Exploring Dark Matter Properties from Cosmic-ray Physics

Ding Ran

Cao Qing-Hong, DR, Xiang Qian-Fei, arXiv:2006.12767

Yuan Guan-Wen , Chen Zhan-Fang , Shen Zhao-Qiang , Guo Wen-Qing , DR, Huang Xiaoyuan , Yuan Qiang, arXiv:2106.05901

第15届TeV物理工作组学术研讨会, 2021.07.18-21

Outline

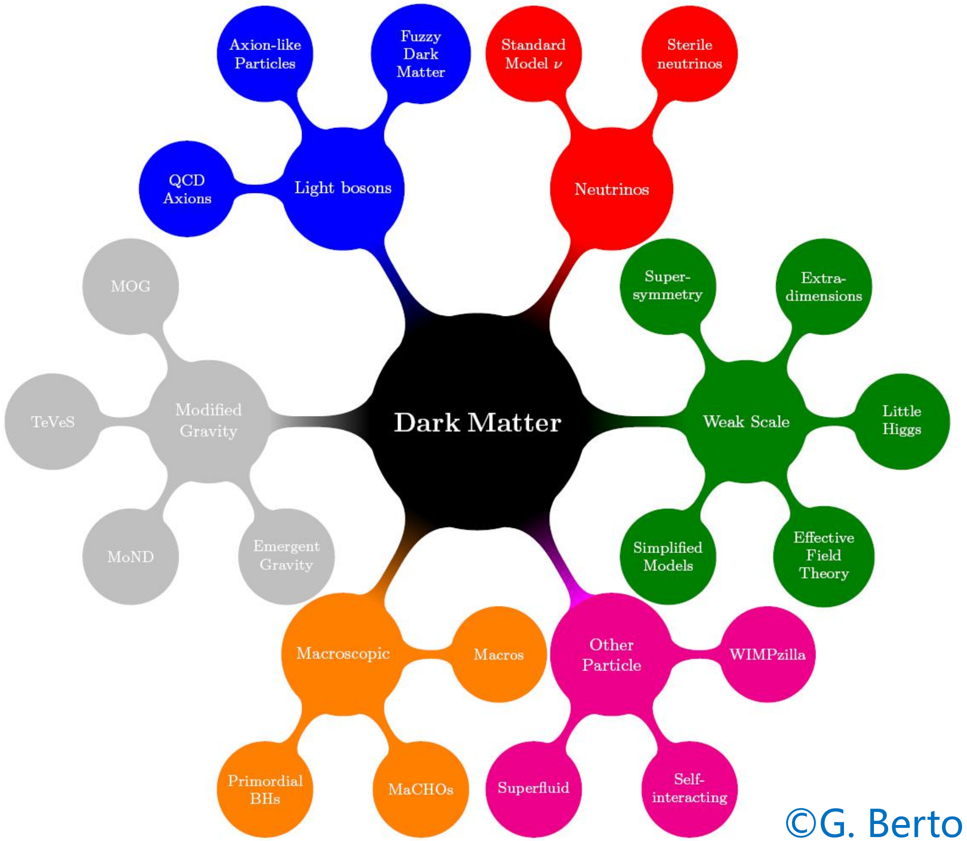
- Introduction

- Exploring Sub-MeV DM from xenon electron direct detections

- Constraining WIMP annihilations from the EHT Observations of M87*

Introduction

DM candidates



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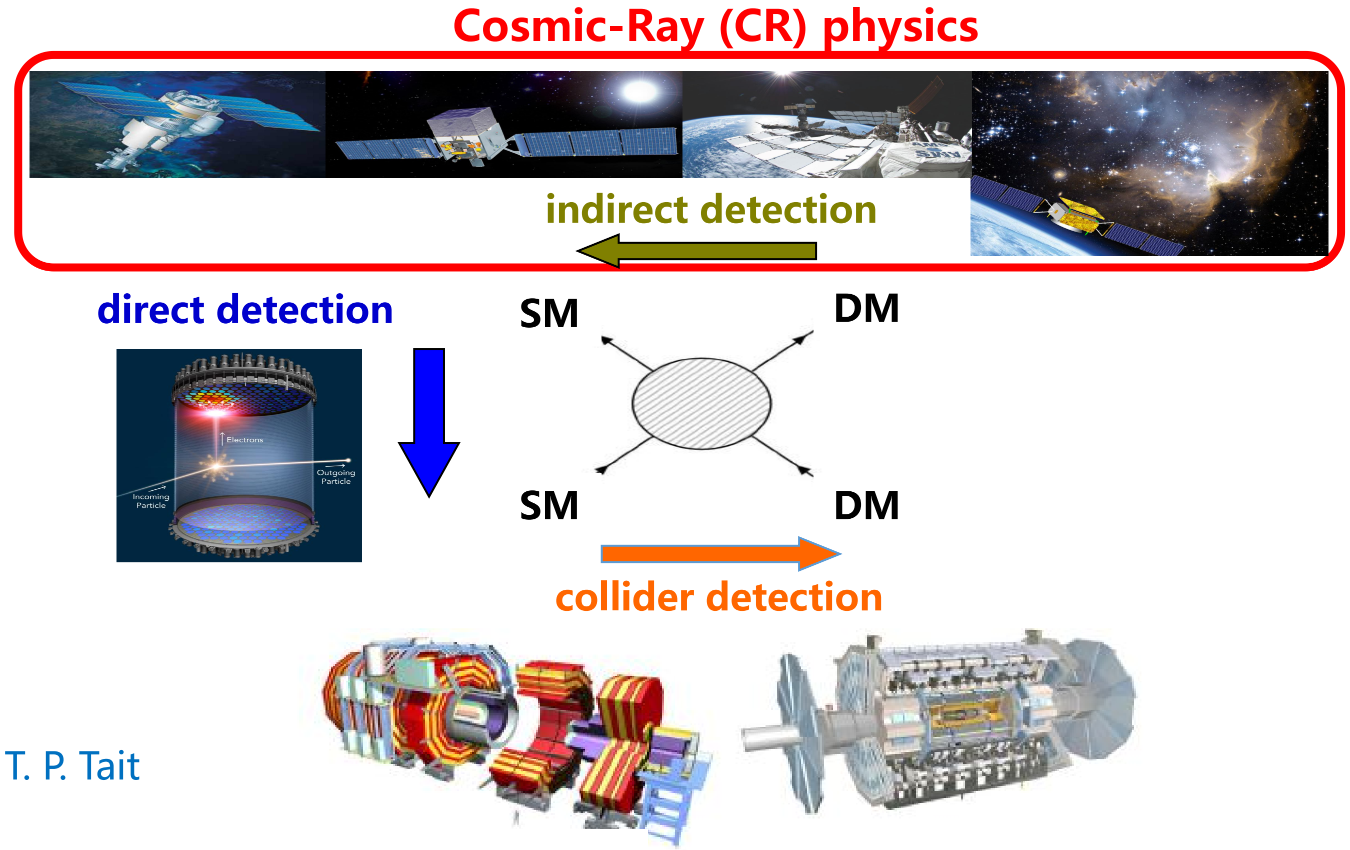
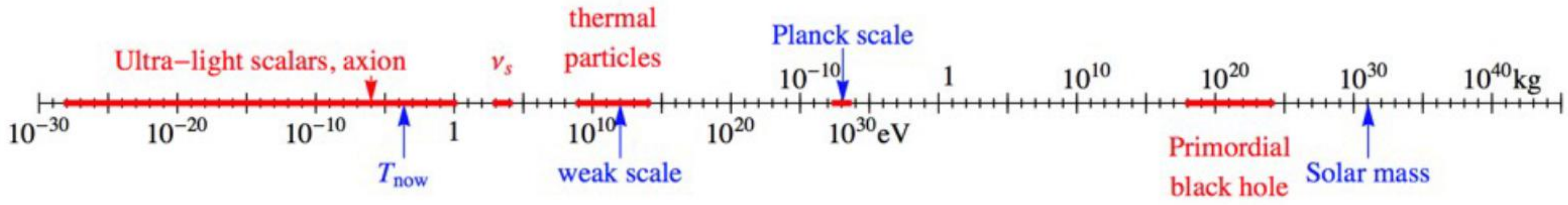
DM detections





Theoretical motivation of light DM

- Dark photon mediator, milli-charged DM, freeze-in DM,Strongly Interacting,MDM/EDM……

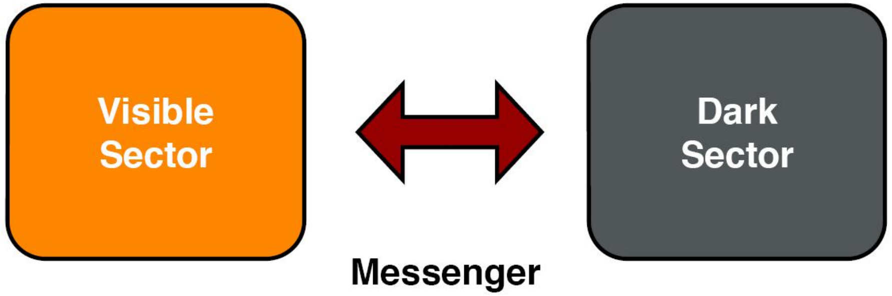
L. J. Hall, K. Jedamzik, J. March-Russell, and S. M. West, arXiv:0911.1120

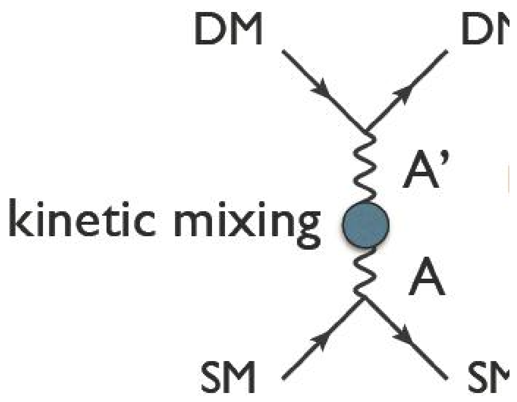
R. Essig, J. Mardon, and T. Volansky, arXiv:1108.5383

