引力波标准汽笛观测与宇宙学参数估计

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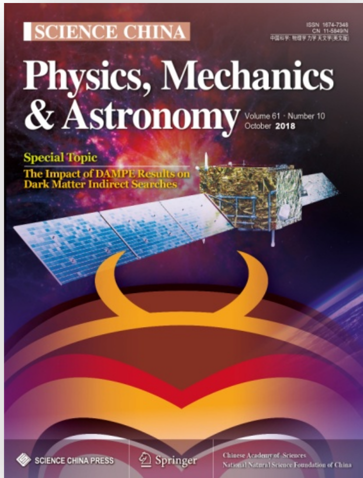
中国科学: 物理学 力学 天文学



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内容

- **当前的宇宙学参数估计情况**

  参数简并，观测不一致性

- **我们关注的科学问题**

- **引力波标准汽笛观测作为宇宙学新探针**

- **一些课题研究进展**

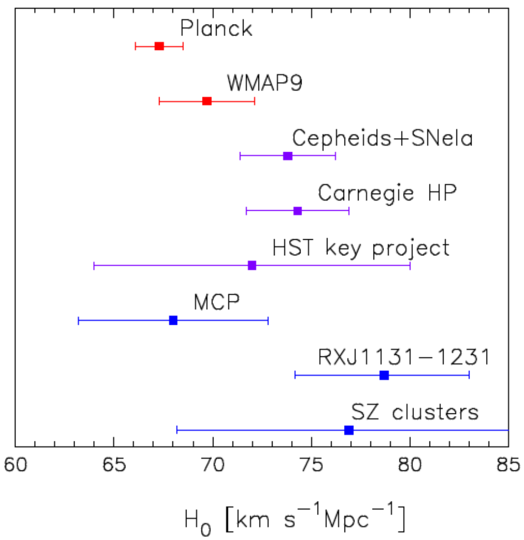
  构建相互作用暗能量宇宙学扰动理论框架

  在宇宙学中测量中微子质量和搜寻惰性中微子的研究

- **引力波观测（ET模拟）对参数估计的影响**

  打破简并，中微子质量限制

Planck之后的宇宙学



- 指向6参数基本宇宙学常数冷暗物质模型
- 不相信只用6个参数就能完整描述宇宙的演化，目前的情况只因数据还不那么精确
- 当前参数估计的问题：

(1) 某些观测之间存在较显著的不一致性

(2) 参数之间存在简并，一些参数之间相关性较强

宇宙学模型需要进一步扩展

宇宙学探针需要进一步发展

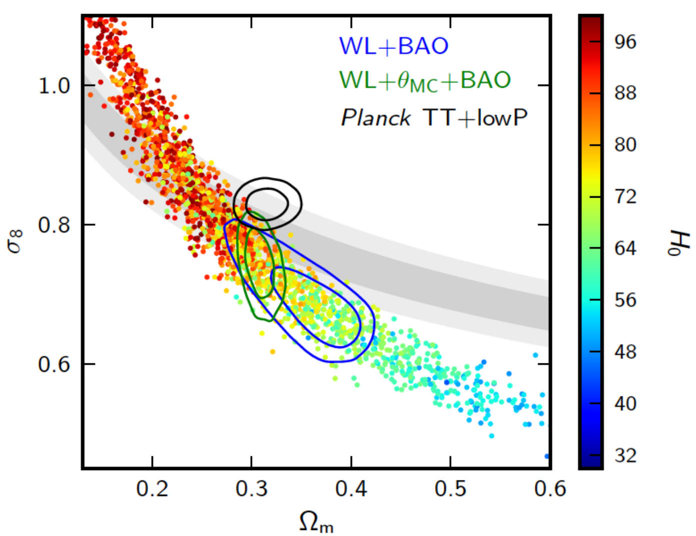


Fig. 16. Comparison of H_0 measurements, with estimates of $\pm 1\sigma$ errors, from a number of techniques (see text for details). These are compared with the spatially-flat ΛCDM model constraints from *Planck* and WMAP-9.

Fig. 18. Samples in the σ_8–Ω_m plane from the H13 CFHTLenS data (with angular cuts as discussed in the text), coloured by the value of the Hubble parameter, compared to the joint constraints when the lensing data are combined with BAO (blue), and BAO with the CMB acoustic scale parameter fixed to $\theta_{MC} = 1.0408$ (green). For comparison, the *Planck* TT+lowP constraint contours are shown in black. The grey bands show the constraint from *Planck* CMB lensing. We impose a weak prior on the primordial amplitude, $2 < \ln(10^{10}A_s) < 4$, which has some impact on the distribution of CFHTLenS-only samples.

Planck 2013, 2015

宇宙学模型的扩展

科学问题：

- 暗能量还是修改引力?
- 暗能量是否有动力学?
- 暗能量与暗物质之间是否存在某种直接的微妙相互作用，如何探测?
- 中微子的质量、质量等级? 有效代数? 有惰性中微子吗?
- 原初引力波?
- 黑暗时代，再电离……

我们近期关注的重点：

（1）暗能量-暗物质耦合参数测量

（2）中微子质量测量

宇宙学探针

当前主流的探针（膨胀历史，结构增长）

- 宇宙微波背景各向异性（CMB）
- Ia型超新星（SNIa）
- 重子声波振荡（BAO）
- 哈勃常数直接测量（H_0）
- 弱引力透镜（WL）
- 星系团计数（CL）
- 红移空间畸变（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 Opt/NIR-S	 $0.8-2.4$ (gals)	WL/CL 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 NIR-S	 $0.7-2.2$ (gals)	WL/CL BAO/RSD
WFIRST	2024-2030	2200	NIR-I NIR-S	 $1.0-3.0$ (gals)	WL/CL/SN BAO/RSD

PDG(rev), CPC2016

未来的新的宇宙学观测手段

- 射电观测（中性氢21厘米巡天：中性氢功率谱，BAO，RSD）
- 引力波观测（标准汽笛：光度距离）

引力波标准汽笛观测

光度距离测量：

SNIa（标准烛光）——不同红移处光度距离之比

GW（标准汽笛）——真正的光度距离

利用引力波波形

赵文，中国科学：物理学 力学 天文学，(2018) in press

- Schutz 1986：通过观测致密双星并合的引力波波形，可以独立测量引力波爆发源的光度距离
- 振幅依赖于波源的啁质量（双星质量的组合）和光度距离
- 啁质量可以被引力波信号的相位测量精确确定
- 因此，利用振幅和相位的测量即可得到波源的光度距离

利用强引力透镜效应

- 朱宗宏小组（2017）提出的新方法
- 强引力透镜效应（如大质量星系或星系团作为透镜源）：可产生多个引力波像，不同像之间存在时间延迟
- 测量到达时间差异，可反推出引力波源距离信息


nature COMMUNICATIONS

ARTICLE

DOI: 10.1038/s41467-017-01152-9 OPEN

Precision cosmology from future lensed gravitational wave and electromagnetic signals

Kai Liao[1,2], Xi-Long Fan[3], Xuheng Ding[1,4,5], Marek Biesiada[4,6] & Zong-Hong Zhu[1,4]

确定波源的红移

赵文，中国科学：物理学 力学 天文学，(2018) in press

- 利用电磁对应体
- 利用宿主星系或宿主星系团的红移分布
- 利用致密双星的红移分布函数
- 利用潮汐效应对引力波相位的修正
- 利用中子星质量分布函数
- 利用宇宙演化导致的引力波相位修正

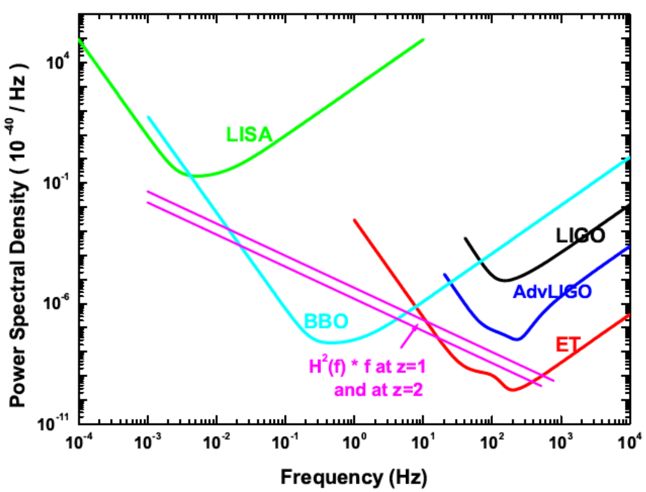


图 1 地基的引力波探测器(LIGO，AdvLIGO，ET)和空间的引力波探测器（LISA，BBO）的噪音功率谱曲线。作为对比，我们同时画出了红移z = 1和z = 2处的双中子星并合的引力波辐射的振幅曲线。

