MULTIMESSENGER ASTRONOMY

(ASTROPHYSICS AS A PROBE OF FUNDAMENTAL PHYSICS)

Rencontres de Vietnam

August 2023

Tamara Davis, University of Queensland

What is Multimessenger Astronomy?

Whenever you have more than one **type** of observation of a source/feature.

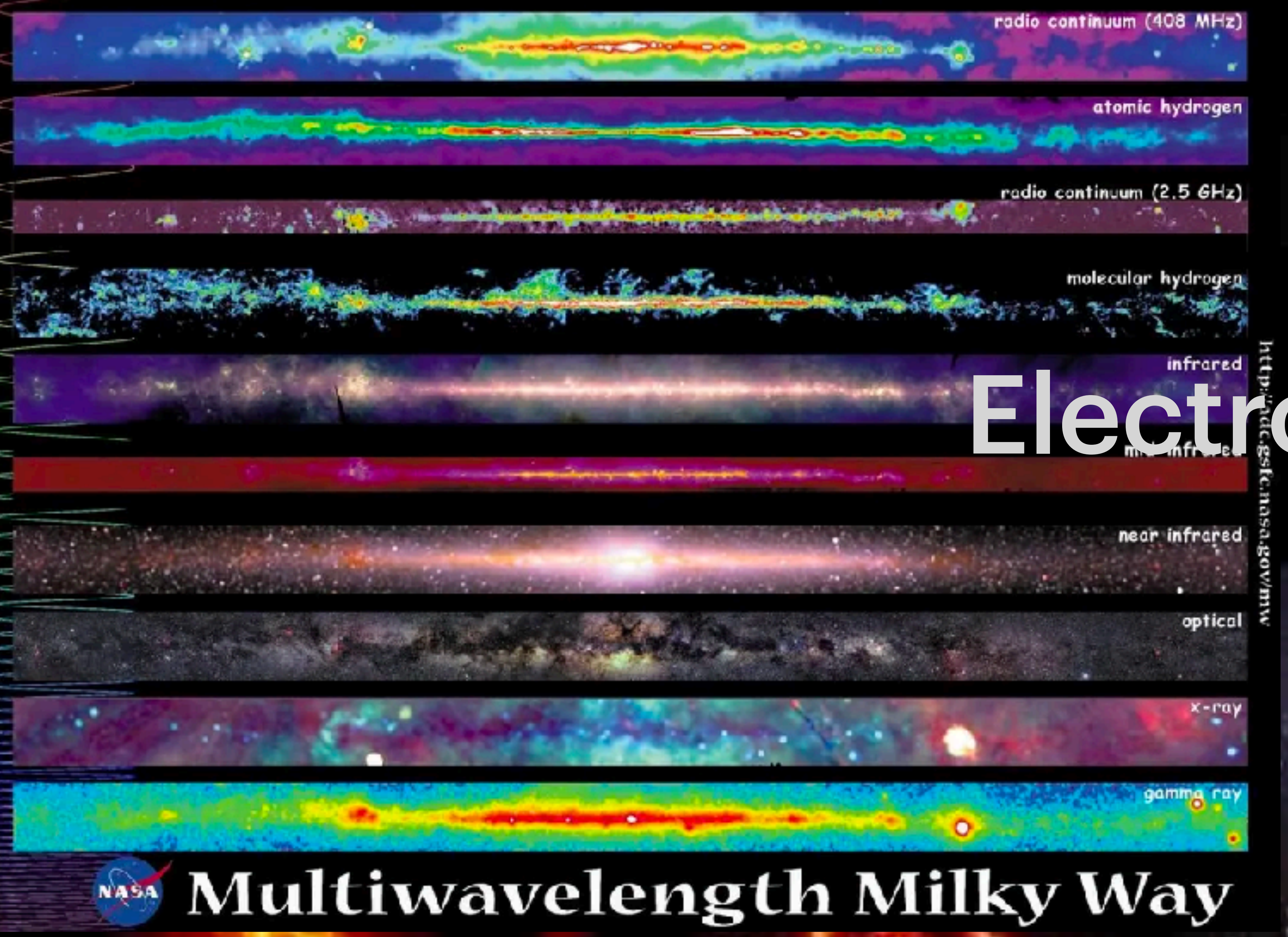
“Messengers” include...

JWST lensing image

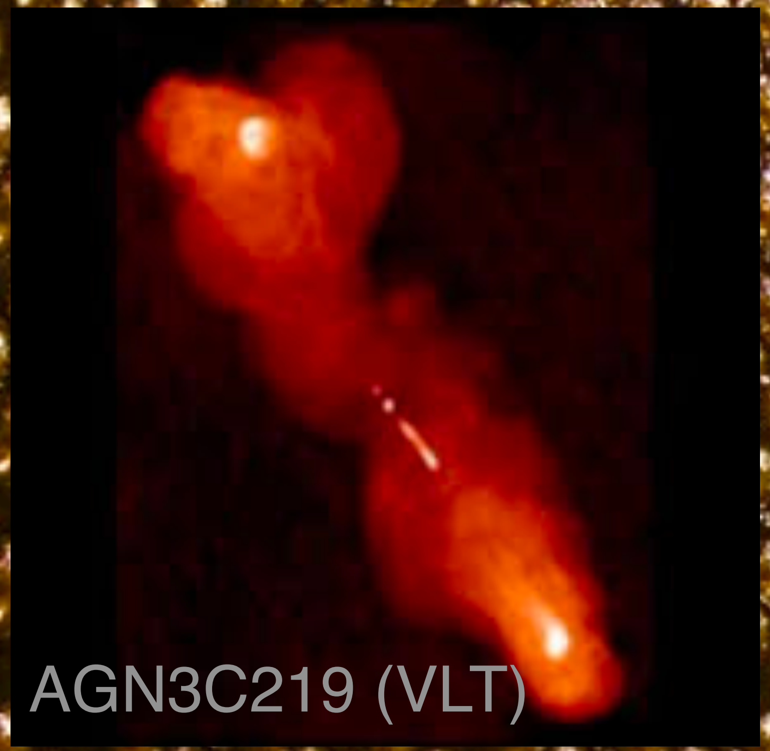
Light

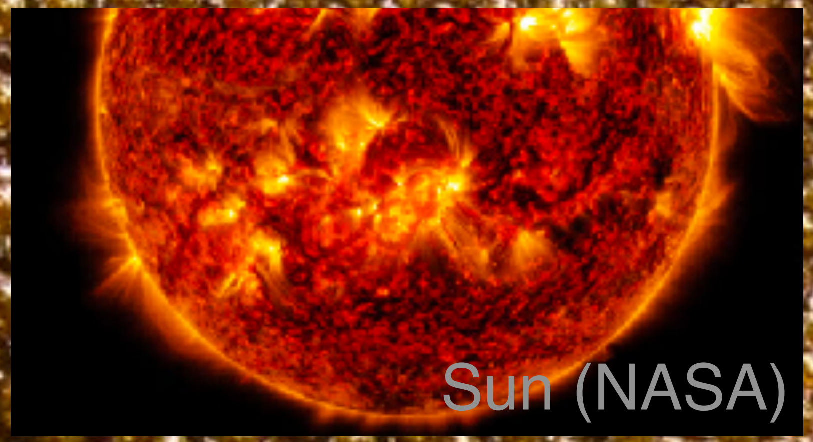
Electromagnetic radiation

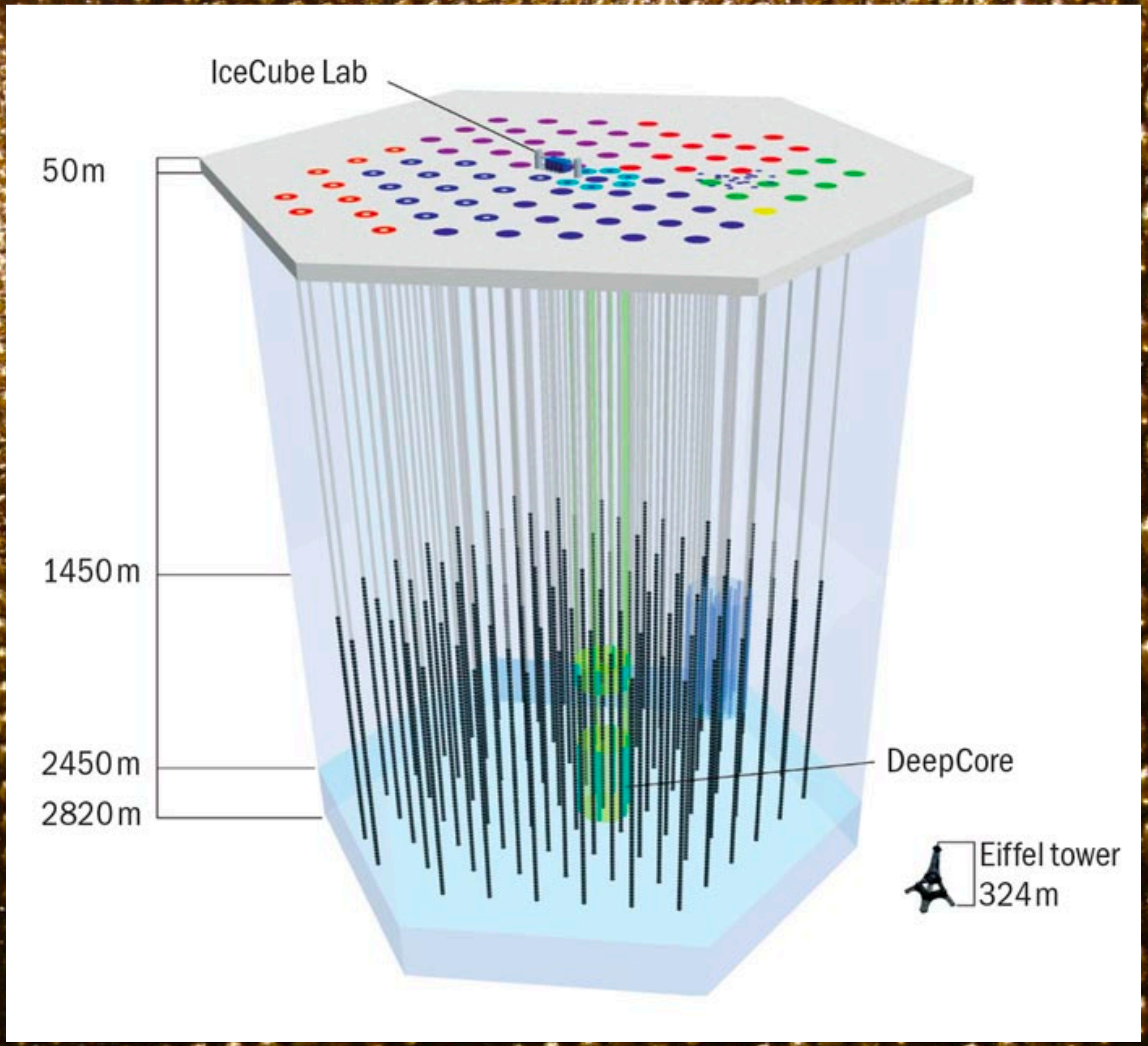
Andromeda (M31): Planck / NASA / ESA




Cosmic Rays
High-energy particles
(usually nuclei)
AGN3C219 (VLT)
Sun (NASA)
SN1987A (Hubble/NASA)
Positron: Anderson 1932
Caltech Archives
Charged particles, so cannot easily localise source
Pierre Auger: ASPERA/G.Toma/A.Saftoiu



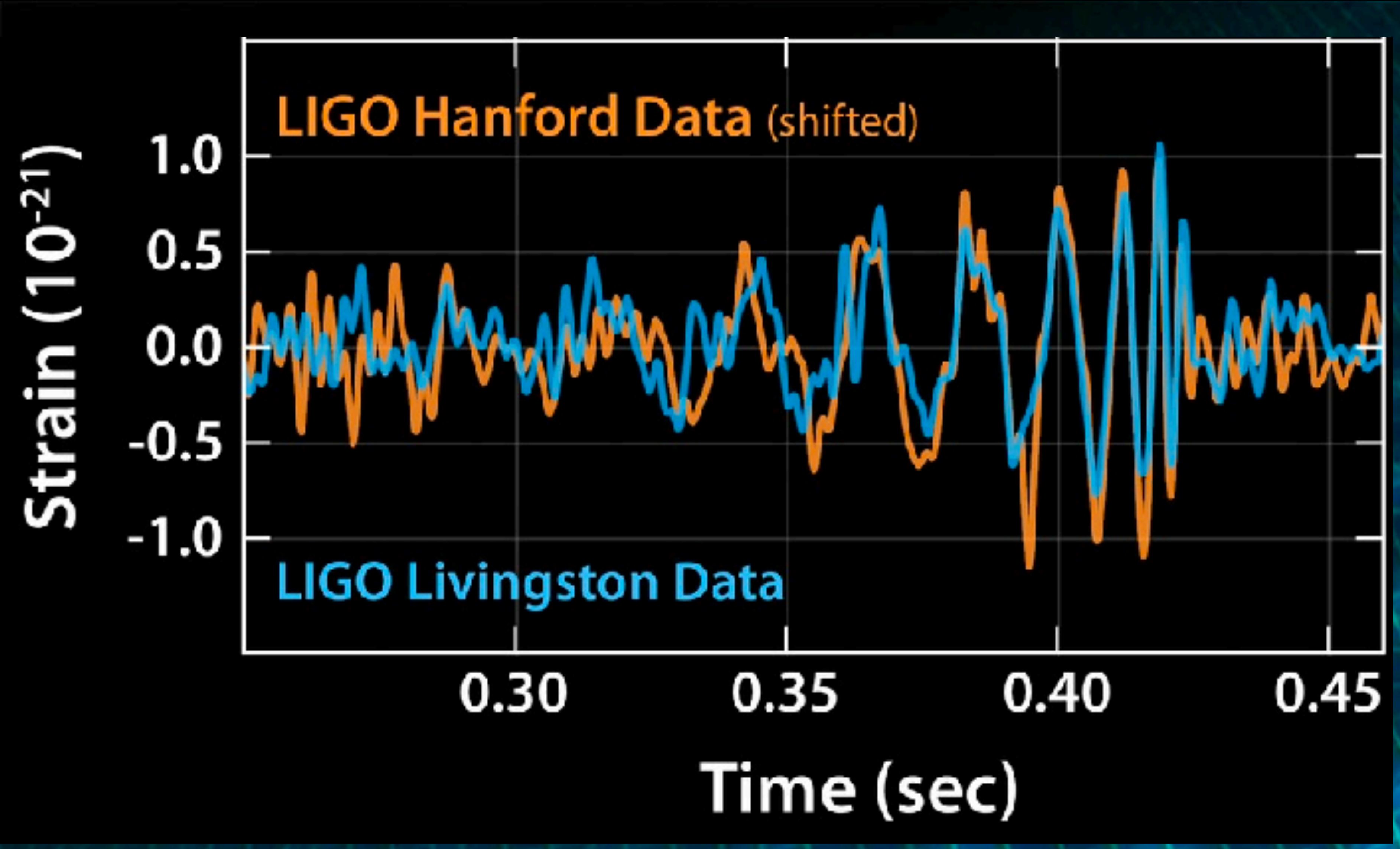




Neutrinos

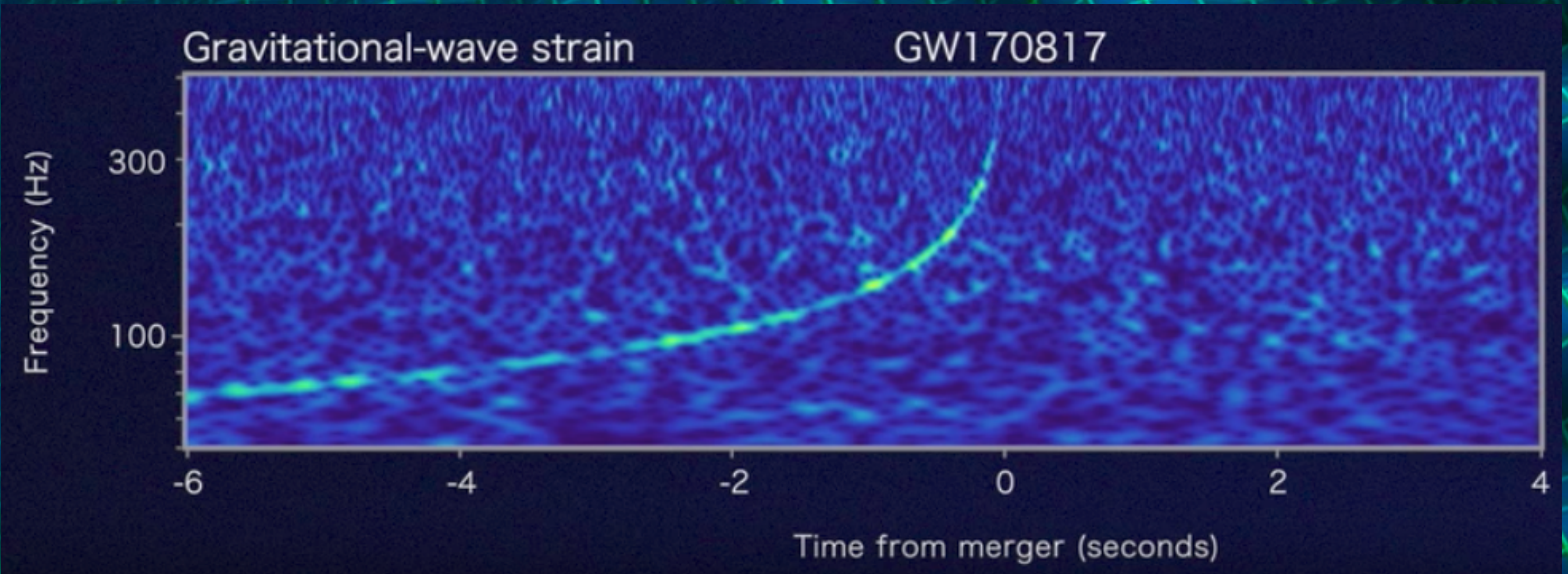
Lightest massive particles

Hyper-Kamiokande (Kamioka Observatory / Inst. for Cosmic Ray Research / U Tokyo)

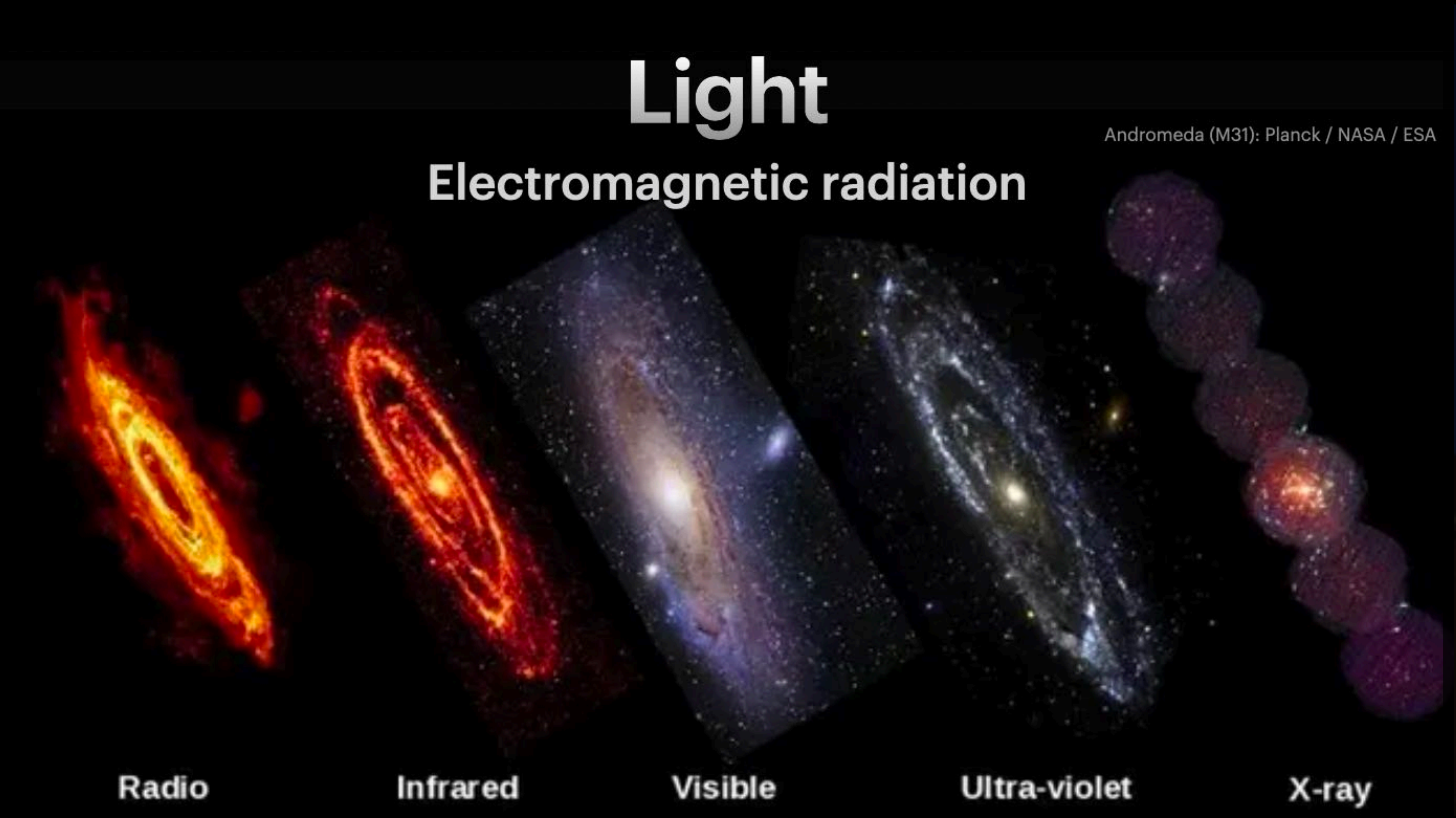


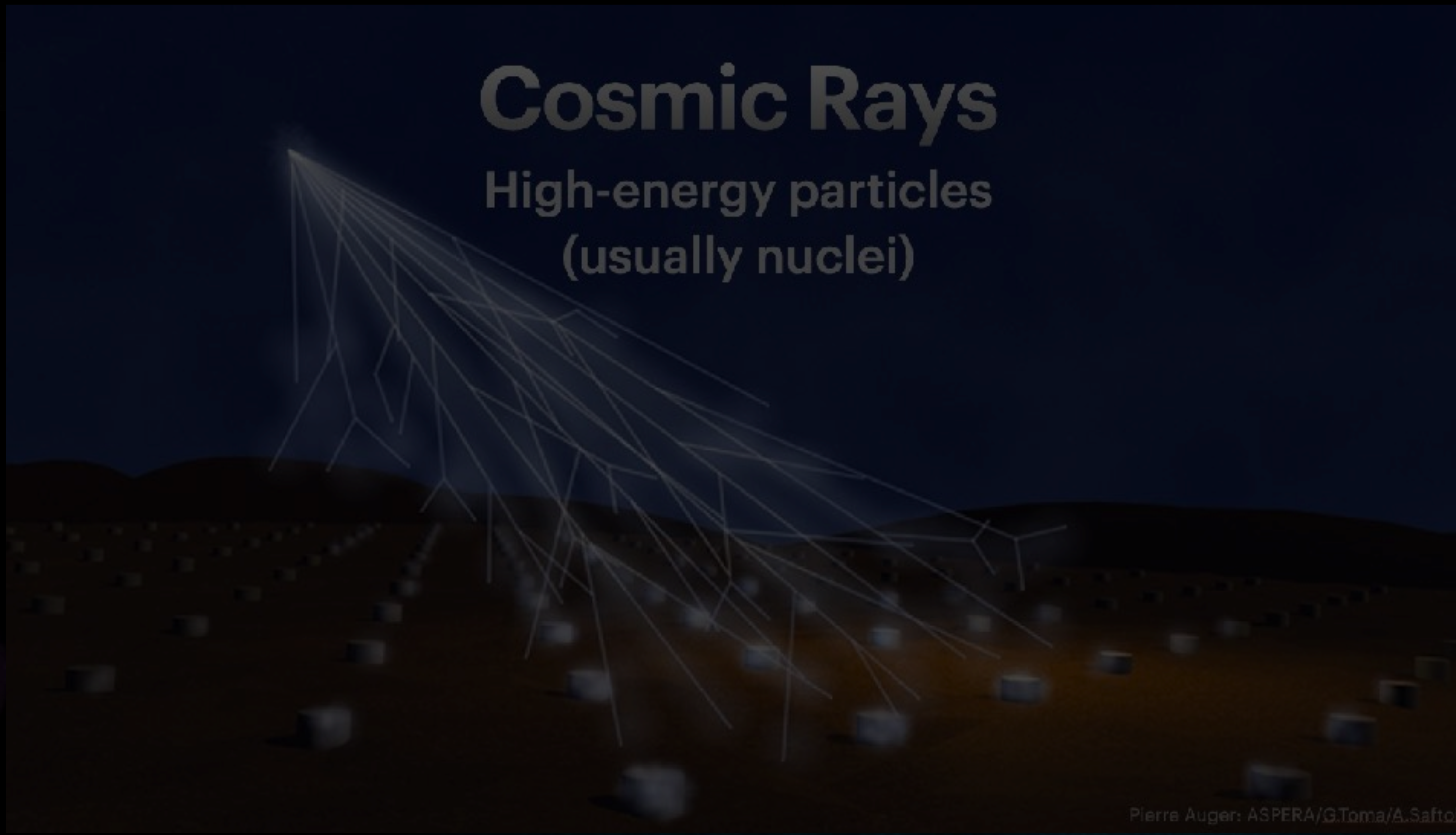
Gravitational Waves

Ripples in spacetime



R. Hurt/Caltech-JPL


Light
Electromagnetic radiation
Andromeda (M31): Planck / NASA / ESA
Radio
Infrared
Visible
Ultra-violet
X-ray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High-energy particles
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Pierre Auger: ASPERA/G.Toma/A.Safto


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Lightest massive particles
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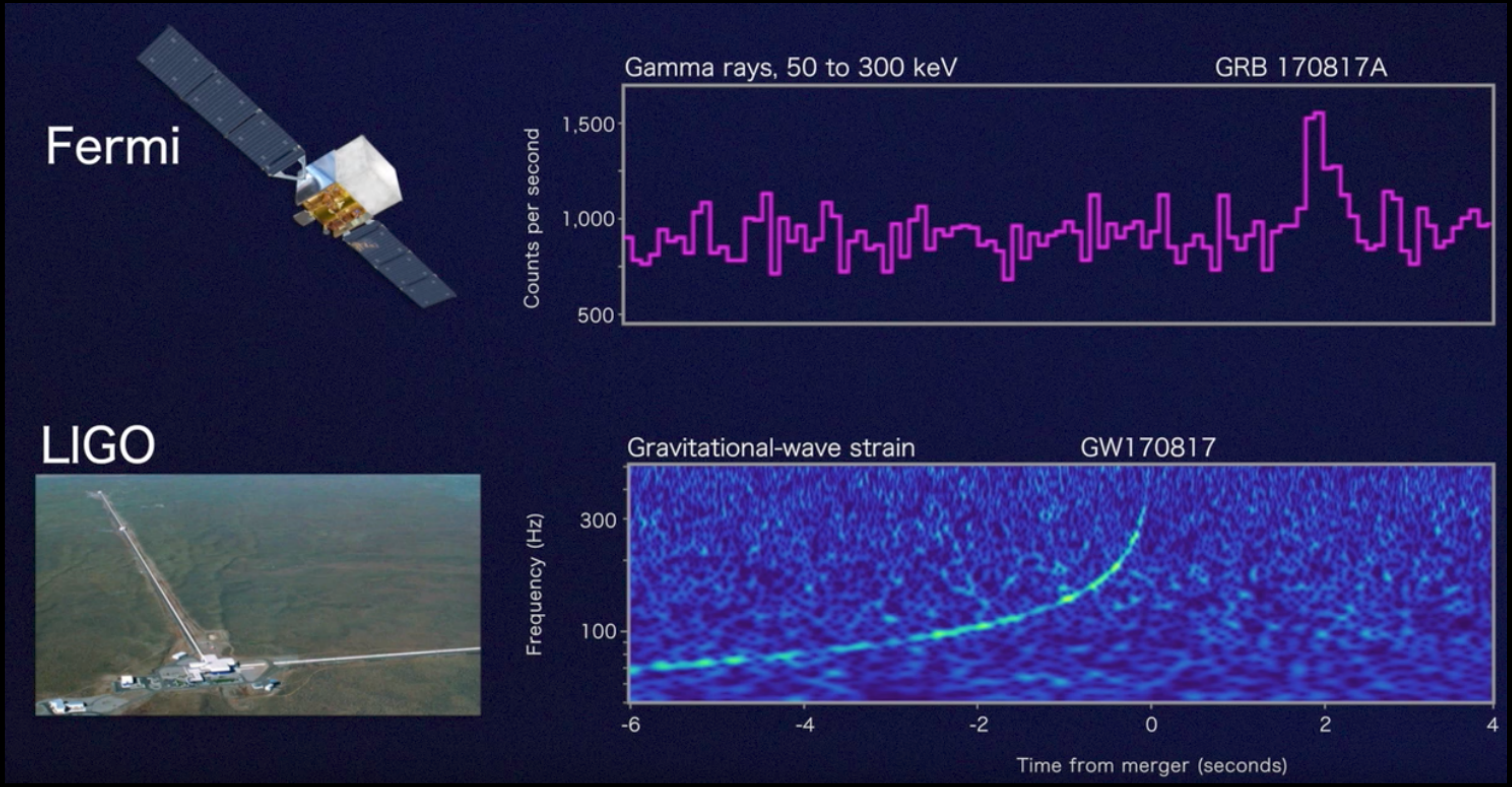
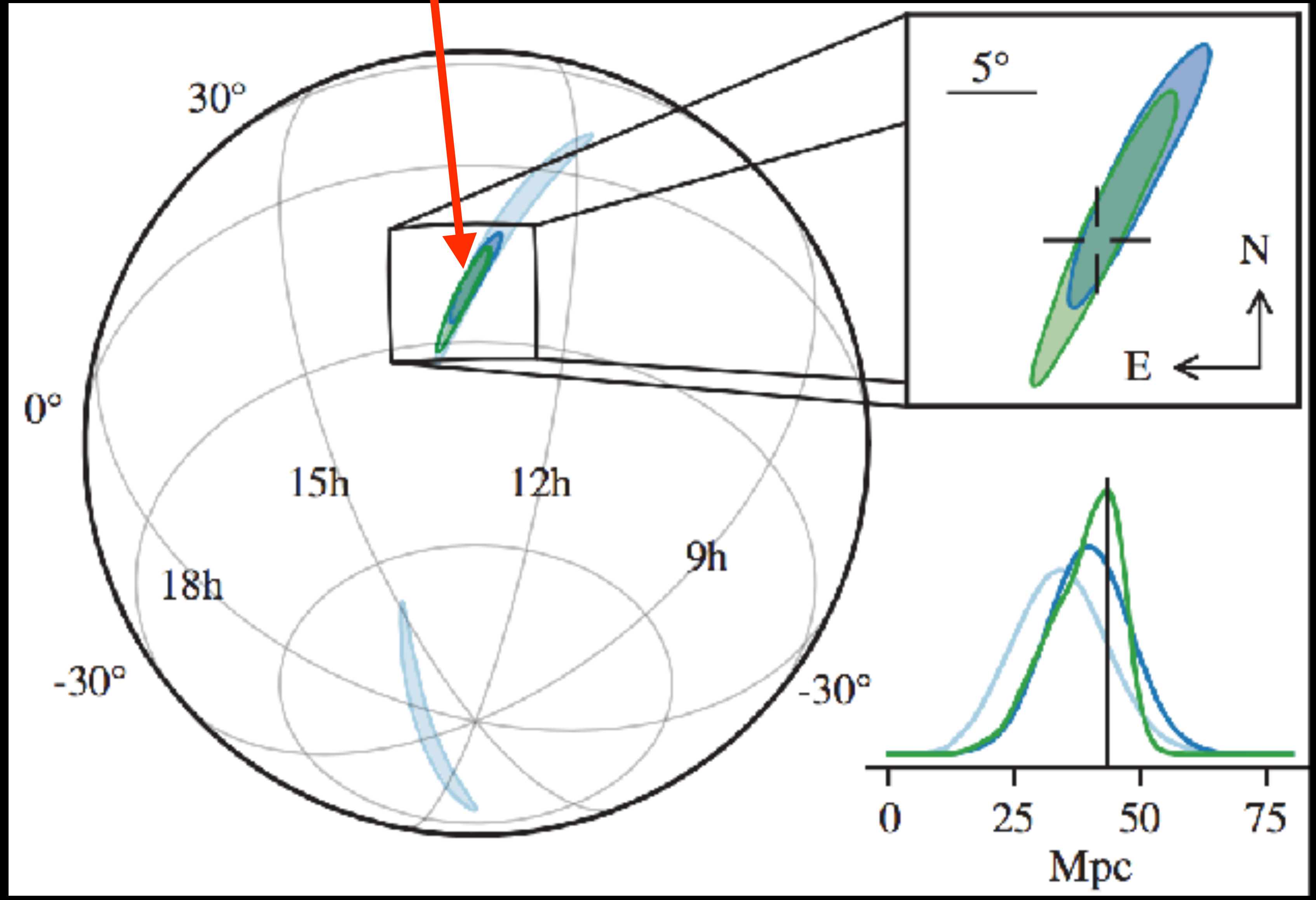
Australian Government
Australian Research Council
OzGrav
ARC Centre of Excellence for Gravitational Wave Discovery
Australian National University
The University of Melbourne
The University of Sydney
The University of Queensland Australia
Swinburne
The University of Adelaide
Monash University
The University of Western Australia
CSIRO

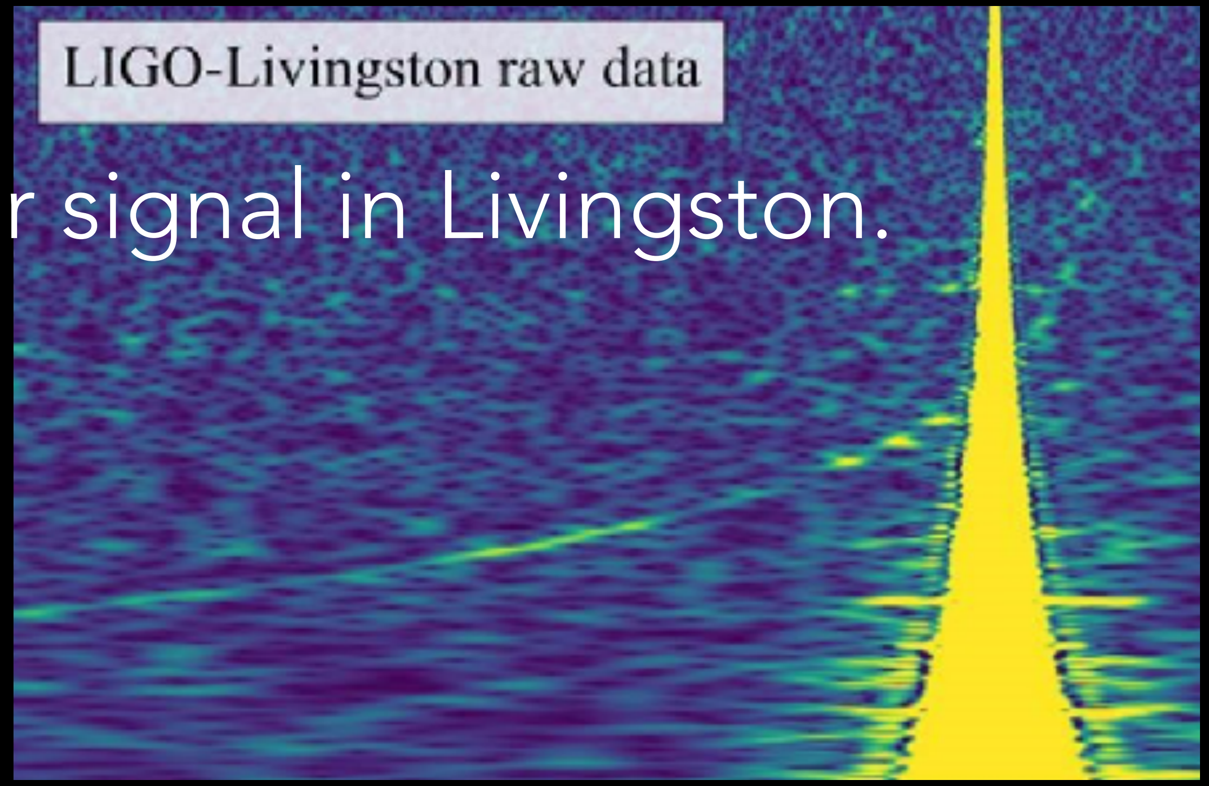
GRAVITATIONAL WAVES - 2017 NEUTRON STAR MERGER!