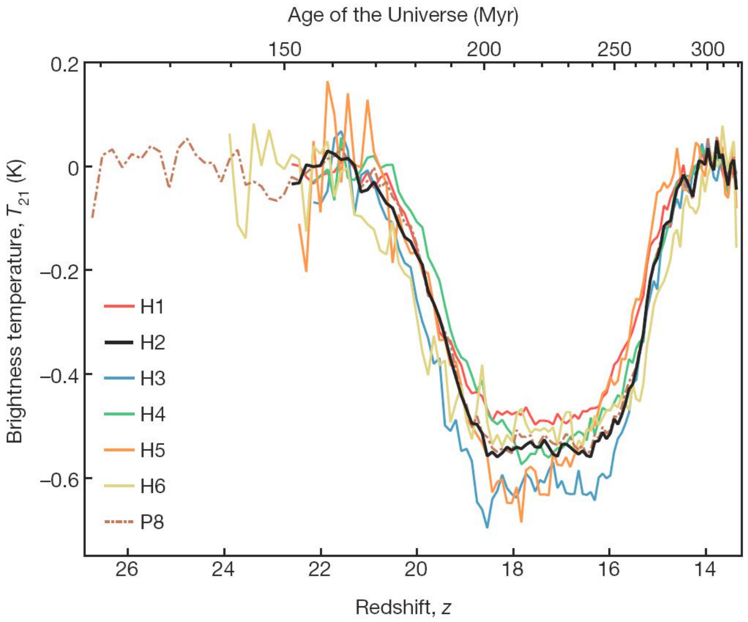
X. Chu, T. Hambye, and M. H. G. Tytgat, arXiv:1112.0493

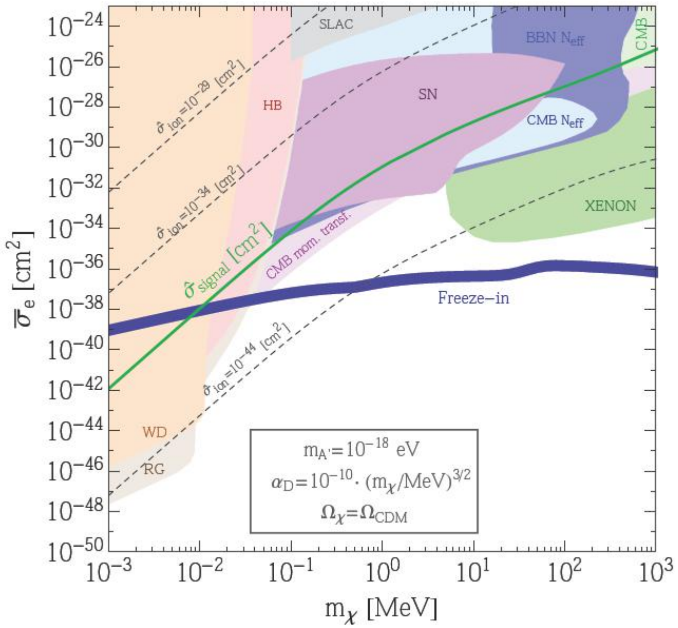
S. Knapen, T. Lin, and K. M. Zurek, arXiv:1709.07882

R. Barkana, N. J. Outmezguine, D. Redigolo and T. Volansky,arXiv:1803.03091









B. Holdom, Phys. Lett. 166B, 196 (1986)

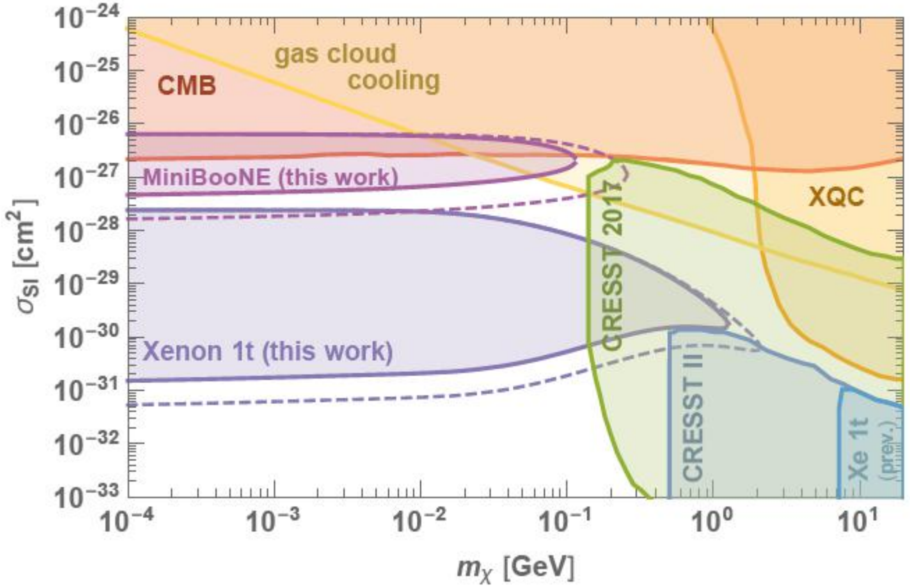
Exploring Sub-MeV DM from xenon electron direct detections

CR-boosted DM

- A fraction of DM in Milky Way halo could be accelerated to high velocities, allowing for sensitivity to very light DM.

