Bounds on Cosmic Ray-Boosted Dark Matter

WANG Wenyu
Beijing University of Technology
@Beijing, 2019.10

With Lei WU, Jin-Min YANG, Hang ZHOU, Bin ZHU

Frontiers of Physics

Outstanding Papers Awards 2019

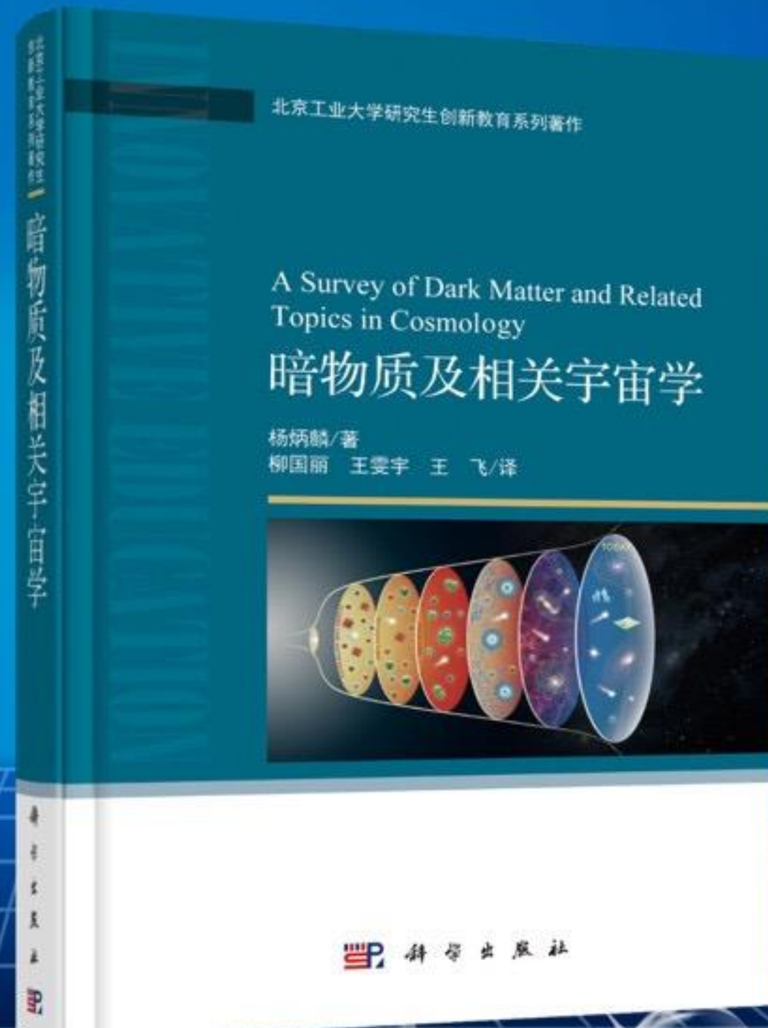
杨炳麟，爱荷华州立大学教授，国际著名理论物理学家，曾任全球华人物理学会会长。多年来关心和支持中国科技发展，为中国物理学事业的发展作出巨大贡献。

以该综述为基础，郑州大学柳国丽、王飞教授和北京工业大学王雯宇教授进行了翻译、内容更新与扩充，将由科学出版社以学术译著的形式出版发行，预计今年12月份面市。

柳国丽

王雯宇

王飞



全书共13章，49万字，由科学出版社出版发行。

上篇：

- 暗物质观测证据
- 银河系暗物质分布
- 暗物质候选者
- 弱相互作用大质量粒子
- 轻暗物质粒子
- 暗物质直接、间接探测以及实验现状总结

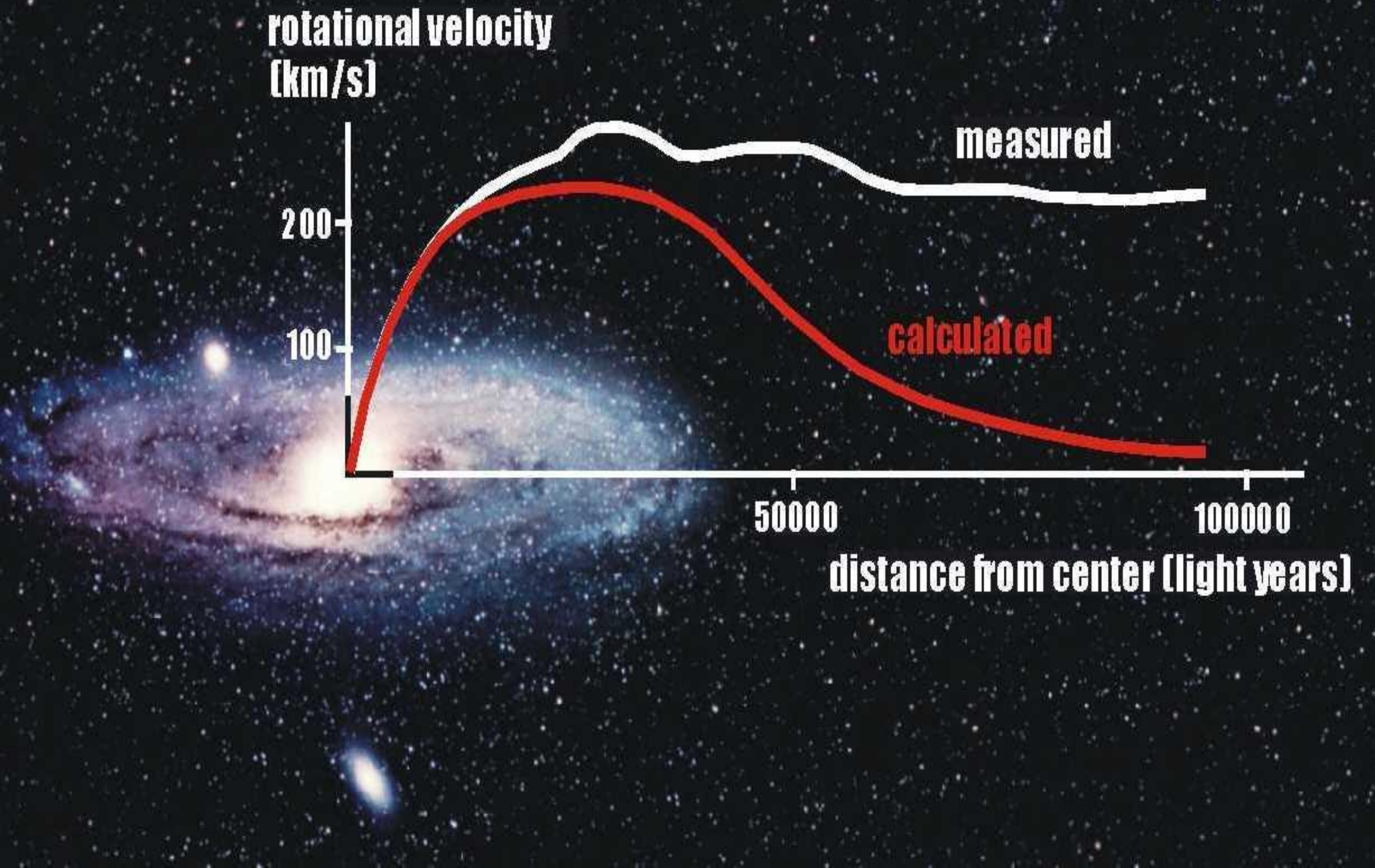
下篇：

- 宇宙学基本知识简介
- 宇宙大爆炸核合成
- 玻尔兹曼输运方程和大质量粒子的冻结
- 宇宙微波背景各向异性和宇宙扰动理论

Content

- Introduction of dark matter
- Status of WIMP dark matter
- Cosmic Ray-boosted dark matter
- Bounds on the light dark matter in the simplified models

Evidence of Dark Matter



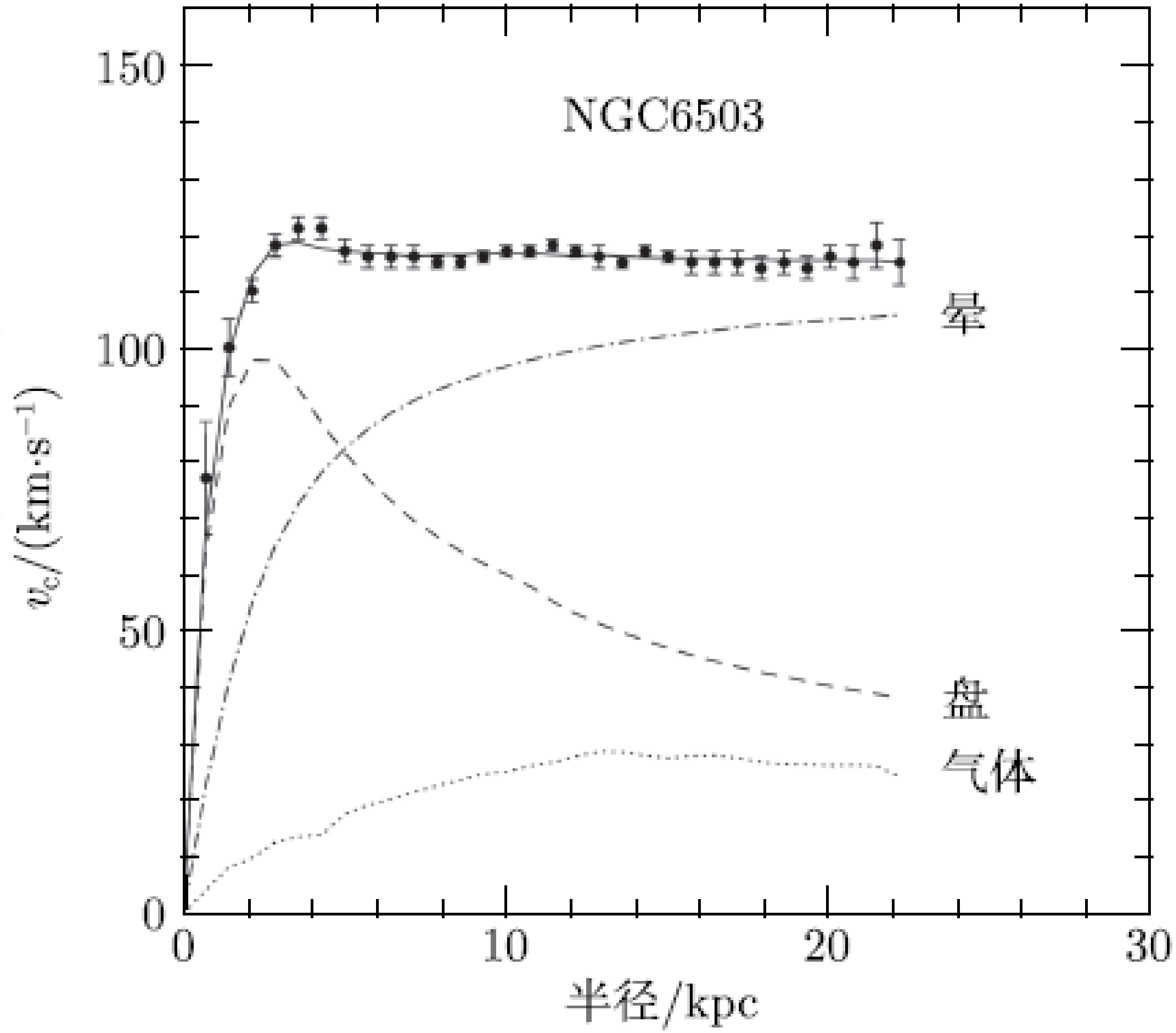
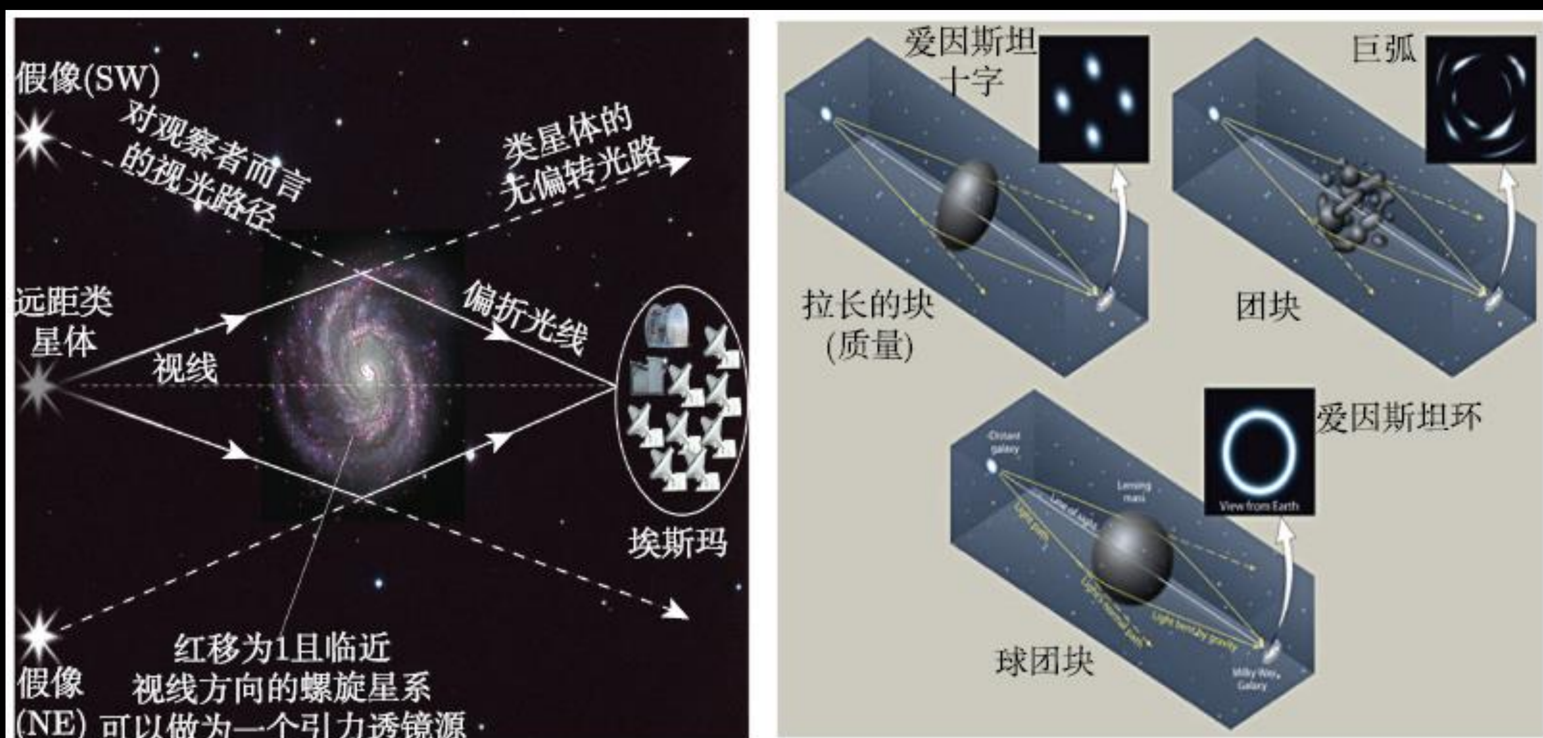


