Gravitational waves, dark energy, and massive neutrinos

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Northeastern University

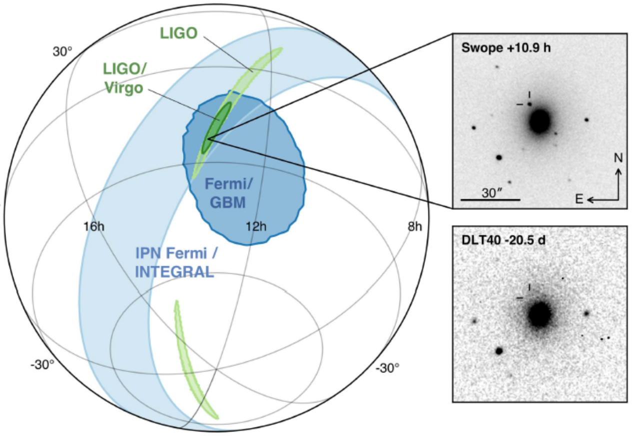
Composite 2019: Hunting New Physics in Higgs, Dark Matter, Neutrinos,
Composite Dynamics and Extra-Dimensions
2019.11.21-24
Sun Yat-sen University (SYSU) in Guangzhou, China

Multi-messenger astronomy era

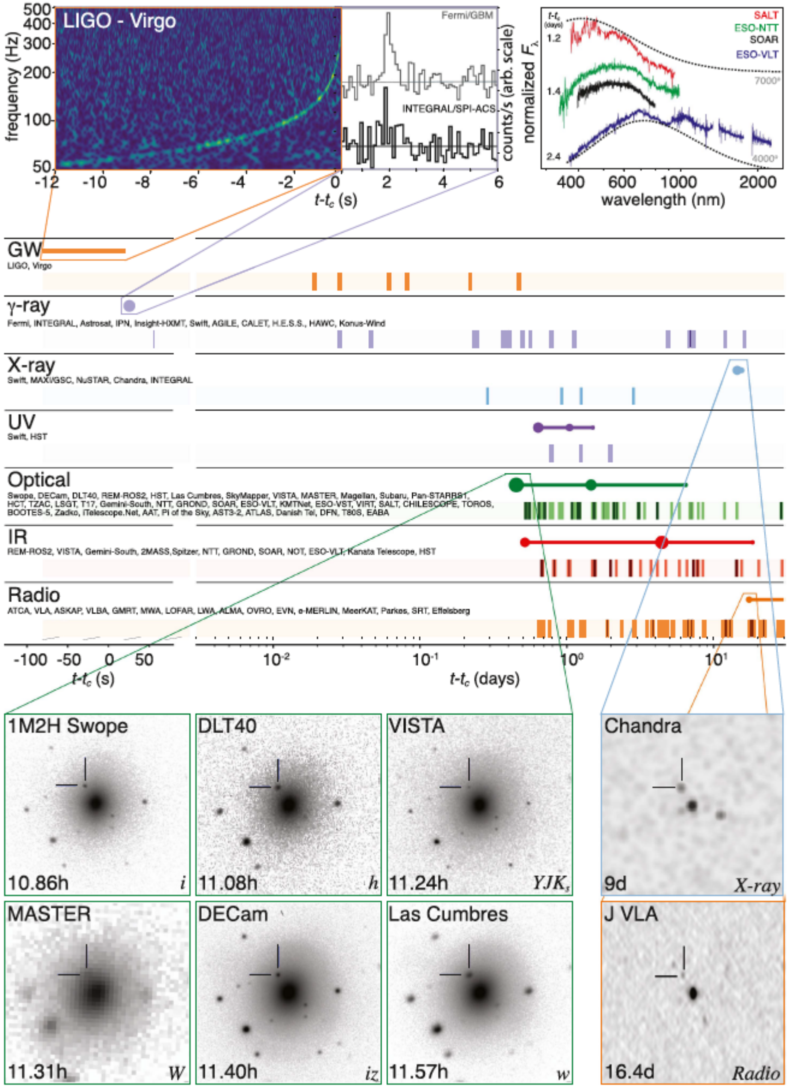
On Aug 17, 2017, LIGO-Virgo detected GW from BNS:
Multi-messenger astronomy era

4 astronomical discoveries:

- GW170817 (GW)
- GRB170817A (GRB)
- SSS17a (kilonova)
- NGC4993 (host galaxy)

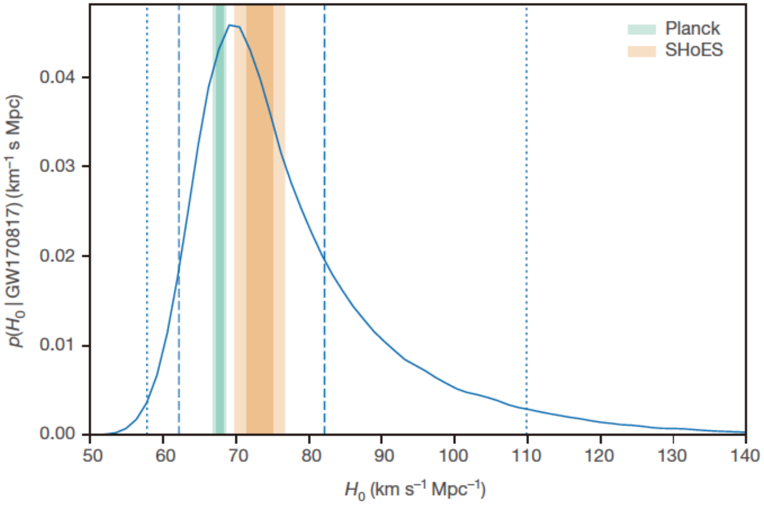


ApJ2017, 848: L12



Standard siren and the Hubble constant

- **GWs can serve as cosmic “standard sirens”: GW’s waveform carries information of luminosity distance**
- **Schutz 1986, Holz & Hughes 2005**
- **BNS merger: GW & EMW**
- **Multi-messenger: study cosmology**
- **Hubble’s law: z (small), d → H_0**
- **Independent H_0 measurement**
- **Advantage: avoid using cosmic distance ladder**
- **One data: error still large (around 15%)**

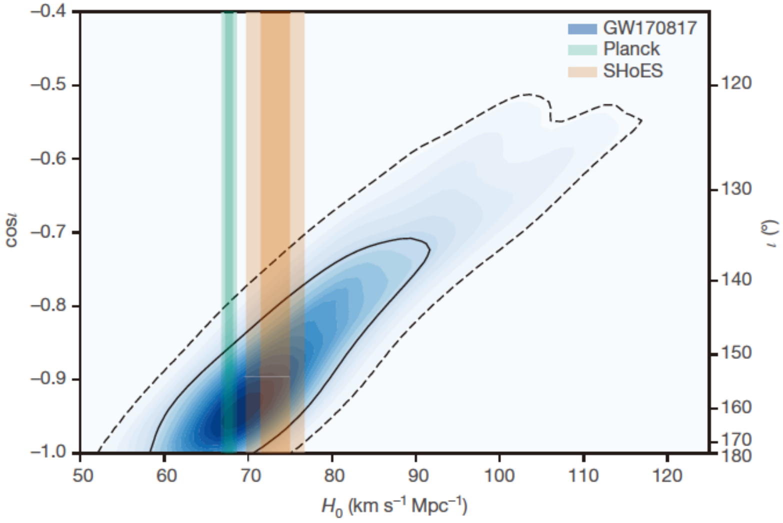


Hubble flow velocity measurement (peculiar velocity), distance measurement (parameter degeneracy, instrument calibration, et al.)

$$v_H = H_0 d$$

$$H_0 = 70.0^{+12.0}_{-8.0}\,\text{km s}^{-1}\text{Mpc}^{-1}$$

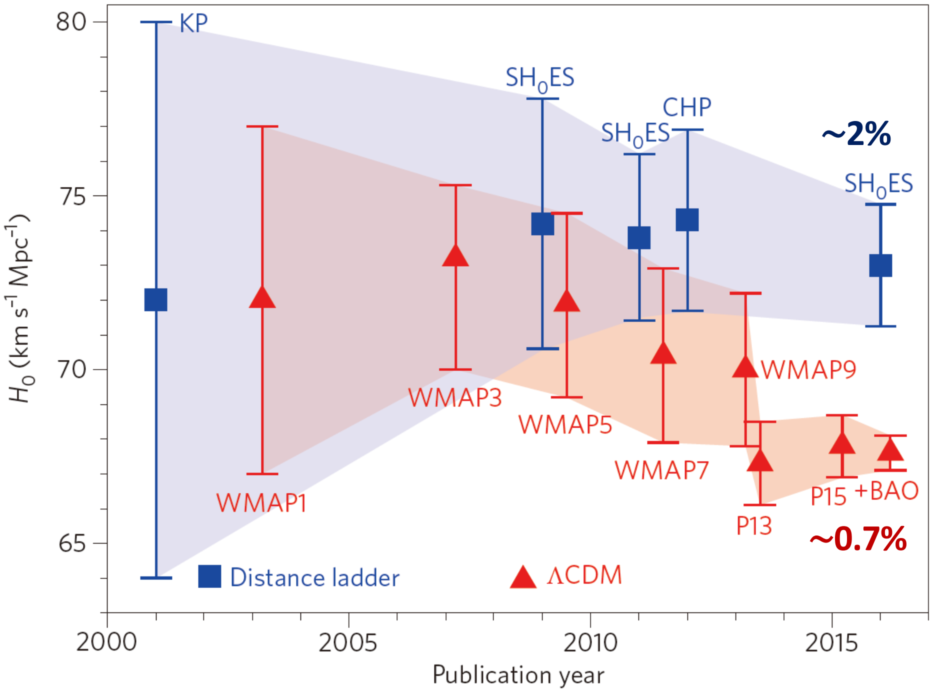
Inclination angles near 180 degree (cos *I*=-1) indicate that the orbital angular momentum is antiparallel to the direction from the source to the detector.



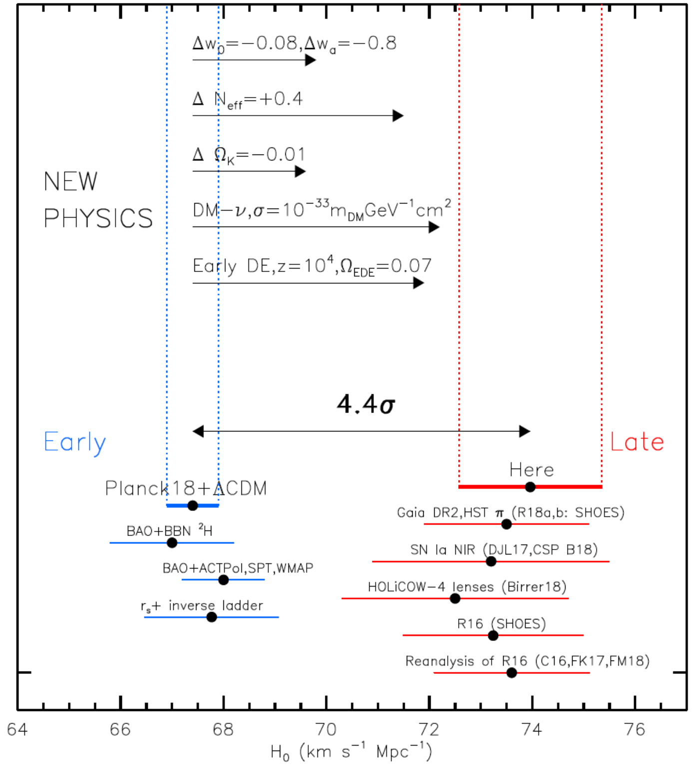
| NATURE | VOL 551 | 2 NOVEMBER 2017

The Hubble constant tension

- The Hubble constant: first cosmological parameter, a century measurement
- Tension: between early-universe and late-universe measurements
- One of the most important problems in current cosmology
- Cosmology at a crossroads



