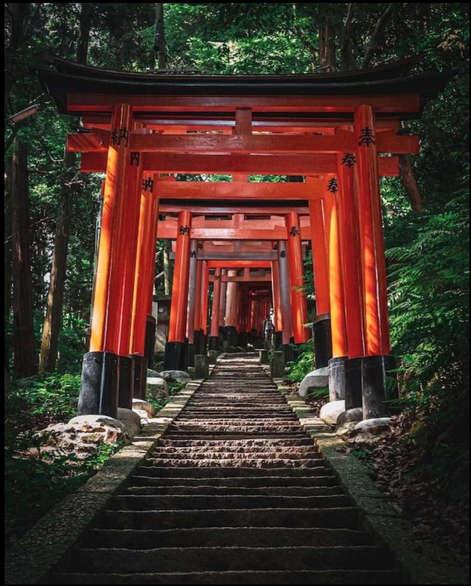
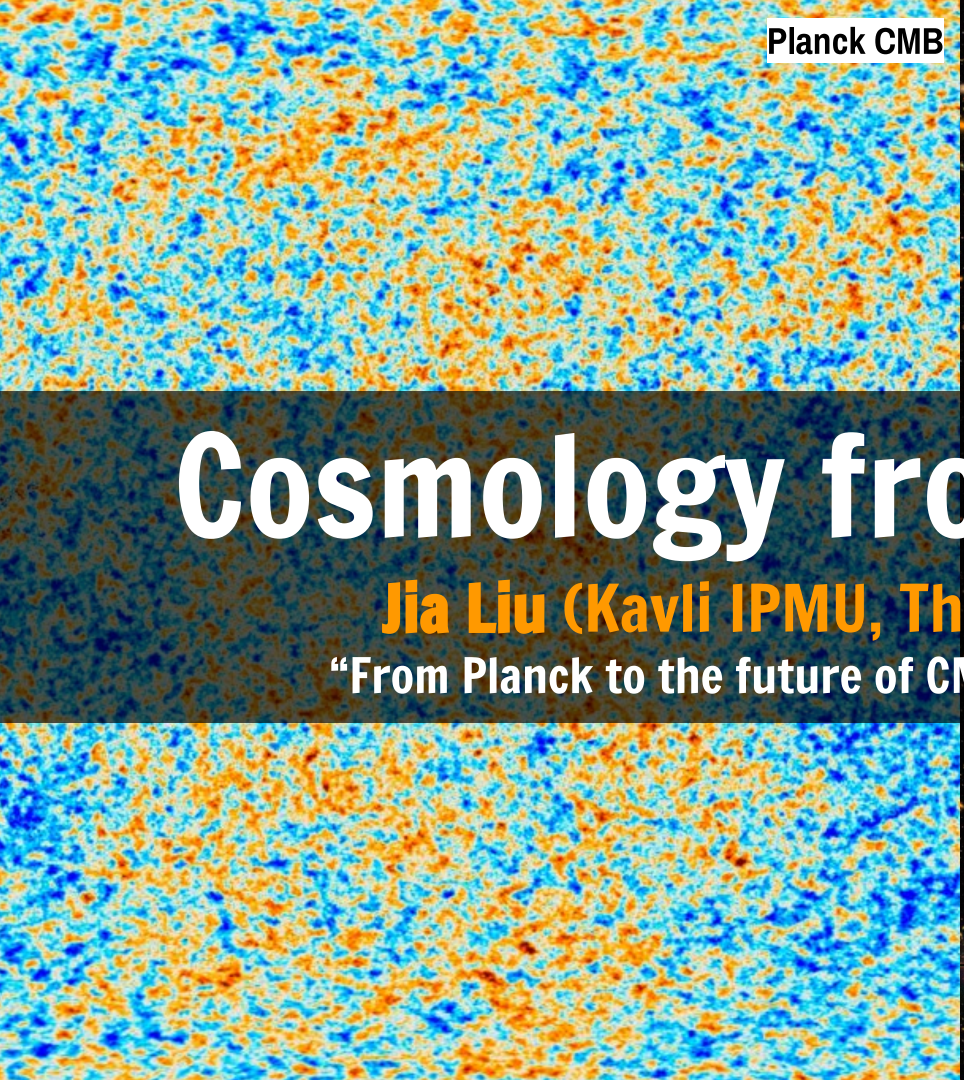
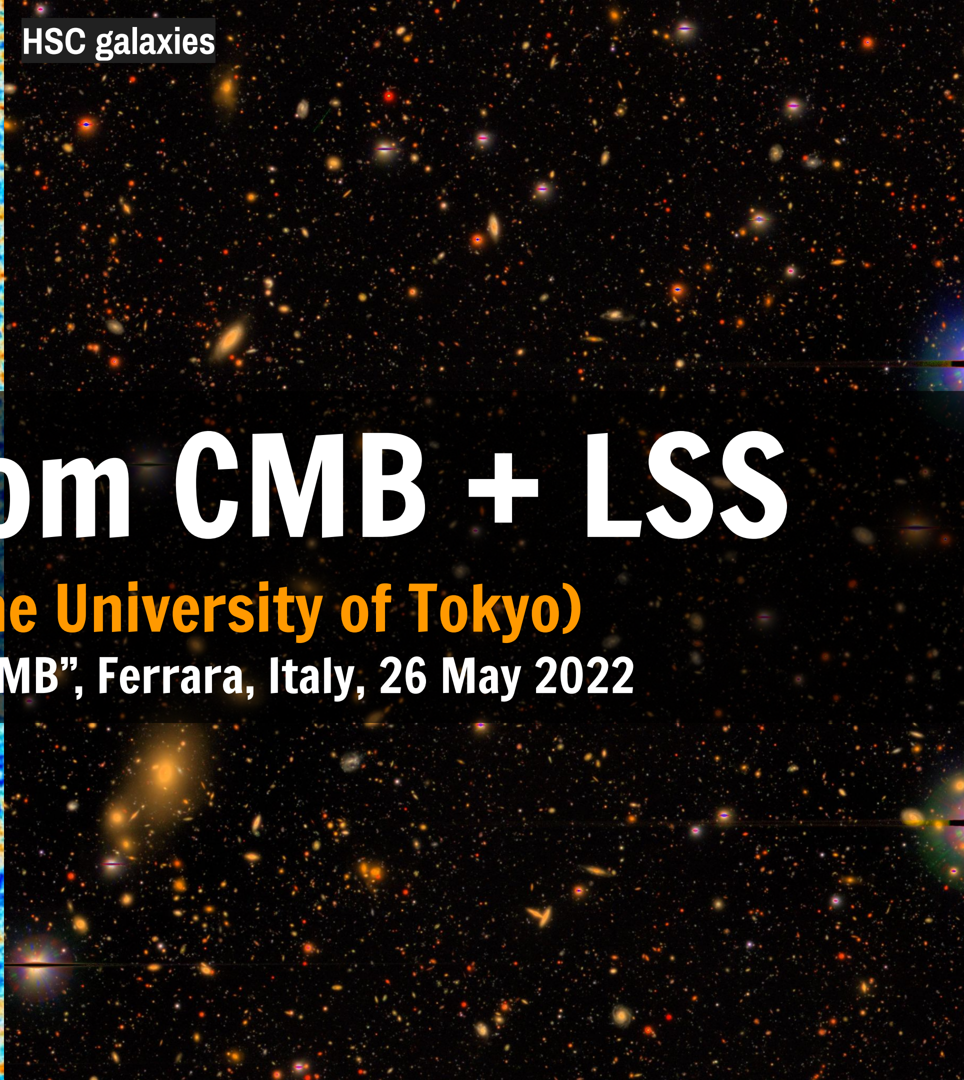



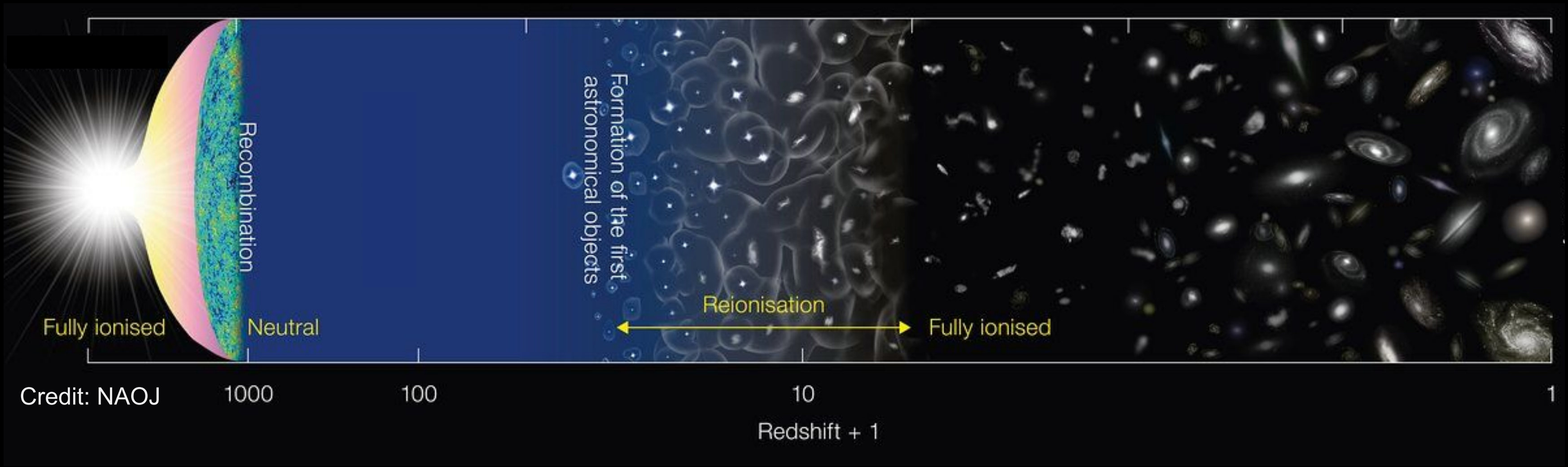



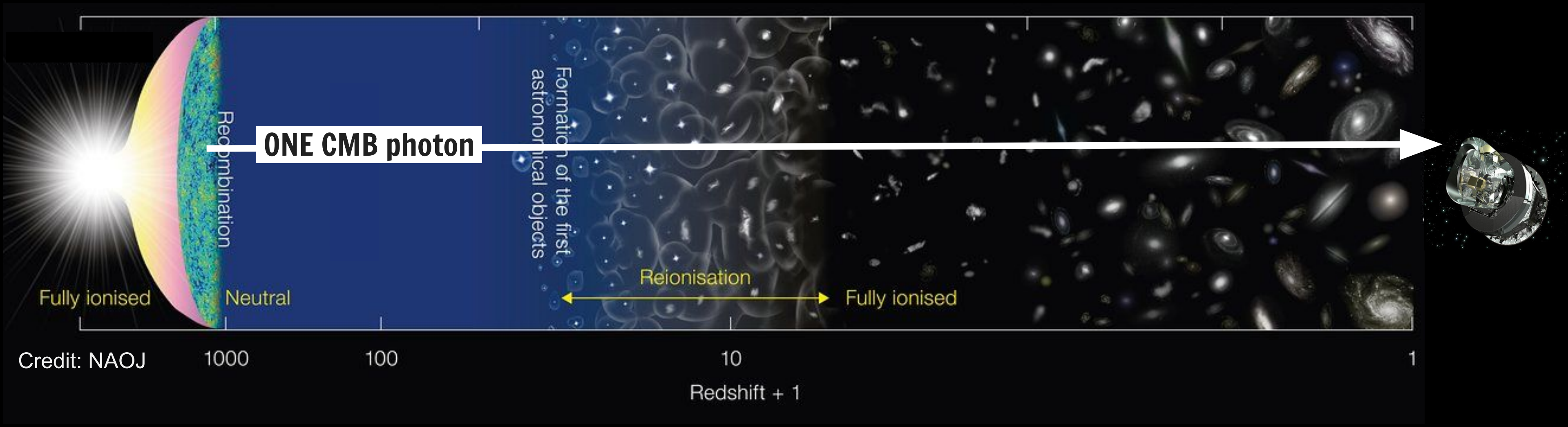


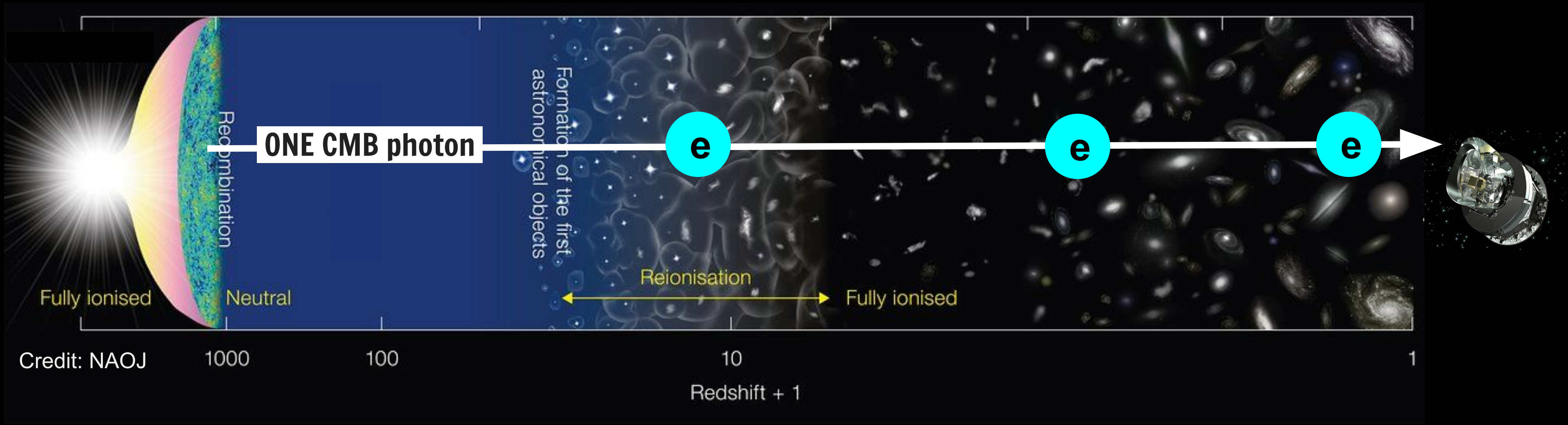
Cosmology from CMB + LSS

Jia Liu (Kavli IPMU, The University of Tokyo)

“From Planck to the future of CMB”, Ferrara, Italy, 26 May 2022


Recombination
Formation of the first astronomical objects
Fully ionised
Neutral
Reionisation
Fully ionised
1000
100
10
1
Redshift + 1
Credit: NAOJ