图 2.1.2　拟合总速度曲线 $v_c = \sqrt{v_{晕}^2 + v_{盘}^2 + v_{气体}^2}$

Observation methods

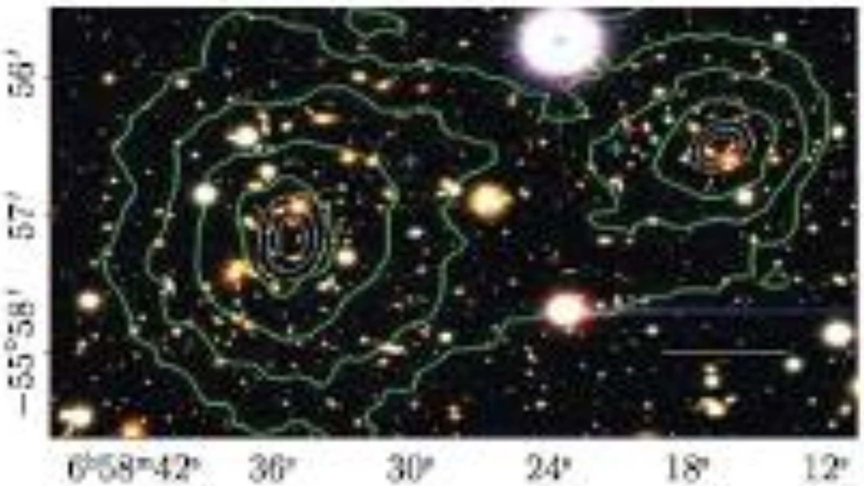
- Optics for the stars
- X-ray for the gas
- Gravitational lensing for the dark matter

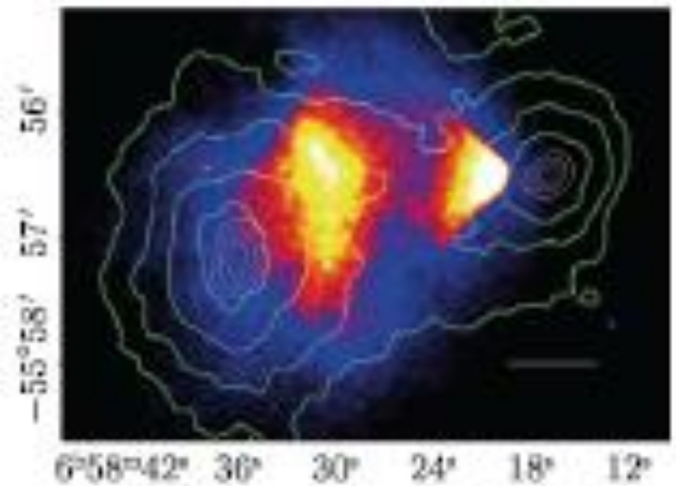


粉色：　　　　蓝色：

图像：光学　X射线气体　透镜质量

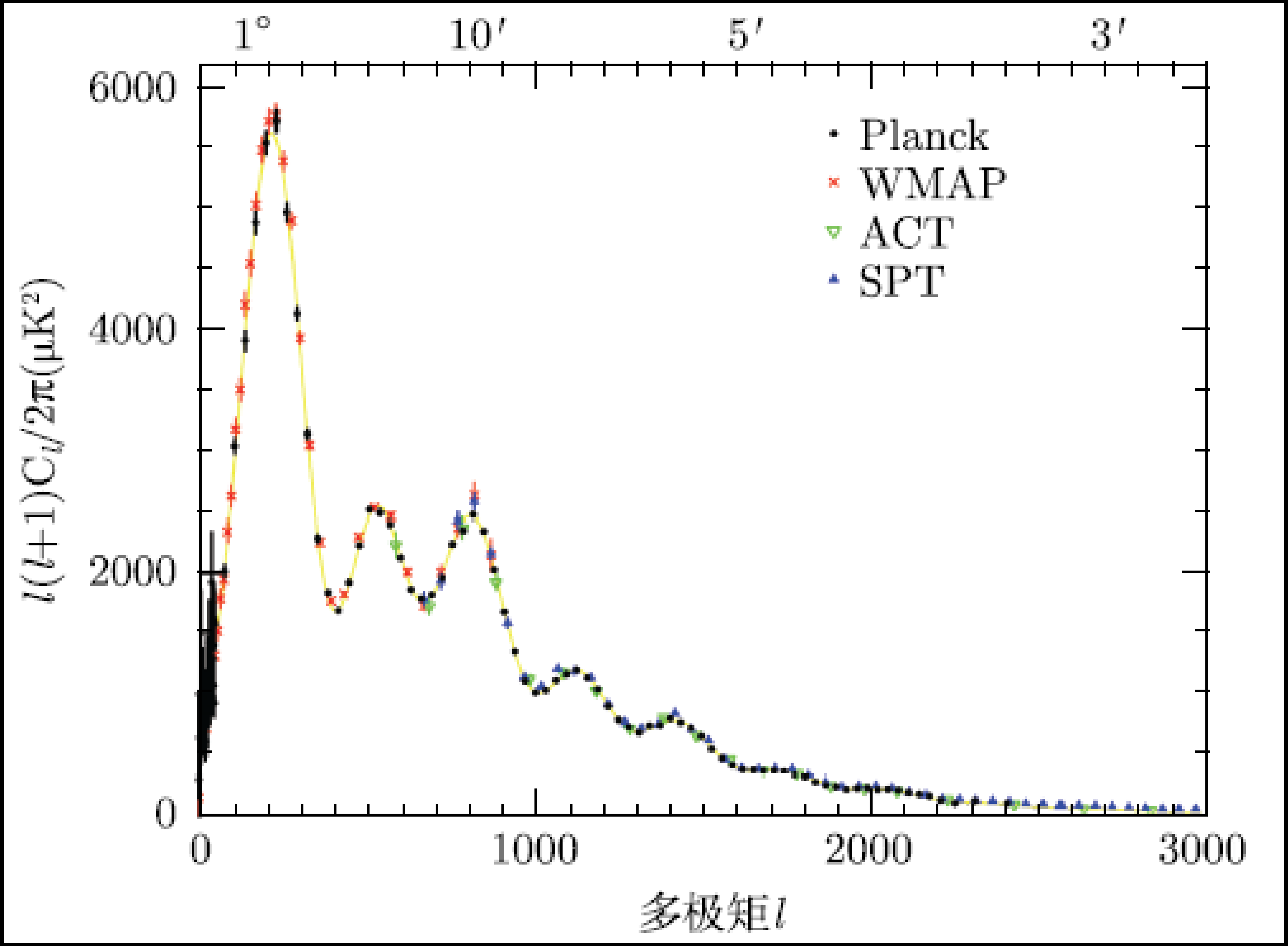
暗物质和光偏移





- 总质量类似于星系那样集中，而不是集中于气体所在位置，$M_{total}:M_{gas}:M_{stars}$~70:10:1
- 气体峰(+)和质量之间的空间偏移非常显著
- 强烈支持暗物质假说而不支持修正引力

Anisotropy of CMB needs dark matter



Though existence of dark matter are believed in astrophysicists, we still need to identify it in the terrestrial laboratory !

