Bounds on Cosmic Ray-Boosted Dark Matter

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Frontiers of Physics
Outstanding Papers Awards 2019

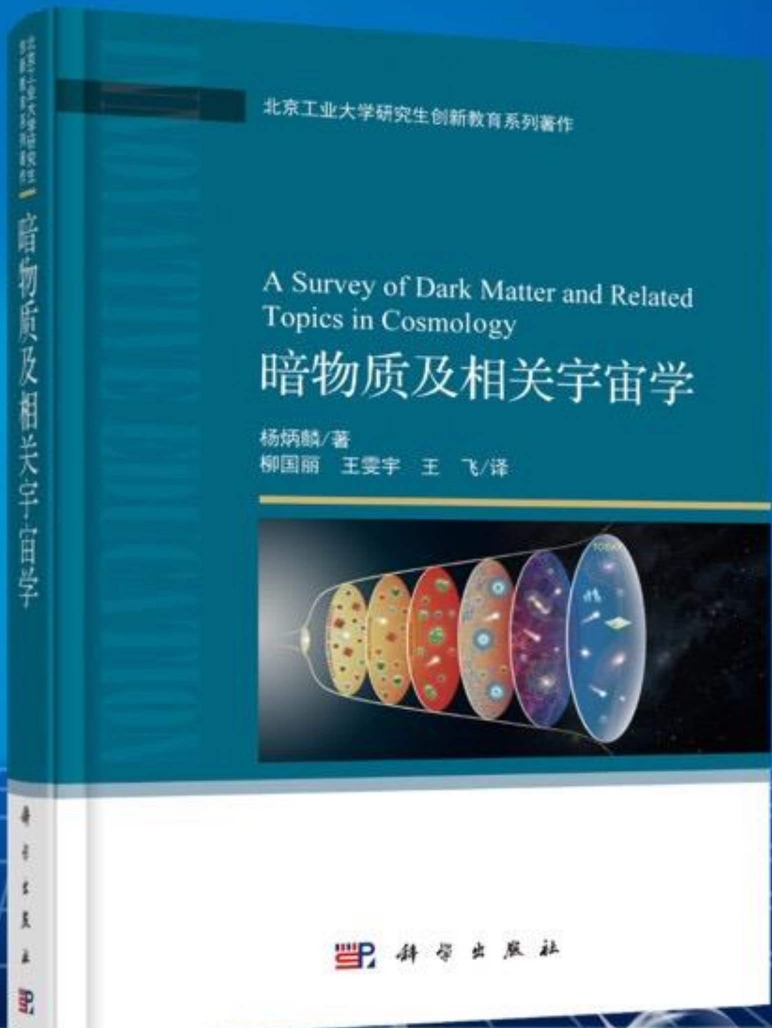
杨炳麟，爱荷华州立大学教授，国际著名理论物理学家，曾任全球华人物理学会会长。多年来关心和支持中国科技发展，为中国物理学事业的发展作出巨大贡献。

柳国丽

王雯宇

王飞

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。



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

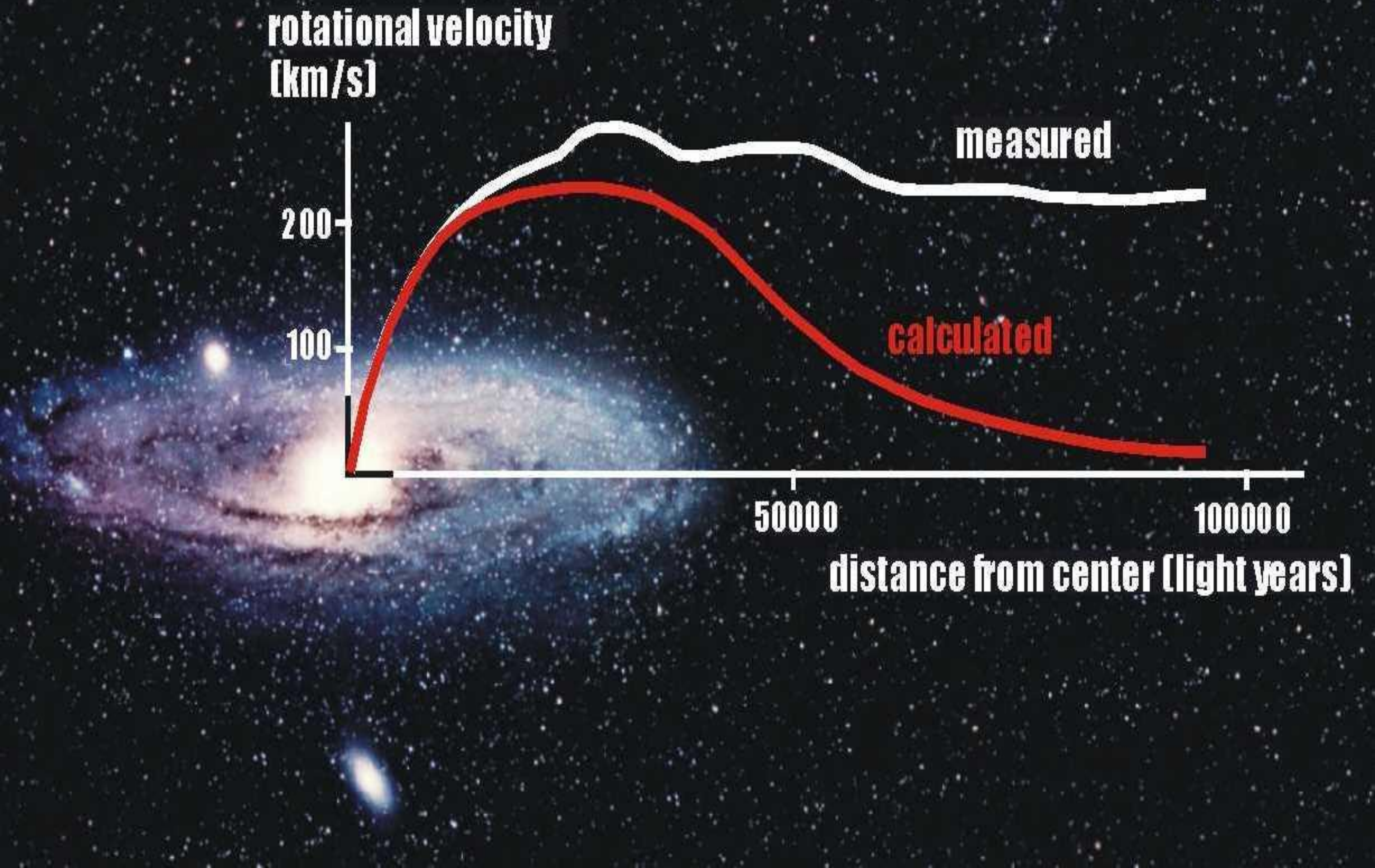
下篇：

- 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



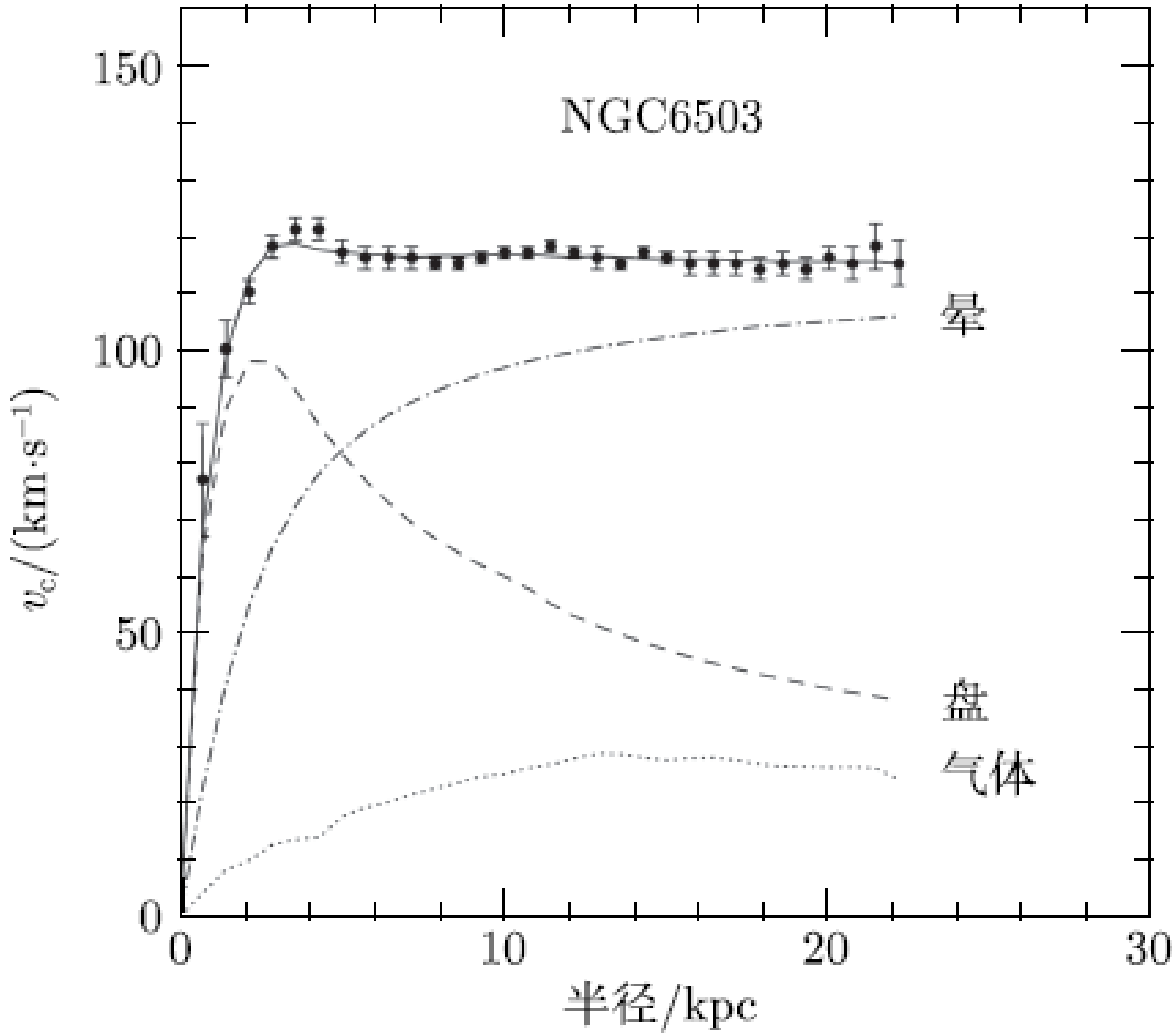
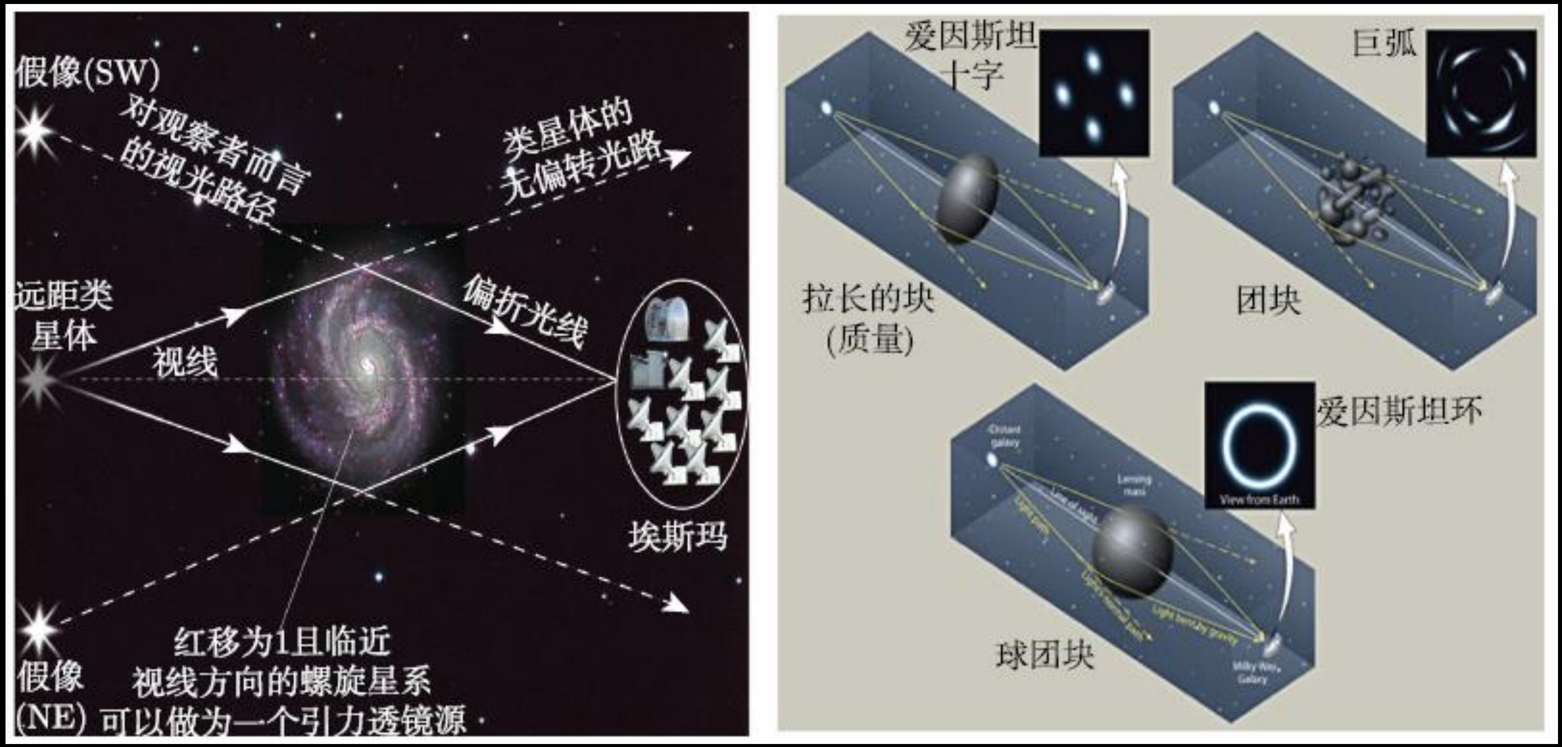