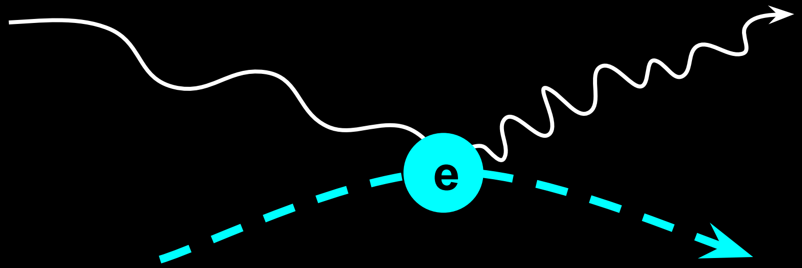

ONE CMB photon
Recombination
Formation of the first astronomical objects
Reionisation
Fully ionised
Neutral
Fully ionised
1000
100
10
1
Redshift + 1
Credit: NAOJ

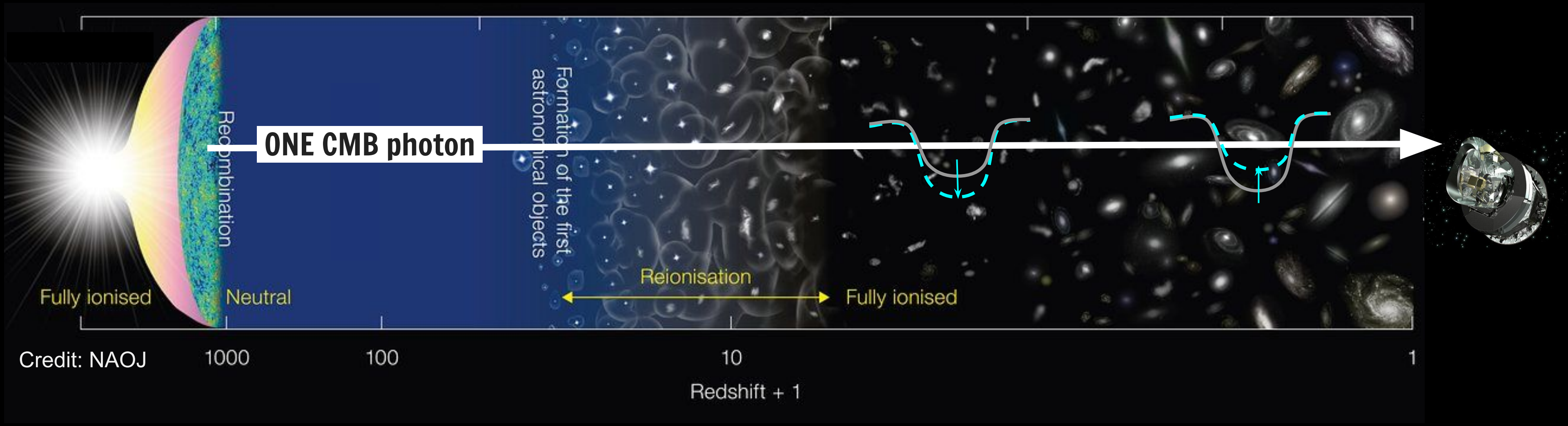


Credit: NAOJ

kinetic SZ
thermal SZ

Interaction with high energy electrons

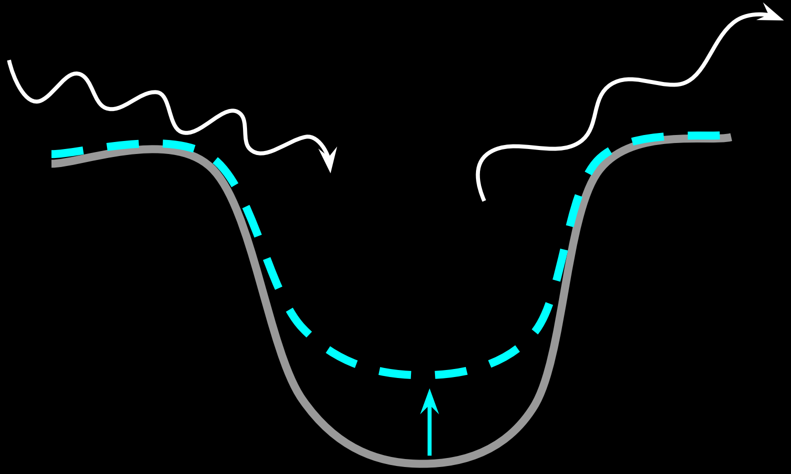


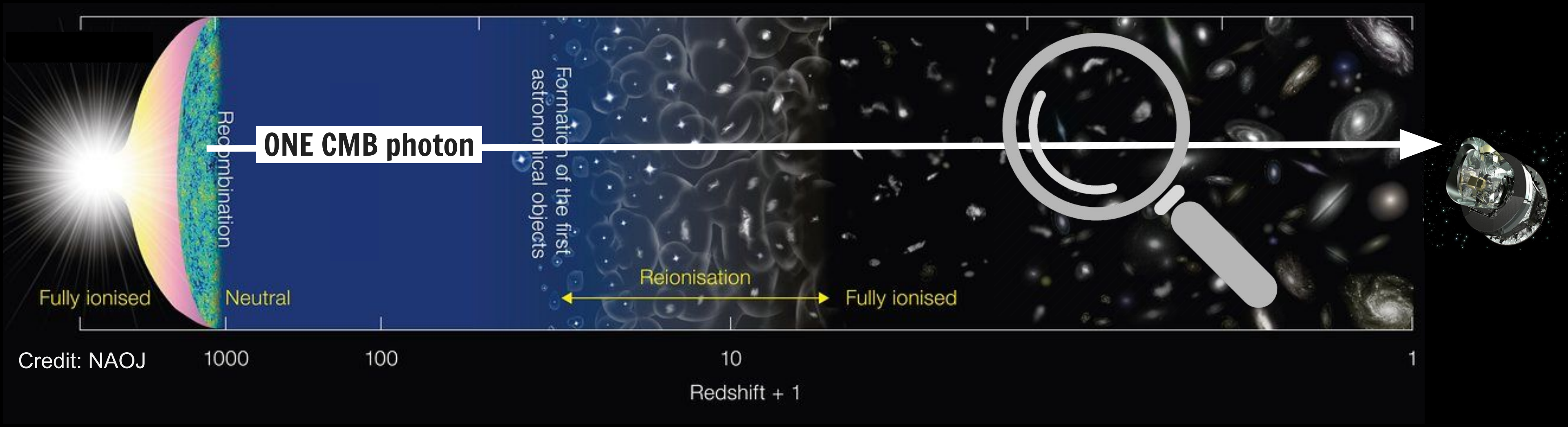


Integrated SW

(also: Rees-Sciama, Moving lens)