Direct detection

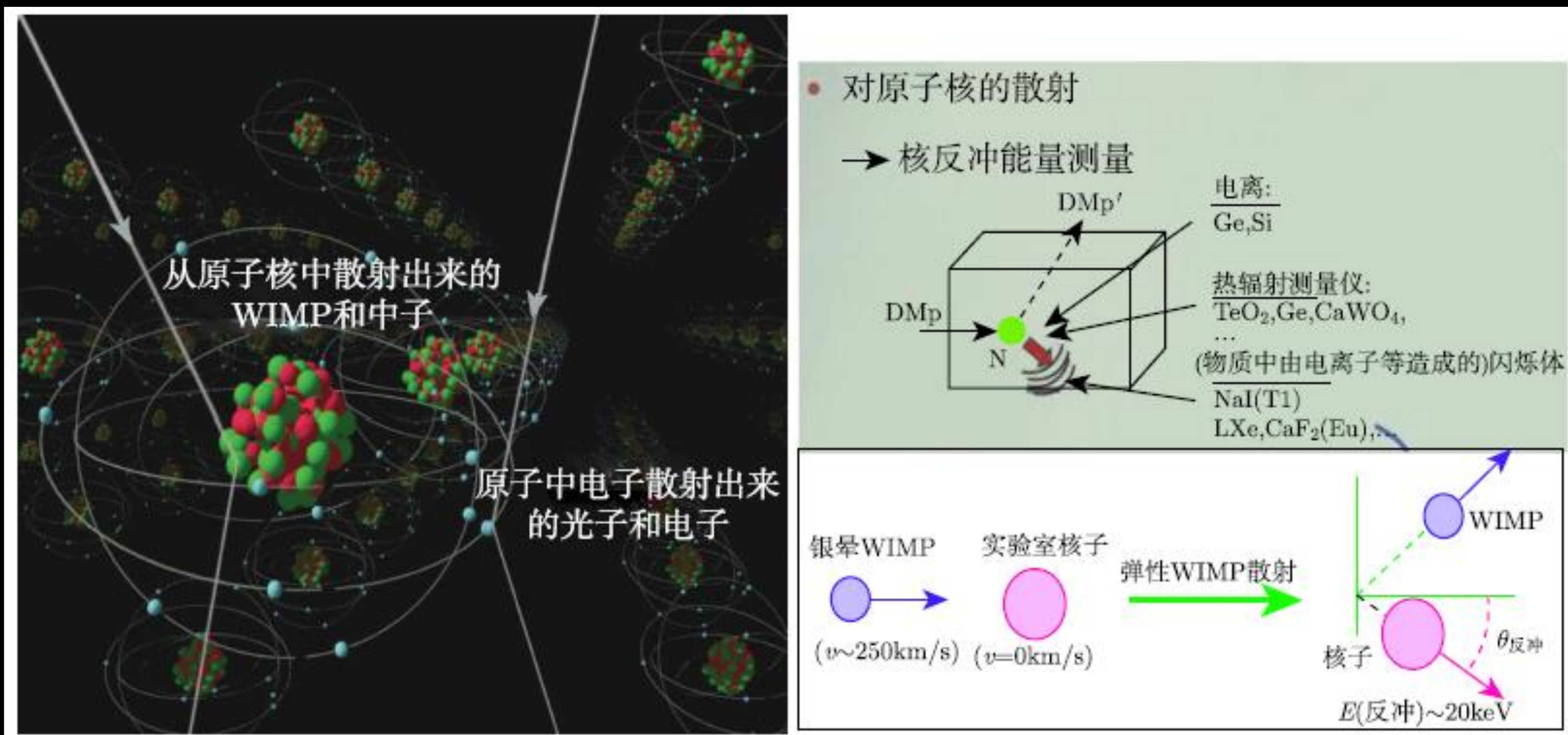
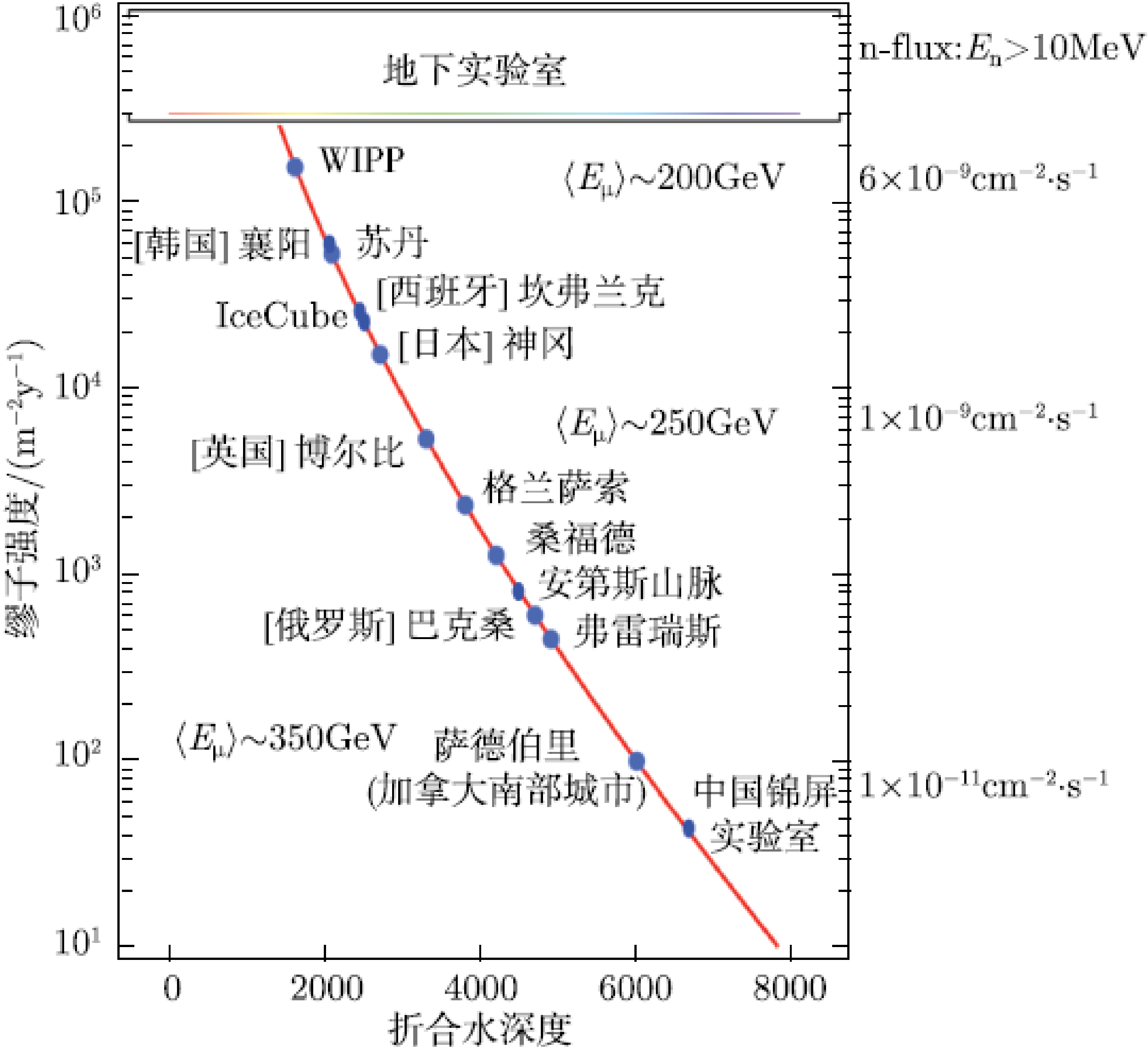
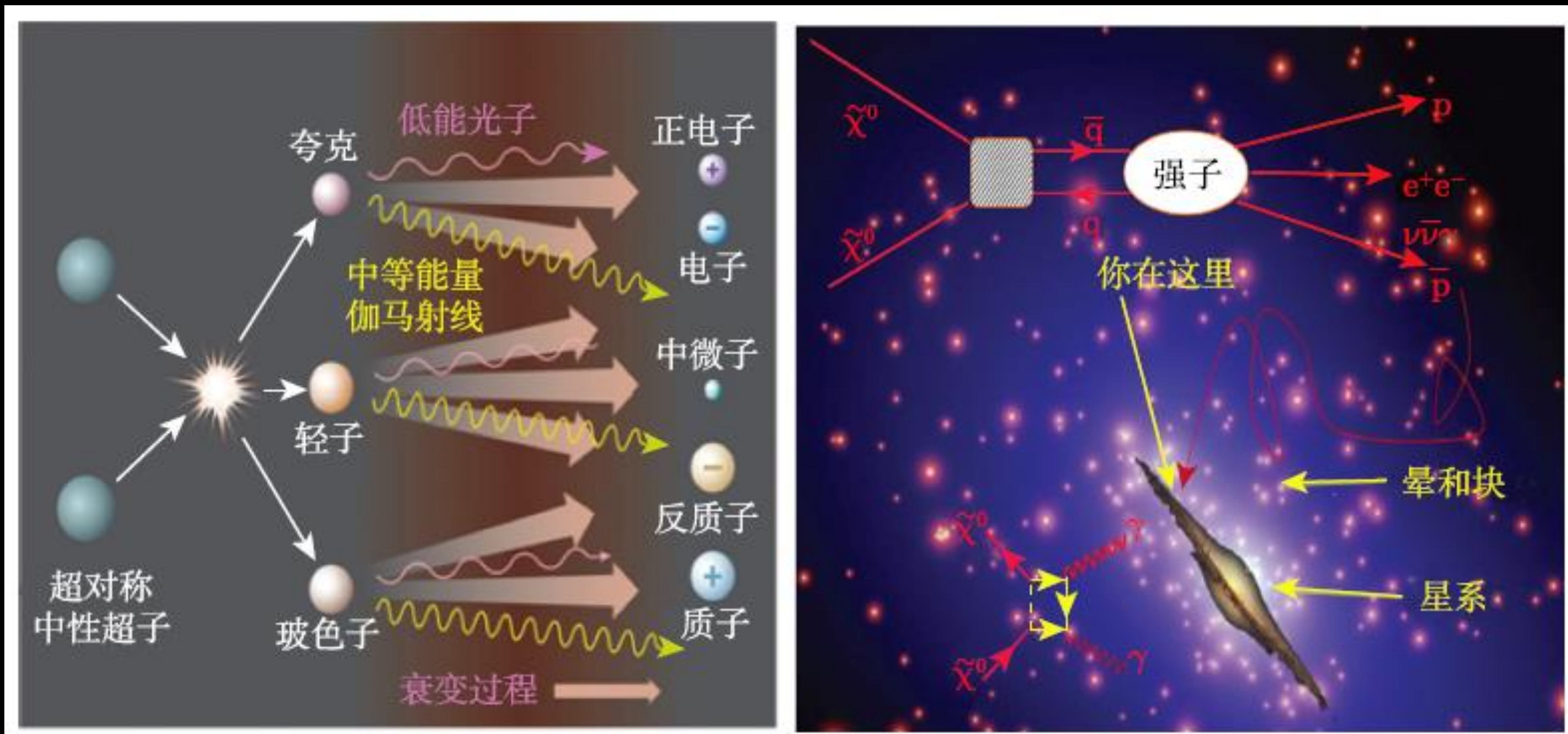


图 6.1.1　全球深地物理探测实验室的分布地图。注意 #26 ANDES 深地实验室，目前还只是一项决议，将是南半球唯一科学地下实验室

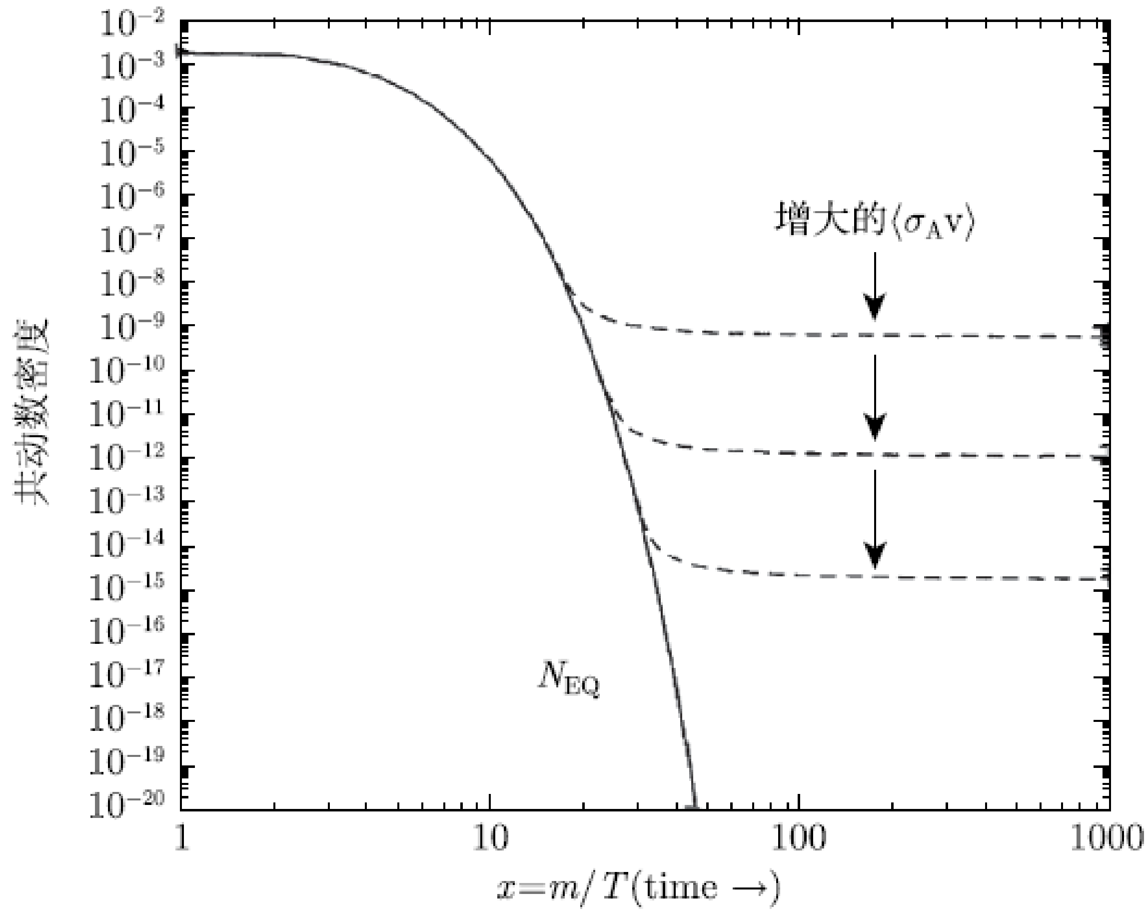


地下实验室
n-flux: E_n>10MeV
WIPP
$\langle E_\mu \rangle$~200GeV
$6\times10^{-9}cm^{-2}\cdot s^{-1}$
[韩国] 襄阳
苏丹
[西班牙] 坎弗兰克
IceCube
[日本] 神冈
$\langle E_\mu \rangle$~250GeV
$1\times10^{-9}cm^{-2}\cdot s^{-1}$
[英国] 博尔比
格兰萨索
桑福德
安第斯山脉
[俄罗斯] 巴克桑
弗雷瑞斯
$\langle E_\mu \rangle$~350GeV
萨德伯里
(加拿大南部城市)
中国锦屏
实验室
$1\times10^{-11}cm^{-2}\cdot s^{-1}$
缪子强度/$(m^{-2}y^{-1})$
10^6
10^5
10^4
10^3
10^2
10^1
0
2000
4000
6000
8000
折合水深度

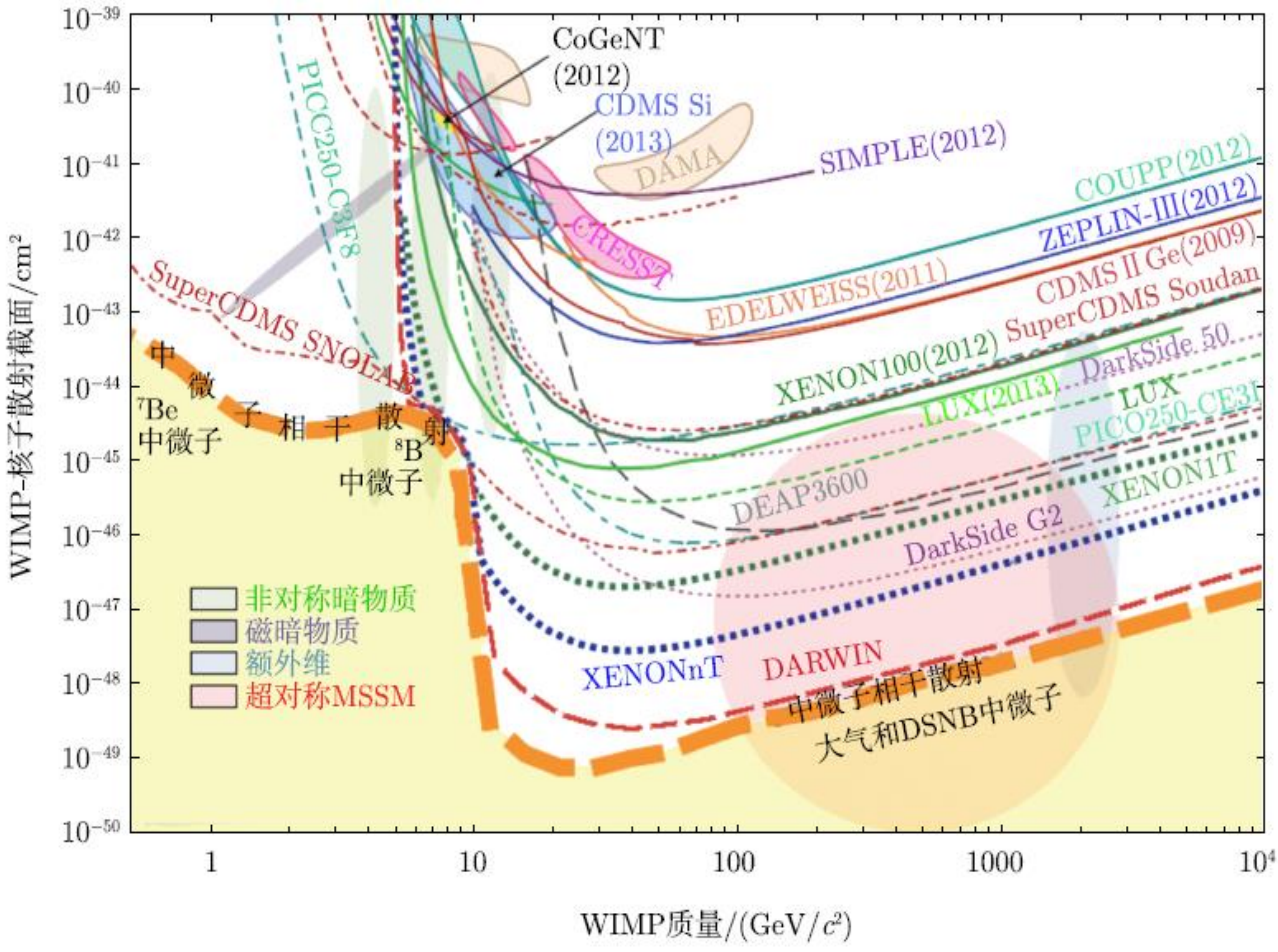
Indirect detection



WIMP miracle



$$\Omega_\chi h^2 = 0.1 \times \left(\frac{x_f}{10}\right)\left(\frac{g_*}{100}\right)^{1/2} \frac{0.282\ \text{pb}}{a + \dfrac{3}{x_f} b},$$

