天文探测暗物质粒子

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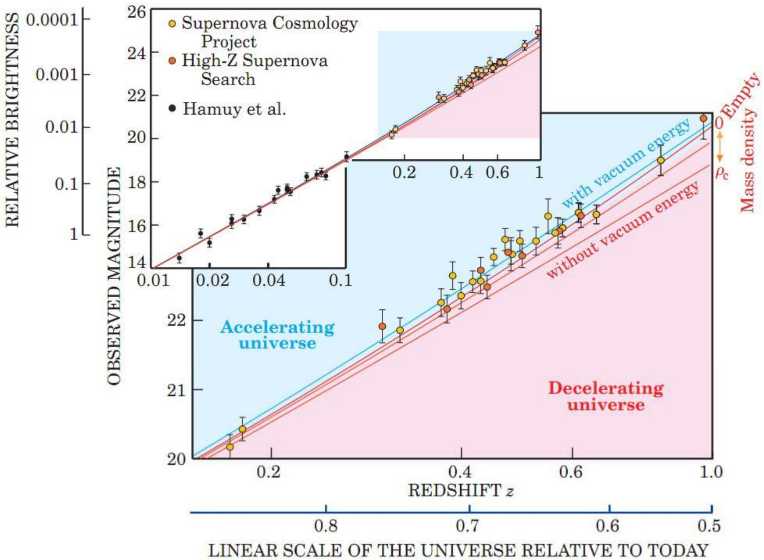
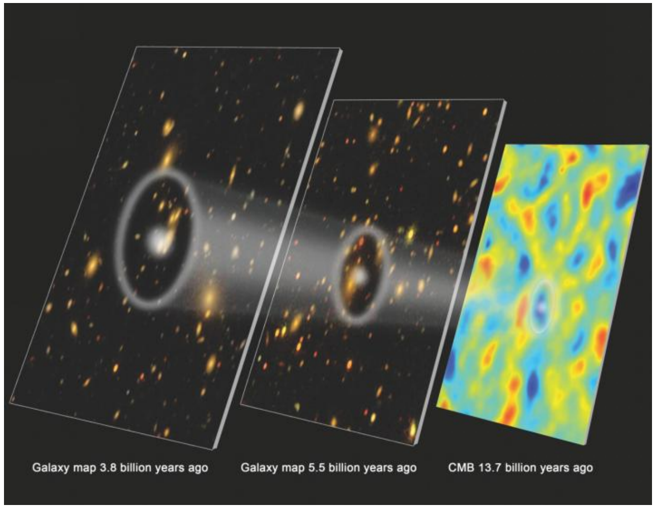
中国科学院紫金山天文台

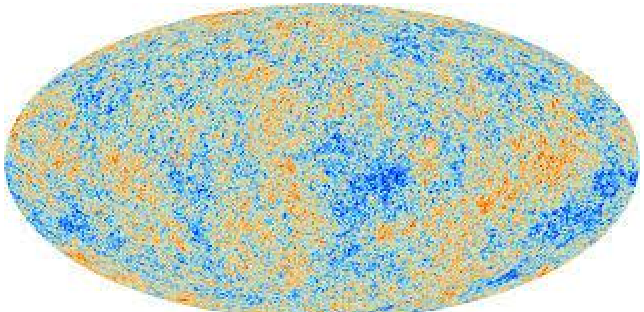
2022.7.20-21

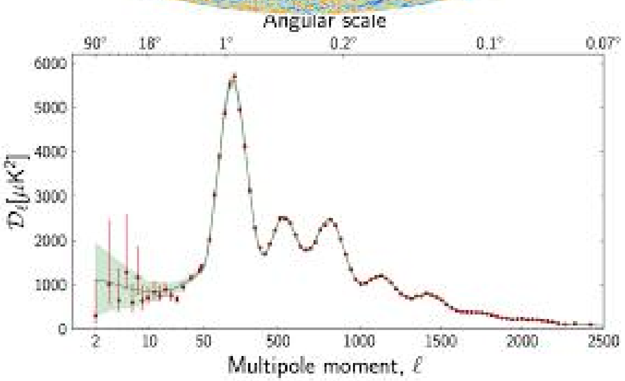
2022年理论物理前沿讲习班：暗物质与新物理暑期学校

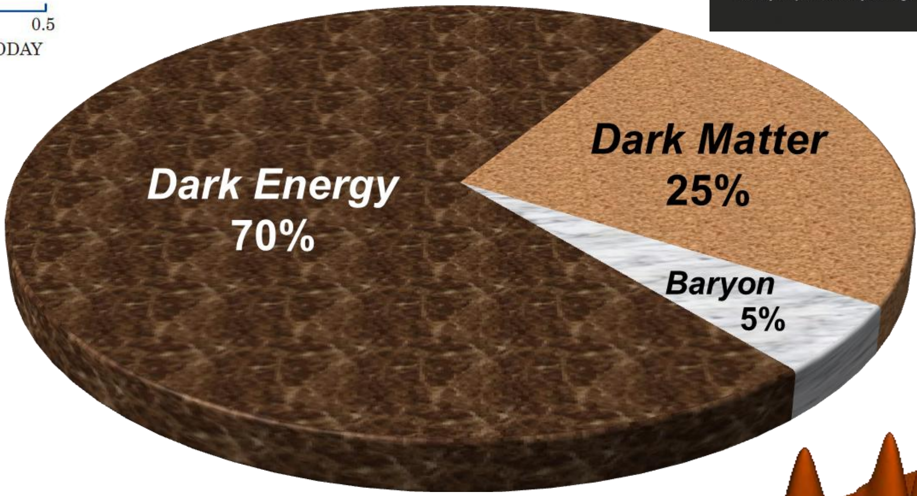
宇宙的组成

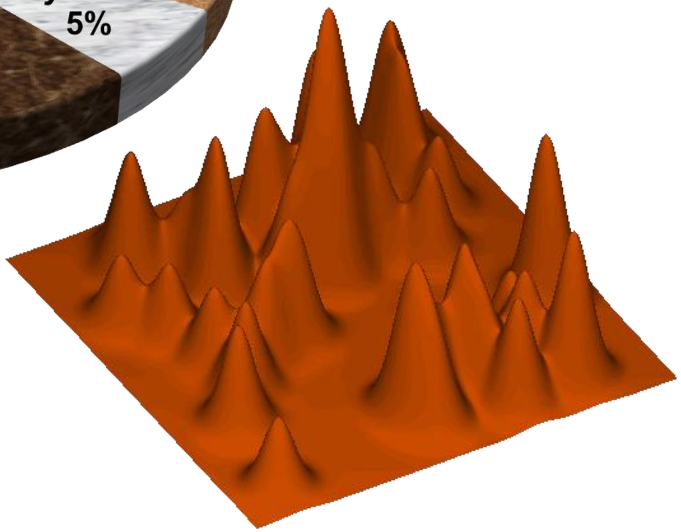

RELATIVE BRIGHTNESS
OBSERVED MAGNITUDE
Supernova Cosmology Project
High-Z Supernova Search
Hamuy et al.
with vacuum energy
without vacuum energy
Empty
Mass density
Accelerating universe
Decelerating universe
REDSHIFT z
LINEAR SCALE OF THE UNIVERSE RELATIVE TO TODAY


Galaxy map 3.8 billion years ago
Galaxy map 5.5 billion years ago
CMB 13.7 billion years ago

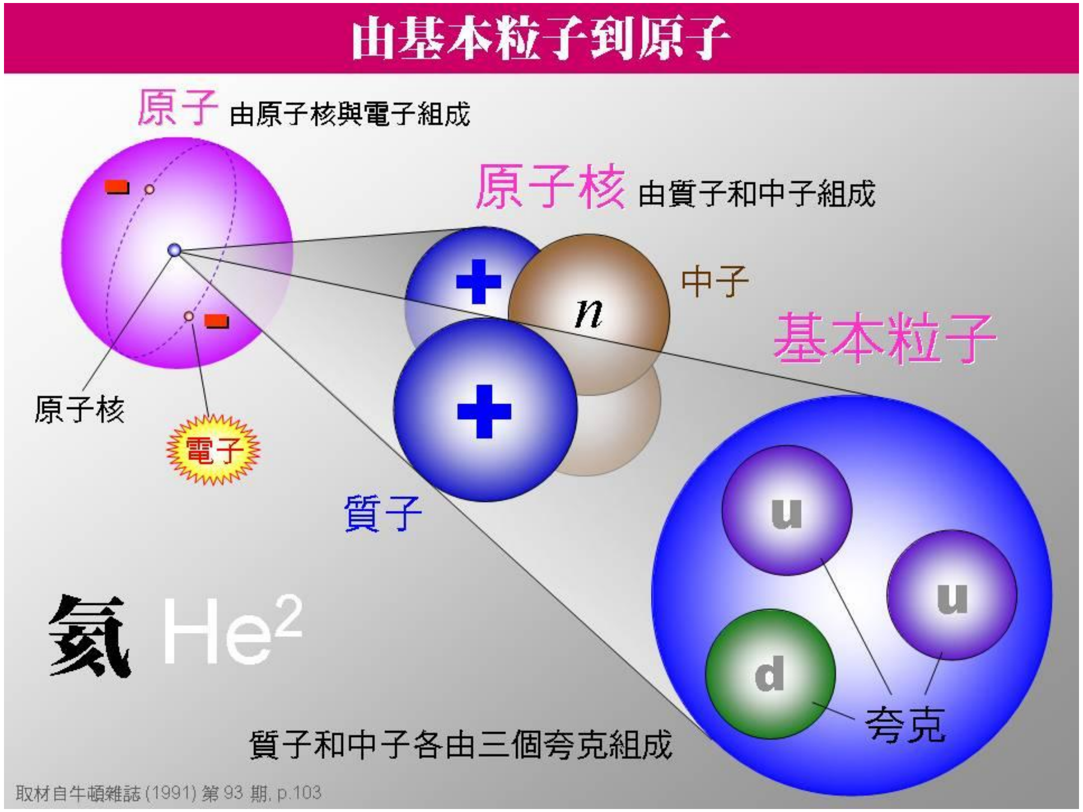



Angular scale
Multipole moment, ℓ


Dark Energy
70%
Dark Matter
25%
Baryon
5%



暗物质是什么？



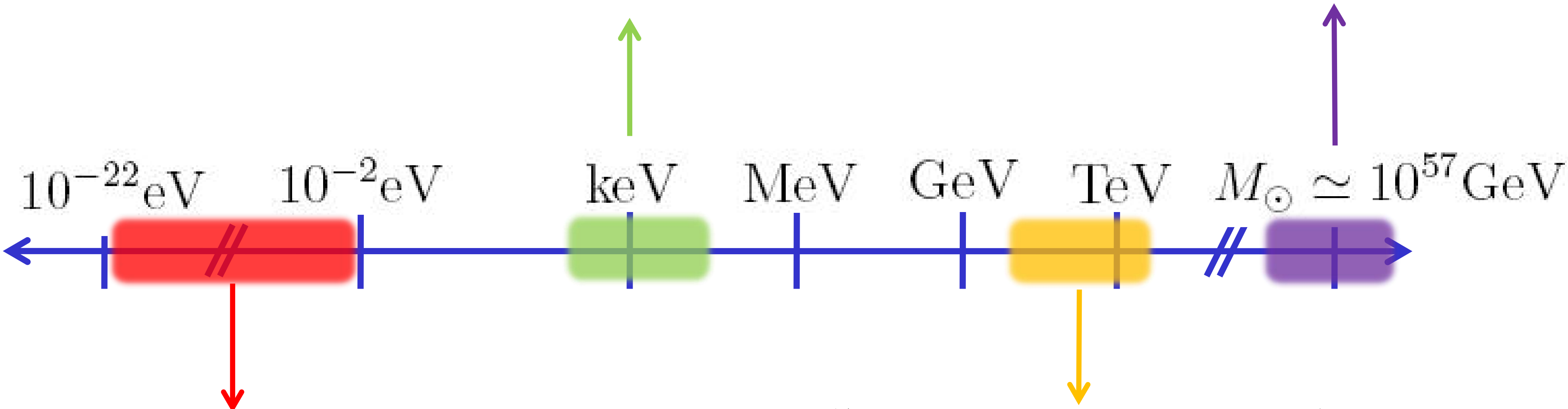
暗物质性质：稳定, 低速(冷), 非重子, 弱作用

暗物质不同于标准模型里的任何粒子，很可能是一种（多种）超出标准模型的新粒子——新物理！

理论学家眼中的暗物质

惰性中微子：
中微子震荡、
X射线天文

黑洞(MACHOs)：
引力透镜、引力波

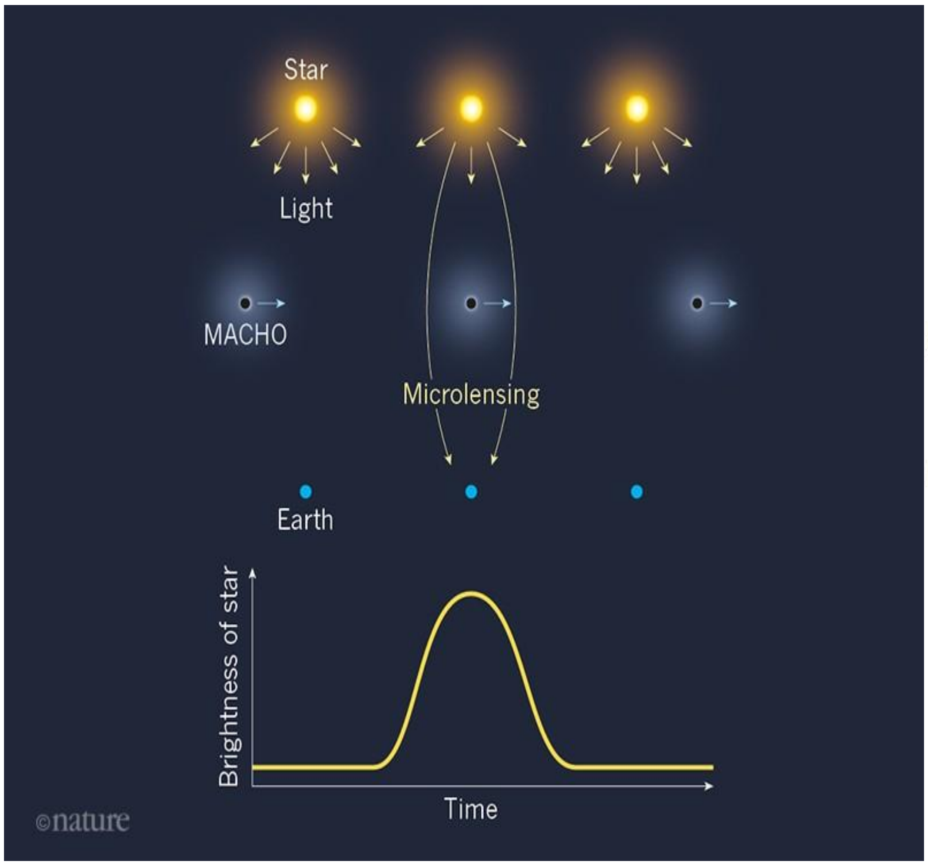


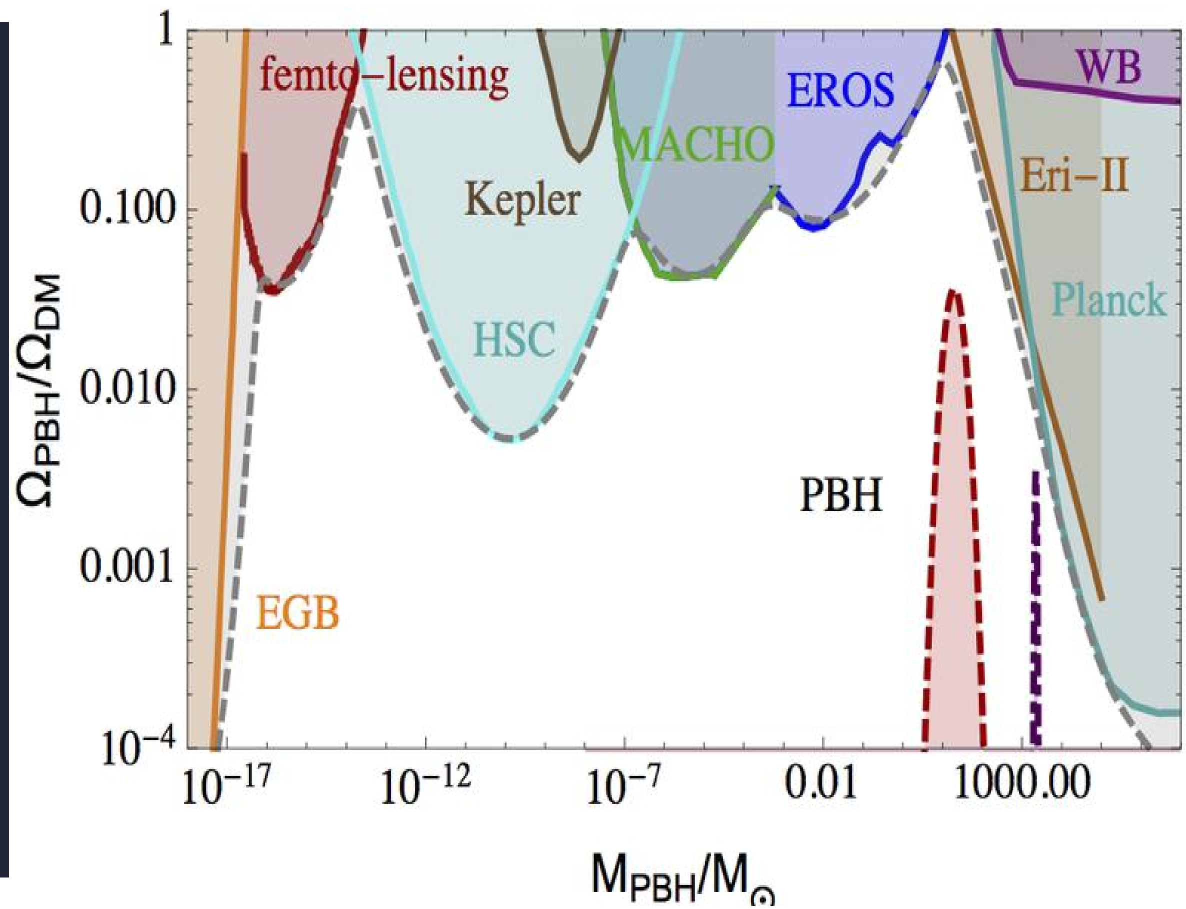
超轻暗物质(轴子、类轴子粒子、暗光子...)：
共振腔实验、射电天文

弱作用重粒子(WIMPs)：直接探测、间接探测、对撞机探测
(见殷鹏飞、蔡岳霖、王雯宇等老师的讲座)

