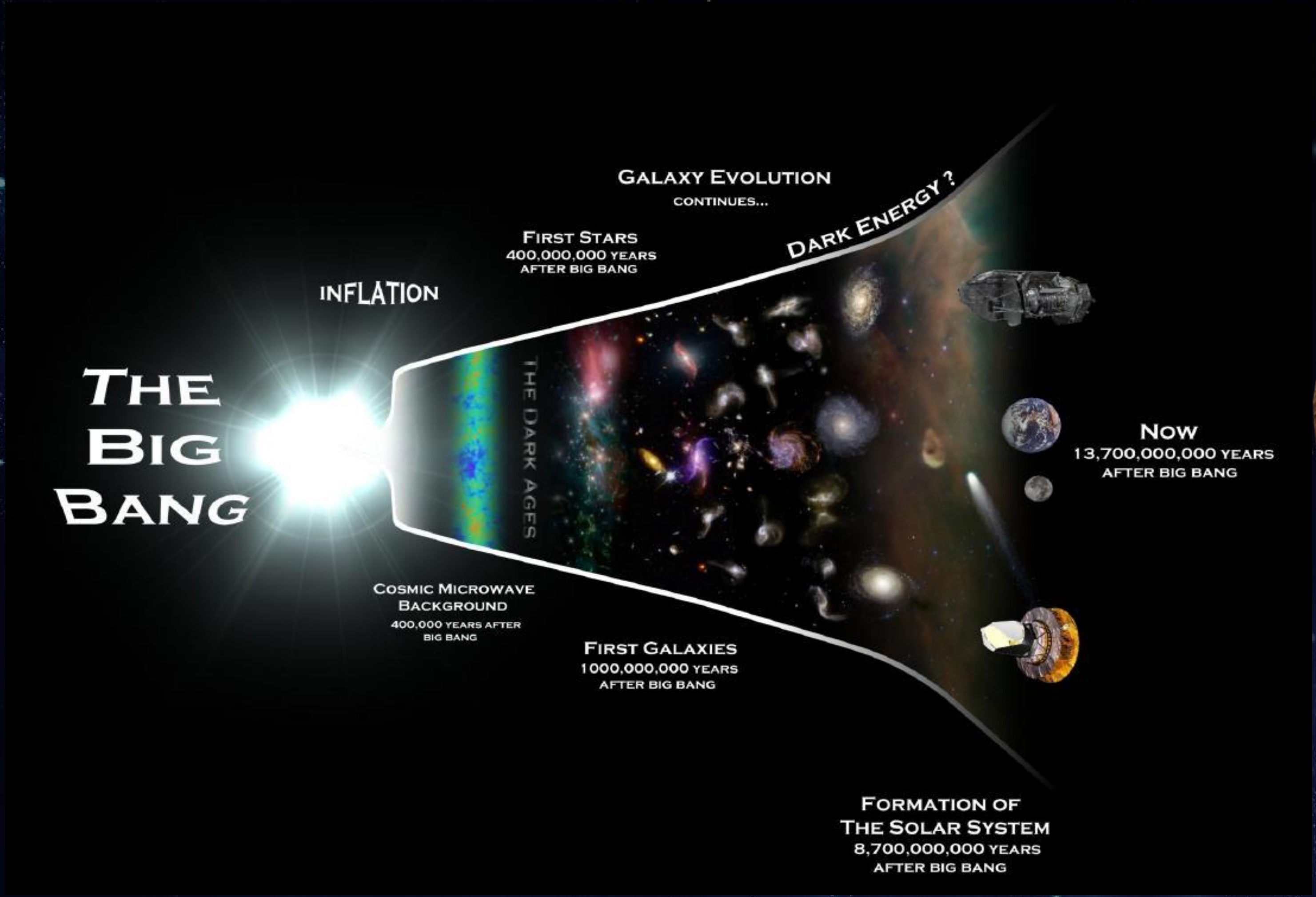
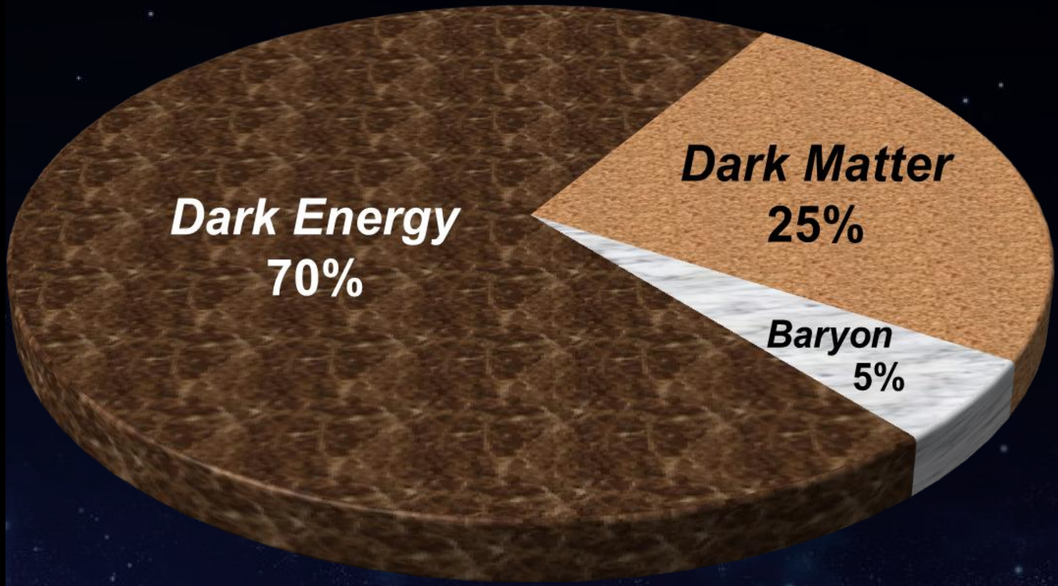
Probing Dark Matter Particles with Astronomical Observations

Qiang Yuan
Purple Mountain Observatory, CAS

17th workshop of TeV physics, Nanjing, 2023.12.15-19

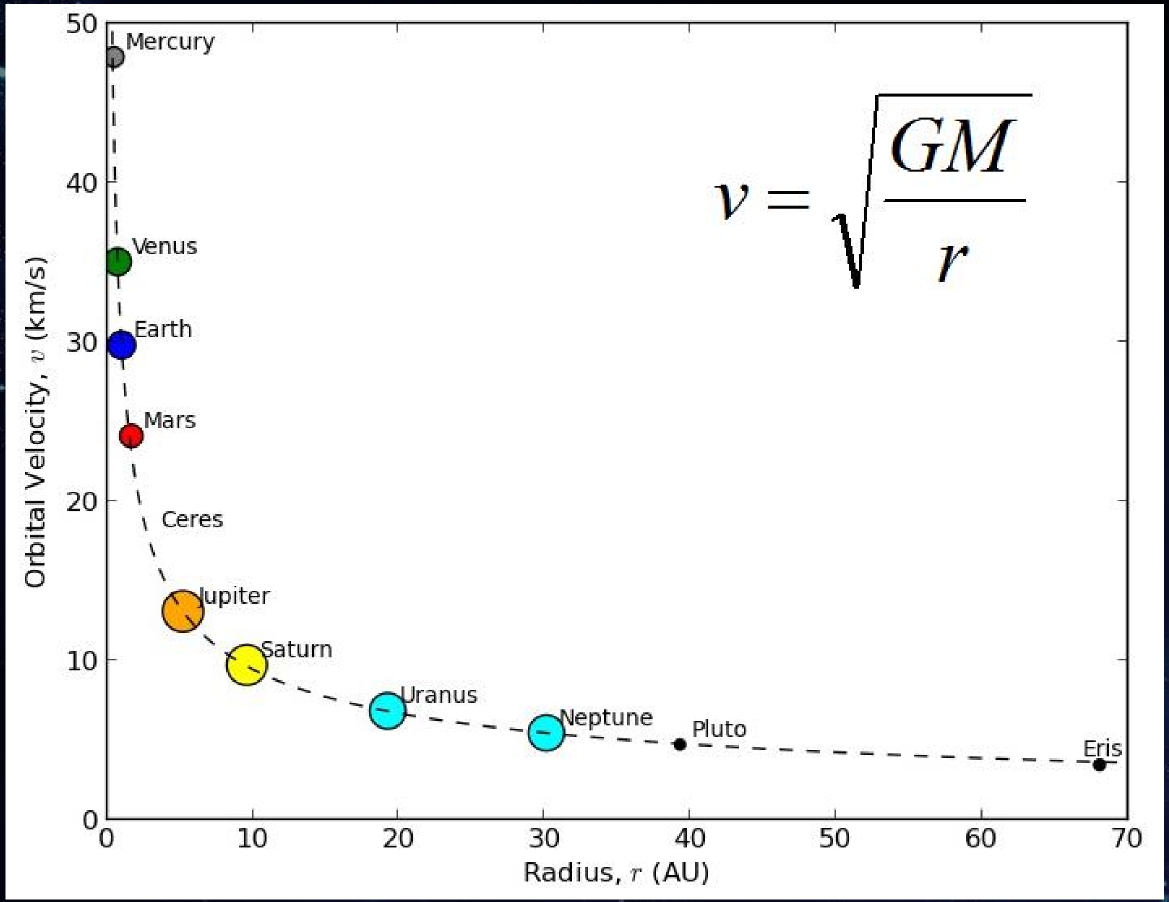
Standard cosmology



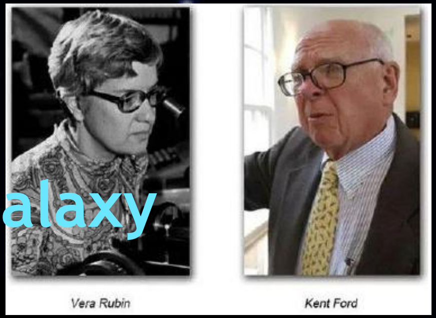


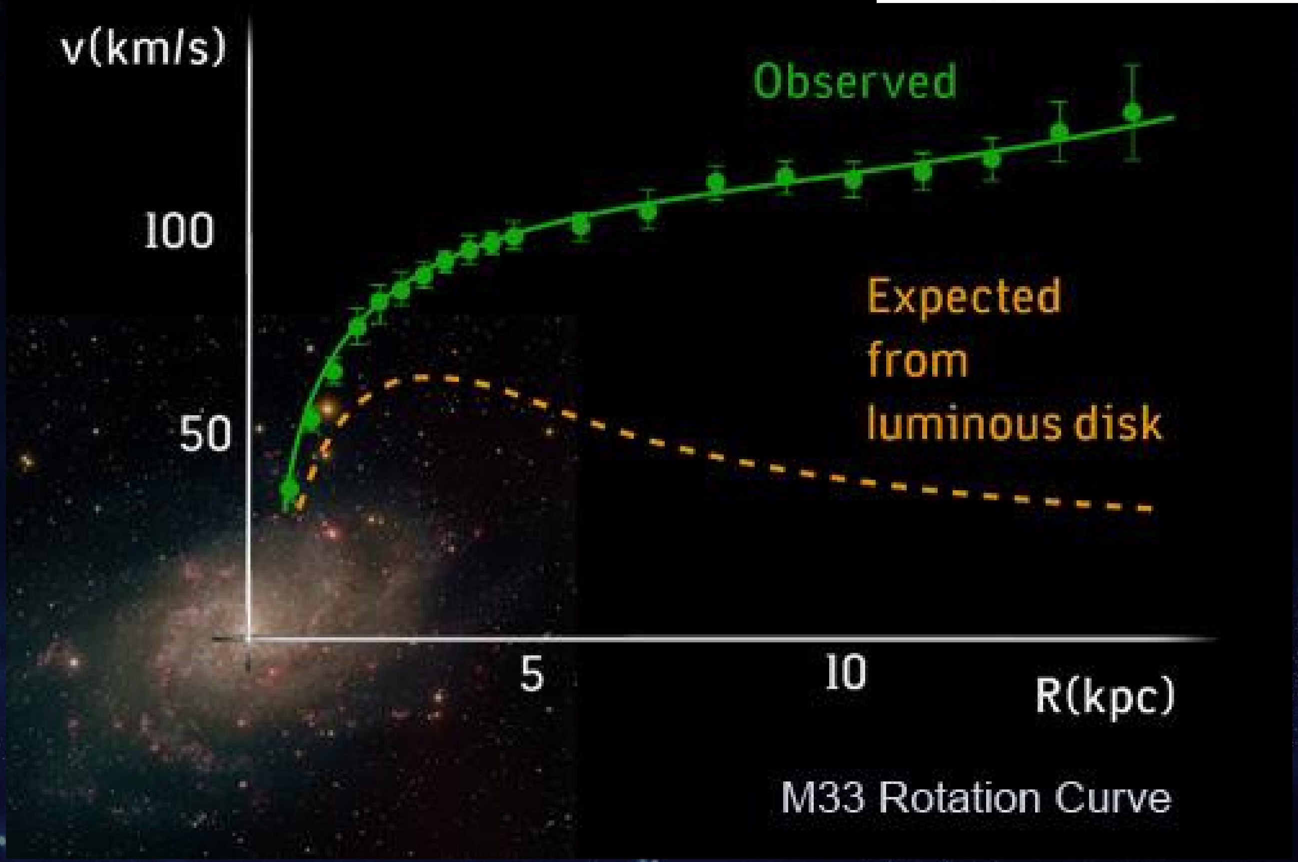
Why we need dark matter?

Rotation curve of plantes orbiting the Sun

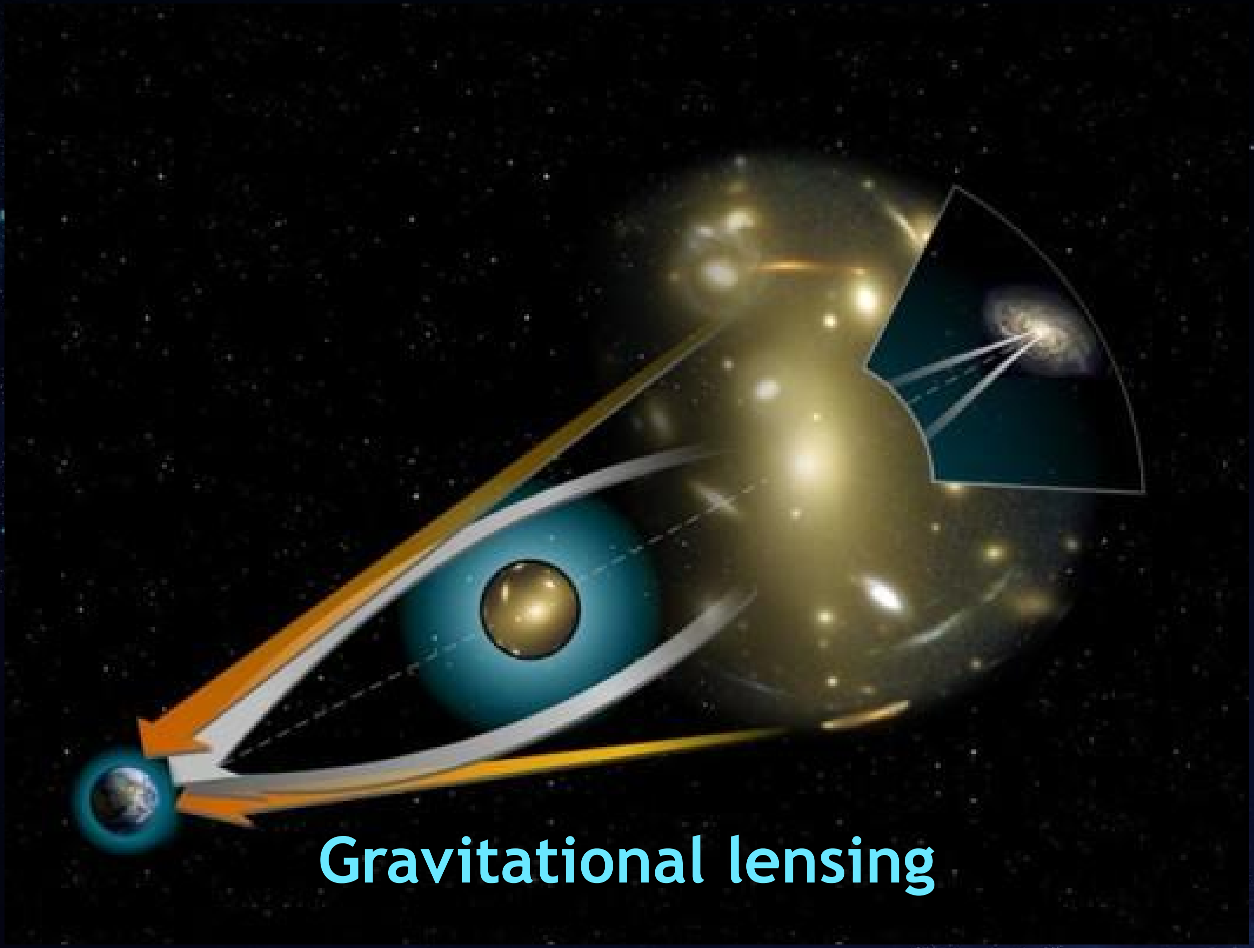


Rotation curve of a Galaxy





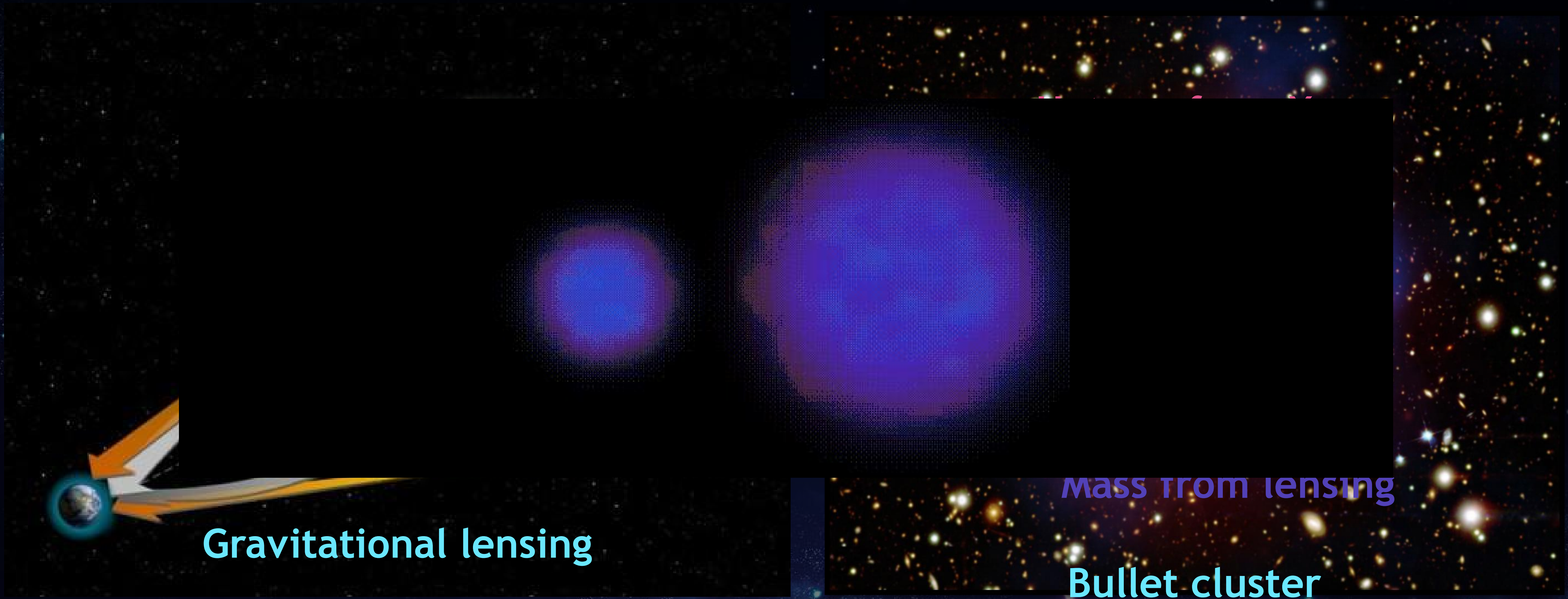
Why we need dark matter?



Bullet cluster

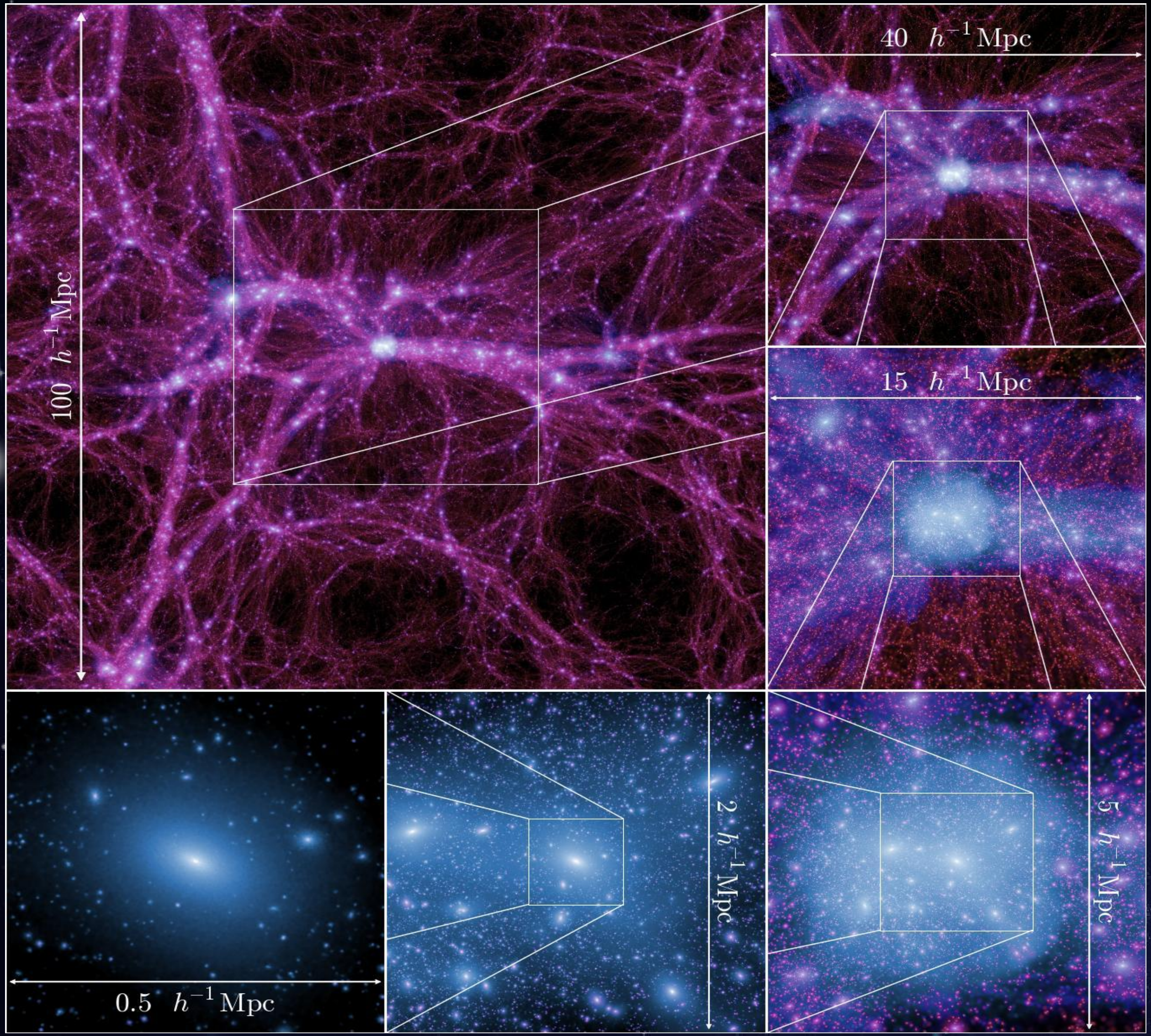
Clowe et al. (2006)

Why we need dark matter?



