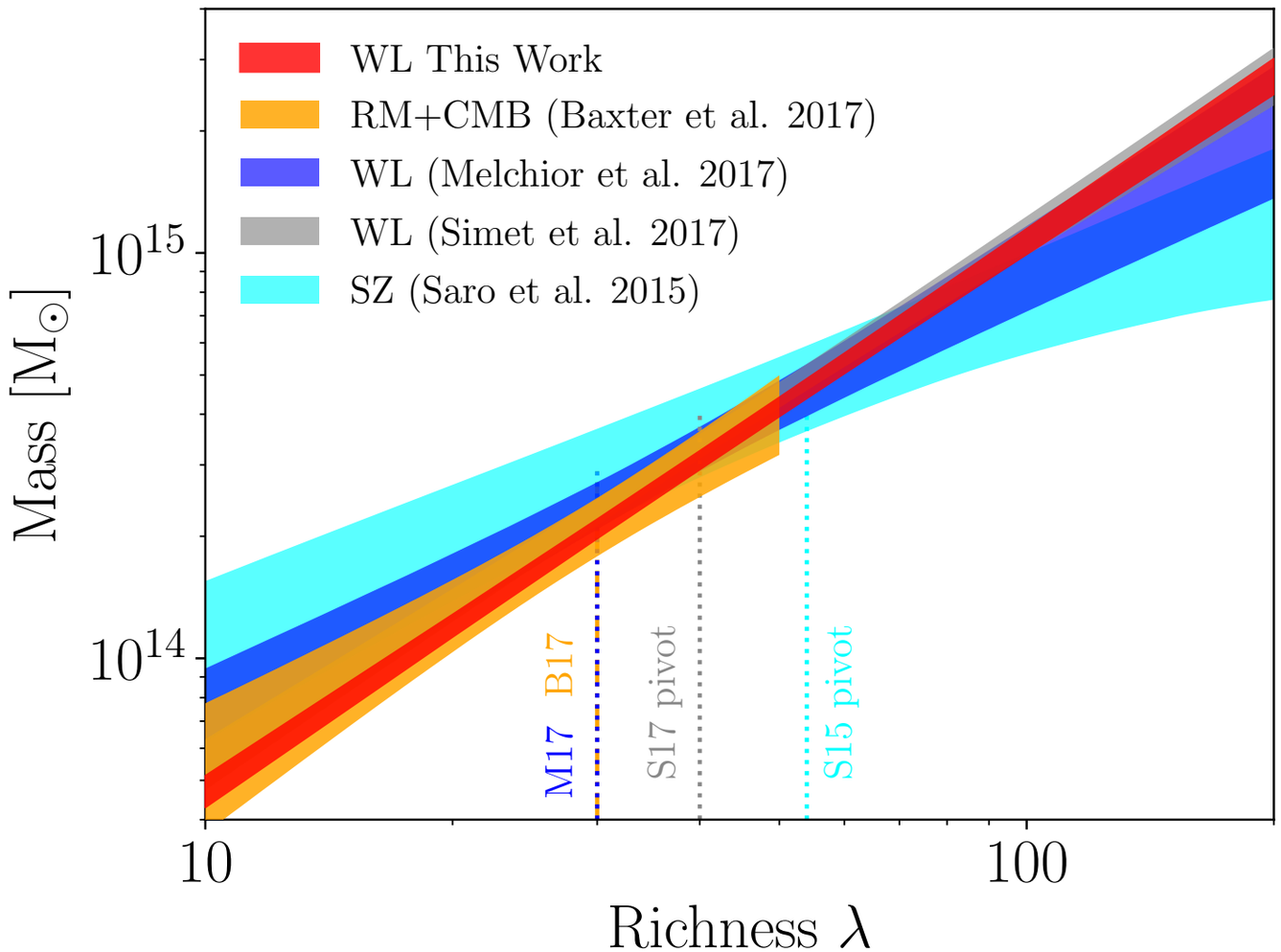
- The redMaGiC galaxies trace structure
  - Large numbers, good statistics
  - Model the correlations at large scales

- The redMaPPer clusters also trace structure
  - Smaller numbers, higher mass
  - Availability of multi-wavelength data (X-rays, Sunyaev-Zeldovich effect)
  - Smaller scales give higher signal … and additional modeling challenges

redMaPPer Lensing

- The “Cluster-shear cross-correlation”





McClintock+2018

DES Y1 Cluster Cosmology

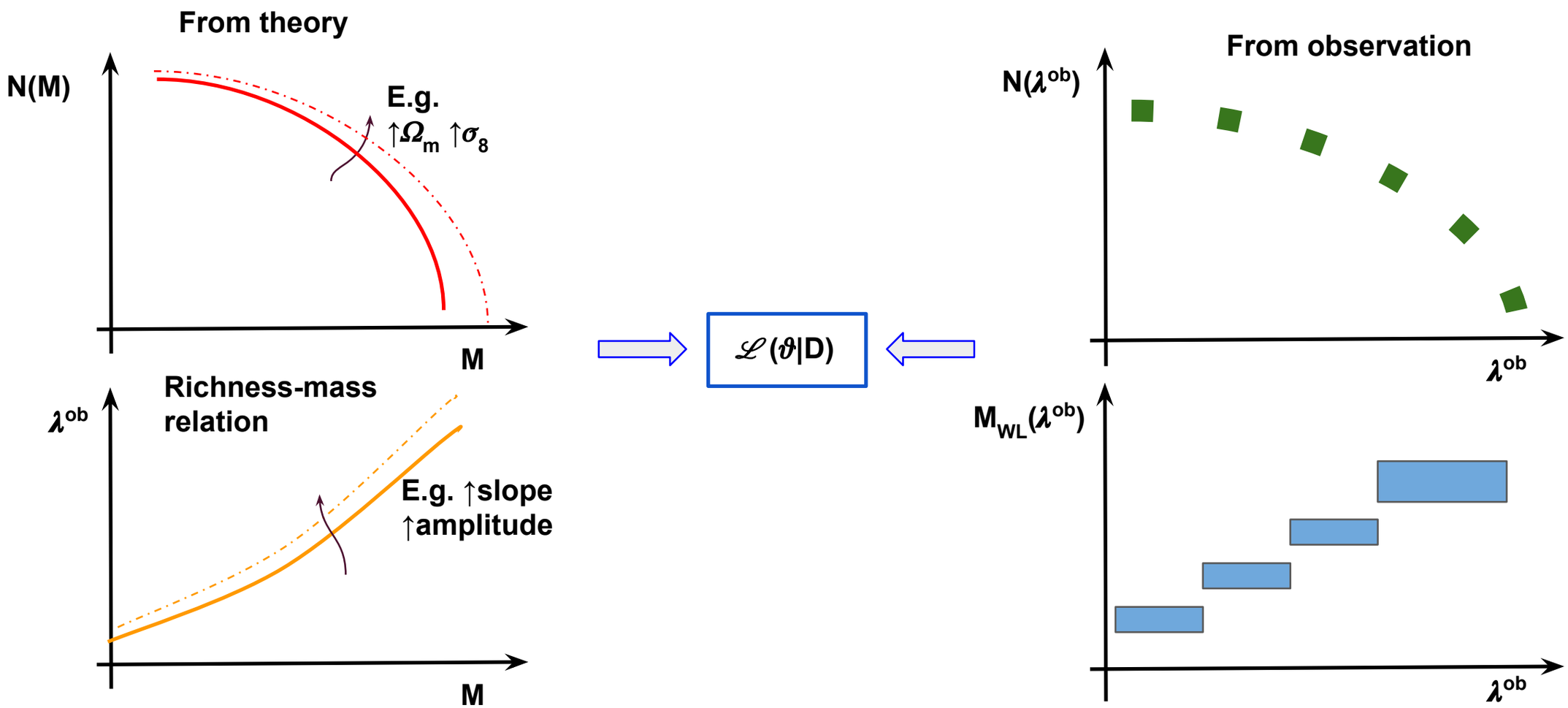
- DES+20, on the arxiv today! https://arxiv.org/abs/2002.11124
  - Matteo Costanzi lead author