暗物质的实验探测极具挑战性，天文观测在多种形式暗物质候选体探测中起着非常重要的作用

MACHO/PBH暗物质





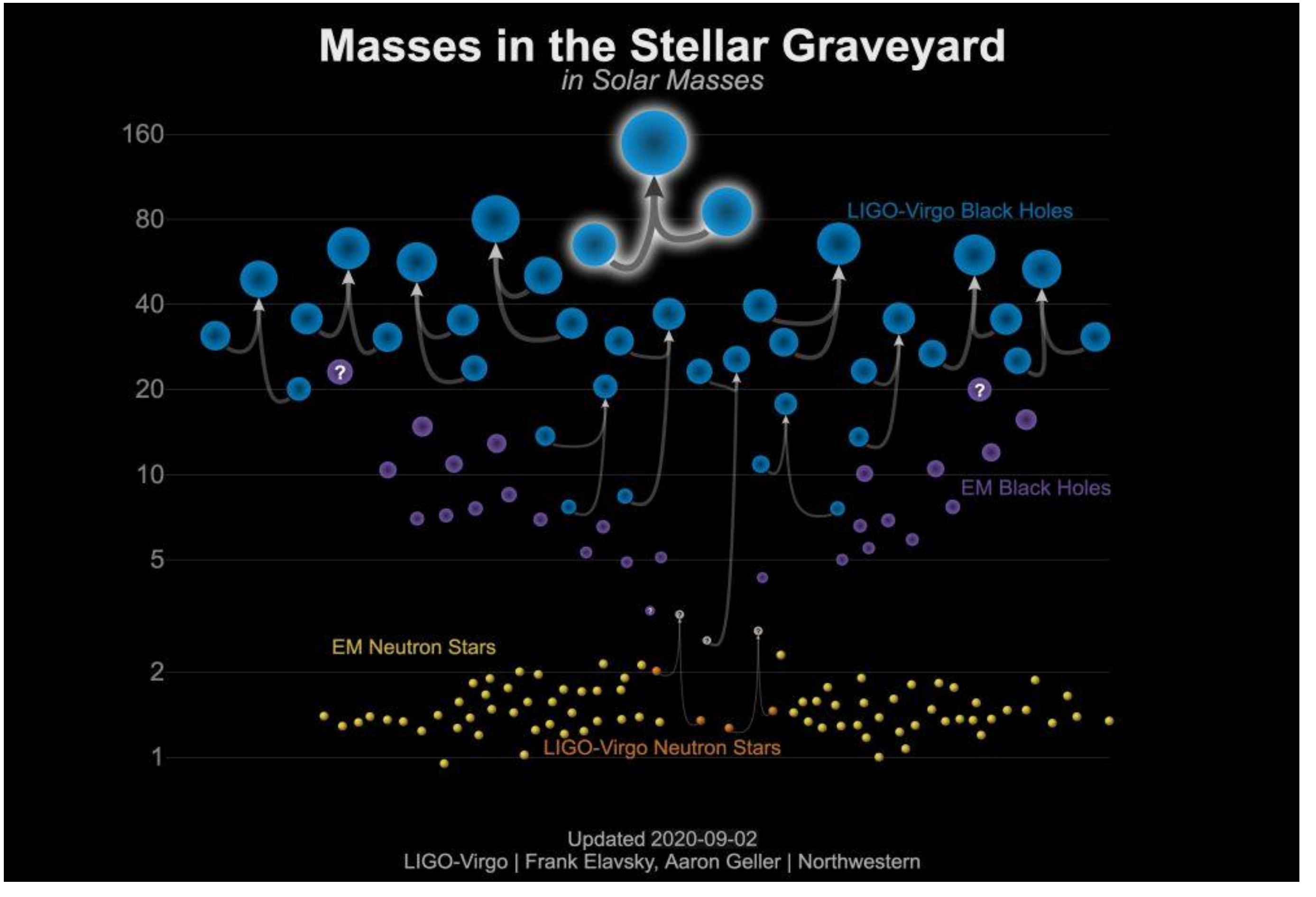
MACHO/PBH暗物质

Did LIGO Detect Dark Matter?

Simeon Bird, Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, and Adam G. Riess

Phys. Rev. Lett. **116**, 201301 – Published 19 May 2016

Physics See Synopsis: Gravitational Waves May Hold Dark Matter Secret



MACHO/PBH暗物质

arXiv:2105.03349

Quantifying the evidence for primordial black holes in LIGO/Virgo gravitational-wave data

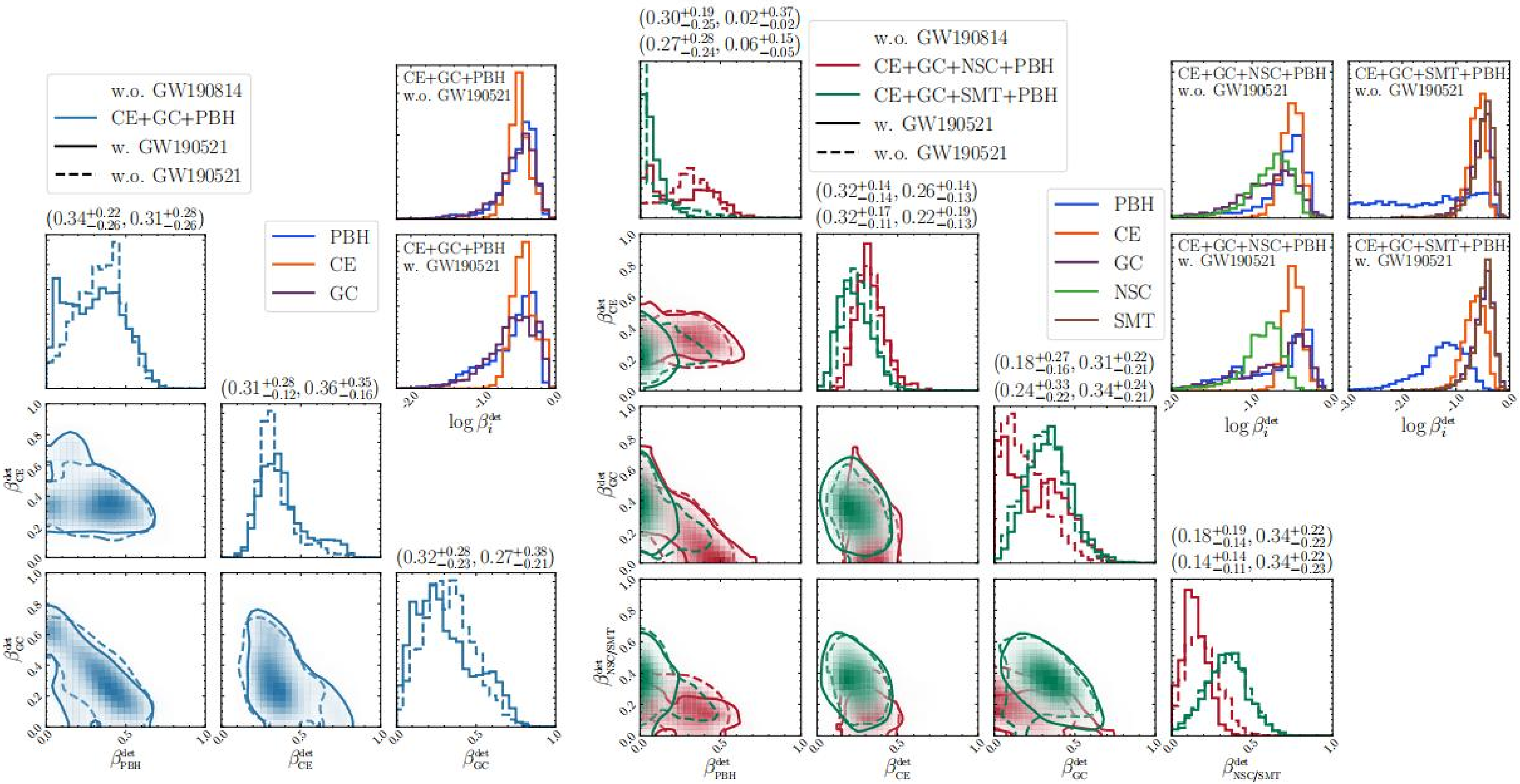
Gabriele Franciolini,[1,*] Vishal Baibhav,[2] Valerio De Luca,[1,3] Ken K. Y. Ng,[4,5] Kaze W. K. Wong,[2] Emanuele Berti,[2] Paolo Pani,[3,6] Antonio Riotto,[1] and Salvatore Vitale[4,5]

analyses to population studies. We perform a hierarchical Bayesian analysis on the GWTC-2 catalog by combining several astrophysical formation models with a population of primordial black holes. We compute the Bayesian evidence for a primordial population compared to the null hypothesis, and the inferred fraction of primordial black holes in the data. We find that these quantities depend on the set of assumed astrophysical models: the evidence for primordial black holes against an astrophysical-only multichannel model is decisively favored in some scenarios, but it is significantly reduced in the presence of a dominant stable-mass-transfer isolated formation channel. The primordial channel can explain mergers in the upper mass gap such as GW190521, but (depending on the astrophysical channels we consider) a significant fraction of the events could be of primordial origin even if we neglected GW190521. The tantalizing possibility that LIGO/Virgo may have already detected black holes formed after inflation should be verified by reducing uncertainties in astrophysical and primordial formation models, and it may ultimately be confirmed by third-generation interferometers.

LIGO/VIRGO黑洞大多数来自天体起源，但也可能有部分为原初黑洞

MACHO/PBH暗物质

arXiv:2105.03349



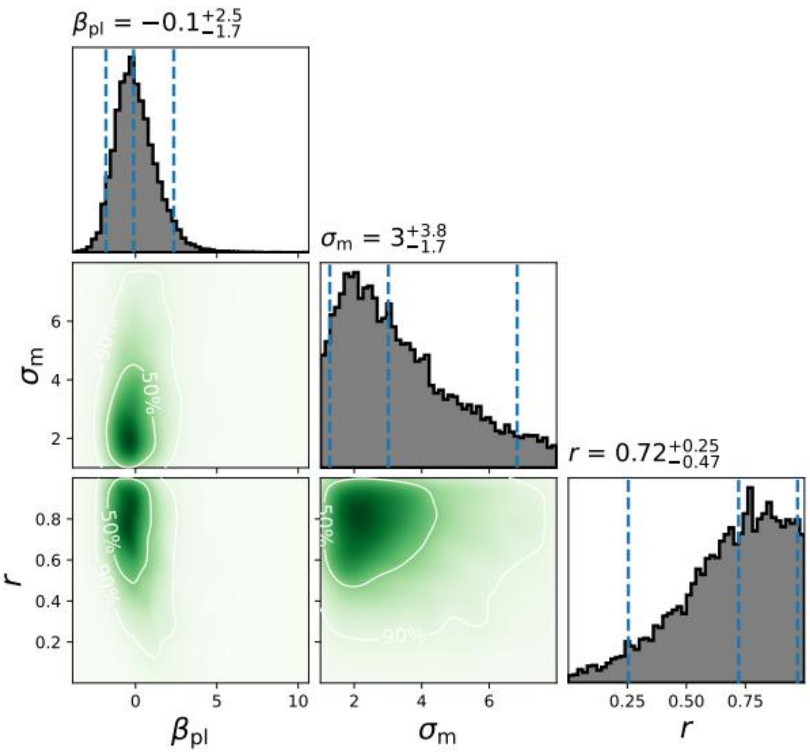
$\log_{10} \mathcal{B}^{\mathcal{M}}_{\rm CE+GC}$	CE+GC+PBH	CE+GC+NSC	CE+GC+SMT	CE+GC+NSC+PBH	CE+GC+SMT+PBH
w.o. GW190521	1.22	0.52	1.39	1.43	1.31
w. GW190521	2.38	-0.15	0.72	2.30	2.58

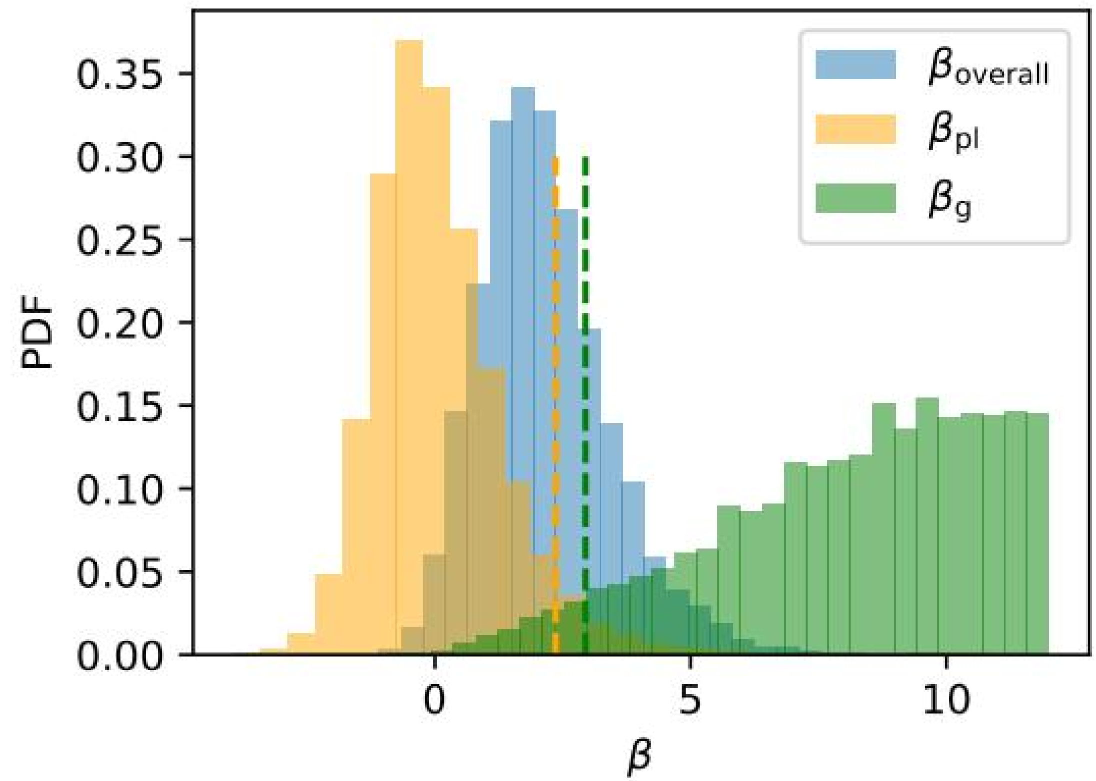
MACHO/PBH暗物质

Find the twins: Evidence for a population of coalescing binary black holes with nearly equal-mass components

Yin-Jie Li,[1,2,*] Yuan-Zhu Wang,[1,*] Shao-Peng Tang,[1,2] Qiang Yuan,[1,2] Yi-Zhong Fan,[1,2,†] and Da-Ming Wei[1,2]