150x the size of full moon

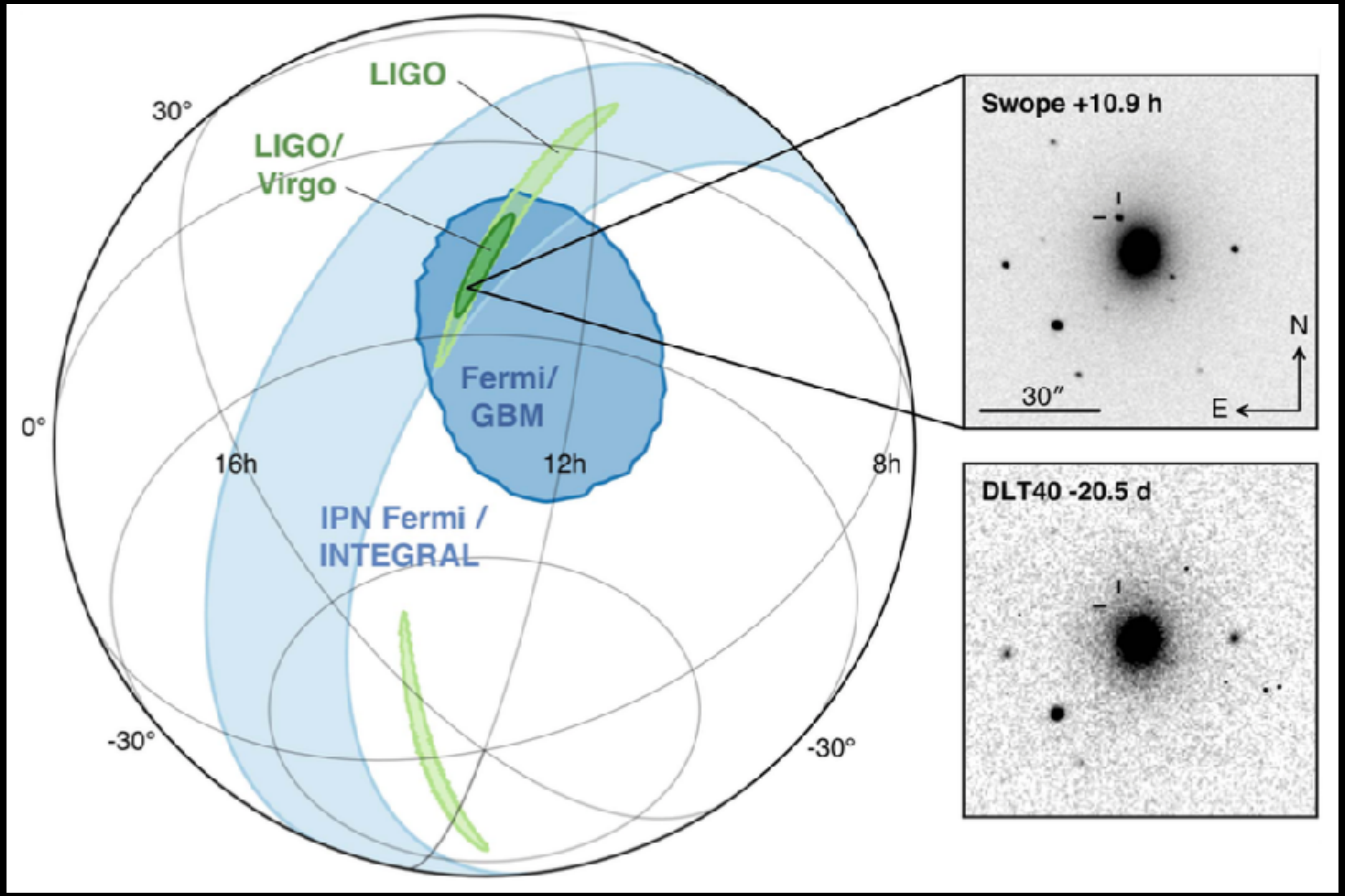


- [0s] GW170817: Lasted ~99s. 24Hz to 1kHz (LIGO Hanford @12:41:04 UTC)
- [100s] GRB170817a: **Detected by Fermi 2s** after coalescence. Announced 14s later.
- Knowledge of coincident GRB triggered visual inspection of LIGO Livingston -> Clear signal in Livingston.
- [40min] Highly significant binary event disseminated @13:21:42 UTC
- Virgo searched, detected (SNR=2).
- [5hr] approx sky map released @17:54:51 UTC
- [11hr] preliminary sky map released @ 23:54:40 UTC



GRAVITATIONAL WAVES - 2017 NEUTRON STAR MERGER!

OPTICAL SOURCE DETECTED!



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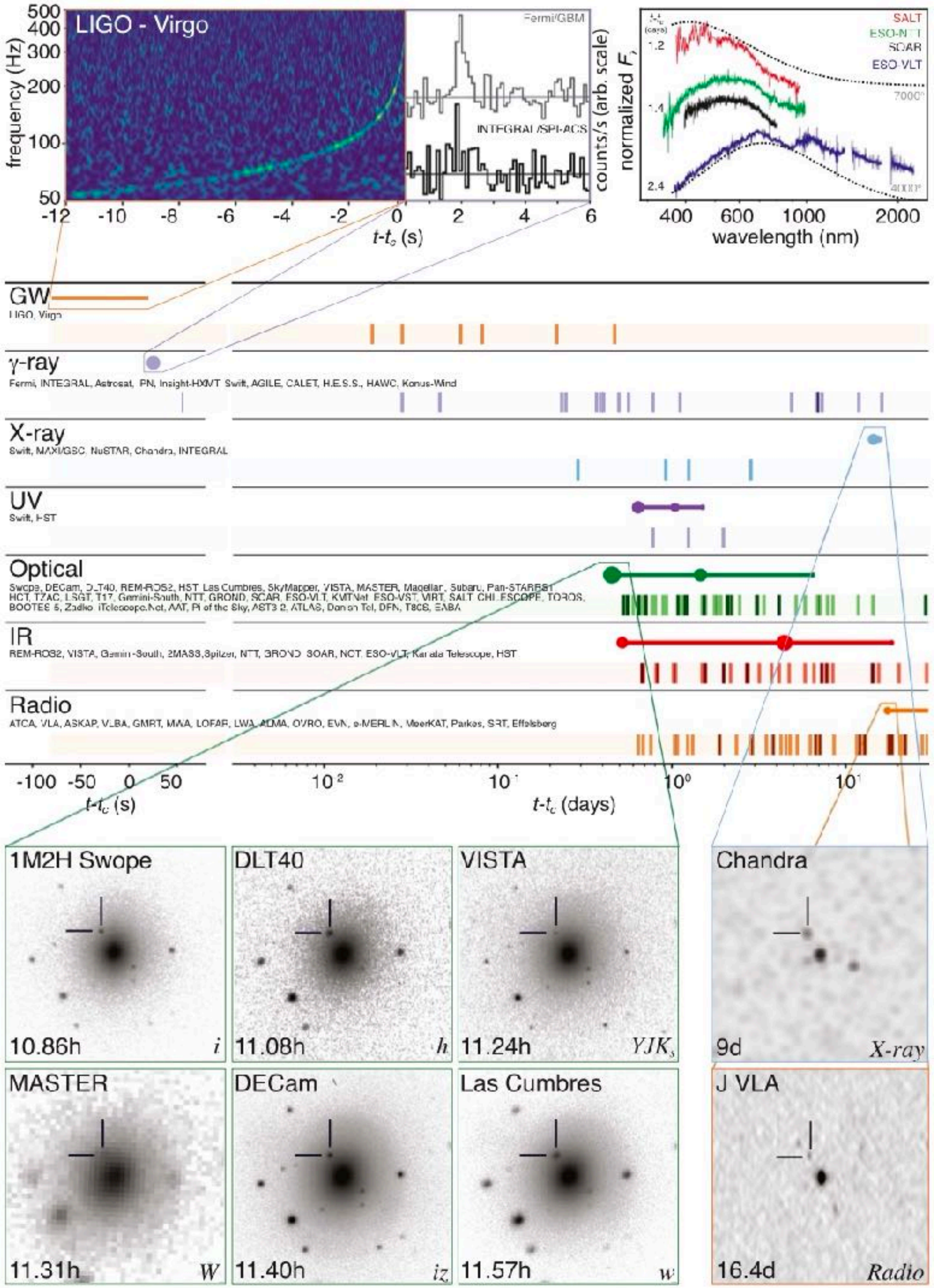
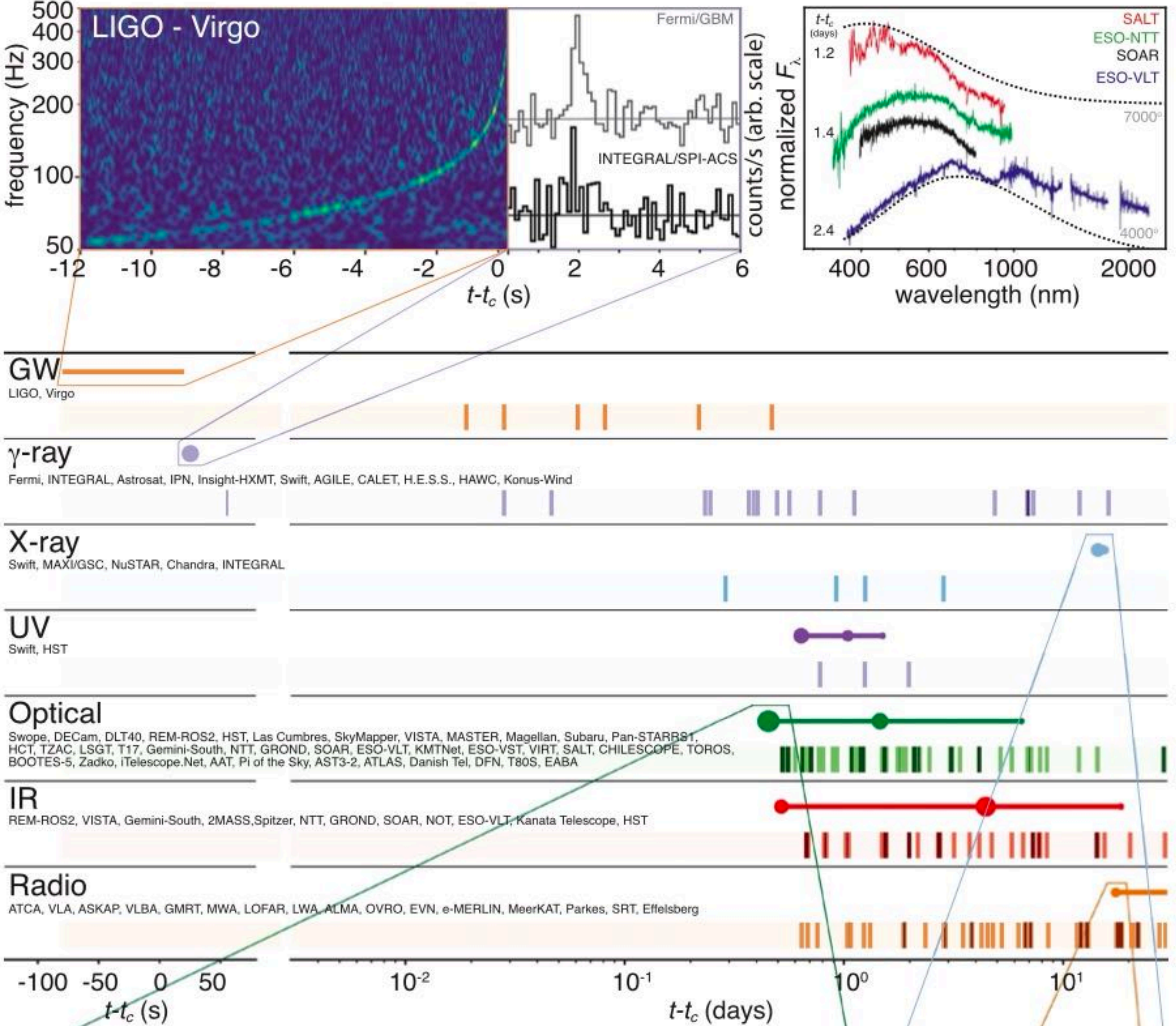
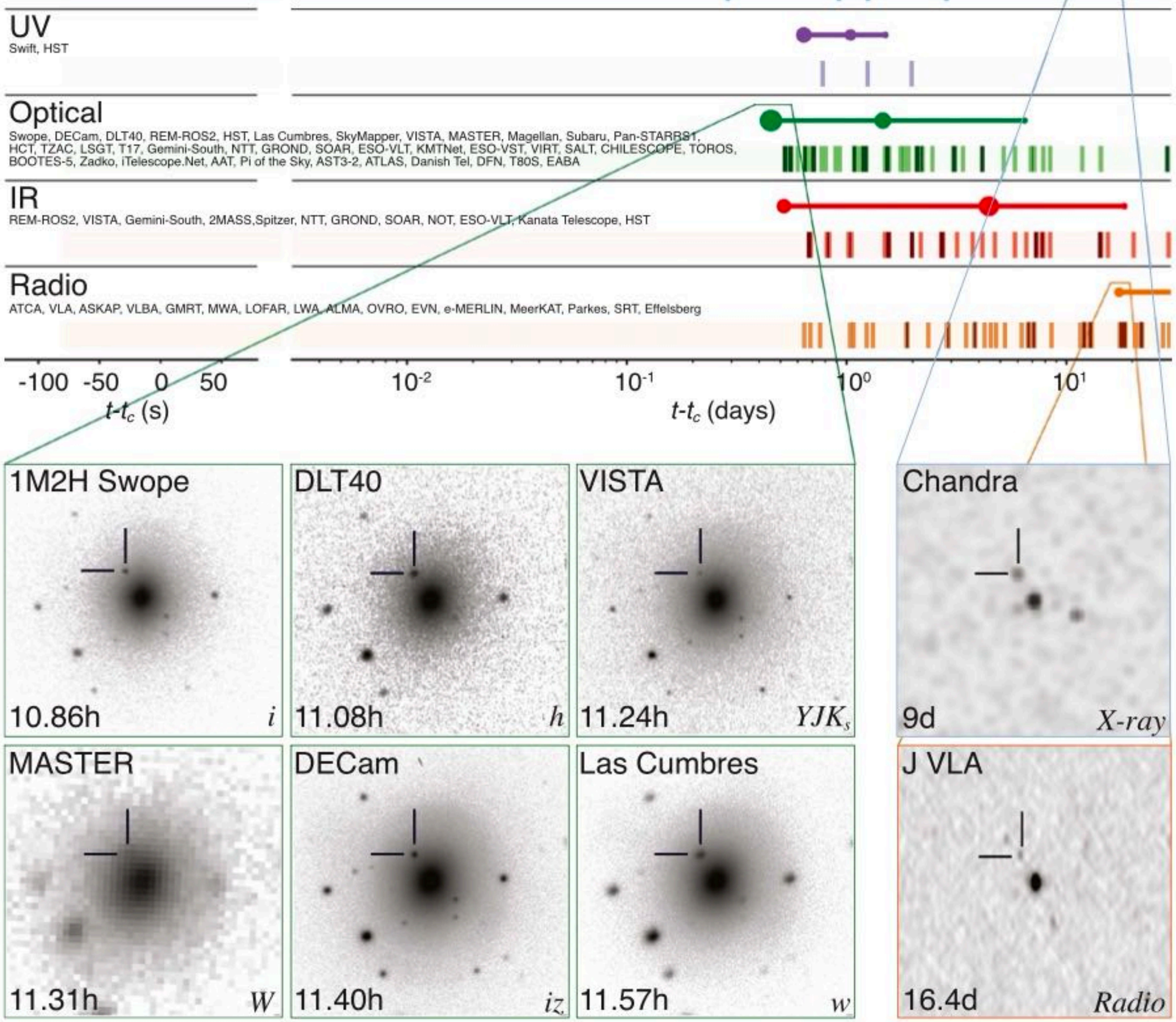

LIGO - Virgo
frequency (Hz)
t-t_c (s)
Fermi/GBM
INTEGRAL/SPI-ACS
counts/s (arb. scale)
SALT
ESO-NTT
SOAR
ESO-VLT
normalized F_λ
wavelength (nm)
GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
UV
Swift, HST
Optical
IR
Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
t-t_c (s)
t-t_c (days)
1M2H Swope
10.86h
DLT40
11.08h
VISTA
11.24h
Chandra
9d
X-ray
MASTER
11.31h
DECam
11.40h
Las Cumbres
11.57h
J VLA
16.4d
Radio



LIGO - Virgo
frequency (Hz)
Fermi/GBM
INTEGRAL/SPI-ACS
counts/s (arb. scale)
t-tc (s)
SALT
ESO-NTT
SOAR
ESO-VLT
normalized Fλ
7000°
4000°
wavelength (nm)
GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
UV
Swift, HST
Optical
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1, HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS, BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN, T80S, EABA
IR
REM-ROS2, VISTA, Gemini-South, 2MASS,Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST
Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
t-tc (s)
t-tc (days)


UV
Swift, HST
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Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1, HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS, BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN, T80S, EABA
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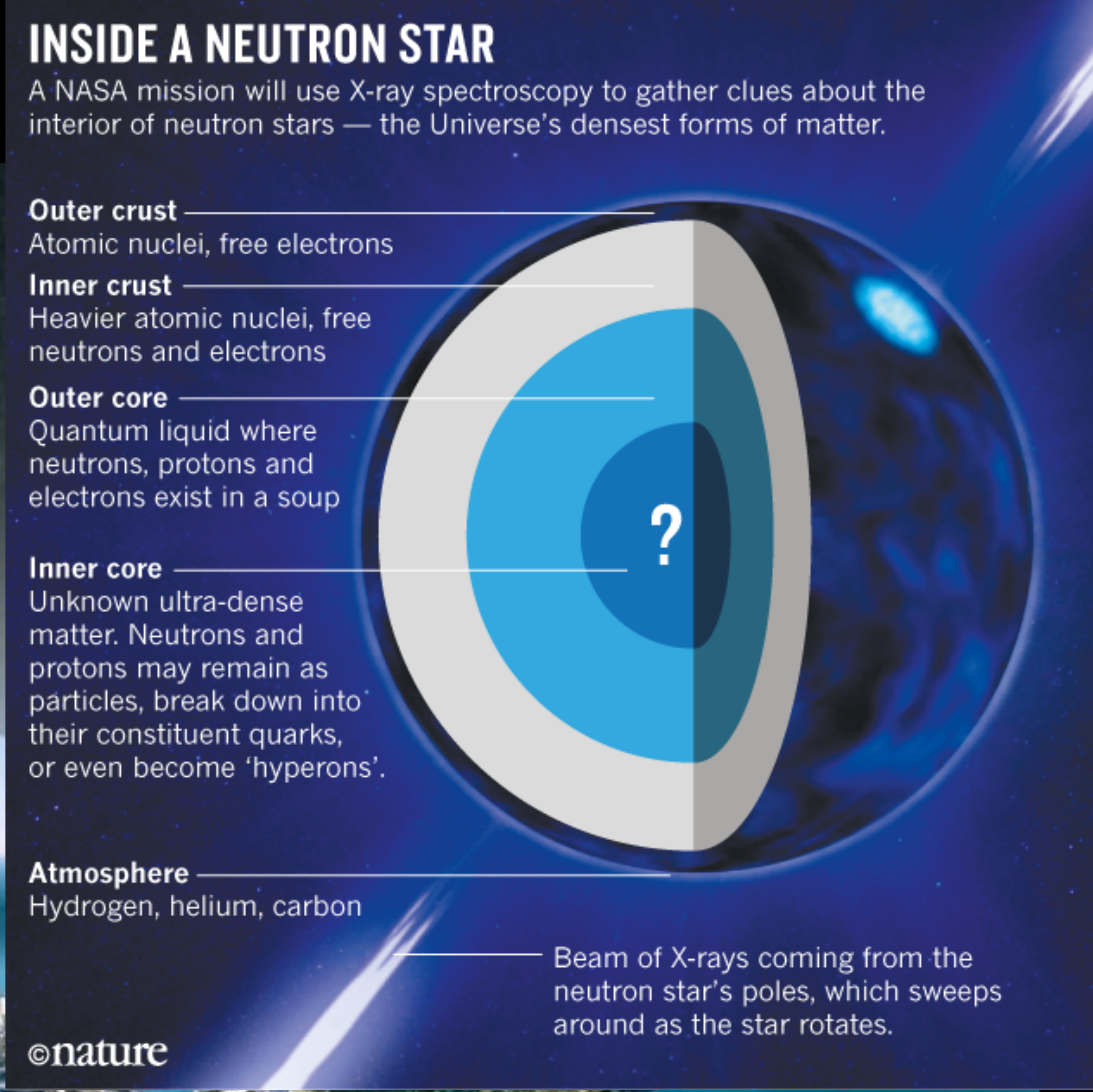
-100 -50 0 50
t-t_c (s)
10^{-2} 10^{-1} 10^0 10^1
t-t_c (days)
1M2H Swope 10.86h i
DLT40 11.08h h
VISTA 11.24h YJK_s
Chandra 9d X-ray
MASTER 11.31h W
DECam 11.40h iz
Las Cumbres 11.57h w
J VLA 16.4d Radio

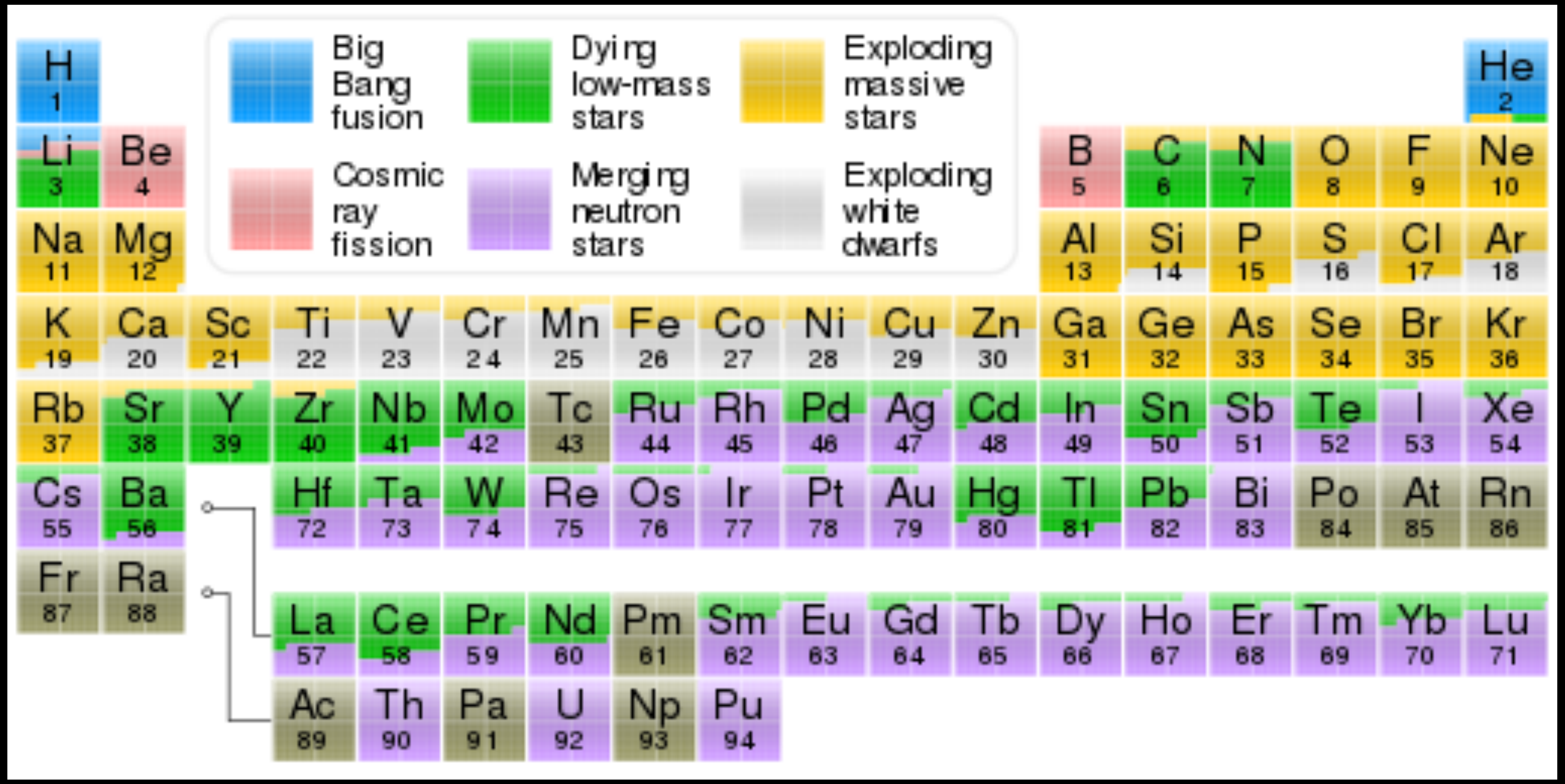
Why all the excitement?

WHAT IS A NEUTRON STAR?

- Mass of the sun in the size of a city.
- Basically an enormous nucleus.
- 1 tsp weighs a billion tonnes
- Stiffest material we know of in the universe
- Magnetic fields 10^8 -10^{15} x Earth's



WHERE DID THE HEAVY ELEMENTS COME FROM?



Confirmed where most of the gold in the universe comes from!!

(1,300-10,000 x Earth Mass precious metals in this one)

GRAVITY TRAVELS AT THE SPEED OF LIGHT

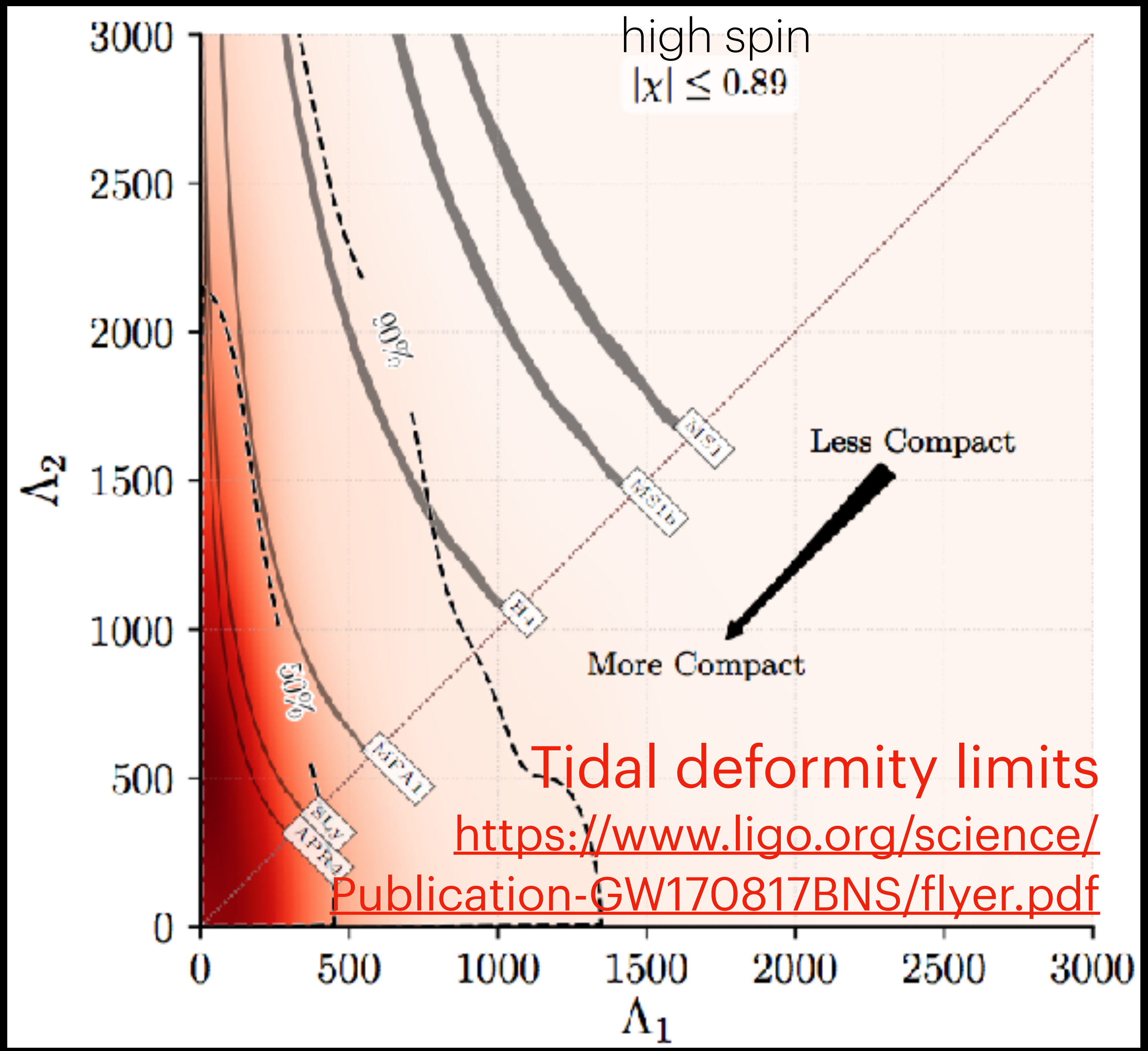
1.7s difference over time since the dinosaurs (130Myr)

$$\Delta v_{grav\text{-}light} = 0c^{+7\times10^{-16}c}_{-3\times10^{-15}c}$$

Also no Lorentz violation and equivalence principle holds.

HOW DOES NUCLEAR MATERIAL BEHAVE?

Also sensitive to point mass, spin, tidal dynamics.
Thus sensitive to stiffness / size / equation of state of star.