NATURE ASTRONOMY 1, 0121 (2017) | DOI: 10.1038/s41550-017-0121

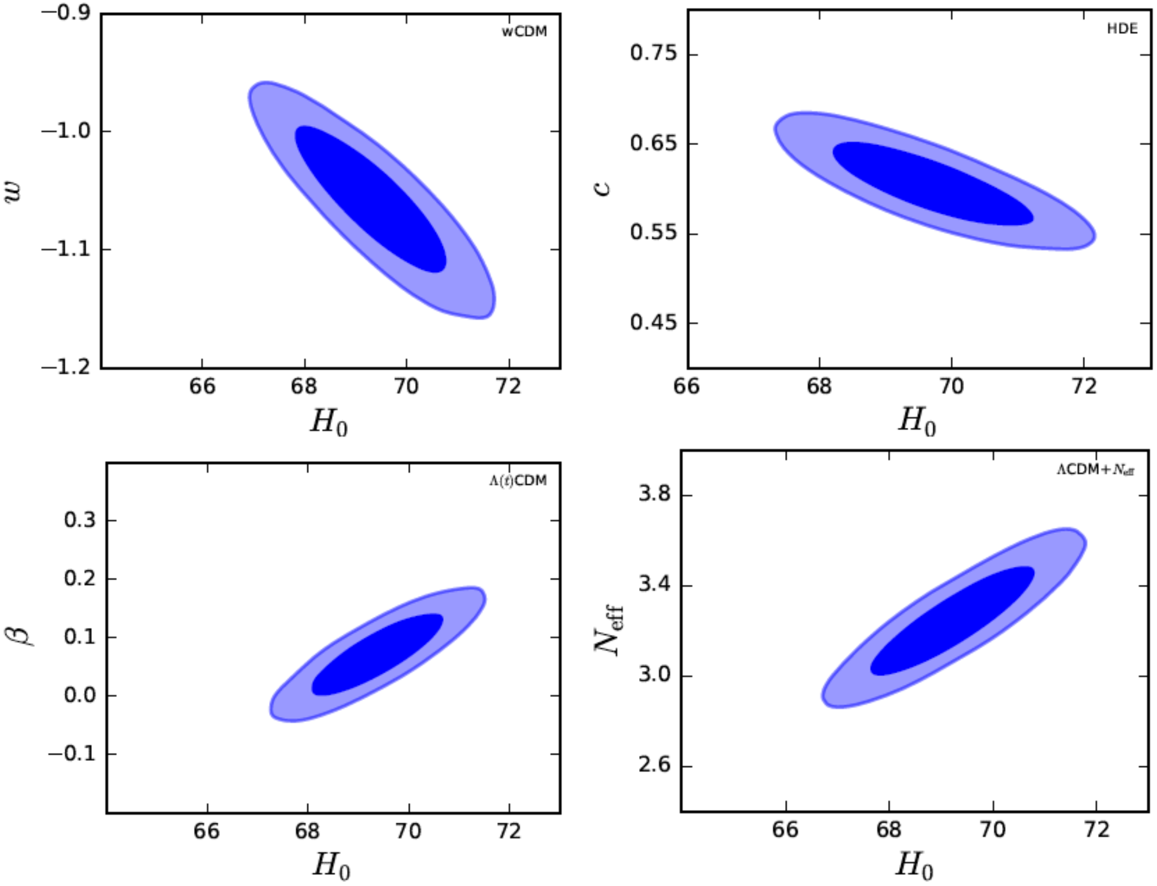


Riess et al., Astrophys. J. 876 (2019) 85 [arXiv:1903.07603]

$$H_0 = 74.03 \pm 1.42 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

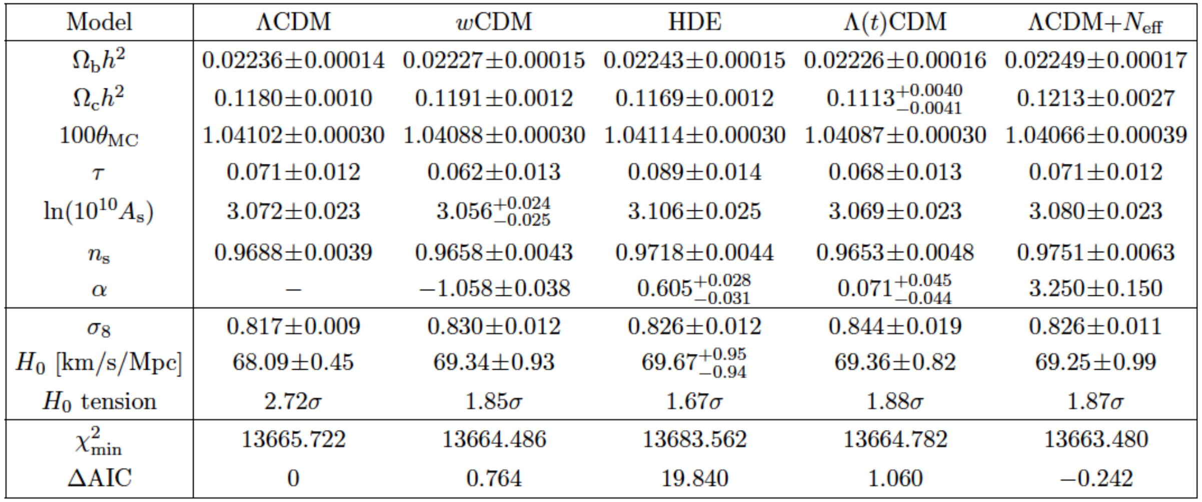
Can the H_0 tension be resolved in extensions to ΛCDM cosmology?

- The H_0 tension: new physics beyond standard model?
- In some extended models, new parameters positively-correlate or anti-correlate with H_0
- Tightly constrained by current observations
- Can the H_0 tension be resolved?

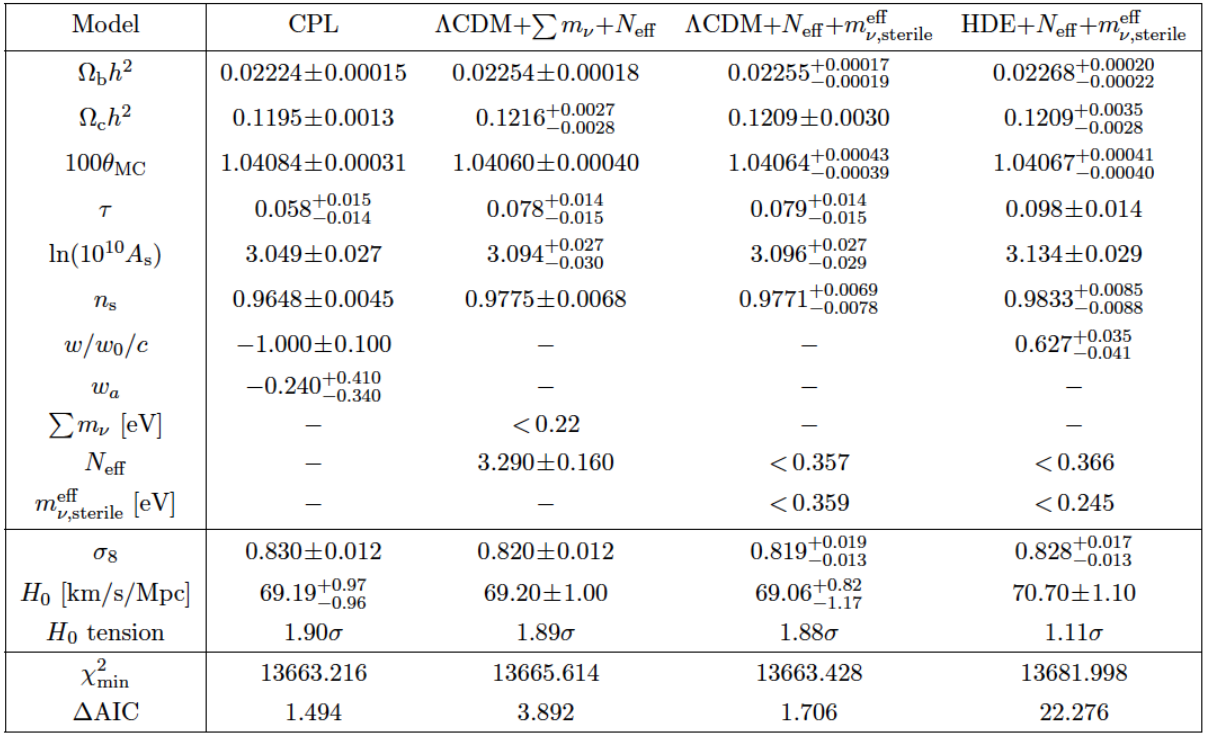


R. Y Guo, J. F. Zhang & X. Zhang, JCAP 02(2019)054

- **Single-parameter & multi-parameter extensions**
- **CMB+BAO+SN+H_0 (for obtaining a larger H_0)**
- **For ΛCDM, still 3σ tension**
- **HDE & HDE + sterile neutrino, can effectively alleviate tension (1.67σ and 1.11σ), but they are excluded by observations**
- **ΛCDM + N_{eff}, looks the best one, 1.87σ, and it is favored by observations (ΔAIC=-0.242), but if H_0 data is not used, then 2.66σ tension**
- **In addition, increasing N_{eff} can increase σ_8 (another tension)**
- **Conclusion: among these extensions, no one can truly resolve the tension**



Model	ΛCDM	wCDM	HDE	$\Lambda(t)$CDM	ΛCDM+$N_{\rm eff}$
$\Omega_{\rm b}h^2$	0.02236 ± 0.00014	0.02227 ± 0.00015	0.02243 ± 0.00015	0.02226 ± 0.00016	0.02249 ± 0.00017
$\Omega_{\rm c}h^2$	0.1180 ± 0.0010	0.1191 ± 0.0012	0.1169 ± 0.0012	$0.1113^{+0.0040}_{-0.0041}$	0.1213 ± 0.0027
$100\theta_{\rm MC}$	1.04102 ± 0.00030	1.04088 ± 0.00030	1.04114 ± 0.00030	1.04087 ± 0.00030	1.04066 ± 0.00039
τ	0.071 ± 0.012	0.062 ± 0.013	0.089 ± 0.014	0.068 ± 0.013	0.071 ± 0.012
$\ln(10^{10}A_{\rm s})$	3.072 ± 0.023	$3.056^{+0.024}_{-0.025}$	3.106 ± 0.025	3.069 ± 0.023	3.080 ± 0.023
$n_{\rm s}$	0.9688 ± 0.0039	0.9658 ± 0.0043	0.9718 ± 0.0044	0.9653 ± 0.0048	0.9751 ± 0.0063
α	–	-1.058 ± 0.038	$0.605^{+0.028}_{-0.031}$	$0.071^{+0.045}_{-0.044}$	3.250 ± 0.150
σ_8	0.817 ± 0.009	0.830 ± 0.012	0.826 ± 0.012	0.844 ± 0.019	0.826 ± 0.011
H_0 [km/s/Mpc]	68.09 ± 0.45	69.34 ± 0.93	$69.67^{+0.95}_{-0.94}$	69.36 ± 0.82	69.25 ± 0.99
H_0 tension	2.72σ	1.85σ	1.67σ	1.88σ	1.87σ
$\chi^2_{\rm min}$	13665.722	13664.486	13683.562	13664.782	13663.480
ΔAIC	0	0.764	19.840	1.060	-0.242

