天文探测暗物质粒子

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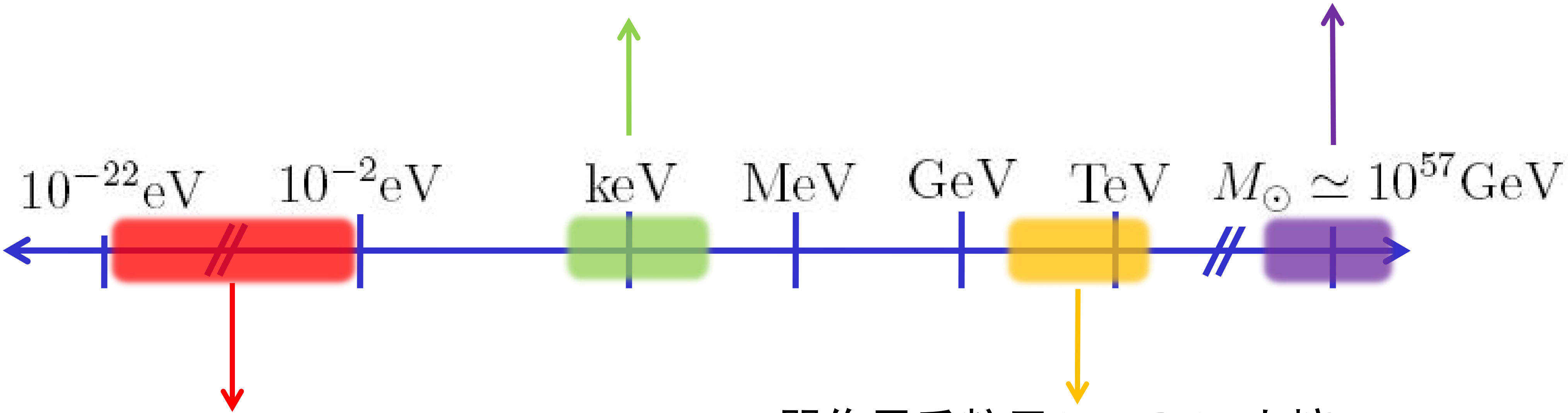
2022年理论物理前沿讲习班：暗物质与新物理暑期学校

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

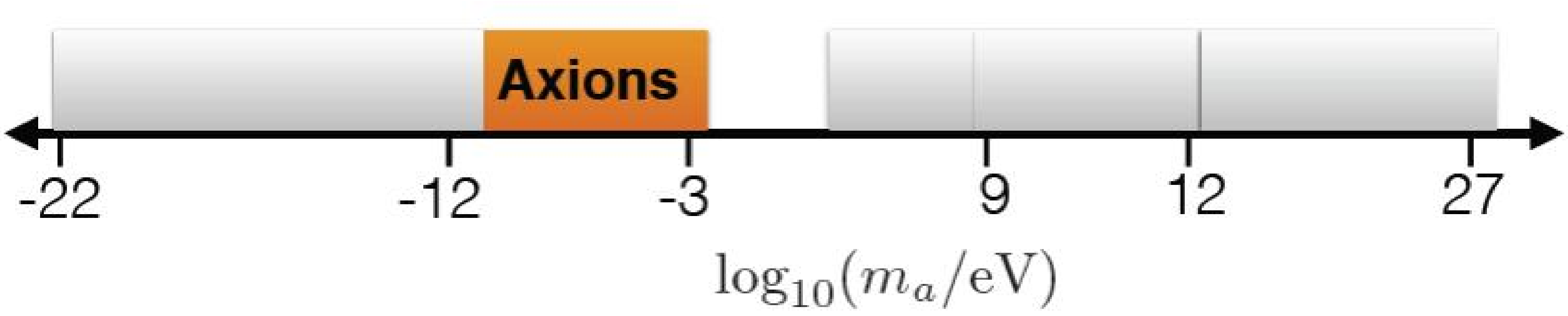
黑洞(MACHOs):
引力透镜、引力波

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

轴子和类轴子粒子



- Invented to solve strong CP problem in Standard Model

$$\mathcal{L}_{\text{axion}} = -\left(\bar{\theta} + \frac{a}{f_a}\right)\frac{g^2}{32\pi^2} G_{\mu\nu}\tilde{G}^{\mu\nu} \qquad (\text{neutron EDM} \propto \bar{\theta})$$

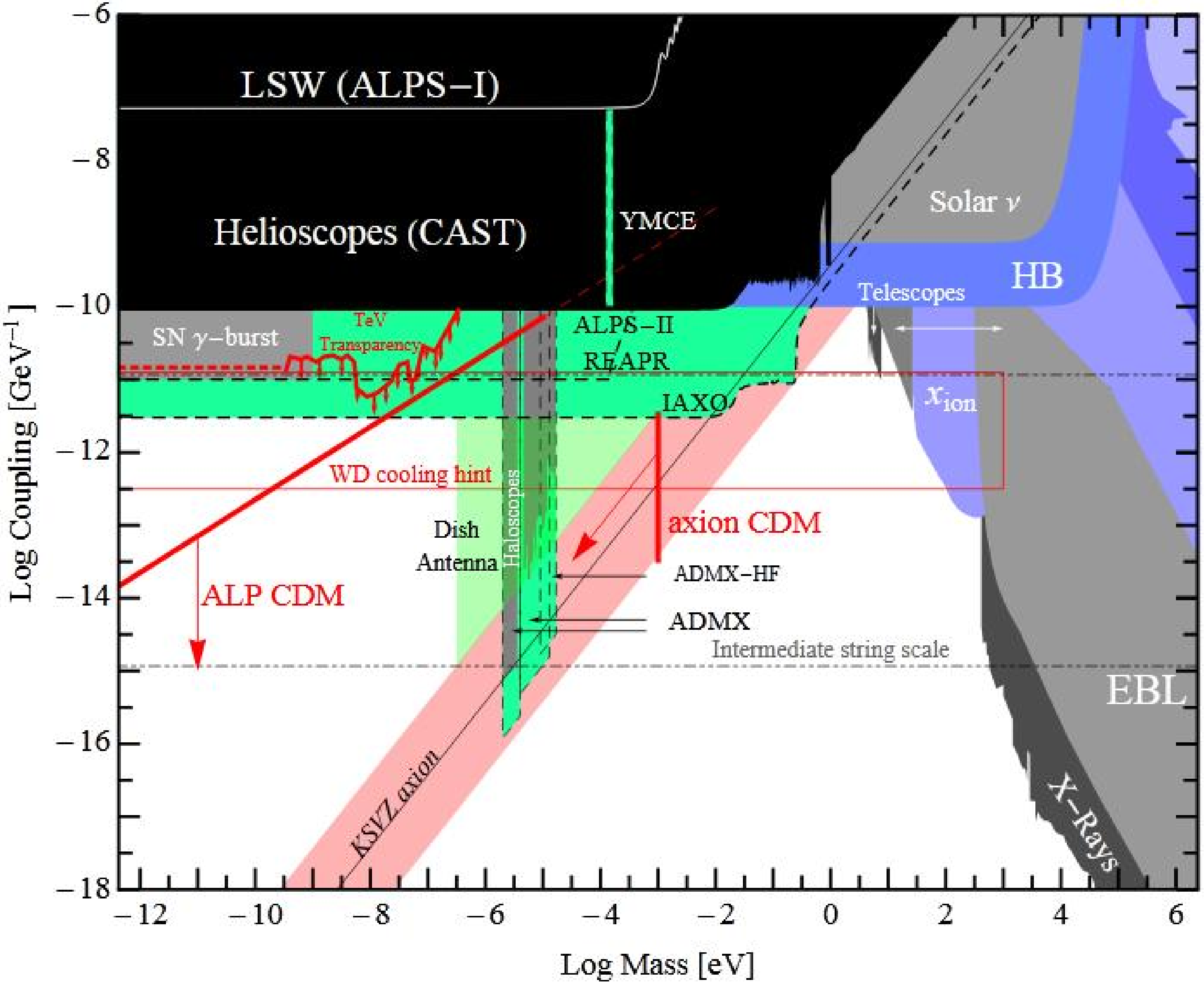
- QCD effect gives axion mass

$$m_a \approx \frac{f_\pi}{f_a} m_\pi \approx 10^{-9}\ \text{eV}\left(\frac{10^{16}\ \text{GeV}}{f_a}\right)$$

- Axion couples with electromagnetic field

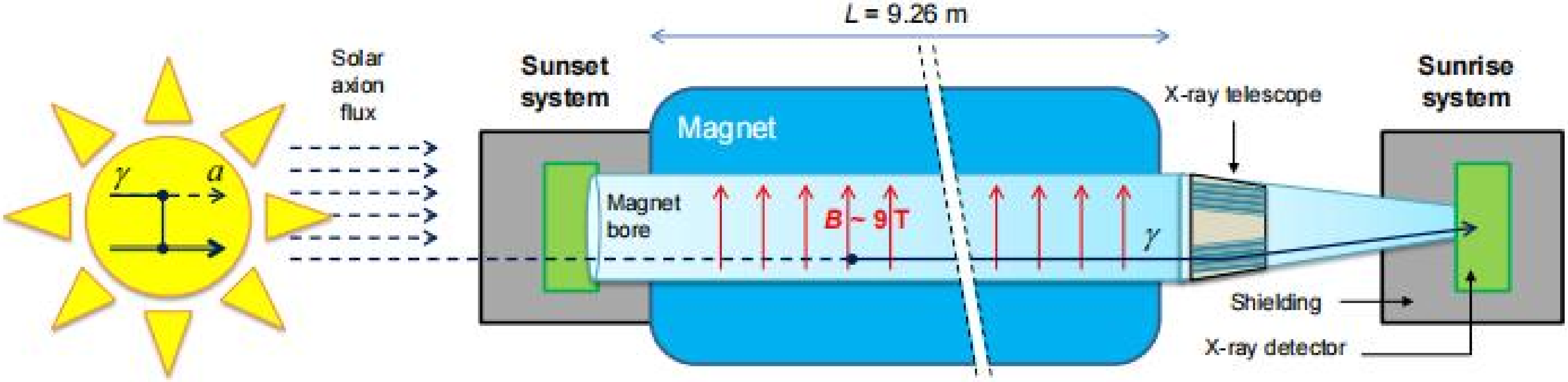
$$\mathcal{L} = -\frac{1}{4} g_{a\gamma\gamma}\, a F_{\mu\nu}\tilde{F}^{\mu\nu} \qquad g_{a\gamma\gamma} \propto \frac{\alpha_{\text{EM}}}{f_a}$$

轴子/类轴子探测实验汇总



Essig et al., 1311.0029

轴子太阳望远镜CAST

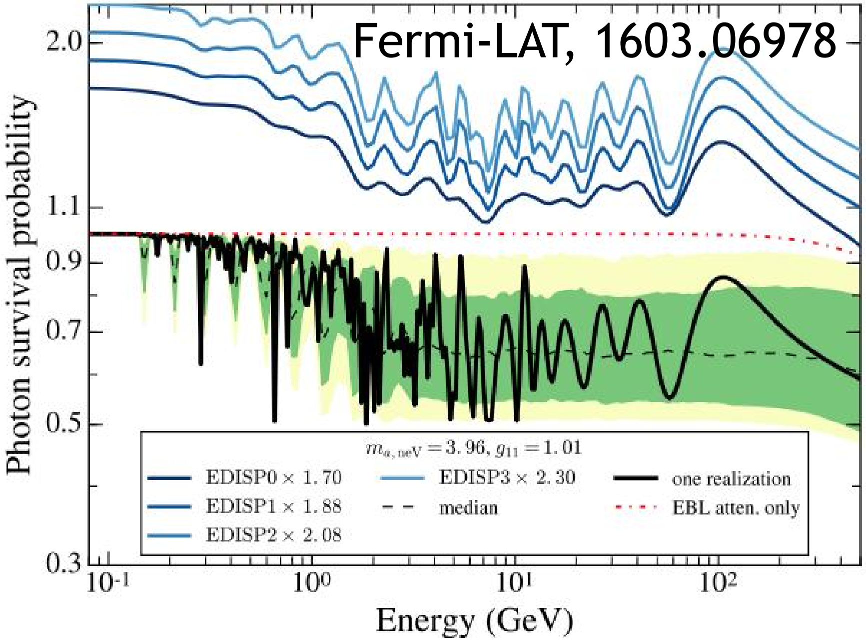


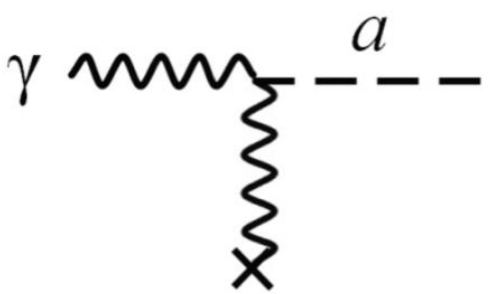
- 太阳内部存在大量的等离子体和光子，温度大约1-10 keV
- 光子在带电粒子库伦场中通过Primarkoff过程转化成为轴子

$$\frac{d\Phi_a}{dE} = 6.02 \times 10^{10}\, cm^{-2}\, s^{-1}\, keV^{-1}\, g_{10}^{2}\, E^{2.481} e^{-E/1.205}$$

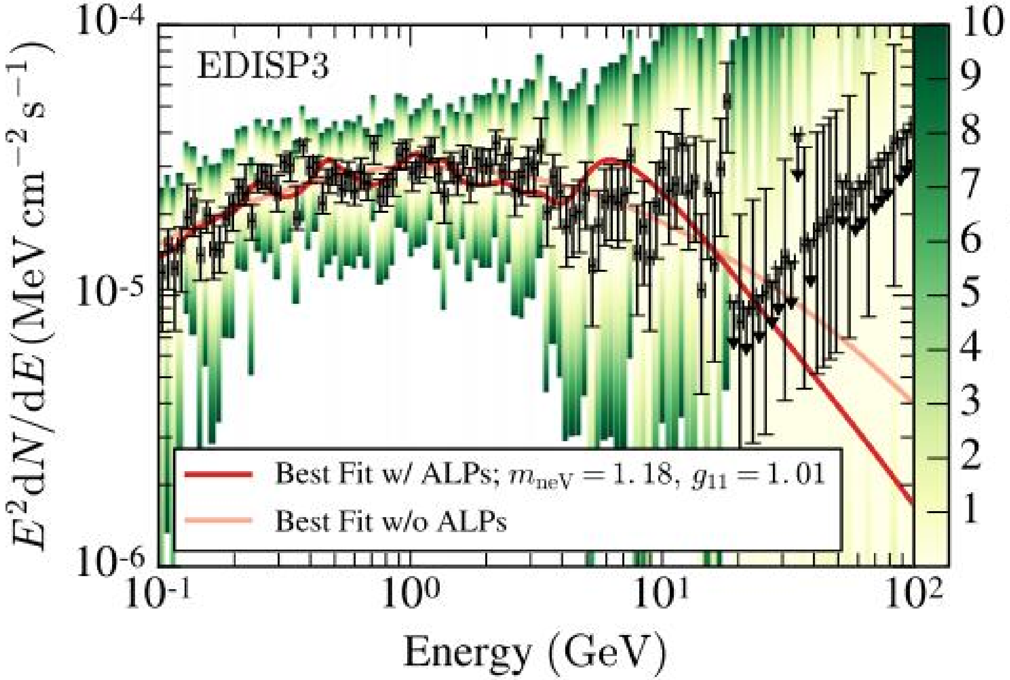
- 在地球上加设磁场将太阳轴子再次转化成为X射线光子
- 通过X射线探测器加以探测

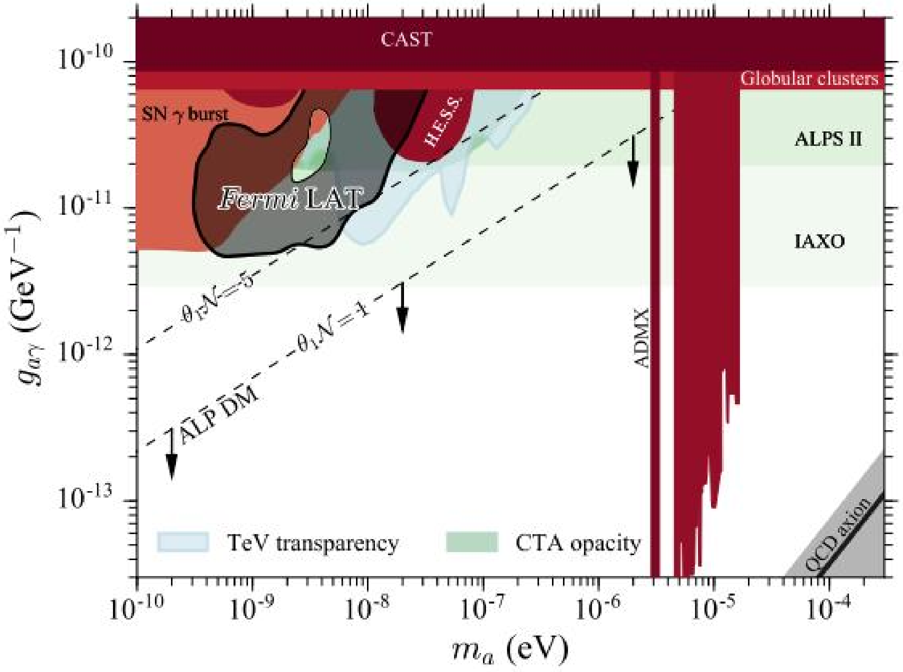
伽马射线探测轴子/类轴子粒子


Fermi-LAT, 1603.06978



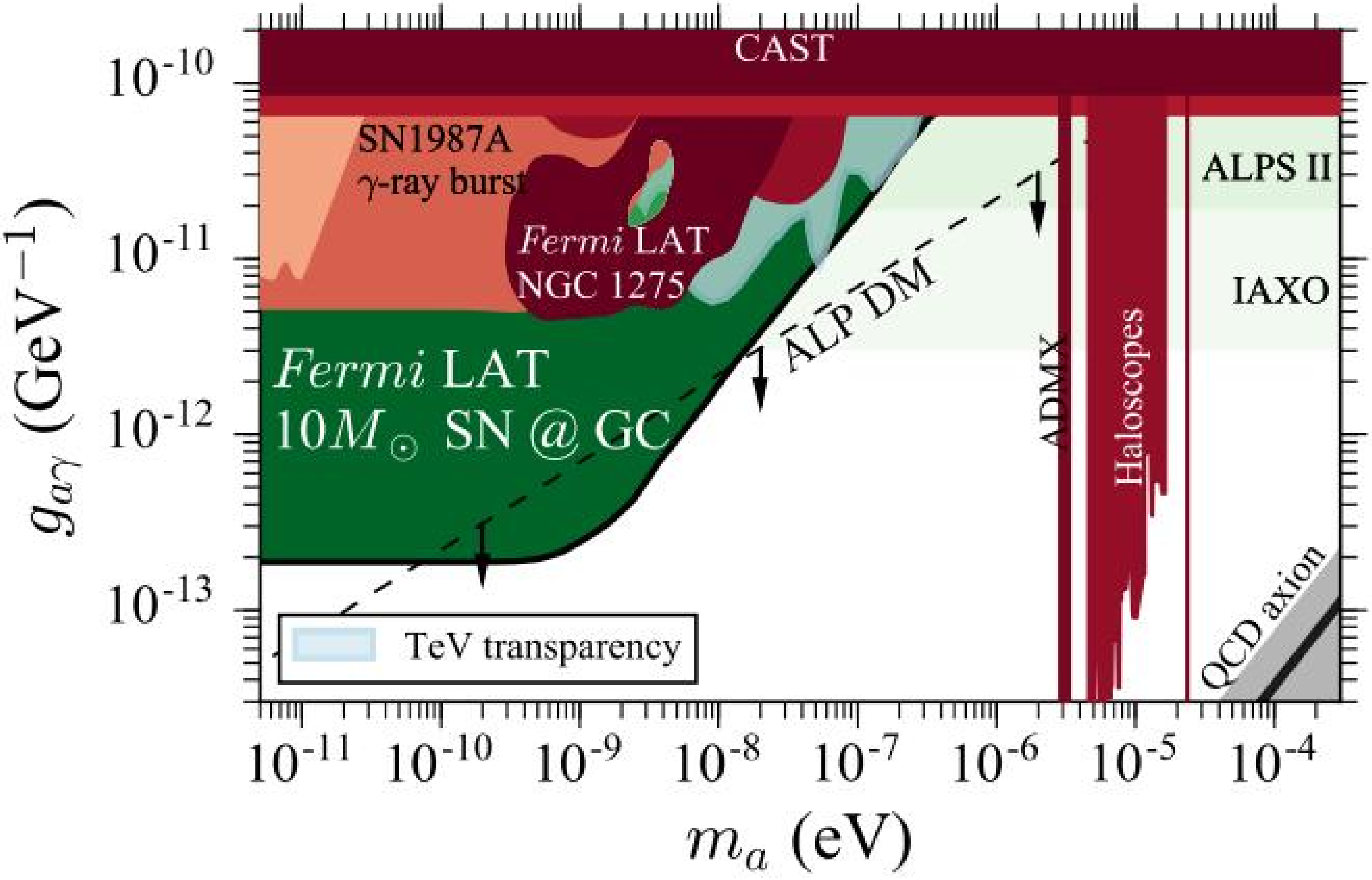
$$P_{\mathrm{ALP}} = 1 - \frac{1}{1+E_c^2/E_\gamma^2}\sin^2\left[\frac{g_{a\gamma}Bl}{2}\sqrt{1+\frac{E_c^2}{E_\gamma^2}}\right]$$