Tidal deformity limits
https://www.ligo.org/science/Publication-GW170817BNS/flyer.pdf

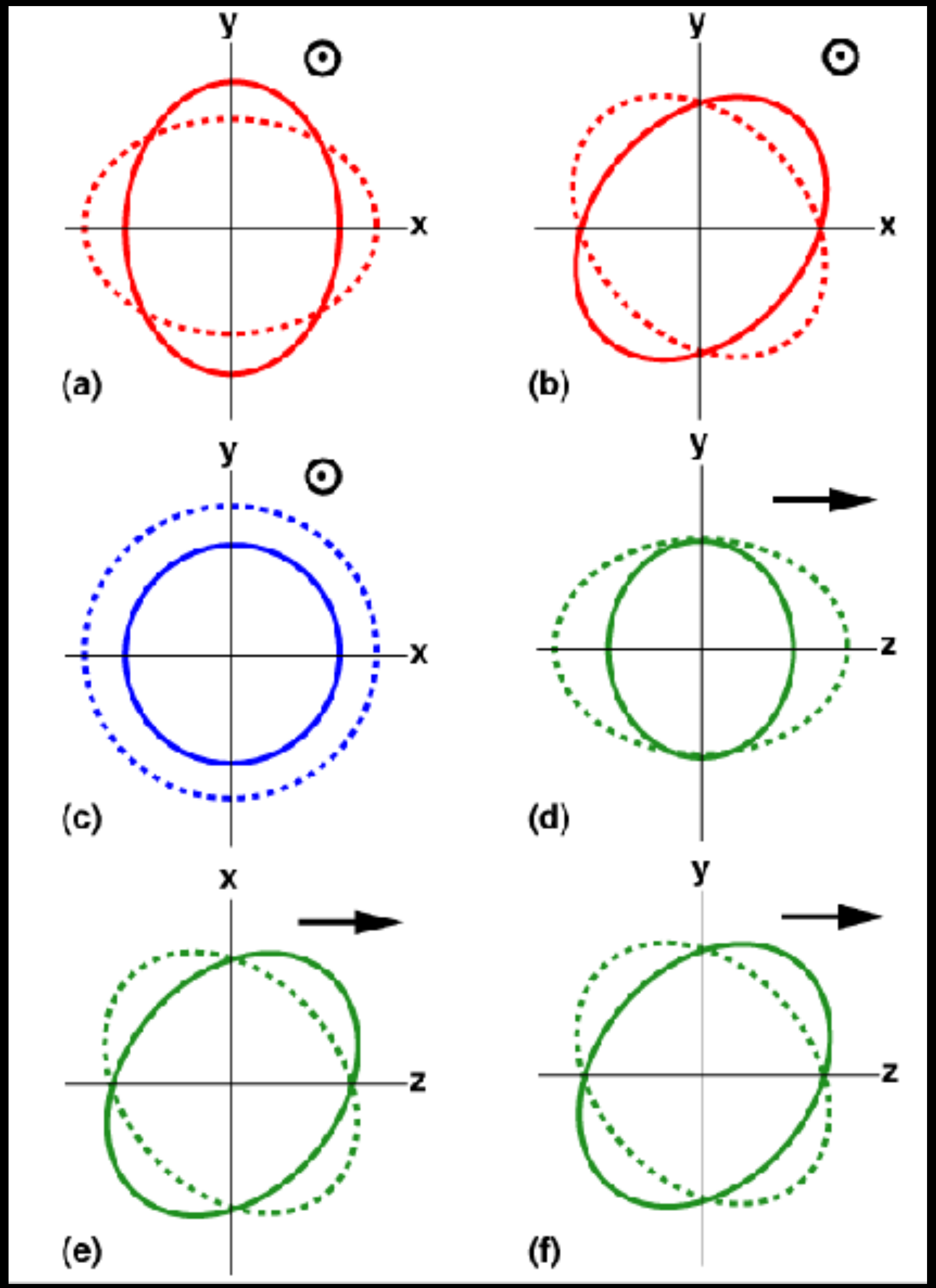
ApJL 848, L13

RULES OUT SOME NON-STANDARD GRAVITY THEORIES

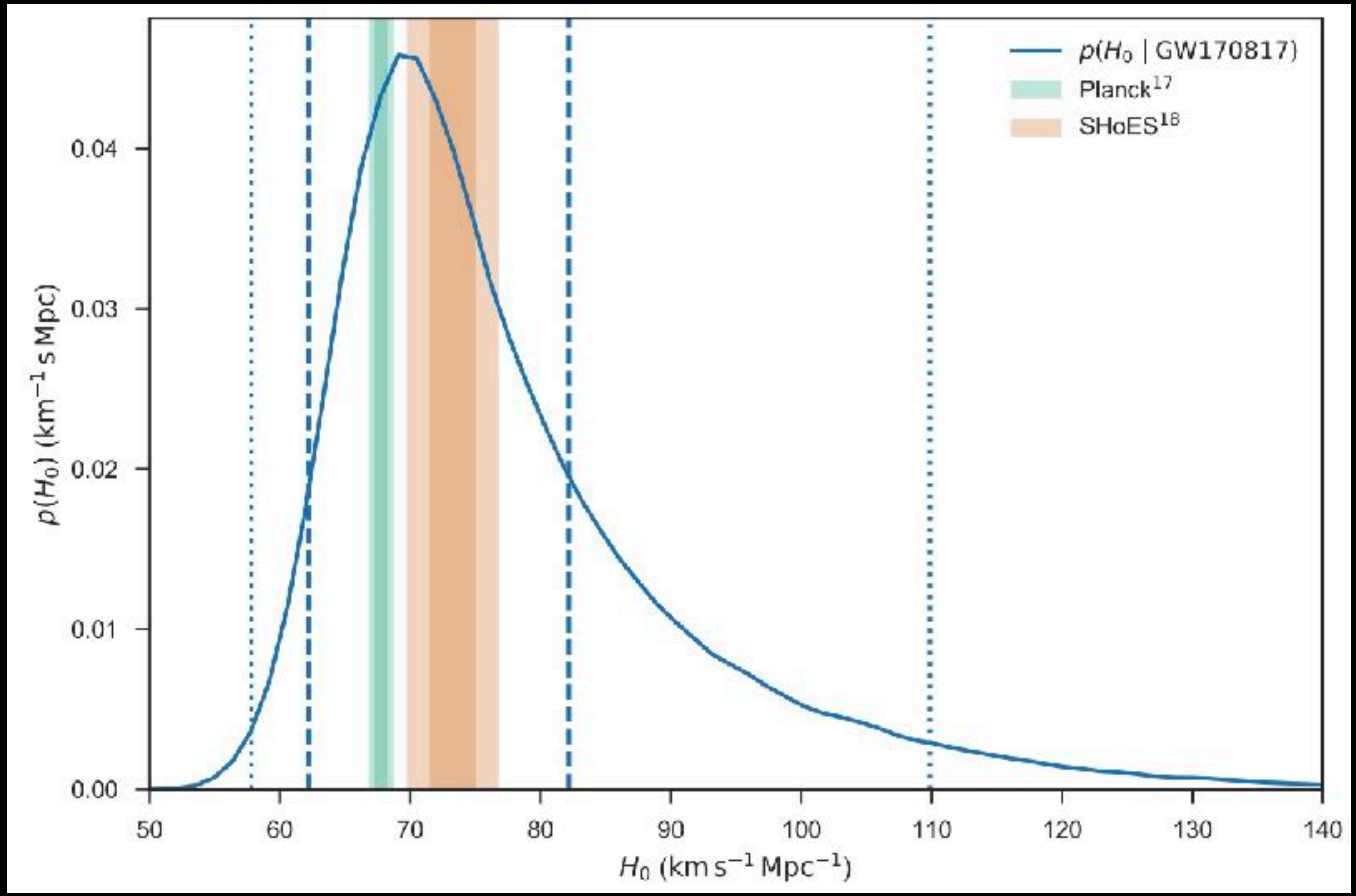
Polarization

Permitted by GR

Forbidden by GR, but possible in other metric theories of gravity



MEASURED EXPANSION RATE OF THE UNIVERSE



$H_0 = 70.0 \pm^{12.0}_{8.0}$ km/s/Mpc

STATE OF COSMOLOGY - CONCORDANCE(?)

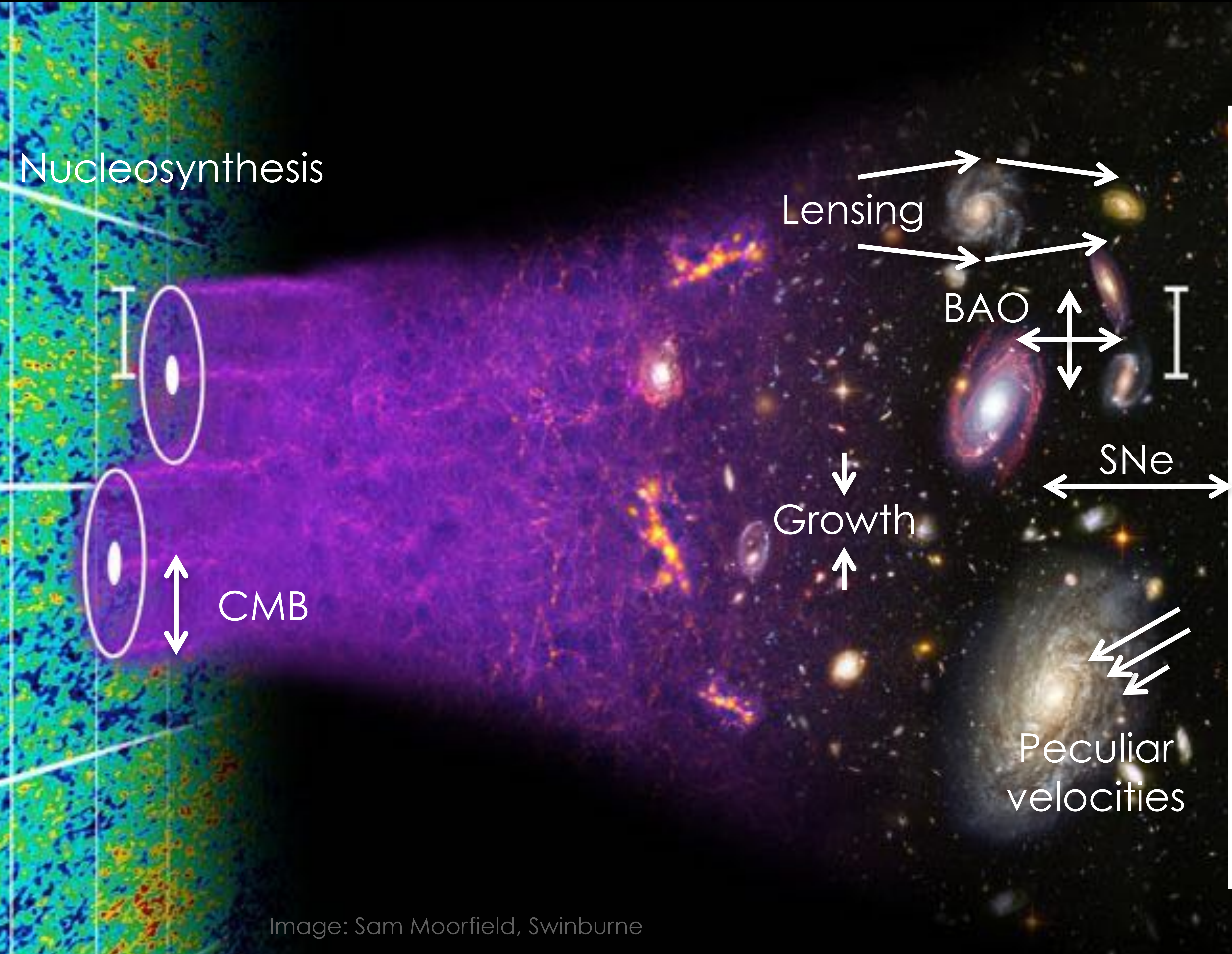


Image: Sam Moorfield, Swinburne

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
$H_0\ [\mathrm{km\,s^{-1}\,Mpc^{-1}}]$		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

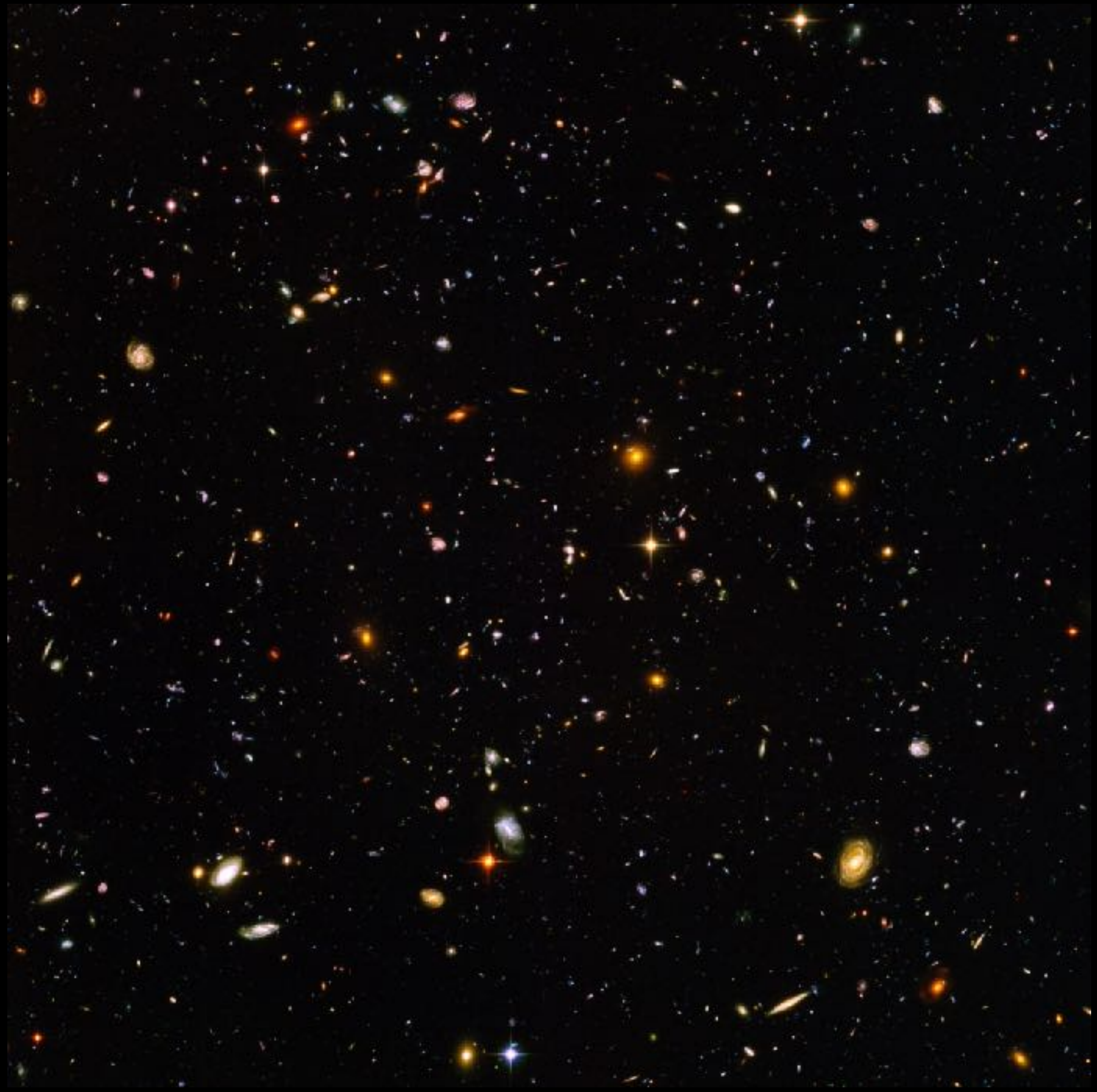
better than 1% precision

Cosmological conundrums

Dark Matter

pulls, clumpy

Dark Energy



pushes, smooth

Cosmological tensions

H_0 tension

Expansion rate of the universe at present day

$$H_0$$

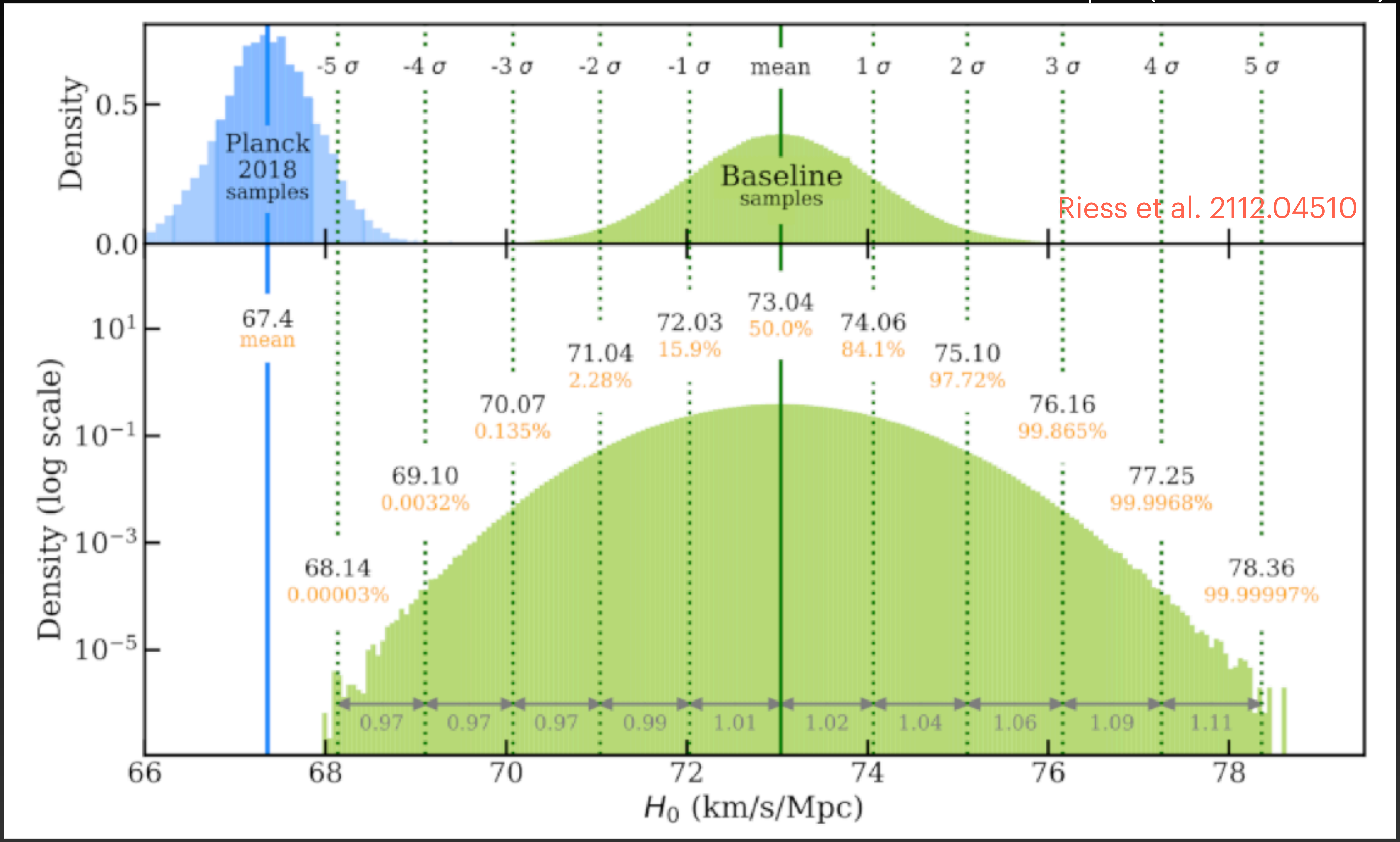
$$v = HD$$

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

$$v(t_0) = H_0 D_0$$

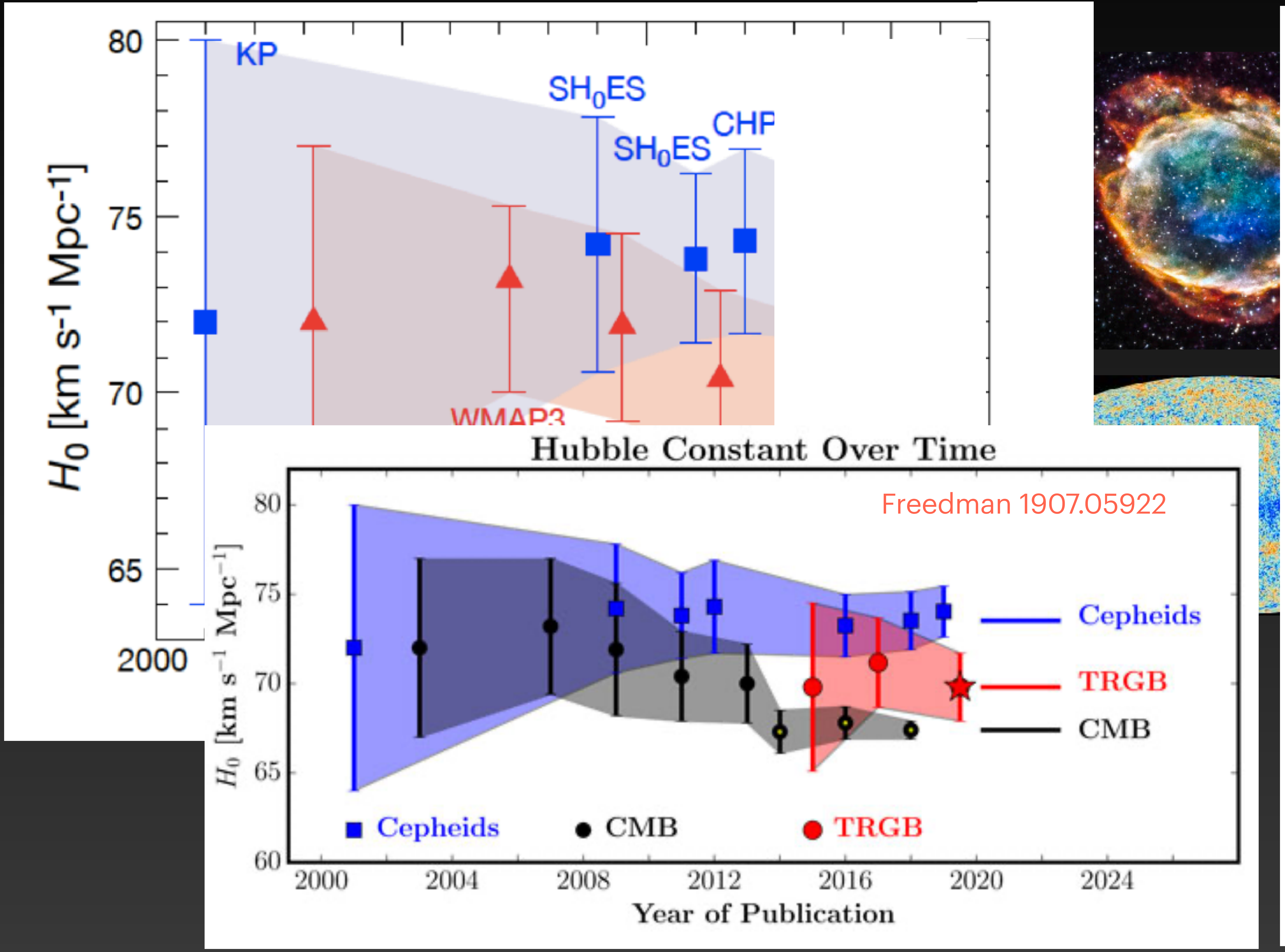
H_0 = Current expansion rate

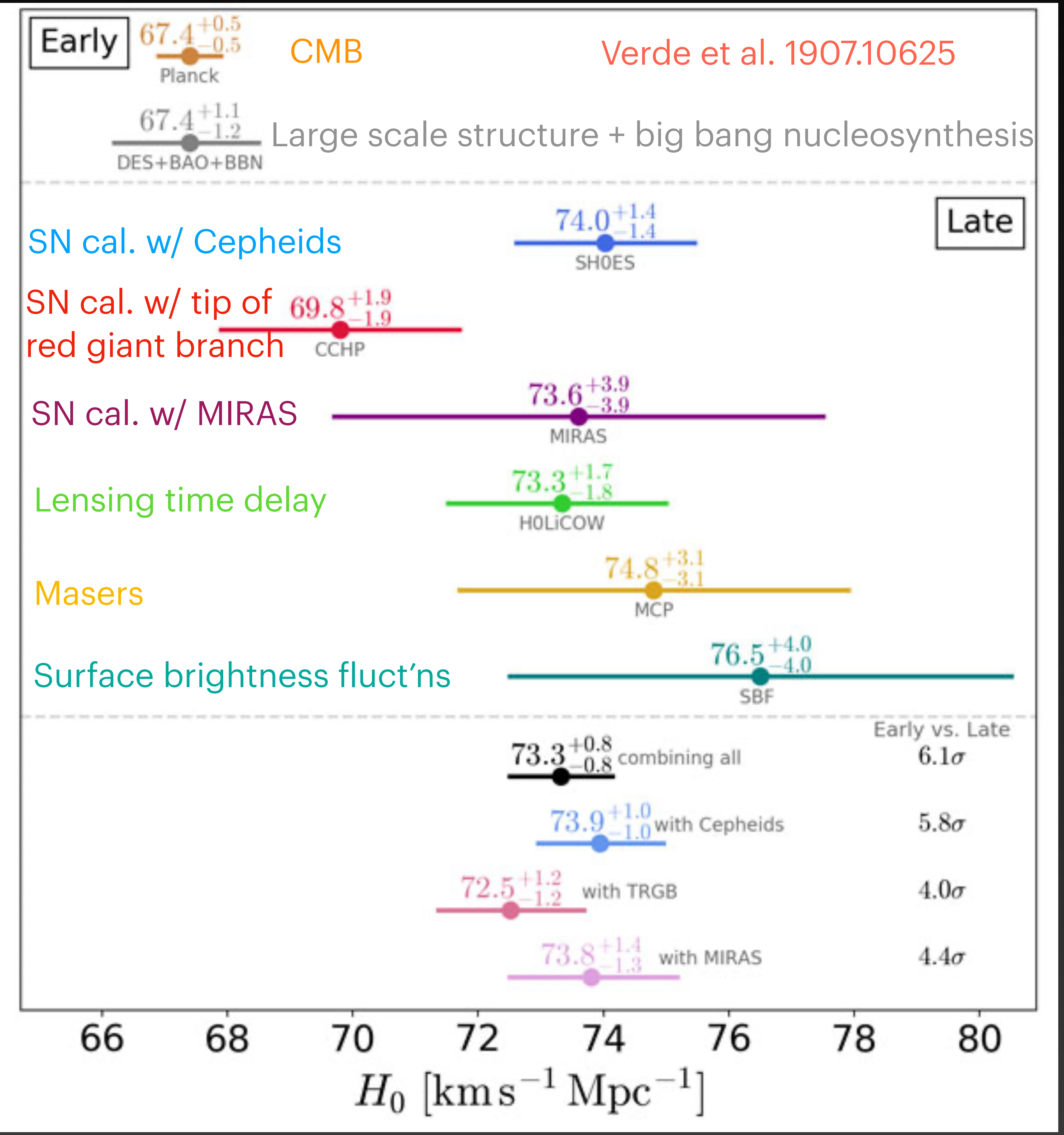
H_0 = 73.04 ± 1.04 km s^{-1} Mpc^{-1} (Riess et al. 2022)



Cosmological tensions

H_0 tension





$H_0 = 69.6 \pm 1.9$ km s^{-1} Mpc^{-1} (Freedman et al. 2020)

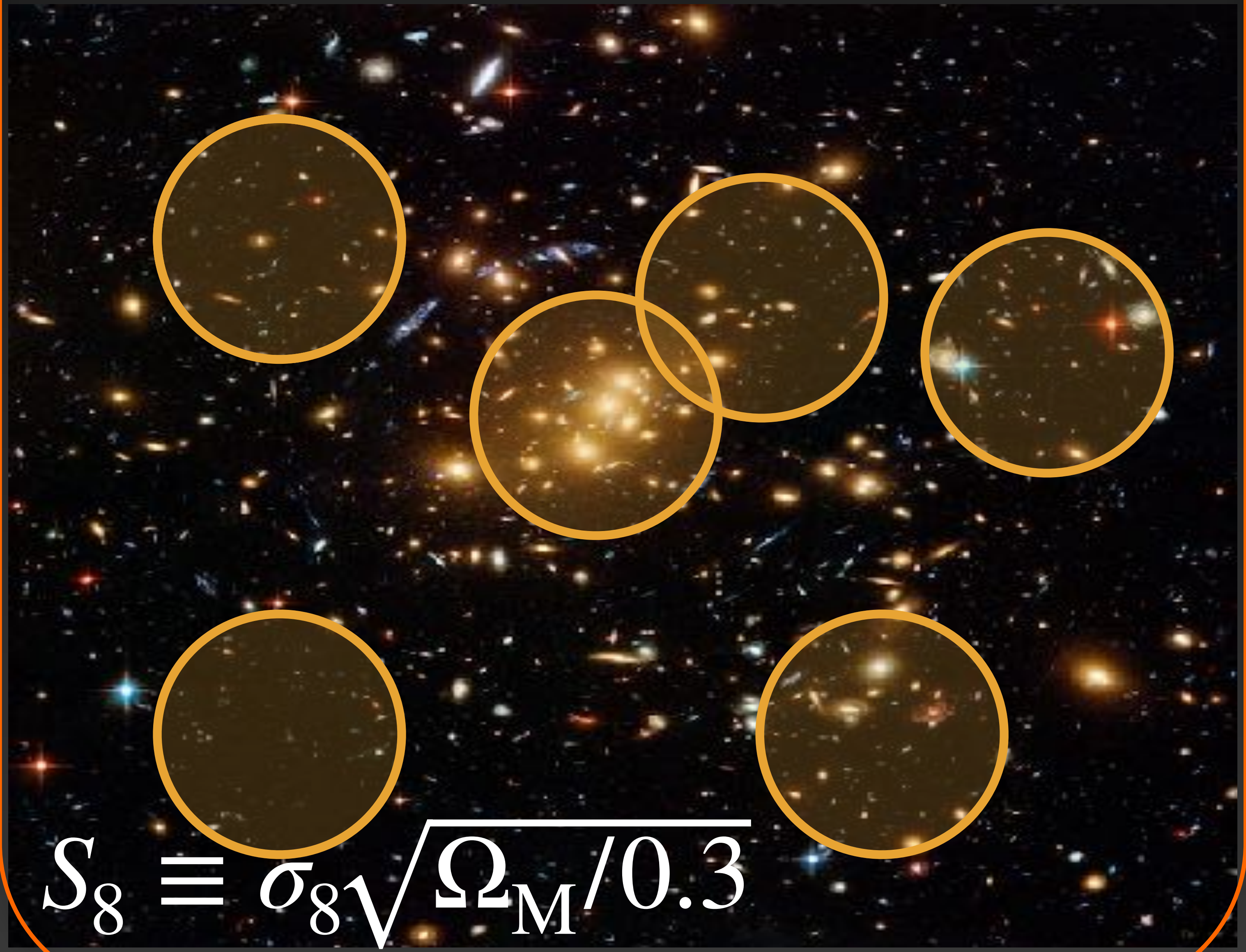
Cosmological tensions

S_8 tension

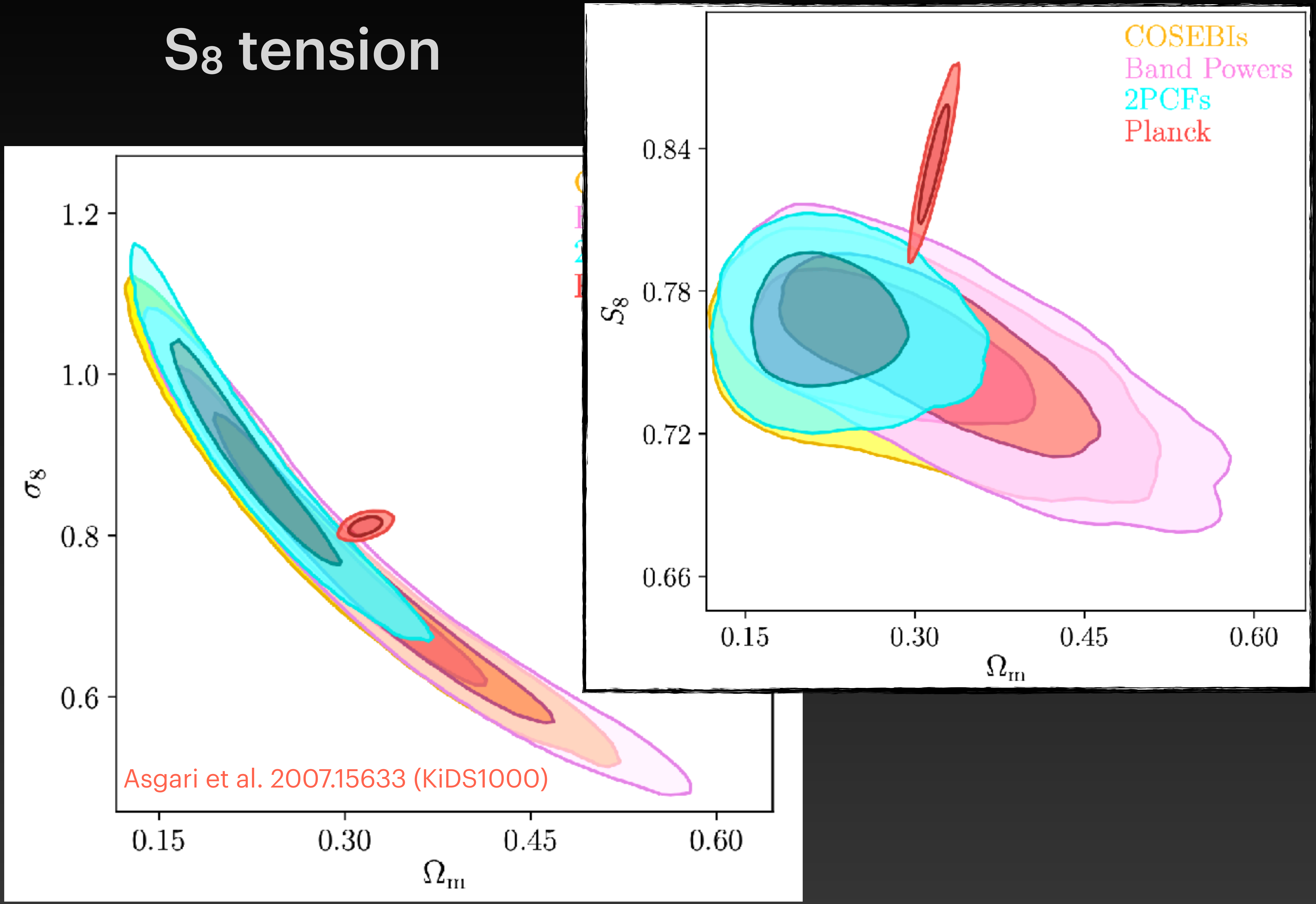
Amplitude of density fluctuations at present day

