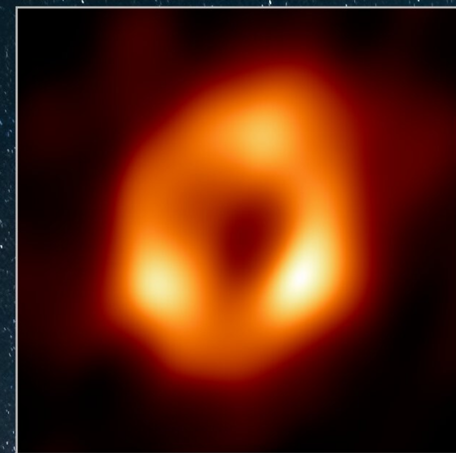

Detecting Dark Matter with the Multi-Messenger Observations of Supermassive Black Holes

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Institute of High Energy Physics, CAS.

With Yifan Chen, Ran Ding, Yi-Zhong Fan, Zhao-Qiang Shen, Zi-Qing Xia, Qiang Yuan, et al.

Based on: JCAP03(2021)018; JHEP04(2022)018; arXiv: 2306.17143.

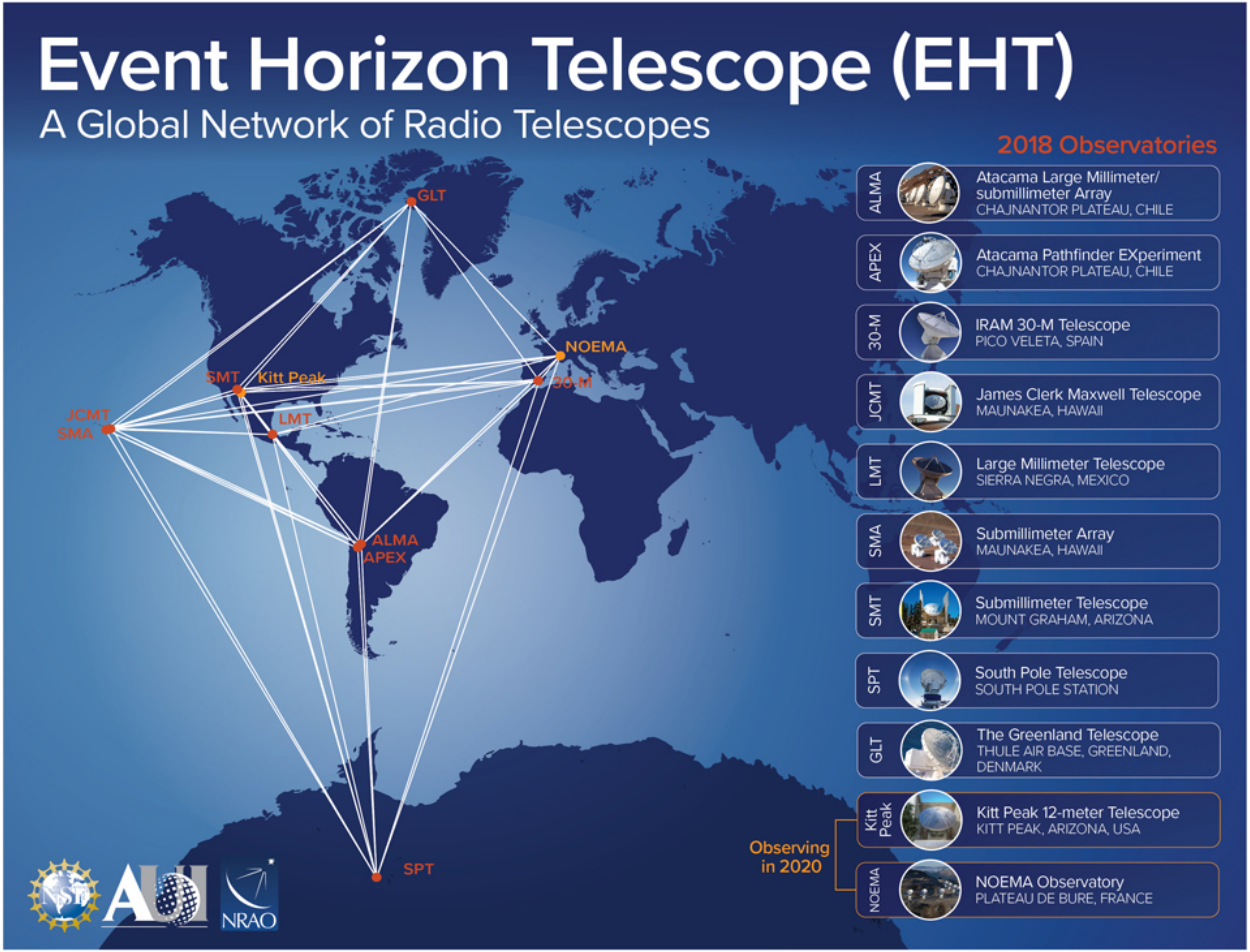
32nd Texas Symposium@Shanghai

Outline

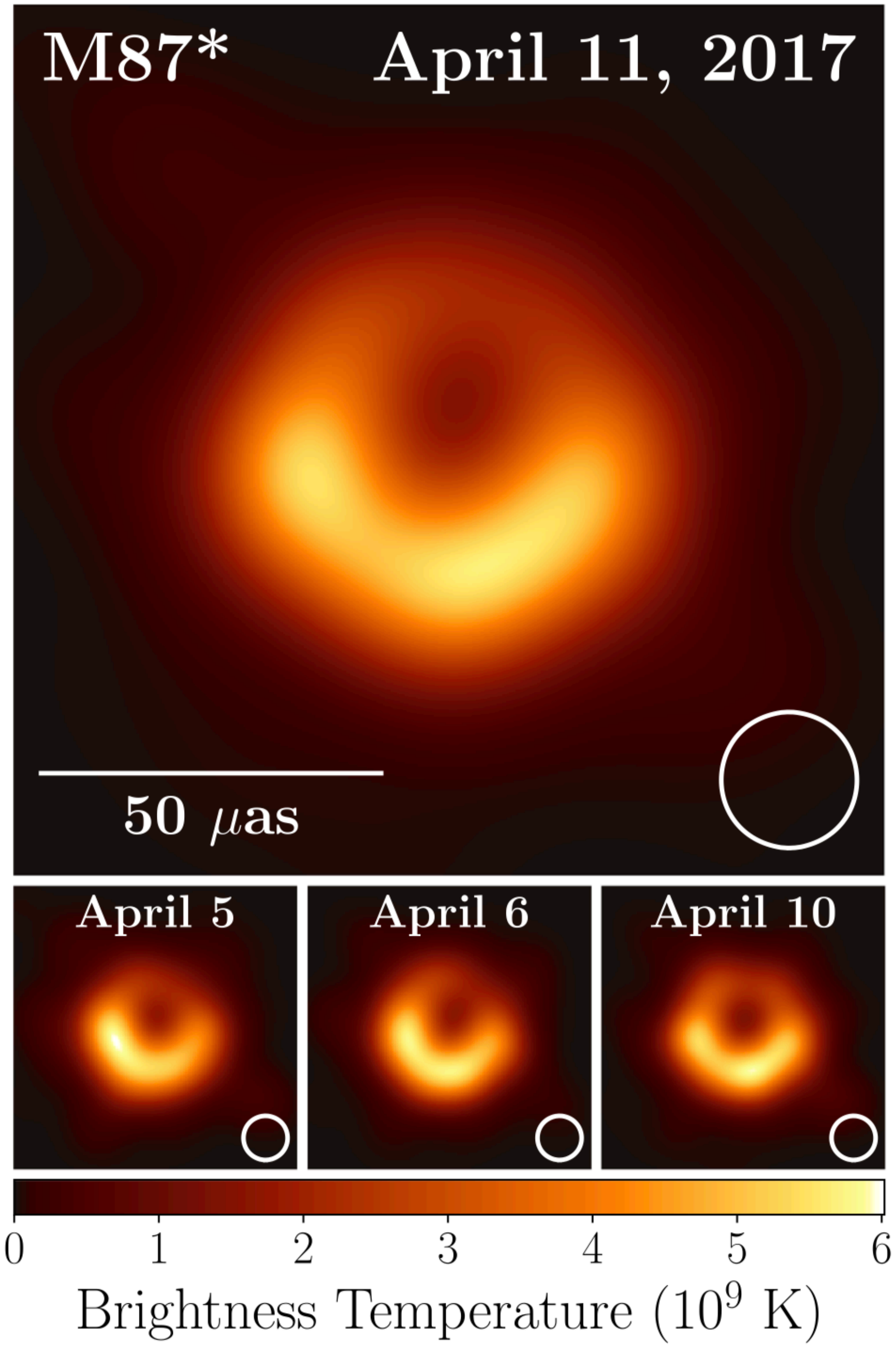
- Part I: Searching for the signal of WIMP annihilation in the shadow of M87*. *[JHEP 04(2022)018]*
- Part II: Detecting the ALP induced polarization oscillation with the observations of Sagittarius A*. *[JCAP 03(2021)018]*
- Part III: Exploring DM distribution with nanohertz stochastic gravitational wave background. *[arXiv:2306.17143]*

Motivation:
when a strong gravitational field is present around an SMBH, dark matter with gravitational interactions can congregate and create an environment that is far more dense than it would be in other regions.