图 2.1.2　拟合总速度曲线 $v_c = \sqrt{v_{\text{晕}}^2 + v_{\text{盘}}^2 + v_{\text{气体}}^2}$

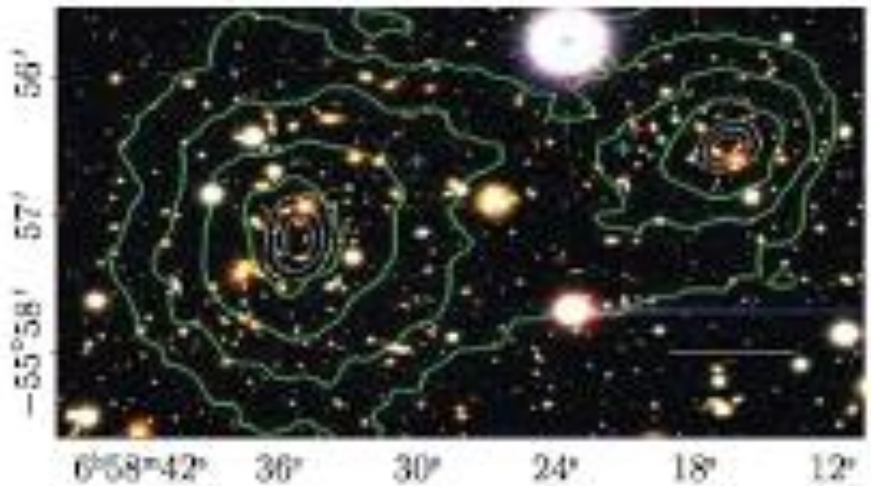
Observation methods

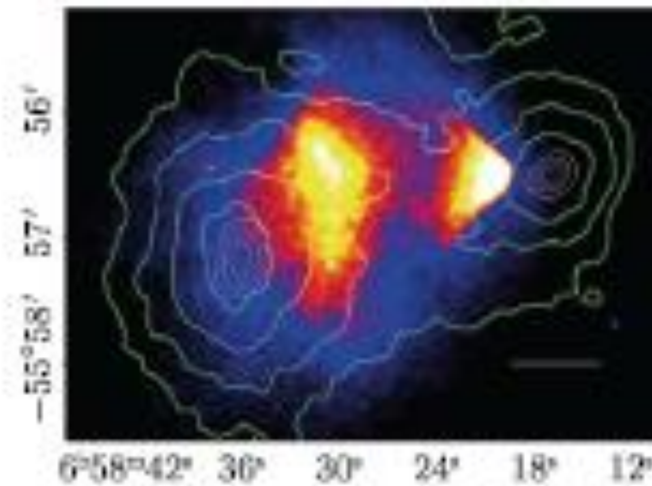
- Optics for the stars
- X-ray for the gas
- Gravitational lensing for the dark matter



图像：光学　粉色：X射线气体　蓝色：透镜质量

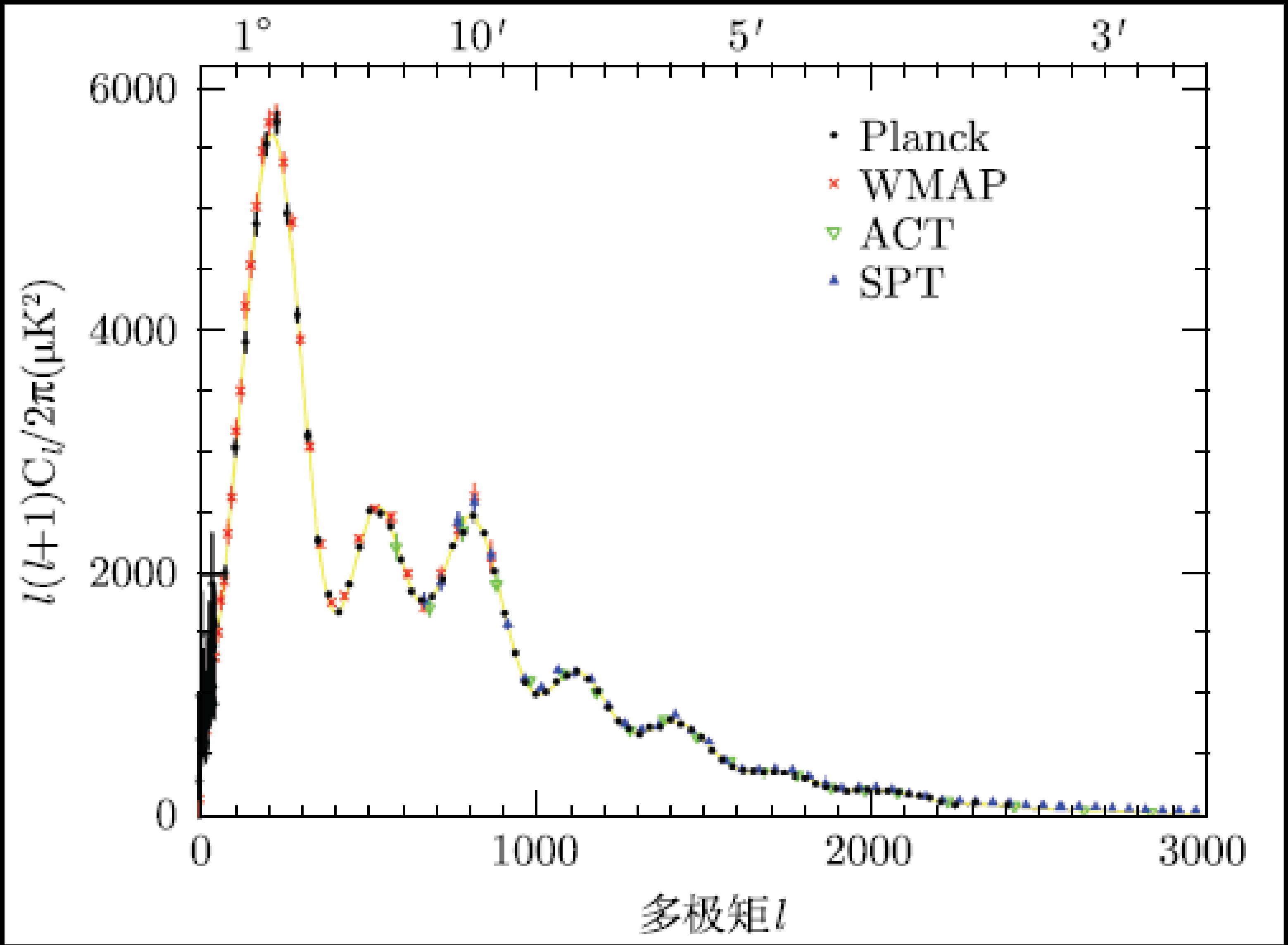
暗物质和光偏移





- 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

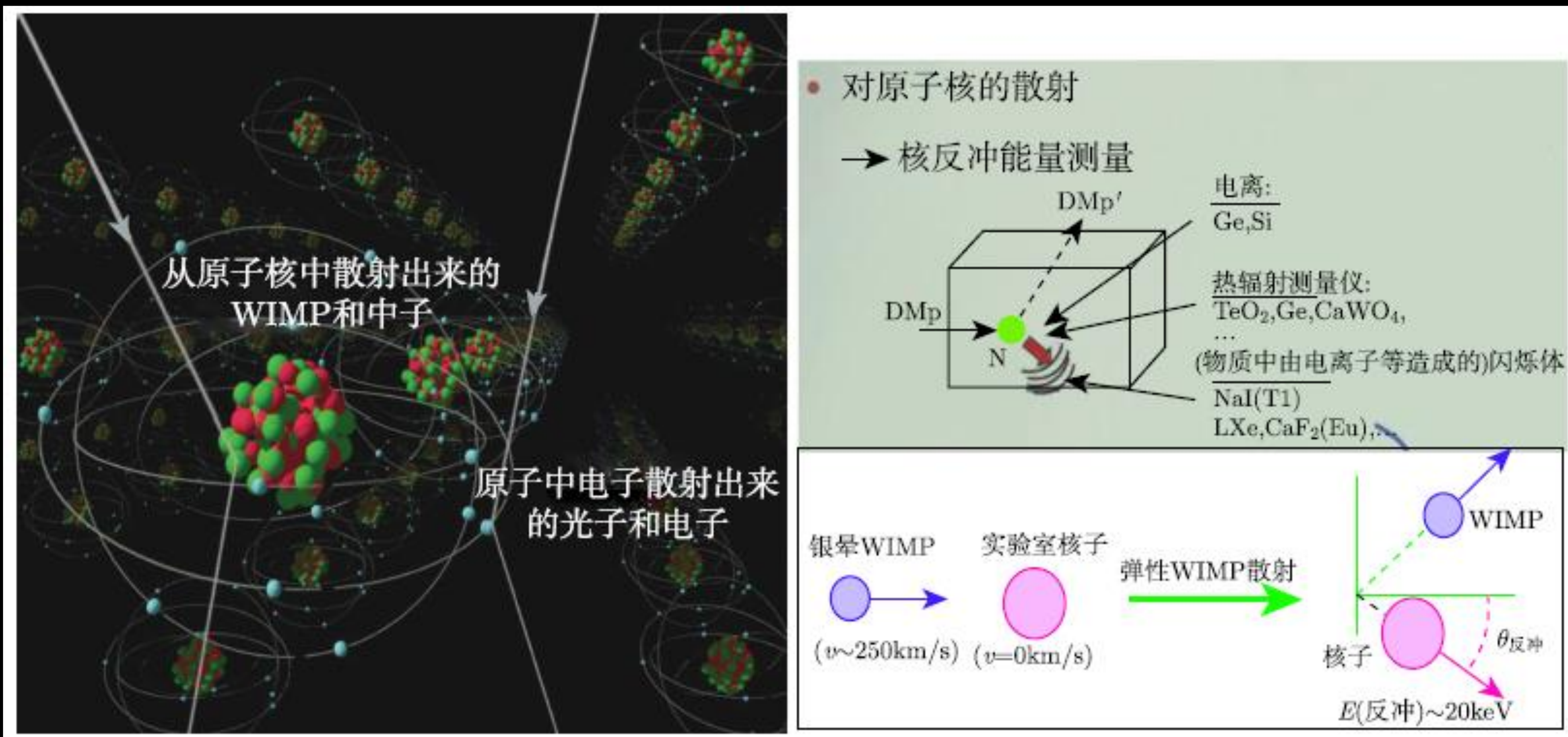
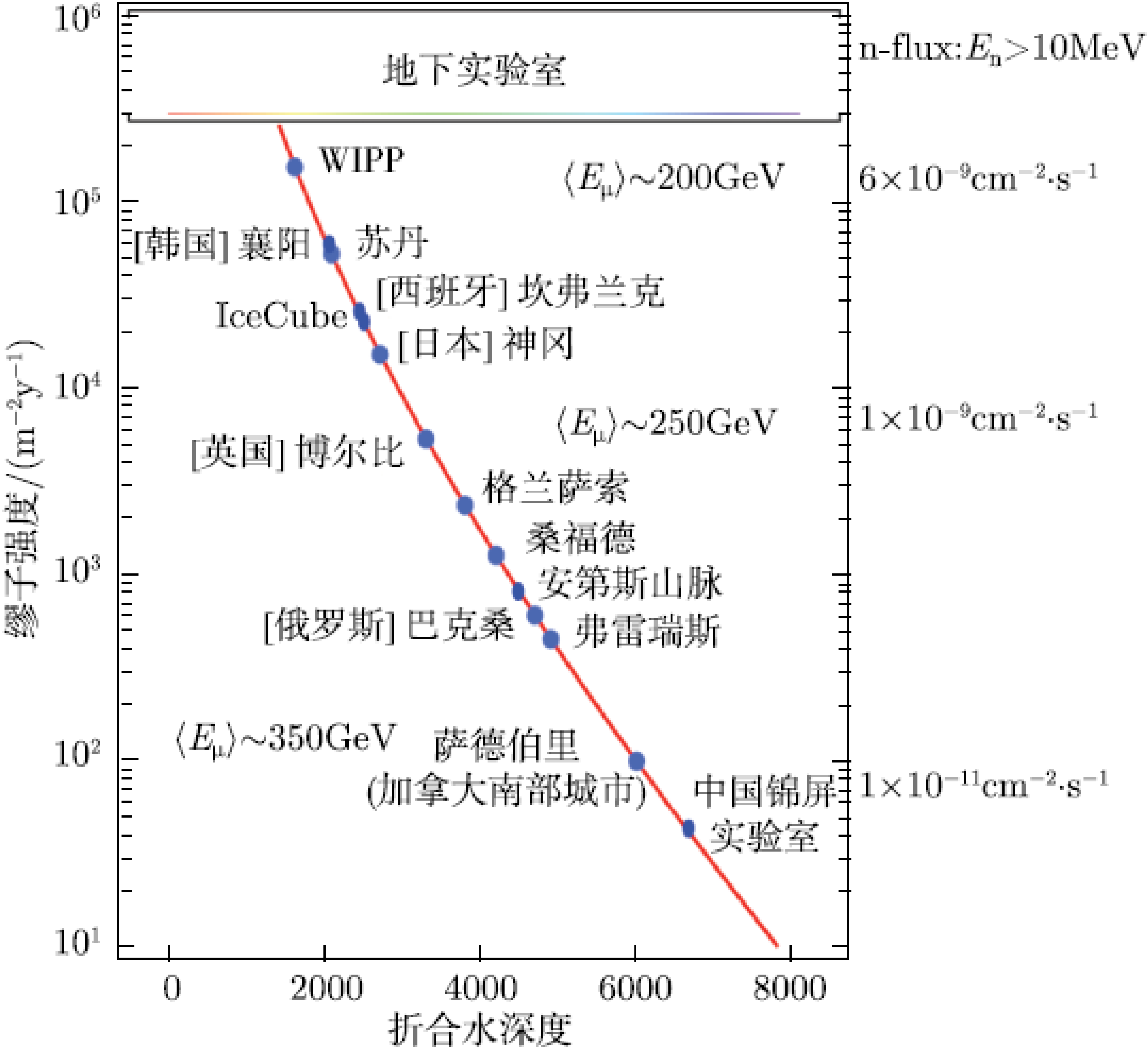
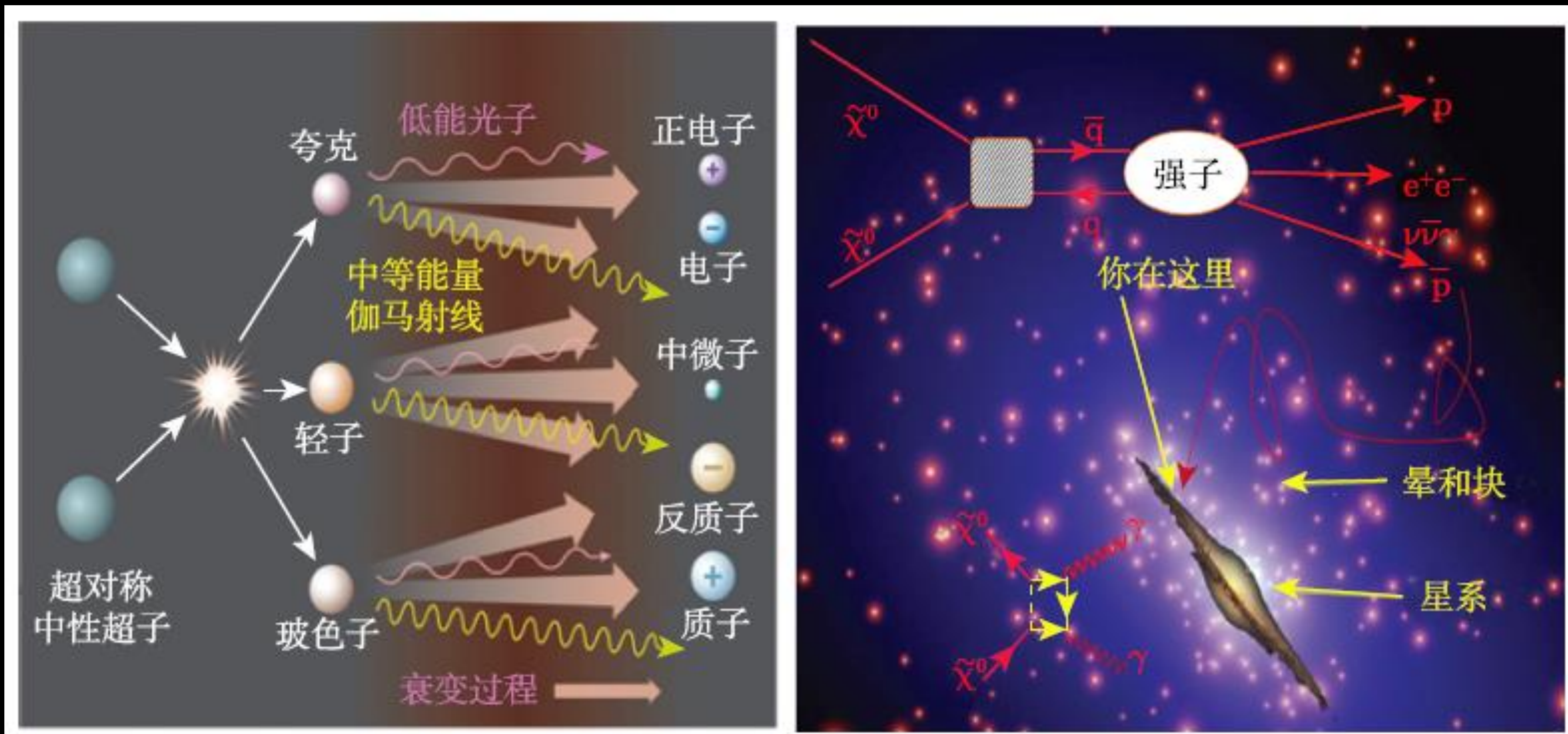