σ_8

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

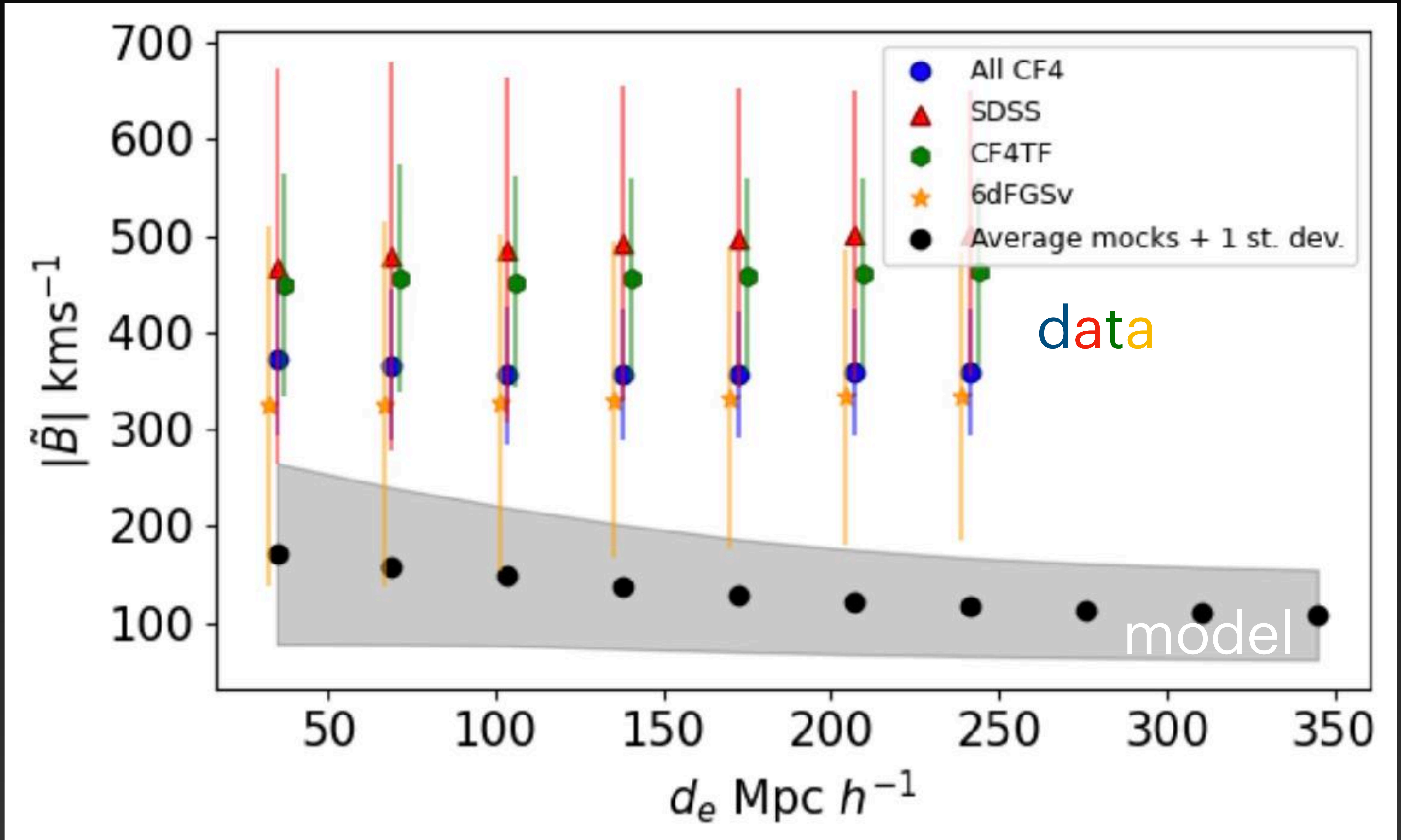


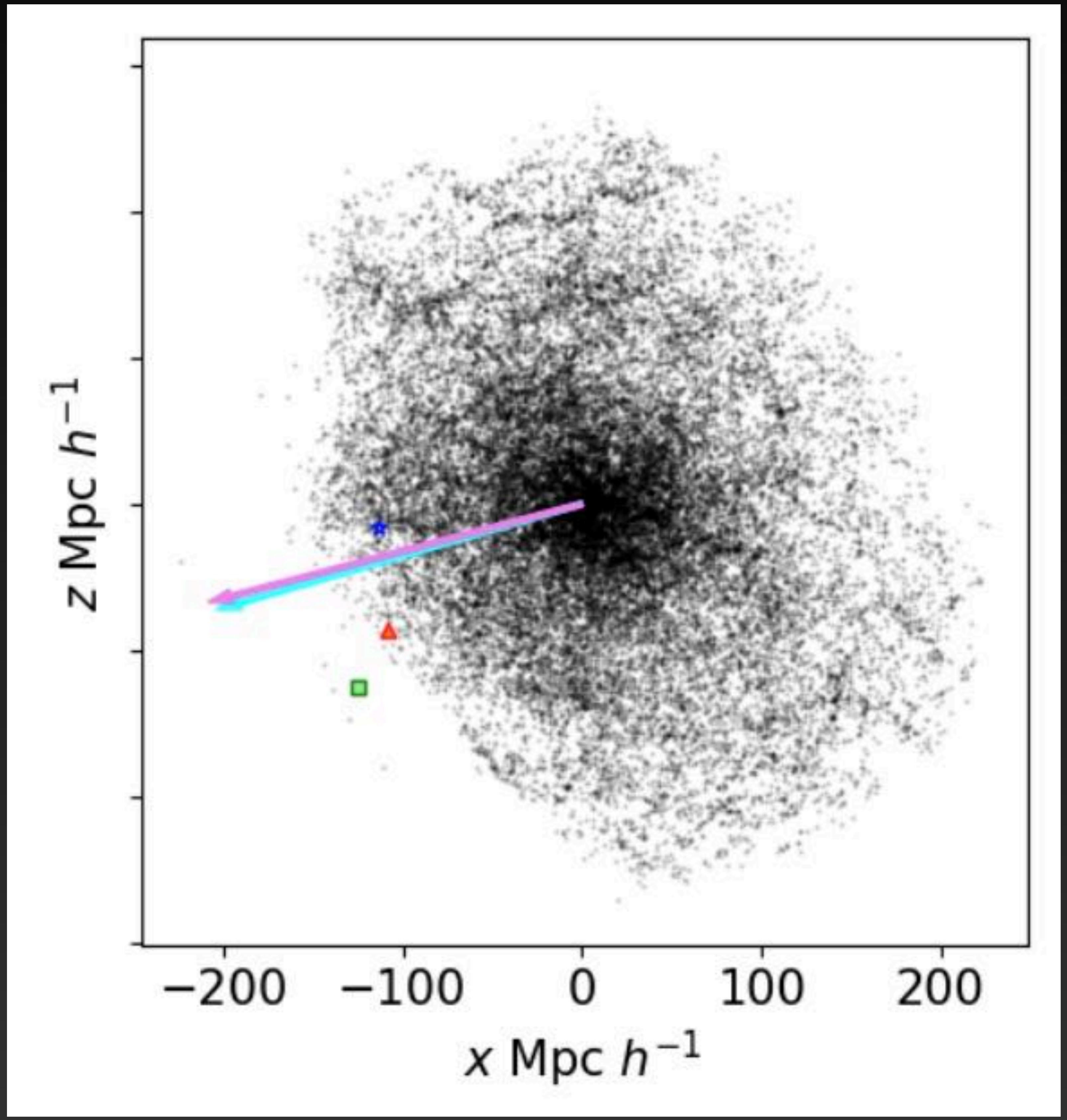
$$S_8 \equiv \sigma_8\sqrt{\Omega_M/0.3}$$



Cosmological tensions

Bulk flow tension?





Whitford, Howlett, Davis 2023
(also see Watkins et al. 2023)

Cosmological tensions

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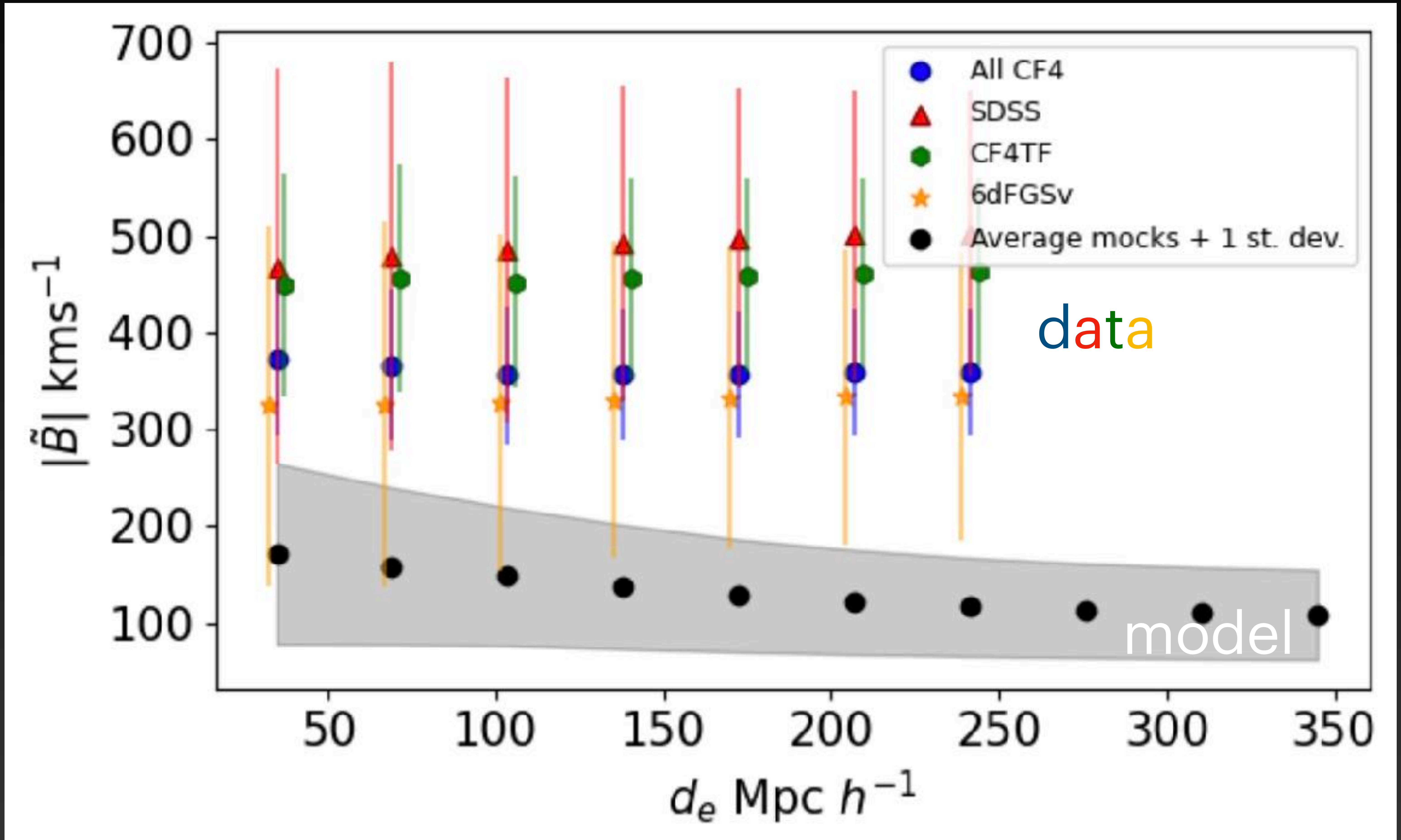

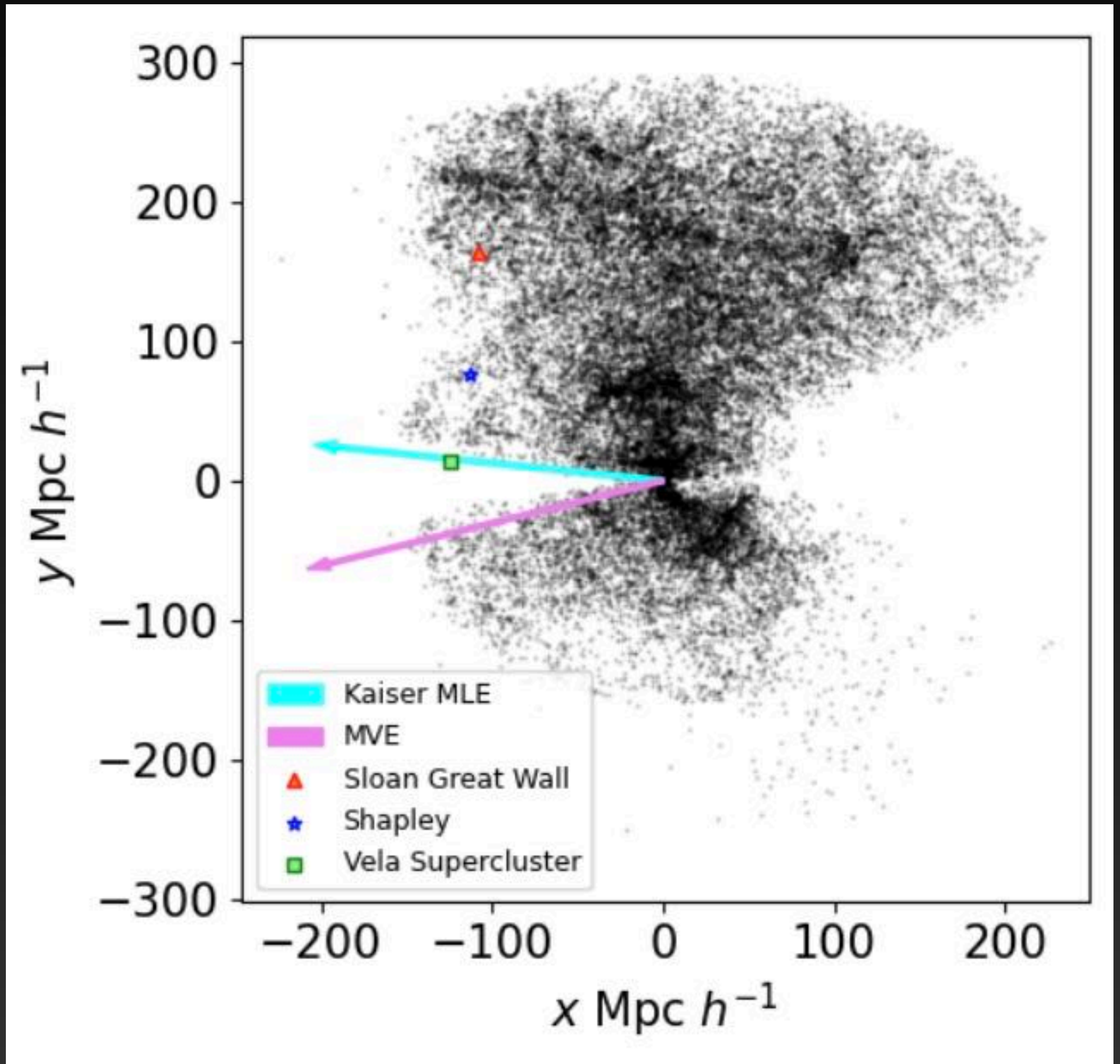

Whitford, Howlett, Davis 2023
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Tensions are intriguing

(e.g. Dark Energy)

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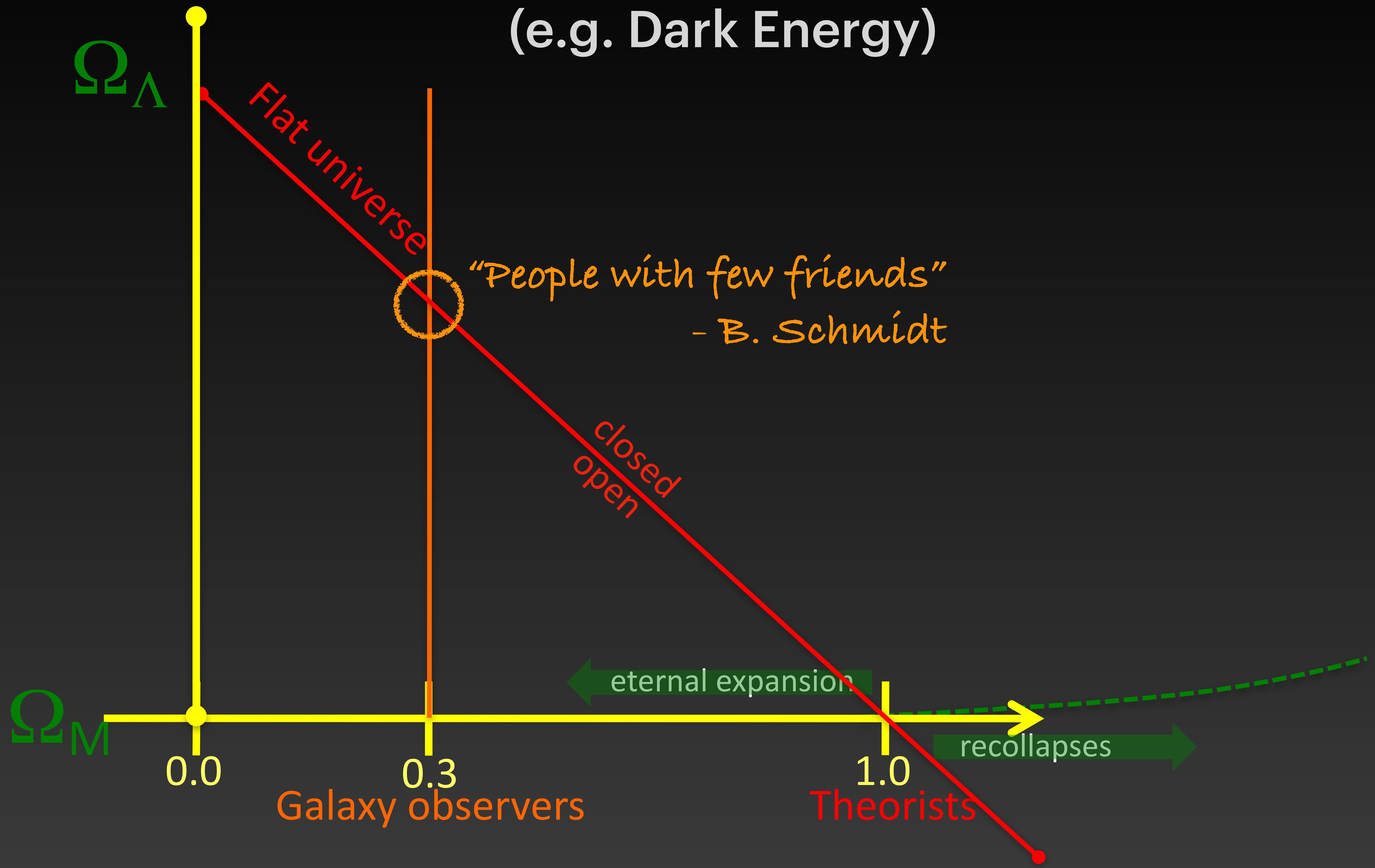


Two papers saying $\Lambda \approx 0.8$ in 1990 and 1995

The cosmological constant and cold dark matter

G. Efstathiou, W. J. Sutherland & S. J. Maddox

Department of Physics, University of Oxford, Oxford OX1 3RH, UK

THE cold dark matter (CDM) model[1–4] for the formation distribution of galaxies in a universe with exactly the crit density is theoretically appealing and has proved to be dura but recent work[5–8] suggests that there is more cosmological st ture on very large scales ($l > 10\ h^{-1}$ Mpc, where h is the Hul constant H_0 in units of 100 km s^{-1} Mpc^{-1}) than simple vers of the CDM theory predict. We argue here that the successe the CDM theory can be retained and the new observat accommodated in a spatially flat cosmology in which as muc 80% of the critical density is provided by a positive cosmological constant, which is dynamically equivalent to endowing the vacuum with a non-zero energy density. In such a universe, expansion was dominated by CDM until a recent epoch, but is now governed by the cosmological constant. As well as explaining large-scale structure, a cosmological constant can account for the lack of fluctuations in the microwave background and the large number of certain kinds of object found at high redshift.

NATURE · VOL 348 · 20/27 DECEMBER 1990

THE ASTROPHYSICAL JOURNAL, 444:15–20, 1995 May 1

INTERPRETATION OF THE FAINT GALAXY NUMBER COUNTS IN THE *K* BAND

YUZURU YOSHII[1,2,3] AND BRUCE A. PETERSON[2,3]
Received 1994 February 28; accepted 1994 November 7

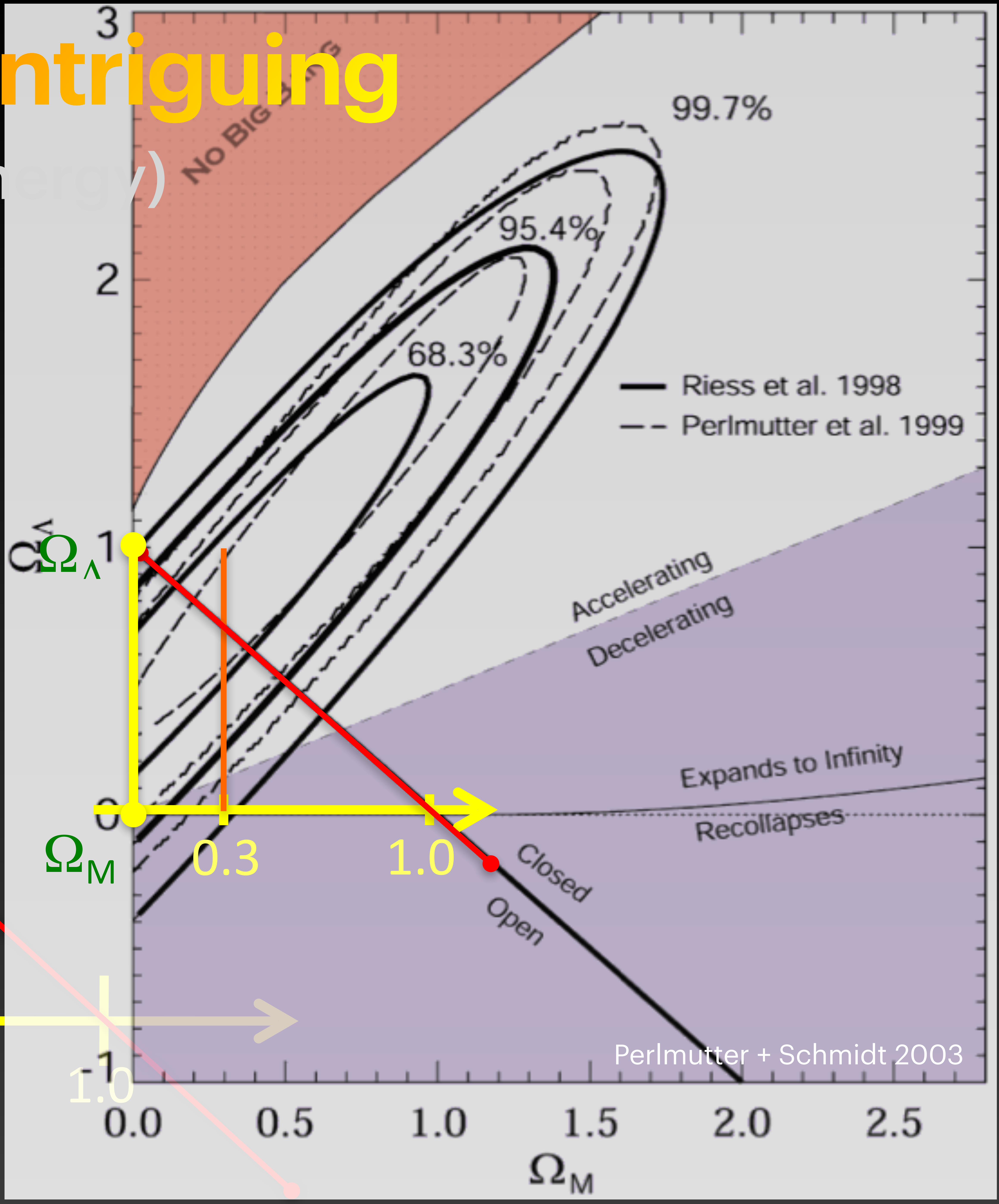
ABSTRACT

Number counts of K(2.2 μm)-selected galaxies reaching to $K = 23$ mag are compared to model predictions which take into account the selection bias against high-redshift galaxies inherent in the methods used to detect faint galaxy images. Using a standard model for galaxy luminosity evolution with a constant comoving density of galaxies, we find that these number count data favor a flat, low-density $\Omega_0 \sim 0.2$ universe with a nonzero cosmological constant. We argue that the agreement with the model predictions for a low-density universe considerably diminishes any need to introduce a hypothetical population to explain the excess galaxies found in deep blue surveys.

FIG. 1 The dots show estimates of the angular correlation function $w(\theta)$ for galaxies in the APM galaxy survey (see ref. 5 for details). These estimates have been scaled to the depth of the Lick galaxy catalogue where 1° corresponds to a spatial scale of $\sim 5h^{-1}$ Mpc. The dotted line shows the predictions of the $\Omega = 1$ CDM model (from ref. 5). The thin solid and dashed lines show the results of the linear theory for $\Omega_0 = 0.2$ scale-invariant CDM models with $h = 1$ and 0.75, respectively. The thick solid line shows N-body results for $\Omega = 0.2$ and $h = 0.9$; the flattening of this curve at angular scales $\lesssim 0.1°$ is an artefact of the resolution of the computer code, but the excess between 0.1° and 1° is real (see Fig. 2).

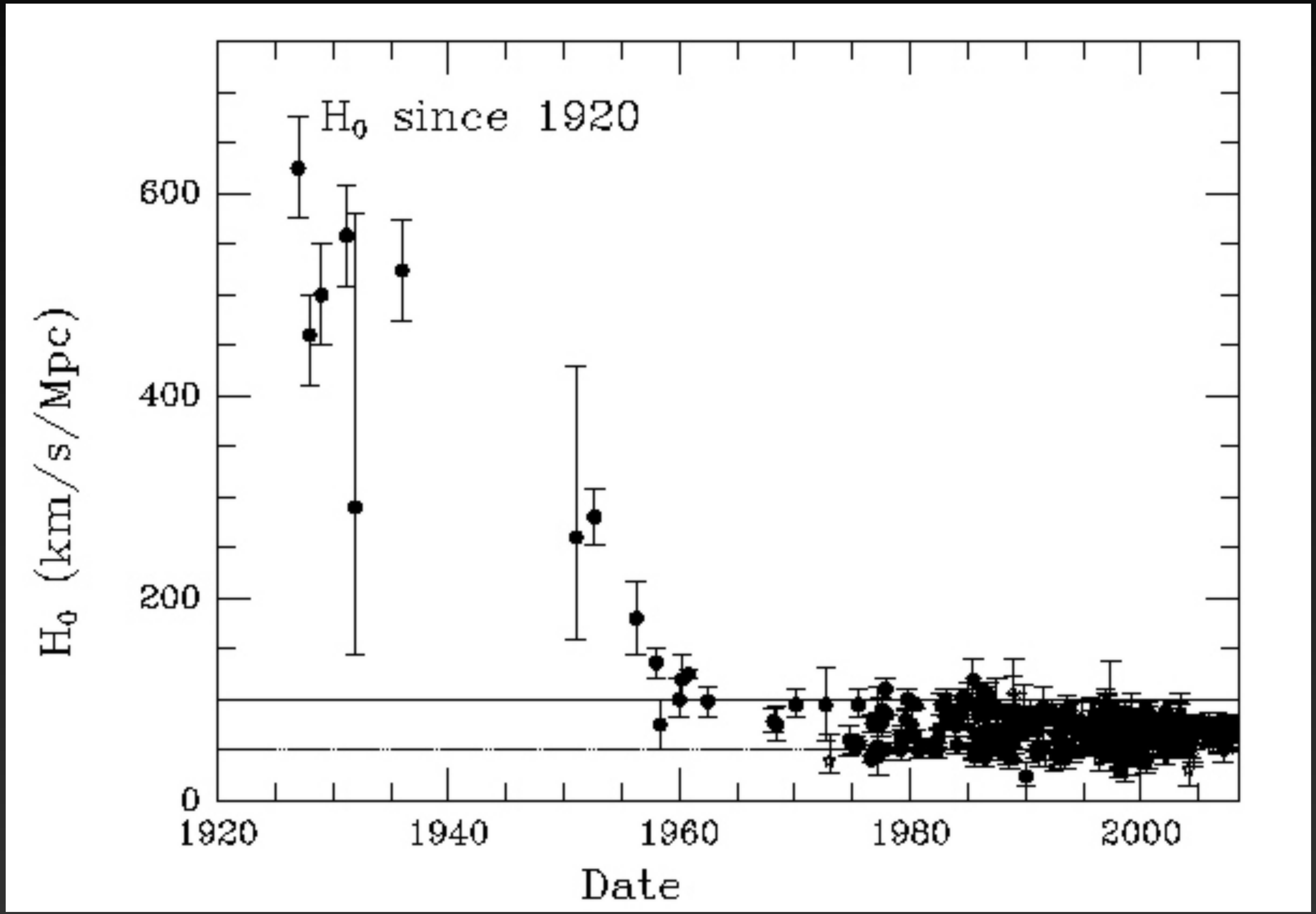
Tensions are intriguing

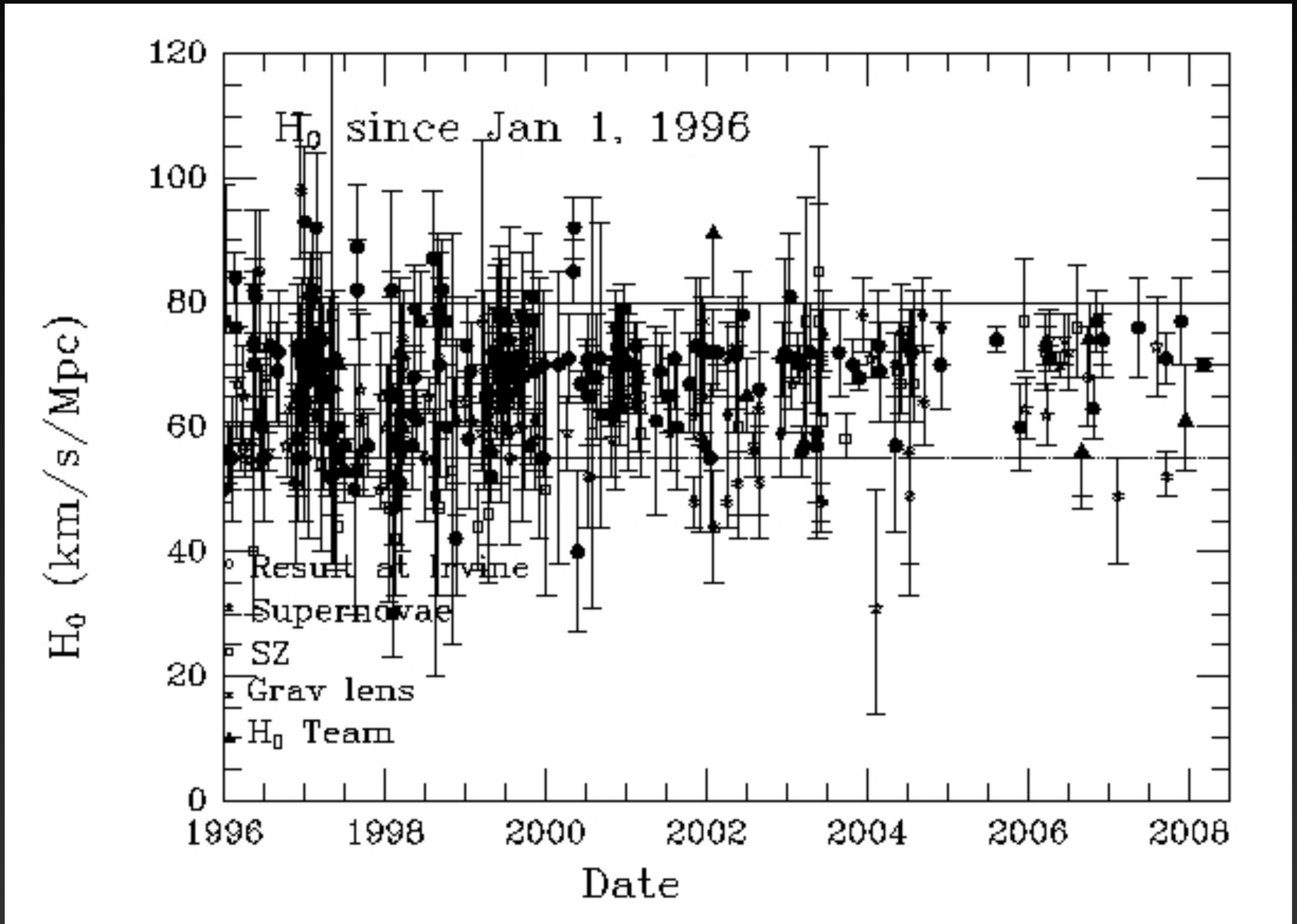
(e.g. Dark Energy)



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...

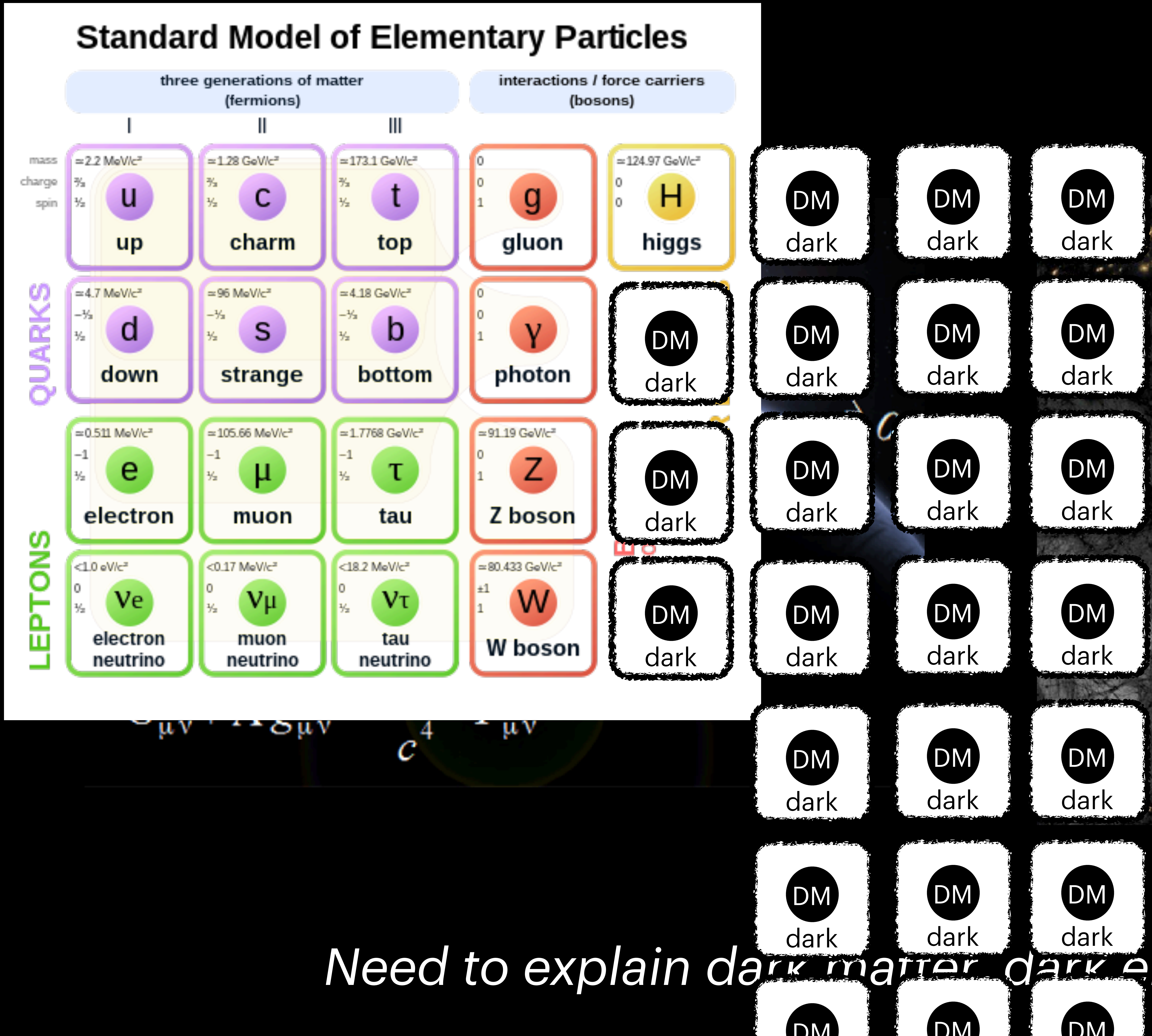
(Results from a search of “tension” in refereed astronomy papers on ADS in 2021.)