- A complete blinded analysis … at first
  - Strong disagreement with concordance
  - A lot of post-unblinding analysis
  - See paper for details

- The main results are from the “post unblinded” analysis, but significant challenges remain.

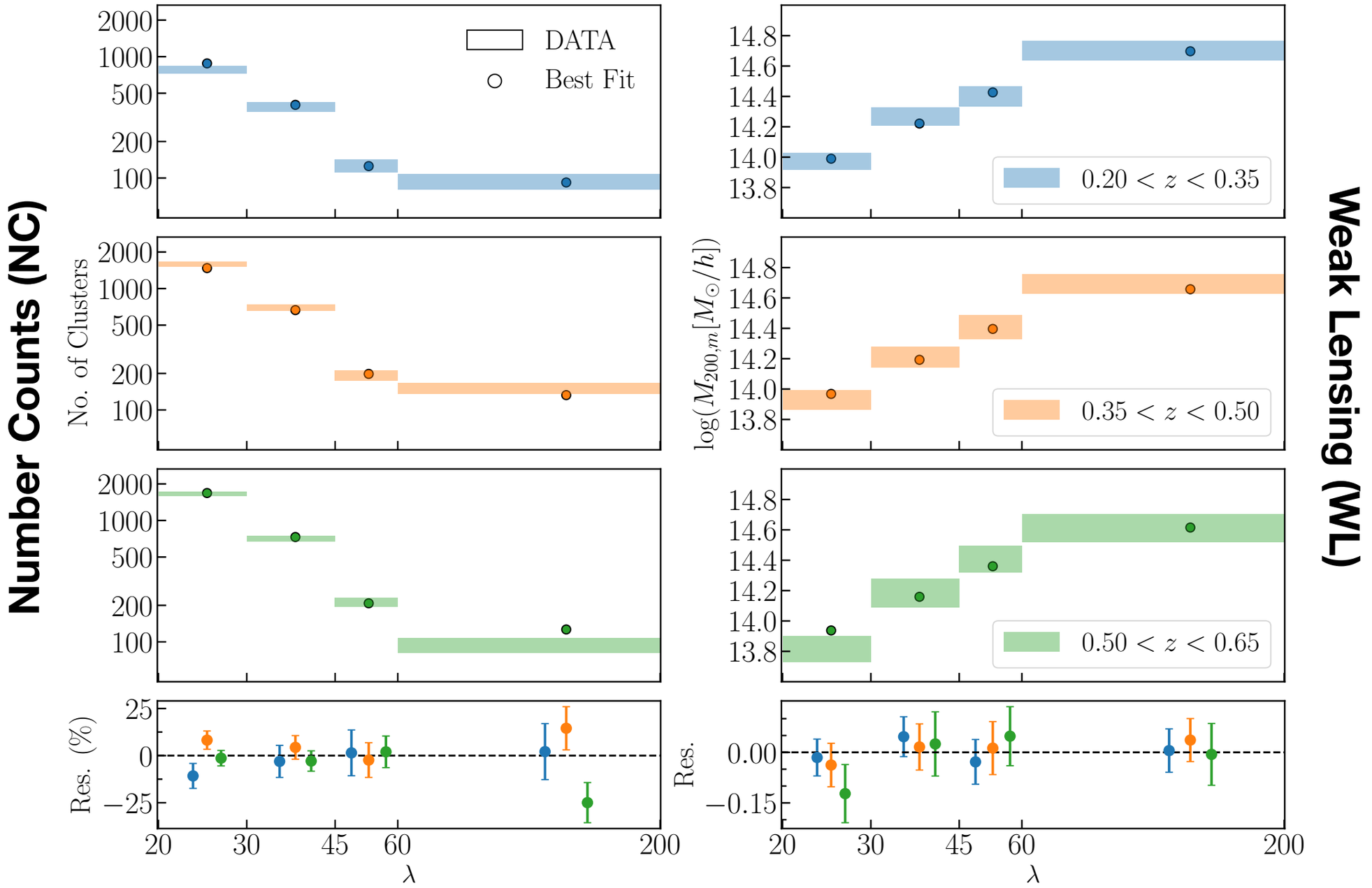
Cosmology from Cluster Number Counts

- Combine cluster abundance and cluster mass estimates to simultaneous constrain cosmology and richness-mass relation (Costanzi+2018 and DES+2020)