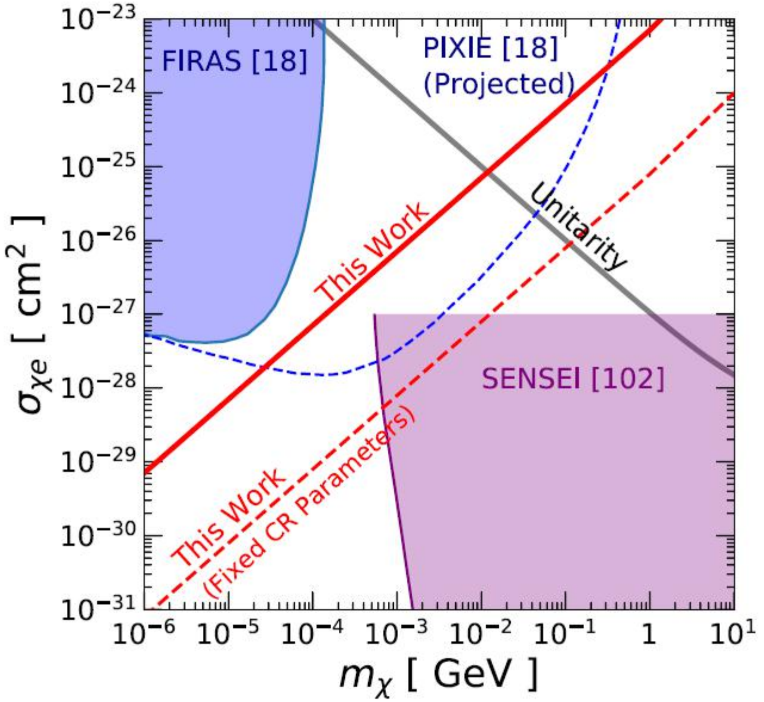
- DM-nucleon direct detection

T. Bringmann & M. Pospelov, arXiv:1810.10543



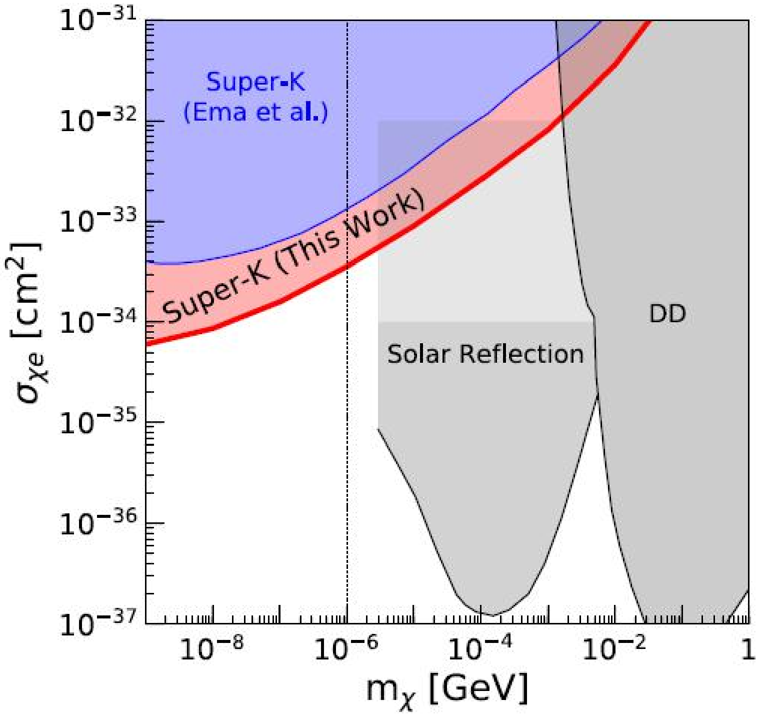
- Reverse direct detection

C. V. Cappiello, K. C. Y. Ng & J. F. Beacom, arXiv:1810.07705

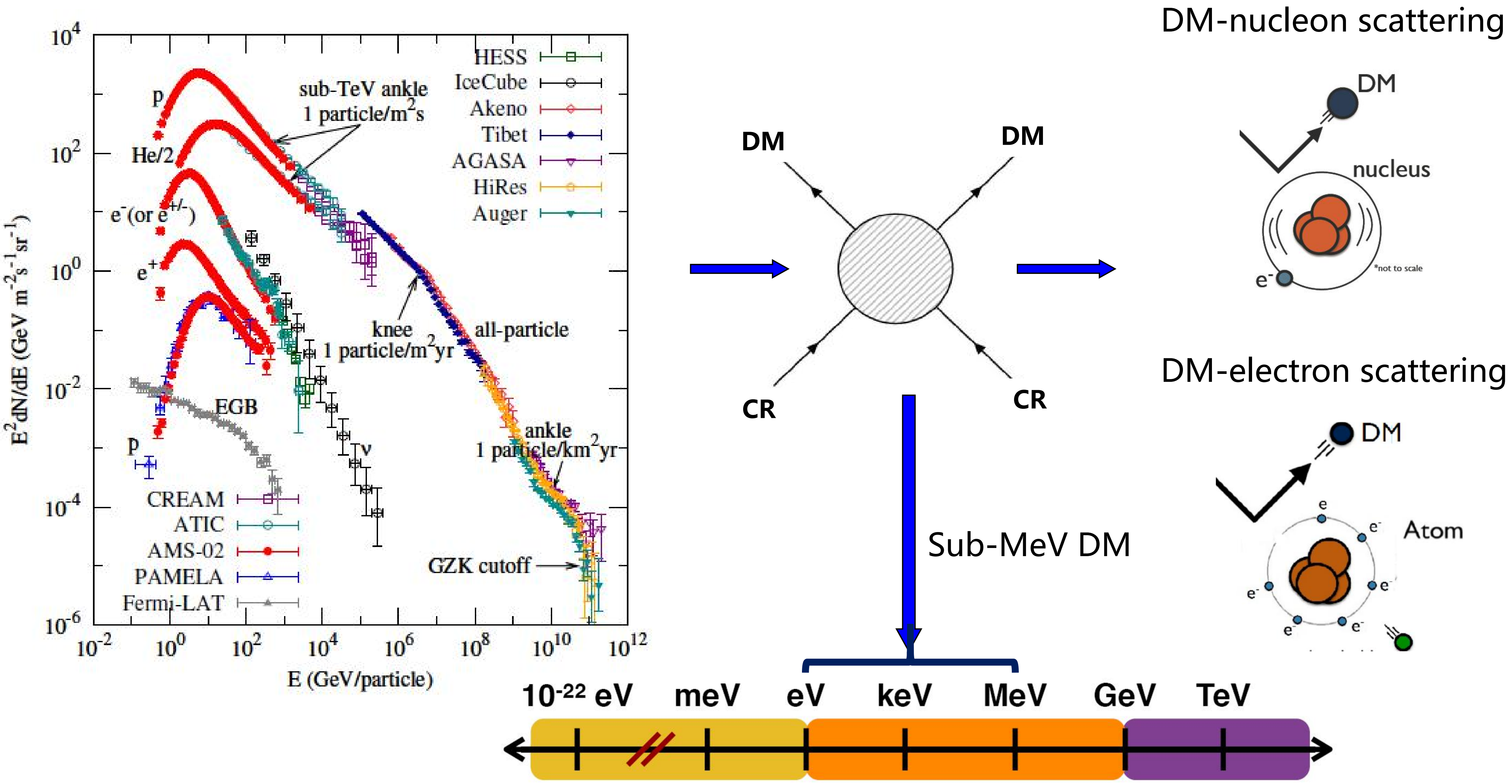


- Neutrino experiments

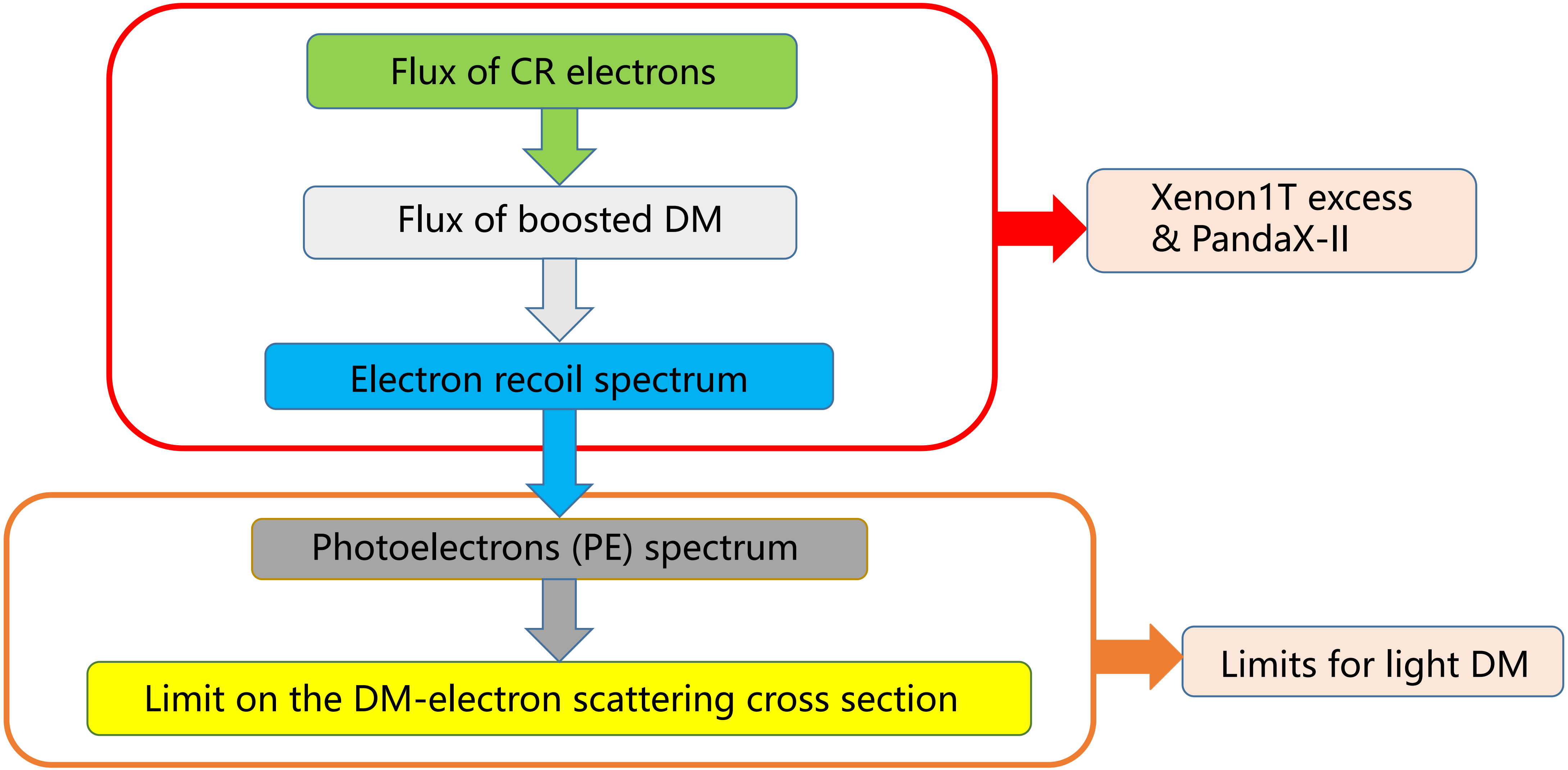
C. Cappiello & J. F. Beacom,arXiv:1906.11283



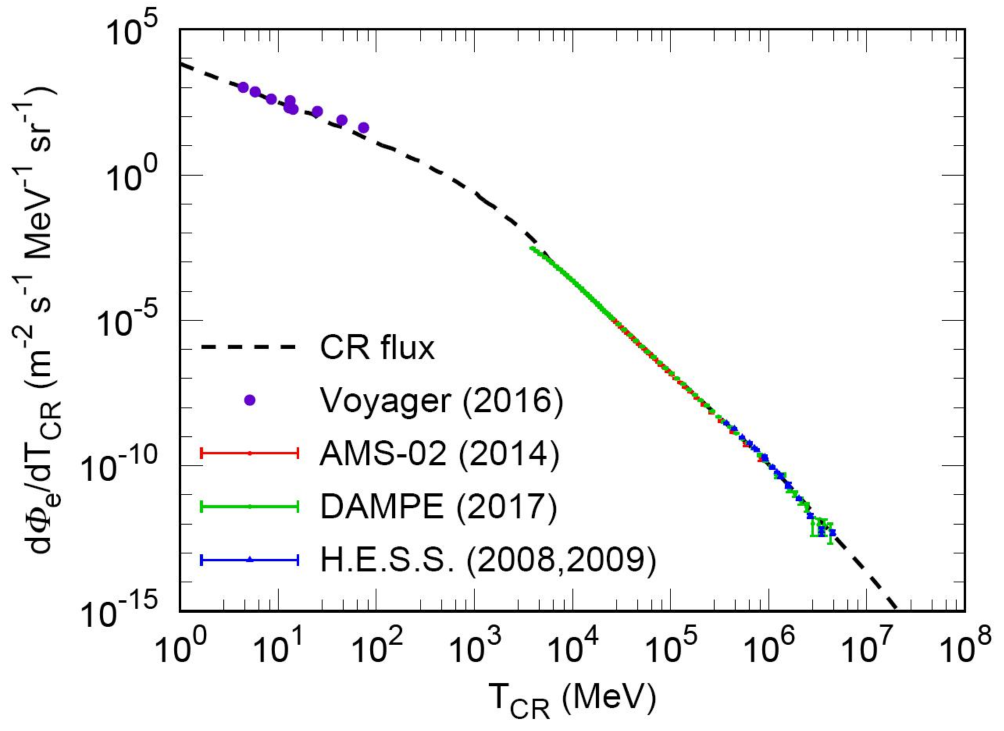
- We consdier the constraints from DM-electron scattering.