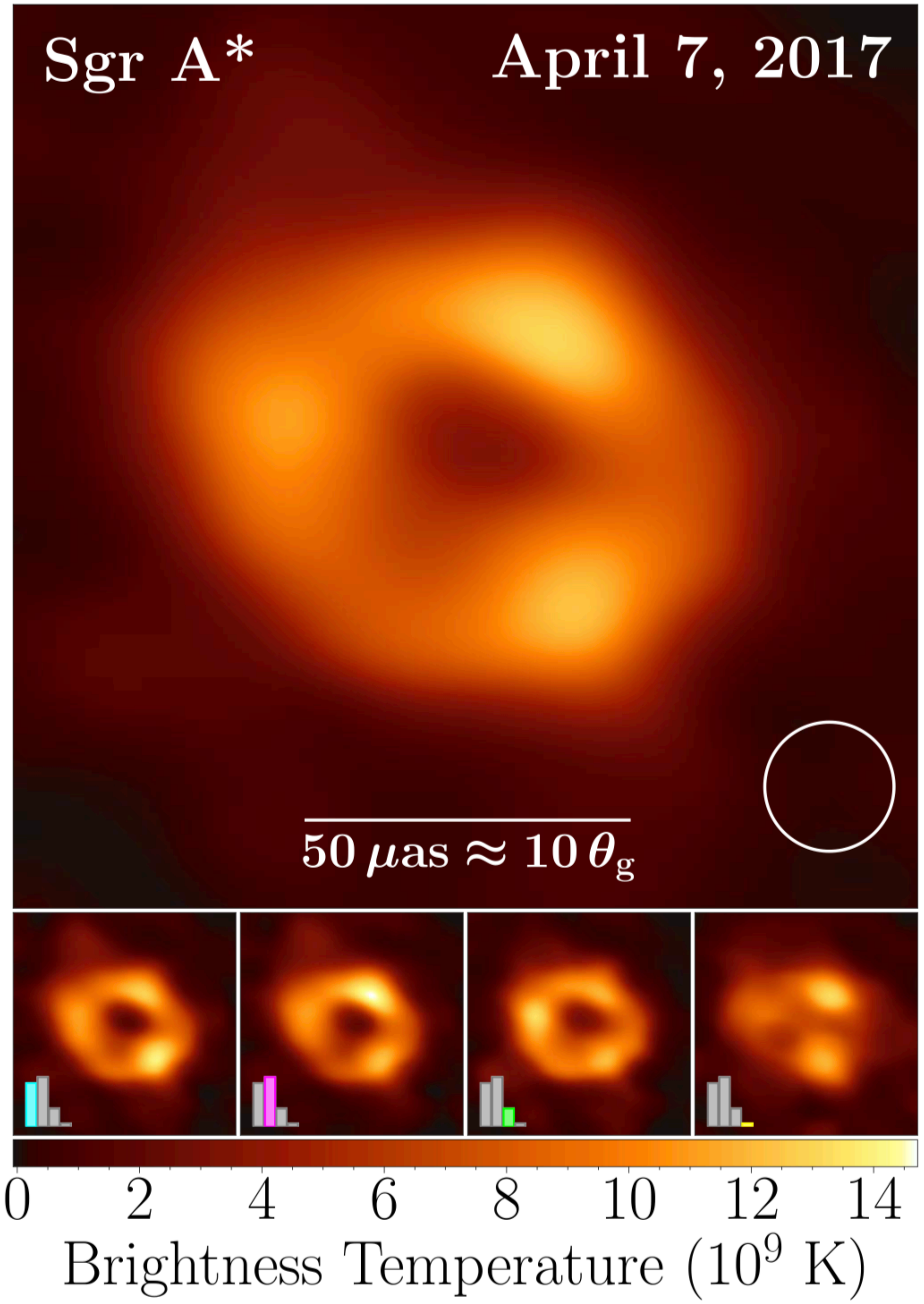
*Part I: Searching for the signal of WIMP annihilation in the shadow of M87**


Event Horizon Telescope (EHT)
A Global Network of Radio Telescopes
GLT
NOEMA
SMT
Kitt Peak
30-M
JCMT
SMA
LMT
ALMA
APEX
SPT
NRAO
2018 Observatories
ALMA
Atacama Large Millimeter/ submillimeter Array
CHAJNANTOR PLATEAU, CHILE
APEX
Atacama Pathfinder EXperiment
CHAJNANTOR PLATEAU, CHILE
30-M
IRAM 30-M Telescope
PICO VELETA, SPAIN
JCMT
James Clerk Maxwell Telescope
MAUNAKEA, HAWAII
LMT
Large Millimeter Telescope
SIERRA NEGRA, MEXICO
SMA
Submillimeter Array
MAUNAKEA, HAWAII
SMT
Submillimeter Telescope
MOUNT GRAHAM, ARIZONA
SPT
South Pole Telescope
SOUTH POLE STATION
GLT
The Greenland Telescope
THULE AIR BASE, GREENLAND, DENMARK
Observing in 2020
Kitt Peak
Kitt Peak 12-meter Telescope
KITT PEAK, ARIZONA, USA
NOEMA
NOEMA Observatory
PLATEAU DE BURE, FRANCE

Milestone Results of Event Horizon Telescope



EHTC+2019



EHTC+2022

We could estimate their mass, distance, magnetic field, temperature, flux, polarization, size…..

Propagation and Radiation of Electron Around SMBH

DM-induced electron synchrotron radiation around SMBH:

source function come from WIMP annihilation

$$q_i(r,p) = \frac{c}{4\pi p^2} Q_i(r,E) = \frac{c}{4\pi p^2} \frac{\langle \sigma v \rangle_i \rho^2(r)}{2m_\chi^2} \frac{\mathrm{d}N_{ann}}{\mathrm{d}E}(E)$$

spatial diffusion

injection term

$$-\frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 D \frac{\partial f_e}{\partial r}\right] + v\frac{\partial f_e}{\partial r} - \frac{1}{3r^2}\frac{\partial}{\partial r}\left(r^2 v\right) p \frac{\partial f_e}{\partial p} + \frac{1}{p^2}\frac{\partial}{\partial p}\left(\dot{p} p^2 f_e\right) = q(r,p)$$

advection current and energy gain due to the adiabatic compression

radiative losses

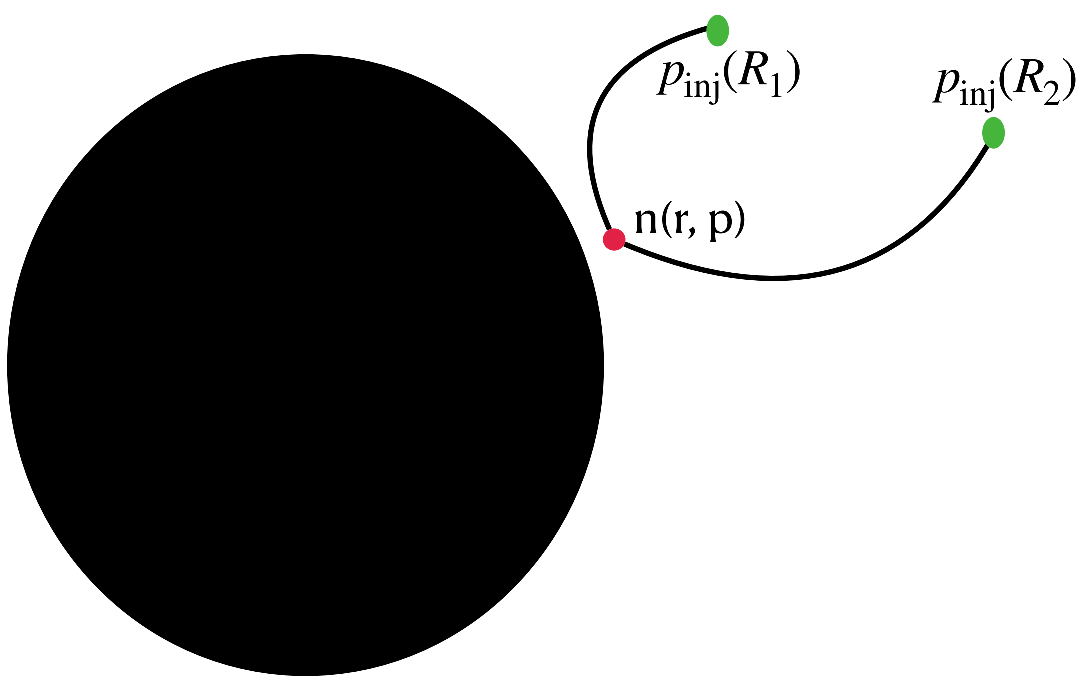
Then, we have the solution of the propagation equation around SMBH:

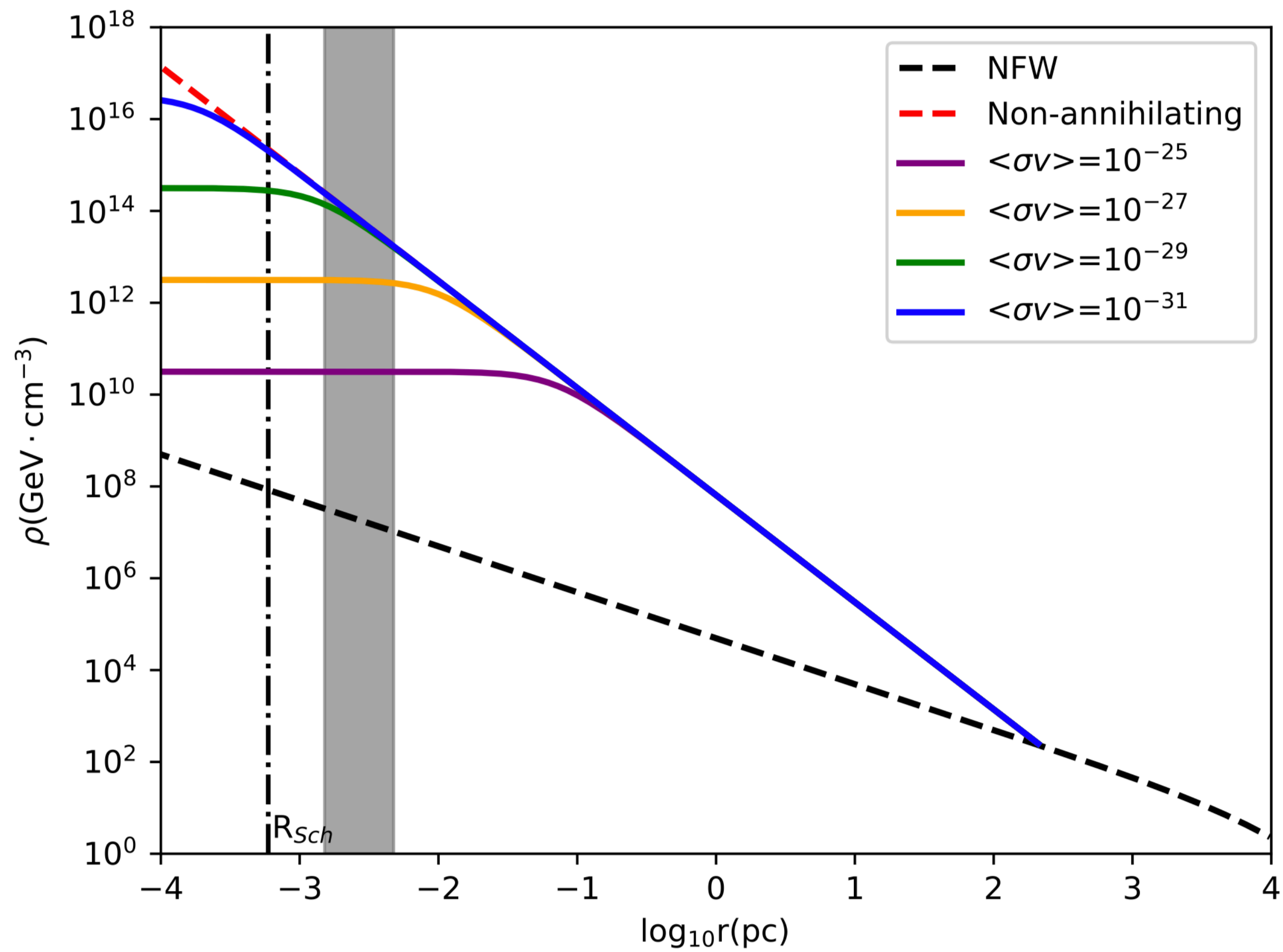
$$p_{\mathrm{inj}}\left(R_{\mathrm{inj}}; r, p\right) = p\left[\frac{k_0 R_{\mathrm{Sch}}^{-\frac{1}{2}}}{c} R_{\mathrm{inj}}^{\frac{3}{2}} p\left(\frac{r}{R_{\mathrm{inj}}} - 1\right) + \left(\frac{R_{\mathrm{inj}}}{r}\right)^{\frac{1}{2}}\right]^{-1}$$