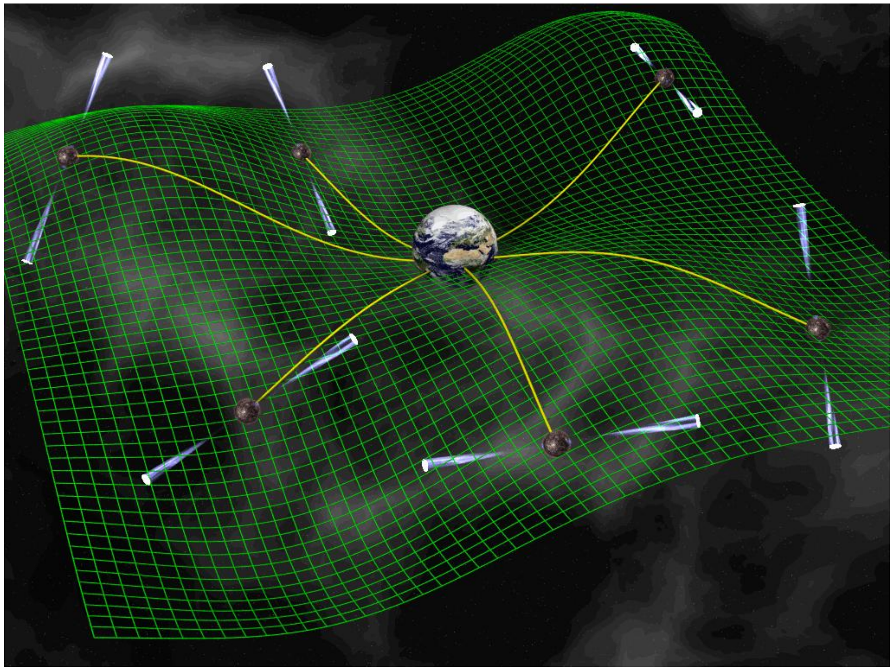
arXiv:2201.01905

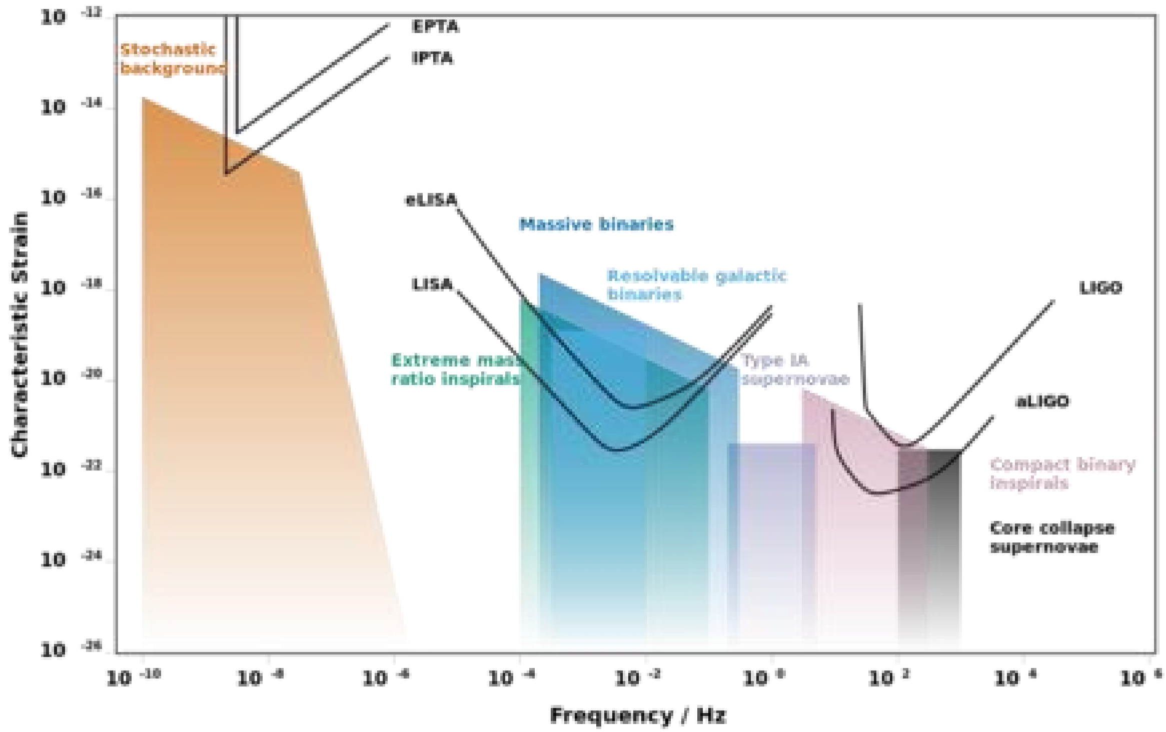




LIGO/VIRGO黑洞质量分布：存在约30 Msun的peak，且peak处的双黑洞质量接近相等，和原初黑洞预言相符

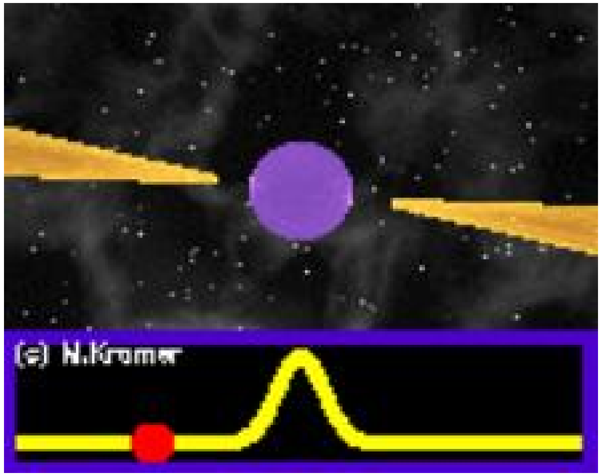
脉冲星计时阵列PTA

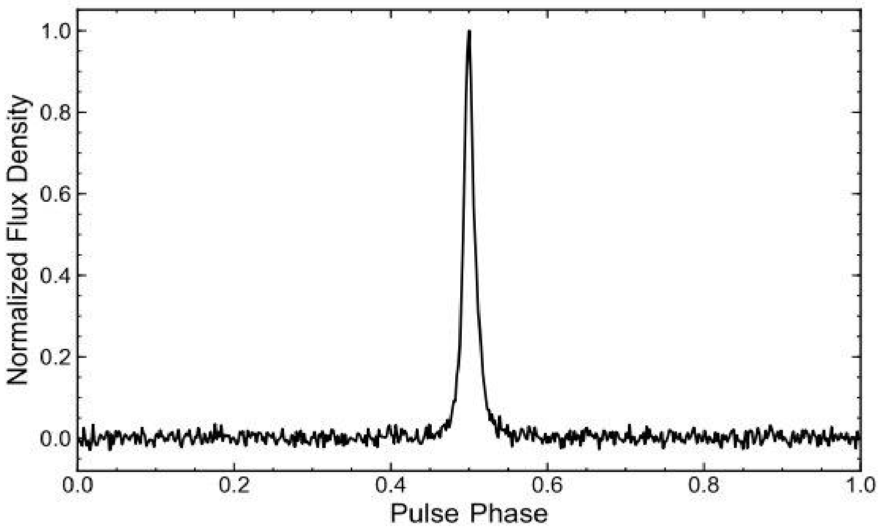




- 主要用于探测nHz引力波(超大质量双黑洞、随机引力波背景)
- PPTA, EPTA, NANOGrav, IPTA, CPTA
- 除了引力波以外还可用于很多精密测量相关的科学问题(DM、PBH、小天体等)

脉冲到达时间TOA





residual

TOA ~ Timing model + White noise + Spin noise + DM noise + SSE noise + Signal

标准模型

噪声项：仪器噪声，pulsar自旋不稳定，DM variations，太阳系内的扰动不确定性等

PBH，dark matter，引力波

脉冲星计时模型

```
PSRJ           J0030+0451
RAJ             00:30:27.4299630          1   0.00000000083327092134
DECJ           +04:51:39.75230            1   0.00000000193016085164
F0             205.53069608827312545      1   1.67354546171138858050e-13
F1             -4.30603883991341772080e-16 1  2.08473194525913969190e-21
PEPOCH         53000
POSEPOCH       53000
DMEPOCH        53000
PMRA           -4.05413525836407985510    1   0.06006537664217530270
PMDEC          -5.03376865001804390130    1   0.14002511698705866205
PX             4.02291243326134355780     1   0.02065704842394362750
EPHVER         5
CLK            UNCORR
MODE 1
EPHEM          DE414
DM             1 1 0
DM1            0 1 0
DM2            0 1 0
```

Right ascension, RA (J2000)
Declination, DEC (J2000)
Proper motion in RA (mas yr^{-1})
Proper motion in DEC (mas yr^{-1})
Spin frequency, f (s^{-1})
$\dot{f}$ (s^{-2})
Parallax, π (mas)
Dispersion measure, DM (cm^{-3} pc)
$\dot{DM}$ (cm^{-3} pc yr^{-1})
$\ddot{DM}$ (cm^{-3} pc yr^{-2})

Binary model
Orbital period, P_b (d)
Epoch of periastron, T_0 (MJD)
Projected semi-major axis, x (lt-s)
Longitude of periastron, ω_0 (deg)
Eccentricity, e
Sine of inclination, $\sin i$
Companion mass, m_c ($M_\odot$)
Derivative of P_b, $\dot{P}_b$
Periastron advance $\dot{\omega}_0$ (deg yr^{-1})
Epoch of ascending node, T_{asc} (MJD)

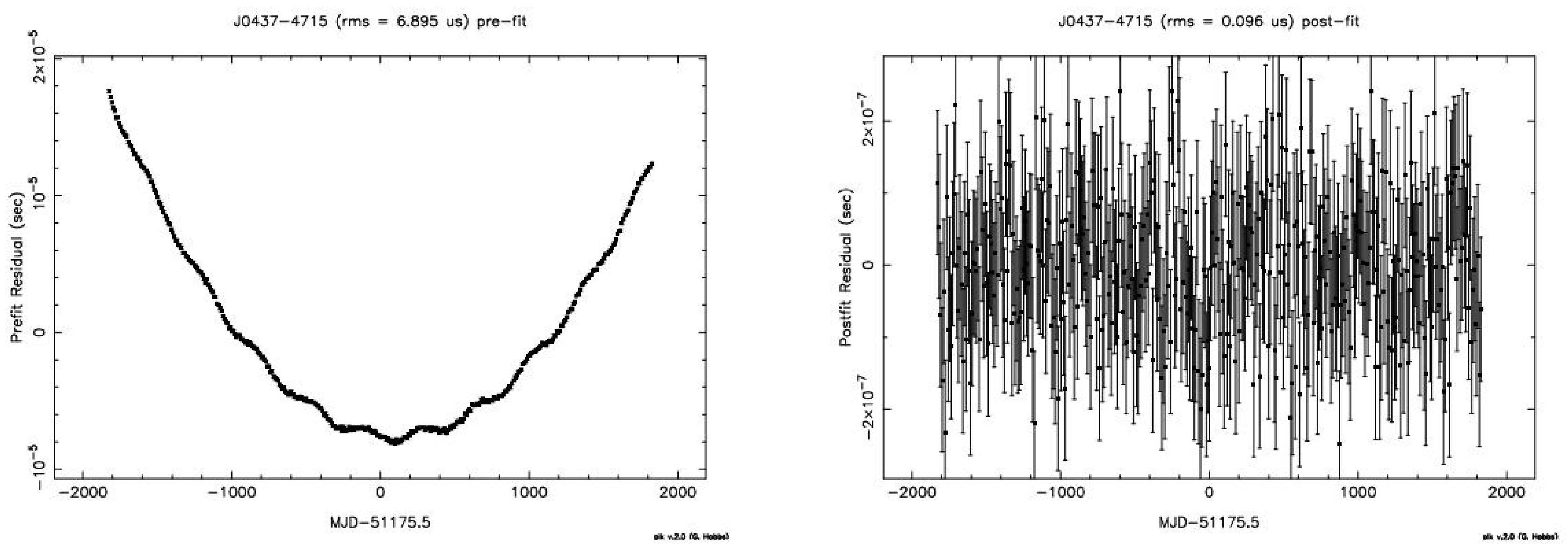


Figure 1: a) pre-fit timing residuals for the test data-set and b) post-fit timing residuals.

噪声模型

- Uncorrelated noise (white noise): instrumental, pulsar template or profile

- Correlated noise (red noise): spin noise, dispersion measure variation noise

$$S_{\rm spin}(f) = \frac{A_s^2}{12\pi^2}\left(\frac{f}{\rm yr^{-1}}\right)^{-\gamma_s} \rm yr^3 \qquad S^{ij}_{\rm DM}(f) = \frac{A_{\rm DM}^2}{12\pi^2}\left(\frac{f}{\rm yr^{-1}}\right)^{-\gamma_{\rm DM}} \rm yr^3 \left(\frac{\nu_i}{\nu_{\rm ref}}\right)^{-2}\left(\frac{\nu_j}{\nu_{\rm ref}}\right)^{-2}$$

- Solar system ephemeris noise: perturbation due to Jupiter, Saturn, Uranus, Neptune ...

- Additional noise term due to specific cases, such as plasma cloud in the line-of-sight

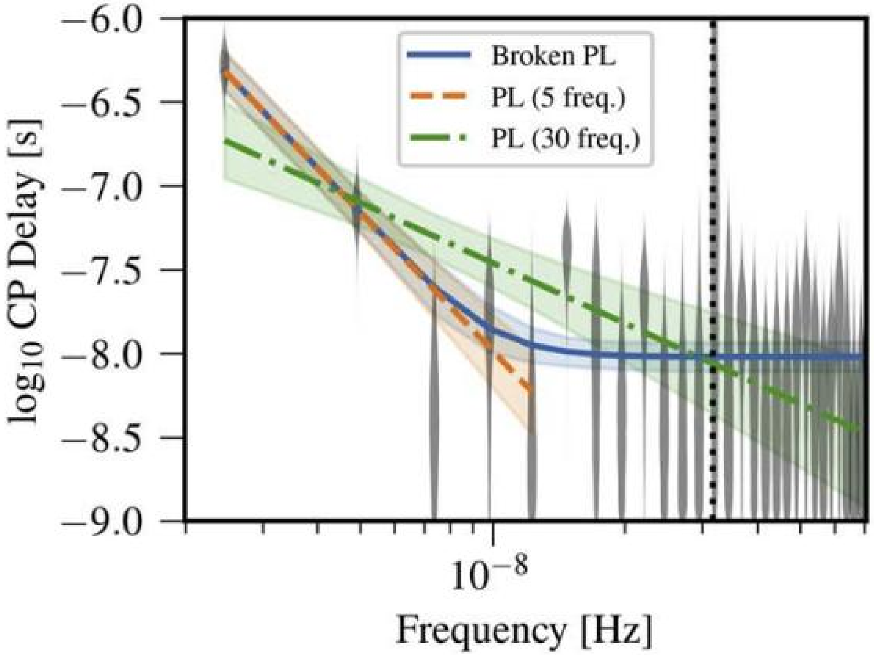
噪声模型参数

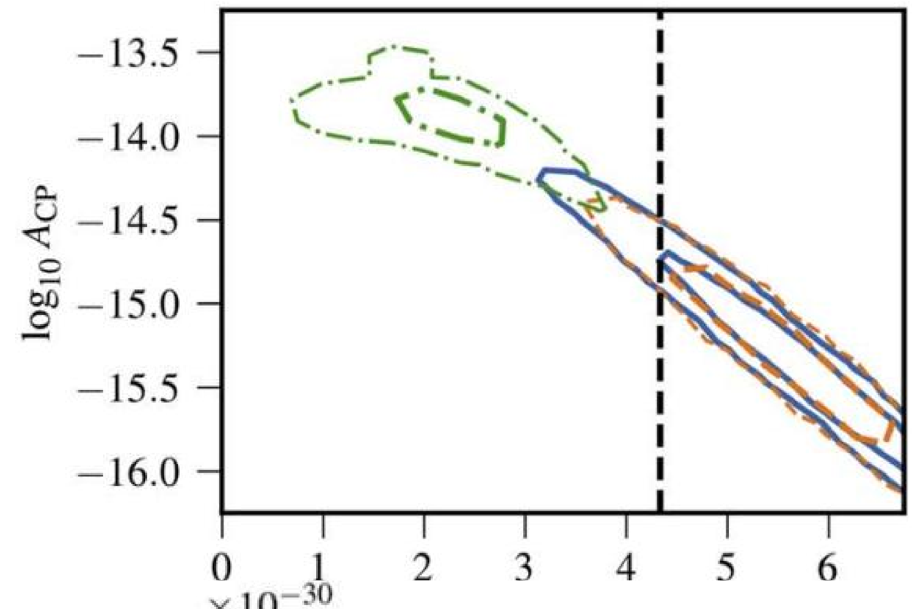
Parameter	Prior	Description
	White noise (ϑ_{W})	
EFAC	U[0.01, 10]	one per backend
EQUAD	log-U[−10, −4]	one per backend
	Spin noise (ϑ_{SP})	
A_{SN}	log-U[−21, −9]	one per pulsar
γ_{SN}	U[0, 7]	one per pulsar
	DM noise (ϑ_{DM})	
A_{DM}	log-U[−21, −9]	one per pulsar
γ_{DM}	U[0, 7]	one per pulsar
	Band noise (ϑ_{BN})	
A_{BN}	log-U[−21, −9]	one per band
γ_{BN}	U[0, 7]	one per band
	SSE noise (BayesEphem **parameters**, ϑ_{SSE})	
z_{drift}^{a}	$U[-10^{-9}, 10^{-9}]$ rad yr^{-1}	one per PTA
$\Delta M_{jupiter}$	$N(0, 1.5 \times 10^{-11}) M_{\odot}$	one per PTA
ΔM_{saturn}	$N(0, 8.2 \times 10^{-12}) M_{\odot}$	one per PTA
ΔM_{uranus}	$N(0, 5.7 \times 10^{-11}) M_{\odot}$	one per PTA
$\Delta M_{neptune}$	$N(0, 7.9 \times 10^{-11}) M_{\odot}$	one per PTA
$PCA_i{}^{b}$	U[−0.05, 0.05]	six per PTA

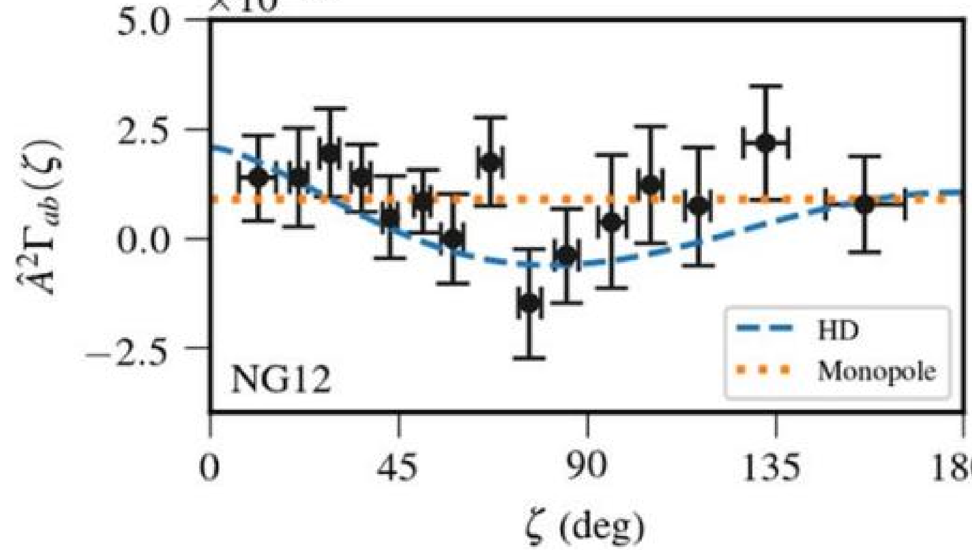
THE ASTROPHYSICAL JOURNAL LETTERS, 905:L34 (18pp), 2020 December 20
https://doi.org/10.3847/2041-8213/abd401