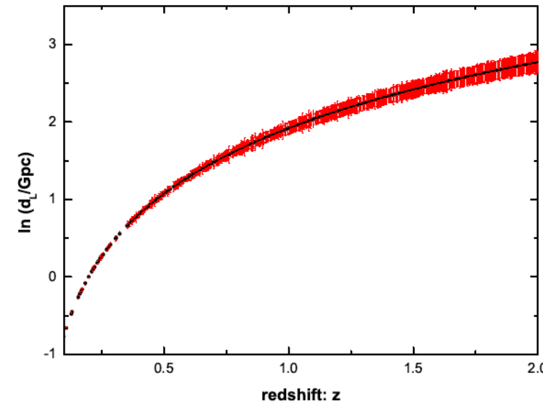


图 6 数值模拟得到的1000个双中子星并合引力波暴的光度距离及其误差分布，这里我们考虑了ET和CE构成的三代探测器网络。

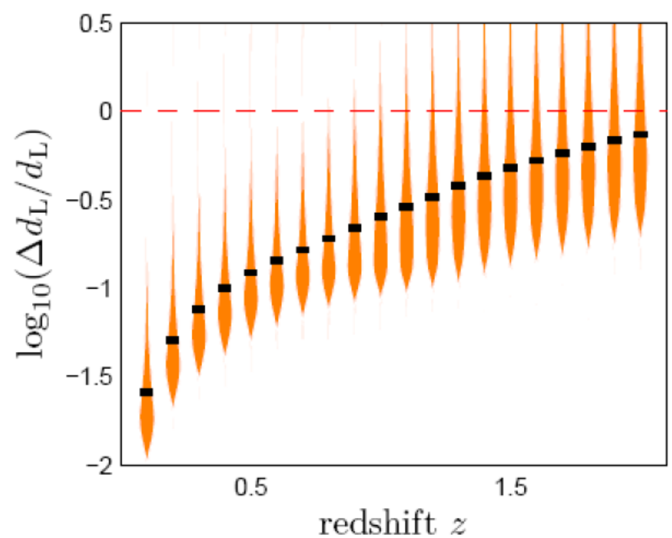


图 5 第三代引力波探测器网络（包含三个ET，分别位于美国、欧洲和澳大利亚）对双中子星并合事件距离测量能力[13]。

Zhao W, Wen L, arXiv:1710.05325 (PRD in press)

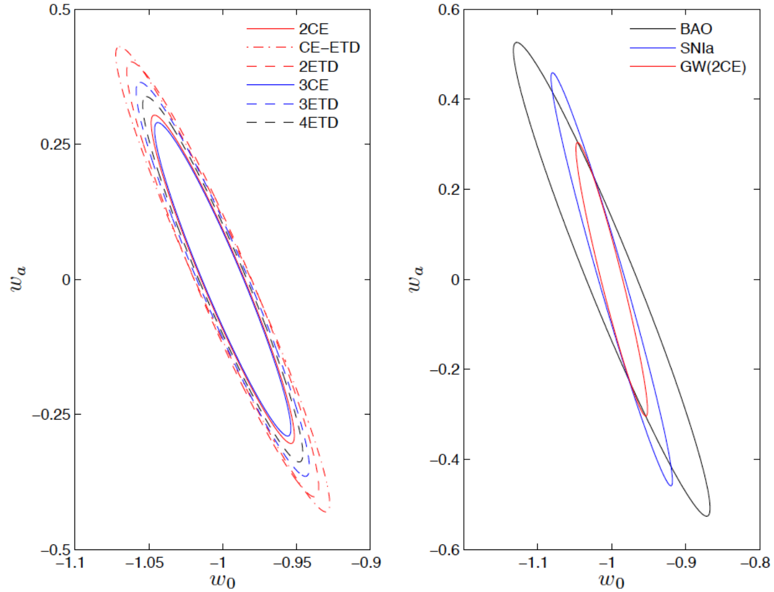


图 7　左图表示各类三代引力波探测器对暗能量参数的限制能力，右图比较了引力波方法和其他传统方法（SNIa和BAO）对暗能量的限制能力。注意，对于引力波探测器，我们都假设了1000个引力波源（详情见参考文献[13]）。

Tamanini N, Caprini C, Barausse E, Sesana A, Klein A, Petiteau A, JCAP, 2016, 1604, 04

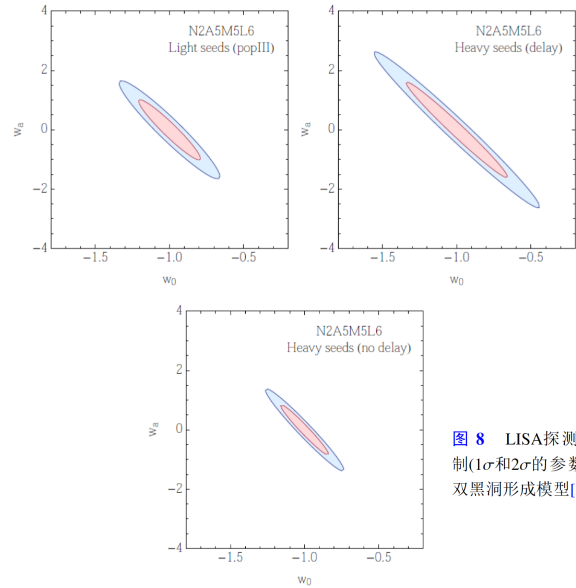
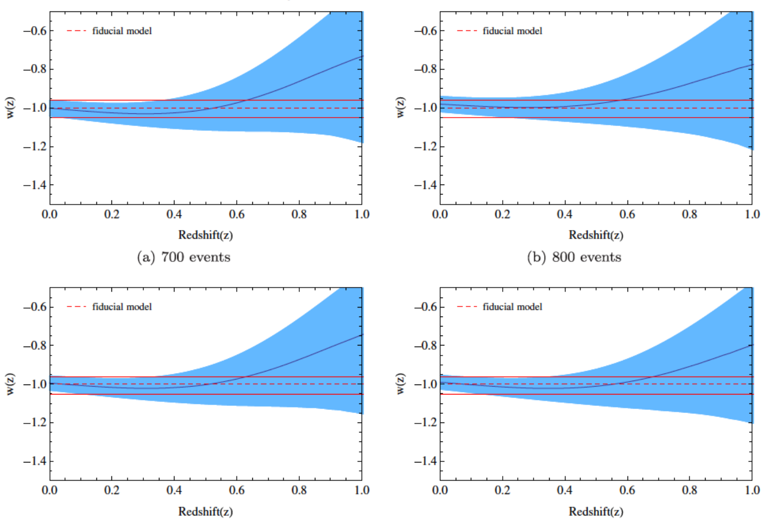


图 8　LISA探测器理想性况下对暗能量模型参数的限制(1σ和2σ的参数限制范围)，三幅图分别考虑了不同的双黑洞形成模型[21]。

R. G. Cai and T. Yang, Phys. Rev. D **95**, no. 4, 044024 (2017)



(a) 700 events　(b) 800 events

(c) 900 events　(d) 1000 events

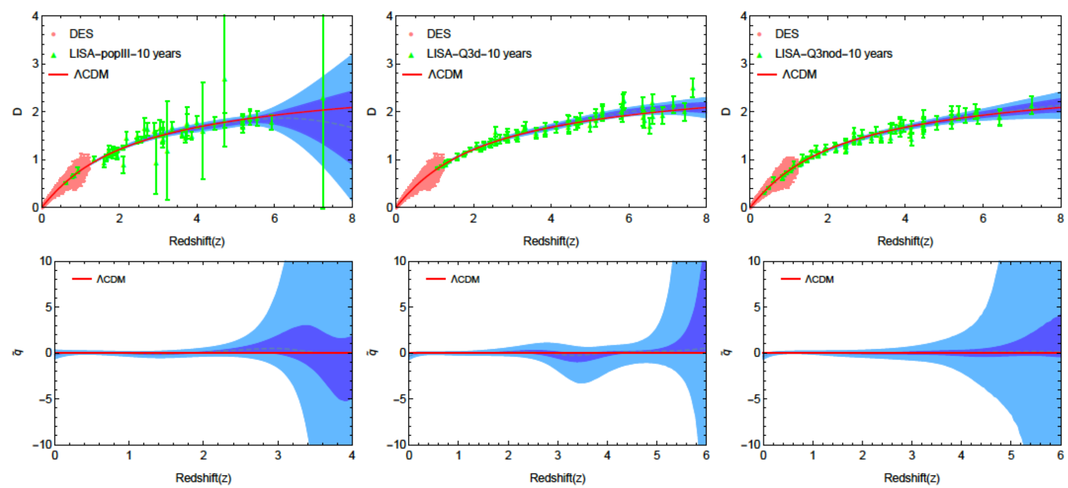


Figure 5. Reconstruction of the interaction using DES+LISA (10 years) data. From left to right each column reports the results for popIII, Q3d, Q3nod.

. **Standard sirens and dark sector with Gaussian process**

Rong-Gen Cai (Beijing, GUCAS & Beijing, Inst. Theor. Phys.), Tao Yang (Beijing Normal U.). Sep 4, 2017. 10 pp.

Published in **EPJ Web Conf. 168 (2018) 01008**

DOI: 10.1051/epjconf/201816801008

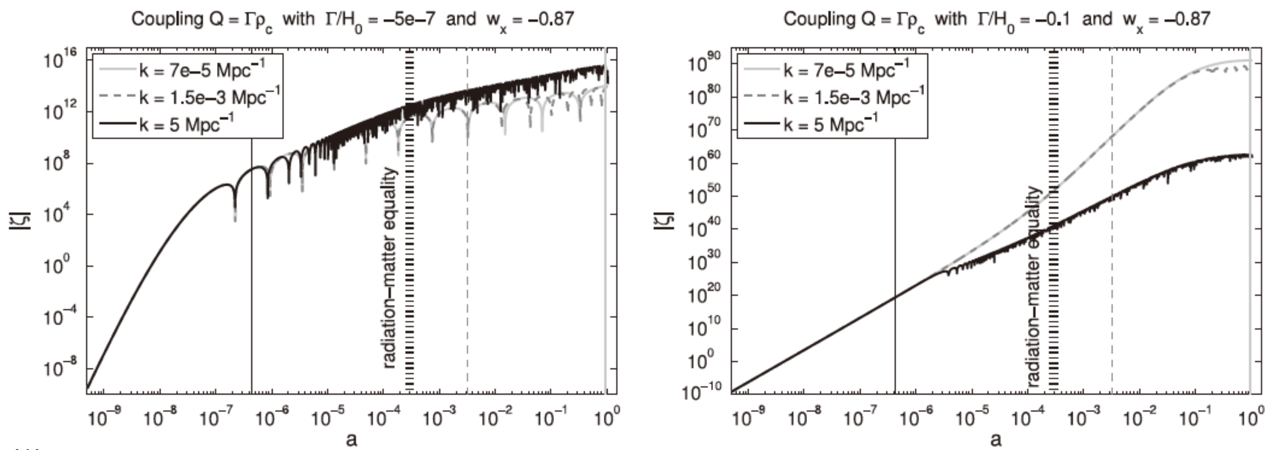
Conference: C17-07-03.12 Proceedings

e-Print: **arXiv:1709.00837** [astro-ph.CO] | PDF

相互作用暗能量的研究

扰动发散问题

- 暗能量-暗物质耦合既修改宇宙膨胀历史，也影响宇宙结构增长；因此对耦合的探测要求我们从膨胀历史和结构增长两个方面理解相互作用暗能量模型
- 然而，2008年发现：在很多情况下（对应于参数空间中某种部分），宇宙学扰动发散（从早期的超视界尺度开始）——灾难性问题 J. Valiviita, E. Majerotto & R. Maartens, JCAP 07 (2008) 020
- 无奈：很多研究只能避开这些带来发散的参数空间，只寻求探索一部分参数空间——不完整探索



Instability: w>-1

J. Valiviita, E. Majerotto, and R. Maartens, J. Cosmol. Astropart. Phys. 07 (2008) 020.

($k = 7 \times 10^{-5}$ Mpc^{-1}) stays super-Hubble all the way up to today. The intermediate scale ($k = 1.5 \times 10^{-3}$ Mpc^{-1}) enters the horizon during matter domination, and the smallest scale ($k = 5$ Mpc^{-1}) enters deep in the radiation era.