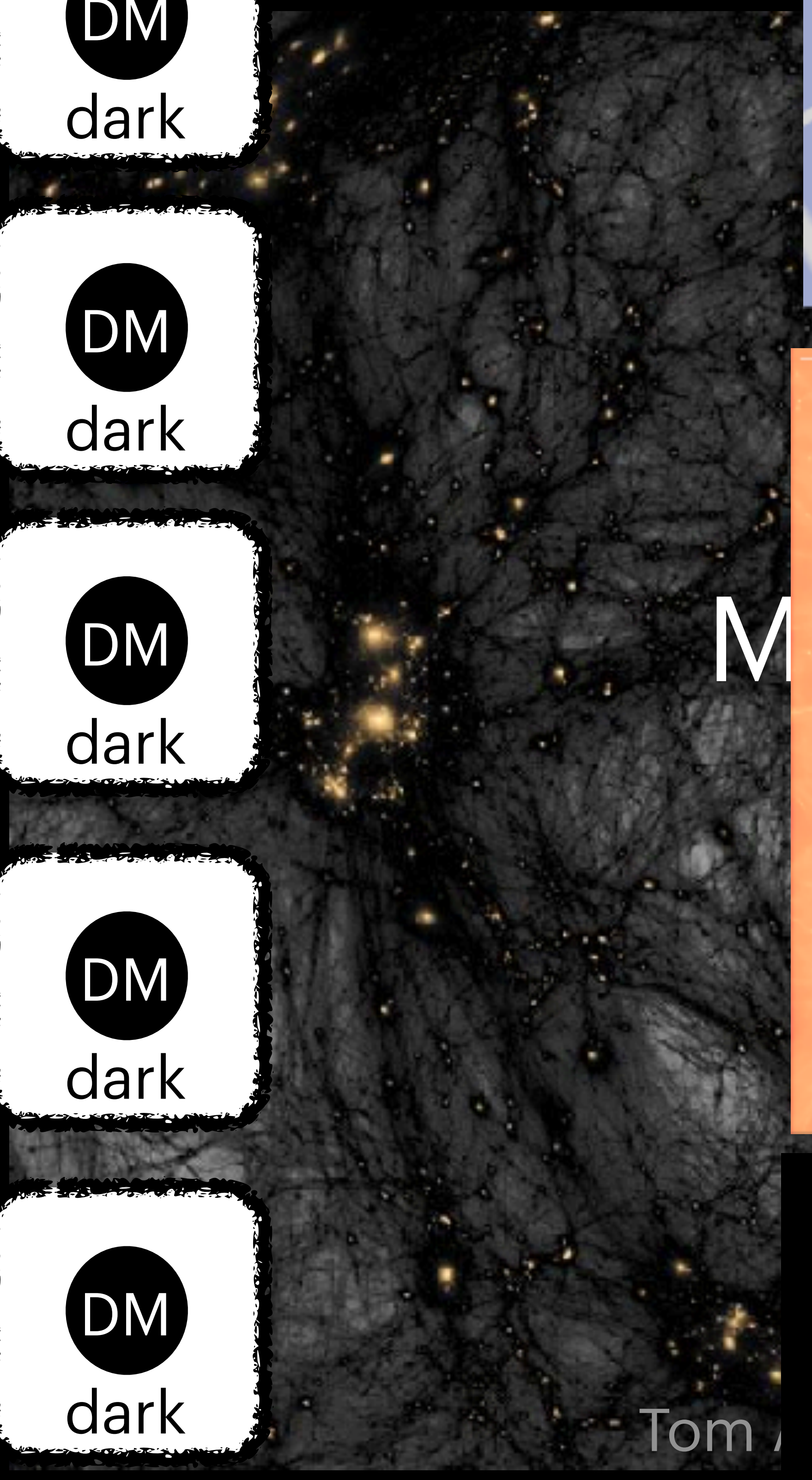
* Quantum origin of dark energy and the Hubble tension
* Cosmological implications of n_s ≈ 1 in light of the Hubble tension
* Integral F(R) gravity and saddle point condition as a remedy for the H0-tension
* Interacting dark sectors in anisotropic universe: Observational constraints and H0 tension
* 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
* 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

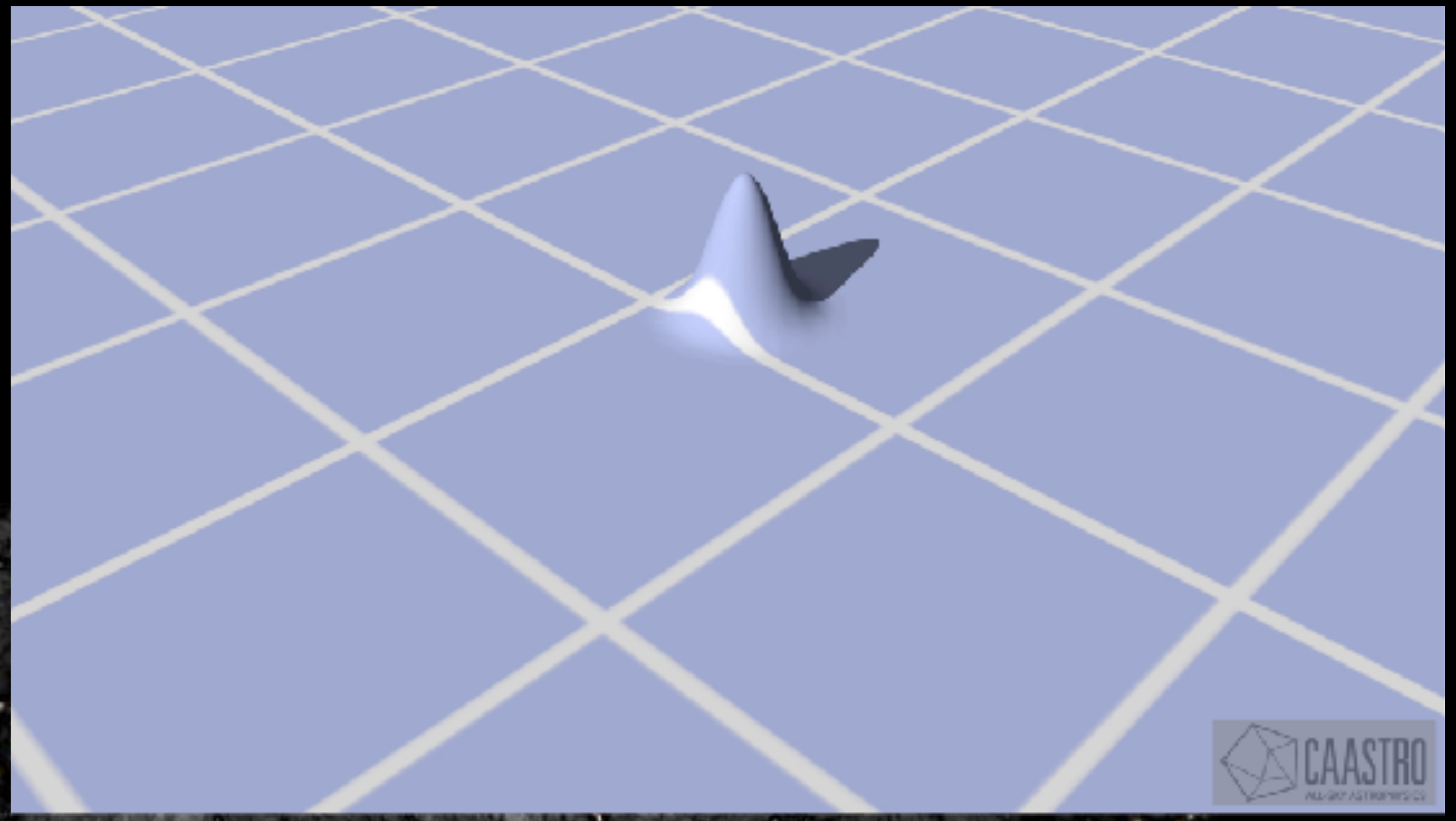
* Decaying dark matter, the H0 tension, and the lithium problem
* Hubble tension vs two flows
* GW170817 and GW190814: Tension on the Maximum Mass
* Cosmic Distances Calibrated to 1% Precision with Gaia EDR3 Parallaxes and Hubble Space Telescope Photometry of 75 Milky Way Cepheids Confirm Tension with 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

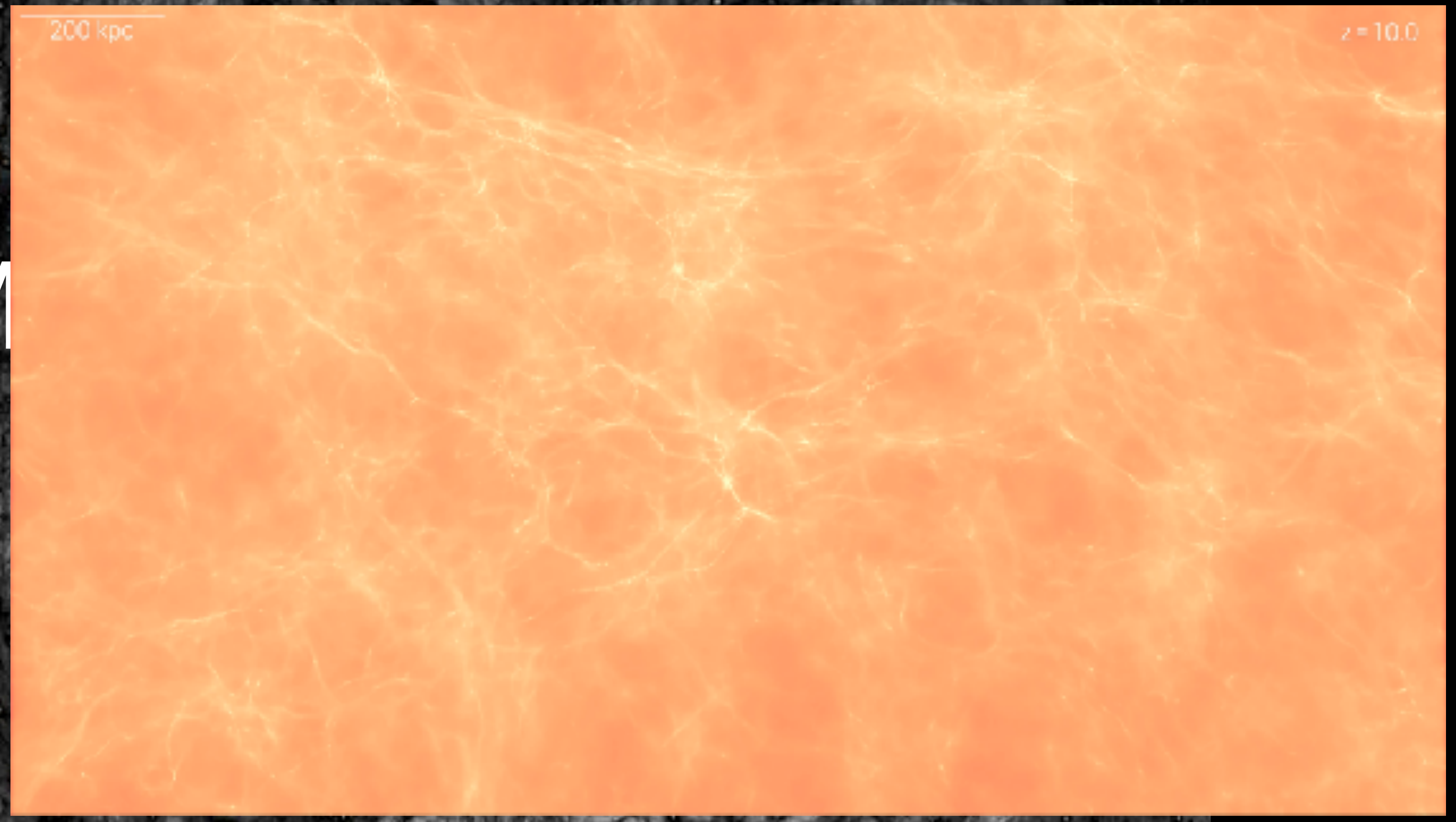
* Early-time thermalization of cosmic components? A hint for solving cosmic tensions
* CMB lensing in a modified Λ CDM model in light of the H0 tension
* Hubble tension in lepton asymmetric cosmology with an extra radiation
* Remedy of some cosmological tensions via effective phantom-like behavior of 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

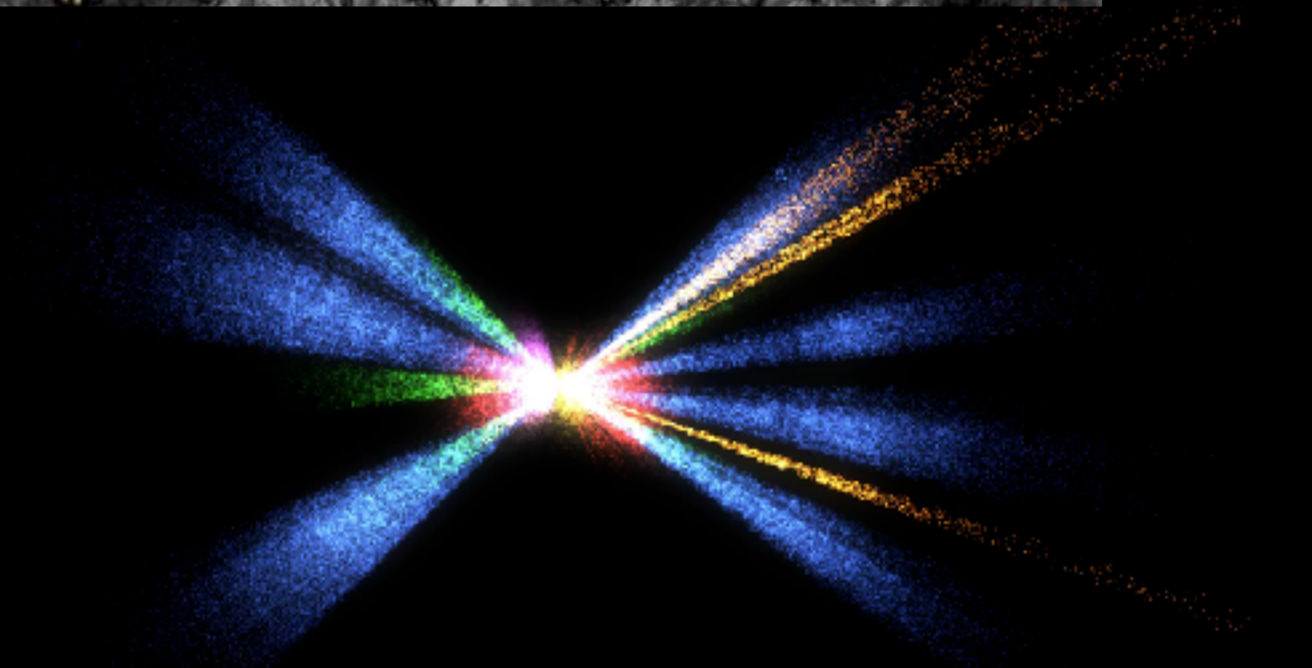
THEORETICAL EFFORTS FALL IN TWO MAIN GROUPS











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.

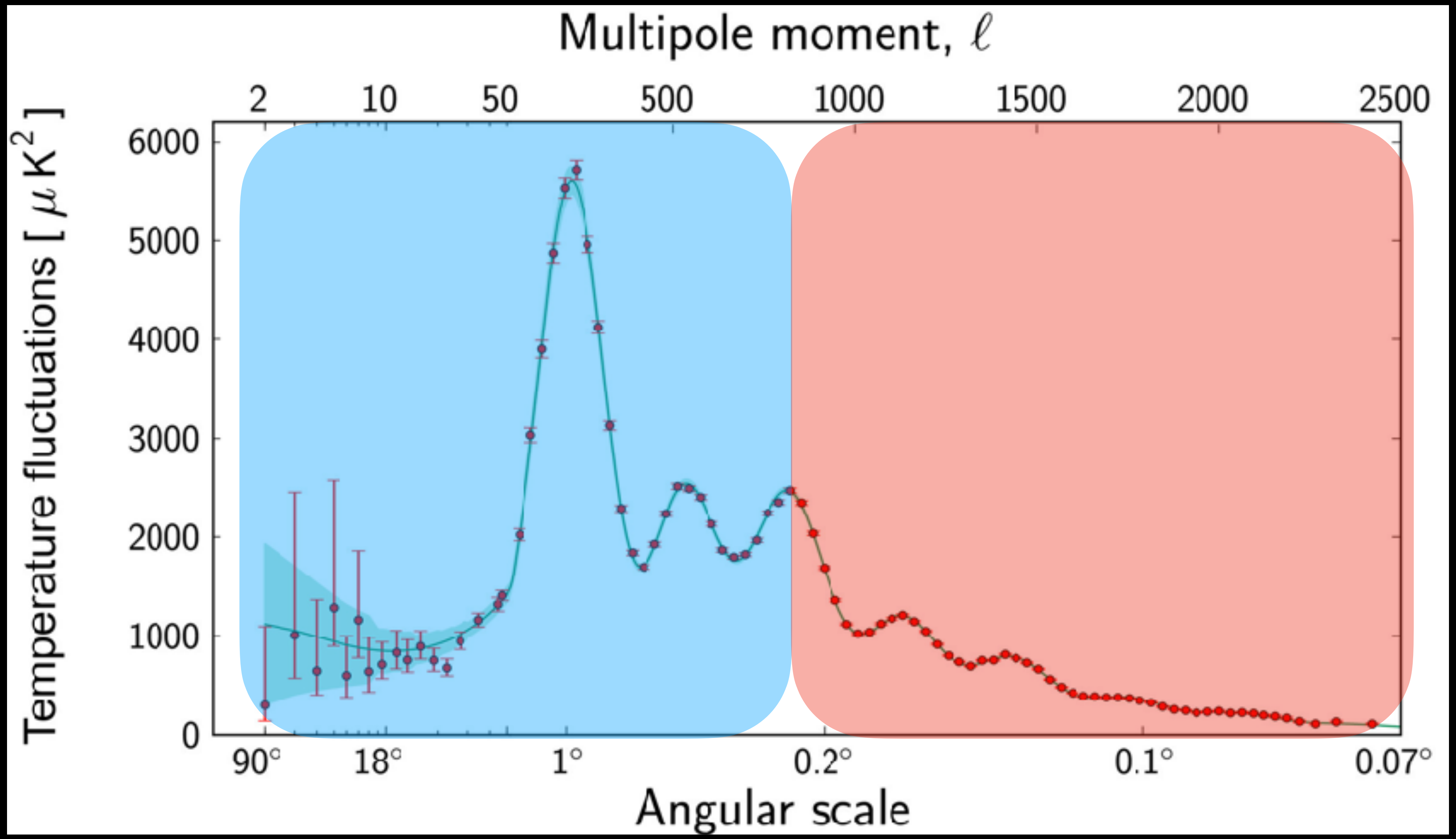
Parameter	Prior range	Definition
A^{PS}_{100}	[0, 400]	Contribution of Poisson point-source power to $\mathcal{D}^{100\times100}_{3000}$ for *Planck* (in μK^2)
A^{PS}_{143}	[0, 400]	As for A^{PS}_{100}, but at 143 × 143 GHz
A^{PS}_{217}	[0, 400]	As for A^{PS}_{100}, but at 217 × 217 GHz
$A^{PS}_{143\times217}$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

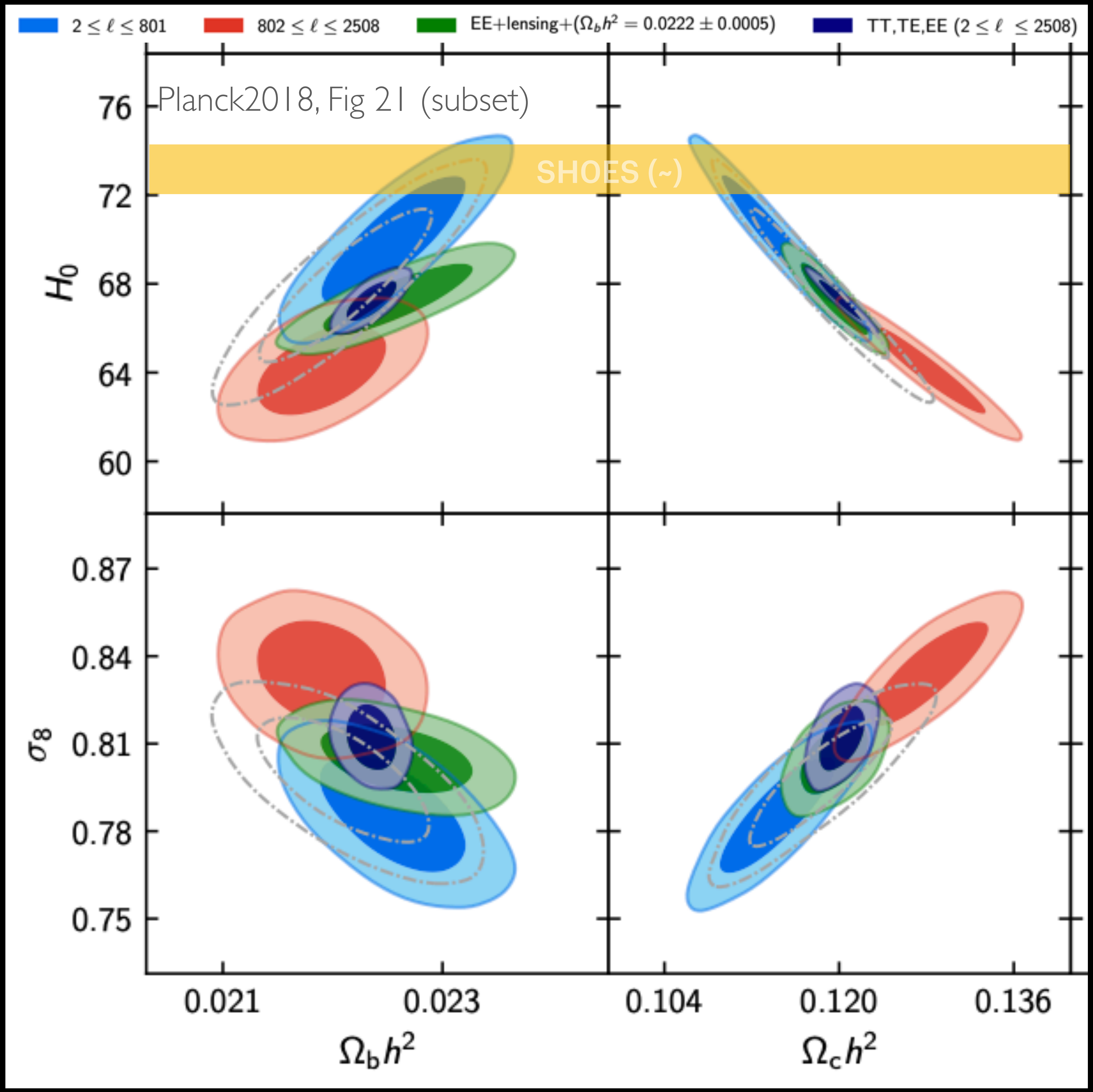
INTERNAL TENSIONS



"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

tensor to scalar ratio

running of the spectral index (dn_s / $d\ln k$)

amplitude of isocurvature fluctuations

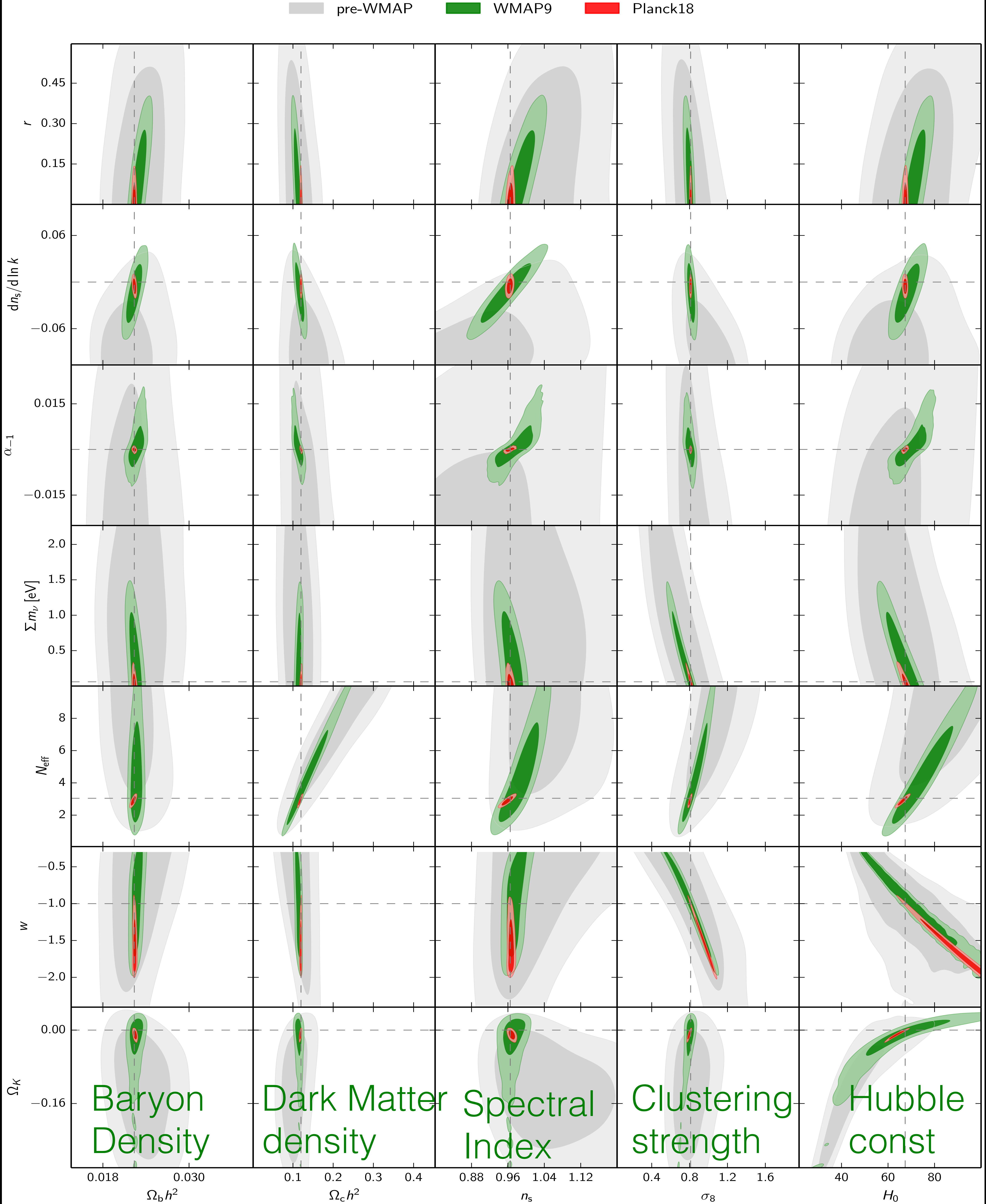
Mass of neutrinos

Extra neutrinos

Equation of state of dark energy

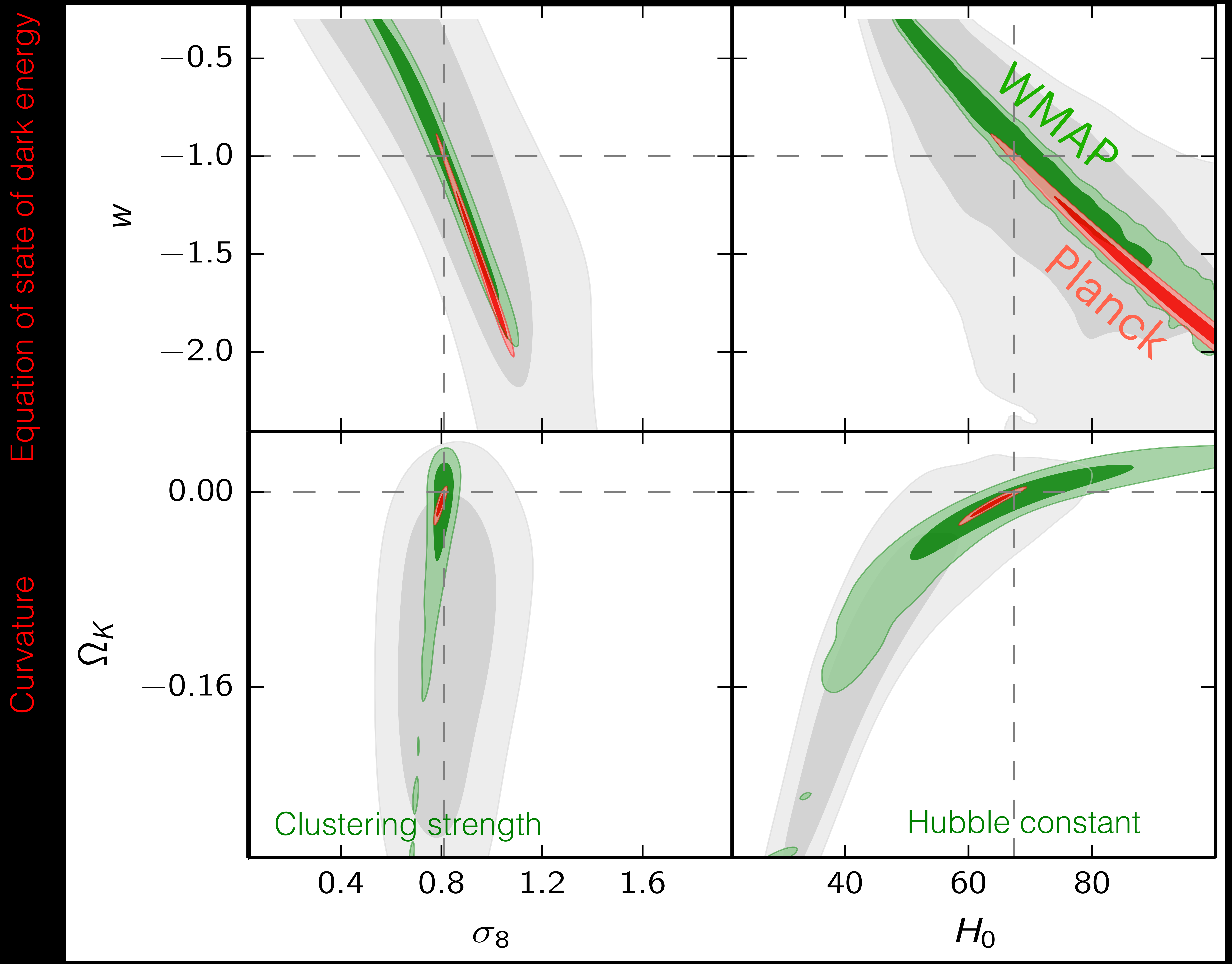
Curvature

Planck VI, 2018 (red)
WMAP (green)

