DM detection: status and prospect

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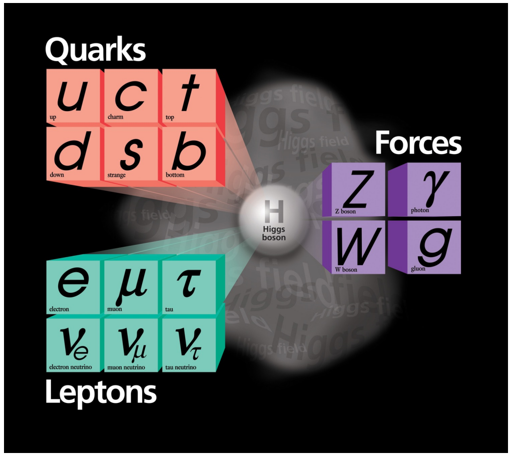
2022.07.15 南师大暑期学校

粒子物理标准模型留下的未解之谜

The Standard Model

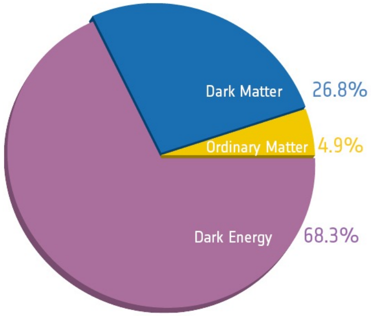


Nobel 2013

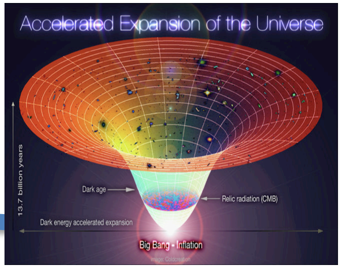
Peter Higgs and Francois Englert

?

物质 - 反物质
不对称性起源？

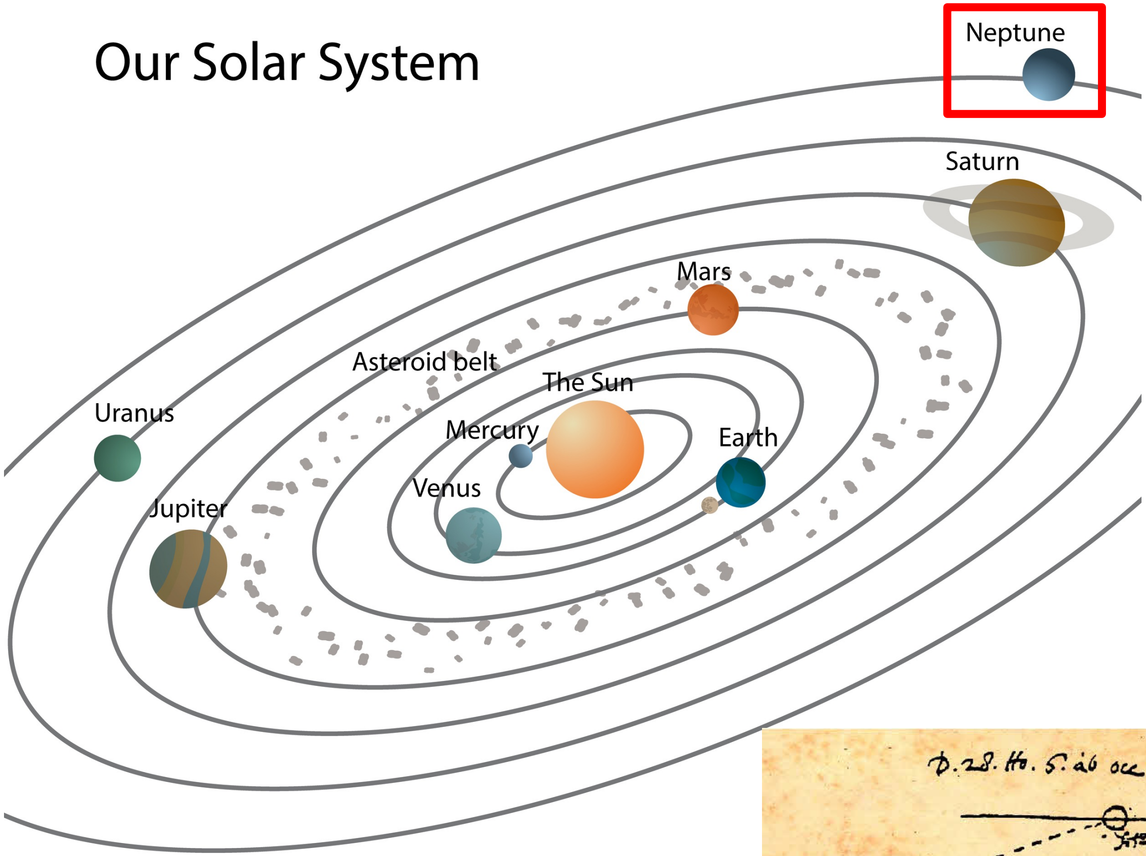


暗物质？



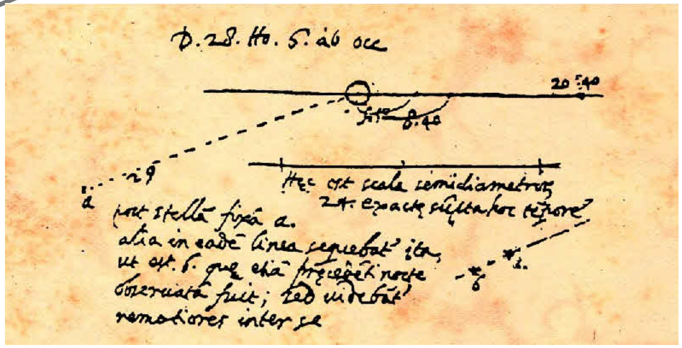
暗能量？

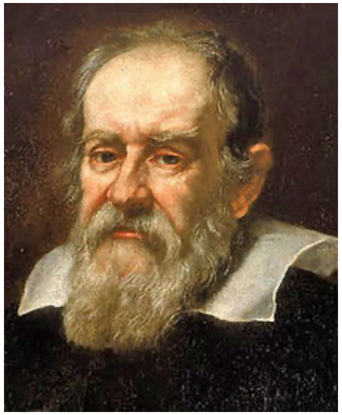
可见物质的运动->引力理论->不可见物质



Urbain Le Verrier. (1845)

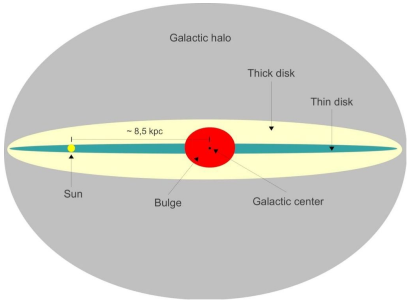
Galileo Galilei (1613)
Jérôme Lalande (1795)
John Herschel in (1830)
recognized as a fixed star





Early history of DM

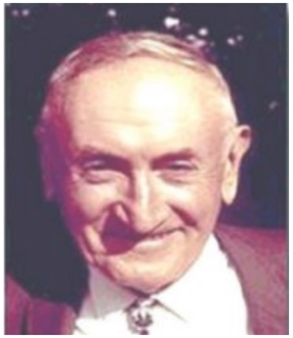
We therefore have the means of estimating the mass of the dark matter in the universe. As matters stand at present, it appears at once that this mass cannot be excessive. If it were otherwise, the average mass as derived from binary stars would have been very much lower than what has been found for the effective mass.



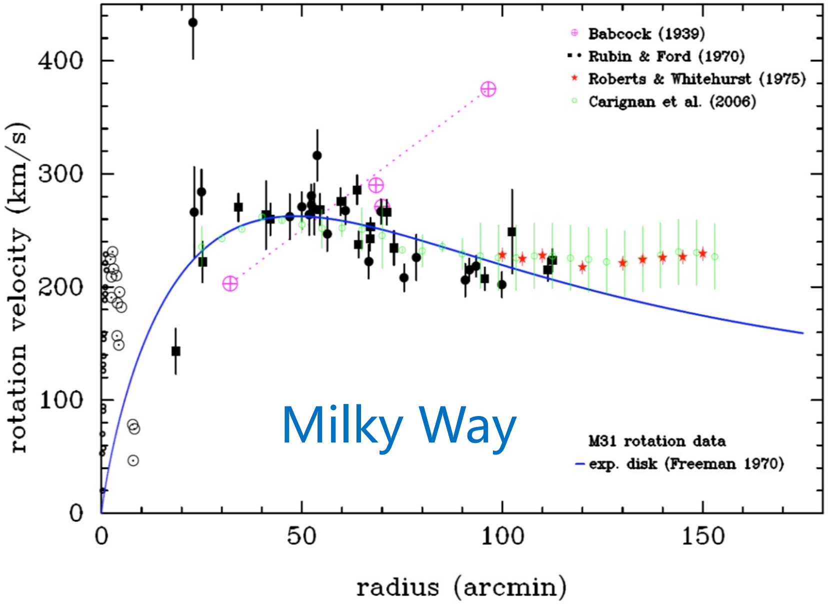
Kapteyn (1922)

If this would be confirmed, we would get the surprising result that dark matter is present in much greater amount than luminous matter.