Evolving gravitational potential

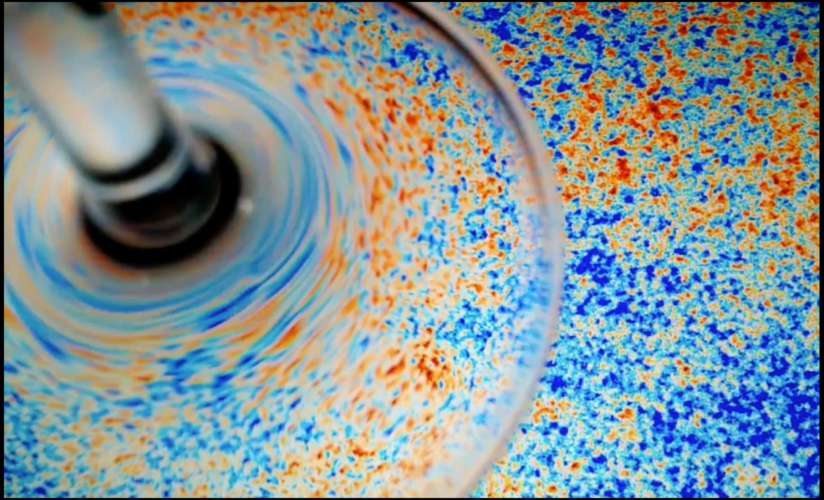




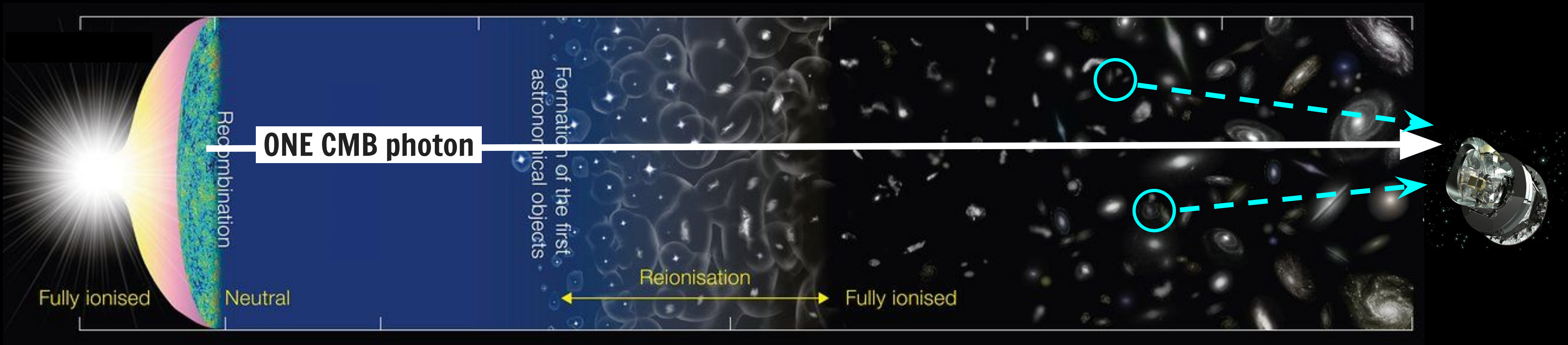
Credit: NAOJ

CMB Lensing

Photon’s path bent by curved spacetime



Credit: Emmanuel Schaan

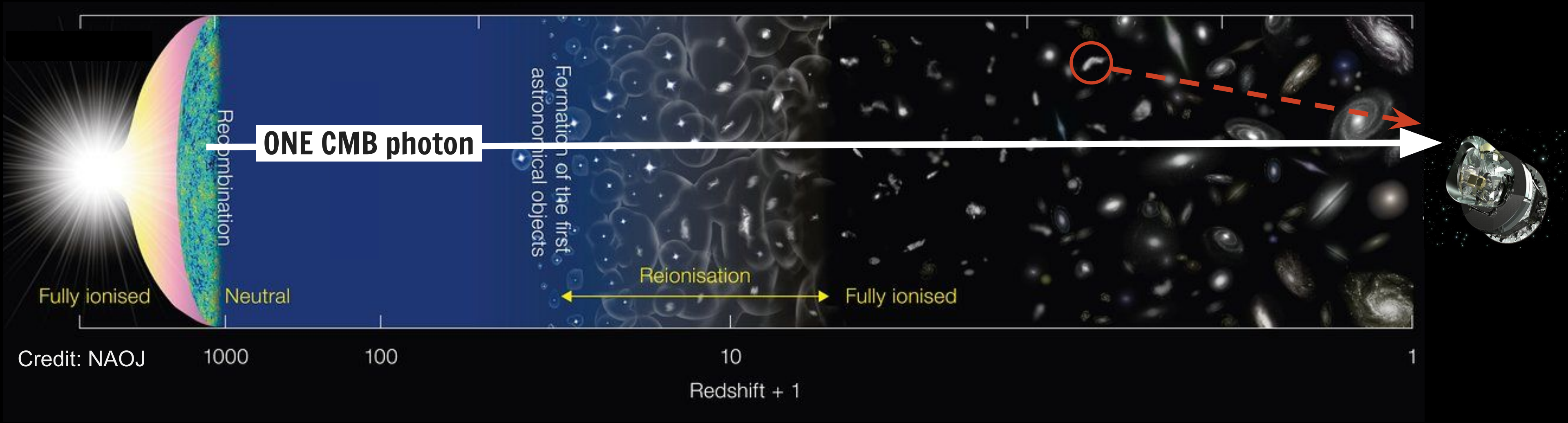


Credit: NAOJ

Cosmic Infrared Background

Emission from dusty galaxies

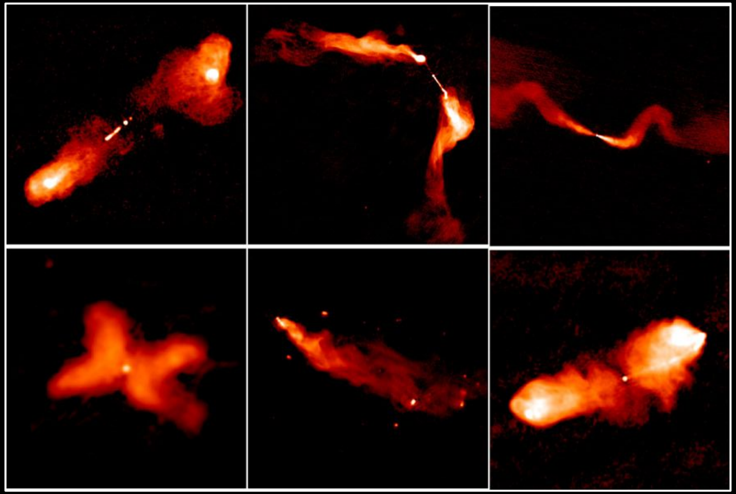
Credit: HST



Credit: NAOJ

Radio Galaxies

Synchrotron emission from AGNs

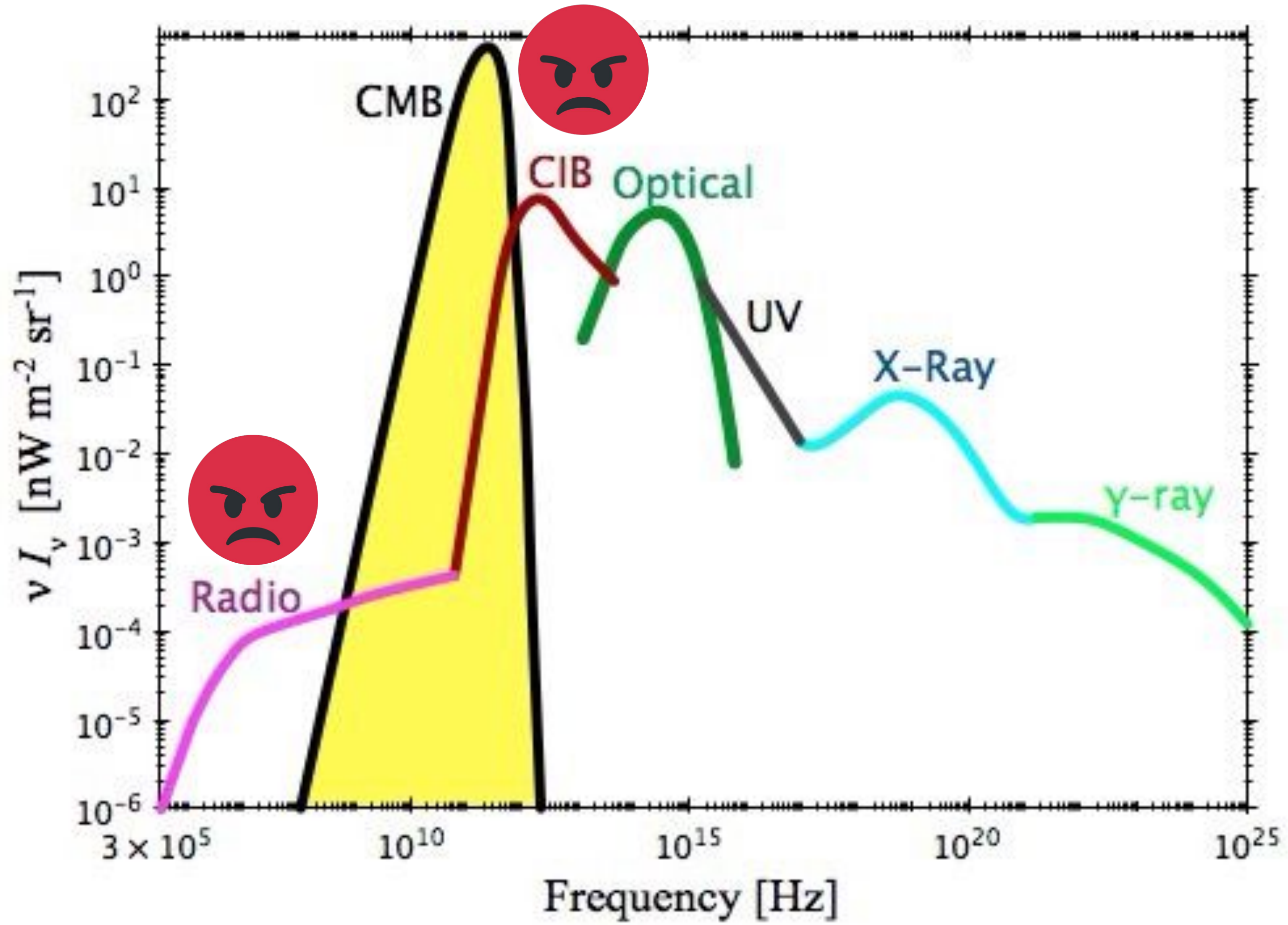


Credit: Hardcastle & Crostonb

In summary, the **PRIMARY CMB** is distorted by **KSZ, TSZ, ISW, CIB, RADIO, GRAVITATIONAL LENSING...**

They are the

Extragalactic Foregrounds

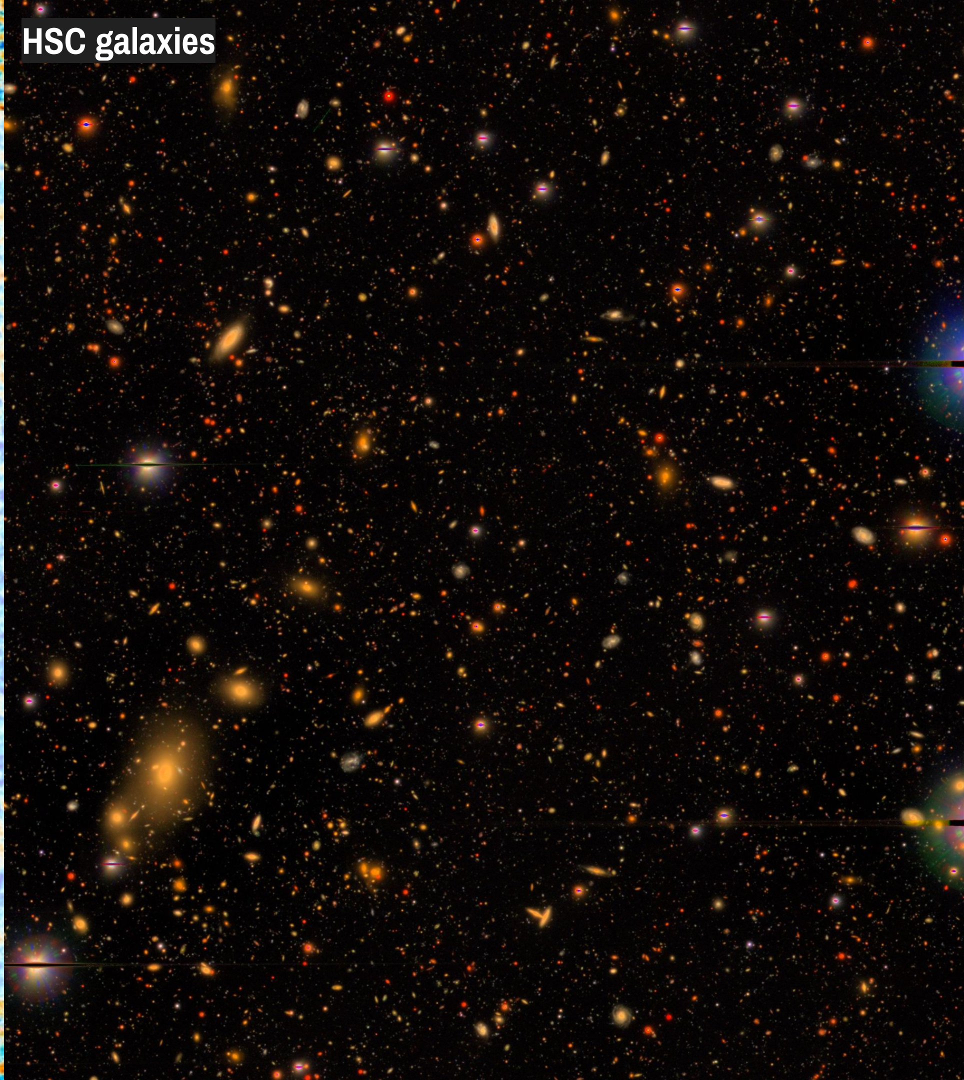


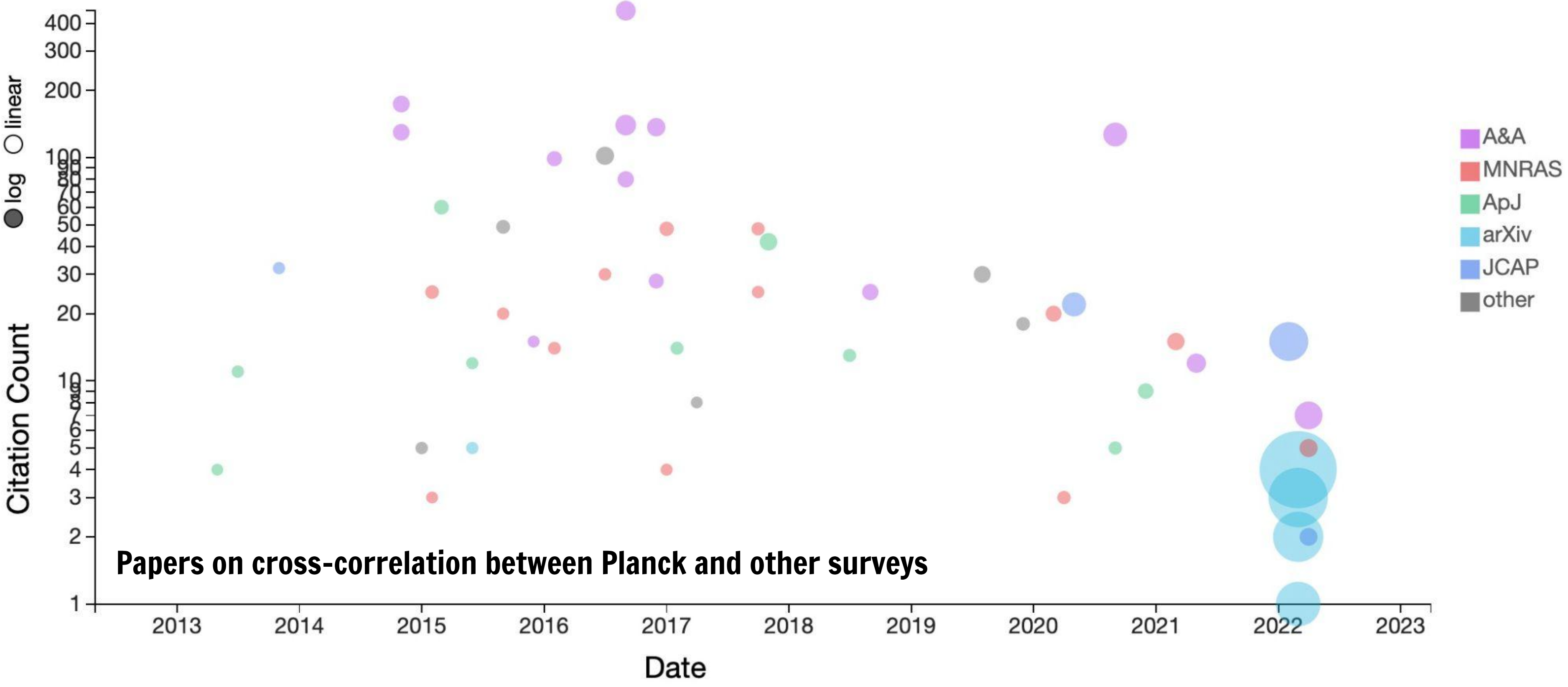
Andrew Jaffe

KSZ, TSZ, ISW, CIB, RADIO, GRAVITATIONAL LENSING...

are part of the large-scale structure →

Planck CMB

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4
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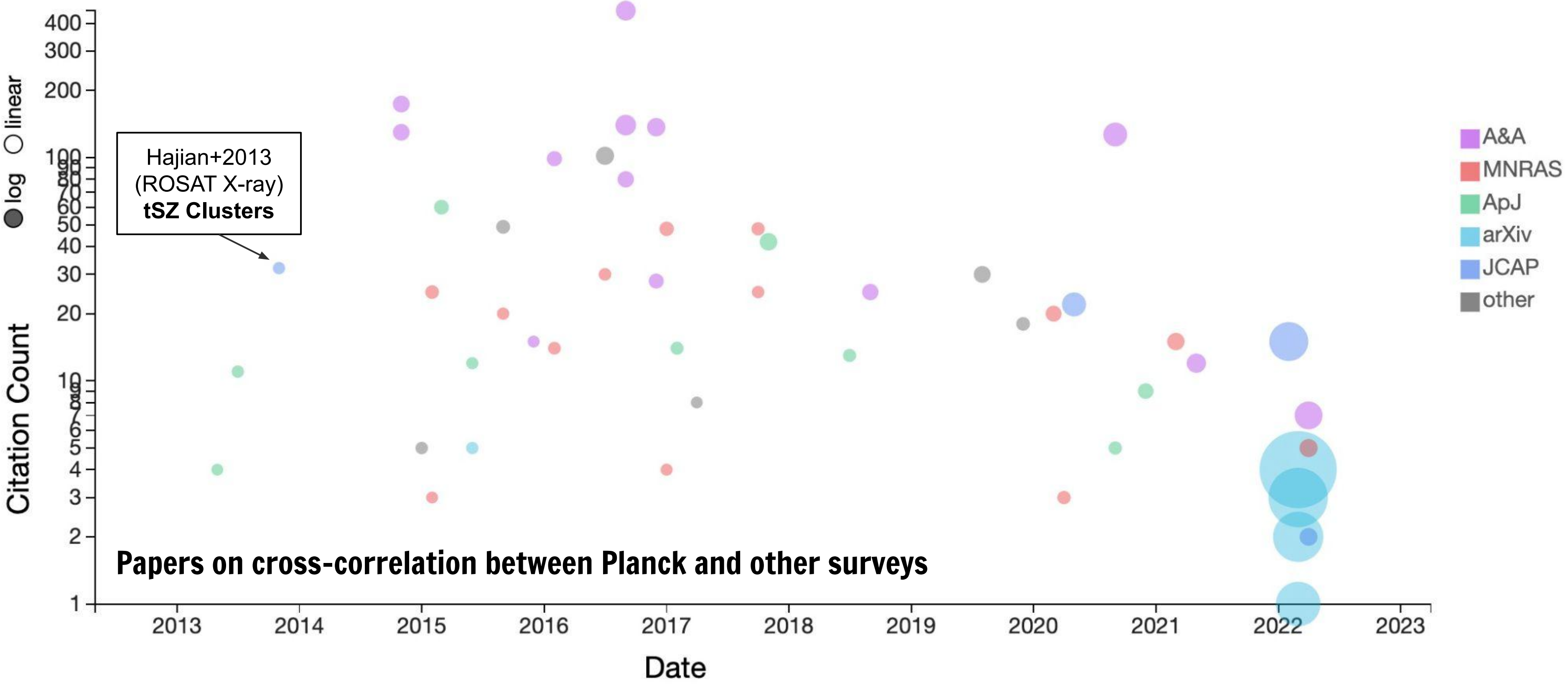
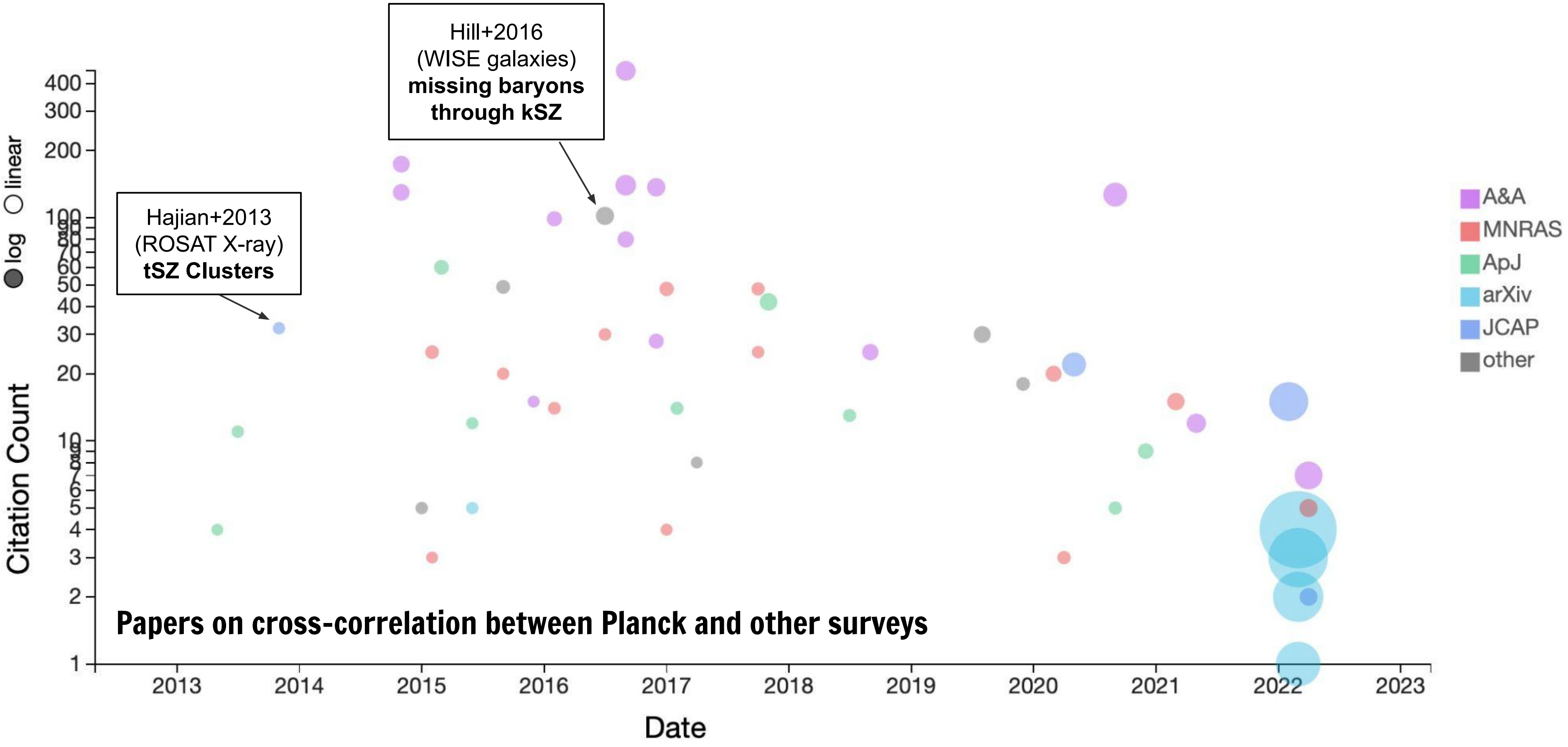
2
1
Citation Count
log
linear
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
Date
A&A
MNRAS
ApJ
arXiv
JCAP
other
Papers on cross-correlation between Planck and other surveys