$$n_i(r,p) = \int_r^{r_{\mathrm{acc}}} \frac{Q_i\left(R_{\mathrm{inj}}, p_{\mathrm{inj}}\right)}{v(R_{inj})} \left(\frac{R_{\mathrm{inj}}}{R_{\mathrm{S}}}\right)^{\frac{5}{2}} \left(\frac{p_{\mathrm{inj}}}{p}\right)^4 \mathrm{d}R_{\mathrm{inj}}$$

Roberto Aloisio etc, Neutralino annihilation at the galactic center revisited, JCAP(2004).
Marco Regis, Piero Ullio, Multi-wavelength signals of dark matter annihilation at the Galactic center, PRD(2008).

The Distribution of WIMP Around SMBH





As the plasma flow onto the central BH, there are two competitive physical processes take place:
(a) the particles' momentum loss due to radiative processes;
(b) the particles gain energy in the adiabatic compression.

Due to the balance of WIMP accretion and annihilation around SMBH, we have the WIMP 'spike' distribution:

$$\rho(r) = \begin{cases} 0 & r < R_{Sch} \\ \frac{\rho_{sp}(r)\rho_{\rm sat}}{\rho_{\rm sp}(r)+\rho_{\rm sat}} & R_{Sch} \le r < R_{\rm sp} \\ \frac{\rho_0}{(r/r_0)(1+r/r_0)^2} & r \ge R_{\rm sp} \end{cases}$$

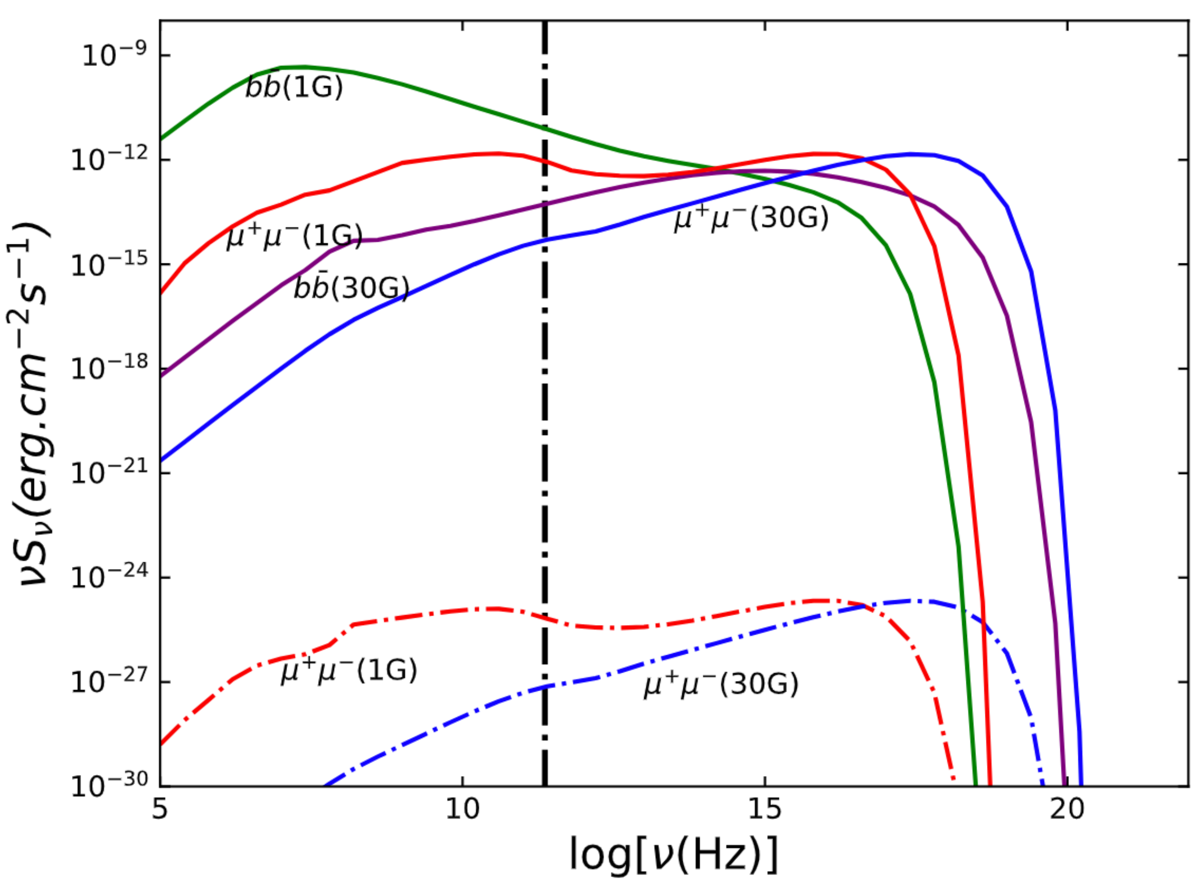
Paolo Gondolo, Joseph Silk, Dark Matter annihilation at the galactic center, PRL(1999)
Thomas Lacroix, etc, Unique probe of dark matter in the core of M87 with EHT, PRD(2017)

Flux Predicted by WIMP Annihilation

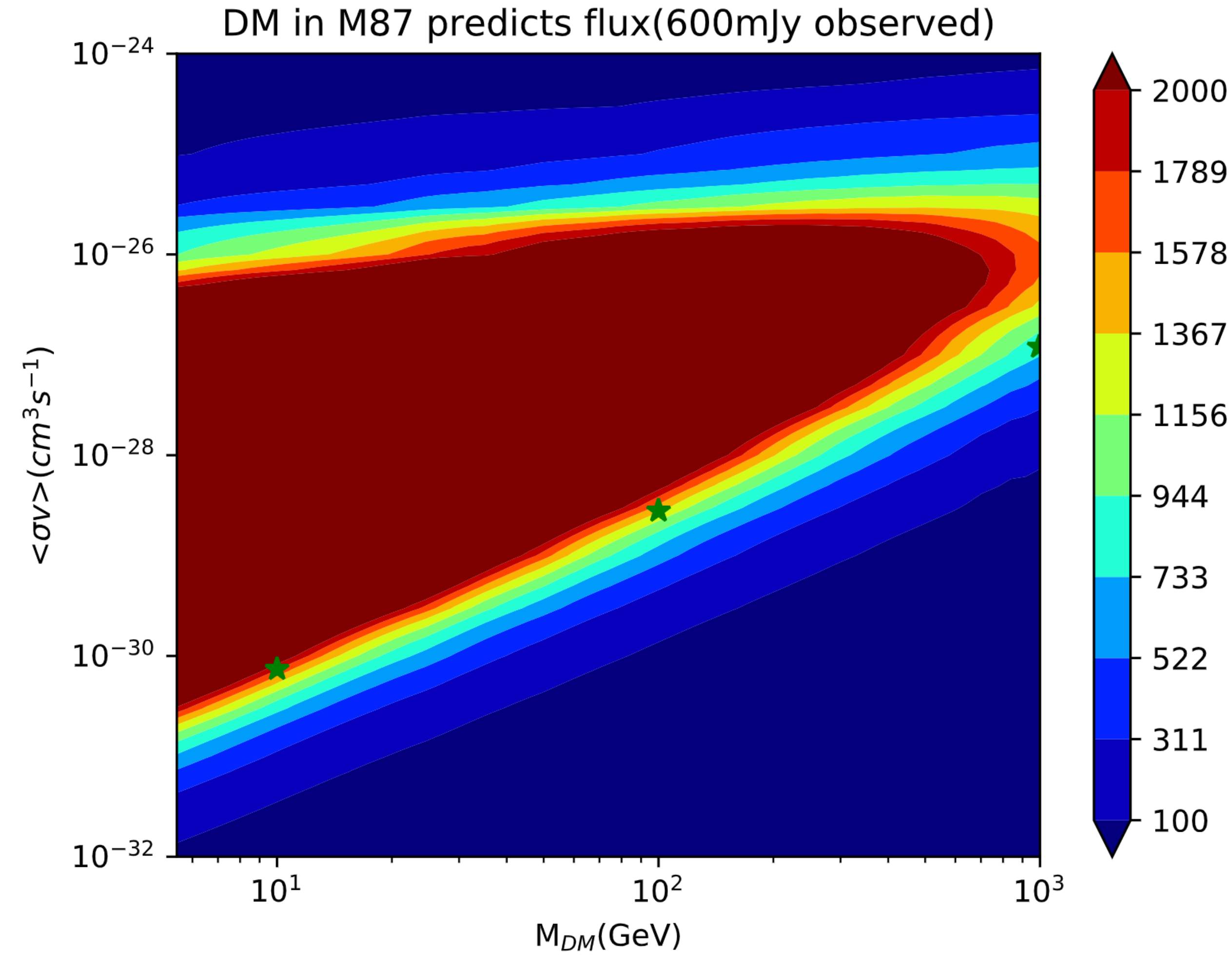
The synchrotron emissivity annihilated from WIMP per unit frequency at ν by an electron of energy E_e present in a magnetic field B is

$$P_{\rm syn}(\nu, E_e, B, \theta) = \frac{\sqrt{3}e^3 B \sin\theta}{m_{\rm e}c^2}\frac{\nu}{\nu_c}\int_{\nu/\nu_c}^{\infty} dy K_{5/3}(y)\,.$$

$$j_{\rm syn}(\nu, r) = 2\int_{m_e}^{M_\chi} dE \langle P_{\rm syn}\rangle(\nu, E, B) n_e(r, E)$$