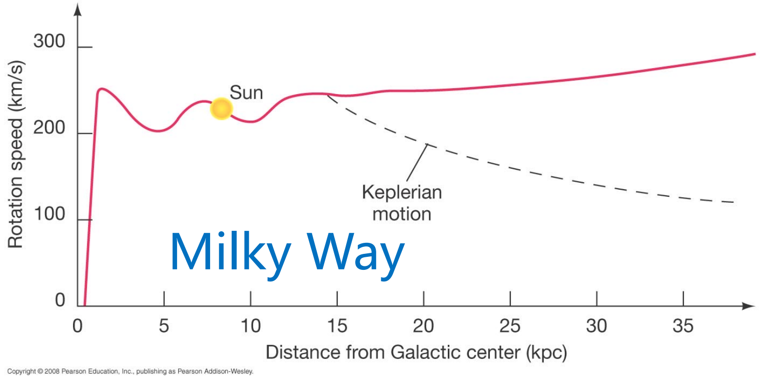
Zwicky (1933)

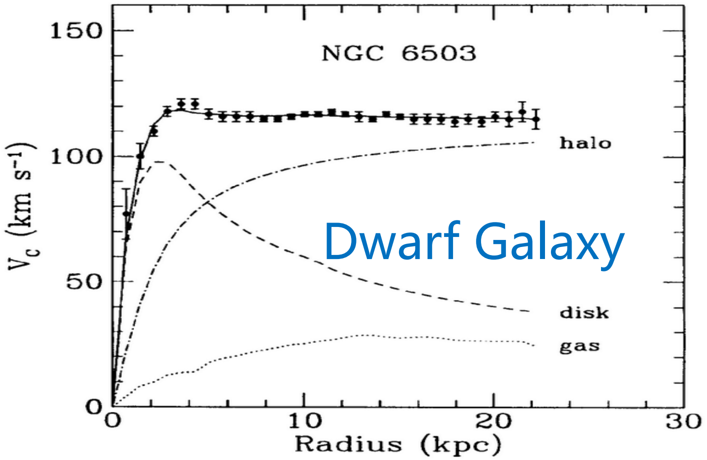


Evidence 1: Galaxy rotation curves

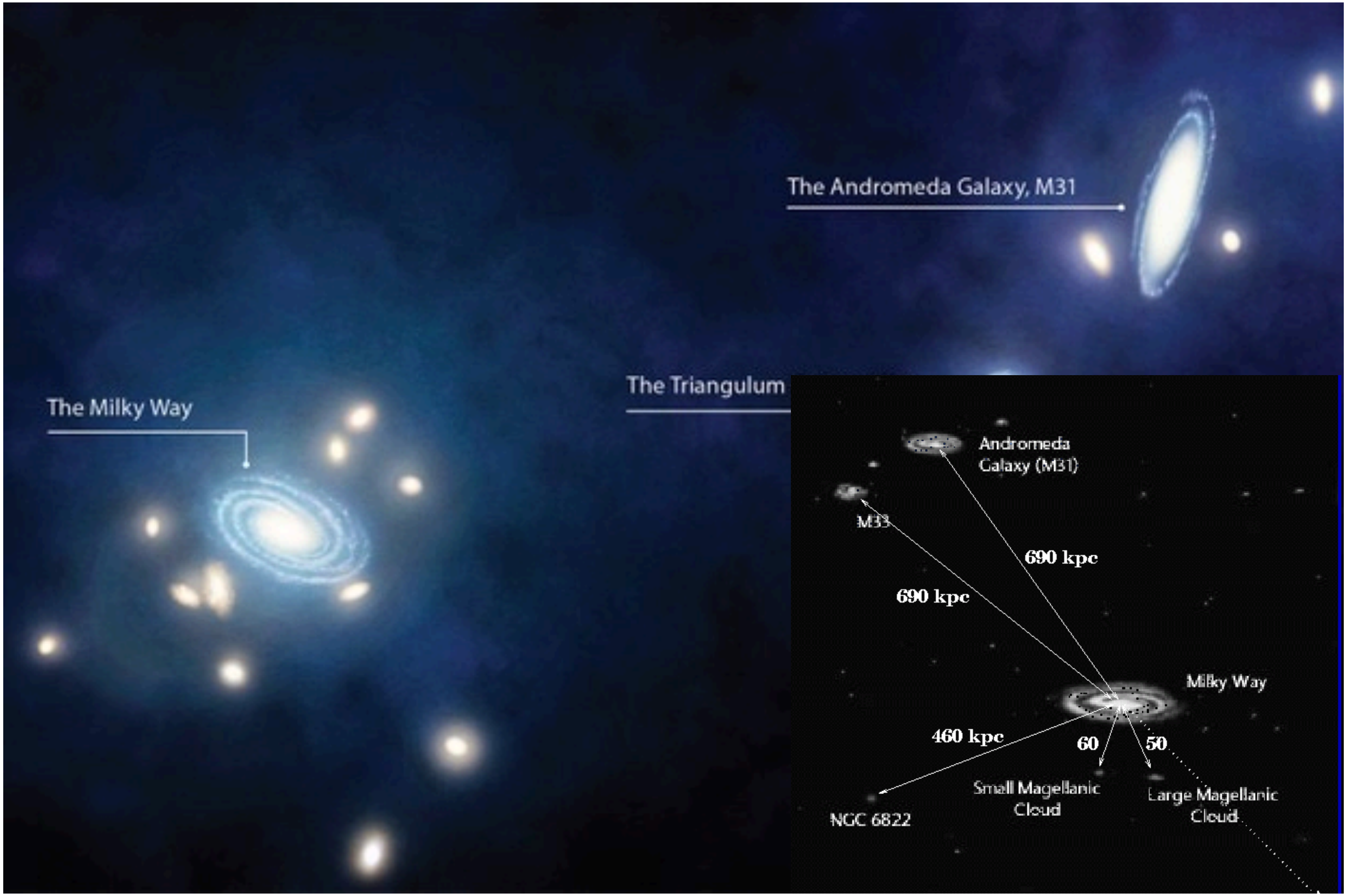


V.Rubin (1928-2016)



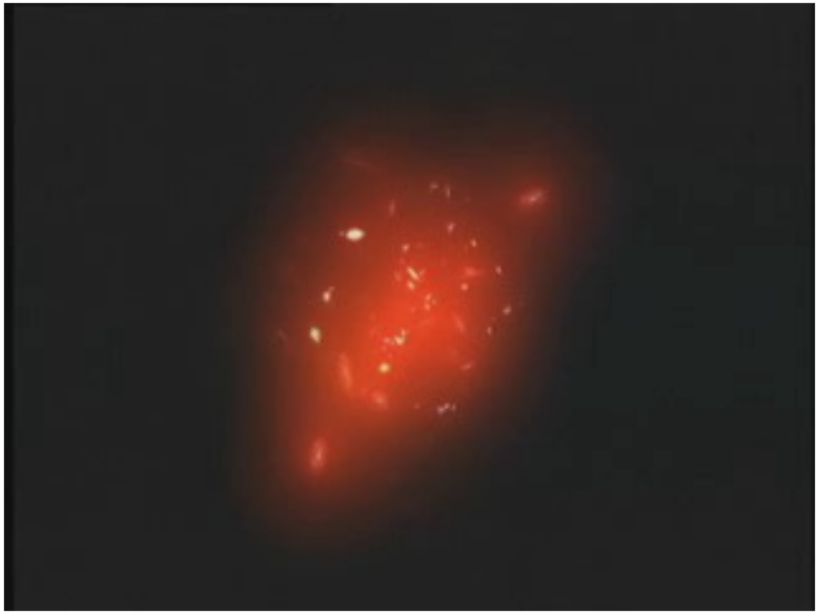


Total mass of the local group: Mwy-M31 infall



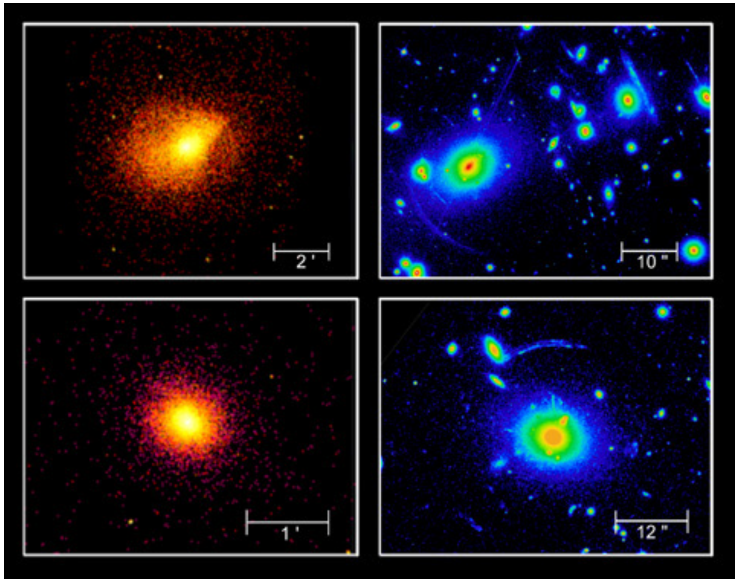
Kahn, Woltjer (1959)