Papers on cross-correlation between Planck and other surveys


Hill+2016
(WISE galaxies)
missing baryons
through kSZ
Hajian+2013
(ROSAT X-ray)
tSZ Clusters
log
linear
Citation Count
400
300
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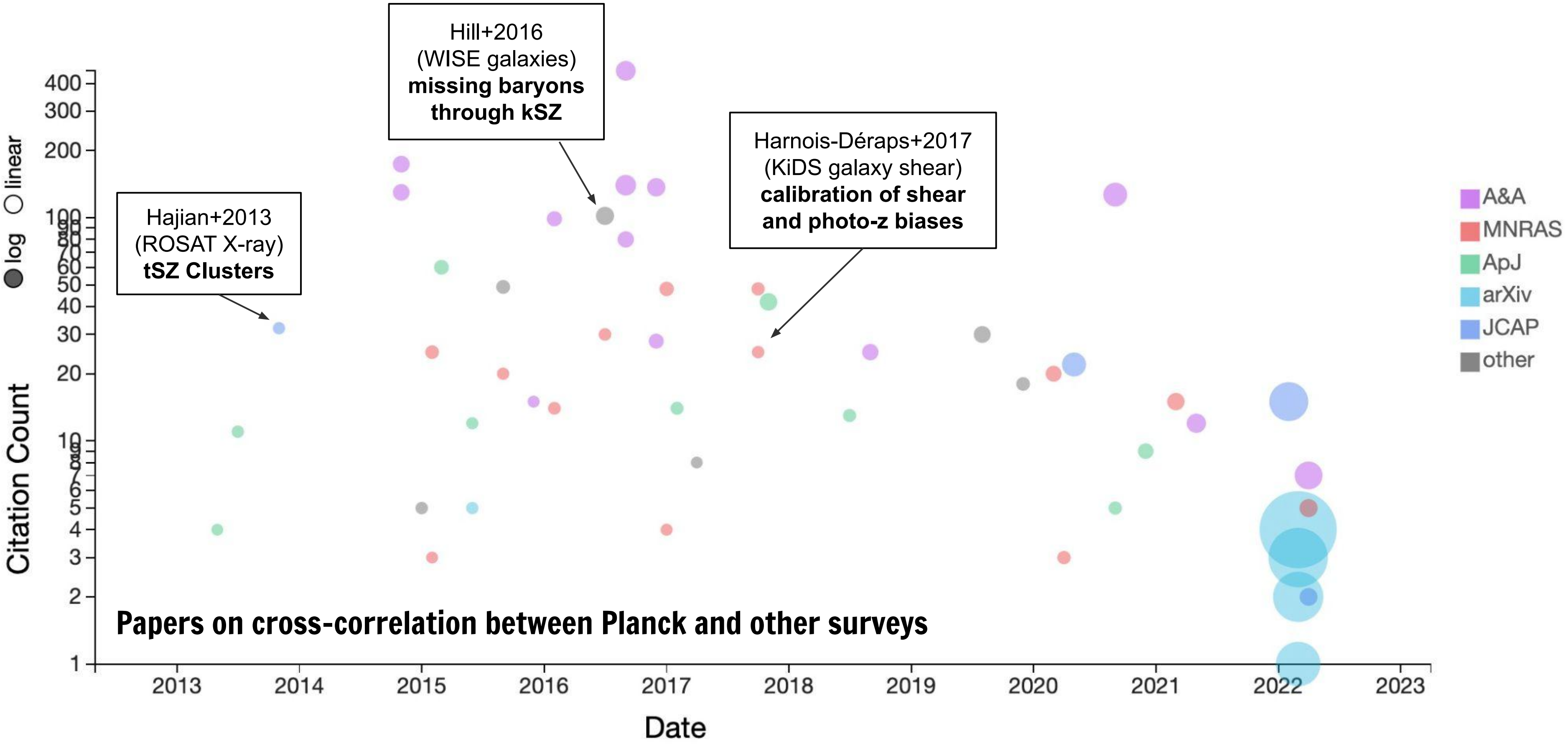
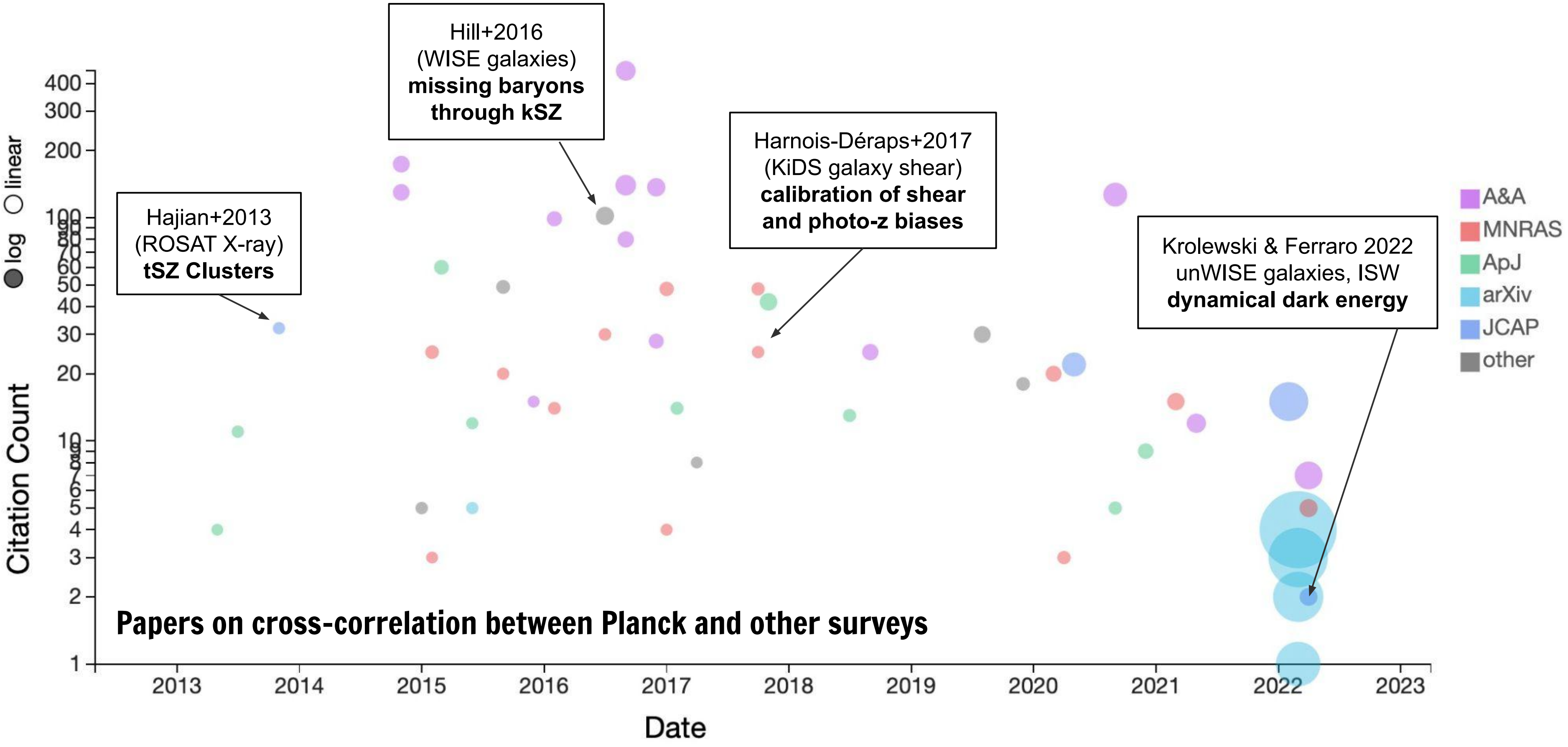
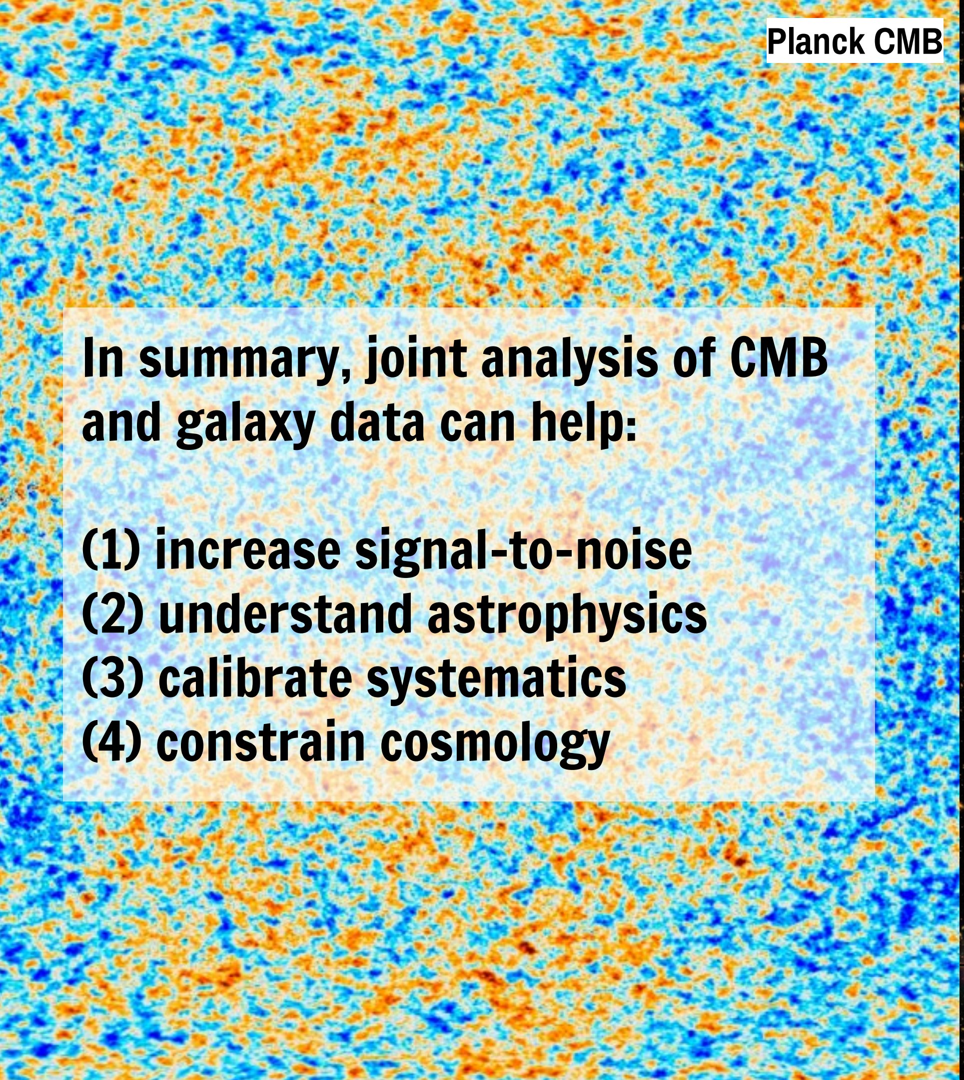
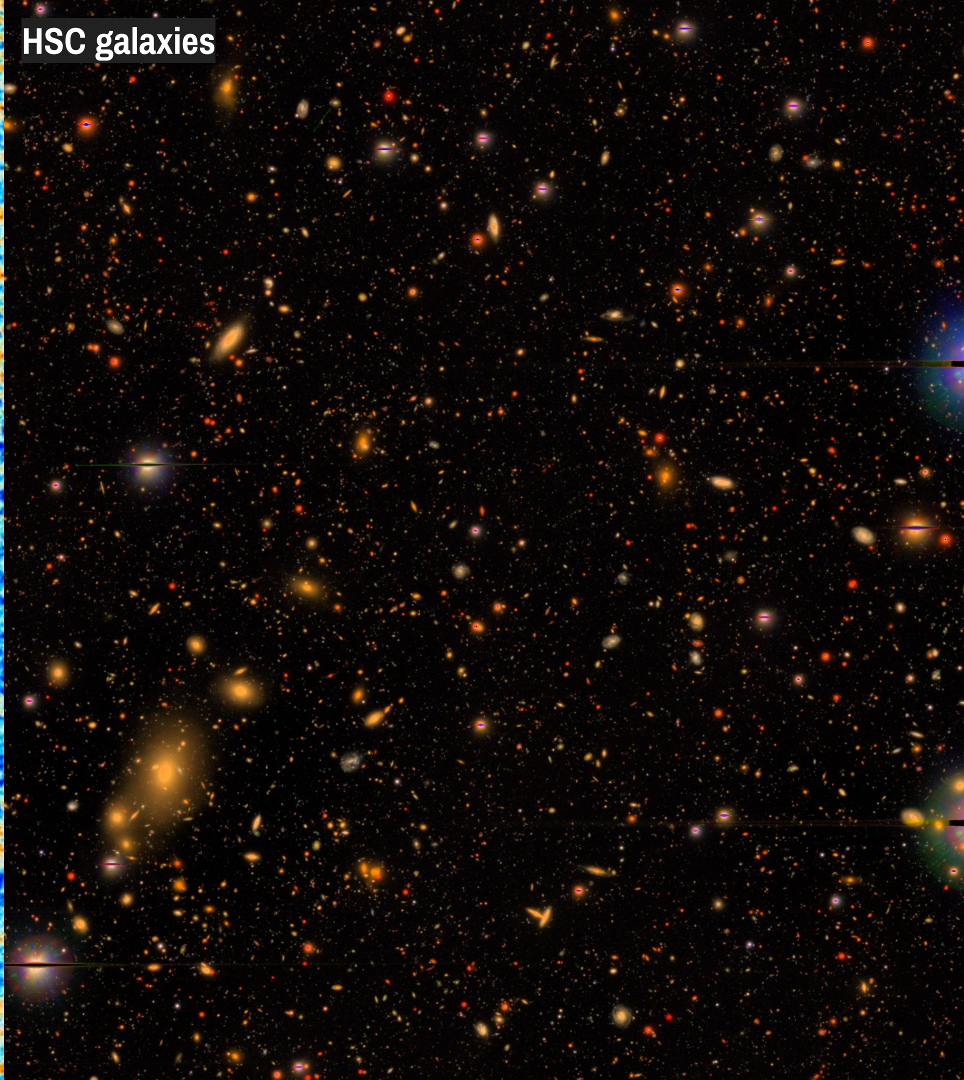
ApJ
arXiv
JCAP
other
Papers on cross-correlation between Planck and other surveys