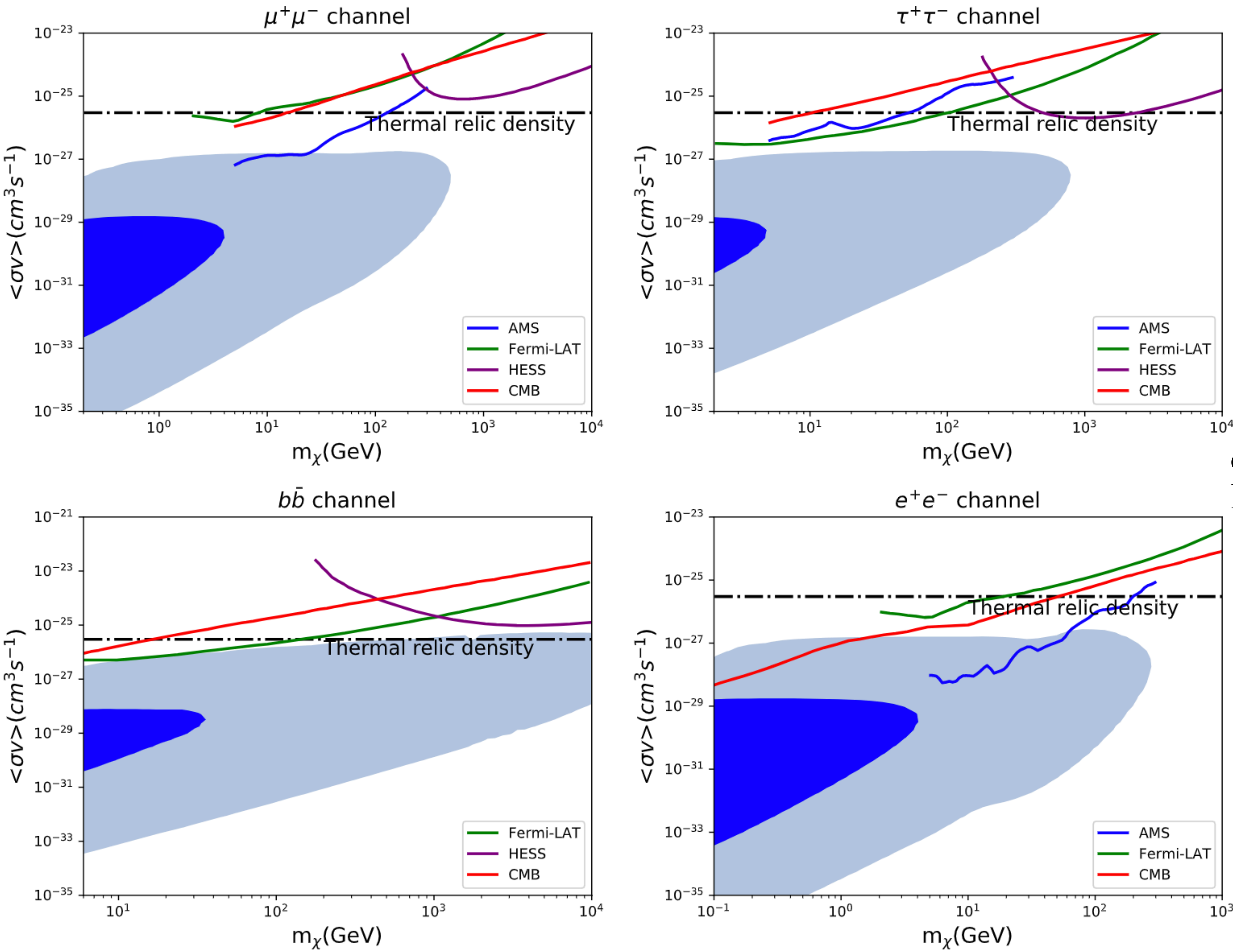


Spectra of synchrotron emission



Flux predicted by WIMP annihilation around M87*

M87* Limitation for Different WIMP Annihilation Channels



dark blue contour(30G)
light blue contour(1G)

Guan-Wen Yuan, et al, Constraints on Dark Matter Annihilation from the Event Horizon Telescope Observations of M87*, JHEP 04(2022) 018, [arXiv: 2106.05901]

*Part II: Detecting the ALP induced polarization oscillation with the observations of Sagittarius A**

Axion/ALP Birefringence Effect

The axion or axion-like particle (ALP) field can interact with the electromagnetic field and give rise to a rotation effect on the photon polarization, which is called the birefringence effect. The relevant Lagrangian terms include

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\left(\partial_\mu a \partial^\mu a - m^2 a^2\right) + \frac{g_{a\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

The dispersion relation of EoM induce two polarization states propagate:

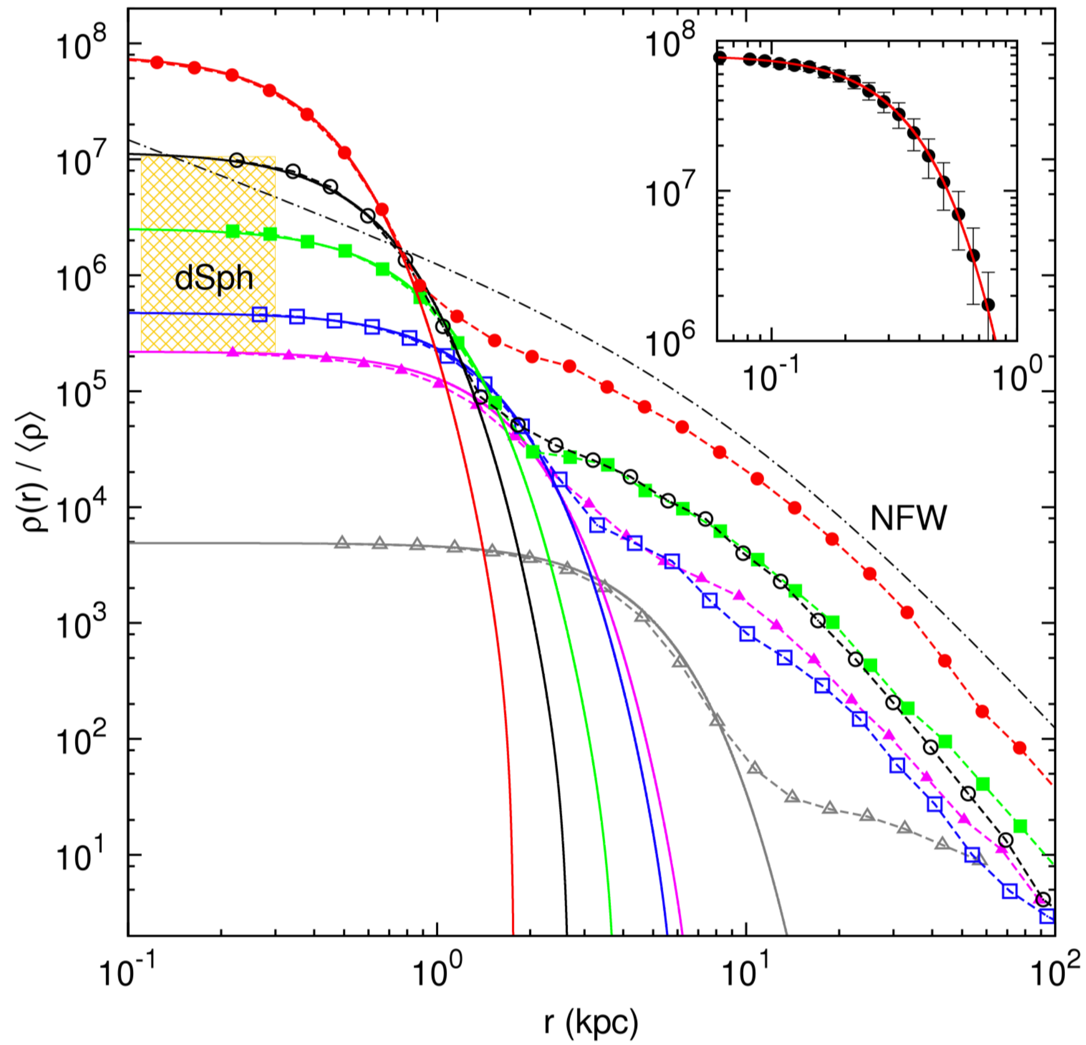
$$w_\pm = k\sqrt{1 \pm \frac{g_{a\gamma}(\dot{a} + \hat{\boldsymbol{k}} \cdot \nabla a)}{k}} \approx k \pm \frac{1}{2} g_{a\gamma}\partial_0 a$$

The difference between the frequencies of the two polarization components is translated into the change of the polarization angle for a linearly polarized emission:

$$\Delta\phi = \frac{1}{2}\int_{t_{emit}}^{t_{obs}} \left(w_+ - w_-\right) dt = \frac{1}{2} g_{a\gamma}\int_{t_{emit}}^{t_{obs}} \partial_0 a dt = \frac{1}{2} g_{a\gamma}\left[a\left(t_{obs}, \boldsymbol{x}_{obs}\right) - a\left(t_{emit}, \boldsymbol{x}_{emit}\right)\right]$$

Where the $a(t_{obs}, \mathbf{x}_{obs})$ and $a(t_{emit}, \mathbf{x}_{emit})$ are the ALP amplitude in observation and emission points, respectively.