相互作用形式	稳定性
$Q \propto \rho_{de}$	$w > -1, \Gamma > 0$ 稳定，其它情形发散
$Q \propto \rho_c$	$w < -1$ 稳定，其它情形发散

J.-H. He, B. Wang, and E. Abdalla, Phys. Lett. B **671**, 139 (2009).

$$\zeta = H_L + \frac{1}{3}H_T - \mathcal{H}\frac{\delta\rho}{\rho'}$$

相互作用暗能量的PPF框架：解决扰动发散问题

- 扰动不稳定性问题说明我们其实根本不懂得如何考虑暗能量的扰动
- 由于不清楚声波如何在暗能量流体中传播，为计算压强扰动，只能人为地为暗能量设定一个静系声速——这导致在暗能量压强扰动中包含非绝热模式（相互作用项出现在该部分中），在某些情况下引起扰动发散
- 我们提出一个解决方案：建立起一个适合相互作用暗能量的参数化后弗里德曼框架（PPF），基于暗能量的已知事实有效地计算暗能量的扰动 Y. H. Li, J. F. Zhang & X. Zhang, Phys. Rev. D 90 (2014) 063005

$$\lim_{k_H\ll 1}\frac{4\pi G}{H^2}(\rho_{\rm de}+p_{\rm de})\frac{V_{\rm de}-V_T}{k_H}=-\frac{1}{3}c_K f_\zeta(a)k_H V_T$$

$$\lim_{k_H\gg 1}\Phi=\frac{4\pi G}{c_K k_H^2 H^2}\Delta_T\rho_T \qquad \Phi+\Gamma=\frac{4\pi G}{c_K k_H^2 H^2}\Delta_T\rho_T$$

$$\Phi=\zeta+V_T/k_H$$

$$F=1+3\frac{4\pi G a^2}{k^2 c_K}(\rho_T+p_T)$$

$$S=\frac{4\pi G}{k_H^2 H^2}\Big\{[(\rho_{\rm de}+p_{\rm de})-f_\zeta(\rho_T+p_T)]k_H V_T+\frac{3a}{k c_K}[Q_c(V-V_T)+f_c]+\frac{1}{H c_K}(\Delta Q_c-\xi Q_c)\Big\}$$

$$\rho_{\rm de}\Delta_{\rm de}=-3(\rho_{\rm de}+p_{\rm de})\frac{V_{\rm de}-V_T}{k_H}-\frac{k^2 c_K}{4\pi G a^2}\Gamma,$$

$$\frac{V_{\rm de}-V_T}{k_H}=\frac{-H^2}{4\pi G(\rho_{\rm de}+p_{\rm de})F}\times\left[S-\Gamma'-\Gamma+f_\zeta\frac{4\pi G(\rho_T+p_T)}{H^2}\frac{V_T}{k_H}\right]$$

$$(1+c_\Gamma^2 k_H^2)[\Gamma'+\Gamma+c_\Gamma^2 k_H^2\Gamma]=S$$

相互作用暗能量的PPF框架：探索完整参数空间

PHYSICAL REVIEW D **90**, 063005 (2014)

Parametrized post-Friedmann framework for interacting dark energy

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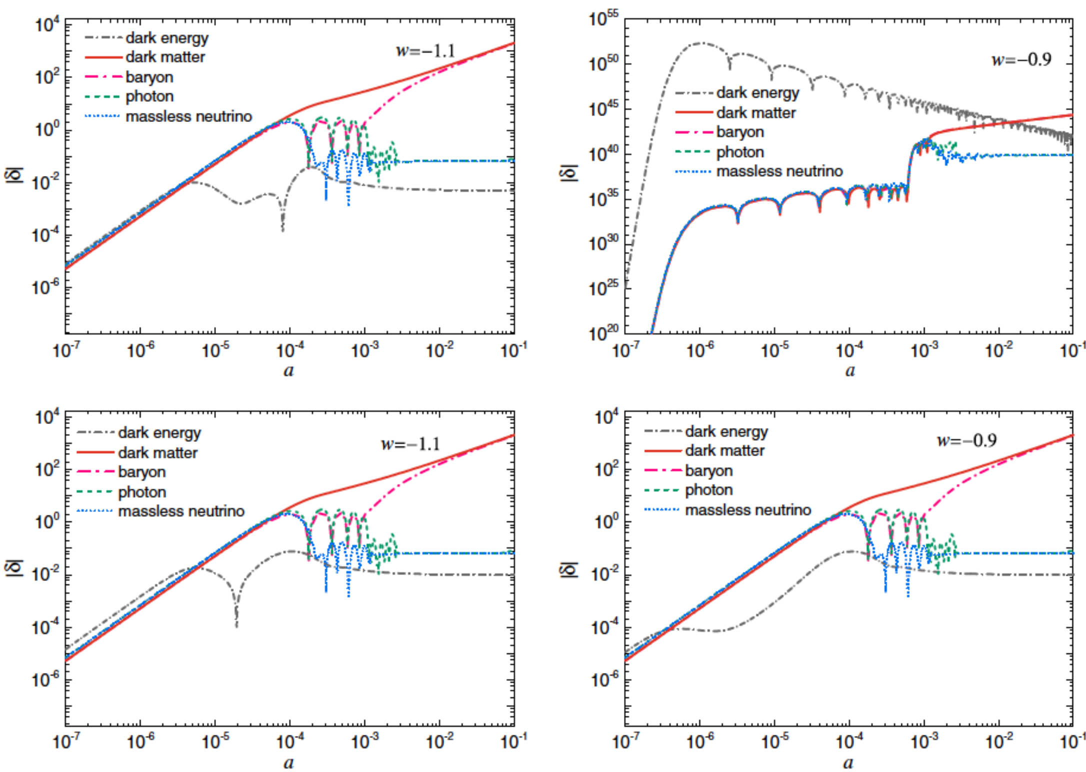
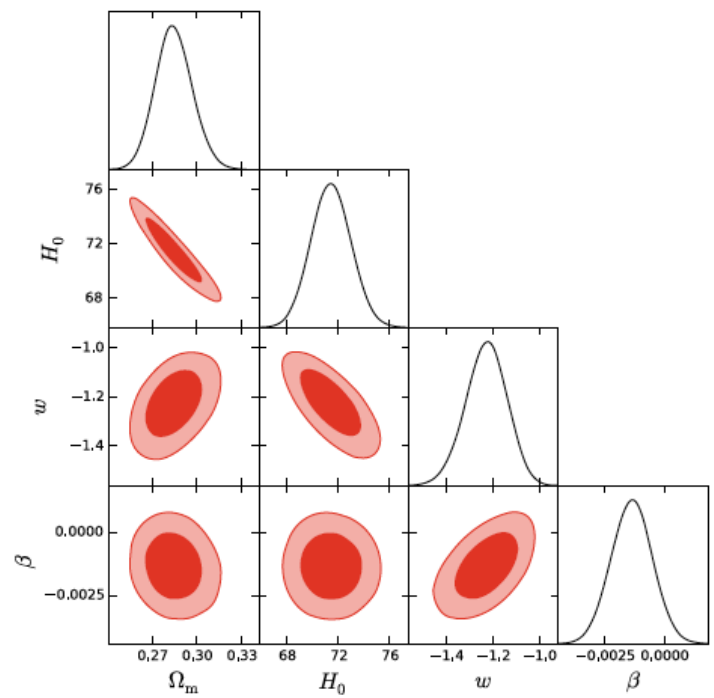
[1]*Department of Physics, College of Sciences, Northeastern University, Shenyang 110004, China*
[2]*Center for High Energy Physics, Peking University, Beijing 100080, China*
(Received 25 April 2014; published 16 September 2014)

① 解决了相互作用暗能量模型的宇宙学扰动不稳定性问题
② 推广了非耦合暗能量的PPF方法，建立了完善的计算暗能量（包括非耦合和耦合模型）宇宙学扰动的有效理论方案，将所有导致暗能量扰动发散的问题在同一个理论框架下消除掉
③ 把所有的理论模型（包括任意暗能量模型和相互作用形式）包括进来，统一进行处理



- $\beta > 0$: DM → DE
- $\beta < 0$: DE → DM
- Example: $k = 0.1\ \mathrm{Mpc}^{-1}$ and $\beta = -10^{-17}$

$$Q^{\mu} = 3\beta H \rho_c u_c^{\mu}$$



- Whole parameter space can be explored
- Prefer $\beta < 0$: DE → DM (1.6σ)
- $\beta = O(10^{-3})$, precision 60%
- CMB itself can constrain β well
- RSD do not improve significantly