Clowe et al. (2006)

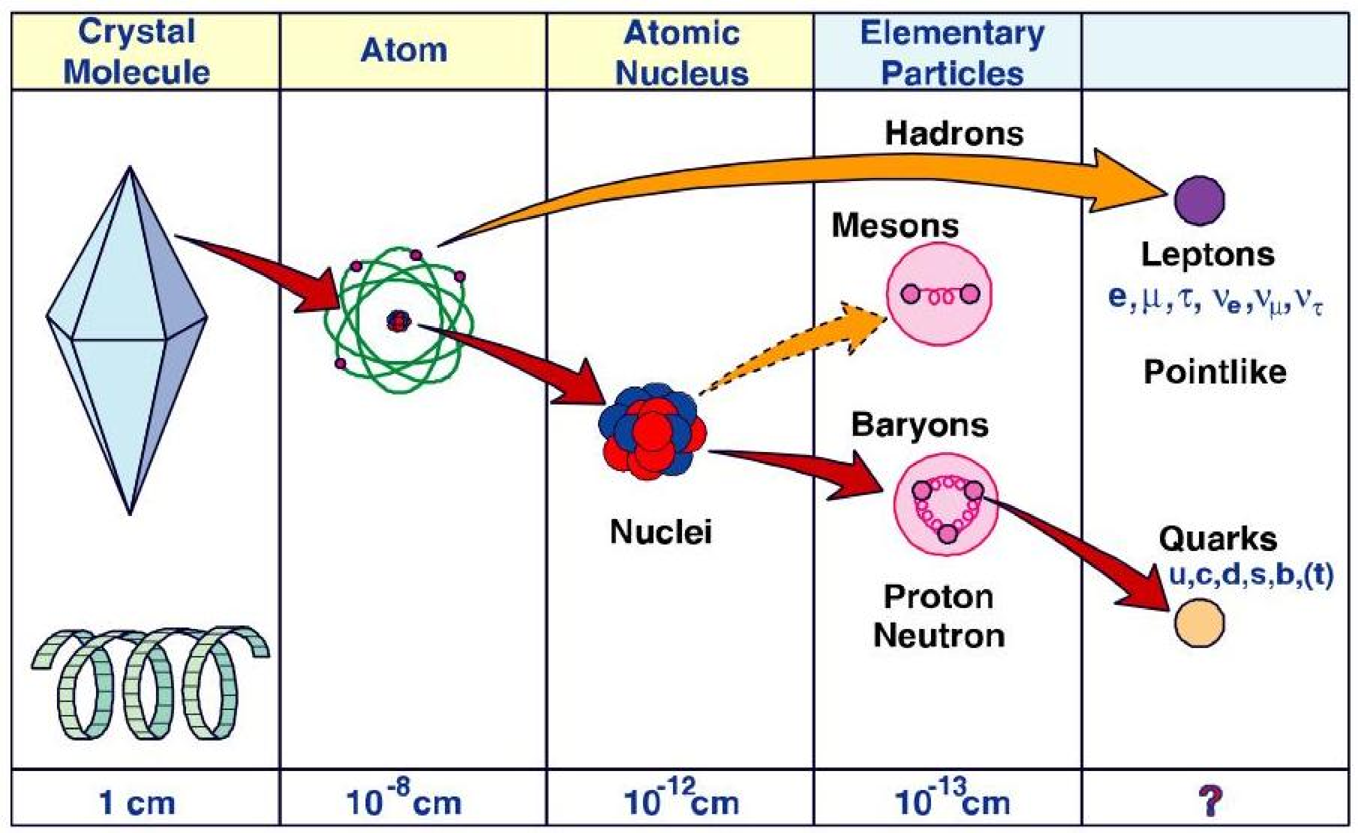
Dark matter in the Universe

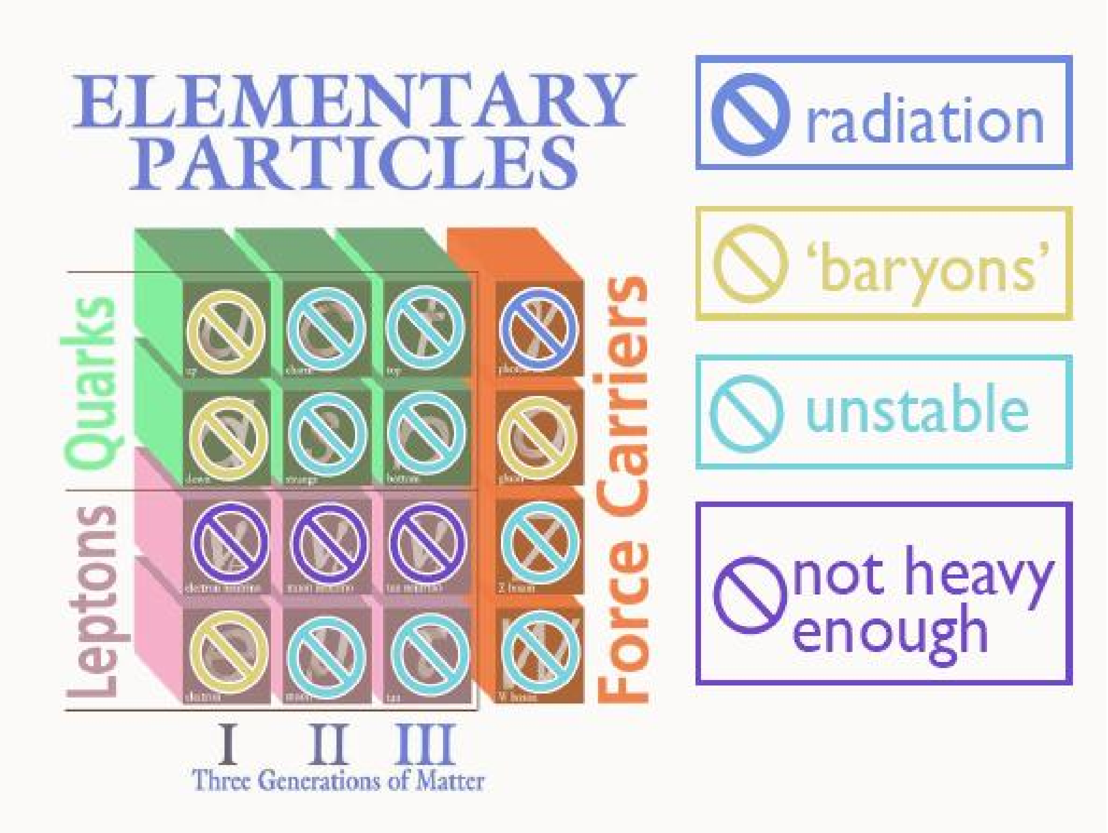


Millennium simulation

- DM interacts very weakly. It does not affect phenomena at small scales, but governs the dynamics of galaxies and Universe at large scales
- DM distributes inhomogeneously in the Universe, forming hierarchical structures
- The local density (around the solar system) of DM is 0.3 hydrogen mass per cm3
- Overall DM is 5 times more than ordinary matter, but its mass density is diverse everywhere

Dark matter in physics

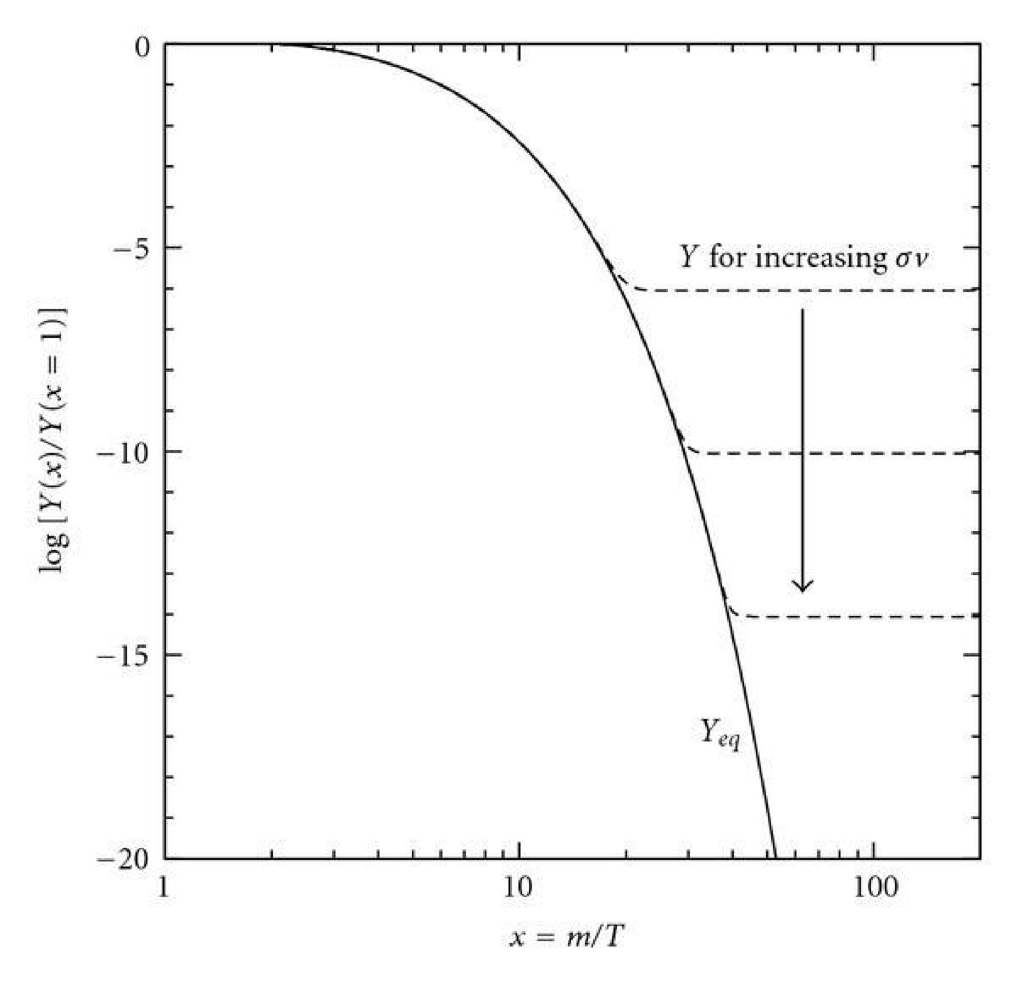




Fundamental particles (quarks and leptons) are bricks of matter. But none of the particle in the standard model can account for dark matter.

Dark matter in physics

Garrett & Duta (2011)



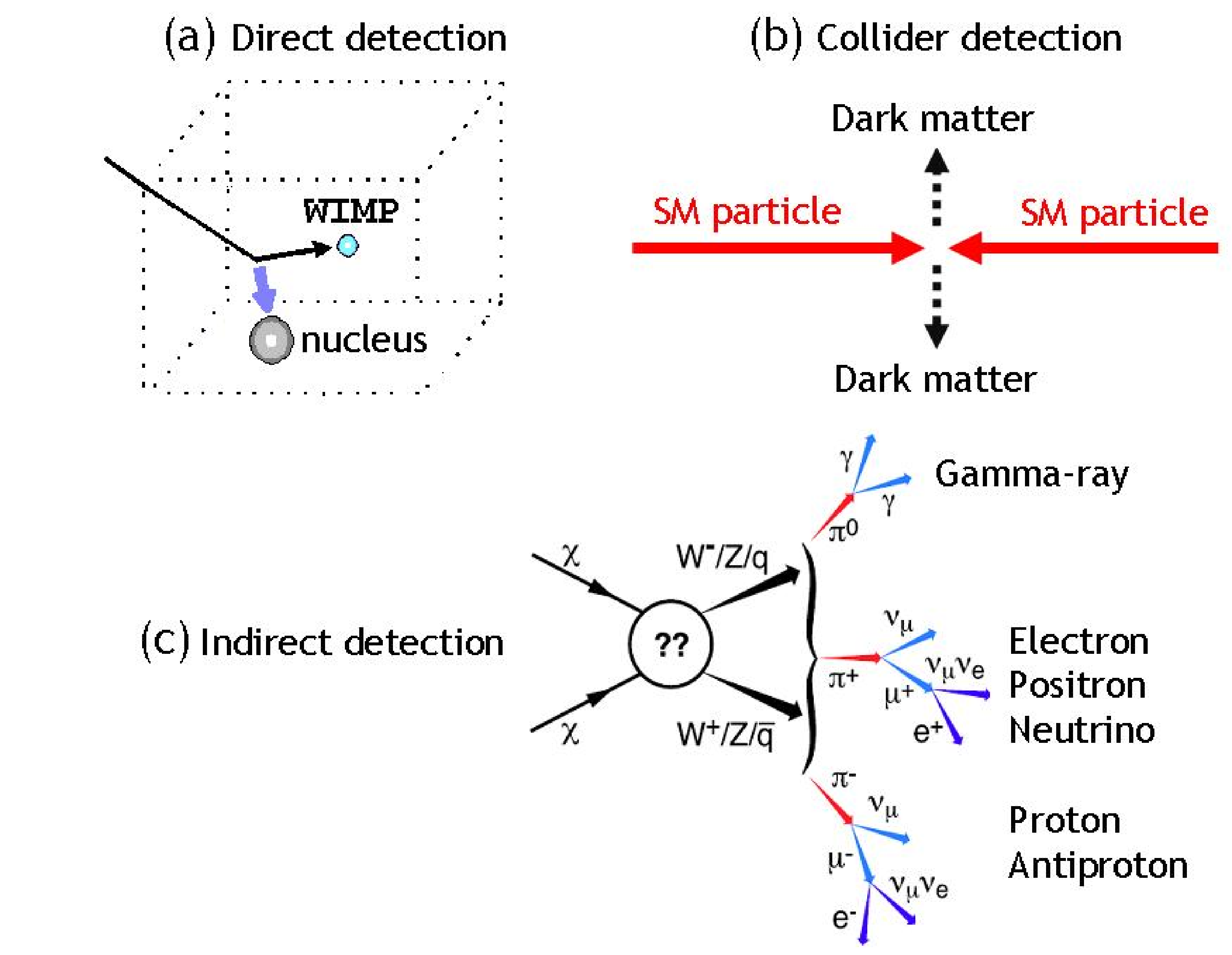
$$\langle \sigma v \rangle \simeq \left(\frac{3 \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1}}{\Omega_\chi h^2} \right)$$

$\sigma \sim 10^{-35}\ \mathrm{cm}^2$ → weak interaction

WIMP miracle: weakly interacting massive particles (WIMPs) as the most natural candidate of dark matter

Testable for many high-energy physics experiments

Detection of WIMP

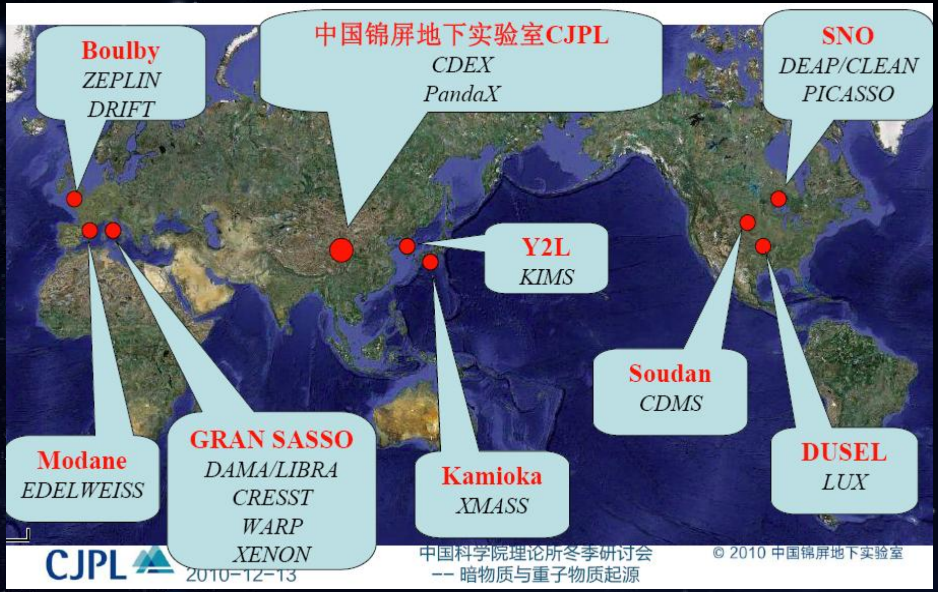


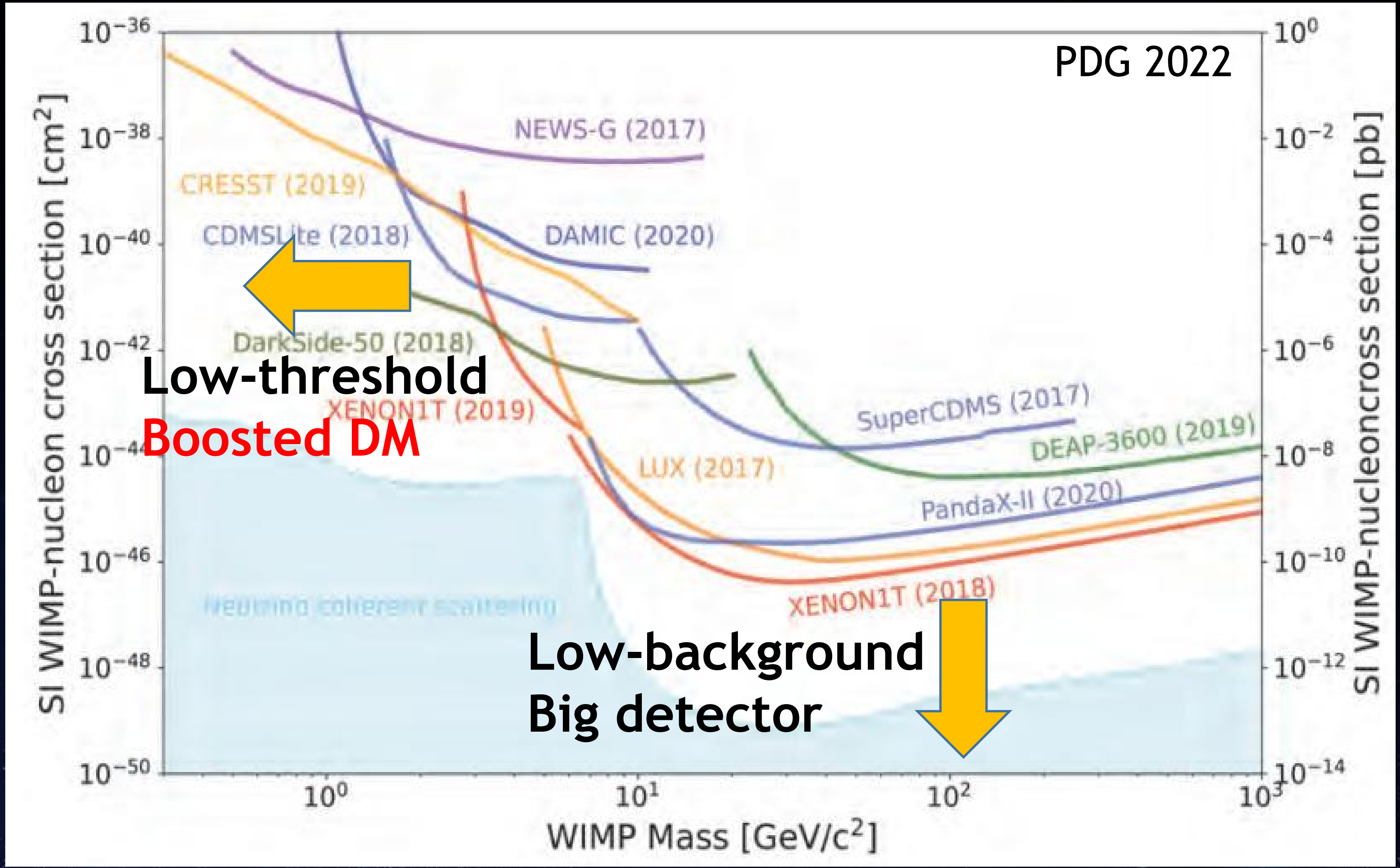
Direct detection: scattering between DM and SM

Collider detection: production of DM from SM

Indirect detection: production of SM from DM

Status of WIMP direct detection





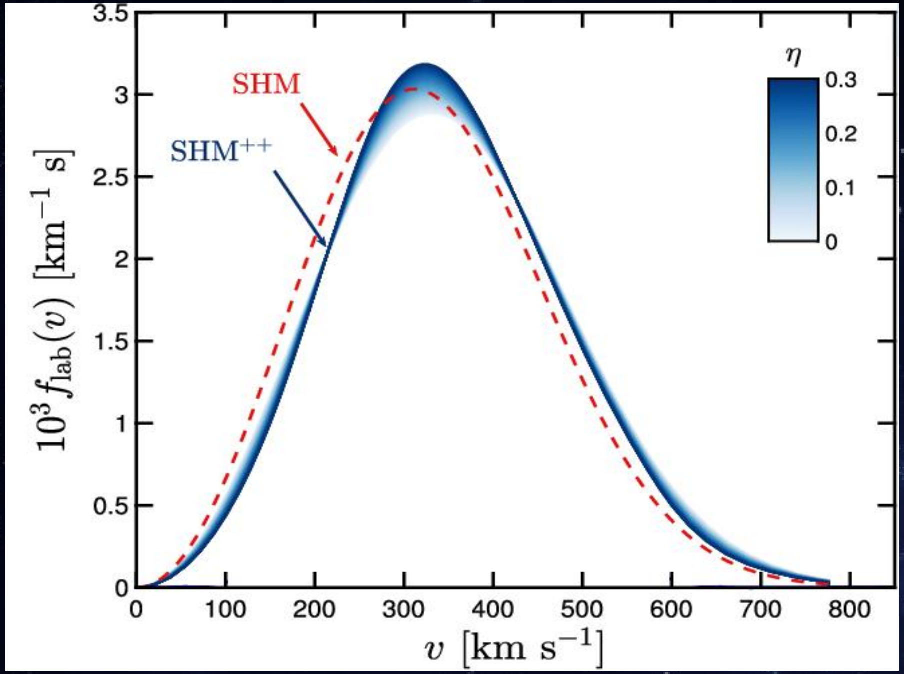
No convincing DM signal has been found in all these experiments, stringent constraints on the DM-SM interaction cross section are placed.