Soliton Core+NFW Dark Matter Profile



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

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

Soliton core for ultralight ALP

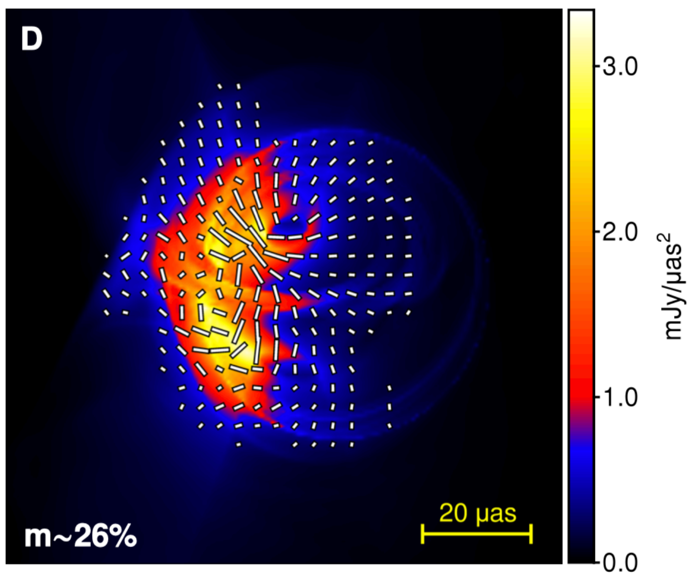
$$\rho_{\rm DM} = \begin{cases} 190 \times \left(\frac{m_a}{10^{-18}\ \rm eV}\right)^{-2}\left(\frac{r_c}{1\ \rm pc}\right)^{-4} M_\odot\ \rm pc^{-3}, & \text{for } r < r_c \\ \frac{\rho_0}{r/R_g(1+r/R_g)^2}, & \text{for } r > r_c \end{cases}$$

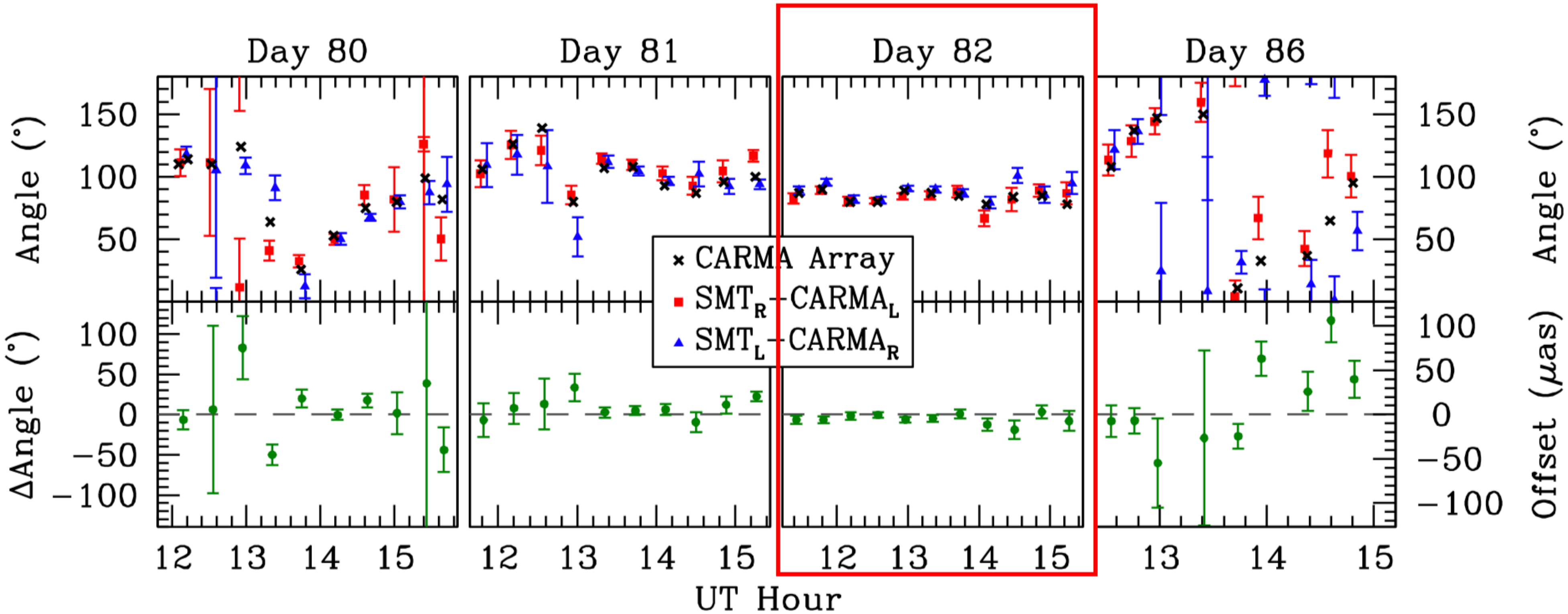
$$\Delta\phi \simeq 5^\circ \sin\left(2\pi\frac{t}{T} + \delta(\boldsymbol{x})\right)\left(\frac{\rho_{\rm DM}}{2\times 10^9 \rm GeV/cm^3}\right)^{\frac{1}{2}}\left(\frac{g_{a\gamma}}{10^{-12}\rm GeV^{-1}}\right)\left(\frac{m}{10^{-18}\rm eV}\right)^{-1}$$

Hsi-Yu Schive, et al, *Nature Physics*, 2014, 10(7) :496-499
Hsi-Yu Schive, et al, *Physical Review Letters*, 113, 261302 (2014)

Data Analysis

The least χ^2 fitting $\chi^2 = \sum_{i=1}^{N} \frac{(\phi_{\mathrm{obs},i} - \phi(t_i))^2}{\sigma_i^2}$, with $\phi(t) = \Delta\phi(t) + \phi_{\mathrm{bkg}}$



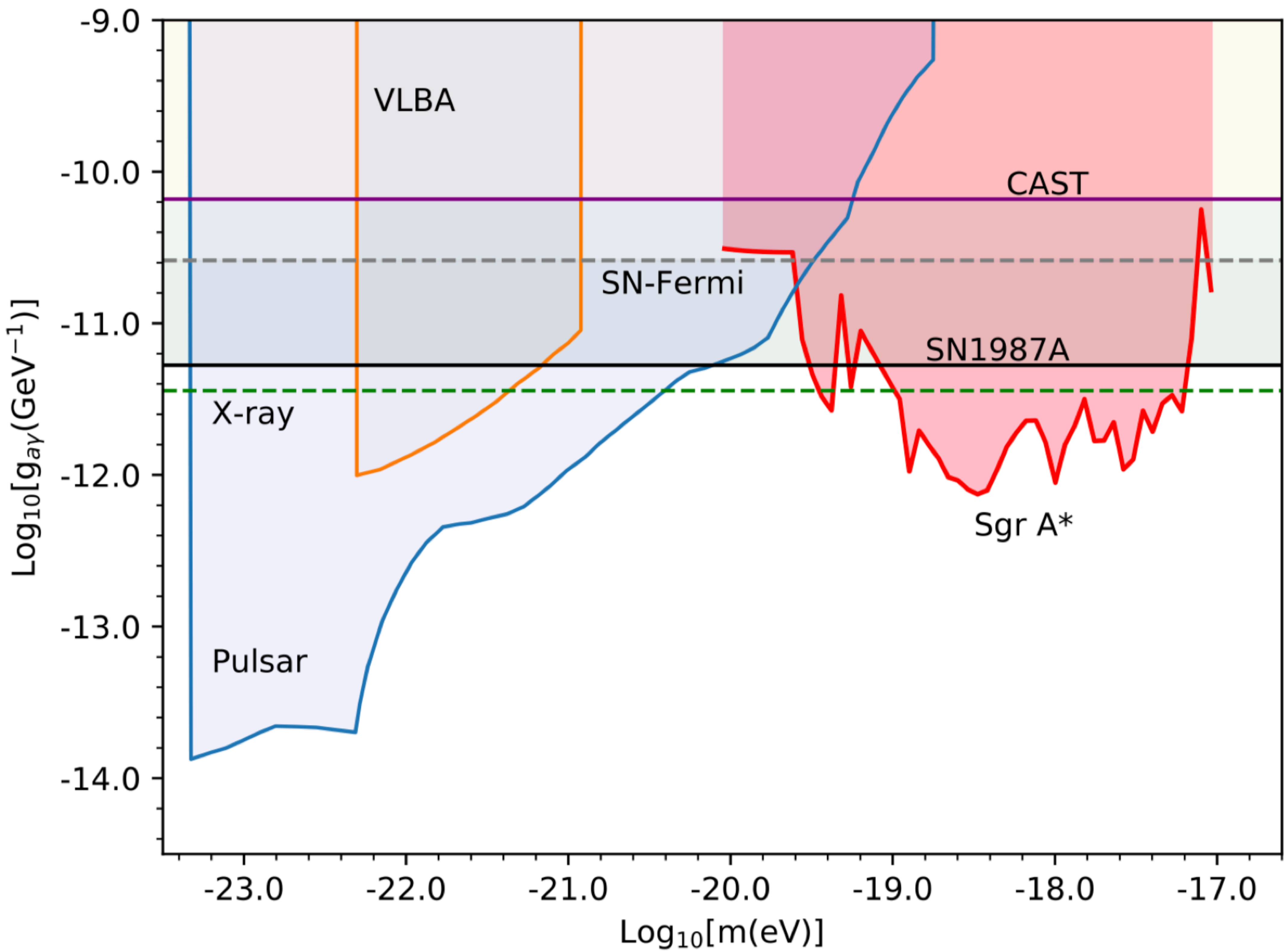


Polarization Data from M.Johnson et al. Fig 3 and Fig.S8

According to the axion typical oscillation period $T = \frac{2\pi}{m_a} \simeq 4 \times 10^3 (\frac{10^{-18}\mathrm{eV}}{m_a})$sec, we could get the experimental sensitivity mass range $(2.9 \sim 29.2) \times 10^{-19}$eV.