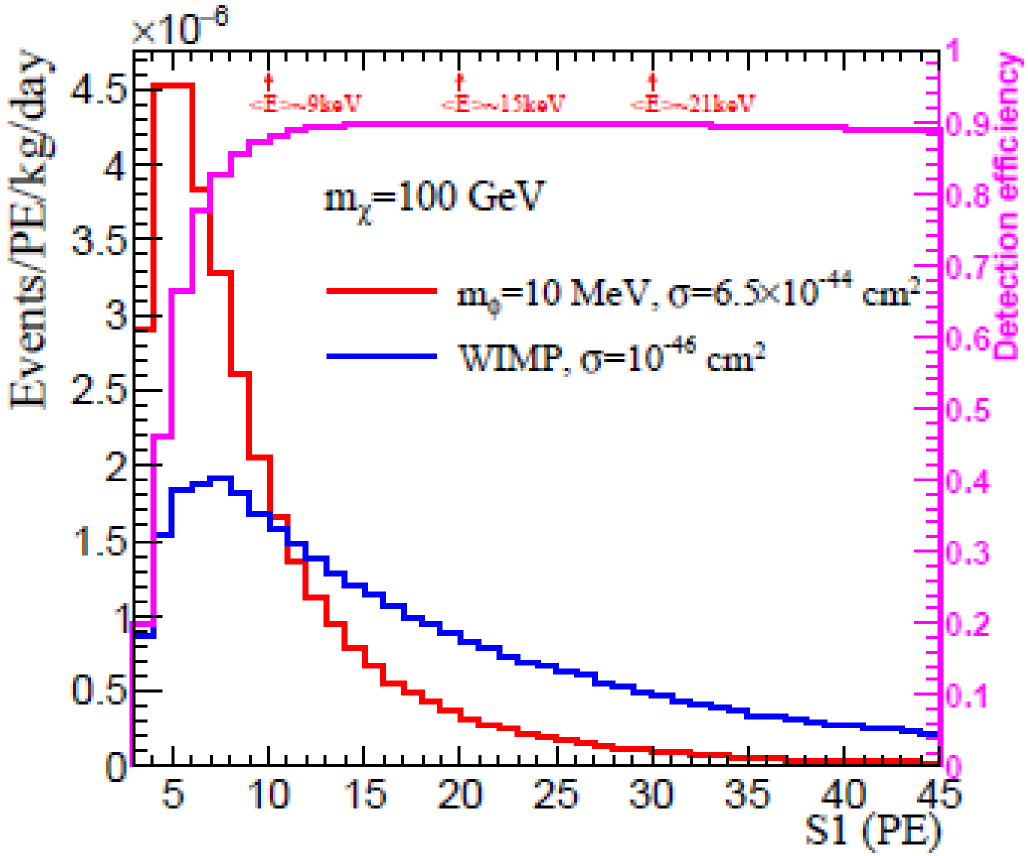


CoGeNT
(2012)
CDMS Si
(2013)
DAMA
SIMPLE(2012)
COUPP(2012)
ZEPLIN-III(2012)
CDMS II Ge(2009)
PICC250-C3F8
CRESST
EDELWEISS(2011)
SuperCDMS Soudan
SuperCDMS SNOLAB
XENON100(2012)
DarkSide 50
LUX(2013)
LUX
PICO250-CF3I
DEAP3600
XENON1T
DarkSide G2
XENONnT
DARWIN
中微子相干散射
^{7}Be
中微子
^{8}B
中微子
中微子相干散射
大气和DSNB中微子
非对称暗物质
磁暗物质
额外维
超对称MSSM
WIMP-核子散射截面/cm^2
WIMP质量/(GeV/c^2)

Summary

- Less and less space for WIMP above 1GeV!
- We are less sensitive to the light dark matter

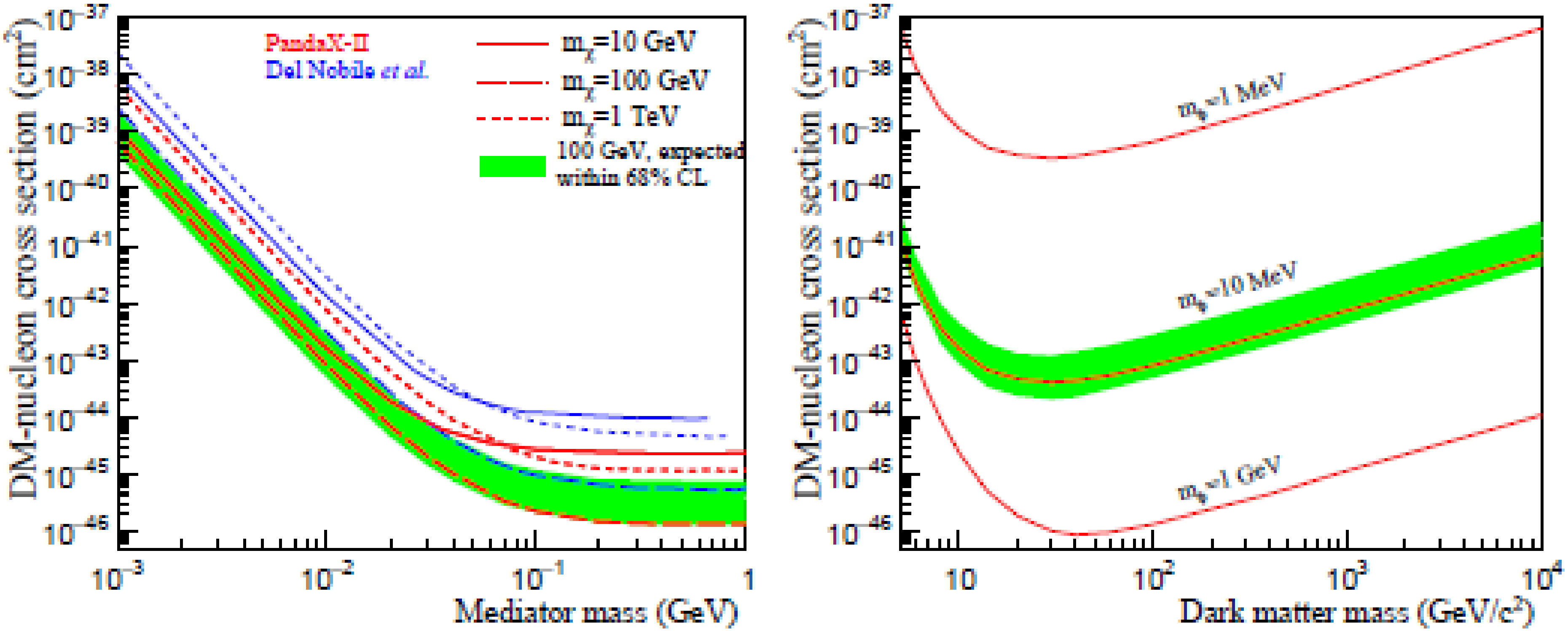
Reasons of the less sensitivity



From PANDX group arXiv:1802.06912

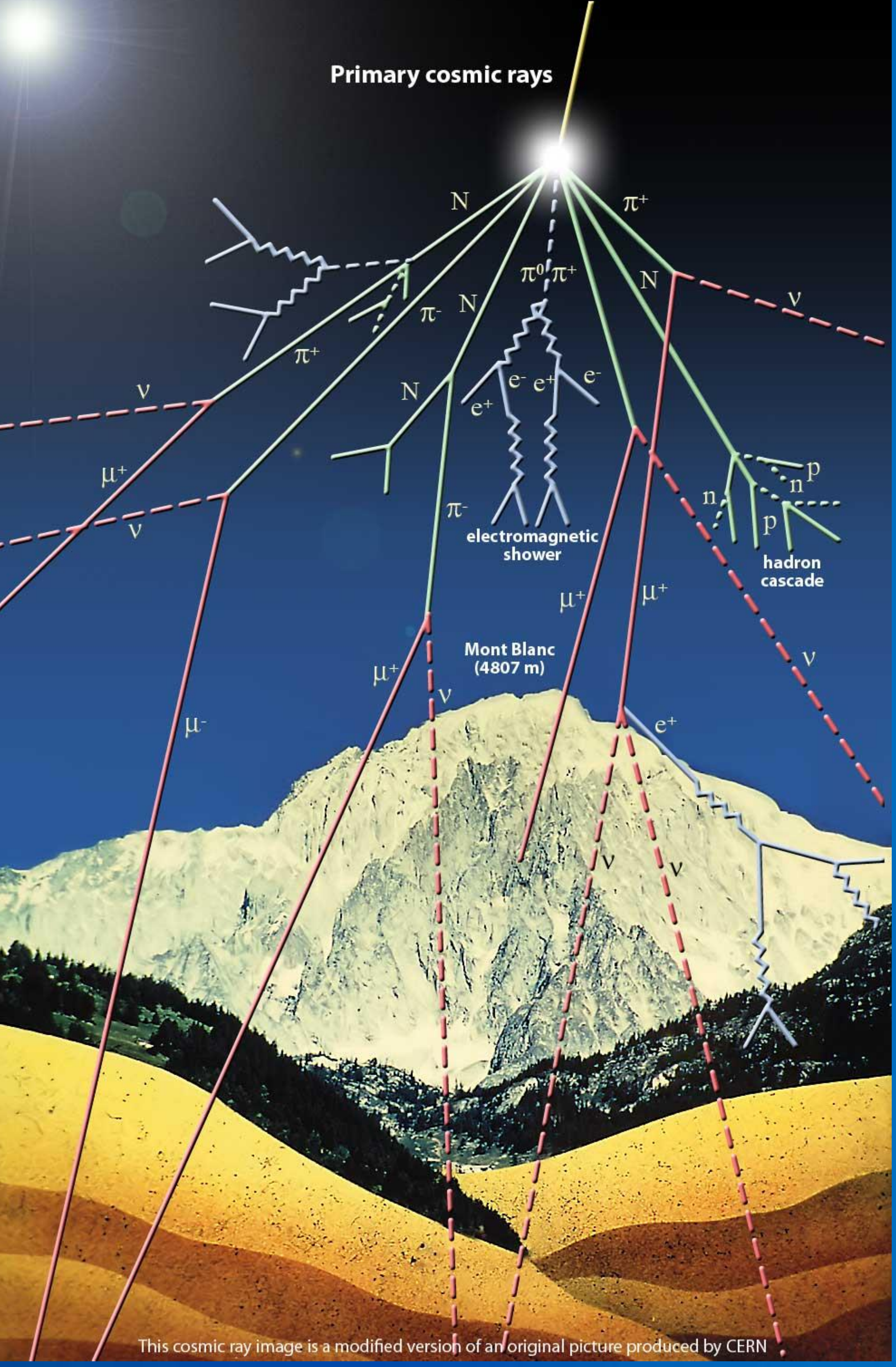
$$\frac{\mathrm{d}R}{\mathrm{d}E_r} = \frac{n_\chi \sigma_0}{4 m_R^2 v_E} F^2(\sqrt{2 m_A E_r}) \left(\mathrm{erf}\left(\frac{v_{\min} + v_E}{v_0}\right) - \mathrm{erf}\left(\frac{v_{\min} - v_E}{v_0}\right) \right)$$