Boost DM to high energies

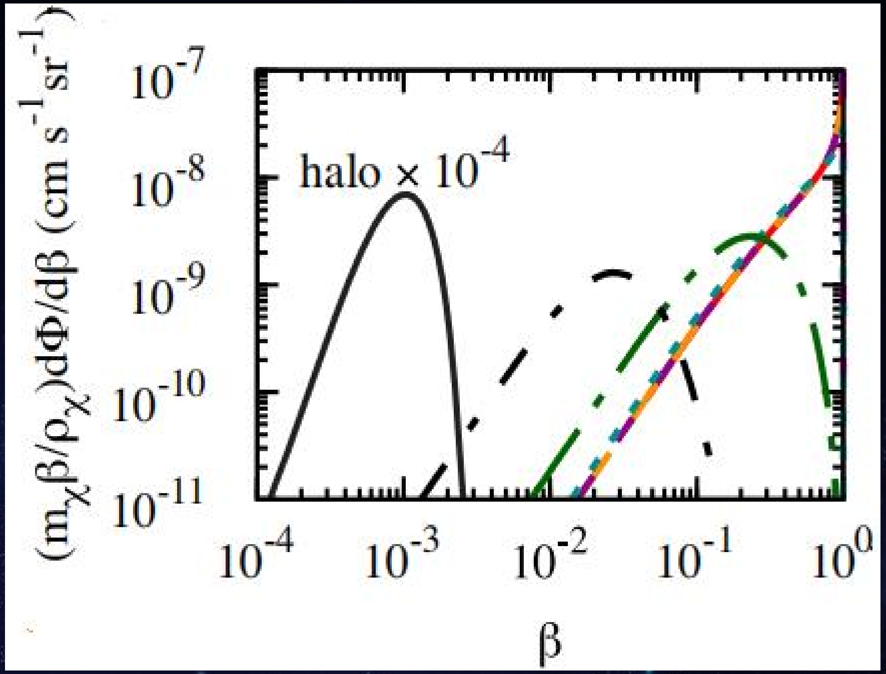
- Multi-component DM models

  $XX \rightarrow YY, \; X \rightarrow X' + \ldots$

- DM scattered by energetic particles

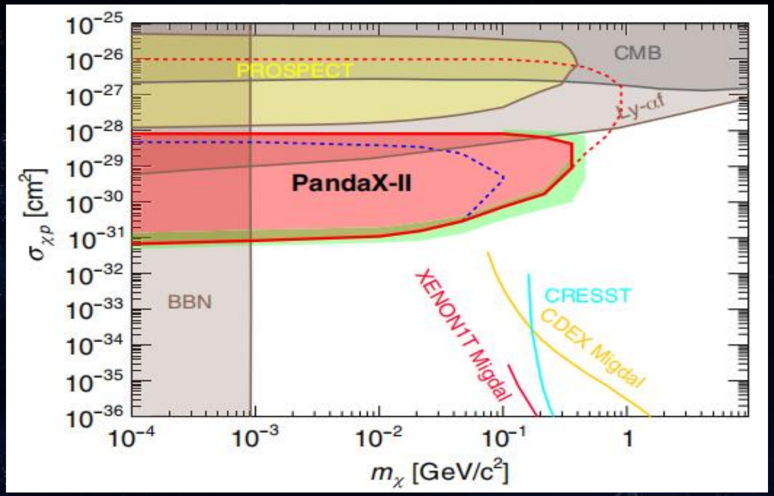


$X + SM \rightarrow X' + SM$

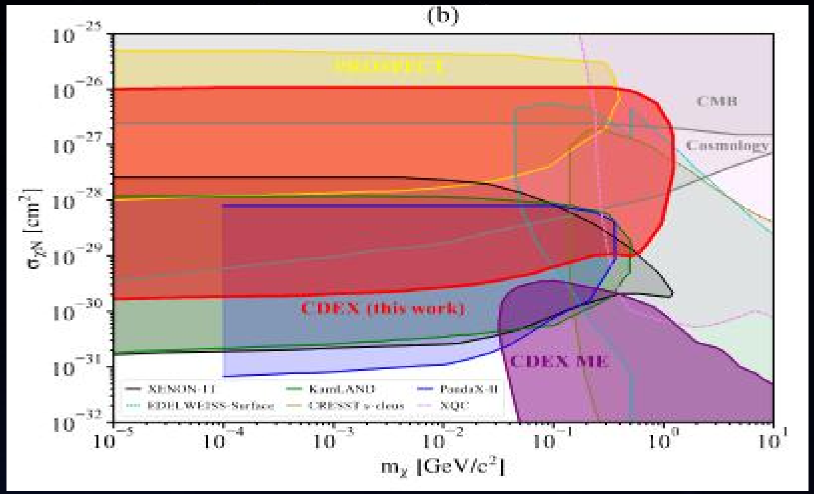


Cosmic rays and other boosters of light DM

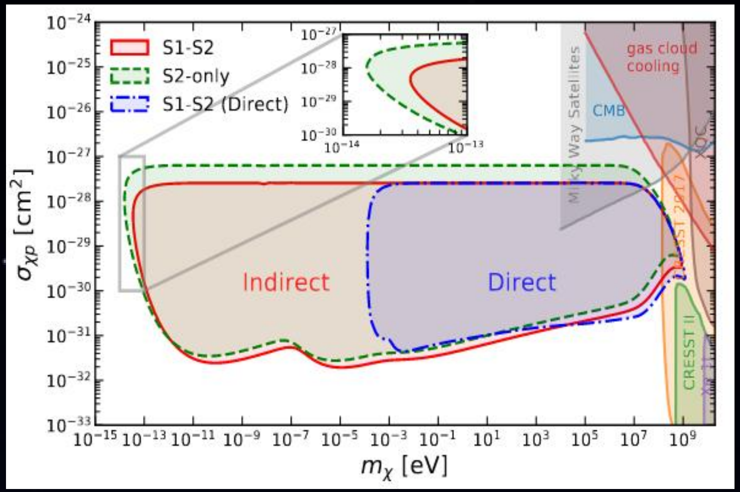
Pandax-II 2022



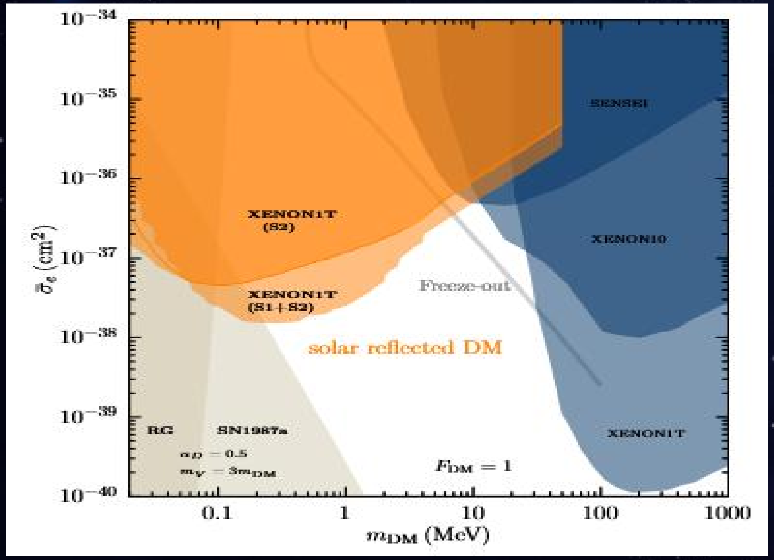
CDEX 2022



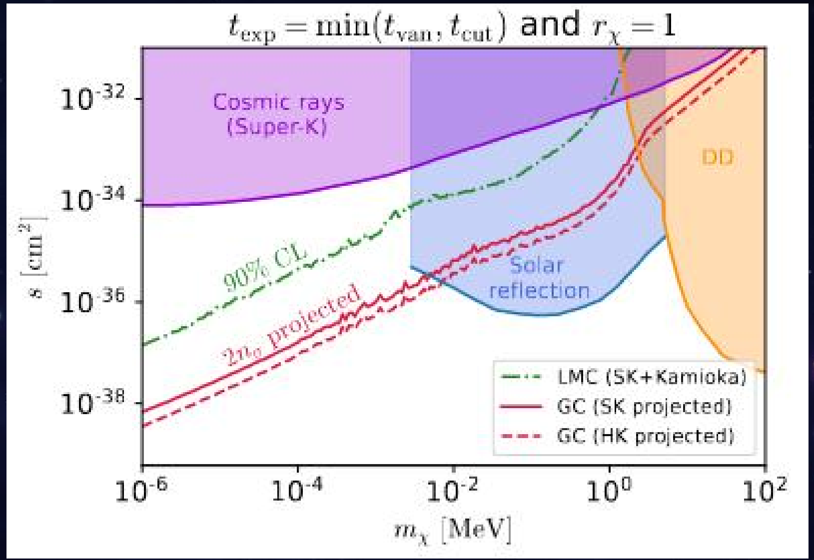
Xia+ 2021



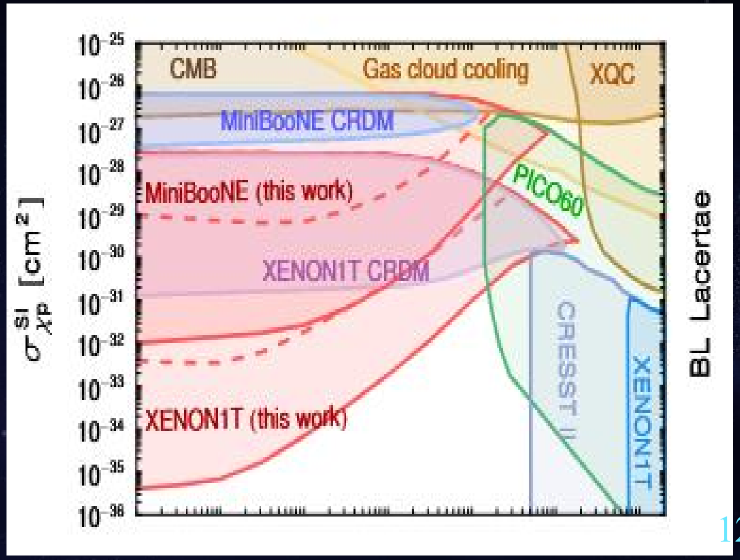
An+ 2021 (sun)



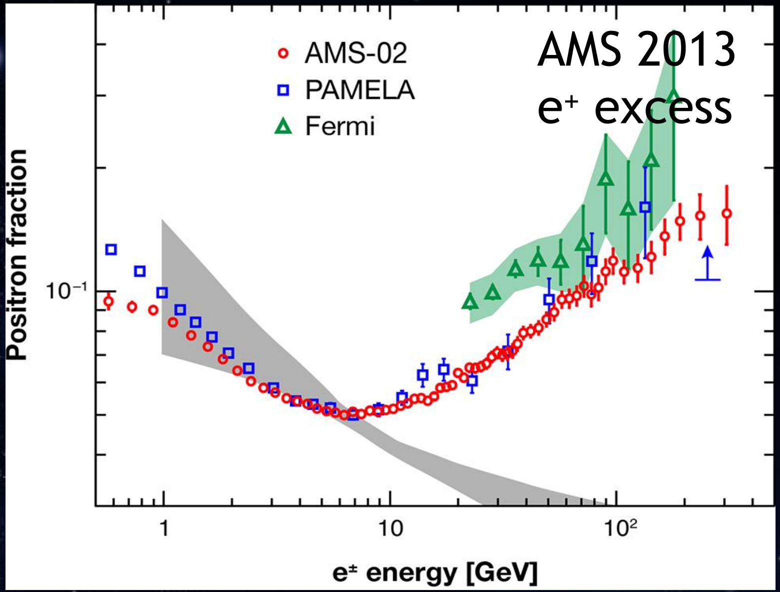
Lin+ 2023 (SN neutrino)

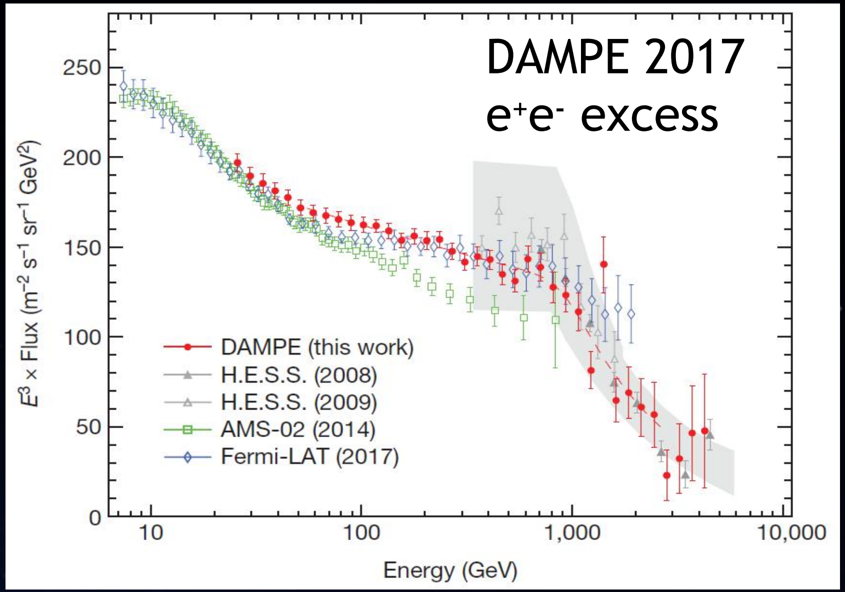


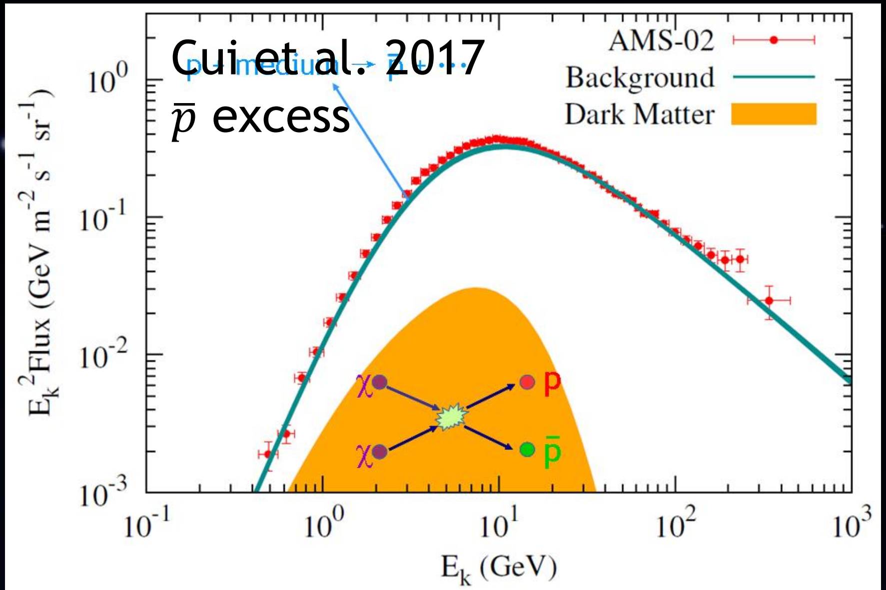
Wang+ 2022 (blazar)

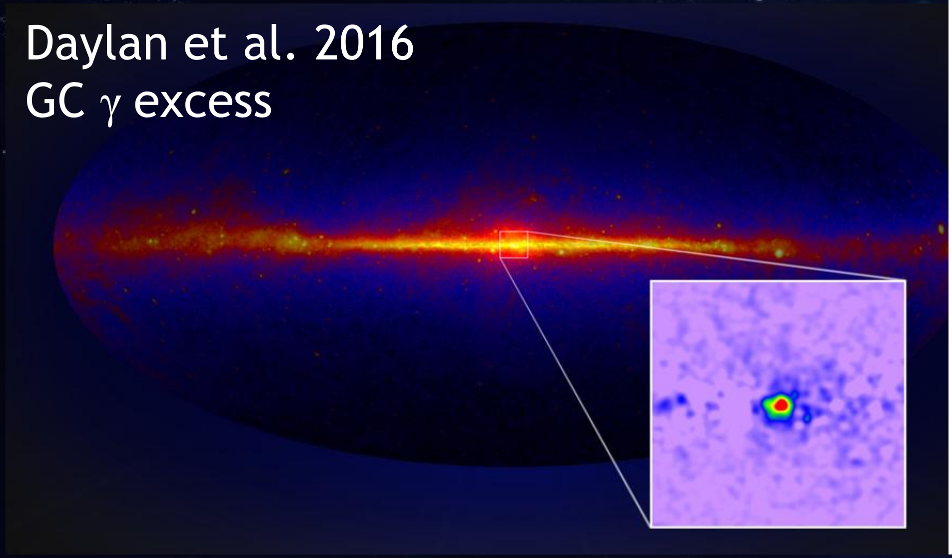


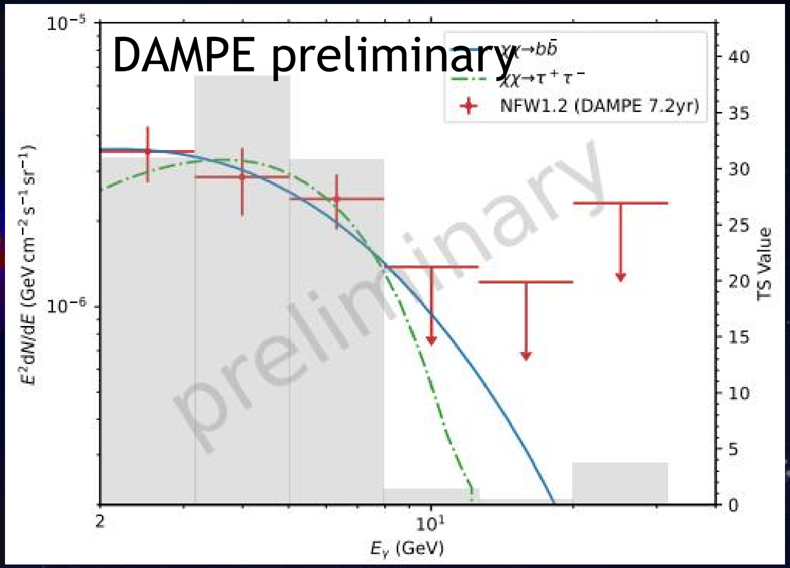
Status of WIMP indirect detection







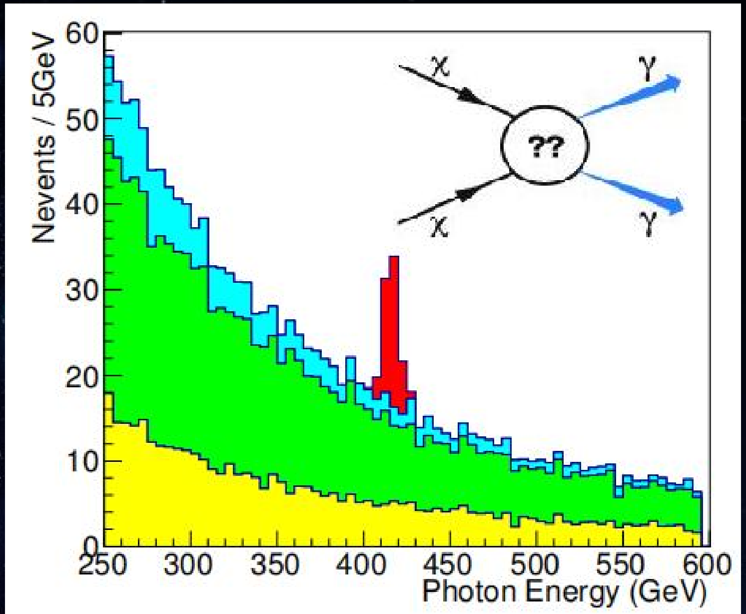


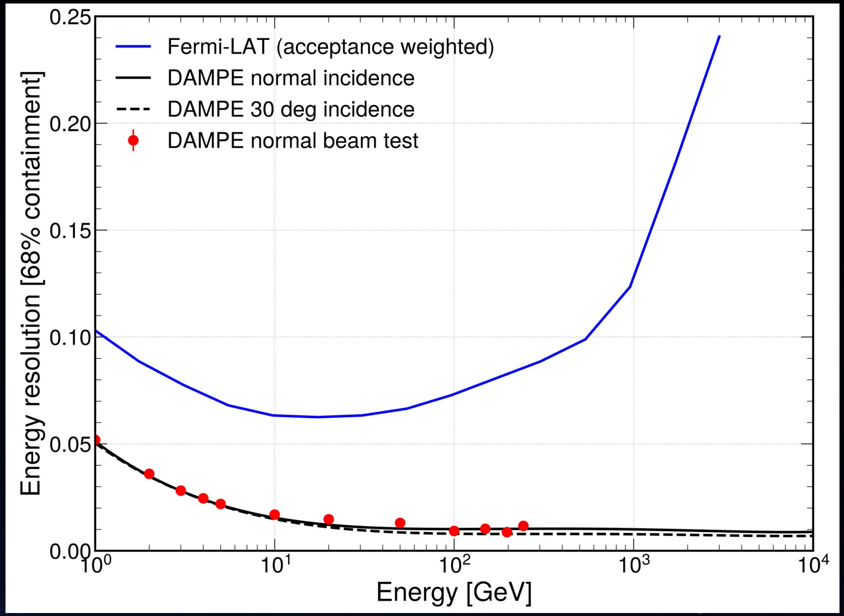


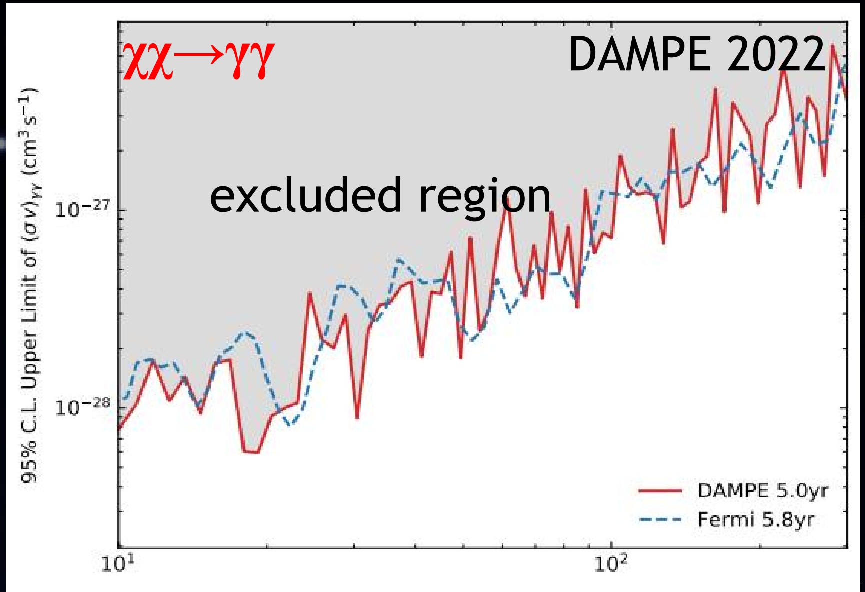
Interesting anomalies have been found in various messengers.

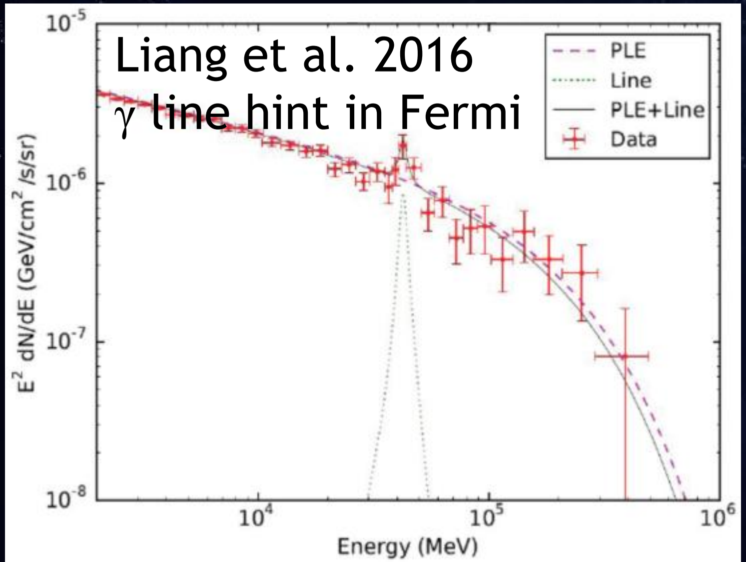
It is hard to dinsinguish from astrophysical sources.