Hajian+2013
(ROSAT X-ray)
tSZ Clusters
Hill+2016
(WISE galaxies)
missing baryons
through kSZ
Harnois-Déraps+2017
(KiDS galaxy shear)
calibration of shear
and photo-z biases
A&A
MNRAS
ApJ
arXiv
JCAP
other
log
linear
Citation Count
Date
Papers on cross-correlation between Planck and other surveys

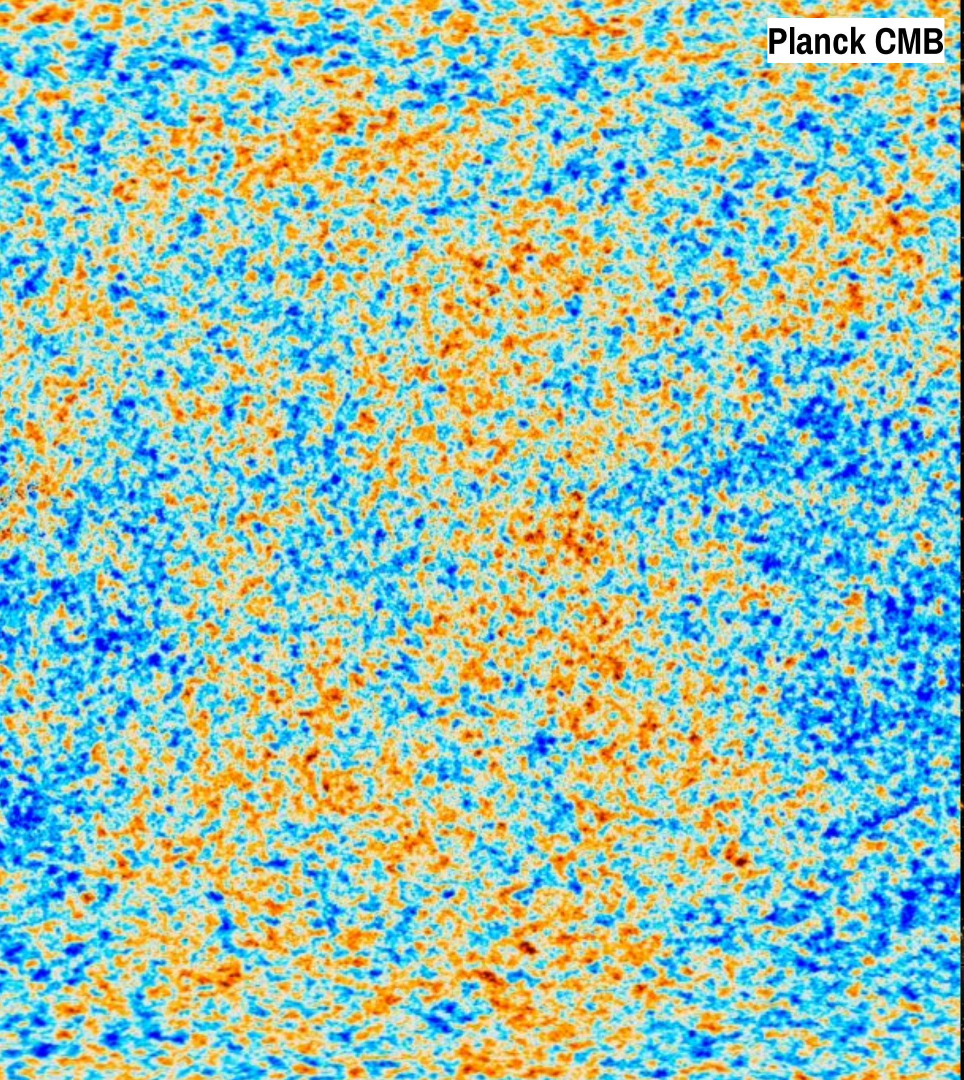

Hill+2016
(WISE galaxies)
missing baryons through kSZ
Harnois-Déraps+2017
(KiDS galaxy shear)
calibration of shear and photo-z biases
Hajian+2013
(ROSAT X-ray)
tSZ Clusters
Krolewski & Ferraro 2022
unWISE galaxies, ISW
dynamical dark energy
log
linear
Citation Count
Date
A&A
MNRAS
ApJ
arXiv
JCAP
other
Papers on cross-correlation between Planck and other surveys

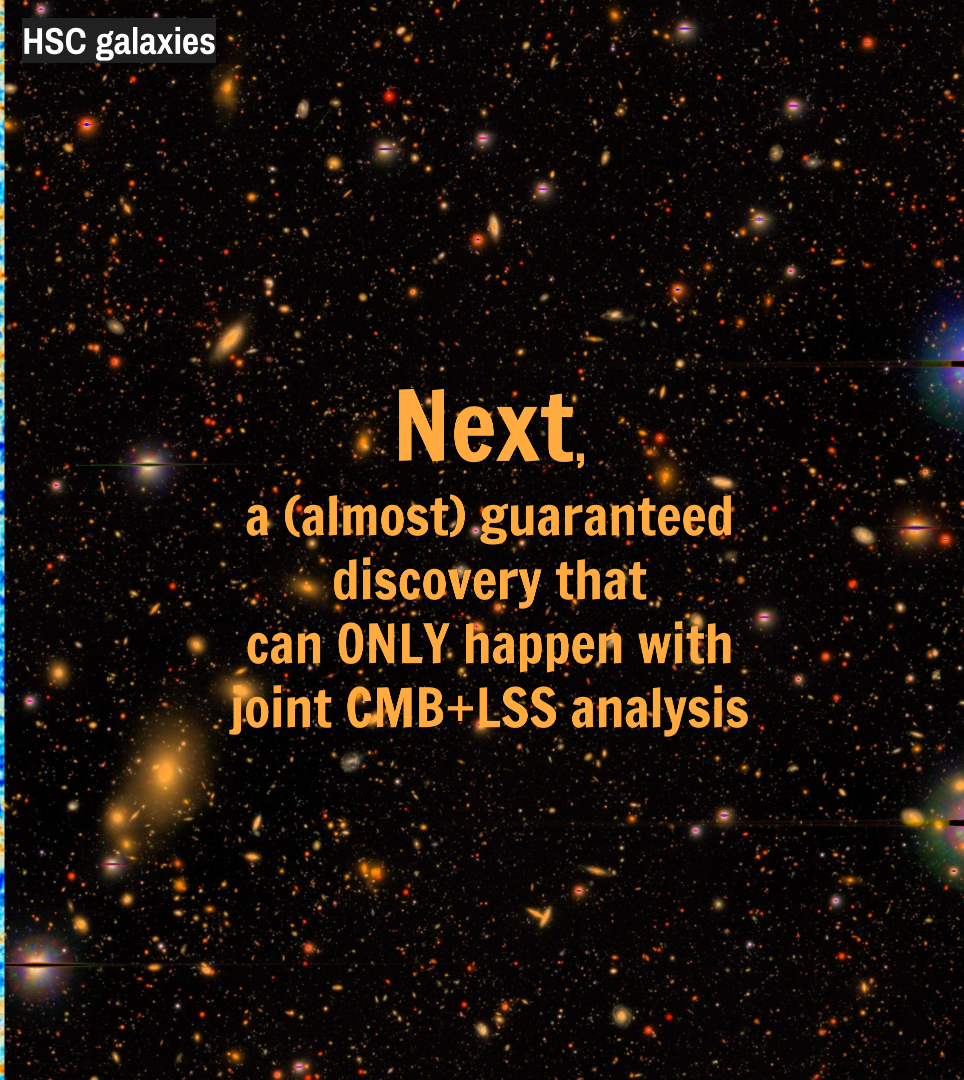




In summary, joint analysis of CMB and galaxy data can help:

(1) increase signal-to-noise
(2) understand astrophysics
(3) calibrate systematics
(4) constrain cosmology





