COSMOLOGY

THE GOLDEN AGE OF OBSERVATIONS

New Directions in Theoretical Physics

Edinburgh, January 2023

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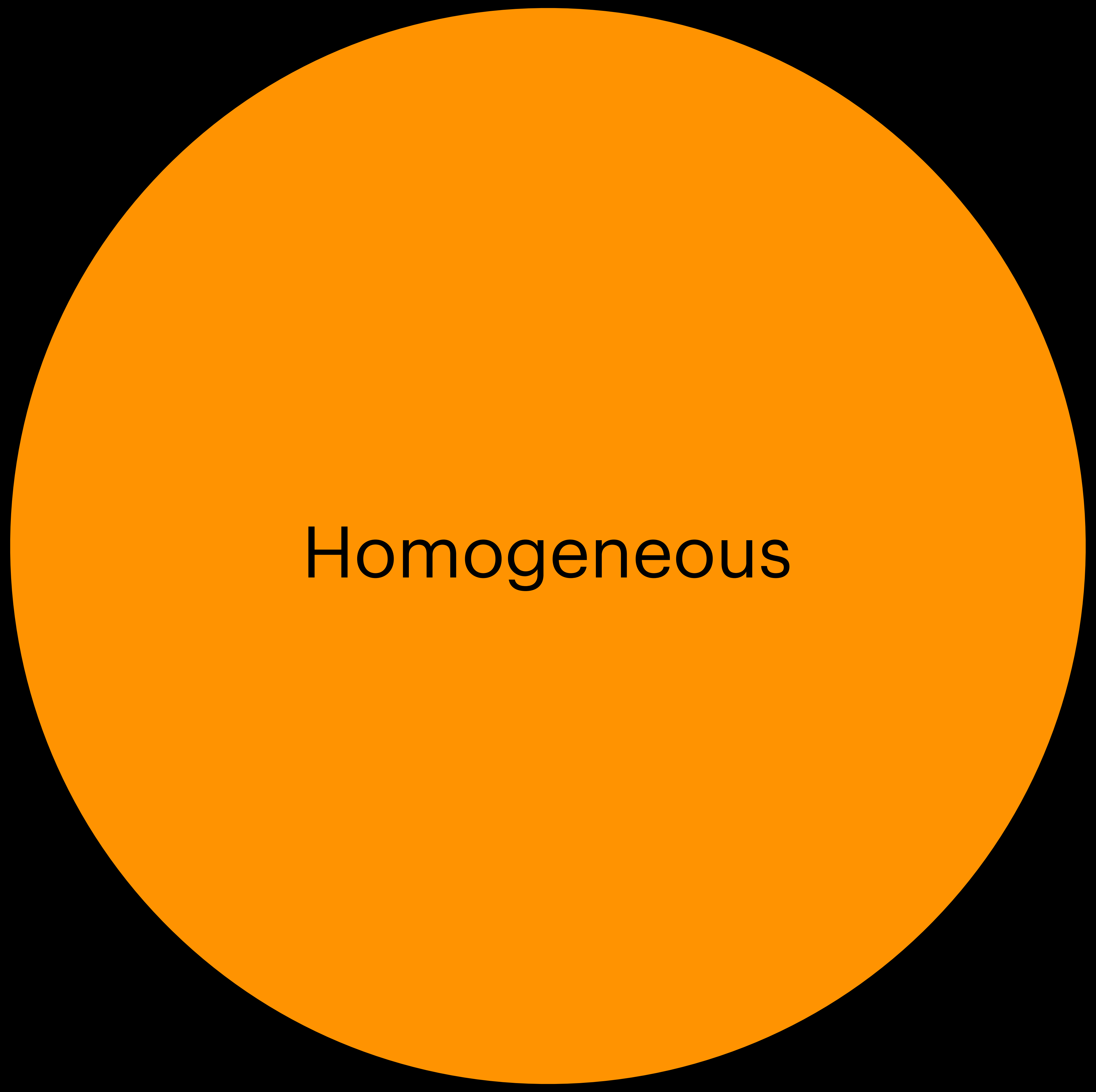
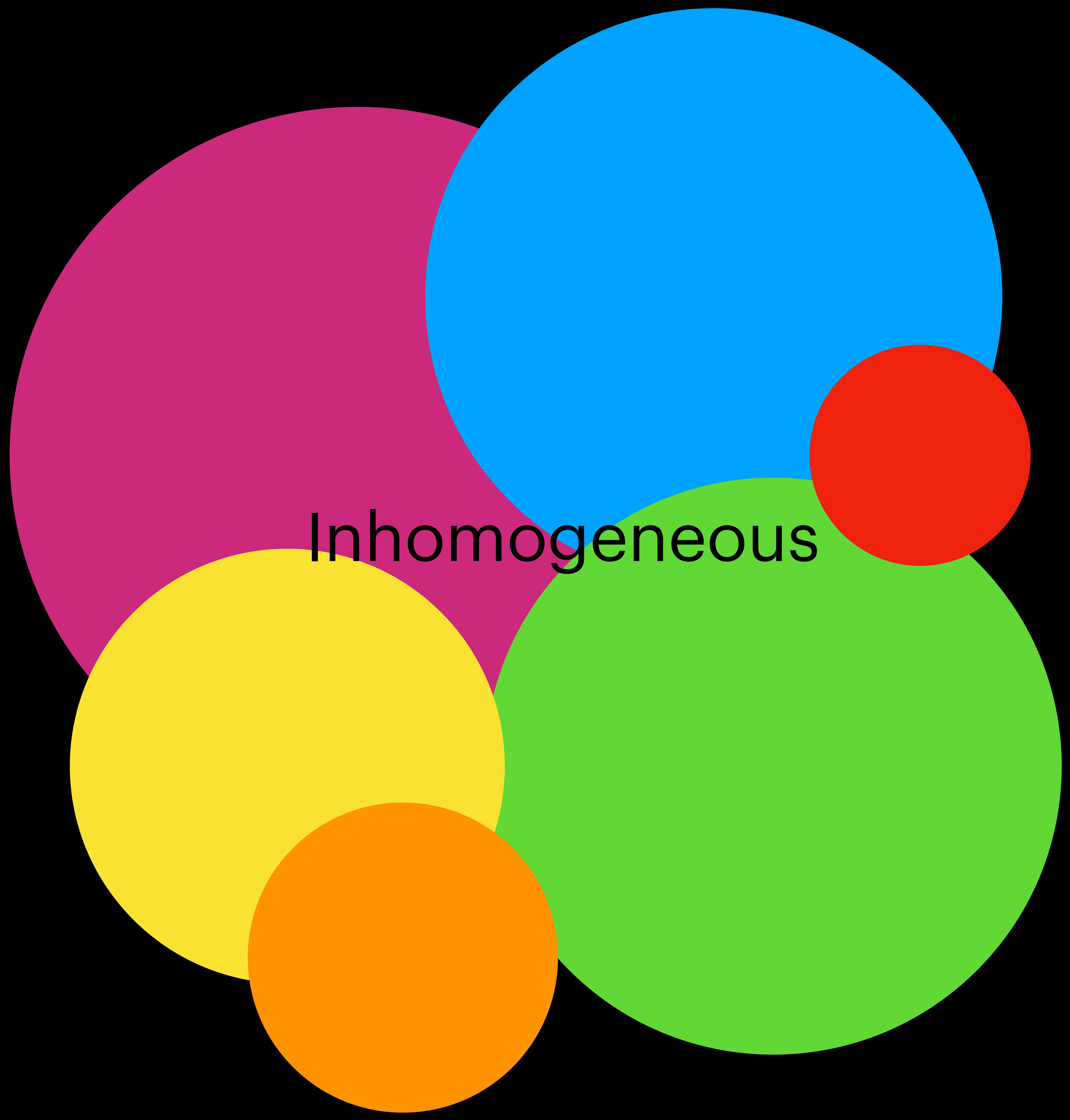
JWST lensing image

COSMOLOGICAL TESTS FALL IN TWO MAIN GROUPS



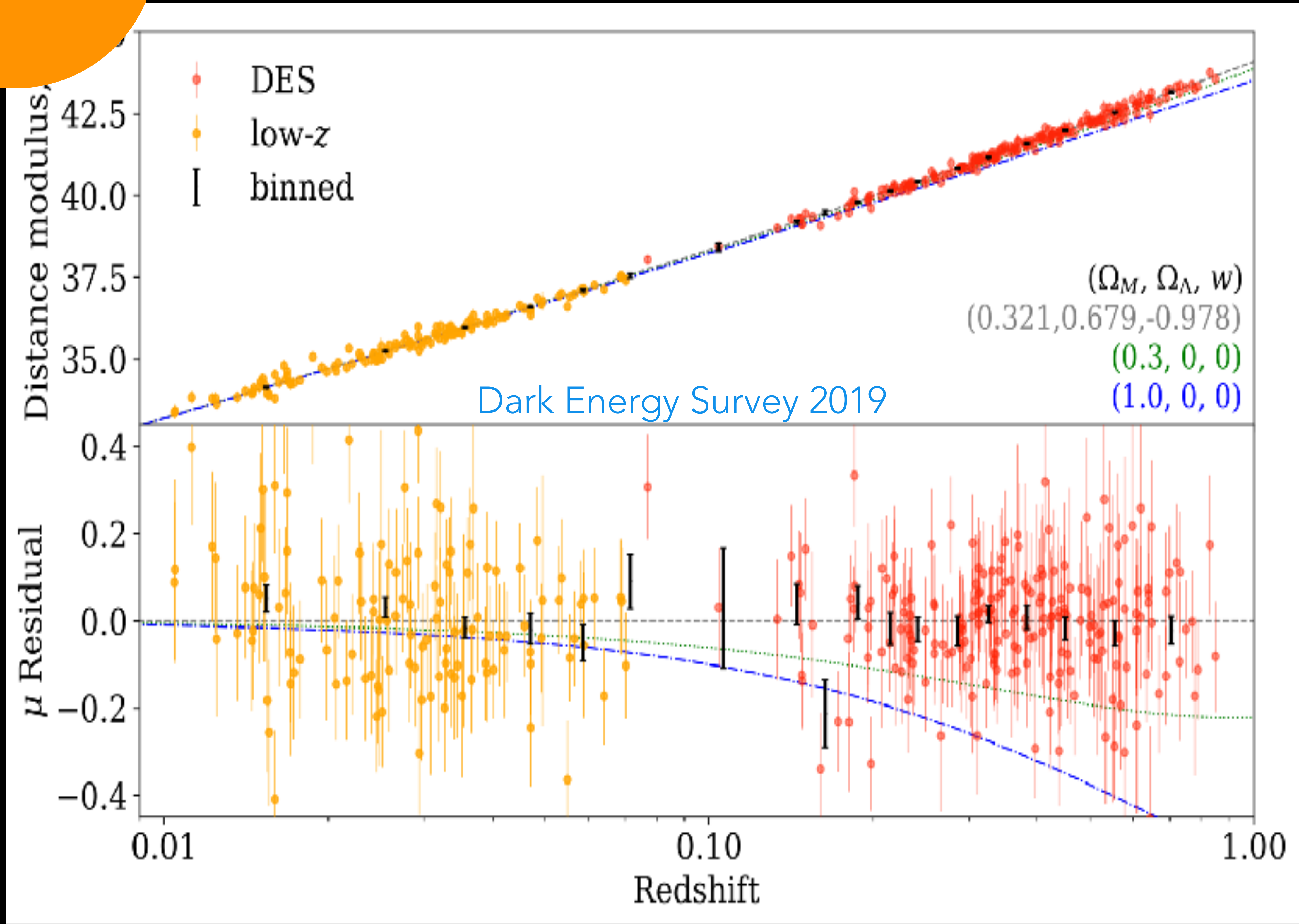
Measures of the expansion



Measures of growth and structure

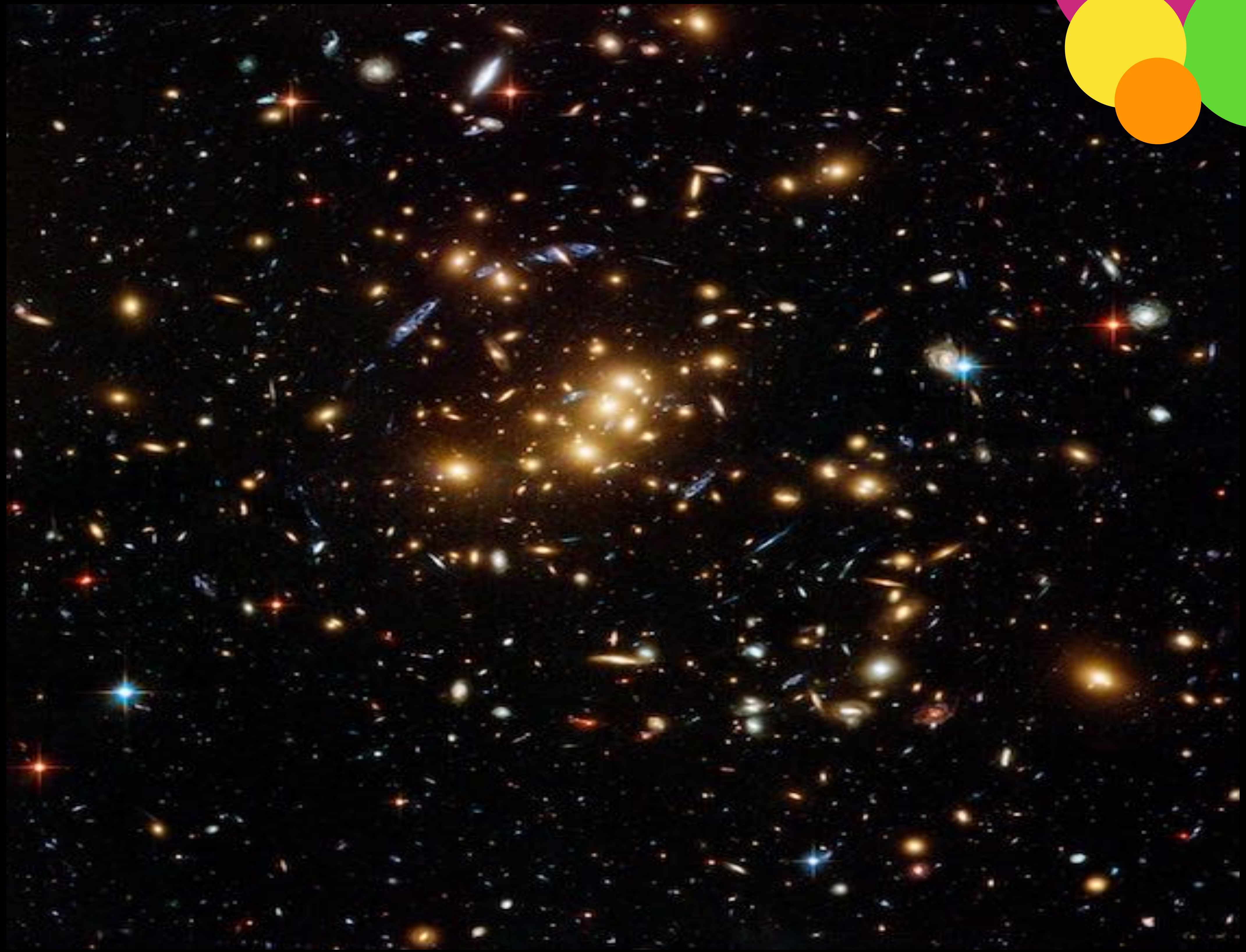
COSMOLOGICAL TESTS FALL IN TWO MAIN GROUPS

Homogeneous



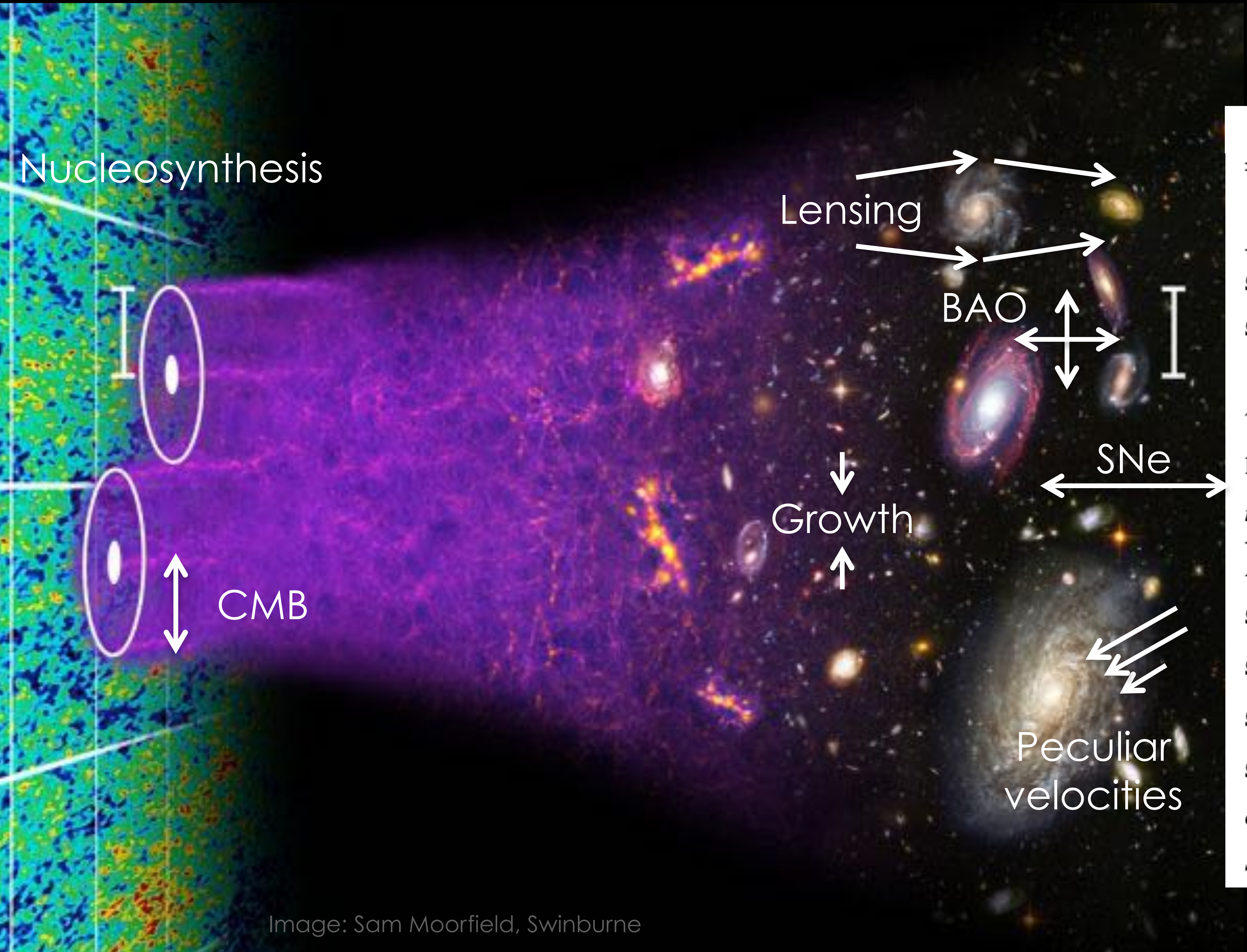
Expansion

Inhomogeneous



Clustering/Lensing/
Velocities/ISW.....

MANY TYPES OF OBSERVATIONS = CONCORDANCE



Planck 2018 (TT, TE, EE + lowE + lensing + BAO)

Parameter		TT,TE,EE+lowE+lensing+BAO 68% limits
$\Omega_b h^2$	baryon density	0.02242 ± 0.00014
$\Omega_c h^2$	cold dark matter	0.11933 ± 0.00091
$100\theta_{MC}$	sound horizon scale	1.04101 ± 0.00029
τ	optical depth	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	initial amplitude	3.047 ± 0.014
n_s	initial slope	0.9665 ± 0.0038
H_0 [km s^{-1} Mpc^{-1}]		67.66 ± 0.42
Ω_Λ	cosmo const density	0.6889 ± 0.0056
Ω_m	matter density	0.3111 ± 0.0056
$\Omega_m h^2$		0.14240 ± 0.00087
$\Omega_m h^3$		0.09635 ± 0.00030
σ_8	fluct'n amplitude	0.8102 ± 0.0060
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$		0.825 ± 0.011

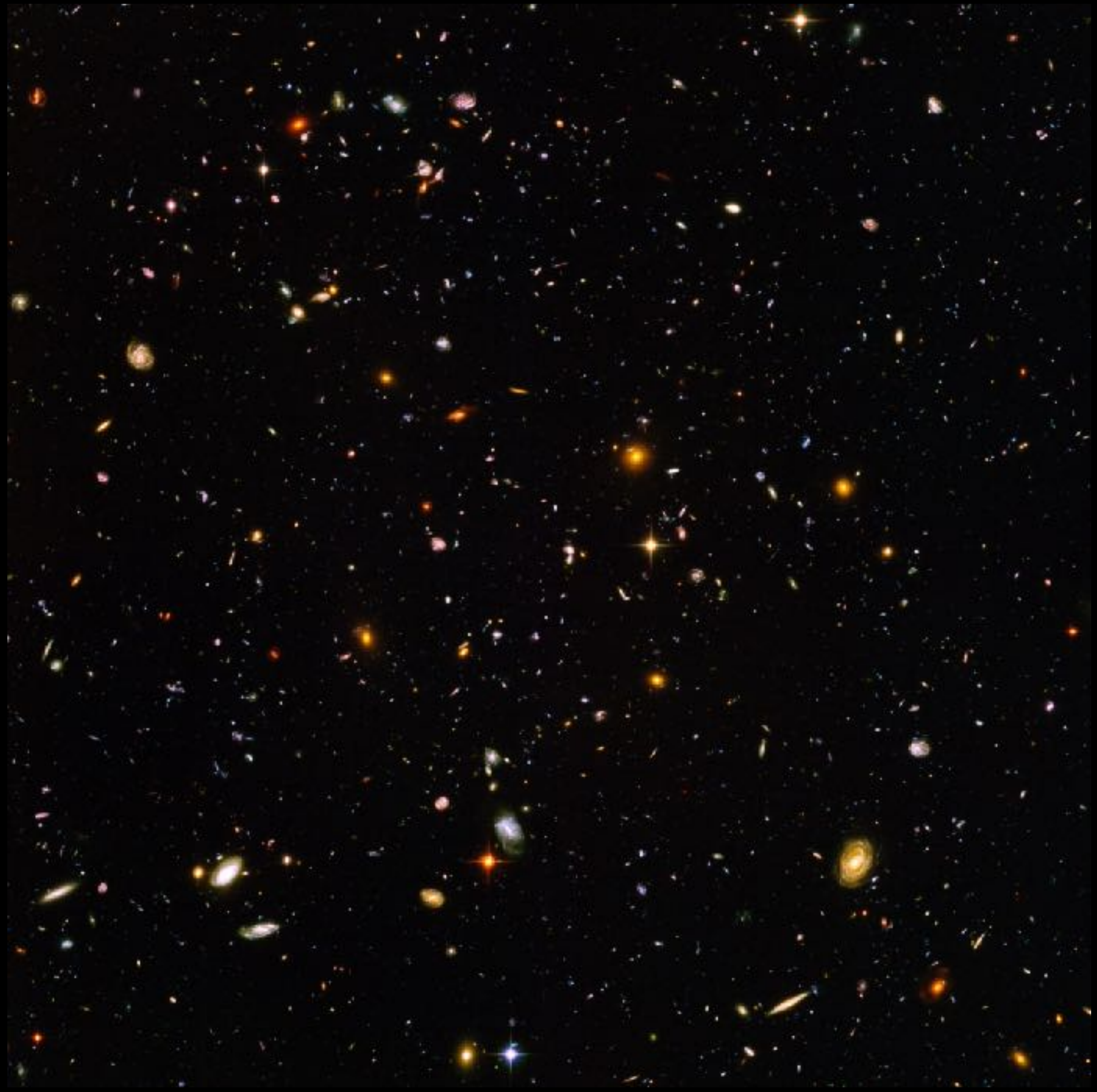
better than 1% precision

Cosmological conundrums

Dark Matter

pulls, clumpy

Dark Energy



pushes, smooth

Cosmological tensions

H_0 tension

Expansion rate of the universe at present day

$$H_0$$

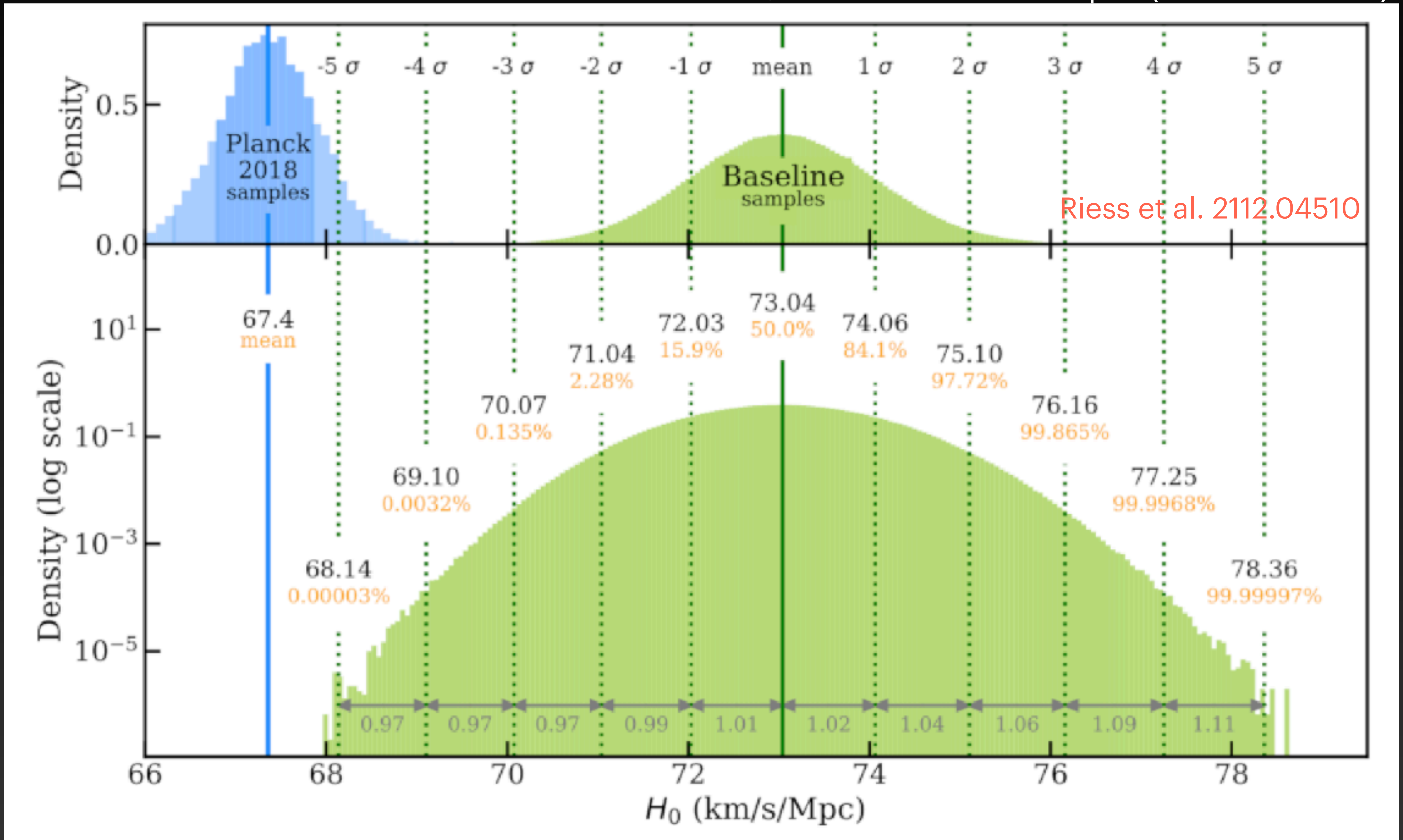
$$v = HD$$

$$H \equiv \frac{\text{Rate of change of scalefactor}}{\text{scalefactor}}$$

$$v(t_0) = H_0 D_0$$

$$H_0 = \text{Current expansion rate}$$

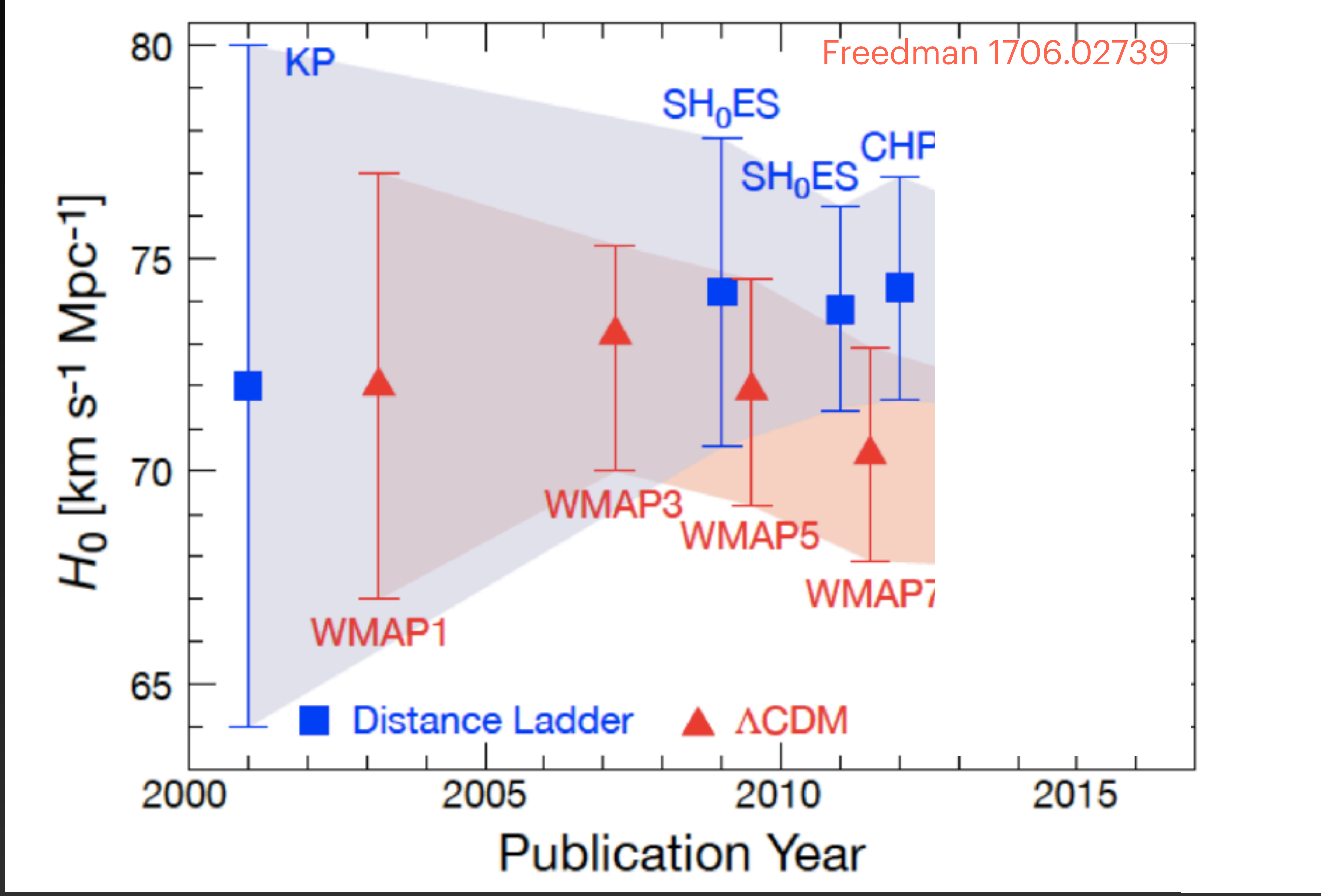
H_0 = 73.04 ± 1.04 km s^{-1} Mpc^{-1} (Riess et al. 2022)

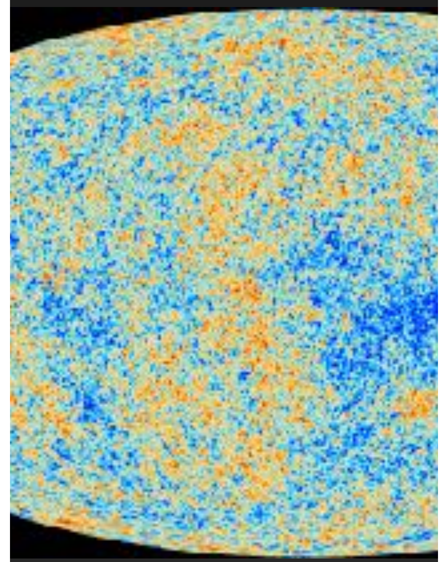


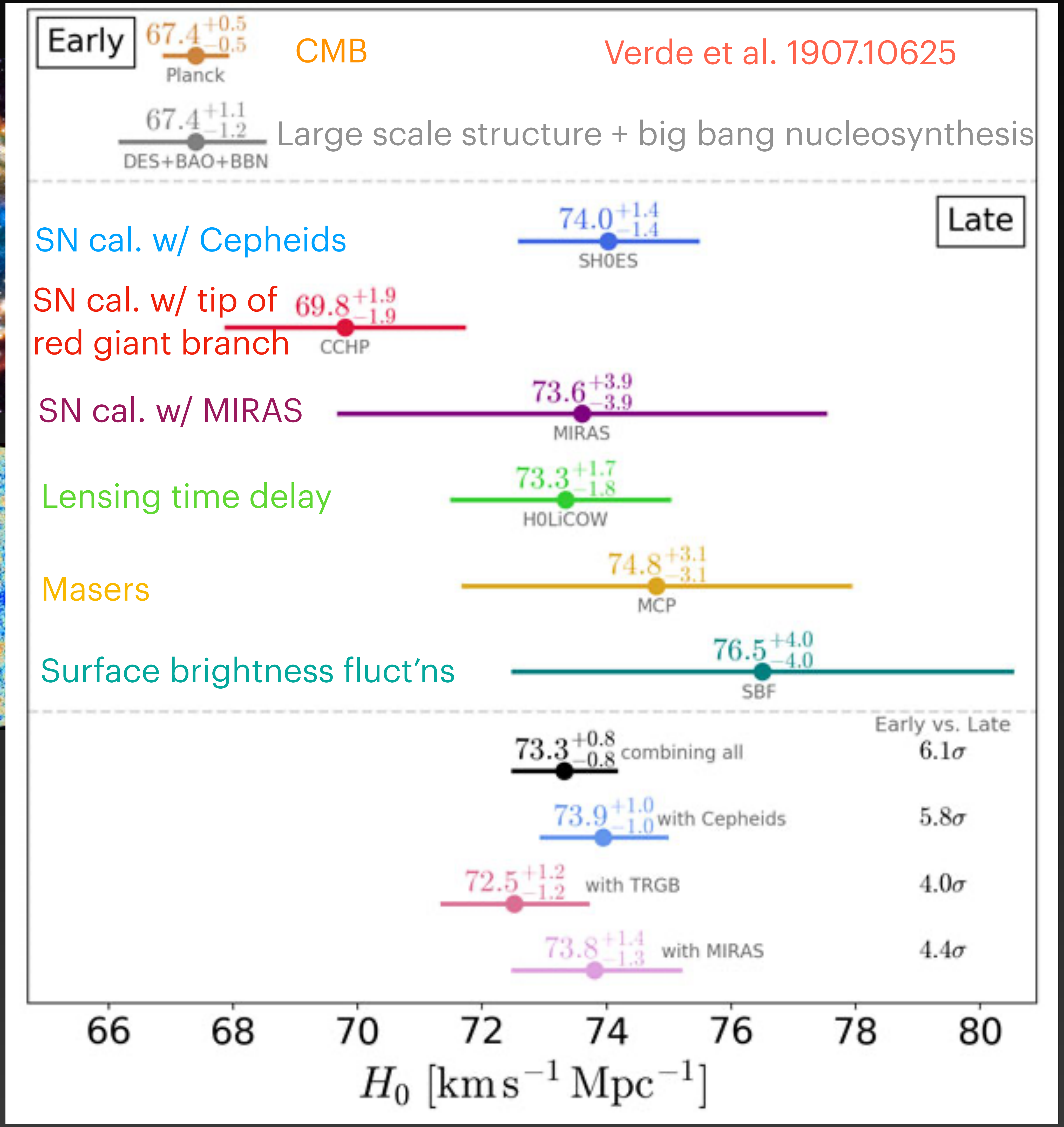
$$D = R\chi \qquad v = \dot{R}\chi = \frac{\dot{R}}{R}R\chi = \frac{\dot{R}}{R}D \qquad H \equiv \frac{\dot{R}}{R}$$

Cosmological tensions

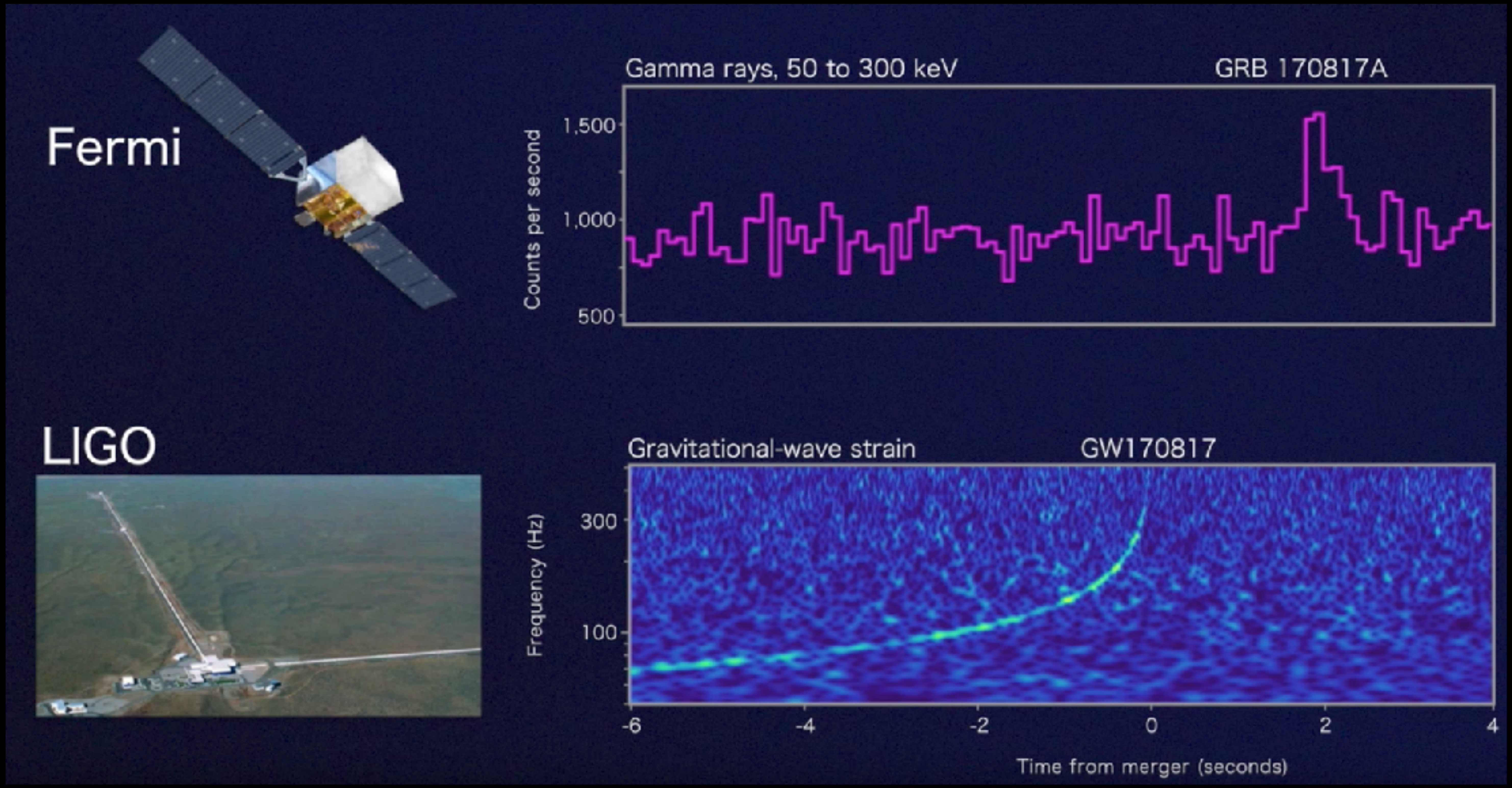
H_0 tension







GRAVITATIONAL WAVES - 2017 NEUTRON STAR MERGER!