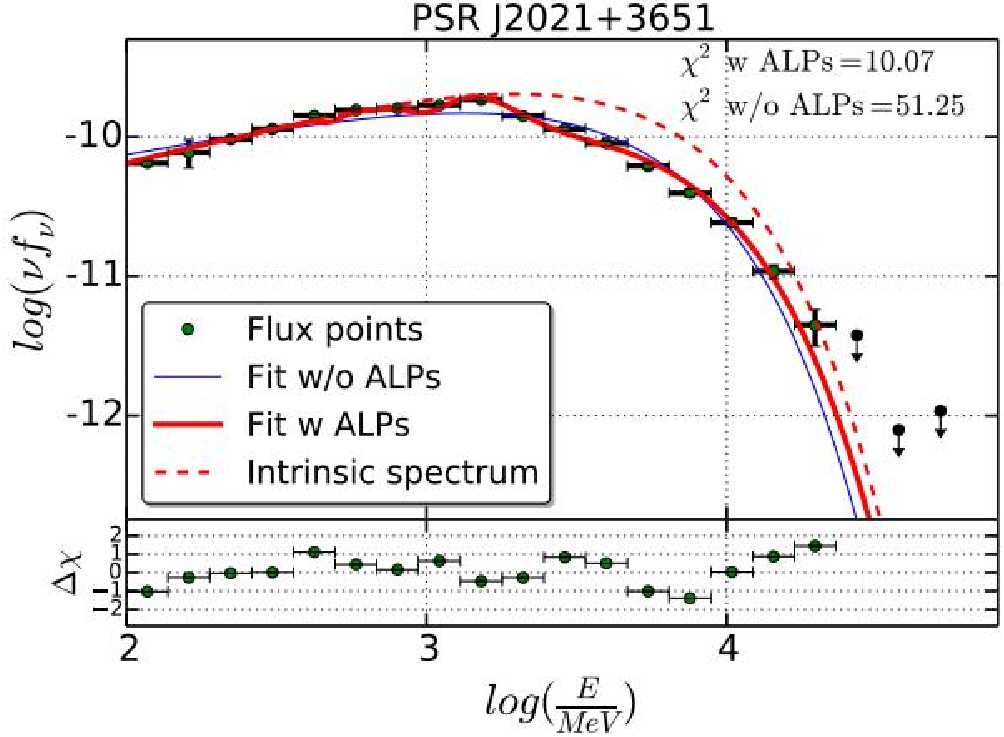
伽马射线探测轴子/类轴子粒子

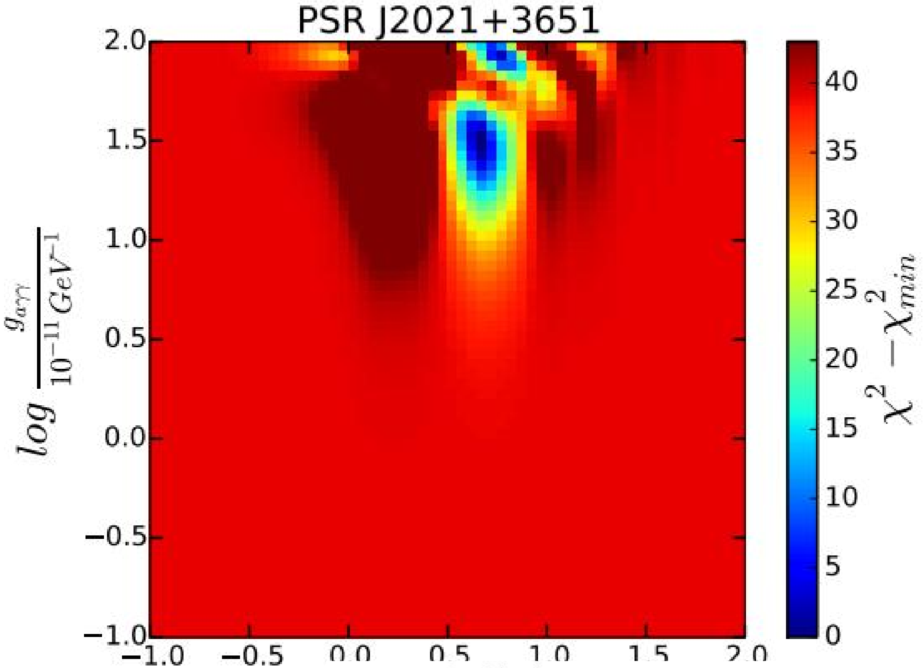
arXiv:1609.02350



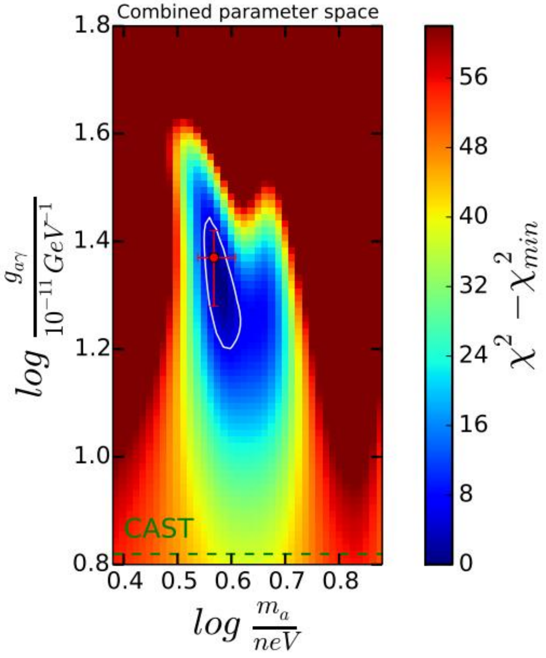
假设银河系中发生超新星爆发，Fermi-LAT将可以非常灵敏地探测来自轴子-光子振荡产生的伽马射线

伽马射线探测轴子/类轴子粒子





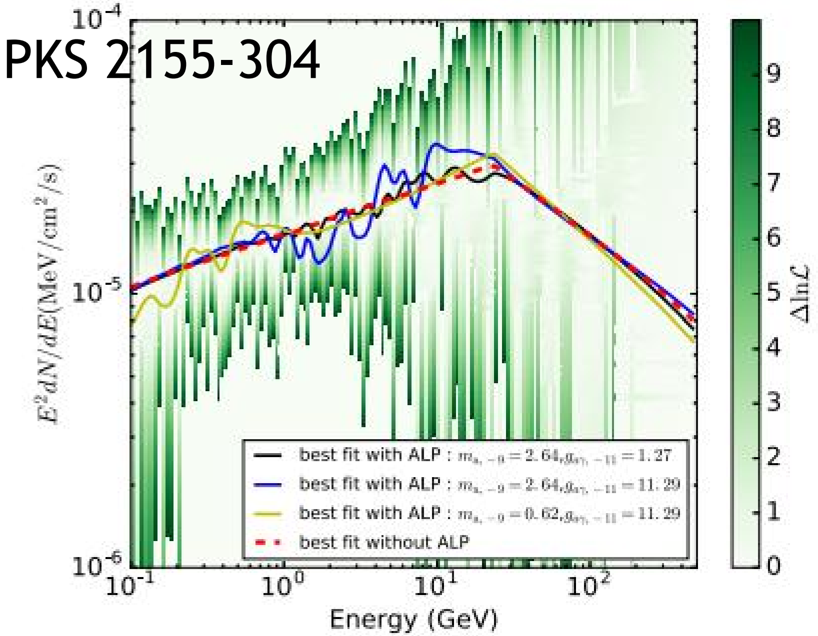
Pulsar name	$\chi^2(dof)\ H_0$	$\chi^2(dof)\ H_1$	Significance (H_1/H_0)	$\chi^2(dof)\ H_2$
J1420-6048	31.10(15)	21.27(13)	1.38 σ	22.46(15)
J1648-4611	47.15(14)	21.37(12)	2.38 σ	41.61(14)
J1702-4128	12.70(8)	3.57(6)	2.01 σ	8.54(8)
J1718-3825	53.57(15)	25.61(13)	2.40 σ	29.52(15)
J2021+3651	51.25(14)	10.07(12)	3.86 σ	41.85(14)
J2240+5832	19.66(11)	8.01(9)	2.11 σ	8.39(11)
Combined	215.42(77)	89.9(65)	5.52 σ	152.37(75)

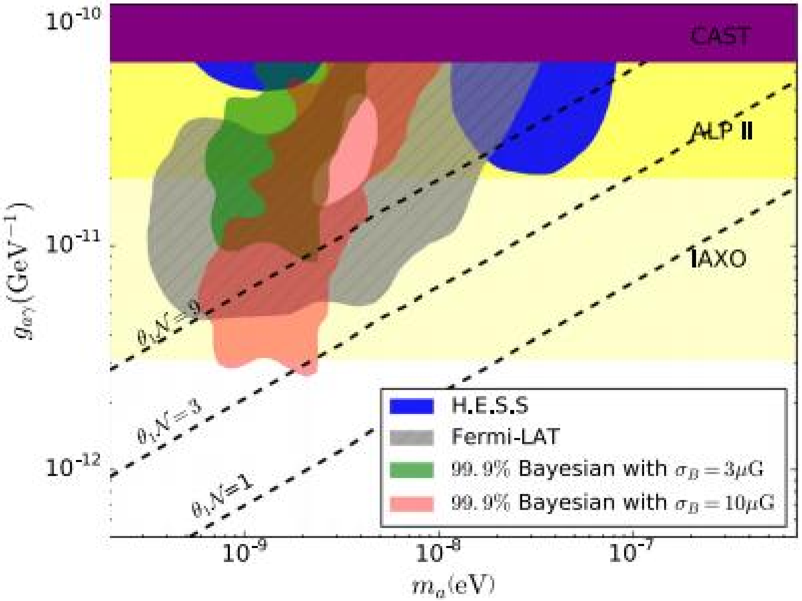


arXiv:1801.08813

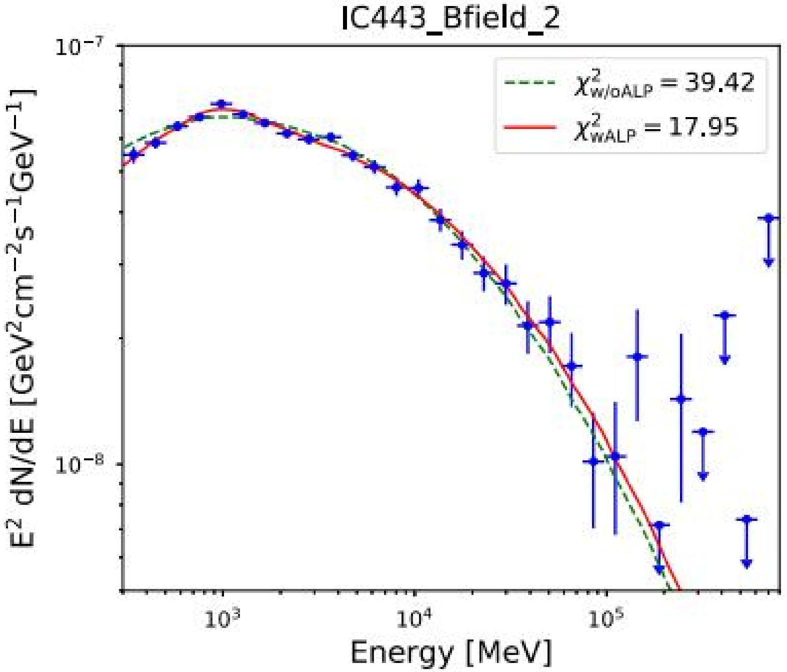
伽马射线探测轴子/类轴子粒子

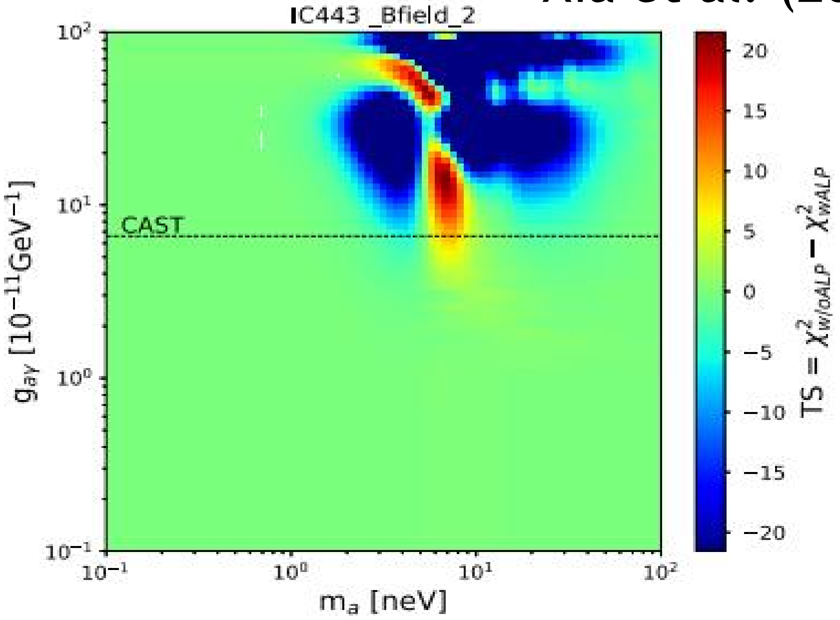
Zhang et al. (2018)





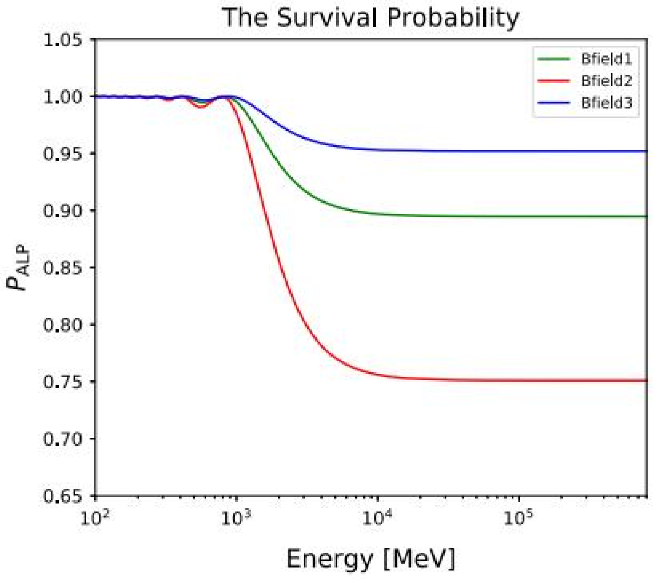
Xia et al. (2018)





伽马射线探测轴子/类轴子粒子

- 轴子-光子振荡在伽马射线能谱上的影响主要是“压低”和“不规则波动”

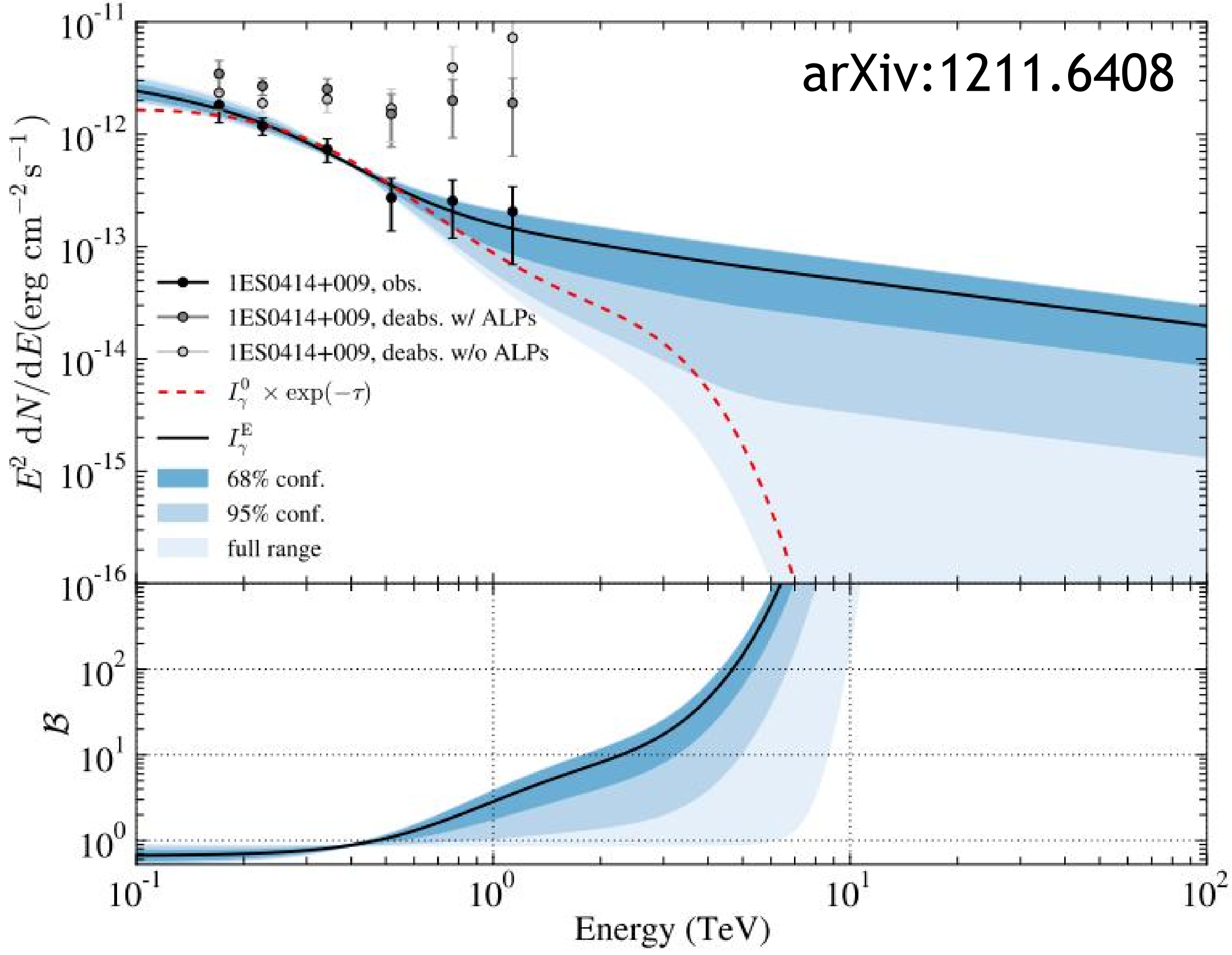


- “压低”效应通常会和源的内禀性质以及传播吸收效应等简并，难以证认

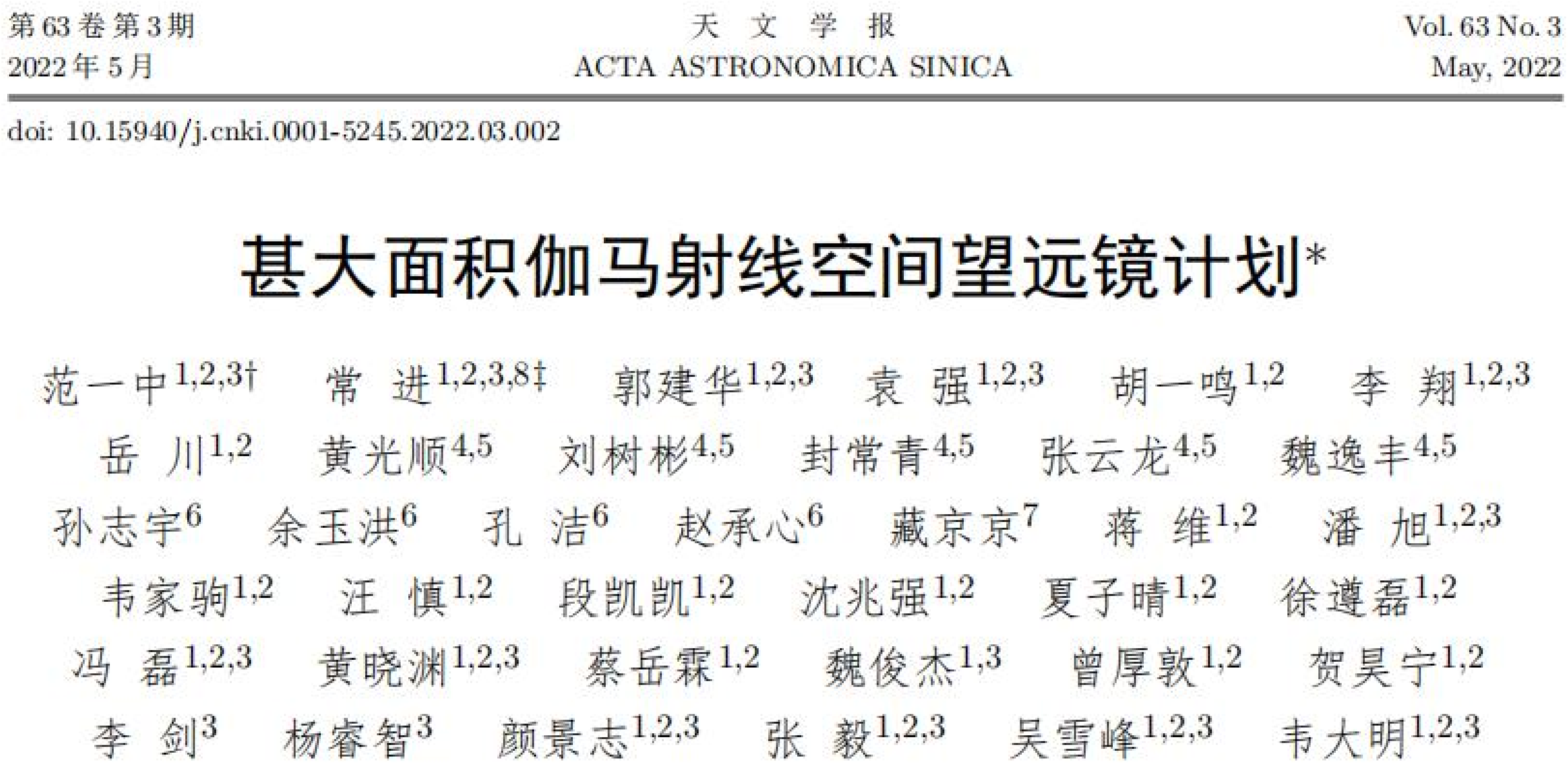
- “不规则波动”对能量分辨率和数据统计量要求很高，Fermi卫星统计量大但能量分辨率较差(~10%)，DAMPE卫星能量分辨率很高(~1%)但统计量较低

- 天体磁场模型也是一项主要的系统误差来源

伽马射线探测轴子/类轴子粒子


arXiv:1211.6408

探测河外辐射源在超高能伽马射线波段的“反常超出”可能是一个行之有效的方法：能量越高由红外光学背景导致的吸收不透明度越高，光子-轴子转换可以有效增加伽马射线传播距离