中微子宇宙学称重的研究

- 中微子振荡实验揭示出中微子是有质量的，但是振荡实验无法测量中微子的绝对质量
- 中微子质量可以影响宇宙的演化，因此利用宇宙学观测可以有效限制中微子质量的值
- 目前宇宙学观测已经可以将中微子质量限制在很小的范围内（小于约0.2电子伏特）

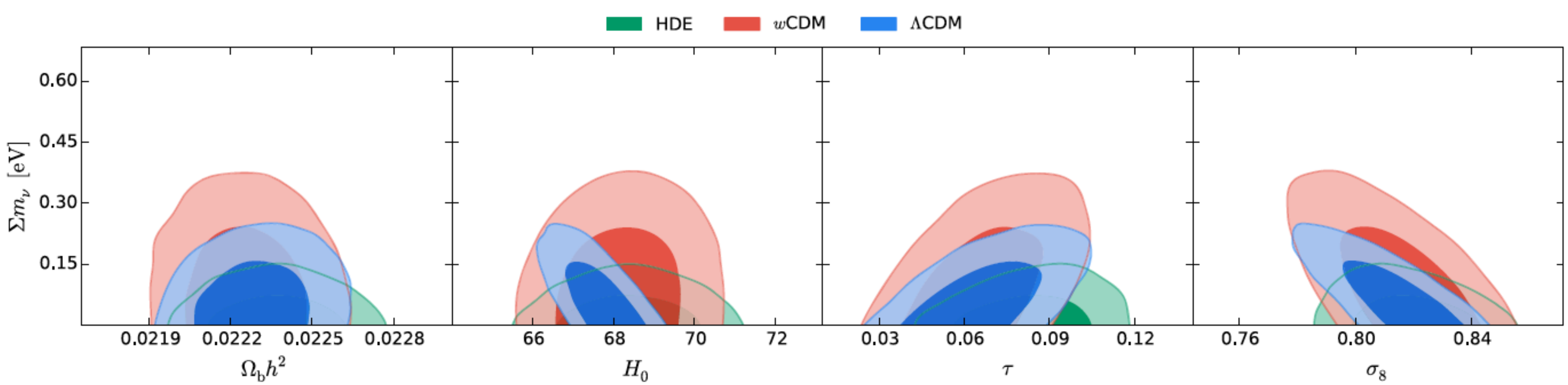
暗能量的性质对于中微子的宇宙学称重有较重要的影响 **X. Zhang, Sci. China Phys. Mech. Astron. 60 (2017) 060431**

PHYSICAL REVIEW D **93,** 083011 (2016)

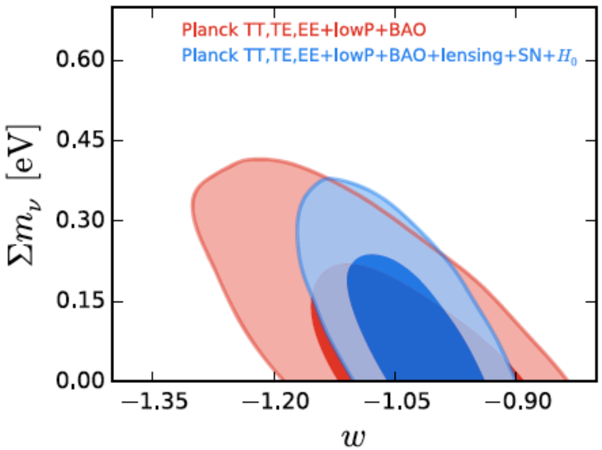
Impacts of dark energy on weighing neutrinos after Planck 2015

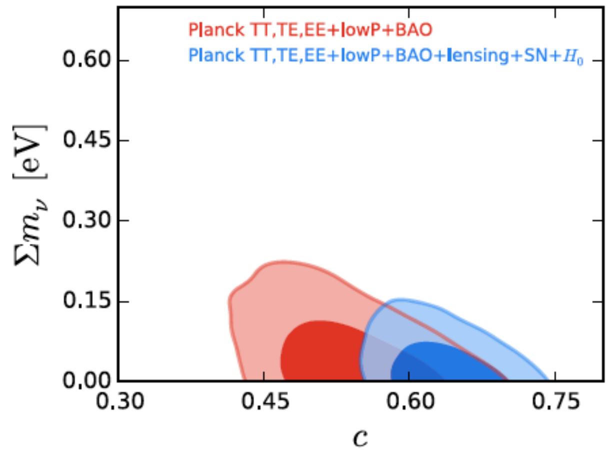
Xin Zhang[1,2,*]

as typical examples, only two simplest dynamical dark energy models that have only one more parameter compared to ΛCDM are considered --- wCDM & HDE



- degeneracy between Σm and H_0 is changed: anti-correlation in ΛCDM, positive-correlation in wCDM & HDE
- limit on Σm becomes much looser in wCDM; becomes much tighter in HDE
- adding CMB lensing helps improve the measurement of τ, but in HDE it is still very high





$\sum m_\nu < 0.197$ eV for ΛCDM

$\sum m_\nu < 0.304$ eV for wCDM

$\sum m_\nu < 0.113$ eV for HDE

- for IH of neutrino mass, the lower limit is approximately **0.1 eV**, thus the upper limit obtained in this work is almost equal to the lower limit, implying that in the HDE model the IH seems to be nearly excluded.
- On the other hand, if the future neutrino oscillation experiments, such as the JUNO experiment, can successfully give the result of the neutrino mass ordering, and if the IH is the final answer, then the HDE would be excluded by the neutrino mass ordering experiment.
- This expectation is very tantalizing because the neutrino oscillation experiments would potentially offer a possible falsifying scheme for the HDE model that currently is still a competitive candidate of dark energy.

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **469,** 1713–1724 (2017) doi:10.1093/mnras/stx978
Advance Access publication 2017 April 25

Constraining neutrino mass and extra relativistic degrees of freedom in dynamical dark energy models using *Planck* 2015 data in combination with low-redshift cosmological probes: basic extensions to ΛCDM cosmology

Ming-Ming Zhao,[1] Yun-He Li,[1] Jing-Fei Zhang[1] and Xin Zhang[1,2]★
[1]*Department of Physics, College of Sciences, Northeastern University, Shenyang 110004, China*
[2]*Center for High Energy Physics, Peking University, Beijing 100080, China*

Data	Planck+BSH+LSS		
Model	ΛCDM	wCDM	w_0w_aCDM
$\Omega_b h^2$	$0.022\,35 \pm 0.000\,14$	$0.022\,31 \pm 0.000\,14$	$0.022\,27 \pm 0.000\,15$
$\Omega_c h^2$	0.1178 ± 0.0011	0.1181 ± 0.0012	0.1184 ± 0.0012
$100\theta_{MC}$	$1.040\,96 \pm 0.000\,30$	$1.040\,90 \pm 0.000\,30$	$1.040\,83 \pm 0.000\,31$
τ	$0.066^{+0.014}_{-0.016}$	0.067 ± 0.015	0.068 ± 0.015
w/w_0	–	$-1.042^{+0.057}_{-0.047}$	-0.96 ± 0.11
w_a	–	–	$-0.47^{+0.59}_{-0.43}$
Σm_ν	<0.22	<0.36	<0.52
n_s	$0.9684^{+0.0040}_{-0.0041}$	$0.9672^{+0.0042}_{-0.0043}$	0.9656 ± 0.0046
$\ln(10^{10}A_s)$	$3.062^{+0.027}_{-0.030}$	3.064 ± 0.029	3.065 ± 0.028
Ω_m	$0.3072^{+0.0071}_{-0.0082}$	$0.3053^{+0.0085}_{-0.0086}$	$0.3090^{+0.0100}_{-0.0101}$
H_0	$67.8^{+0.7}_{-0.6}$	68.3 ± 1.0	68.2 ± 1.0
σ_8	$0.803^{+0.015}_{-0.012}$	$0.800^{+0.017}_{-0.014}$	$0.791^{+0.022}_{-0.019}$
χ^2_{min}	13 906.47	13 905.66	13 904.06

- the CPL has a much larger Σm limit
- in both wCDM and CPL, a larger Σm limit is obtained
- a phantom (w<-1) or an early phantom (w<-1 to w>-1) is slightly more favored

- in HDE, an early quintessence dark energy with $c < 1$ (quintom evolving from $w > -1$ to $w < -1$) is favored, and thus a smaller upper limit of Σm_ν, compared to ΛCDM, is obtained.

X. Zhang, Phys. Rev. D **93**, 083011 (2016)

$$\sum m_\nu < 0.113 \text{ eV}$$

- in quintessence model (the freezing quintessence evolving from $w > -1$ to $w \to -1$), a smaller upper limit of Σm_ν is more favored, compared to ΛCDM.

Y. Chen, and L. Xu, Phys. Lett. B **752**, 66 (2016)

a tracking quintessence model with an inverse power-law potential

$$V(\phi) \propto \phi^{-\alpha} \ (\alpha > 0)$$

- $\Sigma m_\nu < 0.262$ eV for the quintessence model
- $\Sigma m_\nu < 0.293$ eV for the ΛCDM model

Summarizing the results in both the HDE model and the tracking quintessence model, we conclude that, once w evolves from a larger value to a smaller value, a smaller upper limit of Σm_ν, compared to ΛCDM, will be obtained.