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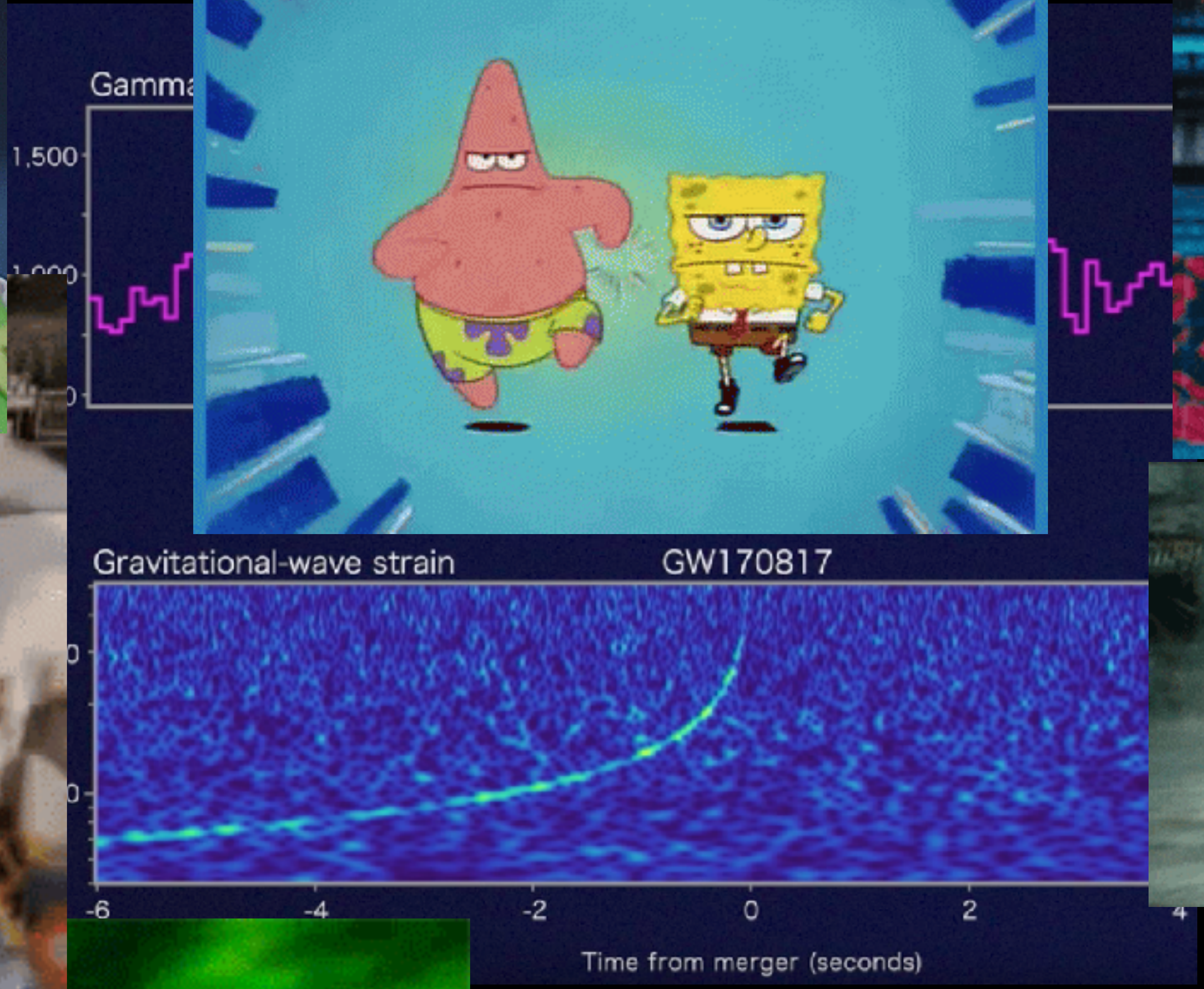
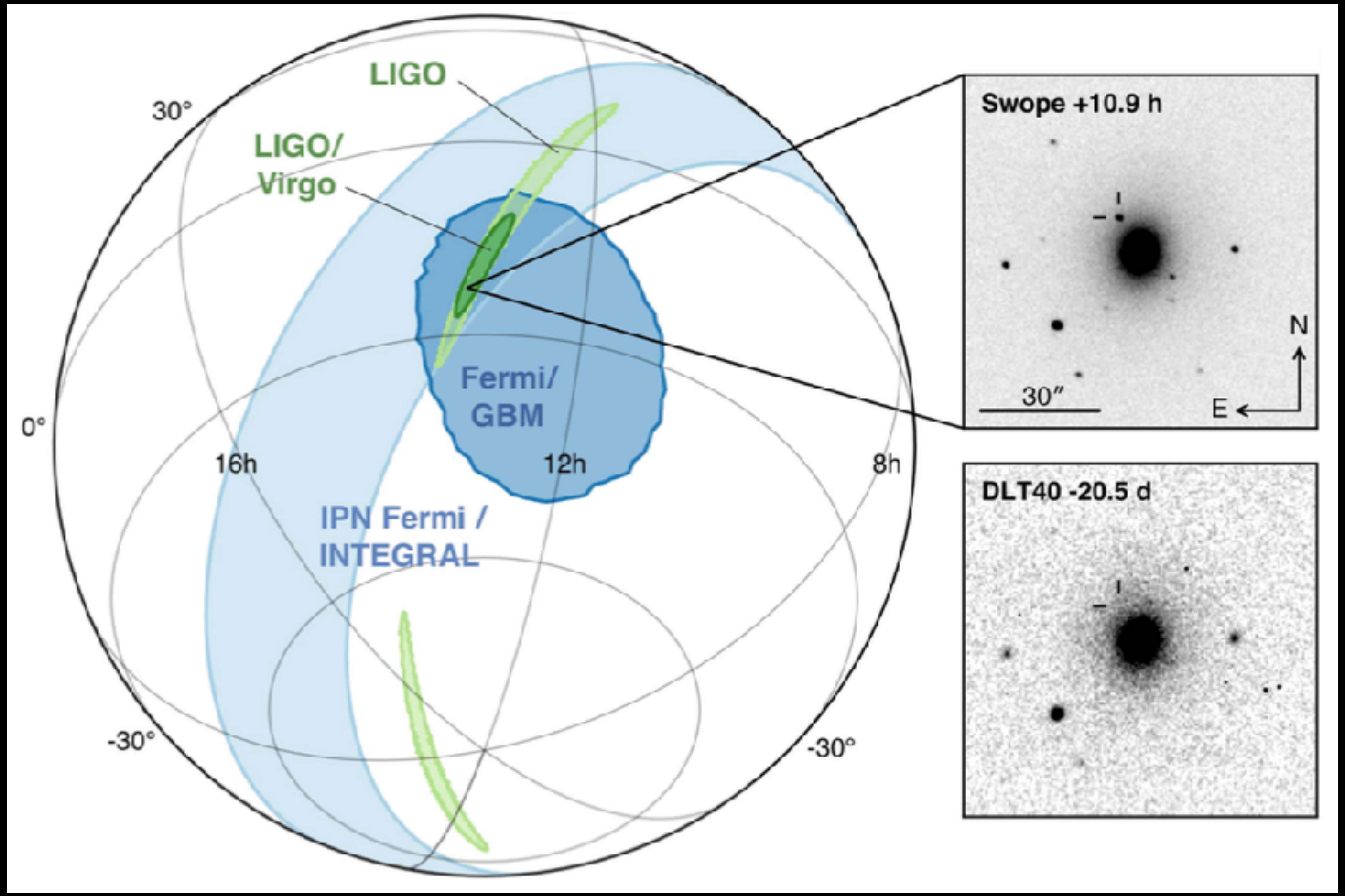
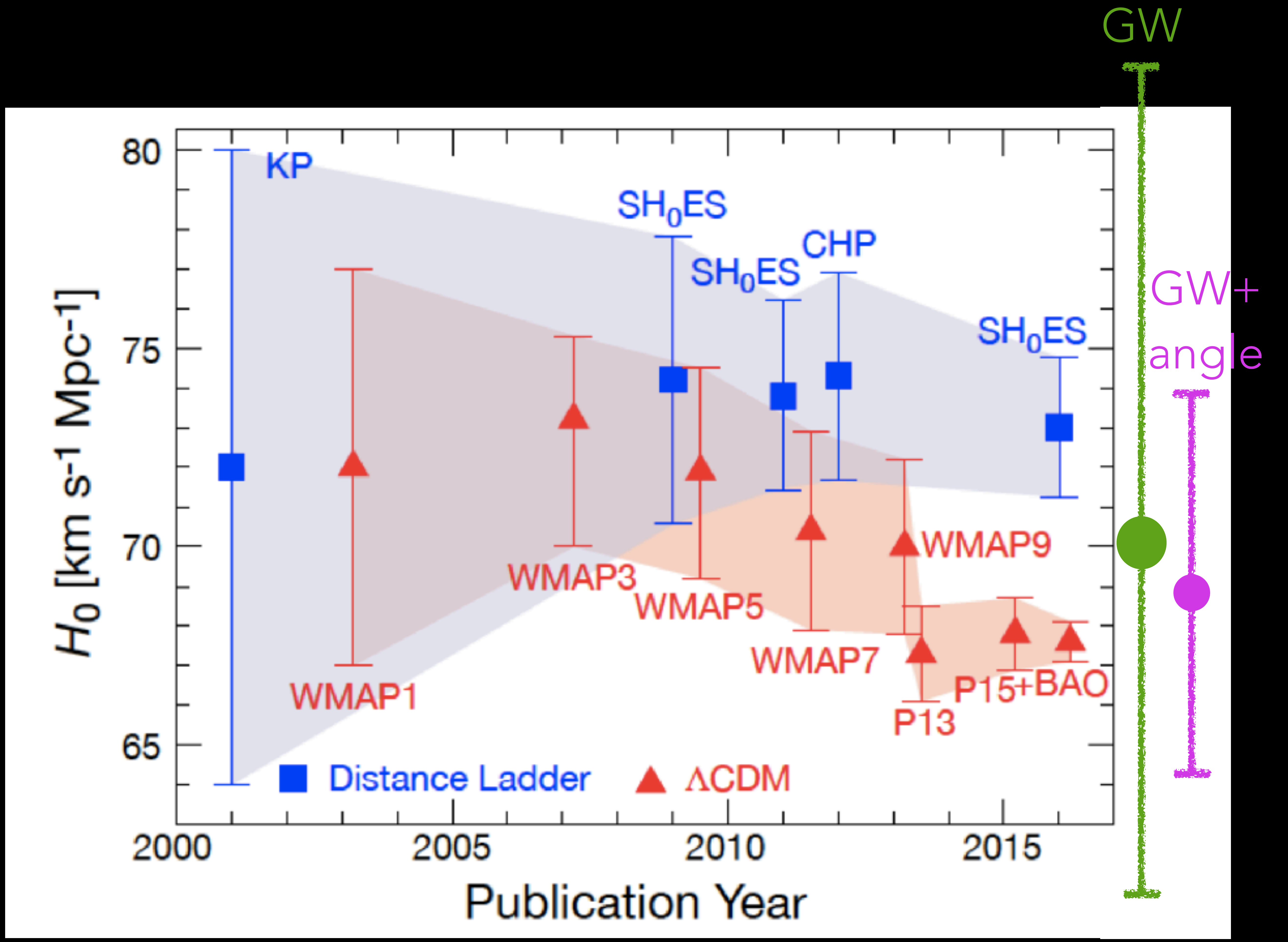


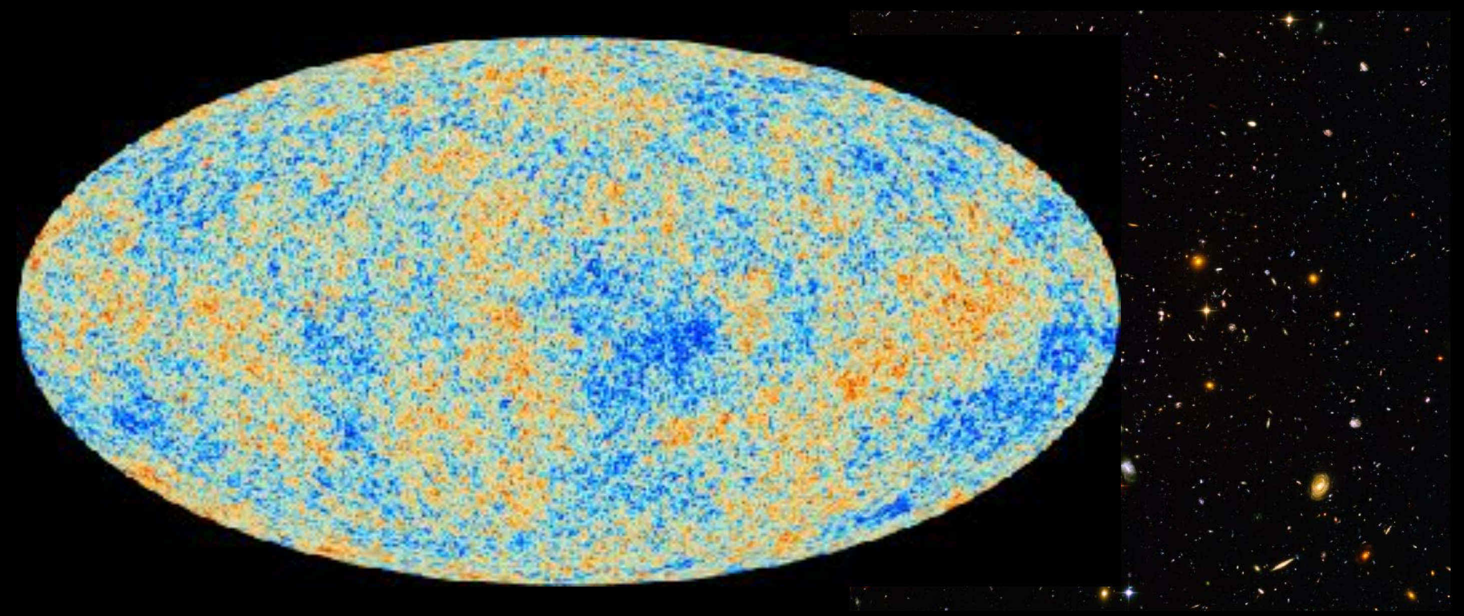
OPTICAL SOURCE DETECTED!



OPTICAL SOURCE DETECTED!

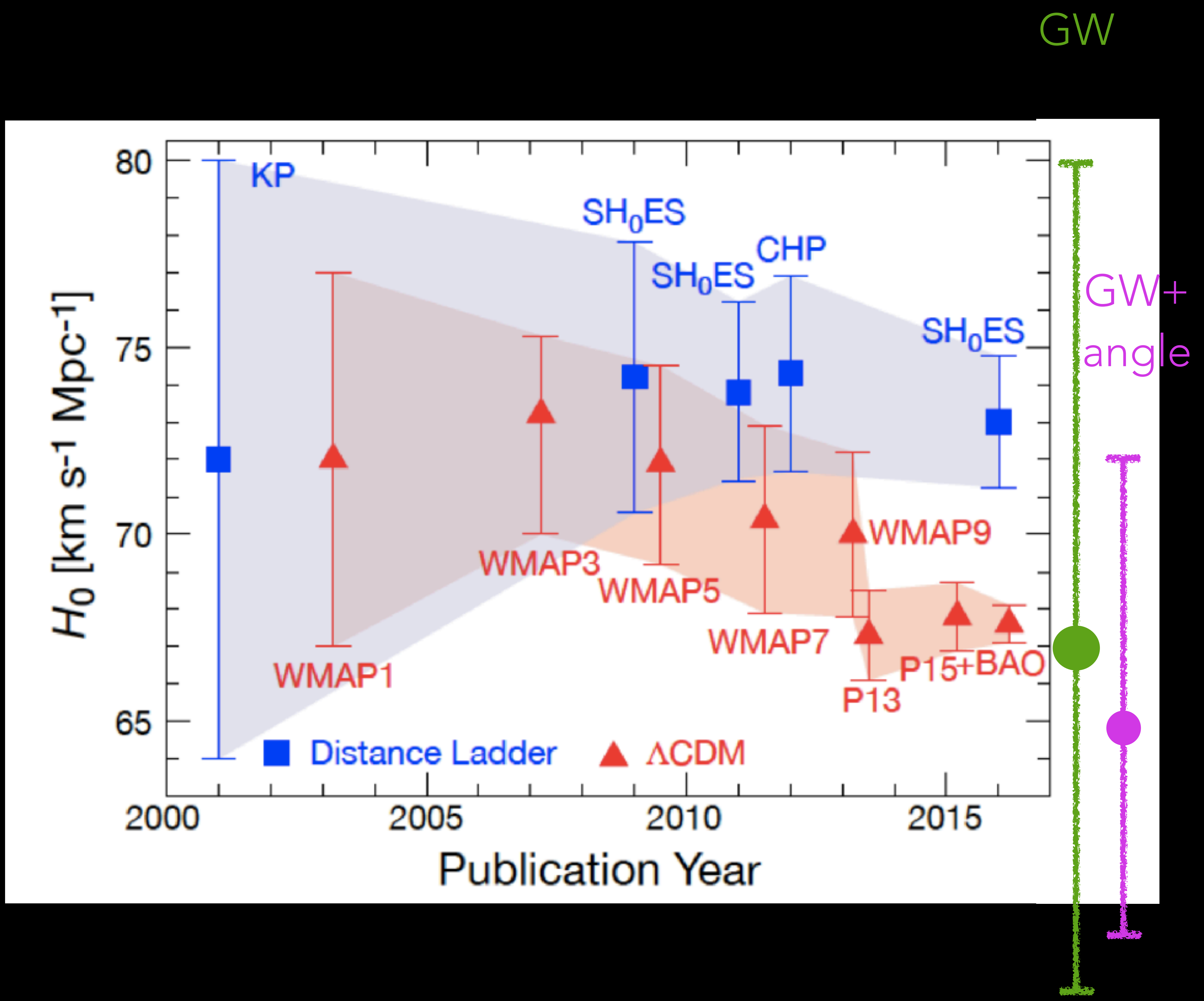
GRAVITATIONAL WAVES

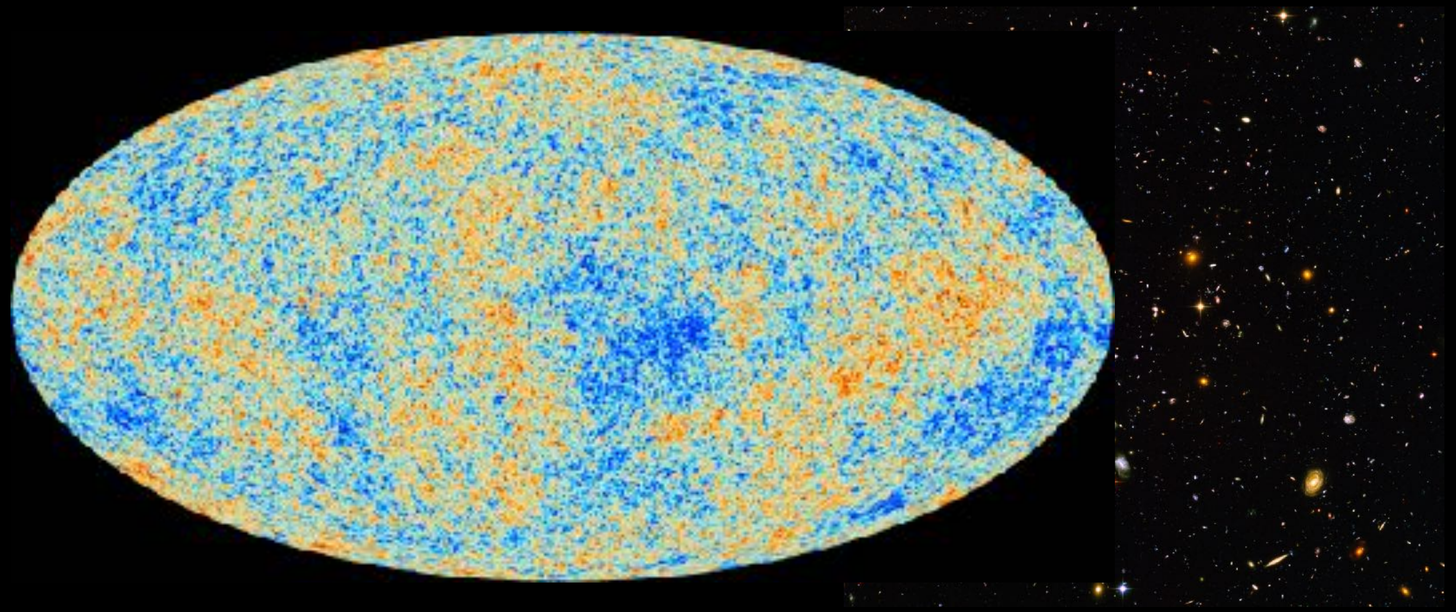




Abbott et al. 2017 Hotokezaka et al. 2019

GRAVITATIONAL WAVES





Howlett et al. 2020 (improving peculiar velocities for Abbott 2017)

Howlett et al. 2020 (improving pec vel for Hotokezaka et al. 2019)

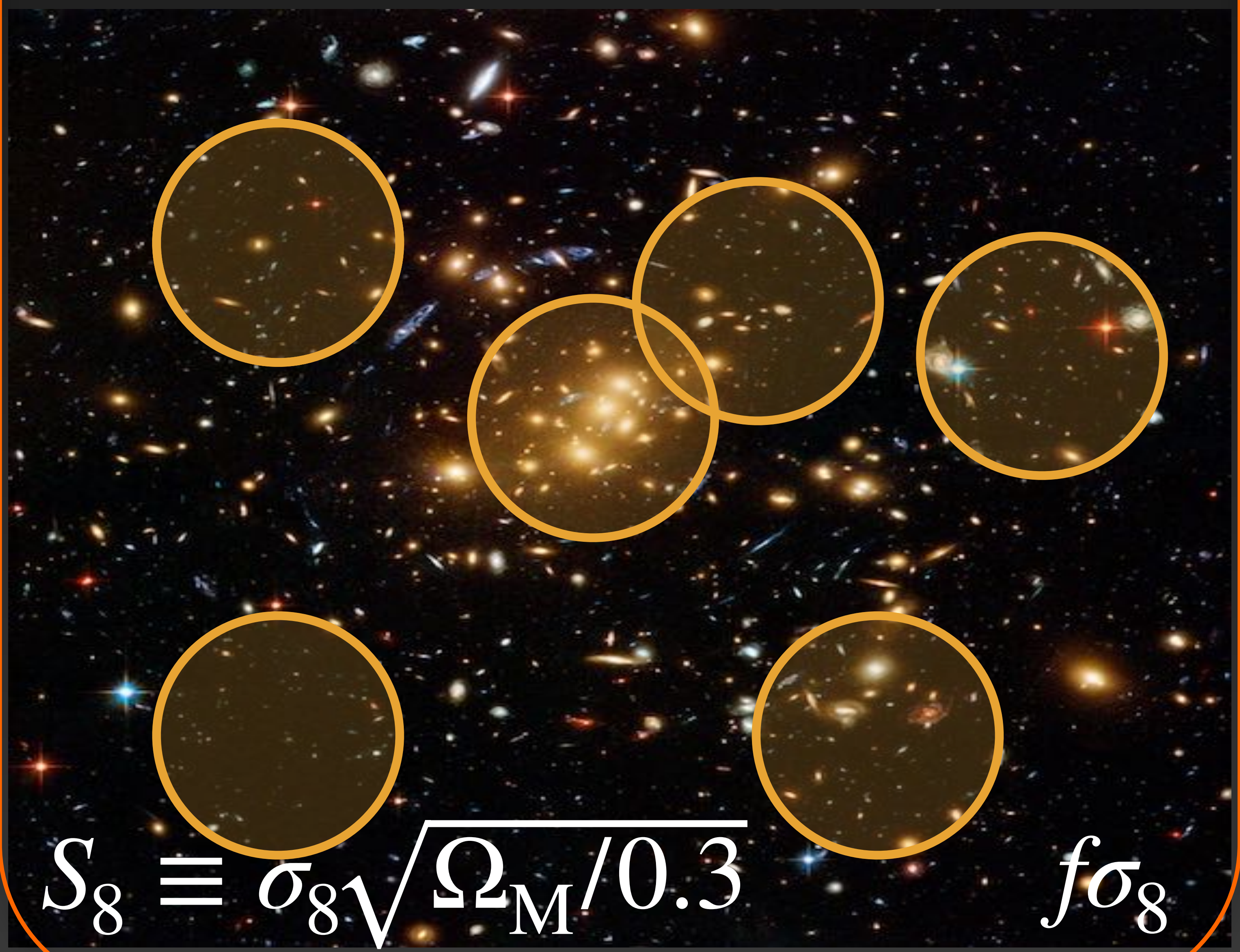
Cosmological tensions

S_8 tension

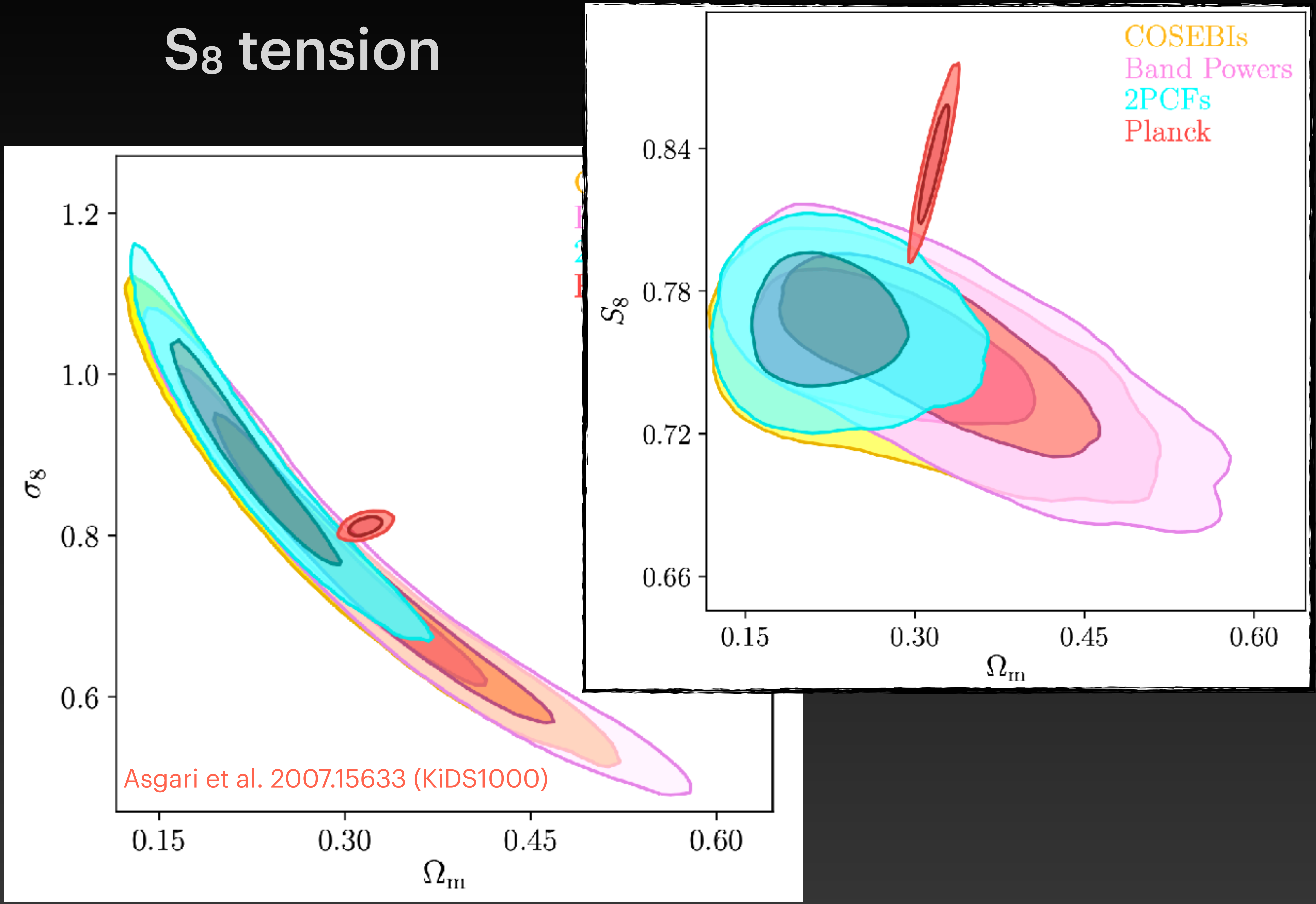
Amplitude of density fluctuations at present day

σ_8

1. measure density in spheres of 8 Mpc radius
2. calculate the dispersion



$S_8 \equiv \sigma_8\sqrt{\Omega_M/0.3}$ $f\sigma_8$



Tensions are intriguing

(e.g. Dark Energy)