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甚大面积伽马射线空间望远镜计划*

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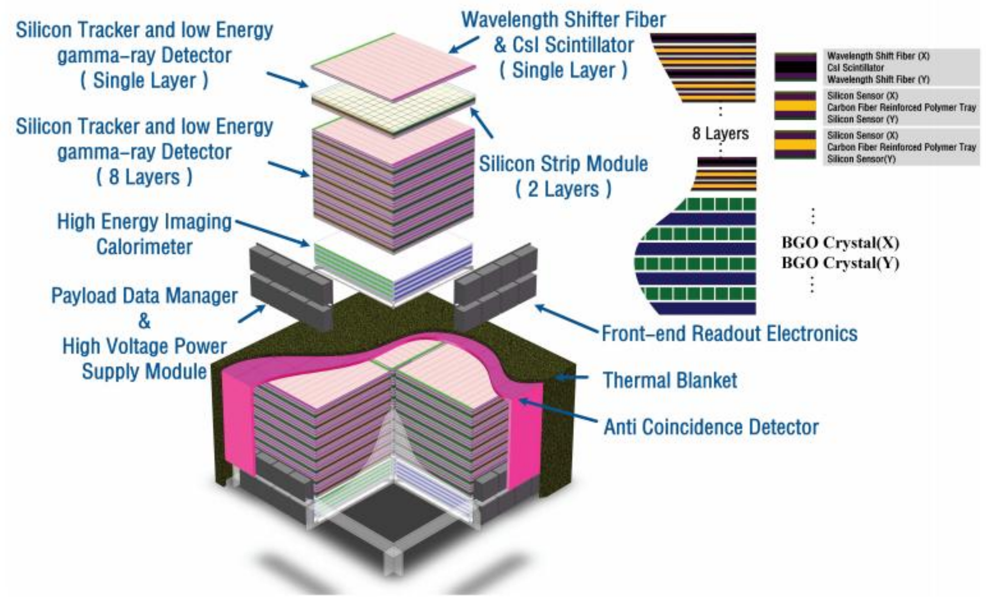
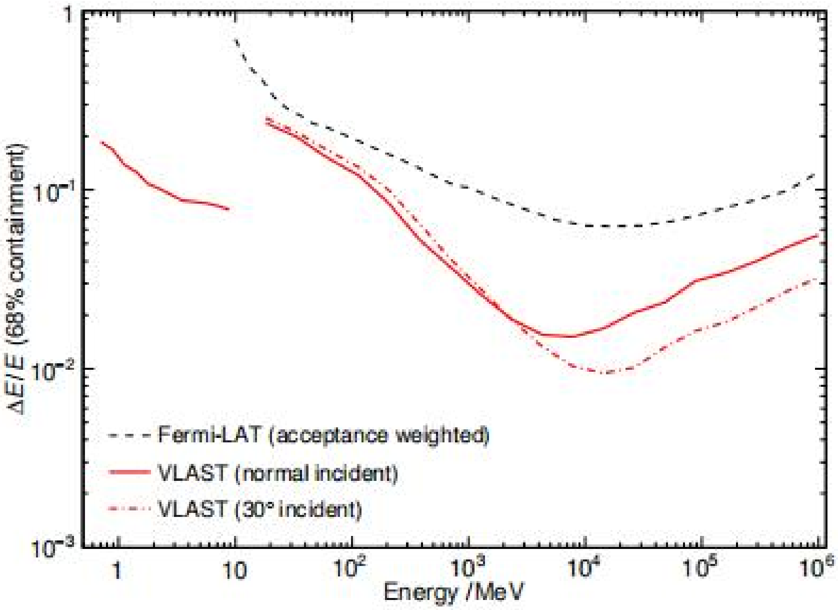
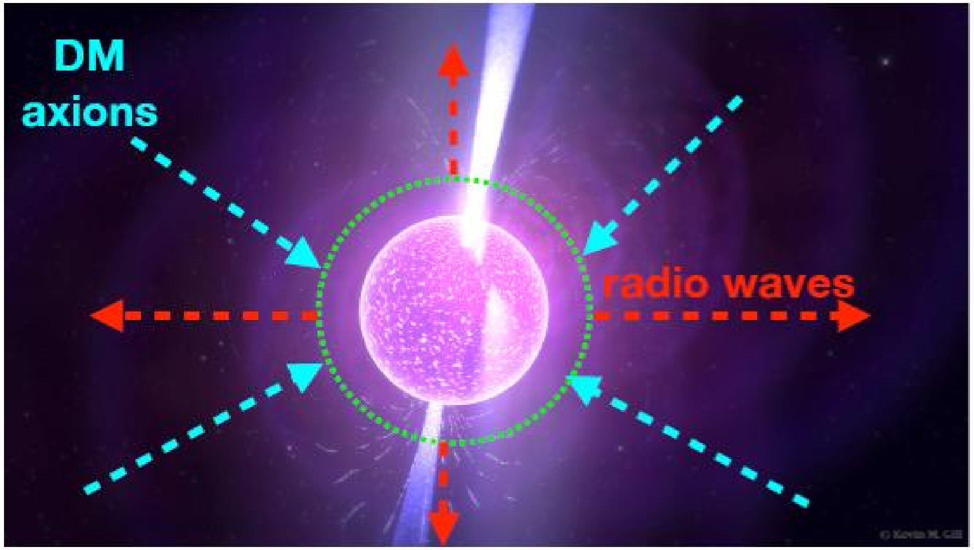




有效接受度达10 m²sr的旗舰型空间探测设施

中子星射电谱线观测轴子

NS with strong B-field and surrounding plasma



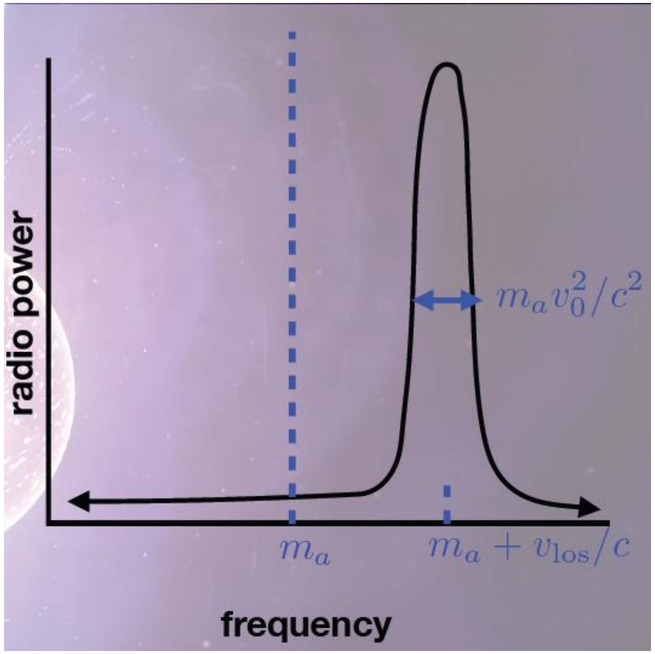
DM axions resonantly convert to radio waves when $m_a = $

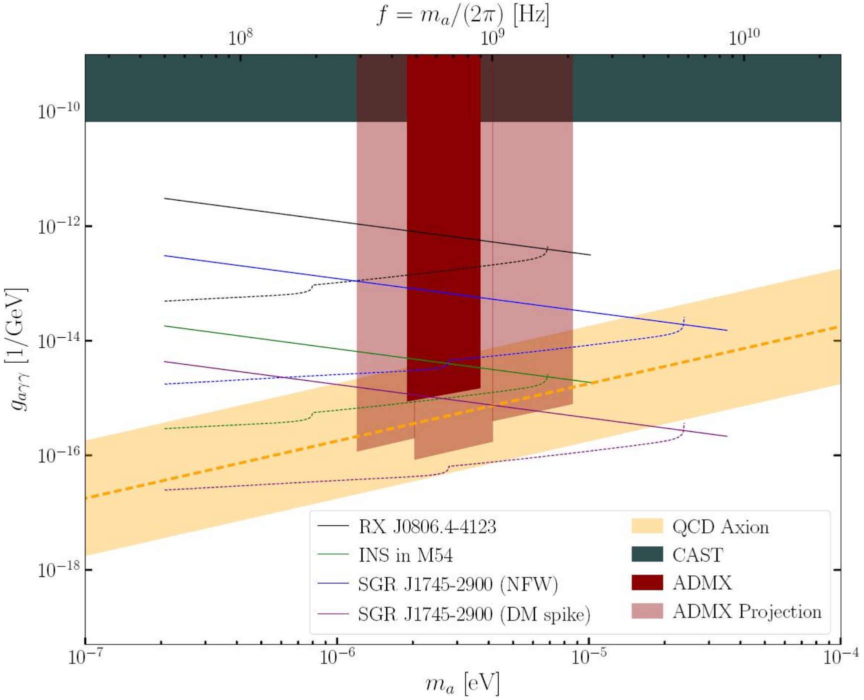
radio waves

radio emission propagates to Earth

射电望远镜的宽频覆盖可以有效探索地面共振腔实验的盲区

Narrow radio line detectable at Earth with $f = m_a/(2\pi)$.





Pshirkov+ JETP 2009;
Huang+ PRD 2018;
Hook+ PRL 2018

中子星射电谱线观测轴子

- **信号特征：近似单一频率的线谱辐射，$f = m_a$**
- **信号强度依赖于中子星磁场、周期、轴子-光子耦合、轴子暗物质密度等**

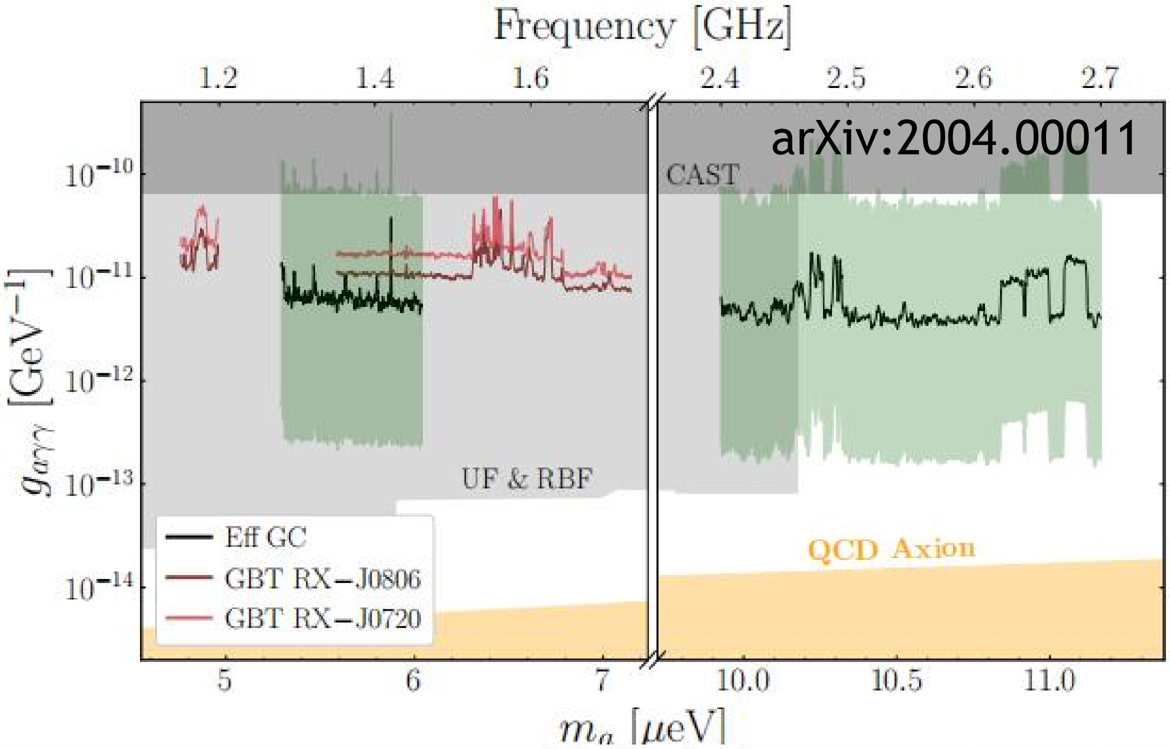
$$\begin{aligned}\bar{S}_{\nu_i} &= \frac{F}{\Delta\nu} = 3.8\times10^{-6}\ \mathrm{Jy}\left(\frac{100\ \mathrm{pc}}{d}\right)^2\left(\frac{16\ \mathrm{kHz}}{\Delta\nu}\right)\\ &\times\left(\frac{\mathrm{d}\mathcal{P}/\mathrm{d}\Omega}{5.7\times10^9\mathrm{W}}\right)\int_{\nu_{i,\min}}^{\nu_{i,\max}}\frac{\mathrm{d}\nu}{\sqrt{2\pi}\sigma_0}\mathrm{e}^{-\frac{(\nu-m_\mathrm{a})^2}{2\sigma_0^2}},\end{aligned}$$

$$\begin{aligned}\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}\Omega} &\simeq 5.7\times10^9\ \mathrm{W}\left(\frac{g_{\mathrm{a}\gamma\gamma}}{10^{-12}\ \mathrm{GeV}^{-1}}\right)^2\left(\frac{r_\mathrm{NS}}{10\ \mathrm{km}}\right)^{5/2}\left(\frac{m_\mathrm{a}}{\mathrm{GHz}}\right)^{4/3}\\ &\times\left(\frac{B_0}{10^{14}\ \mathrm{G}}\right)^{5/6}\left(\frac{P}{\mathrm{sec}}\right)^{7/6}\left(\frac{\rho_\mathrm{DM}^\infty}{0.45\ \mathrm{GeV\,cm^{-3}}}\right)\left(\frac{M_\mathrm{NS}}{\mathrm{M}_\odot}\right)^{1/2}\\ &\times\left(\frac{200\ \mathrm{km\,s^{-1}}}{v_0}\right)\frac{3\,(\hat{\mathbf{m}}\cdot\hat{\mathbf{r}})^2+1}{\left|3\cos\theta\,\hat{\mathbf{m}}\cdot\hat{\mathbf{r}}-\cos\theta_\mathrm{m}\right|^{7/6}},\end{aligned}$$

- **孤立、射电暗弱、强磁场中子星是优选目标**

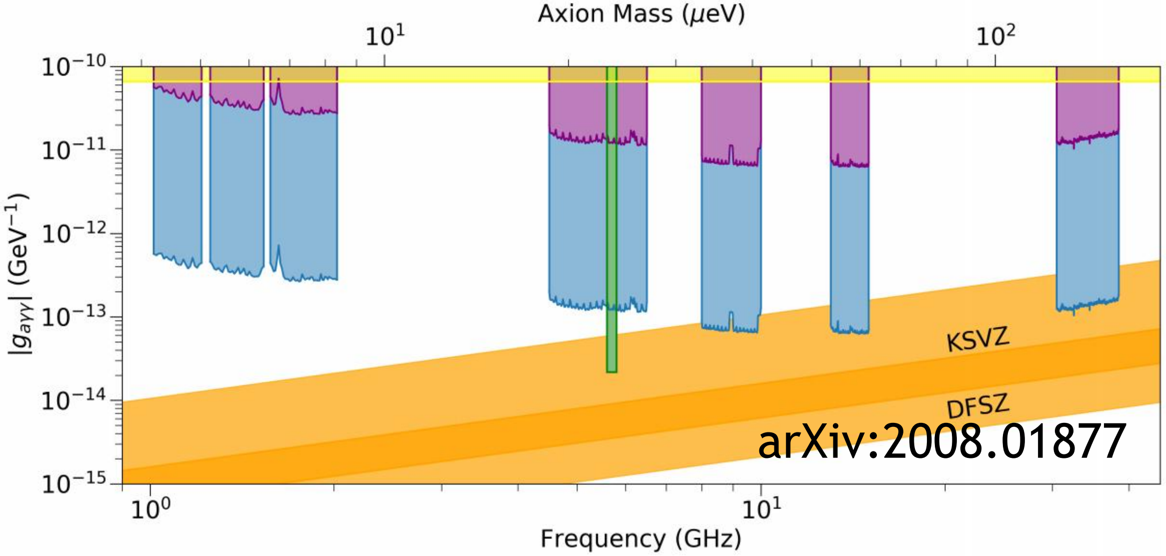
中子星射电谱线观测轴子

- **GBT和Effelsberg观测银心磁星和近邻孤立中子星**



arXiv:2004.00011

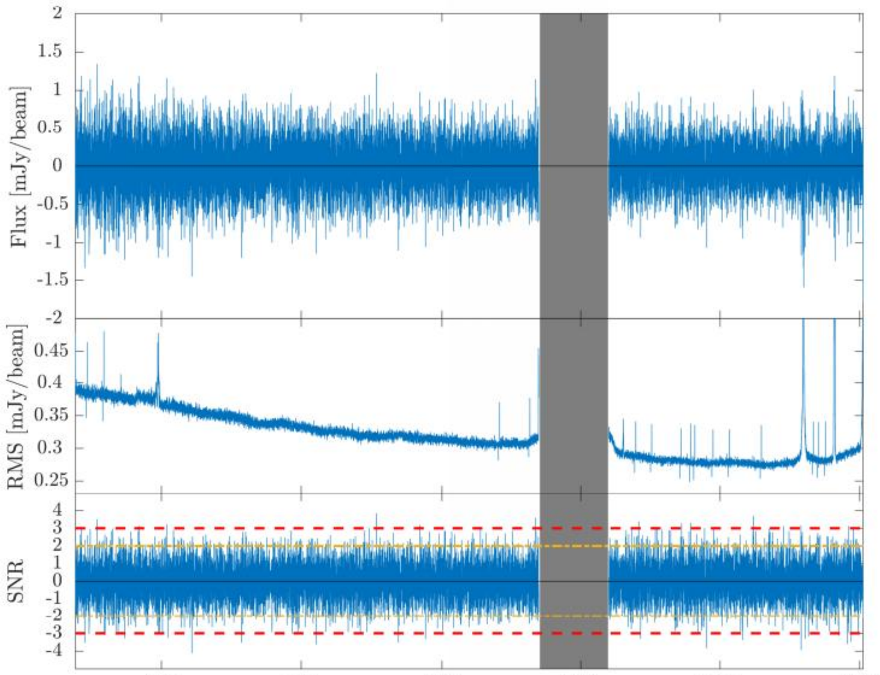
- **VLA观测银心磁星PSR J1745-2900**

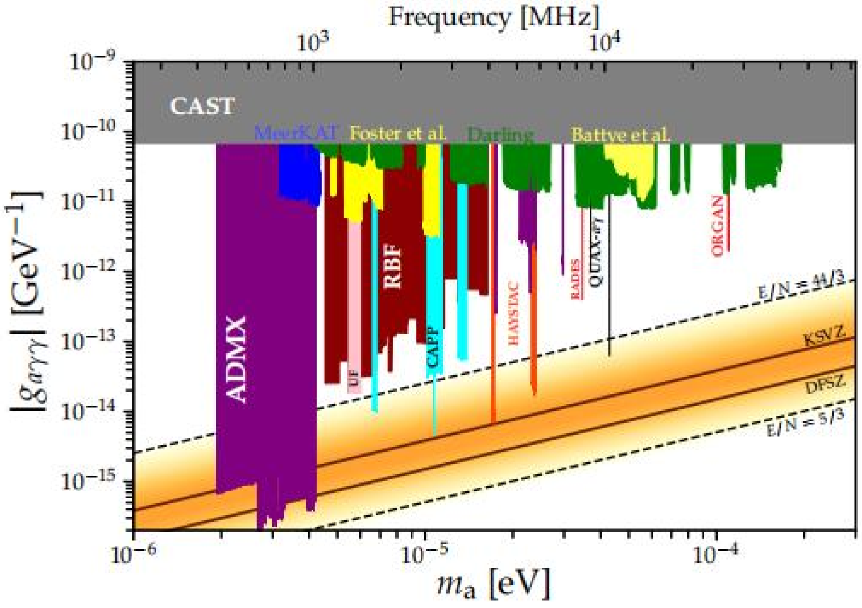


arXiv:2008.01877

MeerKAT观测孤立中子星

MeerKAT as SKA pathfinder

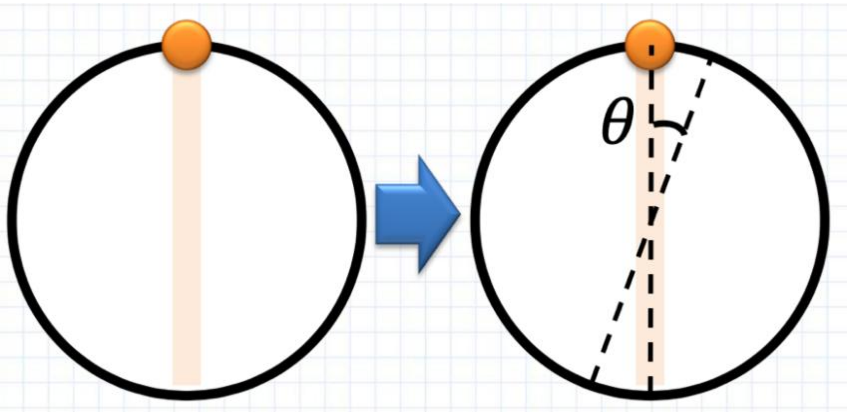




- MeerKAT UHF band: 580-1051 MHz covers the gap between ADMX and RBF
- Reaches better sensitivity than other observations at overlapping frequency

射电偏振辐射探测轴子

arXiv:1901.10981



$$\omega_\pm \approx k \pm \tfrac{1}{2} g \left(\frac{\partial \varphi}{\partial t} + \nabla\varphi \cdot \frac{\boldsymbol{k}}{k} \right)$$

线偏振光在轴子背景场中传播，会由于双折射效应产生偏振角的转动

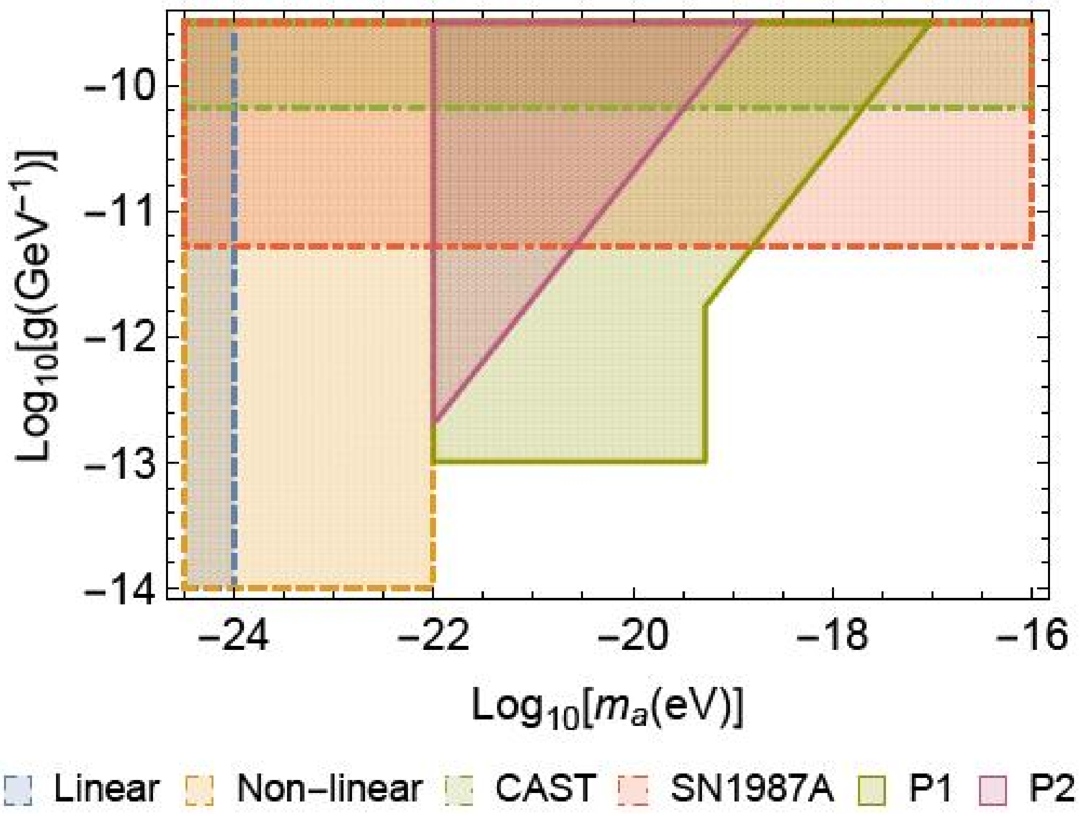
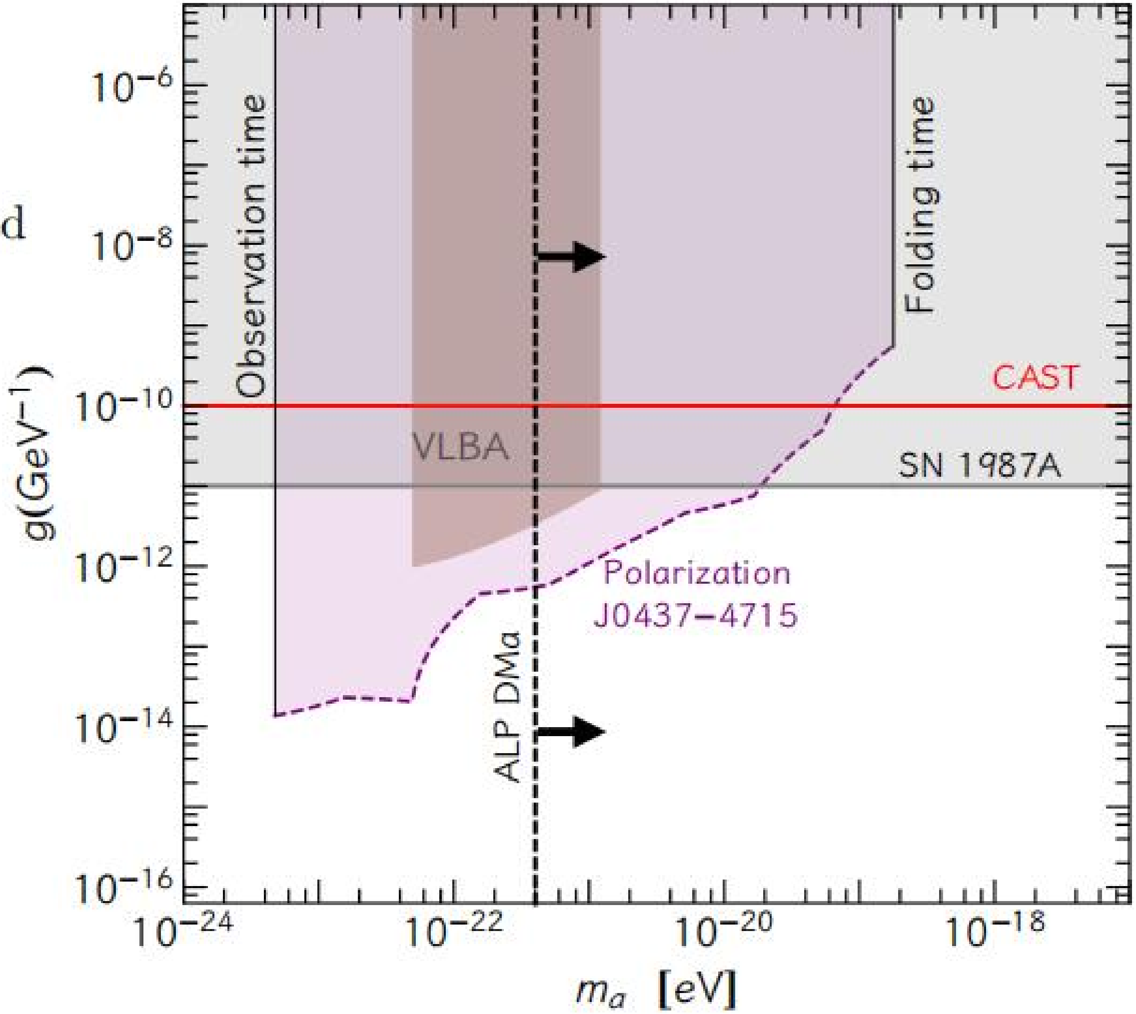


FIG. 1: Projected sensitivities to detect the CAB, using linearly polarized pulsar light as a probe, in the two benchmark scenarios: P_1 and P_2.