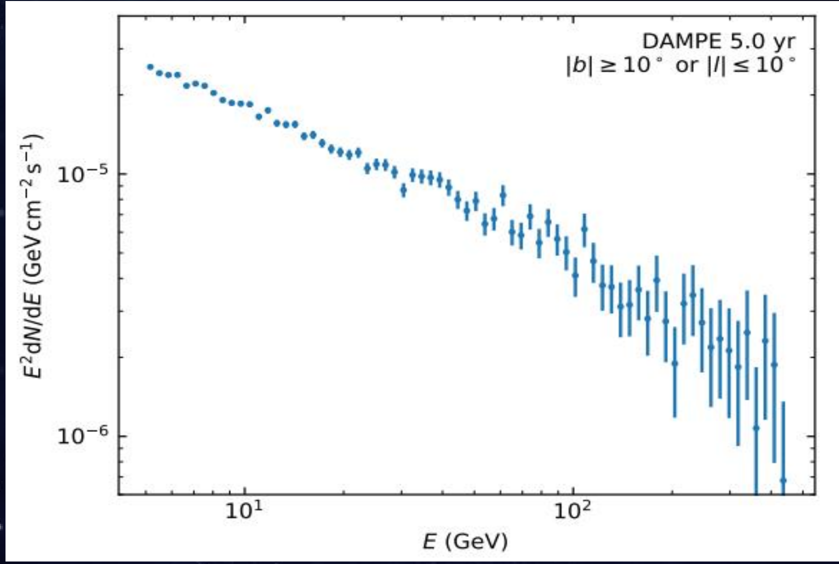
Smoking gun: gamma-ray line

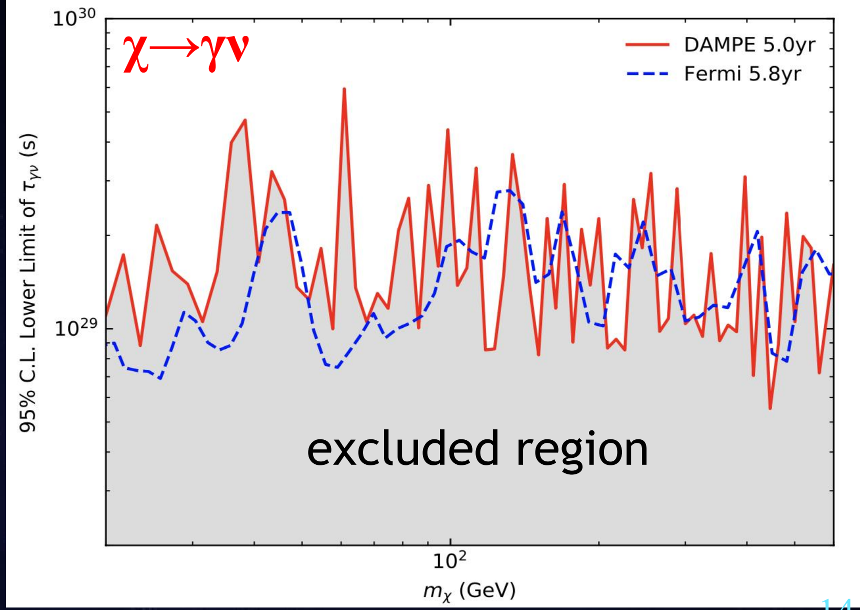




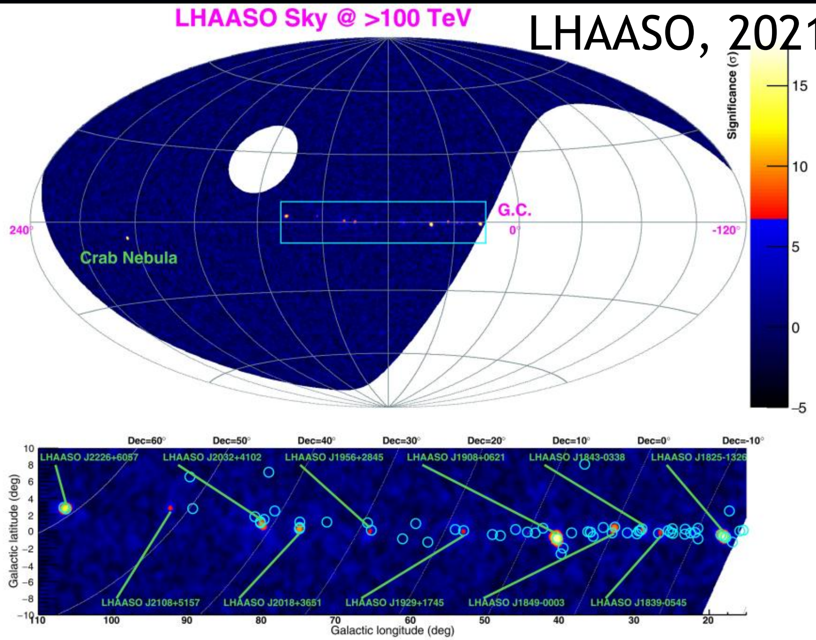




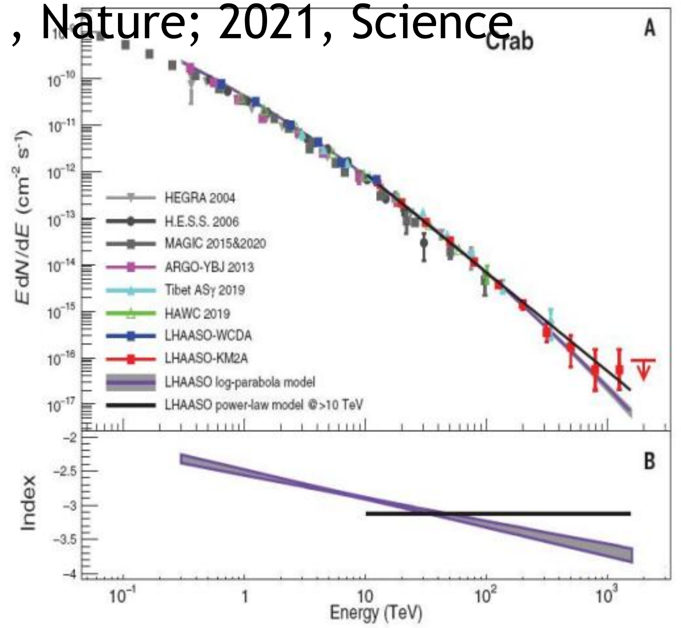


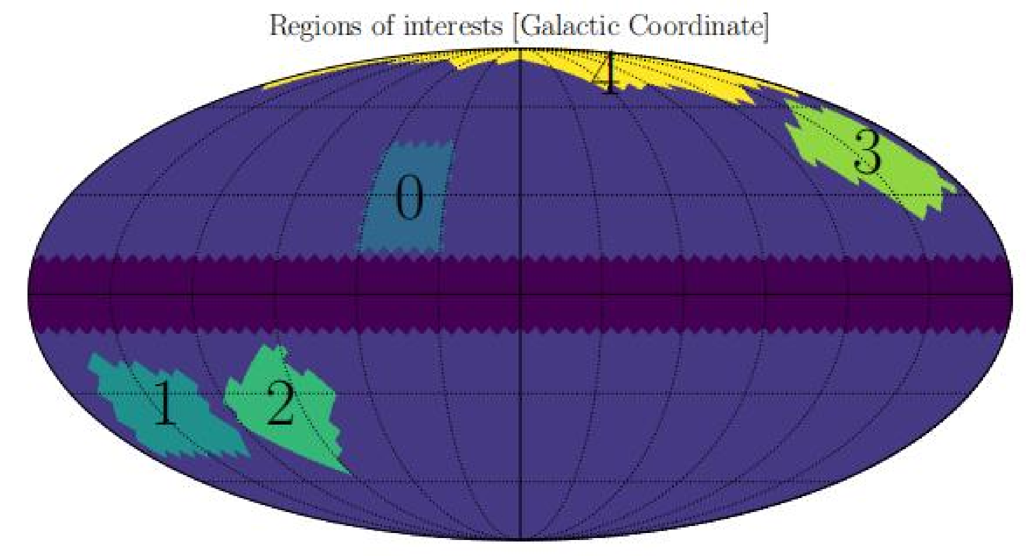


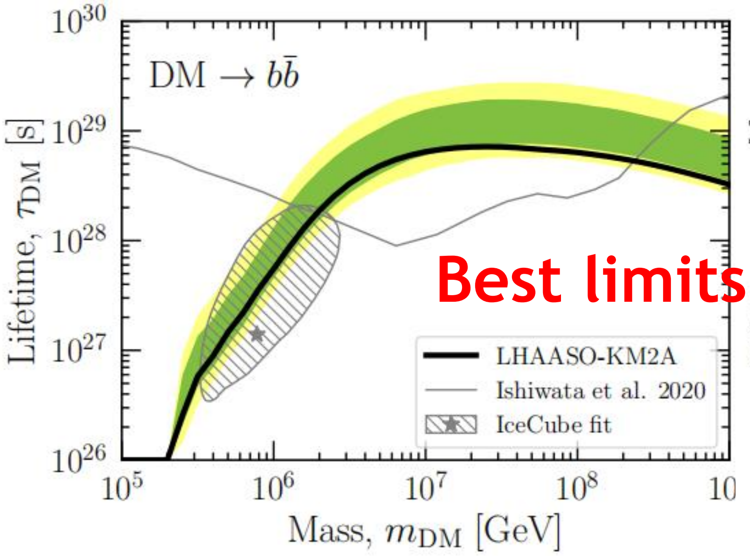
Extending to heavy DM with LHAASO

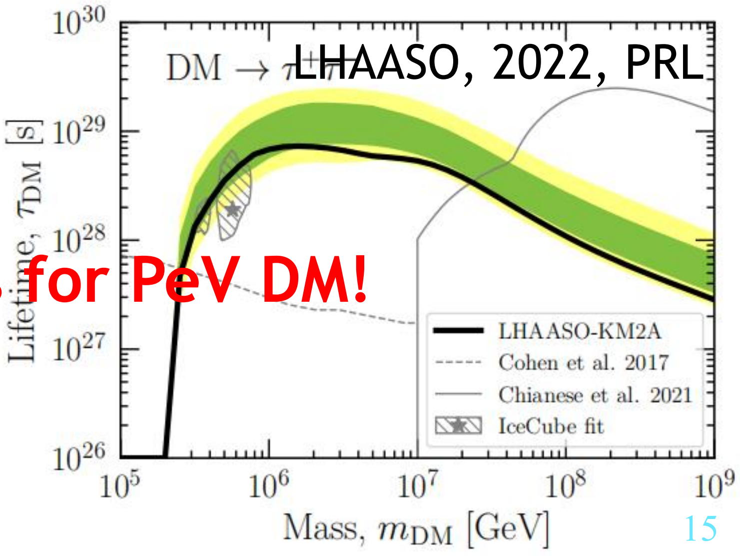


LHAASO, 2021, Nature; 2021, Science





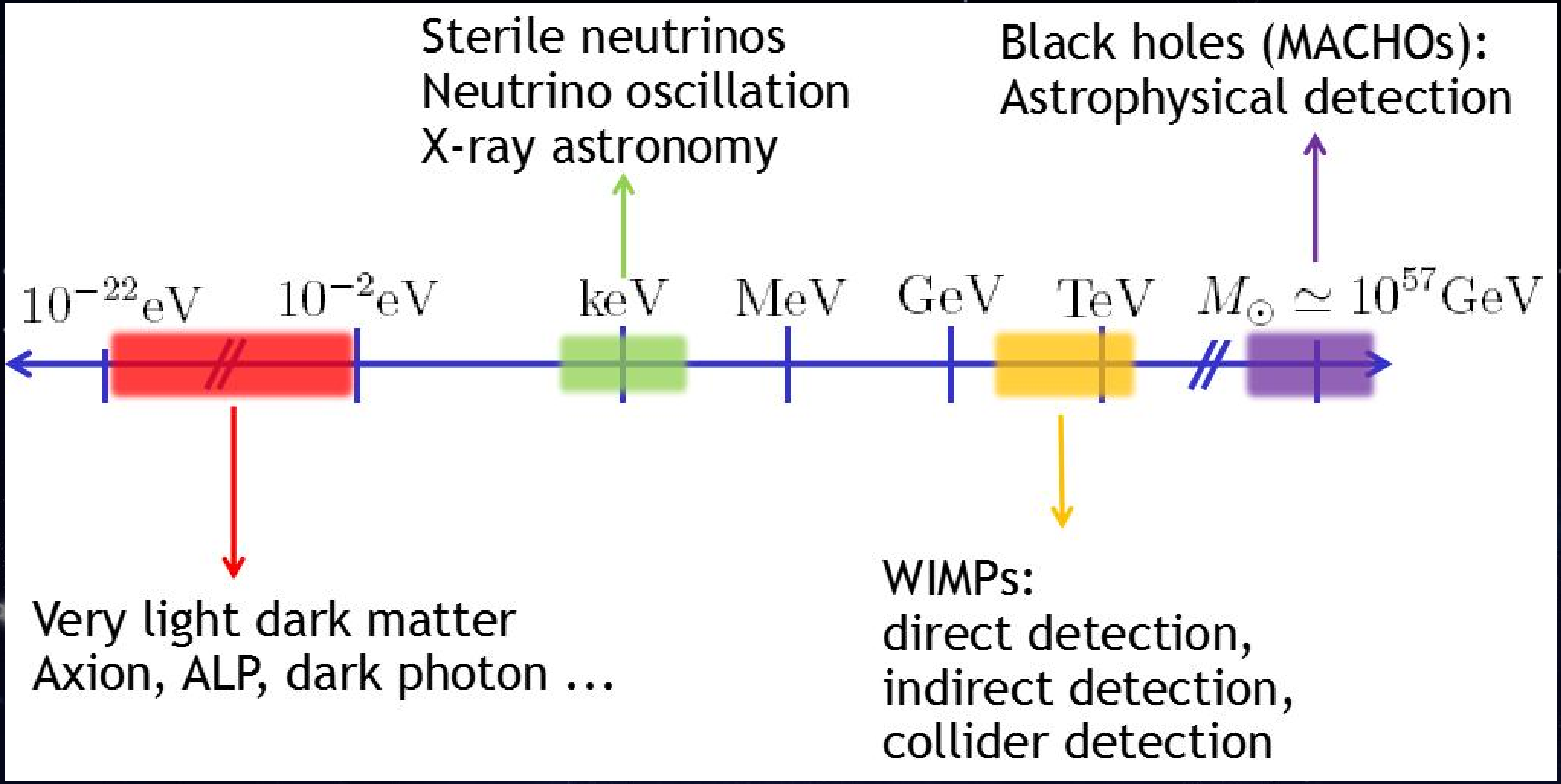




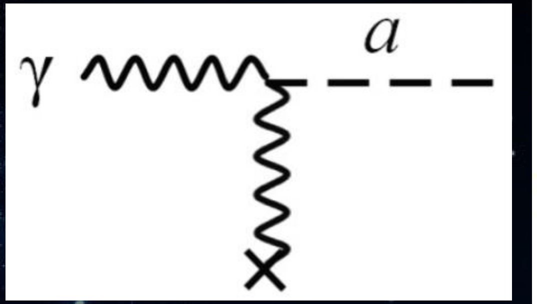
LHAASO, 2022, PRL

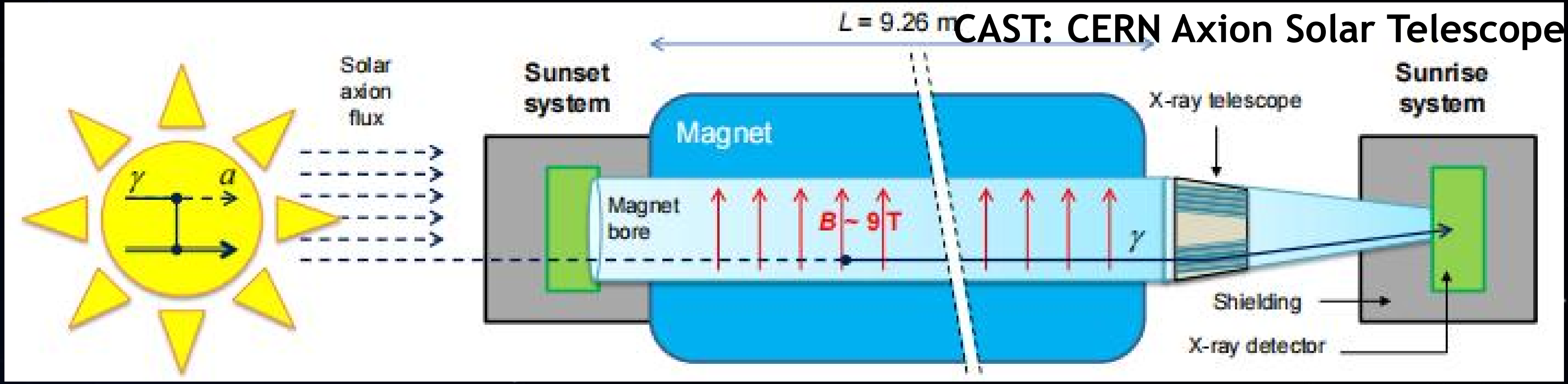
Best limits for PeV DM!

Extending to broad DM mass window with precise astronomical observations

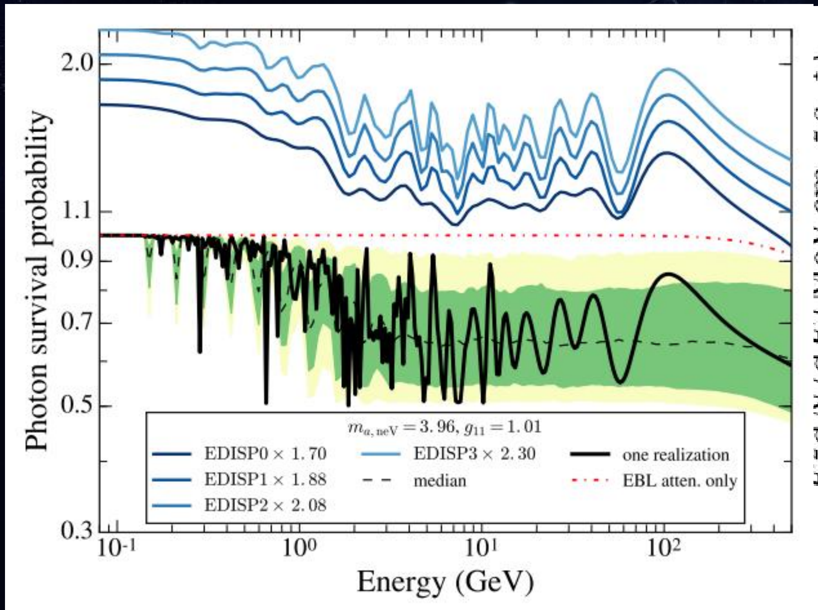


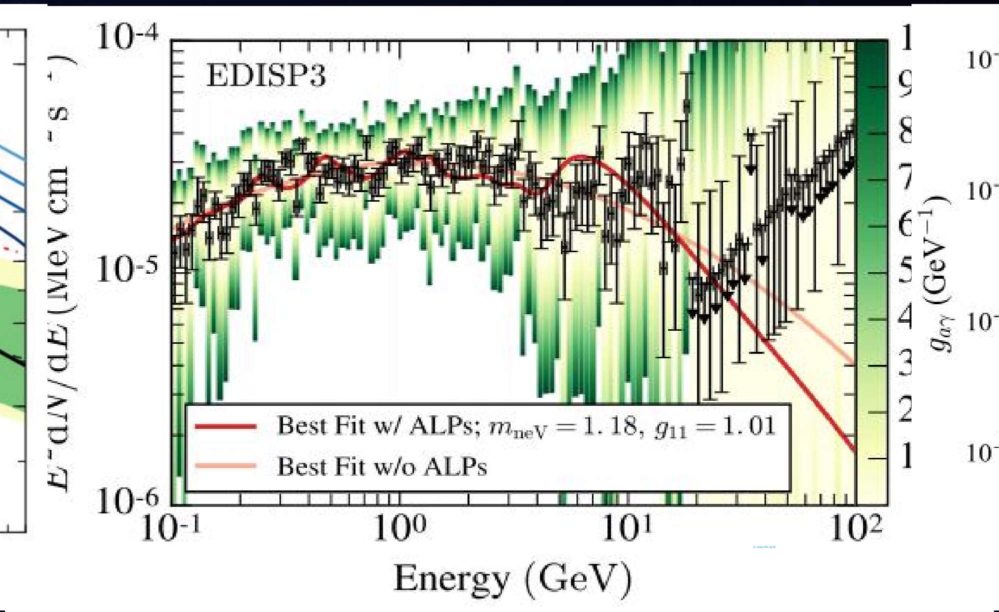
Axion-photon conversion: Primorkoff effect

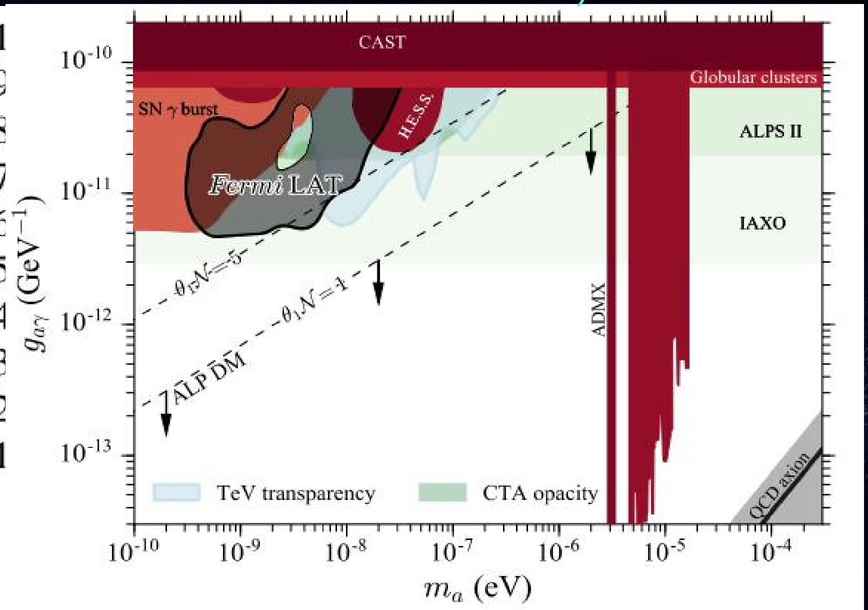




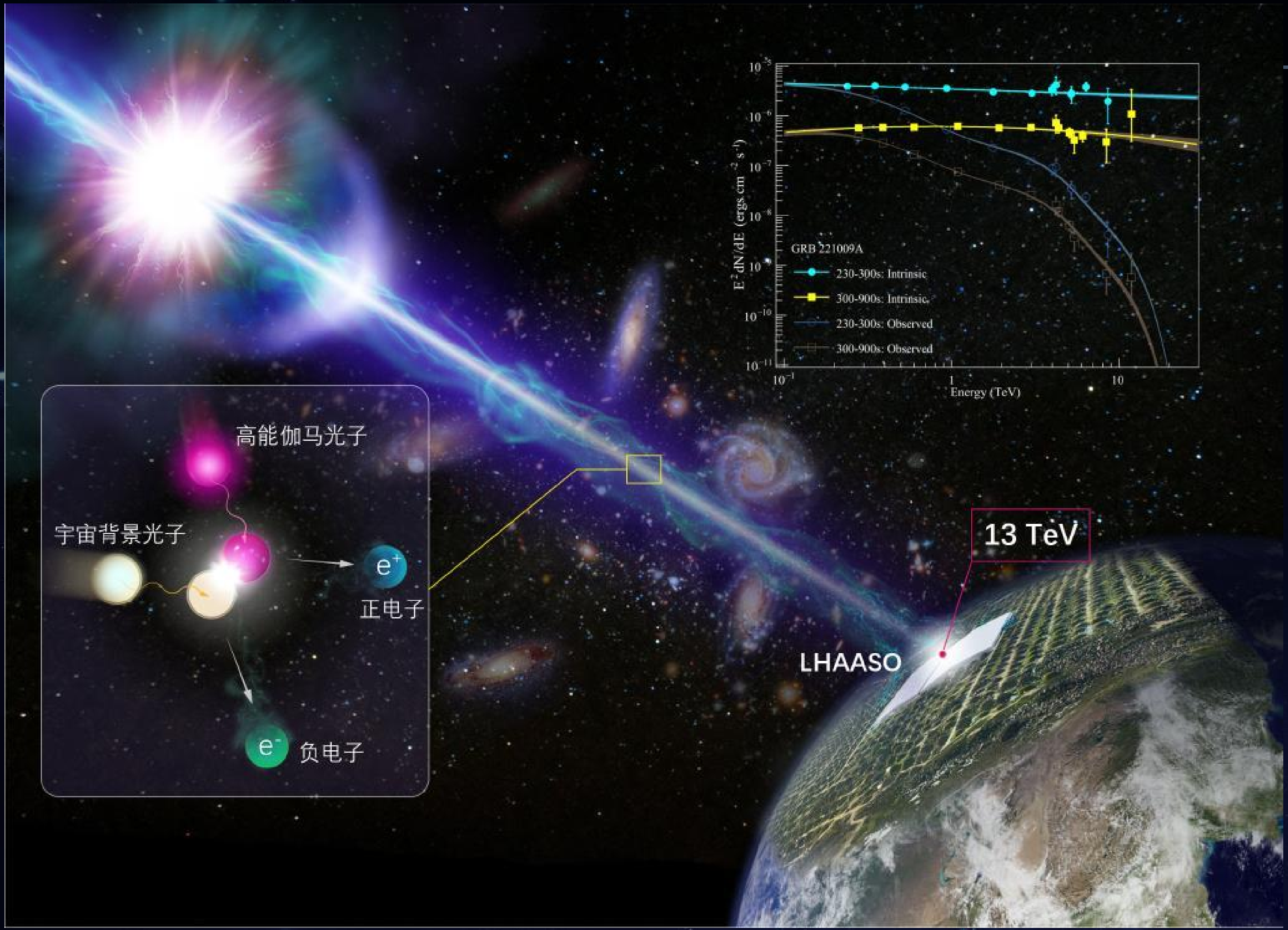
Fermi-LAT, 1603.06978

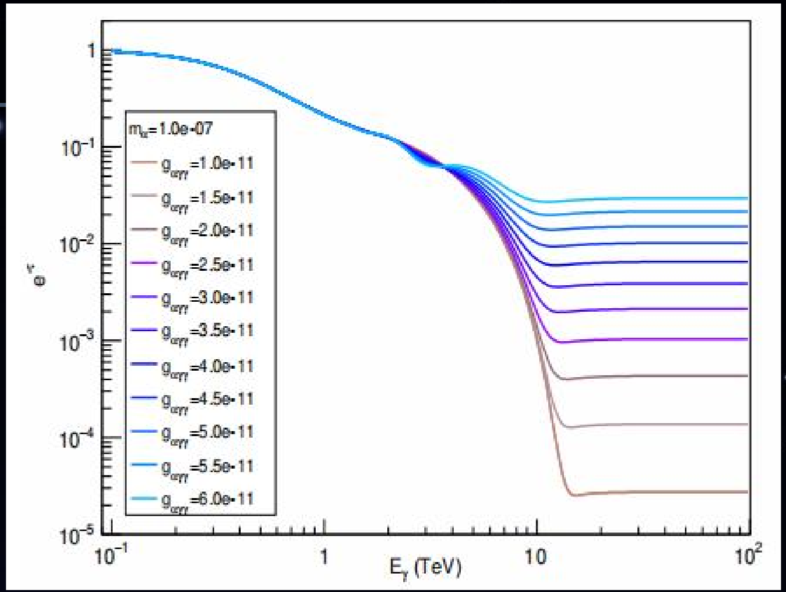


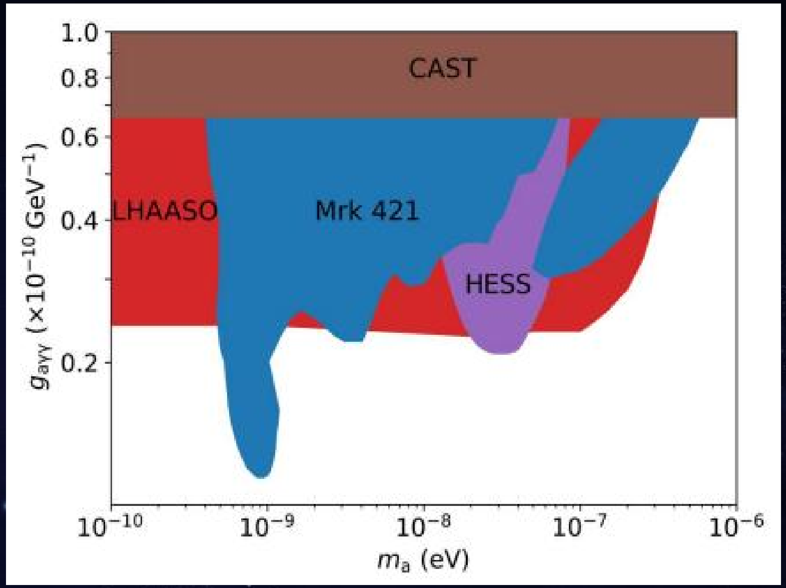




LHAASO observations of GRB 221009A



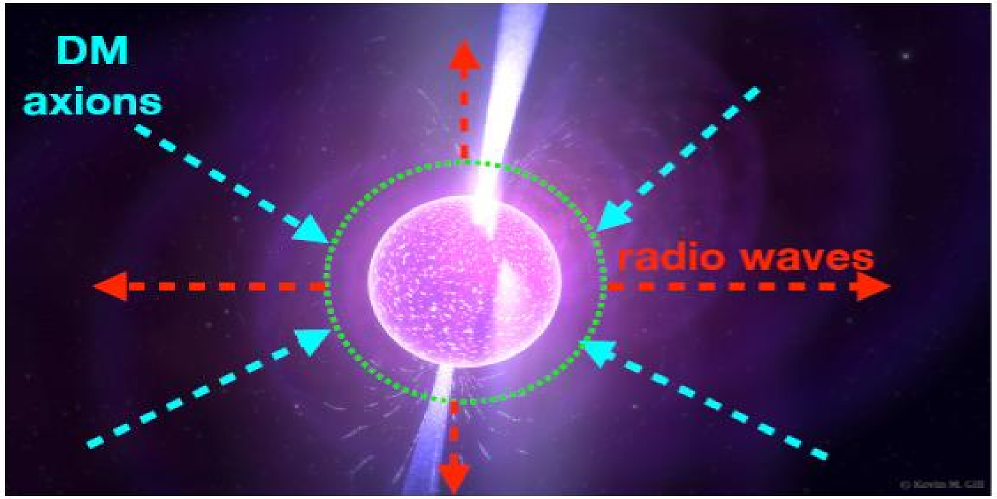




2023, Science Advances, 9, eadj2778

Axion-photon conversion around neutron stars

NS with strong B-field and surrounding plasma



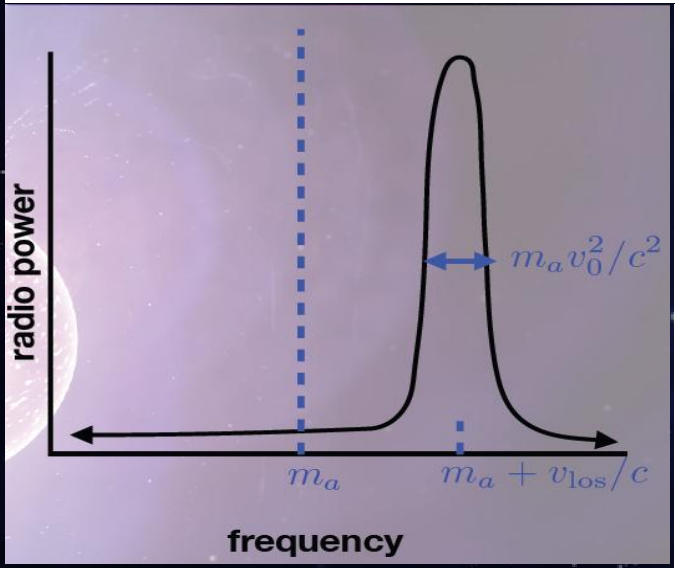
DM axions resonantly convert to radio waves when $m_a = m_\gamma$