图 6.1.1　全球深地物理探测实验室的分布地图。注意 #26 ANDES 深地实验室，目前还只是一项决议，将是南半球唯一科学地下实验室

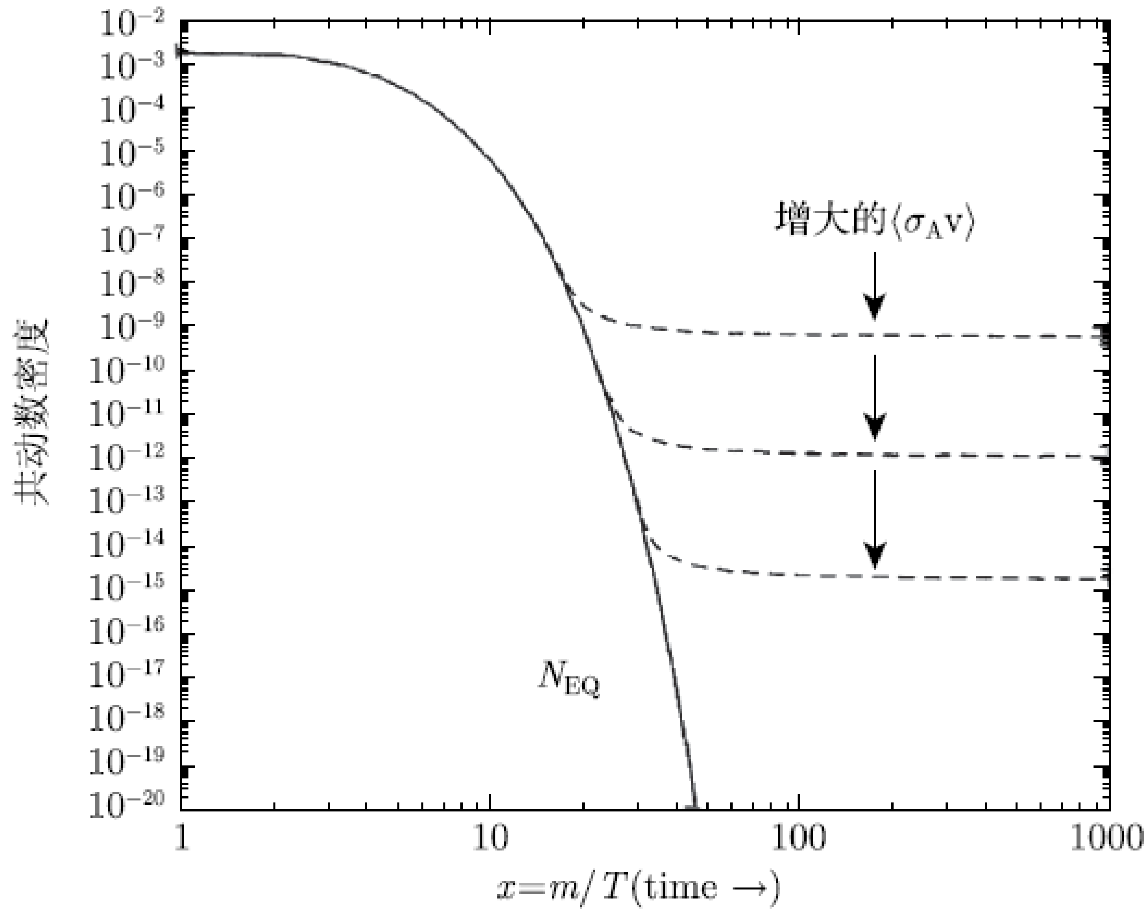


地下实验室
n-flux: E_n>10MeV
WIPP
⟨$E_μ$⟩~200GeV
6×10⁻⁹cm⁻²·s⁻¹
[韩国] 襄阳
苏丹
[西班牙] 坎弗兰克
IceCube
[日本] 神冈
⟨$E_μ$⟩~250GeV
1×10⁻⁹cm⁻²·s⁻¹
[英国] 博尔比
格兰萨索
桑福德
安第斯山脉
[俄罗斯] 巴克桑
弗雷瑞斯
⟨$E_μ$⟩~350GeV
萨德伯里
(加拿大南部城市)
中国锦屏
实验室
1×10⁻¹¹cm⁻²·s⁻¹
缪子强度/(m⁻²y⁻¹)
折合水深度

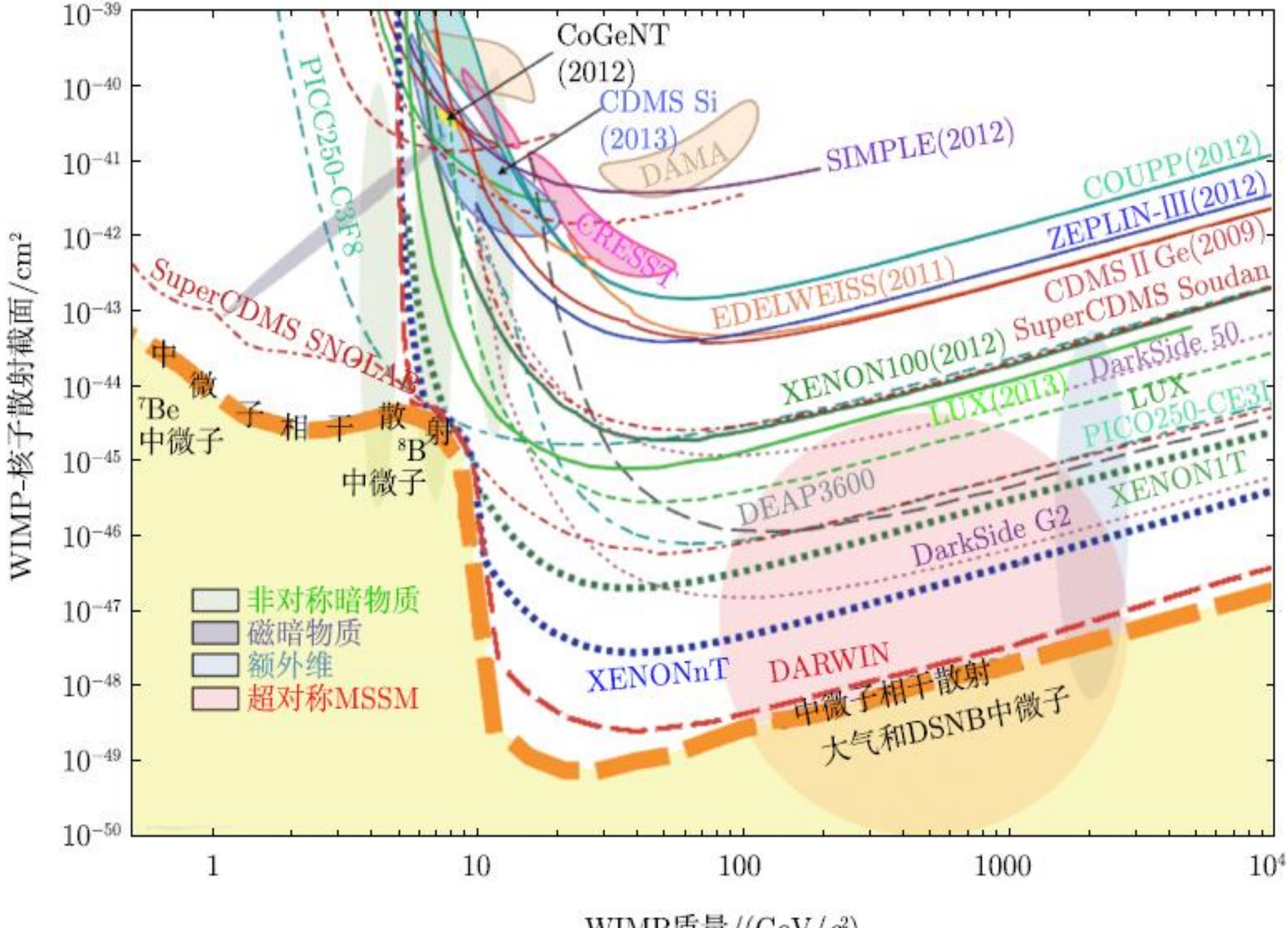
Indirect detection



WIMP miracle



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

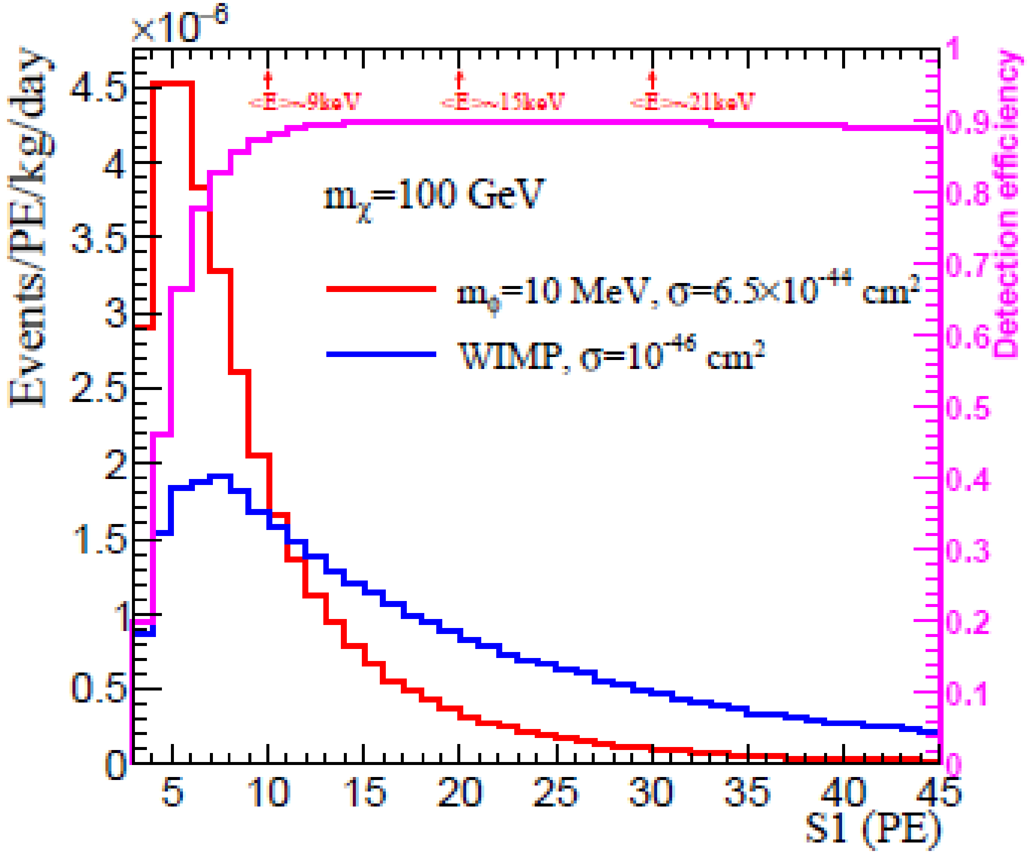


CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE(2012)
COUPP(2012)
ZEPLIN-III(2012)
CDMS II Ge(2009)
CRESST
EDELWEISS(2011)
SuperCDMS Soudan
PICC250-C3F8
SuperCDMS SNOLAB
XENON100(2012)
DarkSide 50
LUX(2013)
LUX
PICO250-CF3I
XENON1T
DEAP3600
DarkSide G2
XENONnT
DARWIN
中微子相干散射
大气和DSNB中微子
^{7}Be 中微子
^{8}B 中微子
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