M.Johnson, et al, Science,2015, 350(6265):1242-1245

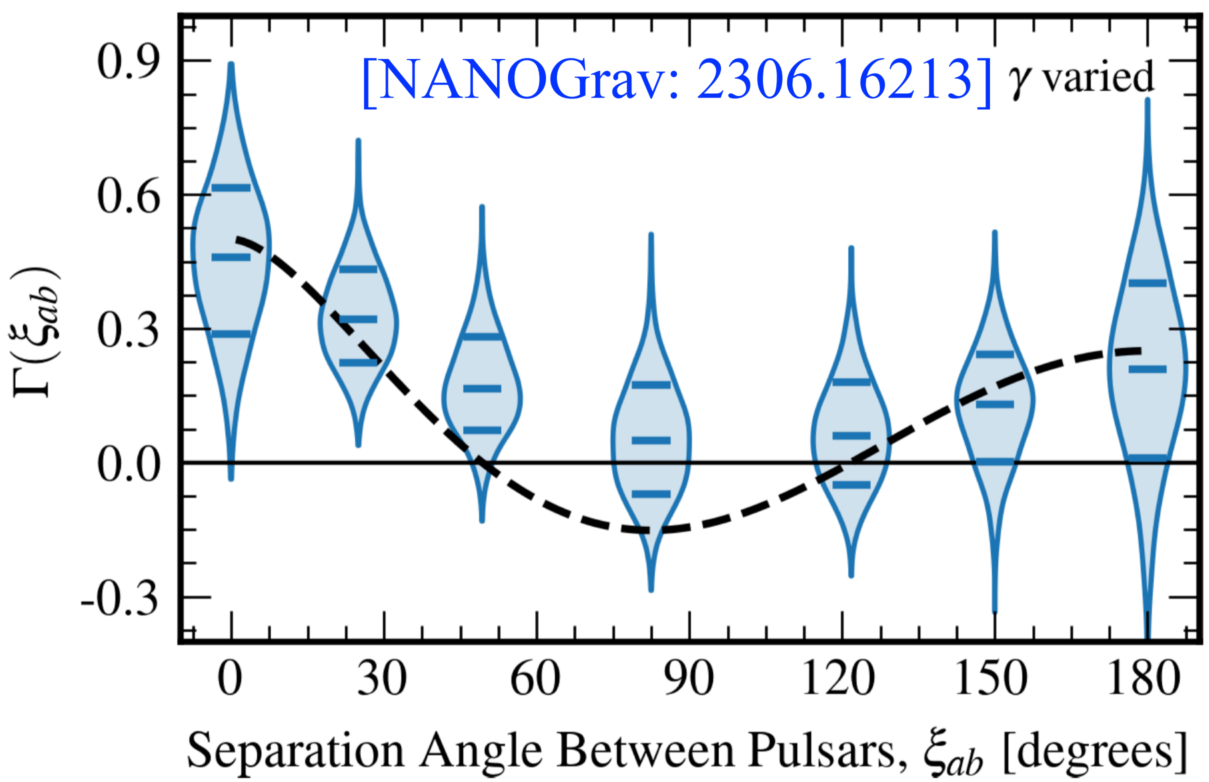
Results



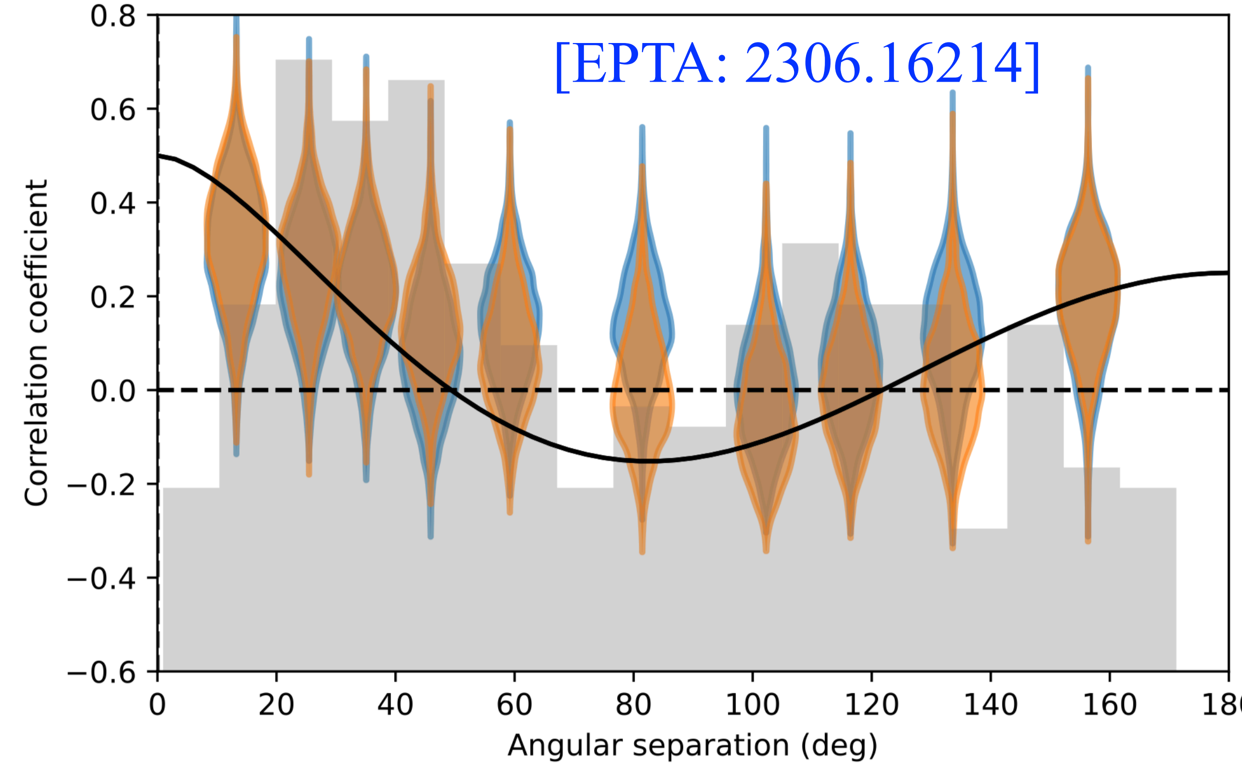
Guan-Wen Yuan, et al, Testing the ALP-photon coupling with polarization measurements of Sagittarius A*, JCAP 03(2021)018, [arXiv:2008.13662]

Part III: Exploring DM distribution with stochastic gravitational wave background