Evidence 2: X-rays from clusters

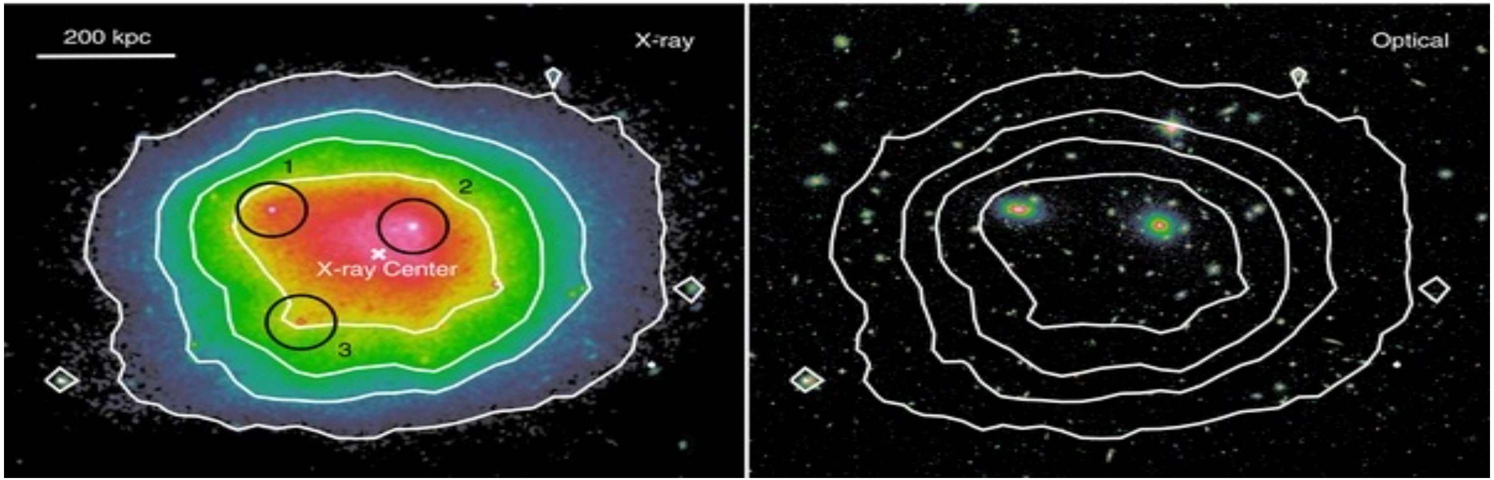


https://www.chandra.harvard.edu/xray_astro/dark_matter/

Chandra HST

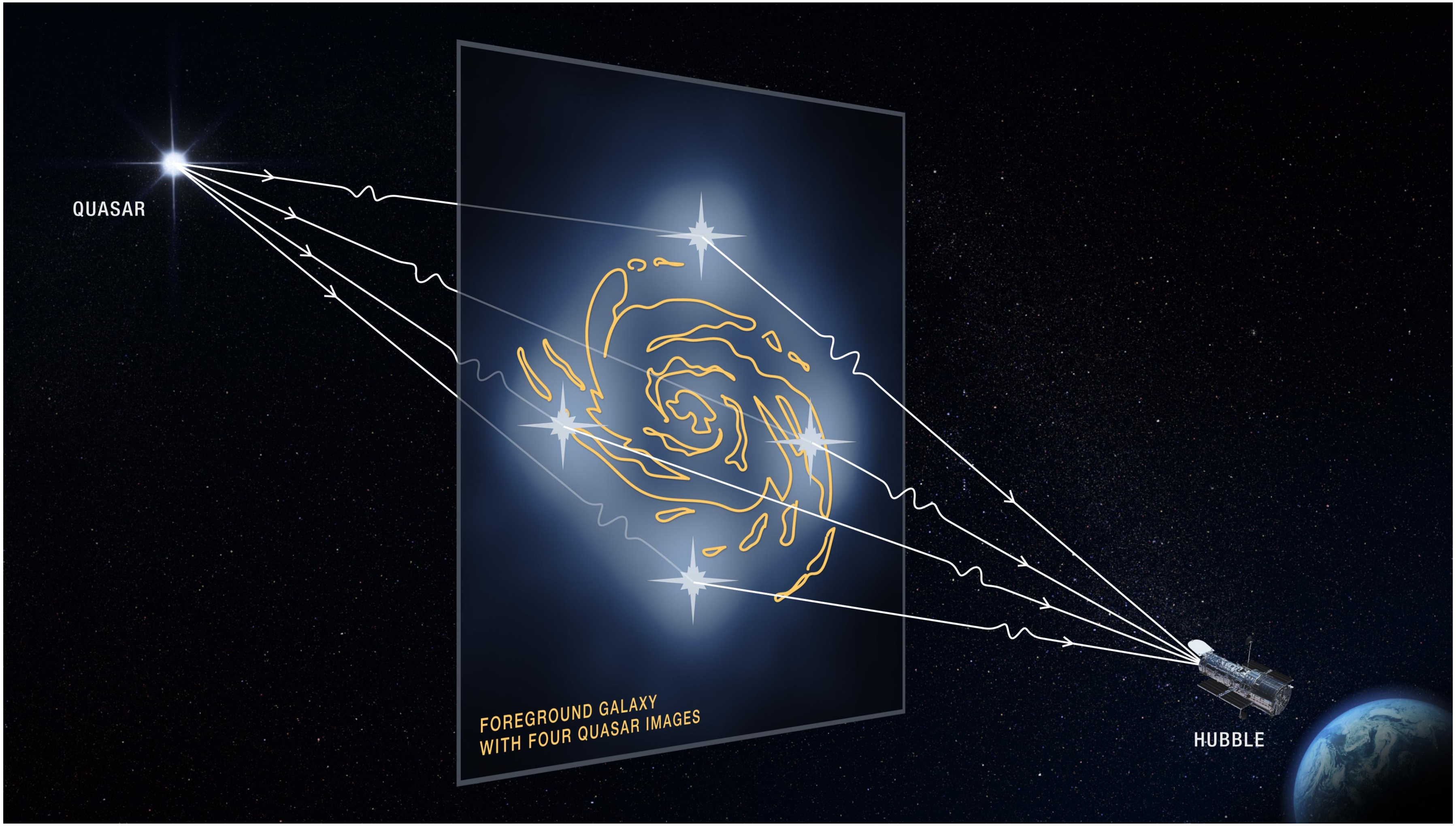


Abell 2390



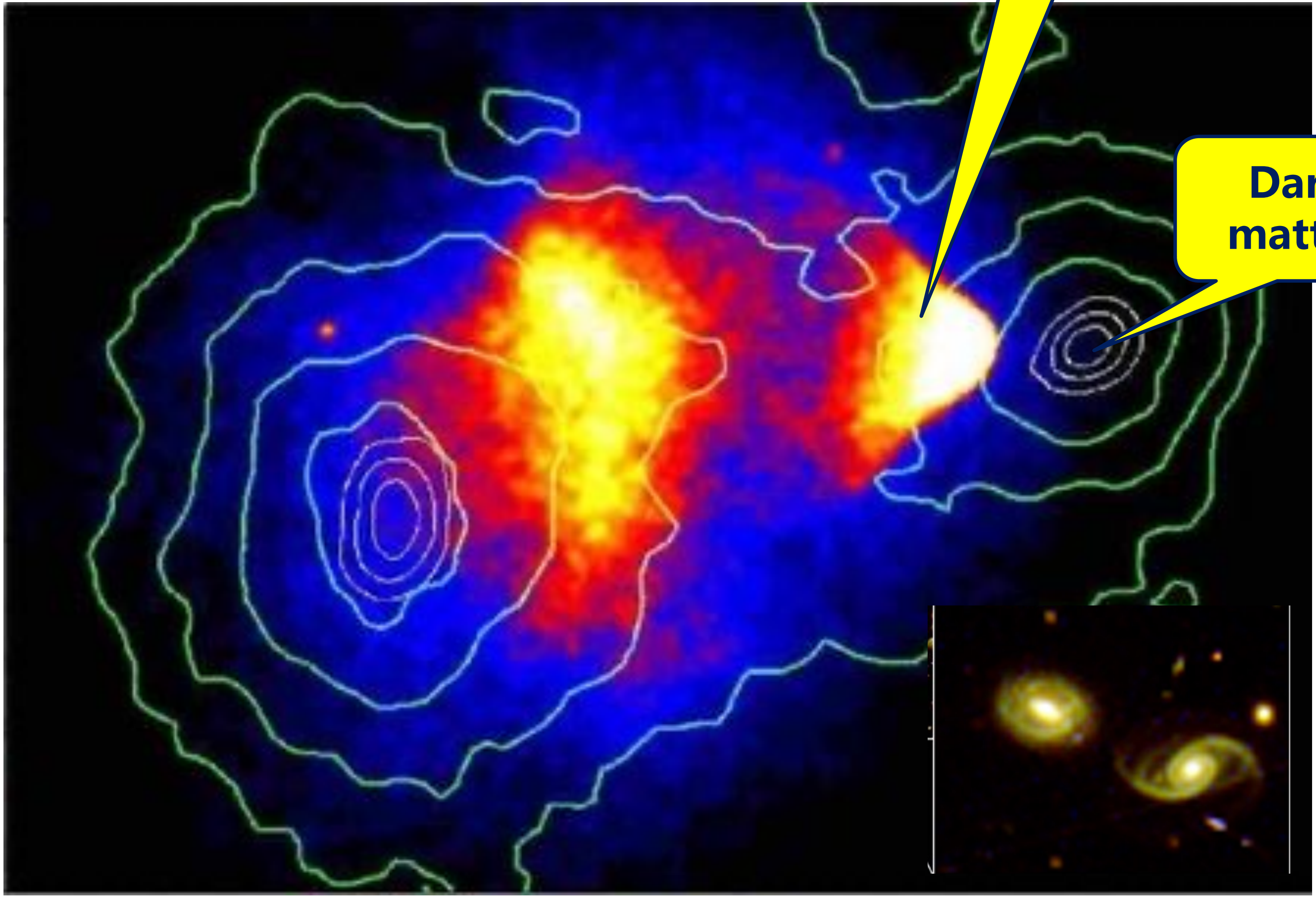
Coma

Evidence 3: gravitational lensing



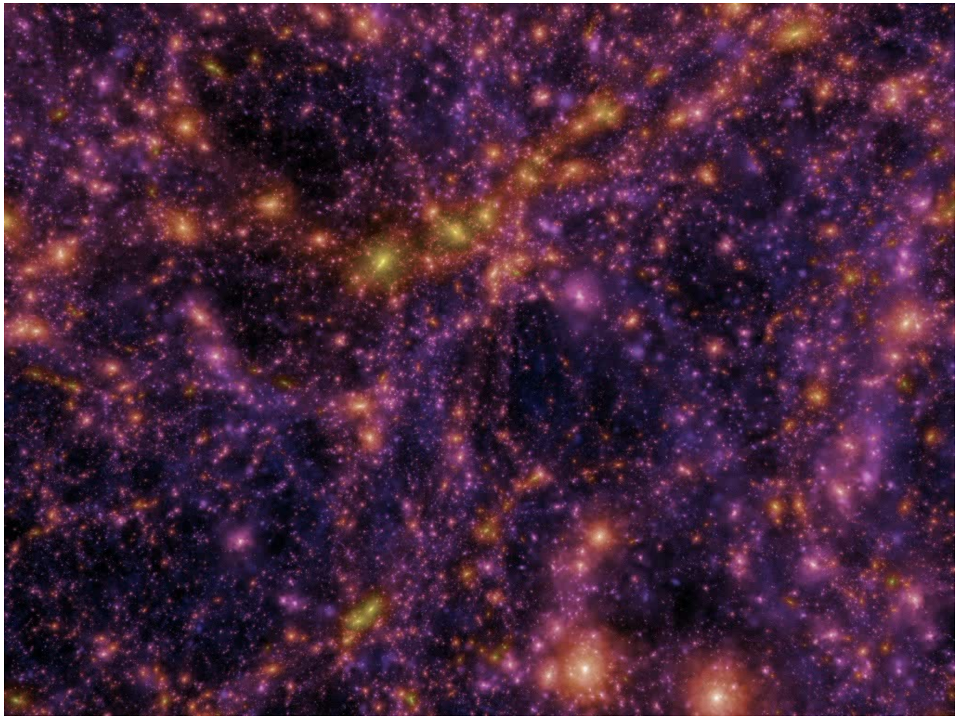