HESS
IceCube
Akeno
Tibet
AGASA
HiRes
Auger
sub-TeV ankle
1 particle/m²s
p
He/2
e⁻(or e⁺/⁻)
e⁺
p̄
EGB
knee
1 particle/m²yr
all-particle
ankle
1 particle/km²yr
ν
GZK cutoff
CREAM
ATIC
AMS-02
PAMELA
Fermi-LAT
E²dN/dE (GeV m⁻²s⁻¹sr⁻¹)
E (GeV/particle)
DM
DM
CR
CR
Sub-MeV DM
DM-nucleon scattering
DM
nucleus
e⁻
*not to scale
DM-electron scattering
DM
Atom
e
e⁻
10⁻²² eV
meV
eV
keV
MeV
GeV
TeV

- Calculation framework

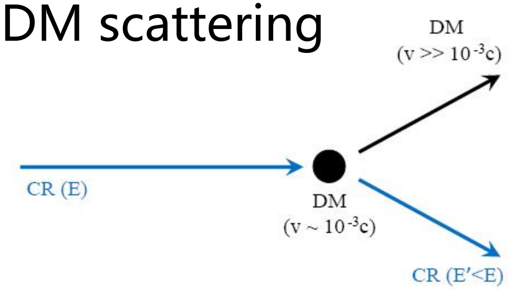


Flux of CR electrons



Flux of boosted DM

- Kinematics of CR-DM scattering



$$T_\chi = T_\chi^{\max}\frac{(1-\cos\theta_{\rm CM})}{2}, \quad T_\chi^{\max} = \frac{2m_\chi T_{\rm CR}(T_{\rm CR}+2m_e)}{(m_e+m_\chi)^2+2T_{\rm CR}m_\chi}$$

$$T_{\rm CR}^{\min} = \left(\frac{T_\chi}{2}-m_e\right)\left(1\pm\sqrt{1+\frac{2T_\chi}{m_\chi}\frac{(m_e+m_\chi)^2}{(2m_e-T_\chi)^2}}\right)$$

- Differential flux at Earth in terms of the CR energy

$$\frac{d\Phi_\chi}{dT_\chi} = D_{\rm eff}\frac{\rho_\chi^{\rm local}}{m_\chi}\int_{T_{\rm CR}^{\min}}^{\infty} dT_{\rm CR}\frac{d\Phi_e}{dT_{\rm CR}}\frac{d\sigma_{\chi e}}{dT_\chi}$$

effective diffusion distance

differential cross section

$$D_{\rm eff} \equiv \int\frac{d\Omega}{4\pi}\int_{l.o.s}dl$$

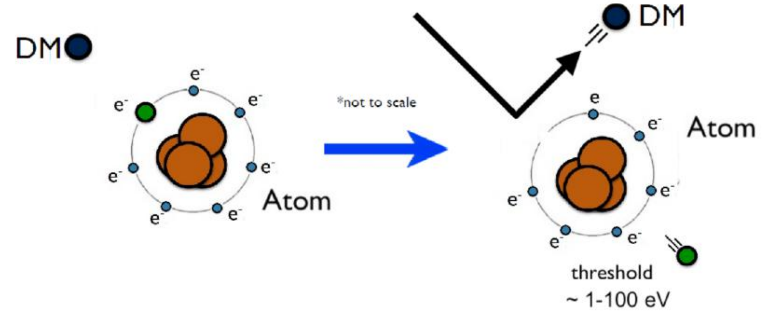
Electron recoil spectrum

- Differential scattering rate   R. Essig, J. Mardon and T. Volansky, arXiv:1108.5383

Particle physics

$$\frac{d\langle\sigma_{ion}^{nl}v\rangle}{d\ln E_R}=\frac{\bar{\sigma}_e}{8\mu_{\chi e}^2}\int q\,dq\left|F_{DM}(q)\right|^2\left|f_{ion}^{nl}(k',q)\right|^2\eta\left(E_{\min}\right)$$

quantum mechanics   CR physics



- Inverse mean speed function

$$\eta\left(E_{\min}\right)=\int_{E_{\min}}dE_\chi\,\Phi_{\rm halo}^{-1}\frac{m_\chi^2}{pE_\chi}\frac{d\Phi_\chi}{dT_\chi}\;\xrightarrow{\text{non-relativstic limit}}\;\eta(v_{\min})=\int_{v_{\min}}\frac{1}{v}f(v)d^3v$$

flux of boosted DM

background DM flux

minimal DM energy required to trigger E_R

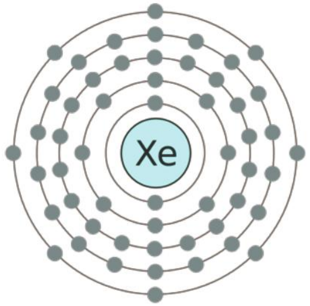
- Ionization from factor   C. F. Bunge, J. A. Barrientos and A. V. Bunge (1993)

J. Kopp, V. Niro, T. Schwetz and J. Zupan, arXiv:0907.3159

$$\left|f_{ion}^{nl}(k',q)\right|^2=\frac{2k'^3}{(2\pi)^3}\sum_{\rm deg}\left|f_{nl}(q)\right|^2=\frac{(2l+1)k'^2}{4\pi^3q}\int_{|k'-q|}^{|k'+q|}k\,dk\sum_{m=-l}^{l}\left|\chi_{nl}(k)\right|^2$$

radial wave functions: RHF method

- Xe electron configuration



$$(5p^6,5s^2,4d^{10},4p^6,4s^2,3d^{10},3p^6,3s^2,2p^6,2s^2,1s^2)$$

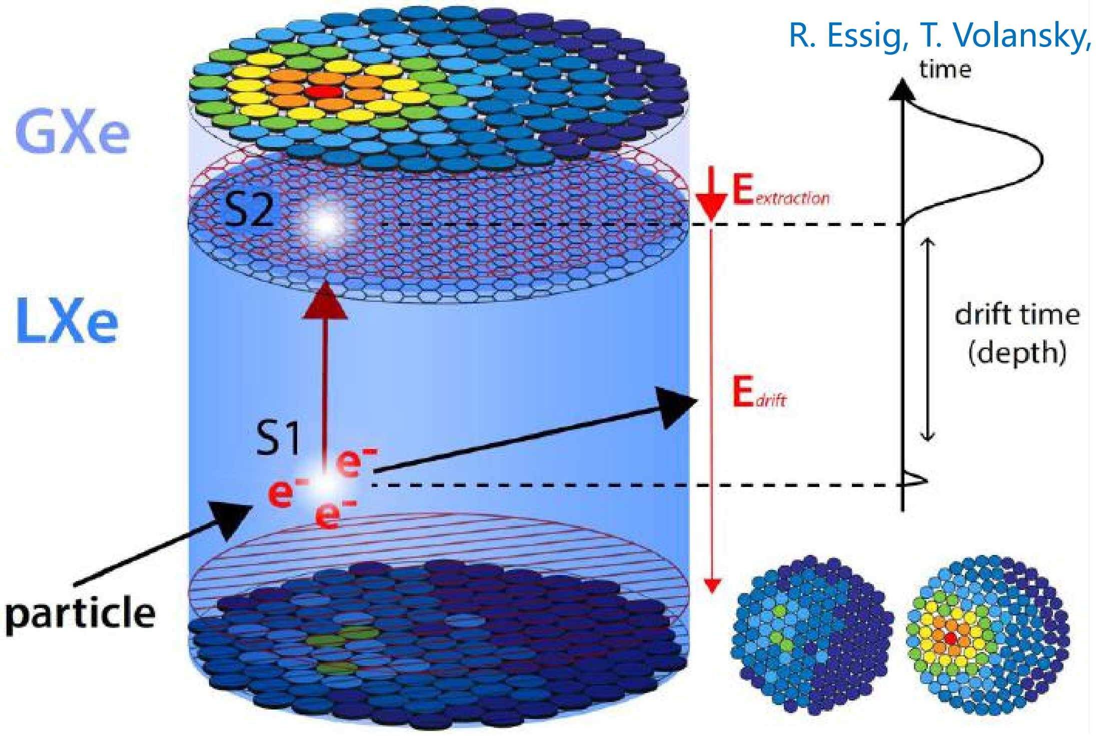
- Total differential ionization rate

$$\frac{dR_{ion}}{d\ln E_R}=N_T\Phi_{\rm halo}\sum_{nl}\frac{d\langle\sigma_{ion}^{nl}v\rangle}{d\ln E_R}$$

PhotoElectrons (PE) spectrum

R. Essig, A. Manalaysay, J. Mardon, P. Sorensen, and T. Volansky, arXiv:1206.2644

R. Essig, T. Volansky, and T.-T. Yu, arXiv:1703.00910



- Event rate for S2 signal responses

$$\frac{dN}{dS2} = T_{\text{exp}} \cdot \varepsilon_{S2} \sum_{nl} \int dE_R \, \text{pdf}\left(S2|\Delta E_e\right) \frac{dR^{nl}_{ion}}{dlnE_R}$$

deposit energy $\Delta E_e = E_R + |E_B^{nl}|$

trigger and acceptance efficiency

Exposure

conversion probability of S2

total differential ionization rate

- S1 (scintillation) signal: prompt scintillation photons
- S2 (ionization) signal: secondary scintillation photons from electroluminescence in Gxe due to drifted electrons

- Benchmark model

$$\mathcal{L} \supset g_\chi \overline{\chi}\gamma^\mu \chi A'_\mu + g_{\rm SM}\overline{f}\gamma^\mu f A'_\mu + \frac{1}{2} m_{A'}^2 A'_\mu A'^\mu$$

ultralight A'