射电偏振辐射探测轴子

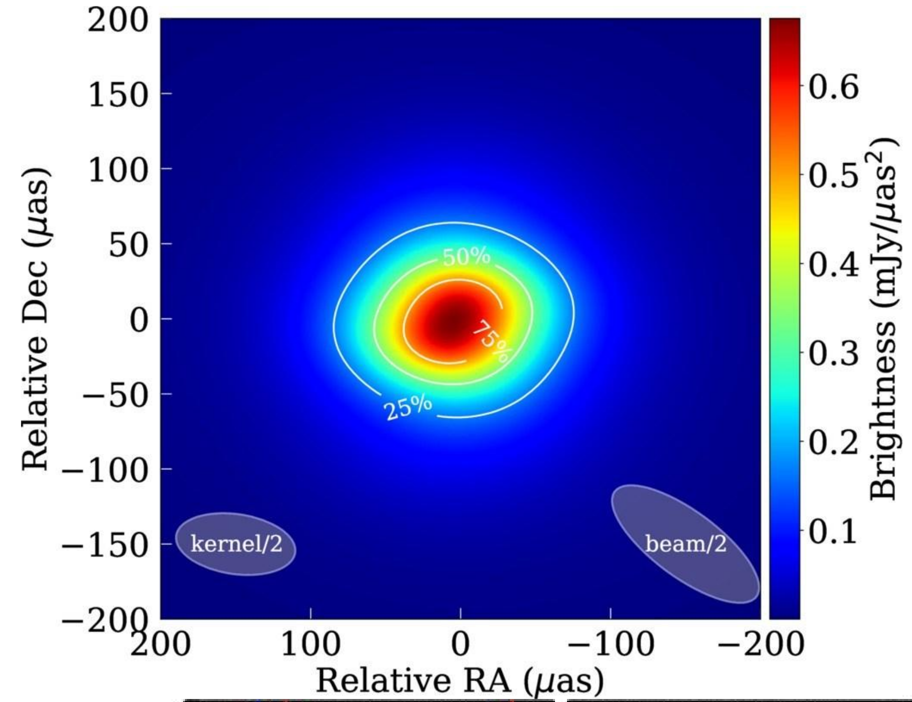
$$\theta(t,T) \sim 1.4\times 10^{-2}\sin(m_a t+\delta)\left(\frac{g}{10^{-12}\,\mathrm{GeV}^{-1}}\right)\frac{10^{-22}\,\mathrm{eV}}{m_a}\ \mathrm{rad}$$

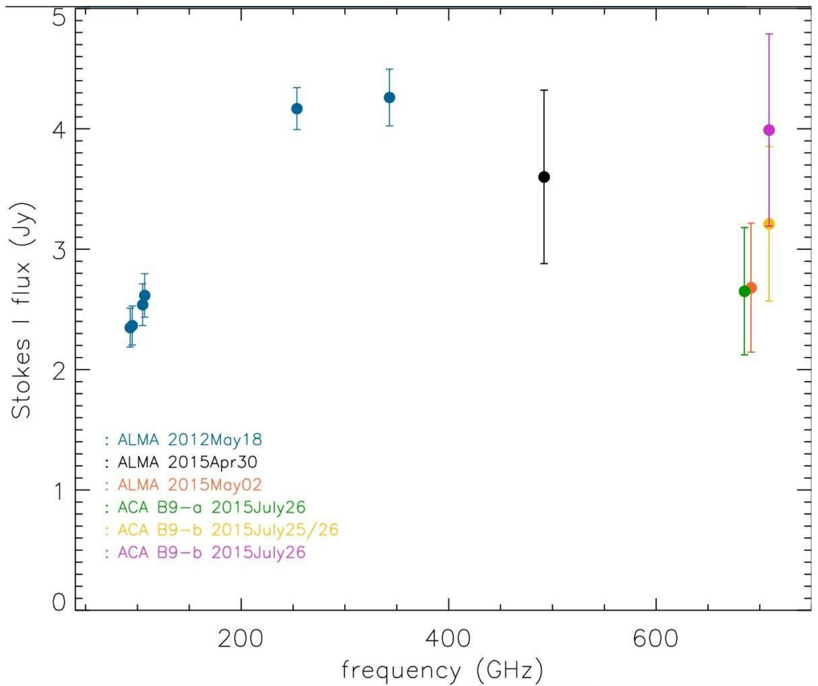
arXiv:1902.02695

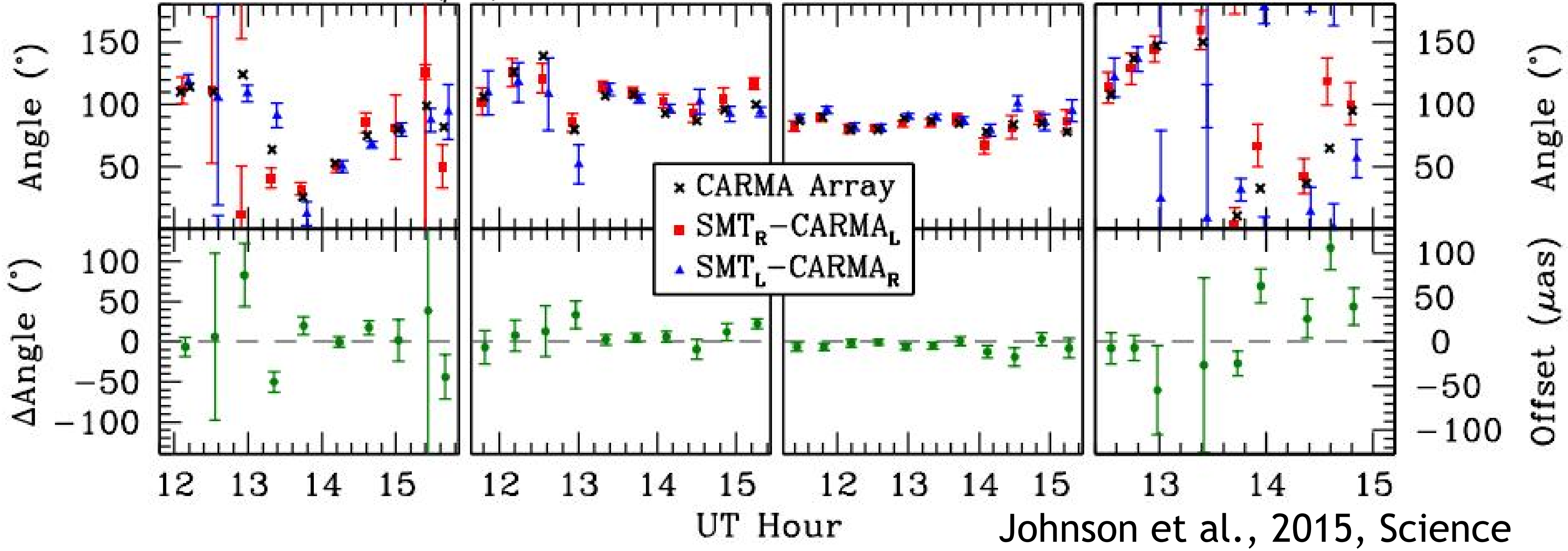


Parkes对PSR J0437-4715的偏振观测对超轻ALP给出严格限制

银河系中心的射电观测



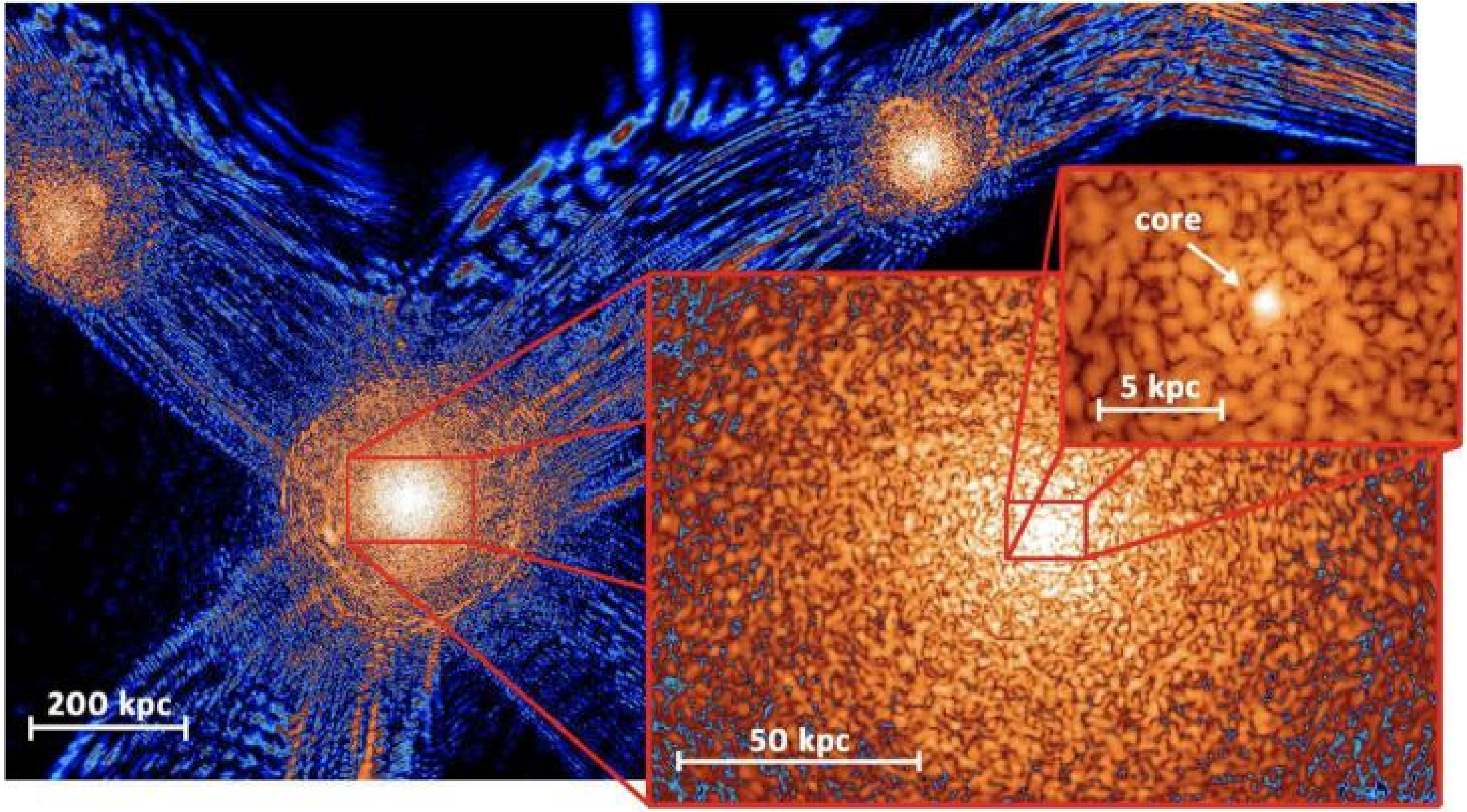




Johnson et al., 2015, Science

银心暗物质分布

质量非常轻的暗物质波动性明显，影响其在小尺度上的结构分布

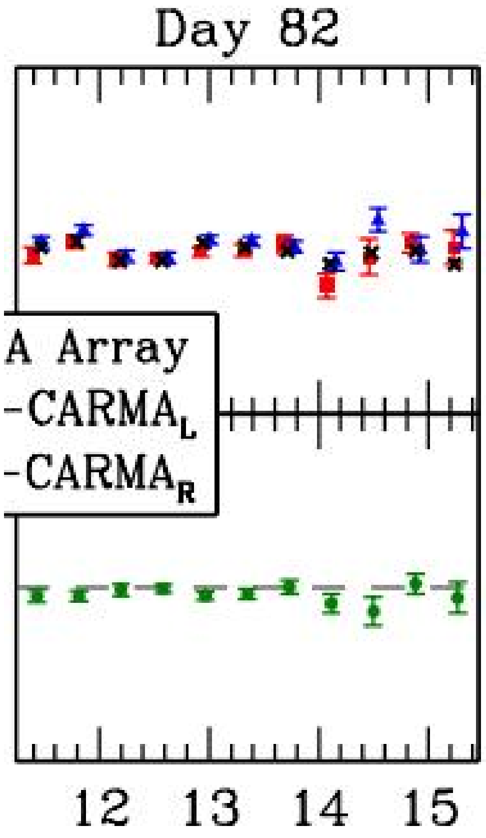


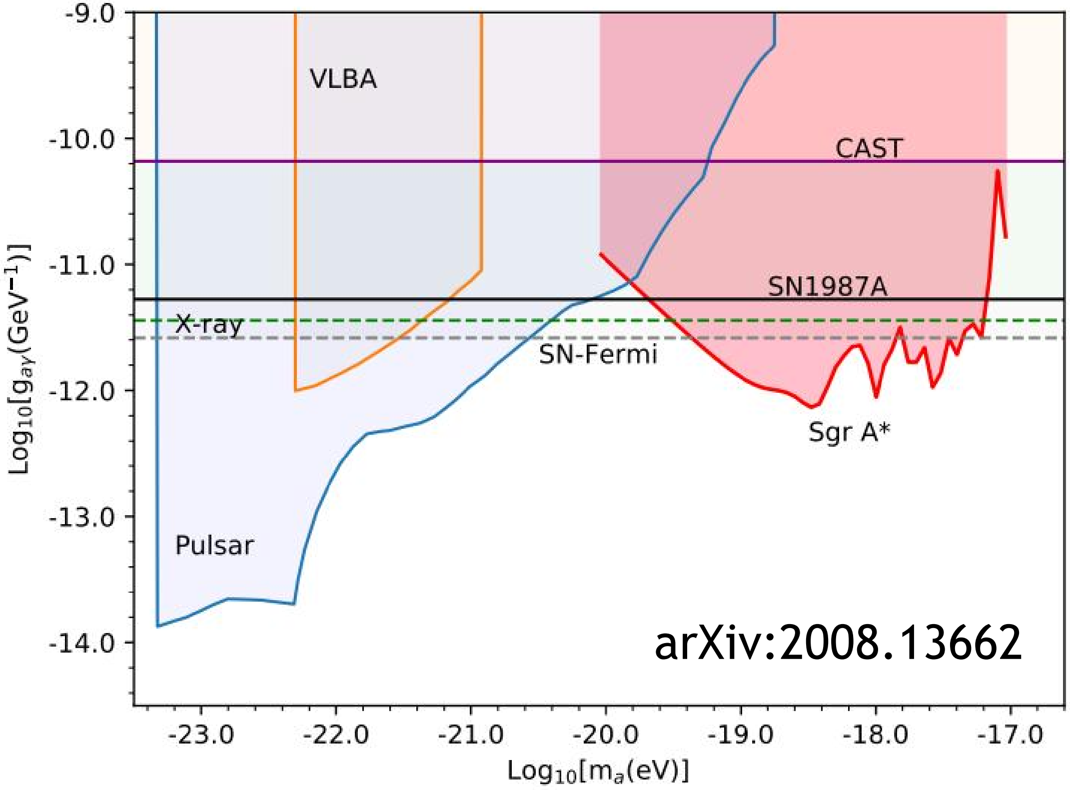
$$\rho_{\rm DM} = \begin{cases} 190 \times \left(\frac{m_a}{10^{-18}{\rm eV}}\right)^{-2} \left(\frac{r_c}{1{\rm pc}}\right)^{-4} M_\odot {\rm pc}^{-3}, & \text{for } r < r_c \\ \frac{\rho_0}{r/R_g(1+r/R_g)^2}, & \text{for } r > r_c \end{cases}$$

Soliton core + NFW

Schive et al., 2014, Nature Physics

银心射电观测限制轴子暗物质模型



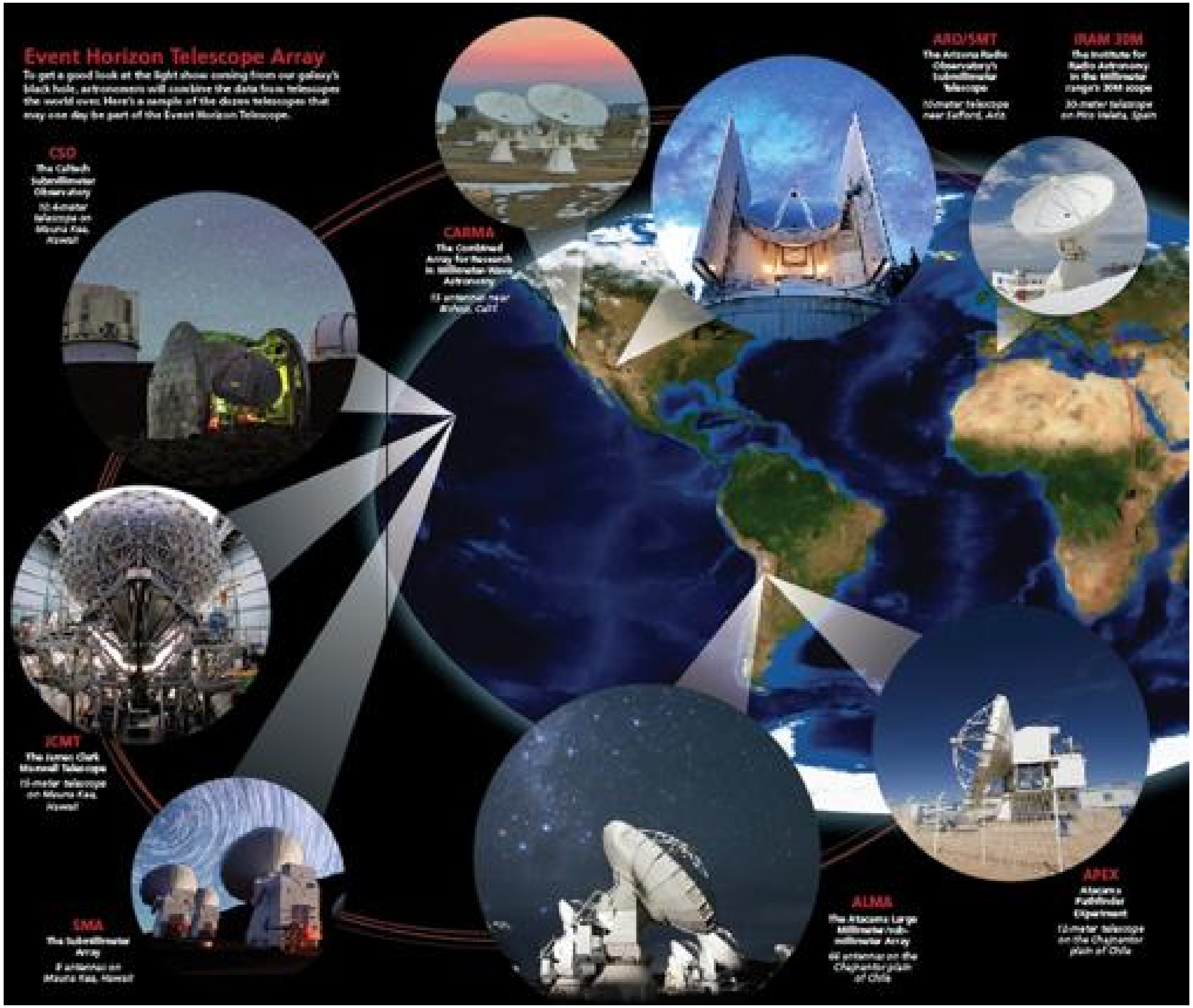


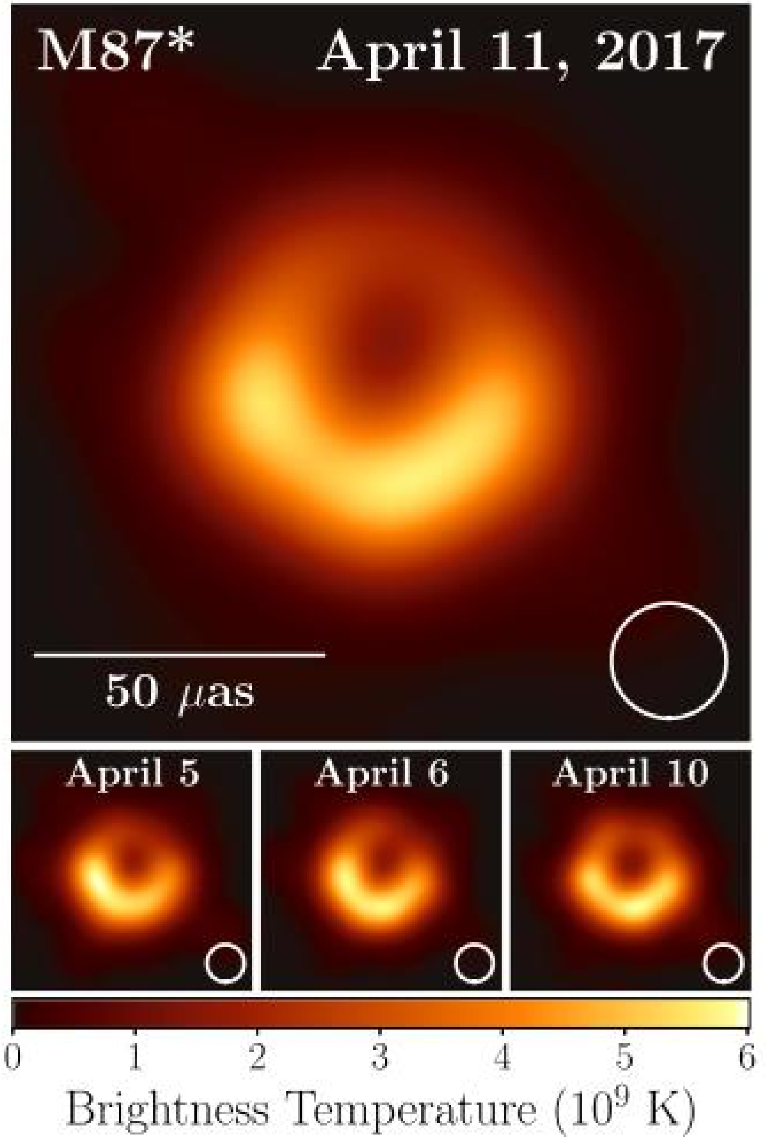
arXiv:2008.13662

$$\Delta\phi(t) \simeq 5^\circ \sin\left(2\pi\frac{t}{T}+\delta(\boldsymbol{x})\right)\left(\frac{\rho_{\rm DM}}{2\times 10^9\ {\rm GeV/cm^3}}\right)^{\frac{1}{2}}\left(\frac{g_{a\gamma}}{10^{-12}\ {\rm GeV^{-1}}}\right)\left(\frac{m_a}{10^{-18}\ {\rm eV}}\right)^{-1}$$