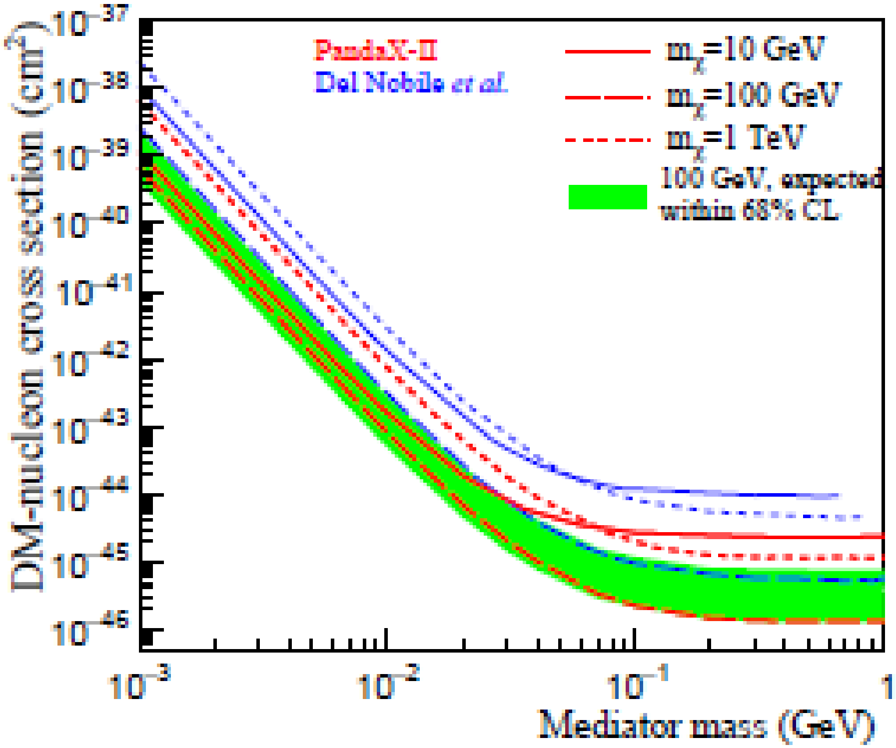
Reasons of the less sensitivity

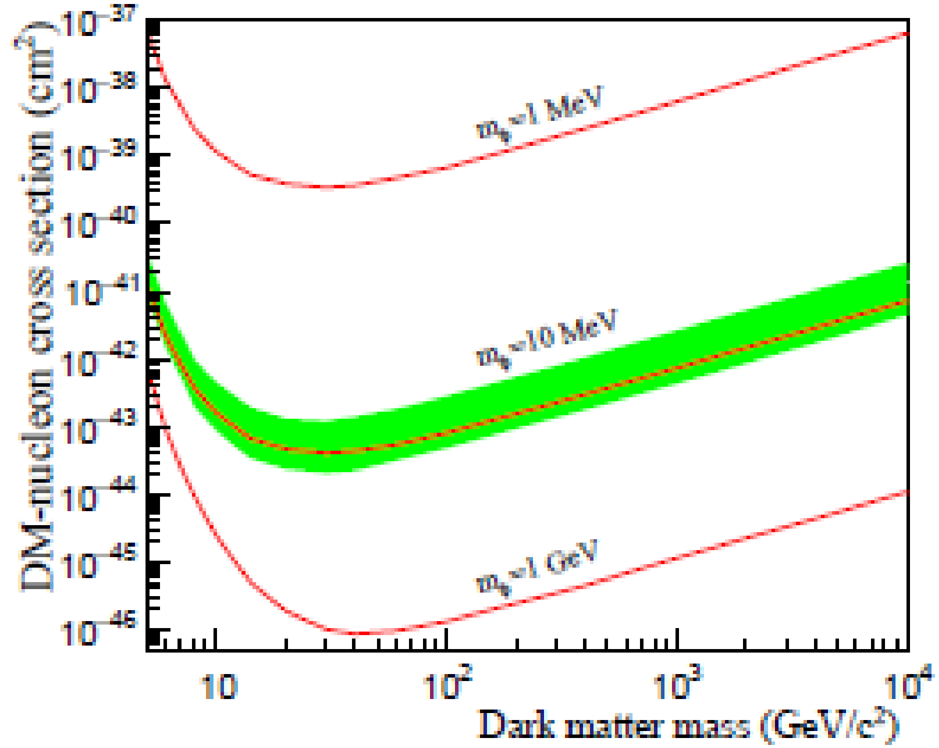


From PANDAX group arXiv:1802.06912

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

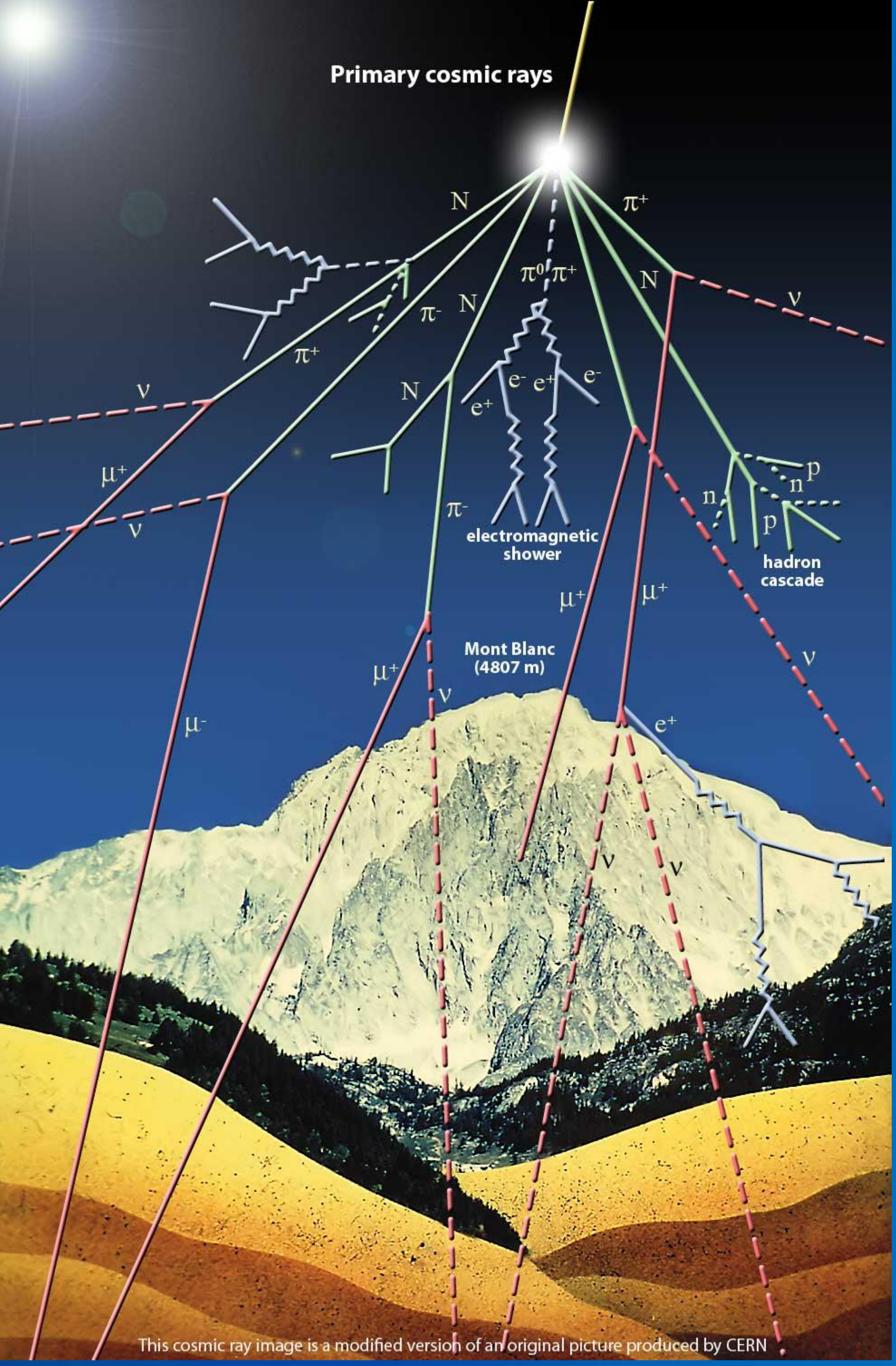
PANDAX constraints on light Mediator





From PANDAX group arXiv:1802.06912

A short introduction to Cosmic Rays



1000个粒子/平米/秒

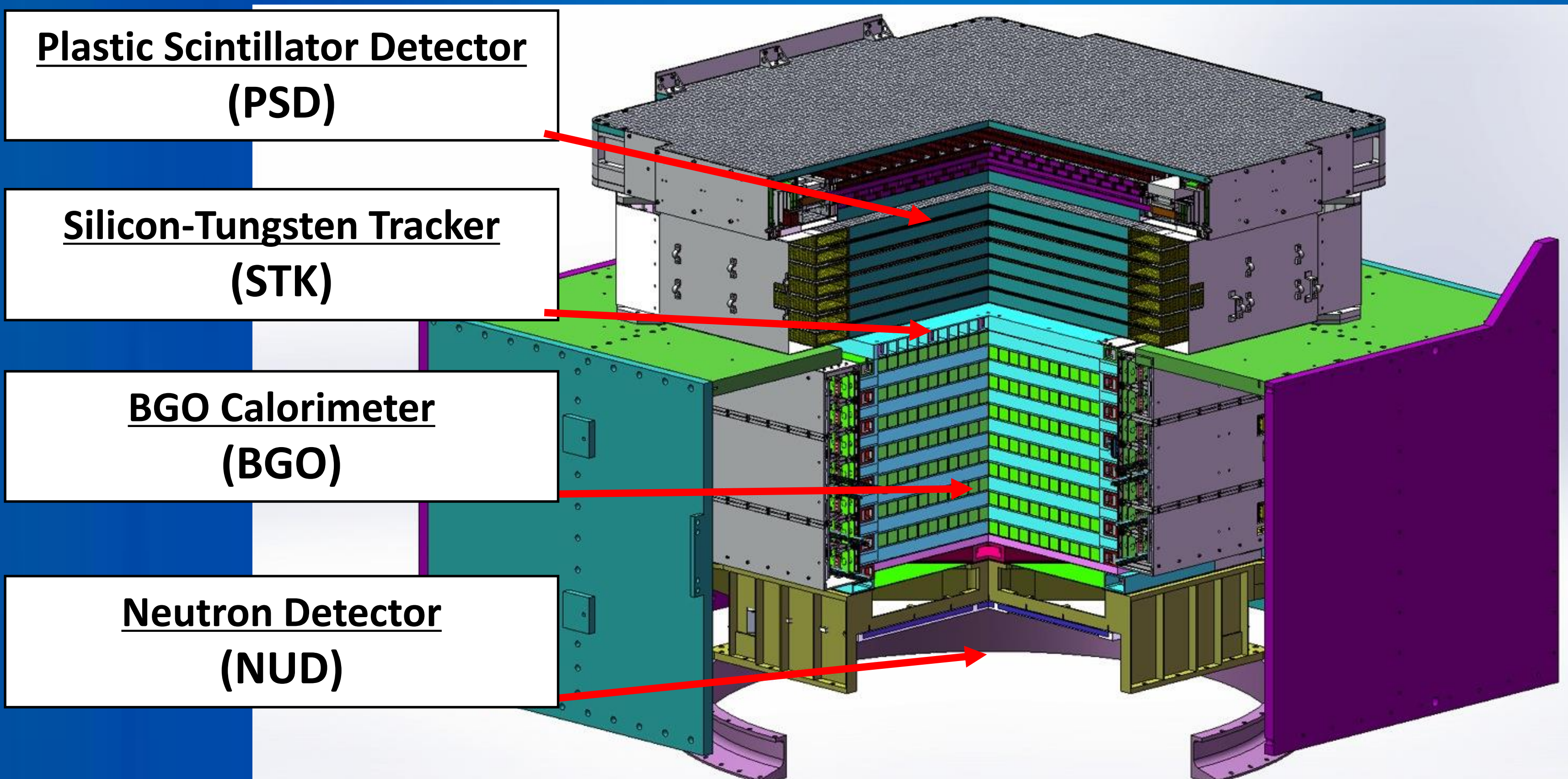
90% 质子
9% α粒子
其它是重核

最高可达10^{20}eV

Where？ How？

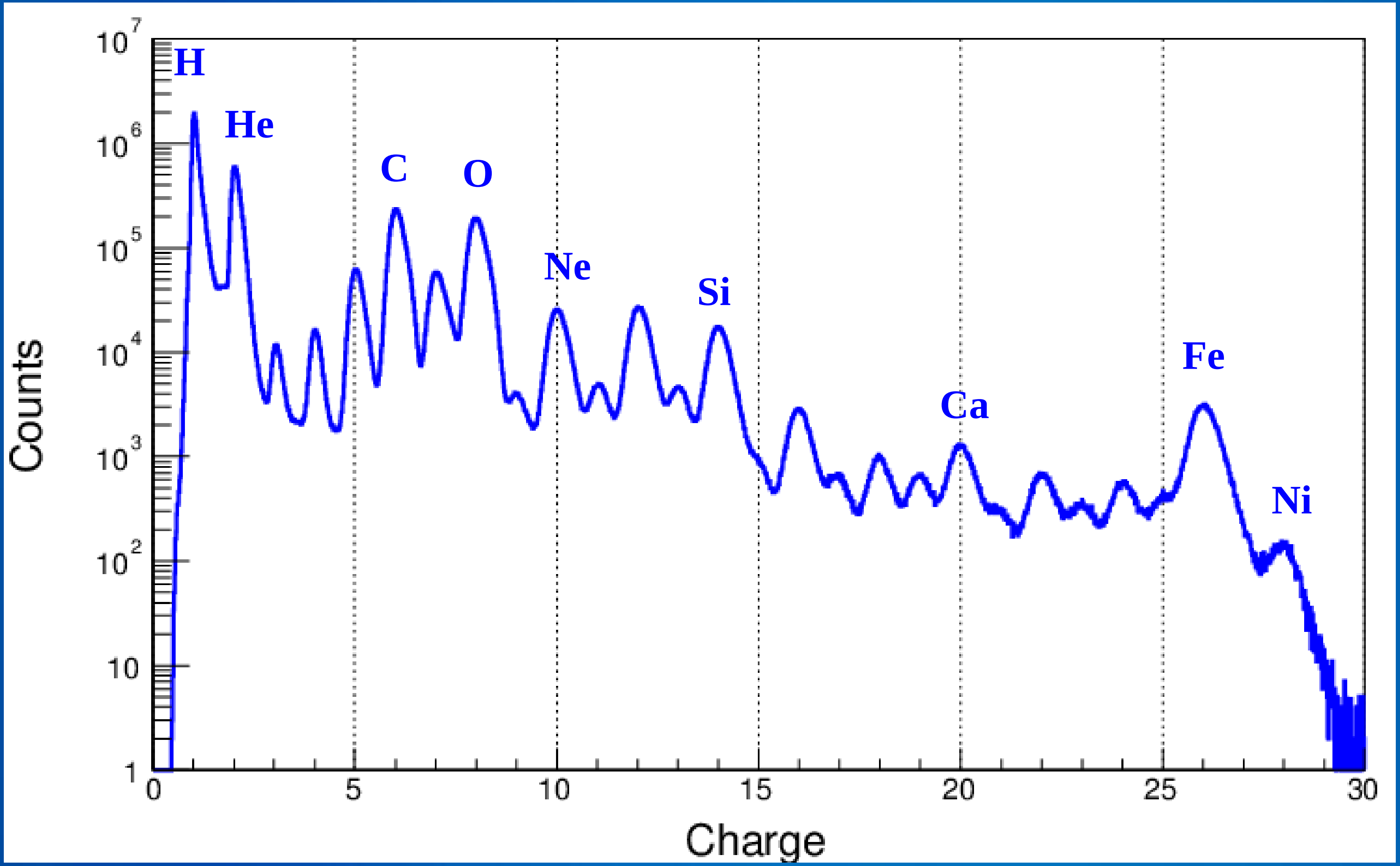
探测手段：云室

手段2:



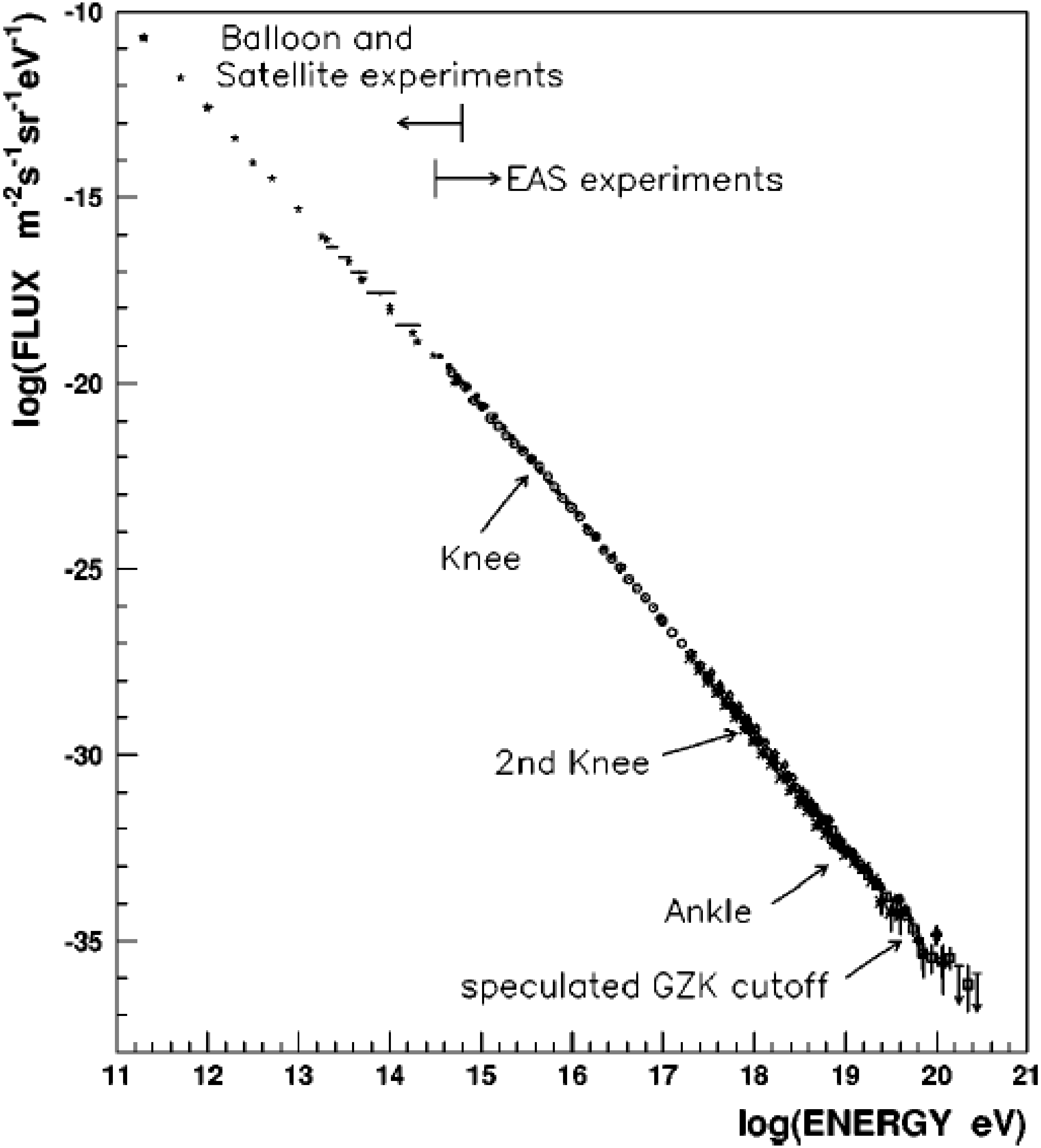
- Charge measurement (dE/dx in PSD, STK and BGO)
- Pair production and tracking (STK and BGO)
- Precise energy measurement (BGO bars)
- Hadron rejection (BGO and neutron detector)

On-orbit performance: Charge measurement

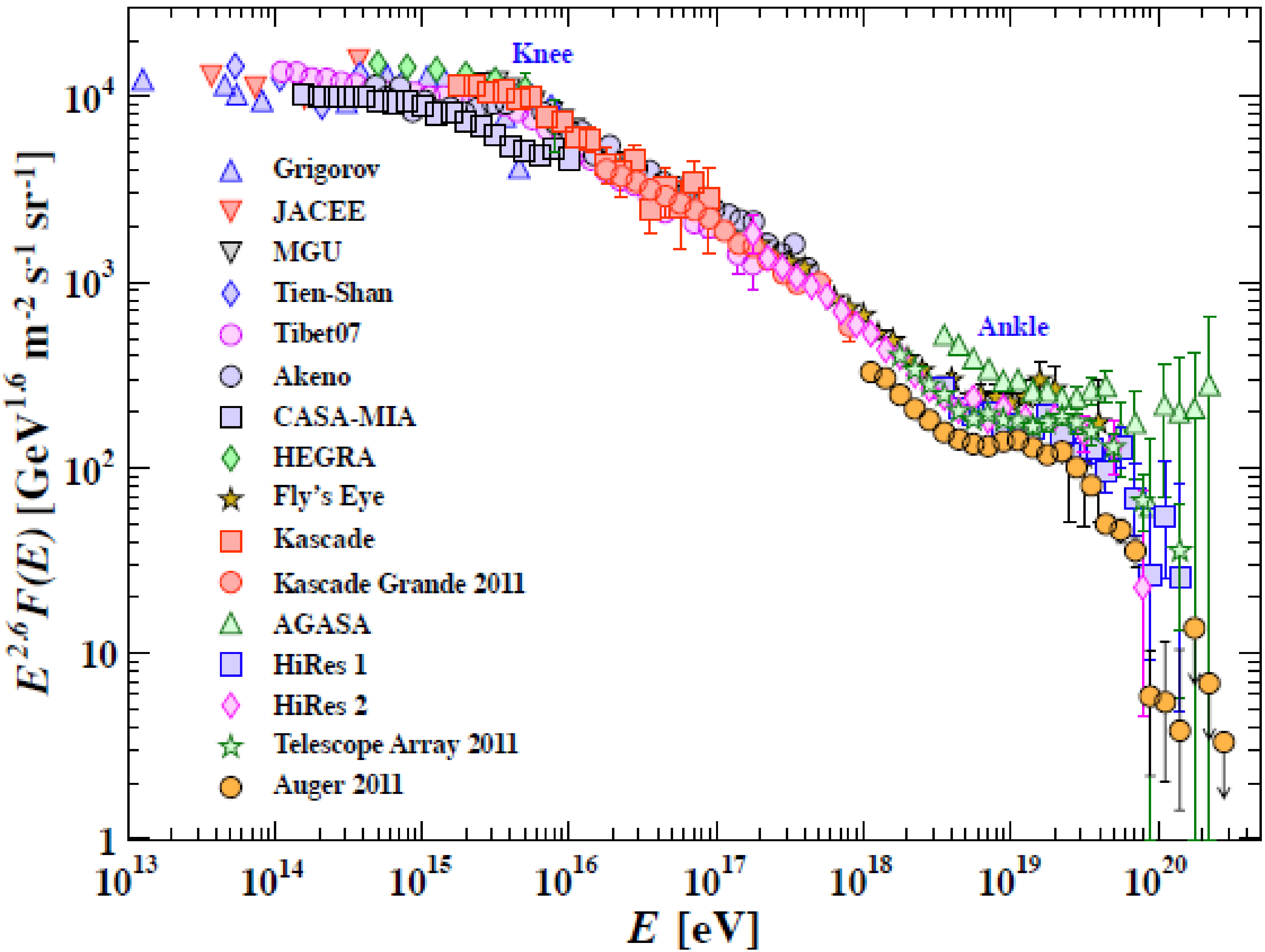