The NANOGrav 12.5 yr Data Set: Search for an Isotropic Stochastic Gravitational-wave Background

Zaven Arzoumanian[1], Paul T. Baker[2], Harsha Blumer[3,4], Bence Bécsy[5], Adam Brazier[6,7], Paul R. Brook[3,4],





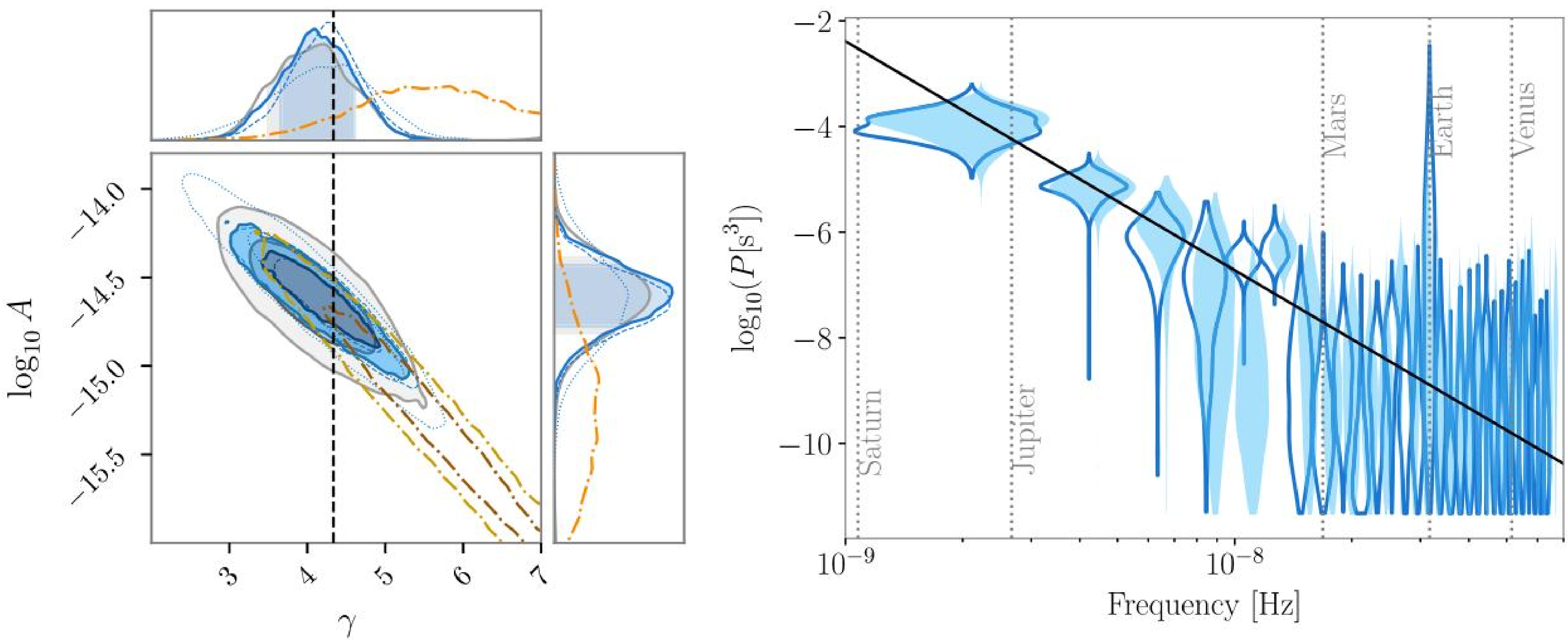


- A common power-law process was revealed by 12.5 yr NANOGrav data
- However, the HD correlation from GW is not significant

The Astrophysical Journal Letters, 917:L19 (8pp), 2021 August 20 https://doi.org/10.3847/2041-8213/ac17f4

On the Evidence for a Common-spectrum Process in the Search for the Nanohertz Gravitational-wave Background with the Parkes Pulsar Timing Array

Boris Goncharov[1,2,3], R. M. Shannon[1,2], D. J. Reardon[1,2], G. Hobbs[4], A. Zic[4,5], M. Bailes[1,2], M. Curyło[6], S. Dai[4,7],

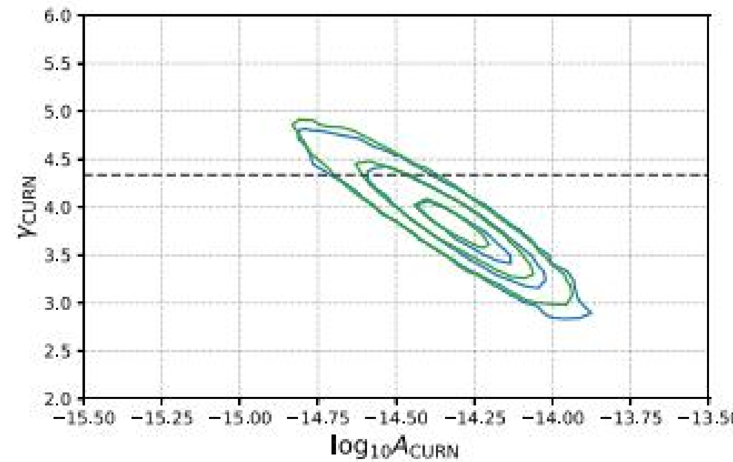


- A similar common power-law excess was shown by PPTA data
- No strong evidence to support or against the HD correlation
- Possible caveat of "common" nature: may not be truly common

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS 508, 4970–4993 (2021) https://doi.org/10.1093/mnras/stab2833

Common-red-signal analysis with 24-yr high-precision timing of the European Pulsar Timing Array: inferences in the stochastic gravitational-wave background search

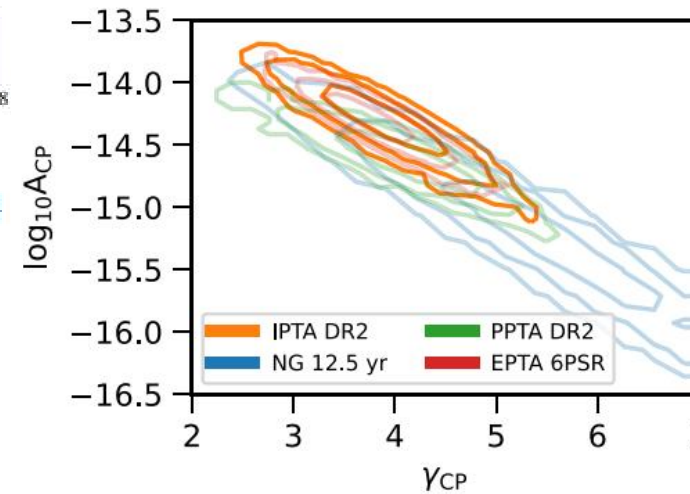
S. Chen,[1,2★] R. N. Caballero,[3★] Y. J. Guo,[4] A. Chalumeau,[1,2,5] K. Liu,[4] G. Shaifullah,[6,7] K. J. Lee,[3,4,8] S. Babak,[5,9] G. Desvignes,[4,10] A. Parthasarathy,[4] H. Hu,[4] E. van der Wateren,[11,12]



Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS 00, 1 (2021) https://doi.org/10.1093/mnras/stab3418

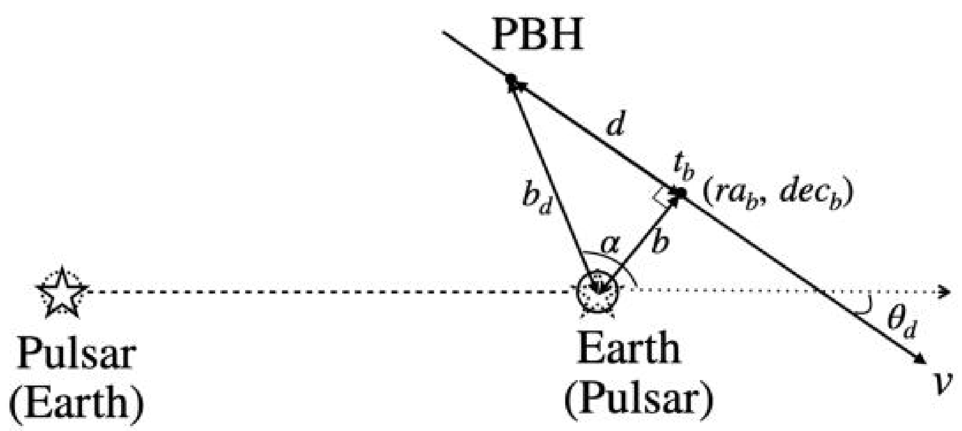
The International Pulsar Timing Array second data release: Search for an isotropic gravitational wave background

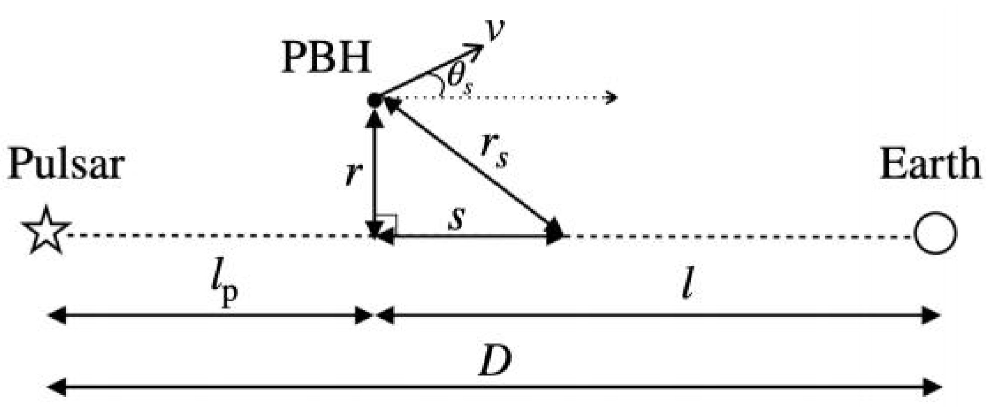
J. Antoniadis,[1,2,3] Z. Arzoumanian,[4] S. Babak,[5,6] M. Bailes,[7,8] A.-S. Bak Nielsen,[2,9] P. T. Baker,[10]



- Confirmed by EPTA and IPTA analyses
- Again, NO strong evidence to support or against HD correlation