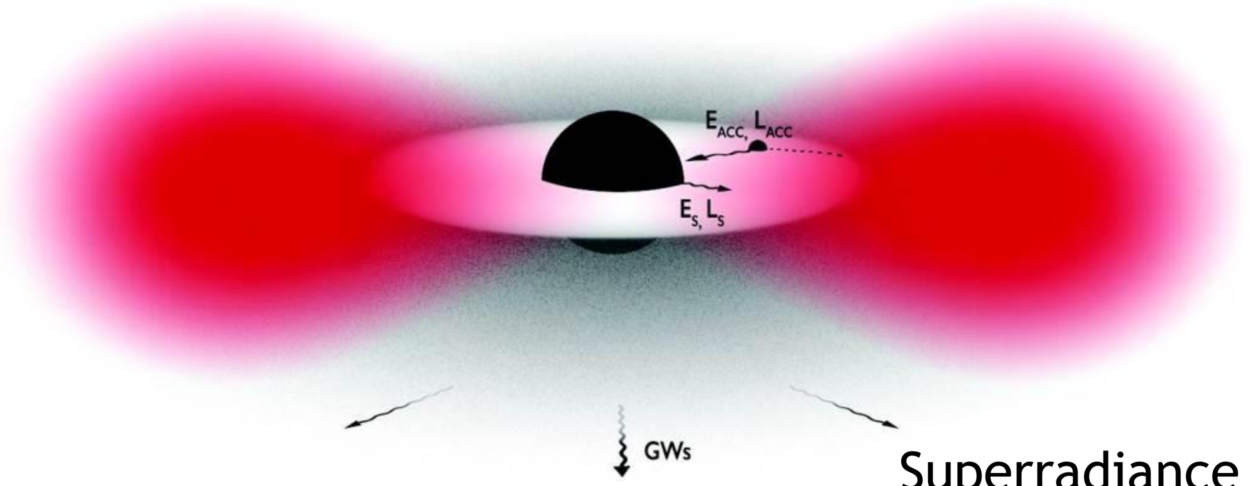
- **VLBI对银心的偏振观测发现偏振度和偏振角呈复杂变化，反映了吸积盘的不稳定性**
- **利用其相对稳定的一天观测结果(Day 82)可以对ALP模型给出限制**

事件视界望远镜


Event Horizon Telescope Array
CSO
CARMA
ARO/SMT
IRAM 30M
JCMT
SMA
ALMA
APEX


M87*
April 11, 2017
50 μas
April 5
April 6
April 10
0
1
2
3
4
5
6
Brightness Temperature (10⁹ K)

黑洞超辐射

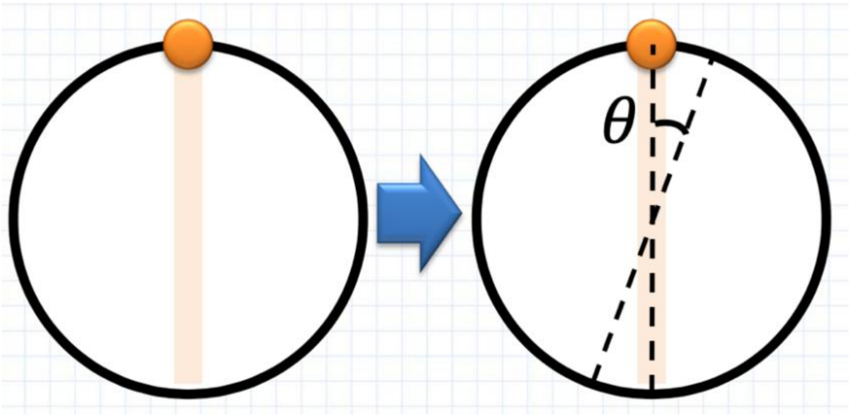


Superradiance condition

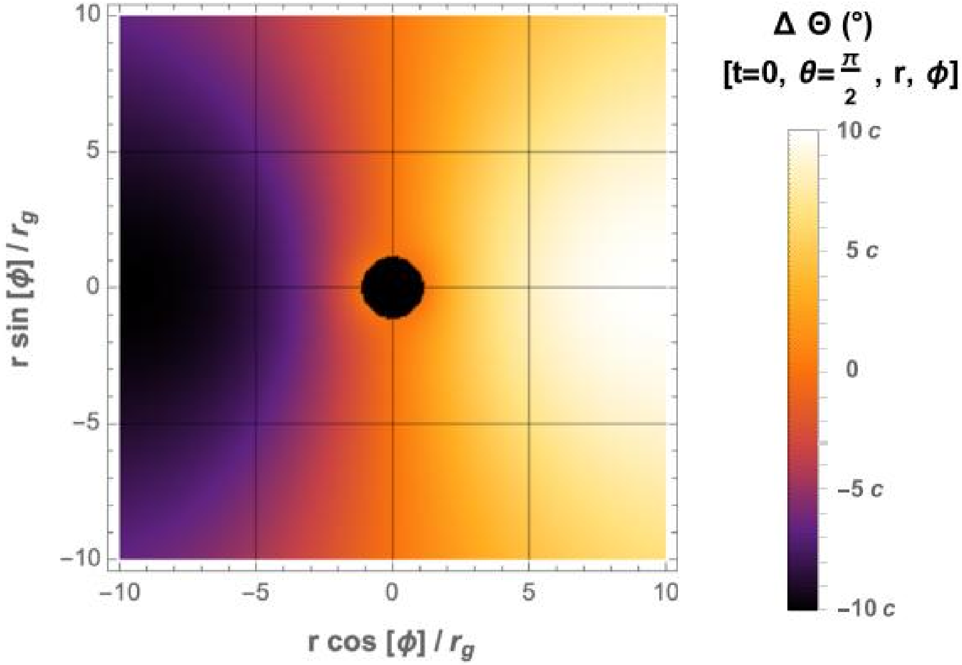
$$\omega < \omega_c = \frac{a_J m}{2r_+}$$

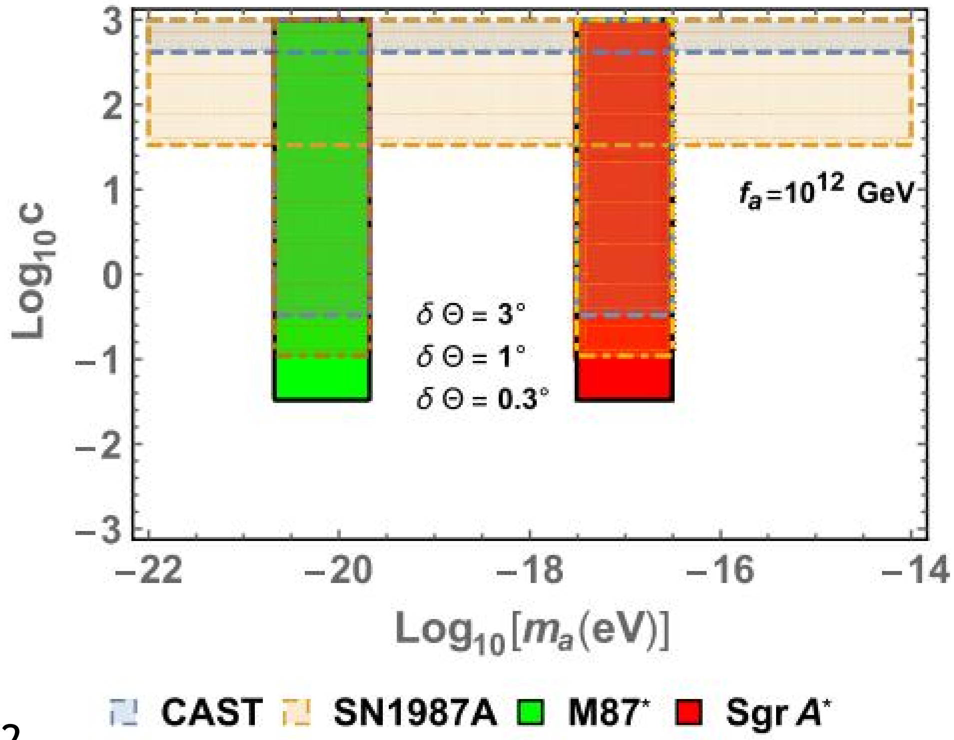
- 满足超辐射条件的玻色子在克尔黑洞外围将增长形成玻色云；类似于氢原子外的电子云，也称作引力原子
- 玻色云的演化（增长、坍缩、外流等）消耗黑洞自转能
- 玻色云的总能量可以很大，和黑洞质量相比拟

EHT偏振探测轴子/类轴子



$$\begin{aligned}\Delta\Theta &= g_{a\gamma}\Delta a(t_{\rm obs},\mathbf{x}_{\rm obs};t_{\rm emit},\mathbf{x}_{\rm emit})\\ &= g_{a\gamma}\int_{\rm emit}^{\rm obs} ds\; n^{\mu}\;\partial_{\mu}a\\ &= g_{a\gamma}[a(t_{\rm obs},\mathbf{x}_{\rm obs})-a(t_{\rm emit},\mathbf{x}_{\rm emit})],\end{aligned}$$

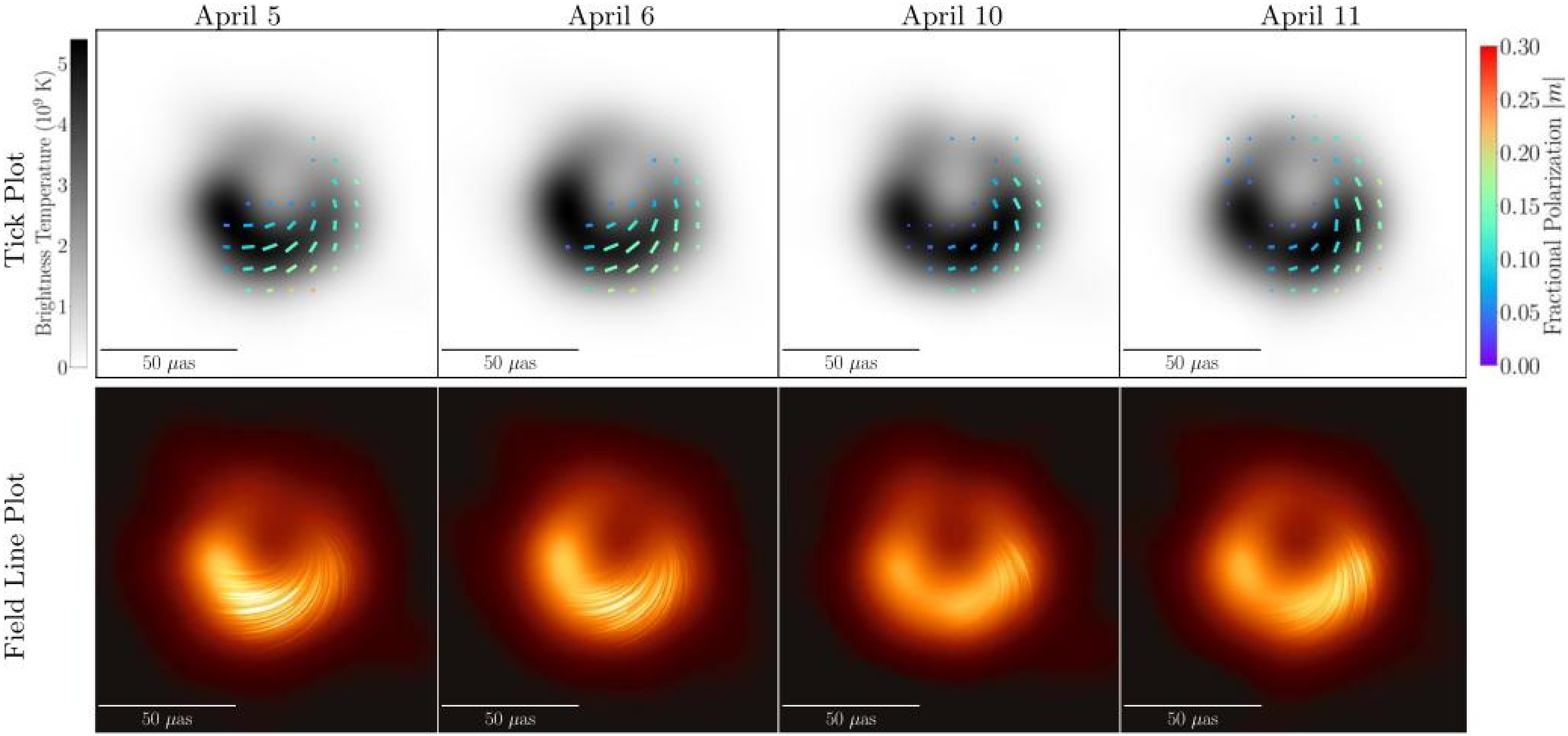




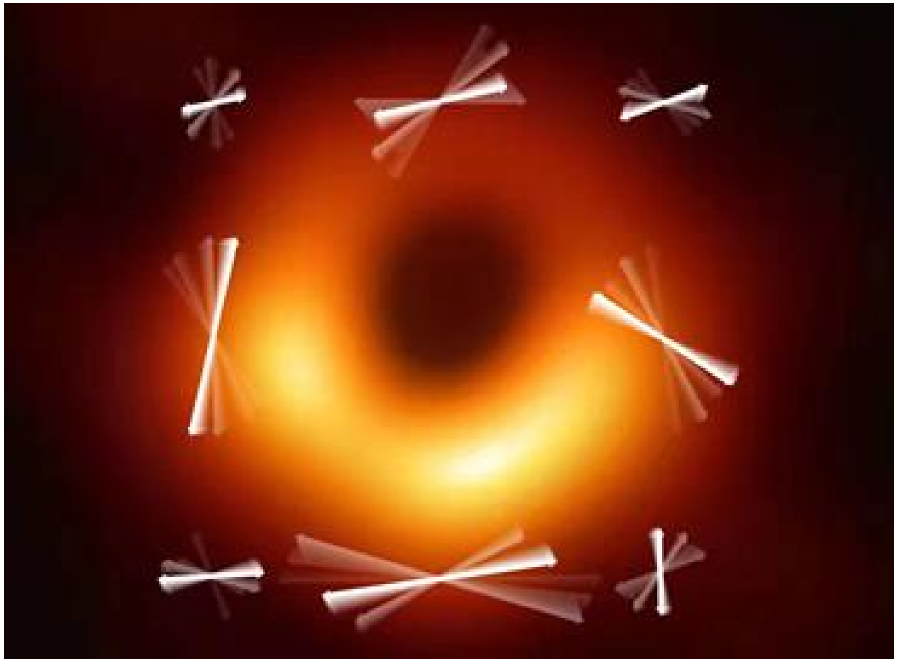
Chen, Shu, Xue, QY, Zhao, 2020, PRL, 124, 061102

EHT M87*偏振成像观测

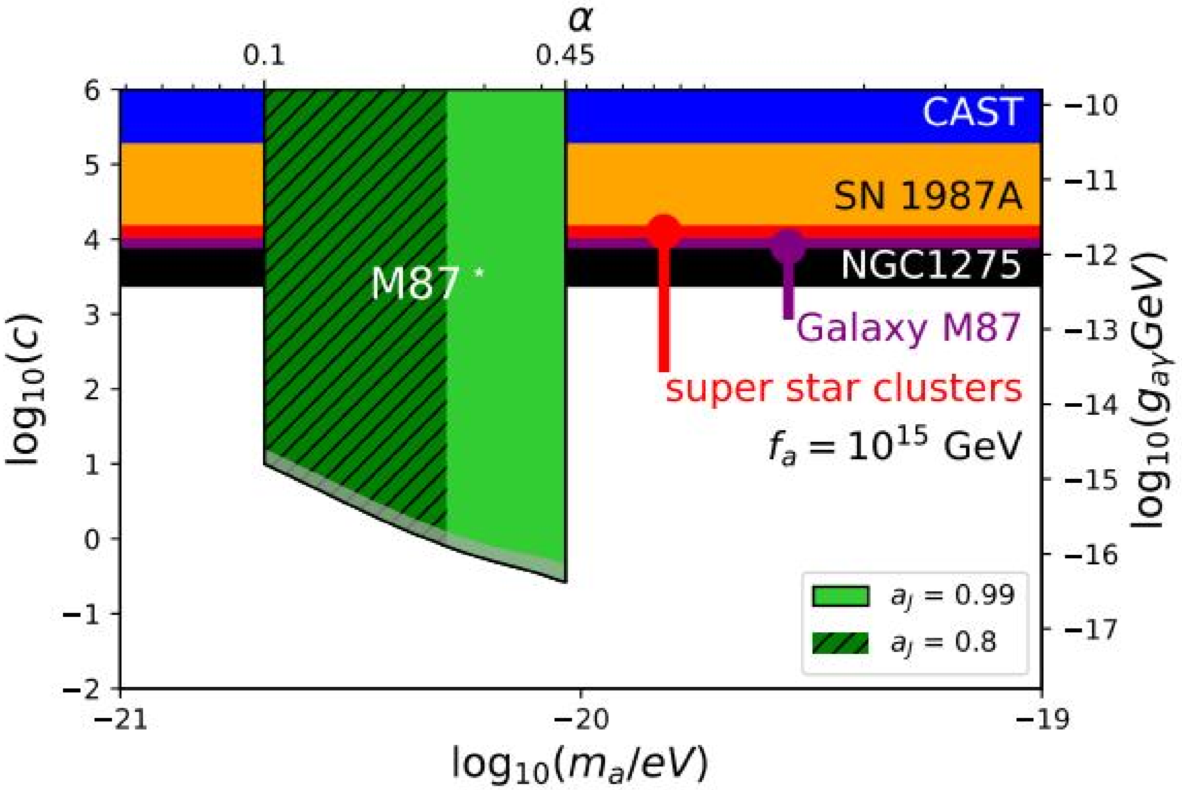
EHT Coll., 2021, ApJL, 910, L12



EHT偏振探测轴子/类轴子



Chen et al., 2105.04572



- ➢ 时间上周期性变化；方位角周期性变化
- ➢ EHT超高分辨的偏振成像正好可以用于探测此类效应

超轻“模糊”暗物质(fuzzy dark matter)

- 超轻的玻色暗物质以玻色-爱因斯坦凝聚状态存在，在大尺度上可以类似冷暗物质

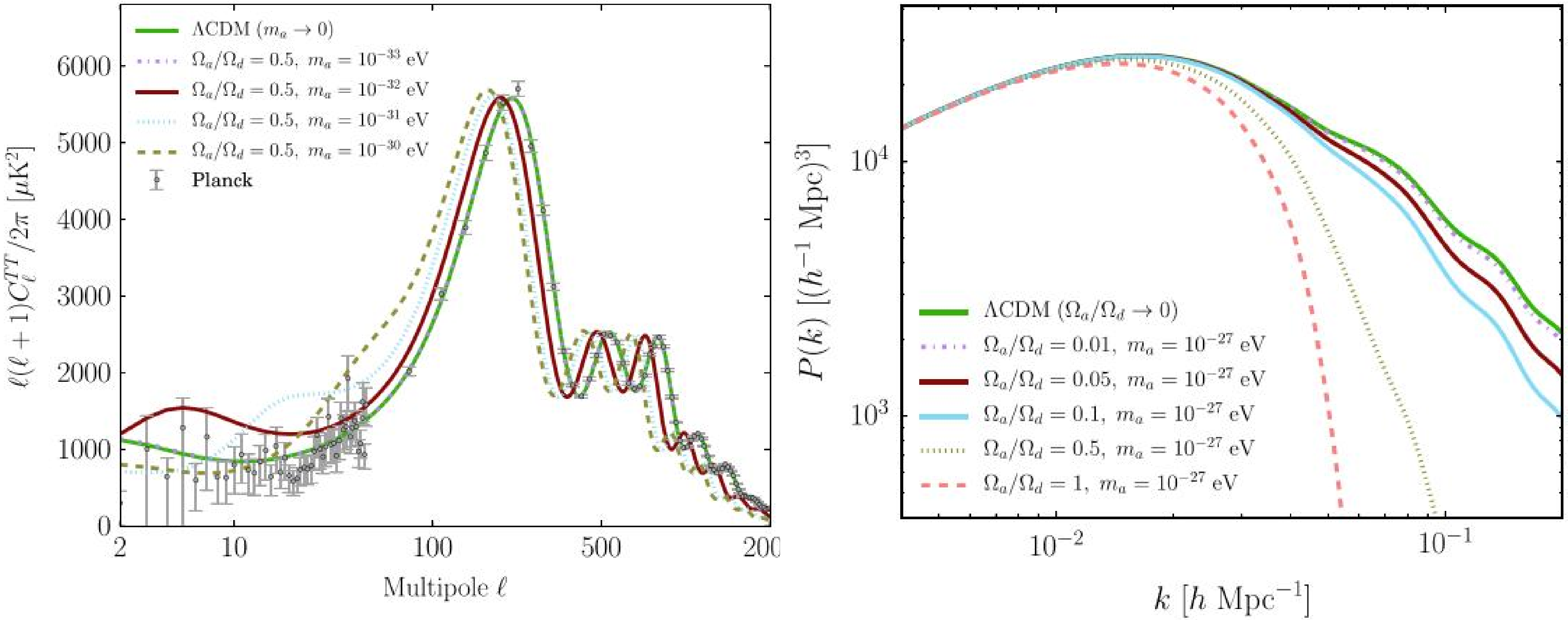
- 质量非常轻的粒子(~10^{-22} eV)更像一个波，波长相当于矮星系的尺度(kpc)，抹平小尺度结构(Hu et al., 2000)，解决冷暗物质模型的“小尺度危机”

$$i\left(\partial_t + \frac{3}{2}\frac{\dot{a}}{a}\right)\psi = \left(-\frac{1}{2m}\nabla^2 + m\Psi\right)\psi$$

$$i\partial_t\psi = \left(-\frac{1}{2m}\nabla^2 + m\Psi\right)\psi\,, \quad \nabla^2\Psi = 4\pi G\delta\rho$$

$$r_{Jh} \sim 3.4(c_{10}/f_{10})^{1/3} m_{22}^{-2/3} M_{10}^{-1/9} (\Omega_m h^2)^{-2/9}\mathrm{kpc}$$