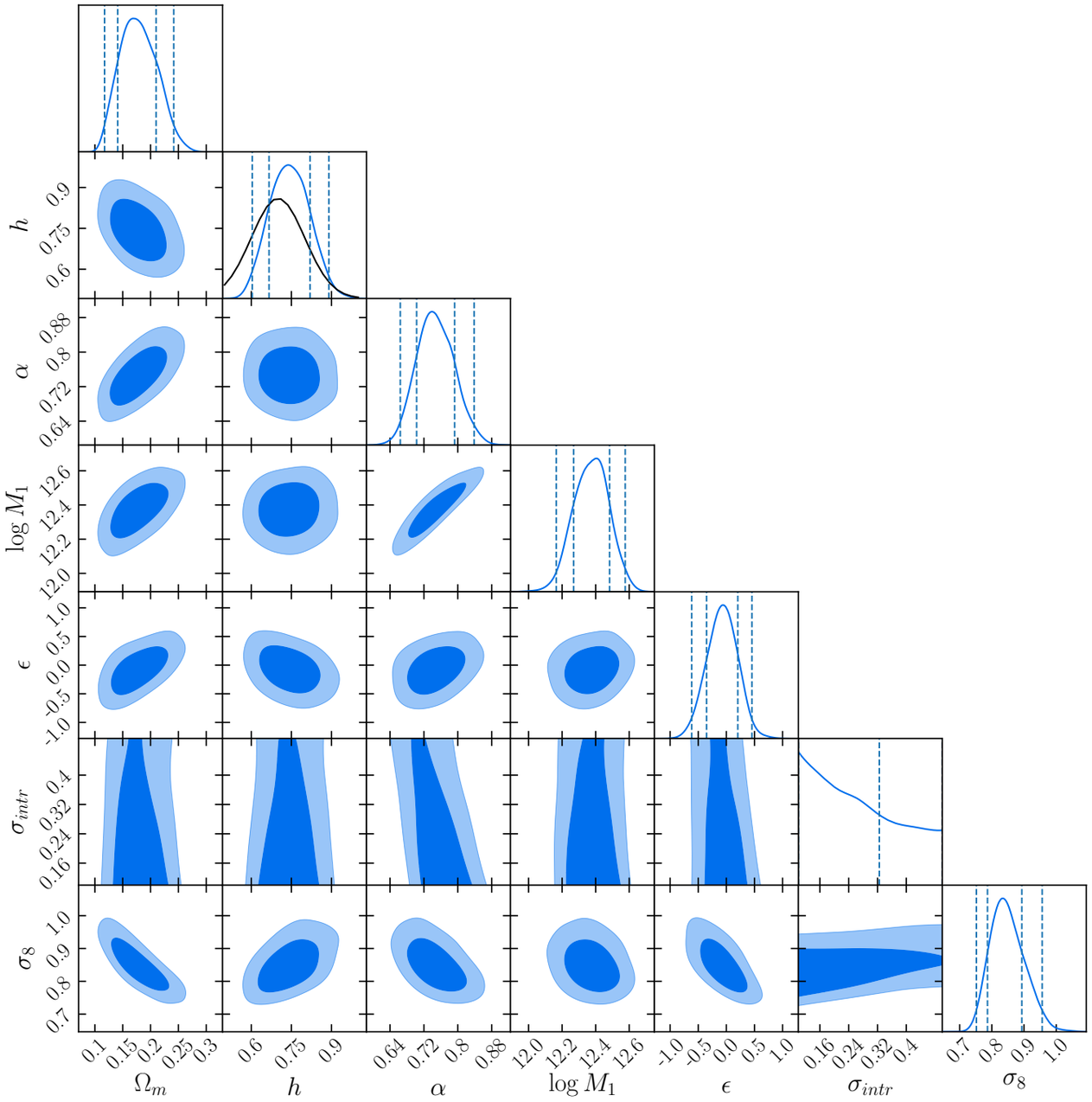
Best-Fit Model

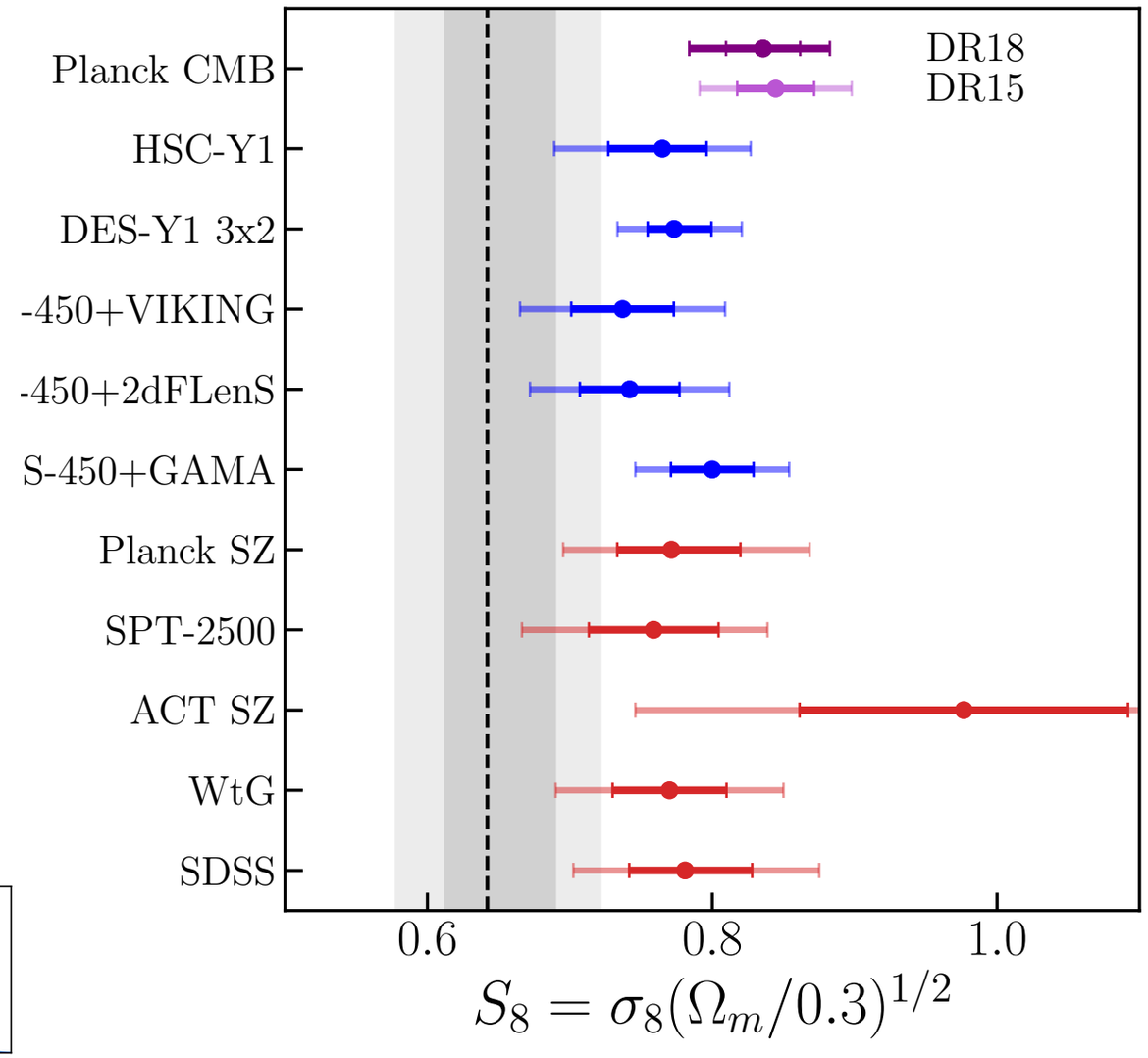
- The model is a good fit to the NC and WL data…