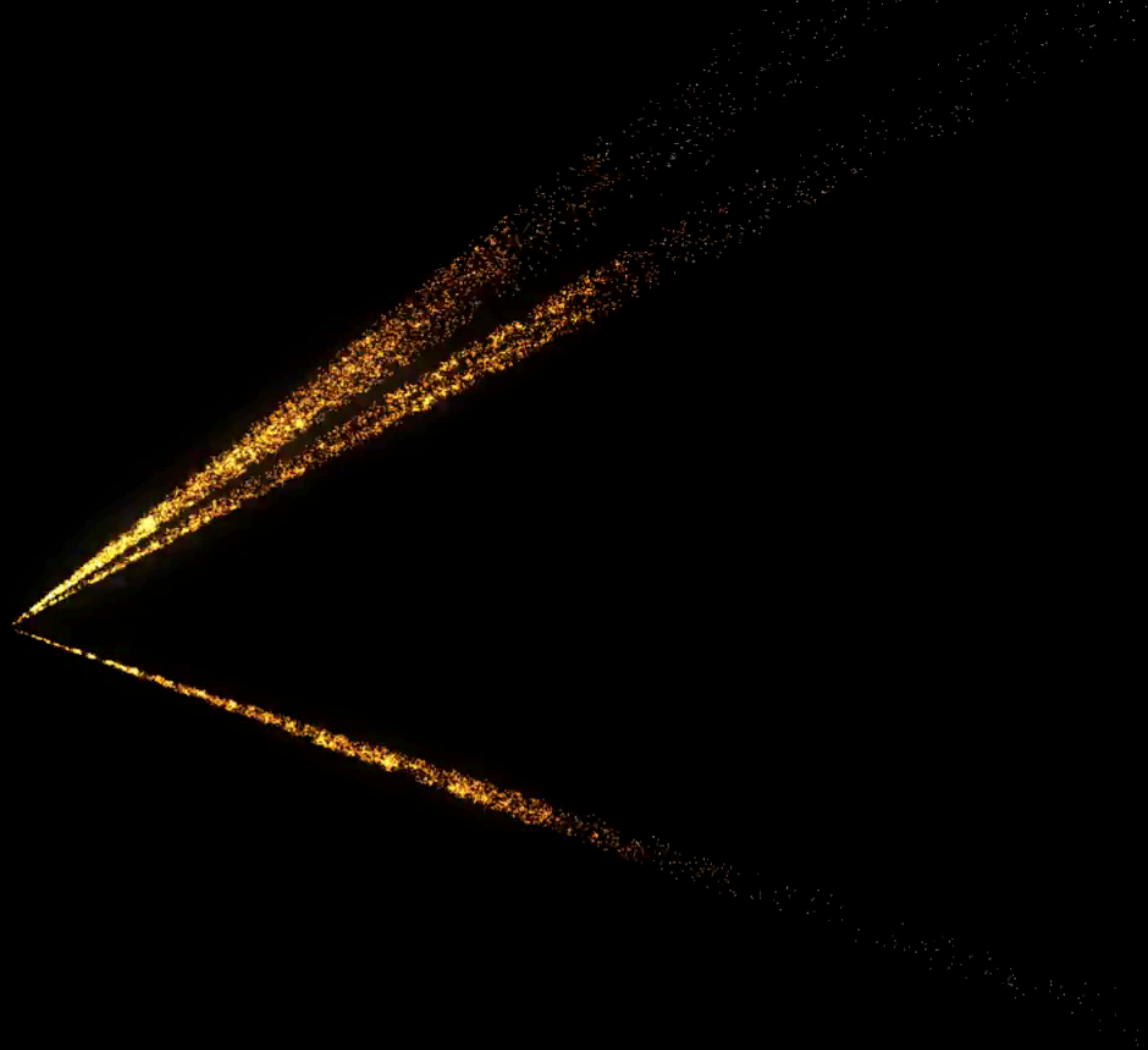


CMB: MODEL EXTENSIONS

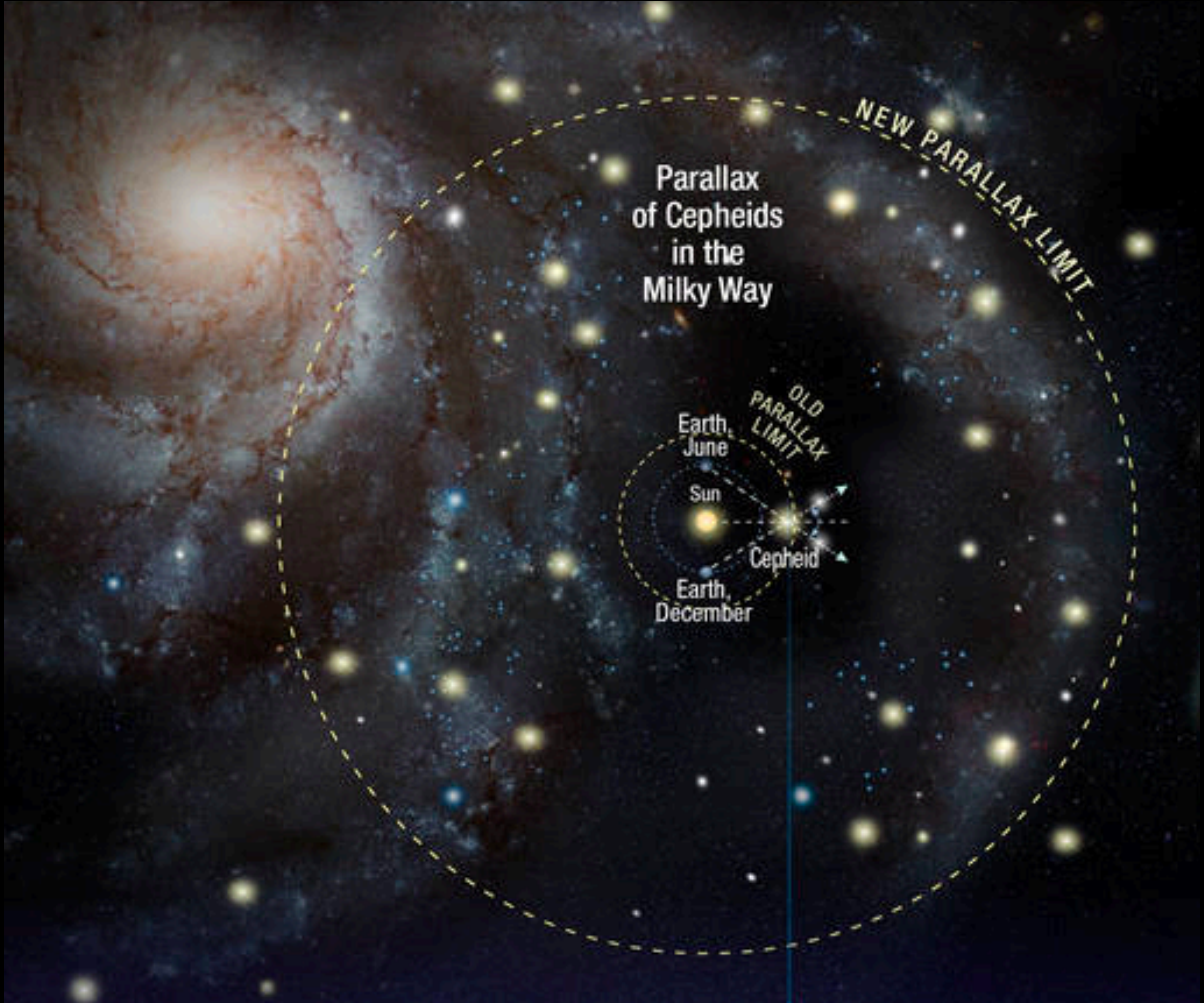
Planck VI, 2018 (red)
WMAP (green)

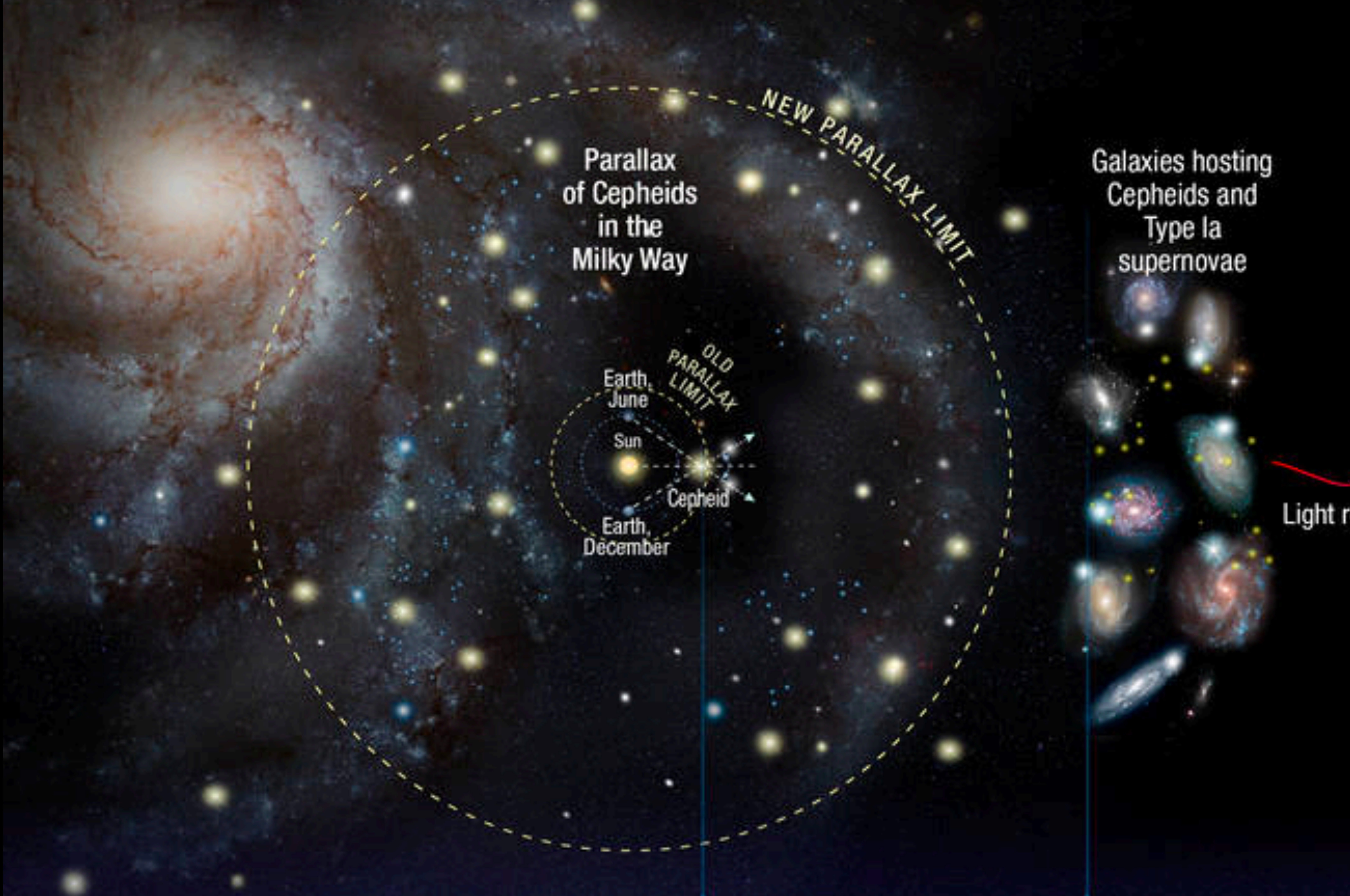


TYPE IA SUPERNOVAE

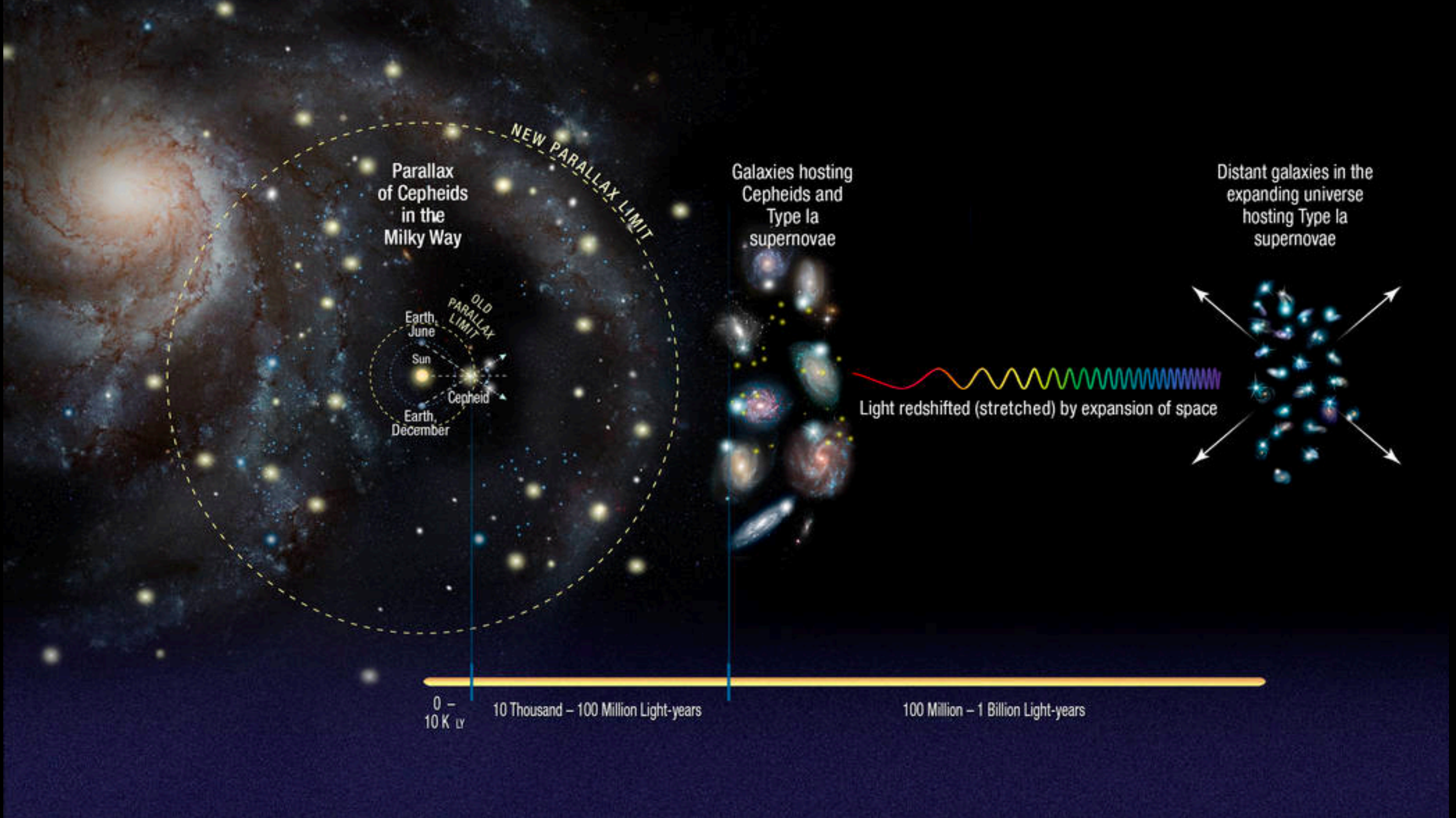


Animation Sam Hinton + Hugh McDougal


NEW PARALLAX LIMIT
Parallax
of Cepheids
in the
Milky Way
OLD
PARALLAX
LIMIT
Earth,
June
Sun
Cepheid
Earth,
December

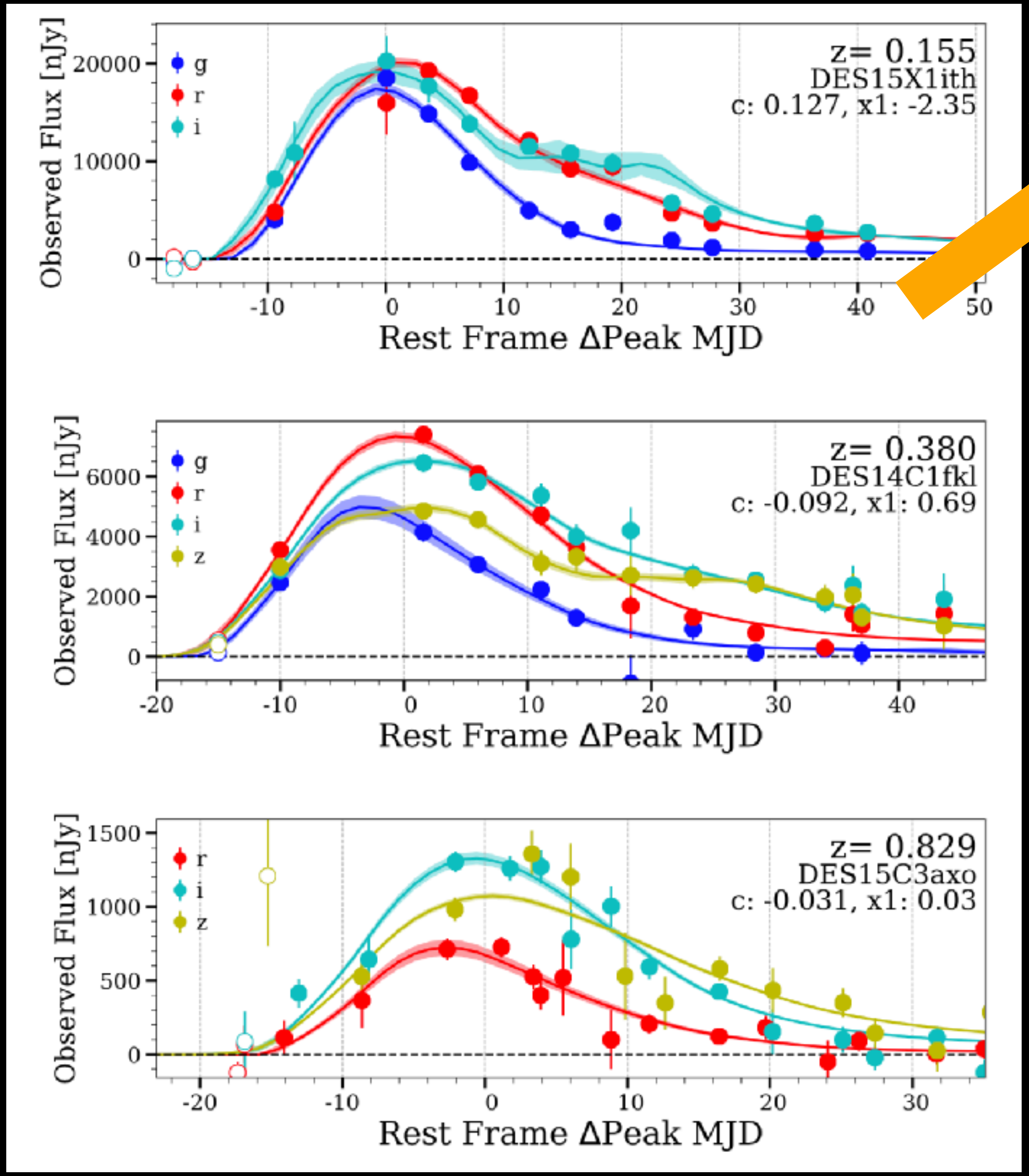

NEW PARALLAX LIMIT
Parallax of Cepheids in the Milky Way
OLD PARALLAX LIMIT
Earth, June
Sun
Cepheid
Earth, December
Galaxies hosting Cepheids and Type Ia supernovae

Three steps to the Hubble Constant



SUPERNOVA COSMOLOGY

Light curves (Brout et al. DES 2019)



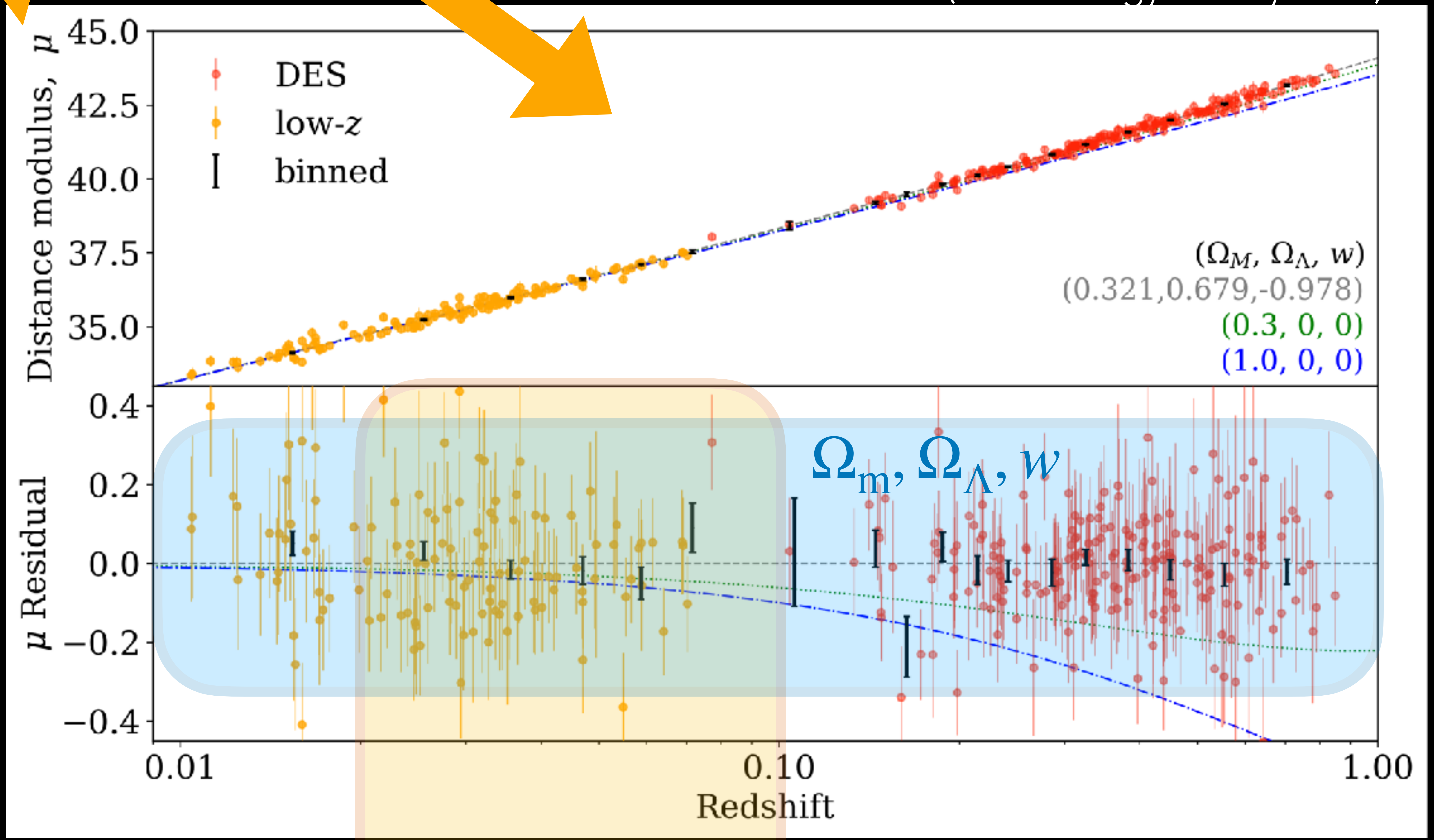
distance modulus: apparent mag, abs mag, stretch scale, stretch, colour scale, colour, host scale, host mass factor, malmquist +selection bias

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

derived from fit to SNIa light curve

can be constrained using cosmo fits

(Dark Energy Survey 2019)