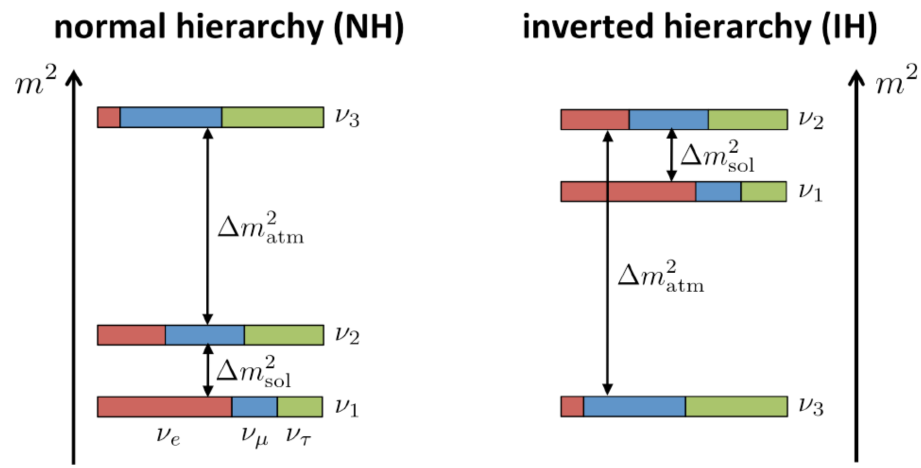
PHYSICAL REVIEW D **94**, 083519 (2016)

Impacts of dark energy on weighing neutrinos: Mass hierarchies considered

Sai Wang,[1,*] Yi-Fan Wang,[1,†] Dong-Mei Xia,[2,‡] and Xin Zhang[3,4,§]

$$\Delta m_{21}^2 \equiv m_2^2 - m_1^2 = 7.5 \times 10^{-5}\ \mathrm{eV}^2,$$

$$|\Delta m_{31}^2| \equiv |m_3^2 - m_1^2| = 2.5 \times 10^{-3}\ \mathrm{eV}^2.$$

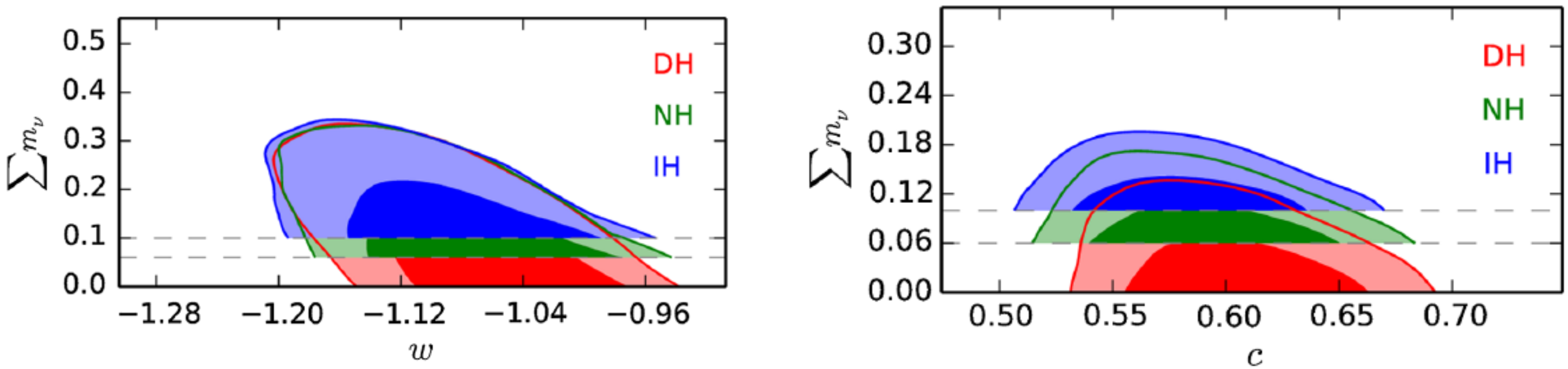


the NH model $$(m_1, m_2, m_3) = \left(m_1, \sqrt{m_1^2 + \Delta m_{21}^2}, \sqrt{m_1^2 + |\Delta m_{31}^2|}\right)$$

the IH model $$(m_1, m_2, m_3) = \left(\sqrt{m_3^2 + |\Delta m_{31}^2|}, \sqrt{m_3^2 + |\Delta m_{31}^2| + \Delta m_{21}^2}, m_3\right)$$

the DH model $$m_1 = m_2 = m_3 = m$$

Q. G. Huang, K. Wang, and S. Wang, Constraints on the neutrino mass and mass hierarchy from cosmological observations, Eur. Phys. J. C **76**, 489 (2016).



- we obtained the upper limit **$\Sigma m_\nu <$ 0. 105 eV** for the case of degenerate hierarchy (DH) of neutrinos in the HDE model, which is comparable to the lower limit of Σm_ν for three inverted hierarchical neutrinos.
- this is perhaps the most stringent upper limit on the total mass of three degenerate neutrinos by far.
- We are on the verge of diagnosing the neutrino mass hierarchy through cosmological observations.
- for all the dark energy models considered in this work, the χ^2 in the NH case is slightly smaller than that in the IH case.
- Thus, the NH case fits the current observations better than the IH one.
- But, actually, the difference $\Delta\chi^2$ is not yet significant enough to distinguish the neutrino mass hierarchy.

中微子宇宙学称重的研究

小节：

- 在动力学暗能量模型中，中微子质量与哈勃常数之间的相关性由标准模型中的反相关变为正相关
- 在动力学暗能量宇宙中，中微子质量上限既可以变大，也可以变小；
- 在全息暗能量模型中可以得到迄今为止最紧的中微子质量上限（1.05电子伏特）
- 中微子质量排序可以影响宇宙学拟合，正等级情况要比反等级情况拟合得更好（相同情况下卡方减少2-4）
- 暗能量与暗物质的耦合也会对中微子的宇宙学称重产生影响

在幽灵和早期幽灵模型中，中微子质量限制变得更宽松；而在精质和早期精质模型中，中微子质量限制变得更紧

已经几乎等于反等级情况的中微子质量下限，因此该项研究与未来江门中微子实验的质量排序测量结果相结合有可能提供一种可证伪全息暗能量模型的方案

X. Zhang, Phys. Rev. D 93 (2016) 083011; S. Wang, Y. F. Wang, D. M. Xia & X. Zhang, Phys. Rev. D 94 (2016) 083519; M. M. Zhao, Y. H. Li, J. F. Zhang & X. Zhang, Mon. Not. Roy. Astron. Soc. 469 (2017) 1713; R. Y. Guo, Y. H. Li, J. F. Zhang & X. Zhang, JCAP 1705 (2017) 040; R. Y. Guo, J. F. Zhang & X. Zhang, arXiv:1803.06910

探测宇宙中微子背景

宇宙遗迹中微子在银河系中的引力结团效应

- PTOLEMY实验计划旨在探测宇宙中微子背景（并可测量质量）
- 中微子在银河系中有结团效应，影响事件率；N单体模拟每次只能模拟一个质量值的情况
- 我们提出了重加权方法，只需要一次模拟，即可得到所有质量的情况

nature COMMUNICATIONS

ARTICLE

DOI: 10.1038/s41467-018-04264-y OPEN

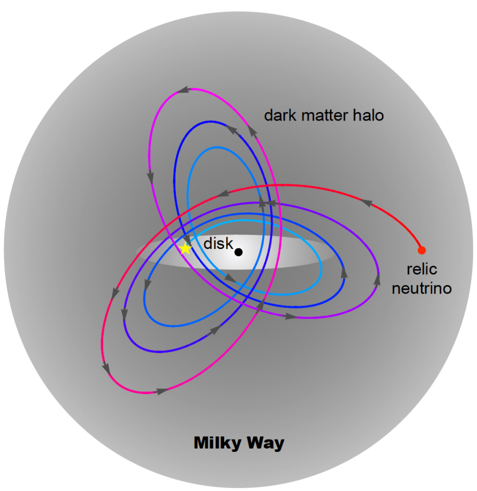
Gravitational clustering of cosmic relic neutrinos in the Milky Way

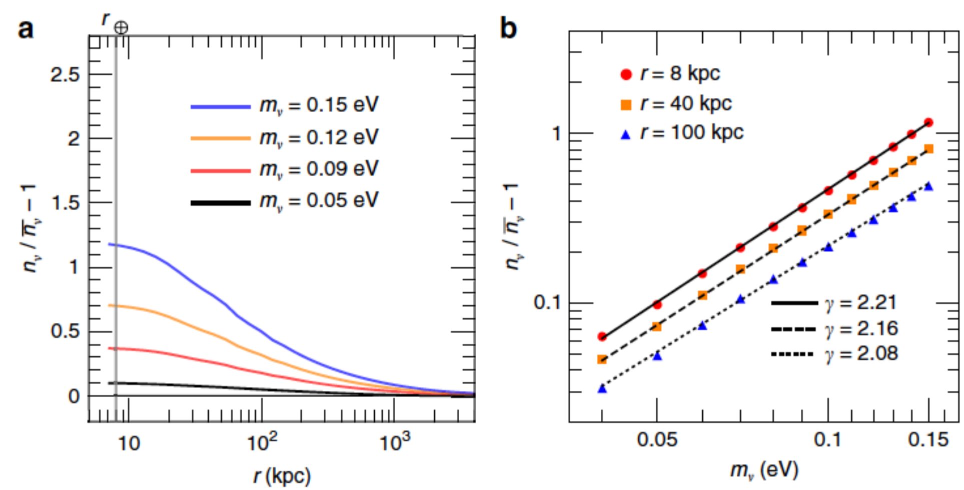
Jue Zhang[1] & Xin Zhang[2]