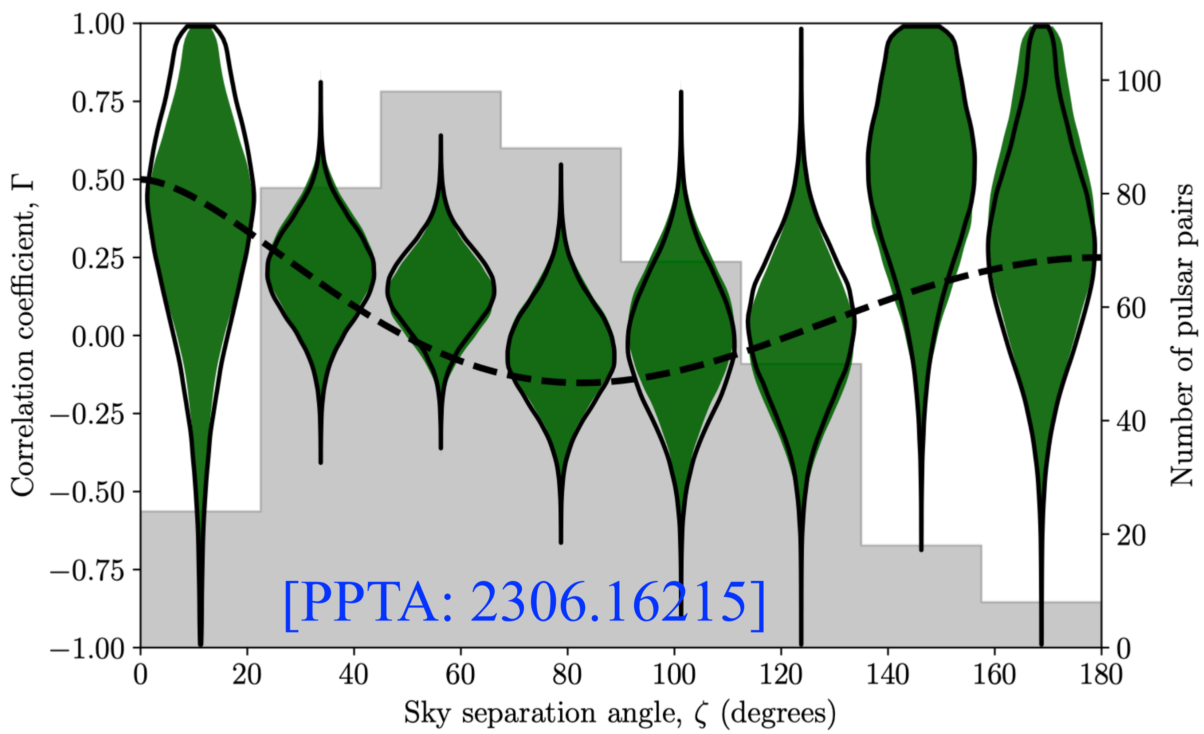
A New Milestone in GW Astronomy@2023



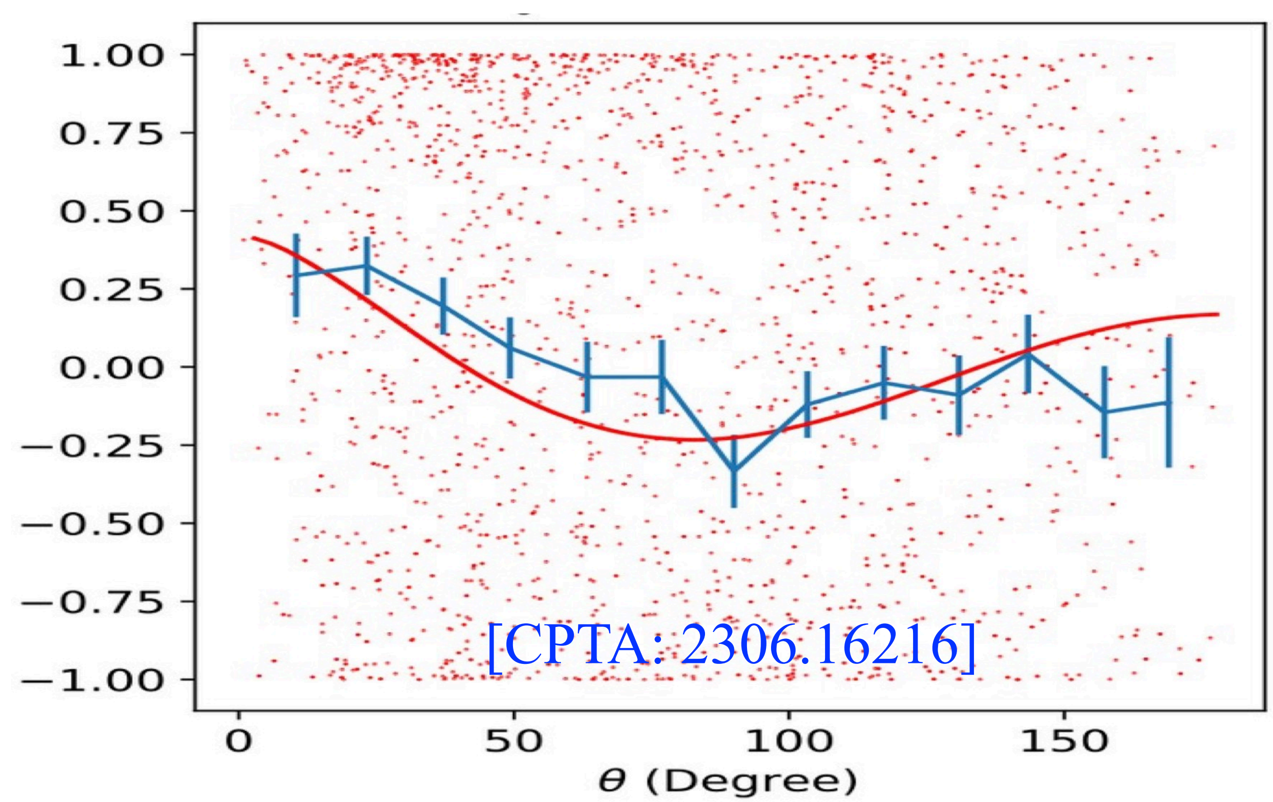
NANOGrav 15yr > 3.5σ



EPTA DR2 > 3σ

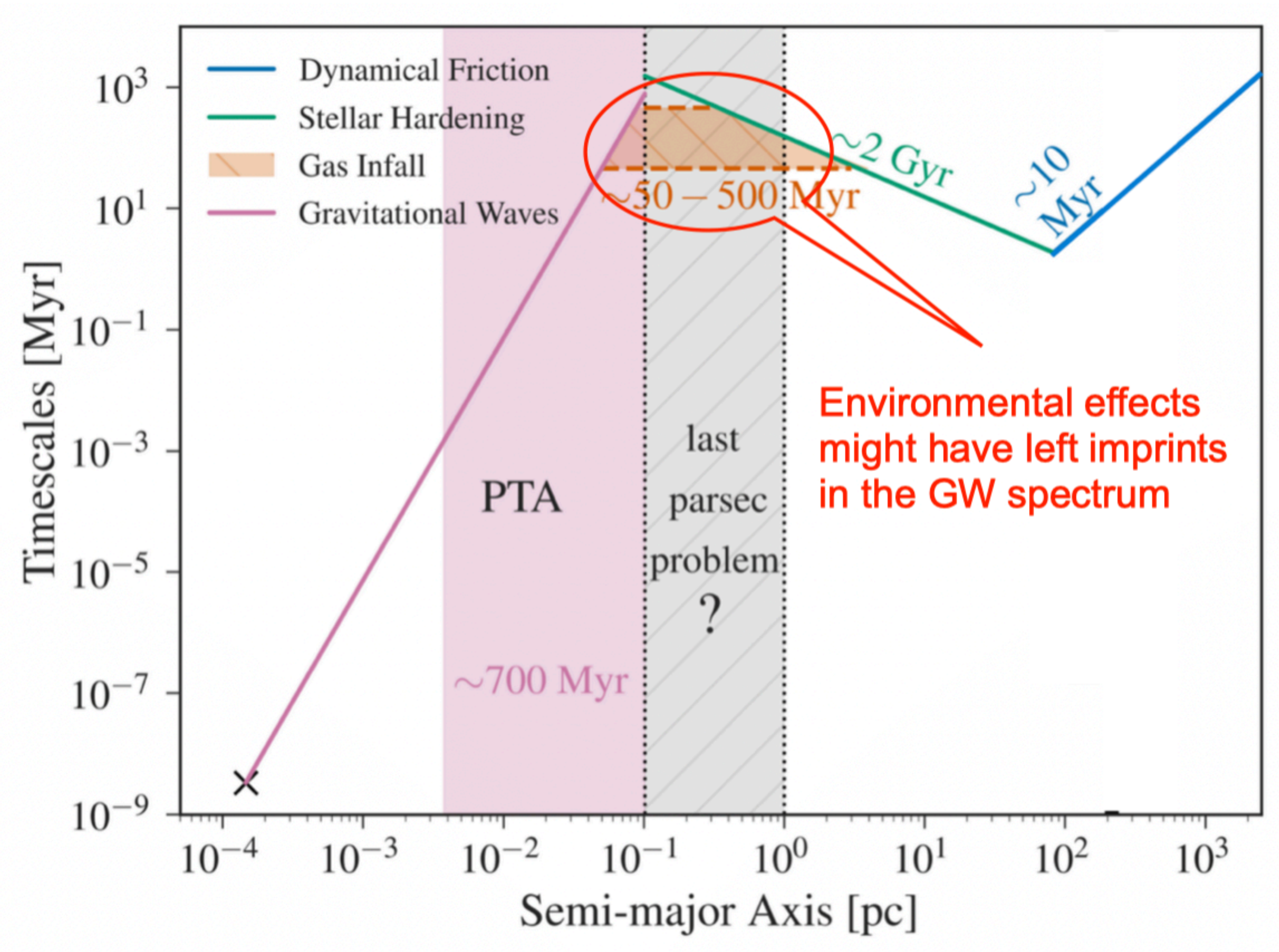


PPTA DR3~2σ



CPTA DR1~4.6σ

Orbital Evolution of SMBH Binary



[J. Weaver: Astrobites (2019)]

Dynamical friction

- Drag force

Stellar Hardening

- Stellar loss-cone scattering

Gas infall

- Viscous circum-binary disk interaction

GW inspiral

- Decouple from astro environment
- GW-driven orbital evolution

Lose energy and angular momentum

Time

Theoretical Analysis

typical time scale associated with the viscous circumbinary gas and disk interaction on GW spectrum can be parametrized as [8, 9]

$$t_{\rm env} \equiv -\frac{R}{\dot{R}} \propto R^{\beta} \propto f_r^{-2\beta/3} \,, \tag{16}$$

where β is determined by the environment model and in general well below the benchmark value 4, as shown below Eq. (14). Since

$$\frac{{\rm d}E_{\rm GW}}{{\rm d}\ln f_r} = \frac{{\rm d}E_{\rm GW}}{{\rm d}t}\frac{{\rm d}t}{{\rm d}\ln f_r} = \frac{{\rm d}E_{\rm GW}}{{\rm d}t}\frac{{\rm d}t}{{\rm d}\ln R}\frac{{\rm d}\ln R}{{\rm d}\ln f_r} = \frac{2}{3}\frac{{\rm d}E_{\rm GW}}{{\rm d}t}t_{\rm env} \,, \tag{17}$$

where $\frac{{\rm d}E_{\rm GW}}{{\rm d}t}$ is calculated by Eq. (11), which is only determined by GW dynamics. We also used Kepler's law, $f_r \sim R^{-\frac{3}{2}}$ and the definition of t_{env}. The energy spectrum of GWs is calculated by

$$\begin{aligned}\Omega_{\rm gw}(f_r) \sim h_c^2(f_r) &\sim \int dz dm_1 dm_2 \frac{\partial n}{\partial m_1 \partial m_2 \partial z}\frac{1}{1+z}\frac{dE_{gw}}{d\ln f_r} \\ &= \int dz dm_1 dm_2 \frac{\partial n}{\partial m_1 \partial m_2 \partial z}\frac{1}{1+z}\frac{2}{3}\frac{dE_{gw}}{dt}t_{env} \\ &= \int dz dm_1 dm_2 \frac{\partial n}{\partial m_1 \partial m_2 \partial z}\frac{1}{1+z}\frac{2}{3}\frac{dE_{gw}}{dt}t_{GW}\frac{t_{env}}{t_{GW}}\end{aligned} \tag{18}$$

If we don't consider the impact of the environment, the energy spectrum

$$\Omega_0 \sim \int dz dm_1 dm_2 \frac{\partial n}{\partial m_1 \partial m_2 \partial z}\frac{1}{1+z}\frac{2}{3}\frac{dE_{gw}}{dt}t_{GW}$$