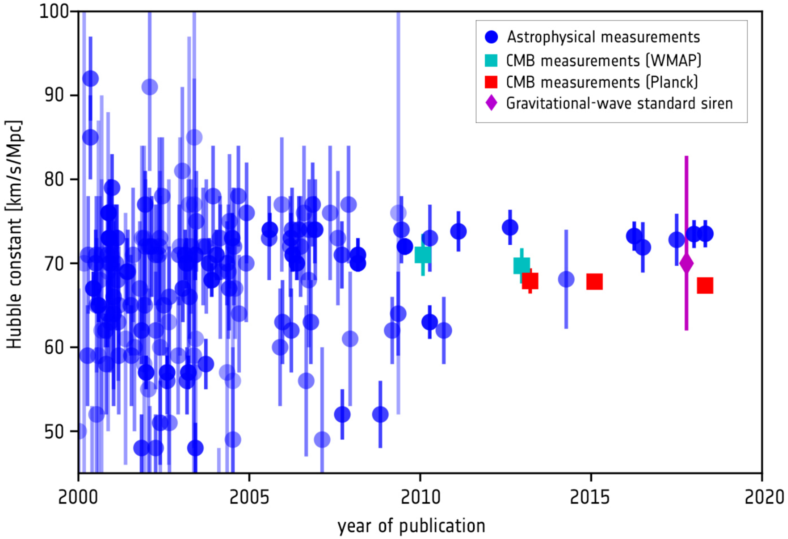


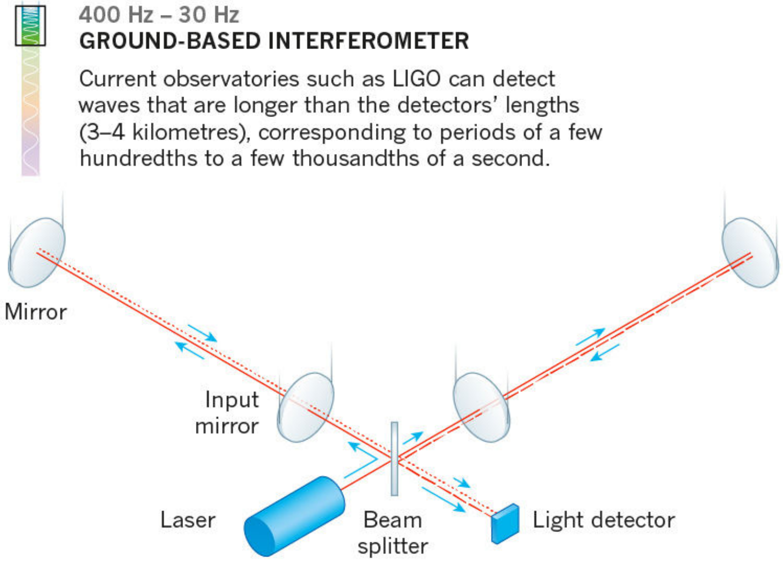
Model	CPL	ΛCDM+$\sum m_\nu$+$N_{\rm eff}$	ΛCDM+$N_{\rm eff}$+$m_{\nu,\rm sterile}^{\rm eff}$	HDE+$N_{\rm eff}$+$m_{\nu,\rm sterile}^{\rm eff}$
$\Omega_{\rm b}h^2$	0.02224 ± 0.00015	0.02254 ± 0.00018	$0.02255^{+0.00017}_{-0.00019}$	$0.02268^{+0.00020}_{-0.00022}$
$\Omega_{\rm c}h^2$	0.1195 ± 0.0013	$0.1216^{+0.0027}_{-0.0028}$	0.1209 ± 0.0030	$0.1209^{+0.0035}_{-0.0028}$
$100\theta_{\rm MC}$	1.04084 ± 0.00031	1.04060 ± 0.00040	$1.04064^{+0.00043}_{-0.00039}$	$1.04067^{+0.00041}_{-0.00040}$
τ	$0.058^{+0.015}_{-0.014}$	$0.078^{+0.014}_{-0.015}$	$0.079^{+0.014}_{-0.015}$	0.098 ± 0.014
$\ln(10^{10}A_{\rm s})$	3.049 ± 0.027	$3.094^{+0.027}_{-0.030}$	$3.096^{+0.027}_{-0.029}$	3.134 ± 0.029
$n_{\rm s}$	0.9648 ± 0.0045	0.9775 ± 0.0068	$0.9771^{+0.0069}_{-0.0078}$	$0.9833^{+0.0085}_{-0.0088}$
$w/w_0/c$	-1.000 ± 0.100	–	–	$0.627^{+0.035}_{-0.041}$
w_a	$-0.240^{+0.410}_{-0.340}$	–	–	–
$\sum m_\nu$ [eV]	–	<0.22	–	–
$N_{\rm eff}$	–	3.290 ± 0.160	<0.357	<0.366
$m_{\nu,\rm sterile}^{\rm eff}$ [eV]	–	–	<0.359	<0.245
σ_8	0.830 ± 0.012	0.820 ± 0.012	$0.819^{+0.019}_{-0.013}$	$0.828^{+0.017}_{-0.013}$
H_0 [km/s/Mpc]	$69.19^{+0.97}_{-0.96}$	69.20 ± 1.00	$69.06^{+0.82}_{-1.17}$	70.70 ± 1.10
H_0 tension	1.90σ	1.89σ	1.88σ	1.11σ
$\chi^2_{\rm min}$	13663.216	13665.614	13663.428	13681.998
ΔAIC	1.494	3.892	1.706	22.276

R.Y Guo, J.F. Zhang & X. Zhang, JCAP 02(2019)054

GW can arbitrate the H_0 measurements

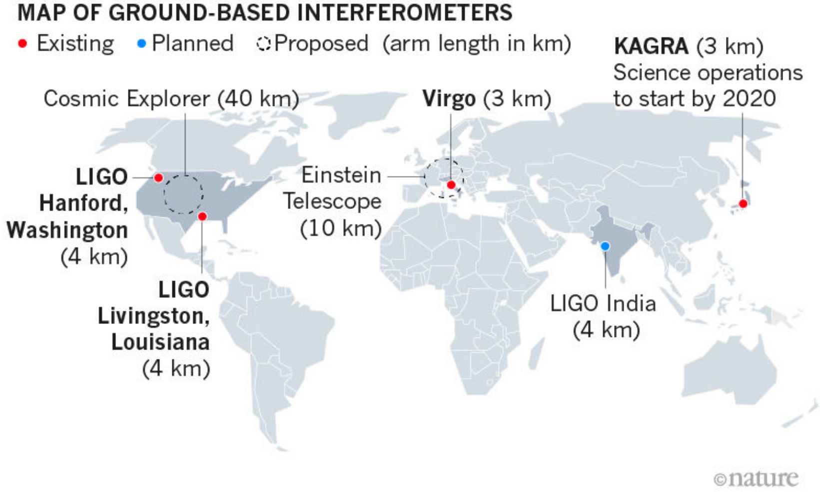
- Need a third party to make an arbitration
- GW standard sirens: pure distance measurement, avoiding complex astrophysical distance ladder and poorly understood calibration process
- Self-calibration (directly calibrated by theory)
- Currently, only one data, about 15% error
- H_0: $15\%/\sqrt{N}$, N is the event number of BNS mergers detected by LIGO-Virgo
- N=50, about 2% error
- + KAGRA & LIGO-India: $13\%/\sqrt{N}$
- Future 3rd generation ground-based GW detectors: CE & ET




400 Hz – 30 Hz

GROUND-BASED INTERFEROMETER

Current observatories such as LIGO can detect waves that are longer than the detectors' lengths (3–4 kilometres), corresponding to periods of a few hundredths to a few thousandths of a second.

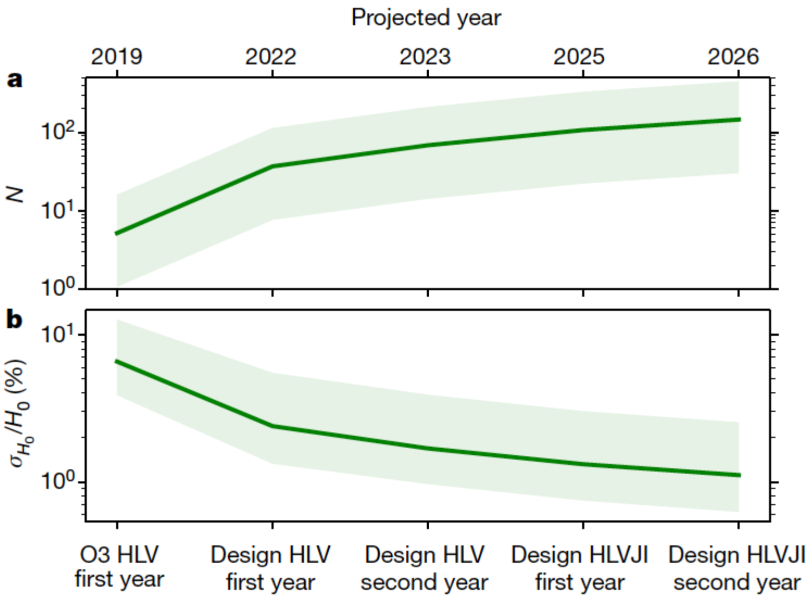

MAP OF GROUND-BASED INTERFEROMETERS

A two per cent Hubble constant measurement from standard sirens within five years

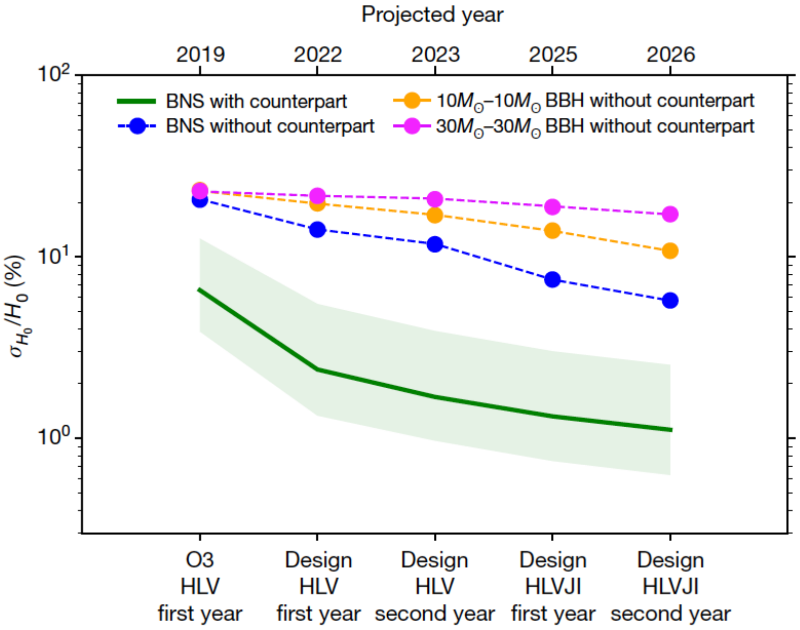
Hsin-Yu Chen[1,2]*, Maya Fishbach[2] & Daniel E. Holz[2,3,4]

25 OCTOBER 2018 | VOL 562 | NATURE | 545

- **2% in 5 years, and 1% in 10 years**
- **In 2023, 50 events, 2%; In 2026, 100 events, about 1.3%**
- **BBH, no EM counterpart, but statistical method can be used**



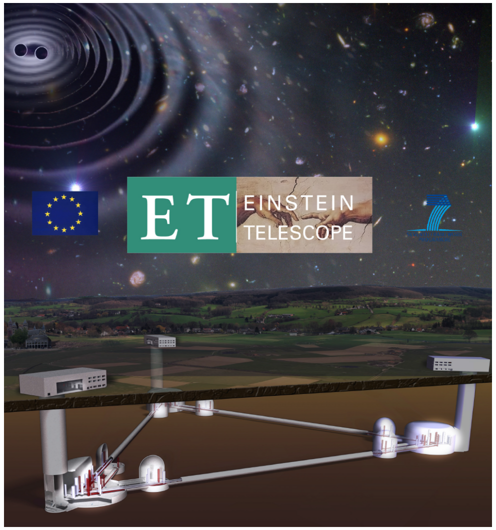
Projected number of BNS detections and corresponding fractional error for the standard siren H_0 measurement

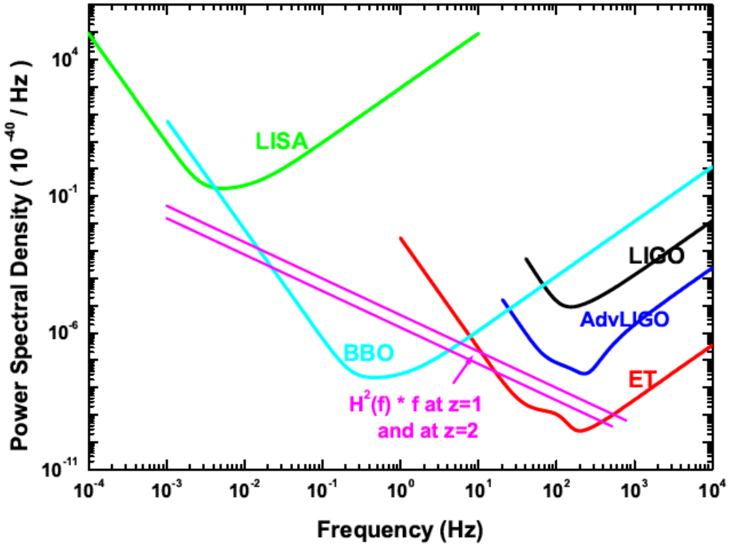


Projected fractional error for the standard siren H_0 measurement for BNSs and BBHs for future GW detector network

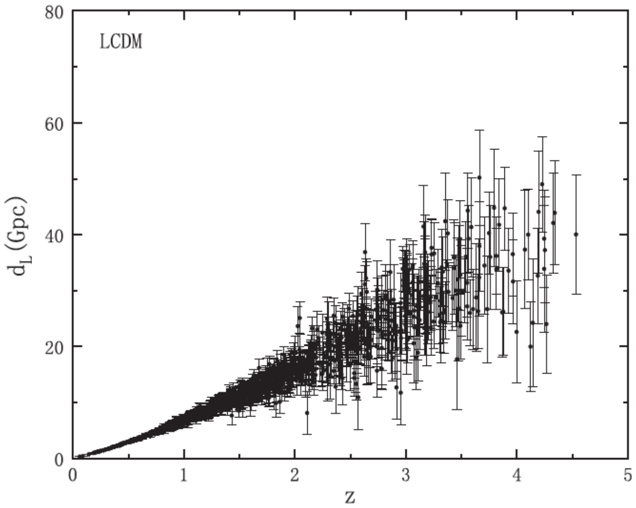
Einstein Telescope

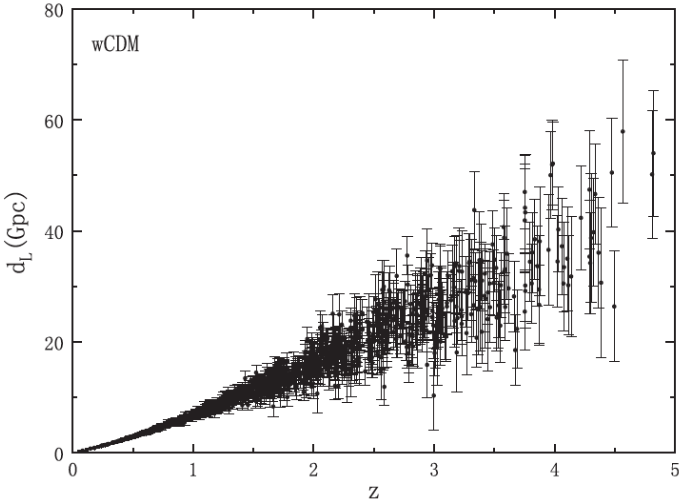
- 3^{rd} generation ground-based
- 100-200 meters underground
- Armlength 10 km
- 3 detectors
- About 1000 standard sirens in 10 years