Evidence 4: Bullet cluster

1E0657-56

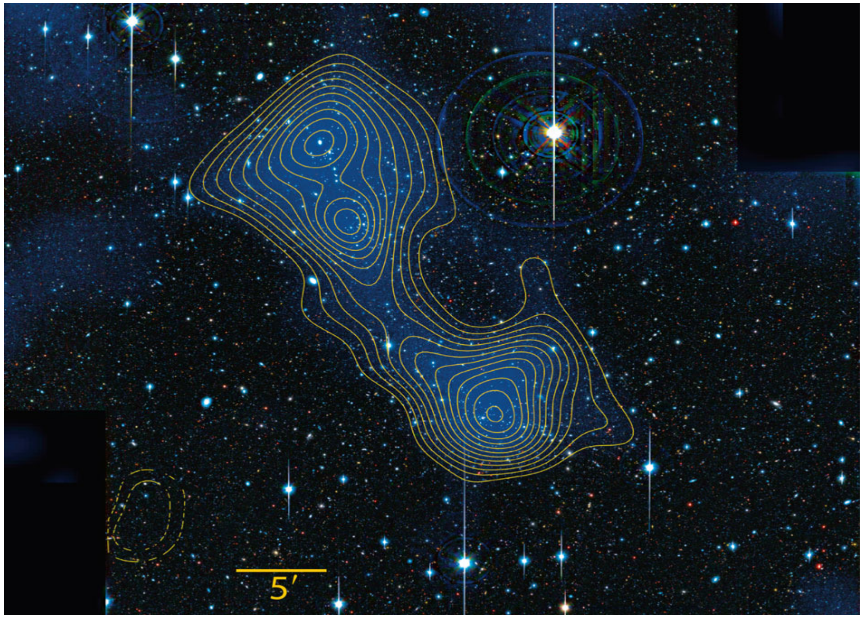


M(total):M(gas):M(stars)=70:10:1

Evidence 5: N-body simulation and DM structure

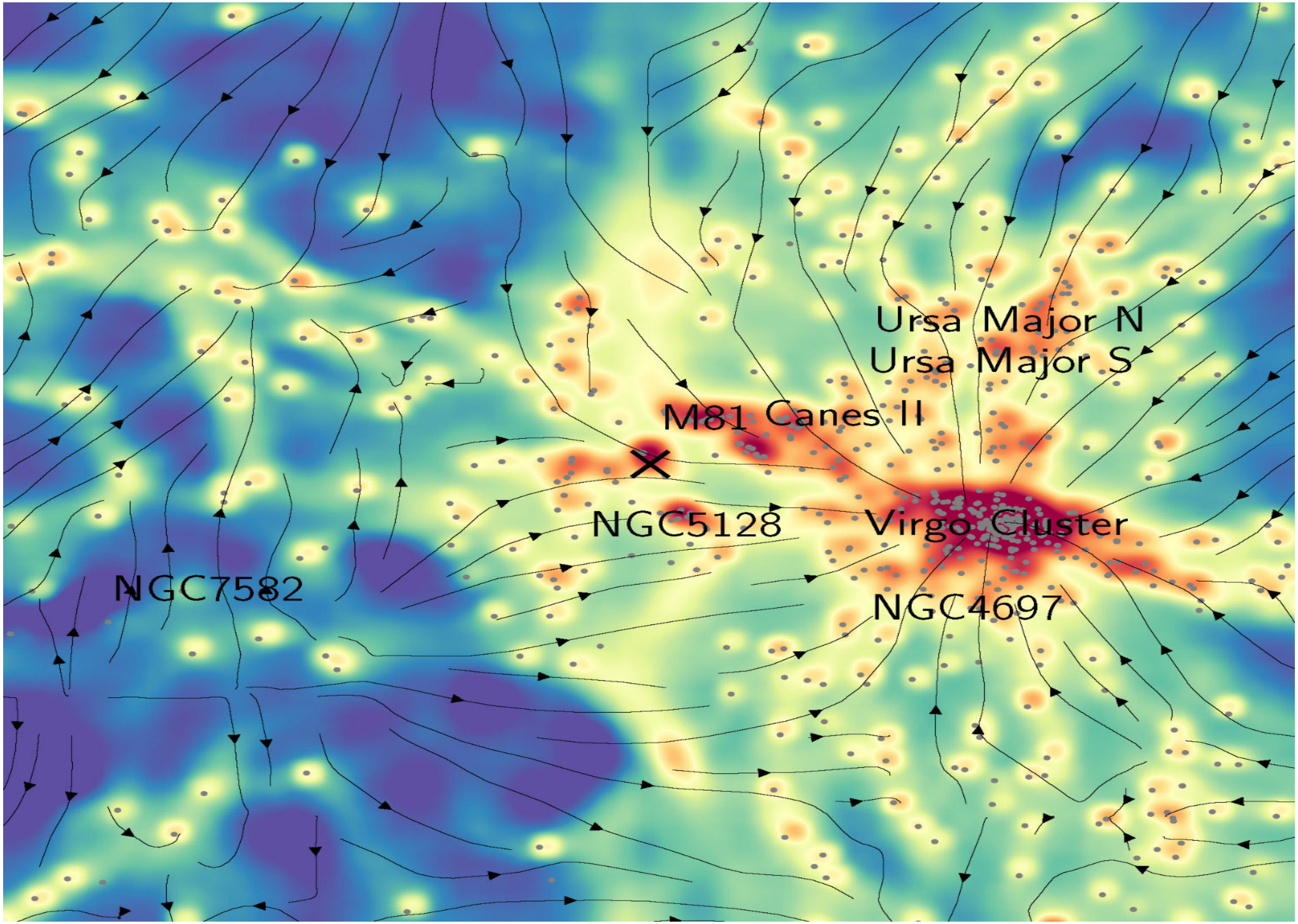


大尺度结构N-体模拟

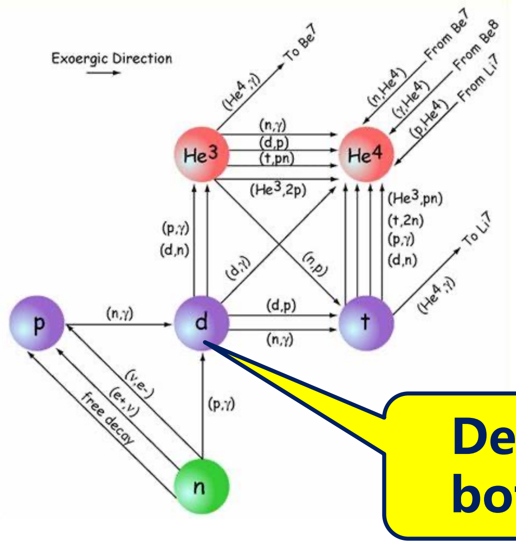


观测结果 J.P. Dierich etal, 1207.8089, Nature

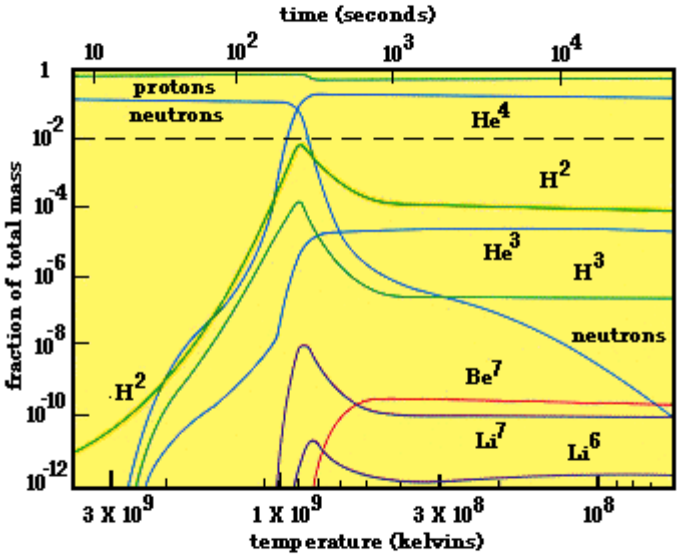