For protons and Irons, the charge resolutions are 0.13e and 0.32e, respectively.

幂律谱

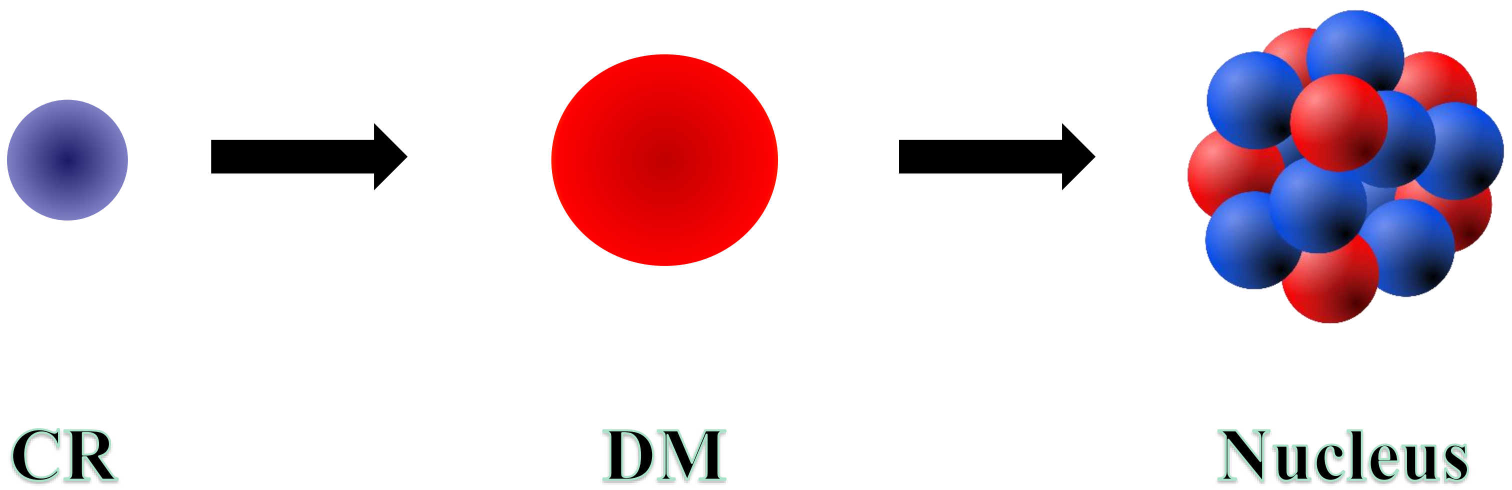


Balloon and
Satellite experiments
EAS experiments
Knee
2nd Knee
Ankle
speculated GZK cutoff
log(FLUX m-2s-1sr-1eV-1)
-10
-15
-20
-25
-30
-35
11
12
13
14
15
16
17
18
19
20
21
log(ENERGY eV)



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}]
10^4
10^3
10^2
10
1
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
E [eV]

Story of CRDM



From CR to DM flux

After a single collision by the CR

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

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

Density of DM

Flux of CRs

$$\frac{d^2\Gamma_{\mathrm{CR_i}\to\chi}}{dT_i dT_\chi} = \frac{\rho_\chi}{m_\chi}\frac{d\sigma_{\chi i}}{dT_\chi}\frac{d\Phi_i^{\mathrm{LIS}}}{dT_i}dV,$$