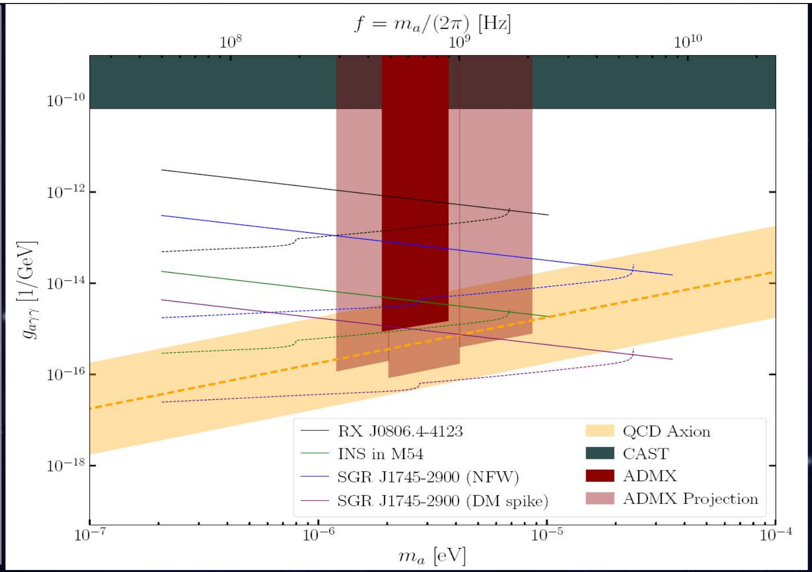
radio waves

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

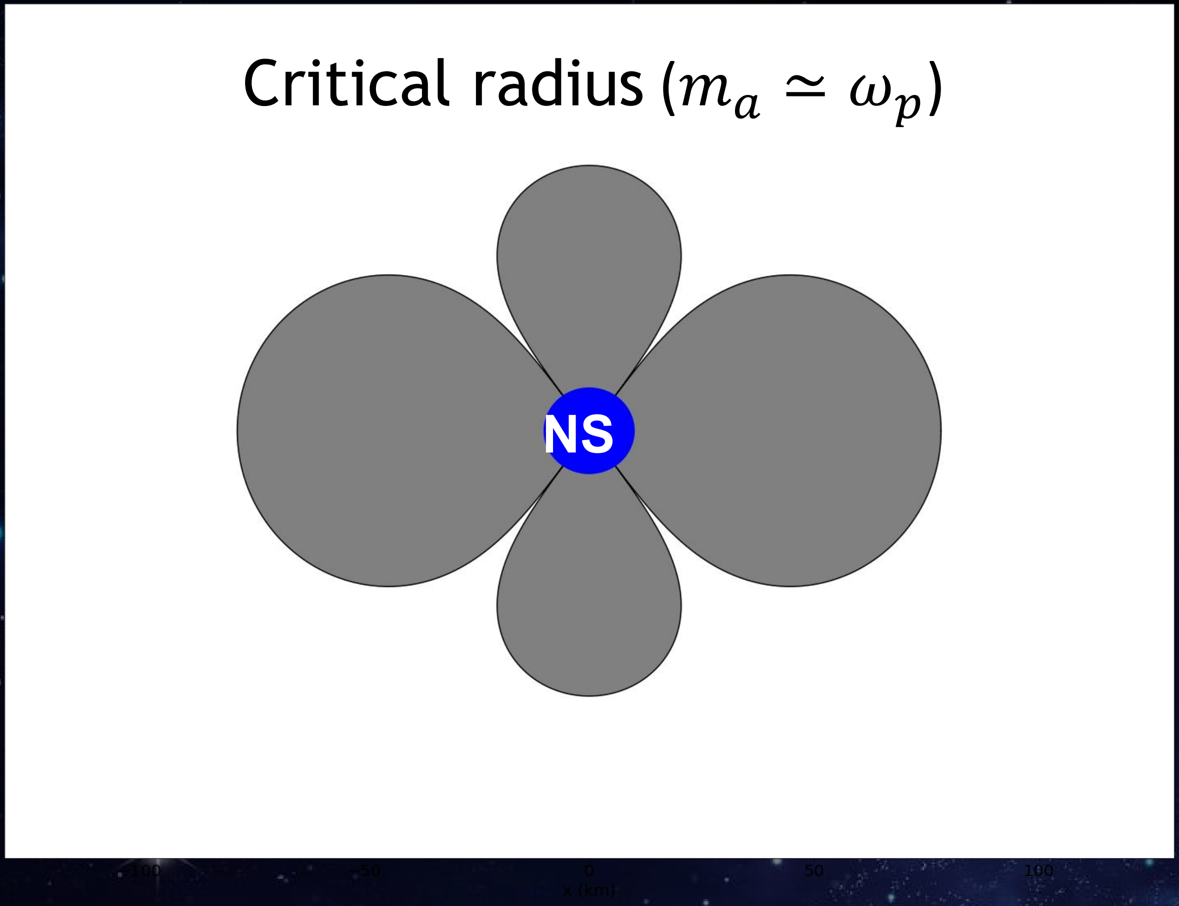
Narrow radio line detectable at Earth with $f = m_a/(2\pi)$.





- Pshirkov+ JETP 2009; Huang+ PRD 2018; Hook+ PRL 2018
- Narrow line in radio frequency
- Can extend to mass range beyond the cavity experiment

Axion-photon conversion around neutron stars



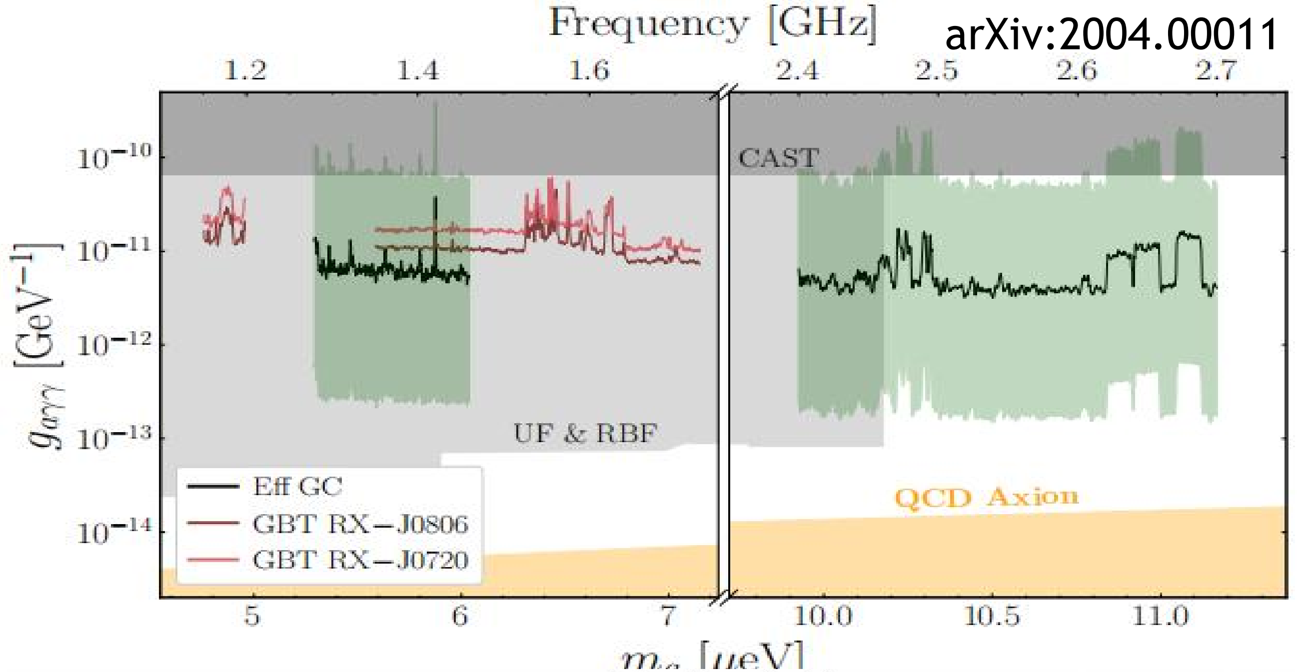
$$\bar{S}_{\nu_i} = \frac{F}{\Delta\nu} = 3.8 \times 10^{-6}\ \mathrm{Jy} \left(\frac{100\,\mathrm{pc}}{d}\right)^2 \left(\frac{16\,\mathrm{kHz}}{\Delta\nu}\right) \times \left(\frac{\mathrm{d}\mathcal{P}/\mathrm{d}\Omega}{5.7\times 10^9\,\mathrm{W}}\right) \int_{\nu_{i,\mathrm{min}}}^{\nu_{i,\mathrm{max}}} \frac{\mathrm{d}\nu}{\sqrt{2\pi}\sigma_0} \mathrm{e}^{-\frac{(\nu - m_\mathrm{a})^2}{2\sigma_0^2}},$$

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

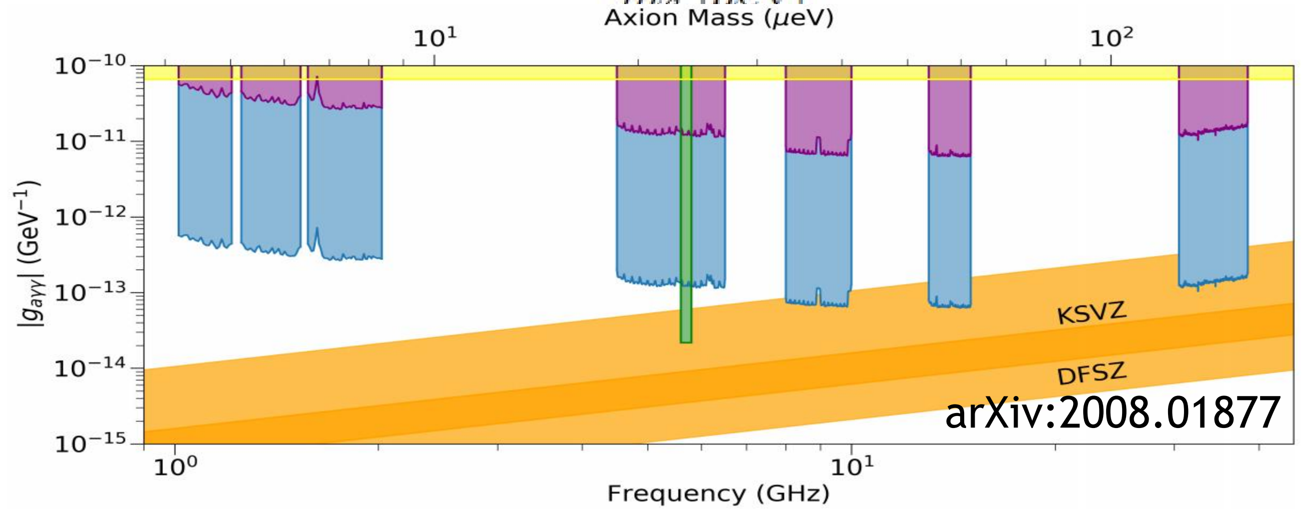
High B-field, nearby, radio-quiet pulsar located in high DM field is optimal

Spectroscopic observations of neutron stars

- GBT and Effelsberg observations of Galactic center magnetar PSR J1745-2900 and nearby NSs
- VLA observations of Galactic center magnetar PSR J1745-2900

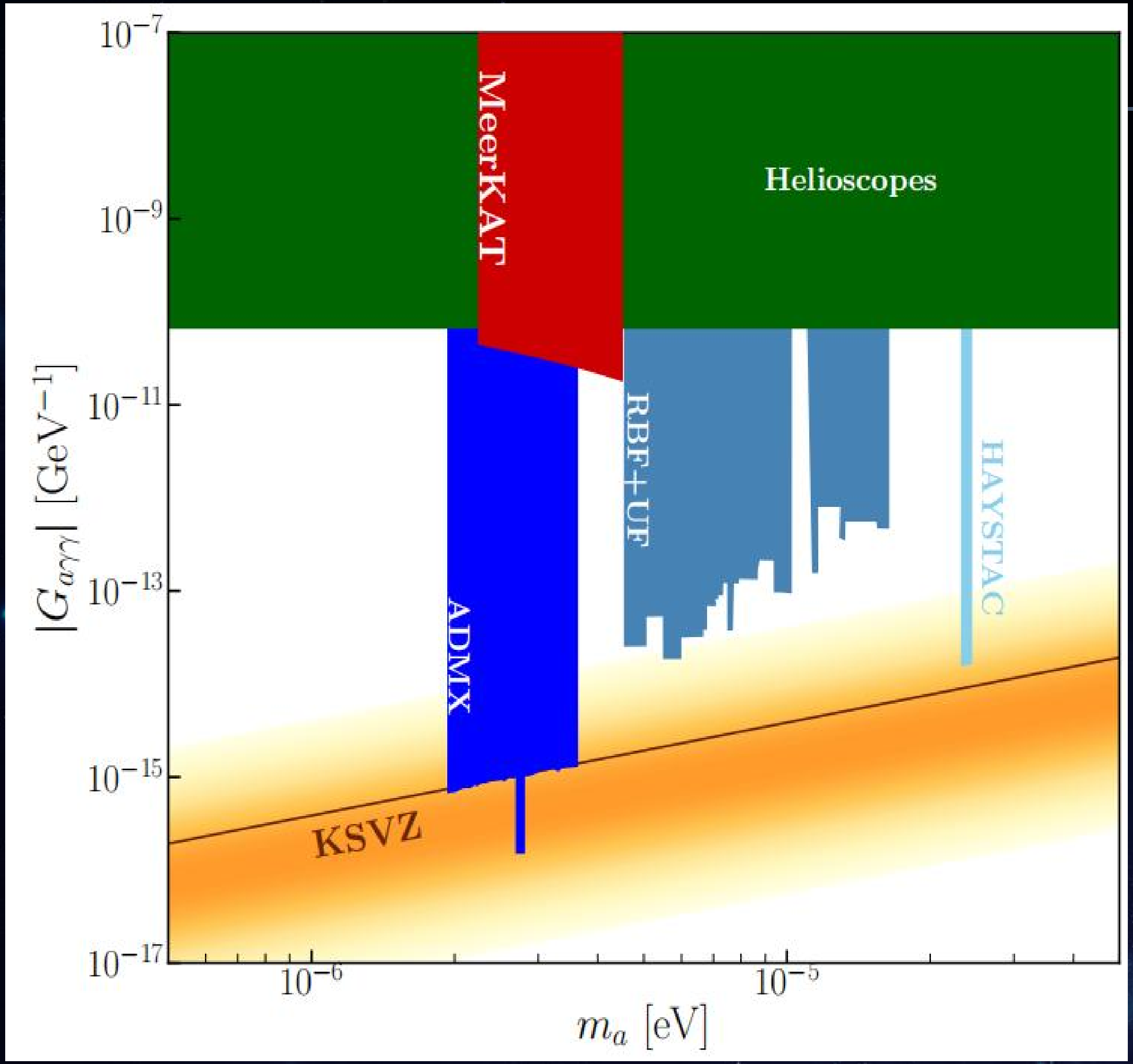


arXiv:2004.00011



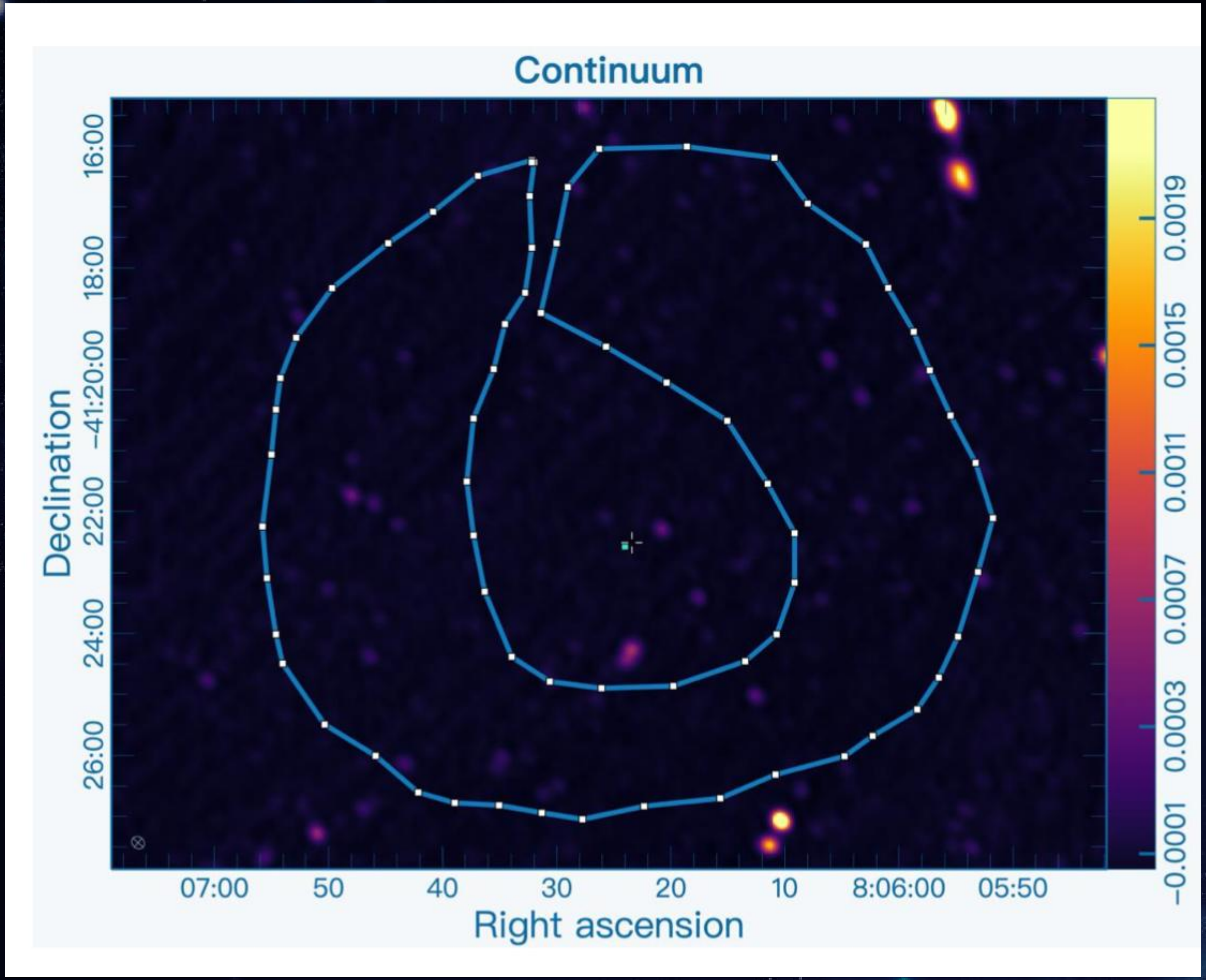
arXiv:2008.01877

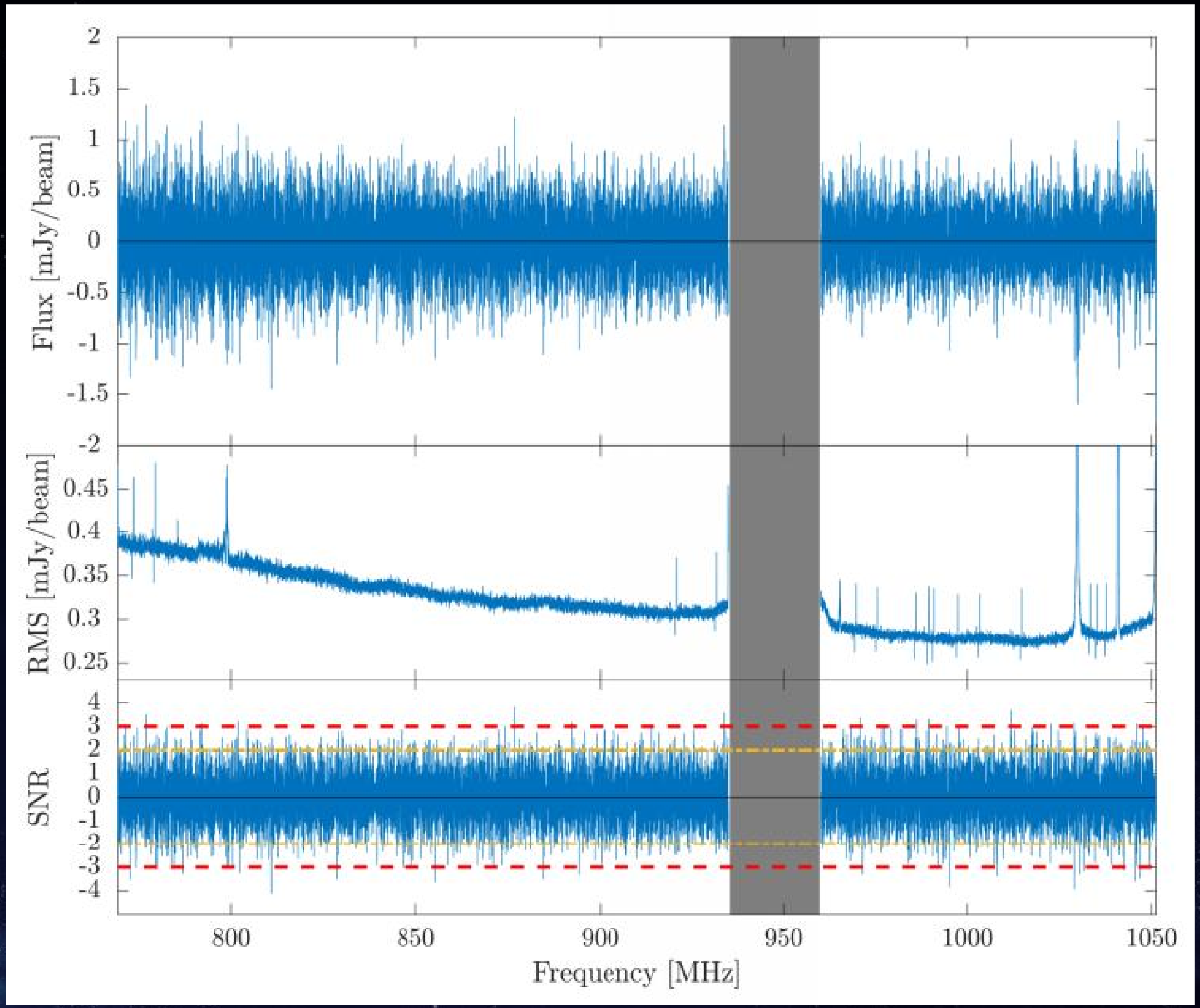
MeerKAT observation of RX J0806.4-4123



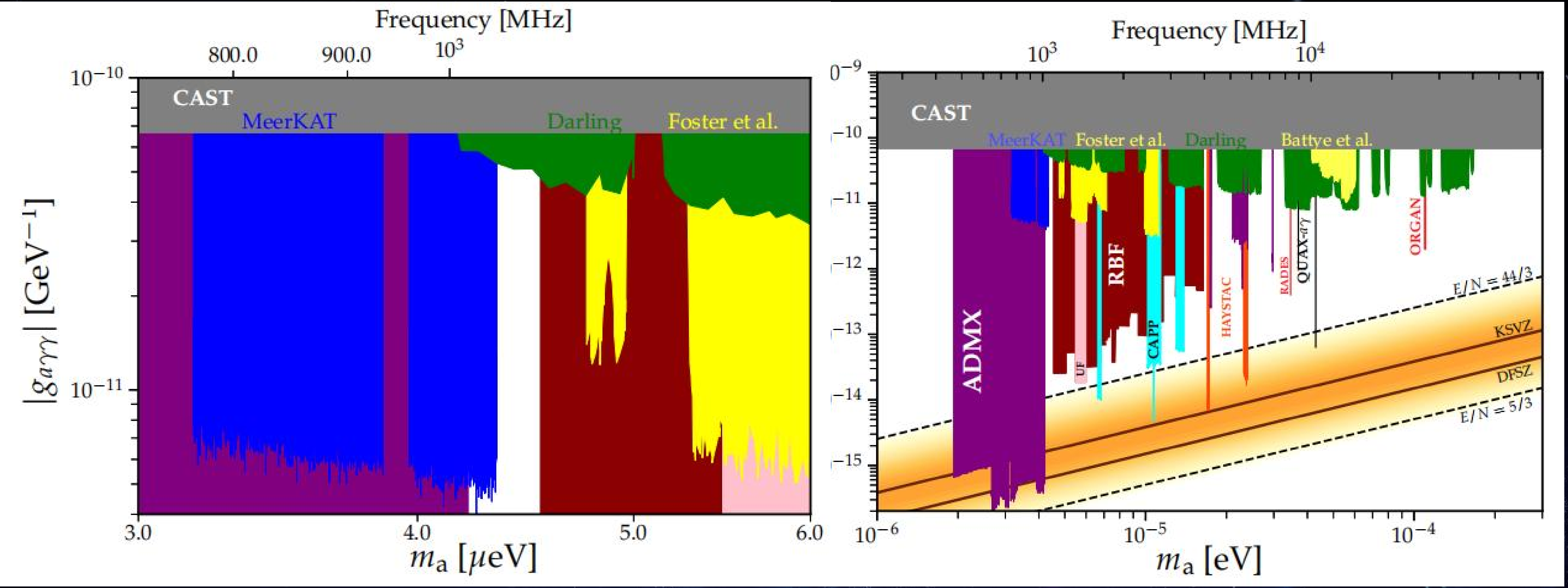
UHF Band MeerKAT
Target: neutron star RX J0806.4-4123
frequency range: 544-1088 MHz
Axion mass range: 2.5-5 μeV
Frequency resolution: 16 kHz
Area observed: 19 arcmin x 14.9 arcmin
Time resolution: 8 seconds