DM map from DES



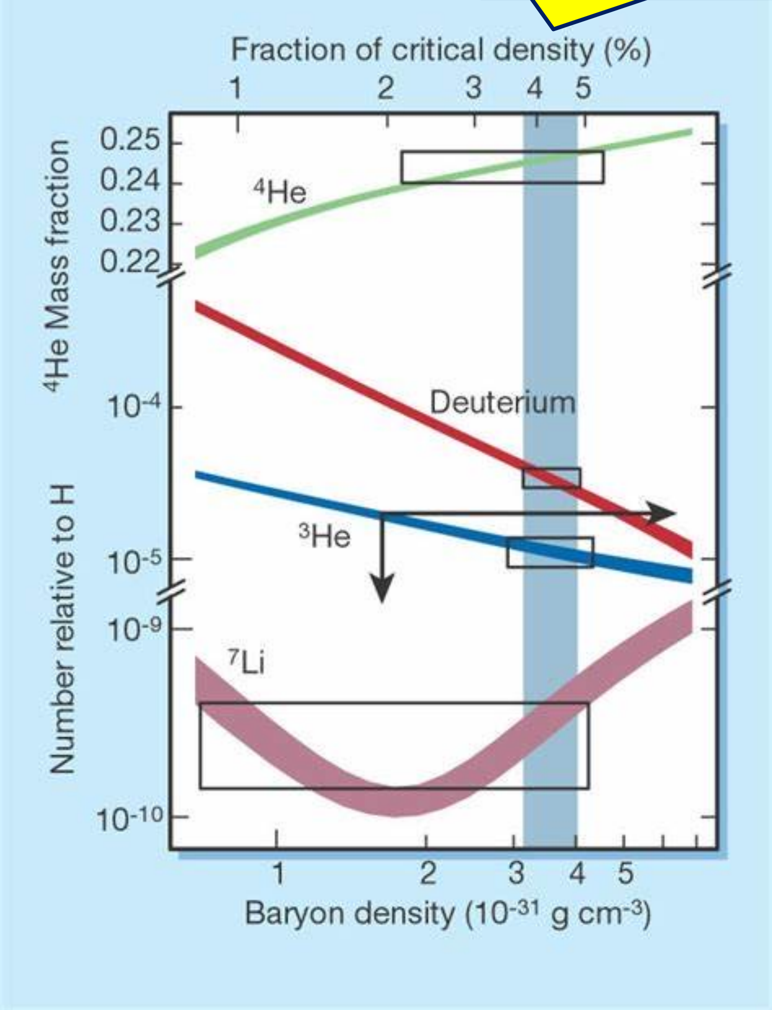
Evidence 6: BBN and CMB

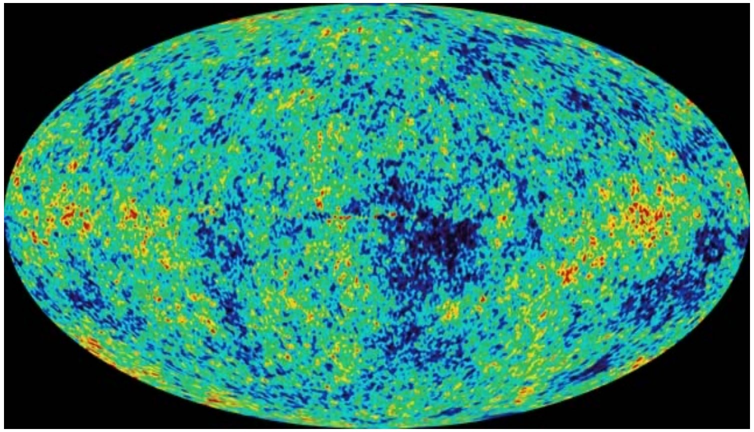


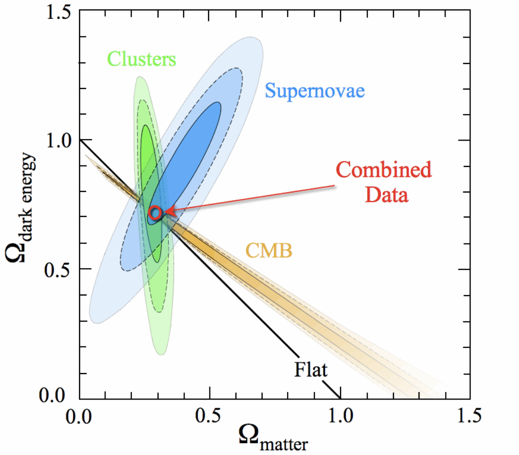
Deuterium bottleneck

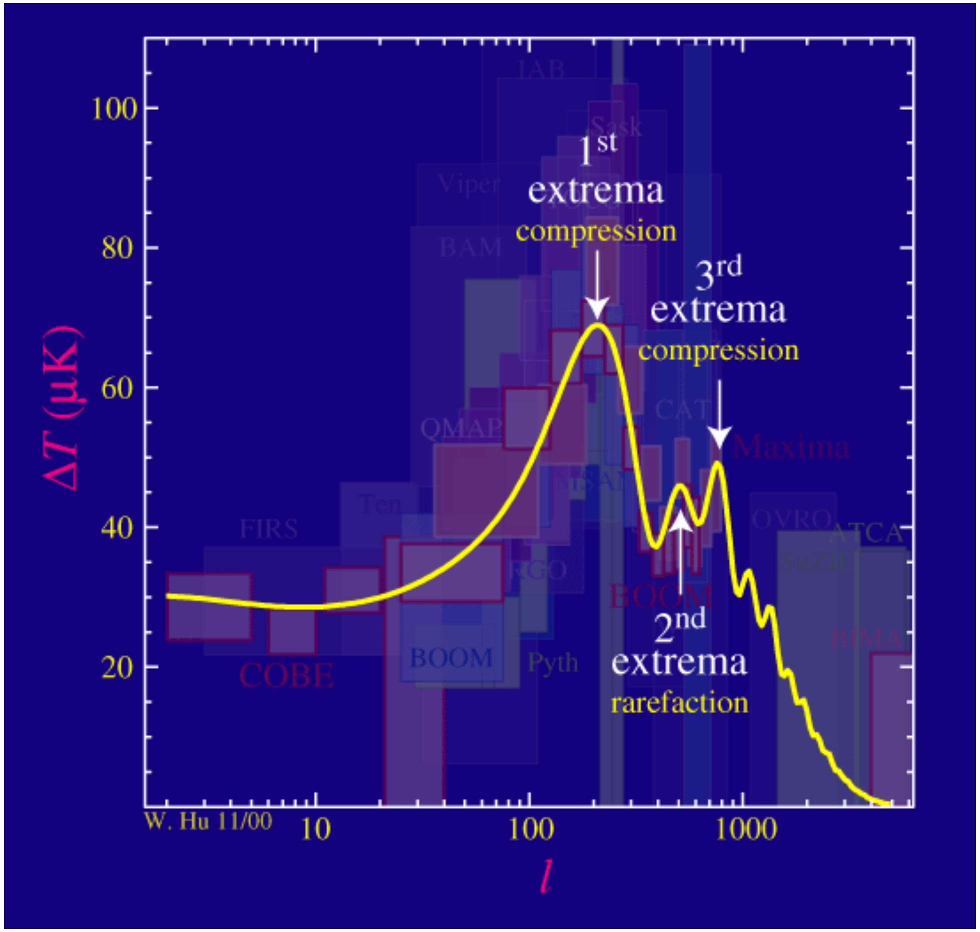


baryonic matter 4-5%



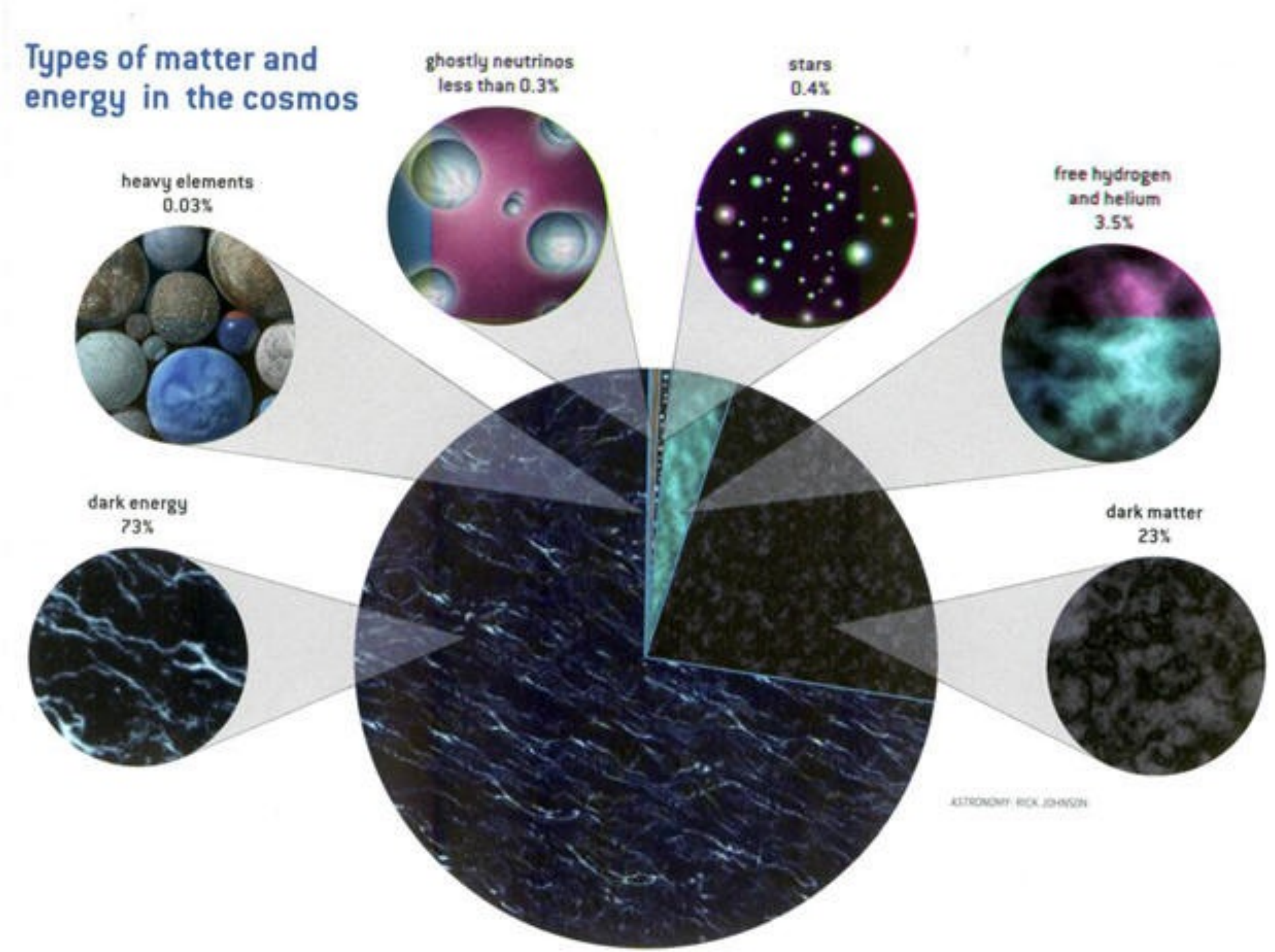






$$\Omega_\Lambda = 0.728^{+0.015}_{-0.016}; \Omega_{DM}h^2 = 0.1123 \pm 0.0035; \Omega_b h^2 = 0.02260 \pm 0.00053$$

宇宙的常规物质是少数

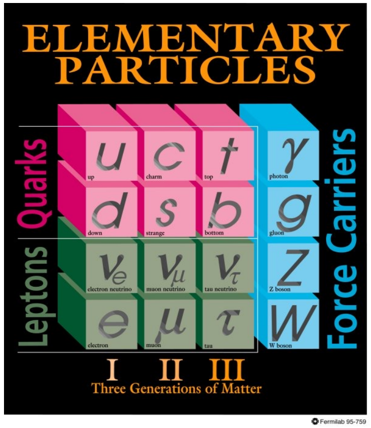

Types of matter and energy in the cosmos
ghostly neutrinos less than 0.3%
stars 0.4%
heavy elements 0.03%
free hydrogen and helium 3.5%
dark energy 73%
dark matter 23%
ASTRONOMY: RICK JOHNSON