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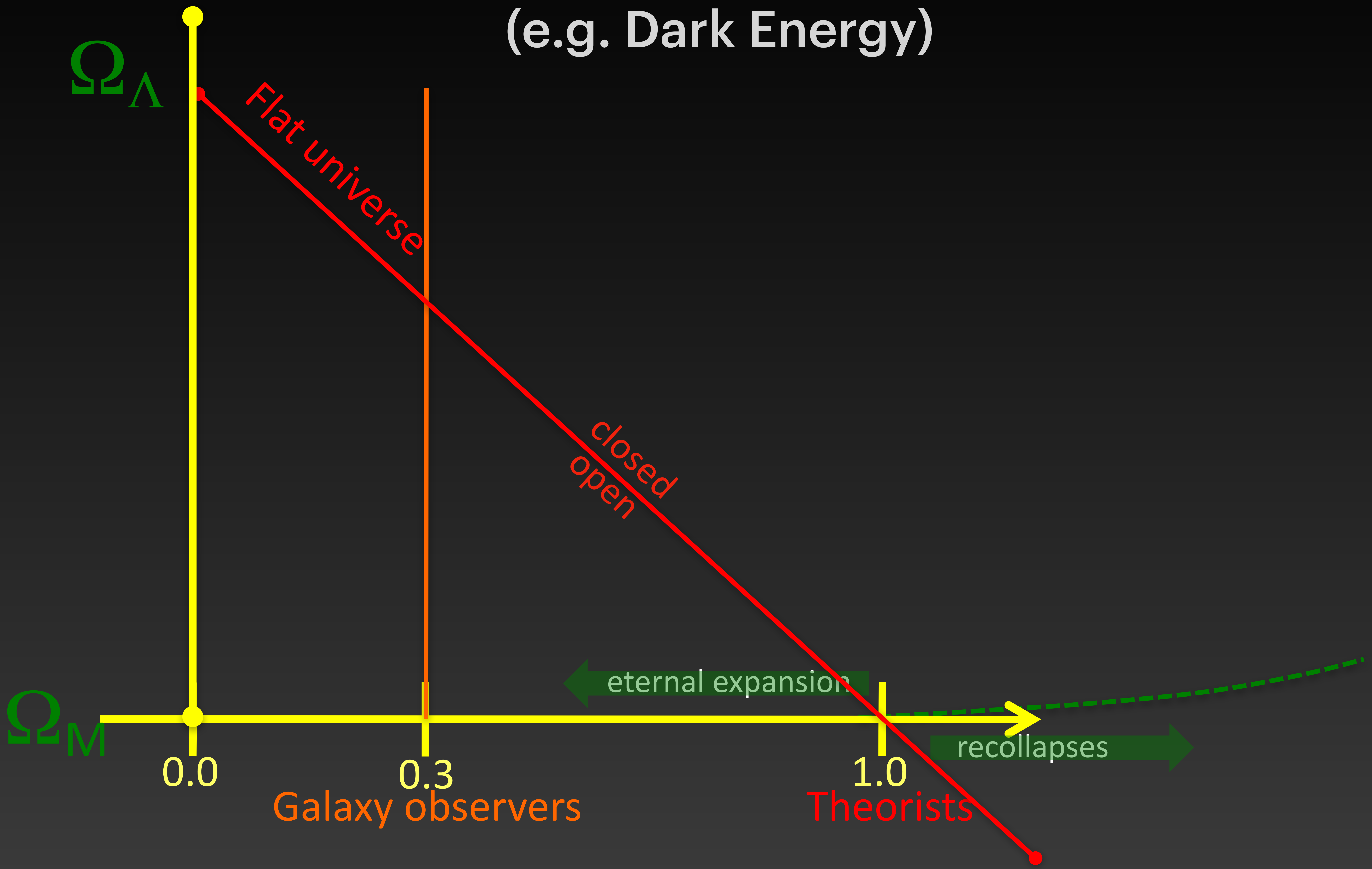
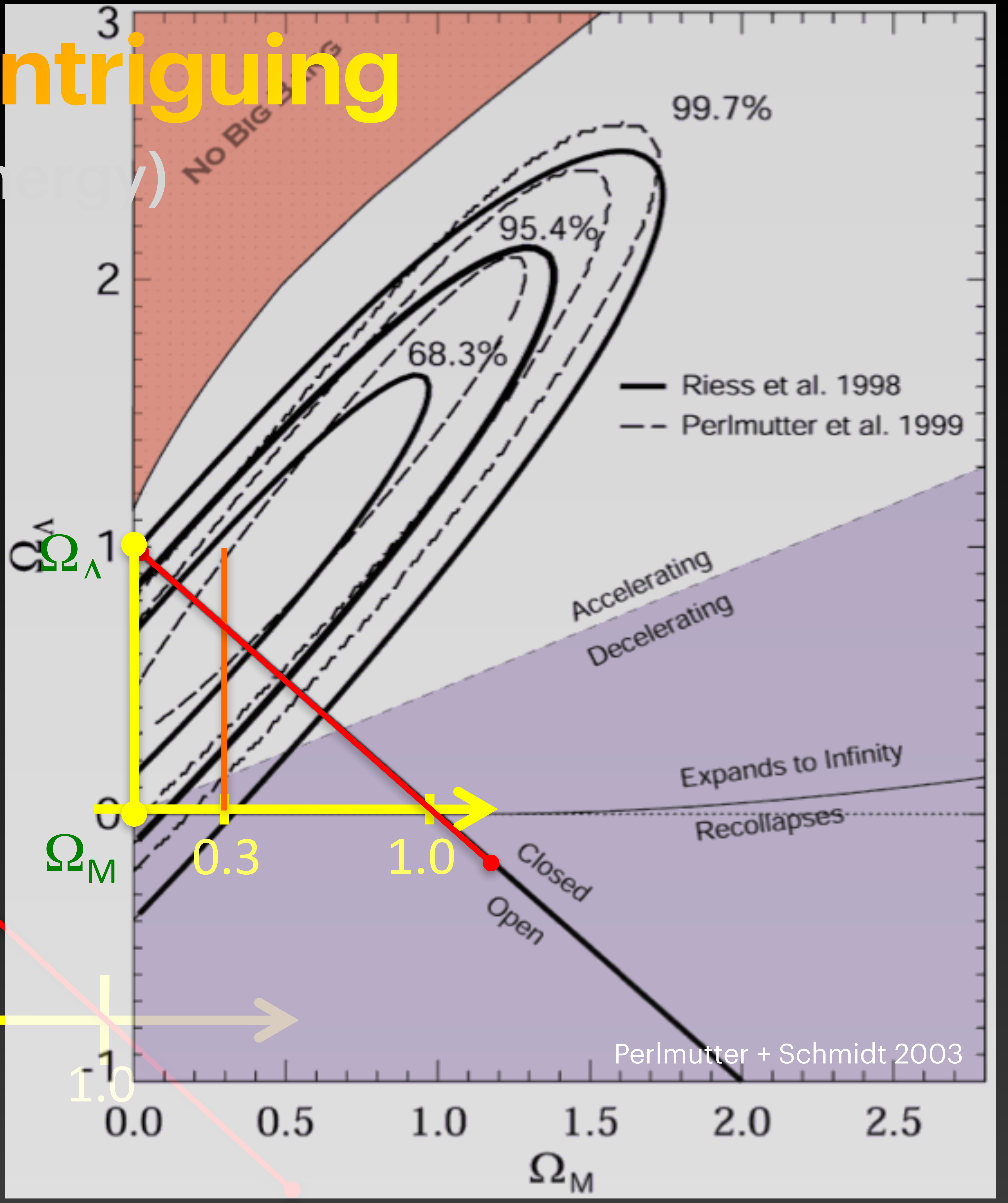


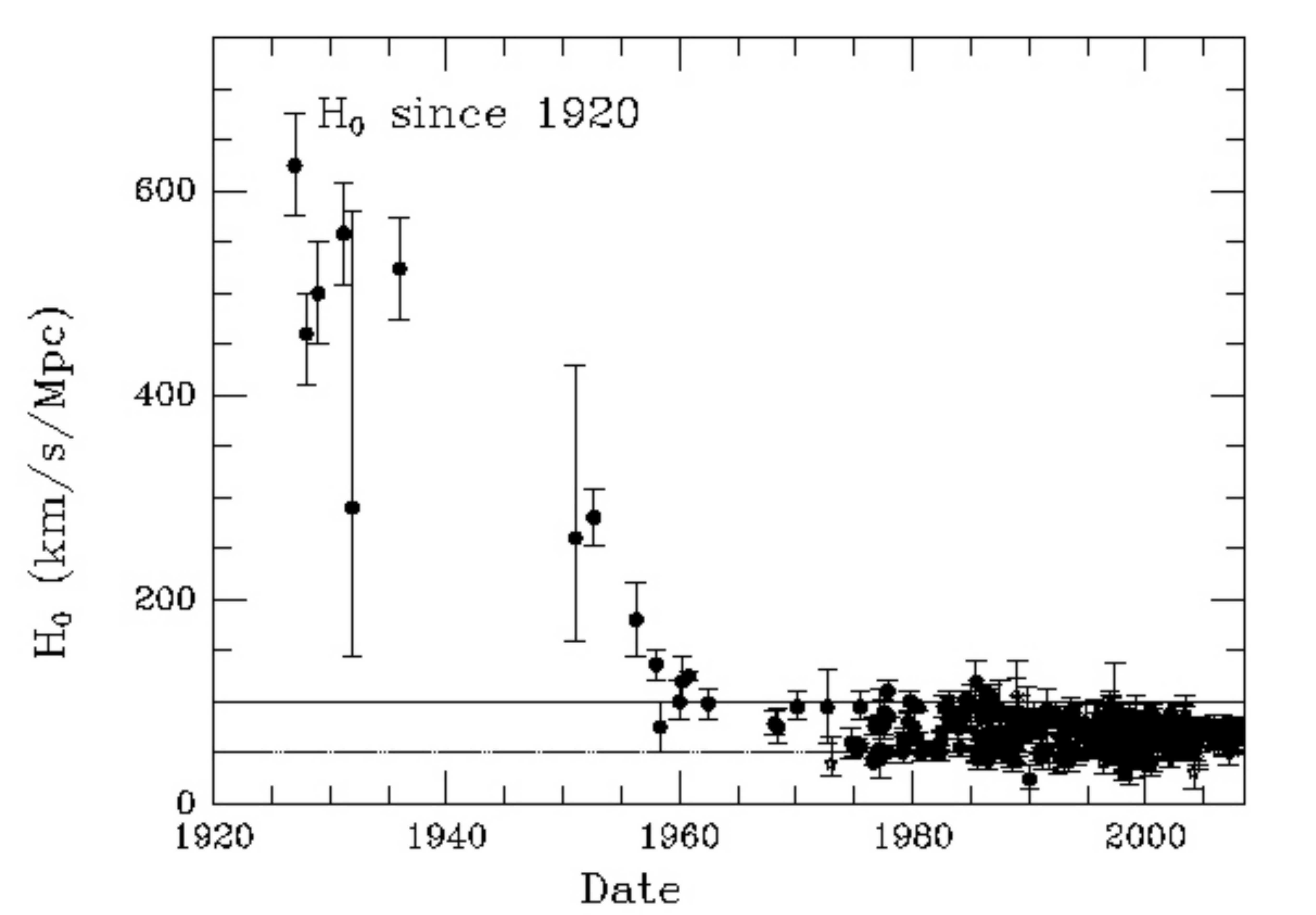
Tensions are intriguing

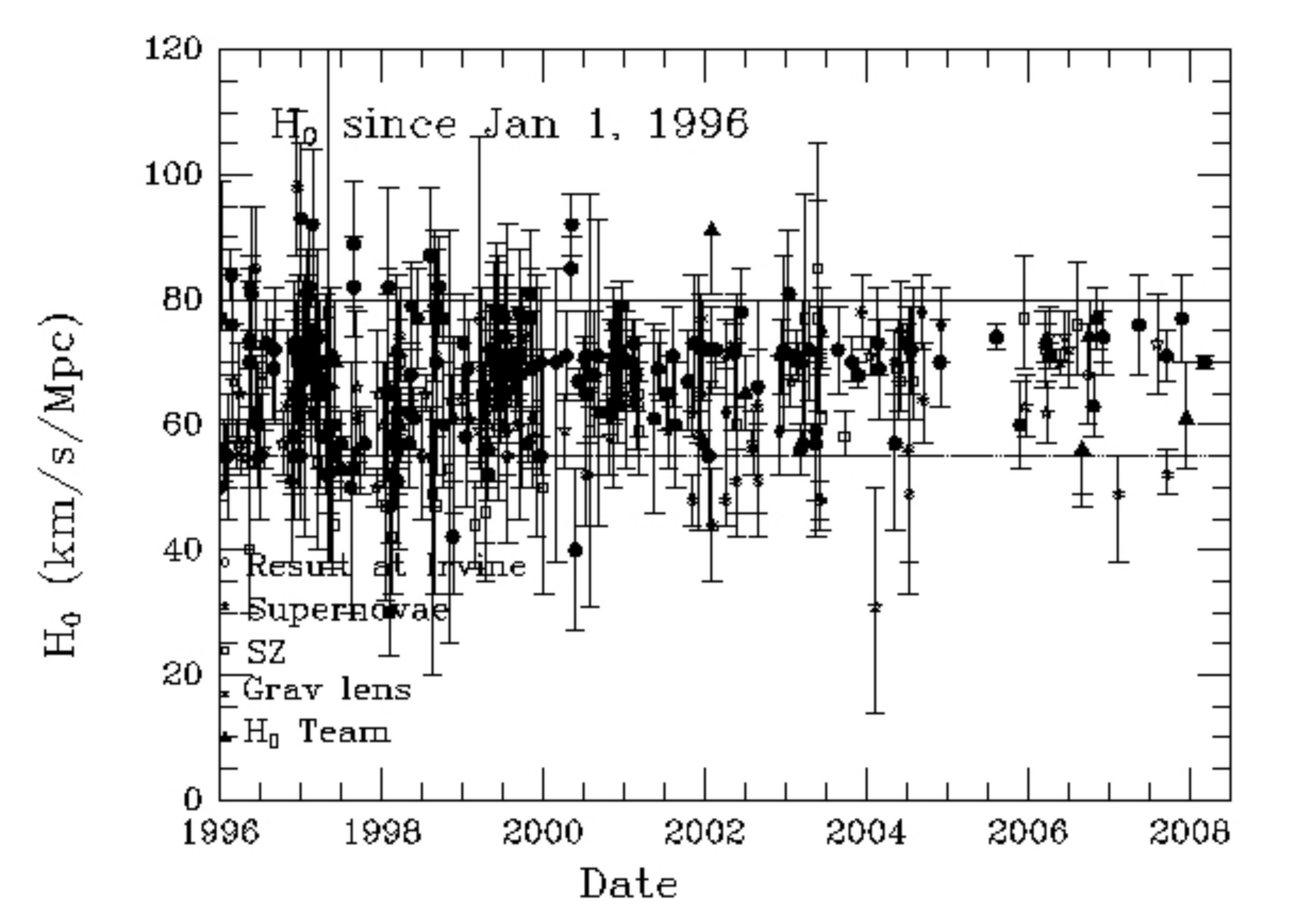
(e.g. Dark Energy)



But tensions can also just be systematic errors

(Optimists and their error bars)





Credit: John Huchra

Some suggested solutions...

(Results from a search of "tension" in refereed astronomy papers on ADS Jan-Jun 2022.)

* **Quantum origin** of dark energy and the Hubble tension
* Cosmological implications of $n_s \approx 1$ in light of the Hubble tension
* Integral **F(R) gravity** and saddle point condition as a remedy for the H_0-tension
* **Interacting dark sectors** in anisotropic universe: Observational constraints and H0 tension
* The Hubble tension in the **non-flat Super-ΛCDM** model
* Cosmology intertwined: A review of the particle physics, astrophysics, and cosmology associated with the cosmological tensions and anomalies
* The Hubble Law: Its **Relational Justification** and the Hubble Tension
* **Neutrino Mass Bounds** in the Era of Tension Cosmology
* **Environment dependent electron mass** and the Hubble constant tension
* **Decay of multiple dark matter particles** to dark radiation in different epochs does not alleviate the Hubble tension
* Minimal dark energy: Key to **sterile neutrino** and Hubble constant tensions?
* **Nonthermal neutrino-like hot dark matter** in light of the S8 tension
* **Axion dark radiation**: Hubble tension and the Hyper-Kamiokande neutrino experiment
* Realistic model of **dark atoms** to resolve the Hubble tension
* On the kinematic cosmic dipole tension
* **Mirror twin Higgs cosmology**: constraints and a possible resolution to the H0 and S8 tensions
* **Free-streaming and coupled dark radiation isocurvature perturbations**: constraints and application to the Hubble tension
* Possible resolution of the Hubble tension with **Weyl invariant gravity**
* Analyzing the Hubble tension through **hidden sector dynamics** in the early universe
* Exploring the Hubble Tension and Spatial Curvature from the Ages of Old Astrophysical Objects
* The S8 tension in light of updated redshift-space distortion data and PAge approximation
* **Chameleon early dark energy** and the Hubble tension
* Implications of the S8 tension for **decaying dark matter with warm decay products**
* Cosmic expansion parametrization: Implication for curvature and H0 tension
* Easing the Hubble constant tension
* **Surface tension of cosmic voids** as a possible source for dark energy
* Can **varying the gravitational constant** alleviate the tensions?
* **Varying fundamental constants** principal component analysis: additional hints about the Hubble tension
* No-go guide for the Hubble tension: **Late-time solutions**
* **Superhorizon Perturbations:** A Possible Explanation of the Hubble-Lemaître Tension and the Large-scale Anisotropy of the Universe

More suggested solutions...

(Results from a search of “tension” in refereed astronomy papers on ADS in 2021.)

* Quantum origin of dark energy and the Hubble tension
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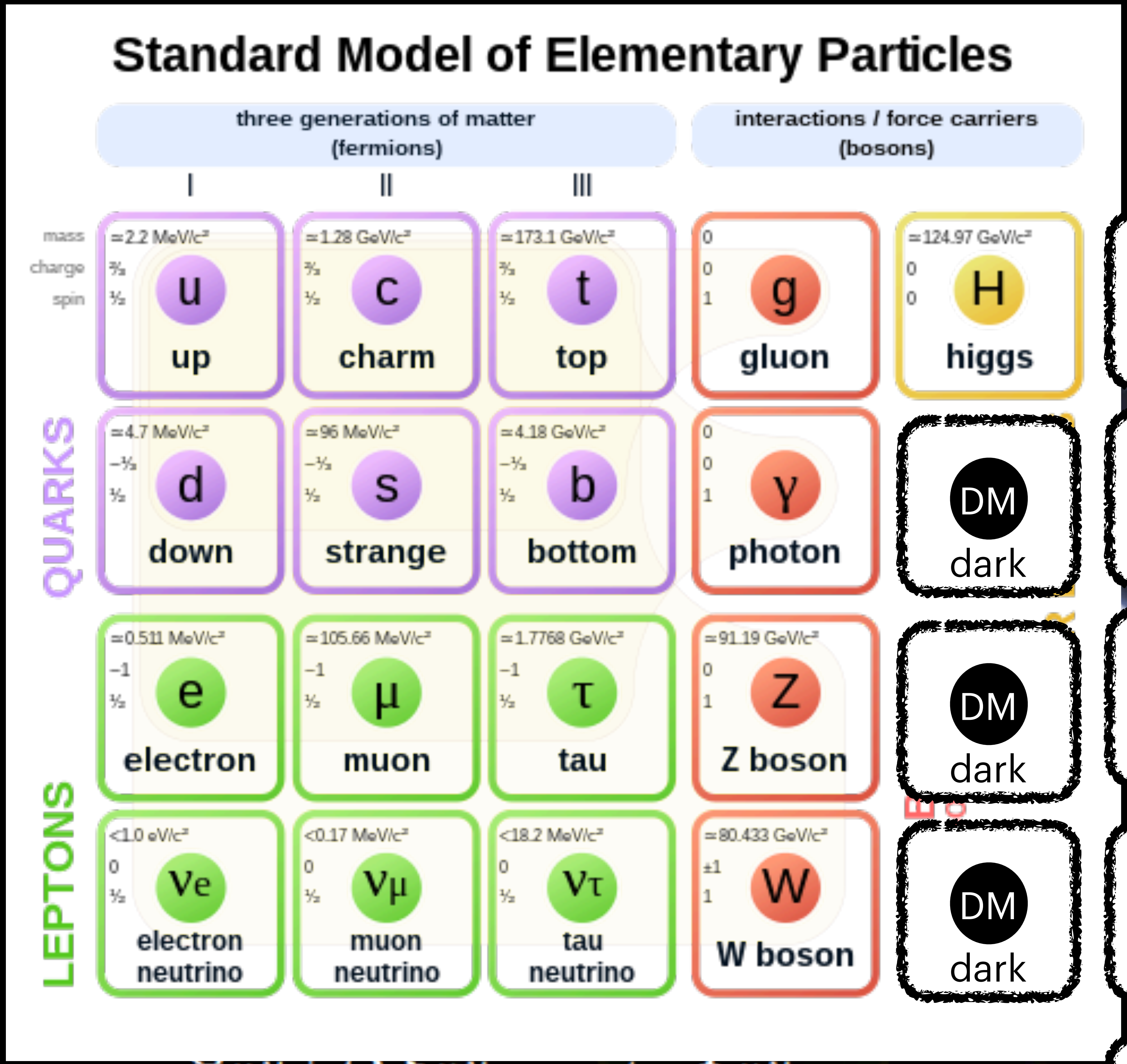
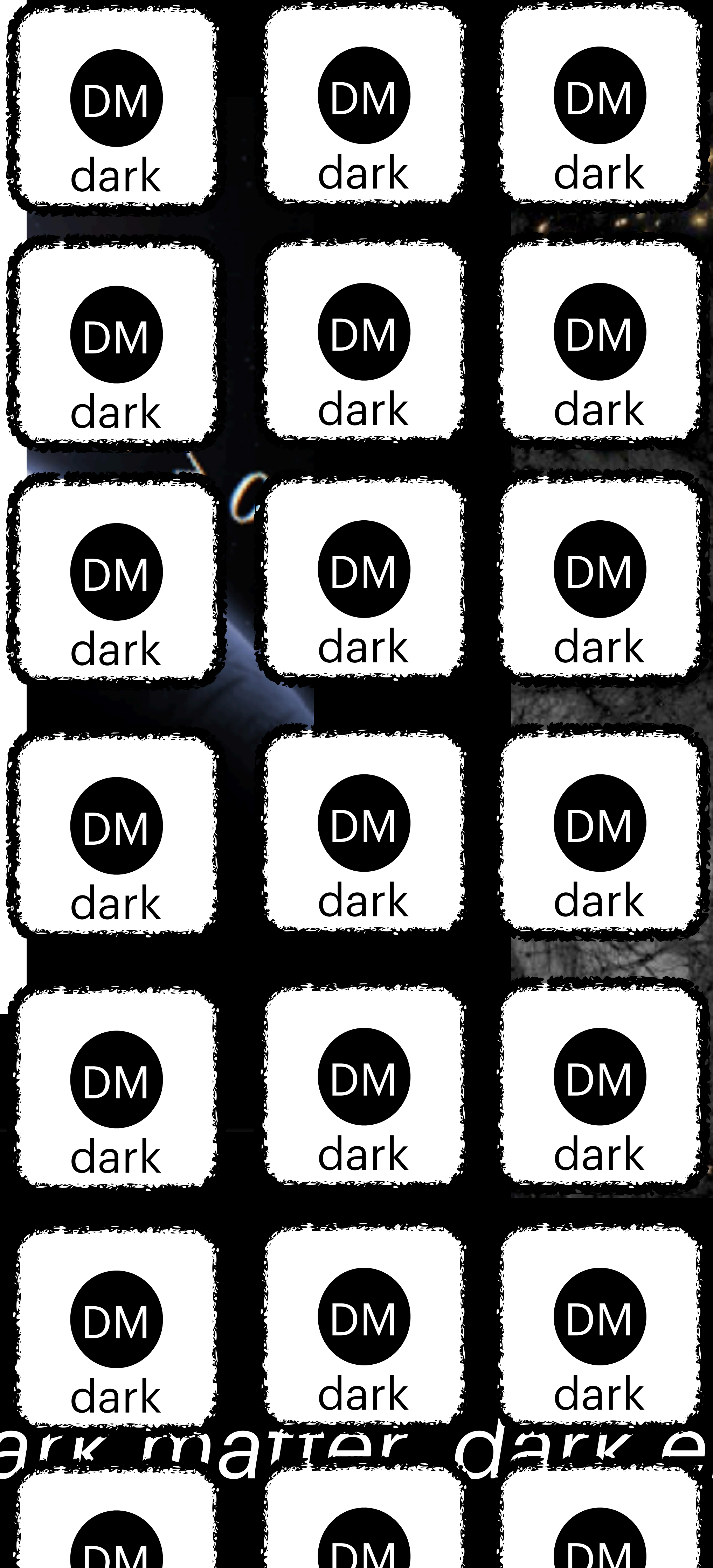
* Possible resolution of the Hubble tension with Weyl invariant gravity
* Analyzing the Hubble tension through hidden sector dynamics in the early universe
* Brane world creation from flat or almost flat space in dynamical tension string theories
* Exploring the Hubble Tension and Spatial Curvature from the Ages of Old Astrophysical Objects
* The S8 tension in light of updated redshift-space distortion data and PAge approximation
* Chameleon early dark energy and the Hubble tension
* Implications of the S8 tension for decaying dark matter with warm decay products
* Cosmic expansion parametrization: Implication for curvature and H0 tension
* Easing the Hubble constant tension
* Surface tension of cosmic voids as a possible source for dark energy
* Can varying the gravitational constant alleviate the tensions?
* Varying fundamental constants principal component analysis: additional hints about the Hubble tension
* Gamma-ray flash in the interaction of a tightly focused single-cycle ultra-intense laser pulse with a solid target
* Towards a solution to the H0 tension
* No-go guide for the Hubble tension: Late-time solutions
* Planck limits on cosmic string tension using machine learning
* Using our newest VLT-KMOS HII galaxies and other cosmic tracers to test the Lambda cold dark matter tension
* Superhorizon Perturbations: A Possible Explanation of the Hubble-Lemaître Tension and the Large-scale Anisotropy of the Universe
* Linear cosmological constraints on two-body decaying dark matter scenarios and the S8 tension
* Relaxing cosmological tensions with a sign switching cosmological constant
* Hubble tension or a transition of the Cepheid SnIa calibrator parameters?
* Gravitational lensing H0 tension from ultralight axion galactic cores
* Dark energy-dark matter interactions as a solution to the S8 tension
* Exploration of interacting dynamical dark energy model with interaction term including the equation-of-state parameter: alleviation of the H0 tension
* Why reducing the cosmic sound horizon alone can not fully resolve the Hubble tension
* Phantom Braneworld and the Hubble Tension
* Closing up the cluster tension?
* Minimal theory of massive gravity in the light of CMB data and the S8 tension
* Late-time acceleration due to a generic modification of gravity and the Hubble tension
* Small-scale clumping at recombination and the Hubble tension
* Assessing the tension between a black hole dominated early universe and leptogenesis
* Lifshitz cosmology: quantum vacuum and Hubble tension
* Dissecting the H0 and S8 tensions with Planck + BAO + supernova type Ia in multi-parameter cosmologies
* Chain early dark energy: A Proposal for solving the Hubble tension and explaining today's dark energy
* Late-time Universe, H0-tension, and unparticles
* Precision cosmology and the stiff-amplified gravitational-wave background from inflation: NANOGrav, Advanced LIGO-Virgo and the Hubble tension
* Implications of the spectrum of dynamically generated string tension theories
* Inverse Seesaw, dark matter and the Hubble tension
* Melvin's 'magnetic universe', the role of the magnetic tension and the implications for gravitational collapse
* Early Universe Physics Insensitive and Uncalibrated Cosmic Standards: Constraints on Ωmand Implications for the Hubble Tension
* Can small-scale baryon inhomogeneities resolve the Hubble tension? An investigation with ACT DR4
* Dark sector interaction and the supernova absolute magnitude tension
* Consistency tests of Λ CDM from the early integrated Sachs-Wolfe effect: Implications for early-time new physics and the Hubble tension
* Self-interacting neutrinos, the Hubble parameter tension, and the cosmic microwave background
* Generalized emergent dark energy model and the Hubble constant tension
* Implication of the Hubble tension for the primordial Universe in light of recent cosmological data

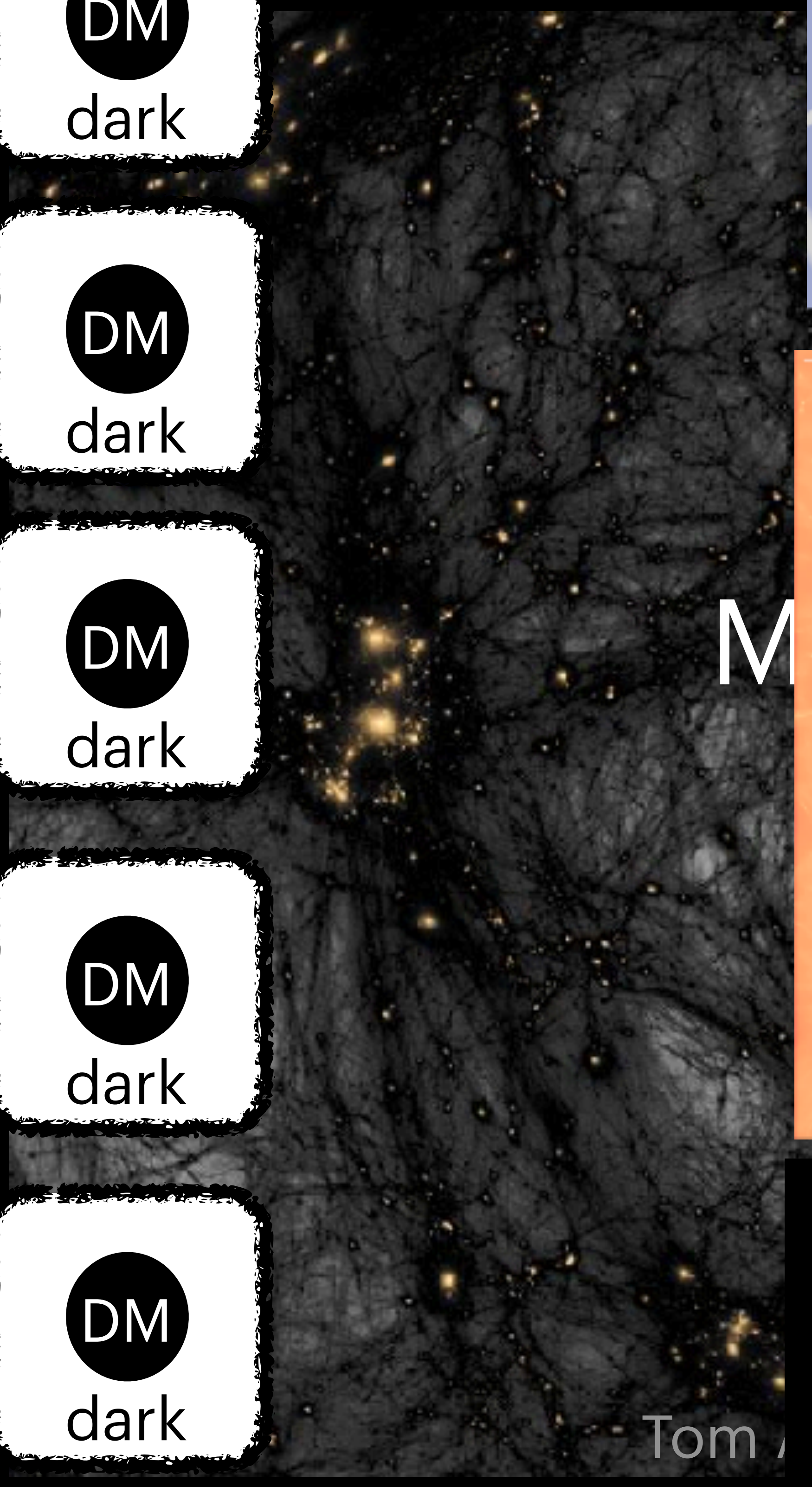
* Decaying dark matter, the H0 tension, and the lithium problem
* Hubble tension vs two flows
* GW170817 and GW190814: Tension on the Maximum Mass
* Cosmic Distances Calibrated to 1% Precision with Gaia EDR3 Parallaxes and Hubble Space Telescope Photometry of 75 Milky Way Cepheids Confirm Tension with ΛCDM
* Resolving the tension in particle discrimination between the Simple and Picasso dark matter projects
* Can conformally coupled modified gravity solve the Hubble tension?
* Self-interacting neutrinos: Solution to Hubble tension versus experimental constraints
* Quantifying the S8 tension with the Redshift Space Distortion data set
* Emergent Dark Energy, neutrinos and cosmological tensions
* Resolving the H0 tension with diffusion
* Thermal evolution of neutron stars described within the equation of state with induced surface tension
* The role of quark matter surface tension in magnetars

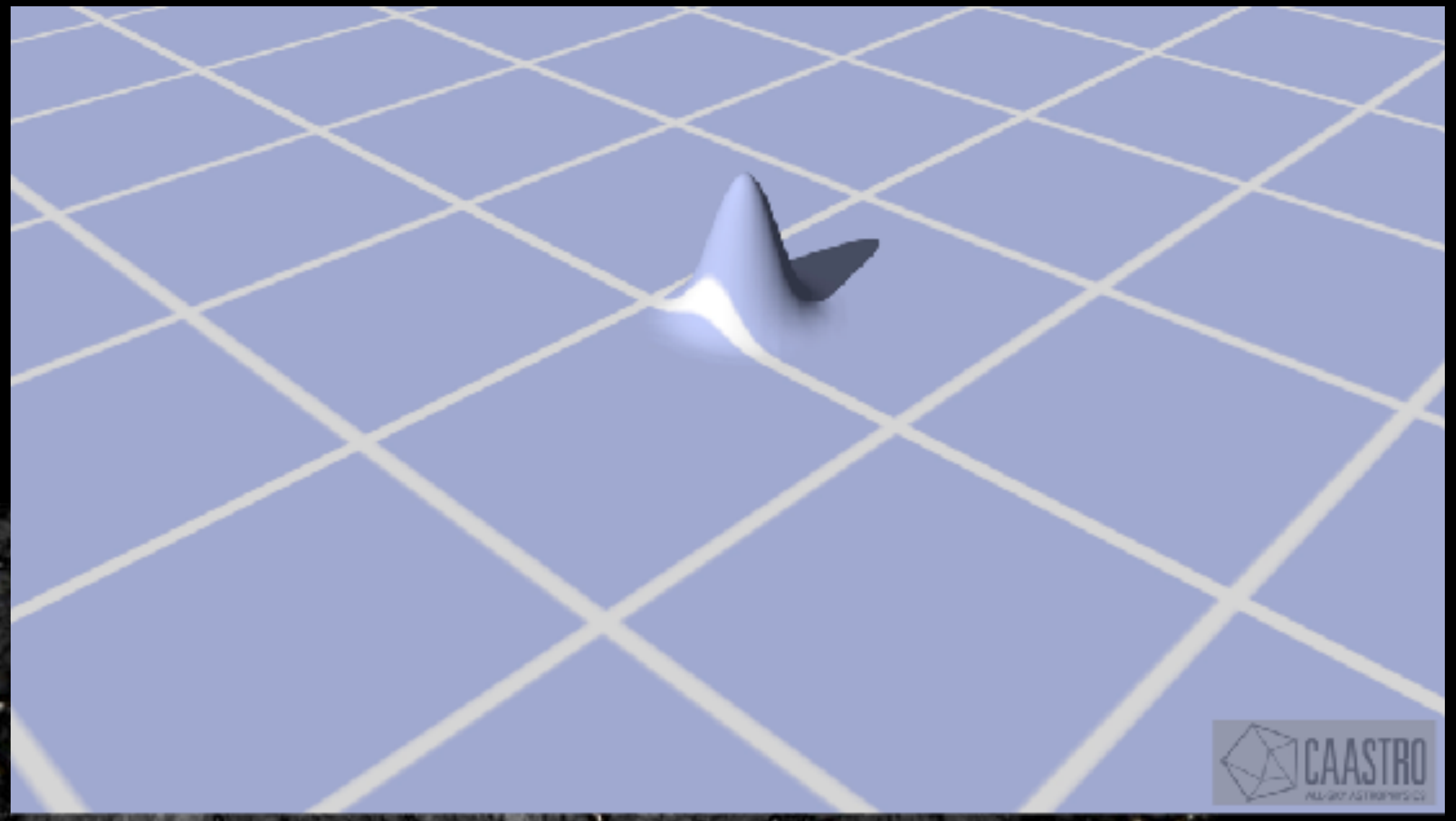
* Early-time thermalization of cosmic components? A hint for solving cosmic tensions
* CMB lensing in a modified Λ CDM model in light of the H0 tension
* Hubble tension in lepton asymmetric cosmology with an extra radiation
* Remedy of some cosmological tensions via effective phantom-like behavior of interacting vacuum energy
* Relieve the H0 tension with a new coupled generalized three-form dark energy model
* Can the Hubble tension be resolved by bulk viscosity?
* Does Hubble tension signal a breakdown in FLRW cosmology?
* Measurements of the Hubble Constant: Tensions in Perspective
* Cosmology Intertwined II: The hubble constant tension
* Hubble tension and absolute constraints on the local Hubble parameter
* The Hubble Tension, the M Crisis of Late Time H(z) Deformation Models and the Reconstruction of Quintessence Lagrangians
* Non-Gaussian estimates of tensions in cosmological parameters
* Assessing tension metrics with dark energy survey and Planck data
* Cosmology from weak lensing alone and implications for the Hubble tension
* Accounting for exotic matter and the extreme radial tension in Morris-Thorne wormholes of embedding class one
* Is there really a Hubble tension?
* Satellites around Milky Way Analogs: Tension in the Number and Fraction of Quiescent Satellites Seen in Observations versus Simulations
* H0 tension without CMB data: Beyond the Λ CDM
* Rapid transition of Geffat zt≈0.01 as a possible solution of the Hubble and growth tensions
* Strongly lensed cluster substructures are not in tension with ΛCDM
* Late-time approaches to the Hubble tension deforming H(z), worsen the growth tension
* Relieving the H0 tension with a new interacting dark energy model
* In the realm of the Hubble tension-a review of solutions
* Resolving the dynamical mass tension of the massive binary 9 Sagittarii
* Comparing early dark energy and extra radiation solutions to the Hubble tension with BBN
* Solving the Hubble tension without spoiling big bang nucleosynthesis
* Can scale-dependent cosmology alleviate the H0 tension?
* Dark energy as a critical phenomenon: a hint from Hubble tension
* The hubble tension as a hint of leptogenesis and neutrino mass generation
* Revisiting the tension between fast bars and the ΛCDM paradigm
* All fundamental electrically charged thin shells in general relativity: From star shells to tension shell black holes, regular black holes, and beyond
* Running Hubble tension and a H0 diagnostic
* Charged dark matter and the H0 tension
* Towards mitigation of apparent tension between nuclear physics and astrophysical observations by improved modeling of neutron star matter
* Gravitational waves and dark radiation from dark phase transition: Connecting NANOGrav pulsar timing data and hubble tension
* Addressing H0 tension by means of VCDM
* Can the quasi-molecular mechanism of recombination decrease the Hubble tension?
* Mergers of primordial black holes in extreme clusters and the H0 tension
* 4D Gauss-Bonnet gravity: Cosmological constraints, H0 tension and large scale structure
* Revisiting cosmological diffusion models in Unimodular Gravity and the H0 tension
* Analyzing the H0 tension in F(R) gravity models
* The Hubble tension in light of the Full-Shape analysis of Large-Scale Structure data
* Can f(R) gravity relieve H0 and σ8 tensions?
* High H0 Values from CMB E-mode Data: A Clue for Resolving the Hubble Tension?
* On the Hubble Constant Tension in the SNe Ia Pantheon Sample
* w -M phantom transition at zt<0.1 as a resolution of the Hubble tension
* Cosmological bound on neutrino masses in the light of H0 tension
* Early recombination as a solution to the H0 tension
* Easing cosmic tensions with an open and hotter universe
* Oscillations of sterile neutrinos from dark matter decay eliminates the IceCube-Fermi tension
* A new tension in the cosmological model from primordial deuterium?
* A solution to the de Sitter swampland conjecture versus inflation tension via supergravity
* The Mechanical Properties of Chelyabinsk LL5 Chondrite Under Compression and Tension
* Sources of H0-tension in dark energy scenarios
* Quantifying the global parameter tensions between ACT, SPT, and Planck
* Early dark energy resolution to the Hubble tension in light of weak lensing surveys and lensing anomalies
* Dynamical dark energy after Planck CMB final release and H0 tension
* Testing the effect of H0 on fσ8 tension using a Gaussian process method
* Updated constraints on massive neutrino self-interactions from cosmology in light of the H0 tension
* Dark Energy with Phantom Crossing and the H0 Tension
* As a Matter of Tension: Kinetic Energy Spectra in MHD Turbulence
* When tension is just a fluctuation. How noisy data affect model comparison
* Exploring an early dark energy solution to the Hubble tension with Planck and SPTPol data
* Early modified gravity in light of the H0 tension and LSS data
* H0 tension, swampland conjectures, and the epoch of fading dark matter
* Cosmological constraints on late-Universe decaying dark matter as a solution to the H0 tension
* Curvature tension: Evidence for a closed universe