MeerKAT observation of RX J0806.4-4123





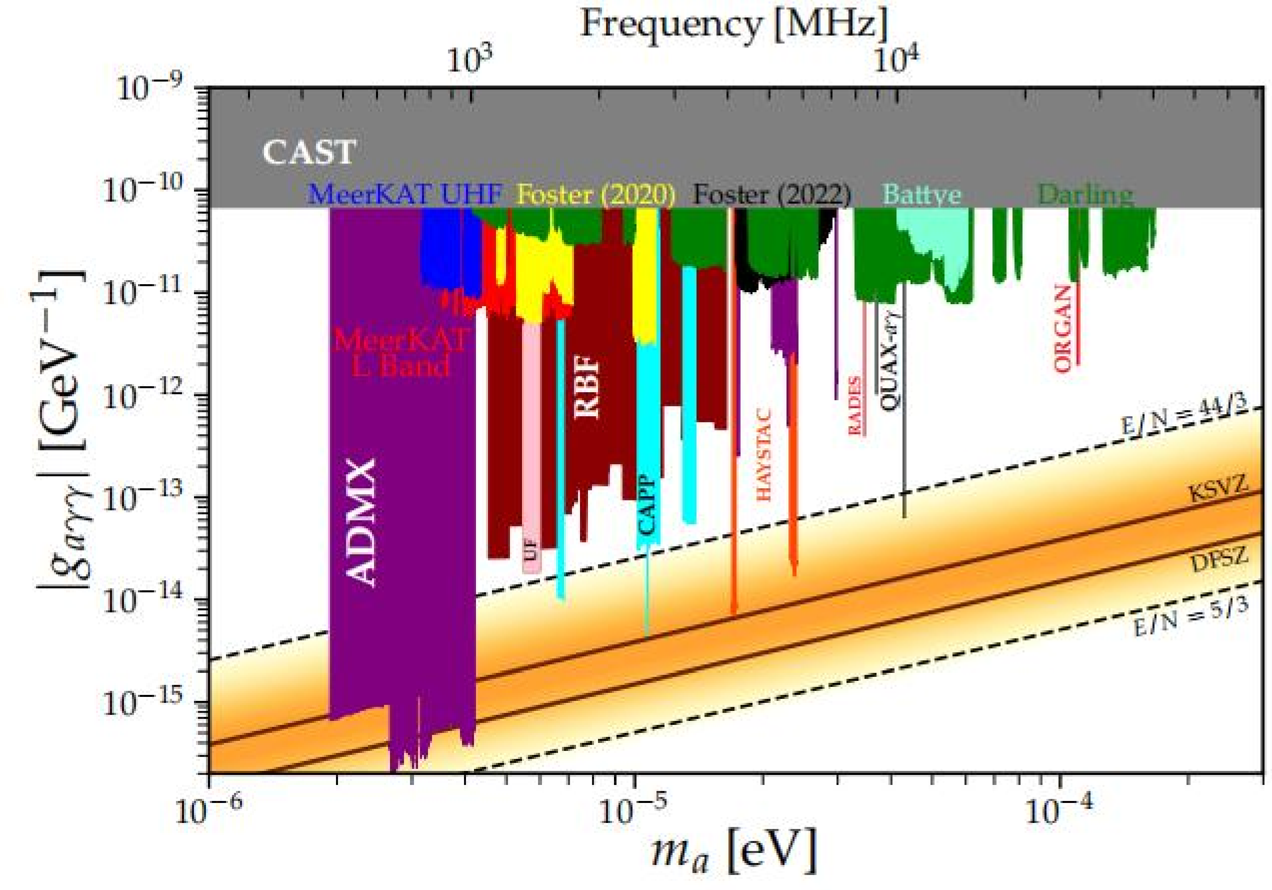
MeerKAT observation of RX J0806.4-4123

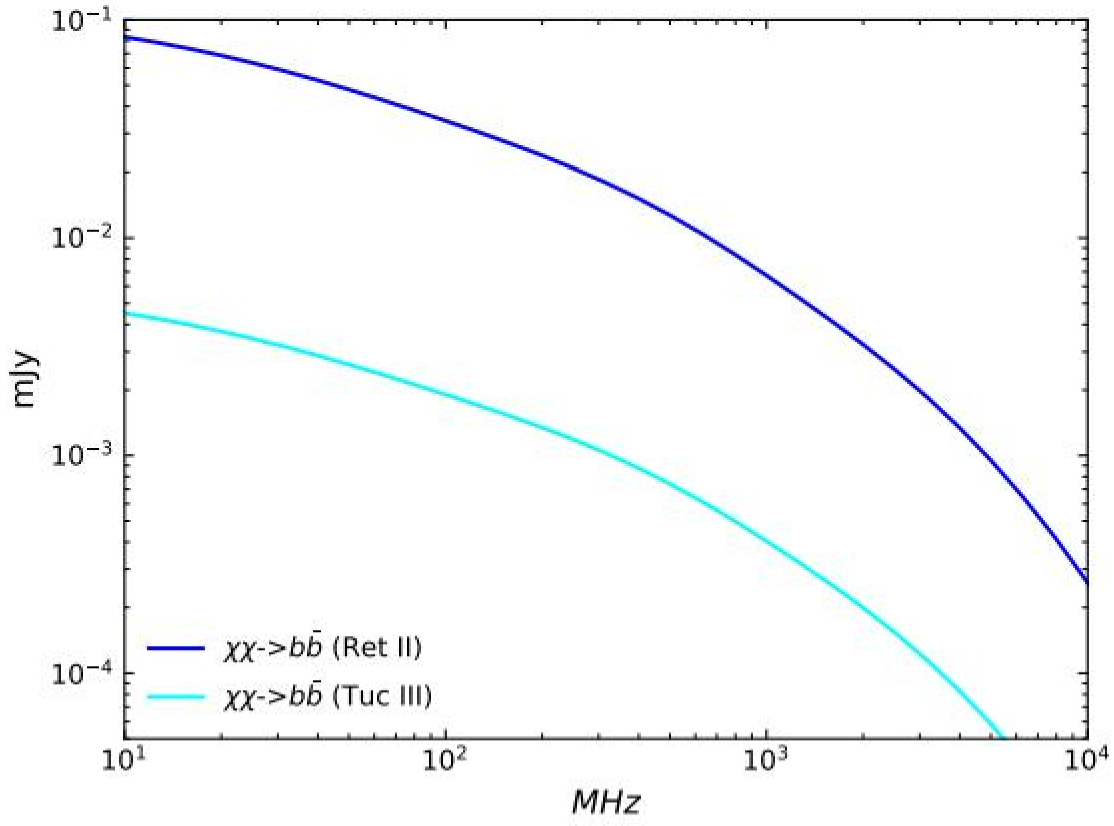


Zhou et al., 2022, PRD, 106, 083006

MeerKAT 2022 call for proposals

Searching for dark matter with MeerKAT observations of dwarf spheroidal galaxies

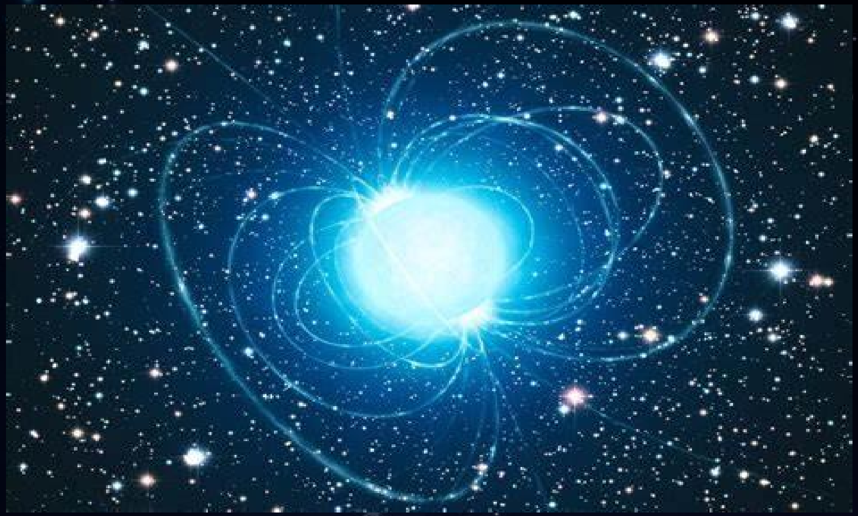




Axion searches

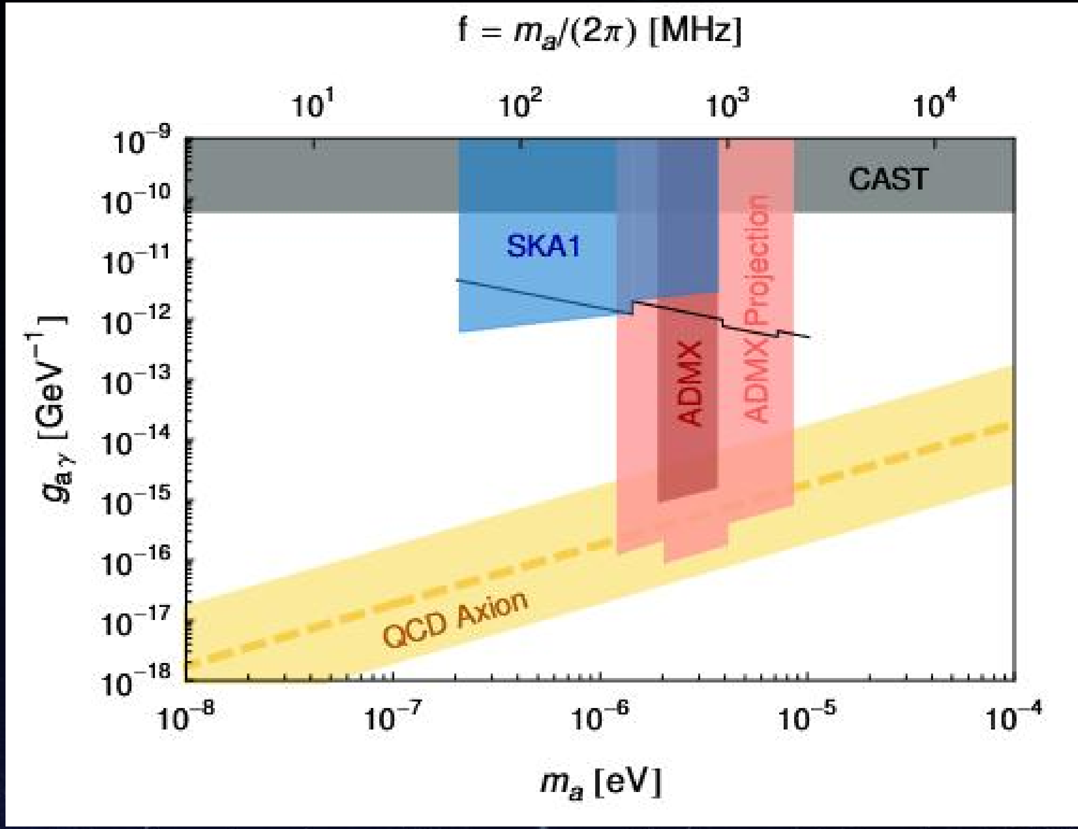
WIMP searches

Magnetic white dwarfs



$$S_{a\gamma}^{\rm WD} \simeq 29.11\ \mu{\rm Jy} \left(\frac{\rho_{\rm DM}^{\infty}}{0.3\ {\rm GeV/cm^3}}\right) \left(\frac{M_{\rm WD}}{M_{\odot}}\right)^{3/2} \left(\frac{v_0}{200\ {\rm km/s}}\right)^{-1} \left(\frac{R_{\rm WD}}{10^4\ {\rm km}}\right)^{-1/2} \left(\frac{T_{\rm cor}}{10^6\ {\rm K}}\right) \times \left(\frac{g_{a\gamma}}{10^{-12}\ {\rm GeV^{-1}}}\right)^2 \left(\frac{B_0}{10^8\ {\rm G}}\right)^2 \left(\frac{m_a}{1\ \mu{\rm eV}}\right)^{-1} \left(\frac{d}{10\ {\rm pc}}\right)^{-2} \left(\frac{\mathcal{B}}{1\ {\rm kHz}}\right)^{-1} . \quad (20)$$

$$S_{a\gamma}^{\rm NS} \simeq 71.97\ \mu{\rm Jy} \left(\frac{\rho_{\rm DM}^{\infty}}{0.3\ {\rm GeV/cm^3}}\right) \left(\frac{M_{\rm NS}}{M_{\odot}}\right)^{1/2} \left(\frac{v_0}{200\ {\rm km/s}}\right)^{-1} \left(\frac{R_{\rm NS}}{10\ {\rm km}}\right)^{5/2} \left(\frac{P}{1\ {\rm sec}}\right)^{7/6} \times \left(\frac{g_{a\gamma}}{10^{-12}\ {\rm GeV^{-1}}}\right)^2 \left(\frac{B_0}{10^{14}\ {\rm G}}\right)^{5/6} \left(\frac{m_a}{1\ \mu{\rm eV}}\right)^{4/3} \left(\frac{d}{100\ {\rm pc}}\right)^{-2} \left(\frac{\mathcal{B}}{1\ {\rm kHz}}\right)^{-1} ,$$

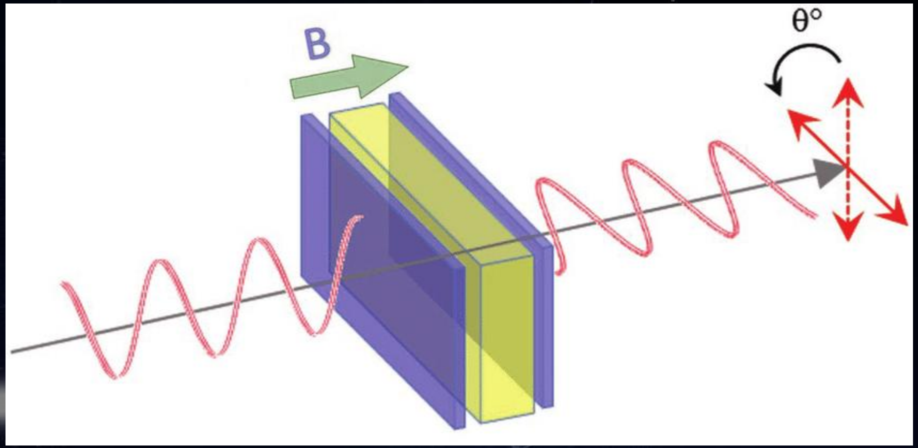


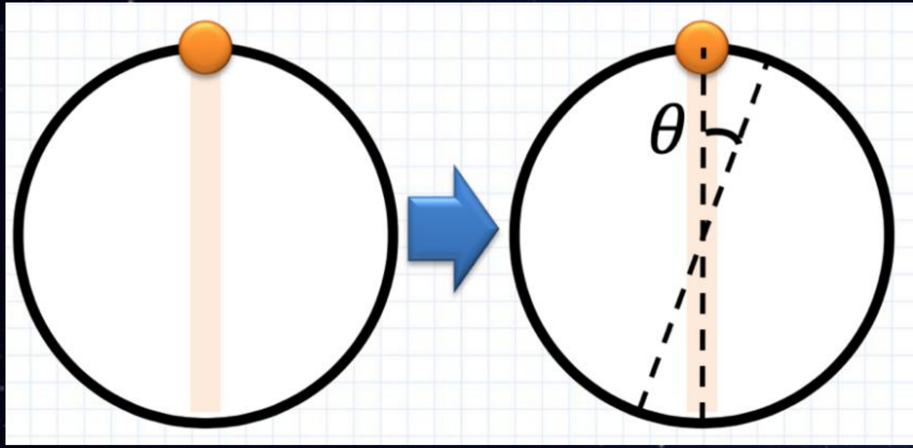
Sensitivity is comparable to neutron stars

Wang+ 2021

Axion induced birefringence

- Faraday rotation in the magnetic field





Carroll et al., 1990, PRD, 41, 1231

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\nabla^{\mu}a\nabla_{\mu}a - V(a)$$

$$\Box A_{\pm} = \pm 2ig_{a\gamma}[\partial_z a\dot{A}_{\pm} - \dot{a}\partial_z A_{\pm}]$$

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

- The equation of motion of photons get modified in the axion background, resulting in periodic oscillation of position angle of linearly polarized photons

- A large axion field is important!

Pulsar polarization constraints

Liu et al., 1901.10981

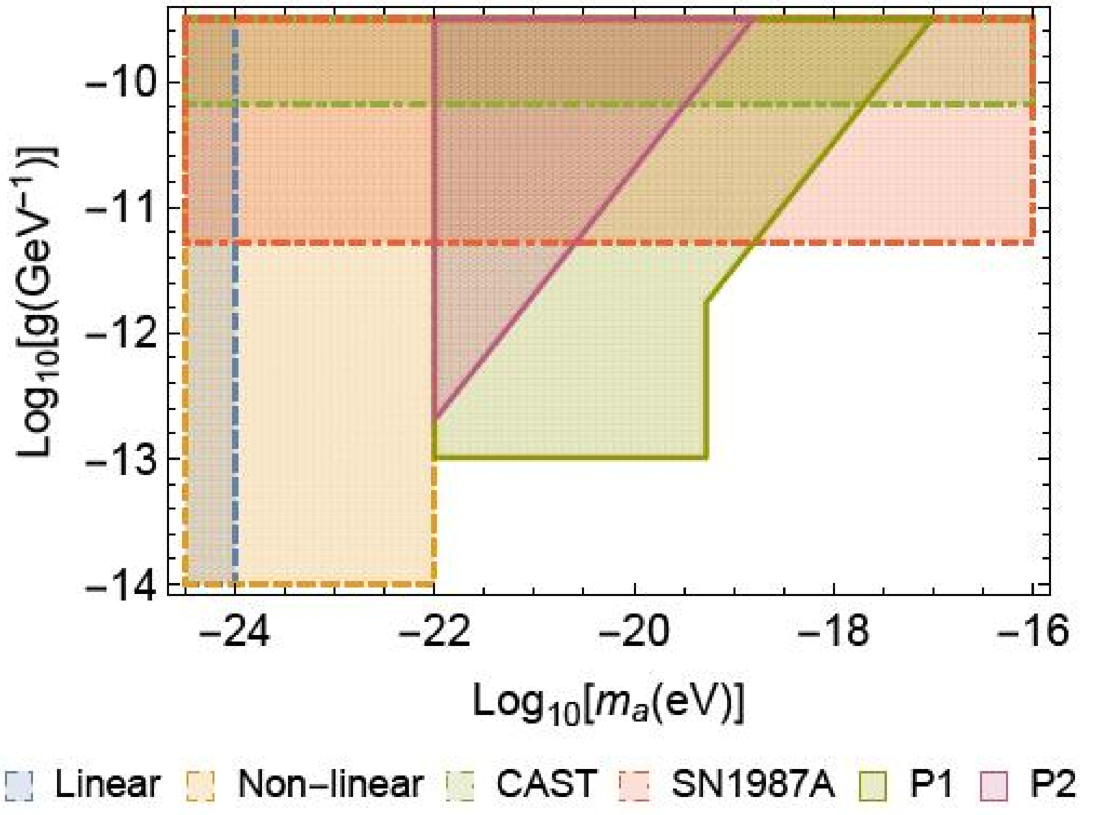
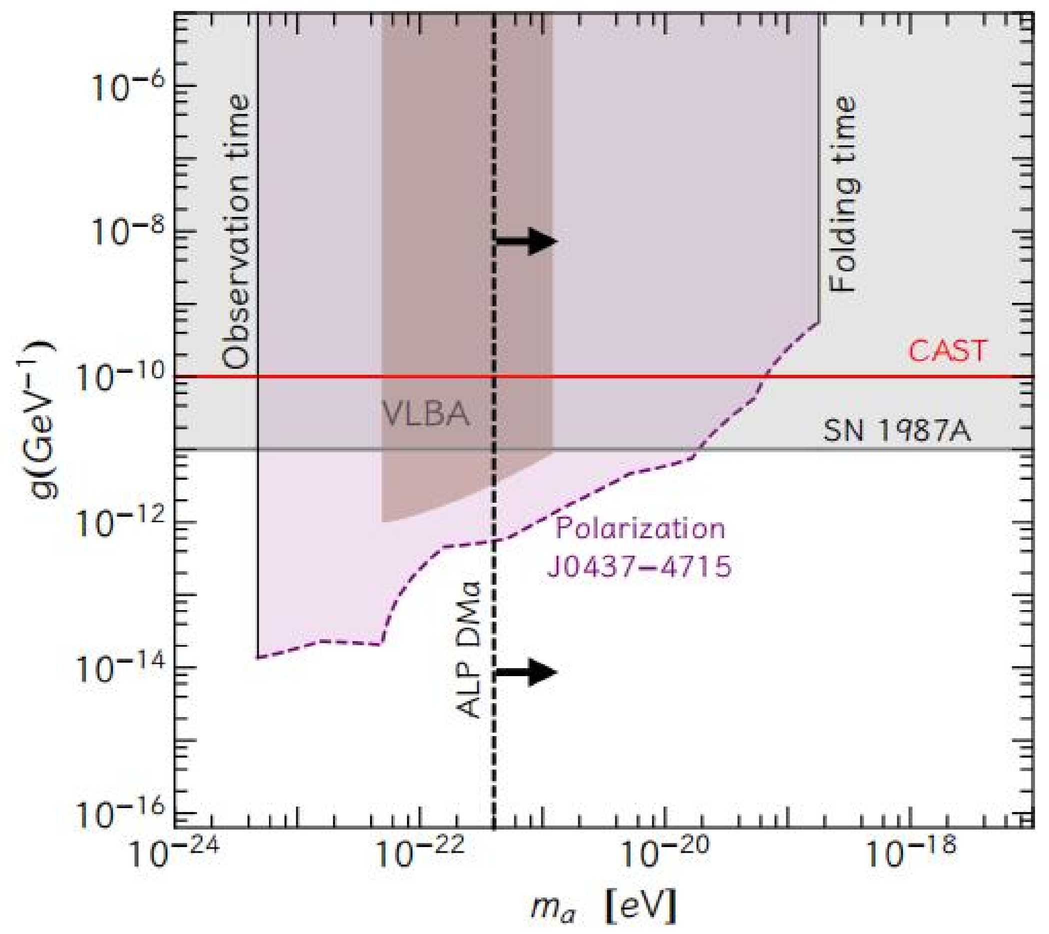


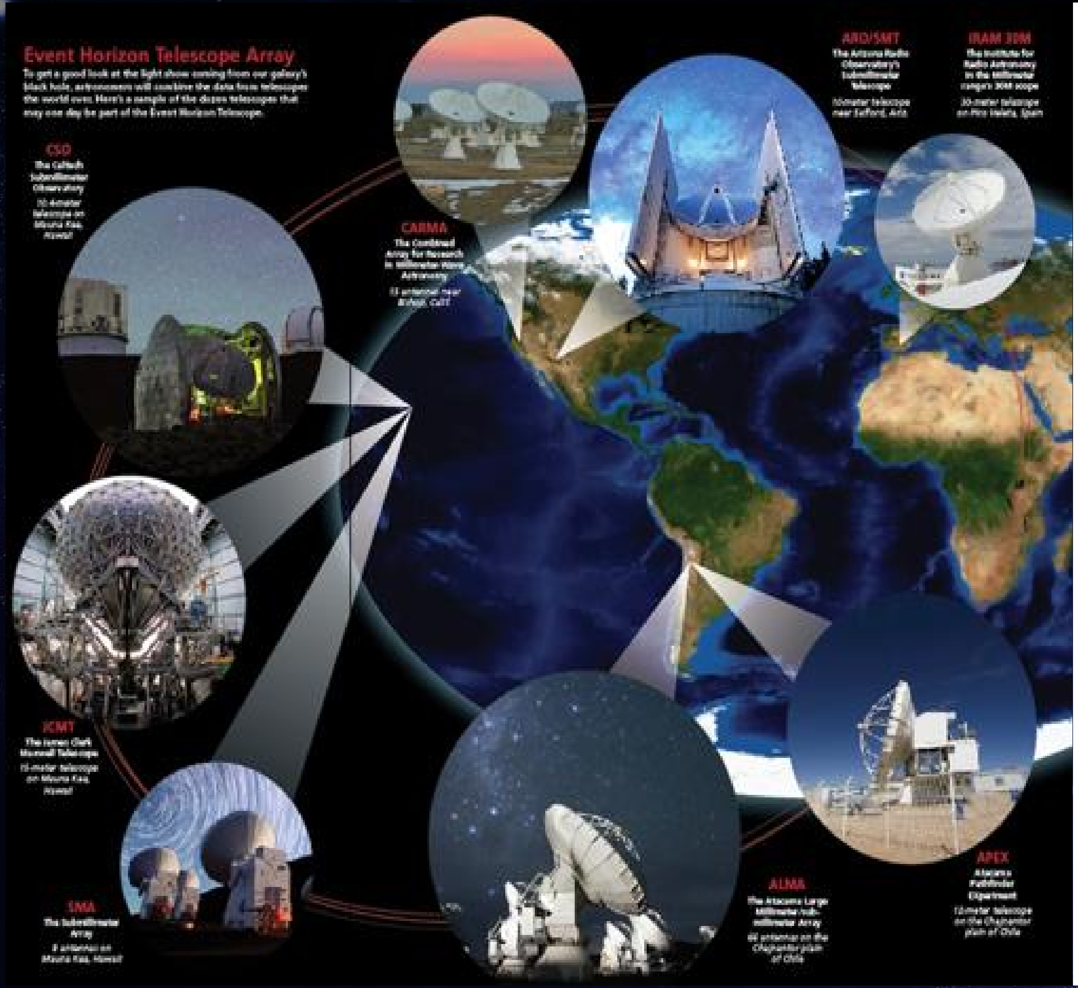
FIG. 1: Projected sensitivities to detect the CAB, using linearly polarized pulsar light as a probe, in the two benchmark scenarios: P_1 and P_2.