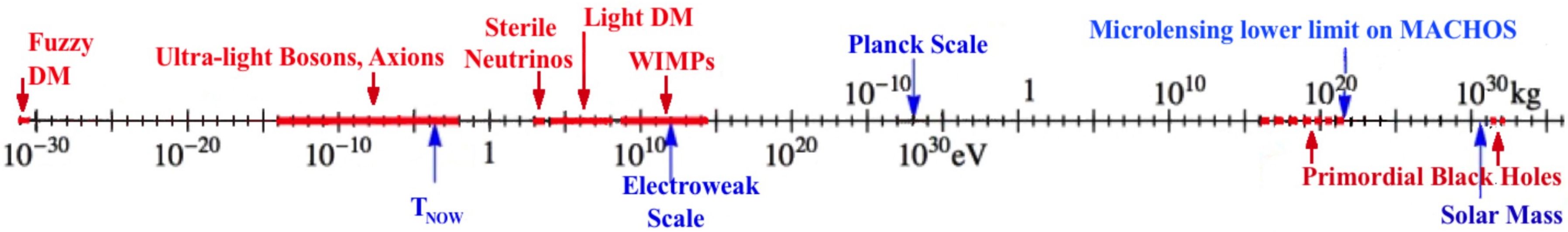
暗物质候选者？

Dark Matter 基本特点

1. 有质量（参与引力作用）
2. 稳定粒子（寿命长于宇宙年龄）
3. 不带电荷（基本无电磁相互作用）
4. 非重子物质（不由夸克组成）
5. 非相对论性运动（冷暗物质）

DM 非任何已知基本粒子 ！

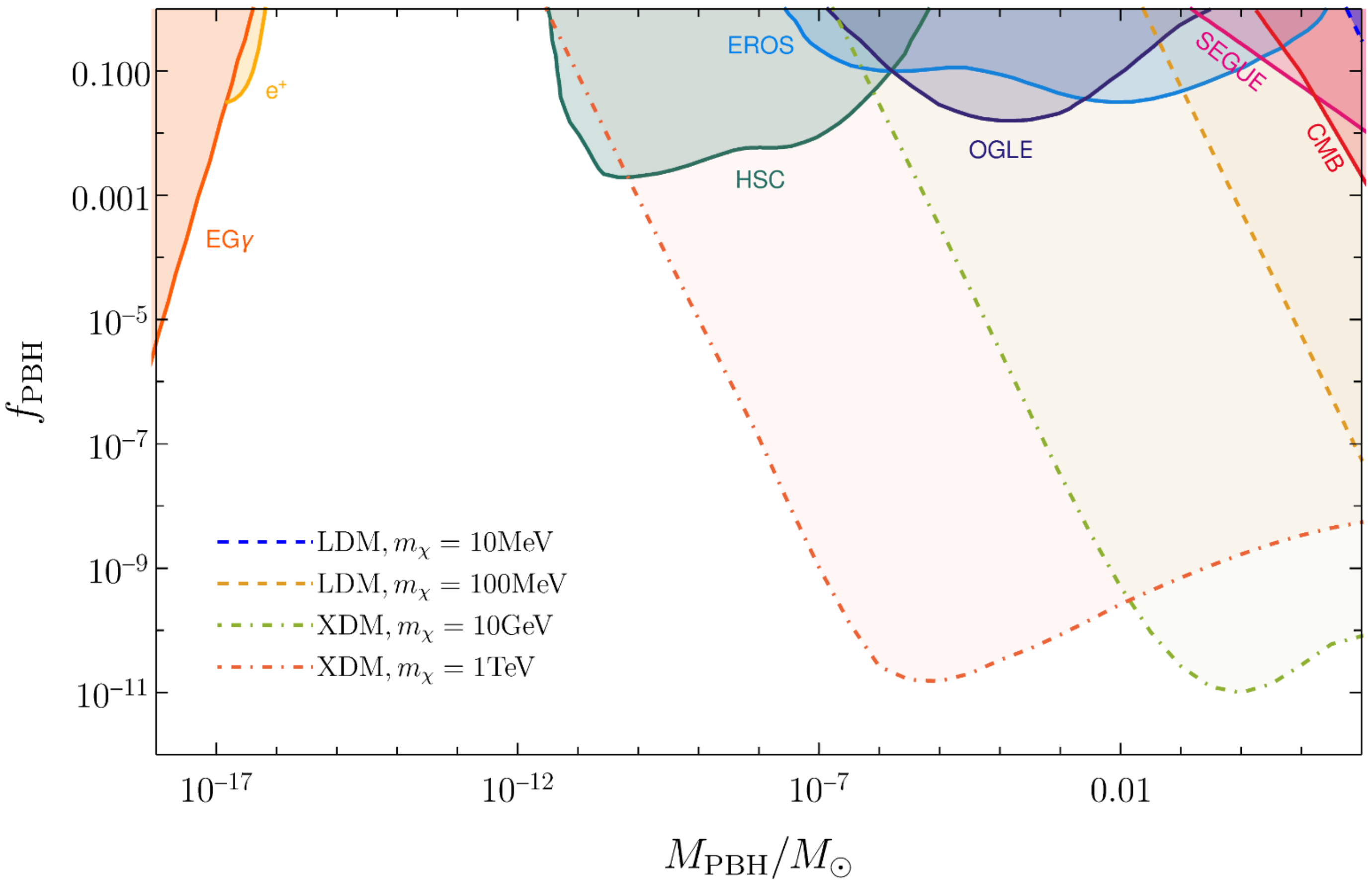




- 原初黑洞 （10^{40} -10^{55} GeV ）
- 超重暗物质：WIMPzilla 10^{15} GeV
- 常规 WIMPs 暗物质理论模型 (GeV- 1 TeV)

  e.g MSSM, Extra dimension, Little Higgs, Singlet DM models
- 轻DM 粒子 (keV) Sterile neutrinos
- 极轻暗物质 (10^{-10}-10^{-22} eV) Axion and Axion-like particles， Fuzzy DM

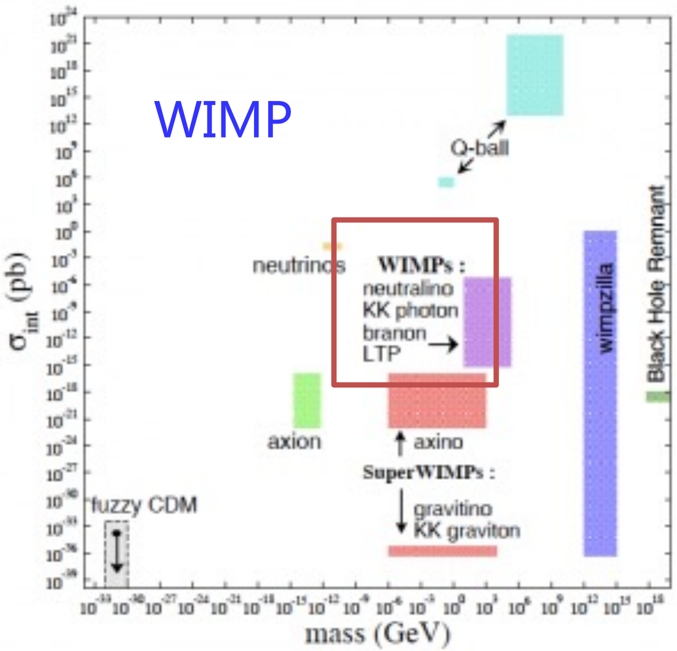
Primordial Black holes (PBH)

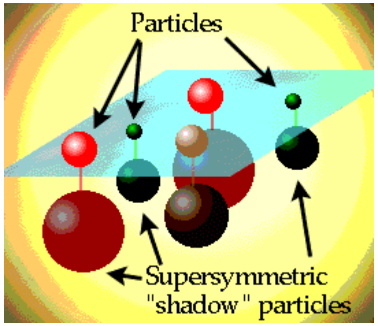


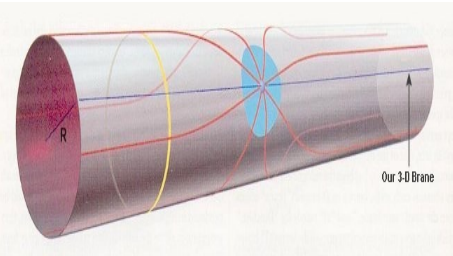
- ❑ 目前各种观测尚未完全排除原初黑洞作为全部暗物质的候选者
- ❑ 原初黑洞与暗物质用相互作用，带来新的探测可能性

Cai, et al (2020)