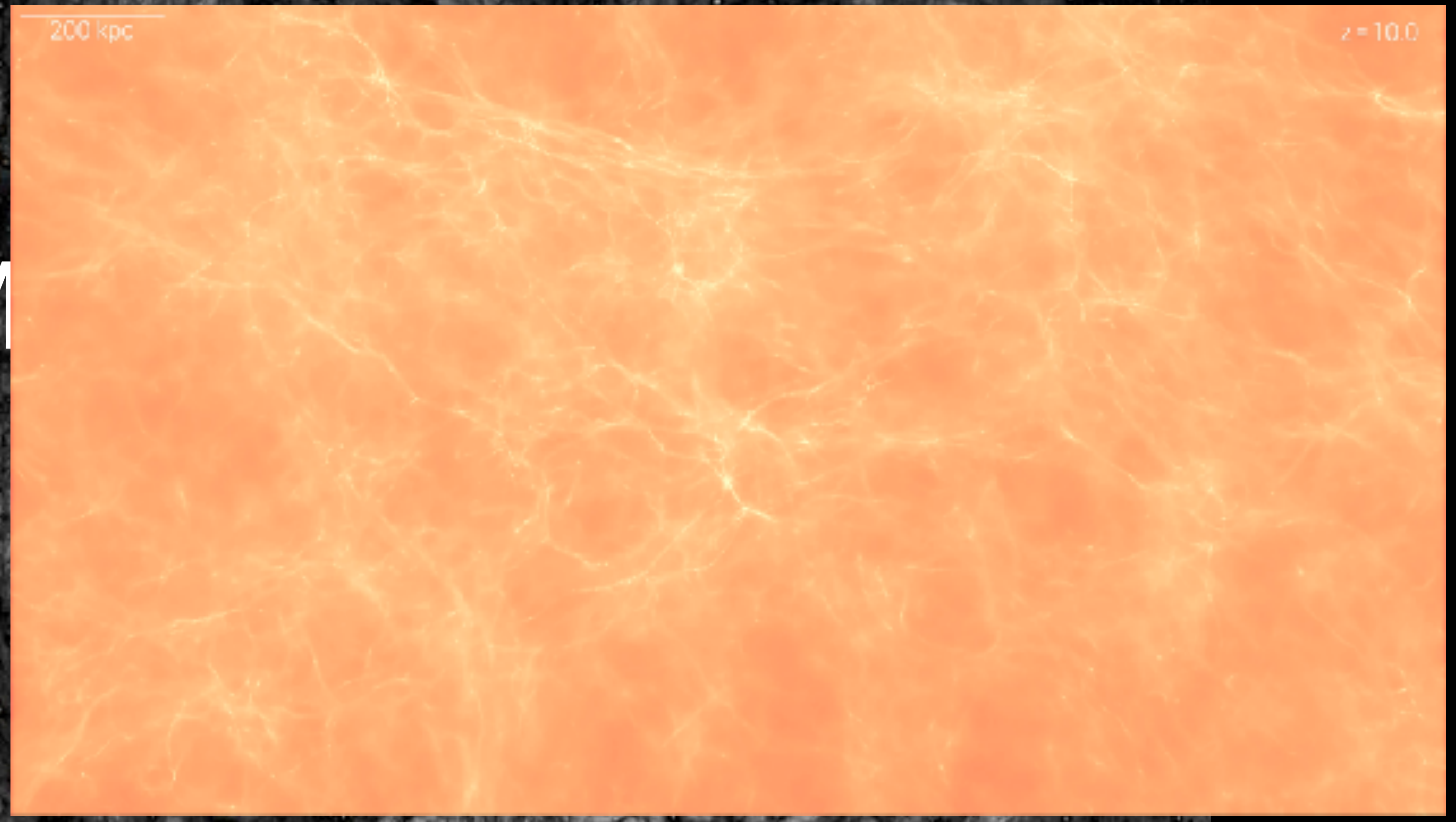
THEORETICAL EFFORTS FALL IN TWO MAIN GROUPS

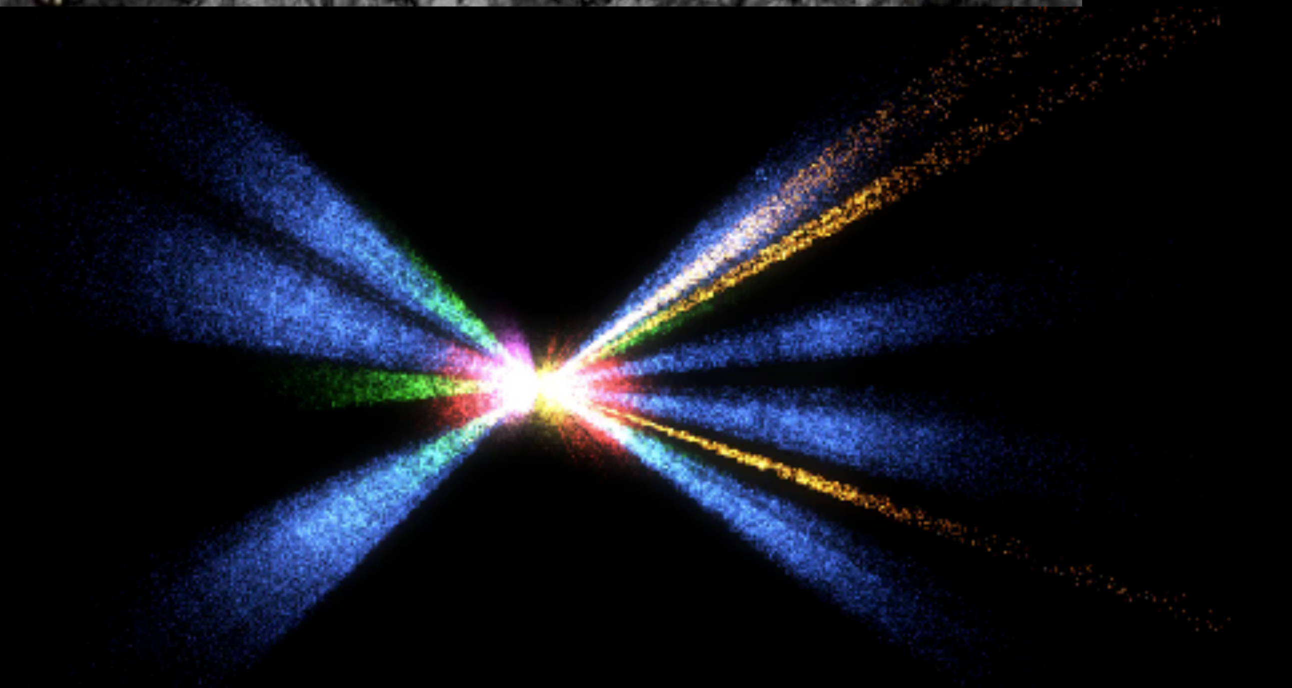












Need to explain dark matter, dark energy, an

Could the tension be systematics?

Let's look at the data...

CMB - A STANDARD RULER (AND MORE)

These are really complex analyses.

Nuisance parameters in CMB fit

A&A 641, A5 (2020)

Table 16. Parameters and priors used for astrophysical foregrounds and instrumental modelling for the baseline likelihood.

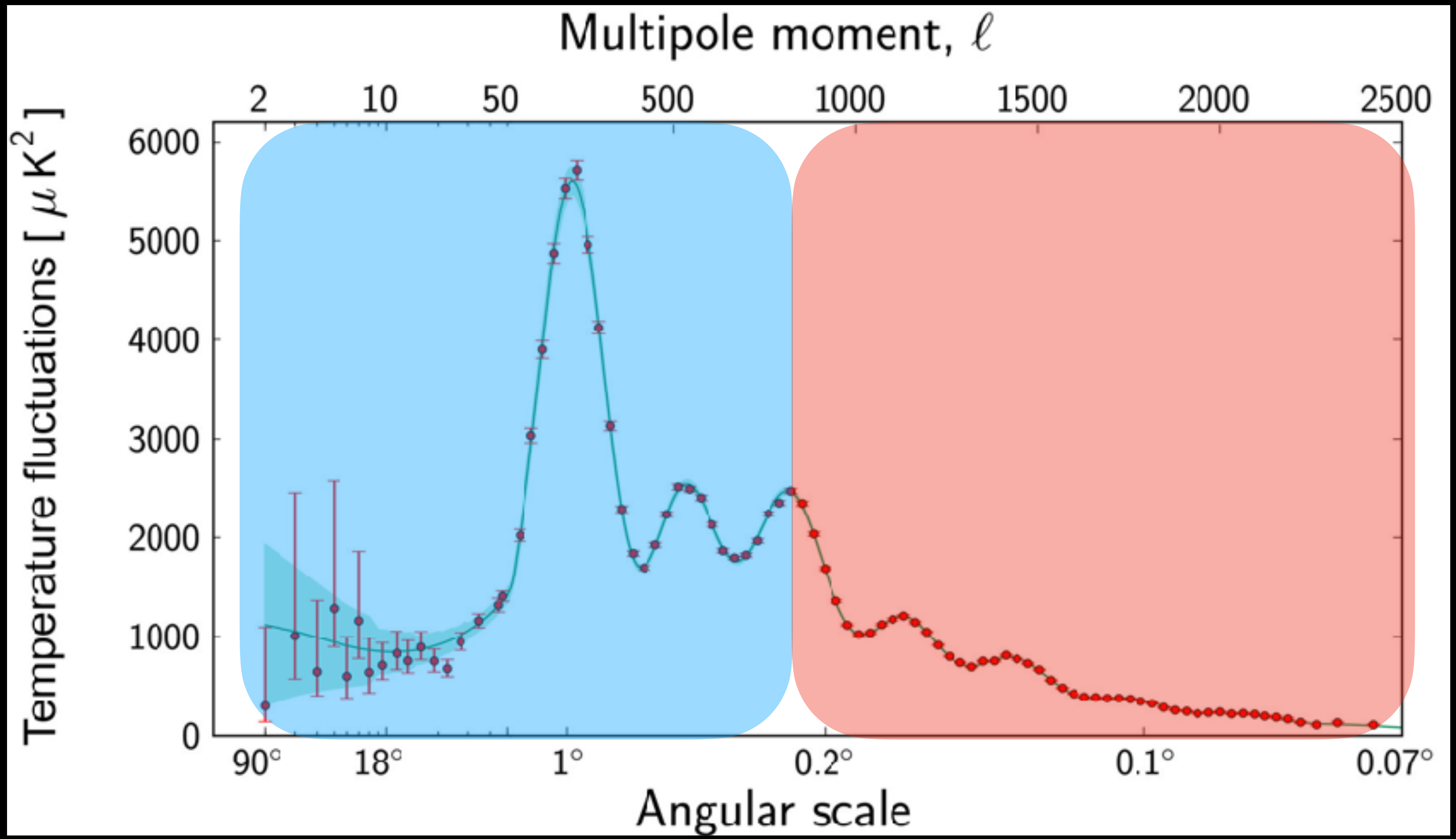
Parameter	Prior range	Definition
$A^{\rm PS}_{100}$	[0, 400]	Contribution of Poisson point-source power to $\mathcal{D}^{100\times100}_{3000}$ for *Planck* (in μK^2)
$A^{\rm PS}_{143}$	[0, 400]	As for $A^{\rm PS}_{100}$, but at 143 × 143 GHz
$A^{\rm PS}_{217}$	[0, 400]	As for $A^{\rm PS}_{100}$, but at 217 × 217 GHz
$A^{\rm PS}_{143\times217}$	[0, 400]	As for $A^{\rm PS}_{100}$, but at 143 × 217 GHz
$A^{\rm CIB}_{217}$	[0, 200]	Contribution of CIB power to $\mathcal{D}^{217}_{3000}$ at the *Planck* CMB frequency for 217 GHz (in μK^2)
$A^{\rm tSZ}$	[0, 10]	Contribution of tSZ to $\mathcal{D}^{143\times143}_{3000}$ at 143 GHz (in μK^2)
$A^{\rm kSZ}$	[0, 10]	Contribution of kSZ to $\mathcal{D}_{3000}$ (in μK^2) [We apply a joint tSZ-kSZ prior with $\mathcal{D}^{\rm kSZ} + 1.6\mathcal{D}^{\rm tSZ} = (9.5 \pm 3)\,\mu$K^2]
$\xi^{\rm tSZ\times CIB}$	[0, 1]	Correlation coefficient between the CIB and tSZ
$A^{{\rm dust}TT}_{100}$	[0, 50] (8.6 ± 2)	Amplitude of Galactic dust power at $\ell = 200$ at 100 GHz (in μK^2)
$A^{{\rm dust}TT}_{143}$	[0, 50] (10.6 ± 2)	As for $A^{{\rm dust}TT}_{100}$, but at 143 × 143 GHz
$A^{{\rm dust}TT}_{143\times217}$	[0, 100] (23.5 ± 8.5)	As for $A^{{\rm dust}TT}_{100}$, but at 143 × 217 GHz
$A^{{\rm dust}TT}_{217}$	[0, 400] (91.9 ± 20)	As for $A^{{\rm dust}TT}_{100}$, but at 217 × 217 GHz
c_{100}	[0, 3] (1.0002 ± 0.0007)	Power spectrum calibration at 100 GHz
c_{217}	[0, 3] (0.99805 ± 0.00065)	Power spectrum calibration at 217 GHz
$y_{\rm cal}$	[0.9, 1.1] (1 ± 0.0025)	Absolute map calibration for *Planck*
$A^{{\rm dust}EE}_{100}$	0.055	Amplitude of Galactic dust power at $\ell = 500$ at 100 GHz (in μK^2)
$A^{{\rm dust}EE}_{100\times143}$	0.040	As for $A^{{\rm dust}EE}_{100}$, but at 100 × 143 GHz
$A^{{\rm dust}EE}_{100\times217}$	0.094	As for $A^{{\rm dust}EE}_{100}$, but at 100 × 217 GHz
$A^{{\rm dust}EE}_{143}$	0.086	As for $A^{{\rm dust}EE}_{100}$, but at 143 × 143 GHz
$A^{{\rm dust}EE}_{143\times217}$	0.21	As for $A^{{\rm dust}EE}_{100}$, but at 143 × 217 GHz
$A^{{\rm dust}EE}_{217}$	0.70	As for $A^{{\rm dust}EE}_{100}$, but at 217 × 217 GHz
$A^{{\rm dust}TE}_{100}$	[0, 10] (0.13 ± 0.042)	Amplitude of Galactic dust power at $\ell = 500$ at 100 GHz (in μK^2)
$A^{{\rm dust}TE}_{100\times143}$	[0, 10] (0.13 ± 0.036)	As for $A^{{\rm dust}TE}_{100}$, but at 100 × 143 GHz
$A^{{\rm dust}TE}_{100\times217}$	[0, 10] (0.46 ± 0.09)	As for $A^{{\rm dust}TE}_{100}$, but at 100 × 217 GHz
$A^{{\rm dust}TE}_{143}$	[0, 10] (0.207 ± 0.072)	As for $A^{{\rm dust}TE}_{100}$, but at 143 × 143 GHz
$A^{{\rm dust}TE}_{143\times217}$	[0, 10] (0.69 ± 0.09)	As for $A^{{\rm dust}TE}_{100}$, but at 143 × 217 GHz
$A^{{\rm dust}TE}_{217}$	[0, 10] (1.938 ± 0.54)	As for $A^{{\rm dust}TE}_{100}$, but at 217 × 217 GHz
c_{EE100}	1.021	Polarization efficiency correction at 100 × 100 GHz (called $c^{\rm PP}_{100}$ in
c_{EE143}	0.966	As for c_{EE100}, but at 143 × 143 GHz
c_{EE217}	1.04	As for c_{EE100}, but at 217 × 217 GHz

Notes. Uniform priors are given as ranges in square brackets, while Gaussian priors are given by their mean and stand
We also give the fixed values of parameters that are not allowed to vary in the baseline likelihood.

(30 nuisance parameters in this table)

Planck 2018 V

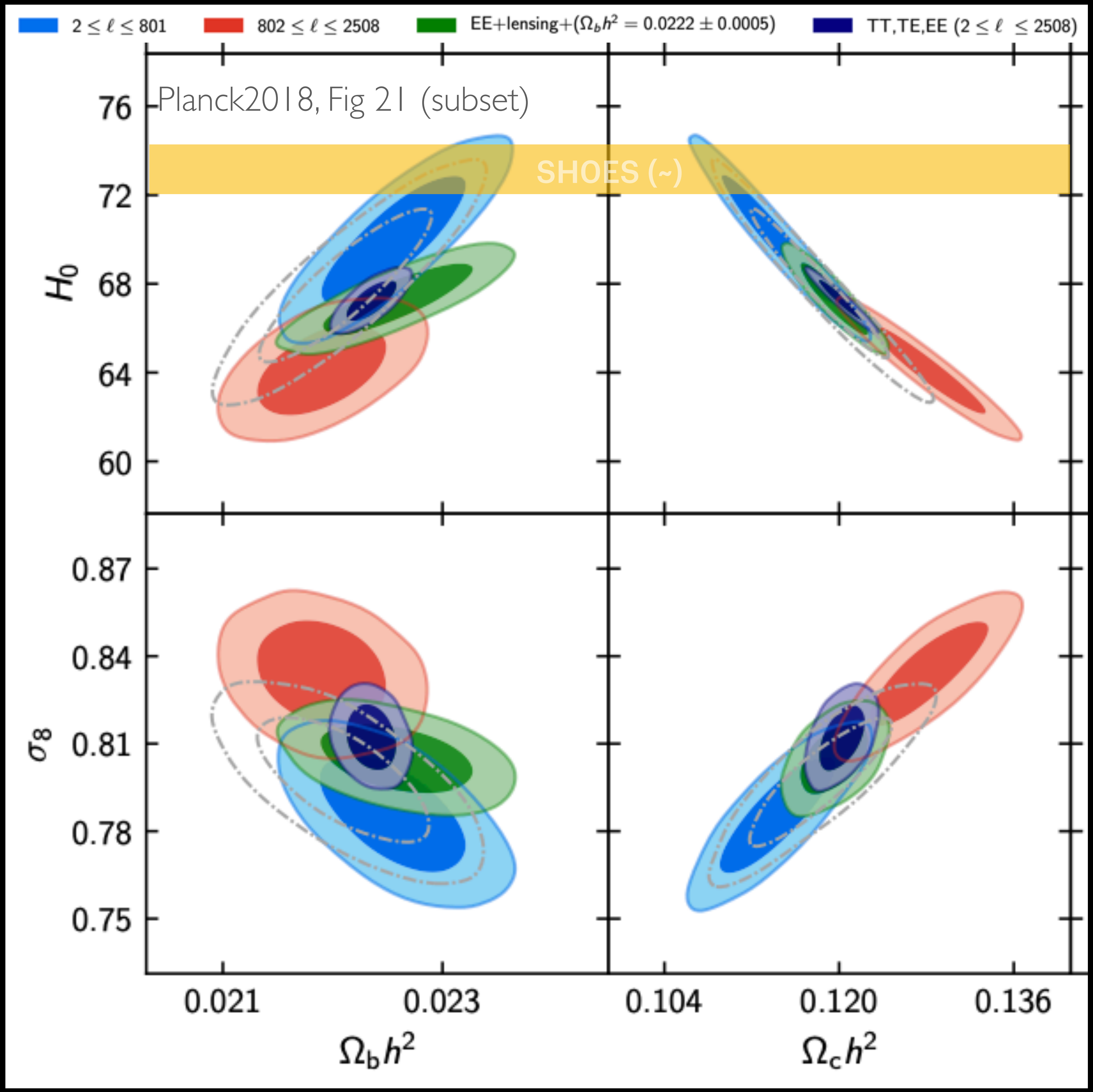
INTERNAL TENSIONS



“there is a very good agreement between Planck and WMAP temperature maps on the scales observed by WMAP (Planck Collaboration I 2016; Huang et al. 2018), but an inconsistency with high multipoles could indicate either new physics beyond ΛCDM, or the presence of some unidentified systematics associated with the Planck data and/or the foreground model.”

“although some cosmological parameters differ by more than 2 σ between < 800 and > 800, accounting for the multi-dimensional parameter space including correlations between parameters, the shifts are at the 10% level and hence not especially unusual.”

“This is consistent with a statistical fluctuation pulling the low and high multipoles in opposite directions, so that their intersection is closer to the truth if ΛCDM is correct.” - Planck 2018 VI



Low-z in tension with high-z?

Low multipoles in slight tension with high multipoles

(Temperature power spectrum)

CMB: MODEL EXTENSIONS

Planck VI, 2018 (red)
WMAP (green)

r

dn/dlnk

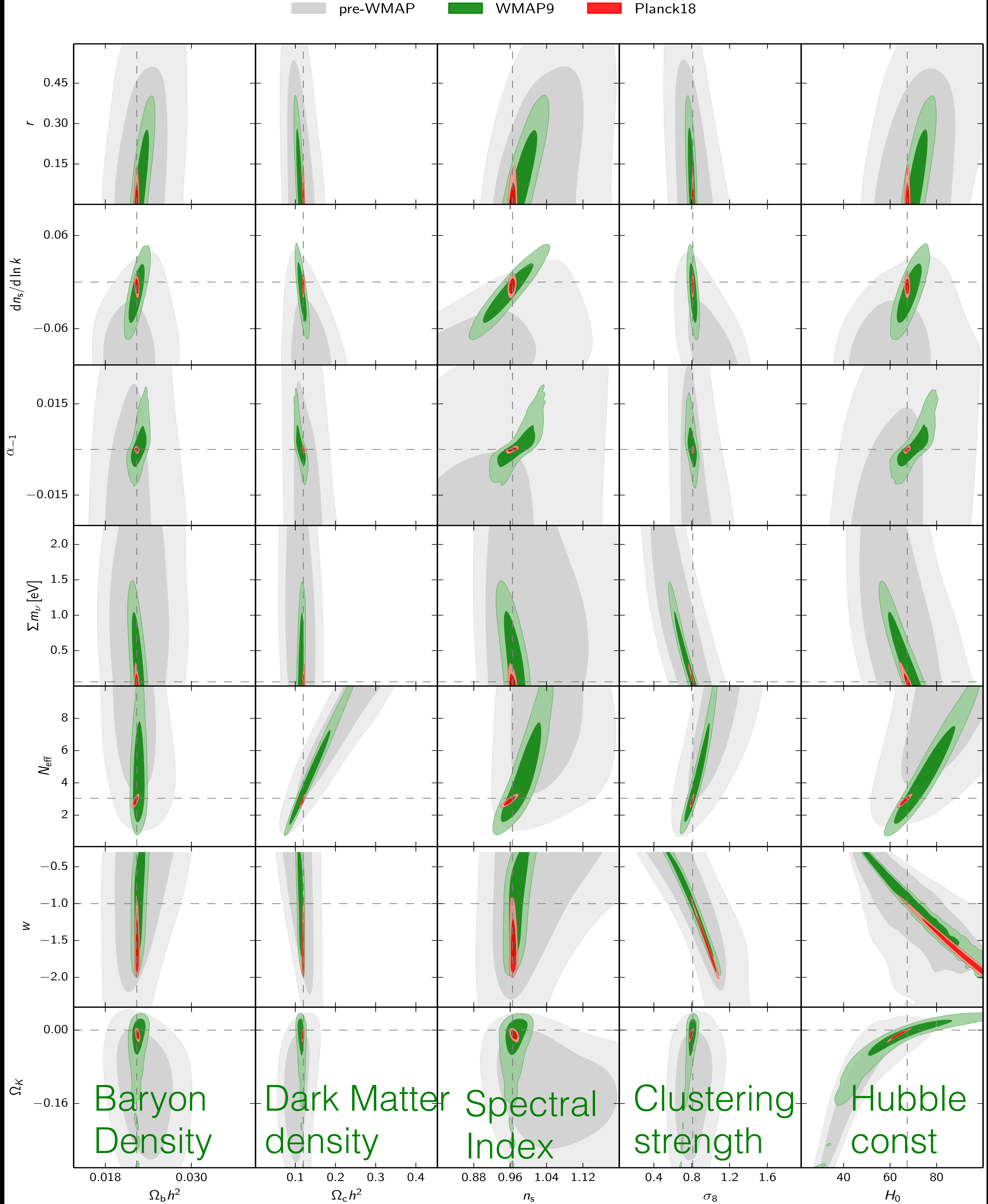
alpha-1

Mass of neutrinos

Extra neutrinos

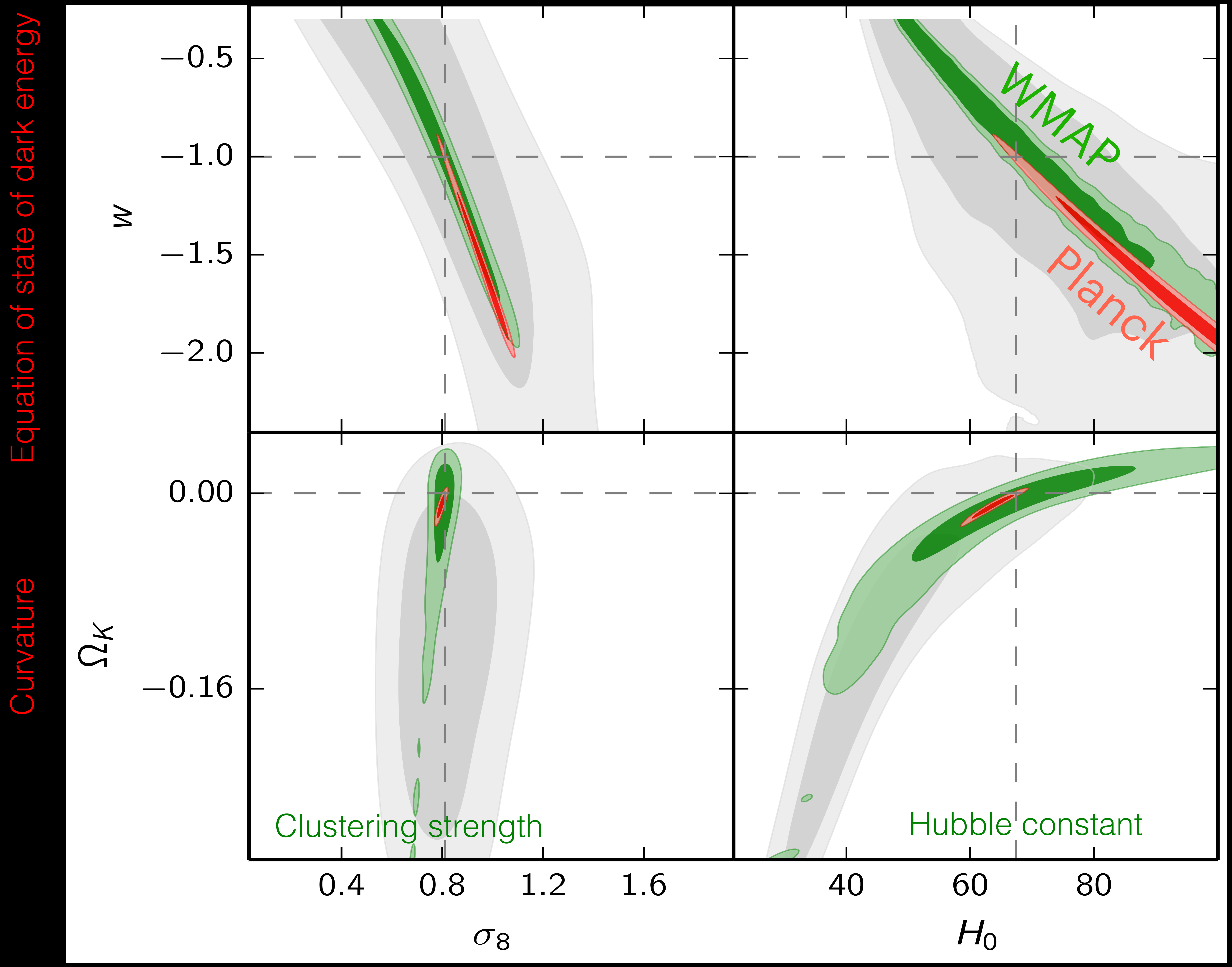
Equation of state of dark energy

Curvature

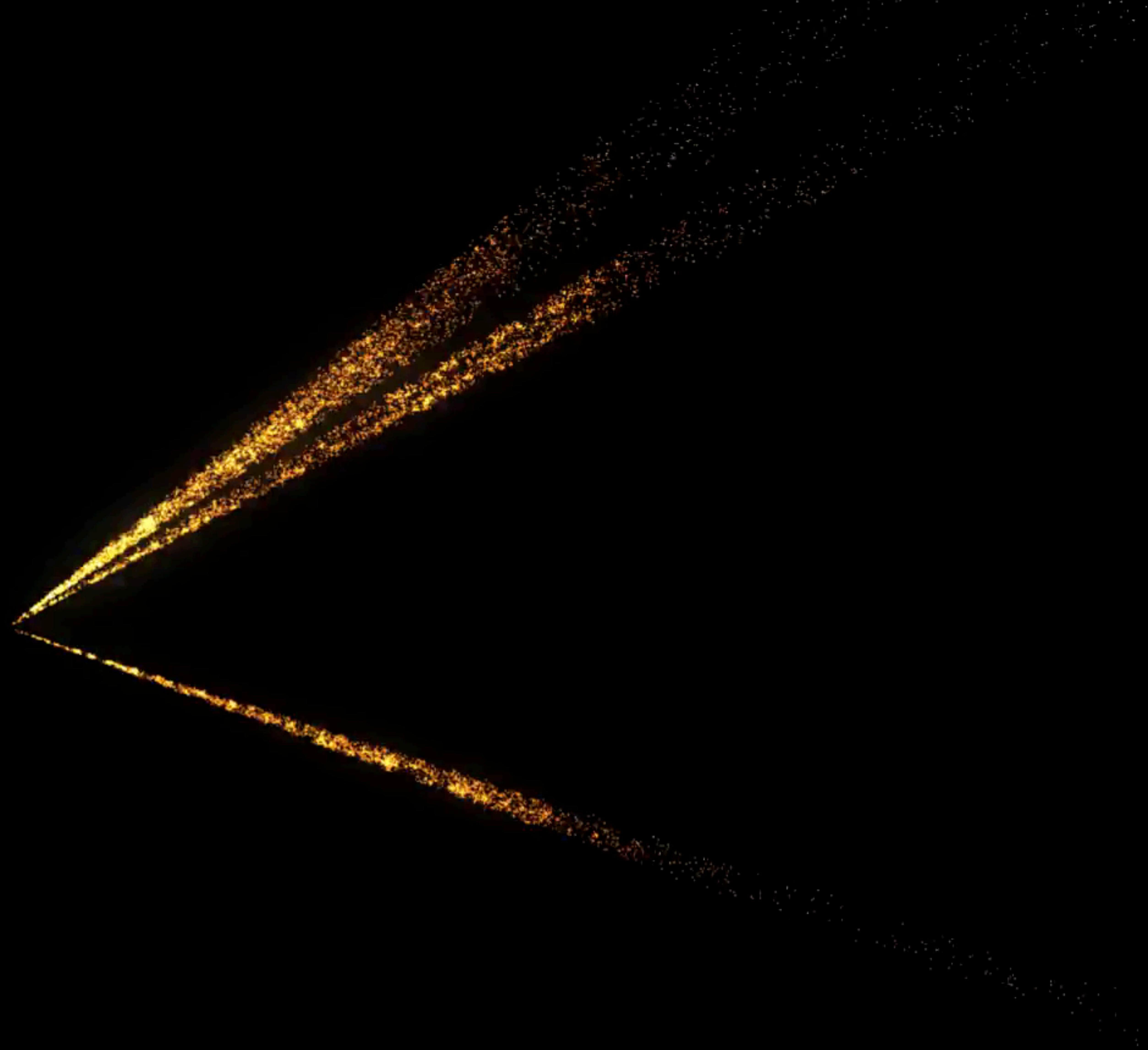


CMB: MODEL EXTENSIONS

Planck VI, 2018 (red)
WMAP (green)