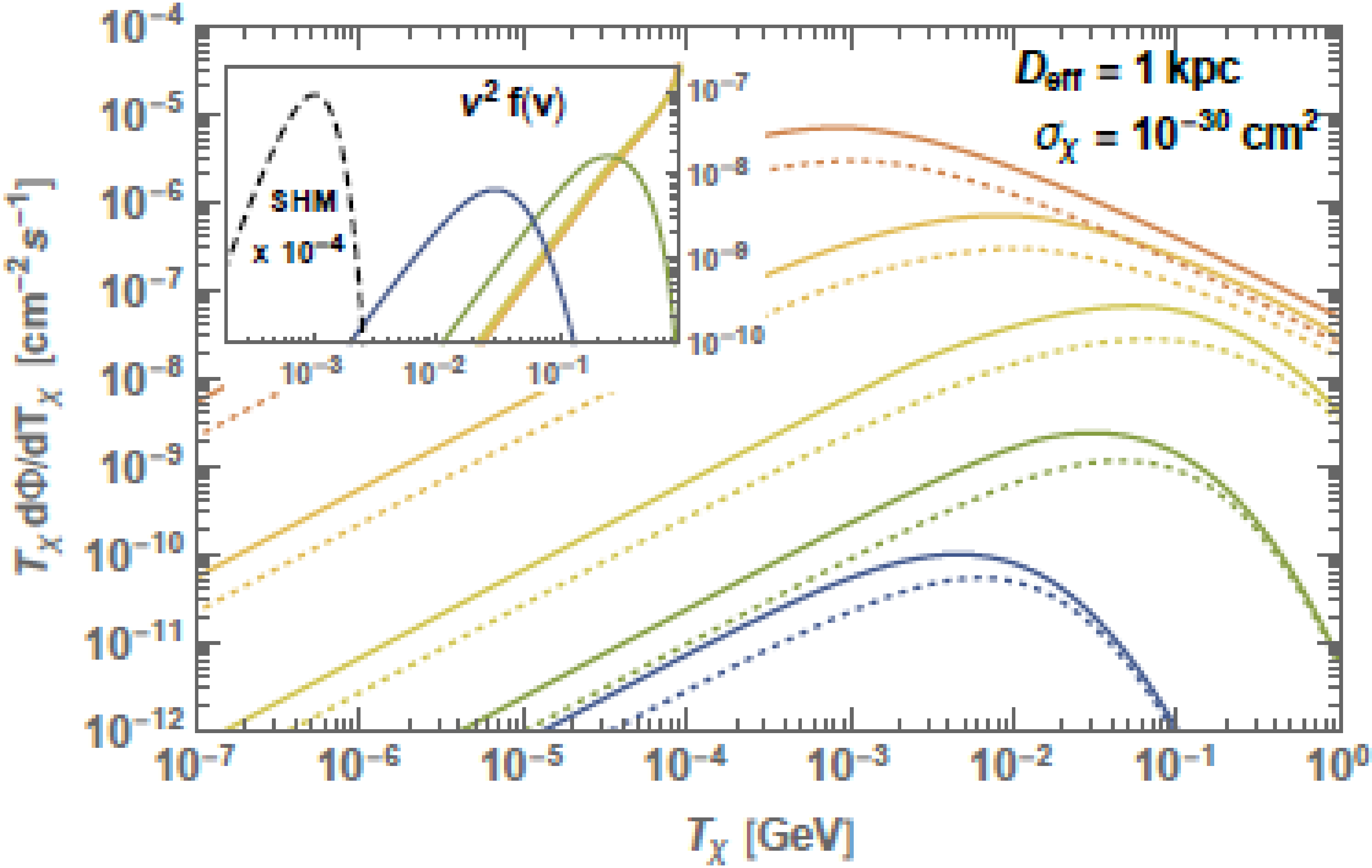
Cross section between DM and CR

The CR induced DM flux

$$\frac{d\Phi_\chi}{dT_\chi} = \int_\Omega \frac{d\Omega}{4\pi d^2}\int_{T_i^{\mathrm{min}}} dT_i \frac{d^2\Gamma_{\mathrm{CR}_i\to\chi}}{dT_i dT_\chi} = D_{\mathrm{eff}}\frac{\rho_\chi}{m_\chi}\sum_i \int_{T_i^{\mathrm{min}}} dT_i \frac{d\sigma_{\chi i}}{dT_\chi}\frac{d\Phi_i^{\mathrm{LIS}}}{dT_i}.$$

Integration in the sight

Effective scattering length



From T. Bringmann et. al.   arXiv:1810.10543

Attenuation of CRDM flux

DM flux at the depth *z*

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

in which

Cross section between DM and dense matter on earth

$$\ell^{-1} \equiv \sum_N n_N \int_0^{T_\chi^{\max}} dT_\chi \frac{d\sigma_{\chi N}}{dT_\chi}$$

is the mean free path of a DM particle.

CRDM scattering in detectors

Cross section between DM and dense matter in detector

$$R = \int_{T_1}^{T_2} dE_T \frac{1}{m_{\rm T}} \int_{T_\chi^{z,\rm min}}^{\infty} dT_\chi^z \frac{d\Phi_\chi}{dT_\chi^z} \frac{d\sigma_{\chi T}}{dE_T}.$$

Recoil Energy of Target

Comparison with the WIMP scattering

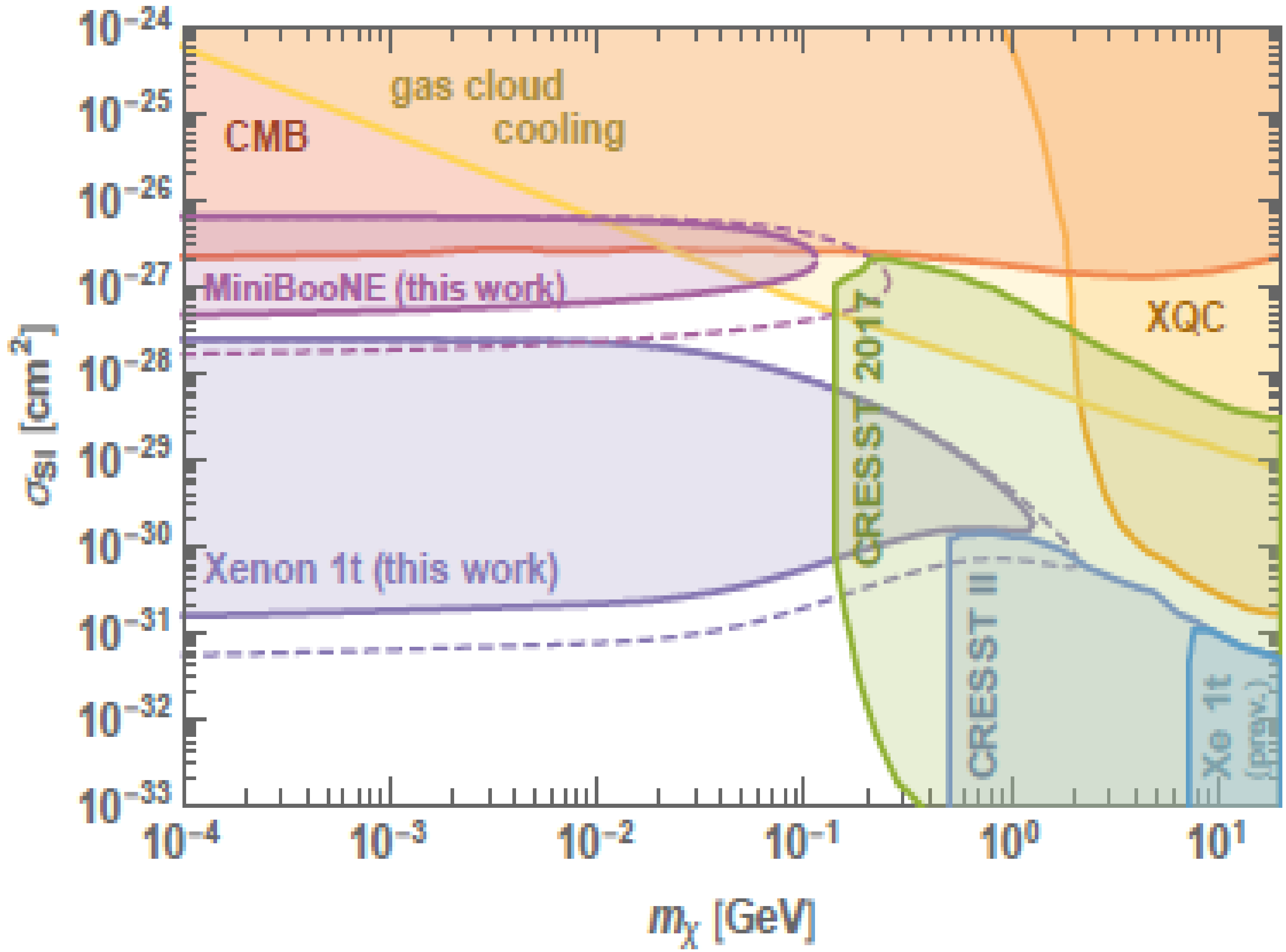
$$\Gamma_N^{\rm DM} = \int_{T_1}^{T_2} dT_N \, \sigma_{\chi N}^{\rm DM} \int_0^\infty dT_{\rm DM} \frac{d\Phi_{\rm DM}}{dT_{\rm DM}} \frac{\Theta\left[T_N^{\rm max}(T_{\rm DM}) - T_N\right]}{T_N^{\rm max}(T_{\rm DM})}$$

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

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

Tensor: $-\frac{c^{\mathrm{SM}}}{\Lambda}\mathcal{G}^{\mu\nu}T^{\mathrm{SM}}_{\mu\nu} - \frac{c^{\mathrm{DM}}}{\Lambda}\mathcal{G}^{\mu\nu}T^{\mathrm{DM}}_{\mu\nu}$

Energy scale

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

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

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

For the tensor

$$\frac{d\sigma_{\chi i}}{dT_\chi}=\frac{A^2c_{\rm DM}^2c_{\rm SM}^2F\left(q^2\right)m_\chi^3\left(6T_im_N+3T_i^2+2m_N^2\right)^2}{18\pi\Lambda^4T_i\left(m_G^2+2m_\chi T_\chi\right)^2\left(T_i+2m_N\right)}$$
$$-\frac{A^2c_{\rm DM}^2c_{\rm SM}^2F\left(q^2\right)m_\chi^2T_\chi\left(6m_N^3\left(3T_i+4m_\chi\right)+m_N^2\left(96T_im_\chi+9T_i^2+8m_\chi^2\right)+18T_im_Nm_\chi\left(6T_i+m_\chi\right)+9T_i^2m_\chi\left(4T_i+m_\chi\right)+8m_N^4\right)}{36\pi\Lambda^4T_i\left(m_G^2+2m_\chi T_\chi\right)^2\left(T_i+2m_N\right)}$$
$$+\frac{A^2c_{\rm DM}^2c_{\rm SM}^2F\left(q^2\right)m_\chi^2T_\chi^2\left(2m_N^2\left(36T_i+89m_\chi\right)+18m_Nm_\chi\left(21T_i+4m_\chi\right)+9T_im_\chi\left(21T_i+8m_\chi\right)+72m_N^3\right)}{288\pi\Lambda^4T_i\left(m_G^2+2m_\chi T_\chi\right)^2\left(T_i+2m_N\right)}$$
$$-\frac{A^2c_{\rm DM}^2c_{\rm SM}^2F\left(q^2\right)m_\chi^2T_\chi^3\left(m_\chi\left(10T_i+3m_\chi-T_\chi\right)+10m_Nm_\chi+3m_N^2\right)}{64\pi\Lambda^4T_i\left(m_G^2+2m_\chi T_\chi\right)^2\left(T_i+2m_N\right)} \tag{5.9}$$

$$\frac{d\sigma_{\chi T}}{dE_T}=\frac{c_{\rm DM}^2c_{\rm SM}^2m_T\left(9{\rm ET}^4\left(-4m_N^2m_T^2+5m_N^4+m_T^4\right)+64m_N^4\left(6m_\chi T_\chi+2m_\chi^2+3T_\chi^2\right)^2\right)}{1152\pi\Lambda^4m_N^2T_\chi\left(2m_\chi+T_\chi\right)\left(2{\rm ET}m_T+m_G^2\right)^2}$$
$$+\frac{{\rm ET}^3c_{\rm DM}^2c_{\rm SM}^2m_T\left(-2m_N^4\left(9\left(m_\chi+T_\chi\right)+2m_T\right)+m_N^2m_T\left(8m_T\left(m_\chi+T_\chi\right)+m_T^2-4m_\chi^2\right)+m_T^3m_\chi^2\right)}{64\pi\Lambda^4m_N^2T_\chi\left(2m_\chi+T_\chi\right)\left(2{\rm ET}m_T+m_G^2\right)^2}$$
$$-\frac{{\rm ET}c_{\rm DM}^2c_{\rm SM}^2m_T\left(m_N^2\left(m_T\left(2m_\chi+3T_\chi\right)\left(4m_\chi+3T_\chi\right)+12\left(m_\chi+T_\chi\right)\left(6m_\chi T_\chi+2m_\chi^2+3T_\chi^2\right)\right)+m_Tm_\chi^2\left(2m_\chi+3T_\chi\right)\left(4m_\chi+3T_\chi\right)\right)}{36\pi\Lambda^4T_\chi\left(2m_\chi+T_\chi\right)\left(2{\rm ET}m_T+m_G^2\right)^2}$$
$$\frac{{\rm ET}^2c_{\rm DM}^2c_{\rm SM}^2m_T\left(3m_N^2\left(150m_\chi T_\chi+24m_T\left(m_\chi+T_\chi\right)+67m_\chi^2+75T_\chi^2\right)+m_T\left(72m_\chi^2\left(m_\chi+T_\chi\right)-m_T\left(72m_\chi T_\chi+23m_\chi^2+36T_\chi^2\right)\right)\right)}{288\pi\Lambda^4T_\chi\left(2m_\chi+T_\chi\right)\left(2{\rm ET}m_T+m_G^2\right)^2} \tag{5.10}$$