PANDX constraints on light Mediator



From PANDX group arXiv:1802.06912

A short introduction to Cosmic Rays



1000个粒子/平米/秒

90% 质子

9% α粒子

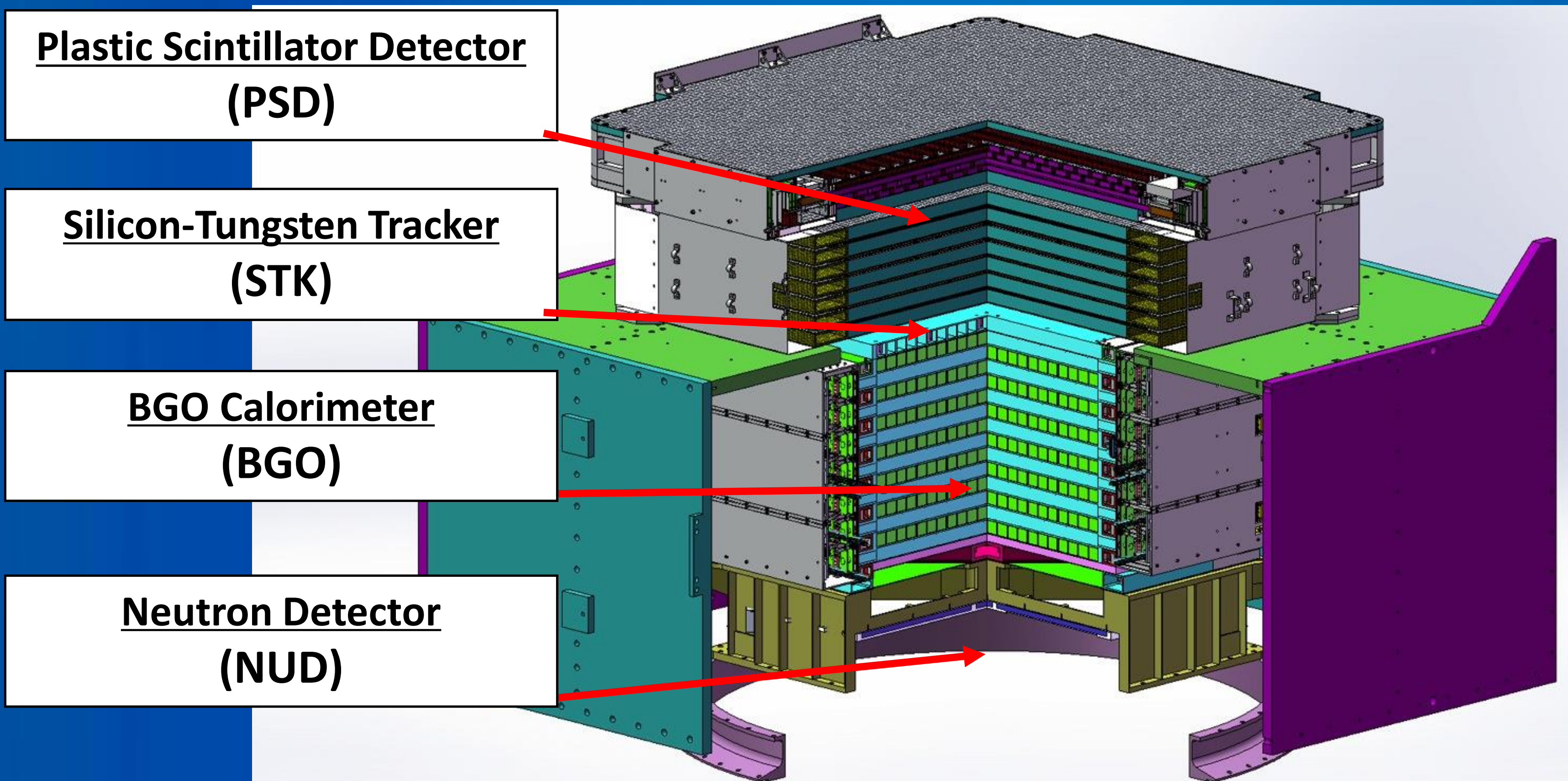
其它是重核

最高可达10^{20}eV

Where？How？

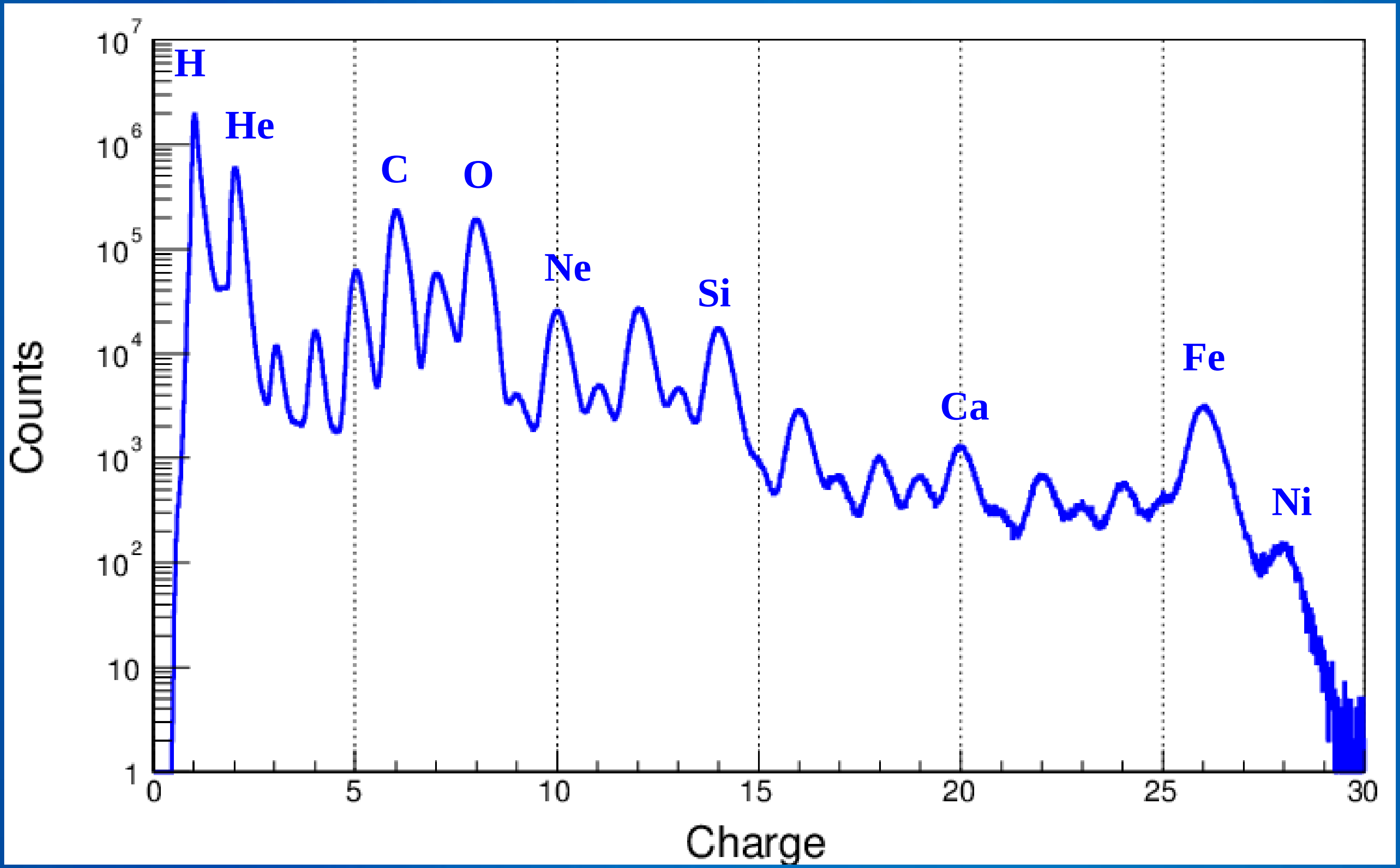
探测手段：云室

手段2:



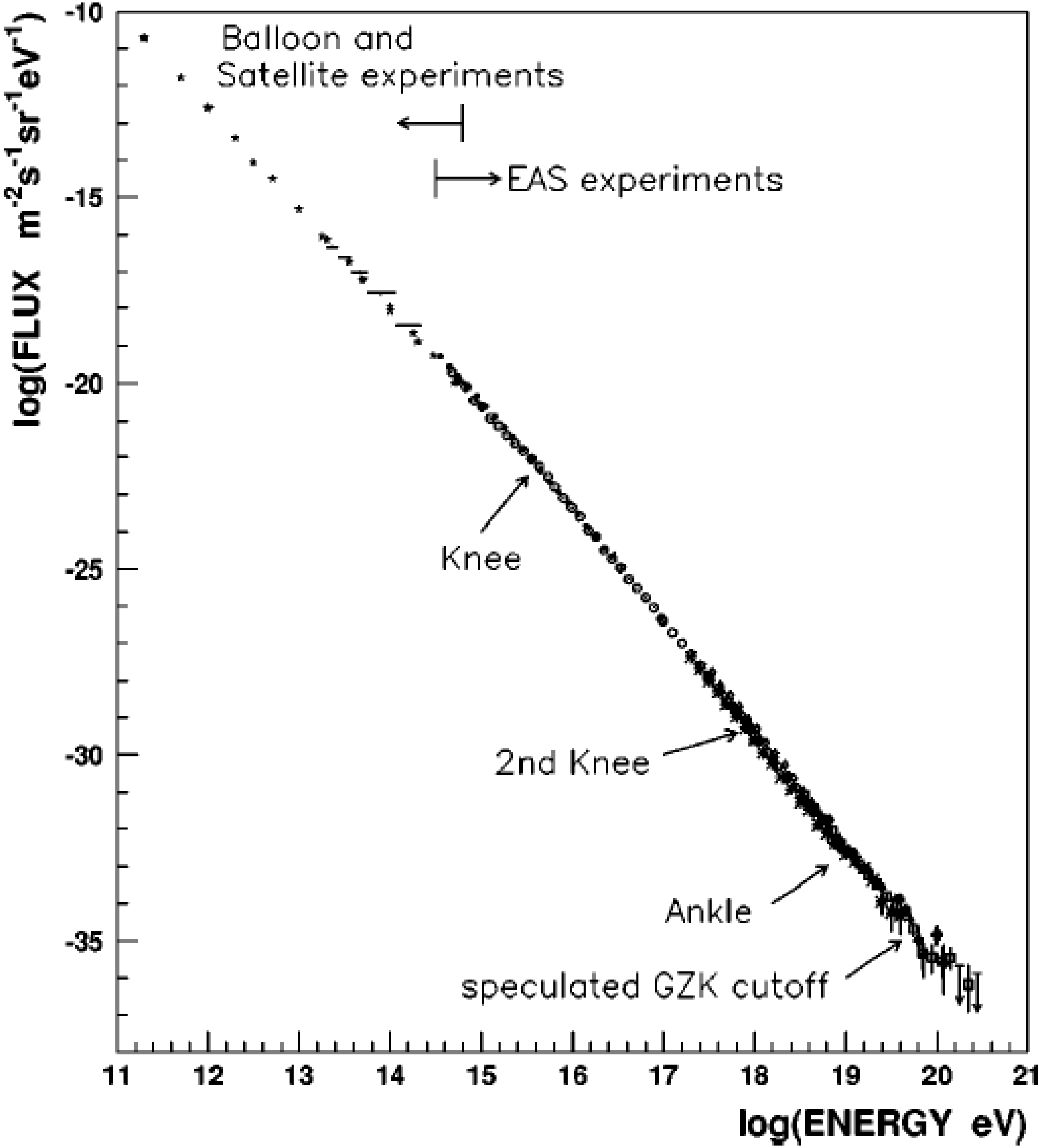
- Charge measurement (dE/dx in PSD, STK and BGO)
- Pair production and tracking (STK and BGO)
- Precise energy measurement (BGO bars)
- Hadron rejection (BGO and neutron detector)

On-orbit performance: Charge measurement

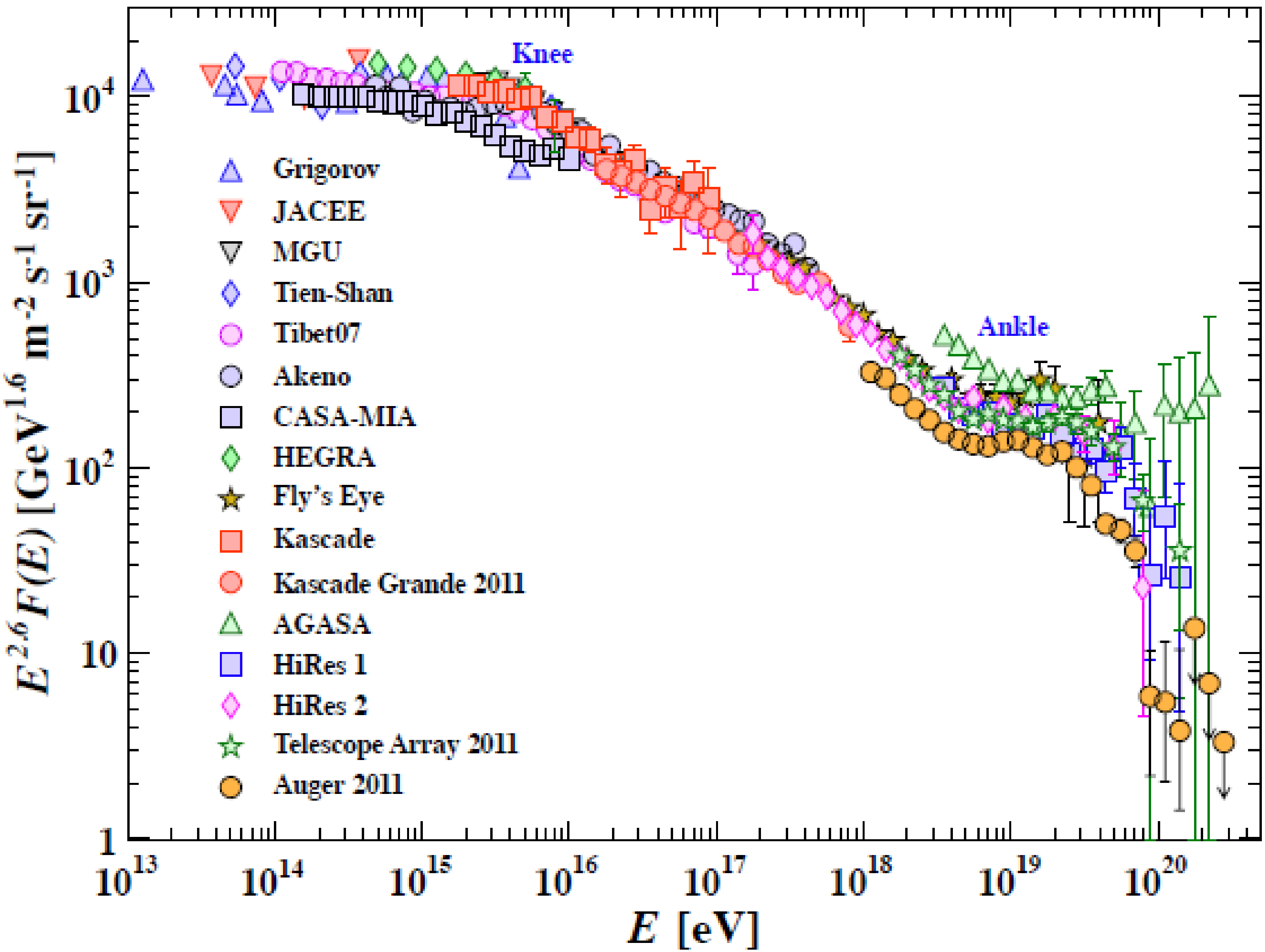


For protons and Irons, the charge resolutions are 0.13e and 0.32e, respectively.