每年10^3–10^7双中子星并合事件（取10^5），短伽玛暴中一小部分角度小（约10^{-3}），因此10年约1000个有用的事件



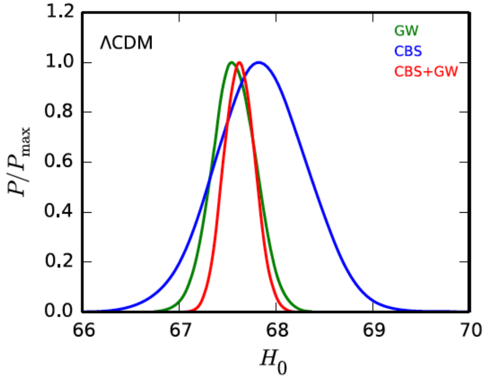


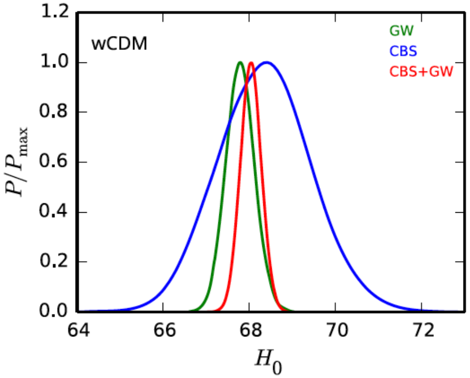
It is expected that standard sirens would be developed into a powerful cosmological probe in the future

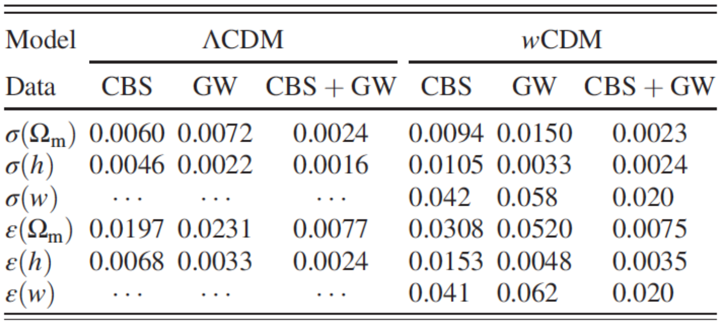
GW standard sirens: Cosmological parameter estimation (dark energy)

X. N. Zhang, L. F. Wang, J. F. Zhang & X. Zhang, Phys. Rev. D 99 (2019) 063510 [arXiv: 1804.08379]

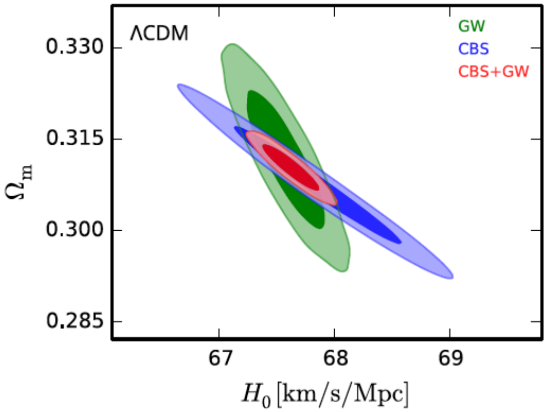
- **Standard sirens: H_0 good (ΛCDM 0.3%, wCDM 0.5%), other parameters not good**
- **But self-calibration, absolute distance measurement, can break parameter degeneracies, rather meaningful for parameter measurements**
- **wCDM: in H_0-Ω_m plane, roughly orthogonal**
- **w also not good (12%) by GW, and 4% by current CBS; degeneracy broken: w 2% by combined data**
- **GW combined with future survey projects, can elucidate the nature of DE?**

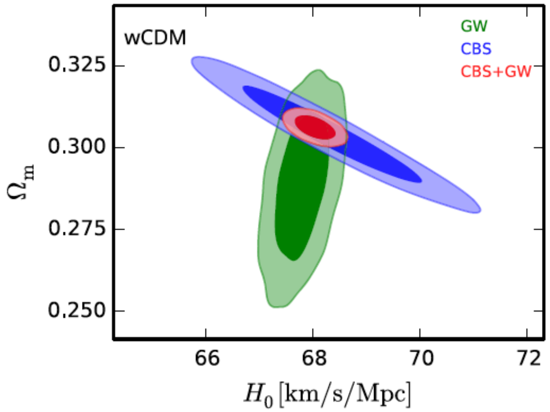


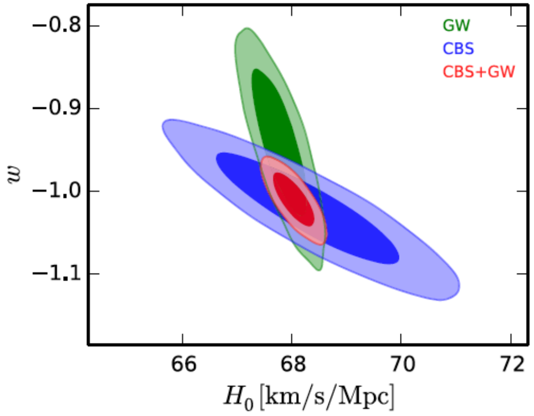




Model	ΛCDM			wCDM		
Data	CBS	GW	CBS + GW	CBS	GW	CBS + GW
$\sigma(\Omega_m)$	0.0060	0.0072	0.0024	0.0094	0.0150	0.0023
$\sigma(h)$	0.0046	0.0022	0.0016	0.0105	0.0033	0.0024
$\sigma(w)$	⋯	⋯	⋯	0.042	0.058	0.020
$\varepsilon(\Omega_m)$	0.0197	0.0231	0.0077	0.0308	0.0520	0.0075
$\varepsilon(h)$	0.0068	0.0033	0.0024	0.0153	0.0048	0.0035
$\varepsilon(w)$	⋯	⋯	⋯	0.041	0.062	0.020

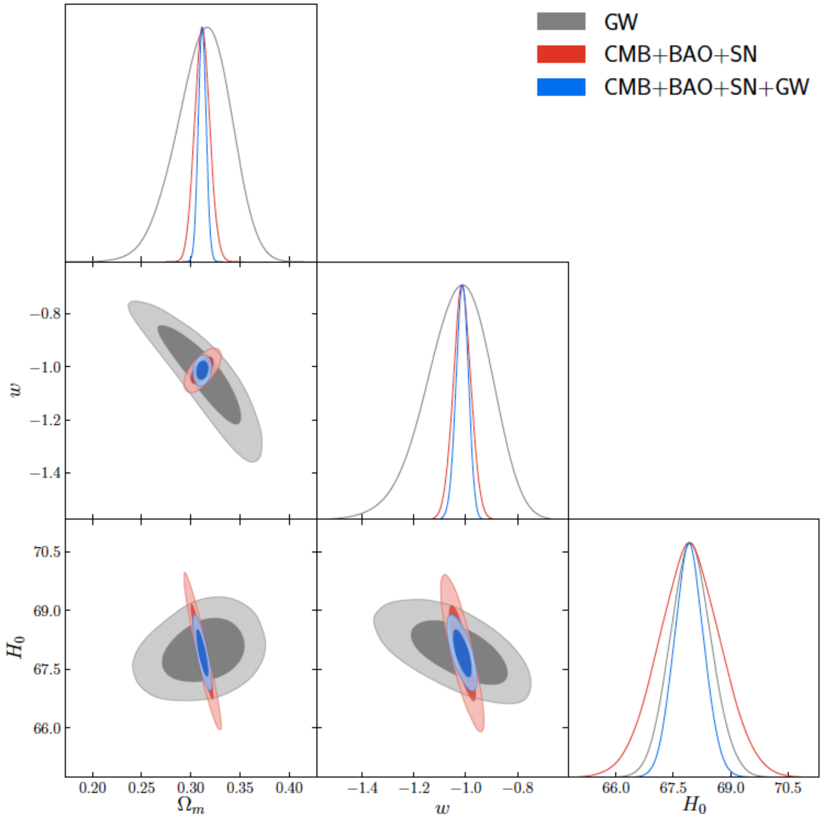


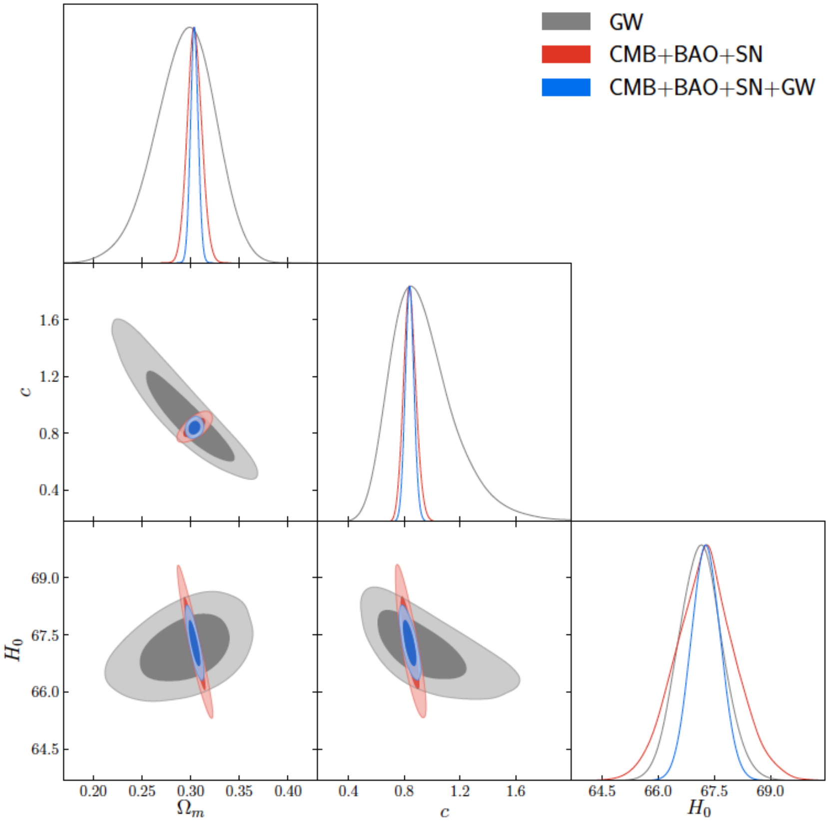




Constraints on DE models from future GW observation: Examples

J. F. Zhang, M. Zhang, S. J. Jin, J. Z. Qi & X. Zhang, JCAP 1909 (2019) 068 [arXiv:1907.03238]
J. F. Zhang, H. Y. Dong, J. Z. Qi & X. Zhang, arXiv:1906.07504

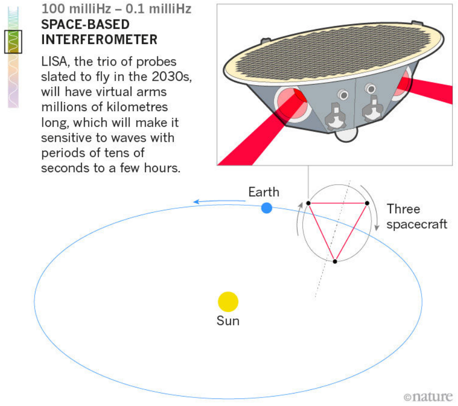




wCDM模型

HDE模型

Space-based GW detectors

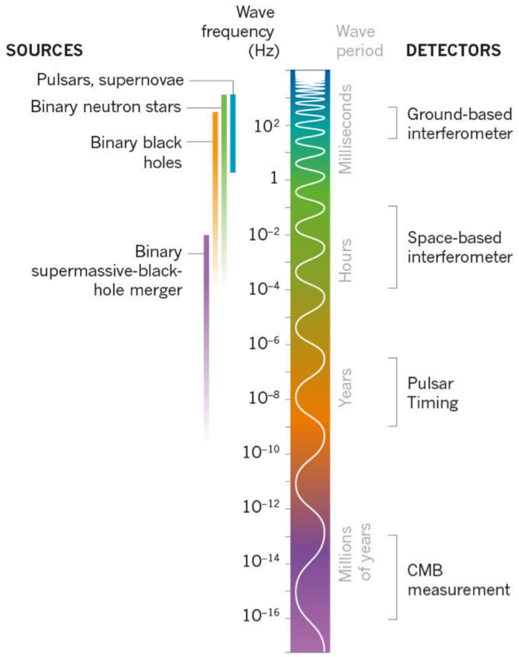


100 milliHz – 0.1 milliHz

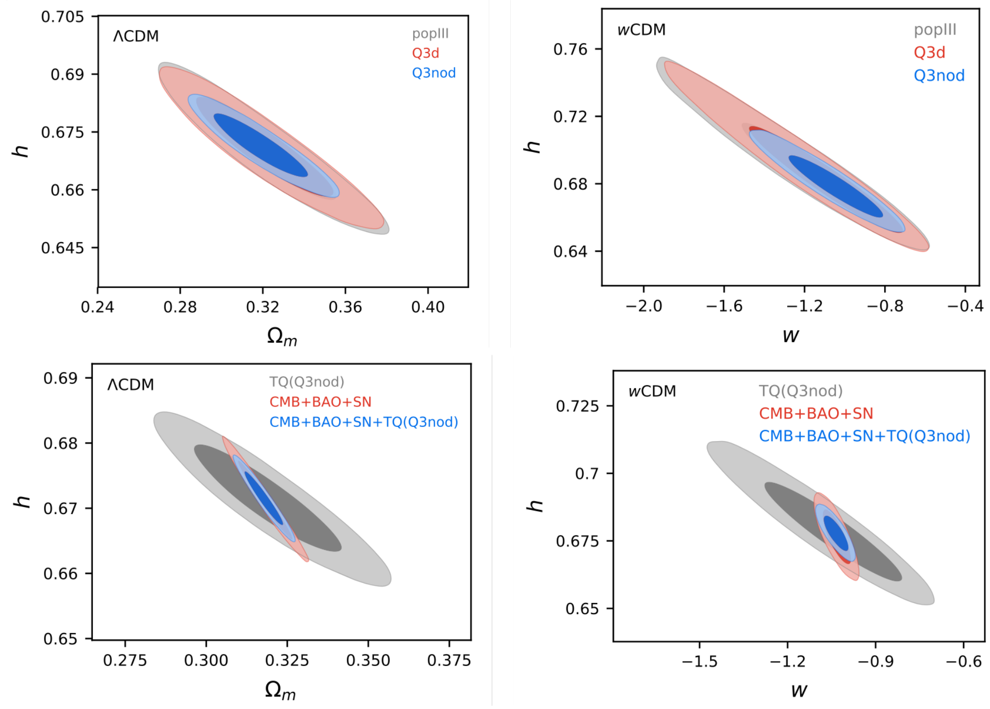
SPACE-BASED INTERFEROMETER

LISA, the trio of probes slated to fly in the 2030s, will have virtual arms millions of kilometres long, which will make it sensitive to waves with periods of tens of seconds to a few hours.