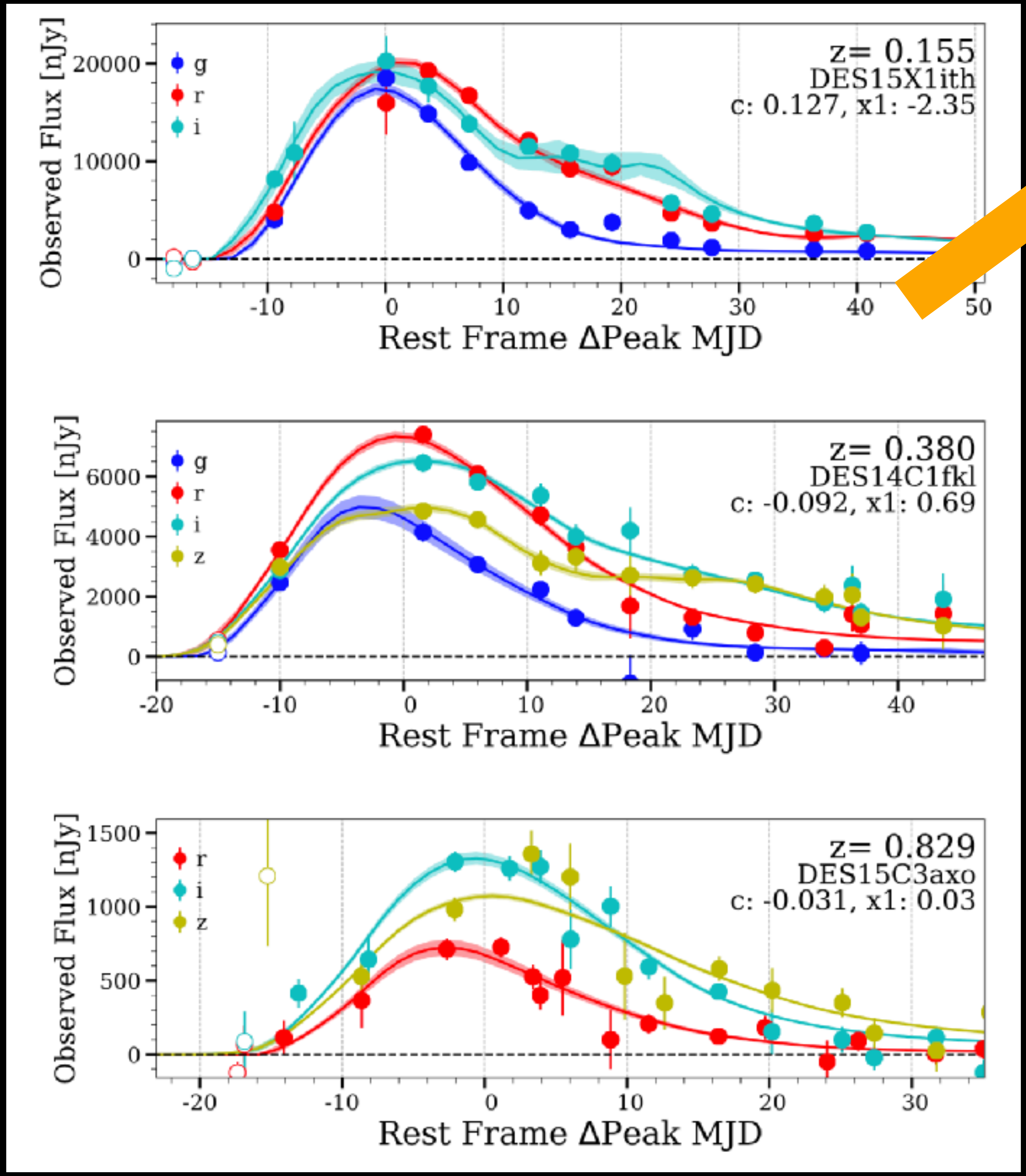
TYPE IA SUPERNOVAE



Animation Sam Hinton + Hugh McDougal

DES SN COSMOLOGY - YEAR 3

Light curves (Brout et al. DES 2019)



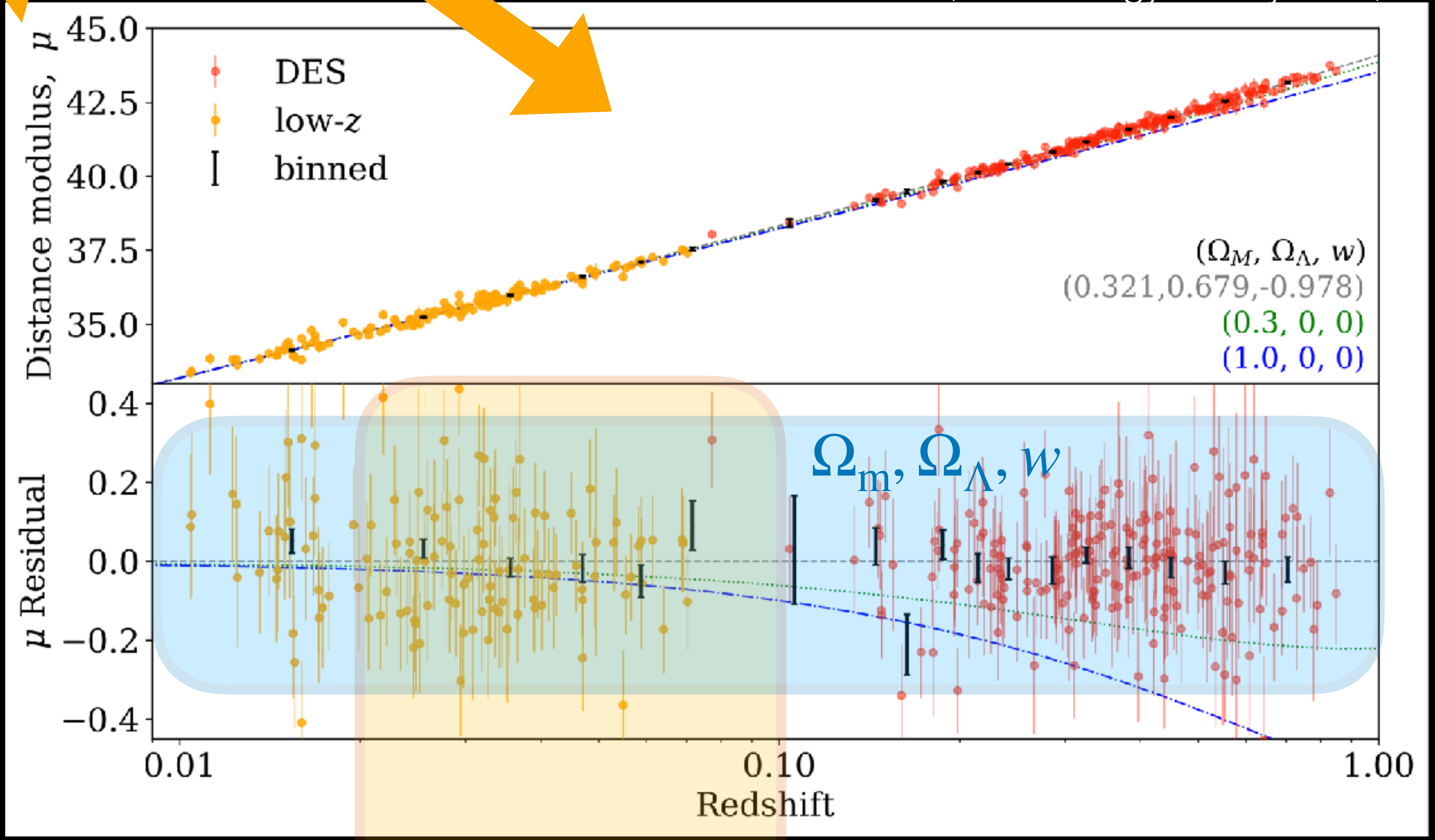
distance modulus: apparent mag, abs mag, stretch scale, stretch, colour scale, colour, host scale, host mass factor, malmquist +selection bias

$$\mu_B = m_B^* - M_B + \alpha\, x_1 - \beta\, C + \gamma G_{\rm host} + \Delta\mu_{\rm bias}$$

derived from fit to SNIa light curve

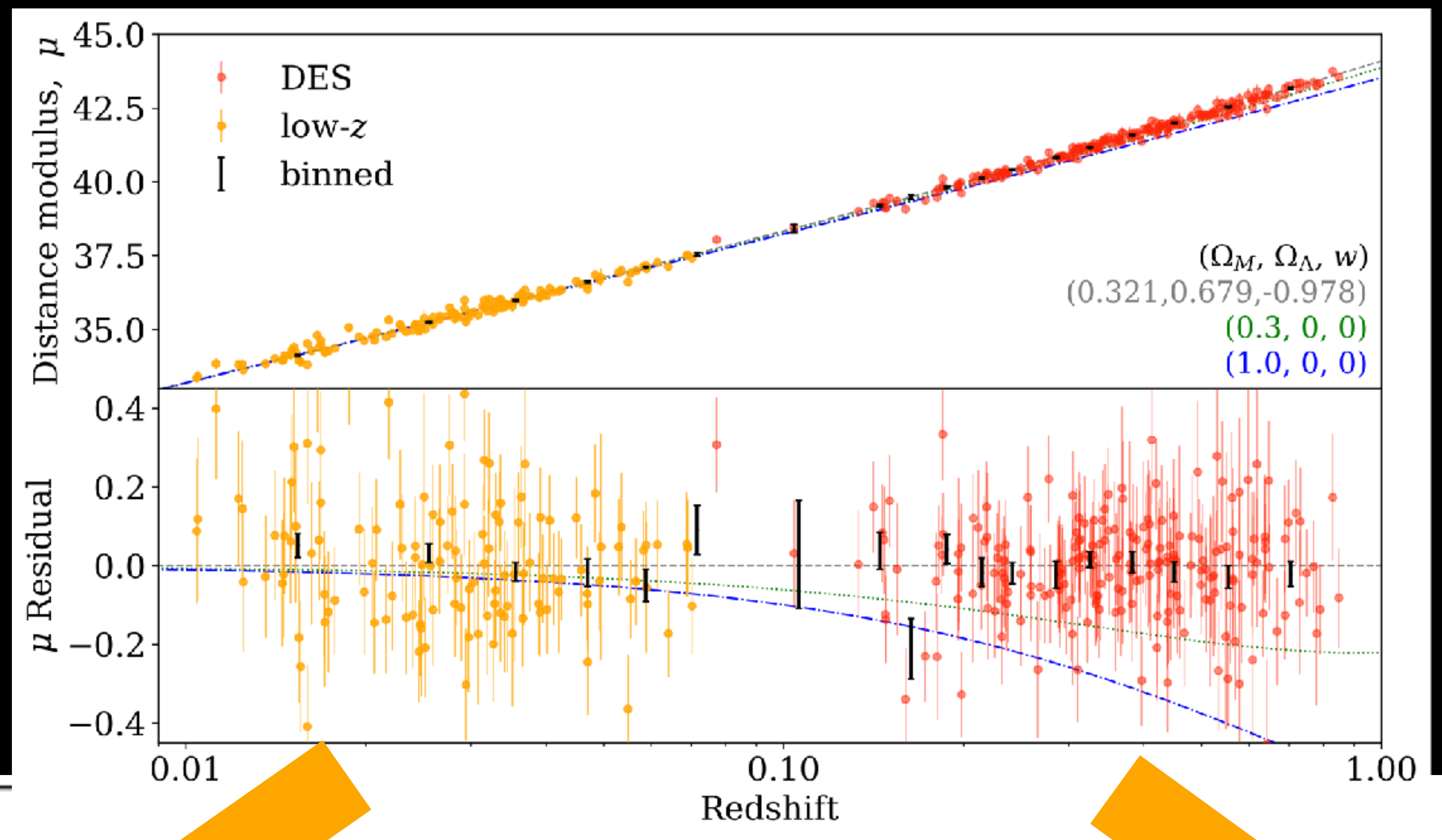
can be constrained using cosmo fits

(Dark Energy Survey 2019)



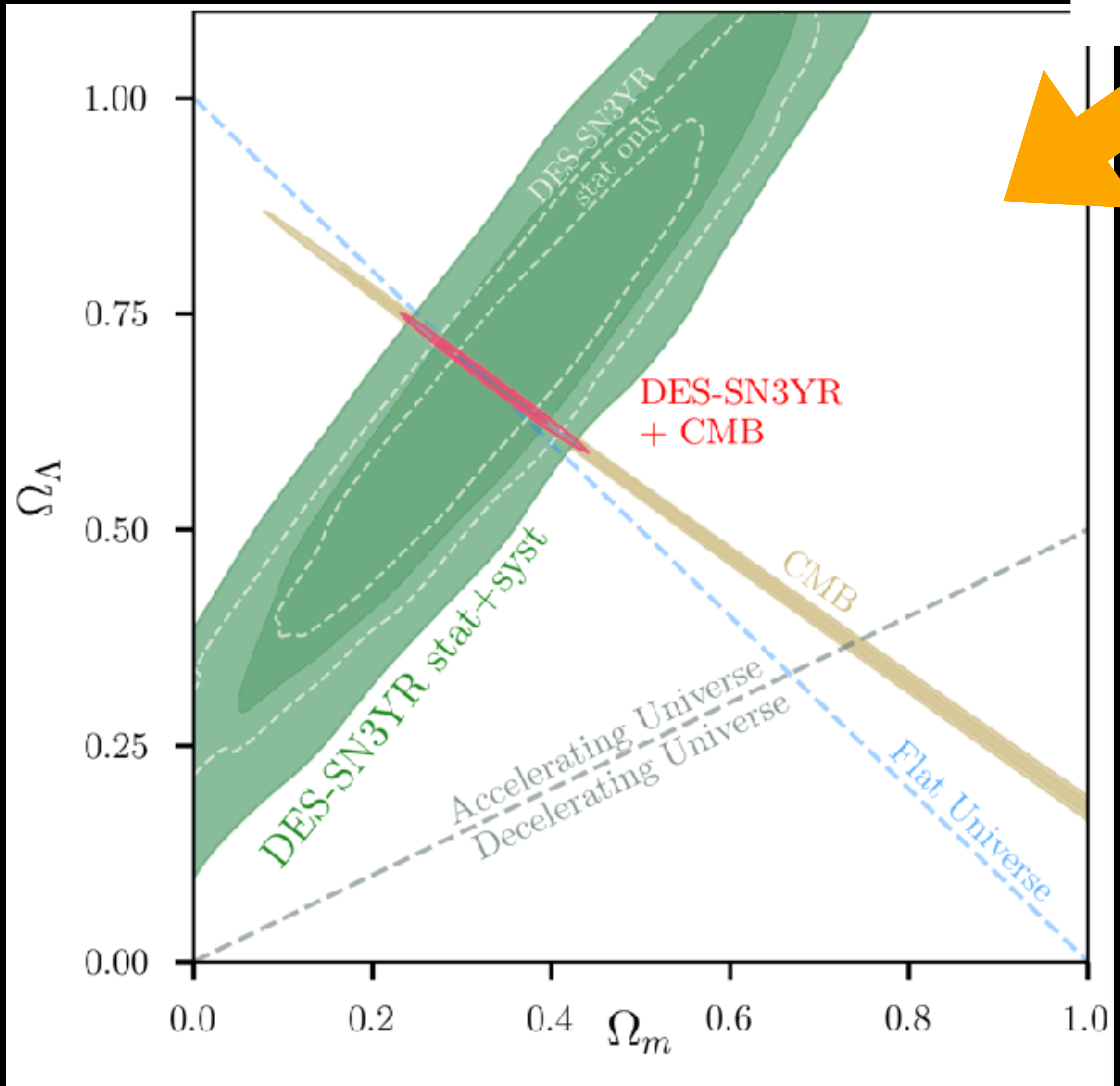
H_0 measurements

DES SUPERNOVA COSMOLOGY - YEAR 3



(Dark Energy Survey 2019)

< 10% of our final sample



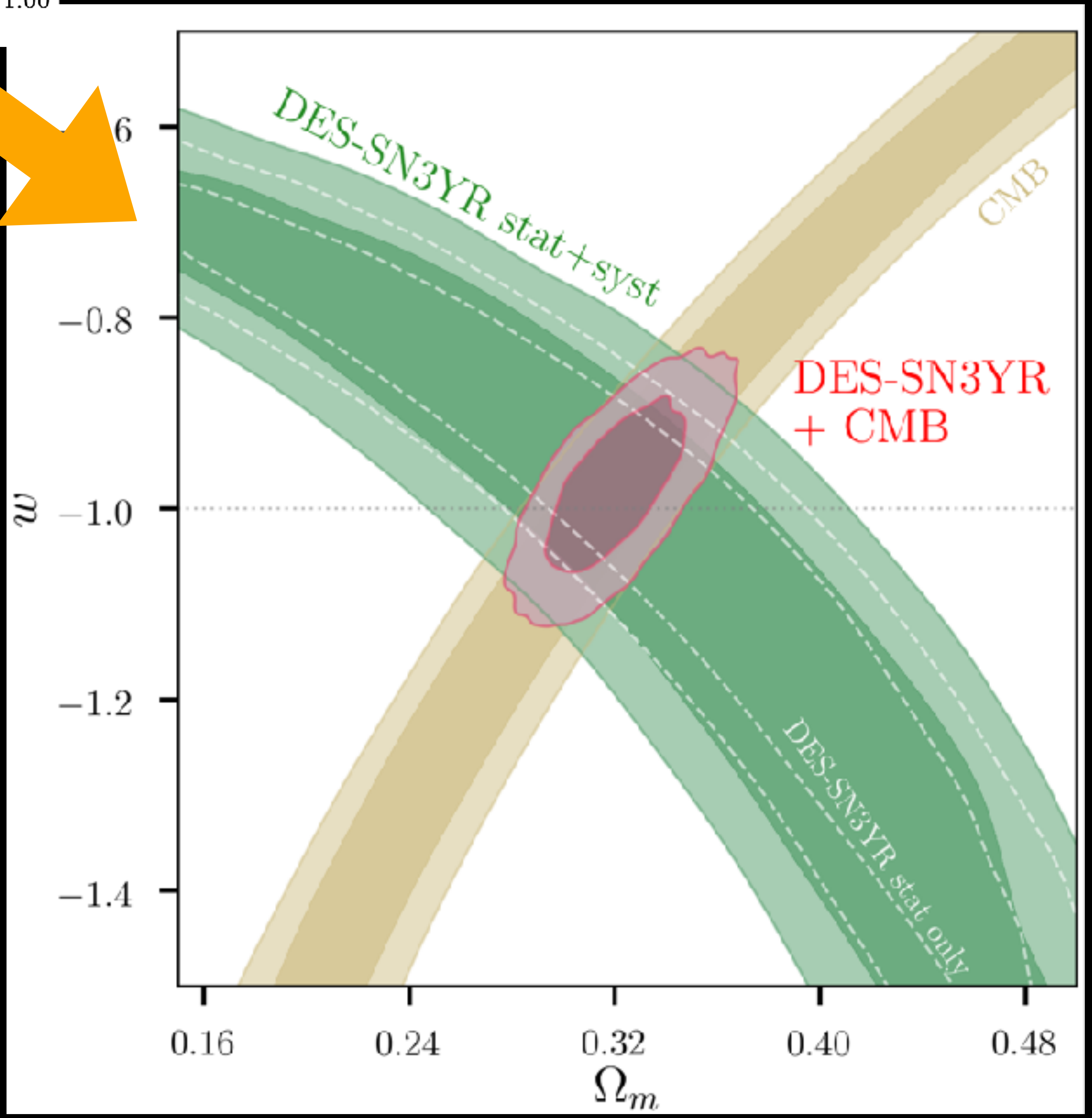
Systematic Control

Categories:

- Calibration (20 low-z bands + 4 DES bands)
- SNeIa Light-curve Model
- Distance Bias Corrections: e.g. malmquist, peculiar velocities
- Milky Way Extinction

→ For DES 2019, total 66 sources of potential systematic error are tracked and quantified

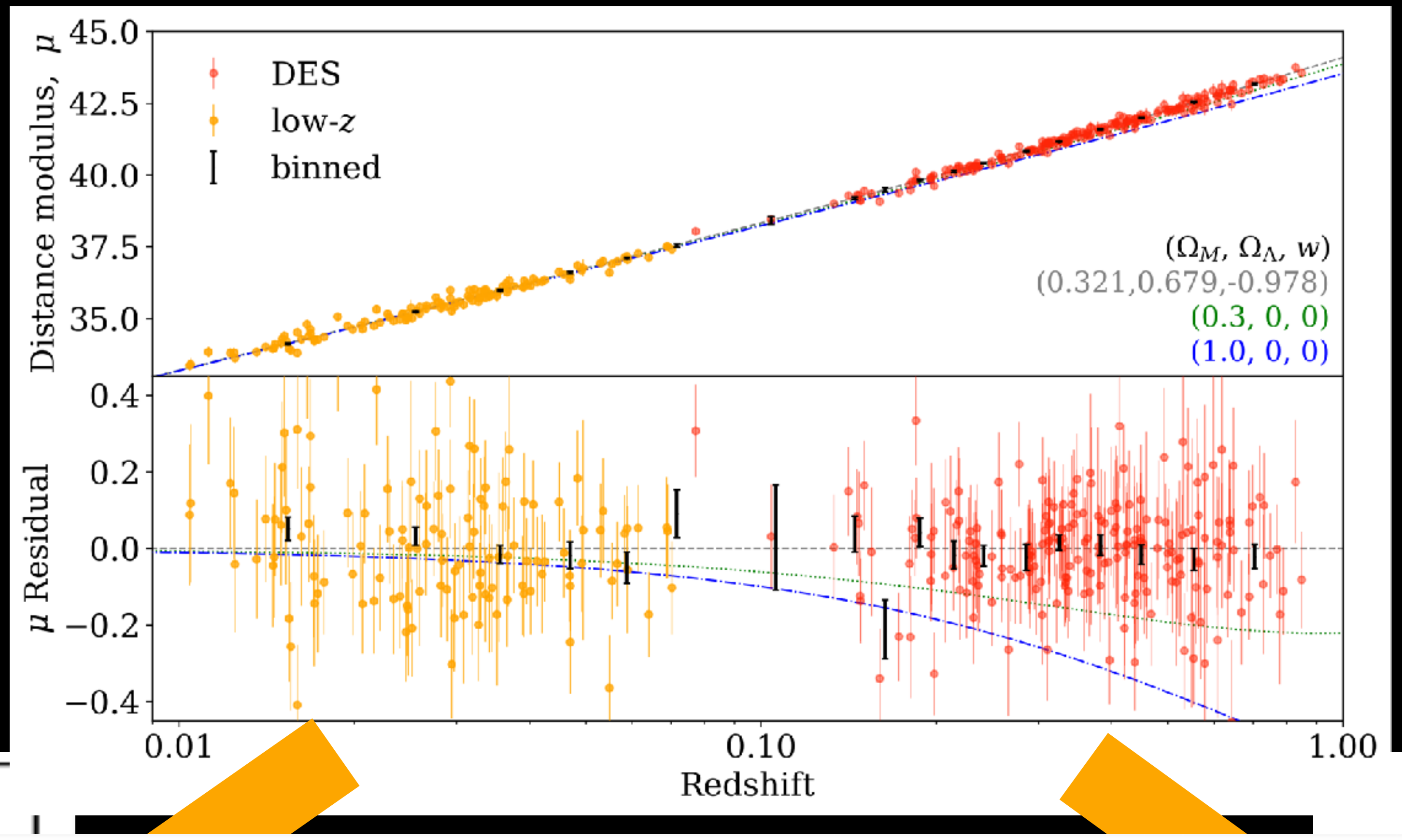
Full testing suite with **rigorous unblinding criteria** using 100 simulated datasets.



DES SUPERNOVA COSMOLOGY - YEAR 3

(Dark Energy Survey 2019)

< 10% of our final sample



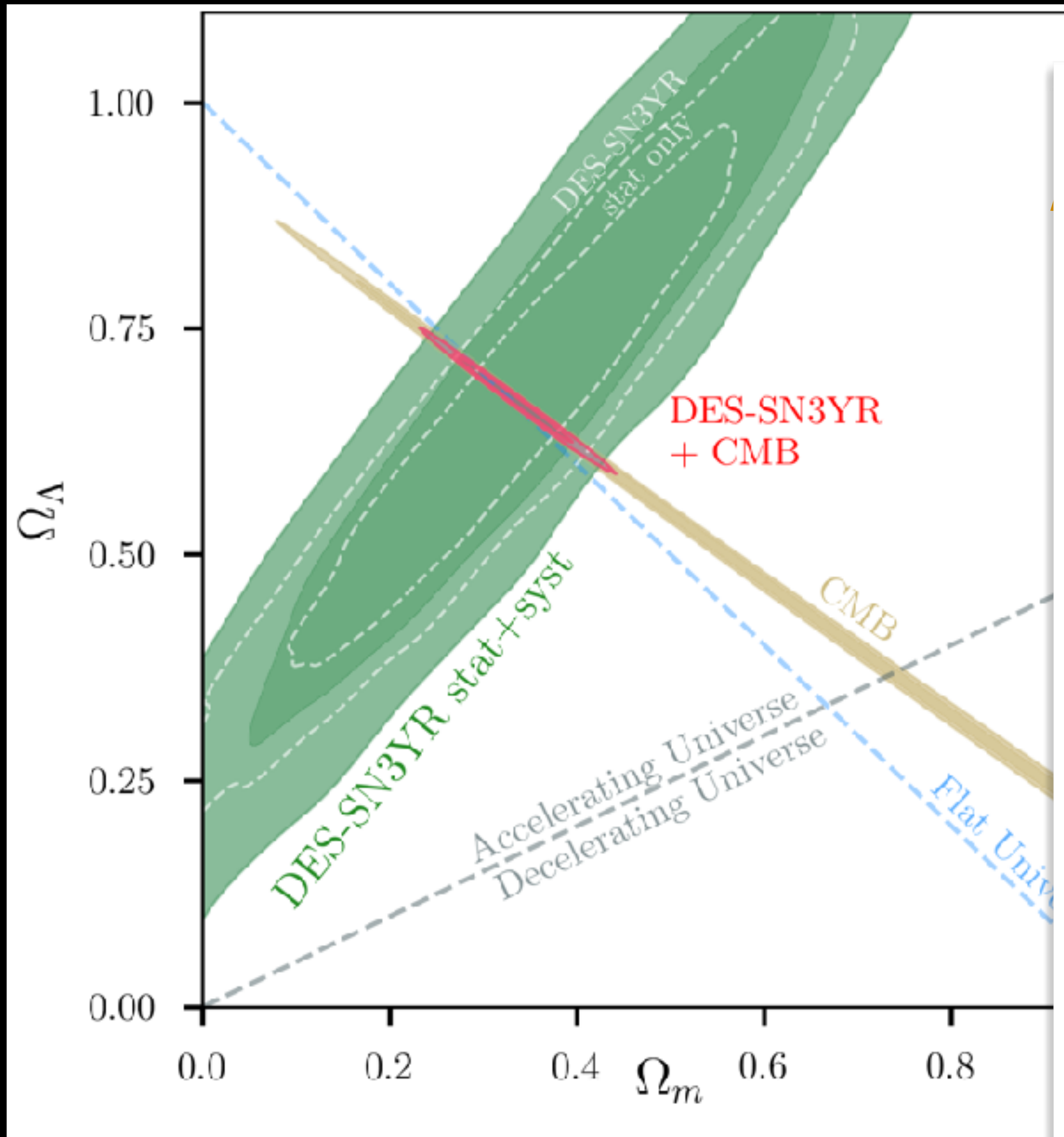
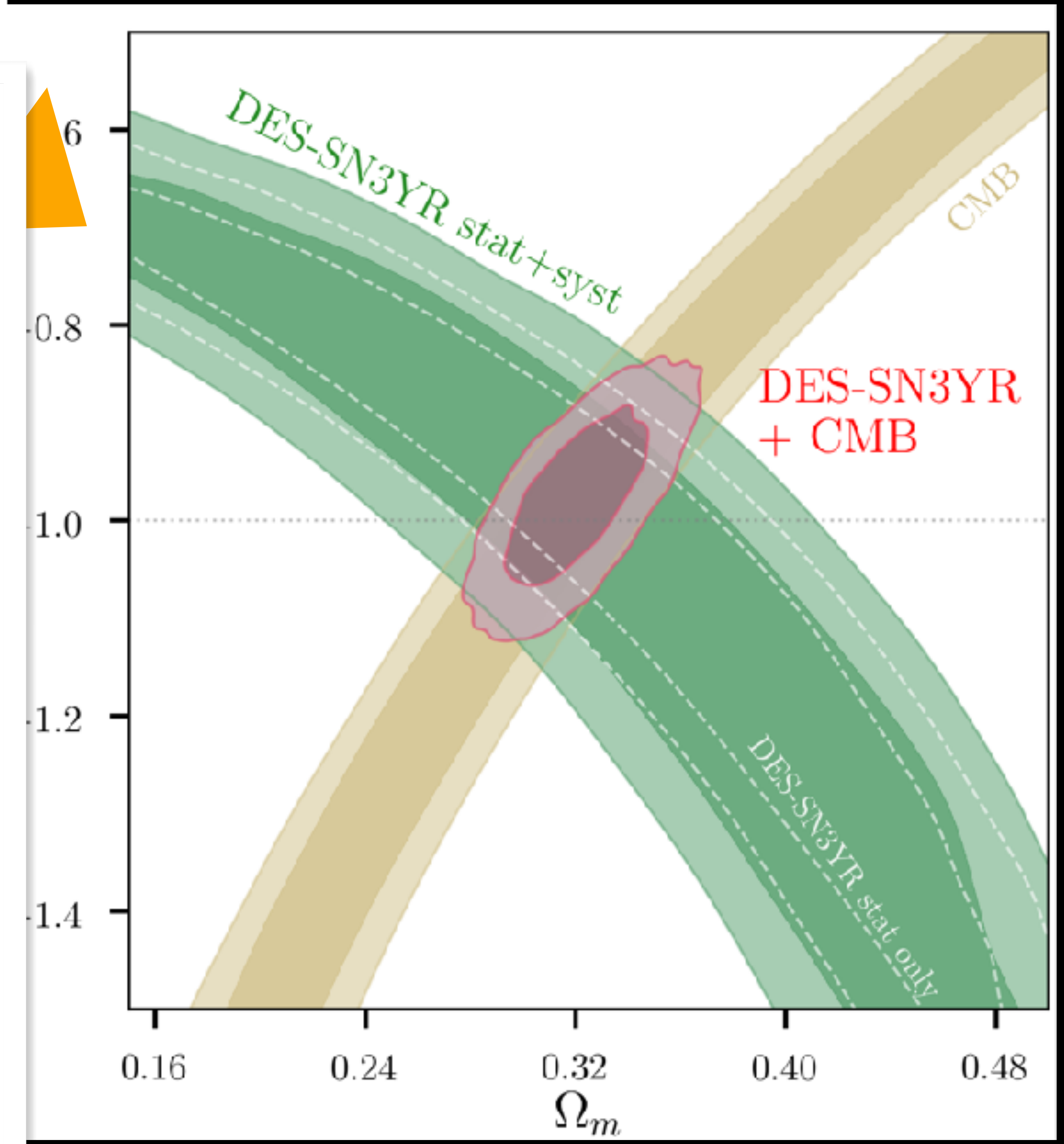


TABLE 1
w UNCERTAINTY CONTRIBUTIONS FOR wCDM MODEL[a]

Description[b]	σ_w	$\sigma_w/\sigma_{w,\mathrm{stat}}$
Total Stat ($\sigma_{w,\mathrm{stat}}$)	0.042	1.00
Total Syst[c]	0.042	1.00
Total Stat+Syst	0.059	1.40
[Photometry & Calibration]	**[0.021]**	**[0.50]**
Low-z	0.014	0.33
DES	0.010	0.24
SALT2 model	0.009	0.21
HST Calspec	0.007	0.17
[μ-Bias Correction: survey]	**[0.023]**	**[0.55]**
†Low-z 3σ Cut	0.016	0.38
Low-z Volume Limited	0.010	0.24
Spectroscopic Efficiency	0.007	0.17
†Flux Err Modeling	0.001	0.02
[μ-Bias Correction: astrophysical]	**[0.026]**	**[0.62]**
Intrinsic Scatter Model (G10 vs. C11)	0.014	0.33
†Two σ_{int}	0.014	0.33
$\mathcal{C}$, x_1 Parent Population	0.014	0.33
†w, Ω_{m} in sim.	0.006	0.14
MW Extinction	0.005	0.12
[Redshift]	**[0.012]**	**[0.29]**
Peculiar Velocity	0.007	0.17
†$z + 0.00004$	0.006	0.14



But there’s more!