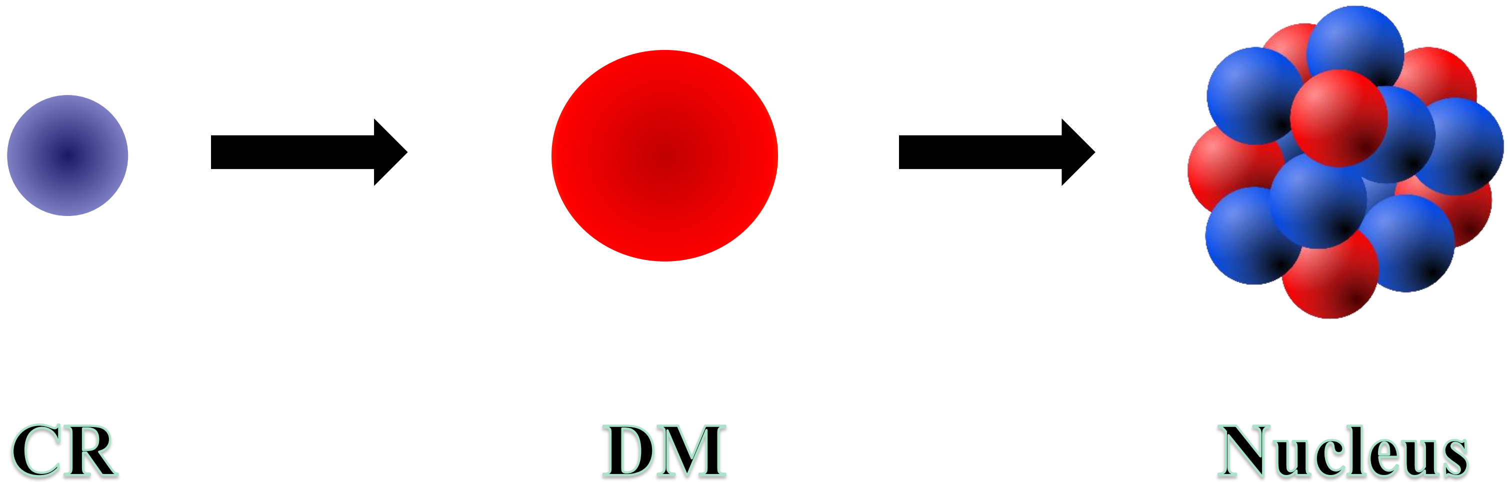
幂律谱



Balloon and
Satellite experiments
EAS experiments
Knee
2nd Knee
Ankle
speculated GZK cutoff
log(FLUX m^-2 s^-1 sr^-1 eV^-1)
-10
-15
-20
-25
-30
-35
11
12
13
14
15
16
17
18
19
20
21
log(ENERGY eV)


Knee
Ankle
Grigorov
JACEE
MGU
Tien-Shan
Tibet07
Akeno
CASA-MIA
HEGRA
Fly's Eye
Kascade
Kascade Grande 2011
AGASA
HiRes 1
HiRes 2
Telescope Array 2011
Auger 2011
$E^{2.6}F(E)$ [GeV$^{1.6}$ m^{-2} s^{-1} sr^{-1}]
E [eV]
1
10
10^2
10^3
10^4
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}

Story of CRDM



From CR to DM flux

After a single collision by the CR

$$T_\chi = T_\chi^{\max} \frac{1-\cos\theta}{2}, \quad T_\chi^{\max} = \frac{T_i^2 + 2m_i T_i}{T_i + (m_i + m_\chi)^2/(2m_\chi)},$$

The minimal incoming energy required for CR

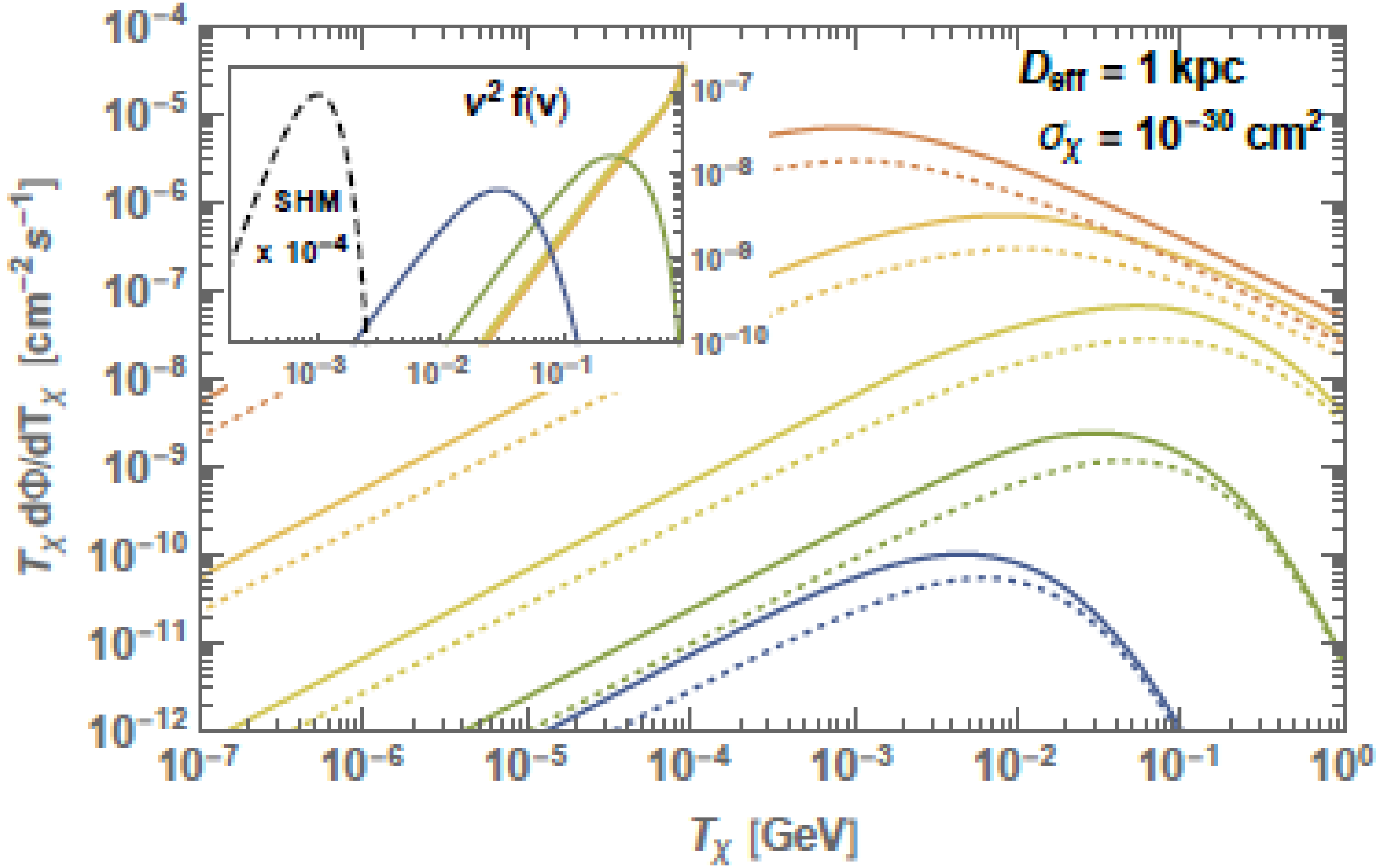
$$T_i^{\min} = \left(\frac{T_\chi}{2} - m_i\right)\left[1 \pm \sqrt{1 + \frac{2T_\chi}{m_\chi}\frac{(m_i+m_\chi)^2}{(2m_i - T_\chi)^2}}\right],$$

CR *i* in a differential volume

$$d\Gamma_{\mathrm{CR}_i \to \chi} = \sigma_{\chi i} \times \frac{\rho_\chi}{m_\chi} \frac{d\Phi_i^{LIS}}{dT_i} dT_i dV$$

The CR induced DM flux

$$\frac{d\Phi_\chi}{dT_\chi} = D_{\mathrm{eff}} \frac{\rho_\chi^{\mathrm{local}}}{m_\chi} \times$$
$$\times \sum_i \sigma_{\chi i}^0 G_i^2(2m_\chi T_\chi) \int_{T_i^{\min}}^{\infty} dT_i \frac{d\Phi_i^{LIS}/dT_i}{T_\chi^{\max}(T_i)}$$



From T. Bringmann et. al. arXiv:1810.10543

Attenuation of CRDM flux

DM flux at the depth *z*

$$\frac{d\Phi_\chi}{dT_\chi^z} = \left(\frac{dT_\chi}{dT_\chi^z}\right)\frac{d\Phi_\chi}{dT_\chi} = \frac{4m_\chi^2 e^{z/\ell}}{(2m_\chi + T_\chi^z - T_\chi^z e^{z/\ell})^2}\frac{d\Phi_\chi}{dT_\chi}$$

in which

$$\ell^{-1} \equiv \sum_N n_N \sigma_{\chi N} \frac{2m_N m_\chi}{(m_N + m_\chi)^2}$$

is the mean free path of a DM particle.

CRDM scattering in detectors

$$\frac{d\Gamma_N}{dT_N} = \sigma^0_{\chi N} G_N^2 (2m_N T_N) \int_{T_\chi(T_\chi^{z,\min})}^{\infty} \frac{dT_\chi}{T_{r,N}^{\max}(T_\chi^z)} \frac{d\Phi_\chi}{dT_\chi} \, .$$