Best-Fit Cosmology

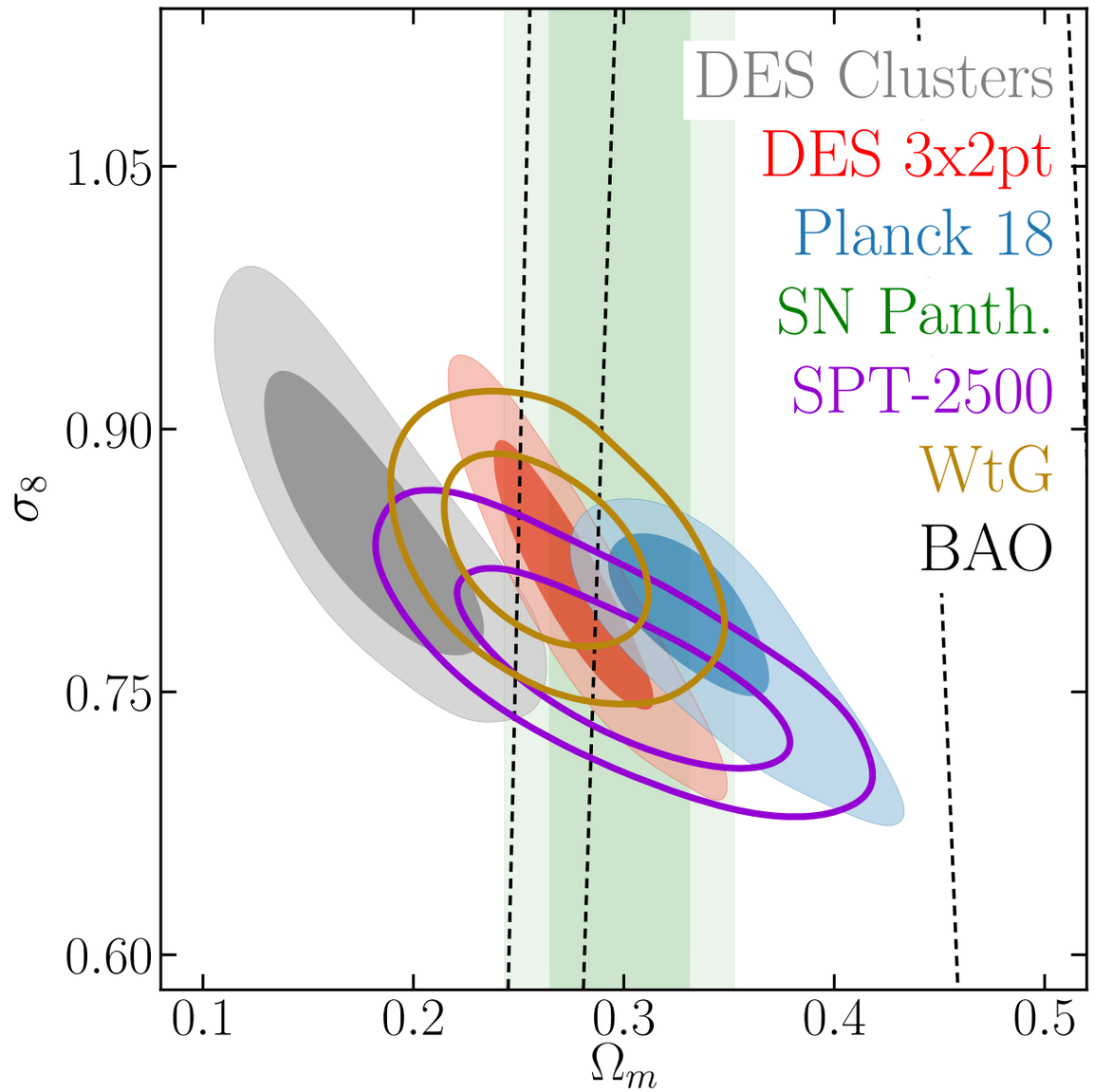
- …but the cosmological constraints are not in "concordance" with Concordance Cosmology.