- Frequency range: 10^{-4} Hz - 1 Hz
- Supermassive black hole (galaxy center) coalescence
- Extreme mass ratio inspiral (EMRI)
- China’s projects: Taiji & TianQin
- Merger events: uncertainty large
- SMBH formation and growth: 3 models

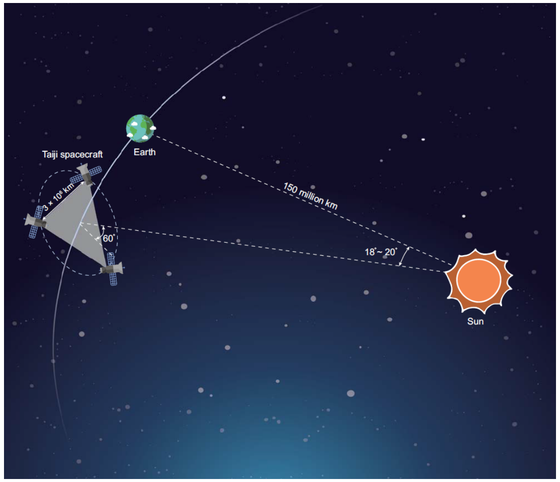


Forecast for TianQin (standard sirens)

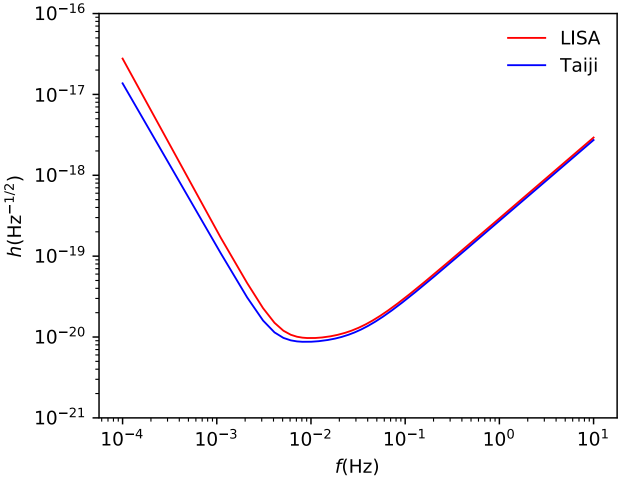


L. F. Wang, Z. W. Zhao, J. F. Zhang & X. Zhang, 1907.01838

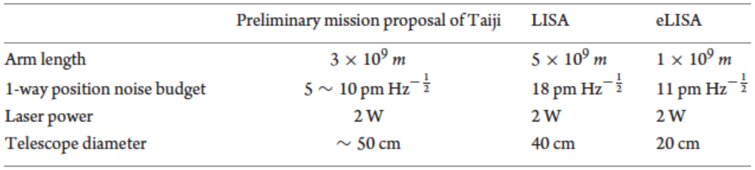
Space-based GW detectors



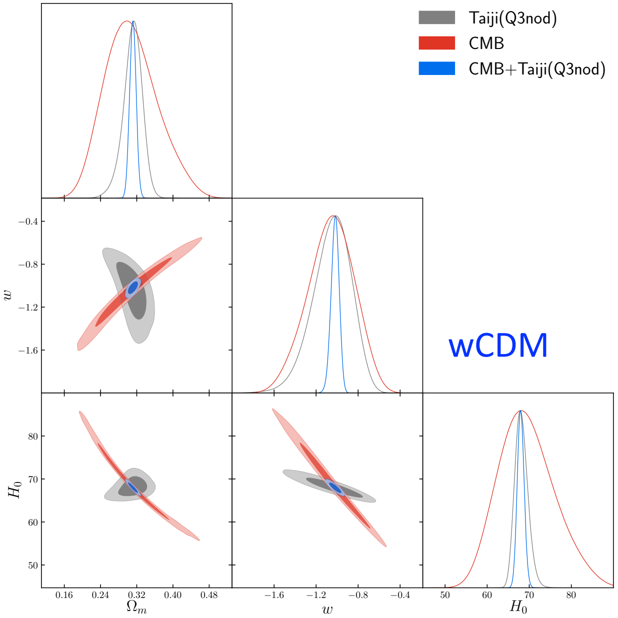
Taiji project, W. R. Hu & Y. L. Wu, Natl. Sci. Rev. 4 (2017) 685



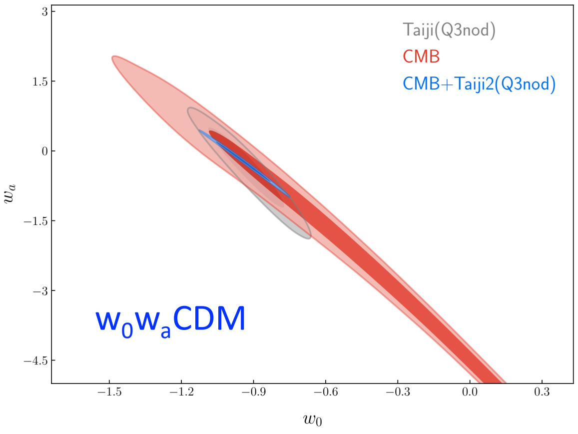
- GW space observation's constraint capability for cosmological parameters is weak (sources rare, WL)
- Constraints on DE still meaningful
- Standard sirens
- Parameter degeneracies broken

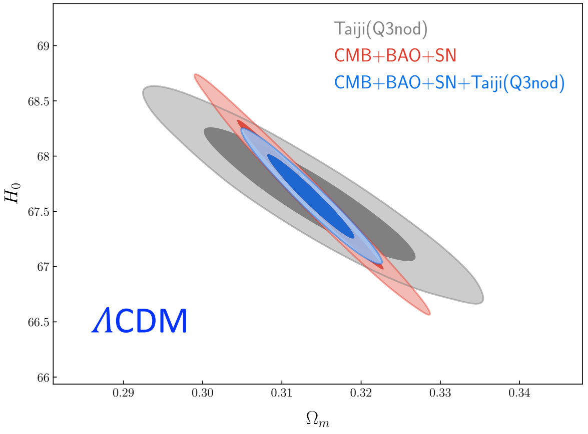


	Preliminary mission proposal of Taiji	LISA	eLISA
Arm length	$3 \times 10^9\ m$	$5 \times 10^9\ m$	$1 \times 10^9\ m$
1-way position noise budget	$5 \sim 10\ \mathrm{pm\ Hz}^{-\frac{1}{2}}$	$18\ \mathrm{pm\ Hz}^{-\frac{1}{2}}$	$11\ \mathrm{pm\ Hz}^{-\frac{1}{2}}$
Laser power	2 W	2 W	2 W
Telescope diameter	~ 50 cm	40 cm	20 cm



Forecast for Taiji (standard sirens)





Z. W. Zhao, L. F. Wang, J. F. Zhang & X. Zhang, in preparation

Neutrino oscillations: beyond SM

PMNS Matrix

$$V=\begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&0&s_{13}e^{-i\delta}\\0&1&0\\-s_{13}e^{i\delta}&0&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}\begin{pmatrix}e^{i\rho}&0&0\\0&e^{i\sigma}&0\\0&0&1\end{pmatrix}$$

$\boldsymbol{\theta_{23} \sim 45^\circ}$

$\boldsymbol{|\Delta m^2_{32}| \sim 2.5\times10^{-3}\ \mathrm{eV}^2}$

Atmospheric,
LBL accelerator

$\boldsymbol{\theta_{13} \sim 9^\circ}$

$\boldsymbol{\delta \sim ?}$

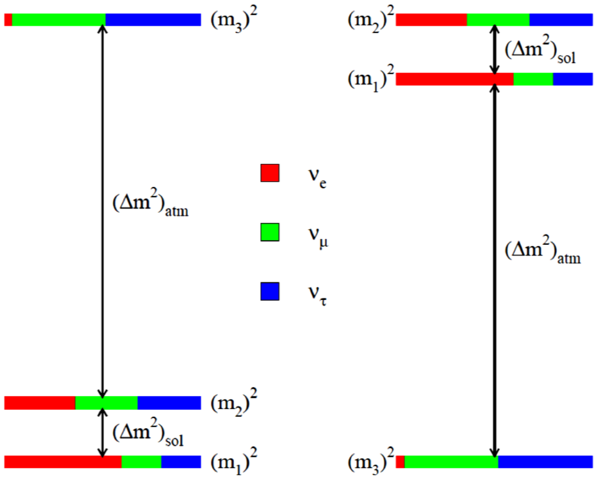
Reactor,
LBL accelerator

$\boldsymbol{\theta_{12} \sim 34^\circ}$

$\boldsymbol{\Delta m^2_{21} \sim 8\times10^{-5}\ \mathrm{eV}^2}$

Solar,
KamLAND

0ν2β, LNV?



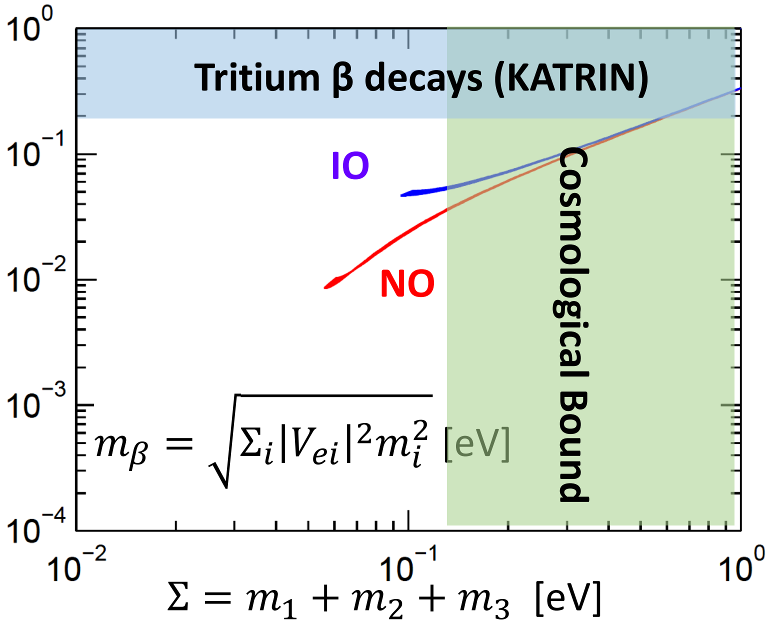
normal hierarchy   inverted hierarchy

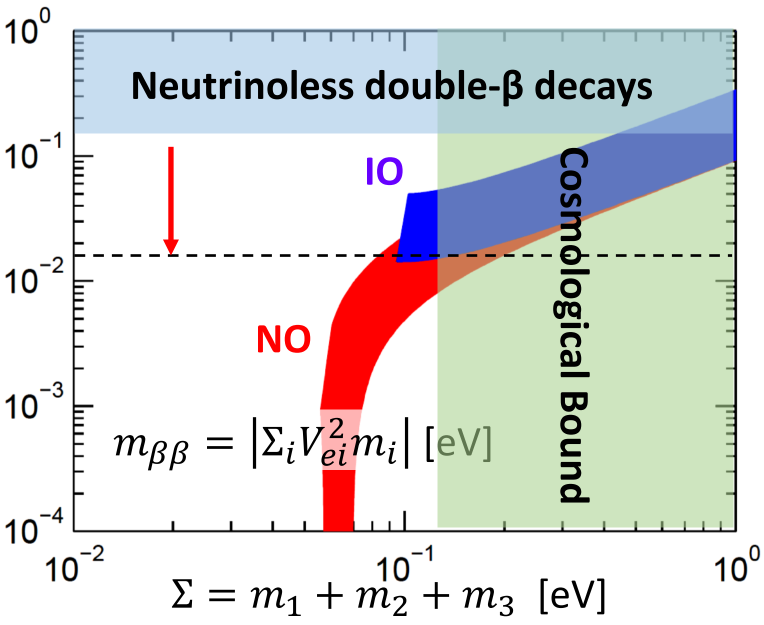
$$\Delta m^2_{21} \equiv m_2^2 - m_1^2 = 7.5\times10^{-5}\ \mathrm{eV}^2,$$