利用PTA探测PBH



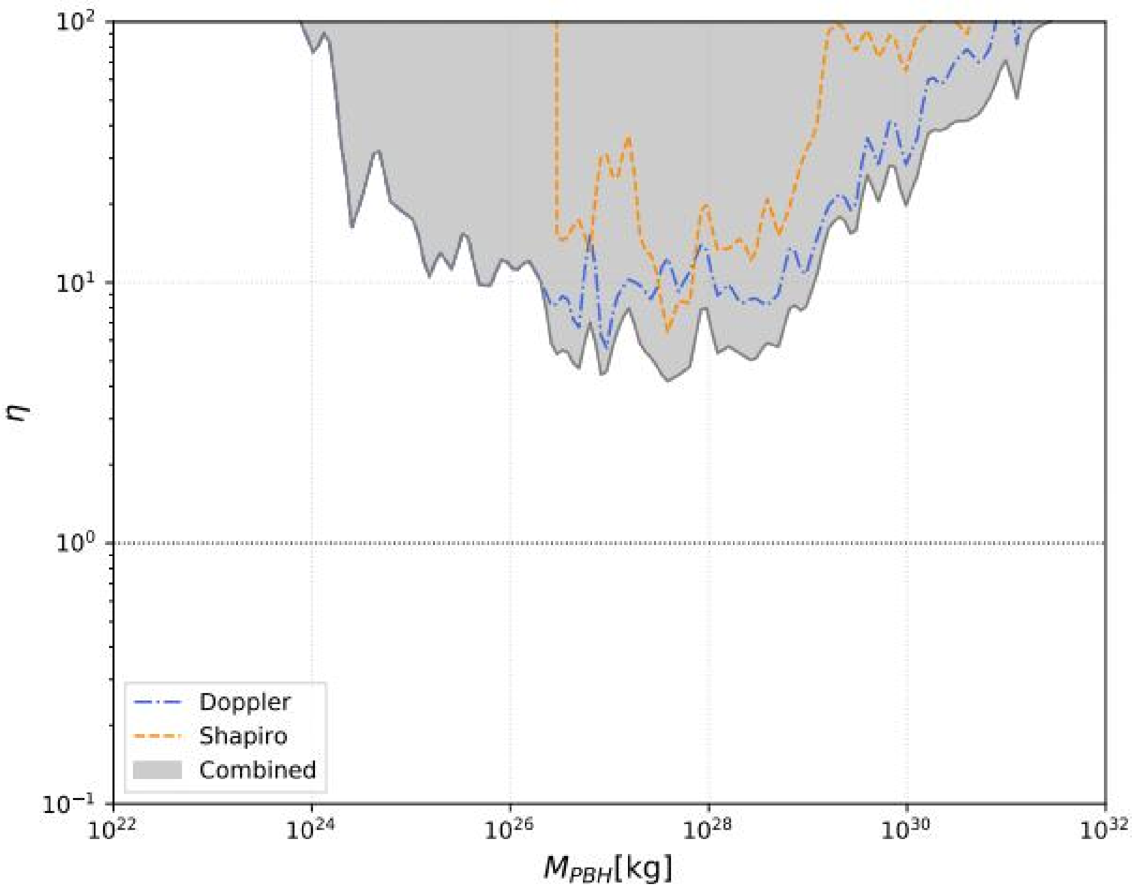


- Doppler效应：PBH经过地球或脉冲星附近时拖拽地球或脉冲星运动

- Shapiro效应：PBH经过脉冲星-地球连线时引力场产生的Shapiro时延

利用PTA探测PBH

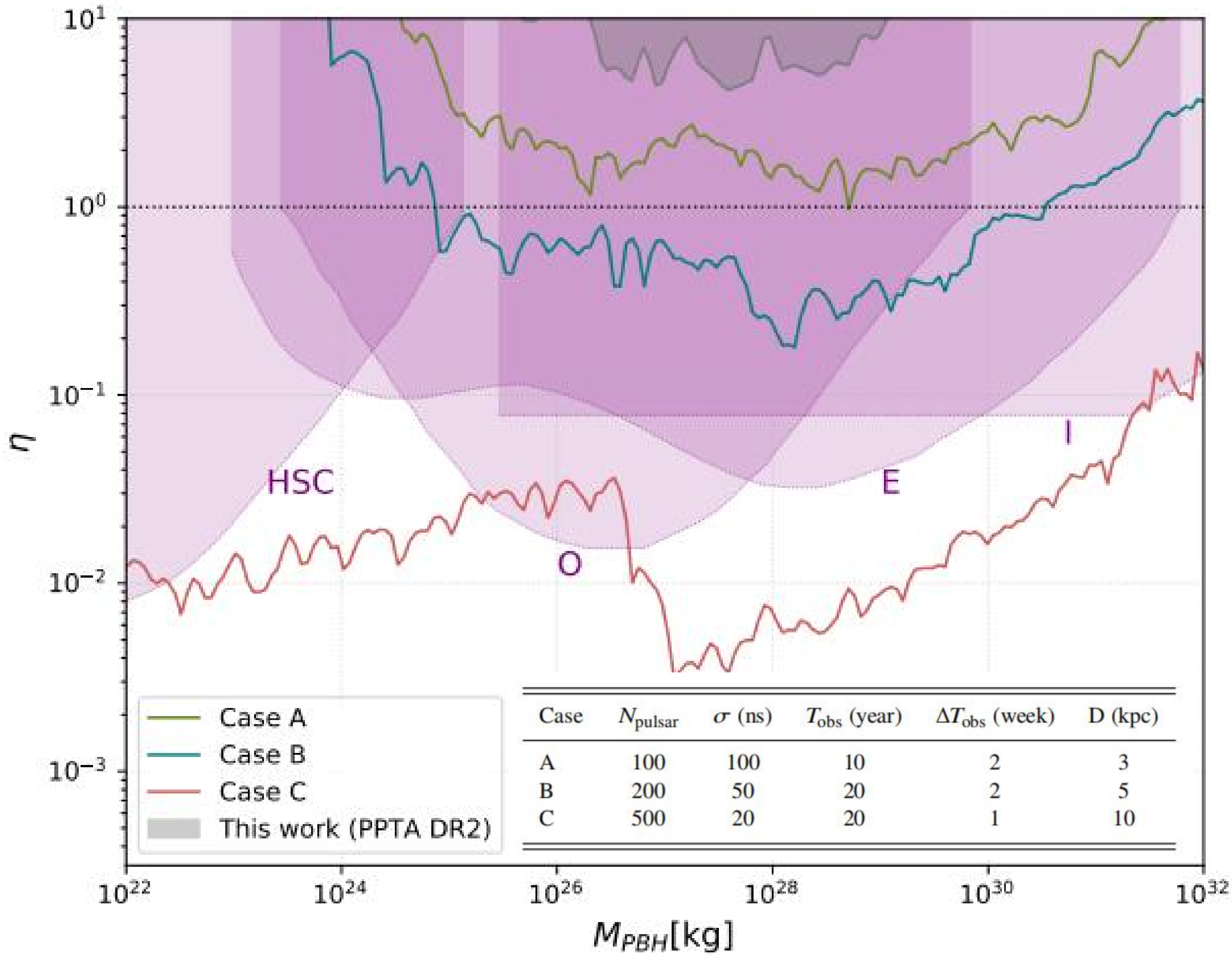
Pulsars	N_{obs}	T(years)	$\overline{\sigma}\times10^{-6}(s)$	$\log_{10}A_{SN}$	γ_{SN}	$\log_{10}A_{DM}$	γ_{DM}
J0437-4715	29262	15.03	0.296	$-15.76^{+0.17}_{-0.18}$	$6.63^{+0.17}_{-0.13}$	$-13.05^{+0.10}_{-0.08}$	$2.26^{+0.32}_{-0.44}$
J0613-0200	5920	14.20	2.504	$-14.63^{+0.77}_{-0.68}$	$4.93^{+1.33}_{-1.61}$	$-13.02^{+0.08}_{-0.08}$	$0.95^{+0.33}_{-0.31}$
J0711-6830	5547	14.21	6.197	$-12.85^{+0.14}_{-0.16}$	$0.97^{+0.64}_{-0.55}$	$-14.54^{+0.72}_{-0.89}$	$4.43^{+1.68}_{-1.72}$
J1017-7156	4053	7.77	1.577	$-12.89^{+0.07}_{-0.07}$	$0.54^{+0.53}_{-0.37}$	$-12.72^{+0.06}_{-0.06}$	$2.18^{+0.45}_{-0.44}$
J1022+1001	7656	14.20	5.514	$-12.79^{+0.12}_{-0.13}$	$0.54^{+0.55}_{-0.37}$	$-13.04^{+0.10}_{-0.12}$	$0.58^{+0.47}_{-0.36}$
J1024-0719	2643	14.09	4.361	$-14.28^{+0.27}_{-0.20}$	$6.51^{+0.35}_{-0.60}$	$-14.53^{+0.54}_{-0.56}$	$5.22^{+1.14}_{-1.18}$
J1045-4509	5611	14.15	9.186	$-12.75^{+0.24}_{-0.40}$	$1.58^{+1.28}_{-0.93}$	$-12.18^{+0.09}_{-0.08}$	$1.86^{+0.36}_{-0.32}$
J1125-6014	1407	12.34	1.981	$-12.64^{+0.11}_{-0.12}$	$0.51^{+0.55}_{-0.37}$	$-13.14^{+0.19}_{-0.21}$	$3.36^{+0.73}_{-0.66}$
J1446-4701	508	7.36	2.200	$-16.46^{+2.88}_{-3.17}$	$2.74^{+2.49}_{-1.89}$	$-13.49^{+0.32}_{-1.87}$	$2.48^{+1.92}_{-1.45}$
J1545-4550	1634	6.97	2.249	$-17.33^{+2.50}_{-2.55}$	$3.25^{+2.45}_{-2.18}$	$-13.40^{+0.24}_{-0.38}$	$3.90^{+1.61}_{-1.09}$
J1600-3053	7047	14.21	2.216	$-17.63^{+2.10}_{-2.29}$	$3.28^{+2.34}_{-2.15}$	$-13.27^{+0.12}_{-0.13}$	$2.79^{+0.43}_{-0.40}$
J1603-7202	5347	14.21	4.947	$-12.82^{+0.14}_{-0.16}$	$1.01^{+0.67}_{-0.60}$	$-12.66^{+0.10}_{-0.09}$	$1.44^{+0.40}_{-0.38}$
J1643-1224	5941	14.21	4.039	$-12.32^{+0.08}_{-0.09}$	$0.51^{+0.42}_{-0.34}$	$-12.27^{+0.07}_{-0.07}$	$0.55^{+0.32}_{-0.29}$
J1713+0747	7804	14.21	1.601	$-14.09^{+0.25}_{-0.38}$	$2.98^{+1.00}_{-0.64}$	$-13.35^{+0.08}_{-0.08}$	$0.53^{+0.32}_{-0.31}$
J1730-2304	4549	14.21	5.657	$-17.39^{+2.39}_{-2.51}$	$3.05^{+2.59}_{-2.12}$	$-14.11^{+0.40}_{-0.57}$	$4.22^{+1.42}_{-1.04}$
J1732-5049	807	7.23	7.031	$-16.51^{+3.04}_{-2.97}$	$3.29^{+2.37}_{-2.97}$	$-13.38^{+0.54}_{-0.84}$	$4.07^{+1.96}_{-1.93}$
J1744-1134	6717	14.21	2.251	$-13.39^{+0.14}_{-0.15}$	$1.49^{+0.66}_{-0.57}$	$-13.35^{+0.09}_{-0.09}$	$0.86^{+0.40}_{-0.33}$
J1824-2452A	2626	13.80	2.190	$-12.56^{+0.13}_{-0.12}$	$3.61^{+0.41}_{-0.39}$	$-12.18^{+0.11}_{-0.10}$	$1.64^{+0.46}_{-0.59}$
J1832-0836	326	5.40	1.430	$-16.47^{+2.63}_{-3.09}$	$3.66^{+2.33}_{-2.52}$	$-13.07^{+0.24}_{-0.63}$	$3.77^{+2.00}_{-1.05}$
J1857+0943	3840	14.21	5.564	$-14.76^{+0.74}_{-0.50}$	$5.75^{+0.91}_{-1.53}$	$-13.40^{+0.20}_{-0.25}$	$2.66^{+0.83}_{-0.67}$
J1909-3744	14627	14.21	0.672	$-13.60^{+0.13}_{-0.12}$	$1.60^{+0.43}_{-0.46}$	$-13.48^{+0.09}_{-0.08}$	$0.69^{+0.38}_{-0.35}$
J1939+2134	4941	14.09	0.468	$-14.38^{+0.22}_{-0.18}$	$6.24^{+0.49}_{-0.62}$	$-11.59^{+0.07}_{-0.07}$	$0.13^{+0.19}_{-0.10}$
J2124-3358	4941	14.21	8.863	$-14.79^{+0.82}_{-0.67}$	$5.07^{+1.37}_{-1.97}$	$-13.35^{+0.18}_{-0.33}$	$0.95^{+1.11}_{-0.66}$
J2129-5721	2879	13.88	3.496	$-15.48^{+1.92}_{-3.54}$	$2.91^{+2.29}_{-1.83}$	$-13.31^{+0.13}_{-0.14}$	$1.07^{+0.65}_{-0.65}$
J2145-0750	6867	14.09	5.086	$-12.82^{+0.10}_{-0.11}$	$0.62^{+0.50}_{-0.40}$	$-13.33^{+0.14}_{-0.16}$	$1.38^{+0.54}_{-0.55}$
J2241-5236	5224	8.20	0.830	$-13.40^{+0.09}_{-0.08}$	$0.44^{+0.40}_{-0.30}$	$-13.79^{+0.10}_{-0.10}$	$1.42^{+0.61}_{-0.59}$



Xia et al., with PPTA collaboration, preliminary

PPTA对PBH占暗物质的比例限制(>1)

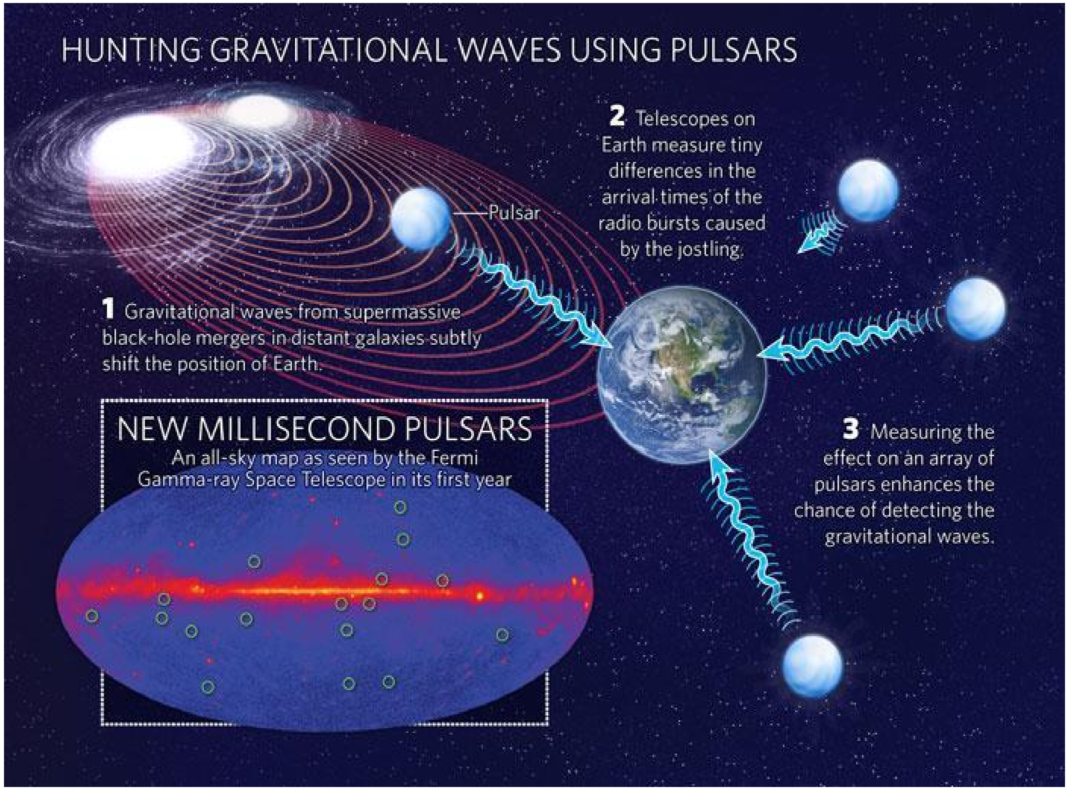
利用PTA探测PBH



Case	$N_{\rm pulsar}$	σ (ns)	$T_{\rm obs}$ (year)	$\Delta T_{\rm obs}$ (week)	D (kpc)
A	100	100	10	2	3
B	200	50	20	2	5
C	500	20	20	1	10

未来SKA将可以非常有效地搜寻PBH

伽马射线PTA

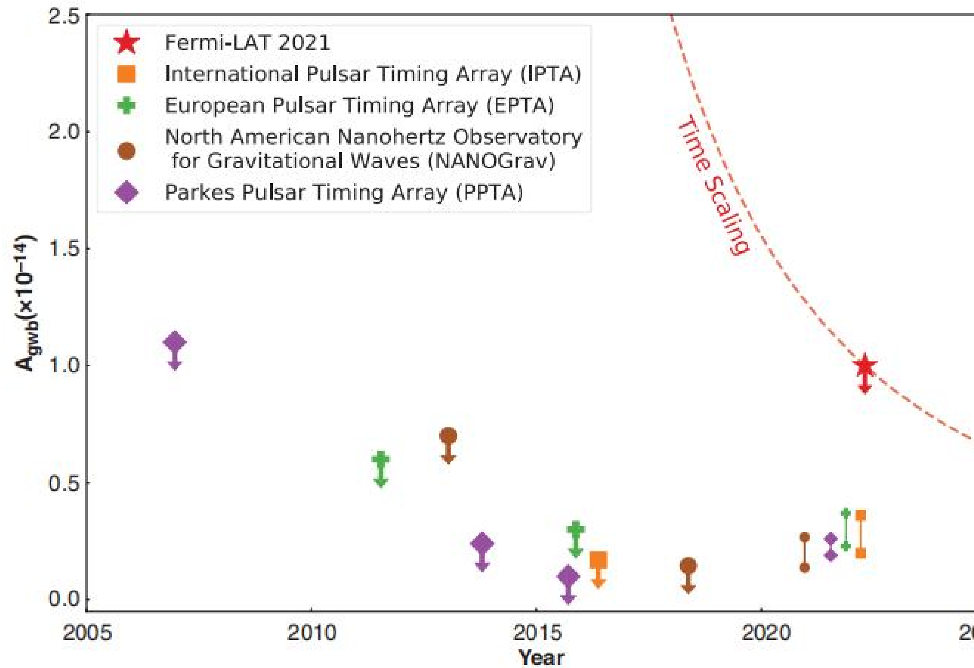


GRAVITATIONAL WAVES

A gamma-ray pulsar timing array constrains the nanohertz gravitational wave background

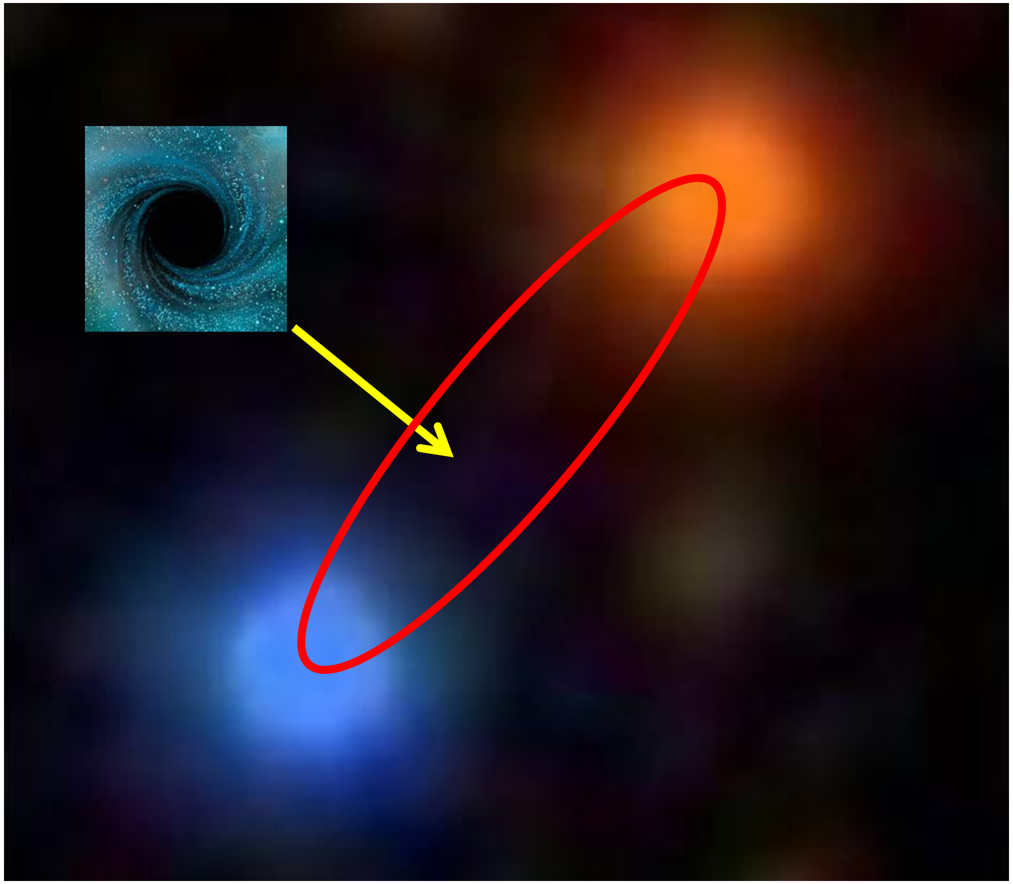
The Fermi-LAT Collaboration*†

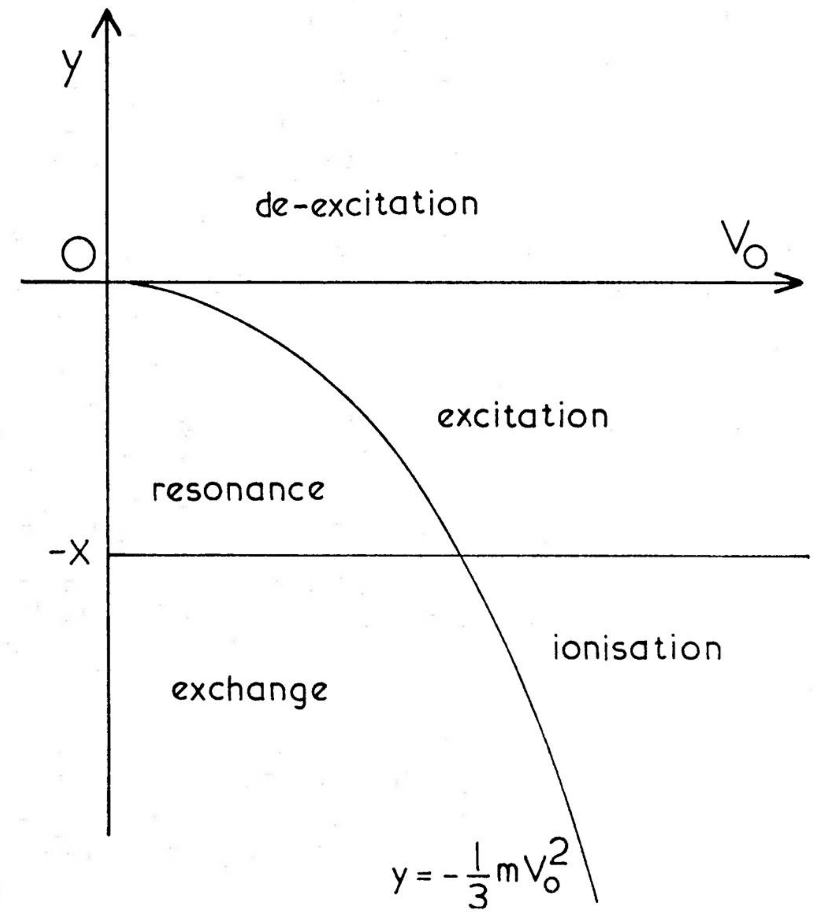
After large galaxies merge, their central supermassive black holes are expected to form binary systems. Their orbital motion should generate a gravitational wave background (GWB) at nanohertz frequencies. Searches for this background use pulsar timing arrays, which perform long-term monitoring of millisecond pulsars at radio wavelengths. We used 12.5 years of Fermi Large Area Telescope data to form a gamma-ray pulsar timing array. Results from 35 bright gamma-ray pulsars place a 95% credible limit on the GWB characteristic strain of 1.0×10^{-14} at a frequency of 1 year^{-1}. The sensitivity