FDM的宇宙学效应

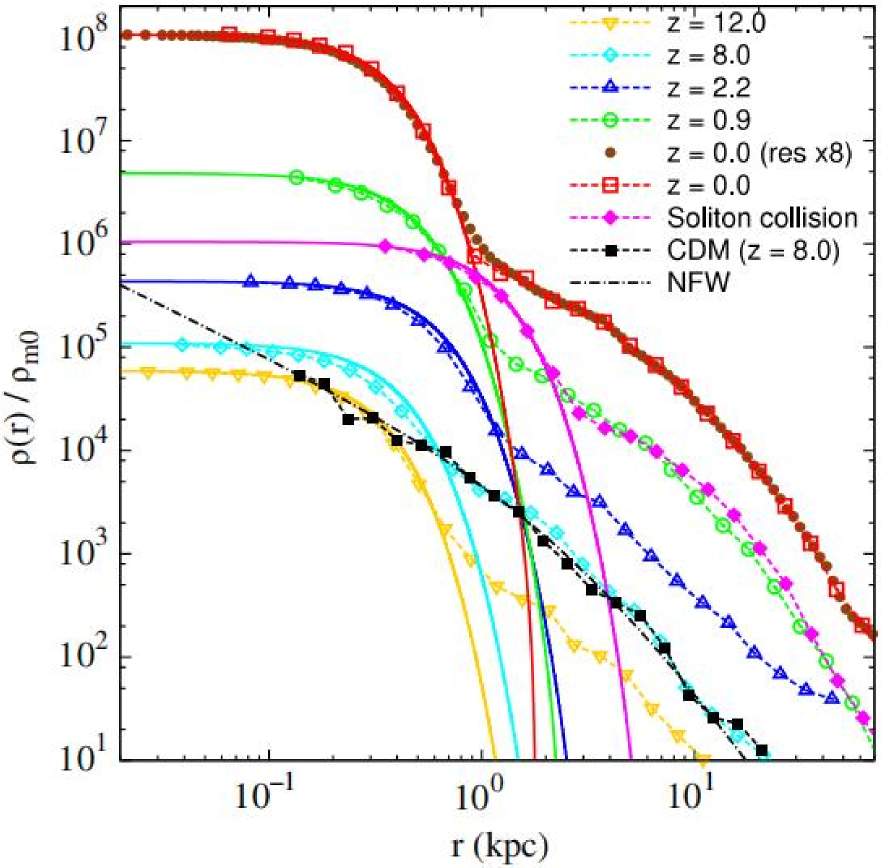


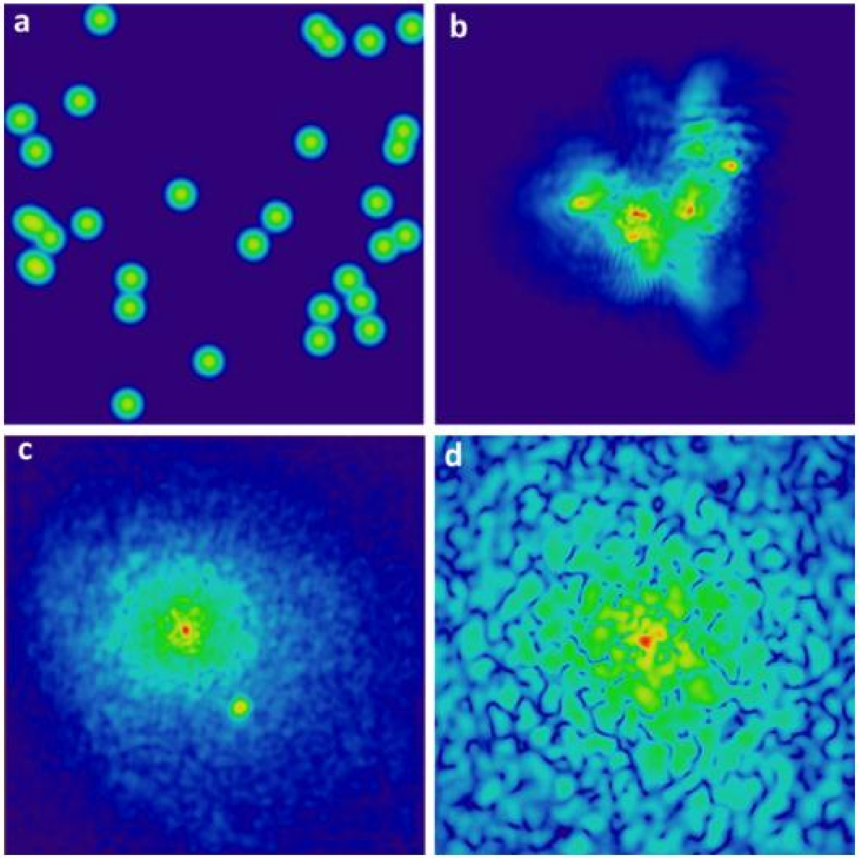
超轻暗物质($w \sim -1$)影响宇宙的膨胀率，从而影响CMB和物质功率谱；物质功率谱上主要体现为对小尺度结构的压低

Marsh, 2016, Phys. Rept.

FDM小尺度结构

Schive et al., 2014, PRL

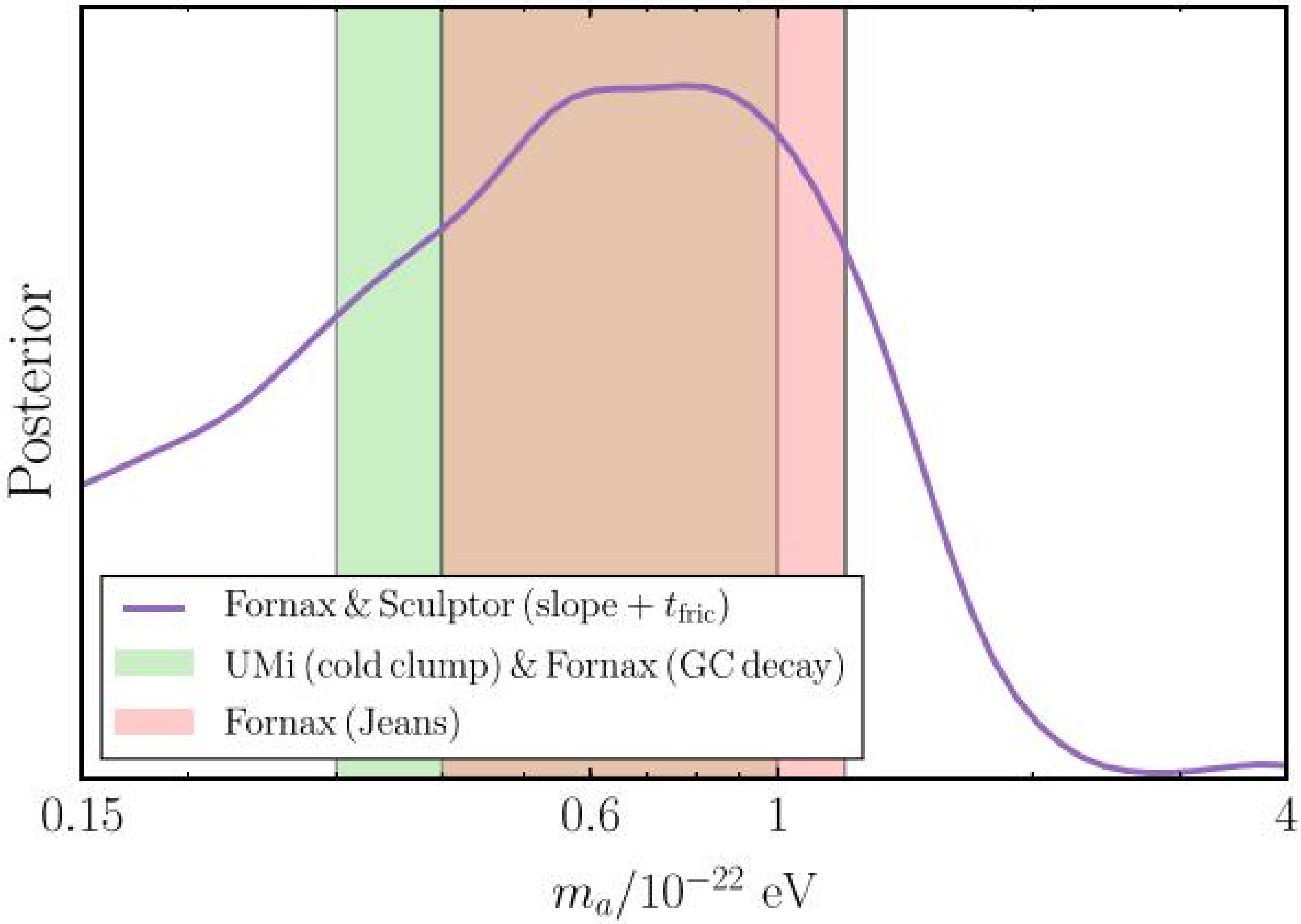




FDM形成的暗晕在小尺度表现为soliton core结构，大尺度和冷暗物质类似，可以解决冷暗物质模型的“小尺度危机”：

- The missing satellites problem [267,268]: CDM predicts more small Milky Way satellites than are observed.
- The too-big-to-fail problem [269]: CDM predicts more massive satellites that should contain stars than are observed.
- The cusp–core problem [270]: many observed low-mass systems contain flat central density profiles, not NFW cusps.

FDM解释矮星系结构

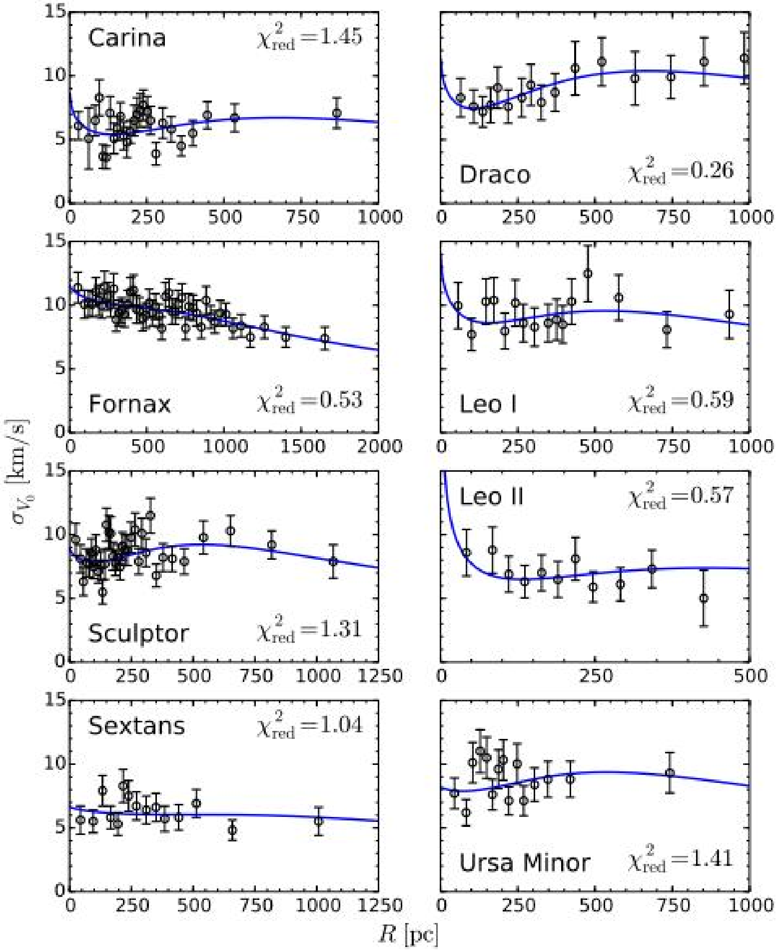


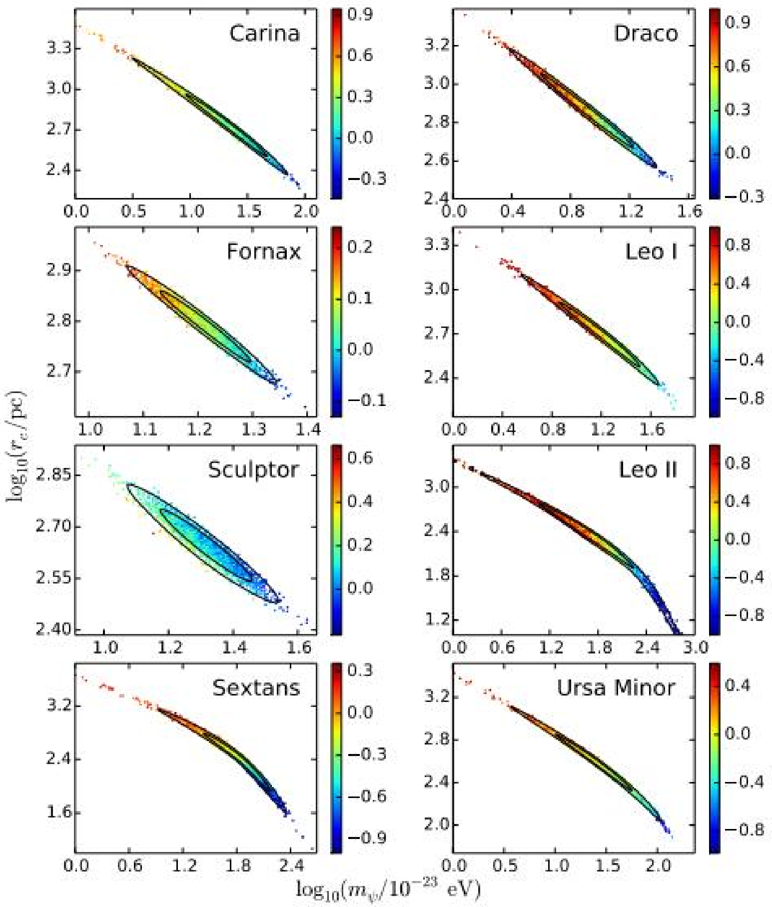
$$0.1 \times 10^{-22}\ \mathrm{eV} < m_a < 1.4 \times 10^{-22}\ \mathrm{eV}$$

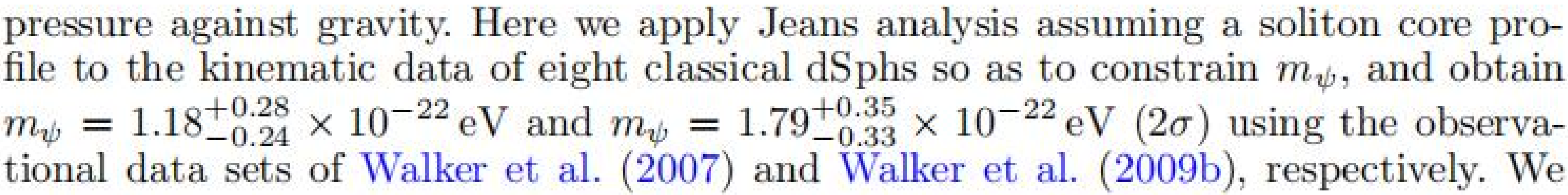
Marsh, 2016, Phys. Rept.

FDM解释矮星系结构

Chen et al., arXiv:1606.09030

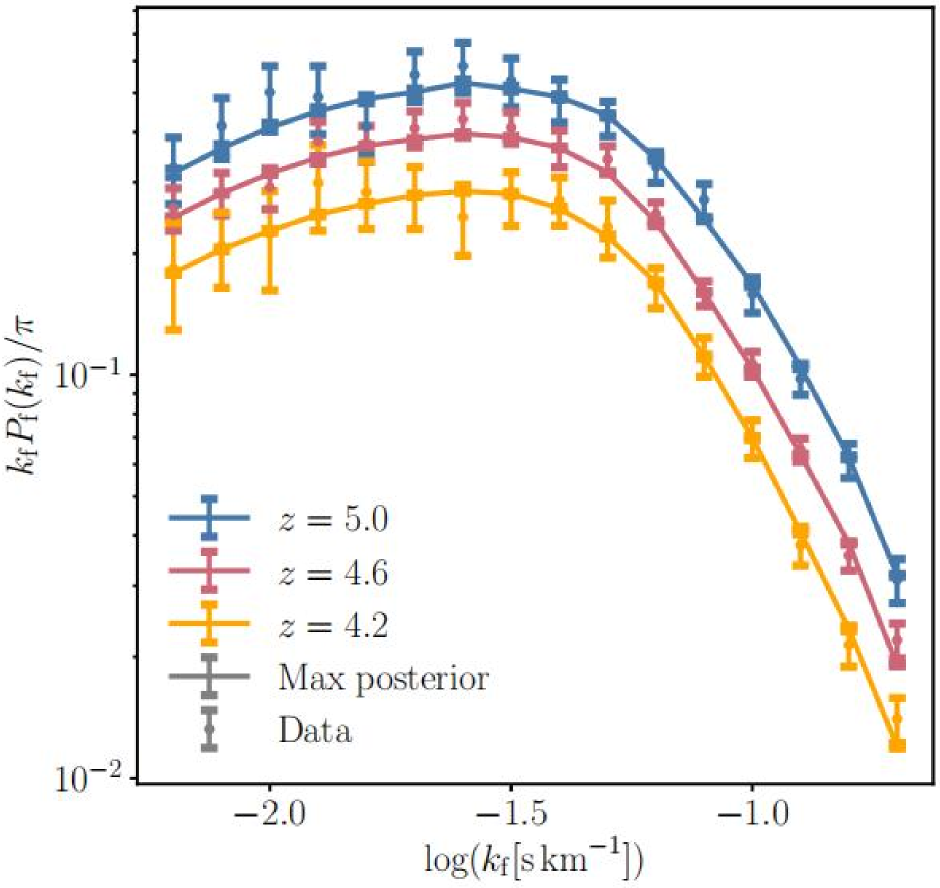


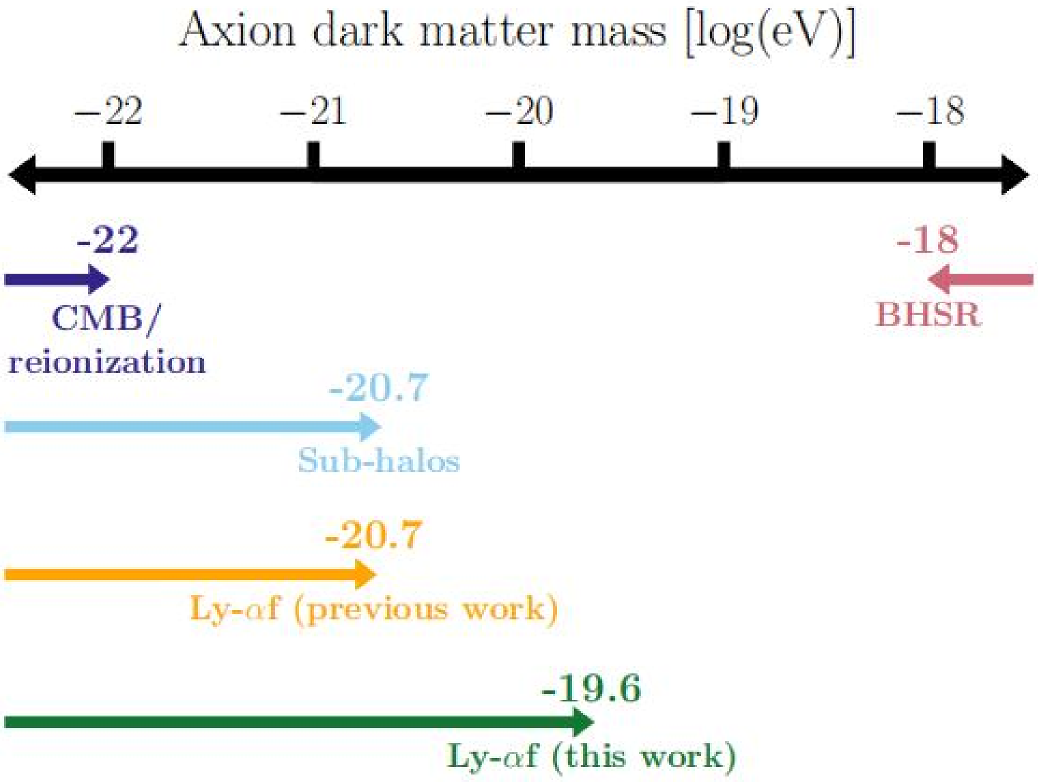



pressure against gravity. Here we apply Jeans analysis assuming a soliton core profile to the kinematic data of eight classical dSphs so as to constrain m_ψ, and obtain $m_\psi = 1.18^{+0.28}_{-0.24} \times 10^{-22}$ eV and $m_\psi = 1.79^{+0.35}_{-0.33} \times 10^{-22}$ eV (2σ) using the observational data sets of Walker et al. (2007) and Walker et al. (2009b), respectively. We

Lyα森林的限制

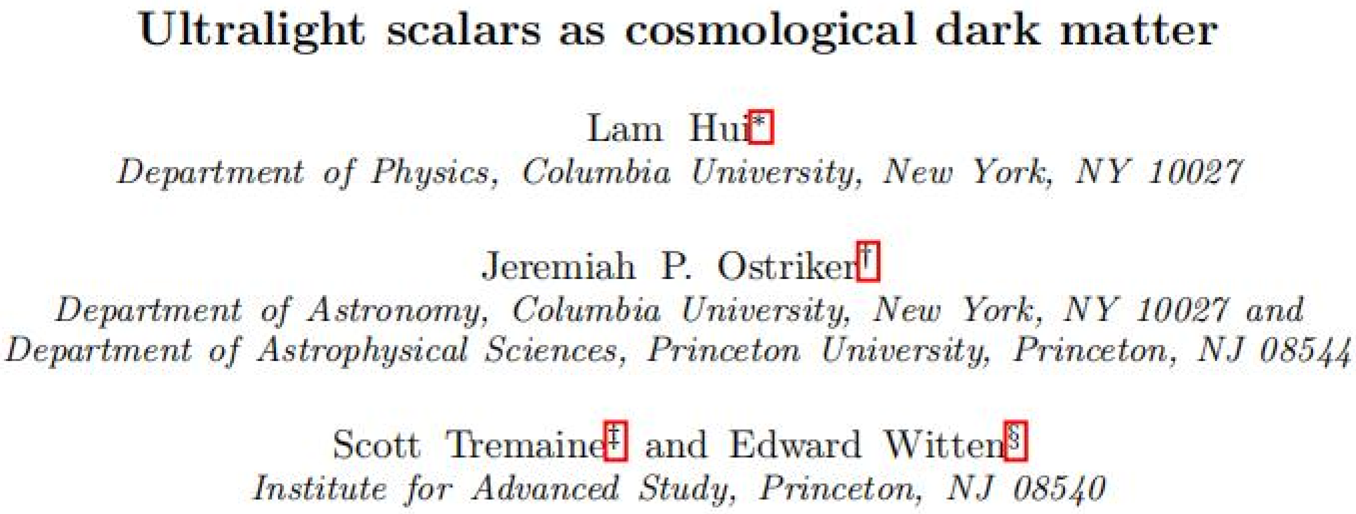
arXiv:2007.12705





We present a new bound on the ultra-light axion (ULA) dark matter mass m_a, using the Lyman-alpha forest to look for suppressed cosmic structure growth: a 95% lower limit $m_a > 2 \times 10^{-20}$ eV.