Flux of CRDM

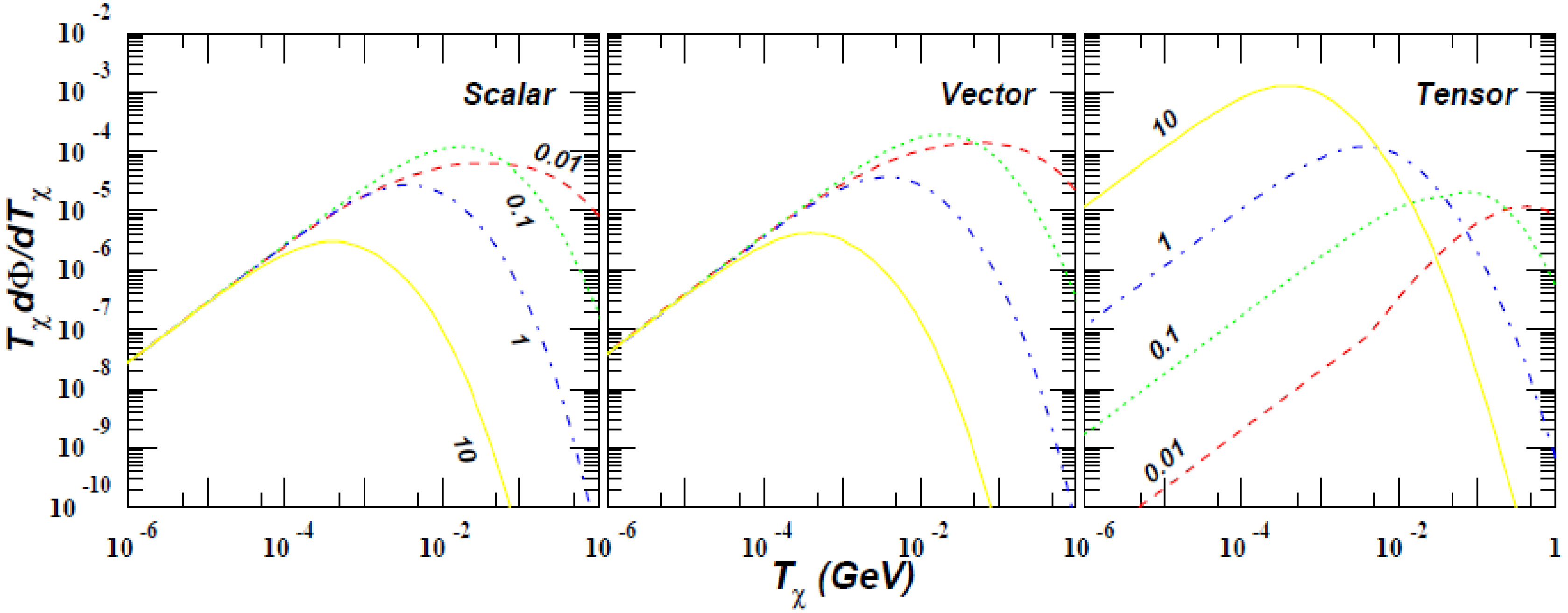


Figure 1. The expected flux of CRDM in simlfied models with different mediators which mass are set at 0.1 GeV and the couplings are set at 1. Masses of the dark matter are shown on the corresponding curve in the figure in GeV unit. The cut scale of tensor mediator $\Lambda = 1\text{GeV}$.

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

$$R = \int_{T_1}^{T_2} dE_T \frac{1}{m_{\rm T}} \int_{T_\chi^{z,\rm min}}^{\infty} dT_\chi^z \frac{d\Phi_\chi}{dT_\chi^z} \frac{d\sigma_{\chi T}}{dE_T}.$$

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

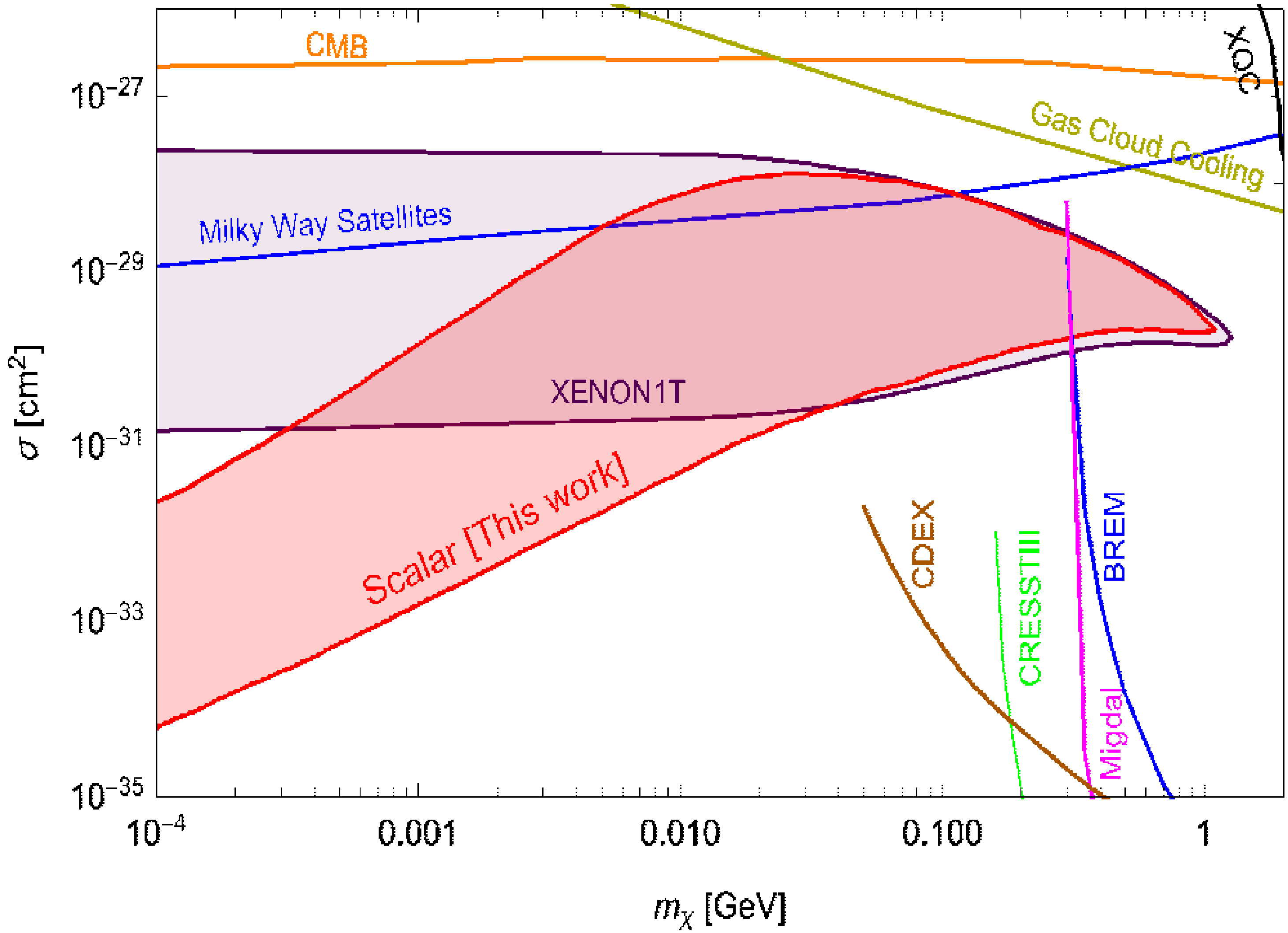
Three cross sections

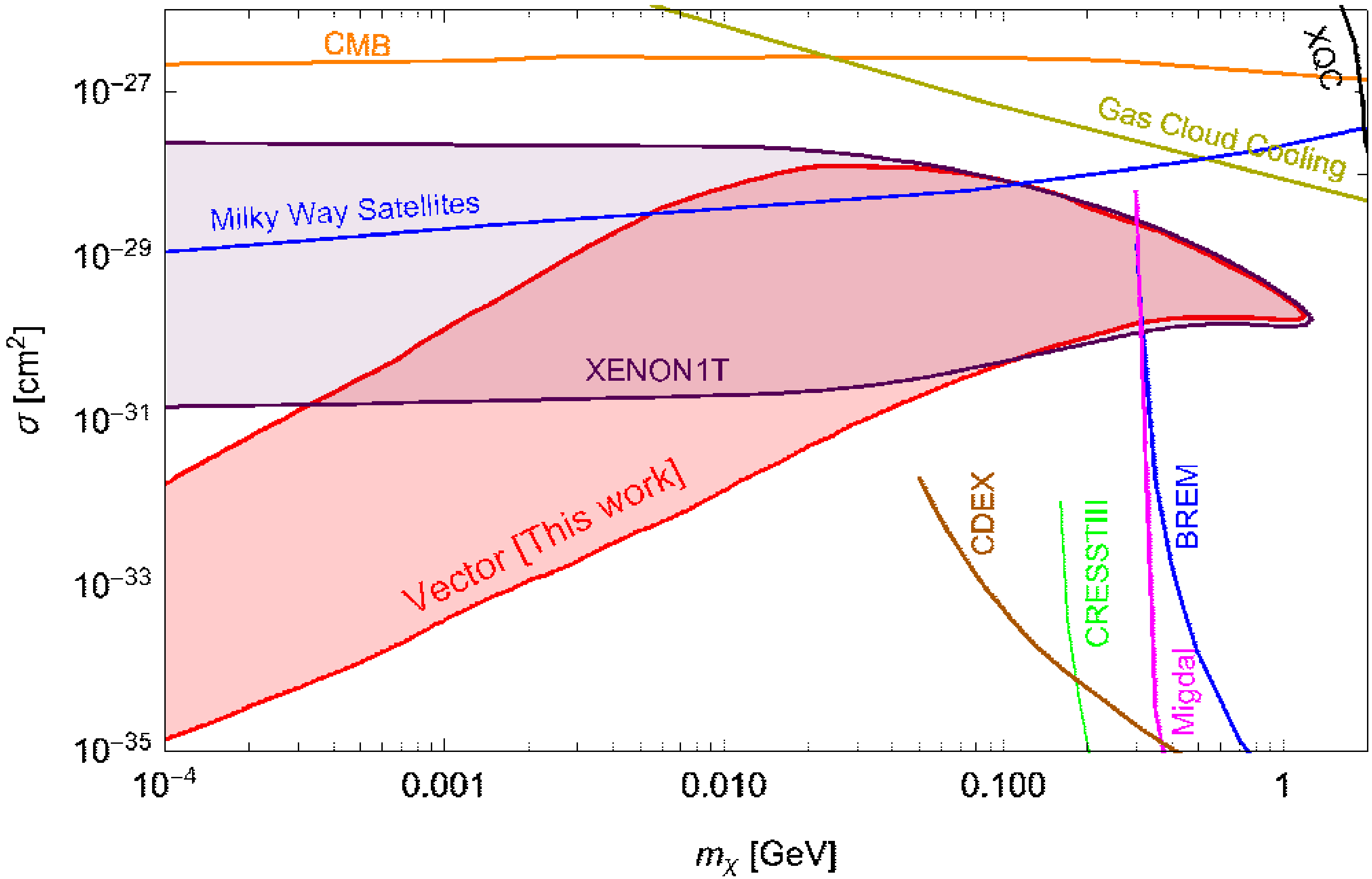
1. Differential cross section between DM and CRs
2. Differential cross section between DM and dense matter on earth
3. Differential cross section between DM and matters in the detector

Our definition of the cross section

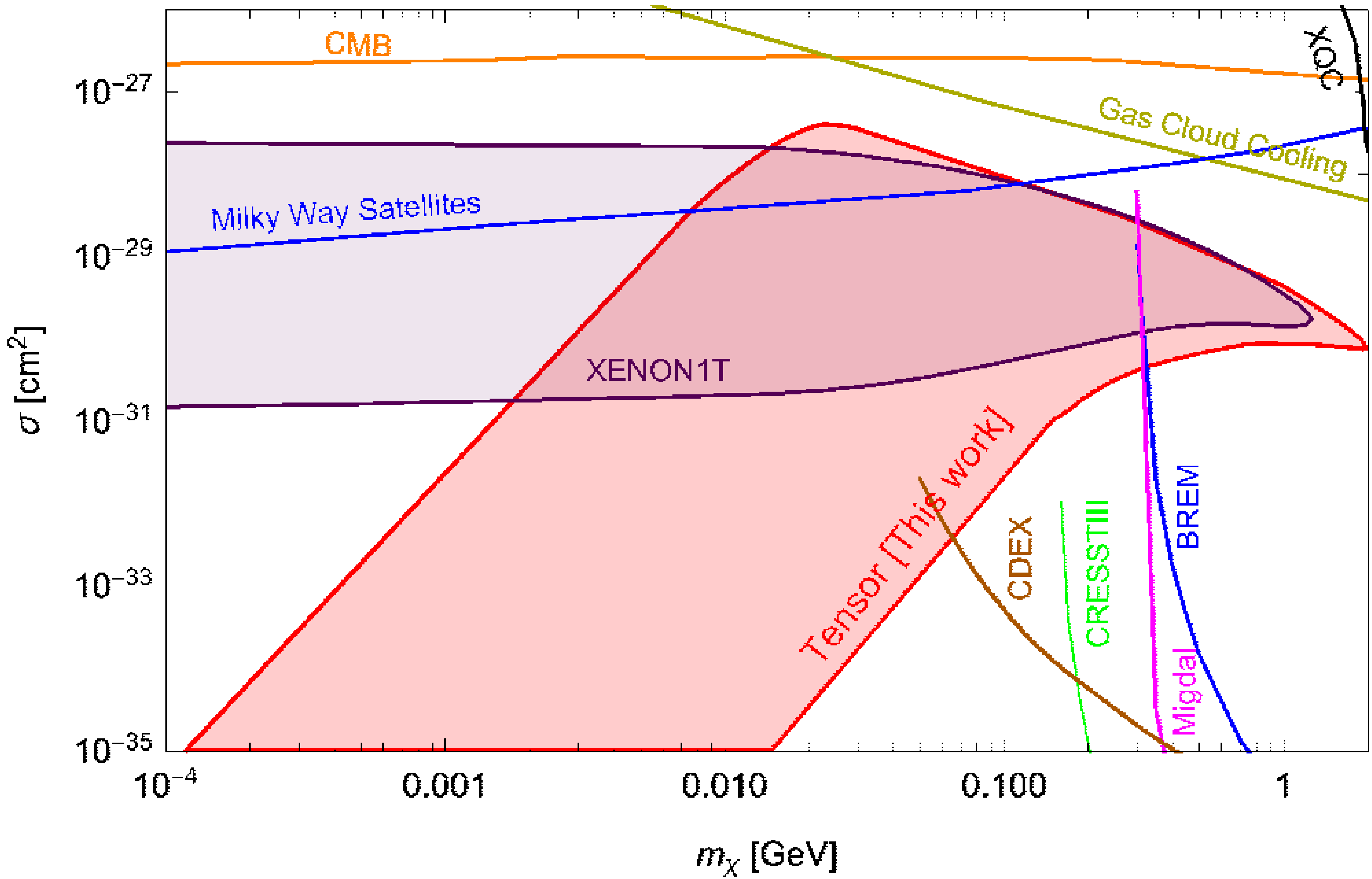
$$\sigma^{\rm Def} \equiv \int_0^{T_\chi^{\rm max}} dT_\chi \frac{d\sigma_{\chi N}}{dT_\chi}$$