- 伽马射线PTA噪声模型比射电PTA更加简单，可以独立检验射电PTA结果
- Fermi-LAT 12.5年结果比和射电PTA相比，灵敏度差大约5倍

银河系宽距双星探测PBH

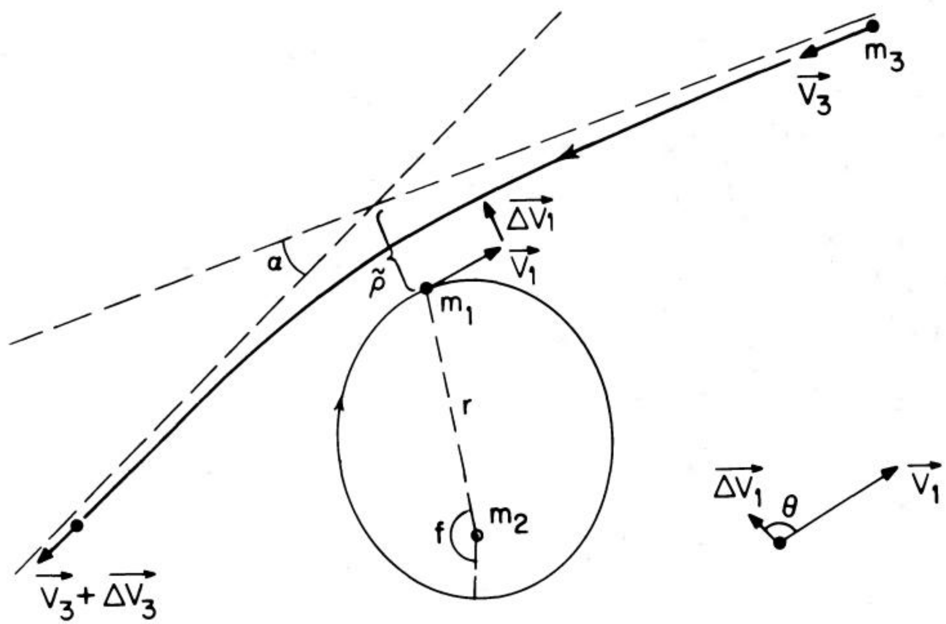




PBH穿过宽距双星间时可能会
对双星轨道产生破坏

V_0: PBH和双星的相对速度
y: 双星束缚能改变量

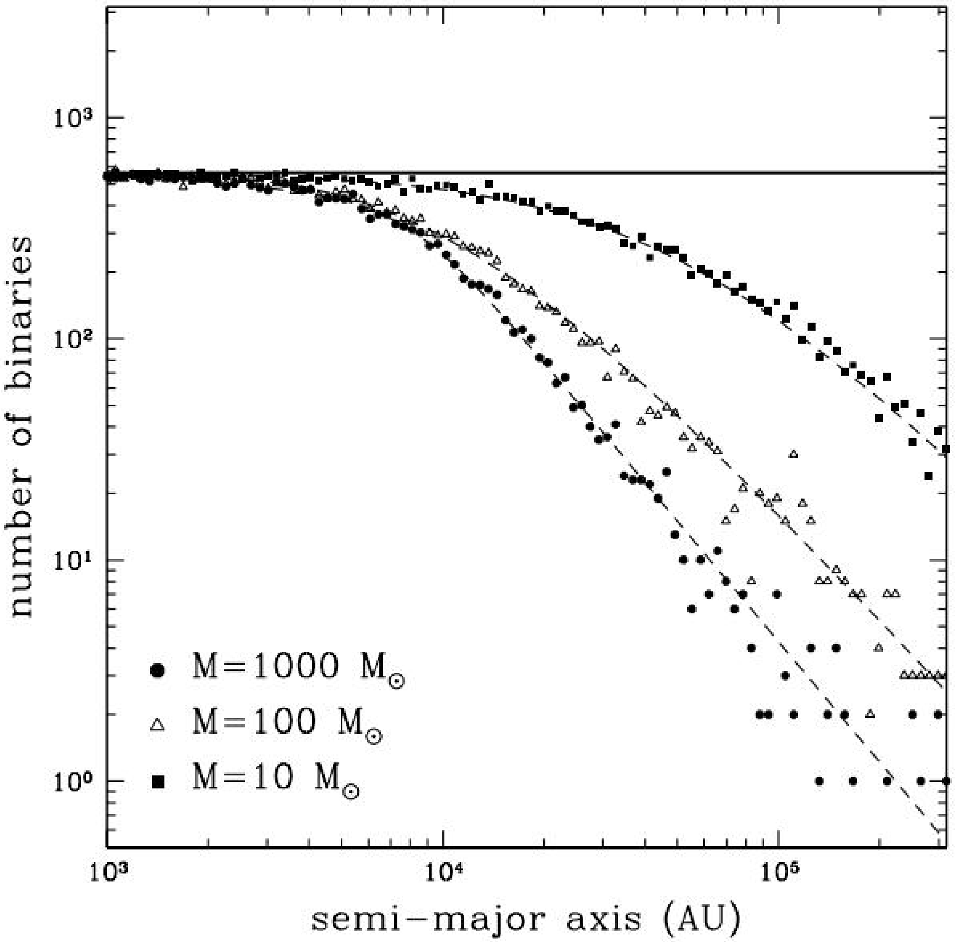
银河系宽距双星探测PBH

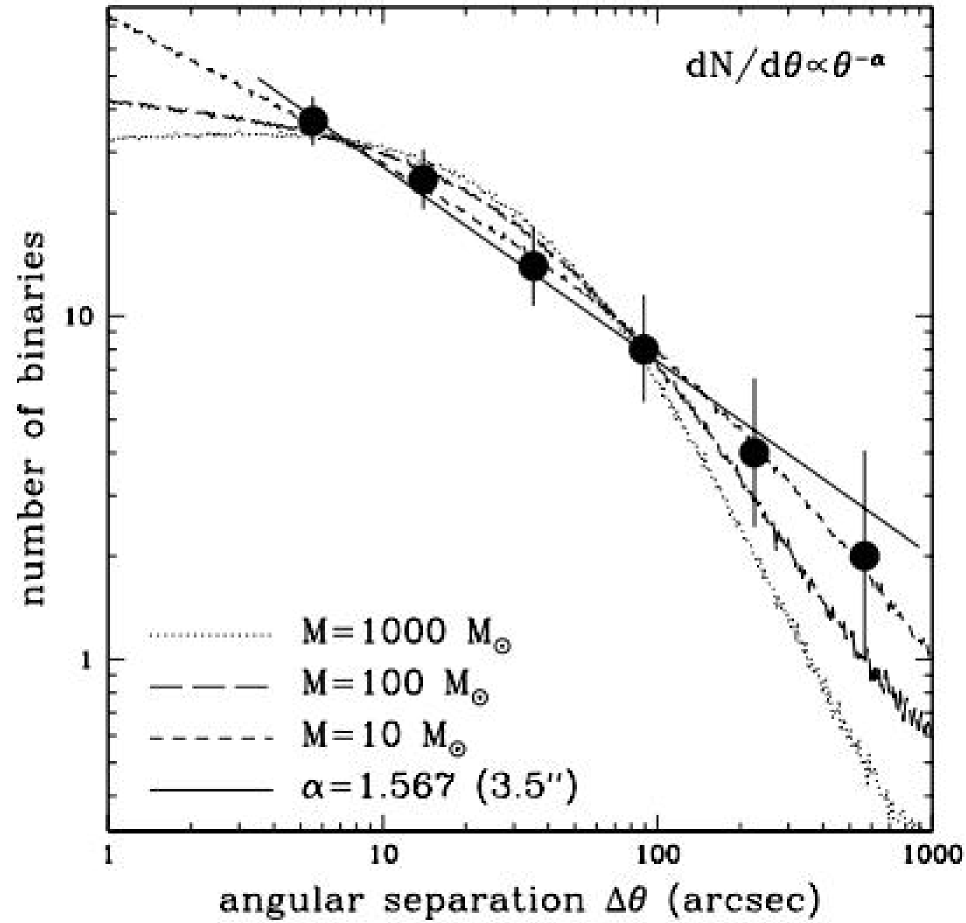


- 冲击模式：PBH非常接近双星中的一个，能量交换明显，双星受严重影响
- 潮汐模式：碰撞参量b大于双星半长轴，轨道受到PBH潮汐力影响

银河系宽距双星探测PBH

Yoo et al., 2004, ApJ, 601, 311

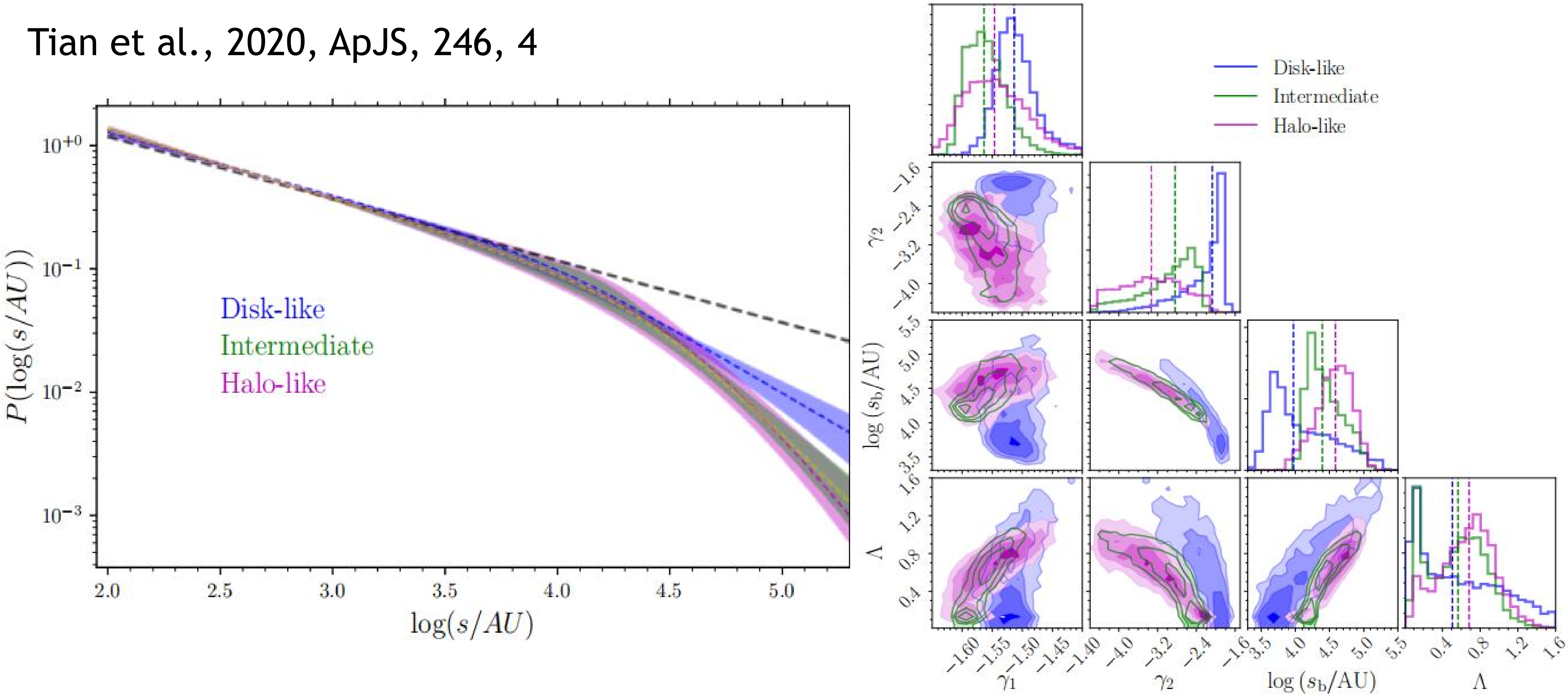




通过双星的轨道分布可以限制PBH的相关物理参数

银河系宽距双星探测PBH

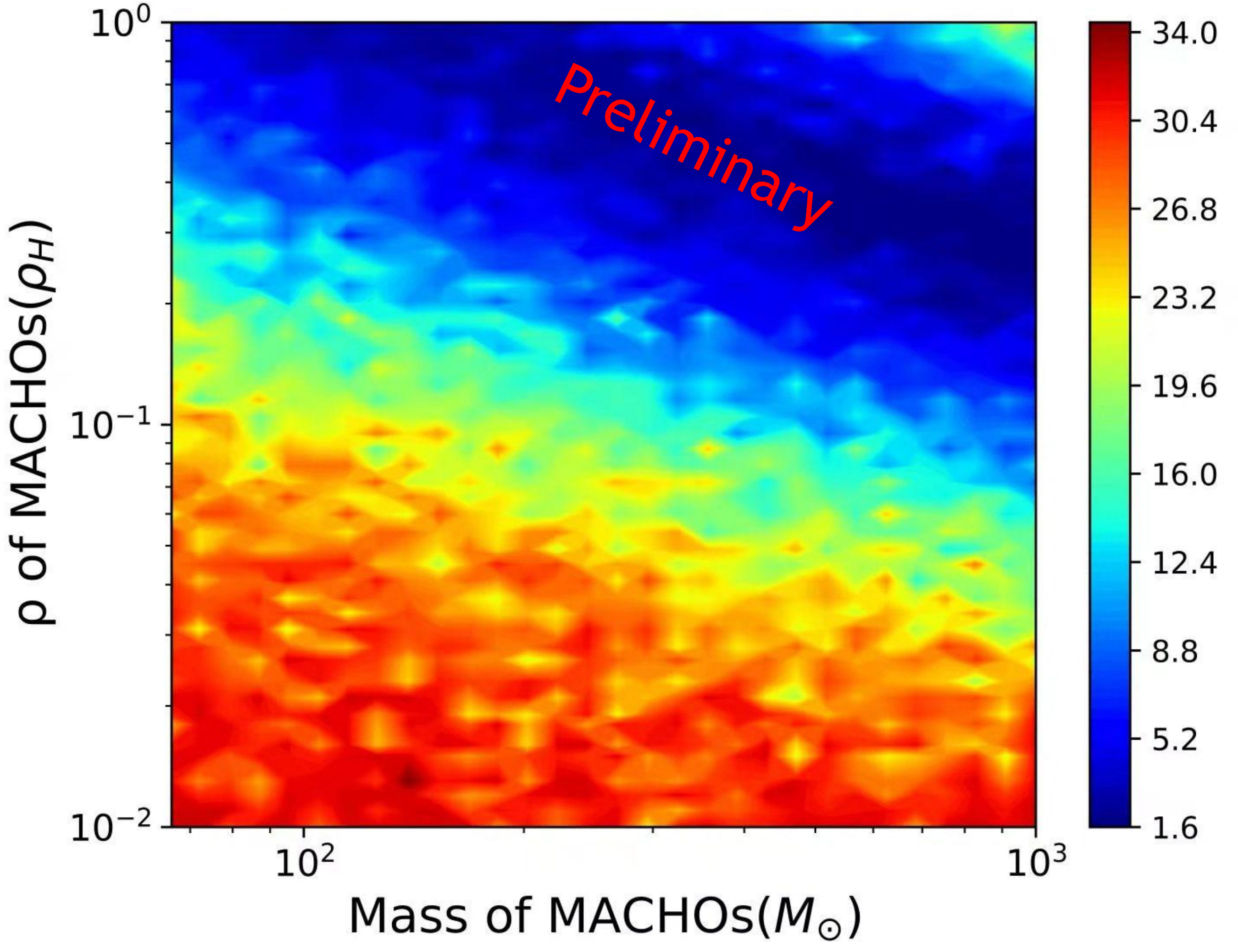
Tian et al., 2020, ApJS, 246, 4



Gaia对银河系宽距双星的观测结果明确揭示存在拐折的现象

银河系宽距双星探测PBH

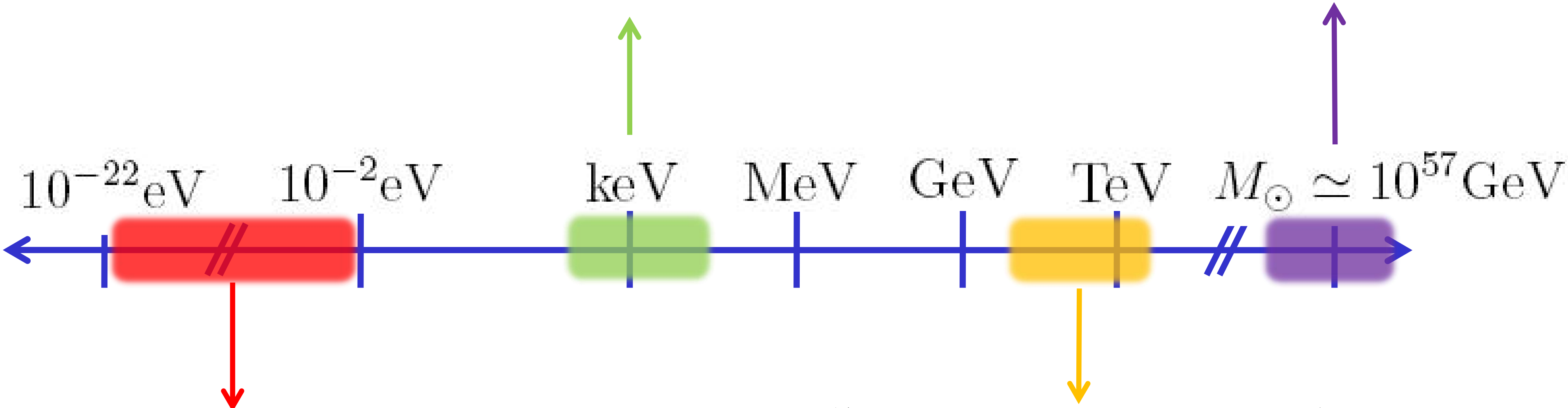
Sun et al., in prep.