Complementary data sets are crucial

STANDARD CANDLES AND RULERS

$$\tilde{D} = \begin{cases} R_0 \sin(\chi) & \text{closed} \\ R_0 \chi & \text{flat} \\ R_0 \sinh(\chi) & \text{open} \end{cases}$$

Candles

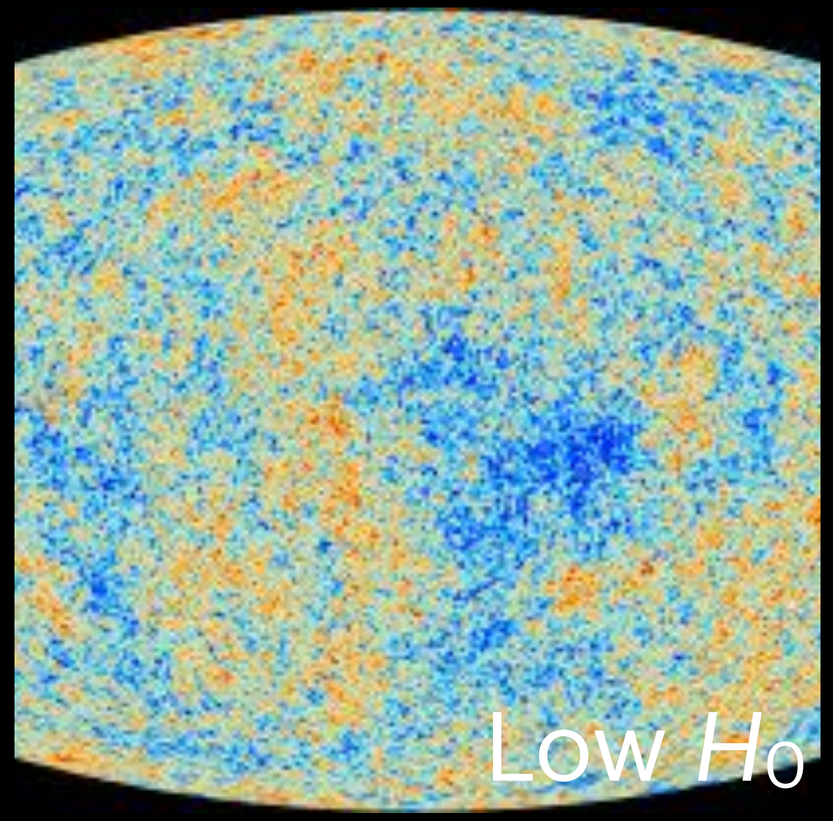
$$D_L = \tilde{D}(1+z)$$

Late Universe (nearby)

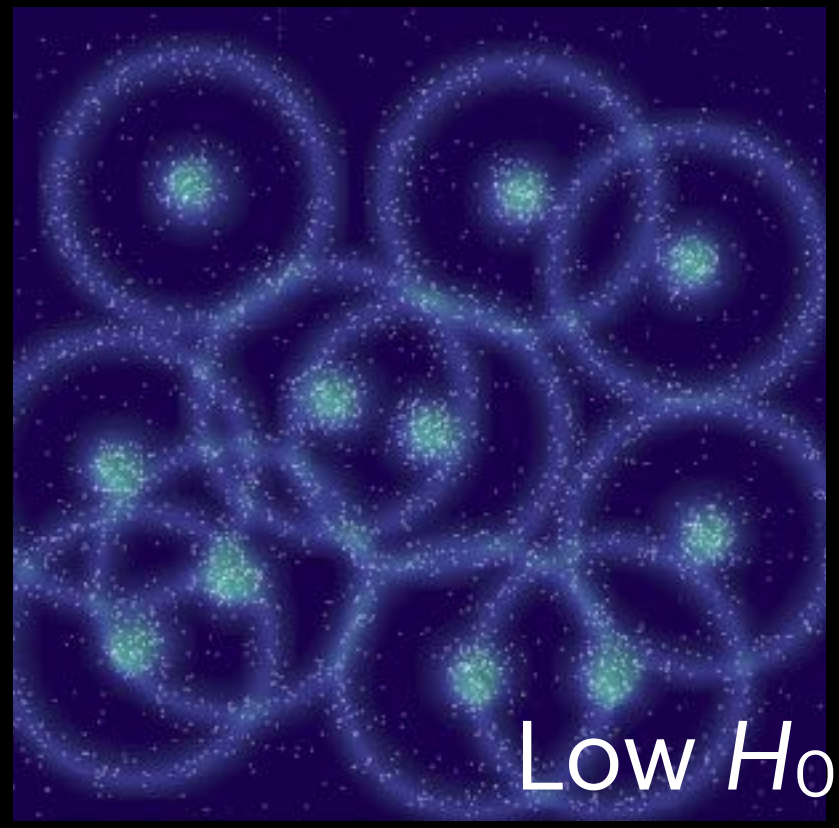
Local (direct)

Rulers

$$D_A = \tilde{D}/(1+z)$$



Early Universe (far)



Global (indirect)

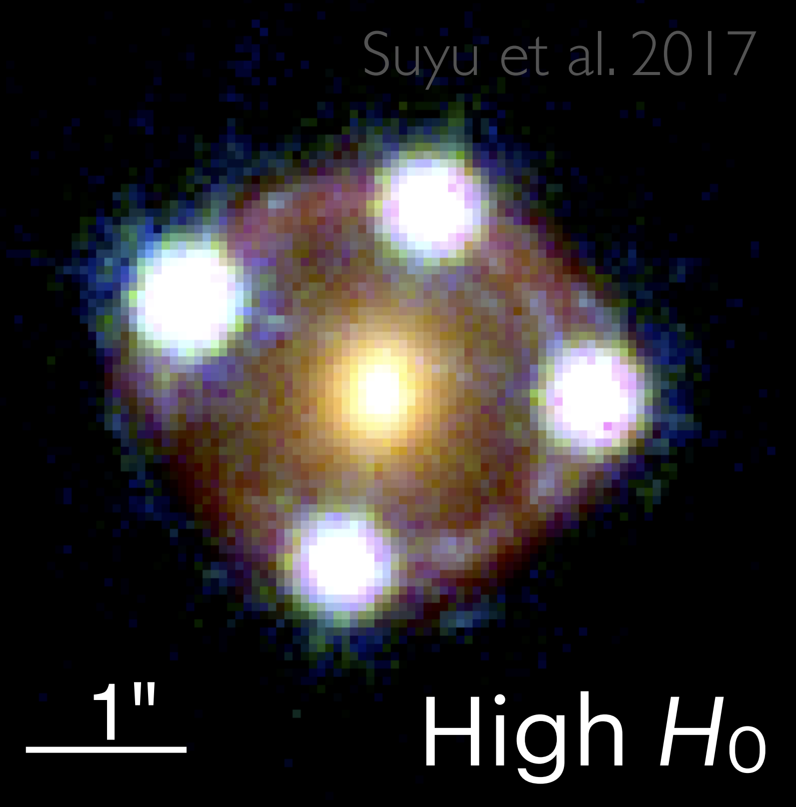
STANDARD CANDLES AND RULERS

$$\tilde{D}(z) = \begin{cases} R_0 \sin(\chi) & \text{closed} \\ R_0 \chi & \text{flat} \\ R_0 \sinh(\chi) & \text{open} \end{cases}$$

Candles

$$D_L = \tilde{D}(1+z)$$

Rulers



angular diameter distances

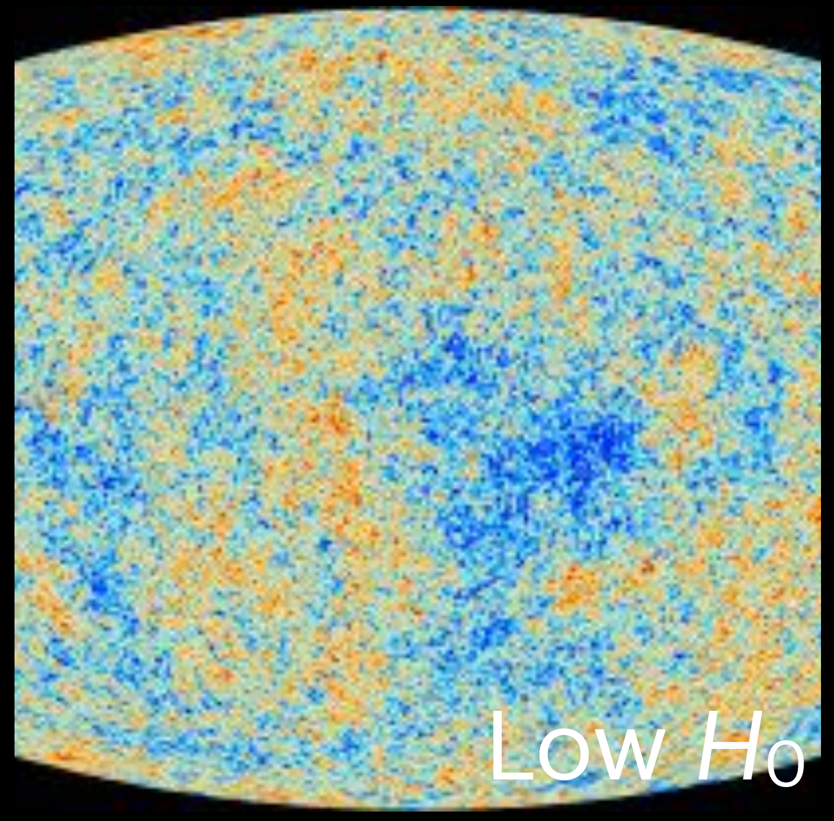
l = lens

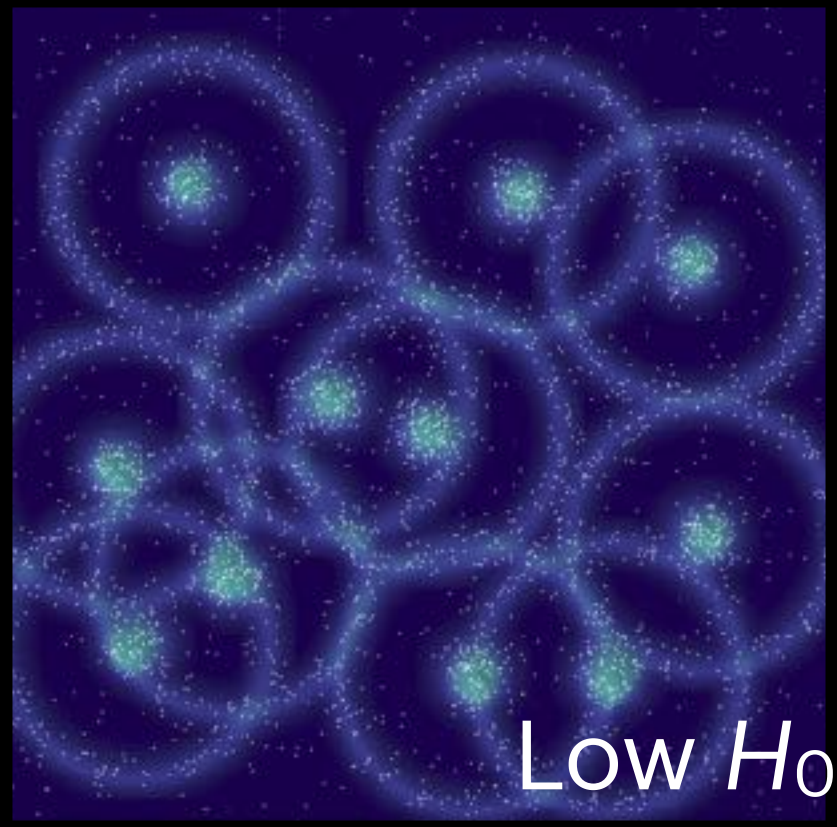
s = source

$$D_{\Delta t} = \frac{D_l D_s}{D_{ls}}(1+z_l)$$

$$D_{\Delta t} = \frac{\tilde{D}_l \tilde{D}_s}{\tilde{D}_{ls}}/(1+z_l)$$

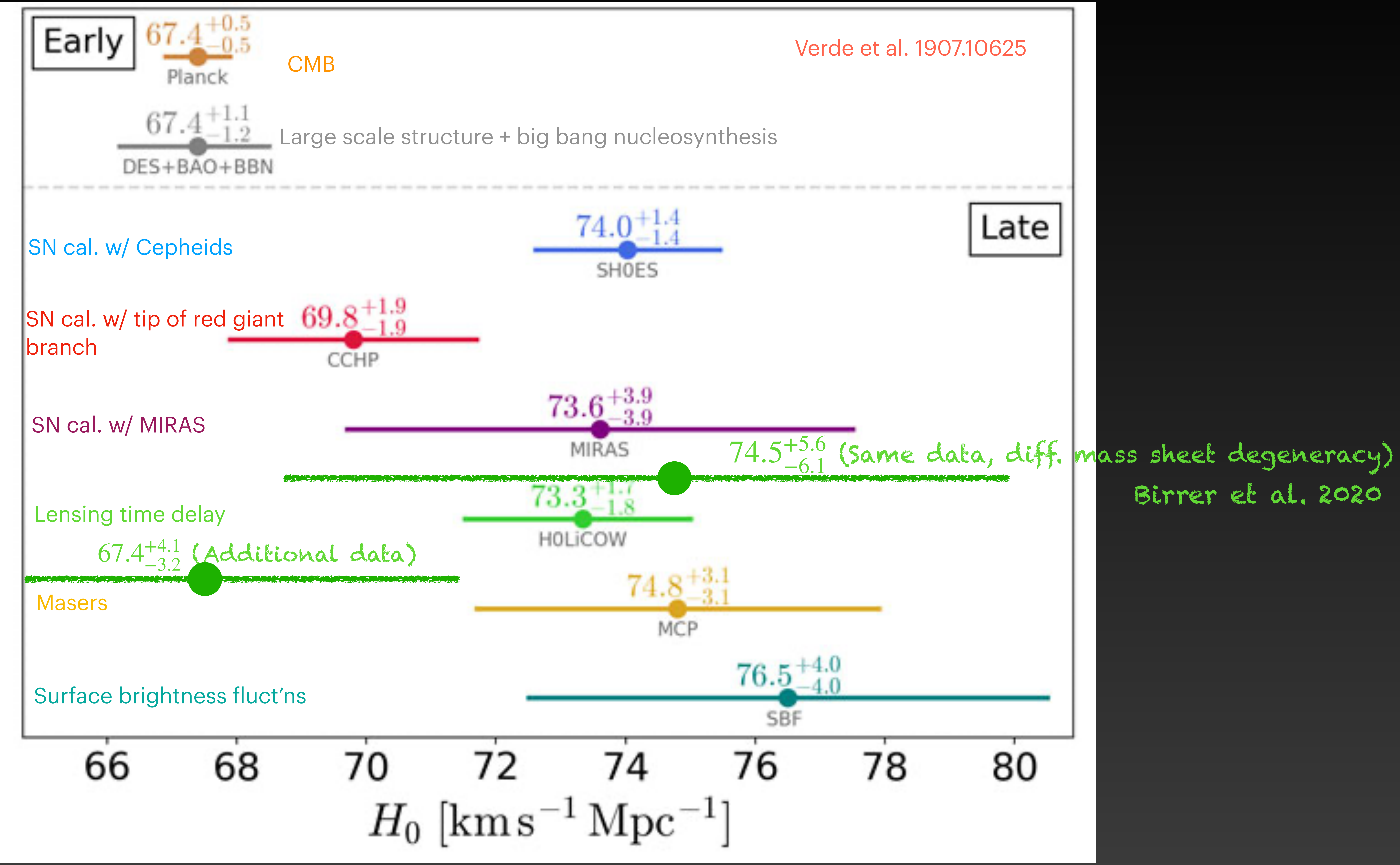
Rulers





$$D_A = \tilde{D}/(1+z)$$

Cosmological tensions

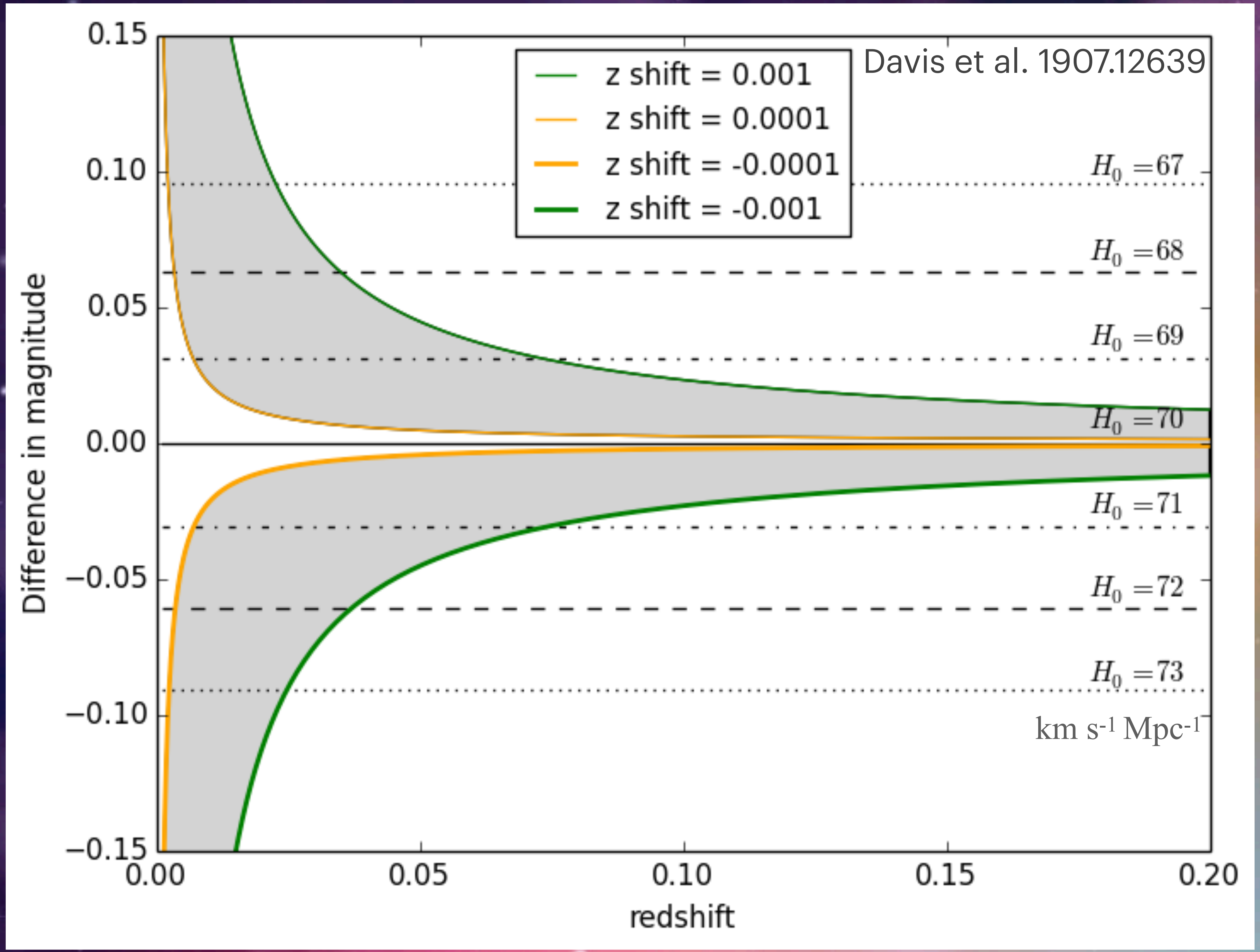


How large a redshift error would matter?

Surprisingly small systematic errors can make a difference (if at low-z).

We need to control systematics at the level of a few by 10^{-4}.

Redshifts used for cosmology are usually quoted with an uncertainty between 10^{-5} and 10^{-3}.



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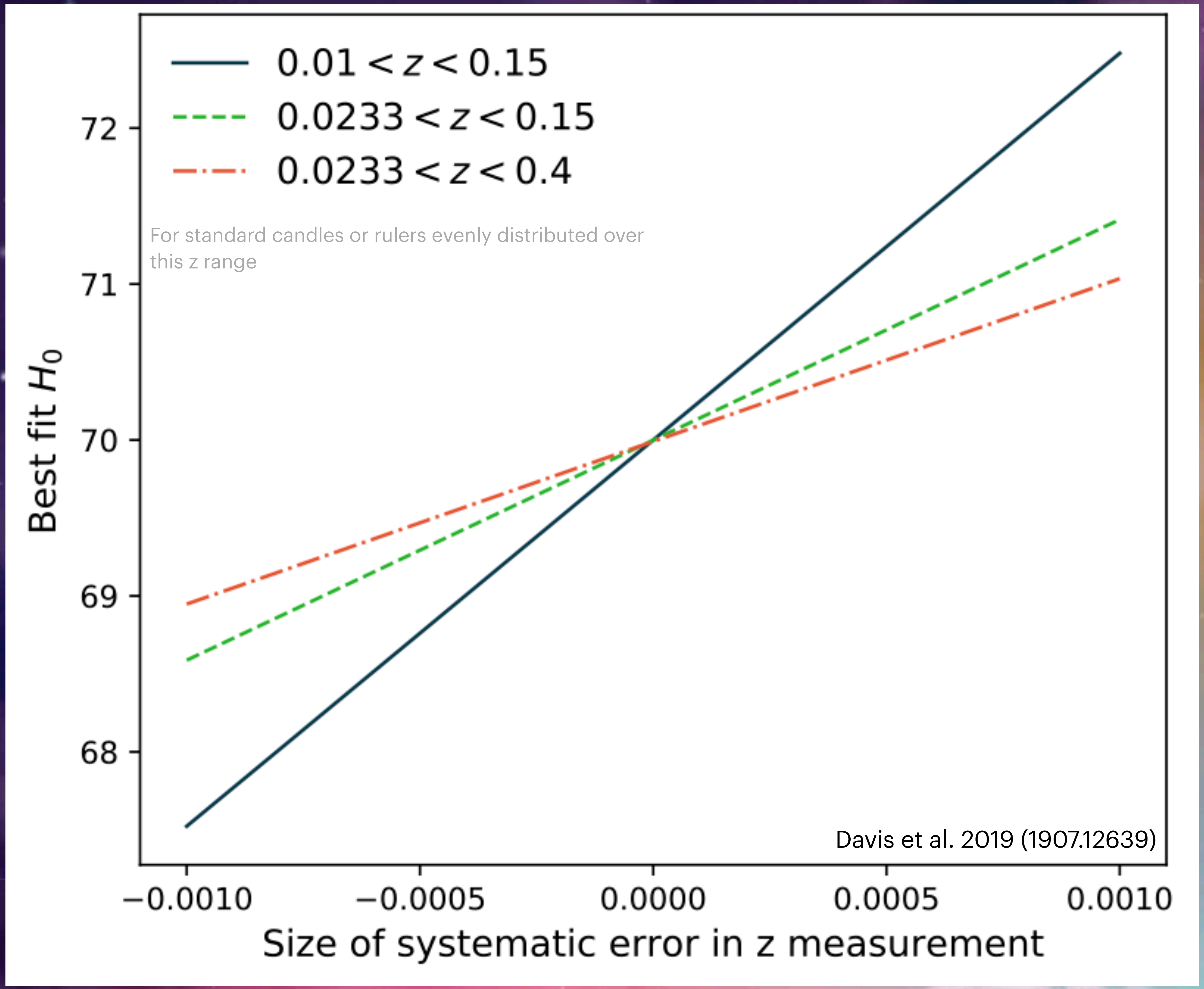
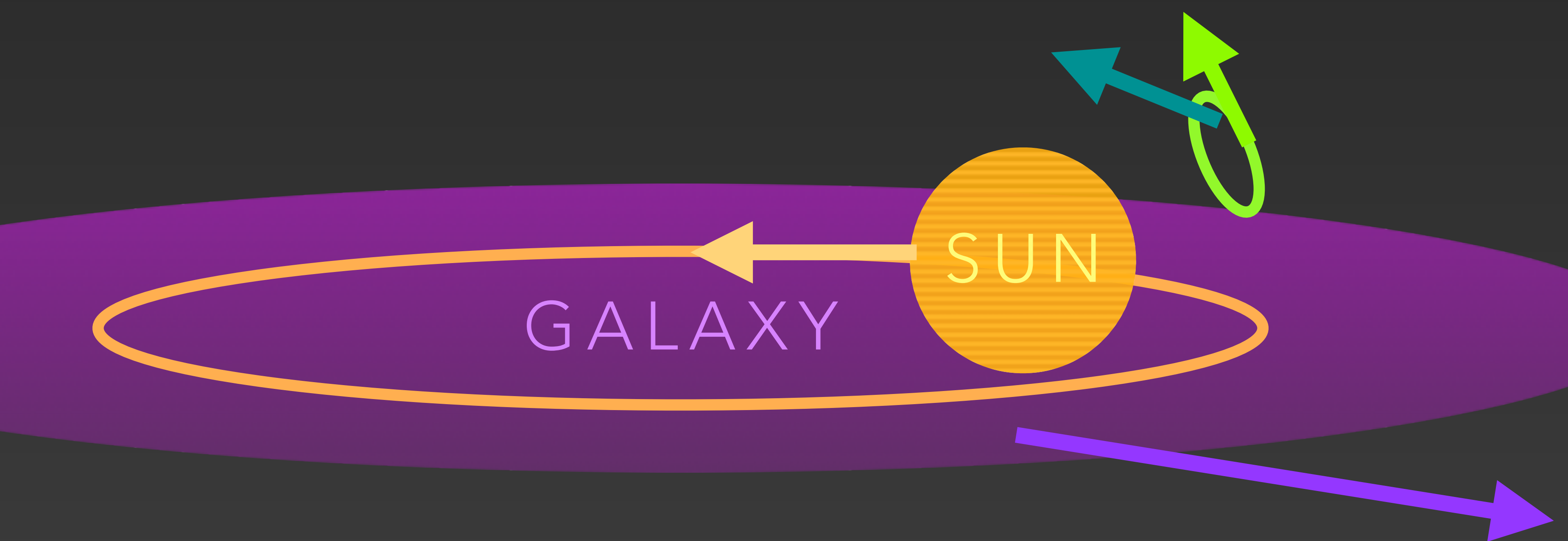


Possible sources of redshift bias

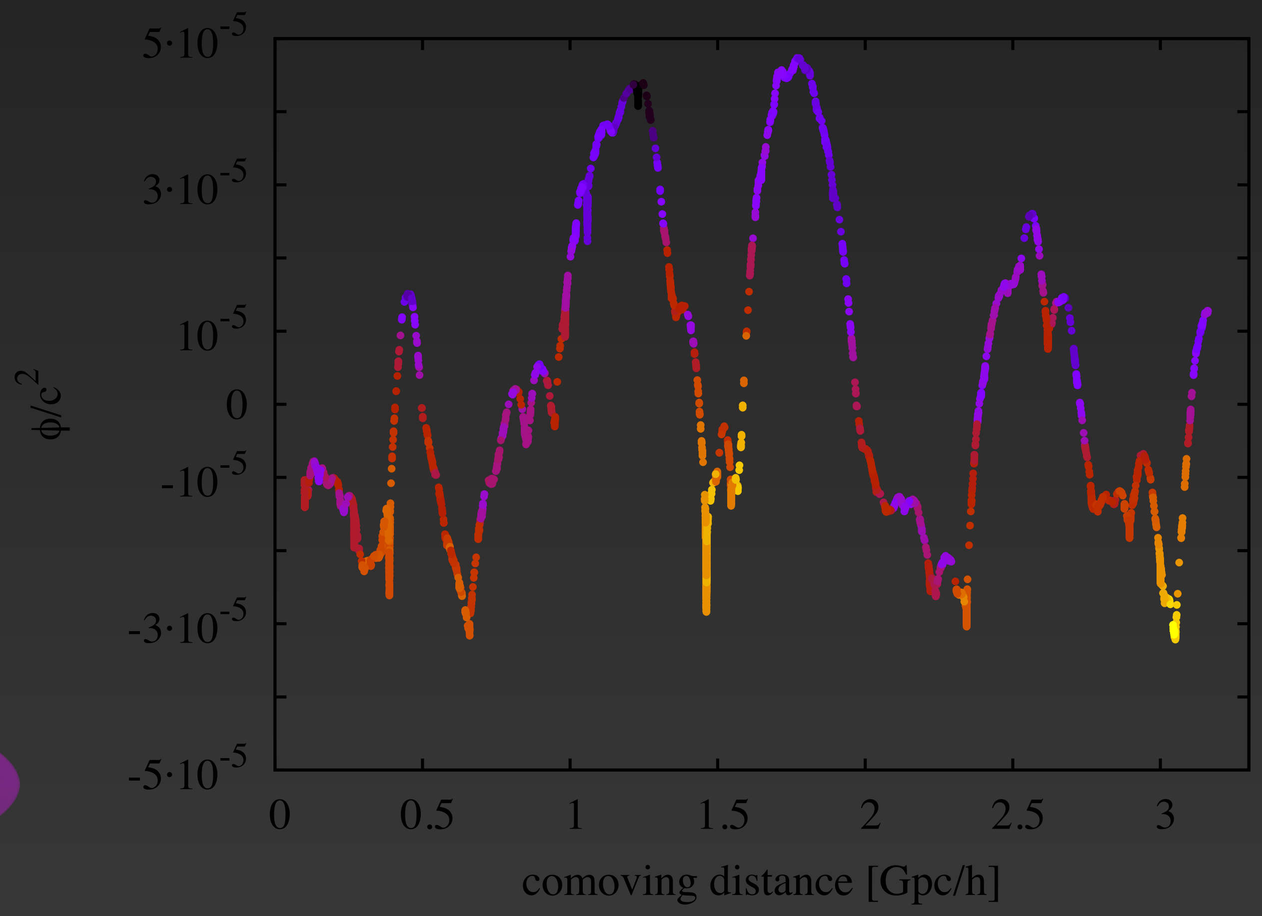
Observational error

- Local peculiar velocity corrections (spin, orbit, helio)
- Air to vacuum conversion
- Spectrograph wavelength calibration
- Continuum tilt



Physical effects

- Gravitational z (local density fluct.)
- Peculiar velocities
- Bulk flows
- Internal velocities



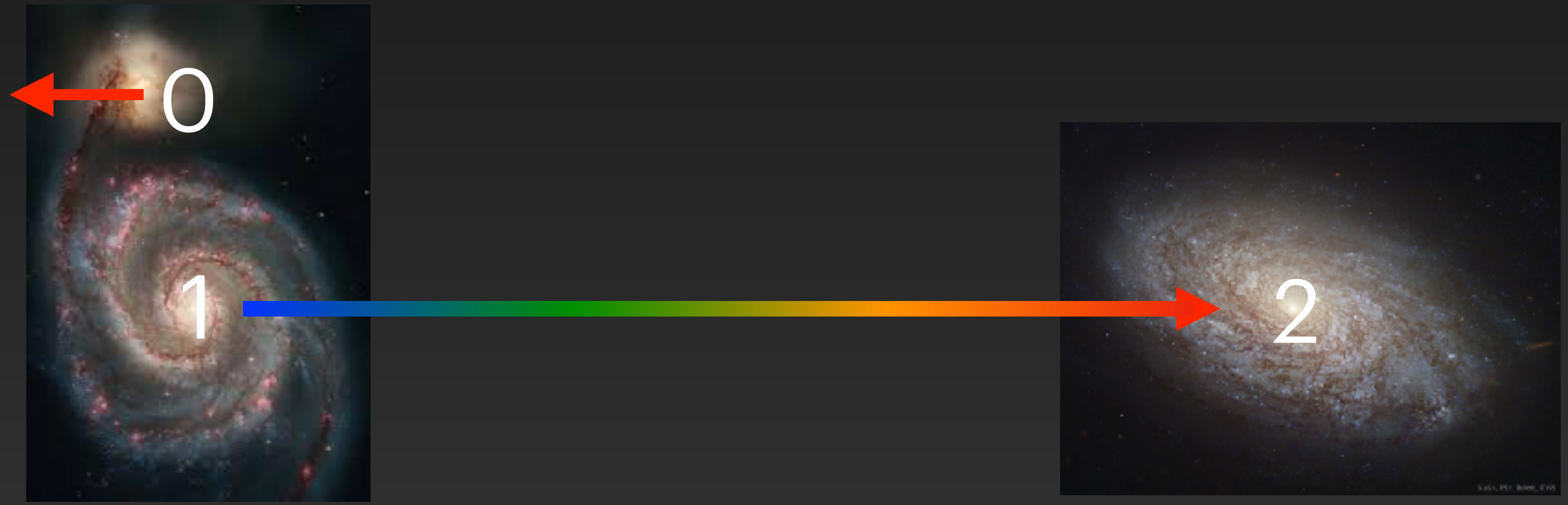
Theoretical error

- Using (1+z) factors incorrectly
  - Redshift addition
  - D_L and D_A
- Peculiar velocity approximations

Theoretical errors

Adding redshifts

$$\cancel{z_{\rm obs} = z_{\rm rec} + z_{\rm pec}}$$



Adding z for heliocentric correction

gives **~10^{-3} error at z=1**

this is VERY COMMON

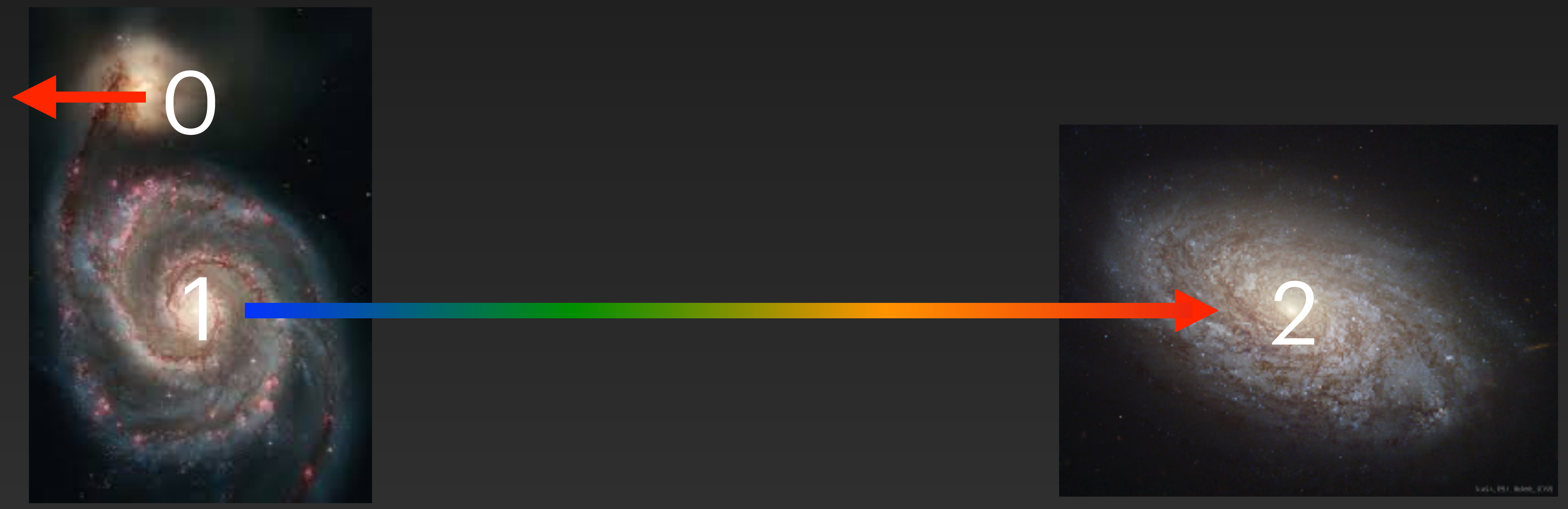
observed emitted

$$z_{10} \equiv \frac{\lambda_1 - \lambda_0}{\lambda_0}$$

Theoretical errors

Adding redshifts

$$\cancel{z_{\text{obs}} = z_{\text{rec}} + z_{\text{pec}}}$$



Adding z for heliocentric correction

gives **~10^{-3} error at z=1**

this is VERY COMMON

$$1 + z_{10} \equiv \frac{\lambda_1}{\lambda_0}$$

$$1 + z_{20} \equiv \frac{\lambda_2}{\lambda_0} = \frac{\lambda_2}{\lambda_1}\frac{\lambda_1}{\lambda_0}$$

$$= (1 + z_{21})(1 + z_{10})$$

$$1 + z_{\text{obs}} = (1 + z_{\text{rec}})(1 + z_{\text{pec}})$$

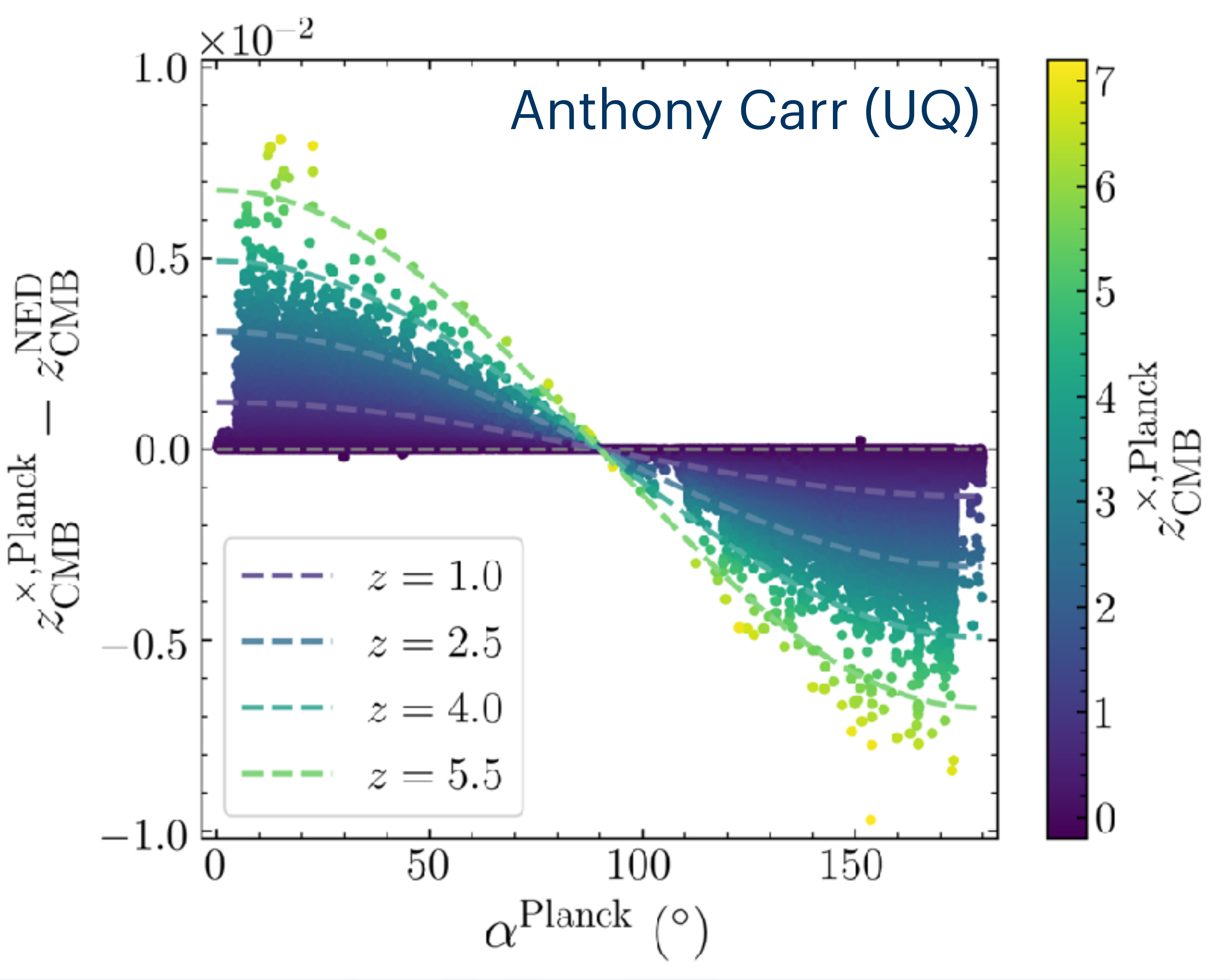
$$\boxed{z_{\text{obs}} = z_{\text{rec}} + z_{\text{pec}}} + z_{\text{rec}} z_{\text{pec}}$$

low-redshift approximation

Theoretical errors

e.g. NASA Extragalactic Database (NED) uses redshift addition in their velocity calculator and heliocentric to CMB correction.