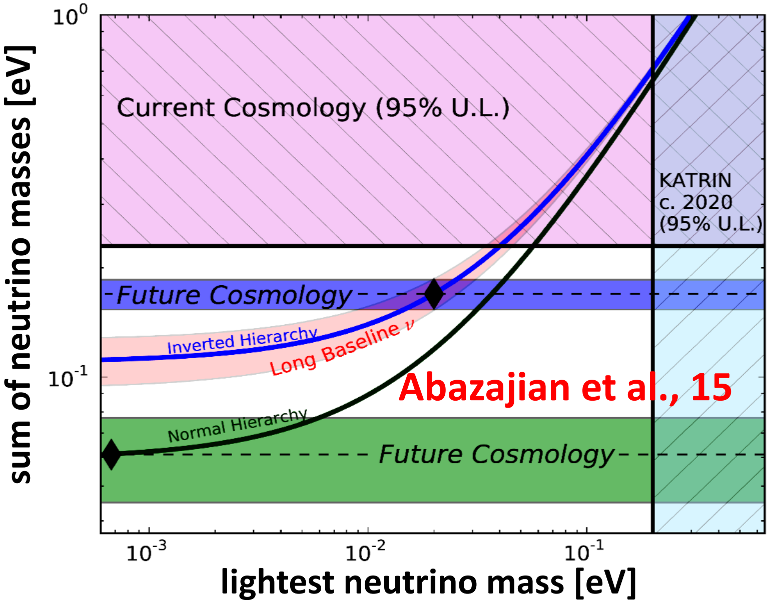
$$|\Delta m^2_{31}| \equiv |m_3^2 - m_1^2| = 2.5\times10^{-3}\ \mathrm{eV}^2.$$

- Have known some basic facts about neutrinos
- Some parameters have been precisely measured
- Neutrino mass ordering?
- Absolute masses of neutrinos?
- Particle physics experiments are difficult to measure the neutrino masses
- Cosmology is important for neutrino mass measurement

Neutrino mass measurements







Abazajian et al., 15

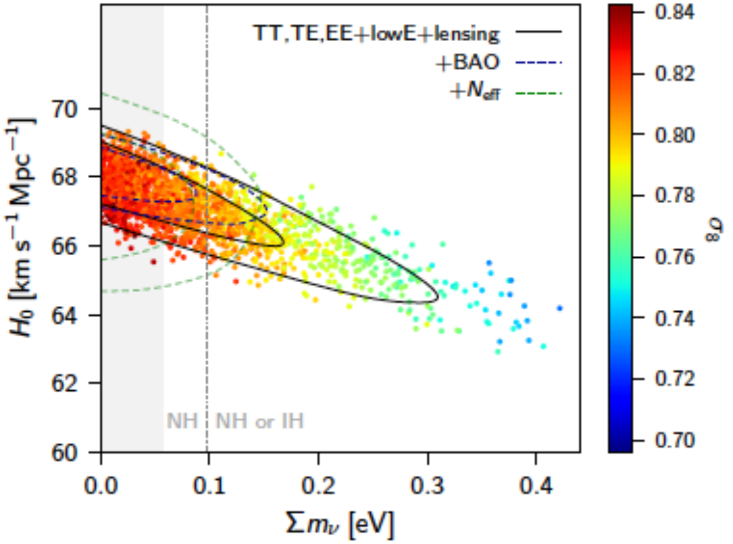
Constraints on absolute neutrino masses

- Tritium β decays (90% CL)
  $m_\beta < 1.1$ eV (KATRIN, first result 2019)
- Neutrinoless double-β decays (90% CL)
  $m_{\beta\beta} < (0.05 \sim 0.16)$ eV (KamLAND-Zen)
  $(0.17 \sim 0.49)$ eV (EXO)
  $(0.12 \sim 0.26)$ eV (GERDA)
  $(0.11 \sim 0.50)$ eV (CUORE)
- Cosmological observations (95% CL)
  $\Sigma m_\nu < 0.12$ eV (Planck)

Taken from Shun Zhou

Planck 2018 constraints on neutrino mass

- **Constraints on the total neutrino mass**
- **Degenerate mass model ($m_1=m_2=m_3$); mass splittings are neglected**
- **New tighter constraint on optical depth leads to tighter constraints on neutrino mass**
- **Both polarization and lensing tighten the constraints**



Planck 2018, 1807.06209

$\sum m_\nu < 0.54$ eV (95 %, *Planck* TT+lowE).

$\sum m_\nu < 0.26$ eV (95 %, *Planck* TT,TE,EE+lowE).

$\sum m_\nu < 0.16$ eV (95 %, *Planck* TT+lowE+BAO),

$\sum m_\nu < 0.13$ eV (95 %, *Planck* TT,TE,EE+lowE +BAO),

$\sum m_\nu < 0.13$ eV (95 %, *Planck* TT+lowE+lensing +BAO),

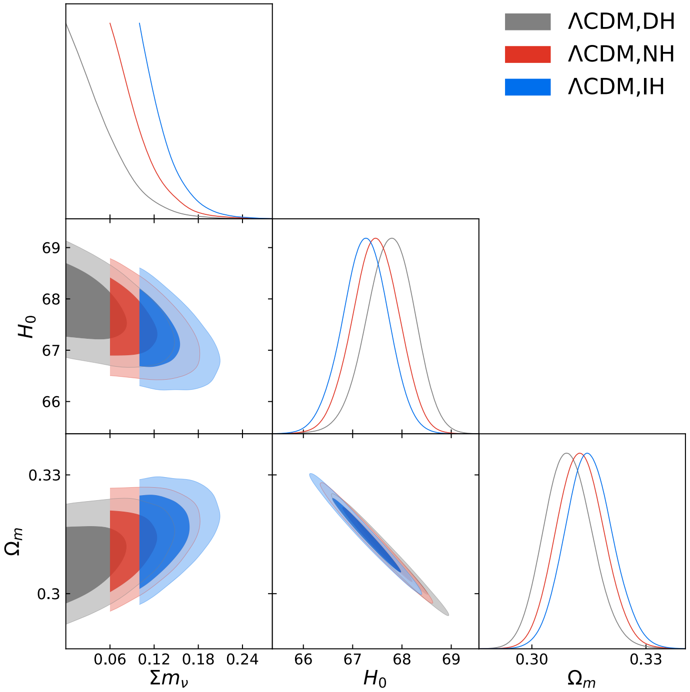
$\sum m_\nu < 0.12$ eV (95 %, *Planck* TT,TE,EE+lowE +lensing+BAO).

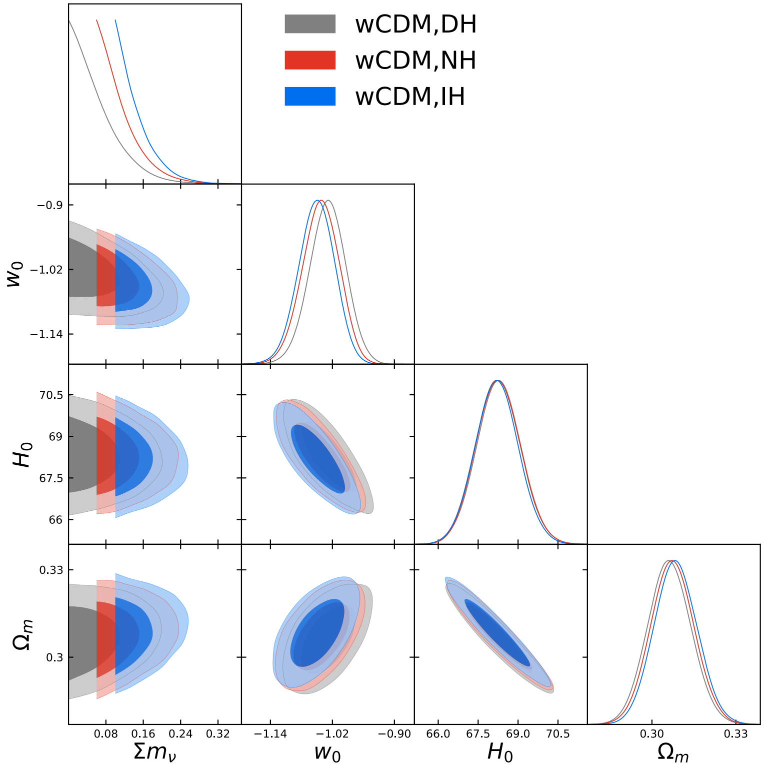
- $\sum m_\nu$ is in anti-correlation with H_0: Adding H_0 measurement will tighten mass constraints, but this is due to Hubble tension
- This anti-correlation is changed if dynamical dark energy is considered [X. Zhang, Phys. Rev. D 93 (2016) 083011, arXiv:1511.02651]
- Dynamical dark energy affects the constraints on neutrino mass greatly [X. Zhang, Sci. China Phys. Mech. Astron. 60 (2017) 060431, arXiv:1703.00651]
- Tight limit of $\sum m_\nu < 0.12$ eV puts pressure on IH ($\sum m_\nu > 0.1$ eV)
- Consistent with constraints from neutrino laboratory experiments which also slightly prefer NH at 2-3σ

Planck 2018 constraints on neutrino mass

M. Zhang, J. F. Zhang & X. Zhang, in preparation

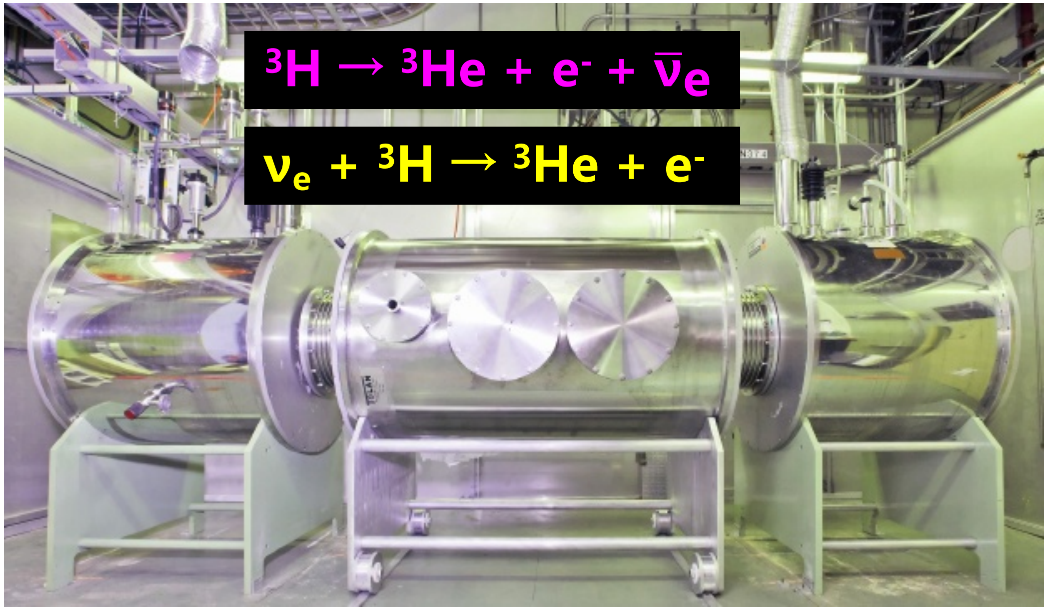
- Consider mass hierarchies
- Consider impacts of dynamical dark energy
- NH: $\sum m_\nu > 0.06$ eV
- IH: $\sum m_\nu > 0.1$ eV





- Planck 2018+BAO+SN
- ΛCDM: $\sum m_\nu < 0.12$ eV (DH), < 0.16 eV (NH), < 0.19 eV (IH)
- wCDM: $\sum m_\nu < 0.16$ eV (DH), < 0.20 eV (NH), < 0.22 eV (IH)
- w_0w_aCDM: $\sum m_\nu < 0.25$ eV (DH), < 0.28 eV (NH), < 0.31 eV (IH)
- NH is more favored over IH ($\chi^2_{\mathrm{NH}} < \chi^2_{\mathrm{IH}}$) [see a series of works by XZ's group]

Detection for cosmic neutrino background



$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$

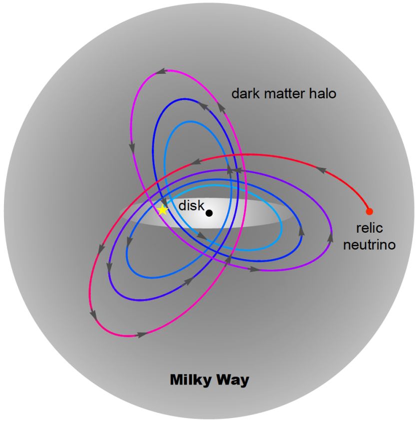
$\nu_e + {}^3H \rightarrow {}^3He + e^-$

PTOLEMY Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield (Betts et al, arXiv:1307.4738)

- Cosmic relic neutrinos: decoupled from thermal bath at 1s when T was 1MeV
- Current: 56 cm^{-3} for each flavor
- PTOLEMY: the first experiment
- 100 g of tritium, graphene target, planned energy resolution 0.15 eV
- Majorana vs. Dirac
- CνB capture rate: 4 yr^{-1} (Dirac), 8 yr^{-1} (Majorana)
- Can constrain neutrino mass
- Massive neutrinos: gravitational clustering in the MW? Impacts on the experiment?