Lyα森林和矮椭球星系的结果稍微存在矛盾



Ultralight scalars as cosmological dark matter

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Jeremiah P. Ostriker[†]
Department of Astronomy, Columbia University, New York, NY 10027 and
Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544

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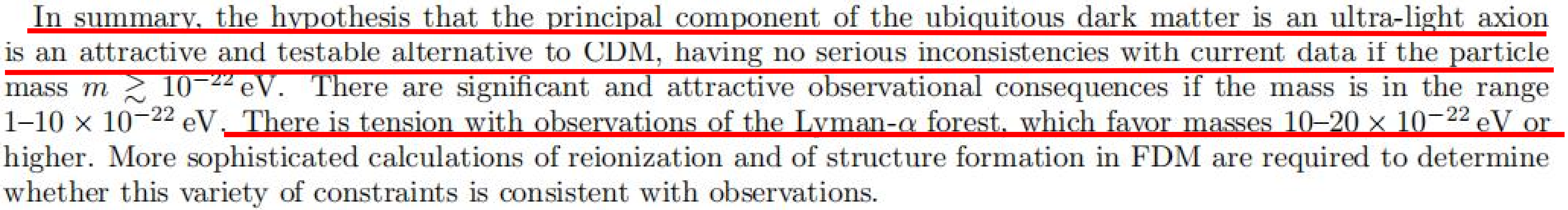


In summary, the hypothesis that the principal component of the ubiquitous dark matter is an ultra-light axion is an attractive and testable alternative to CDM, having no serious inconsistencies with current data if the particle mass $m \gtrsim 10^{-22}\,\mathrm{eV}$. There are significant and attractive observational consequences if the mass is in the range $1\text{–}10 \times 10^{-22}\,\mathrm{eV}$. There is tension with observations of the Lyman-α forest, which favor masses $10\text{–}20 \times 10^{-22}\,\mathrm{eV}$ or higher. More sophisticated calculations of reionization and of structure formation in FDM are required to determine whether this variety of constraints is consistent with observations.

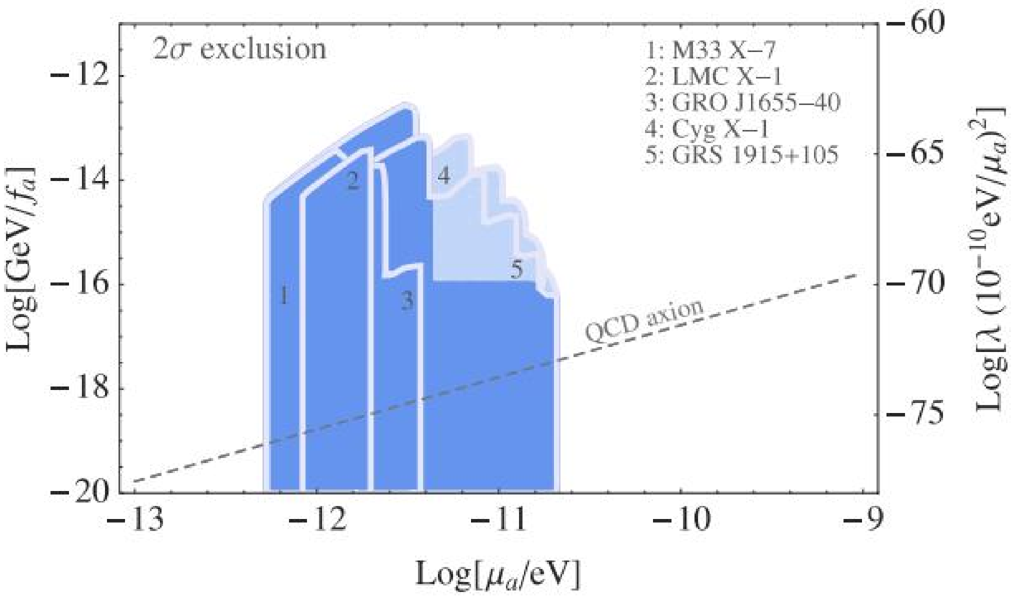
黑洞自旋和超轻暗物质

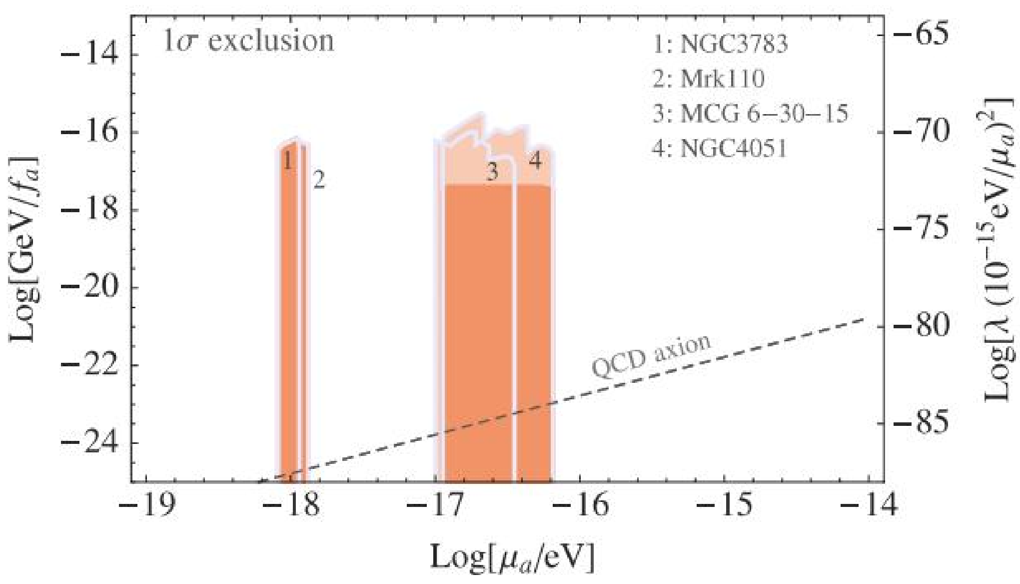
- 满足一定条件的玻色粒子会通过提取黑洞转动能形成玻色云，称为超辐射(Penrose过程)
- 考虑玻色子的自相互作用，玻色云密度增长至某临界值后会发生坍缩(bosenova)，最大容许玻色云粒子数变为$N_{bosenova}$
- 通过测量黑洞自旋可以对该过程给出限制

$$N_{\rm max} \simeq \frac{G M_{\rm bh}^2}{\mu} \Delta a_* ,$$

$$\Gamma \tau_{\rm bh} > \ln N_{\rm max}$$

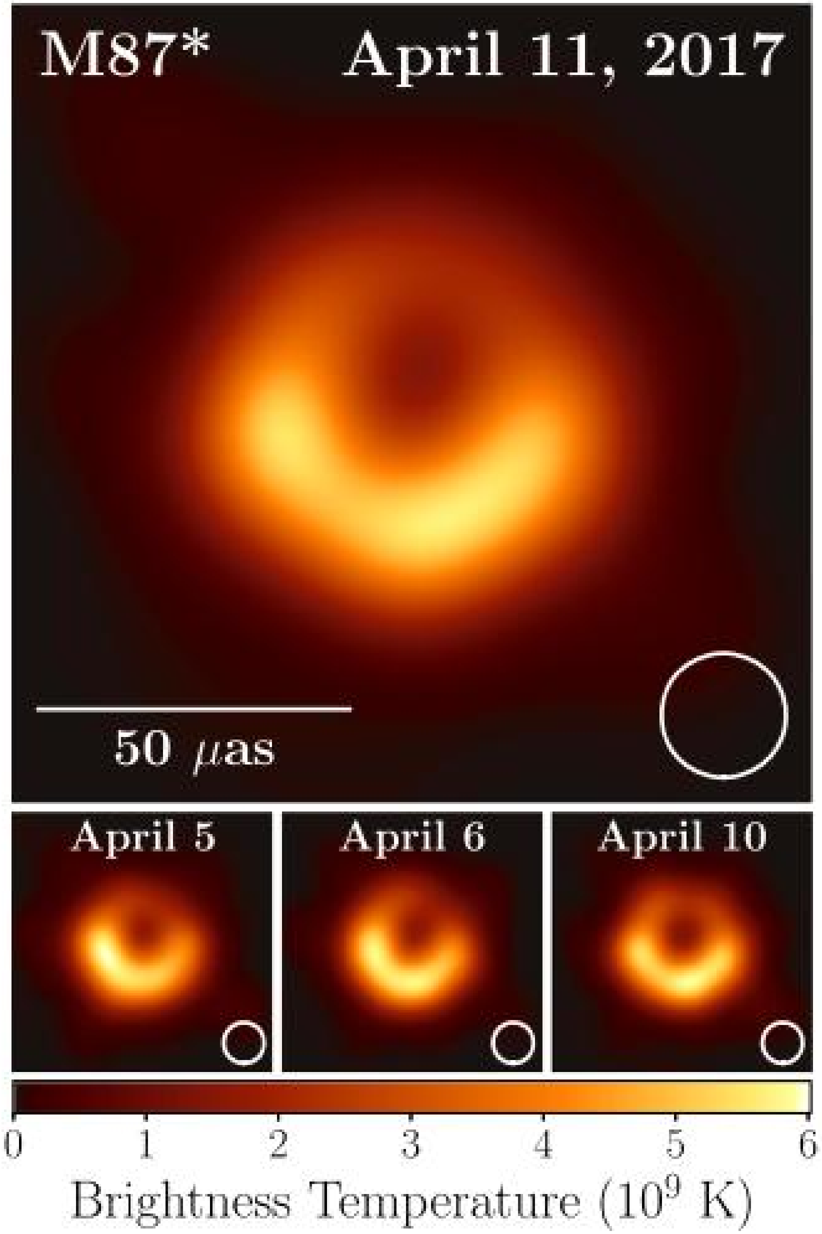
$$\Gamma \tau_{\rm bh} (N_{\rm bosenova}/N_{\rm max}) > \ln N_{\rm bosenova}$$





Marsh, 2016, Phys. Rept.

黑洞自旋和超轻暗物质

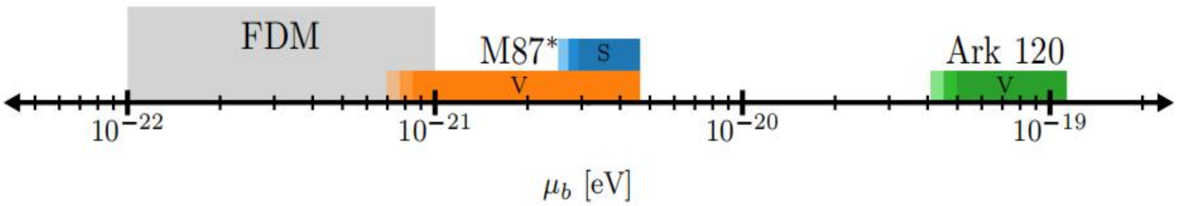


Ultralight Boson Dark Matter and Event Horizon Telescope Observations of M87*

Hooman Davoudiasl and Peter B. Denton
Phys. Rev. Lett. **123**, 021102 – Published 10 July 2019

Physics See Viewpoint: Supermassive Black Hole May Constrain Superlight Dark Matter

$$|a| \gtrsim 0.5$$



黑洞自旋和超轻暗物质

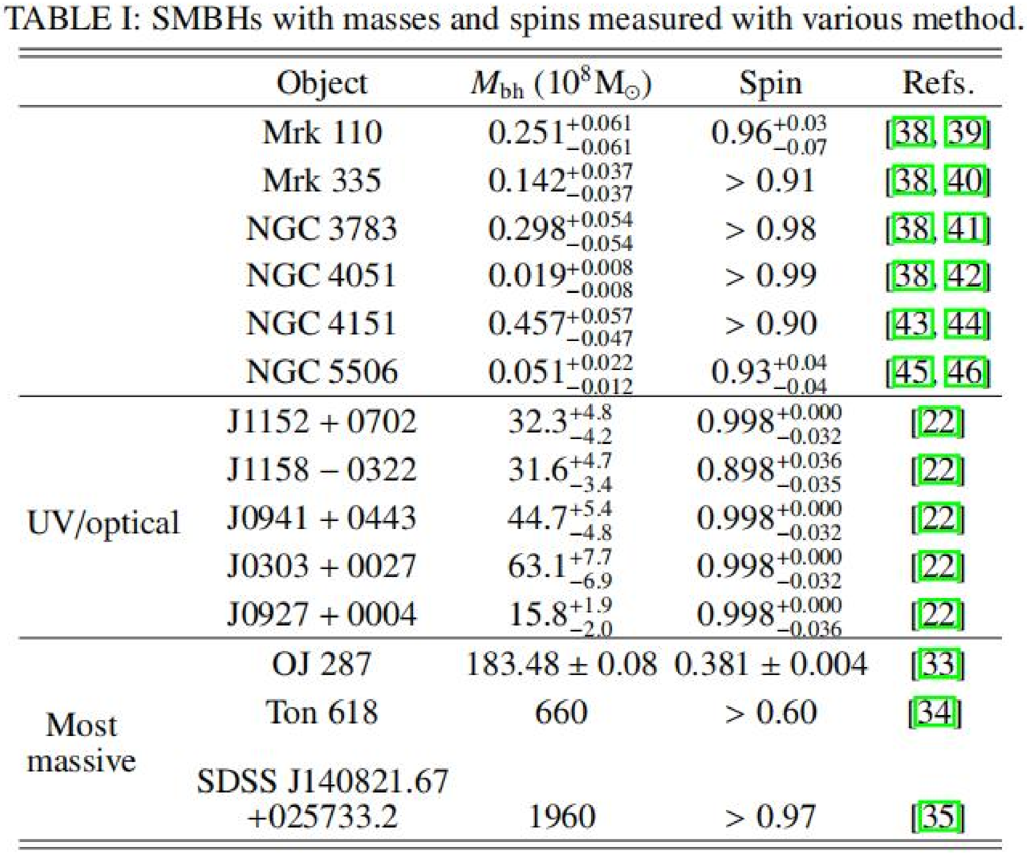


TABLE I: SMBHs with masses and spins measured with various method.

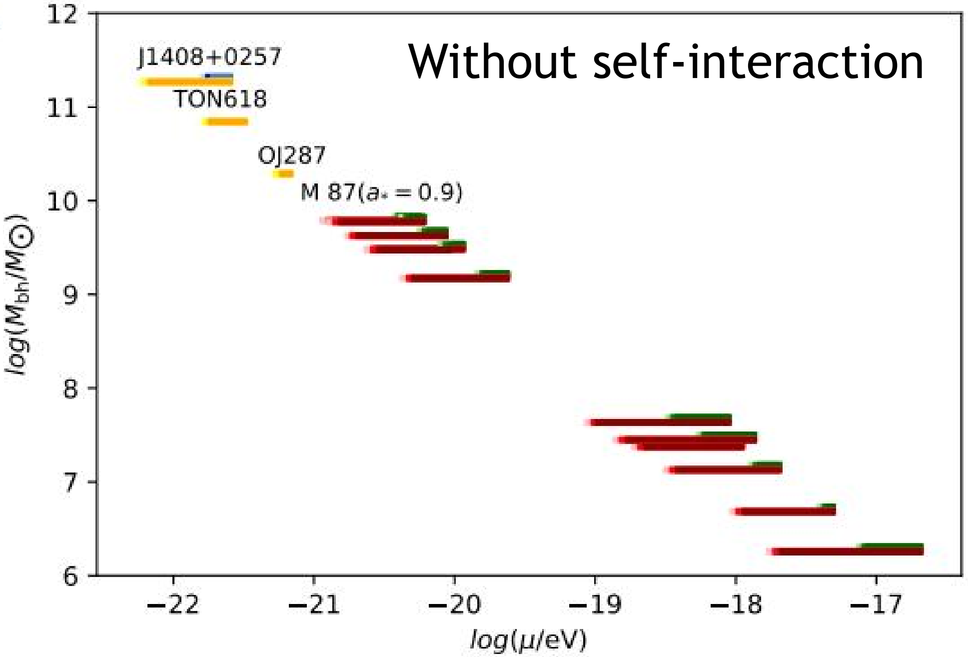
	Object	$M_{\rm bh}$ ($10^8 M_\odot$)	Spin	Refs.
	Mrk 110	$0.251^{+0.061}_{-0.061}$	$0.96^{+0.03}_{-0.07}$	[38, 39]
	Mrk 335	$0.142^{+0.037}_{-0.037}$	> 0.91	[38, 40]
	NGC 3783	$0.298^{+0.054}_{-0.054}$	> 0.98	[38, 41]
	NGC 4051	$0.019^{+0.008}_{-0.008}$	> 0.99	[38, 42]
	NGC 4151	$0.457^{+0.057}_{-0.047}$	> 0.90	[43, 44]
	NGC 5506	$0.051^{+0.022}_{-0.012}$	$0.93^{+0.04}_{-0.04}$	[45, 46]
UV/optical	J1152 + 0702	$32.3^{+4.8}_{-4.2}$	$0.998^{+0.000}_{-0.032}$	[22]
	J1158 − 0322	$31.6^{+4.7}_{-3.4}$	$0.898^{+0.036}_{-0.035}$	[22]
	J0941 + 0443	$44.7^{+5.4}_{-4.8}$	$0.998^{+0.000}_{-0.032}$	[22]
	J0303 + 0027	$63.1^{+7.7}_{-6.9}$	$0.998^{+0.000}_{-0.032}$	[22]
	J0927 + 0004	$15.8^{+1.9}_{-2.0}$	$0.998^{+0.000}_{-0.036}$	[22]
Most massive	OJ 287	183.48 ± 0.08	0.381 ± 0.004	[33]
	Ton 618	660	> 0.60	[34]
	SDSS J140821.67 +025733.2	1960	> 0.97	[35]