We are working with them to fix this, see Carr and Davis 2102.06874

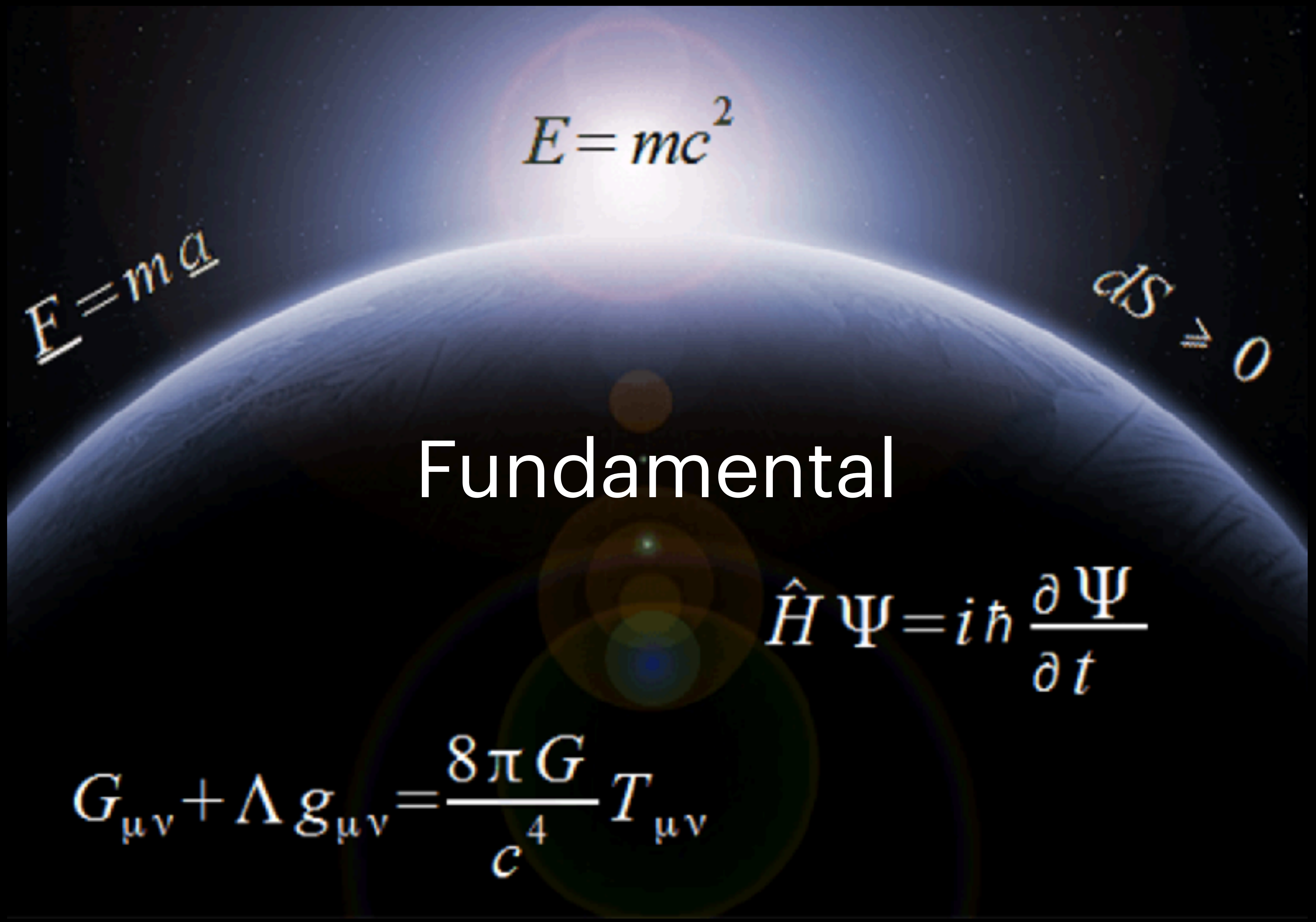


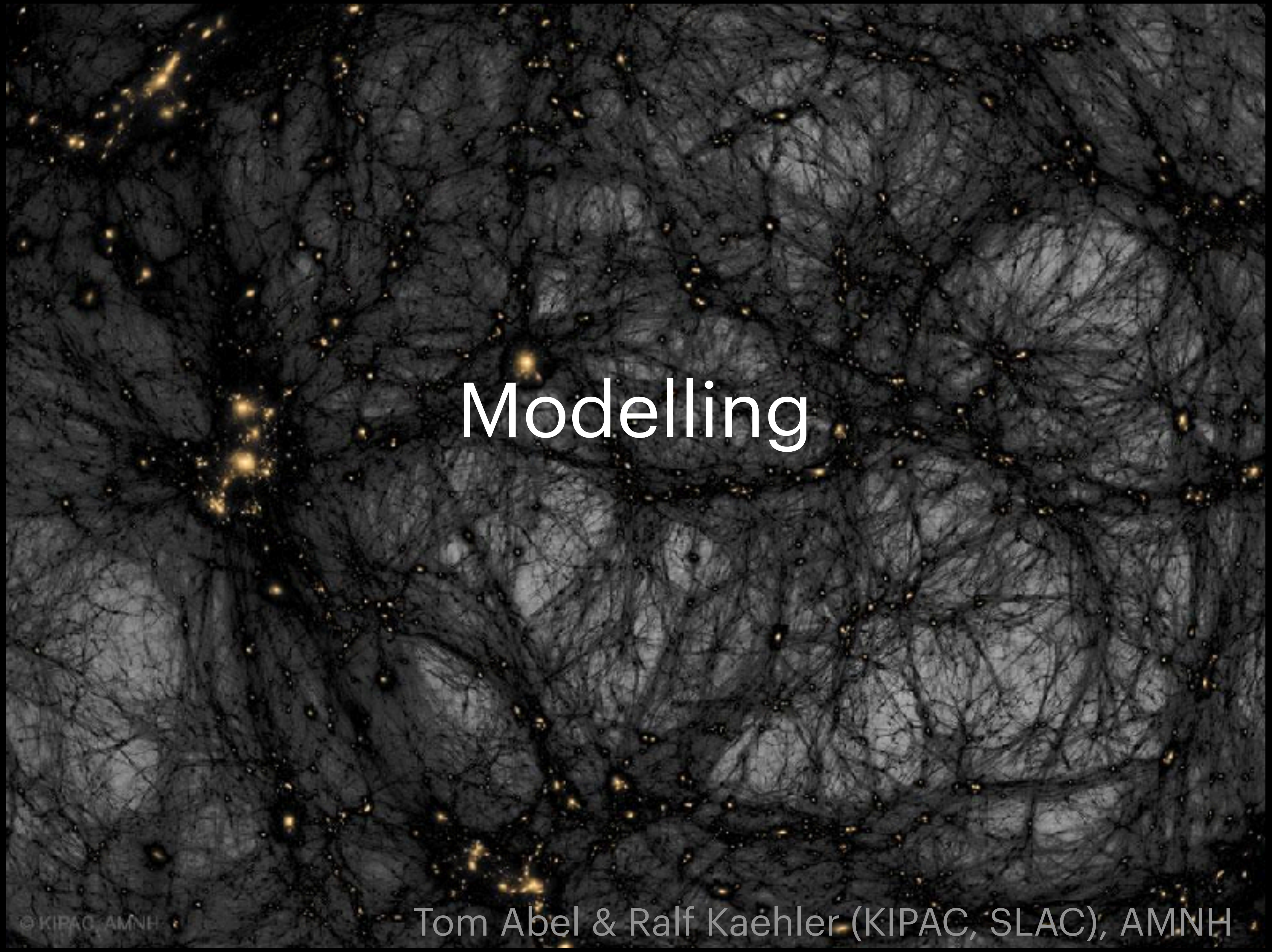
My redshift systematics-related papers:

1907.12639 Davis, Hinton, Howlett, & Calcino "Can redshift errors bias measurements of the Hubble Constant?"
1909.00587 Howlett & Davis "Standard siren speeds: improving velocities in gravitational-wave measurements of H_0"
2006.00449 Lidman et al. "OzDES multi-object fibre spectroscopy for the Dark Energy Survey: results and second data release"
1912.01175 Hinton, Howlett & Davis "BARRY and the BAO model comparison"
1610.07695 Calcino & Davis "The need for accurate redshifts in supernova cosmology"
1609.04022 Andersen, Davis, & Howlett "Cosmology with peculiar velocities: observational effects"
1603.09438 Hinton et al. "MARZ: Manual and automatic redshifting software"
1504.00718 Wojtak, Davis, & Wiis "Local gravitational redshifts can bias cosmological measurements"
1405.0105 Davis & Scrimgeour "Deriving accurate peculiar velocities (even at high redshift)"
1012.2912 Davis et al. "The Effect of Peculiar Velocities on Supernova Cosmology"
1006.0911 Sinclair, Davis, & Haugbølle "Residual Hubble-bubble Effects On Supernova Cosmology"

Anthony Carr

THEORETICAL EFFORTS FALL IN TWO MAIN GROUPS

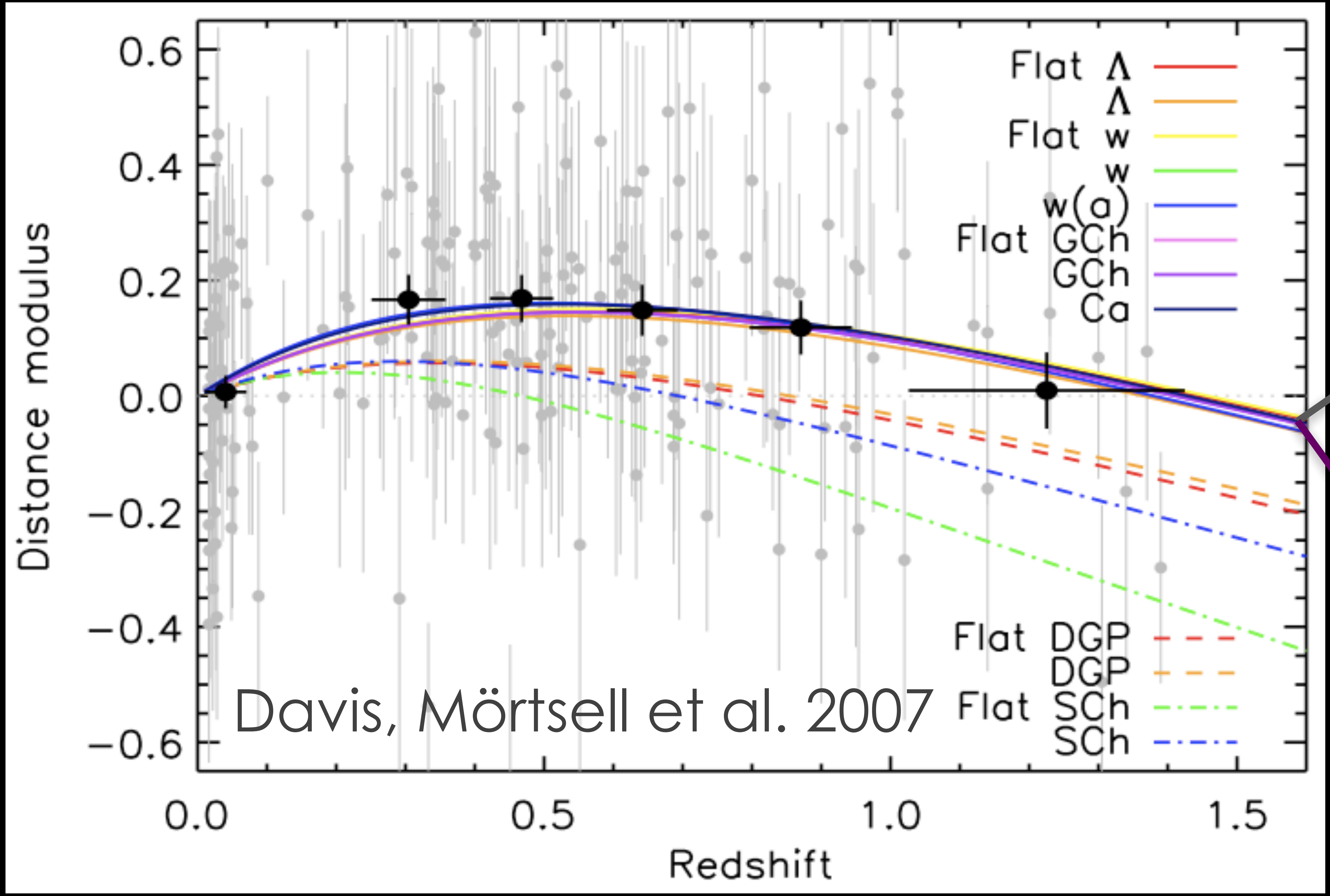


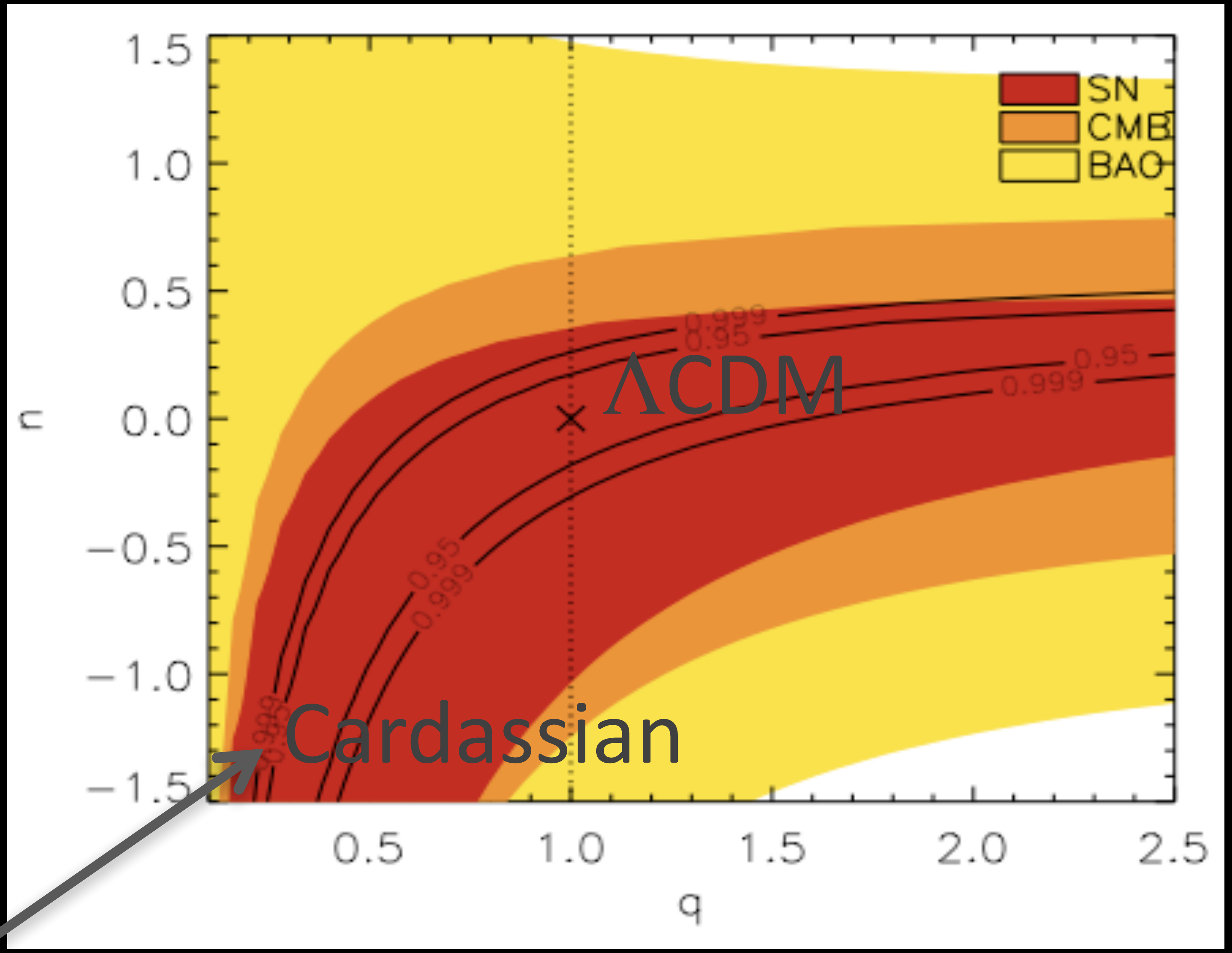


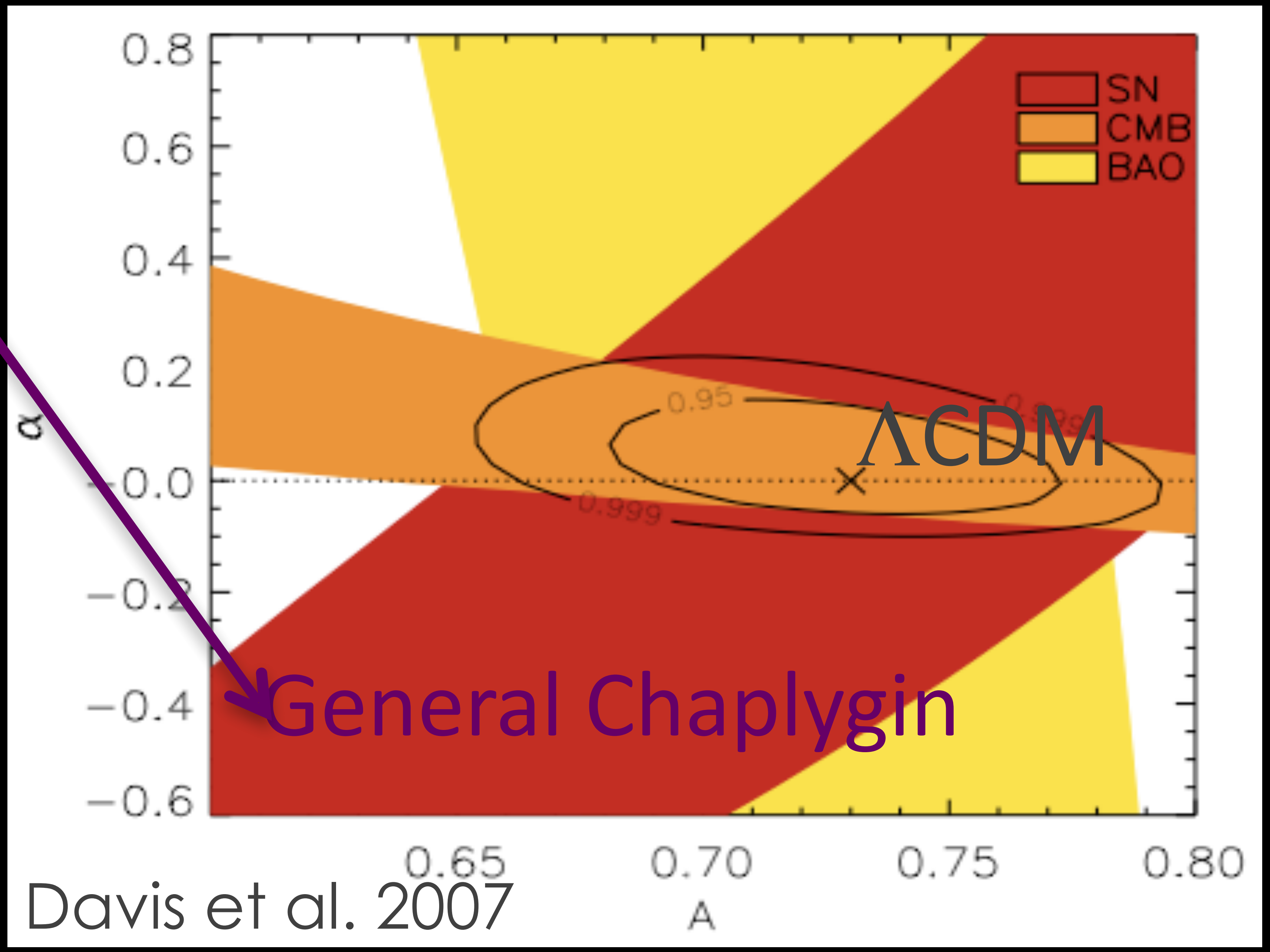
Need to explain dark matter, dark energy, and tensions

THE LIMITS OF DISTANCES

Some models can't be distinguished using only distance data





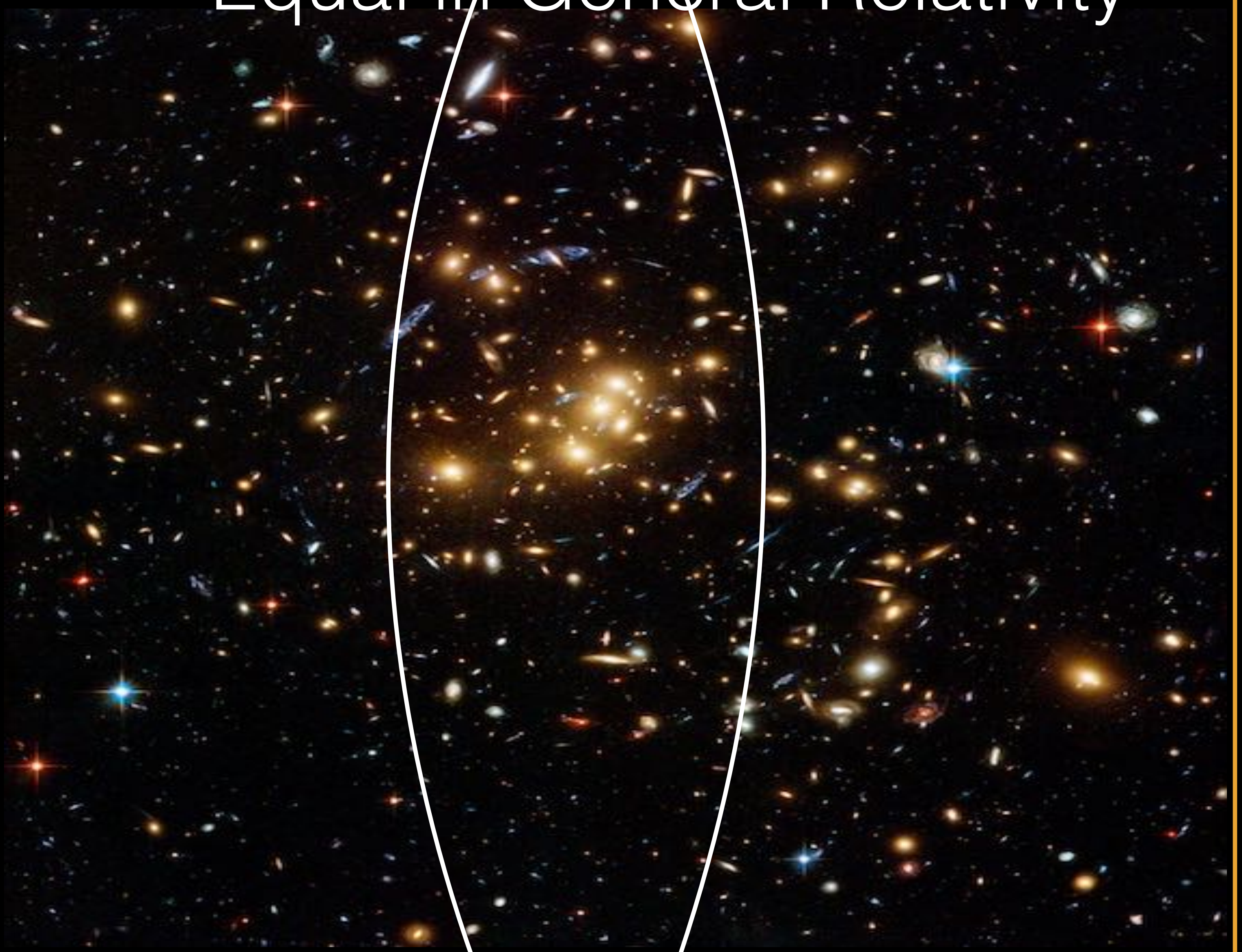


COMPLEMENTARY MEASUREMENTS CRITICAL

Lensing vs clustering

$$ds^2 = a^2\left[-(1+2\boxed{\Psi})d\tau^2 + (1-2\boxed{\Phi})dx^2\right]$$

Equal in General Relativity



Clustering sensitive to Φ

Lensing sensitive to $\Psi+\Phi$

Growth

$$f = \frac{d(\ln \delta)}{d(\ln a)} \sim \Omega_M(z)^\gamma$$

overdensity

scalefactor

γ different for different models of gravity

Amplitude of density fluctuations at present day

σ_8

1. measure density in spheres of 8Mpc radius
2. calculate the dispersion

COMPLEMENTARY MEASUREMENTS CRITICA

+ Age of the Universe, Existence of galaxies, Flatness,…

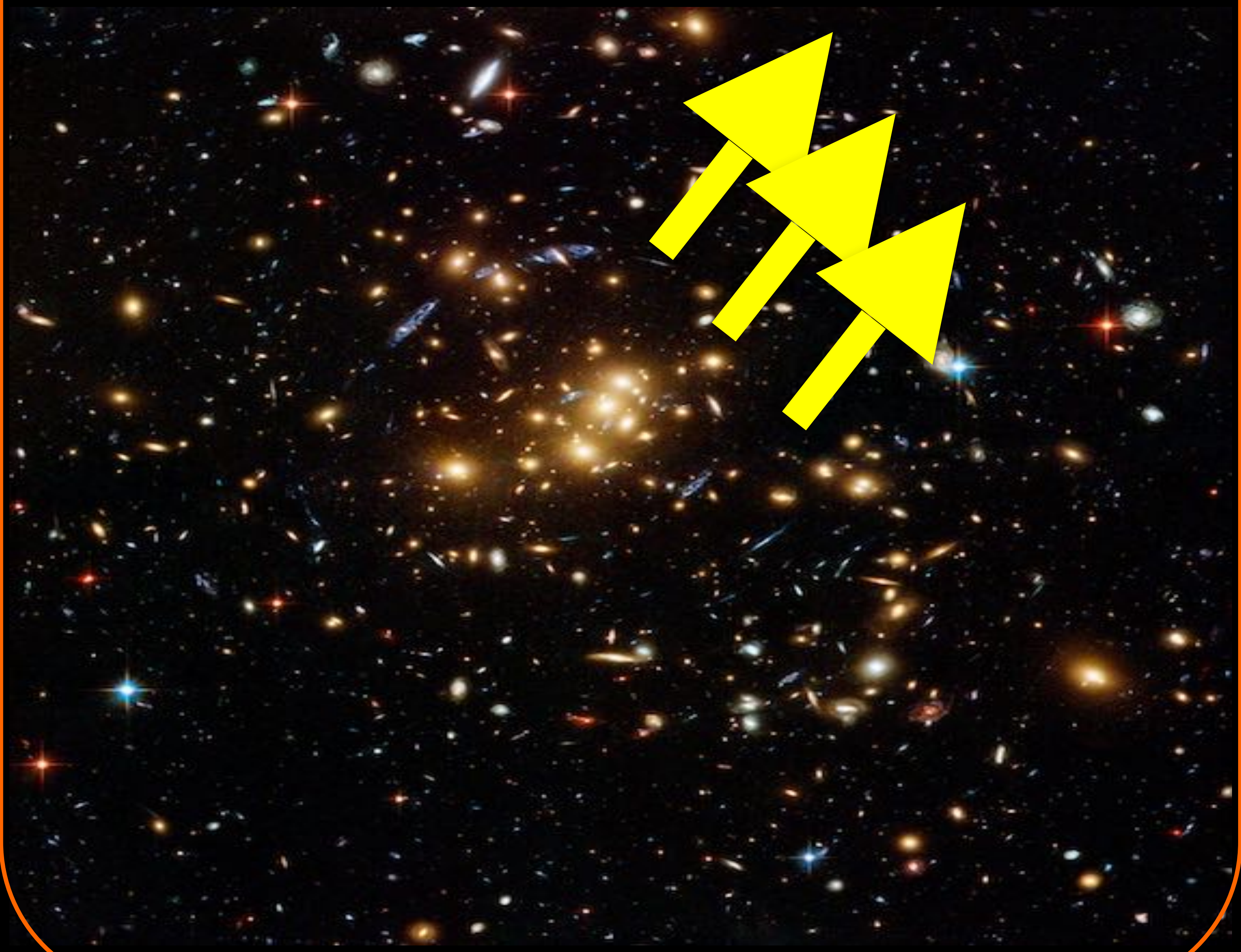
non-Gaussianity $f_{\rm NL}$

$$\Phi(\mathbf{x}) = \Phi_G(\mathbf{x}) + \boxed{f_{\rm NL}} \left(\Phi_G(\mathbf{x})^2 - \langle \Phi_G(\mathbf{x})^2 \rangle\right)$$

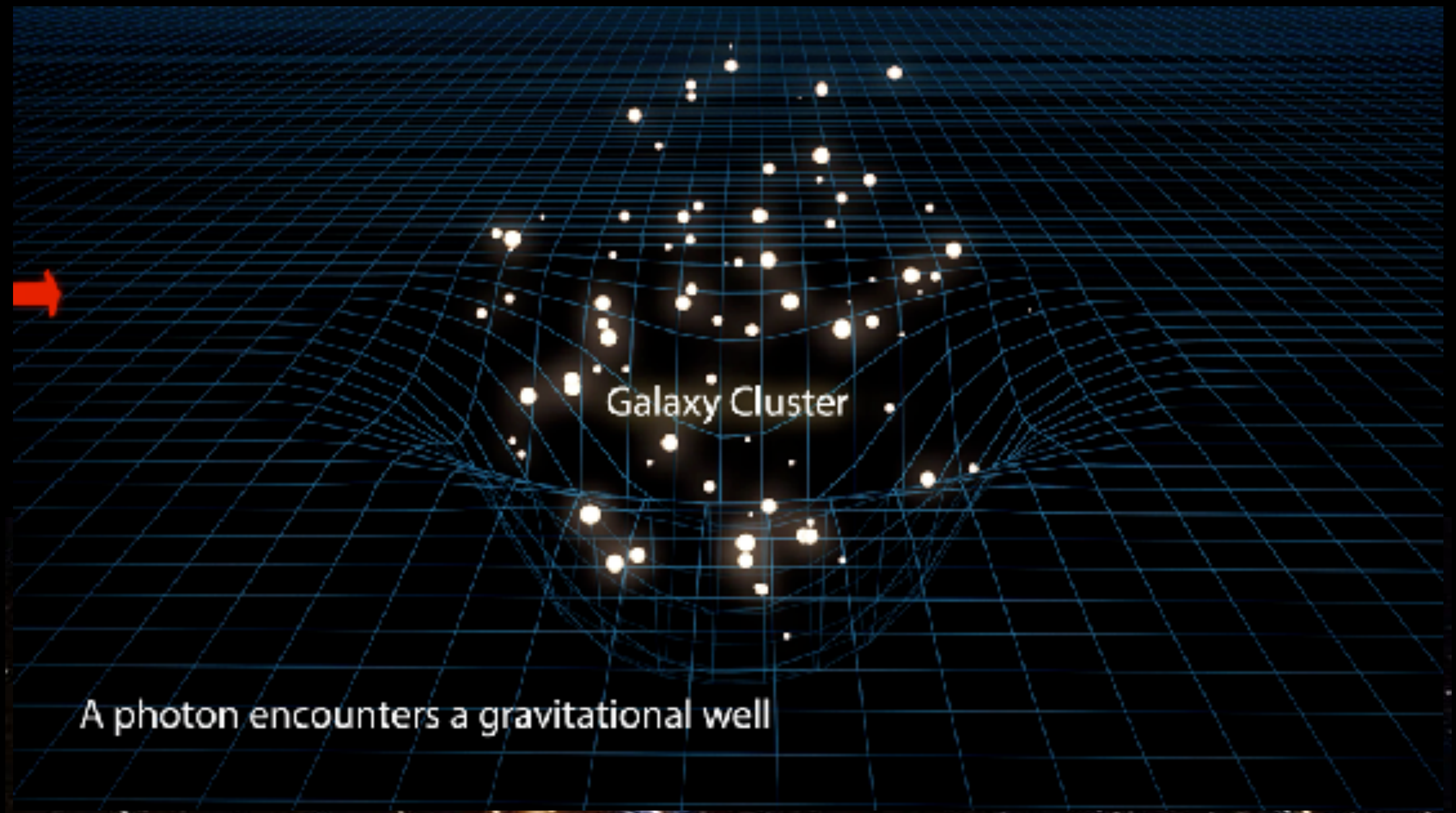
quantifies skewness in density distribution

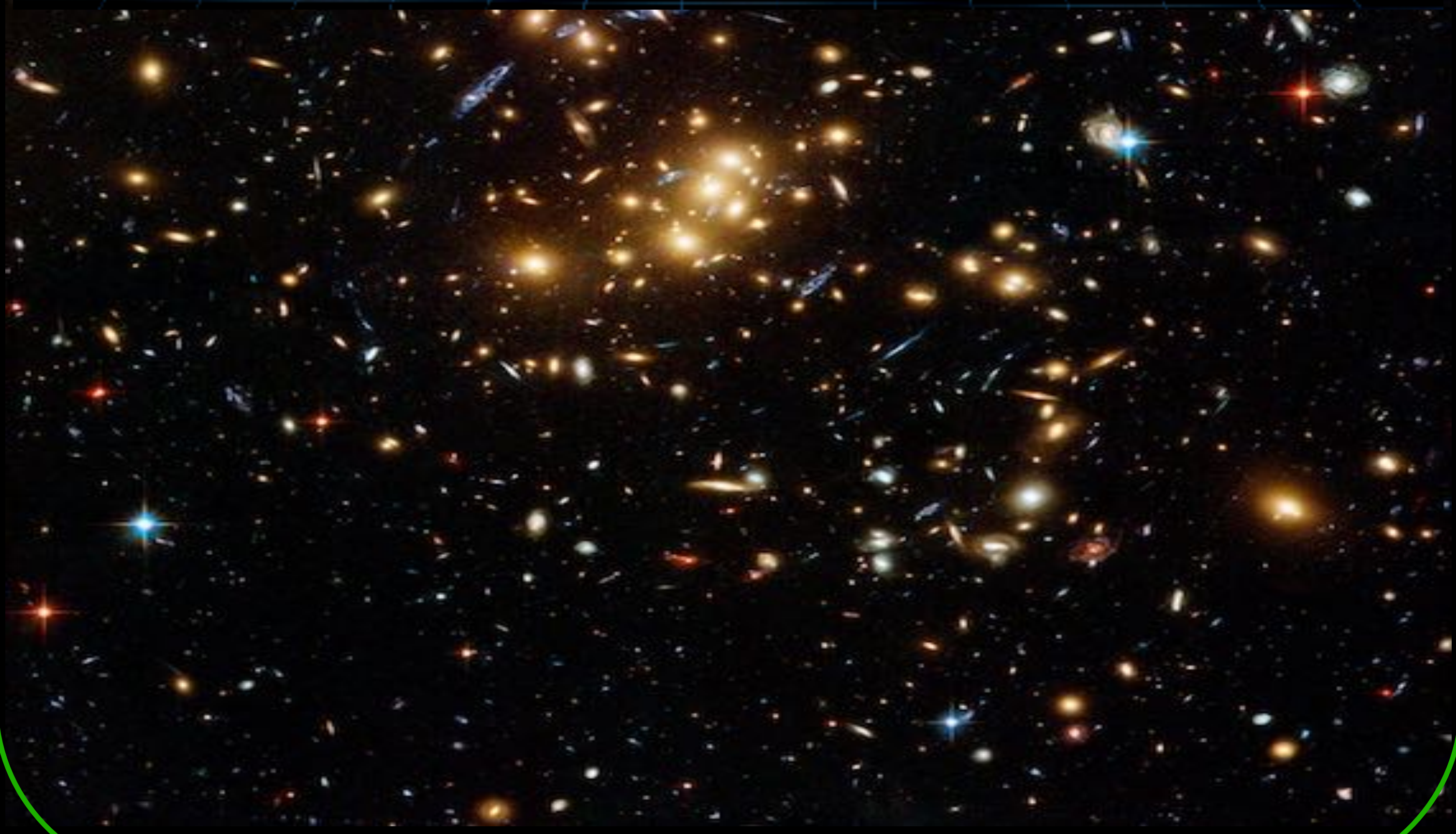
Peculiar velocities

Bulk Flow
+
Higher order modes
(Peculiar velocity power spec.)