Gravitational clustering of cosmic relic neutrinos in the Milky Way

J. Zhang & X. Zhang, Nature Communications [arXiv: 1712.01153]



- Detect cosmic relic neutrinos in the vicinity of the Earth
- Necessary to evaluate the gravitational clustering effects on relic neutrinos in the MW
- Develop a reweighting technique in the N-one-body simulation
- A single simulation can yield neutrino density profiles for different neutrino masses and phase space distributions
- Current observations: small neutrino masses
- Neutrino number density contrast around the Earth is found to be almost proportional to the square of neutrino mass

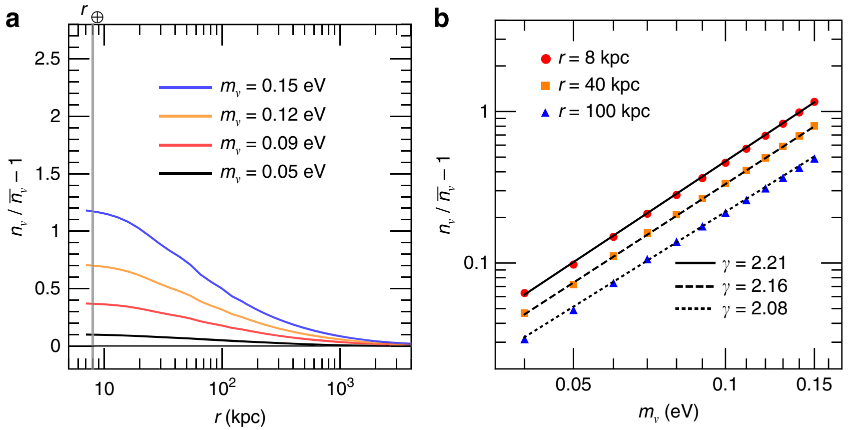
$$\frac{\mathrm{d}r}{\mathrm{d}z} = -\frac{u_r}{\mathrm{d}a/\mathrm{d}t}, \quad \frac{\mathrm{d}u_r}{\mathrm{d}z} = -\frac{1}{\mathrm{d}a/\mathrm{d}t}\left(\frac{u_\theta^2}{r^3} - a^2\frac{\partial\phi}{\partial r}\right)$$

$$\mathrm{d}w = 8\pi^2 T_{\nu,0}^3 \int_{r_a}^{r_b} r^2\,\mathrm{d}r \int_{y_a}^{y_b} f(y)y^2\,\mathrm{d}y \int_{\psi_a}^{\psi_b} \sin\psi\,\mathrm{d}\psi$$

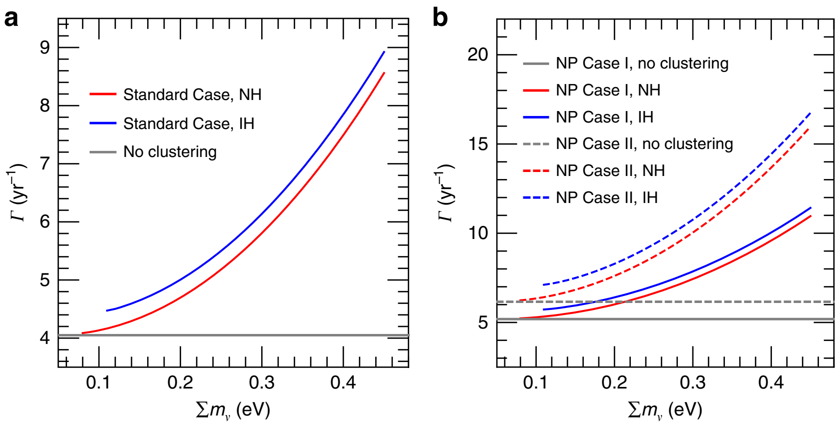
- The equations of motions can be written in a form independent of neutrino mass
- Neutrino mass is in the lower limit (y_a) and upper limit (y_b) of the associated weight
- Only need to perform a benchmark simulation with definite neutrino mass and phase space distribution

The fitted power-law function for thermal relic neutrinos

$$\delta_\nu^{\rm FD}(r_\oplus) = 76.5\left(\frac{m_\nu}{\rm eV}\right)^{2.21}, m_\nu \in [0.04, 0.15]\ \mathrm{eV}$$



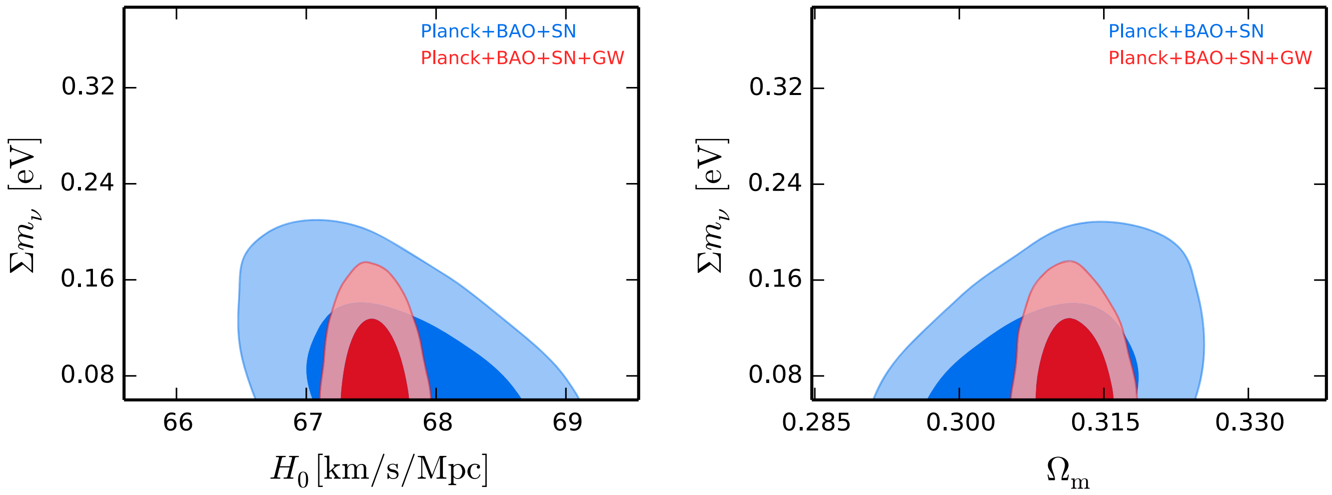
Clustering of thermal relic neutrinos in the MW



Capture rate Γ in the PTOLEMY experiment

GW standard sirens: Cosmological parameter estimation (neutrino mass)

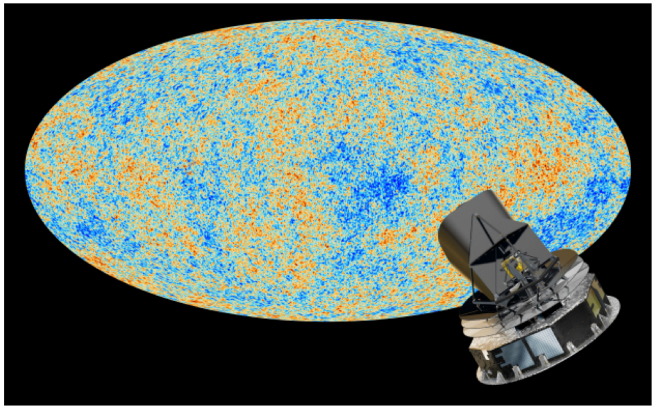
L. F. Wang, X. N. Zhang, J. F. Zhang & X. Zhang, Phys. Lett. B 782 (2018) 87 [arXiv:1802.04720]

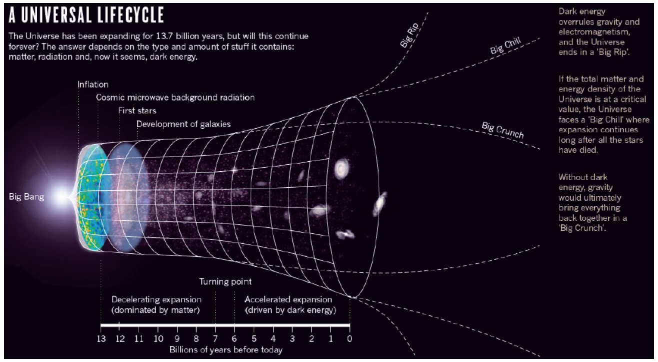


GW can improve constraints on neutrino mass by about 10%

- **Also take ET as an example**
- **Comparison: Planck+BAO+SN & Planck+BAO+SN+GW**
- **GW can help reduce upper limits by 14%, 8%, and 10% for NH, IH, and DH, respectively**
- **GW can also help break degeneracies between $\sum m_\nu$ and other parameters**

Precision cosmology era





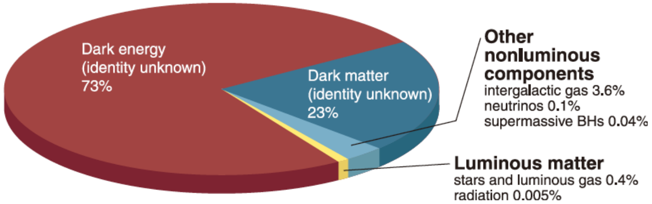
A UNIVERSAL LIFECYCLE

The Universe has been expanding for 13.7 billion years, but will this continue forever? The answer depends on the type and amount of stuff it contains: matter, radiation and, now it seems, dark energy.

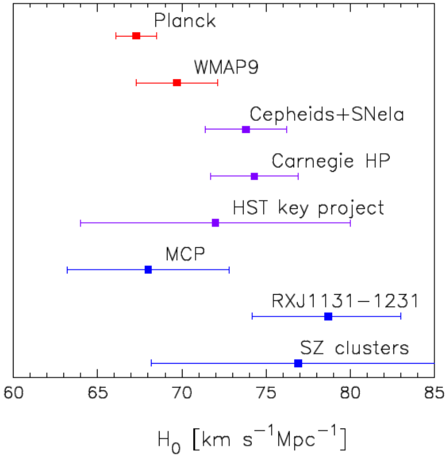
Dark energy overrules gravity and electromagnetism, and the Universe ends in a 'Big Rip'.

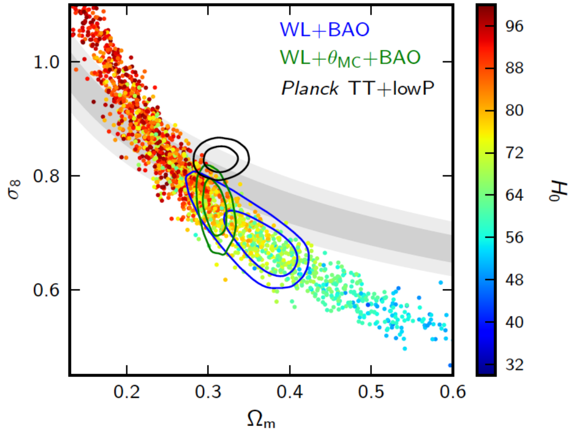
If the total matter and energy density of the Universe is at a critical value, the Universe faces a 'Big Chill' where expansion continues long after all the stars have died.

Without dark energy, gravity would ultimately bring everything back together in a 'Big Crunch'.