$$\Gamma_s = \frac{1}{24} a_* r_g^8 \mu^9,$$

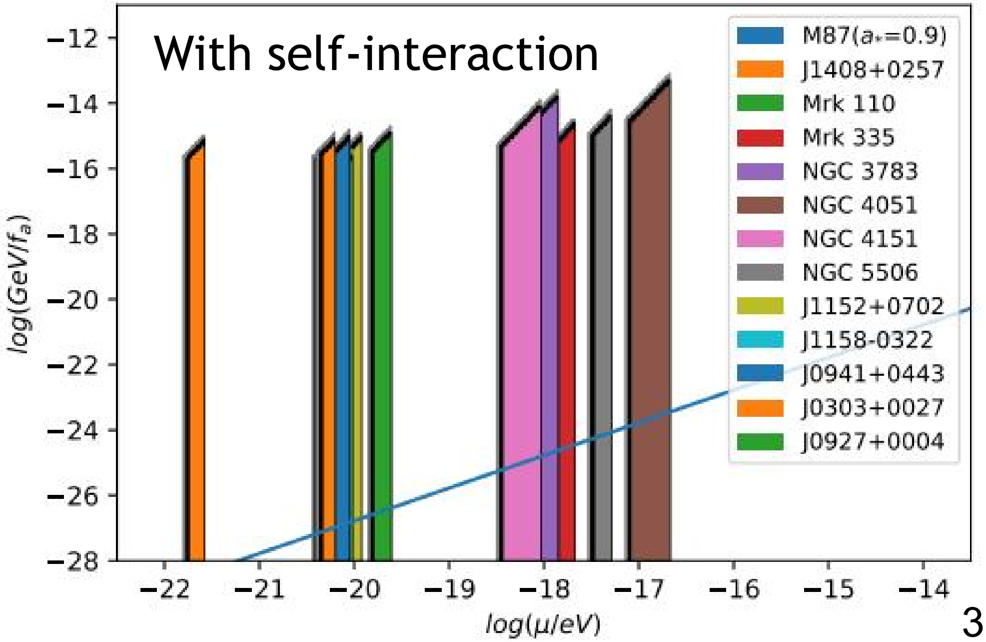
$$\frac{dN}{dt} = \Gamma N.$$

$$\Gamma_v = 4 a_* r_g^6 \mu^7,$$

Zu et al., 2020, EPJP, 135, 709

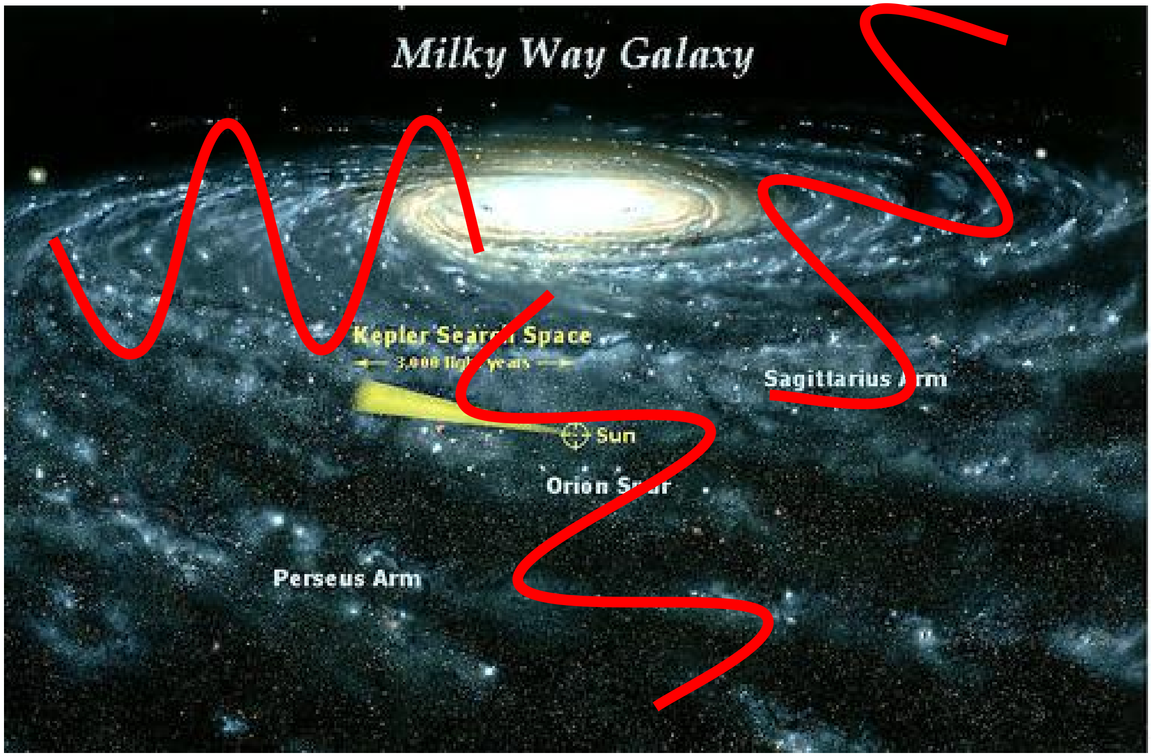


Without self-interaction

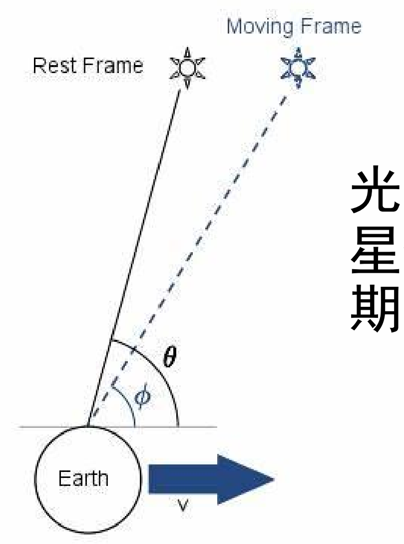


With self-interaction

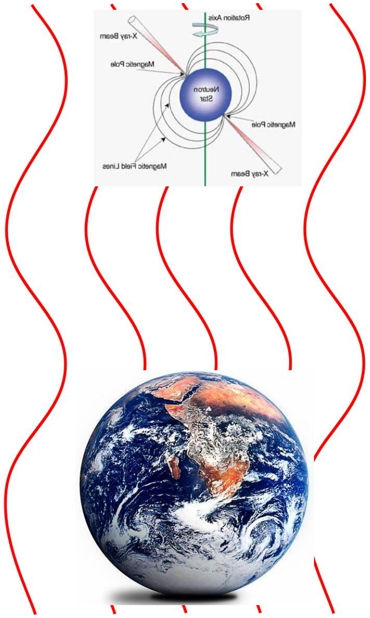
恒星位置和脉冲星计时探测超轻暗物质



质量非常轻(<10^{-20} eV)的暗物质表现出宏观的波动性，其和物质的相互作用与引力波导致的时空扰动相似，可以在天体位置或者脉冲到达时间上留下印记

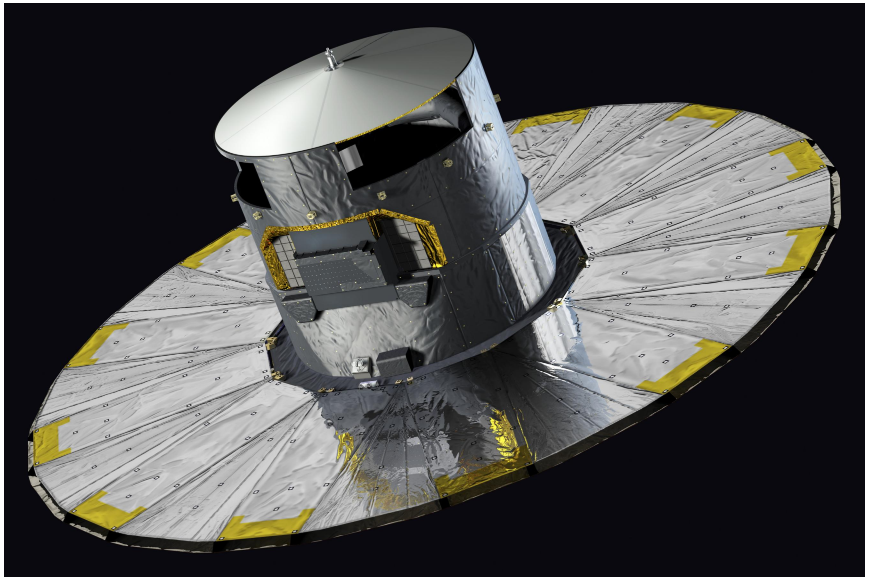


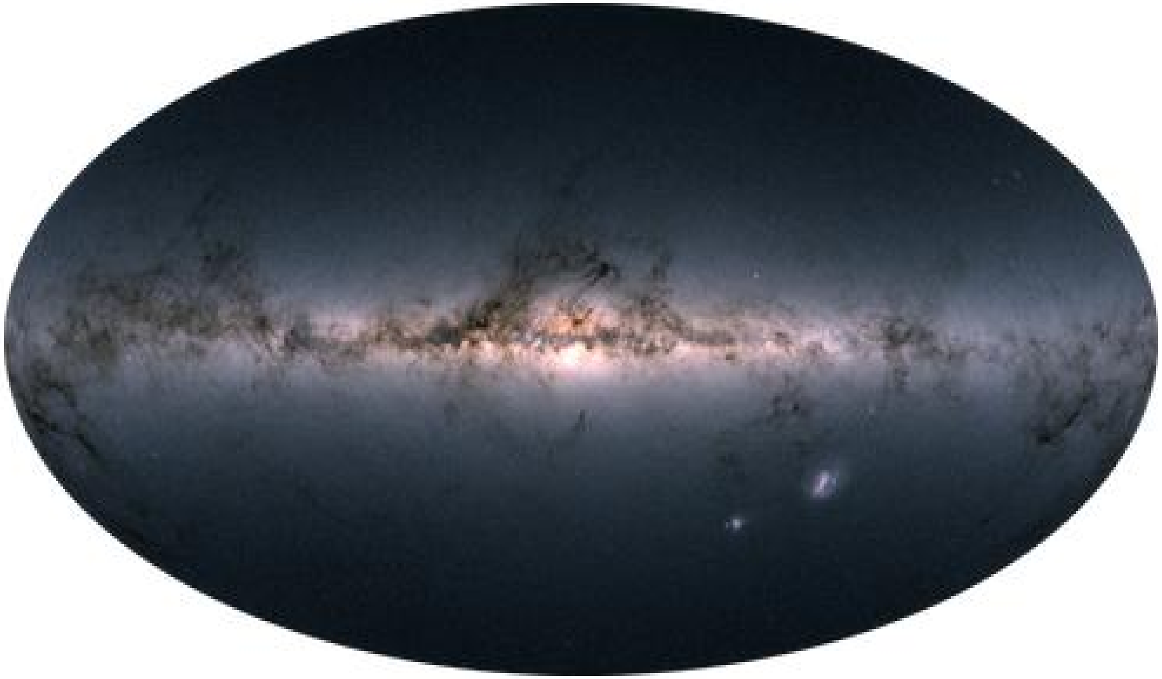
光行差导致恒星位置产生周期性额外摆动



脉冲星或地球运动导致脉冲到达时间超前或滞后

Gaia高精度天体位置测量





- Gaia将以非常高的精度(~100 μas)观测大量(~10^9)恒星的位置和运动
- 将带来银河系结构和动力学、恒星物理、地外行星、基础物理等领域的革命性突破

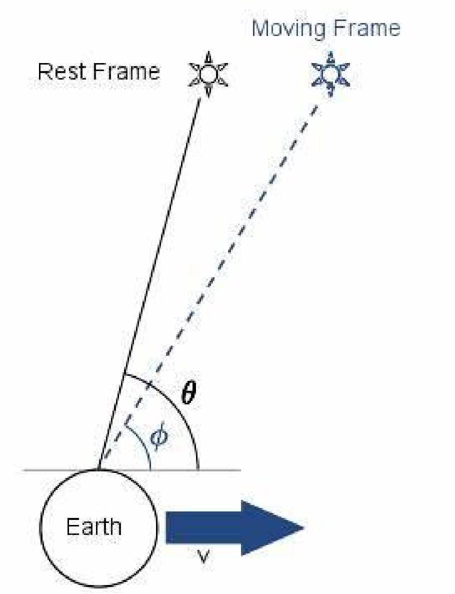
超轻暗光子导致天体位置变化

- 考虑一类暗光子模型：它们以微弱的耦合强度和重子数B或者重子-轻子之差B-L (dark charge)不为零的物体相互作用

- Gaia卫星在暗光子场中会感受到一个周期性振荡的加速度

$$\boldsymbol{a}(t,\boldsymbol{x}) \simeq \epsilon e \frac{q}{m} m_A \boldsymbol{A}_0 \cos(m_A t - \boldsymbol{k}\cdot\boldsymbol{x})$$

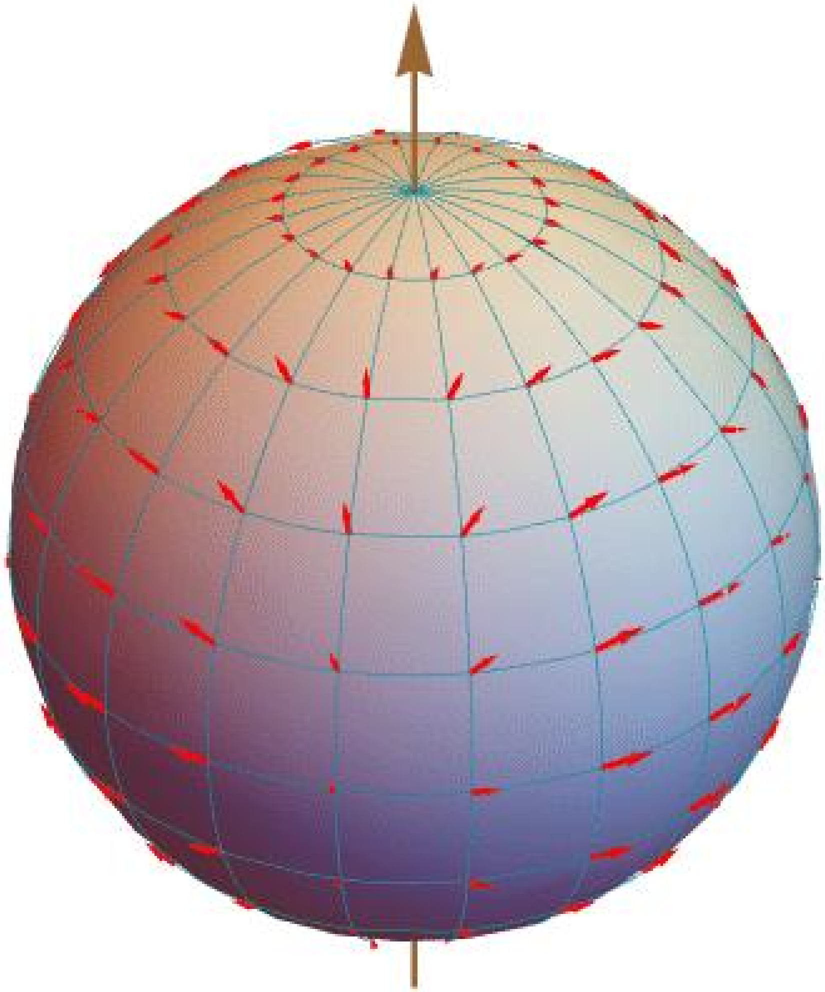
- 该加速度导致卫星产生一项额外的周期性运动，由于光行差现象使得远处的恒星视位置发生改变

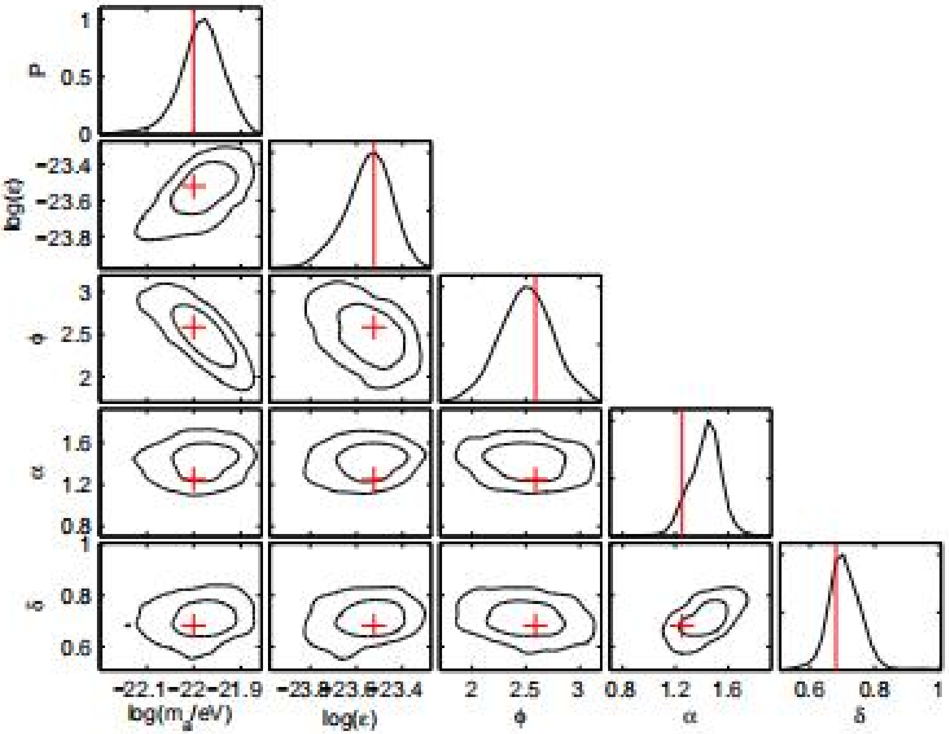


$$\Delta\boldsymbol{v}(t,\boldsymbol{x}) \simeq \epsilon e \frac{q}{m} \boldsymbol{A}_0 \sin(m_A t - \boldsymbol{k}\cdot\boldsymbol{x}). \qquad \Delta\theta \simeq -\Delta v \, \sin\theta$$

- 大量恒星的运动会形成一个规律的图案，反映暗光子场的性质

模拟和参数重建



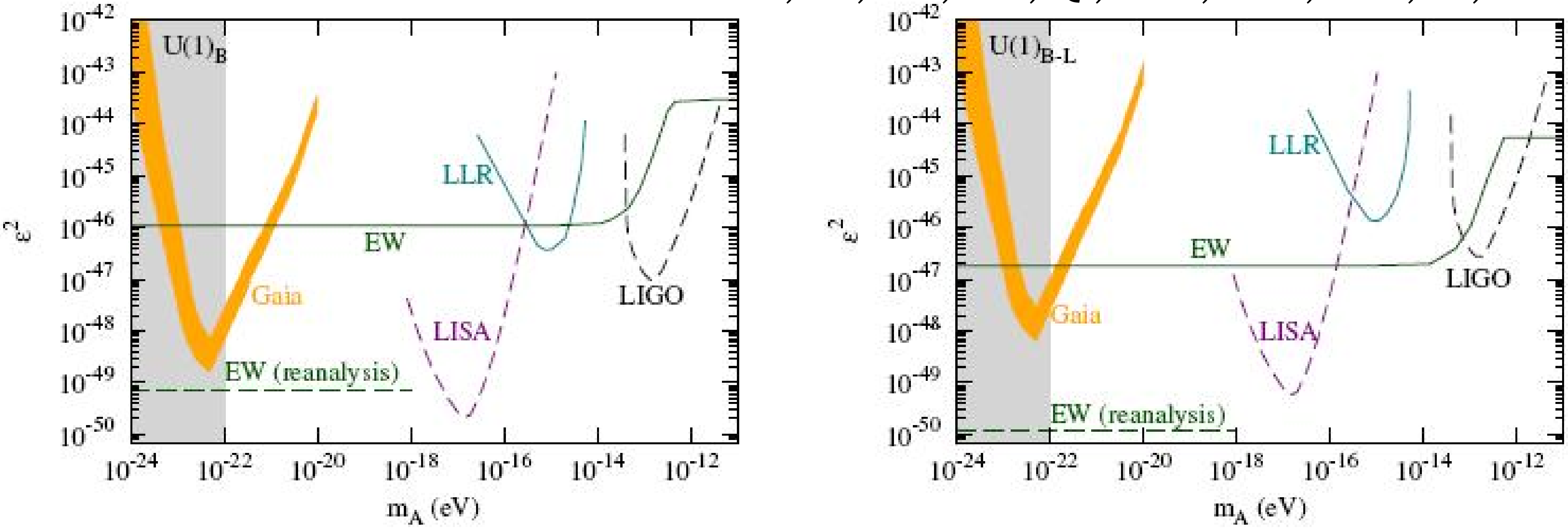


$$(m_A, \epsilon, \phi, \alpha, \delta) = (10^{-22}\ \mathrm{eV}, 3\times 10^{-24}, 2.59, 1.25, 0.68)$$

Guo, Ma, Shu, Xue, QY, Zhao, 2019, JCAP, 05, 015

Gaia对超轻暗光子的灵敏度

Guo, Ma, Shu, Xue, QY, Zhao, 2019, JCAP, 05, 015



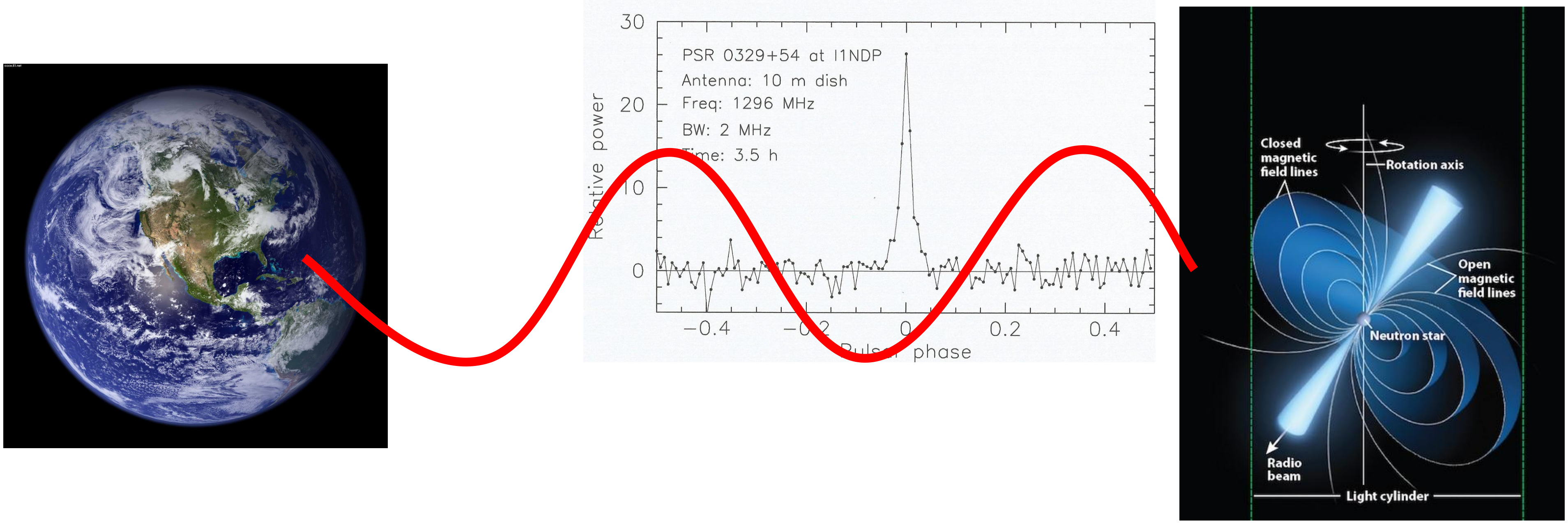
- ➢ 对$m_A<10^{-21}$ eV区间将达到比实验室探测更好的灵敏度
- ➢ 很低质量区间($m_A<10^{-22}$ eV)灵敏度变差是由于长周期振荡和恒星自行的简并；高质量区间灵敏度变差是因为暗光子场振幅变小

PTA探测超轻暗光子

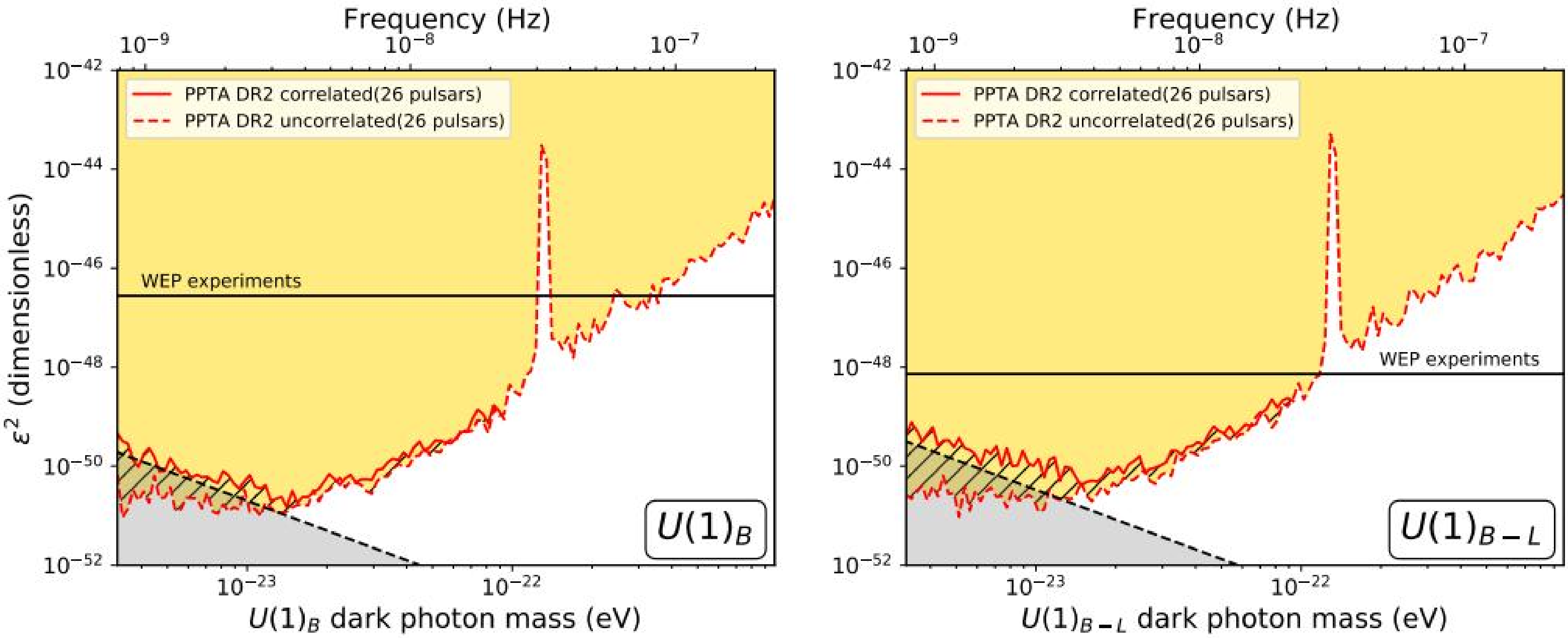
脉冲星和地球在暗光子场中均会产生振荡，导致脉冲到达时间出现残差：

$$\delta \boldsymbol{x}_{e,p}(t) \simeq -\frac{\epsilon e q}{m_A m} \boldsymbol{A}_0^{e,p} \cos\left[m_A(t-t_0)+\alpha_{e,p}\right]$$

$$\Delta t_r^d(t) = \frac{\left|\boldsymbol{d}+\delta\boldsymbol{x}_p\left(t-\frac{|\boldsymbol{d}|}{v(t)}\right)-\delta\boldsymbol{x}_e(t)\right|-|\boldsymbol{d}|}{v(t)} \simeq \frac{\boldsymbol{n}_p\cdot\Delta\boldsymbol{x}(t)}{v(t)},$$



暗光子模型参数限制



Xue et al., with PPTA
(2022, Phys. Rev. Res., 4, L012022)

天文观测的发展趋势

- **测量准**：空间分辨率高、时间分辨率高、能量分辨率高
- **样本多**：大视场、大深度、高采样
- **手段全**：全波段、多信使

天文精测在暗物质粒子探测中发挥的重要作用越来越得以凸显！

总结 & 展望

- 暗物质候选体形形色色，跨越非常大的能段，实验探测具有很大挑战

- 天文观测是通常粒子物理实验方法的重要补充，而且更为重要的是天文观测可以覆盖比实验室探测更宽的质量范围，探索更多的可能性

- 未来的天文学观测将更倾向于大数据、高精度、高分辨、全波段，将在暗物质探测领域大有可为

- 中国的机会：FAST、LHAASO、SKA、CSST、ngEHT、eXTP、VLAST