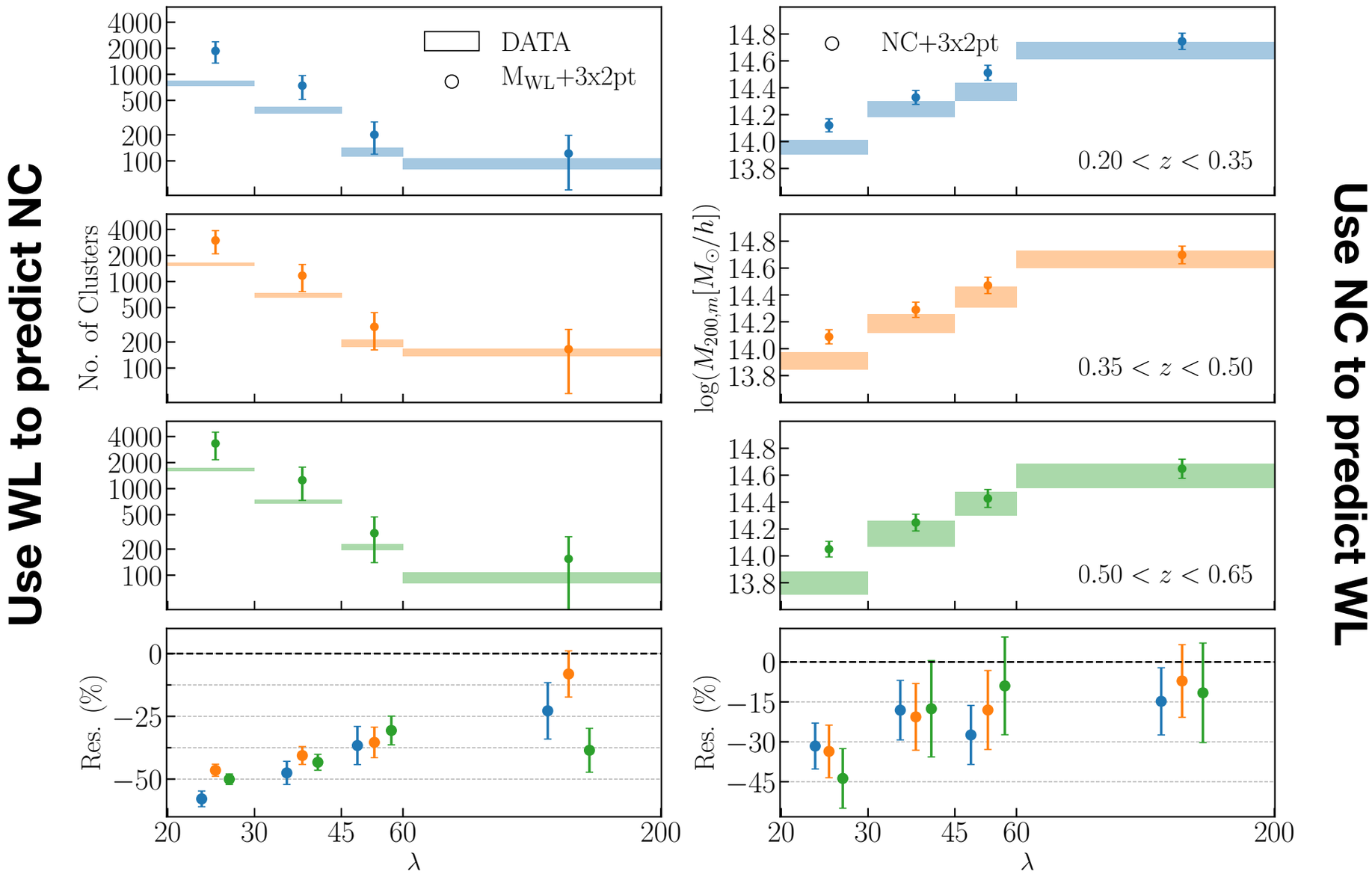
Multi-Probe Tension

- Comparing to all the other probes…the DES Y1 Clusters are a significant outlier.



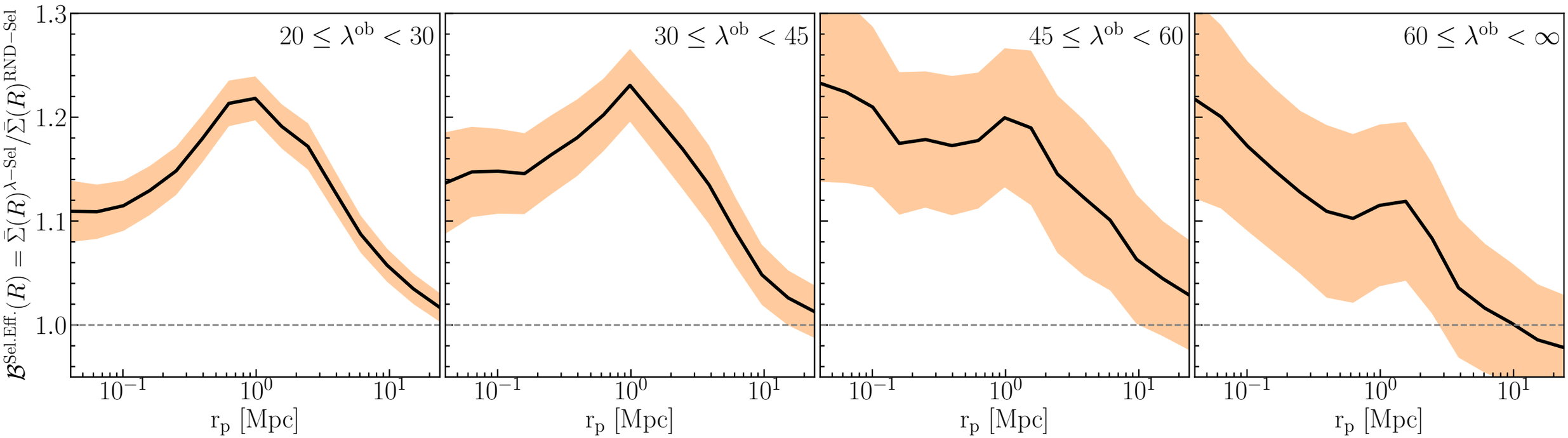
Is it NC or WL?

- Use the DES 3x2pt best-fit cosmology.
- If we use the NC to predict WL and vice versa?