J. Zhang & X. Zhang, Nature Communications 9 (2018) 1833

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

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





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

惰性中微子的宇宙学搜寻

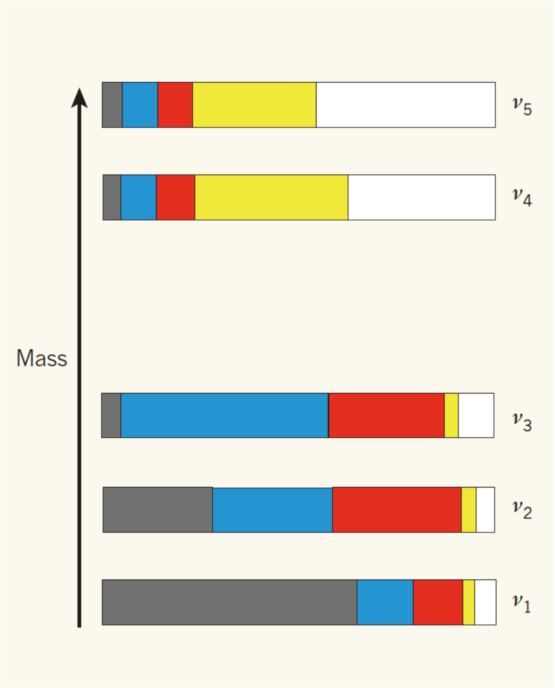
Sterile neutrinos

Δm^2 of about 7×10^{-5} eV^2
Sun, long-baseline reactor

Δm^2 of around 2×10^{-3} eV^2
atmosphere, long-baseline accelerator

Δm^2 of about 1 eV^2
short-baseline accelerator, reactor

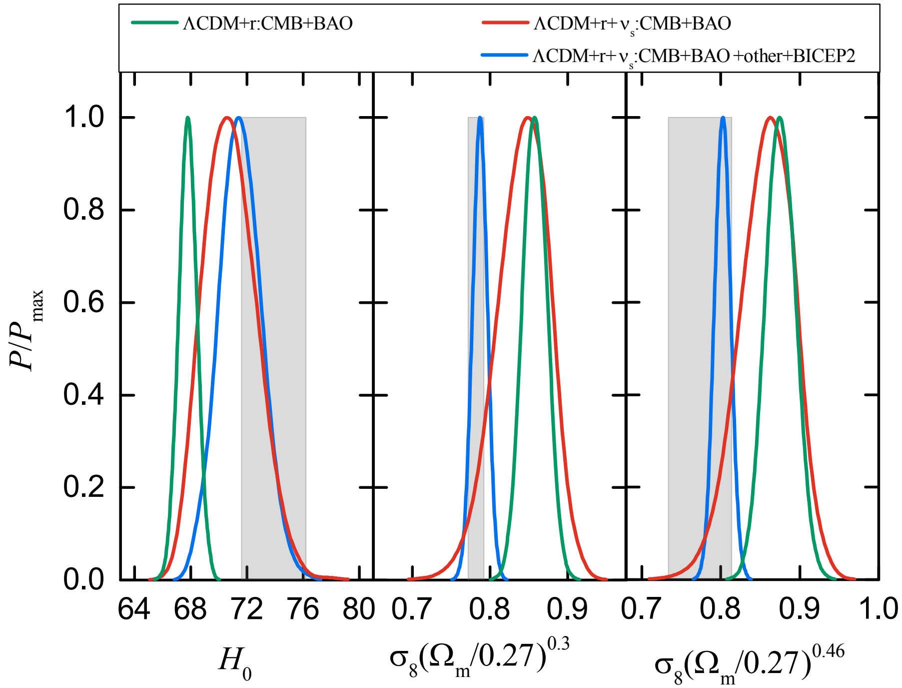
Anomaly! Sterile?



- Sterile: they interact only by gravity, and not by weak interaction (would not affect the width of Z^0)
- Through their mixing with active neutrinos and their interactions with gravity, sterile neutrinos could have a big effect on astrophysics and cosmology
- Detection: search for oscillations between active and sterile neutrinos
- Cosmological evidence: through their gravitational effects on galaxy formation and the evolution of the universe

motivation in cosmology:

- search for sterile neutrinos from the cosmological data
- solve the tension between Planck (based on LCDM) and other observations



2.4σ → 1.0σ 4.3σ → 2.0σ 2.3σ → 1.7σ

Sterile neutrino: A new concordance model?

J.F. Zhang, X. Zhang, Sterile neutrinos help reconcile the observational results of primordial gravitational waves from Planck and BICEP2. Phys. Lett. B **740**, 359 (2015). arXiv:1403.7028 [astro-ph.CO]

consider the case of one massive sterile neutrino parameterized by

$$m_{\nu,\,\mathrm{sterile}}^{\mathrm{eff}} \equiv (94.1\,\Omega_{\nu,\mathrm{sterile}} h^2)\ \mathrm{eV}$$

for thermally-distributed sterile neutrinos

$$m_{\nu,\,\mathrm{sterile}}^{\mathrm{eff}} = (T_{\mathrm{s}}/T_{\nu})^3 m_{\mathrm{sterile}}^{\mathrm{thermal}} = (\Delta N_{\mathrm{eff}})^{3/4} m_{\mathrm{sterile}}^{\mathrm{thermal}}$$

for the cosmologically-equivalent Dodelson-Widrow (DW) case

$$m_{\nu,\,\mathrm{sterile}}^{\mathrm{eff}} = \chi_{\mathrm{s}}\, m_{\mathrm{sterile}}^{\mathrm{DW}}$$

Dodelson, S., & Widrow, L. M. 1994, Phys. Rev. Lett., 72, 17

$$\Delta N_{\mathrm{eff}} = \chi_{\mathrm{s}}$$

$$\left.\begin{aligned} N_{\mathrm{eff}} &< 3.7 \\ m_{\nu,\,\mathrm{sterile}}^{\mathrm{eff}} &< 0.52\ \mathrm{eV} \end{aligned}\right\} 95\%,\ \textit{Planck}\ \mathrm{TT{+}lowP{+}lensing{+}BAO}$$

***Planck* 2015 results**
XIII. Cosmological parameters

- Massive sterile neutrinos with mixing angles large enough to help resolve the reactor anomalies would typically imply full thermalization in the early Universe, and hence give $\Delta N_{eff} = 1$ for each additional species.
- Such a high value of N_{eff}, especially combined with $m_{sterile} = 1$ eV, as required by reactor anomaly solutions, were virtually ruled out by previous cosmological data.
- This conclusion is strengthened by the analysis presented here, since $N_{eff} = 4$ is excluded at greater than 99% confidence.

Eur. Phys. J. C (2017) 77:418
DOI 10.1140/epjc/s10052-017-4986-3
THE EUROPEAN PHYSICAL JOURNAL C
Regular Article - Theoretical Physics

A search for sterile neutrinos with the latest cosmological observations

Lu Feng[1], Jing-Fei Zhang[1], Xin Zhang[1,2,a]
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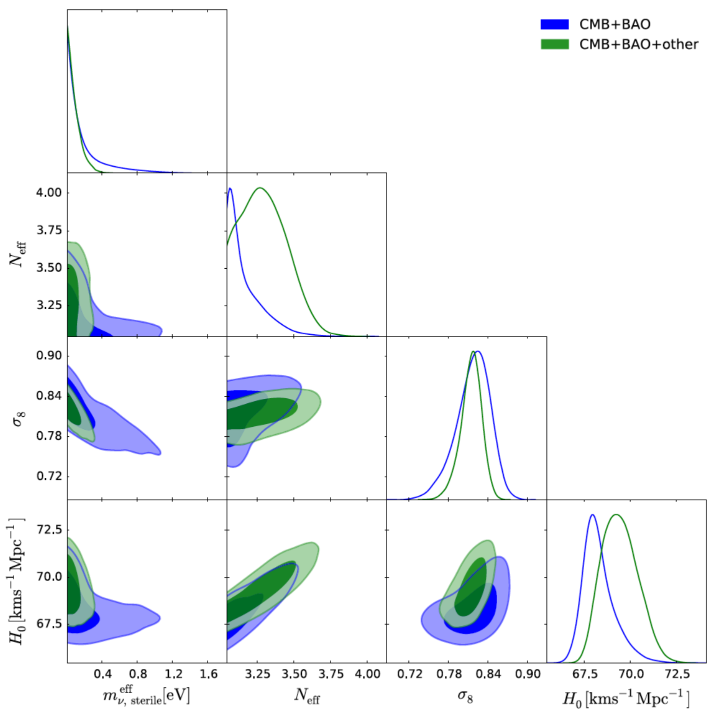
[2] Center for High Energy Physics, Peking University, Beijing 100080, China



P. Adamson et al. (Daya Bay and MINOS Collaborations), Limits on active to sterile neutrino oscillations from disappearance searches in the MINOS, Daya Bay, and Bugey-3 experiments. Phys. Rev. Lett. **117**(15), 151801 (2016). arXiv:1607.01177 [hep-ex] [Addendum: Phys. Rev. Lett. **117**(20), 209901 (2016)]
M.G. Aartsen et al. (IceCube Collaboration), Searches for sterile neutrinos with the IceCube detector. Phys. Rev. Lett. **117**(7), 071801 (2016). arXiv:1605.01990 [hep-ex]

$$\left.\begin{array}{r}N_{\rm eff} < 3.4273\\ m^{\rm eff}_{\nu,\rm sterile} < 0.7279\ {\rm eV}\end{array}\right\}\quad \text{CMB+BAO},$$

$$\left.\begin{array}{r}N_{\rm eff} = 3.30^{+0.12}_{-0.20}\\ m^{\rm eff}_{\nu,\rm sterile} < 0.2417\ {\rm eV}\end{array}\right\}\quad \text{CMB+BAO+other}.$$

$$\Delta N_{\rm eff} > 0 \text{ at the } 1.27\sigma$$

$$\Delta\text{AIC} = 4.632 \text{ and } 4.828$$

在当前的宇宙学观测数据中没有找到惰性中微子存在的证据

- 当前的宇宙学观测数据可在超过1个标准偏差置信水平上给出无质量惰性中微子存在的迹象
- 考虑额外的无质量惰性中微子确实可以在一定程度上缓解宇宙学数据之间的不一致，并可以改进宇宙学拟合
- 对于有质量惰性中微子，当前的观测数据只能给出其有效质量的一个相当紧的上限
- 相较于无质量情况，有质量惰性中微子并不被当前观测数据所支持
- 我们的结果与最近大亚湾与MINOS合作组所得到的中微子振荡实验的结果以及IceCube合作组所得到的宇宙线实验的结果是相一致的

Neutrino models and tension with external data

Planck Collaboration: *Planck* 2015 results. XIII.