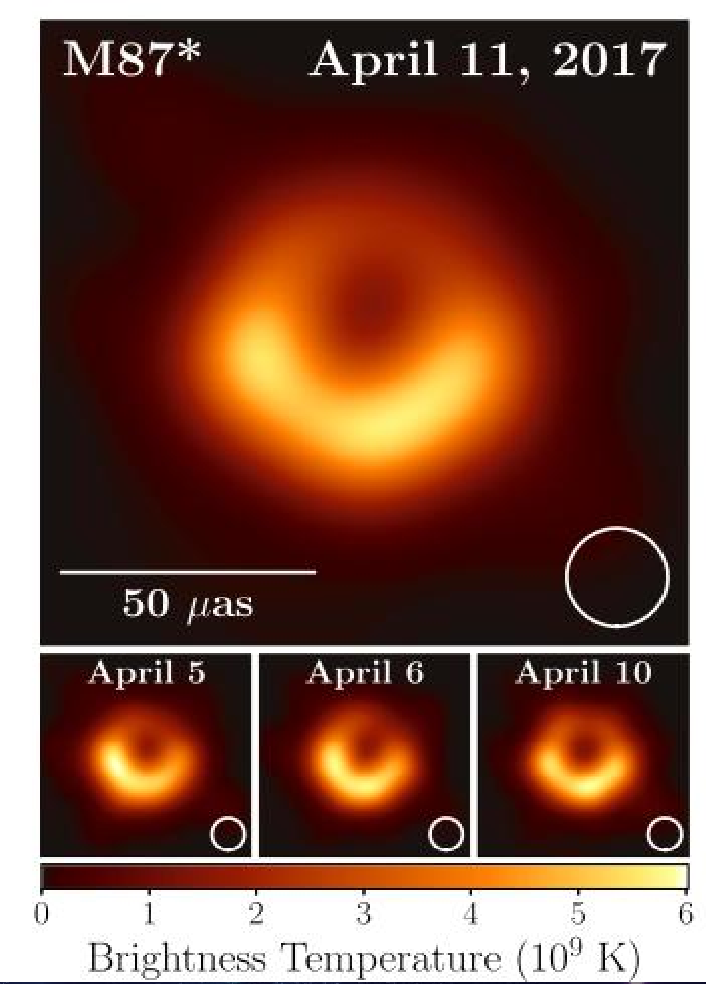
Caputo et al., 1902.02695

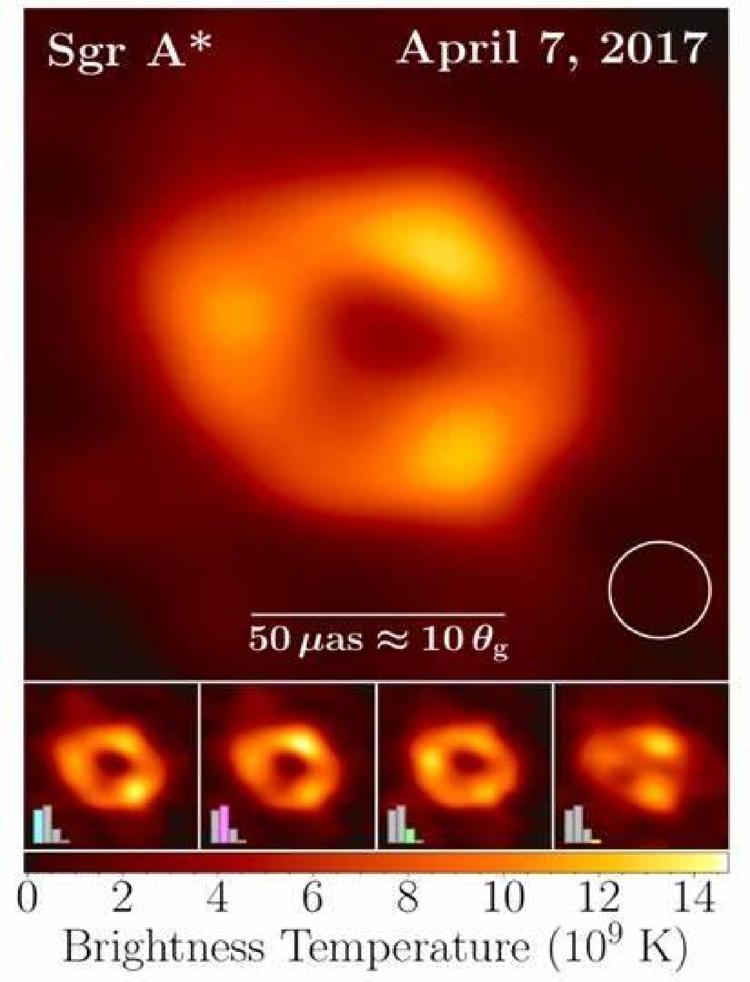


Parkes observations of PSR J0437-4715

EHT high-precision imaging of BHs

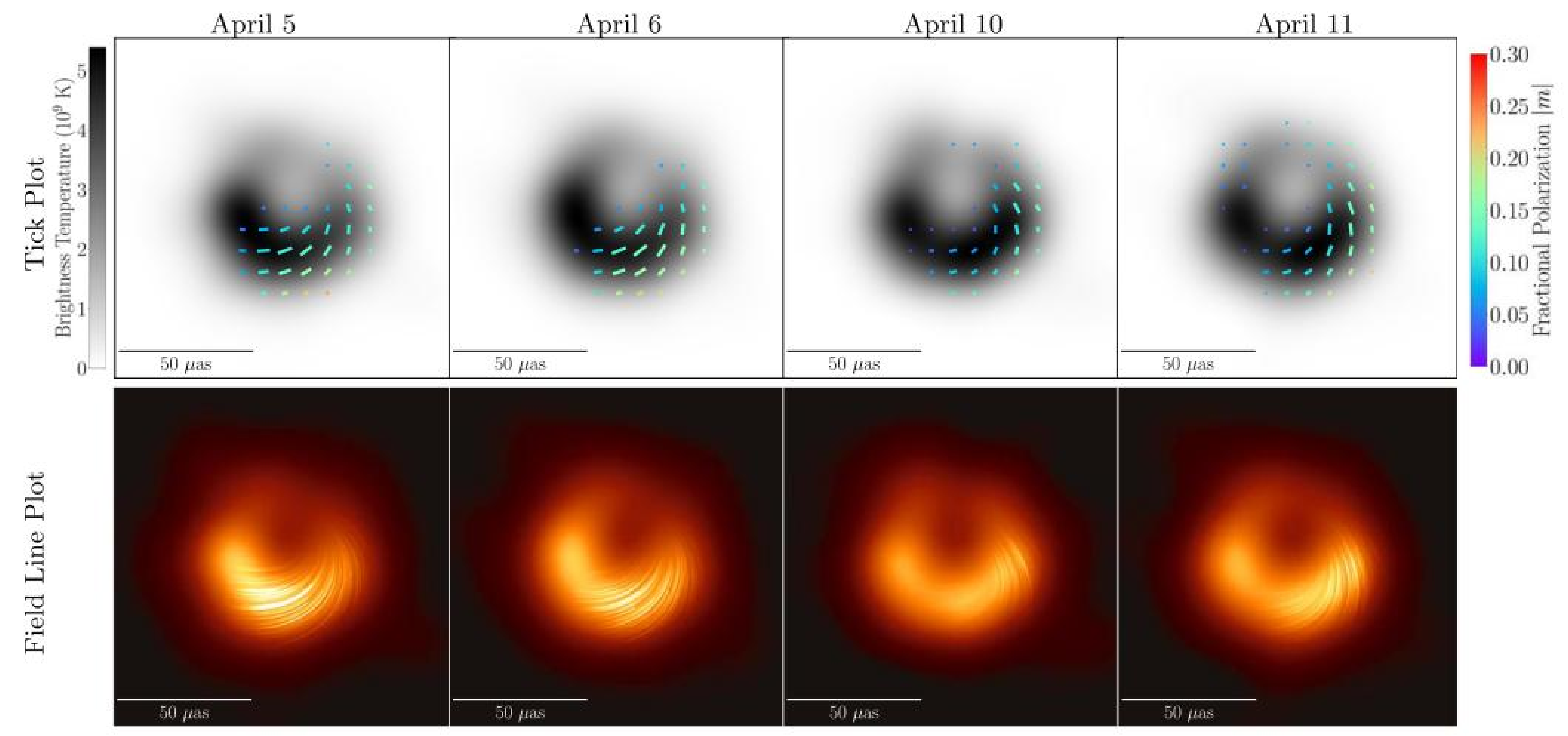






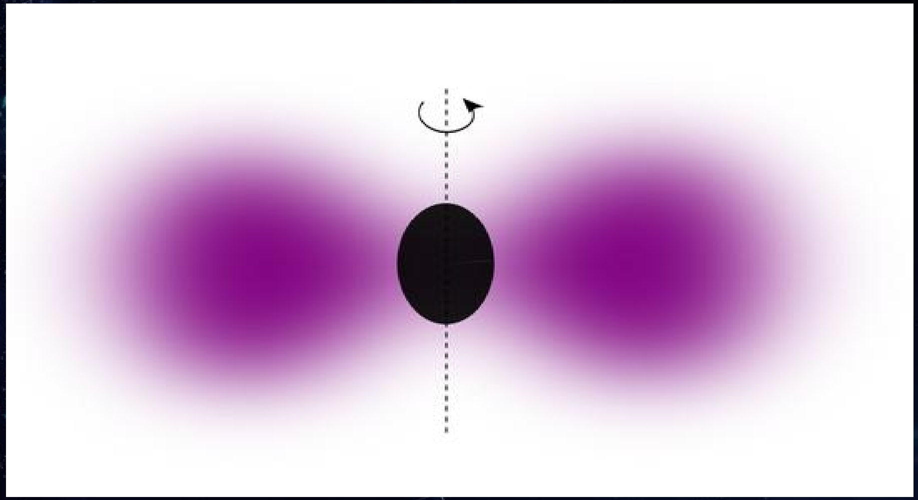
EHT Collaboration, 2019, 2022

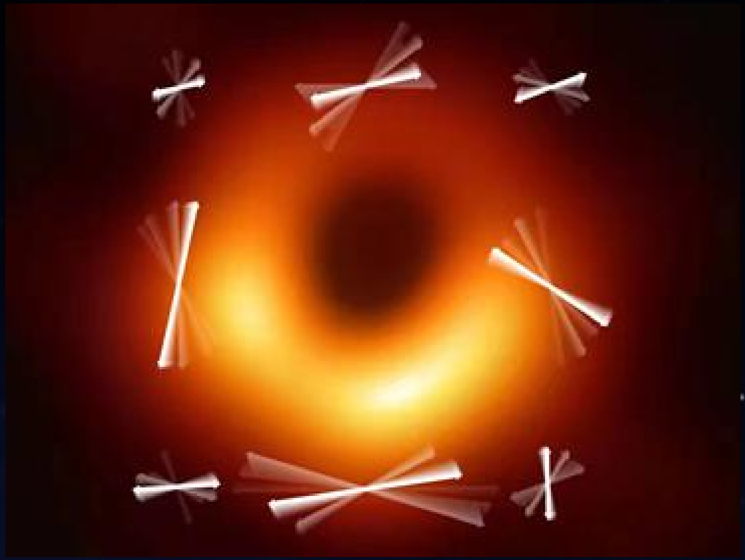
EHT polarimetric imaging of BHs

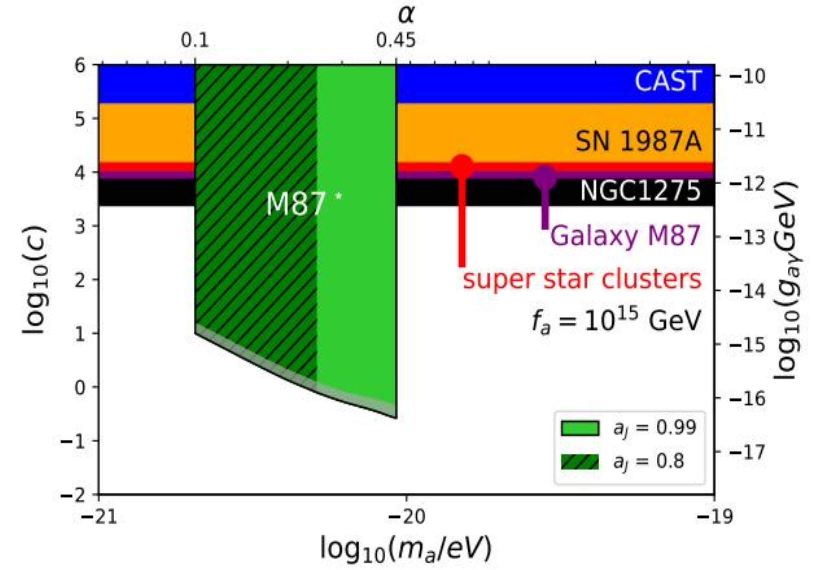


EHT, 2021, ApJL, 910, L12

Probing axionlike particles with EHT polarimetric imaging of BHs





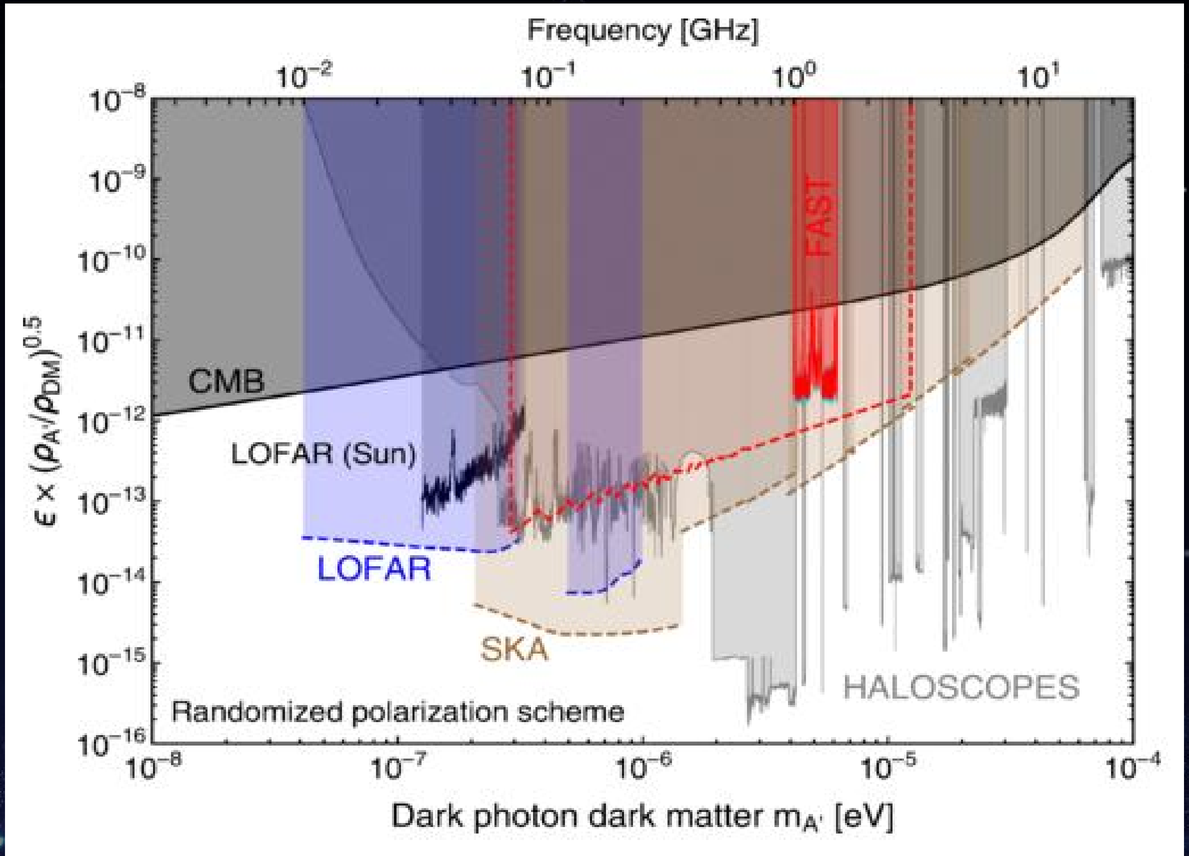


- Axionlike particle density may get significantly enhanced around a Kerr black hole through the superradiance mechanism
- Using the polarimetric imaging observations of BHs by EHT, one can probe axionlike particles with specific mass to a previously unreached region

Chen et al., 2020, PRL, 124, 061102; Chen et al., 2022, Nature Astronomy, 6, 592

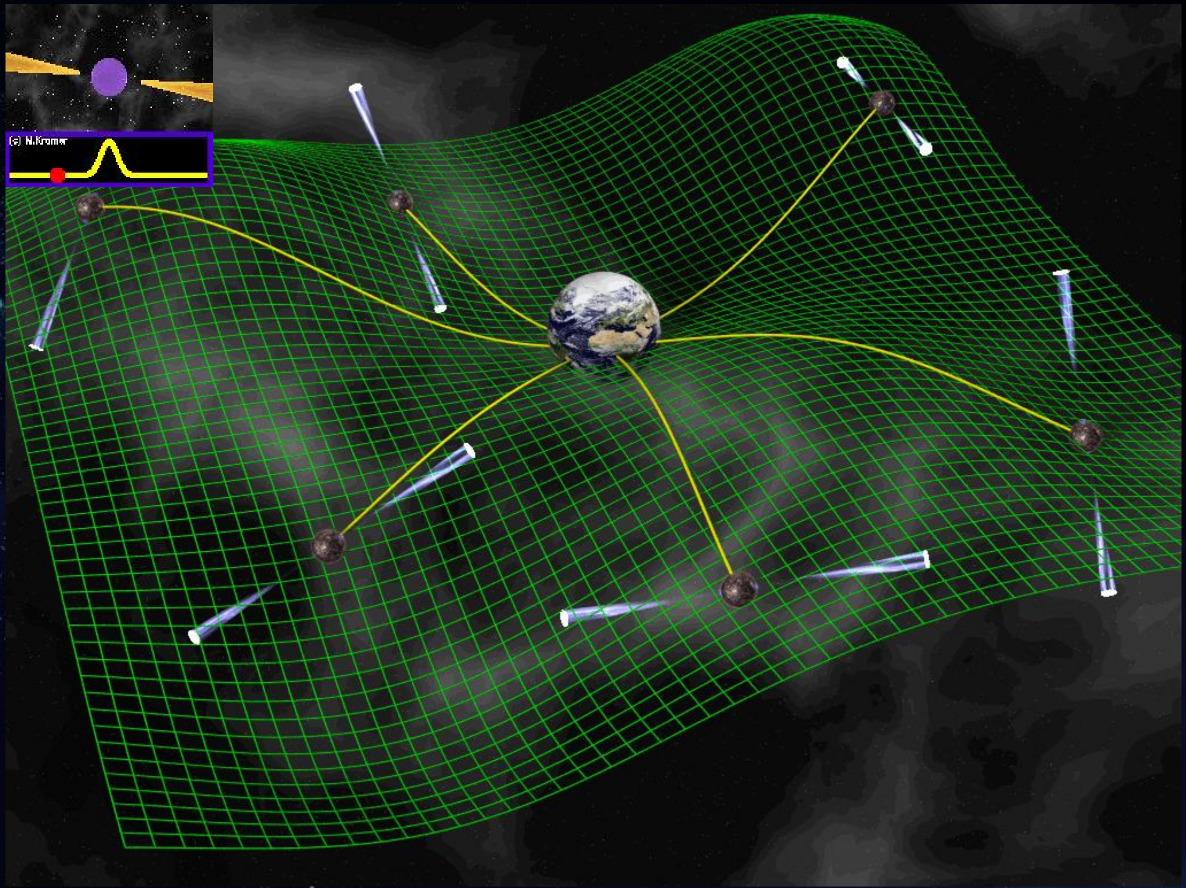
FAST detection of dark photon dark matter

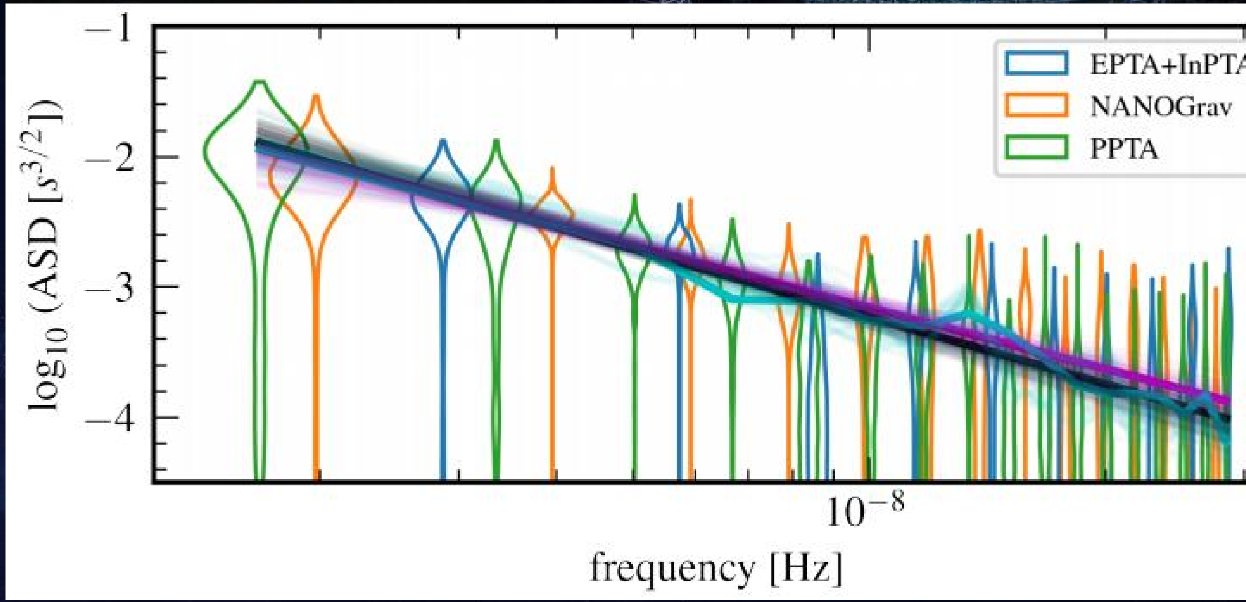
A novel method to probe dark photons with direct conversion at the mirror



2023, PRL, 130, 181001

Pulsar timing array (PTA)