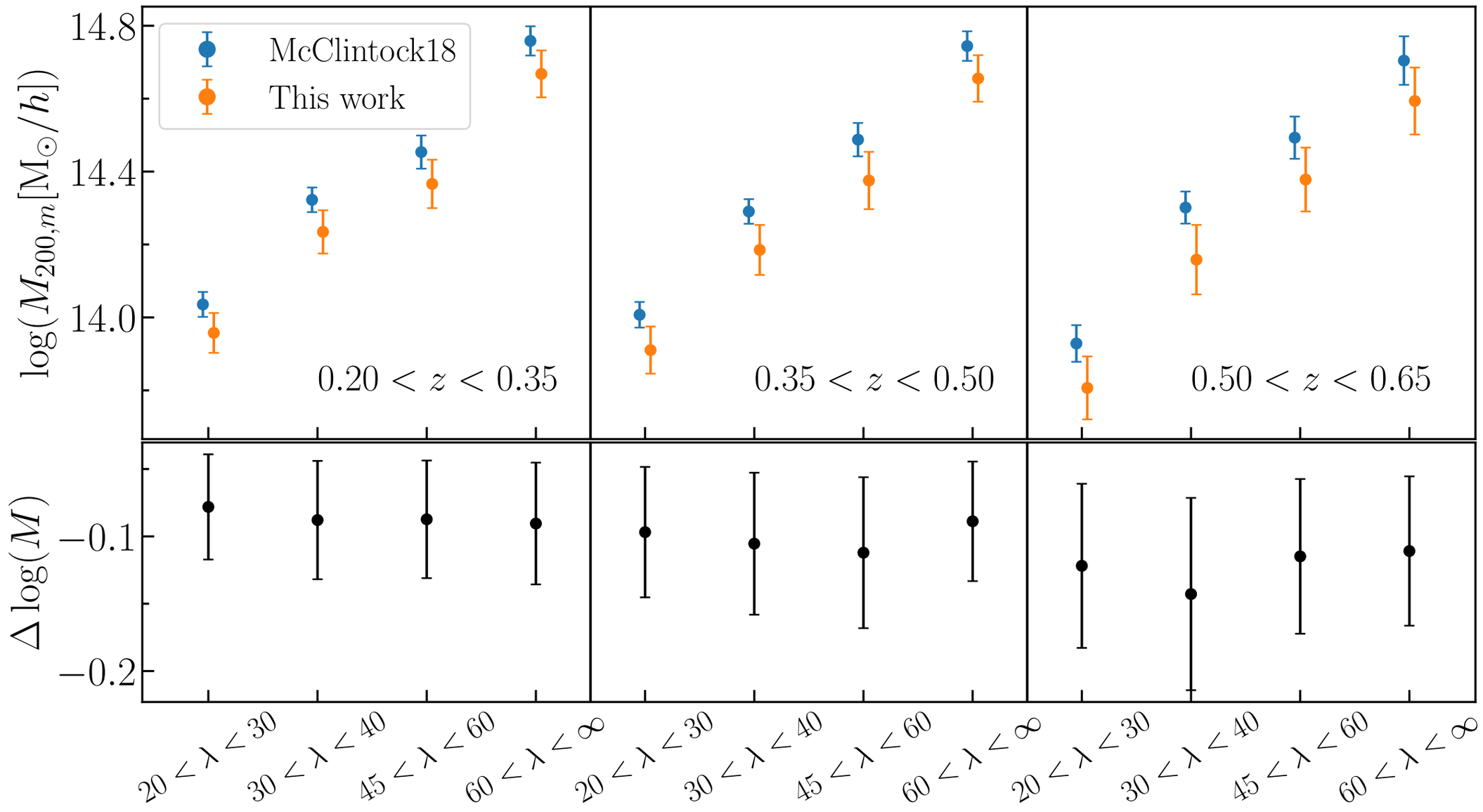
Updated Projection Effects

- Post-unblinding, more numerical simulations (Buzzard; deRose+19) were available
- Further investigation of projection effects
- Compute redMaPPer richness on 12 Buzzard Flock simulations, compare Σ(R) to a halos with same mass/ richness distribution (work by Heidi Wu, in prep)



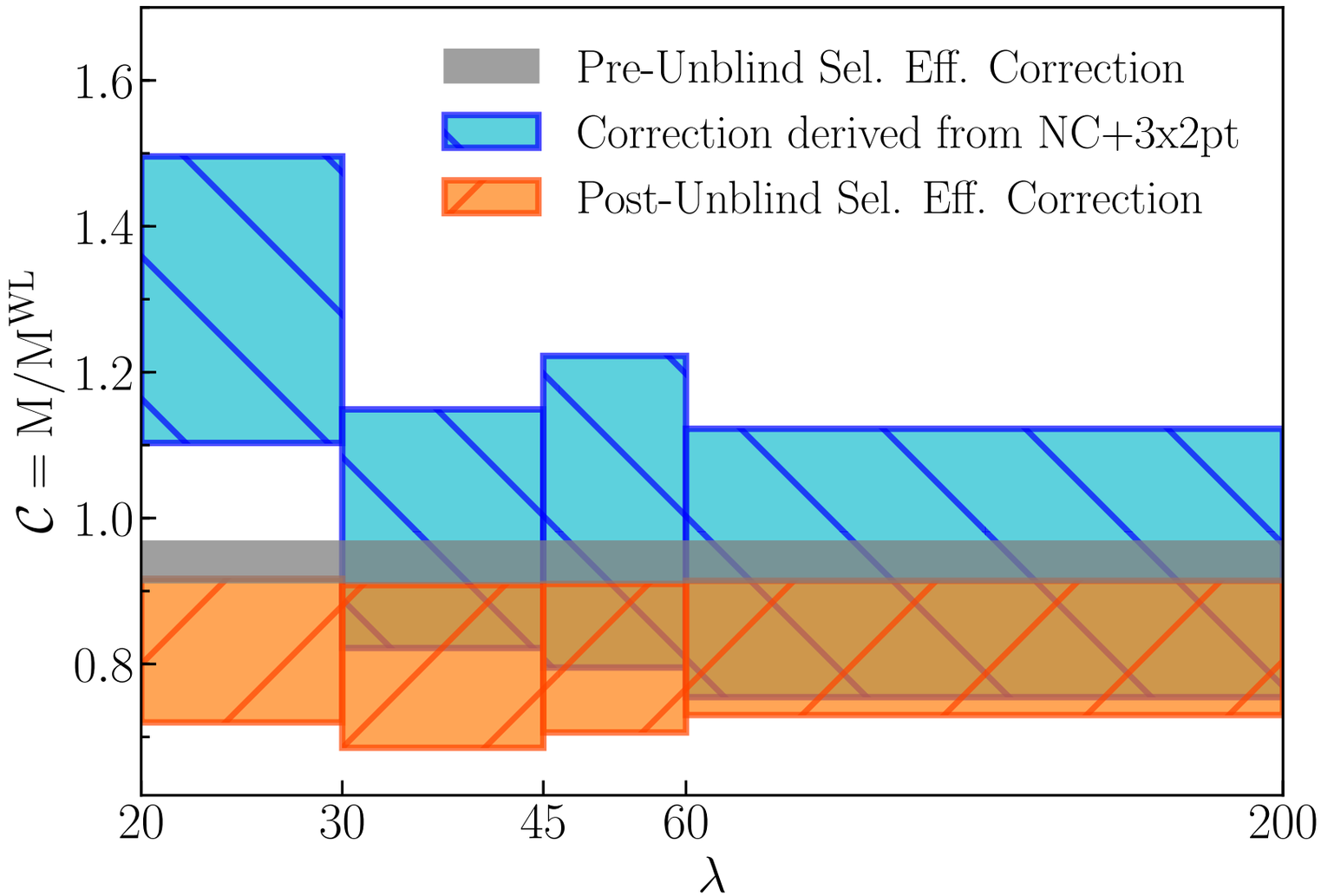
Updated Projection Effects

- Masses go down 20-30% taking this into account
  - Depends on richness/redshift