H_0 measurements

The role of gravitational waves

STANDARD CANDLES / SIRENS

Supernovae

THE DARK ENERGY SURVEY

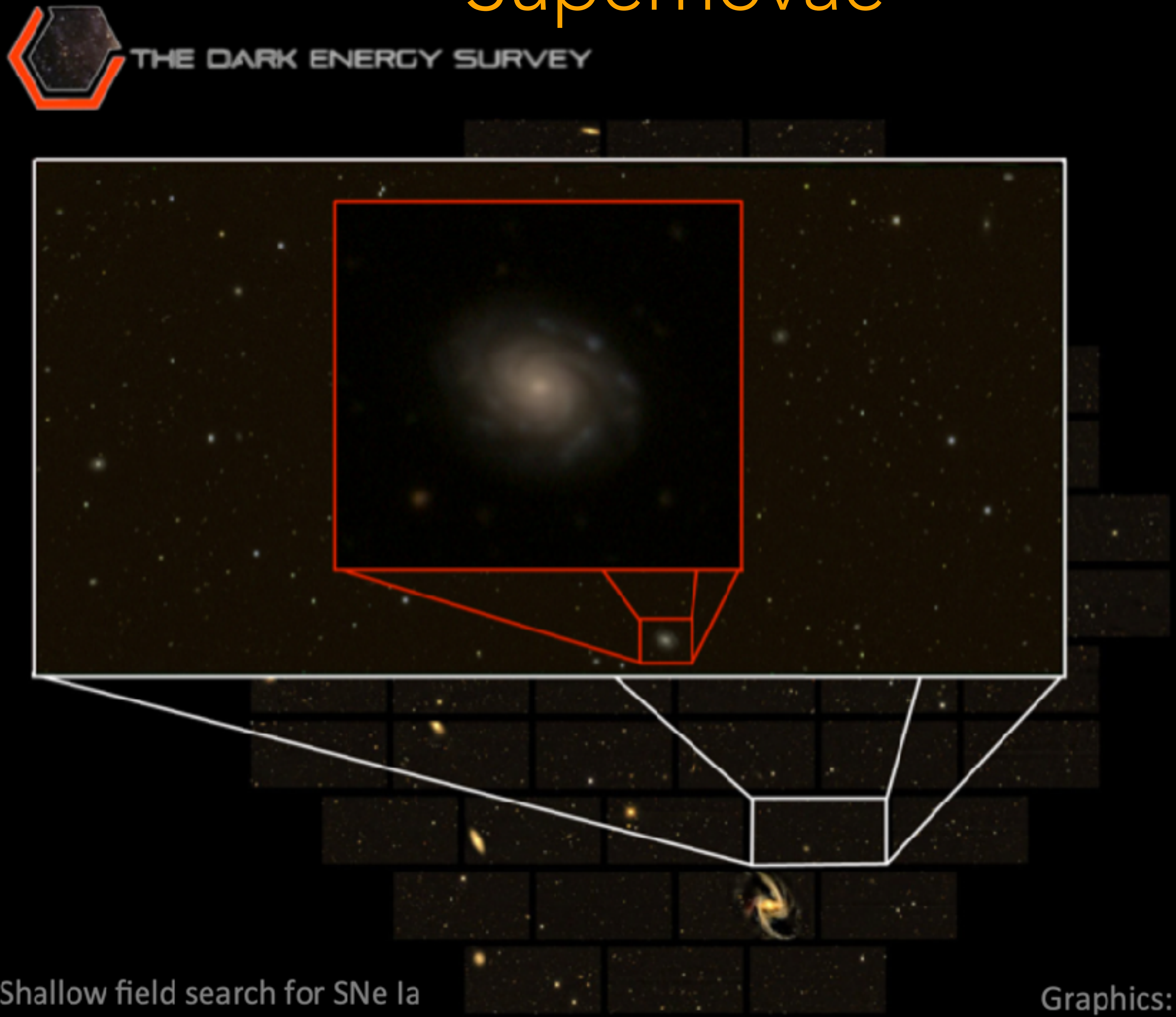
Shallow field search for SNe Ia

Graphics: C. D'Andrea

Gravitational Waves

STANDARD CANDLES / SIRENS

Supernovae



Shallow field search for SNe Ia

Graphics: C. D'Andrea

Gravitational Waves

STANDARD CANDLES / SIRENS

Supernovae

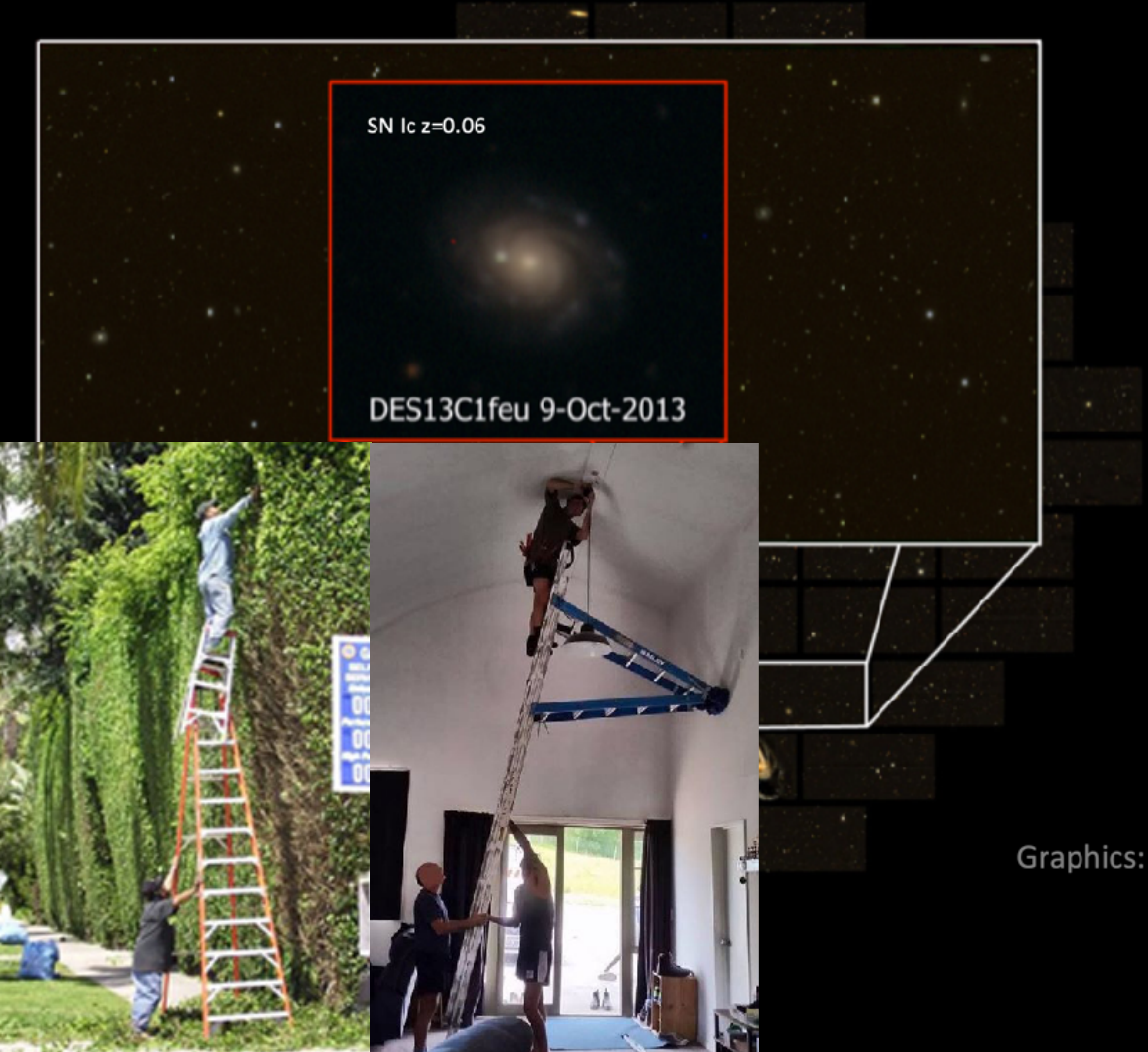
Graphics: C. D'Andrea

Gravitational Waves

STANDARD CANDLES

Supernovae

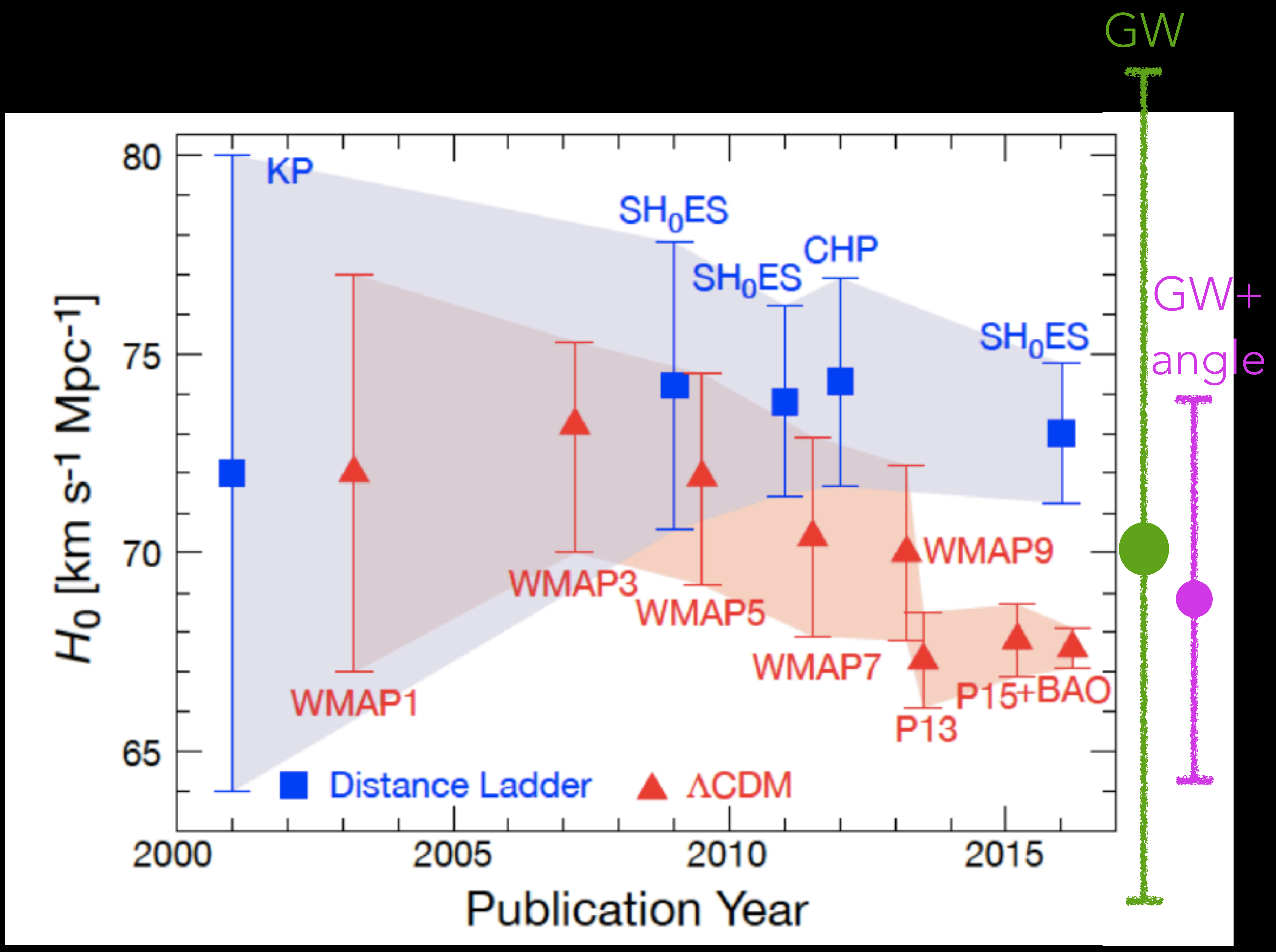
THE DARK ENERGY SURVEY

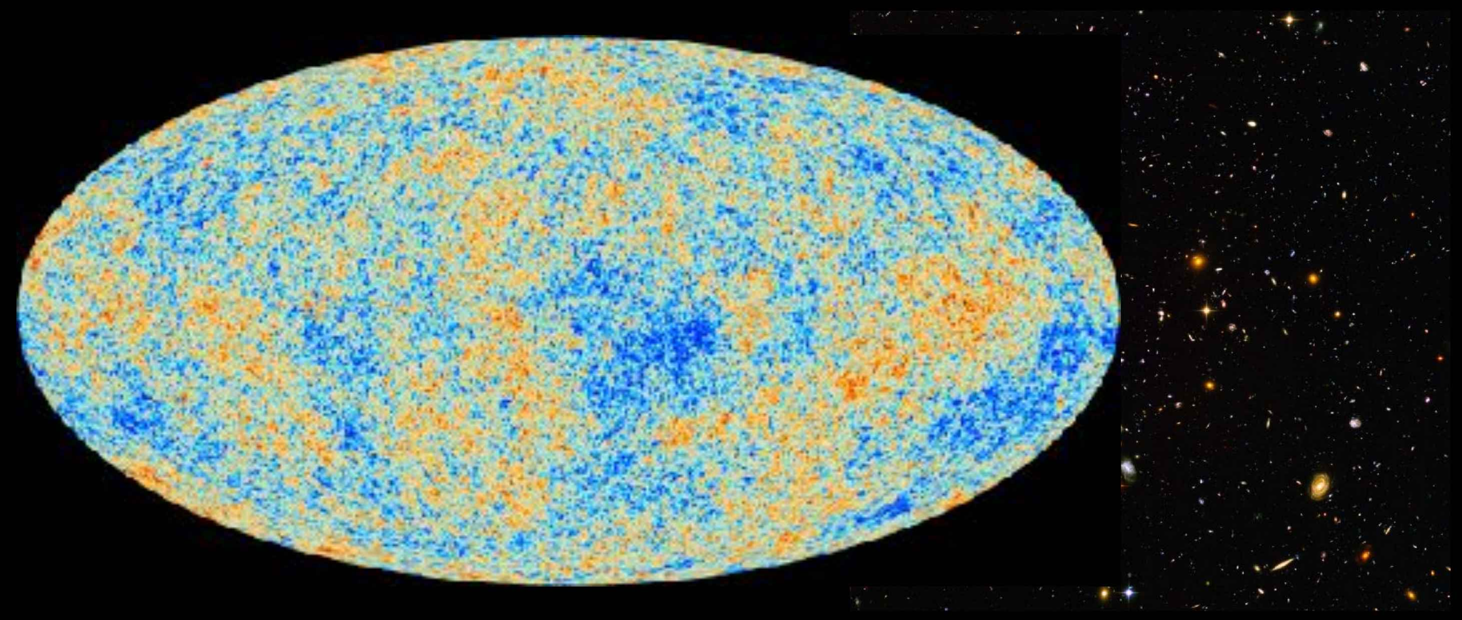


Graphics: C. D'Andrea

Gravitational Waves

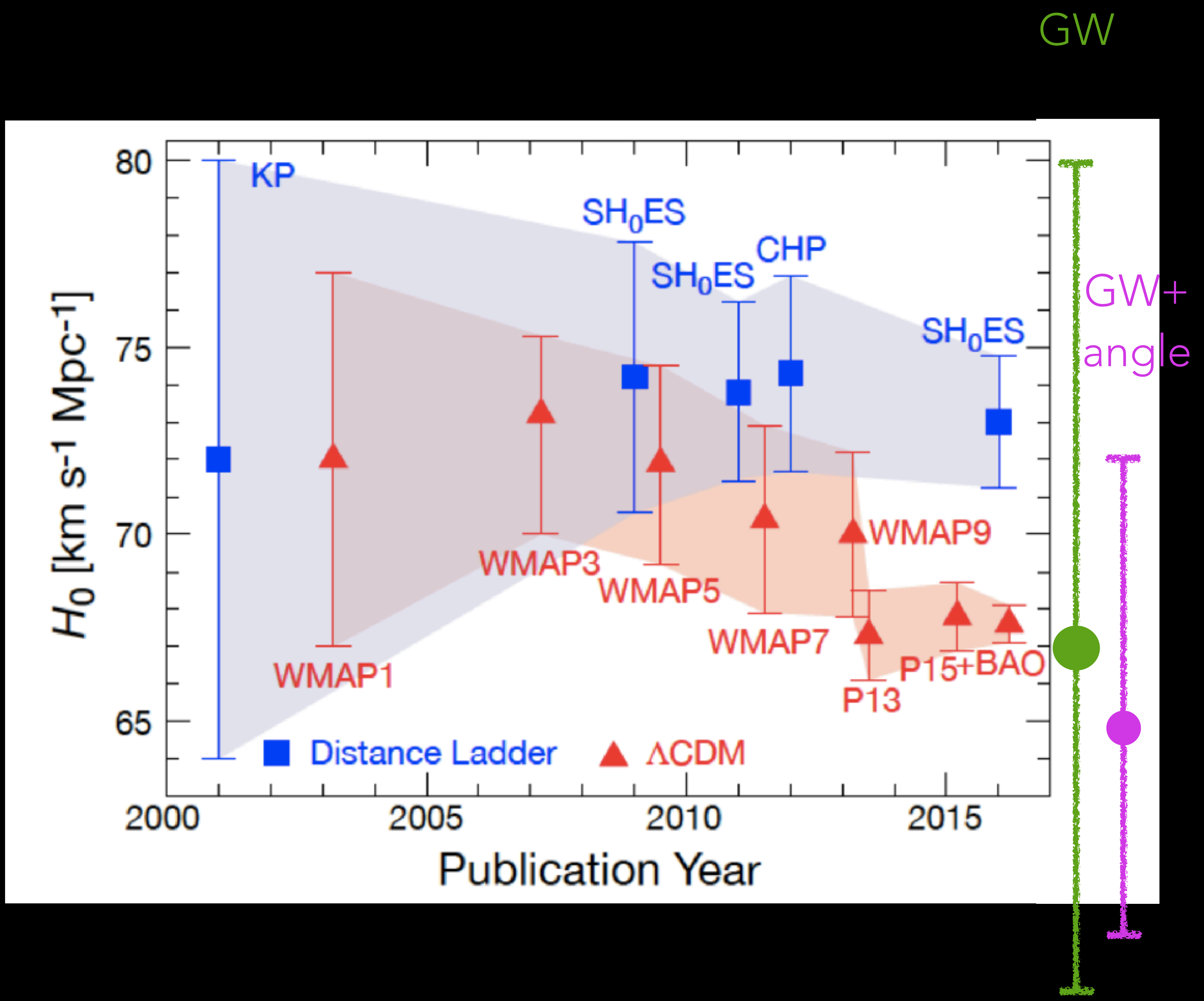
GRAVITATIONAL WAVES

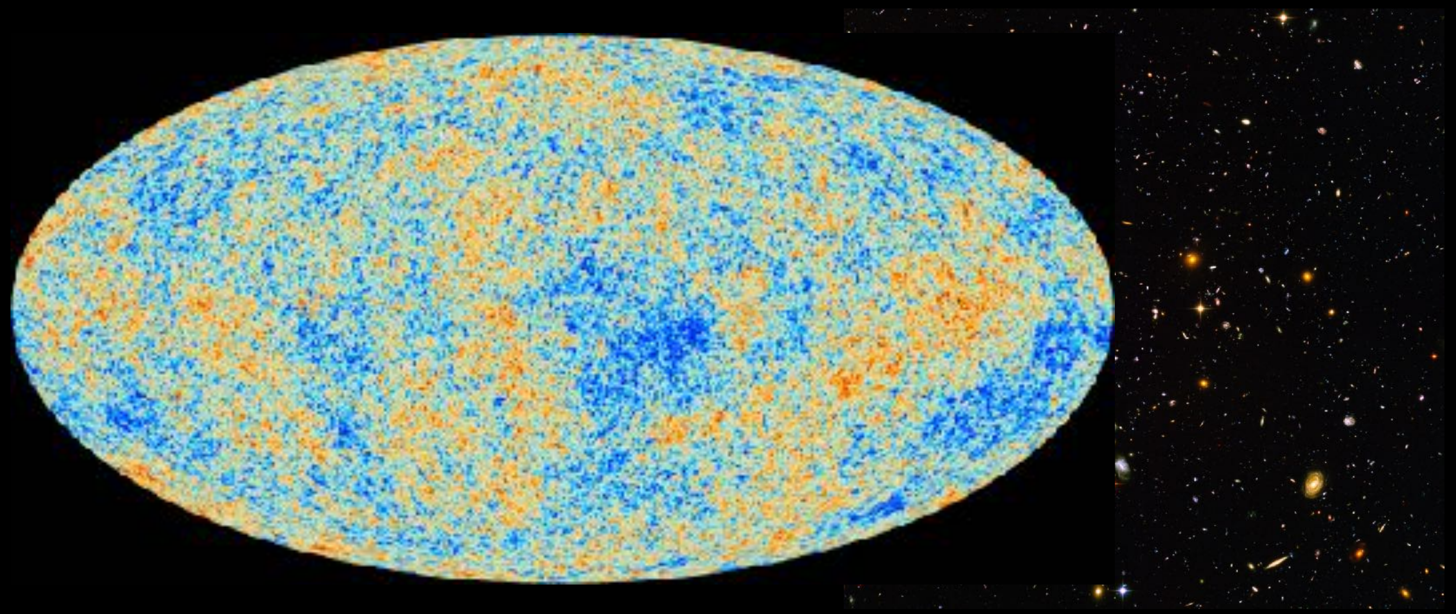




Abbott et al. 2017 Hotokezaka et al. 2019

GRAVITATIONAL WAVES





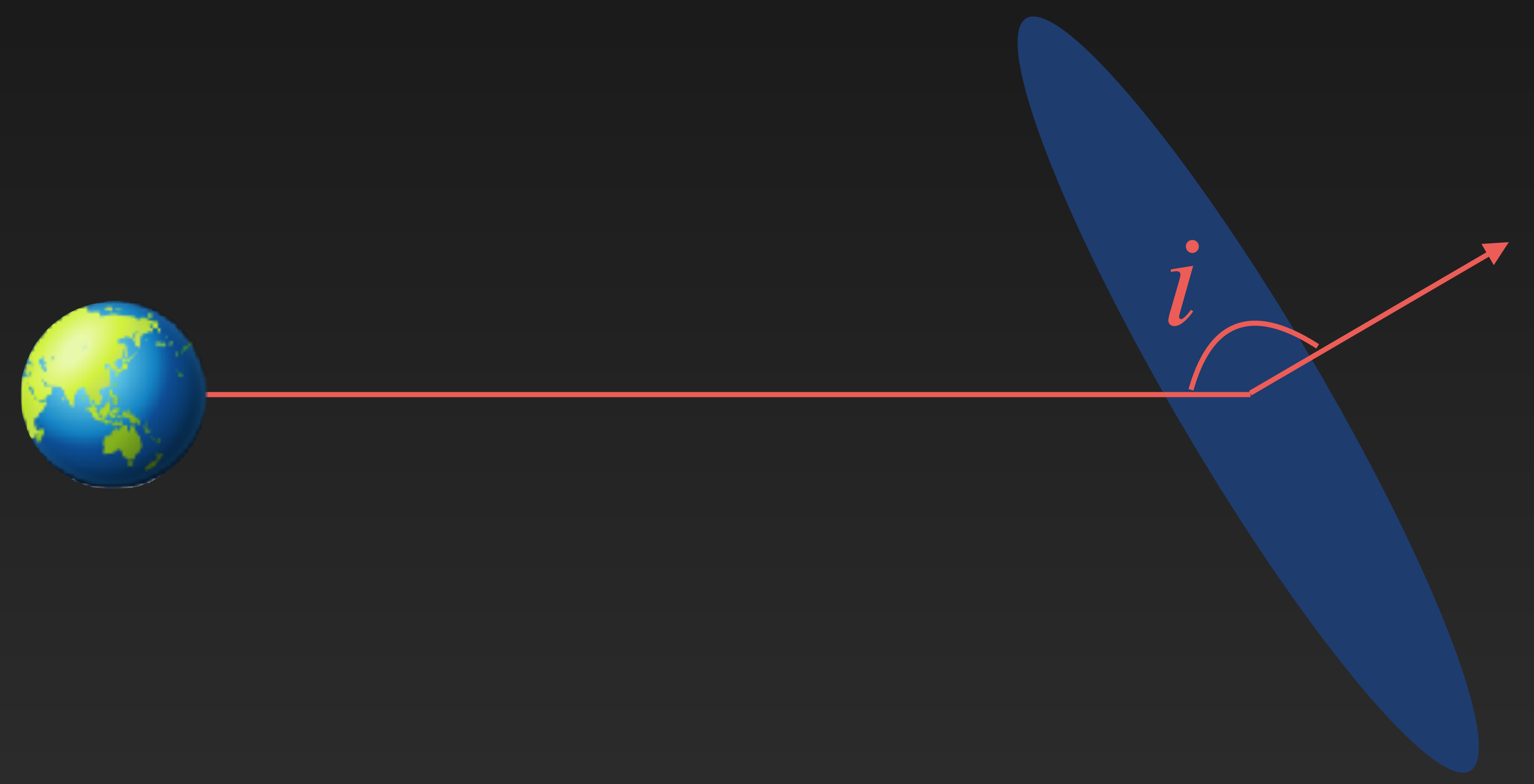
Howlett et al. 2020 (improving peculiar velocities for Abbott 2017)

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

H_0 from gravitational waves: pec vel correction

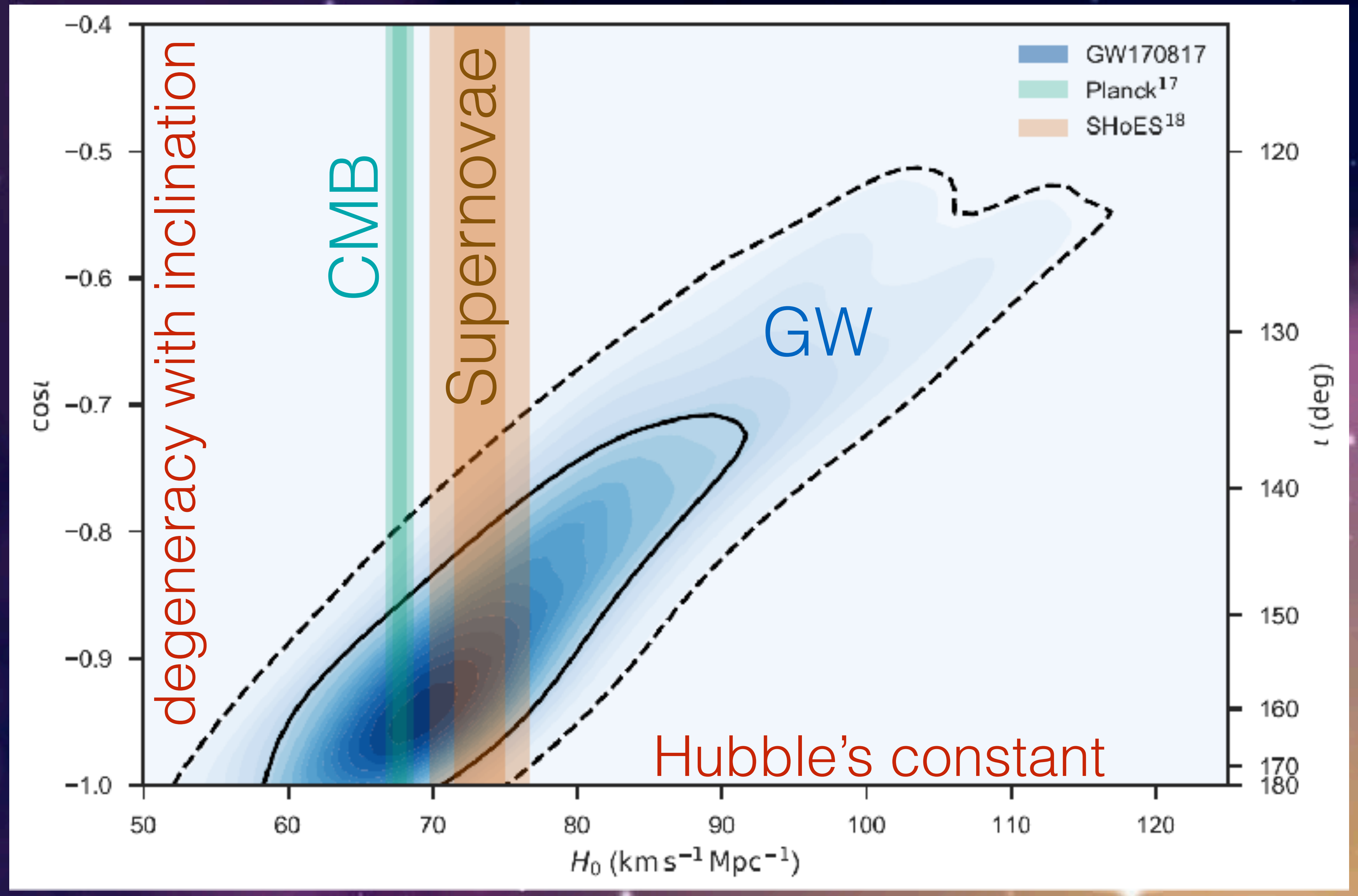
$$D = 43.8^{+2.9}_{-6.9}\ \mathrm{Mpc}$$

(z~0.01)



$$H_0 = 70^{+12}_{-8}\ \mathrm{km\,s^{-1}Mpc^{-1}}$$

pec. vel. correction is ~7 km s^{-1} Mpc^{-1}



Peculiar velocity correction:

1. Assume it has the v_{tot} of the group 3327 ± 72 km/s
   Gives peak H_0~76 km s^{-1} Mpc^{-1}

2. Measure v_{pec} = 310 ± 69 km/s by mapping the velocity field (6dF; Springob et al. 2014)

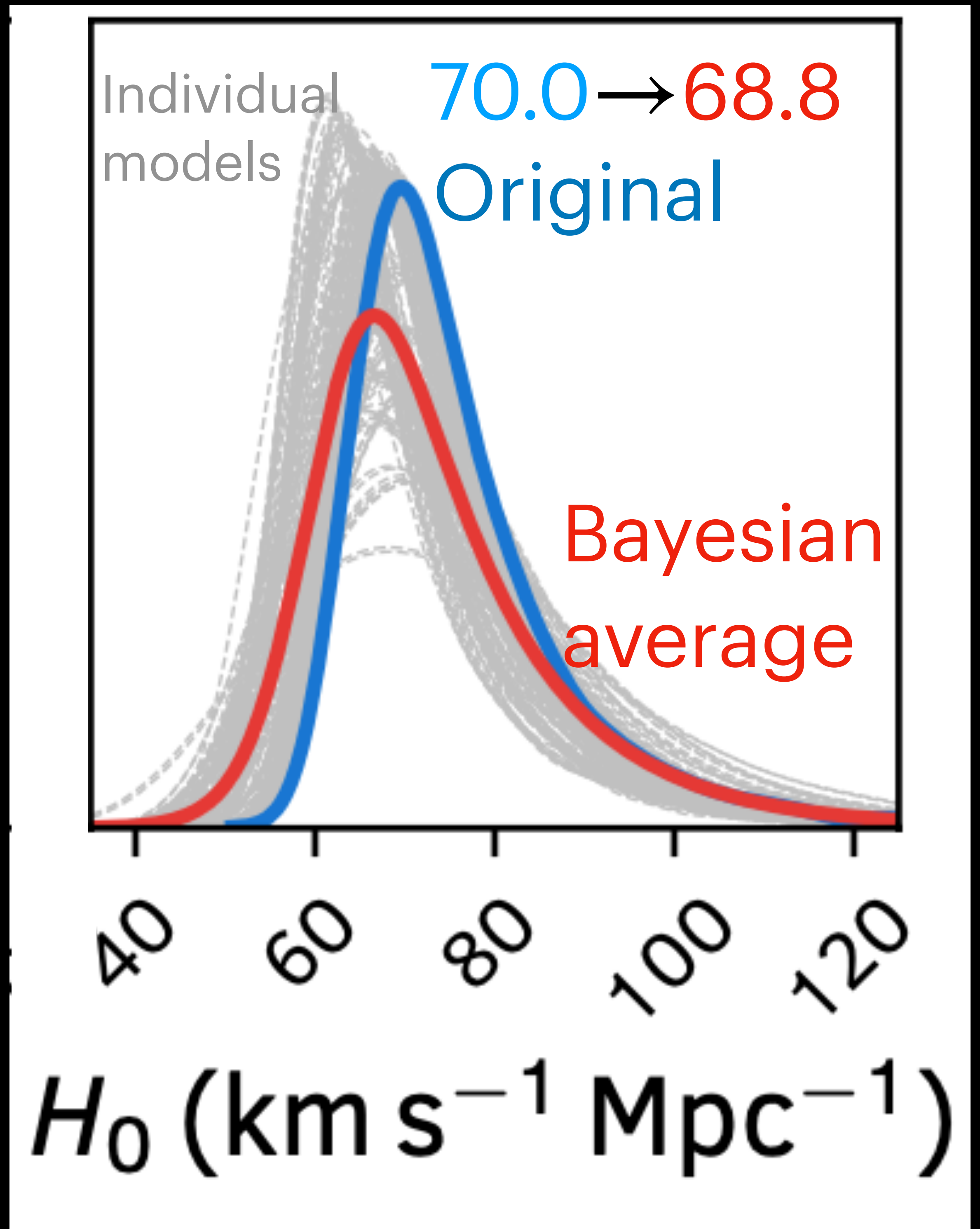
3. Subtract v_{pec} to get v_{rec} = 3017 ± 166 km s^{-1}

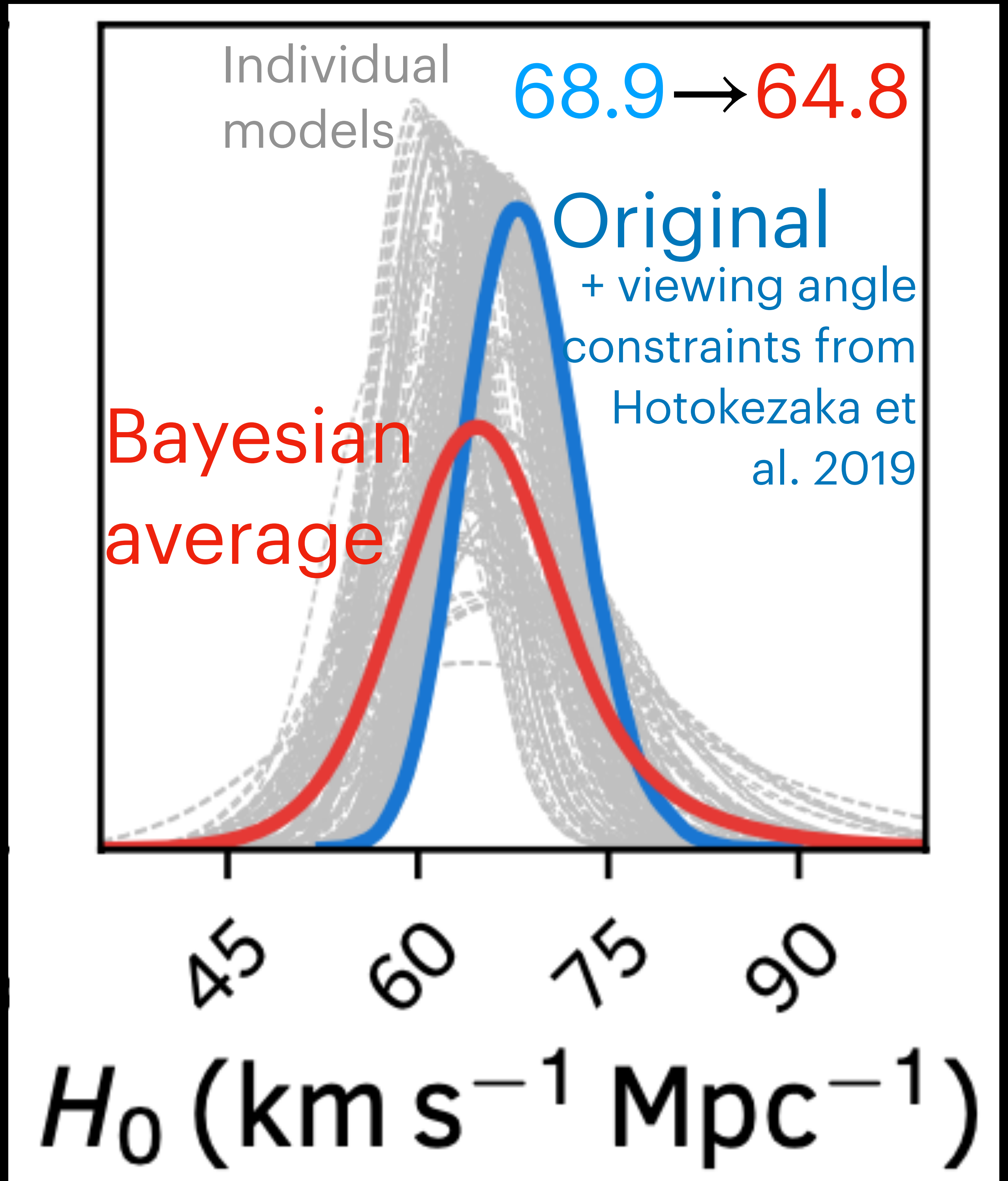
   Gives peak H_0~69 km s^{-1} Mpc^{-1}

The importance of peculiar velocities

(When you don't have many measurements yet.)

The peculiar velocity correction applied to the first GW standard siren corresponded to a change in H_0 of **7km/s/Mpc**





A more thorough peculiar velocity analysis estimates a slightly lower H_0 (but still within errors)

H_0 Dropped by 0.3σ and 0.9σ

(See Howlett and Davis 1909.00587)

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

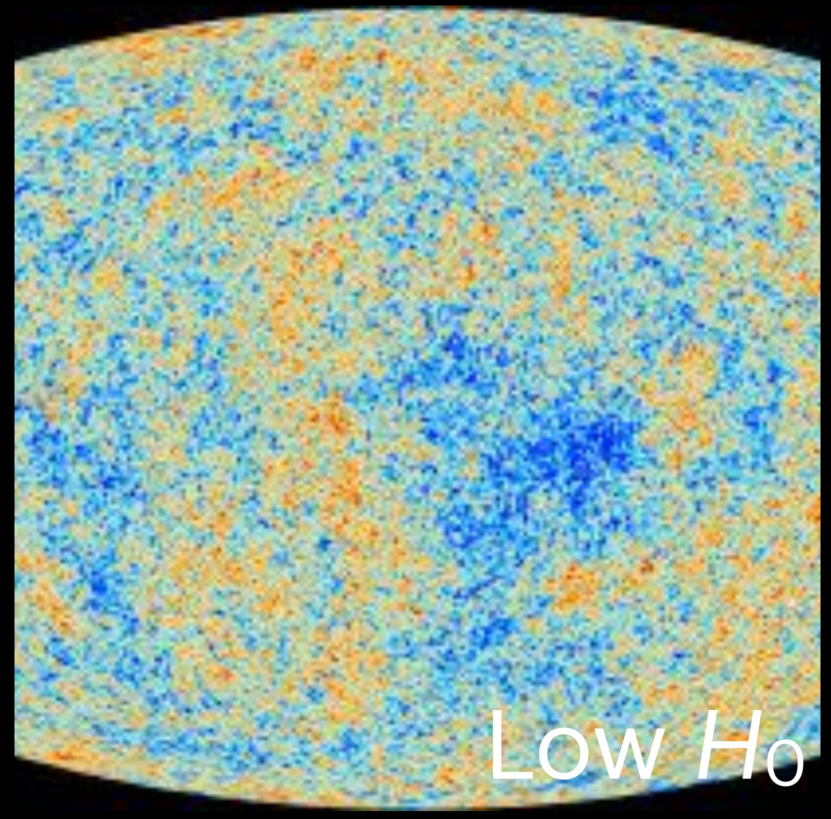
$$D_L = \tilde{D}(1+z)$$

Late
Universe
(nearby)

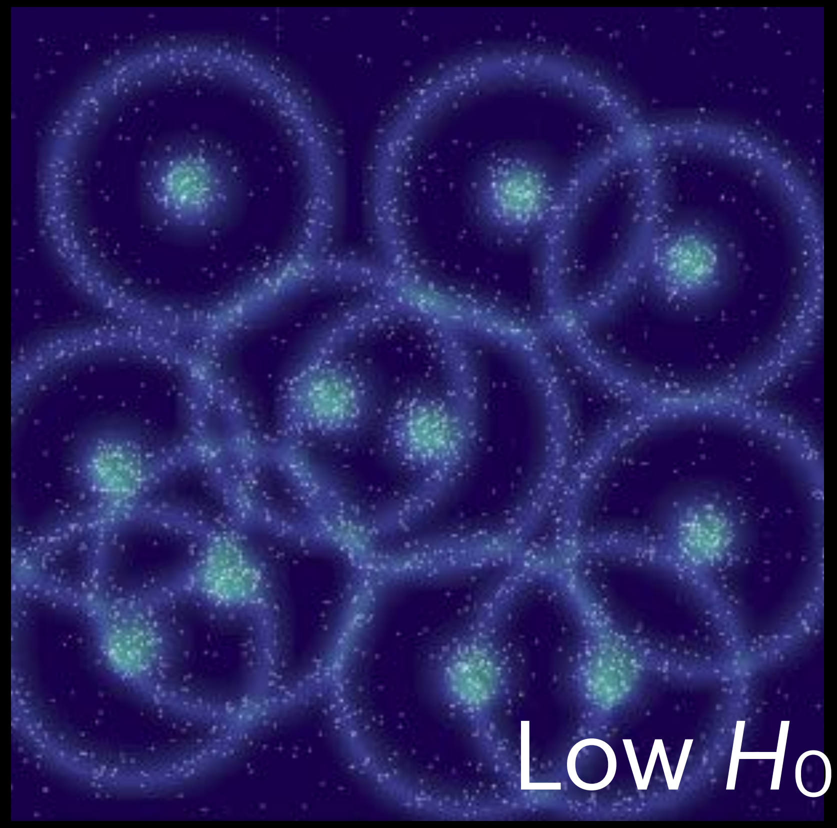
Local
(direct)

Rulers

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



Early
Universe
(far)

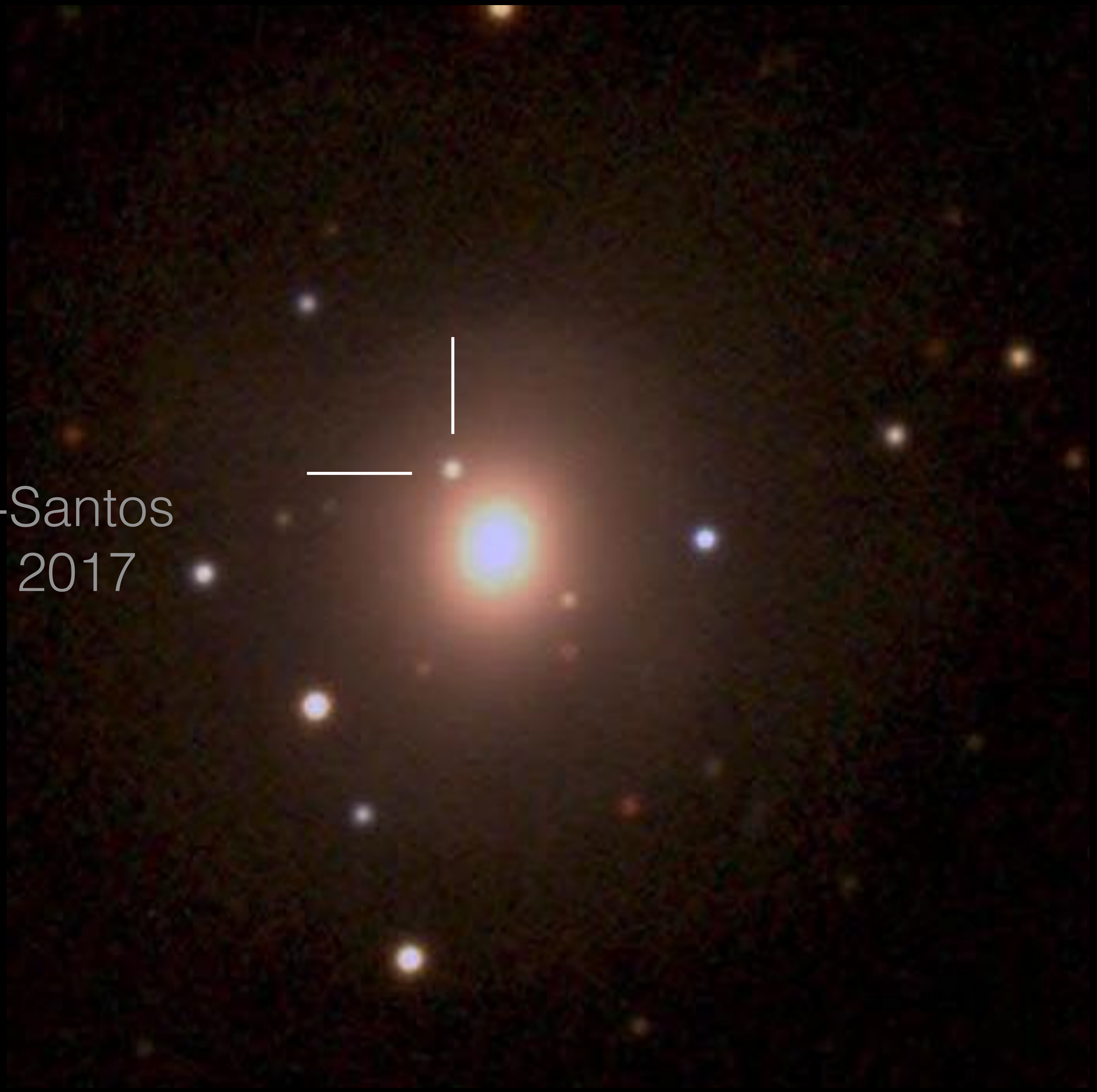


Global
(indirect)