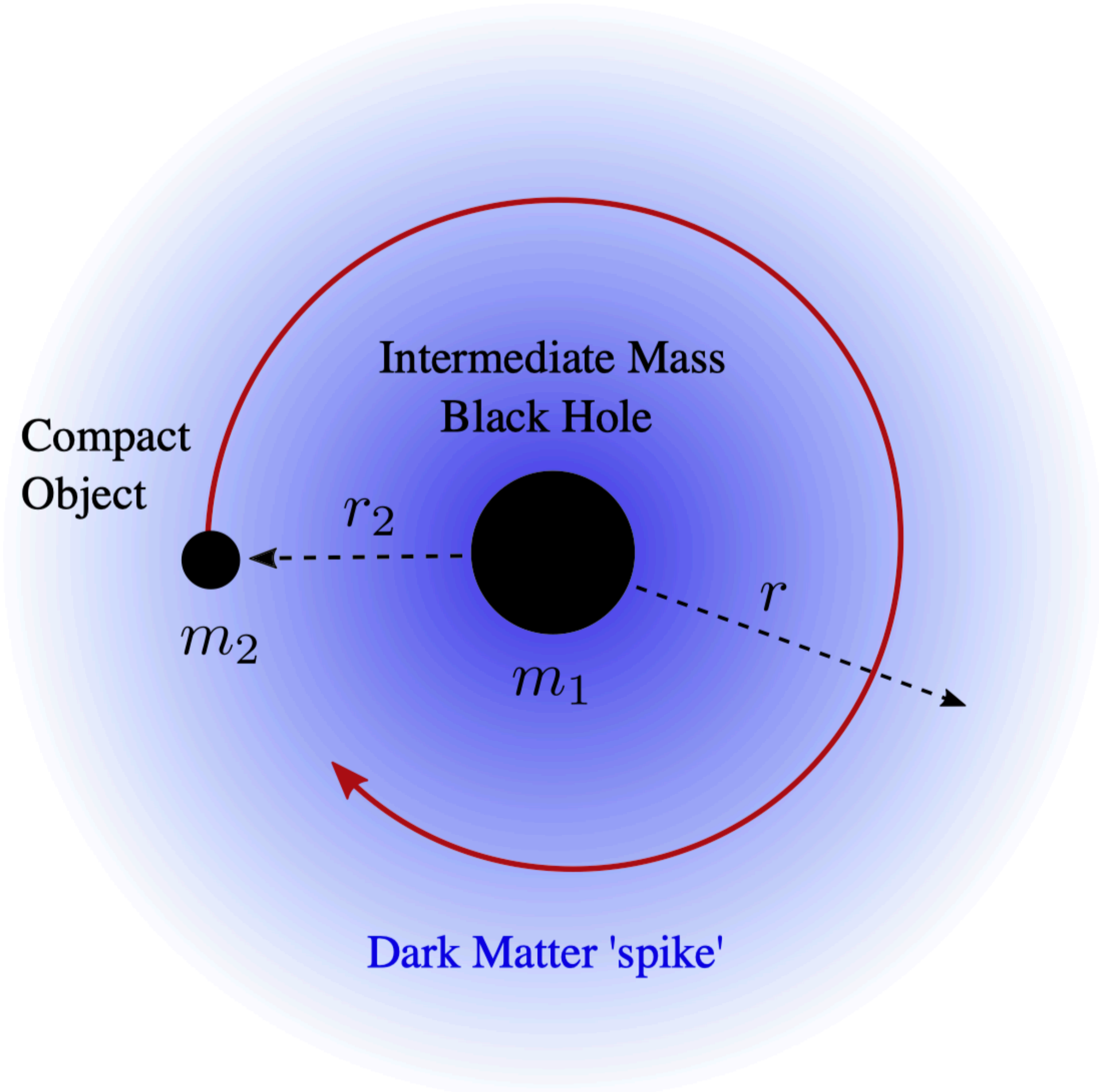
$$-\frac{{\rm d}E_{\rm orb}}{{\rm d}t} = \frac{{\rm d}E_{\rm GW}}{{\rm d}t} + \frac{{\rm d}E_{\rm env}}{{\rm d}t}$$

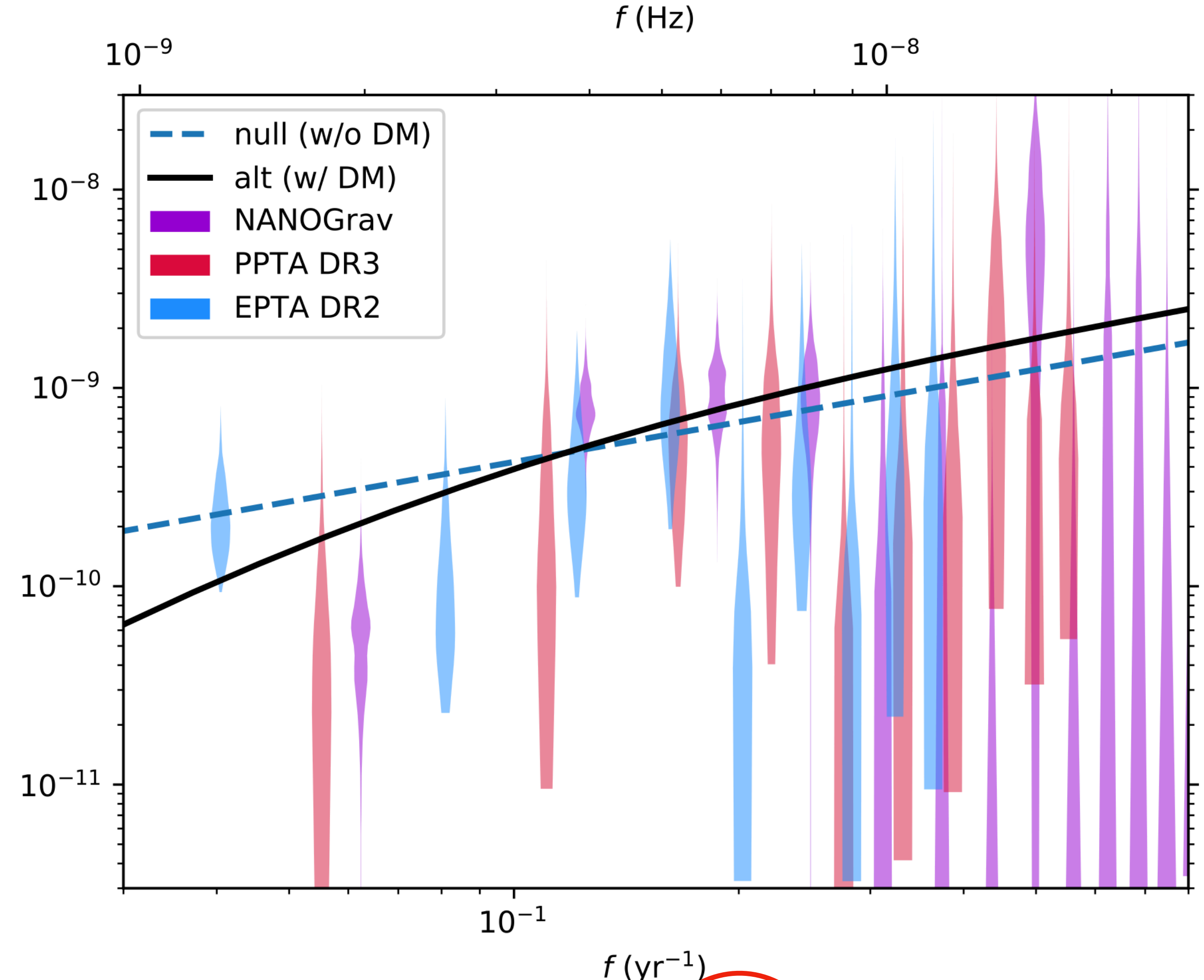
The emitted power $\frac{dE_{GW}}{dt}$ is solely determined by the masses of the objects involved and the geometry of their orbit, thus $\Omega_{gw}(f_r)$ can be expressed as [9]

$$\Omega_{\rm gw}(f_r) = \Omega_0(f_r)\frac{t_{\rm env}}{t_{\rm GW}} \,, \tag{20}$$

where $\Omega_0(f_r)$ refers to the pure GW case, given by $\Omega_0(f_r) = A_{gw}^2 \frac{2\pi^2}{3H_0^2}\left(\frac{f_r}{f_{ref}}\right)^{\frac{2}{3}}$.

Dark Matter Surrounding SMBHB enhance SGWB





$$-\frac{\mathrm{d}E_{\mathrm{orb}}}{\mathrm{d}t} = \frac{\mathrm{d}E_{\mathrm{GW}}}{\mathrm{d}t} + \frac{\mathrm{d}E_{\mathrm{env}}}{\mathrm{d}t}$$

Braadly Kavanagh, et al, PRD(2020)

$$\rho(r) = \begin{cases} 0 & r < R_{Sch} \\ \frac{\rho_{sp}(r)\rho_{\mathrm{sat}}}{\rho_{sp}(r)+\rho_{\mathrm{sat}}} & R_{Sch} \le r < R_{\mathrm{sp}} \\ \frac{\rho_0}{(r/r_0)(1+r/r_0)^2} & r \ge R_{\mathrm{sp}} \end{cases}$$

$$\left|\tilde{h}_+(f)\right| = \frac{1}{2d_{\mathrm{L}}} \frac{4G\mu\omega_s^2(t)R^2(t)}{c^4} \sqrt{\frac{2\pi}{\ddot{\Phi}(t)}} \frac{1+\cos^2\iota}{2},$$

$$\left|\tilde{h}_\times(f)\right| = \frac{1}{2d_{\mathrm{L}}} \frac{4G\mu\omega_s^2(t)R^2(t)}{c^4} \sqrt{\frac{2\pi}{\ddot{\Phi}(t)}} \cos\iota,$$

Zhao-Qiang Shen, *Guan-Wen Yuan*, Yi-Ying Wang, Yuan-Zhu Wang, Dark Matter Spike surrounding Supermassive Black Holes Binary and the nanohertz Stochastic Gravaitational Wave Background, [arXiv: 2306.17143].

Summary

Combine two important topics

Observations involved SMBH
Such as: EHT/PTA

Dark Matter Detection —
WIMP/ALP

Muti-messenger era
BH Physics
Formation&Evolution

Annihilation
Oscillation
Accretion
Density

Searching for the possible signals of DM candidates in the observations of SMBH

+

Analyze the phenomenological behavior of **DM candidates** in **SMBH observations** by **Statistical Analysis**

Our findings can not only shed light on the role that dark matter played in the formation and evolution of SMBH, but they can also offer fresh physical motivation of future multi-messenger observations of SMBH.

Thanks for Your Attention!