…But that's not all

- Ask the question: what is the mean correction required so that WL masses are consistent with NC+3x2
- The low richness bin is most problematic
- Opposite sign to that expected from projection effect problems!

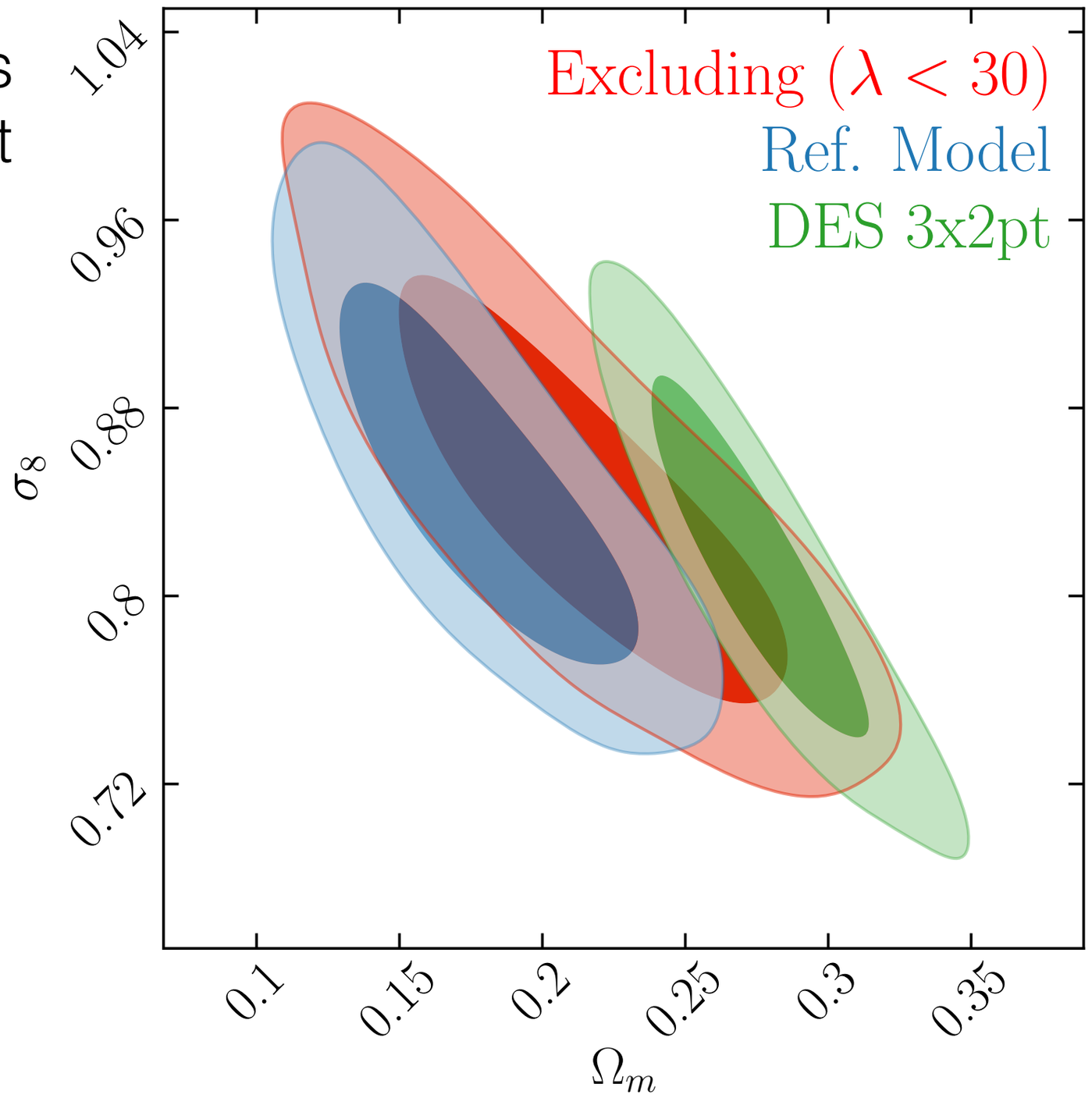


Is it the 20<λ<30 bin?