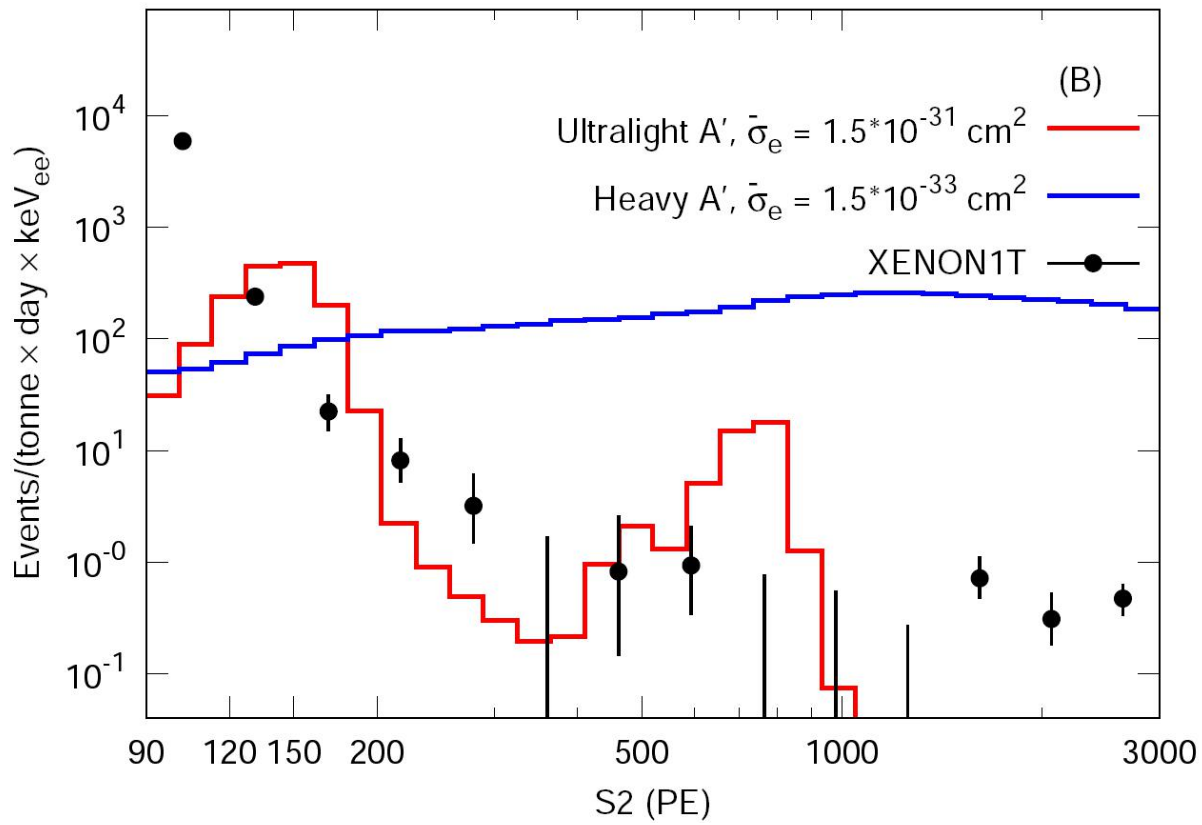
Dark photon mediator, milli-charged DM

$$g_\chi g_{\rm SM} = g_\chi \kappa e = \epsilon e^2$$

heavy A'

Z'-portal, leptophilic DM

- XENON1T recoil spectrum



($T_{\rm exp}$ = 22 tonne-days)

- Constant cross section/matrix element

$$\frac{d\sigma_{\chi e}}{dT_\chi} = \bar{\sigma}_e \begin{cases} \frac{1}{T_\chi^{\rm max}}, & \text{const } \sigma_{\chi e} \\ \frac{(m_\chi+m_e)^2}{(m_\chi+m_e)^2+2m_\chi T_{\rm CR}} \frac{1}{T_\chi^{\rm max}}, & \text{const } \overline{|\mathcal{M}|^2} \end{cases}$$

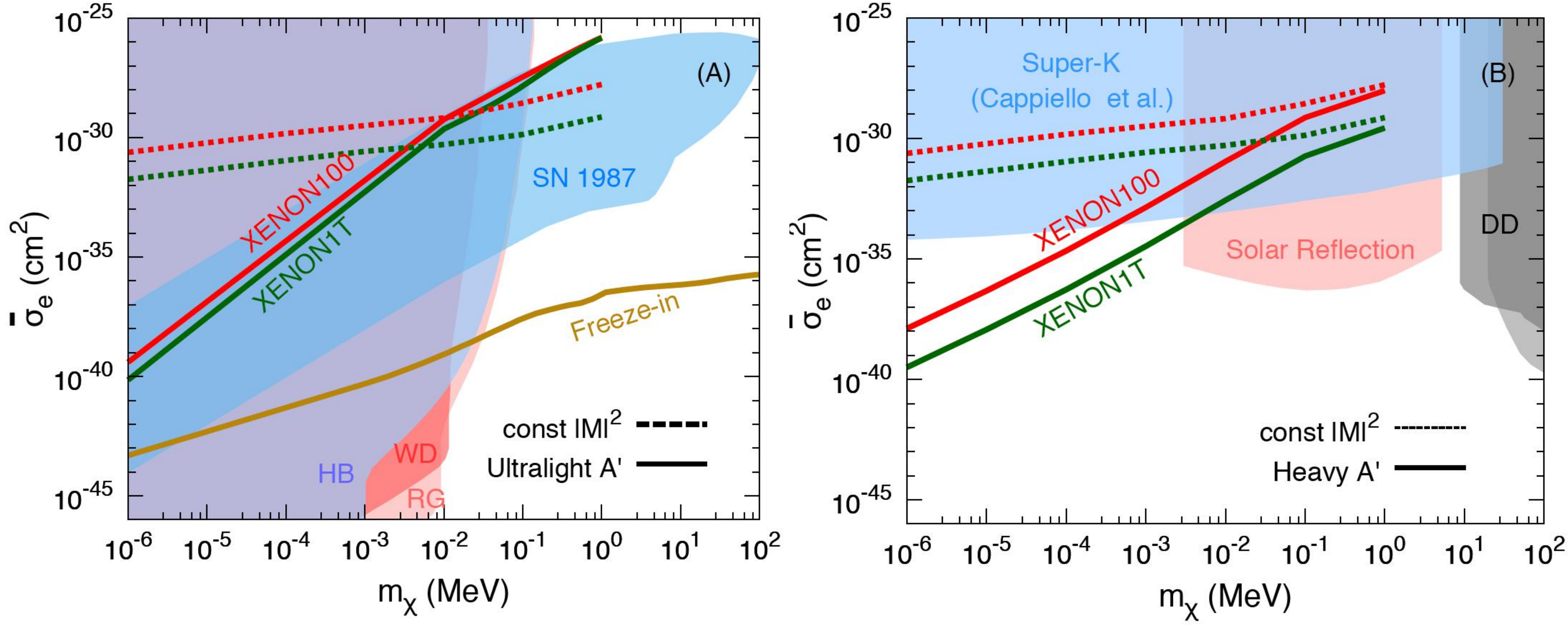
- Energy dependence in differential cross section

$$\frac{d\sigma_{\chi e}}{dT_\chi} = \bar{\sigma}_e \frac{(\alpha^2 m_e^2 + m_{A'}^2)^2}{\mu_{\chi e}^2} \frac{2m_\chi (m_e + T_{\rm CR})^2 - T_\chi \left((m_e+m_\chi)^2 + 2m_\chi T_{\rm CR}\right) + m_\chi T_\chi^2}{4(2m_e T_{\rm CR} + T_{\rm CR}^2)(2m_\chi T_\chi + m_{A'}^2)^2}$$

$$\simeq \bar{\sigma}_e \begin{cases} \frac{2m_\chi(m_e+T_{\rm CR})^2 - T_\chi\left((m_e+m_\chi)^2+2m_\chi T_{\rm CR}\right)+m_\chi T_\chi^2}{4\mu_{\chi e}^2 (2m_e T_{\rm CR}+T_{\rm CR}^2)}, & \text{heavy } A' \\ \frac{\alpha^4 m_e^4}{16 m_\chi^2 T_\chi^2} \frac{2m_\chi(m_e+T_{\rm CR})^2 - T_\chi\left((m_e+m_\chi)^2+2m_\chi T_{\rm CR}\right)+m_\chi T_\chi^2}{\mu_{\chi e}^2 (2m_e T_{\rm CR}+T_{\rm CR}^2)}, & \text{ultralight } A' \end{cases}$$

Limit on the DM-electron scattering cross section

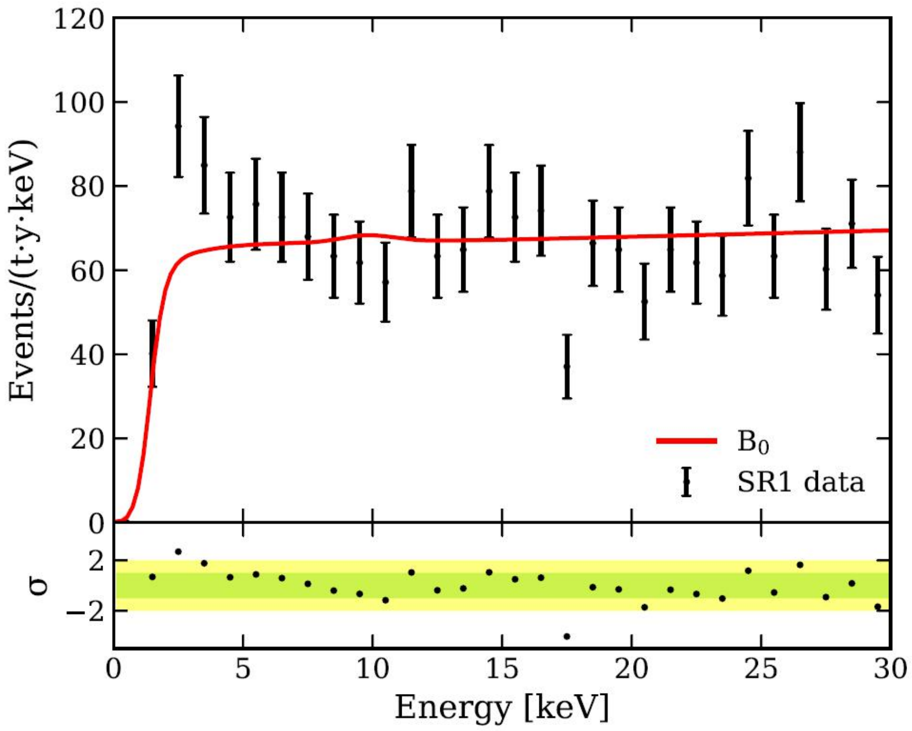
ultralight A'　　heavy A'