Comparison with the WIMP scattering

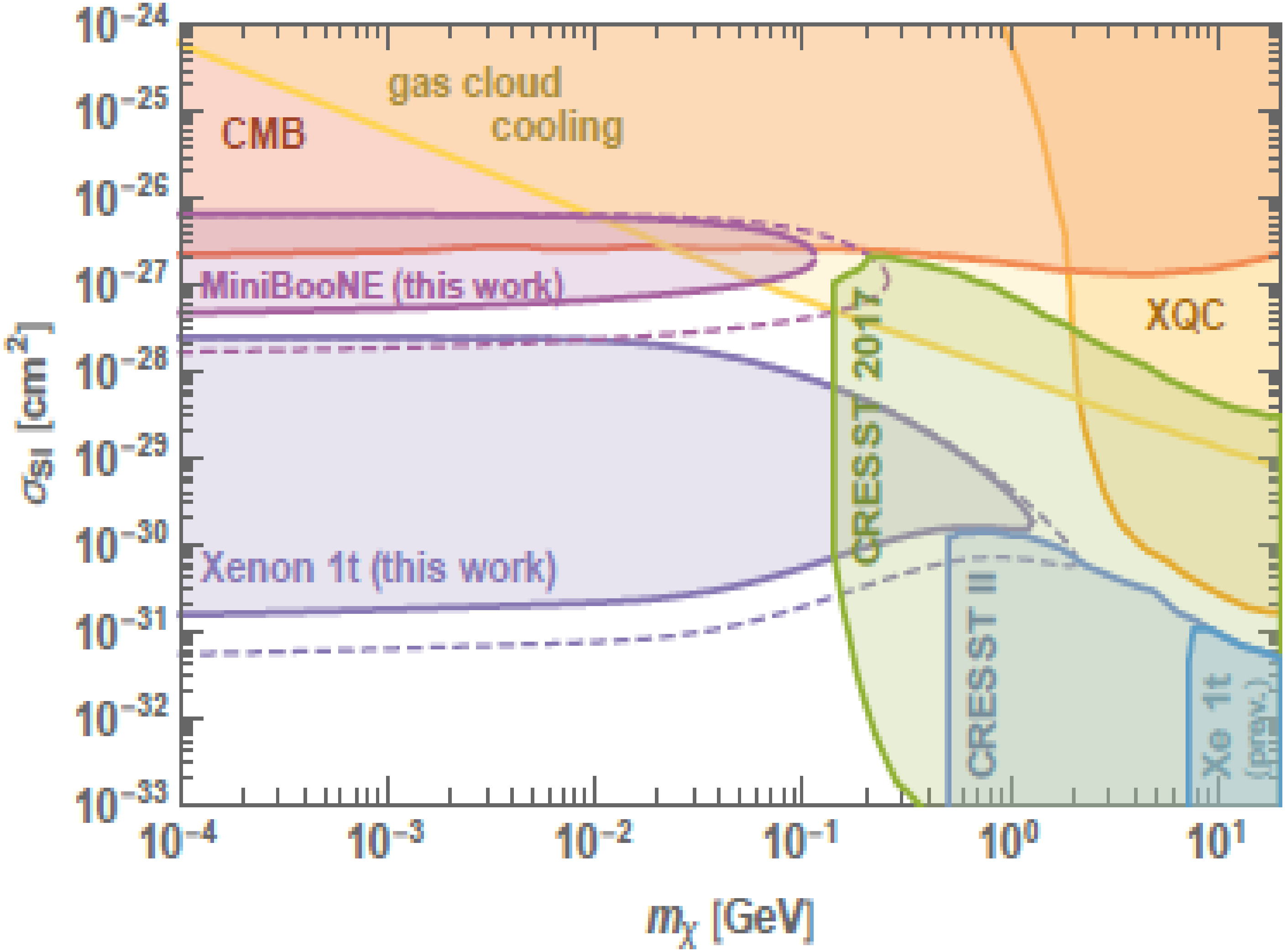
$$\Gamma_N^{\rm DM} = \int_{T_1}^{T_2} dT_N\, \sigma_{\chi N}^{\rm DM} \int_0^\infty dT_{\rm DM} \frac{d\Phi_{\rm DM}}{dT_{\rm DM}} \frac{\Theta\left[T_N^{\rm max}(T_{\rm DM}) - T_N\right]}{T_N^{\rm max}(T_{\rm DM})}$$

$$\simeq \kappa \frac{\sigma_{\chi N}^{\rm DM}}{m_{\rm DM}} \left(\bar{v}\, \rho_{\rm DM}\right)^{\rm local} \quad \text{for } m_{\rm DM} \gg m_N\,, \qquad (15)$$

We can get

$$\sigma_\chi^{\rm SI.lim} = \kappa \left(\bar{v}\, \rho_{\rm DM}\right)^{\rm local} \left(\frac{m_\chi + m_N}{m_\chi + m_p}\right)^2 \left(\frac{\sigma_{\rm DM}^{\rm SI,lim}}{m_{\rm DM}}\right)_{m_{\rm DM}\to\infty}$$

$$\times \left(\int_{T_1}^{T_2} dT_N \int_{T_\chi(T_\chi^{z,\rm min})}^\infty \frac{dT_\chi}{T_{r,N}^{\rm max}} \frac{d\Phi_\chi}{dT_\chi}\right)^{-1} \qquad (16)$$



From T. Bringmann et. al.   arXiv:1810.10543

Our work

Simplified models for scalar and vector mediator

Scalar： $g_{\chi s}\phi\bar{\chi}\chi + g_{Ns}\phi\bar{N}N$

Vector： $g_{\chi v}V_{\mu}\bar{\chi}\gamma^{\mu}\chi + g_{Nv}V_{\mu}\bar{N}\gamma^{\mu}N$

For the scalar

$$\left(\frac{d\sigma_{\chi N}}{dT_\chi}\right)_{\text{scalar, CR}} = \frac{g_{Ns}^2 g_{\chi s}^2 A^2 F(q^2)\left(2m_\chi + T_\chi\right)\left(2m_N^2 + m_\chi T_\chi\right)}{8\pi T_i\left(T_i + 2m_i\right)\left(m_s^2 + 2m_\chi T_\chi\right)^2}$$

$$\frac{d\sigma_{\chi T}}{dE_T} = \frac{g_{Ns}^2 g_{\chi s}^2 A^2 F(q^2) m_T\left(2m_N^2 + E_T m_T\right)\left(E_T m_T + 2m_\chi^2\right)}{8\pi m_N^2 T_\chi\left(m_s^2 + 2E_T m_T\right)^2\left(2m_\chi + T_\chi\right)}$$

For the vector

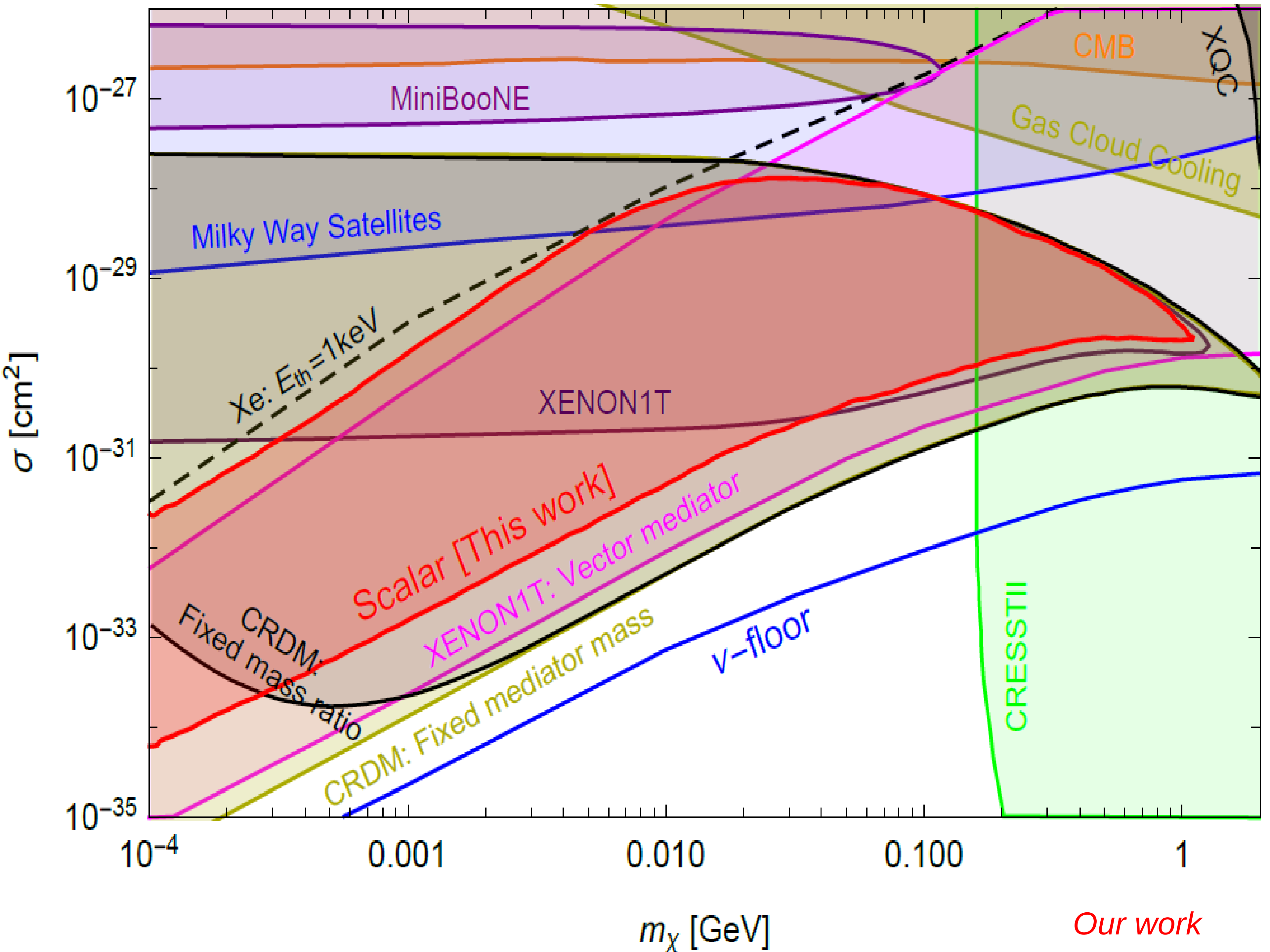
$$\left(\frac{d\sigma_{\chi N}}{dT_\chi}\right)_{\text{vector, CR}} = g_{\chi v}^2 g_{N v}^2 A^2 F^2\left(q^2\right) \frac{\left(2m_\chi\left(m_N+T_i\right)^2 - T_\chi\left(\left(m_N+m_\chi\right)^2 + 2m_\chi T_i\right) + m_\chi T_\chi^2\right)}{4\pi\left(2m_\chi T_\chi + m_v^2\right)^2\left(T_i^2 + 2m_i T_i\right)} \tag{7}$$

$$\frac{d\sigma_{\chi T}}{dE_T} = \frac{g_{\mathrm{N}v}^2 g_{\chi v}^2 m_T\left(2m_N^2\left(m_\chi+T_\chi\right)^2 - E_T\left(m_N^2\left(2\left(m_\chi+T_\chi\right)+m_T\right) + m_T m_\chi^2\right) + E_T^2 m_N^2\right)}{4\pi m_N^2 T_\chi\left(2E_T m_T + m_v^2\right)^2\left(2m_\chi + T_\chi\right)} \times A^2 F(q^2) \tag{5}$$

We calculate the mean free path of a DM particle in the integral .

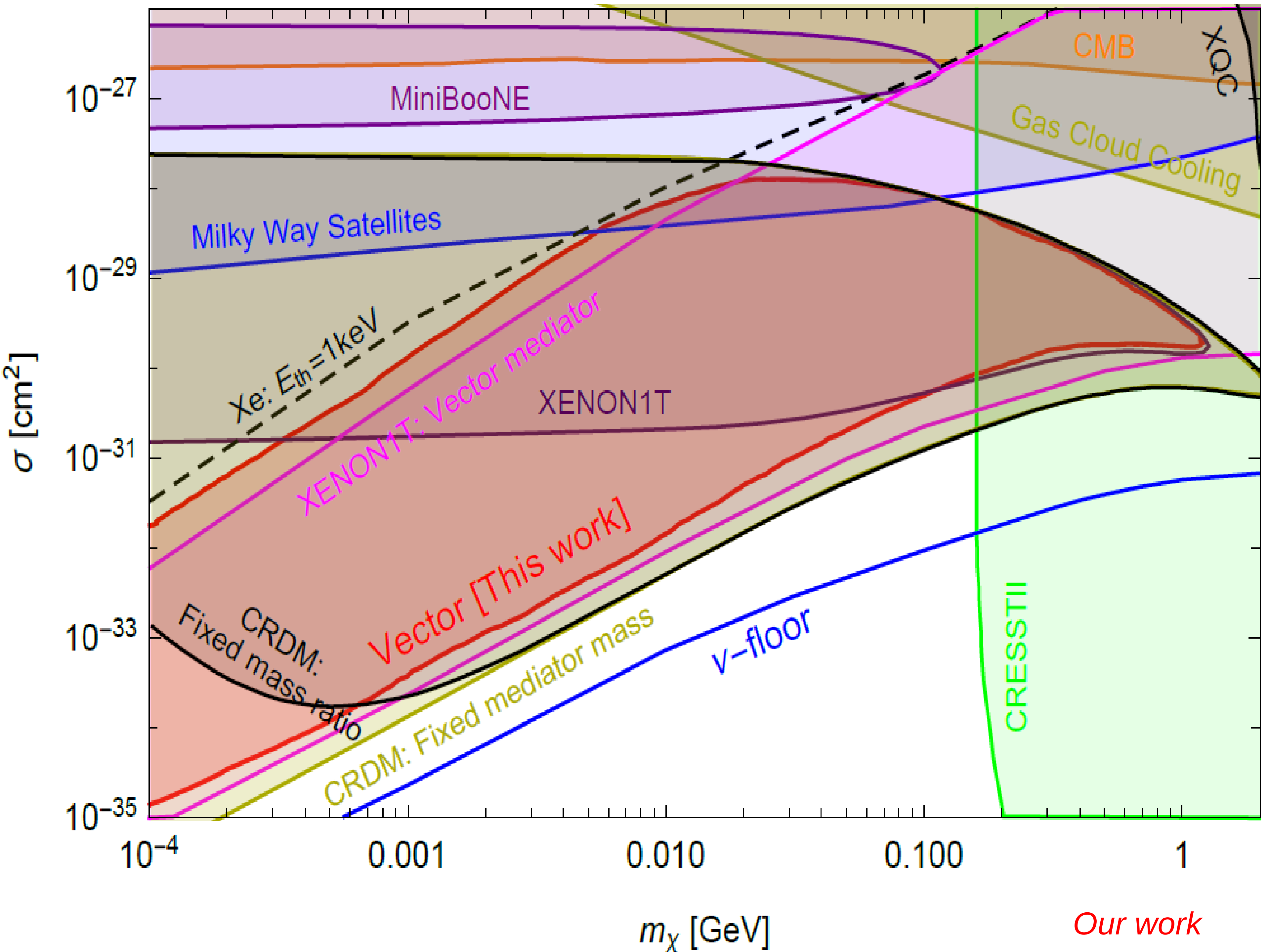
$$\frac{d\Gamma_N}{dT_N} = \sigma^0_{\chi N} G^2_N (2m_N T_N) \int_{T_\chi(T_\chi^{z,\min})}^{\infty} \frac{dT_\chi}{T^{\max}_{r,N}(T_\chi^z)} \frac{d\Phi_\chi}{dT_\chi} .$$

$$\ell^{-1} \equiv \sum_N n_N \sigma_{\chi N} \frac{2m_N m_\chi}{(m_N + m_\chi)^2}$$