- Excluding these clusters brings things into better agreement

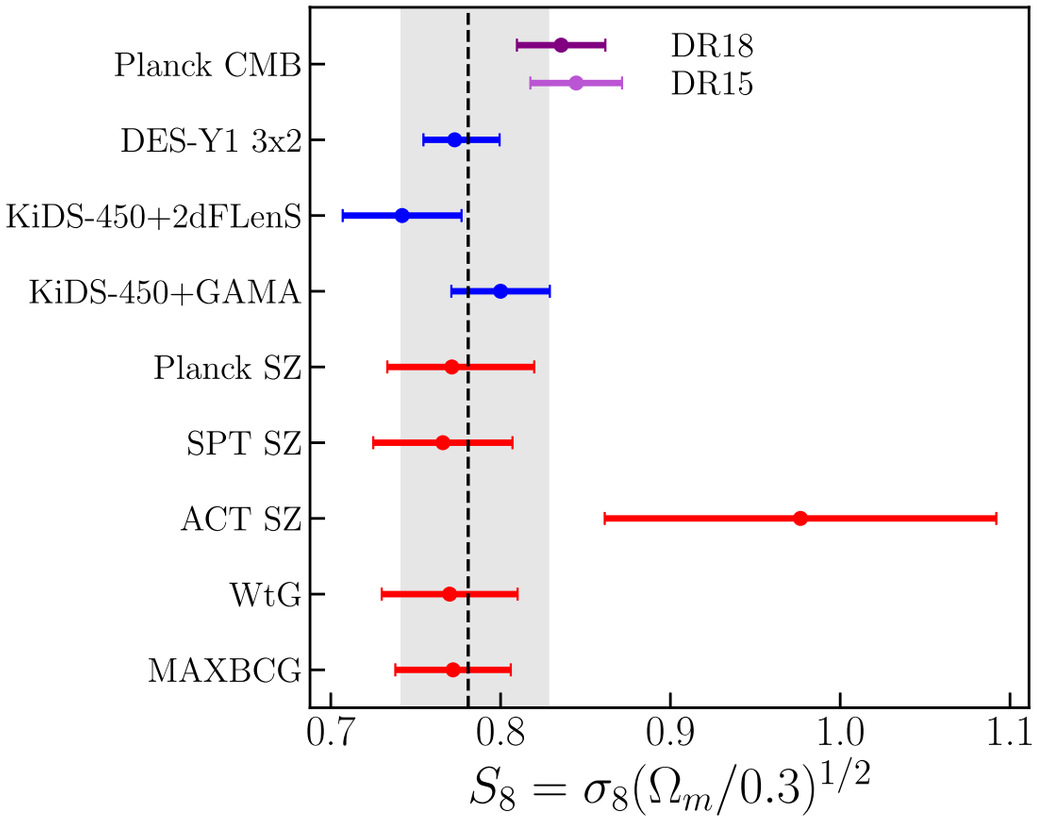
- Removing other bins does not shift the contours noticeably

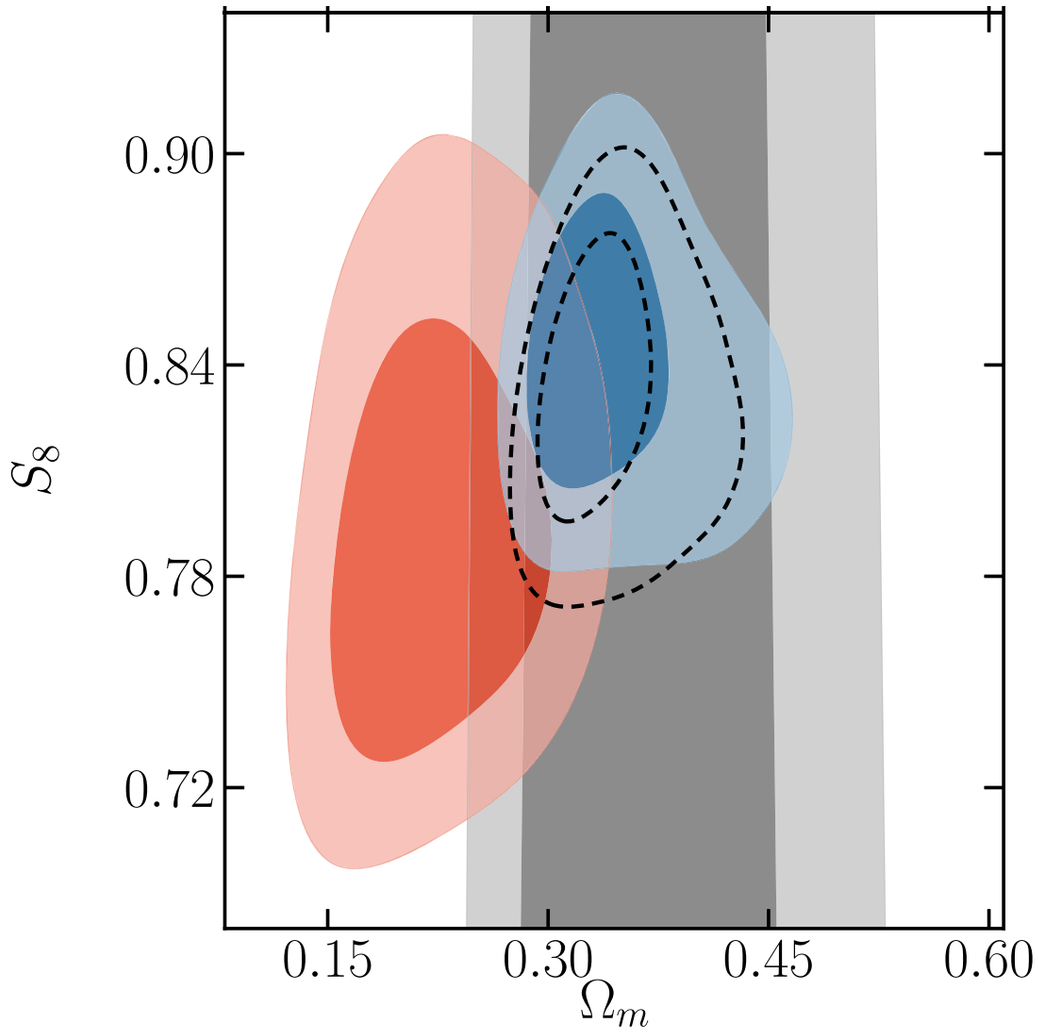
- Is an issue for all redshifts



SDSS Cosmology

- Costanzi+19 SDSS Cosmology, used as part of our pre-blind testing





DES Y1 Clusters

- Cosmological posteriors have 5.6σ tension with Planck; 2.4σ with DES 3x2 point
  - Driven by very low Ω_m posterior

- Internal inconsistency with DES 3x2pt is worrying
- Cross-checks with X-ray and SZ suggest abundance data are fine — incorrect interpretation of stacked WL signal

- Low richness bin is the main driver
  - Sign of offset is opposite to that expected from projection effects!

From DES to LSST

- More area! More depth!
  - Better statistics! Higher redshifts!
  - The LSST y-band will allow efficient red sequence cluster finding and redMaGiC selection to z<~1.2
  - Of course, red galaxies are less common going back in time, but there are still plenty
    - Photometric supernovae in the wide-fast-deep survey
    - Other science goals…
- With better statistics come more stringent requirements on systematics
  - Photometric Calibration
  - Deblending

The Future

- Finish DES analysis using the full survey

- Improve handling of optical cluster selection function for cosmology (!!)

- Increase number density of redMaGiC galaxies without compromising performance

- Even after 1 year of LSST survey, will be able to push beyond z>1 with high quality red galaxies