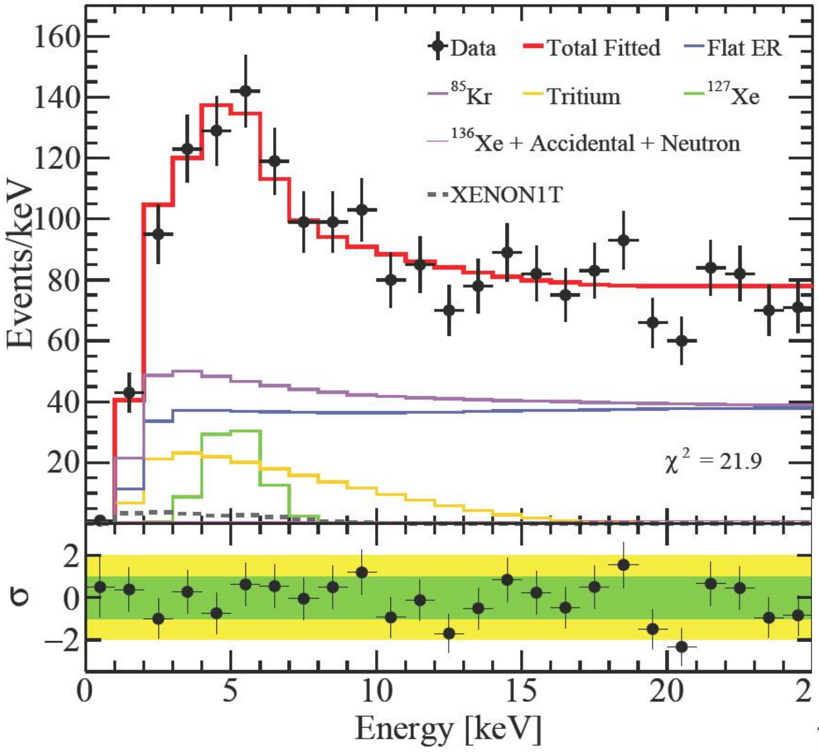


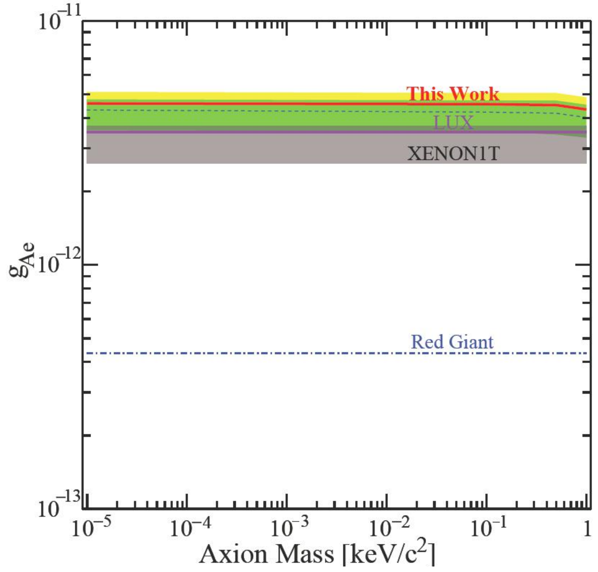
● XENON1T excess & PandaX-II constraint

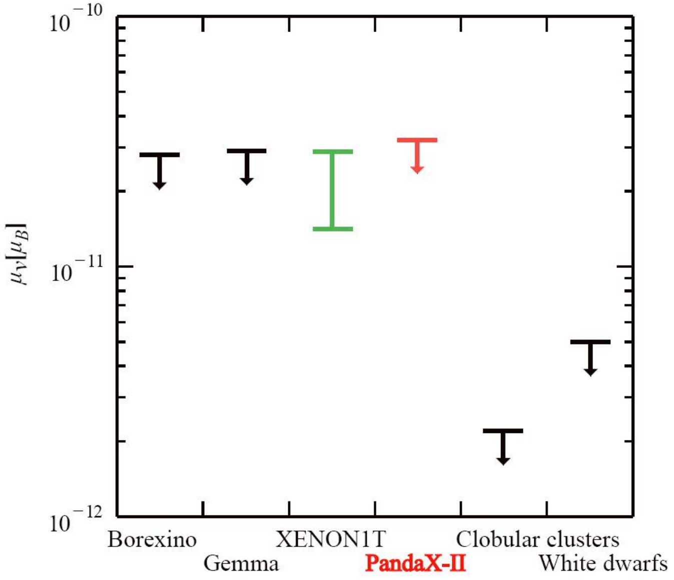
XENON Collaboration, E. Aprile et al.arXiv:2006.09721

PandaX-II Collaboration, Xiaopeng Zhou et al. arXiv: 2008.06485

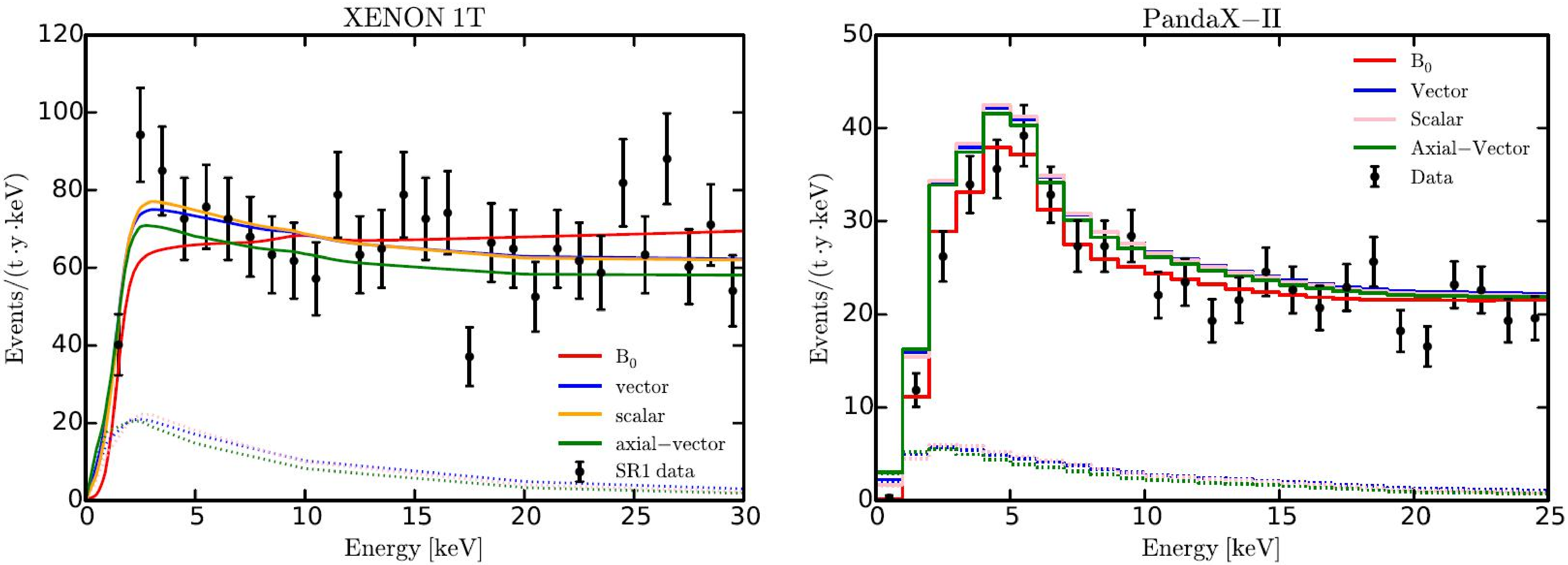








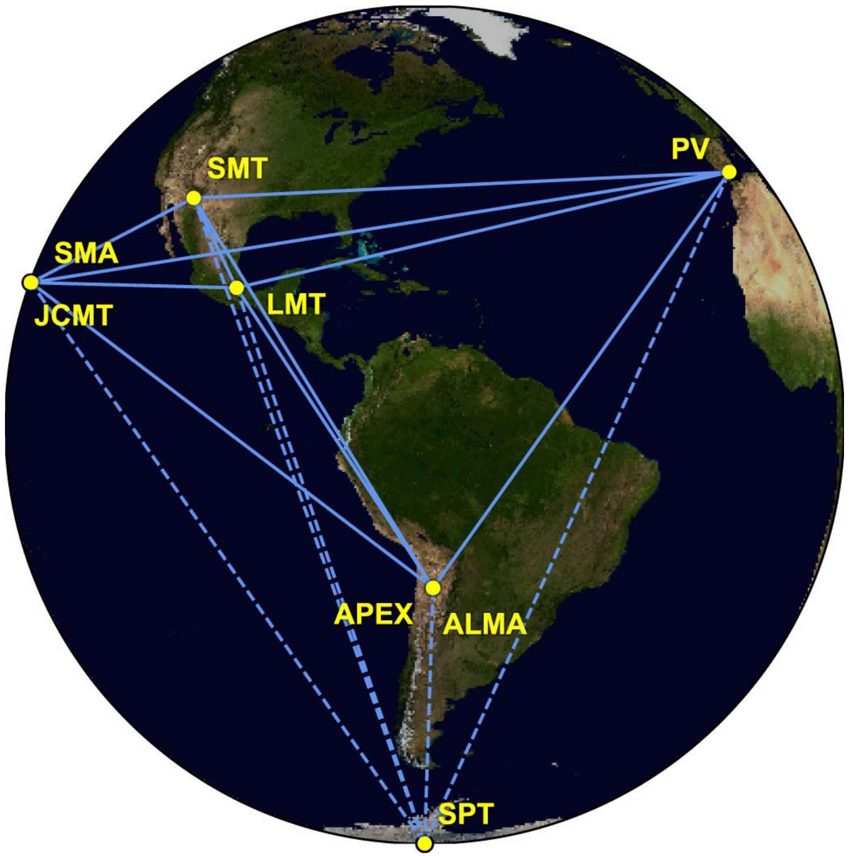
● Best fit spectra in XENON1T with PandaX-II constraint