CMB
XQC
MiniBooNE
Gas Cloud Cooling
Milky Way Satellites
Xe: E_{th}=1keV
XENON1T
Scalar [This work]
XENON1T: Vector mediator
CRDM: Fixed mass ratio
CRDM: Fixed mediator mass
ν−floor
CRESSTII
10^{-27}
10^{-29}
10^{-31}
10^{-33}
10^{-35}
σ [cm^2]
10^{-4}
0.001
0.010
0.100
1
m_χ [GeV]

Our work



CMB
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XENON1T
Vector [This work]
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ν−floor
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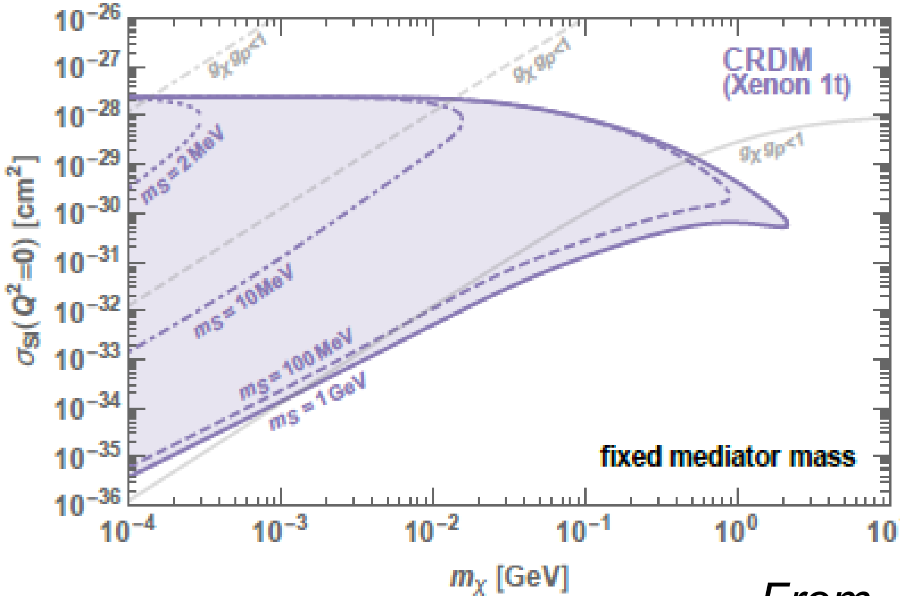
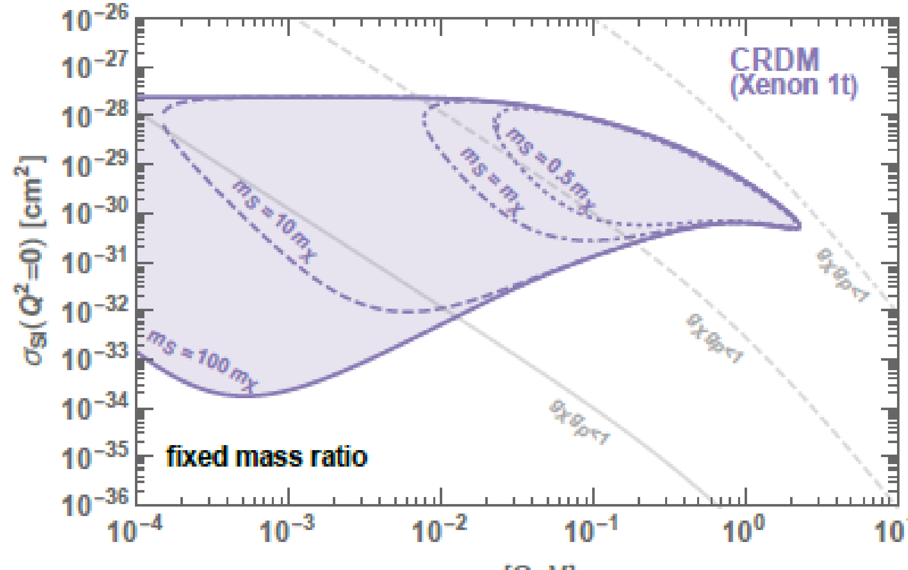
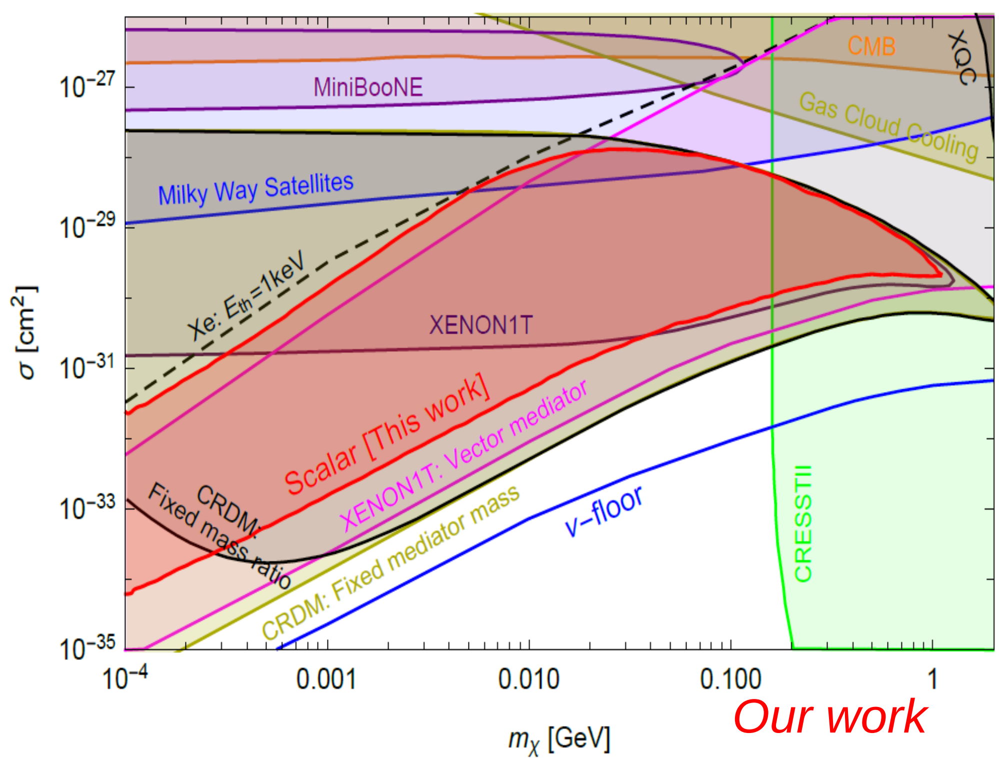
10^{-27}
10^{-29}
10^{-31}
10^{-33}
10^{-35}
σ [cm^2]
10^{-4}
0.001
0.010
0.100
1
m_χ [GeV]

Our work



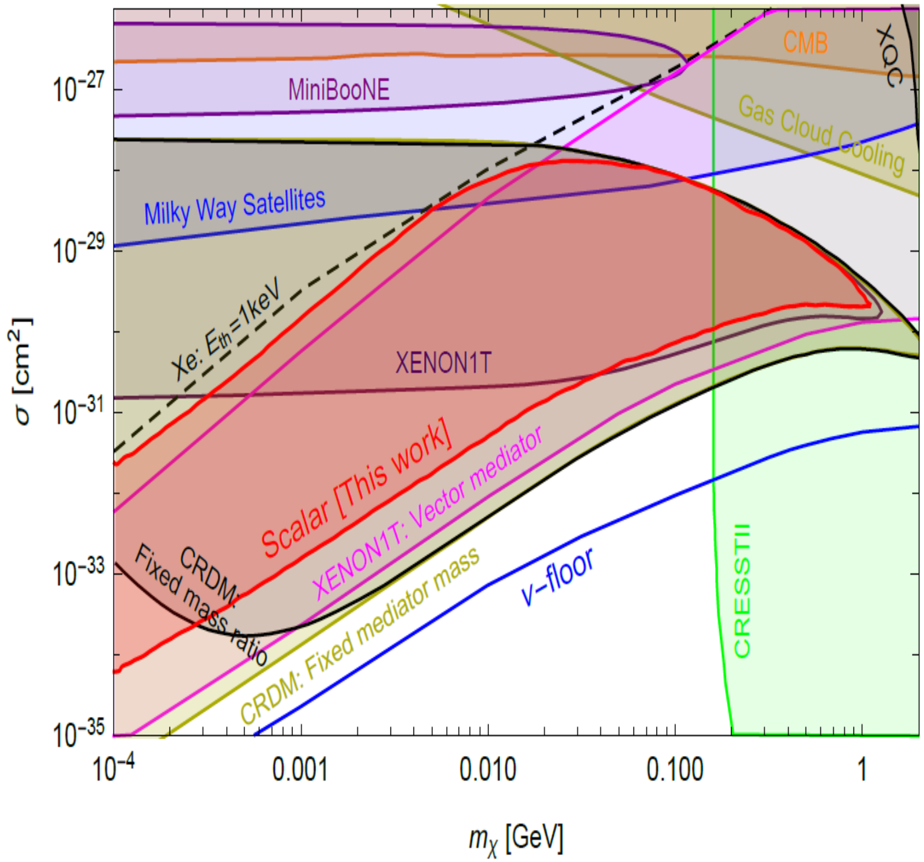


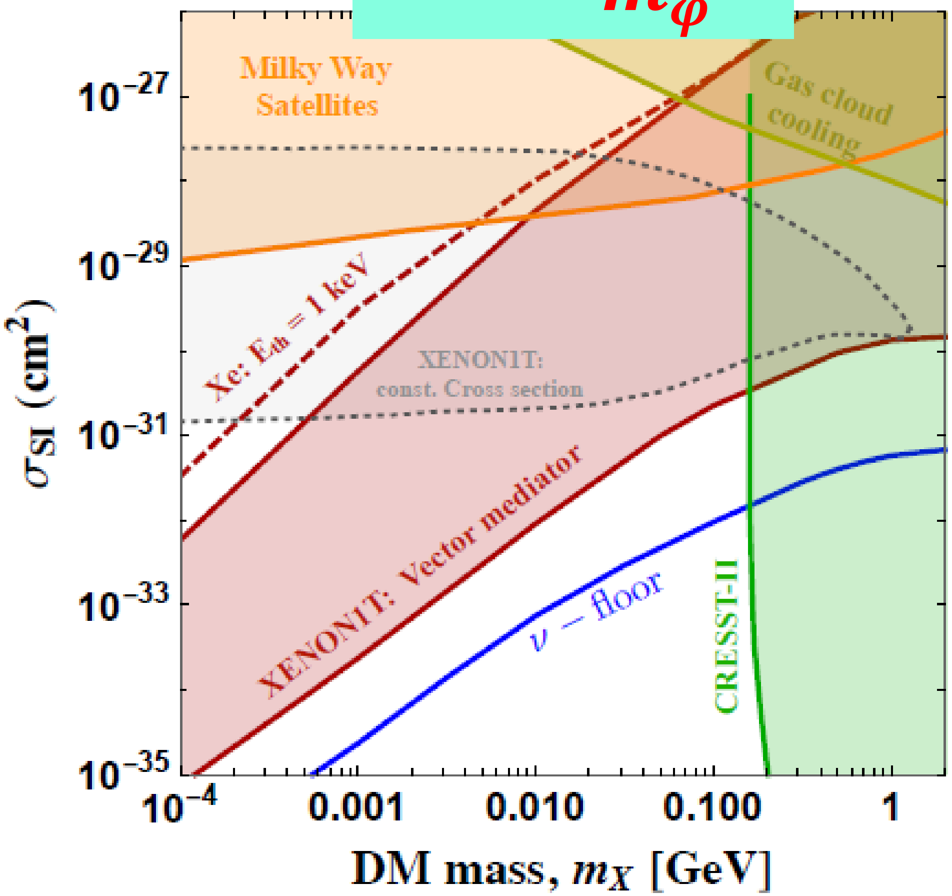
From … T. Bringmann et. al. arXiv:1909.08632



Our work

$$\sigma^{SI} = \frac{4g^4\mu^2}{m_\varphi{}^4}$$





From J. Dent et. al. arXiv:1907.03782

Note that: **Definition of the cross section is also important!**

$$\frac{d\Gamma_N}{dT_N} = \sigma^0_{\chi N} G_N^2(2m_N T_N) \int_{T_\chi(T_\chi^{z,\min})}^{\infty} \frac{dT_\chi}{T_{r,N}^{\max}(T_\chi^z)} \frac{d\Phi_\chi}{dT_\chi} .$$

$$\frac{d\Phi_\chi}{dT_\chi} = D_{\rm eff} \frac{\rho_\chi^{\rm local}}{m_\chi} \times \sum_i \sigma^0_{\chi i} G_i^2(2m_\chi T_\chi) \int_{T_i^{\min}}^{\infty} dT_i \frac{d\Phi_i^{LIS}/dT_i}{T_\chi^{\max}(T_i)}$$

The cross section in the fundamental theory is a differential form

CONCLUSION

- Space in Dark Matter less than 1GeV has rich physics
- CRDM is very good scenario for light DM
  - The attenuation is important
  - The definition of cross section is an issue

THANKS!