GRAVITATIONAL WAVES

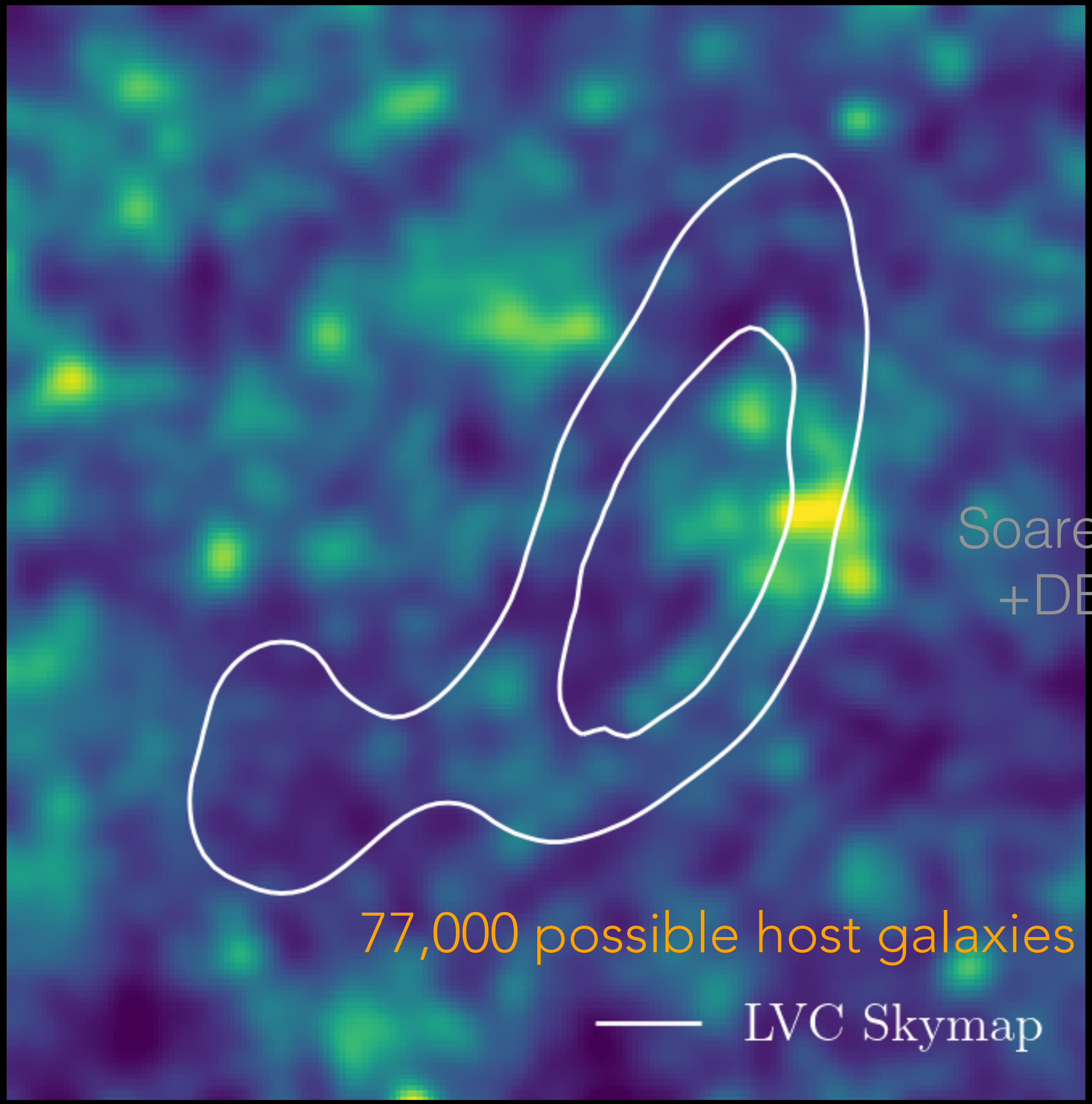
Bright sirens

Soares-Santos +DES 2017



Known host galaxy

Dark sirens



Soares-Santos +DES 2019

Many possible host galaxies

GRAVITATIONAL WAVES

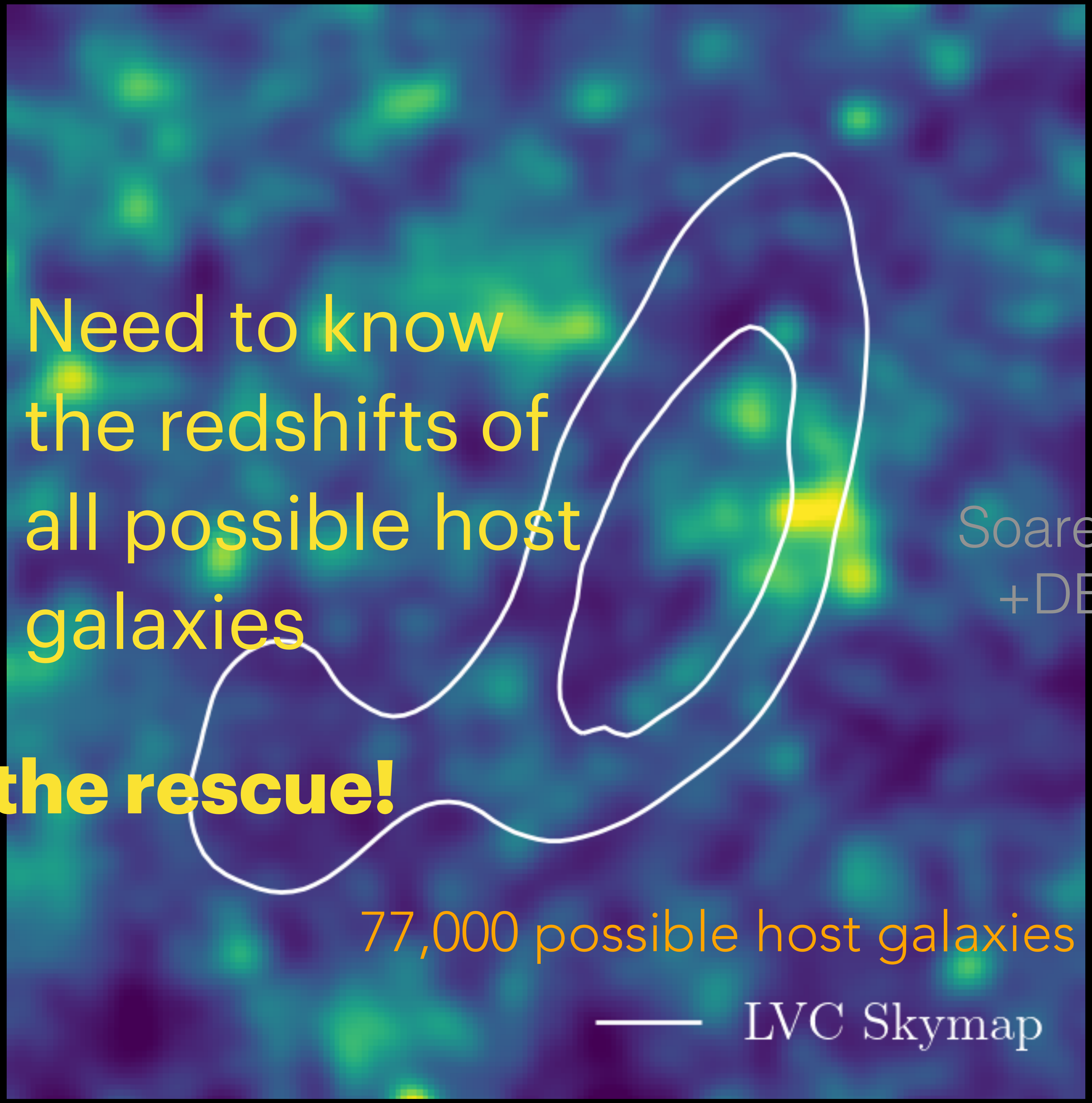
Bright sirens

Soares-Santos +DES 2017

Need to know the peculiar velocity

Known host galaxy

Dark sirens



Need to know the redshifts of all possible host galaxies

Soares-Santos +DES 2019

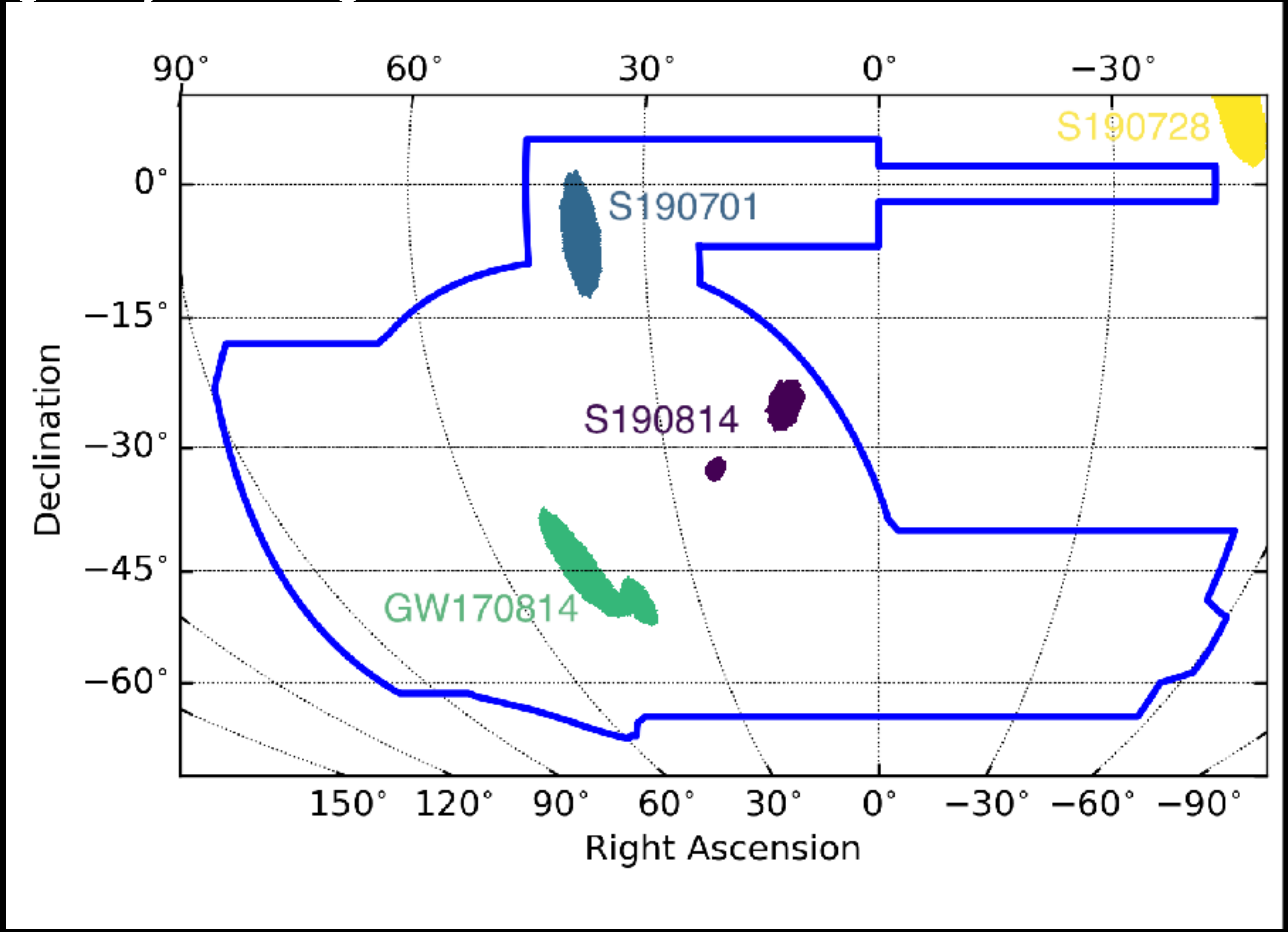
Many possible host galaxies

Galaxy surveys to the rescue!

DARK SIREN MEASUREMENT

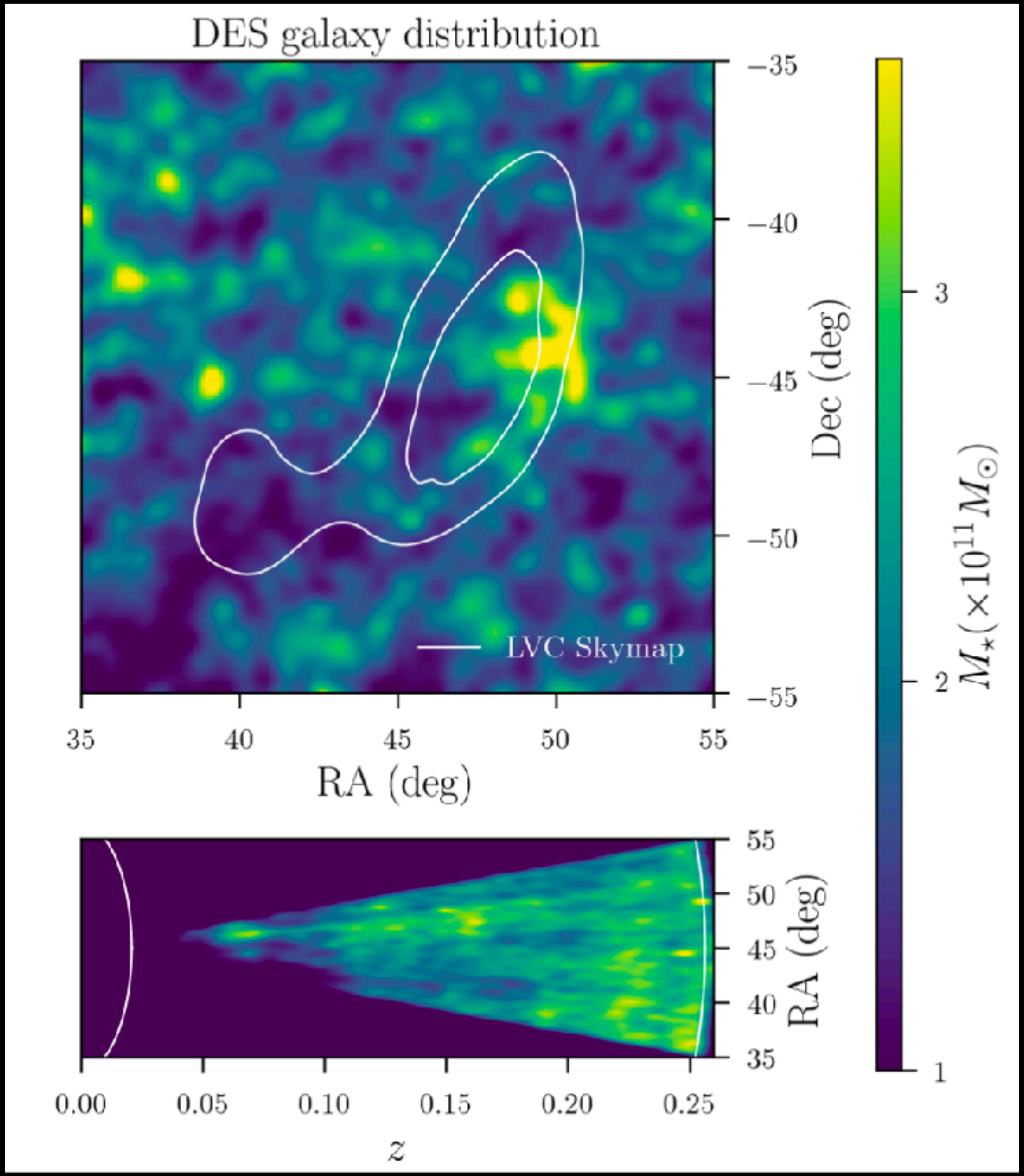
GW170814 - first well localised binary black hole

Falls in the middle of DES footprint - complete galaxy catalog



Soares-Santos, Palmese et al. 2019

77,000 possible host galaxies



DARK SIREN MEASUREMENT

GW170814 - first well localised binary black hole

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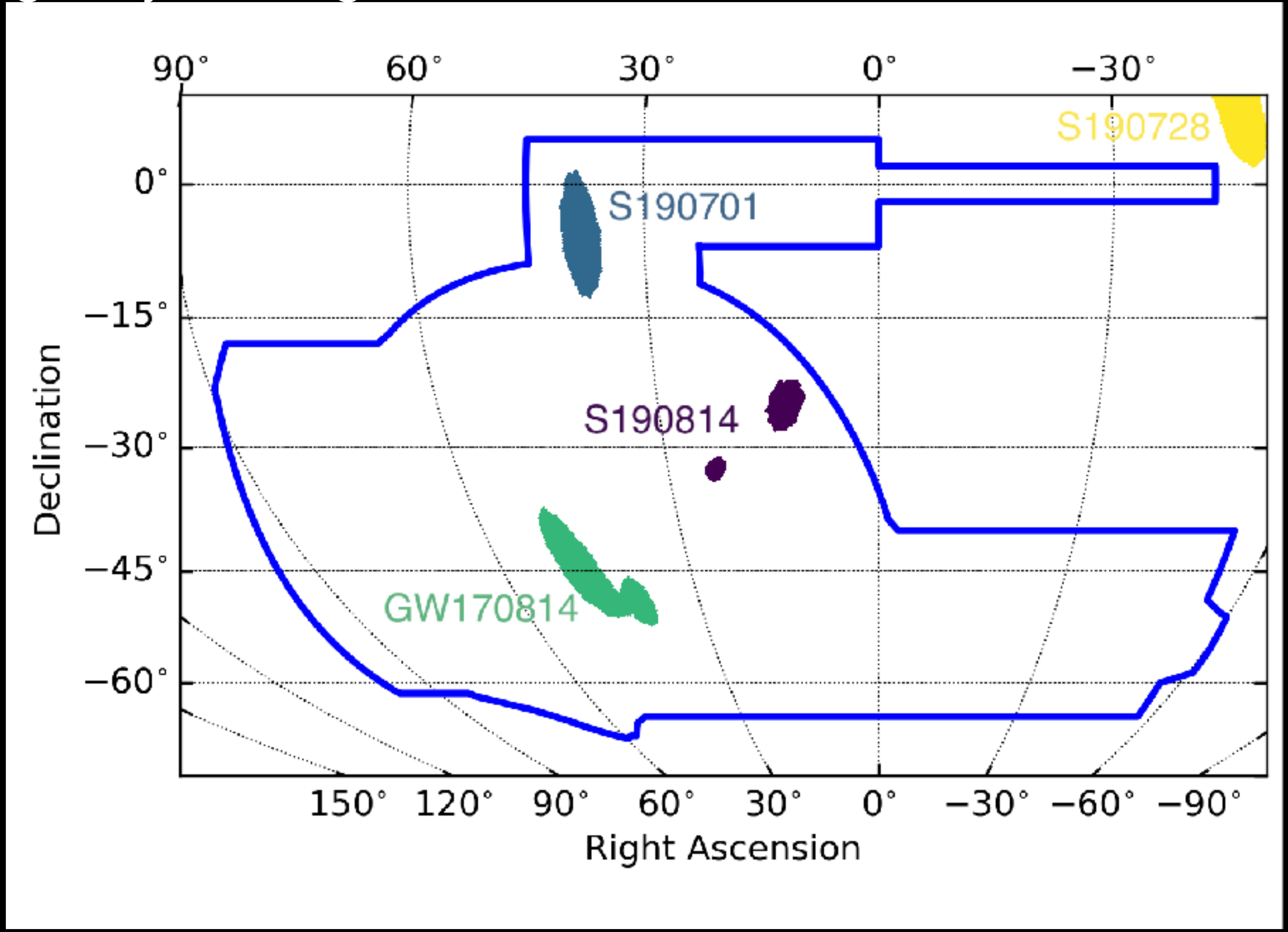
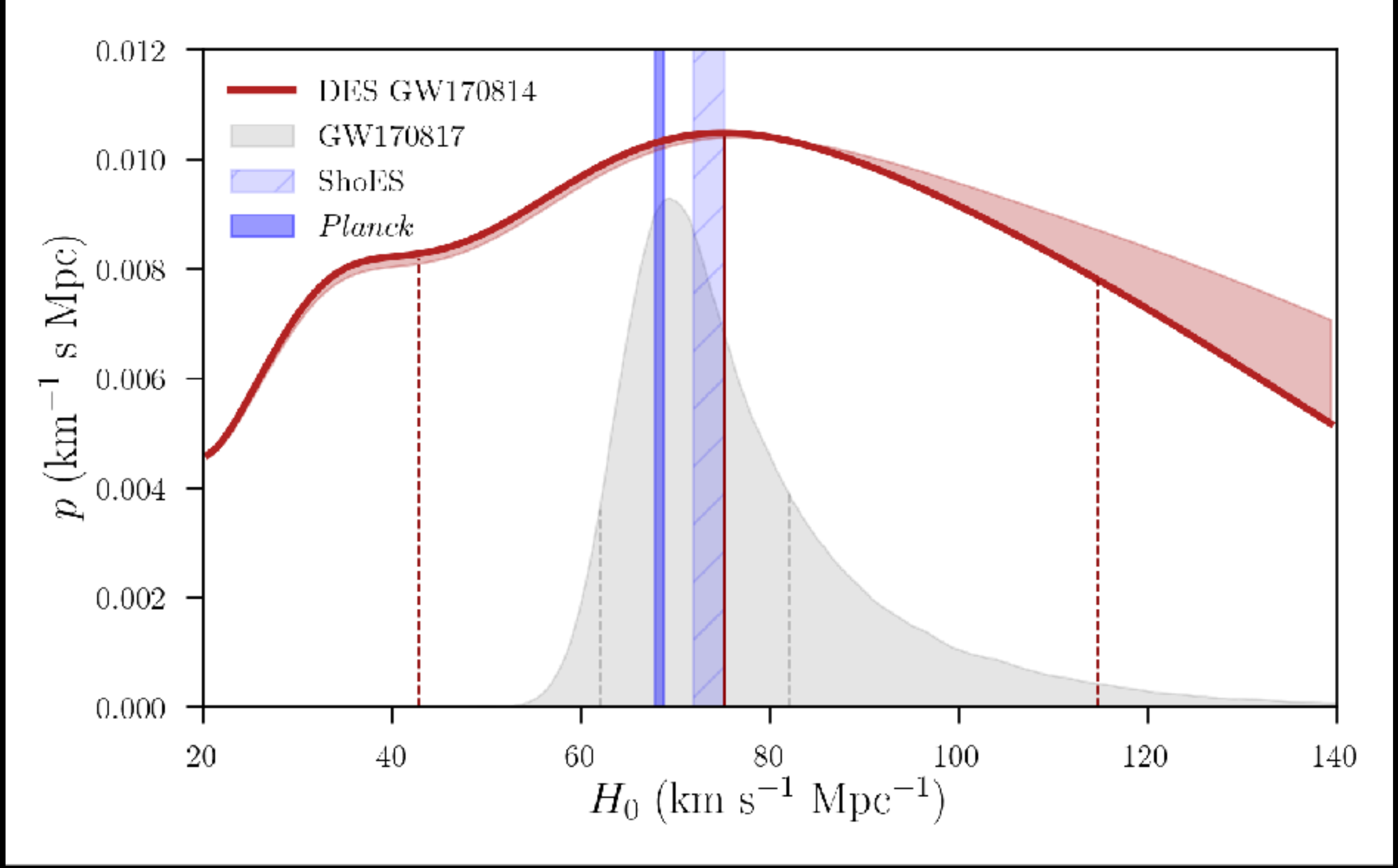


First measurement of H_0 using a binary black hole

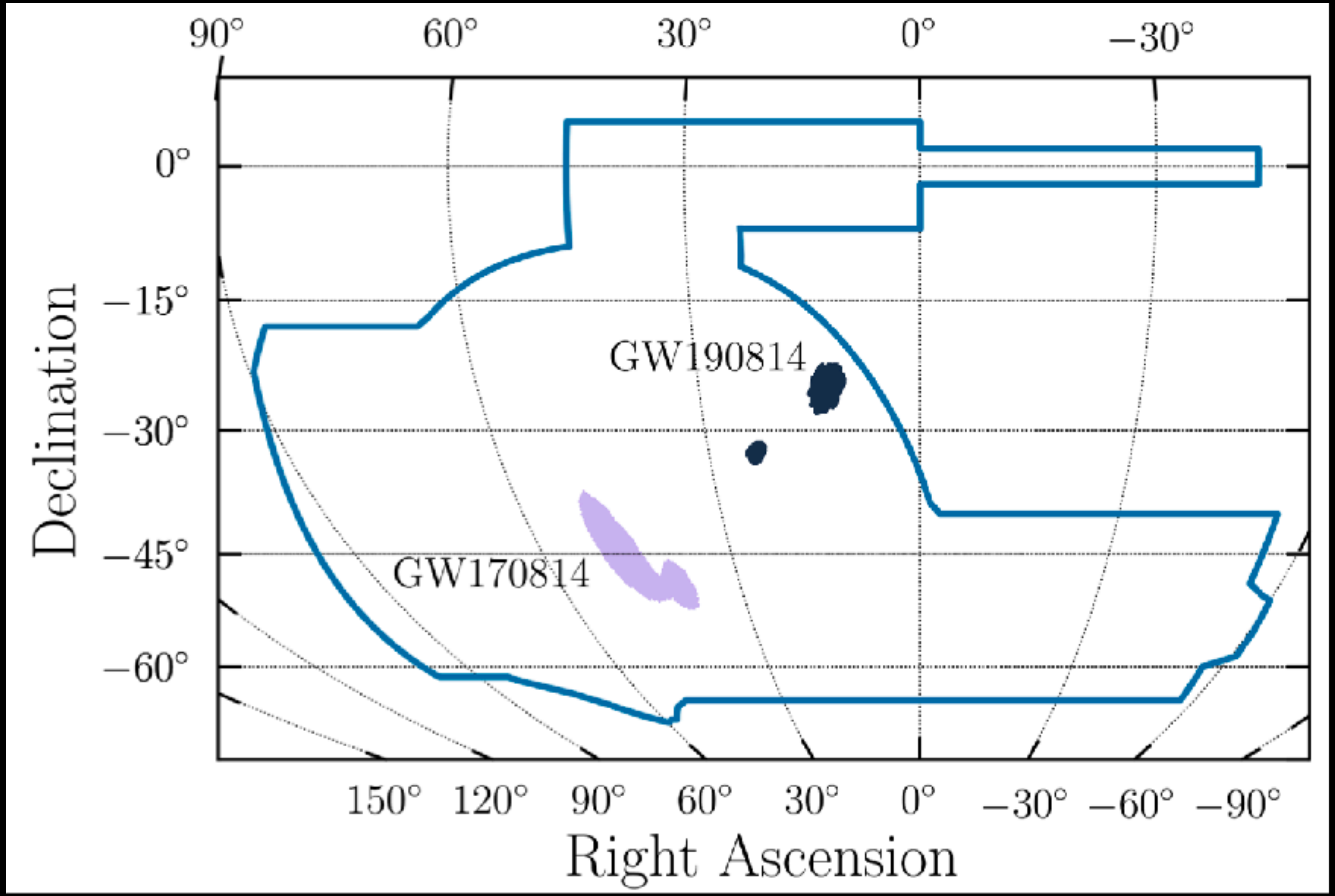
Soares-Santos et al. 2019 (DES & LVC)



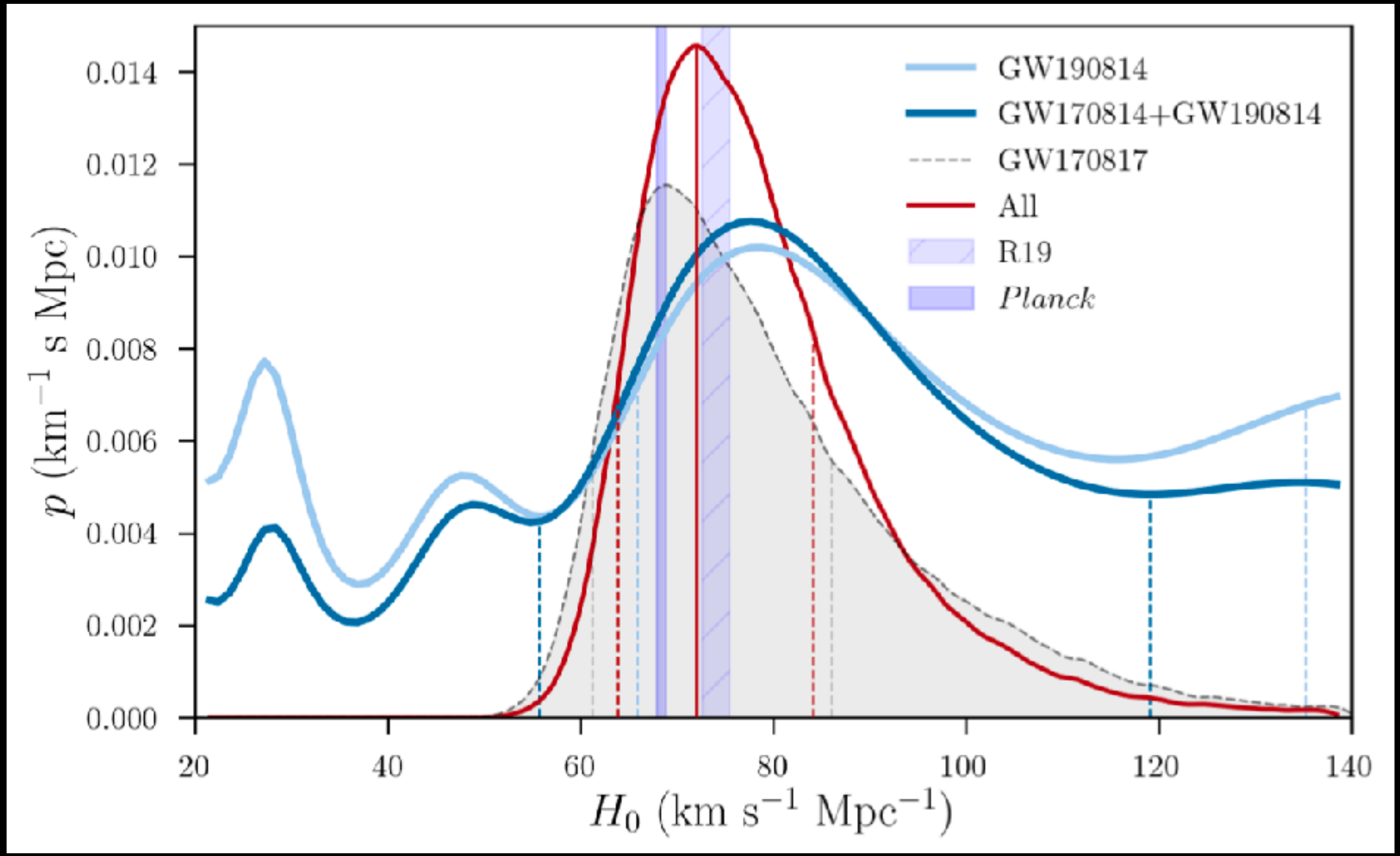
$$H_0 = 75.2^{+39.5}_{-32.4} \mathrm{km s^{-1} Mpc^{-1}}$$

DARK SIREN MEASUREMENT

Palmese et al. 2020 added GW190814

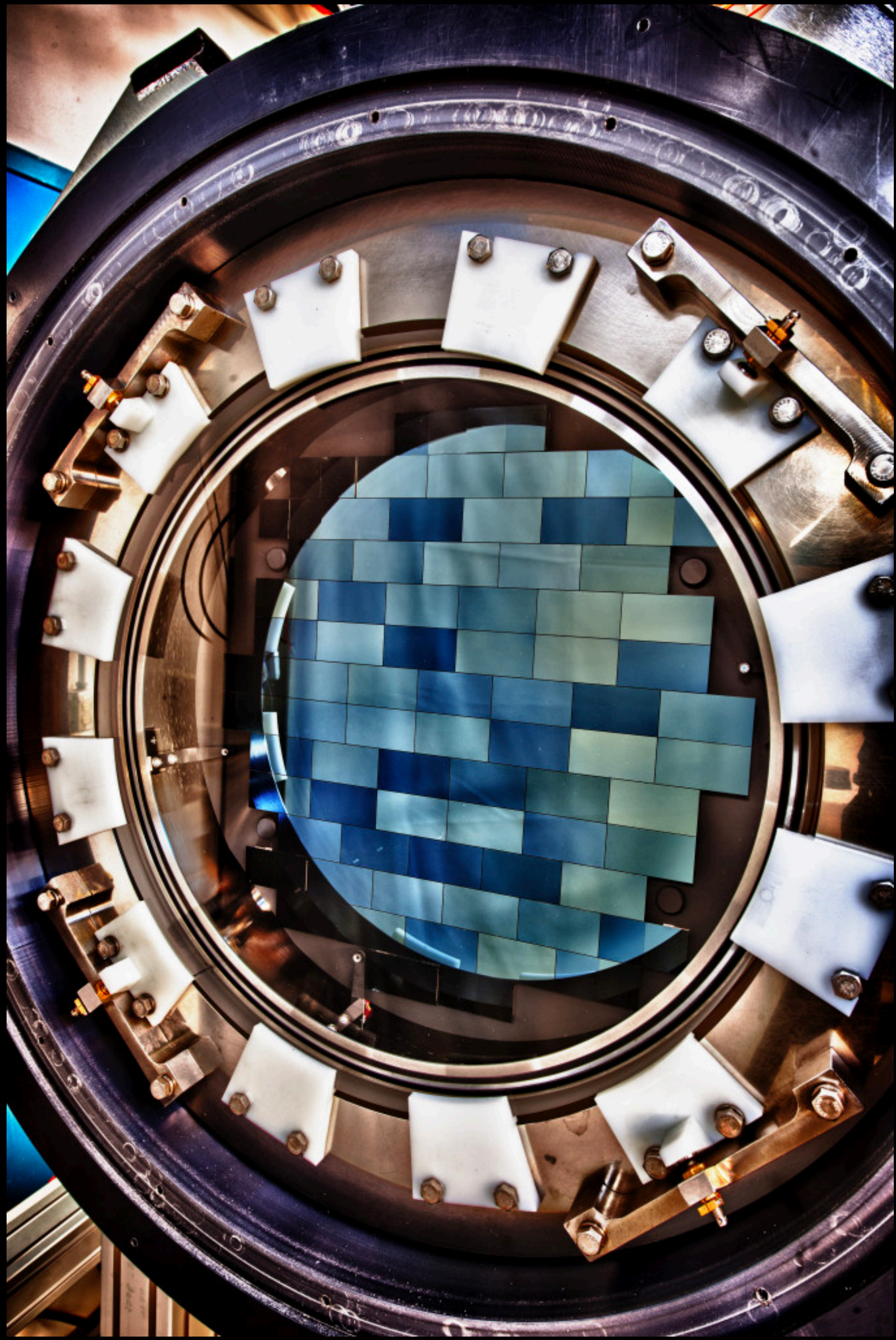


Combining



$$H_0 = 78^{+57}_{-13} \mathrm{kms}^{-1}\mathrm{Mpc}^{-1}$$

DARK ENERGY SURVEY (DES)



DARK ENERGY SPECTROSCOPIC INSTRUMENT (DESI)

Conclusions

- Multimessenger astrophysics has come of age, with cosmic rays, neutrinos, and gravitational waves all complementing traditional electromagnetic observations.
- Tensions are a great place to look for new physics… but these are complex analyses and we need to rule out systematic errors.
- Gravitational waves have the chance to replace supernovae as the gold standard low-redshift direct measurement of H_0 (and high-z too eventually)