Constraining WIMP annihilations from the EHT Observations of M87*

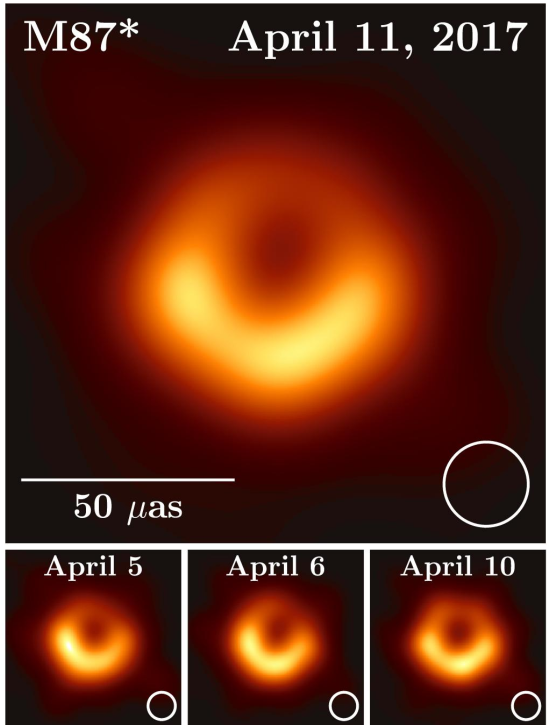
The EHT project

- VLBI: Very Long Baseline Interferometry, an Earth-sized interferometer.
- EHT collaboration: focus on improving the capability of VLBI at short wavelengths.



- First image of a SMBH

EHT collaboration, Astrophys. J. Lett. 875 (2019) L1, [1906.11238]

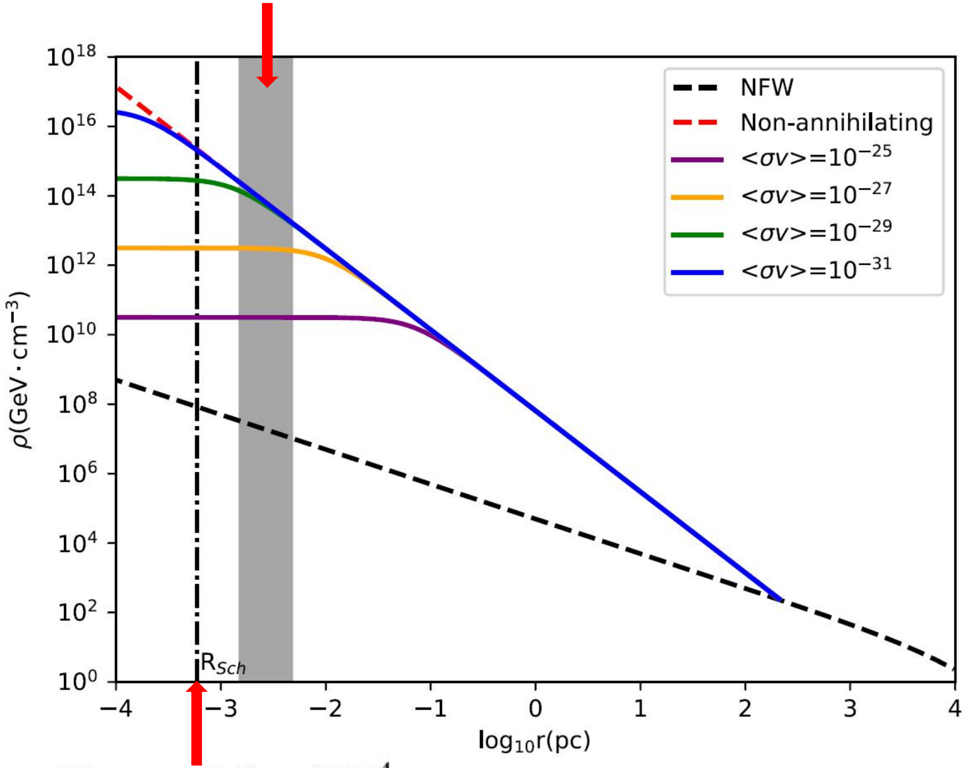


Symbol	Value	Property
M	$6.2 \times 10^9\ M_\odot$	Compact object mass
D	16.9 Mpc	Compact object distance
$\nu_{\mathrm{obs},0}$	230 GHz	Observing frequency

DM spike model

- Adiabatic growth of SMBH will significantly enhance the DM density and form a spike structure.

EHT observational areas



$R_{\rm Sch} = 5.9 \times 10^{-4}$ pc. ⟶ 7.3 μas

P. Gondolo & J. Silk,PRL 83(1999) 1719{1722, [astro-ph/9906391]

O. Y. Gnedin & J. R. Primack, PRL 93 (2004) 061302, [astro-ph/0308385]

P. Ullio, H. Zhao & M. Kamionkowski, PRD 64 (2001) 043504, [astro-ph/0101481]

R. Aloisio, P. Blasi & A. V. Olinto, JCAP 05 (2004) 007, [astro-ph/0402588]

T. Lacroix, M. Karami, A. E. Broderick, J. Silk & C. Boehm, PRD 96 (2017) 063008,[1611.01961]

- DM density profile with Spike

$$\rho_\chi(r) = \begin{cases} 0 & r < R_{\rm Sch}, \\ \frac{\rho_{\rm sp}(r)\rho_{\rm sat}}{\rho_{\rm sp}(r)+\rho_{\rm sat}} & R_{\rm Sch} \le r < R_{\rm sp}, \quad R_{\rm sp} \simeq 220 \text{ pc} \\ \rho_{\rm NFW}(r) & r \ge R_{\rm sp}. \end{cases}$$

spike radius

- Saturate DM density

$$\rho_{\rm sat} = m_\chi / \langle\sigma v\rangle t_{\rm BH}$$ ⟶ age of SMBH $t_{\rm BH} = 10^9$ yr

- Synchrotron emission due to WIMP annihilations can be stringently constrainted!

Calculation framework

R. Aloisio, P. Blasi & A. V. Olinto, JCAP 05 (2004) 007, [astro-ph/0402588]
T. Lacroix, M. Karami, A. E. Broderick, J. Silk & C. Boehm, PRD 96 (2017) 063008,[1611.01961]

$$S_{\text{syn}}(\nu) = \int d\Omega_{\text{obs}} \int_{l.o.s} dI_{\text{syn}}(\nu)$$

Specific intensity: radiative transfer equation

$$\frac{dI_{\text{syn}}(\nu, s)}{ds} = -\alpha(\nu, s) I_{\text{syn}}(\nu, s) + \frac{j_{\text{syn}}(\nu, s)}{4\pi}$$

relativistic Doppler effect and gravitational redshift

$$I_{\text{obs}}(\nu_{\text{obs}}) = \left(\frac{\nu_{\text{obs}}}{\nu_{\text{em}}}\right)^3 I_{\text{em}}(\nu_{\text{em}}) = g^3 I_{\text{em}}(\nu_{\text{em}})$$

emissivity

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

power of synchrotron emission

$$P_{\text{syn}}(\nu, E_e, B, \theta_p) = \frac{\sqrt{3}e^3 B \sin\theta_p}{m_e c^2} F(\nu/\nu_c)$$

$B \sim 1 - 30$ G

electron and positron energy spectrum

$$n_e(r, E) = \frac{4\pi p^2}{c} f_e(r, p)$$

outside accretion radius : propagation equation

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

source function

$$q(r, p) = \frac{c}{4\pi p^2} Q(r, E) = \frac{c}{4\pi p^2}\frac{\langle\sigma v\rangle \rho_\chi^2(r)}{2m_\chi^2}\sum_i \text{BR}_i \frac{dN_{e^\pm}^{\text{inj}}}{dE}(E)$$