Integrated Sachs Wolfe

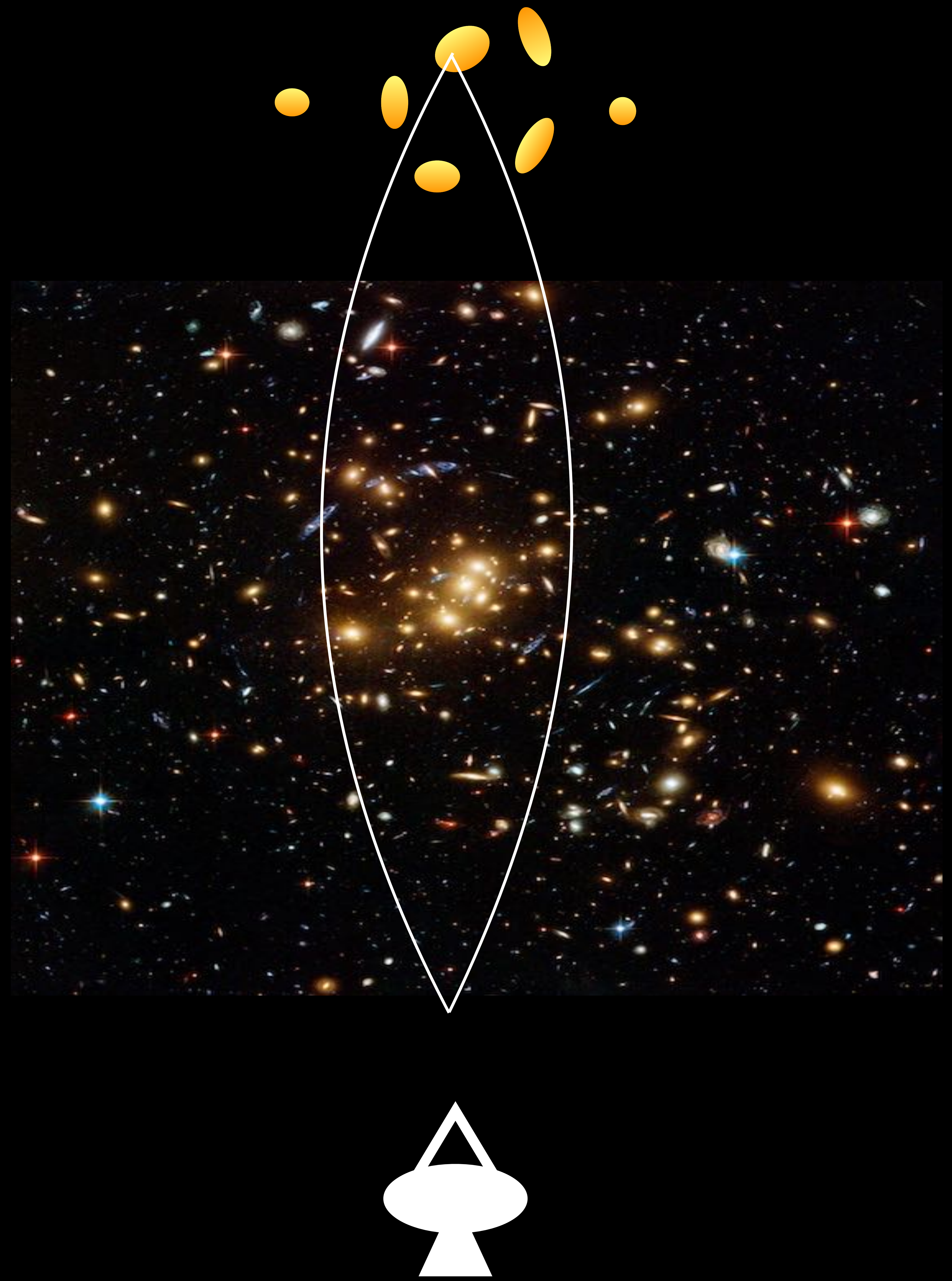




COMPLEMENTARY MEASUREMENTS CRITICAL

3x2PT

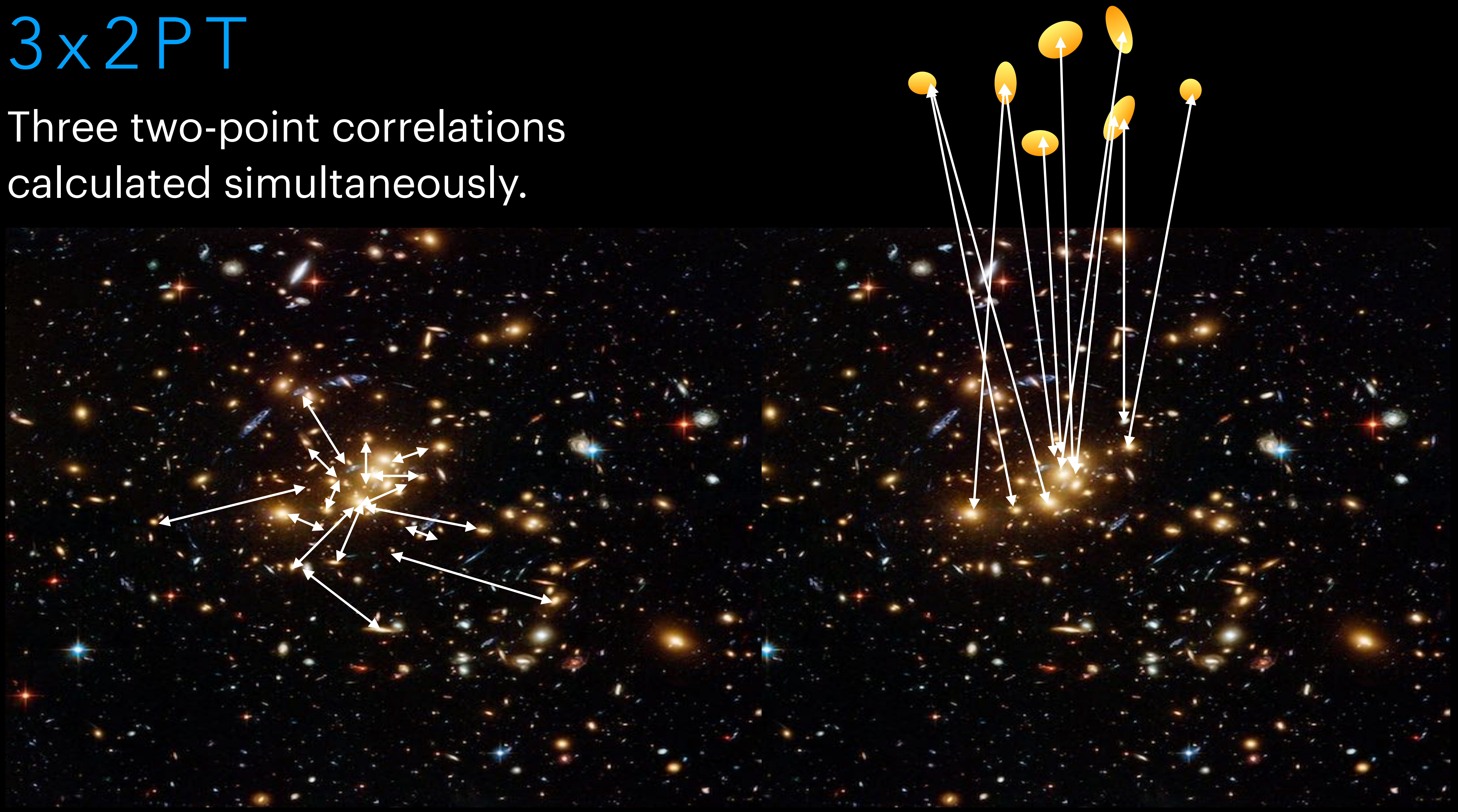
Three two-point correlations calculated simultaneously.

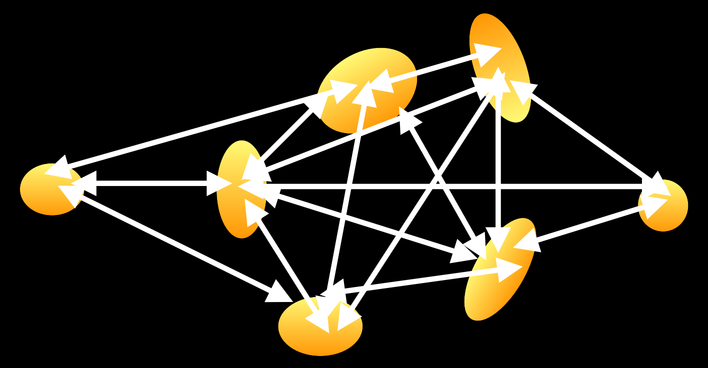


COMPLEMENTARY MEASUREMENTS CRITICAL

3x2PT

Three two-point correlations calculated simultaneously.



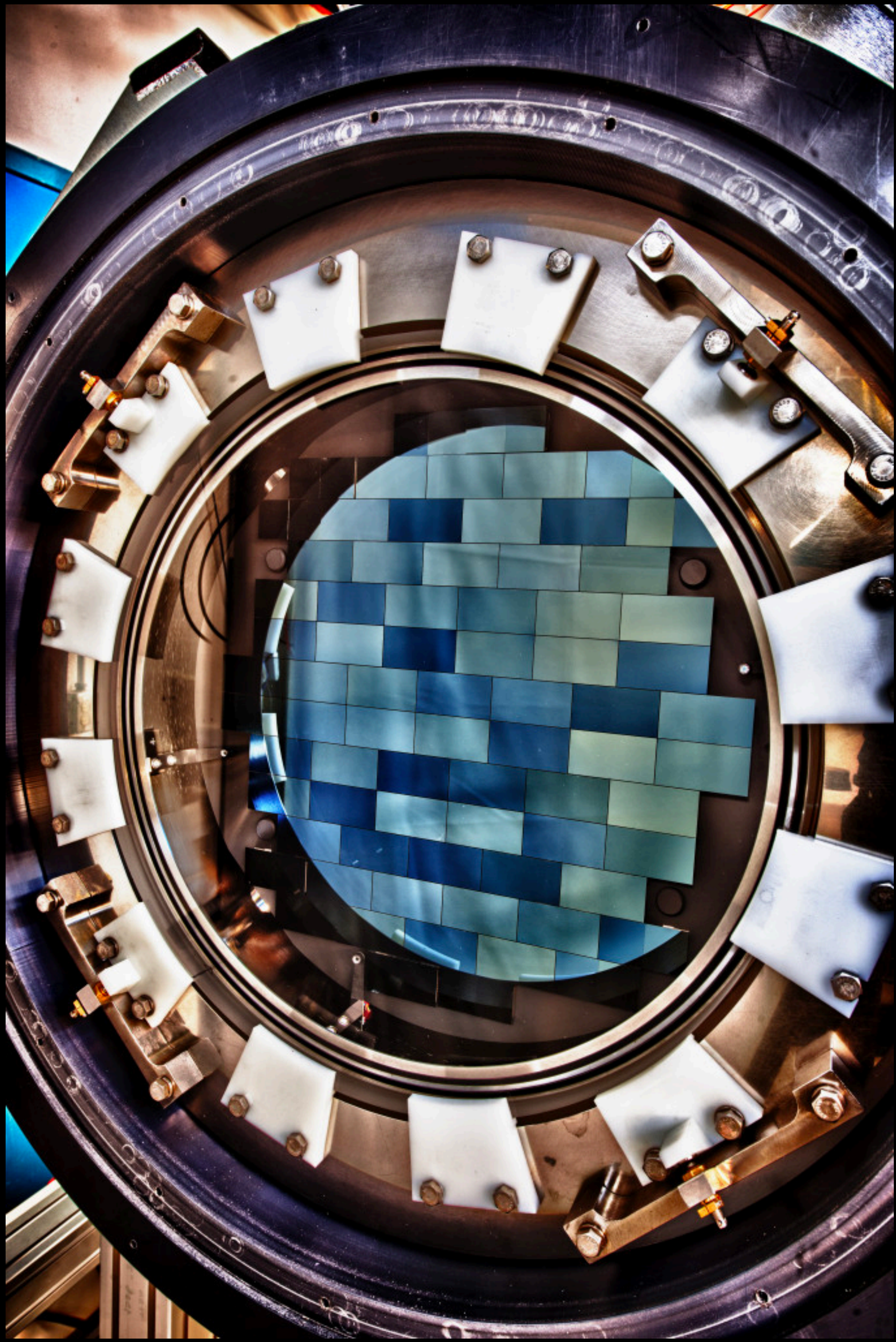


galaxy-galaxy

galaxy-lens

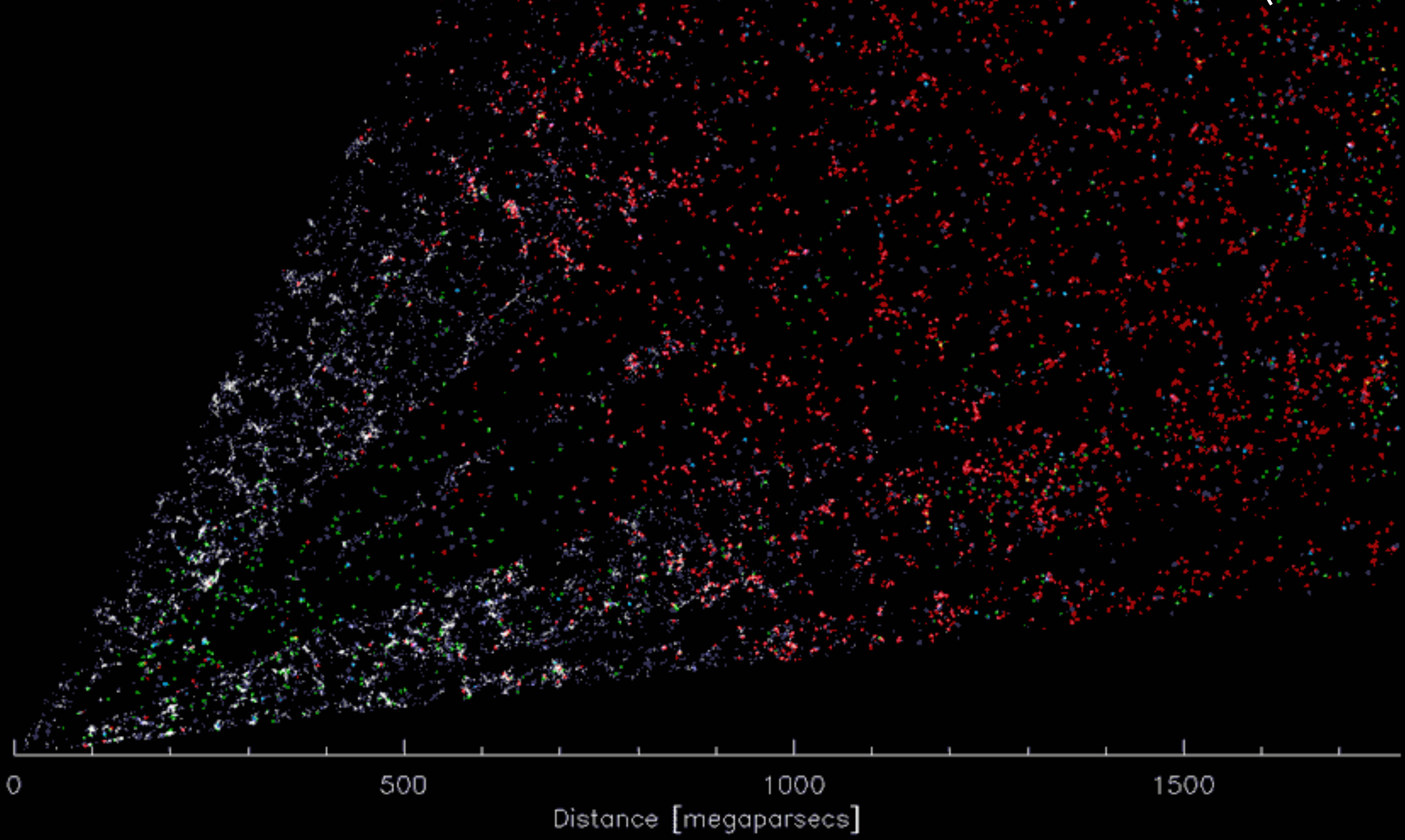
lens-lens

DARK ENERGY SURVEY (DES)



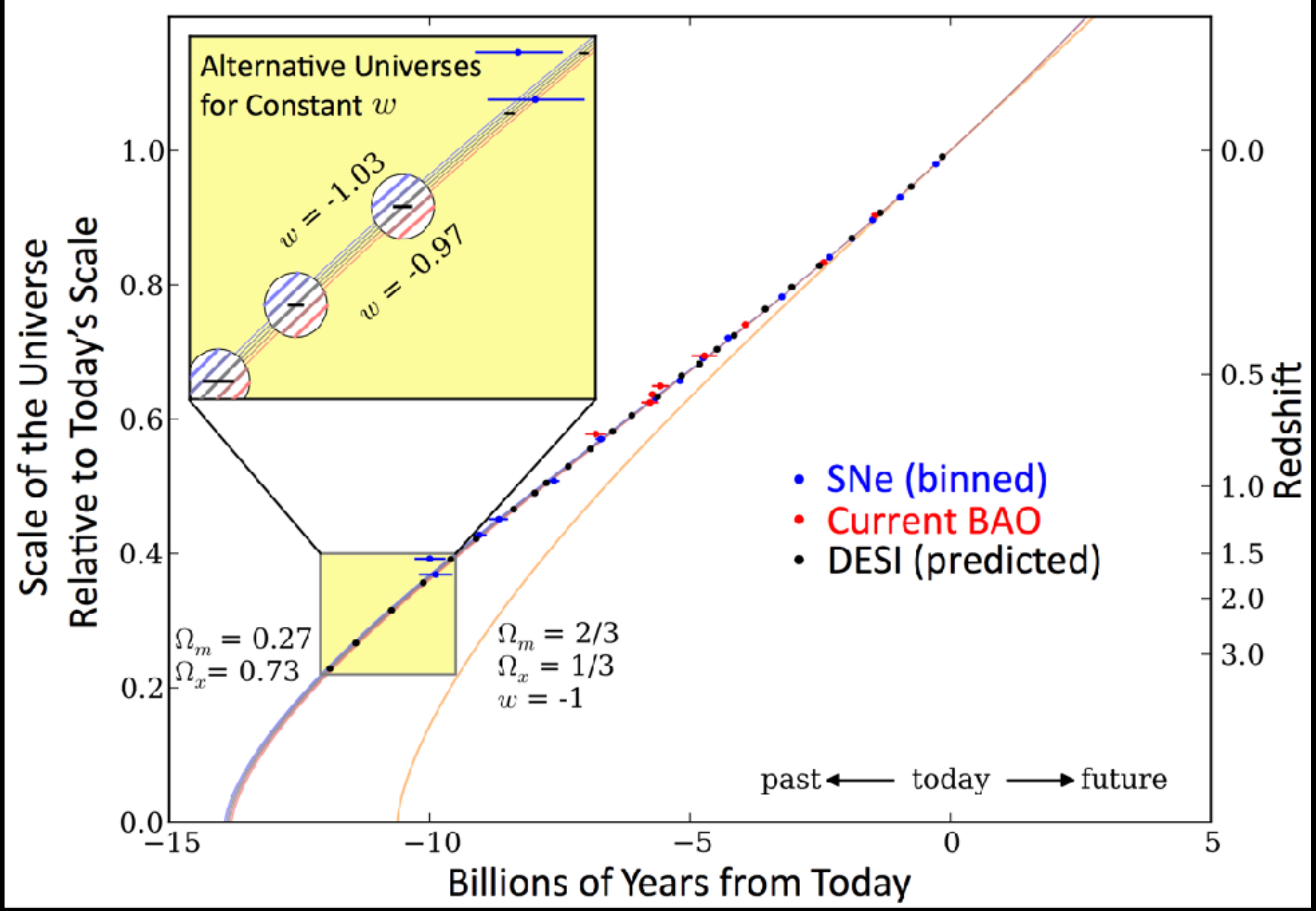
DARK ENERGY SPECTROSCOPIC INSTRUMENT (DESI)

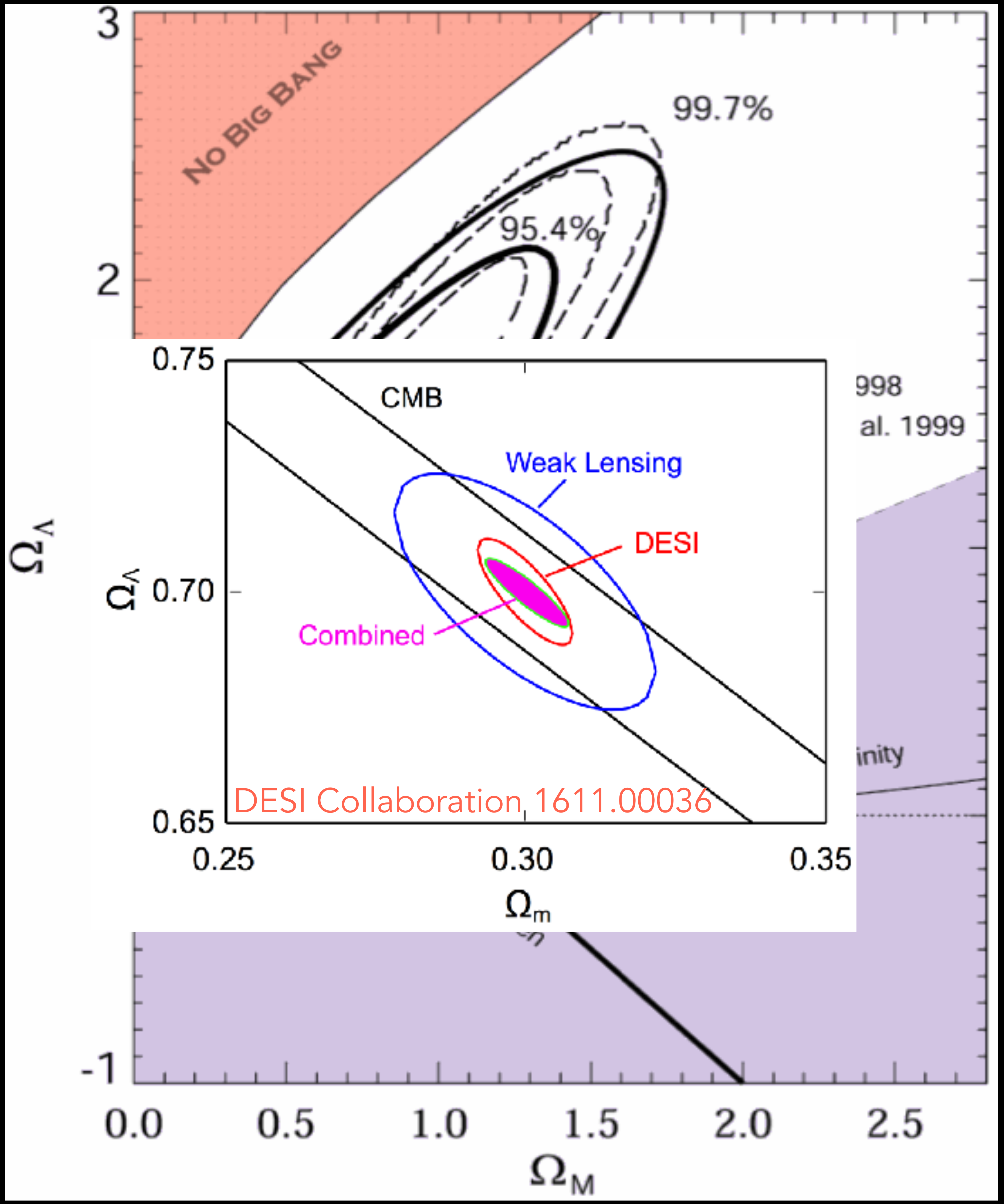
DARK ENERGY SPECTROSCOPIC INSTRUMENT (DESI)



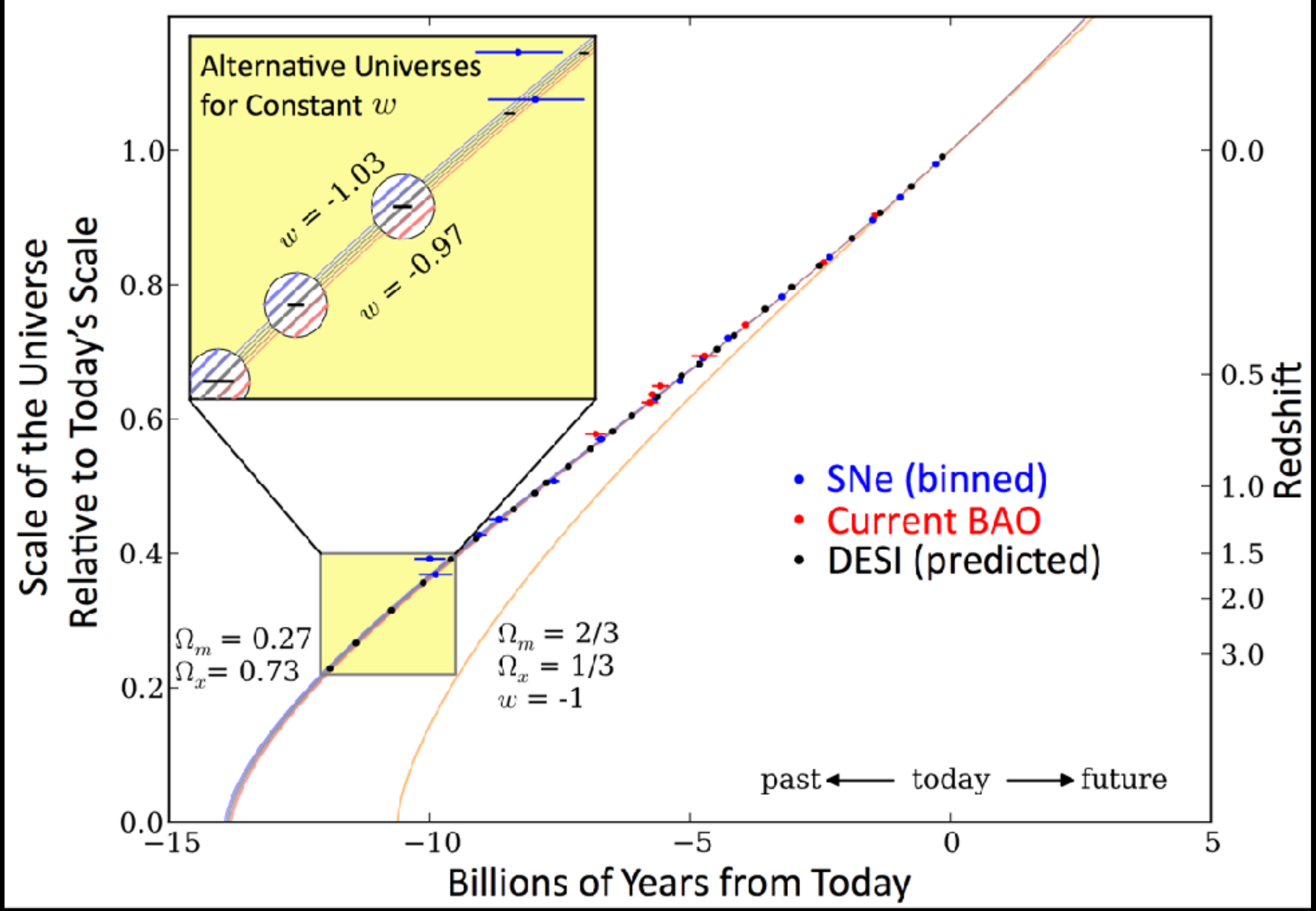
Already mapped more than 10 million galaxies

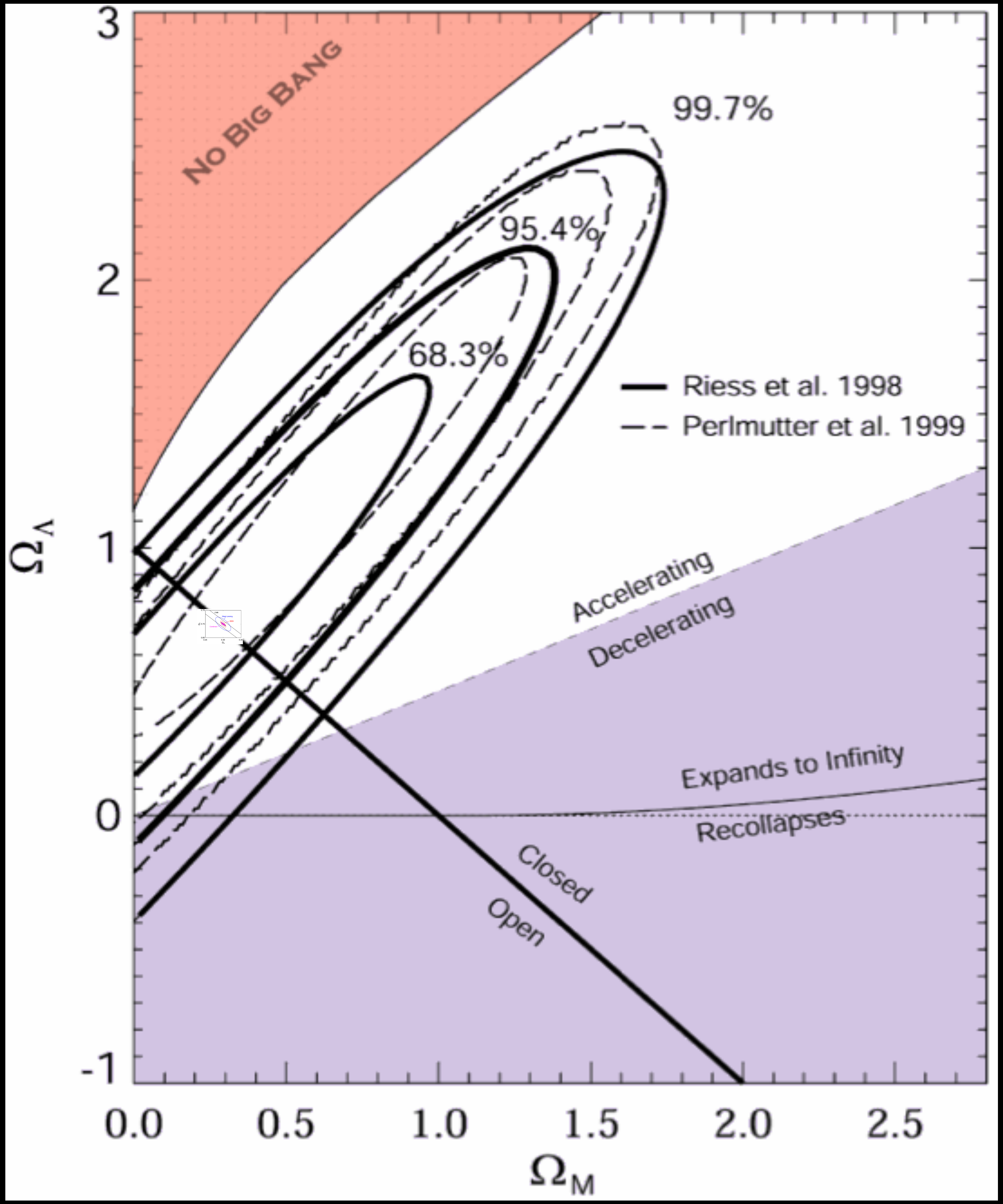
DESI PREDICTION





DESI PREDICTION





OBSERVING IS NOT EXPLAINING

- **Theoretical** advances are going to be as important as **observational** ones, if we are to understand the mysteries of cosmology
- We need both:
    - **fundamental theory** (e.g. quantum gravity) and
    - **modelling theory** (simulations, modelling of observables, and statistics)

Image: HI4PI: "A new all-sky survey of neutral hydrogen"

Theoretical errors

Luminosity and angular diameter distance

$$D_L(z) = \tilde{D}(z)(1+z)$$

$$D_A(z) = \tilde{D}(z)/(1+z)$$

But which redshift should we use?

$$\tilde{D}(z) = \begin{cases} R_0 \sin(\chi) & \text{closed} \\ R_0 \chi & \text{flat} \\ R_0 \sinh(\chi) & \text{open} \end{cases}$$

Angular diameter distance

Luminosity distance

$$\theta = \frac{\text{Size}}{D_A}$$

$$\text{Flux} = \frac{\text{Luminosity}}{4\pi \mathrm{D_L^2}}$$

Reciprocity relation
(distance duality)
Etherington 1933

Theoretical errors

Luminosity and angular diameter distance

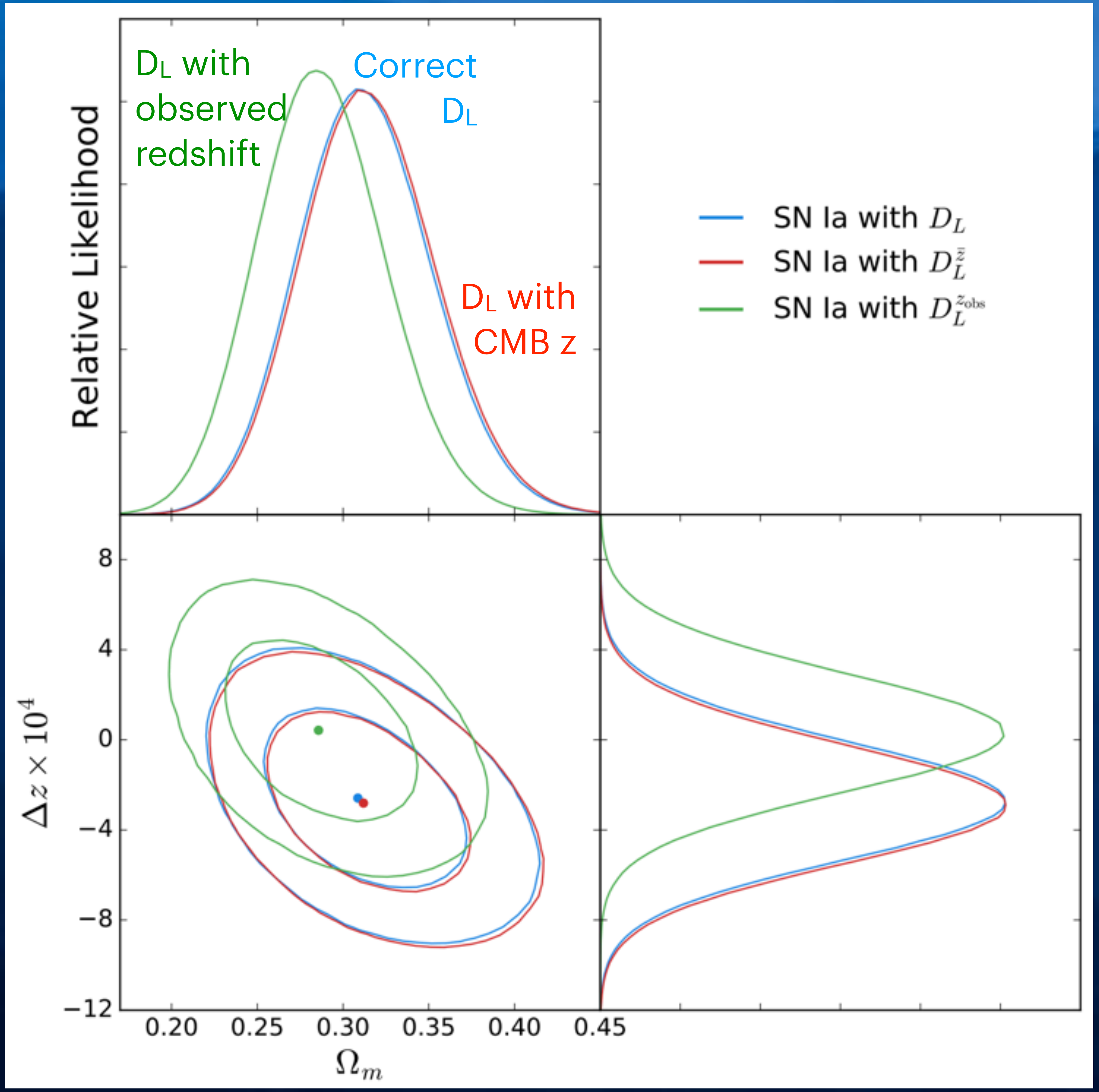
$$D_L(\bar{z}, z_{obs}) = \tilde{D}(\bar{z})(1 + z_{obs})$$

$$D_A(\bar{z}, z_{obs}) = \tilde{D}(\bar{z})/(1 + z_{obs})$$

CMB frame (cosmological) redshift

observed redshift

$$\tilde{D}(z) = \begin{cases} R_0 \sin(\chi) & \text{closed} \\ R_0 \chi & \text{flat} \\ R_0 \sinh(\chi) & \text{open} \end{cases}$$



Calcino et al. 2017 (arXiv:1610.07695)