理论学家眼中的暗物质

惰性中微子：
中微子震荡、
X射线天文

黑洞(MACHOs):
引力透镜、引力波

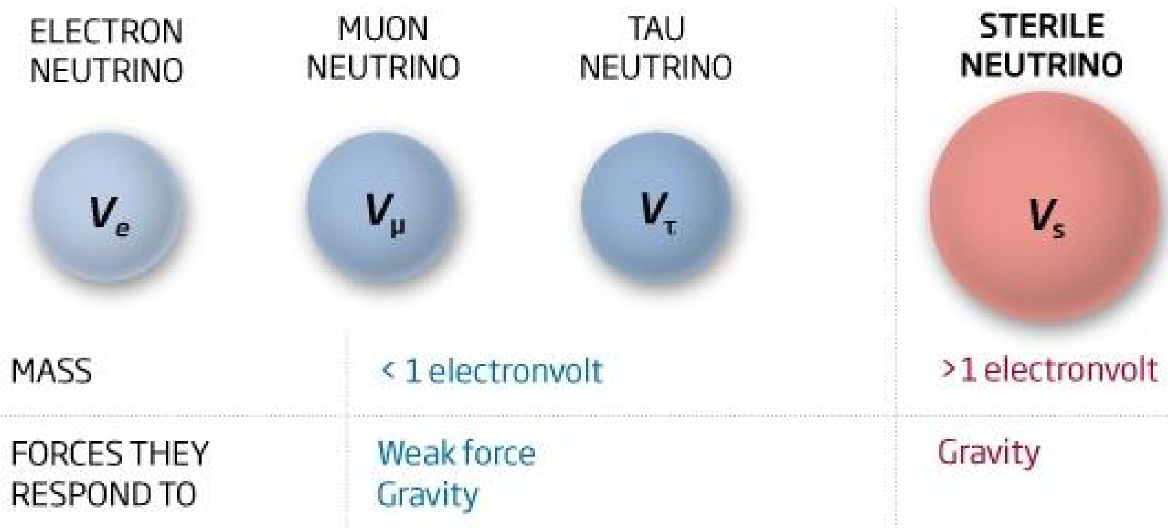


超轻暗物质（轴子、类轴子
粒子、暗光子...）:
共振腔实验、射电天文

弱作用重粒子(WIMPs): 直接
探测、间接探测、对撞机探测
(见殷鹏飞、蔡岳霖、王雯宇
等老师的讲座)

暗物质的实验探测极具挑战性，天文观测在多种形式暗物质
候选体探测中起着非常重要的作用

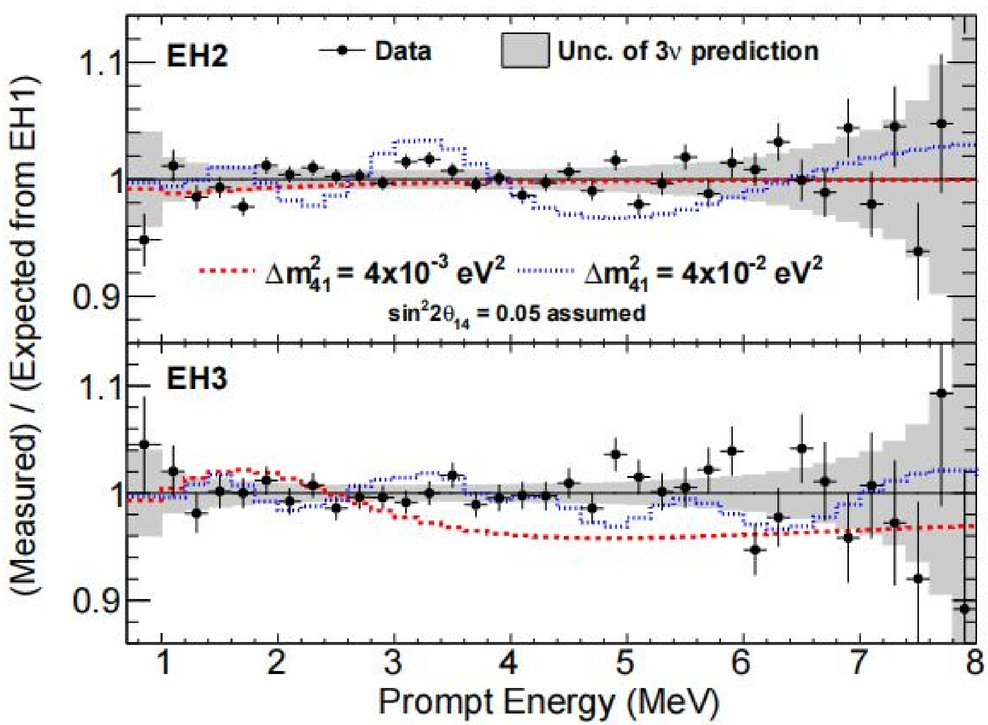
惰性中微子

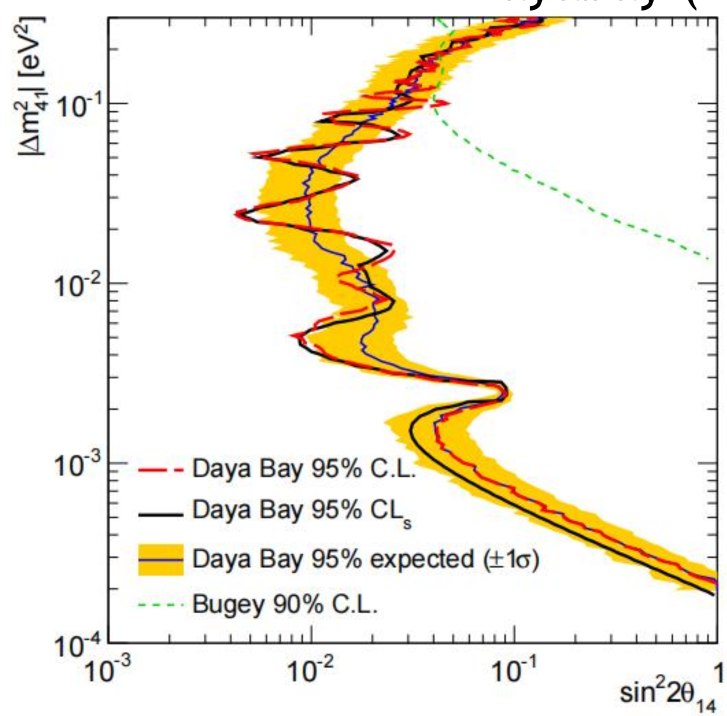


$$\nu_\alpha = \sum_{i=1}^{4} U_{\alpha i}\nu_i$$

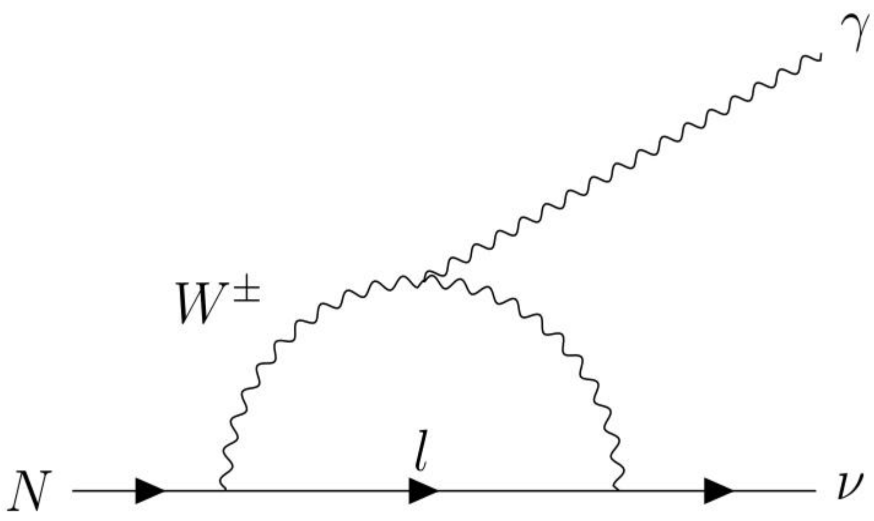
$$P_{\nu_\alpha \to \nu_\alpha} = 1 - 4\sum_{i=1}^{3}\sum_{j>i}^{4} |U_{\alpha i}|^2 |U_{\alpha j}|^2 \sin^2 \Delta_{ji}$$

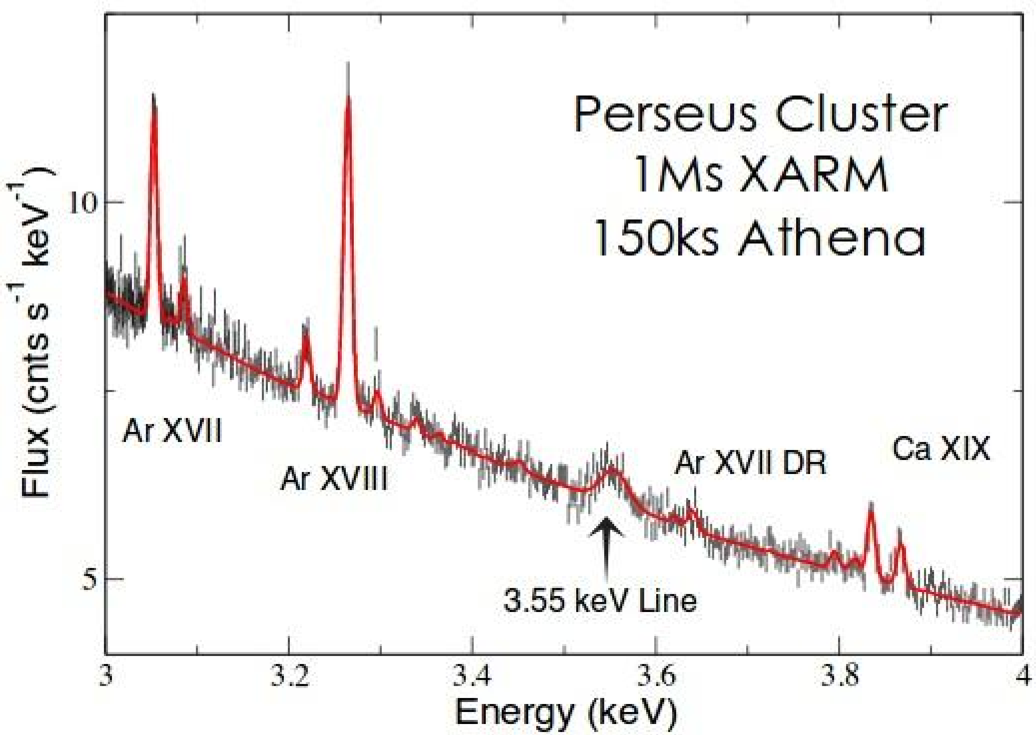
Dayabay (2016)





3.55 keV线谱？





- 惰性中微子可能衰变产生常规中微子和光子，由于常规中微子质量接近为零，光子具有近似单一能量
- 2014年，Bulbul et al.和Boyarsky et al.两个小组报道了从星系团和M31的X射线观测中存在3.55 keV的反常发射线

3.55 keV线谱：原子能级跃迁？

Discovery of a 3.5 keV line in the Galactic Center and a Critical Look at the Origin of the Line Across Astronomical Targets

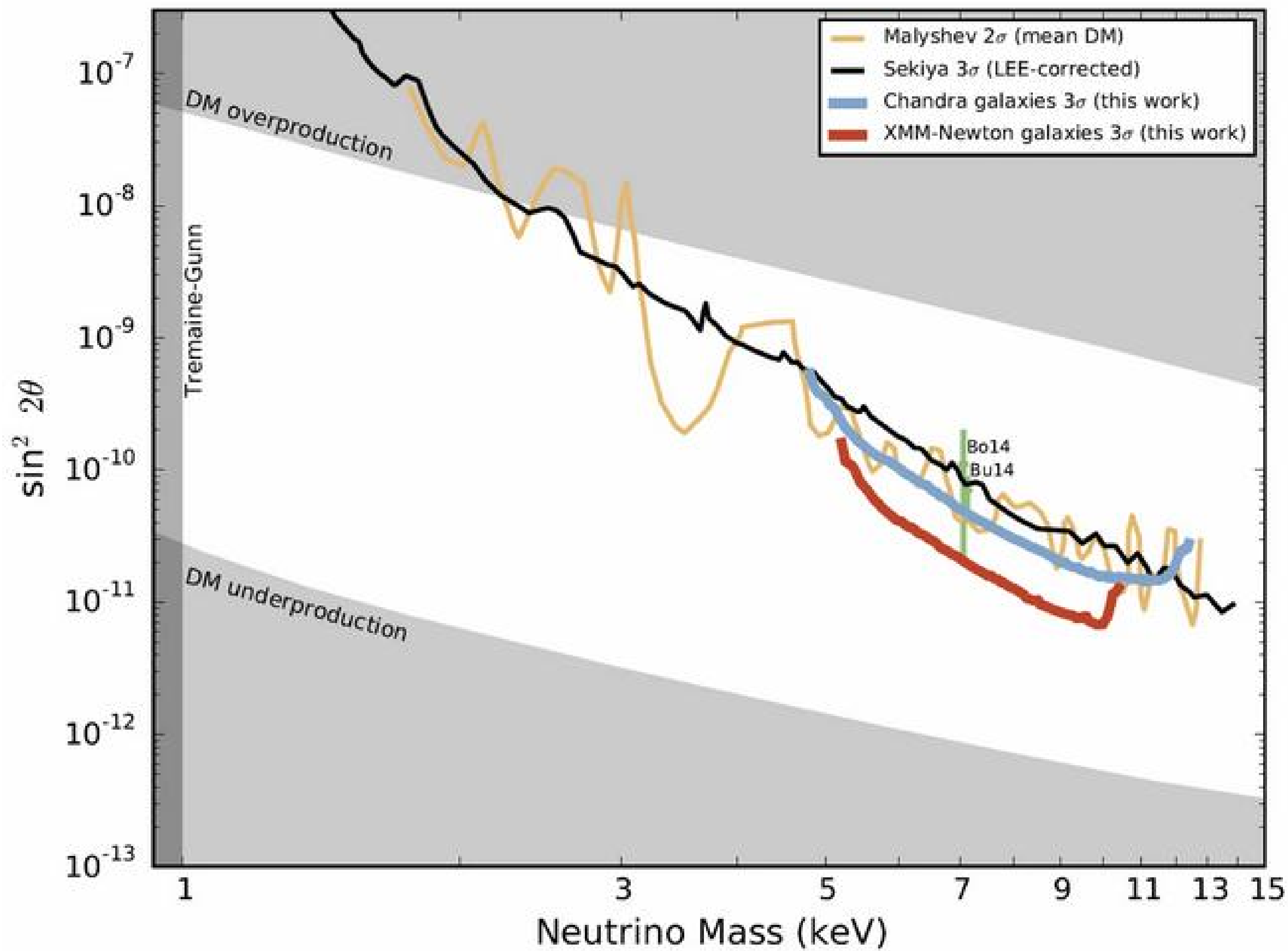
arXiv:1408.1699

Tesla Jeltema[1*] and Stefano Profumo[1†]
[1]Department of Physics and Santa Cruz Institute for Particle Physics University of California, Santa Cruz, CA 95064, USA

ABSTRACT
We examine the claimed excess X-ray line emission near 3.5 keV including both a new analysis of *XMM-Newton* observations of the Milky Way center and a reanalysis of the data on M 31 and clusters. In no case do we find conclusive evidence for an excess. In the case of the Galactic center we show that known plasma lines, including in particular K XVIII lines at 3.48 and 3.52 keV, provide a satisfactory fit to the *XMM* data. We estimate the expected flux of the K XVIII lines and find that the measured line flux falls squarely within the predicted range based on the brightness of other well-measured lines in the energy range of interest and on detailed multi-temperature plasma models. We then re-assess the evidence for excess emission from clusters of galaxies, allowing for systematic uncertainty in the expected flux from known plasma lines and additional uncertainty due to potential variation in the abundances of different elements. We find that no conclusive excess line emission can be advocated when considering systematic uncertainties in Perseus or in other clusters. We also re-analyze the *XMM* data for M 31 and find no statistically significant line emission near 3.5 keV to a level greater than one sigma. Finally, we analyze the Tycho supernova remnant, which shows similar plasma features to the sources above, but does not host any significant dark matter. We detect a 3.55 keV line from Tycho, which points to possible systematic effects in the flux determination of weak lines, or to relative elemental abundances vastly different from theoretical expectations.