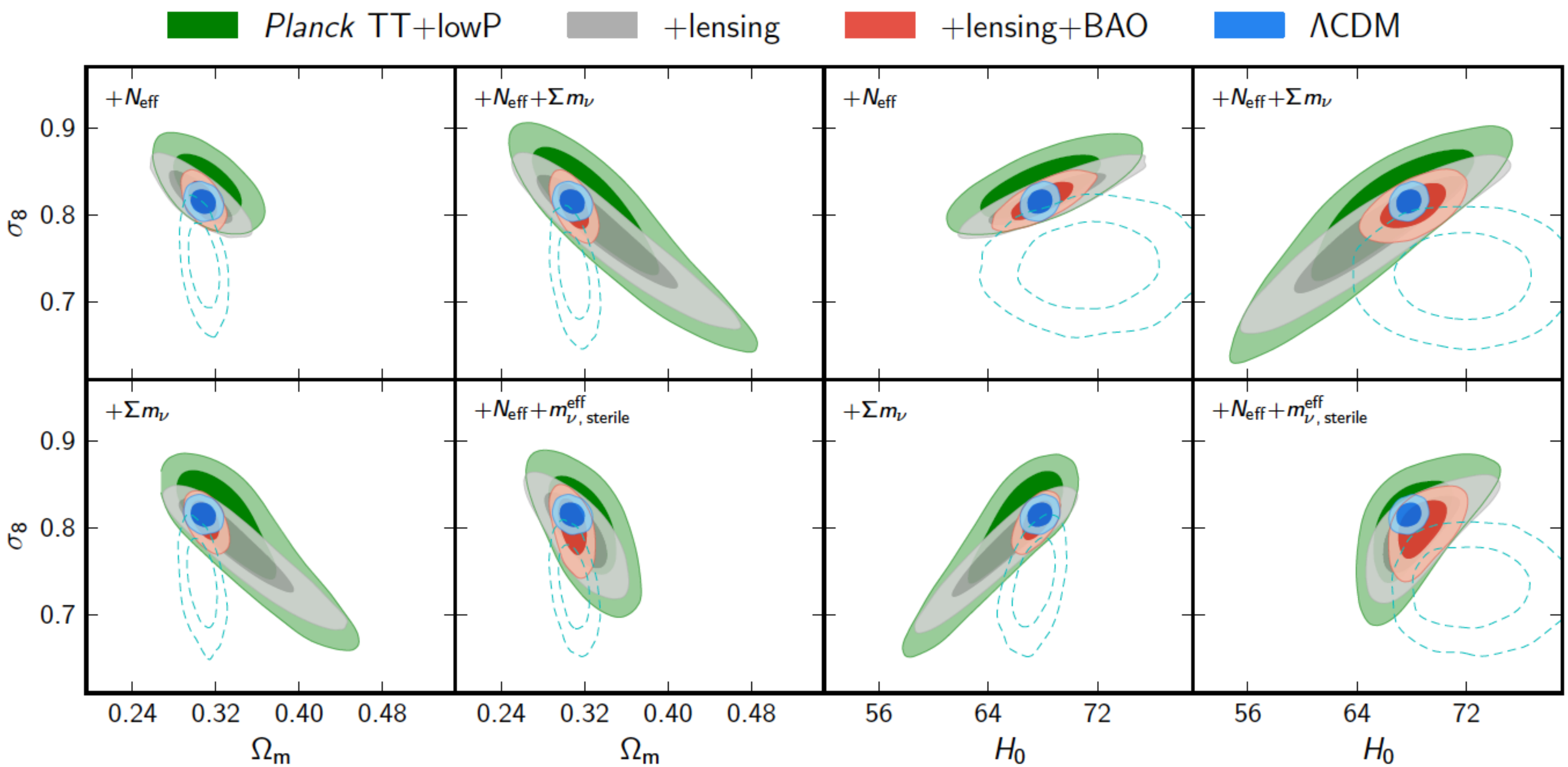


Fig. 33. 68% and 95% constraints from *Planck* TT+lowP (green), *Planck* TT+lowP+lensing (grey), and *Planck* TT+lowP+lensing+BAO (red) on the late-Universe parameters H_0, σ_8, and $\Omega_{\rm m}$ in various neutrino extensions of the base ΛCDM model. The blue contours show the base ΛCDM constraints from *Planck* TT+lowP+lensing+BAO. The dashed cyan contours show joint constraints from the H13 CFHTLenS galaxy weak lensing likelihood (with angular cuts as in Fig. 18) at constant CMB acoustic scale $\theta_{\rm MC}$ (fixed to the *Planck* TT+lowP ΛCDM best fit) combined with BAO and the Hubble constant measurement of Eq. (30). These additional constraints break large parameter degeneracies in the weak lensing likelihood that would otherwise obscure the comparison with the *Planck* contours. Here priors on other parameters applied to the CFHTLenS analysis are as described in Sect. 5.5.2.

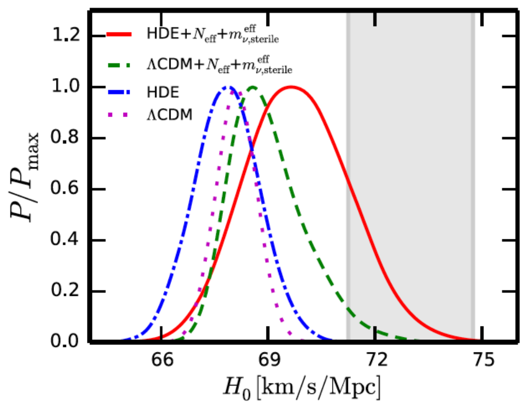
The red contours are broader than the blue contours and there is greater overlap with the CFHTLenS contours, ***but this offers only a marginal improvement compared to base LCDM***

PHYSICAL REVIEW D **96,** 043520 (2017)

Search for sterile neutrinos in holographic dark energy cosmology: Reconciling Planck observation with the local measurement of the Hubble constant

Ming-Ming Zhao,[1] Dong-Ze He,[1] Jing-Fei Zhang,[1] and Xin Zhang[1,2,*]
[1] *Department of Physics, College of Sciences, Northeastern University, Shenyang 110004, China*
[2] *Center for High Energy Physics, Peking University, Beijing 100080, China*

我们发现在动力学暗能量模型中，惰性中微子的存在确实可以更好地解释观测数据的不一致性，但是这样的模型的数据拟合表现并不好，因此利用惰性中微子来解释数据矛盾的做法似乎正在失去吸引力



$H_0 = 73.00 \pm 1.75\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$

A. G. Riess *et al.*, Astrophys. J. **826**, 56 (2016)

FIG. 1. The one-dimensional marginalized distributions of H_0 for HDE + $N_{\rm eff}$ + $m_{\nu,\rm sterile}^{\rm eff}$ (red solid curve), ΛCDM + $N_{\rm eff}$ + $m_{\nu,\rm sterile}^{\rm eff}$ (green dashed), HDE (blue dashed-dotted), and ΛCDM (purple dotted) under the constraints of the CMB + BAO + SN + RSD + WL + lensing data combination. The result of the latest local measurement of Hubble constant ($H_0 = 73.00 \pm 1.75\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$) is shown by the grey band.

In the HDE+sterile model, the H_0 tension is indeed furthest relieved, but this does not mean that the problem is really solved because the HDE+sterile model is not favored by the current observations from a model comparison analysis.

Physics Letters B 779 (2018) 473–478

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Physics Letters B

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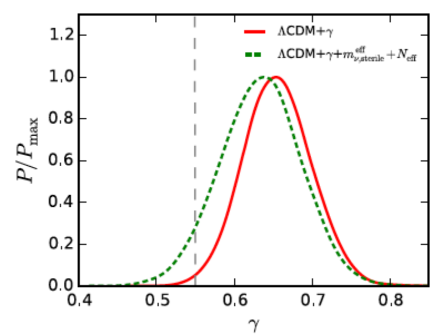
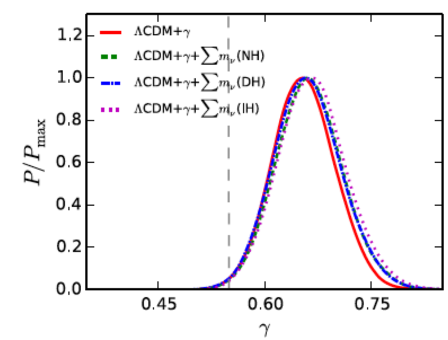
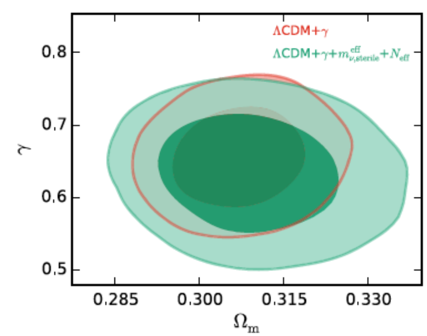
Measuring growth index in a universe with massive neutrinos: A revisit of the general relativity test with the latest observations

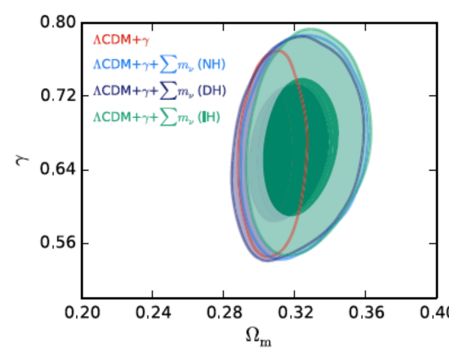
Ming-Ming Zhao [a], Jing-Fei Zhang [a], Xin Zhang [a,b,*]
[a] Department of Physics, College of Sciences, Northeastern University, Shenyang 110004, China
[b] Center for High Energy Physics, Peking University, Beijing 100080, China