Implication of the cross section





CMB
XQC
Gas Cloud Cooling
Milky Way Satellites
XENON1T
Vector [This work]
CDEX
CRESSTIII
BREM
Migdal
σ [cm^2]
m_χ [GeV]
10^{-27}
10^{-29}
10^{-31}
10^{-33}
10^{-35}
10^{-4}
0.001
0.010
0.100
1



CMB
XQC
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XENON1T
Tensor [This work]
CDEX
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Migdal
10^{-27}
10^{-29}
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σ [cm^2]
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0.001
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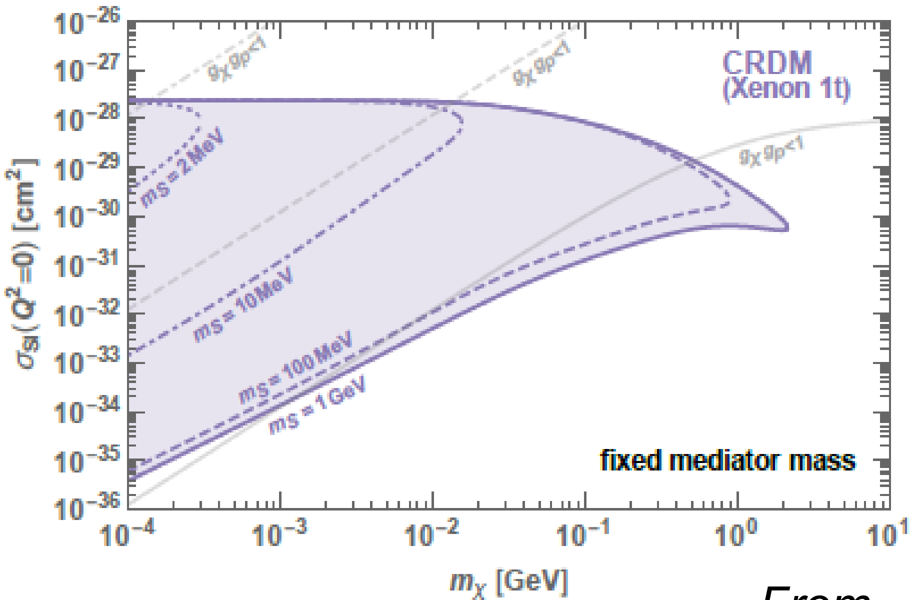
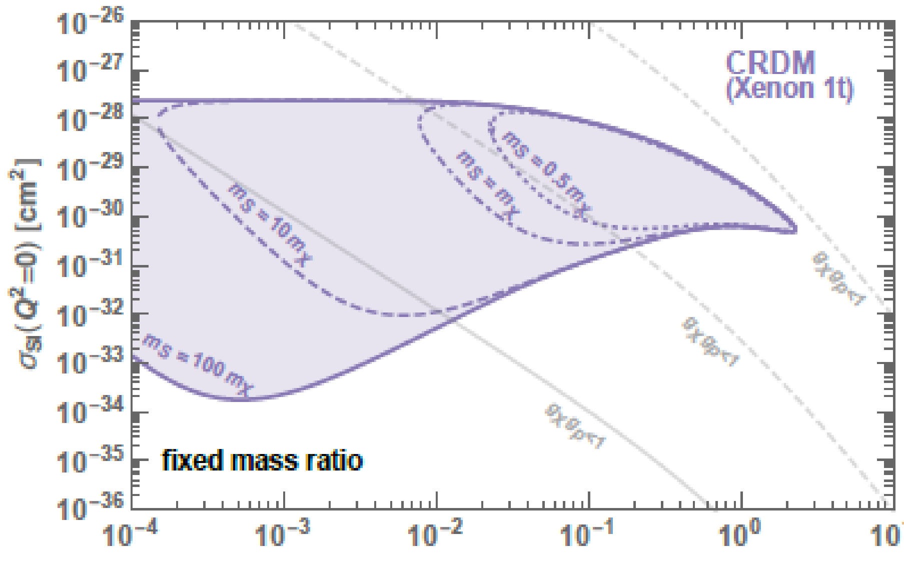
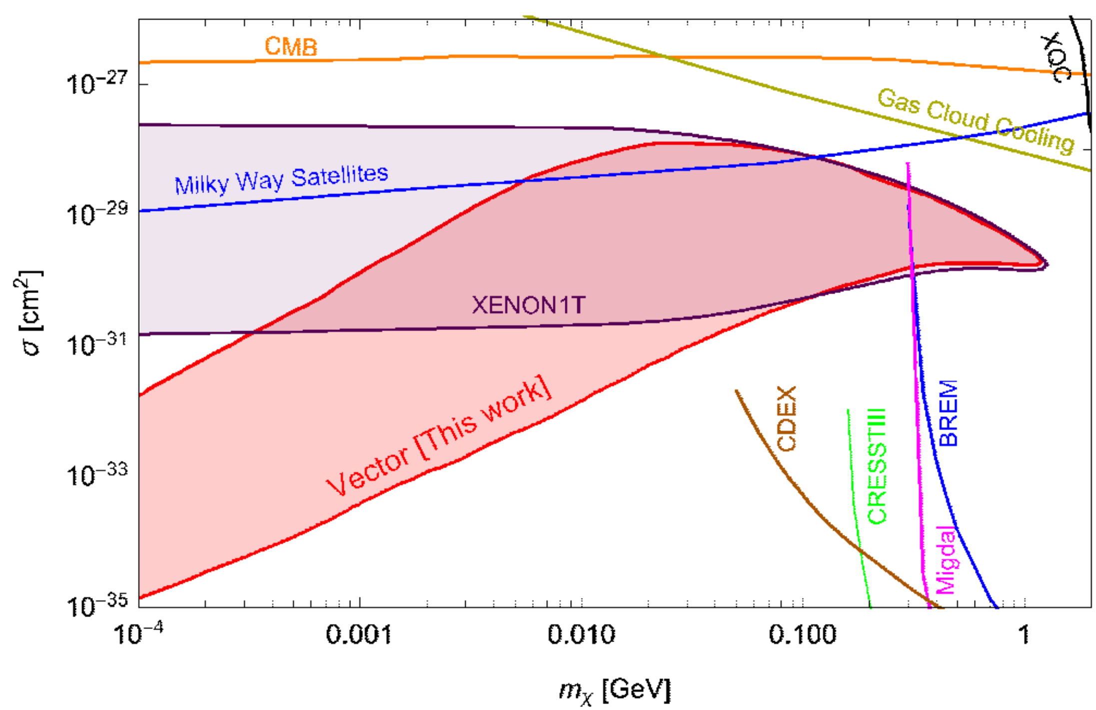
m_χ [GeV]



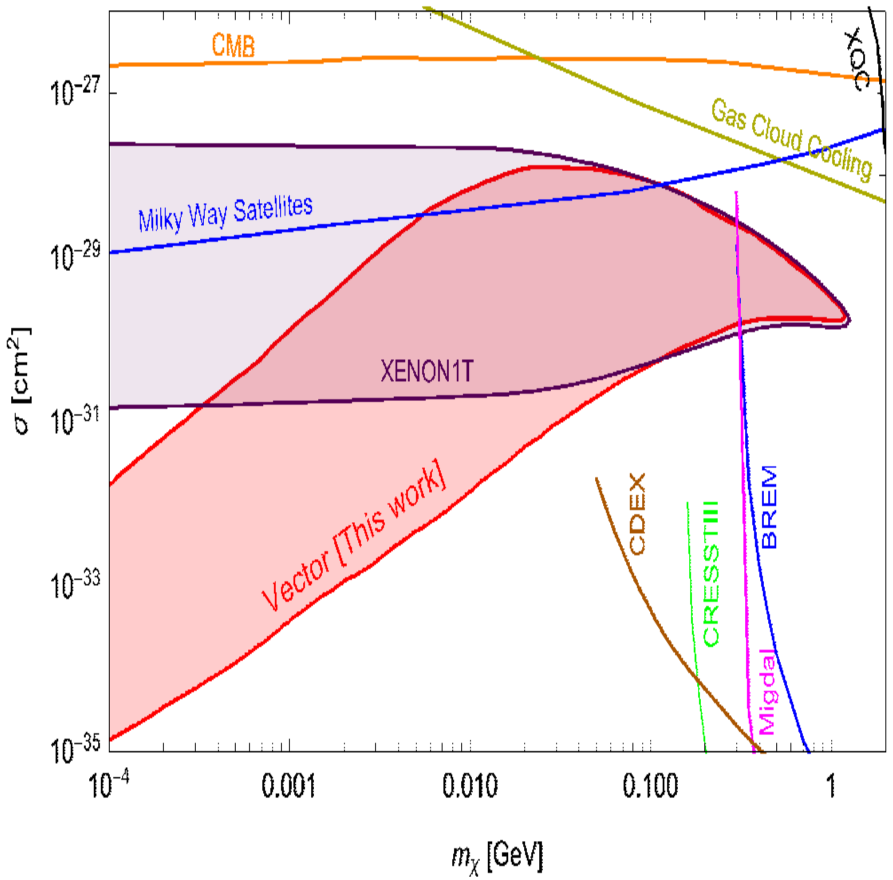


From … T. Bringmann et. al. arXiv:1909.08632

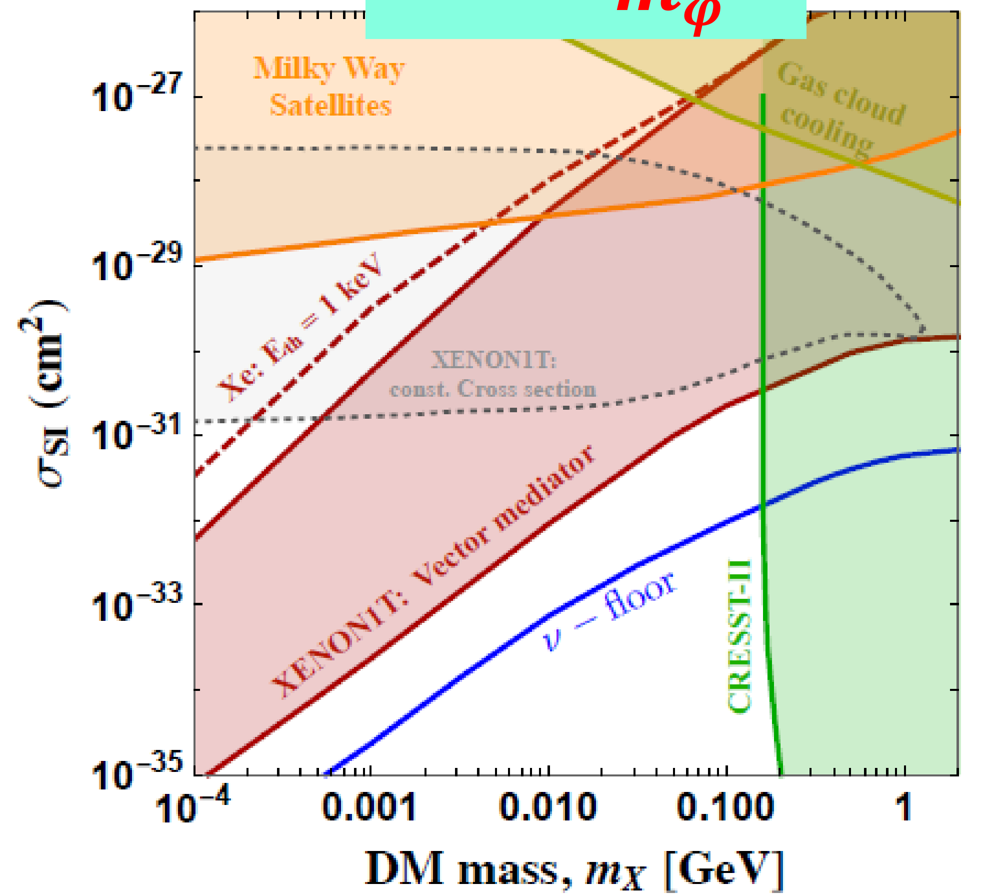
Our work



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



Our work



From J. Dent et. al. arXiv:1907.03782

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

$$R = \int_{T_1}^{T_2} dE_T \frac{1}{m_T} \int_{T_\chi^{z,\min}}^{\infty} dT_\chi^z \frac{d\Phi_\chi}{dT_\chi^z} \frac{d\sigma_{\chi T}}{dE_T}.$$

$$\frac{d\Phi_\chi}{dT_\chi} = \int_\Omega \frac{d\Omega}{4\pi d^2} \int_{T_i^{\min}} dT_i \frac{d^2\Gamma_{\mathrm{CR}_i \to \chi}}{dT_i dT_\chi} = D_{\mathrm{eff}} \frac{\rho_\chi}{m_\chi} \sum_i \int_{T_i^{\min}} dT_i \frac{d\sigma_{\chi i}}{dT_\chi} \frac{d\Phi_i^{\mathrm{LIS}}}{dT_i}.$$

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!