Next,

a (almost) guaranteed
discovery that
can ONLY happen with
joint CMB+LSS analysis

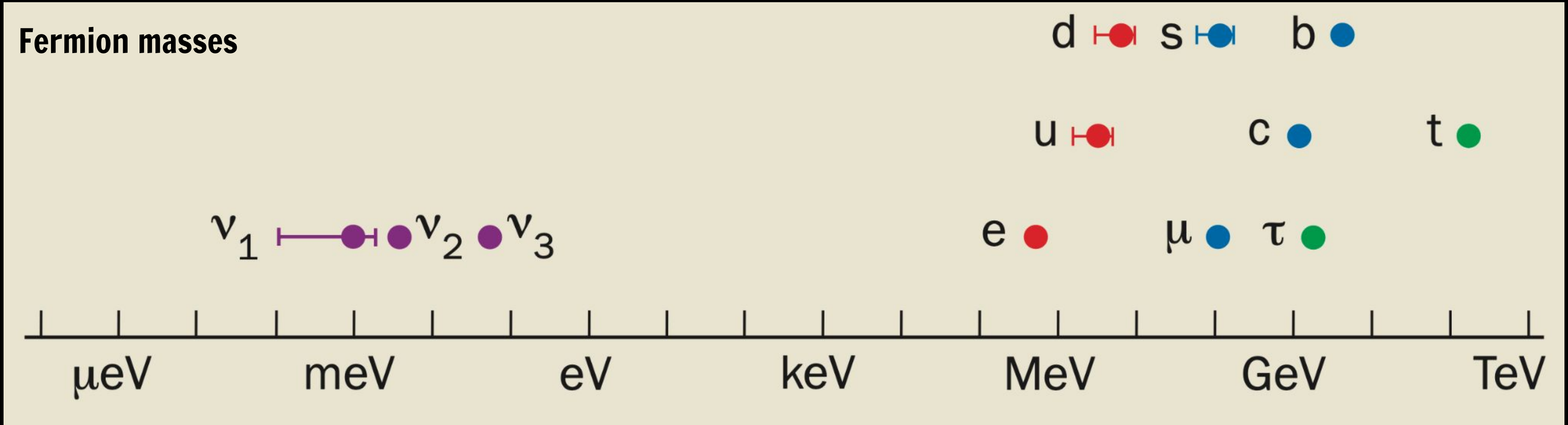


Illustration: Hitoshi Murayama

Neutrinos' tiny mass holds the key to NEW PHYSICS

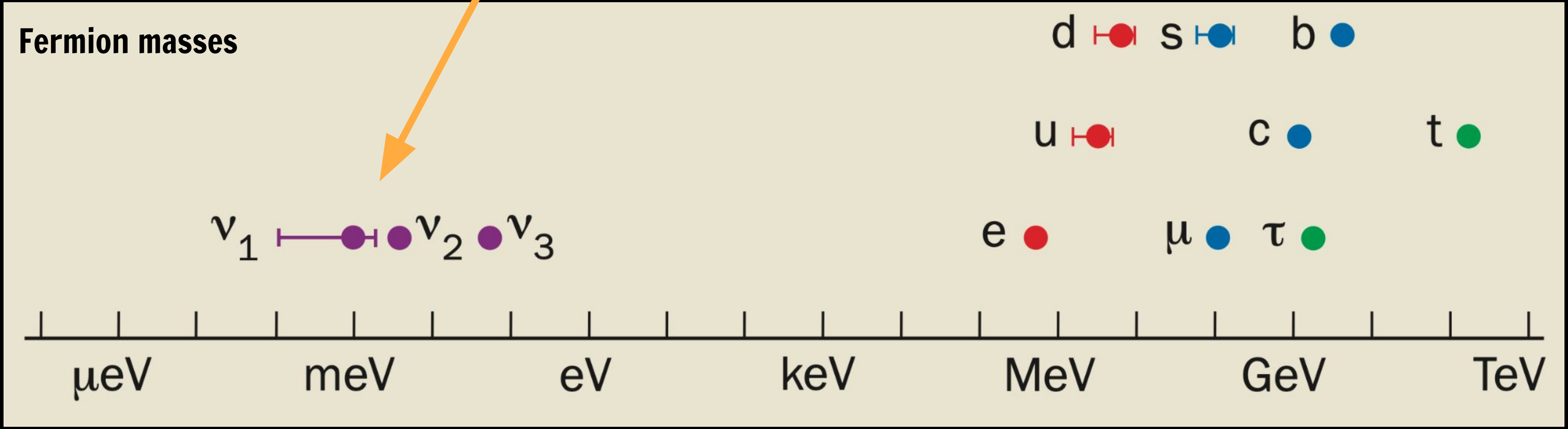
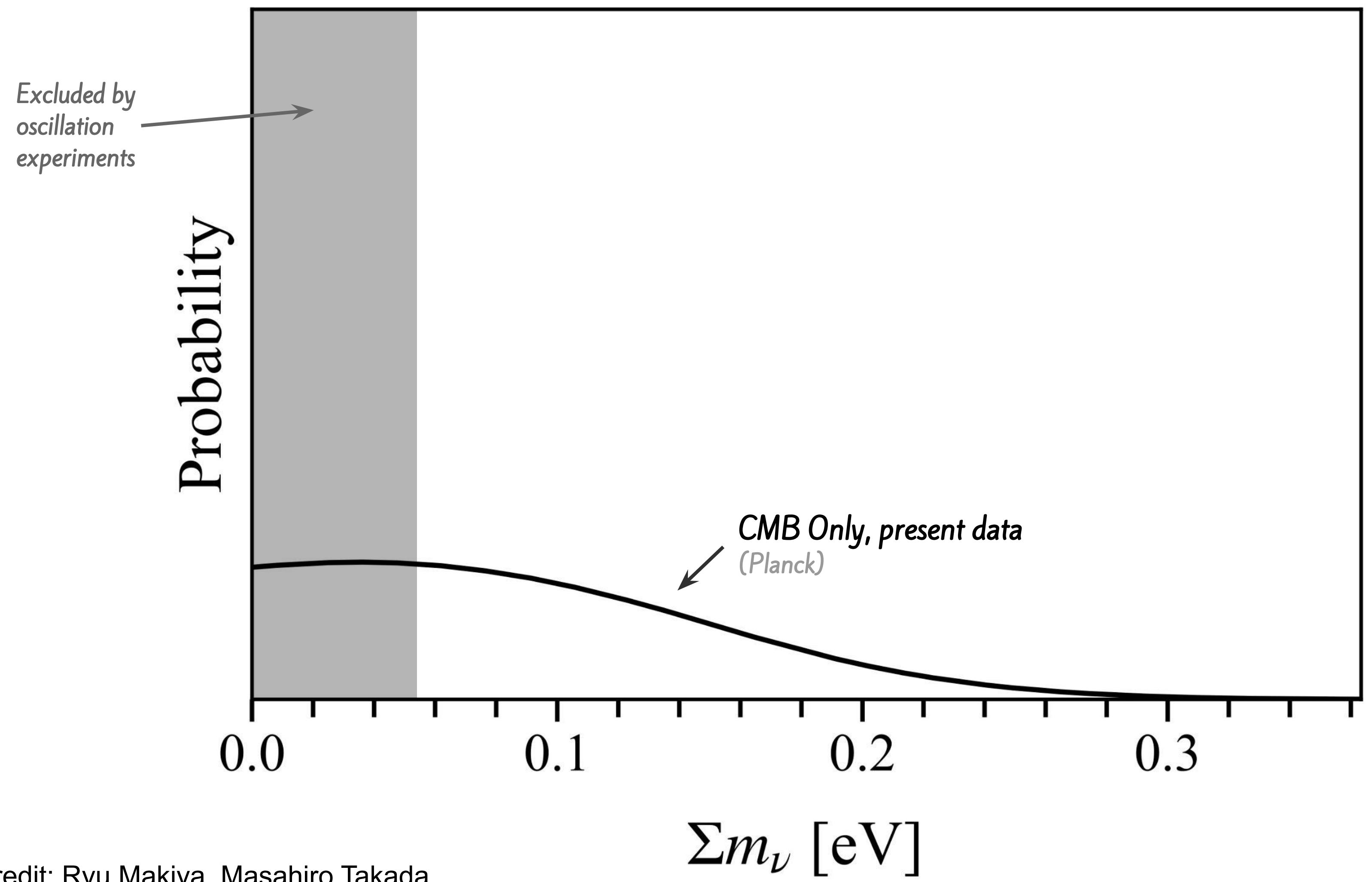
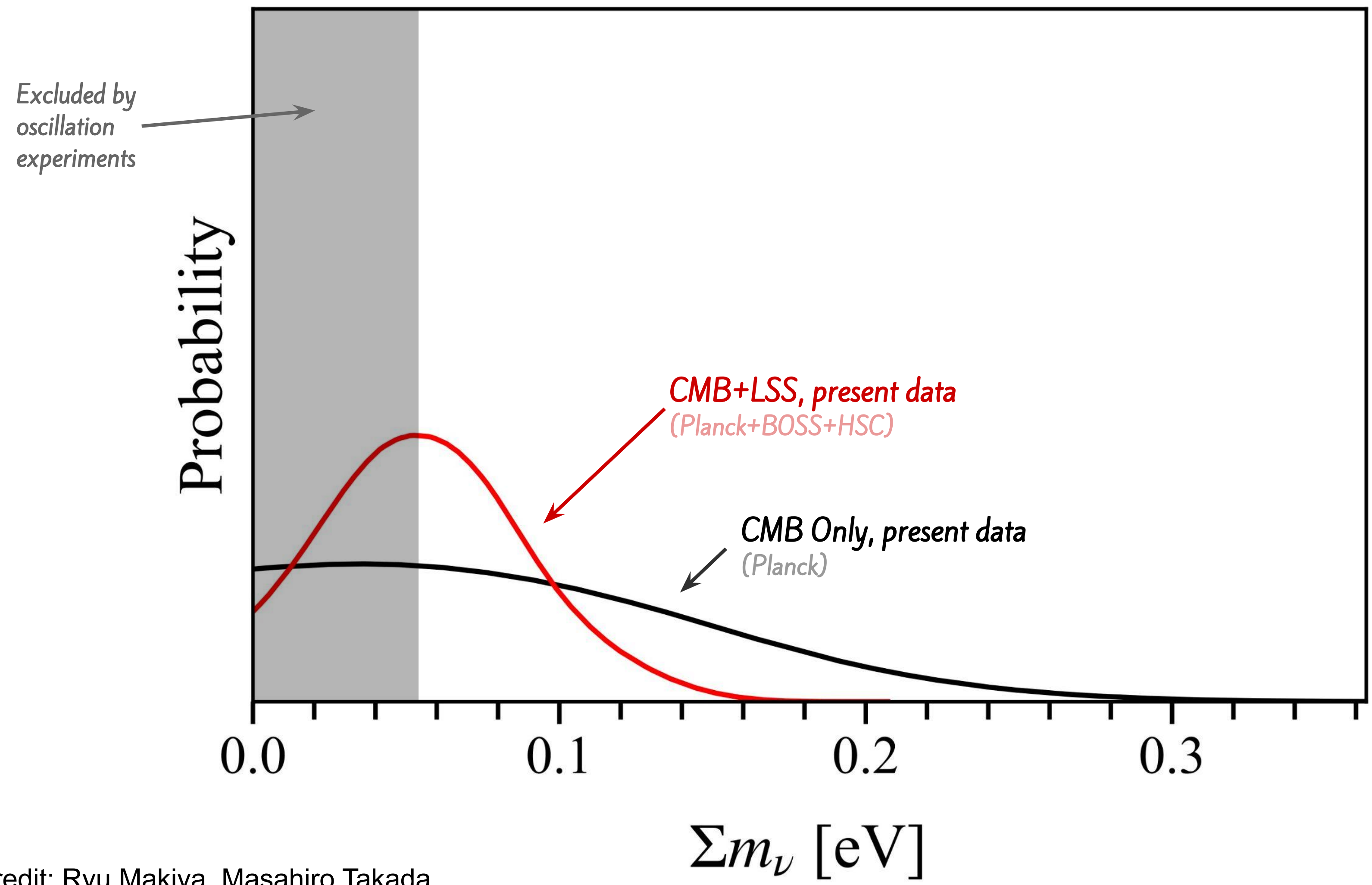


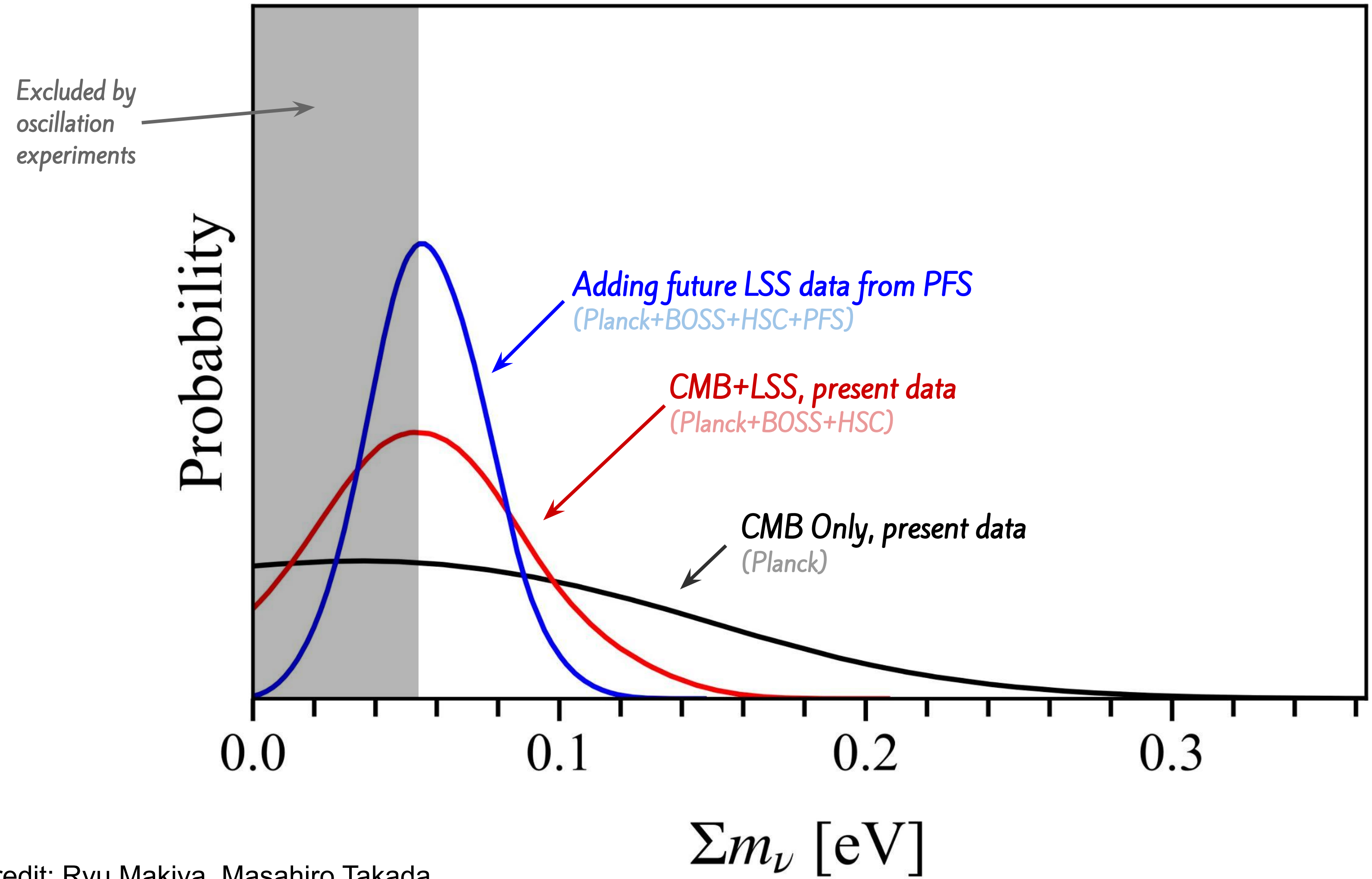
Illustration: Hitoshi Murayama



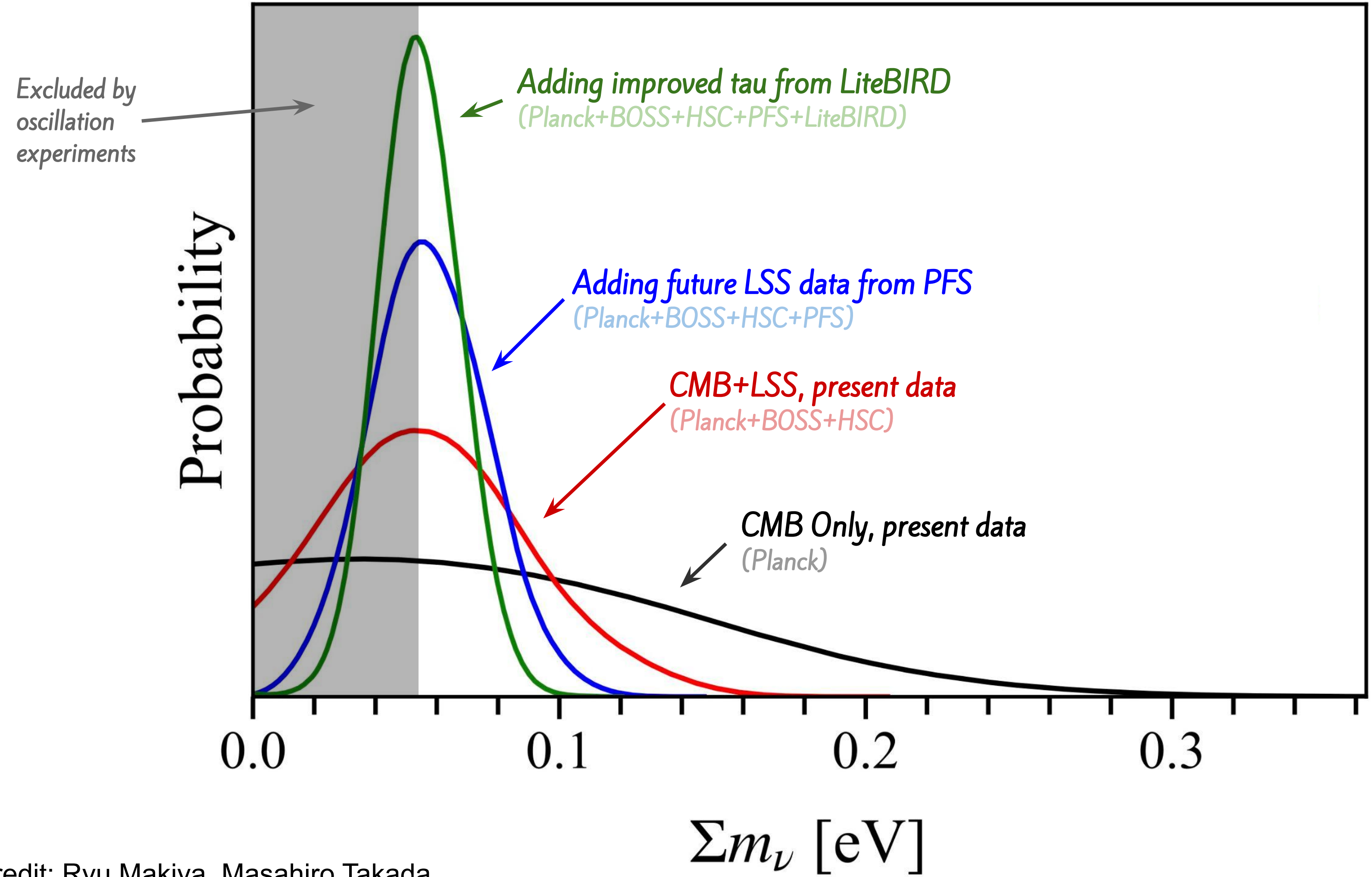
Credit: Ryu Makiya, Masahiro Takada



Credit: Ryu Makiya, Masahiro Takada



Credit: Ryu Makiya, Masahiro Takada



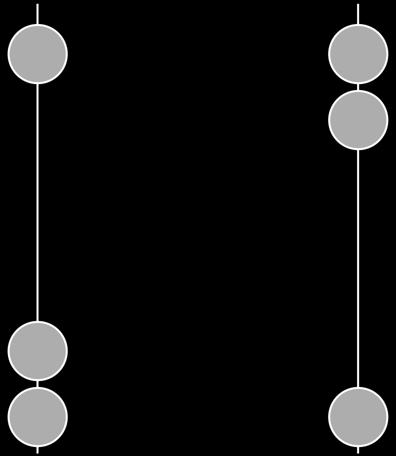
Credit: Ryu Makiya, Masahiro Takada

	PARTICLE EXPERIMENT	COSMOLOGY
Present Upper Limit	0.8 eV KATRIN (2022, 90% CL)	0.13 eV Planck + BAO (2018, 95% CL)