最新的对GR检验的工作表明：考虑惰性中微子和有质量中微子对增长指数测量都影响很小







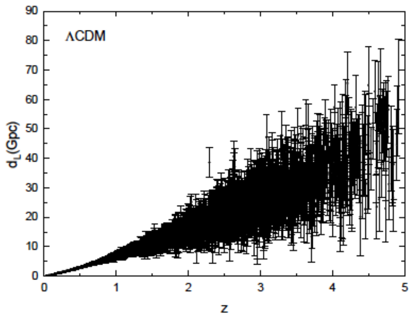


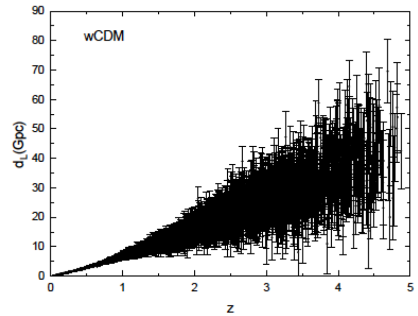
引力波标准汽笛：宇宙学参数估计（破除简并）

X. N. Zhang, L. F. Wang, J. F. Zhang & X. Zhang, arXiv:1804.08379

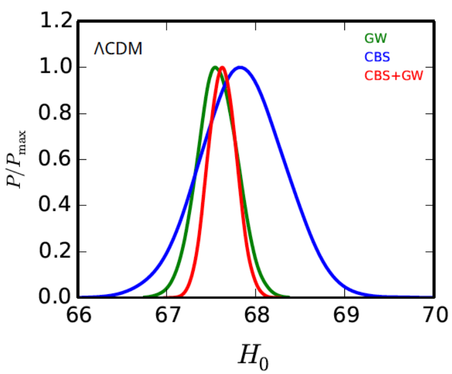
ET: 1000个模拟数据

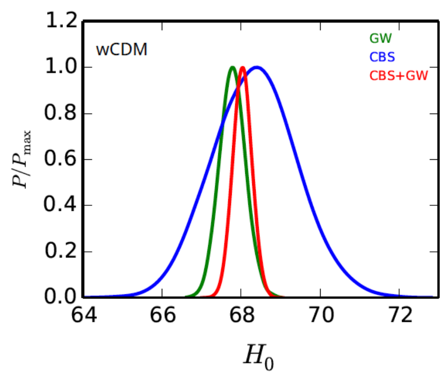
- 在打破简并方面发挥重要作用，因此可以极大地改进参数估计
- 对动力学暗能量模型更明显
- 对w限制也不太好，但是由于打破简并，联合限制有很大提升

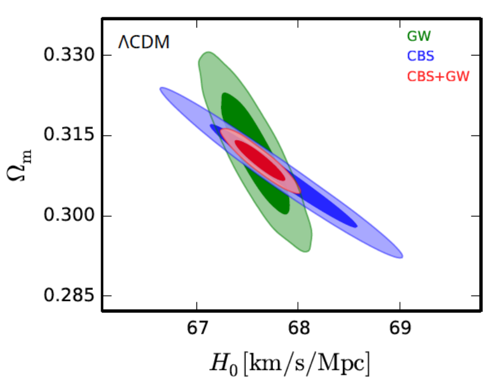


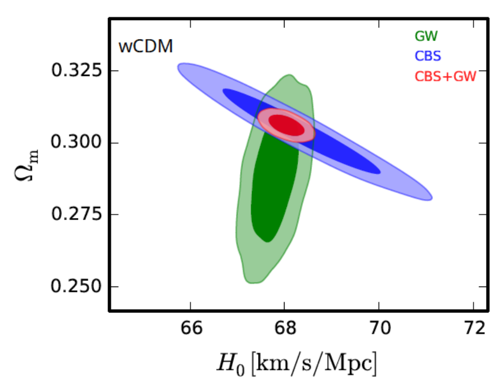


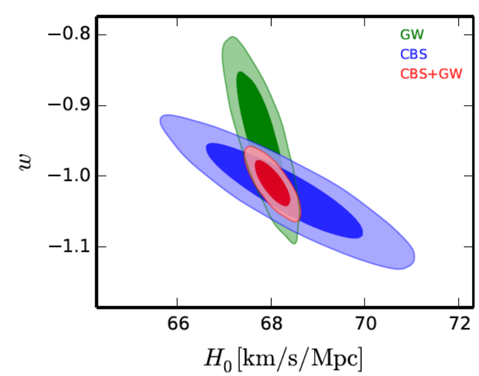
model	ΛCDM			wCDM		
Data	CBS	GW	CBS+GW	CBS	GW	CBS+GW
$\sigma(\Omega_m)$	0.0060	0.0072	0.0024	0.0094	0.0150	0.0023
$\sigma(h)$	0.0046	0.0022	0.0016	0.0105	0.0033	0.0024
$\sigma(w)$	–	–	–	0.042	0.058	0.020
$\varepsilon(\Omega_m)$	0.0197	0.0231	0.0077	0.0308	0.0520	0.0075
$\varepsilon(h)$	0.0068	0.0033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





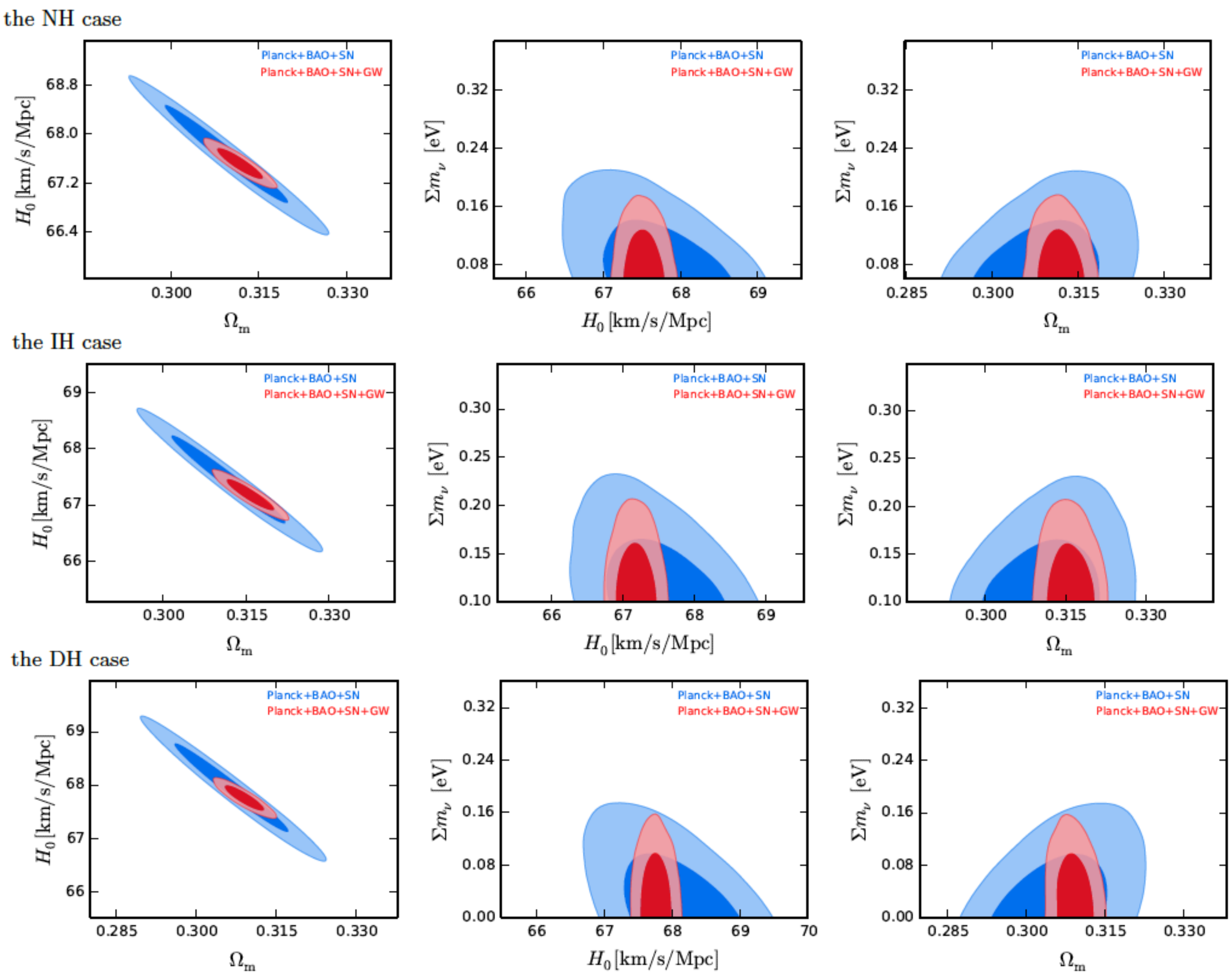






引力波标准汽笛：宇宙学参数估计（中微子质量）

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



对中微子质量的限制能力提高约10%左右

总结

- 宇宙学中的重要科学问题的解答依赖于参数精确测量
- 未来光学巡天项目对宇宙学有很大推动，但还需要发展新探针（射电，引力波），有助于避免系统误差、打破简并
- 课题研究取得一些积极进展：
    - 建立了相互作用暗能量PPF框架（编写IDECAMB程序包）
    - 系统研究了暗能量性质对中微子质量测量的影响
    - 当前观测数据并不支持惰性中微子
- 引力波观测有助于打破光学（电磁）观测的参数简并，提高参数限制能力
- 接下来研究未来引力波观测与光学和射电观测（DESI, Euclid, WFIRST, SKA）相结合，将把暗能量本质属性探索推进至何种程度

谢谢！