annihilation rate

injection spectrum

inside accretion radius: integral analytic solution

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

injection momentum

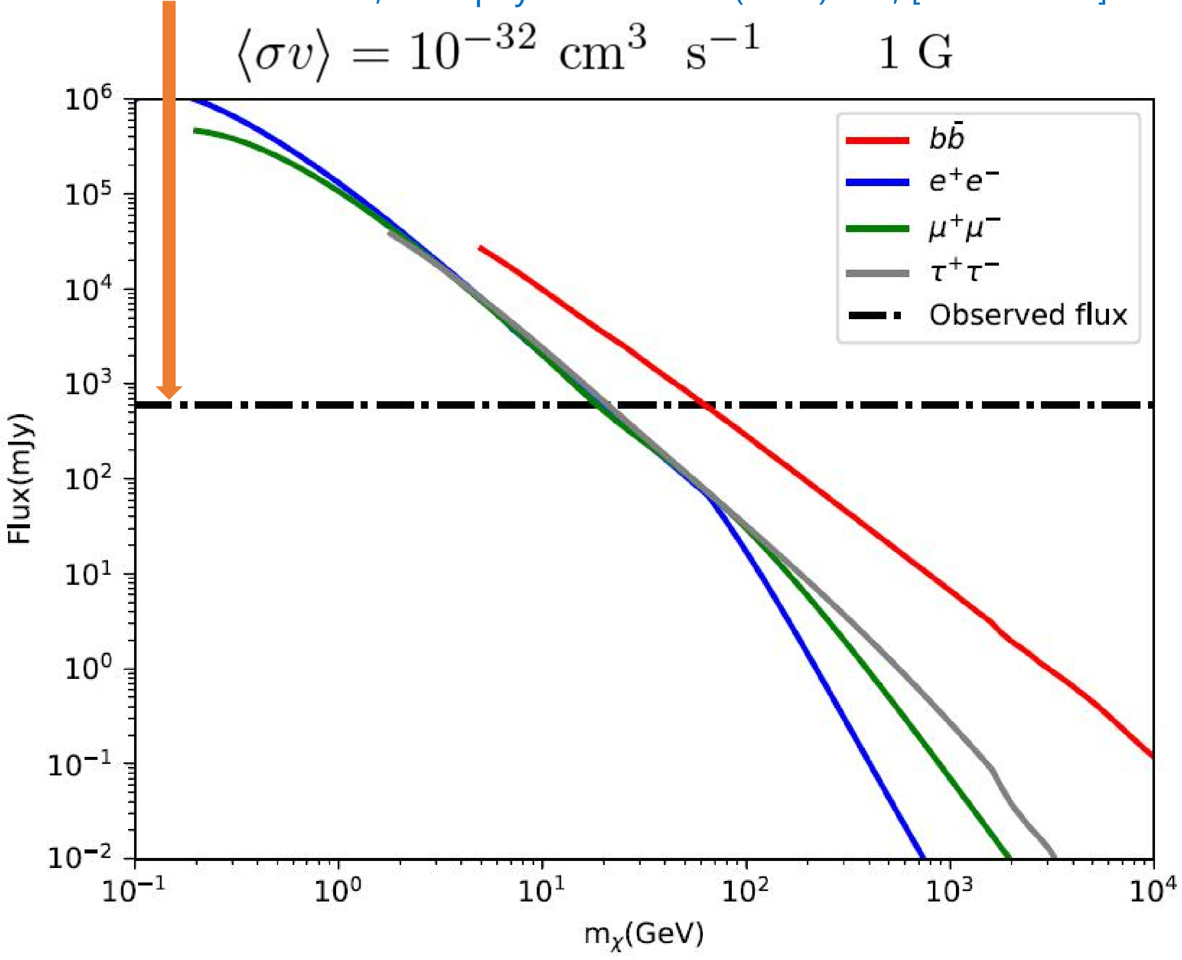
$$p_{\text{inj}}(R_{\text{inj}}; r, p) = p\left[\frac{k_0 R_{\text{Sch}}^{-\frac{1}{2}}}{c} R_{\text{inj}}^{\frac{3}{2}} p\left(\frac{r}{R_{\text{inj}}} - 1\right) + \left(\frac{R_{\text{inj}}}{r}\right)^{\frac{1}{2}}\right]^{-1}$$

● Bnechmark flux for four annihilation channels

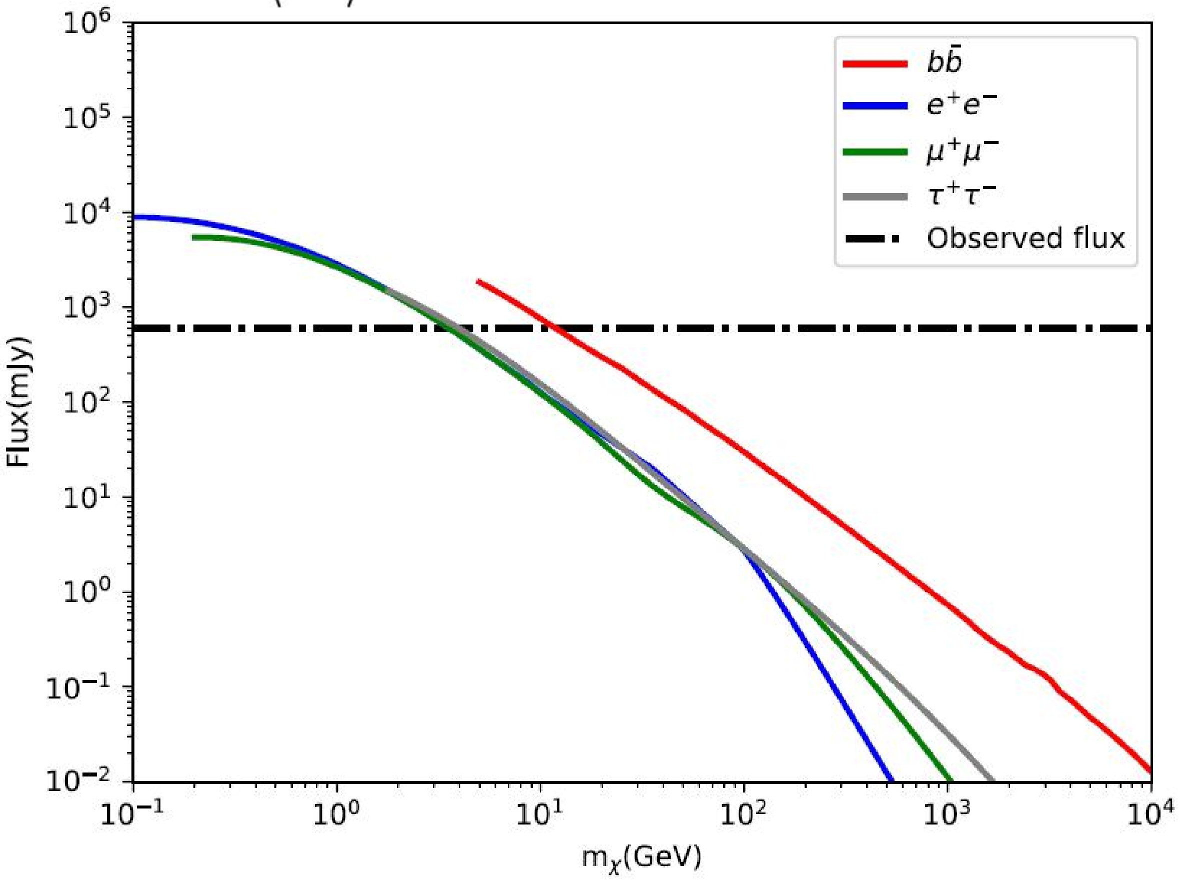
EHT collaboration, Astrophys. J. Lett. 910 (2021) L12,[2105.01169]

EHT collaboration, Astrophys. J. Lett. 910 (2021) L13, [2105.01173]

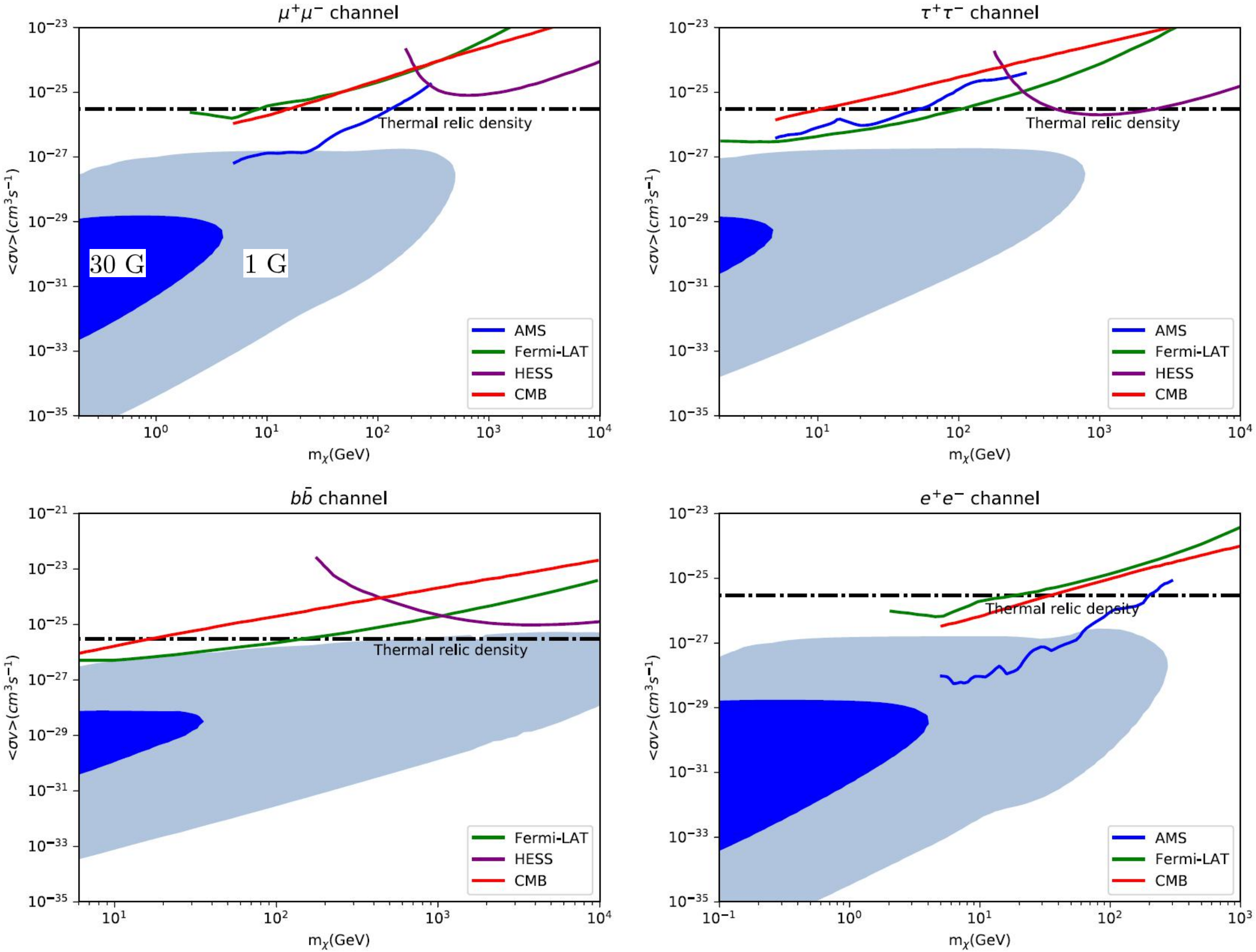
$\langle \sigma v \rangle = 10^{-32}\ \mathrm{cm}^3\ \ \mathrm{s}^{-1}$ 1 G



$\langle \sigma v \rangle = 10^{-30}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$ 30 G



Limits on WIMP annihilation cross sections



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