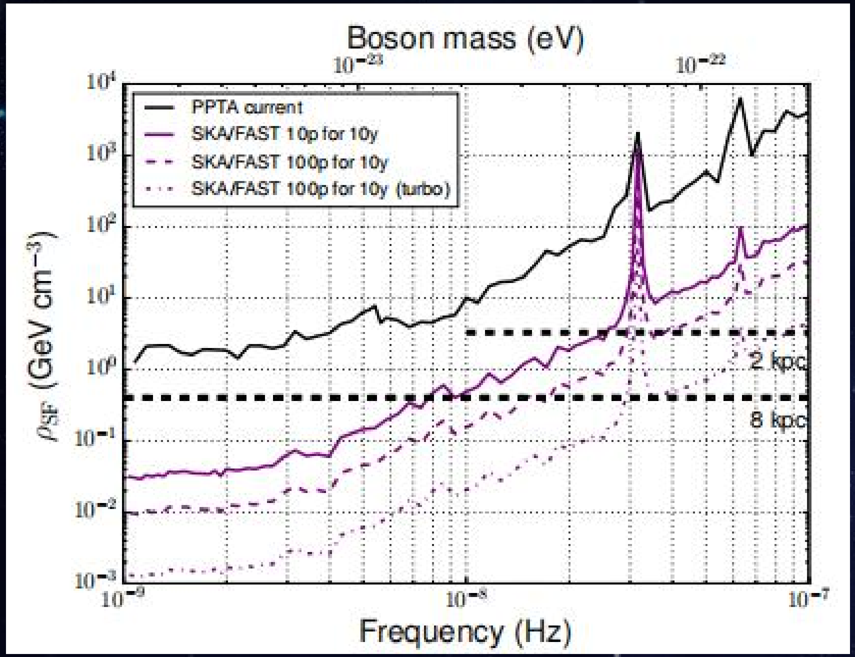


The open of nano-hertz GW window!
CPTA, EPTA, NANOGrav, PPTA

PTA detection of ultralight DM

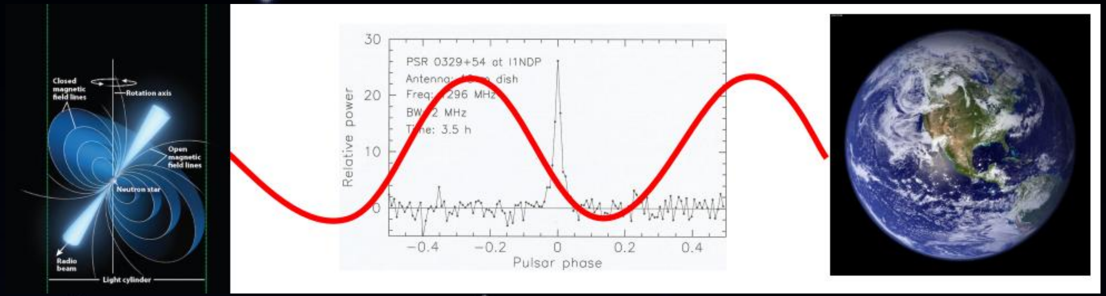
- Gravitational effect

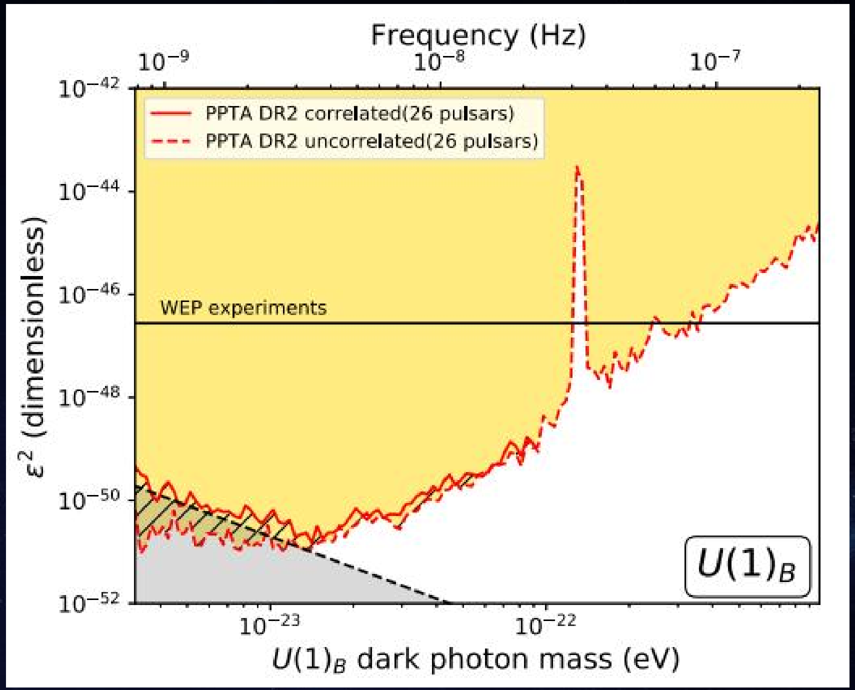
$$s(t) = \int_0^t \frac{\delta\nu}{\nu} dt = \frac{\Psi_c(x_e)}{2\pi f}\sin[2\pi f t + 2\alpha(x_e)] - \frac{\Psi_c(x_p)}{2\pi f}\sin\left[2\pi f\left(t - \frac{d_p}{c}\right) + 2\alpha(x_p)\right] + \left(\frac{\Psi+\Phi}{2\pi f}\right)\mathcal{O}\left(\frac{v}{c}\right),$$



Porayko+ (PPTA) 2018

- Fifth-force effect

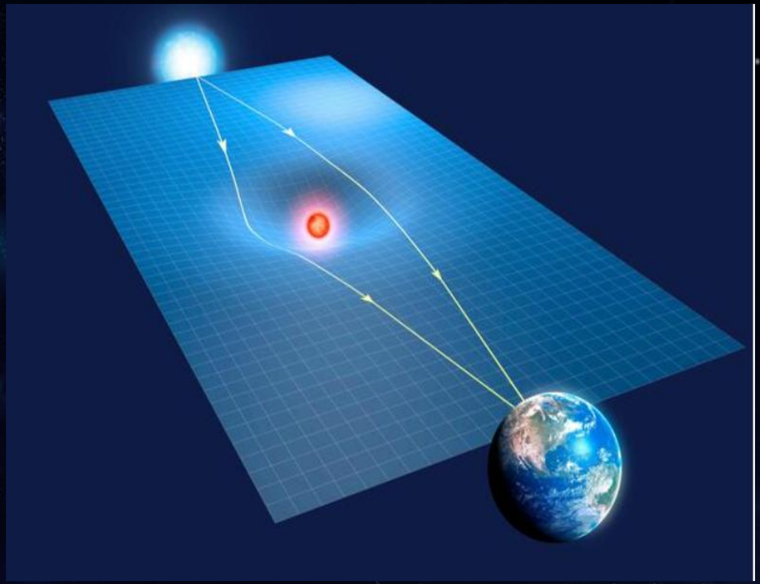


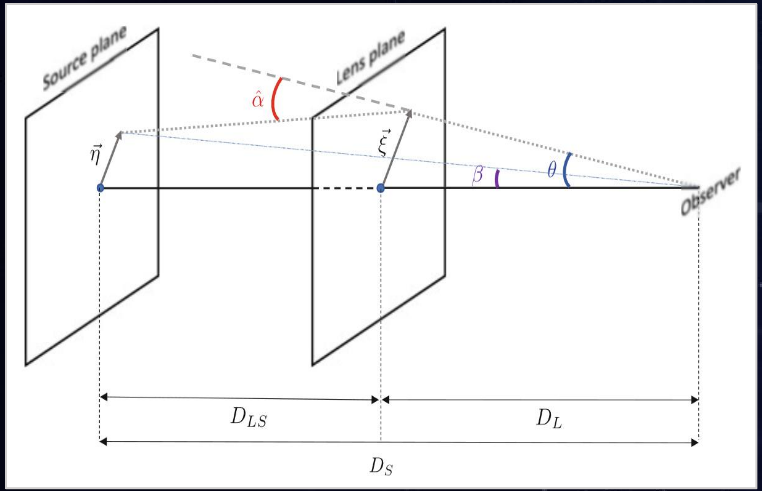


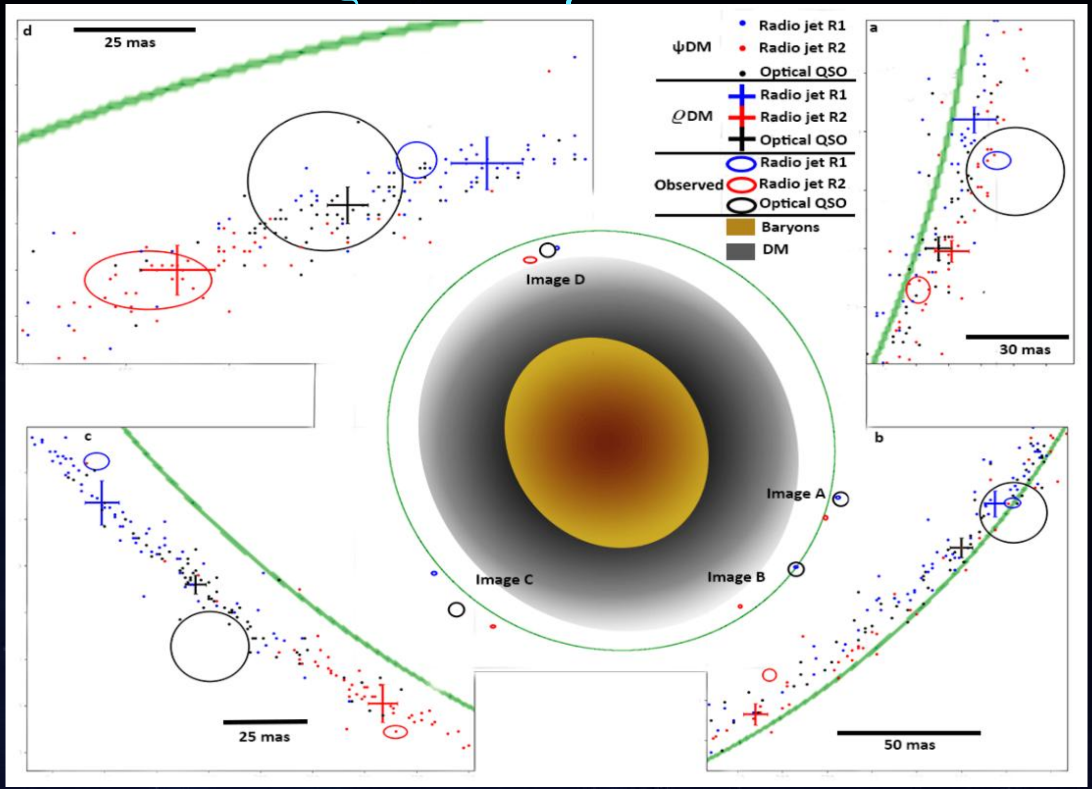
Xue+ (PPTA) 2022

Gravitational lensing

ϱDM vs ψDM





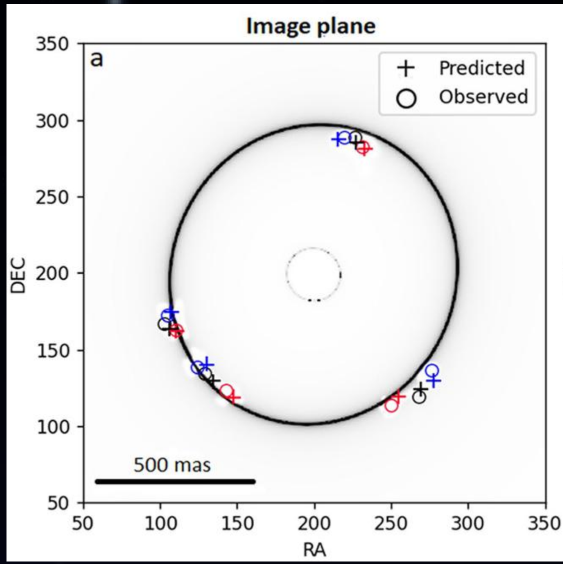


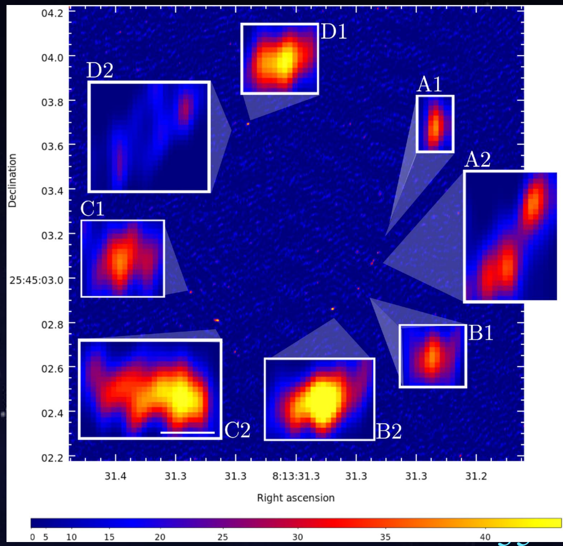
nature astronomy

Article

https://doi.org/10.1038/s41550-023-01943-9

Einstein rings modulated by wavelike dark matter from anomalies in gravitationally lensed images





Rubin observatory (LSST)

Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 4 Feb 2019 (v1), last revised 24 Apr 2019 (this version, v2)]

Probing the Fundamental Nature of Dark Matter with the Large Synoptic Survey Telescope

Alex Drlica-Wagner, Yao-Yuan Mao, Susmita Adhikari, Robert Armstrong, Arka Banerjee, Nilanjan Banik, Keith Bechtol, Simeon Bird, Kimberly K. Boddy, Ana Bonaca, Jo Bovy, Matthew R. Buckley, Esra Bulbul, Chihway Chang, George Chapline, Johann Cohen-Tanugi, Alessandro Cuoco, Francis-Yan Cyr-Racine, William A. Dawson, Ana Díaz Rivero, Cora Dvorkin, Denis Erkal, Christopher D. Fassnacht, Juan García-Bellido, Maurizio Giannotti, Vera Gluscevic, Nathan Golovich, David Hendel, Yashar D. Hezaveh, Shunsaku Horiuchi, M. James Jee, Manoj Kaplinghat, Charles R. Keeton, Sergey E. Koposov, Casey Y. Lam, Ting S. Li, Jessica R. Lu, Rachel Mandelbaum, Samuel D. McDermott, Mitch McNanna, Michael Medford, Manuel Meyer, Moniez Marc, Simona Murgia, Ethan O. Nadler, Lina Necib, Eric Nuss, Andrew B. Pace, Annika H. G. Peter, Daniel A. Polin, Chanda Prescod-Weinstein, Justin I. Read, Rogerio Rosenfeld, Nora Shipp, Joshua D. Simon, Tracy R. Slatyer, Oscar Straniero, Louis E. Strigari, Erik Tollerud, J. Anthony Tyson, Mei-Yu Wang, Risa H. Wechsler, David Wittman, Hai-Bo Yu, Gabrijela Zaharijas, Yacine Ali-Haïmoud, James Annis, Simon Birrer, Rahul Biswas, Jonathan Blazek, Alyson M. Brooks, Elizabeth Buckley-Geer, Regina Caputo, Eric Charles, Seth Digel, Scott Dodelson, Brenna Flaugher, Joshua Frieman, Eric Gawiser, Andrew P. Hearin, Renee Hložek, Bhuvnesh Jain, Tesla E. Jeltema, Savvas M. Koushiappas, Mariangela Lisanti, Marilena LoVerde, Siddharth Mishra-Sharma, Jeffrey A. Newman, Brian Nord, Erfan Nourbakhsh, Steven Ritz, Brant E. Robertson, Miguel A. Sánchez-Conde, Anže Slosar, Tim M. P. Tait, Aprajita Verma, Ricardo Vilalta, Christopher W. Walter, Brian Yanny, Andrew R. Zentner

Astrophysical and cosmological observations currently provide the only robust, empirical measurements of dark matter. Future observations with Large Synoptic Survey Telescope (LSST) will provide necessary guidance for the experimental dark matter program. This white paper represents a community effort to summarize the science case for studying the fundamental physics of dark matter with LSST. We discuss how LSST will inform our understanding of the fundamental properties of dark matter, such as particle mass, self-interaction strength, non-gravitational couplings to the Standard Model, and compact object abundances. Additionally, we discuss the ways that LSST will complement other experiments to strengthen our understanding of the fundamental characteristics of dark matter. More information on the LSST dark matter effort can be found at this https URL .

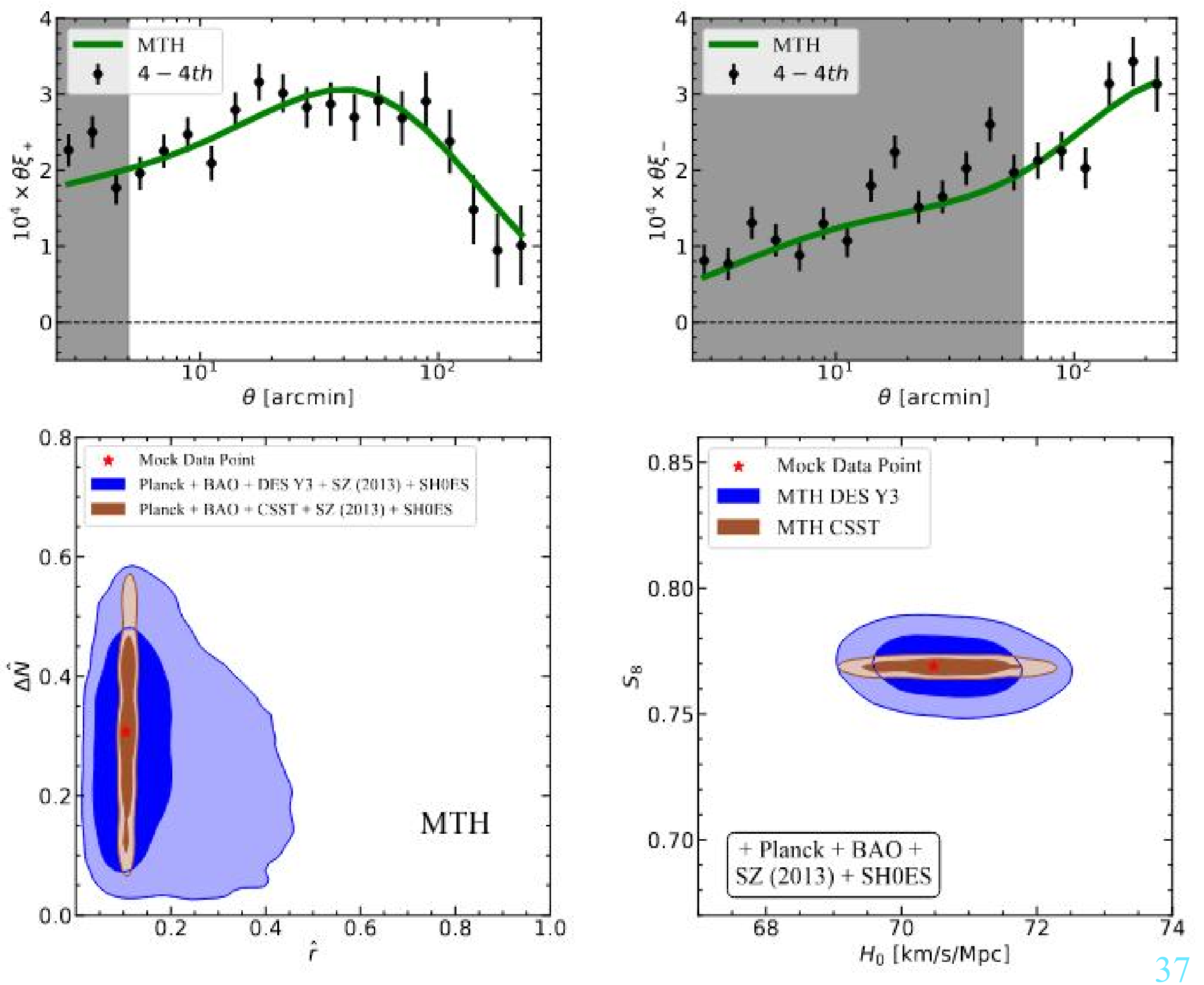
Comments: 96 pages, 22 figures, 1 table

WFST (2023)

CSST (2024?)

Exploring Mirror Twin Higgs Cosmology with Present and Future Weak Lensing Surveys

Lei Zu[1],[a,b] Chi Zhang[2],[a,b] Hou-Zun Chen,[a,b] Wei Wang,[a,b] Yue-Lin Sming Tsai[3],[a,b] Yuhsin Tsai[4],[c] Wentao Luo,[d] Yi-Zhong Fan[a,b]



2023年紫金山暗物质研讨会

2023年12月29日 到 2024年1月1日
Asia/Shanghai 时区

输入您的搜索词

- 概览
- 征集摘要
- 注册
- 参会人名单

Contact

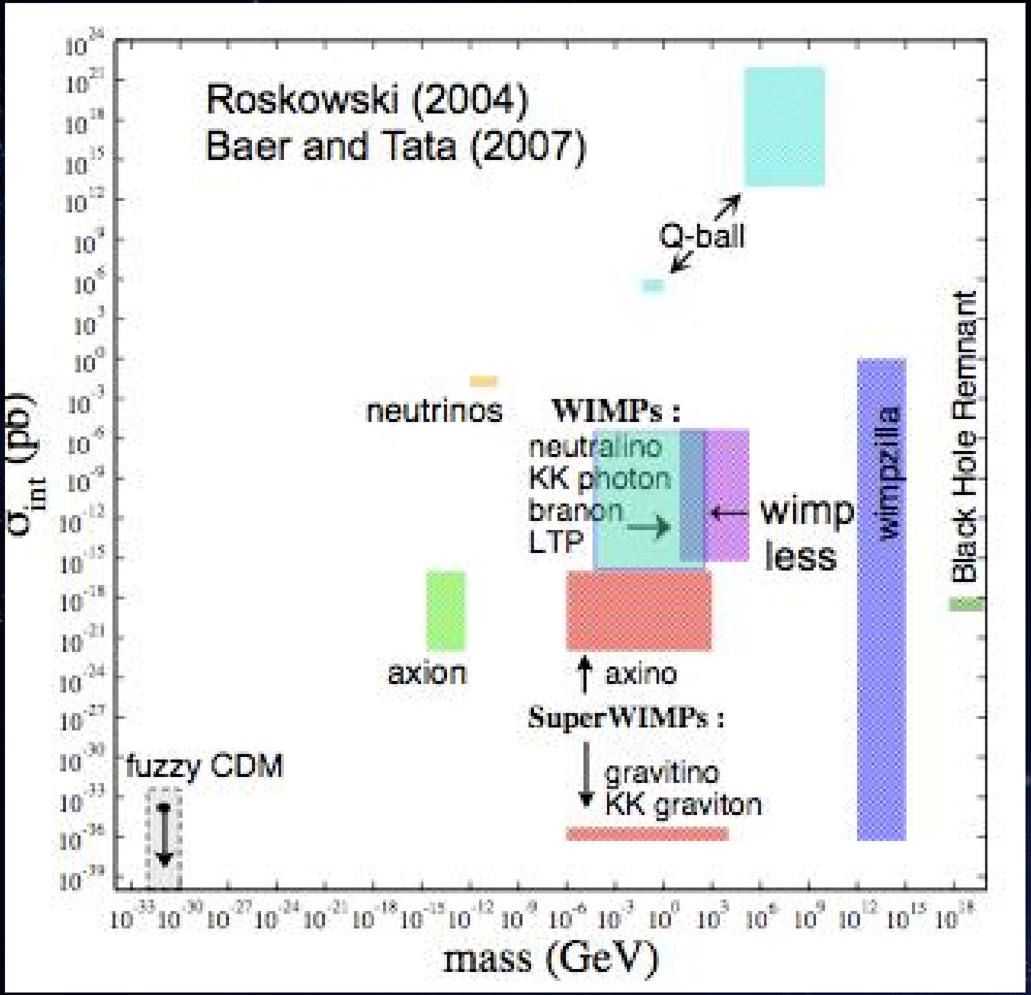
ctlu@njnu.edu.cn
leiwu@njnu.edu.cn
ycwu@njnu.edu.cn

尊敬的各位同仁：

探索暗物质本质是粒子物理、天文学和宇宙学共同关注的前沿课题。近年来，世界各科技大国均在积极开展暗物质相关理论和实验的研究。我国也将暗物质的研究纳入了国家中长期科学规划，成功发射了首颗暗物质科学卫星DAMPE，建成了锦屏地下实验室开展暗物质直接探测实验CDEX和PandaX，并取得了国际领先的科研成果。 为进一步推动暗物质理论和实验研究，南京师范大学将于2023年12月29日至31日举办2023年紫金山暗物质研讨会。该系列研讨会于2019年由中国科学院暗物质与空间天文重点实验室首次举办。会议内容将包括但不限于：最新暗物质实验结果、理论进展综述、暗物质探测新方法等。我们相信通过学科间交叉，将更有助于激发新的科研思路和合作机会。

会议组委会特邀请您参加本次研讨会，一同探索暗物质之谜，为这一领域的研究贡献力量！

Summary



- Experimental detection of DM is physically very important, but is technically very challenging
- It is very important to develop new technologies, new methods, and new ideas to enhance the sensitivity and mass coverage
- Precision astronomical measurements could play a crucial role in DM detection

Thank you!