	PARTICLE EXPERIMENT	COSMOLOGY
Present Upper Limit	0.8 eV KATRIN (2022, 90% CL)	0.13 eV Planck + BAO (2018, 95% CL)
Future Sensitivity	~ 0.2 eV KATRIN 2023	~ 0.02 eV Euclid, LSST, PFS, DESI, SO, CMB-S4, LiteBIRD

0.02 eV Sensitivity =

DISCOVERY



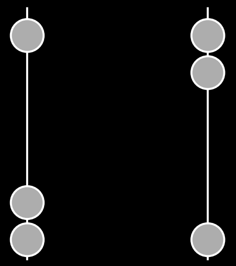
Normal
$\Sigma m_\nu > 0.06$ eV

Inverted
$\Sigma m_\nu > 0.1$ eV

0.02 eV Sensitivity =

DISCOVERY

	Neutrino Mass	Mass Hierarchy
$\Sigma m_\nu > 0.1$eV	Yes	No



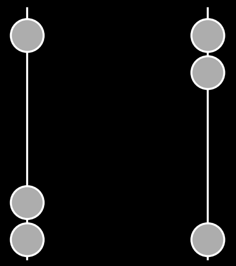
Normal
$\Sigma m_\nu > 0.06$ eV

Inverted
$\Sigma m_\nu > 0.1$ eV

0.02 eV Sensitivity =

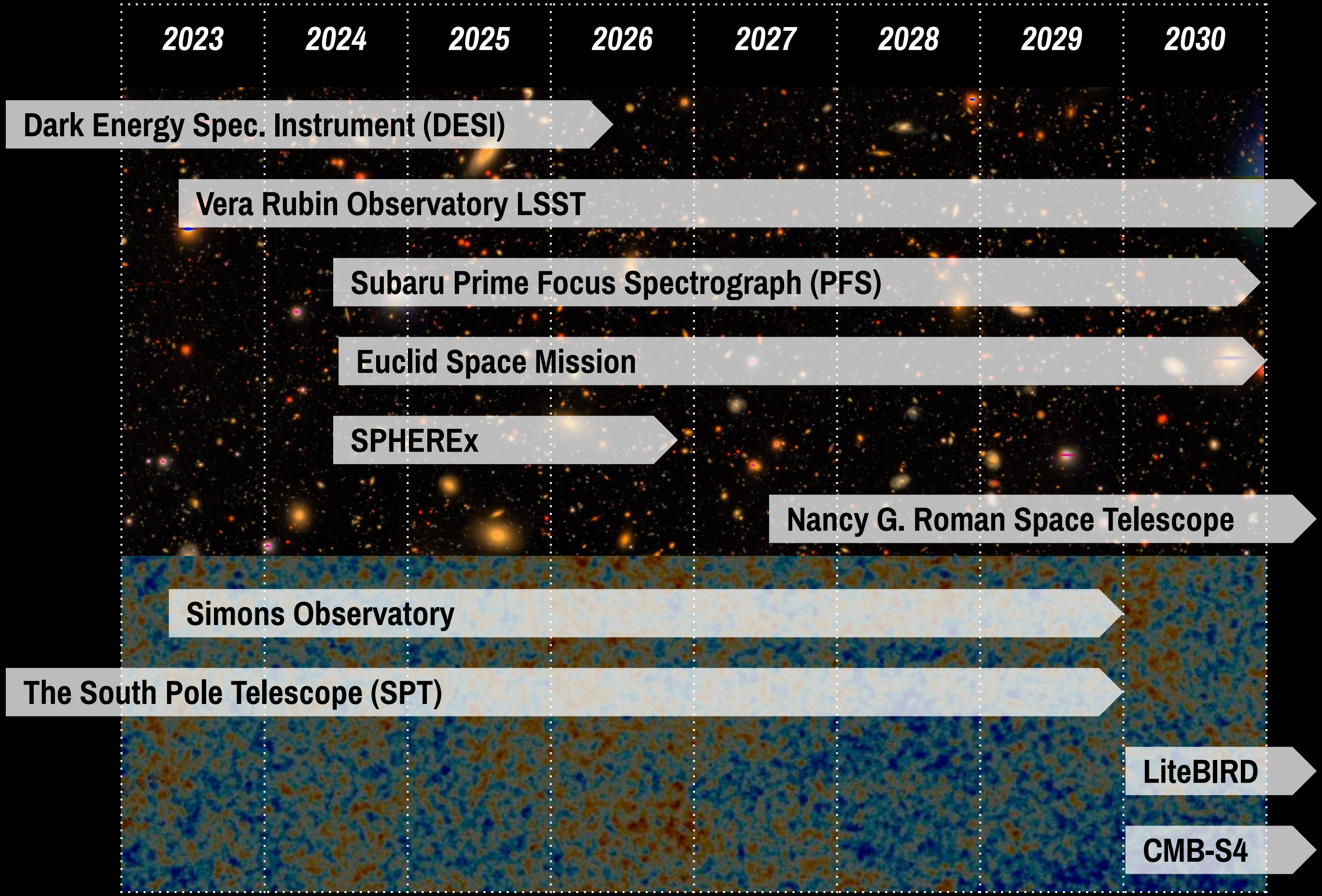
DISCOVERY

	Neutrino Mass	Mass Hierarchy
$\Sigma m_\nu > 0.1$eV	Yes	No
$\Sigma m_\nu < 0.1$eV	Maybe	Yes



Normal
$\Sigma m_\nu > 0.06$ eV

Inverted
$\Sigma m_\nu > 0.1$ eV


2023
2024
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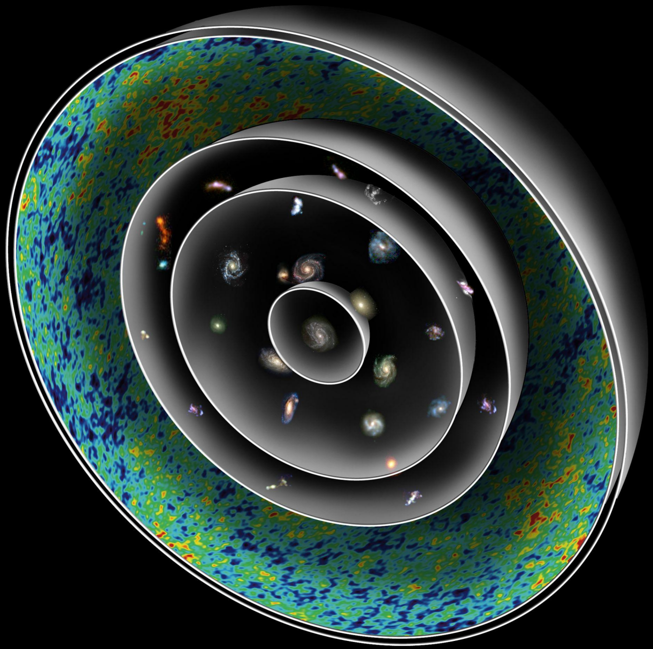
Dark Energy Spec. Instrument (DESI)
Vera Rubin Observatory LSST
Subaru Prime Focus Spectrograph (PFS)
Euclid Space Mission
SPHEREx
Nancy G. Roman Space Telescope
Simons Observatory
The South Pole Telescope (SPT)
LiteBIRD
CMB-S4

Correlated Simulation of the Universe

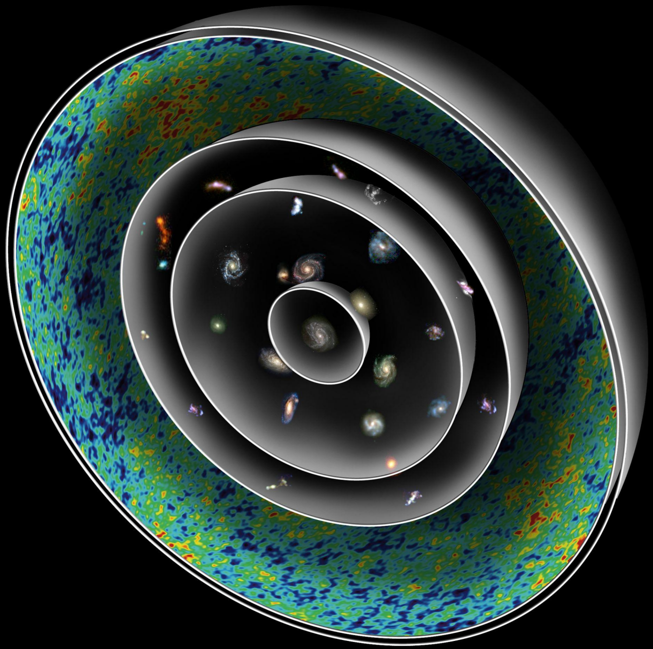
HALF DOME

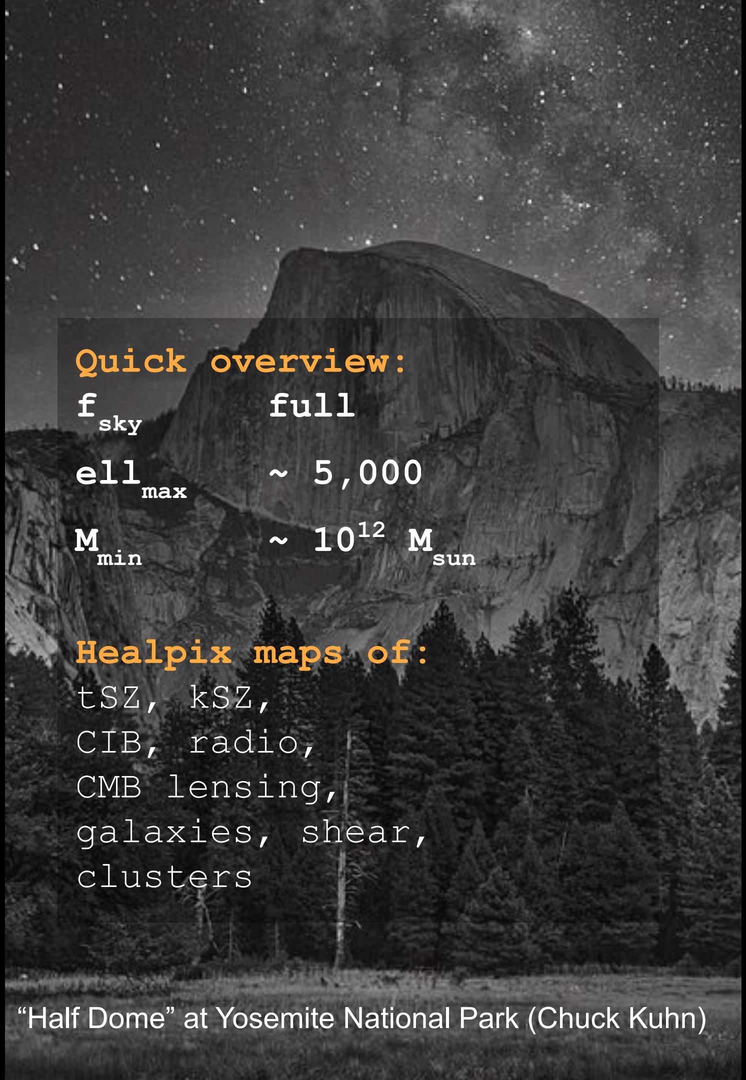


“Half Dome” at Yosemite National Park (Chuck Kuhn)

Correlated Simulation of the Universe

Half Dome





Quick overview:

f_{sky}	full
ell_{max}	~ 5,000
M_{min}	~ 10^{12} M_{sun}

Healpix maps of:

tSZ, kSZ,
CIB, radio,
CMB lensing,
galaxies, shear,
clusters

“Half Dome” at Yosemite National Park (Chuck Kuhn)

Why Simulations?

Survey pipeline

map → statistics → cosmology

Systematics — instrumentation

(beam, bandpass, electronics...)

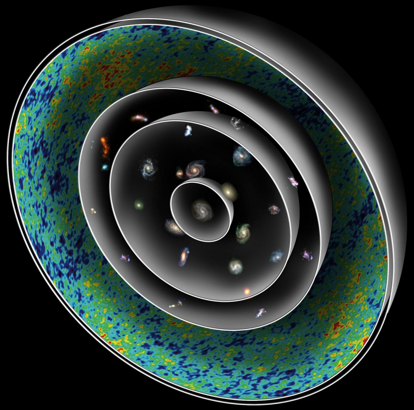
Astrophysics

(baryons, intrinsic alignments...)

Covariance

Modeling

Why **Correlated** Simulations?



Survey pipeline
e.g. 6x2 analysis, CMB FGs x LSS

~~**Systematics — instrumentation**~~
~~(beam, bandpass, electronics...)~~

Astrophysics
(baryons, intrinsic alignments...)