- 🍎 **Precision cosmology era has been coming**
  - **Precise measurement of cosmological parameters**
  - **Discovery of acceleration of cosmic expansion**
  - **Cosmological standard model (6 parameters) has occurred**
    - **Believe that only six parameters can entirely describe the evolution of the universe?**
    - **Observations are not accurate enough**
    - **Parameter measurement problems:**
    - **(i) Inconsistencies between some observations**
    - **(ii) Degeneracies between some parameters**





Cosmological models should be further extended

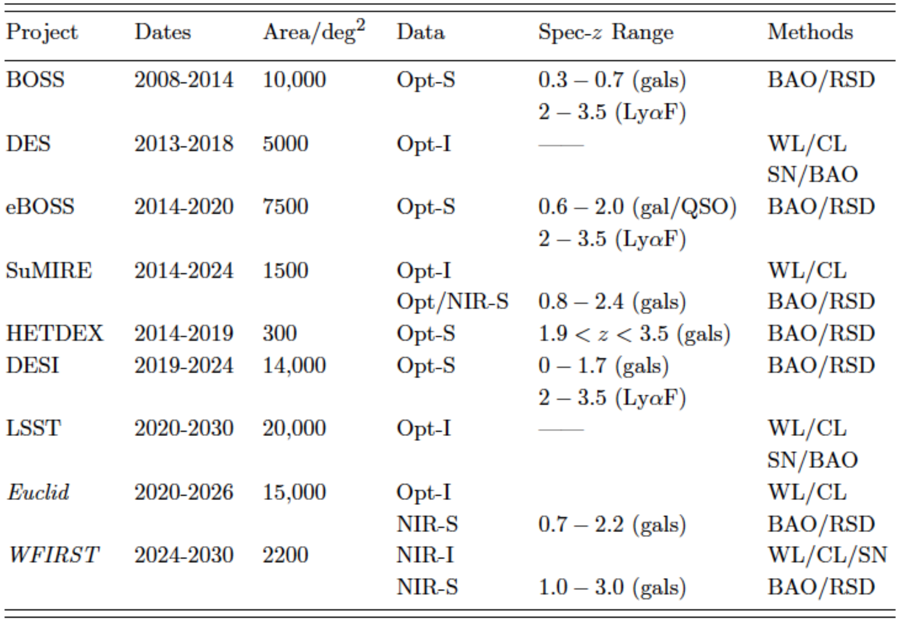
Cosmological probes should be further developed

Cosmological probes

Current mainstream probes (expansion history & structure growth)

- CMB anisotropies (CMB)
- Type Ia supernovae (SNIa)
- Baryon acoustic oscillations (BAO)
- Hubble constant (H_0)
- Weak gravitational lensing (WL)
- Clusters of galaxies (CL)
- Redshift-space distortions (RSD)

未来10-15年的光学和近红外巡天项目（光谱，成像）



Project	Dates	Area/deg^2	Data	Spec-z Range	Methods
BOSS	2008-2014	10,000	Opt-S	$0.3 - 0.7$ (gals) $2 - 3.5$ (LyαF)	BAO/RSD
DES	2013-2018	5000	Opt-I	——	WL/CL SN/BAO
eBOSS	2014-2020	7500	Opt-S	$0.6 - 2.0$ (gal/QSO) $2 - 3.5$ (LyαF)	BAO/RSD
SuMIRE	2014-2024	1500	Opt-I		WL/CL
			Opt/NIR-S	$0.8 - 2.4$ (gals)	BAO/RSD
HETDEX	2014-2019	300	Opt-S	$1.9 < z < 3.5$ (gals)	BAO/RSD
DESI	2019-2024	14,000	Opt-S	$0 - 1.7$ (gals) $2 - 3.5$ (LyαF)	BAO/RSD
LSST	2020-2030	20,000	Opt-I	——	WL/CL SN/BAO
Euclid	2020-2026	15,000	Opt-I		WL/CL
			NIR-S	$0.7 - 2.2$ (gals)	BAO/RSD
WFIRST	2024-2030	2200	NIR-I		WL/CL/SN
			NIR-S	$1.0 - 3.0$ (gals)	BAO/RSD

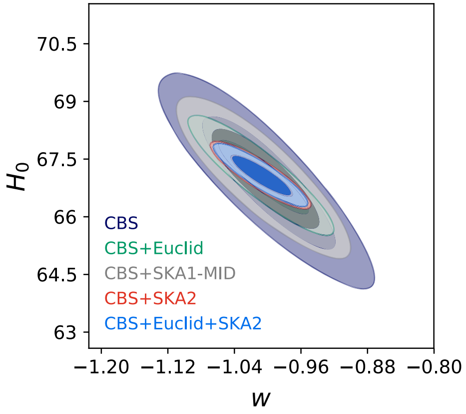
PDG(rev), CPC2016

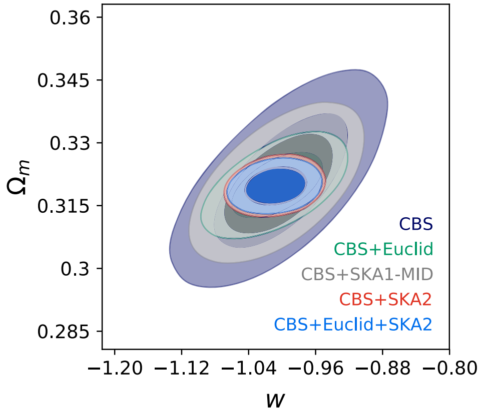
Future new cosmological probes

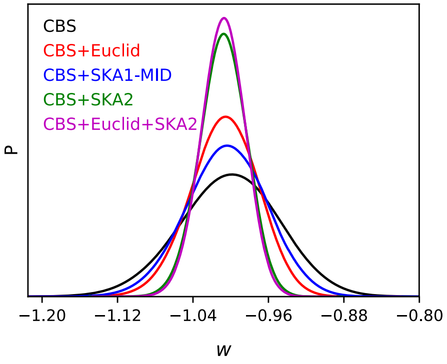
- Radio observation (neutral hydrogen 21 cm intensity mapping survey: neutral hydrogen power spectrum, BAO & RSD)
- GW observation (standard sirens: luminosity distance)

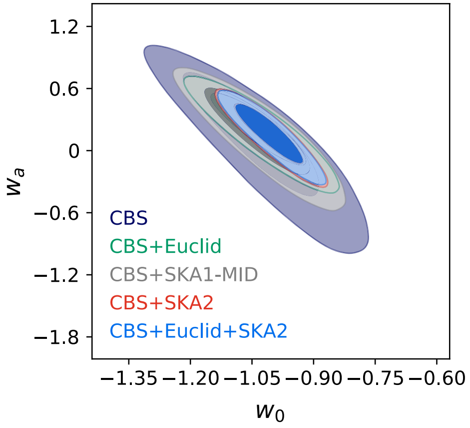
SKA 21 cm IM: Cosmological parameter estimation (DE & neutrino mass)

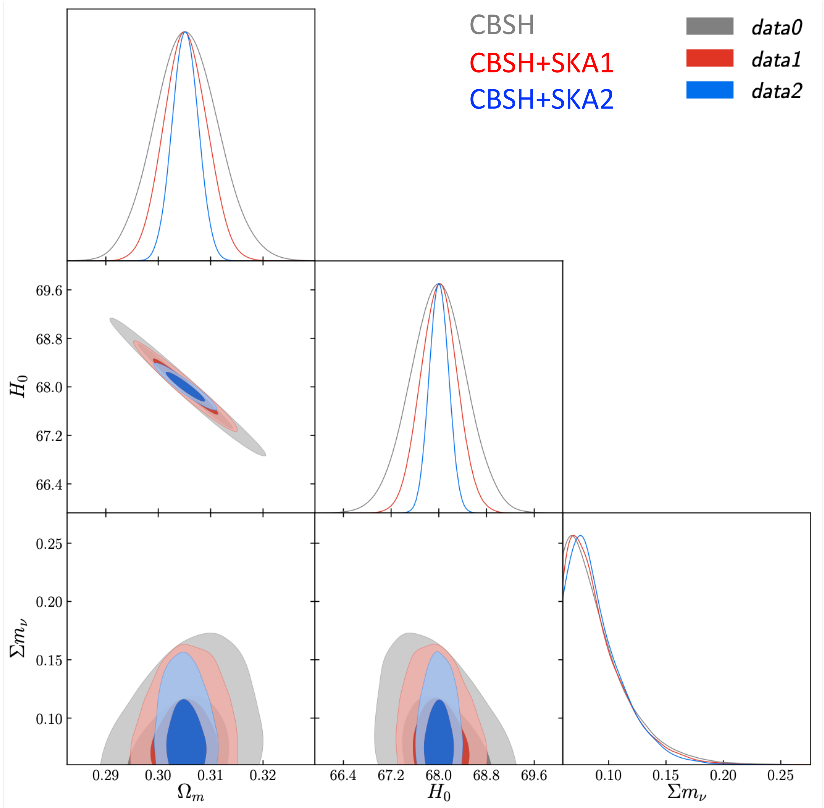
J. F. Zhang, L. Y. Gao, D. Z. He & X. Zhang, Phys. Lett. B 799 (2019) 135064 [arXiv:1908.03732]
J. F. Zhang, B. Wang & X. Zhang, arXiv:1907.00179





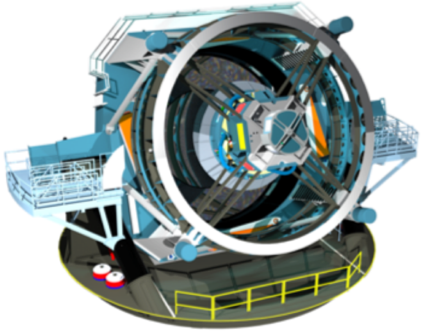




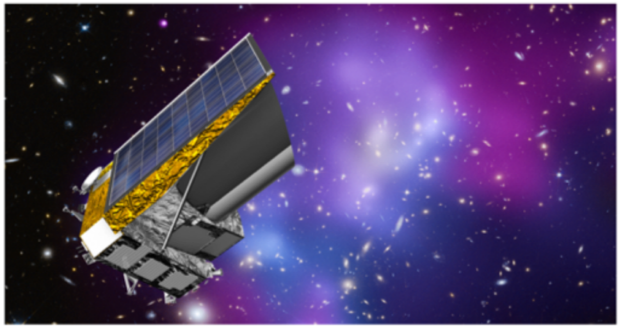


- SKA HI 21 cm IM observation can play an important role in helping improve cosmological parameter estimation
- Consider SKA1-MID and SKA2 simulated data (BAO)
- CBS+SKA1: $\sigma(w_0)=0.08$, $\sigma(w_a)=0.25$
- CBS+SKA2: $\sigma(w_0)=0.05$, $\sigma(w_a)=0.18$
- SKA1: constraints on $\sum m_\nu$ are improved by 4%, 3%, and 10% for NH, IH, and DH, respectively
- SKA2: constraints on $\sum m_\nu$ are improved by 7%, 7%, and 16% for NH, IH, and DH, respectively

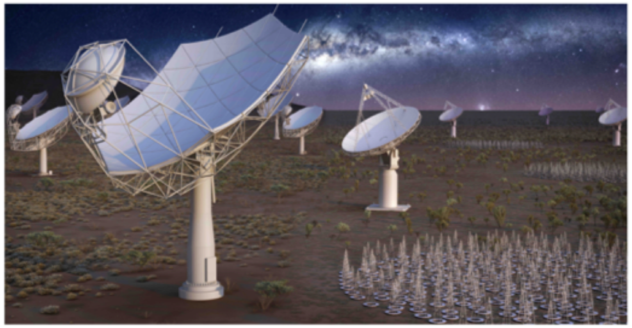
WFIRST



LSST



Euclid



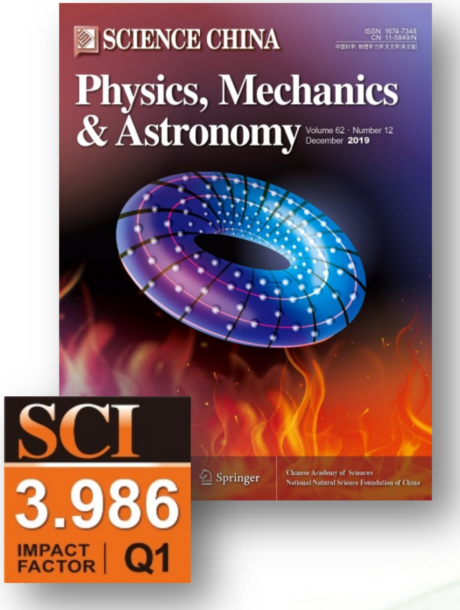
SKA

Gravitational wave standard siren observation combined with the optical, near-infrared, and radio survey observations will greatly promote the development of cosmology

Summary

- Binary neutron star collision observations opened a new era to multi-messenger astronomy
- Gravitational wave standard sirens do not depend on the distance ladder (self-calibration) and measure the absolute distance
- Tension in the Hubble constant measurements: it seems that the extended cosmological models cannot resolve the problem
- Future gravitational wave observations may arbitrate the H_0 tension
- Standard sirens will be developed into a new cosmological probe in the future: breaking parameter degeneracies
- Future gravitational wave observations combined with other survey observations: can elucidate the nature of dark energy?

谢谢！



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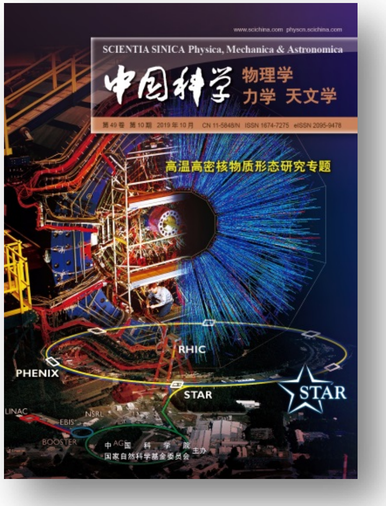

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