Line	Energy keV	MOS Flux photons cm^{-2} s^{-1}	PN Flux photons cm^{-2} s^{-1}
S XV	2.45	$3.1 \pm 0.2 \times 10^{-3}$	$2.55 \pm 0.04 \times 10^{-3}$
S XVI	2.62	$4.8 \pm 0.3 \times 10^{-4}$	$2.9 \pm 0.1 \times 10^{-4}$
Ar XVII	3.13	$6.1 \pm 0.1 \times 10^{-4}$	$5.74 \pm 0.07 \times 10^{-4}$
Ar XVIII	3.32	$1.16 \pm 0.05 \times 10^{-4}$	$6.5 \pm 1.0 \times 10^{-5}$
Ca XIX	3.90	$2.55 \pm 0.03 \times 10^{-4}$	$2.4 \pm 0.1 \times 10^{-4}$
Ca XX	4.1	$4.1 \pm 0.3 \times 10^{-5}$	$4.2 \pm 0.4 \times 10^{-5}$
K XVIII (?)	3.5	$4.5 \pm 0.4 \times 10^{-5}$	$3.9 \pm 0.7 \times 10^{-5}$

3.55 keV线谱：其它星系观测



该结果和Chandra/XMM-Newton对其它星系观测结果存在一定的矛盾

Anderson et al., 2015, MNRAS, 452, 3905

3.55 keV线谱：争论再起？

The dark matter interpretation of the 3.5-keV line is inconsistent with blank-sky observations

Christopher Dessert, Nicholas L. Rodd, Benjamin R. Safdi

Observations of nearby galaxies and galaxy clusters have reported an unexpected X-ray emission line around 3.5 kilo-electron volts (keV). Proposals to explain this line include decaying dark matter—in particular, that the decay of sterile neutrinos with a mass around 7 keV could match the available data. If this interpretation is correct, the 3.5 keV line should also be emitted by dark matter in the halo of the Milky Way. We used more than 30 megaseconds of XMM-Newton (X-ray Multi-Mirror Mission) blank-sky observations to test this hypothesis, finding no evidence of the 3.5-keV line emission from the Milky Way halo. We set an upper limit on the decay rate of dark matter in this mass range, which is inconsistent with the possibility that the 3.5-keV line originates from dark matter decay.

Technical Comment on "The dark matter interpretation of the 3.5-keV line is inconsistent with blank-sky observations"

Kevork N. Abazajian

I show that model dependencies in the analysis by Dessert, Rodd & Safdi (2020) relax their claimed constraint by a factor of ~20. After including conservative model choices, the derived limits are comparable to or slightly better than limits from previous searches. Further model tests and expansion of the data energy may enhance or relax sensitivity of the methodology.

Technical comment on the paper of Dessert et al. "The dark matter interpretation of the 3.5 keV line is inconsistent with blank-sky observations"

Alexey Boyarsky, Denys Malyshev, Oleg Ruchayskiy, Denys Savchenko

An unidentified line at energy around 3.5 keV was detected in the spectra of dark matter-dominated objects. Recent work of Dessert et al. [1812.06976] used 30 Msec of XMM-Newton blank-sky observations to constrain the admissible line flux, challenging its dark matter decay origin. We demonstrate that these bounds are overestimated by more than an order of magnitude due to improper background modeling. Therefore the dark matter interpretation of the 3.5 keV signal remains viable.

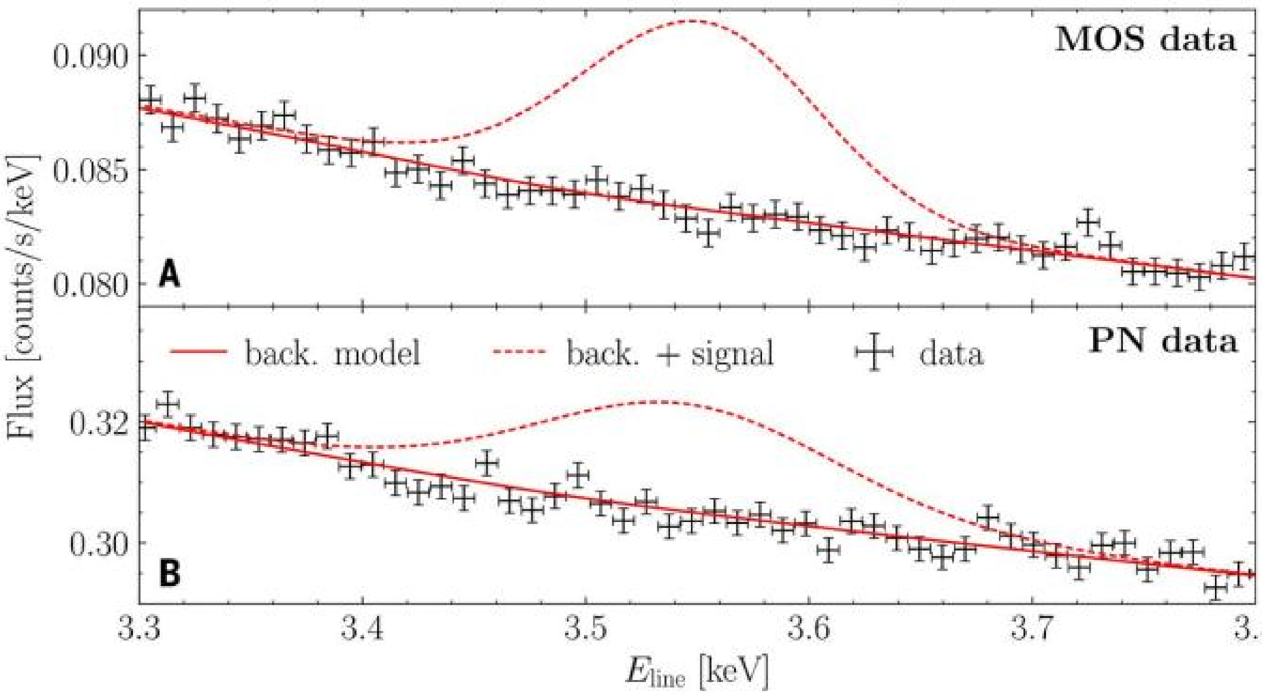
3.55 keV线谱?

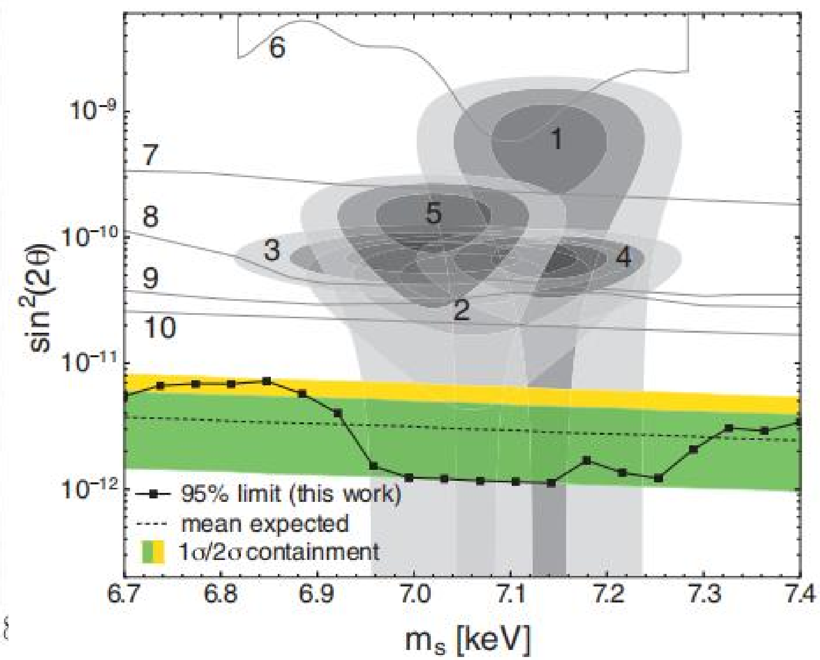
ASTROPARTICLE PHYSICS

The dark matter interpretation of the 3.5-keV line is inconsistent with blank-sky observations

Christopher Dessert[1], Nicholas L. Rodd[2,3], Benjamin R. Safdi[1]*

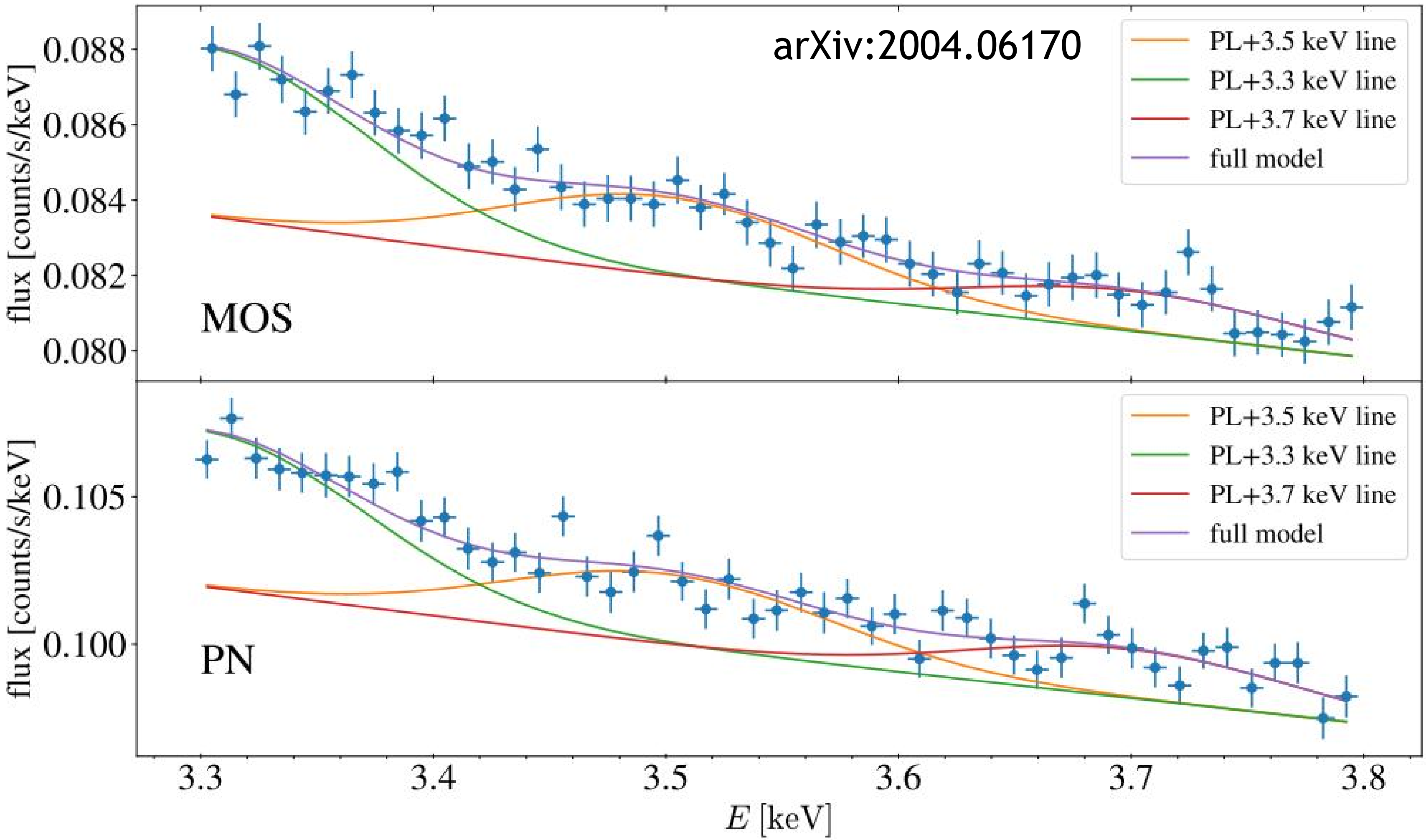
Observations of nearby galaxies and galaxy clusters have reported an unexpected x-ray emission line around 3.5 kilo–electron volts (keV). Proposals to explain this line include decaying dark matter —in particular, that the decay of sterile neutrinos with a mass around 7 keV could match the available data. If this interpretation is correct, the 3.5-keV line should also be emitted by dark matter





使用30 Ms XMM-Newton观测结果发现不存在3.5 keV的线谱辐射

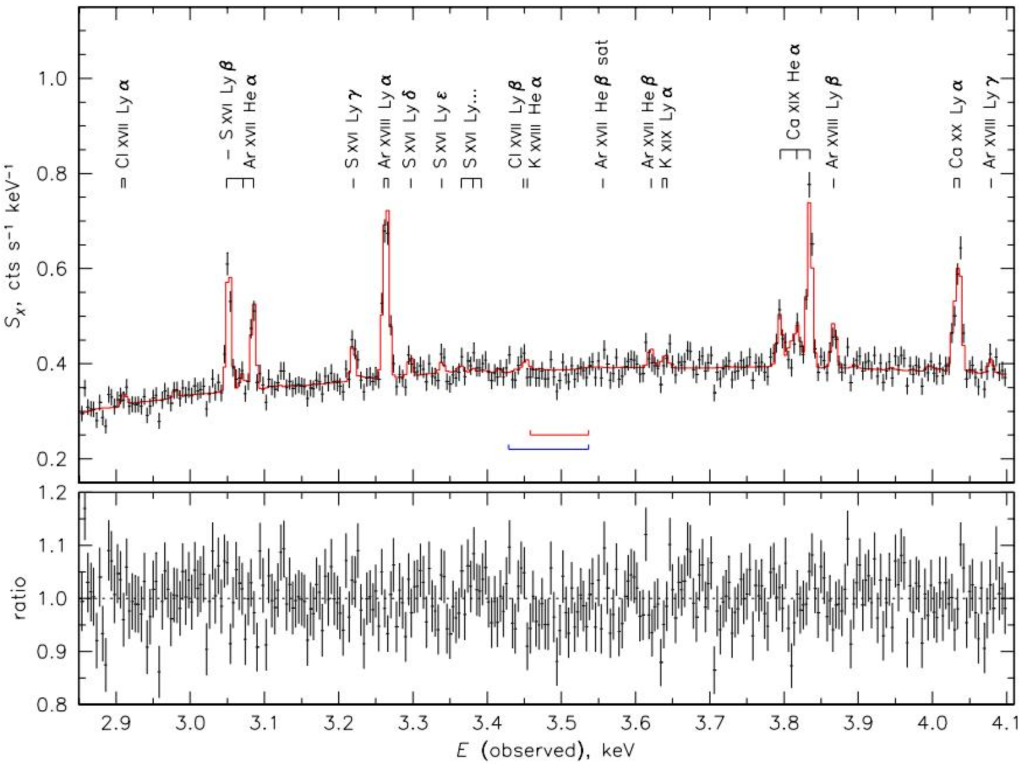
3.55 keV线谱?



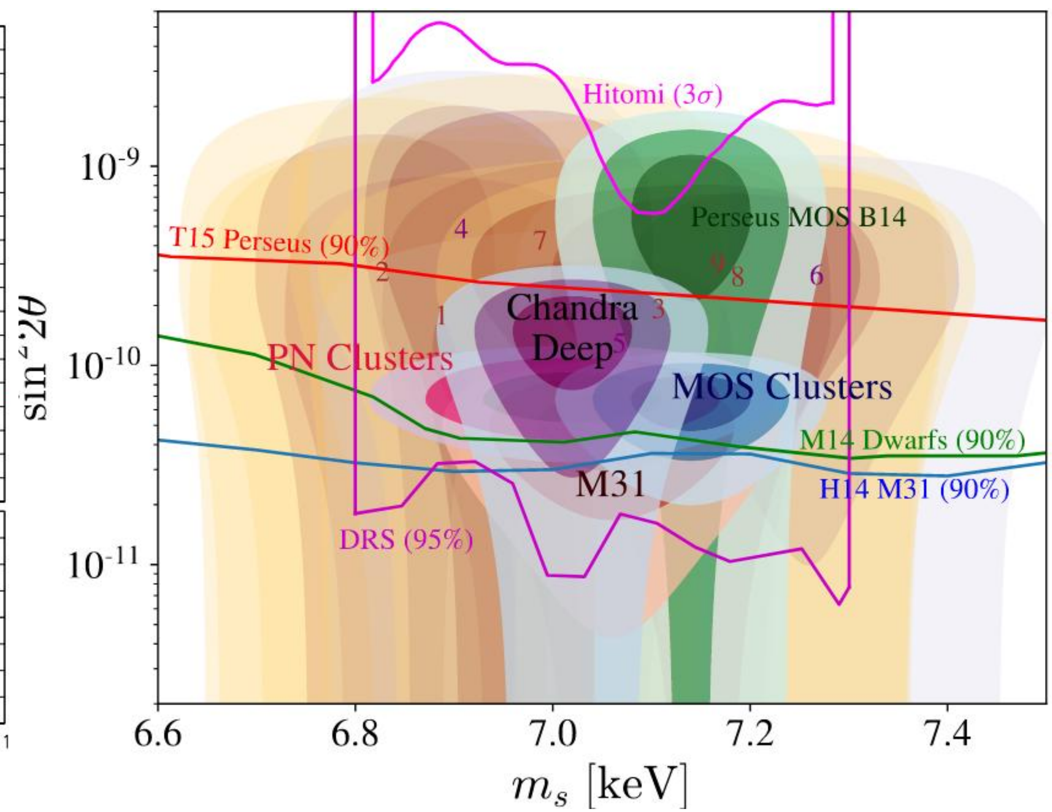
- Dessert et al. (2020)的处理中忽略了3.3 keV和3.7 keV处的两条线，加上这两条线的话结果会显著地改变
- 3.5 keV线谱相关的争论仍在持续，需要更高分辨率的观测设备和更加仔细的背景模型处理

Hitomi (瞳)

arXiv:1607.07420



arXiv:2004.06170



Hitomi对Persus极高能量分辨观测未发现线谱存在的证据，其结果不足以排除Chandra/XMM-Newton等观测结果