Covariance between CMB x LSS

Modeling beyond the linear theory

The Half Dome Simulation Team

N-body
linecones, particles, velocities, halos, lensing

LSS
Shear, clusters, HOD…

CMB
tSZ, kSZ, CIB, Radio…

Yici Zhong | Adrian Bayer | Yu Feng | Joe DeRose | Zack Li | Giuseppe Puglisi | Mat Madhavacheril | Marcelo Alvarez

FastPM a particle-mesh gravity solver

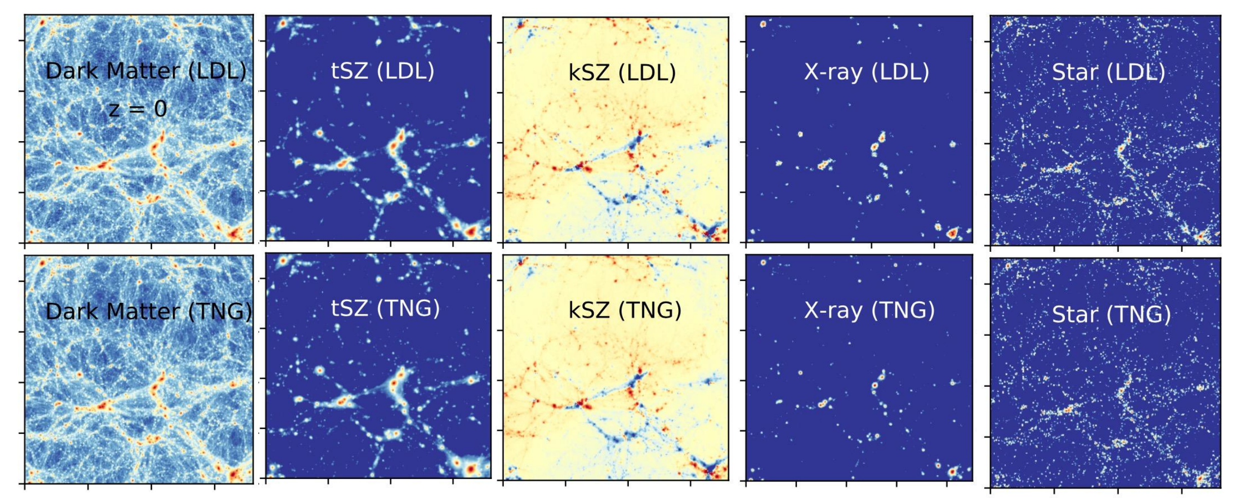
Speed:
10^7 faster than hydro simulation
10^4 faster than tree-PM sims
x10 slower than Websky (2LPT+peakpatch)

Opportunities:
Lagrangian Deep Learning (field-based painting)
MADlens (differentiable lensing)
flowPM (tensorflow-based)

N-body
linecones, particles, velocities, halos, lensing

LSS
Shear, clusters, HOD…

CMB
tSZ, kSZ, CIB, Radio…

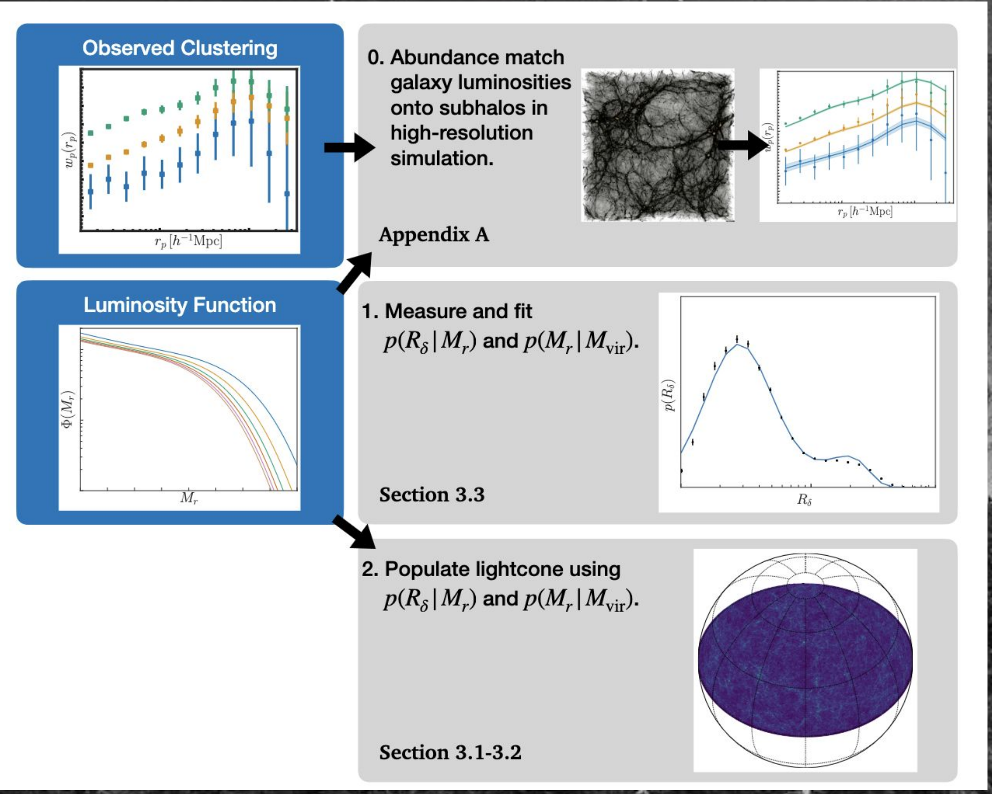


Yici Zhong

FastPM: Feng+2016
PGD: Dai+2018
LDL (*left img*): Dai & Seljak 2020
MADLens: Böhm+2020
FlowPM: Modi+2020

ADDGALS

populate galaxies with positions, velocities, shapes, and NIR-UV SEDs



N-body
linecones, particles, velocities, halos, lensing

LSS
Shear, clusters, HOD…

CMB
tSZ, kSZ, CIB, Radio…

Joe DeRose

DeRose+2021
Wechsler+ 2021

Websky+Radio halo-based foreground painting

tSZ, kSZ, CIB, lensing: Stein, Alvarez+2020
Radio: Li, Puglisi+2022 (SEDs fitted to Planck, ALMA, SPT, and ACT)

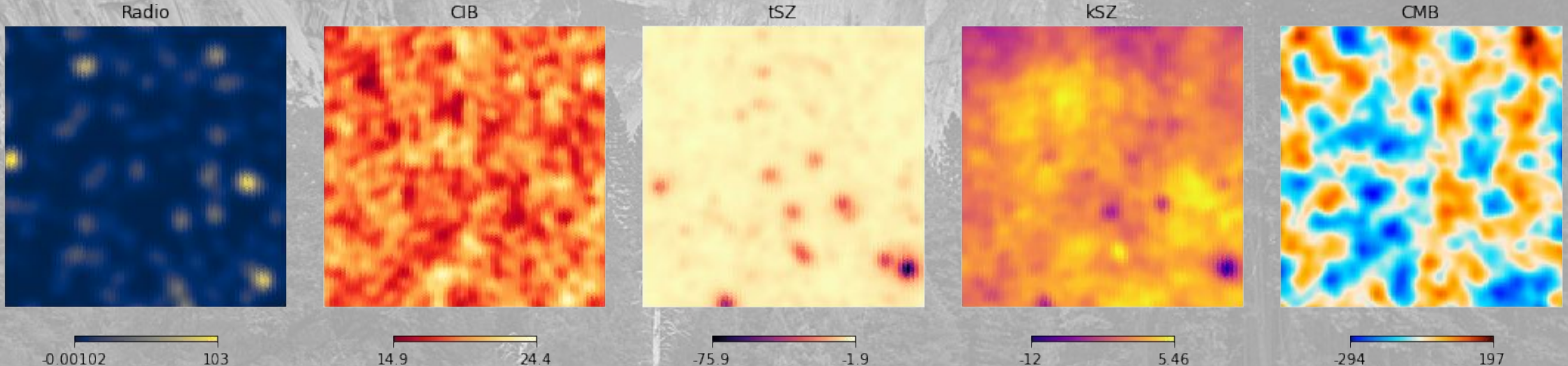

Zack Li


Giuseppe Puglisi

N-body
linecones, particles, velocities, halos, lensing

LSS
Shear, clusters, HOD…

CMB
tSZ, kSZ, CIB, Radio…



CHALLENGES assuming we need at least 1000 simulations*

1. **Computing time: ~500 million CPU hours**
   1.1 NERSC is ideal: almost everyone (DESI, LSST, SO, S4..) has access
   1.2 Large memory needs: ~all NERSC Cori KNL nodes (260,000 Cores) simultaneously, ~0.5 million CPU-hr/run
   1.3 Currently entirely supported by the CMB side (mp107 PI Julian Borrill)

2. **Storage: ~10-100s PB**
   2.1 Data products: 500TB/run (currently working on strategy to downsample to ~20% ->100TB per run)
   2.2 Currently no mechanism for collaborations to jointly contribute

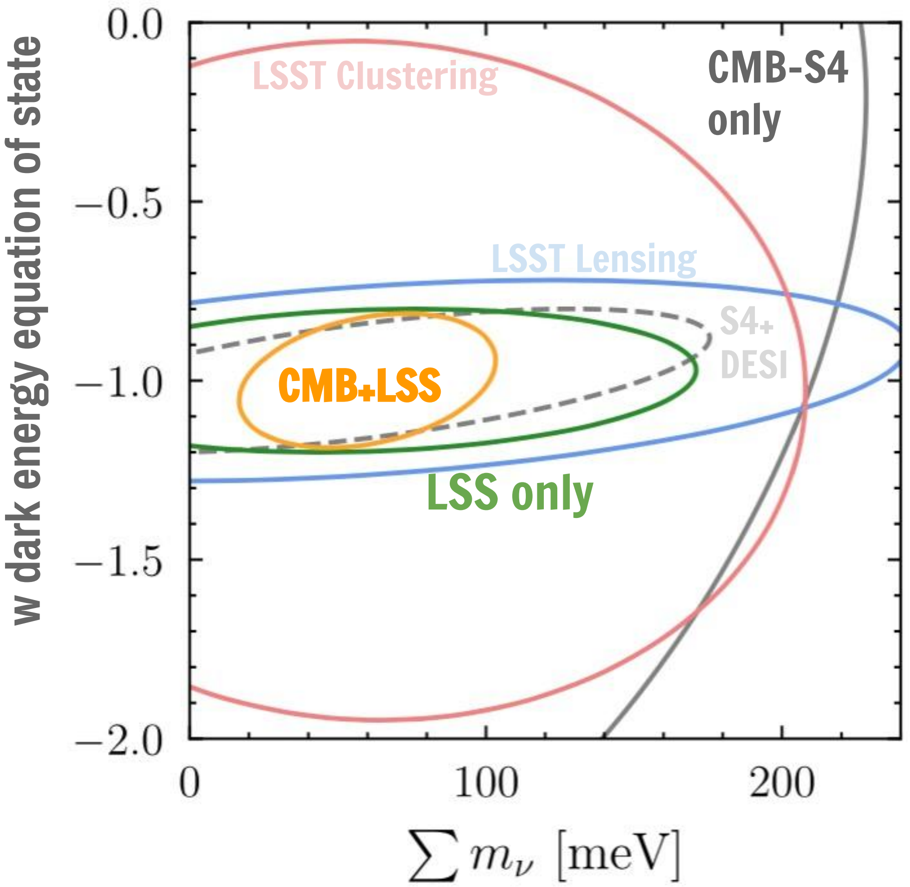
3. **Cross-collaboration collaboration mechanisms**
   3.1 Data access: future (rolling) upgrades may need access to internal pipelines & proprietary data
   3.2 Testbed for cross-collaboration collaboration where there is observational data (N^2 MOUs??)
   3.3 Training and acknowledging the simulation scientists
   3.4 Maintenance: documentation, data release (PYSM sets a great example!)

* A very conservative assumption..
Also see "Report from the Tri-Agency Cosmological Simulation Task Force" by Battaglia+2020

Important slides but no time to show

Public CMB x LSS Simulations

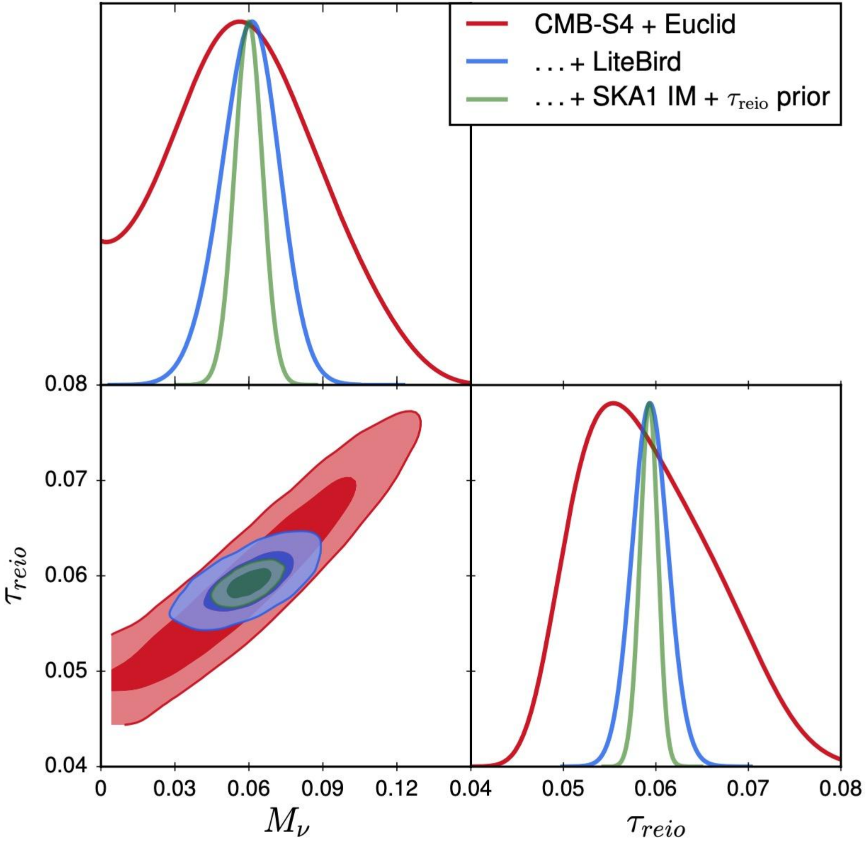
- From LSS experts:
  - Takahashi+2017, Osato & Nagai 2022 [κ^{gal}, κ^{CMB} + tSZ, kSZ]: 108 maps x full-sky, WMAP9
  - BAHAMAS (McCarthy+2018) [κ^{gal}, κ^{CMB}, tSZ]: 25 maps x 25 deg^2, Planck15, WMAP9
  - MassiveNuS (Liu+2018) [κ^{gal}, κ^{CMB}]: 10,000 maps x 12.25 deg^2, 100 cosmologies (M_ν, A_s, Ω_m)
- From CMB experts:
  - MillimeterDL (Han+2021) [κ^{gal}, κ^{CMB}, tSZ, kSZ, CIB, Radio, lensed CMB]: 500 maps x full-sky, WMAP5
  - MDPL2synsky (Omori in prep) [δ, κ^{gal}, κ^{CMB}, tSZ, kSZ, CIB, Radio]: 1 map x full-sky, Planck15



Mishra-Sharma, Alonso, Dunkley 2018

** LSS=Large-scale structure, including weak lensing and galaxy clustering.*

** Dark energy equation of state and spacetime curvature are free parameters.*



Brinckmann et al. 2019

** **τ_{reio} : reionization optical depth, highly degenerate with neutrino mass***

** Neutrino mass vs τ_{reio} for the three configurations CMB-S4 + Euclid, CMB-S4 + Euclid + LiteBIRD, CMB-S4 + Euclid + SKA1 Intensity Mapping + τ_{reio} prior in the minimal 7 parameter ΛCDM+M_ν model. τ_{reio} prior assumes σ(τreio) = 0.001.*