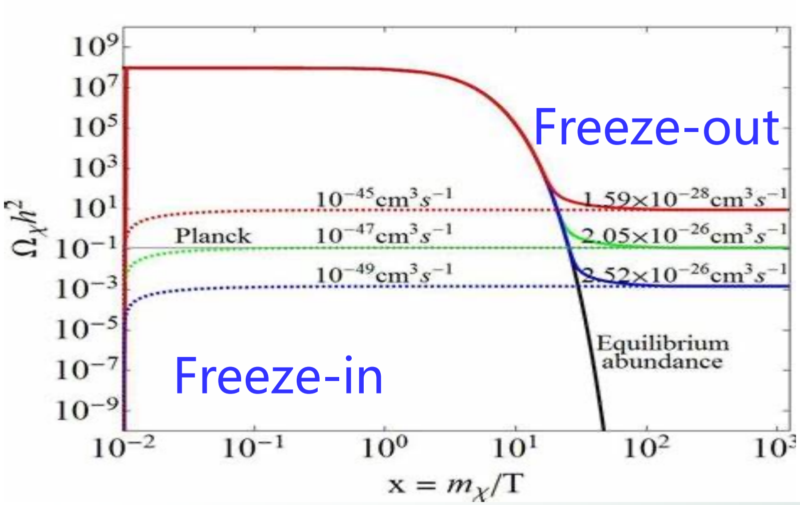
WIMP, SuperWIMP, Freeze-out (in)


WIMP

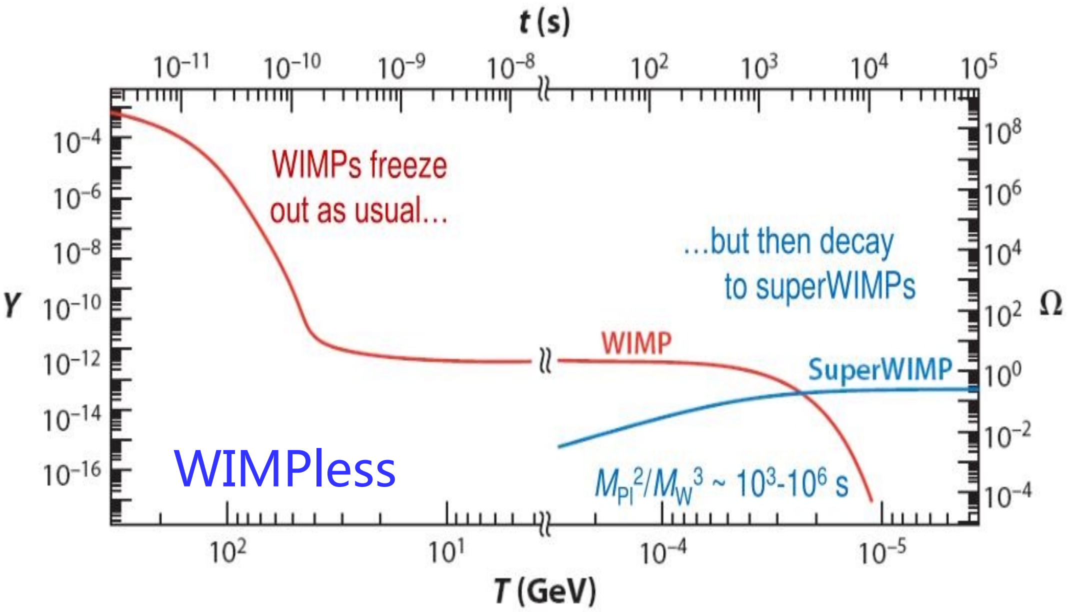




SMALL EXTRA DIMENSION wrapped in a circle (*circumference of tube*) modifies how gravity (*red lines*) spreads in space. At distances smaller than the circle radius (*blue patch*), the lines of force spread apart rapidly through all the dimensions. At much larger distances (*yellow circle*), the lines have filled the extra dimension, which has no further effect on the lines of force.


Freeze-out

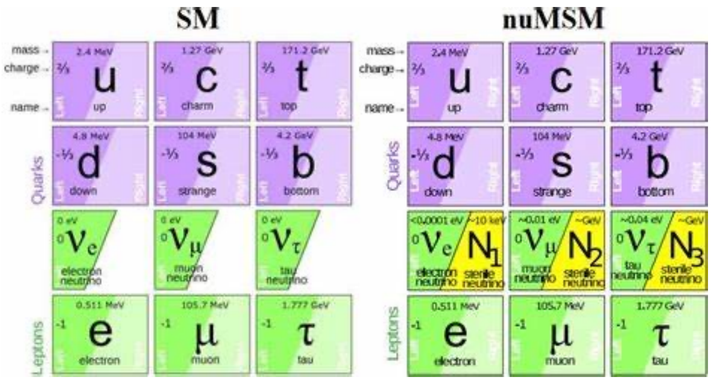
Freeze-in

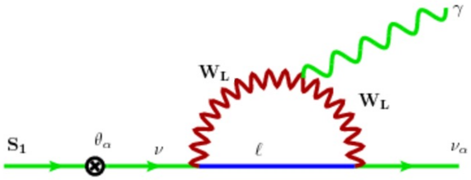

WIMPless

Sterile neutrino

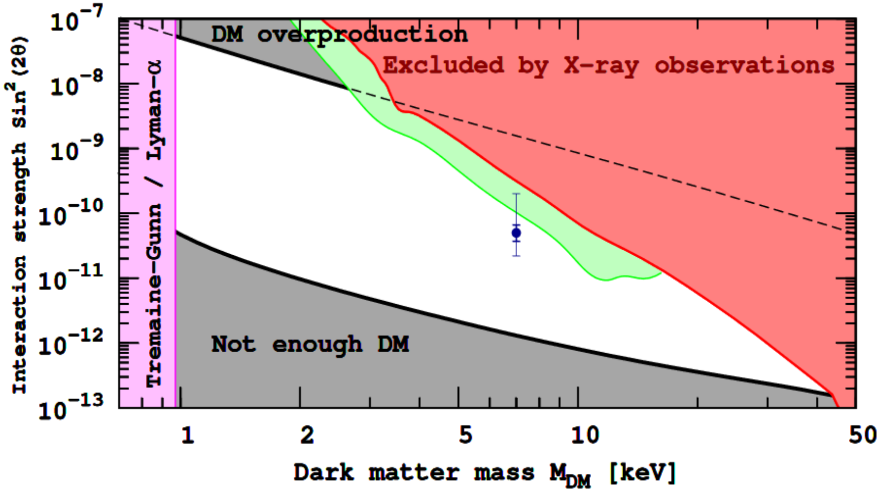
惰性中微子是标准模型的最小扩展之一

- 中微子振荡，LSND， MiniBooNE
- 宇宙中物质-反物质不对称 Leptogenesis
- 暗物质粒子， warm dark matter
- The 3.5 keV X-ray line

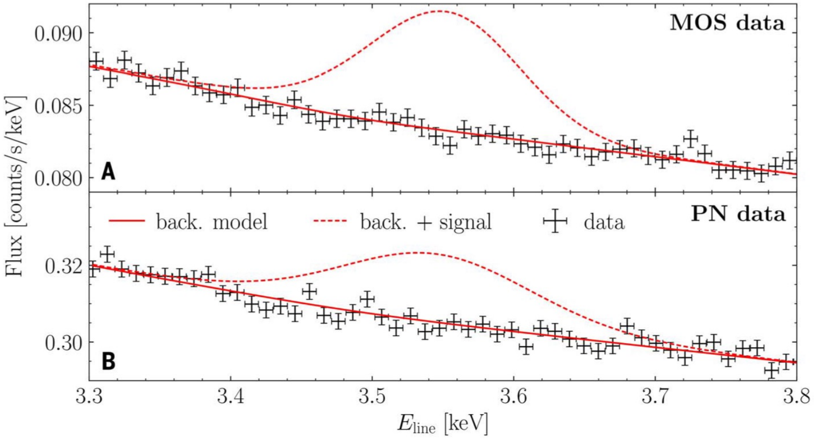




大范围观测未证实3.5 keV 线谱存在



A. Boyarsky, et al, 1402.4119

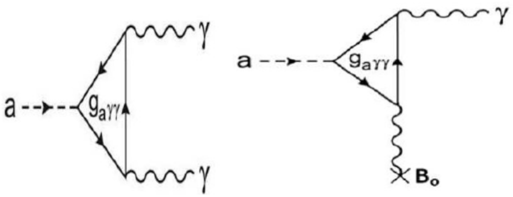


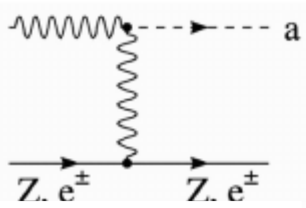
C. Desser, et al (2020) Science.

Axion and Axion-like-particles (ALP)

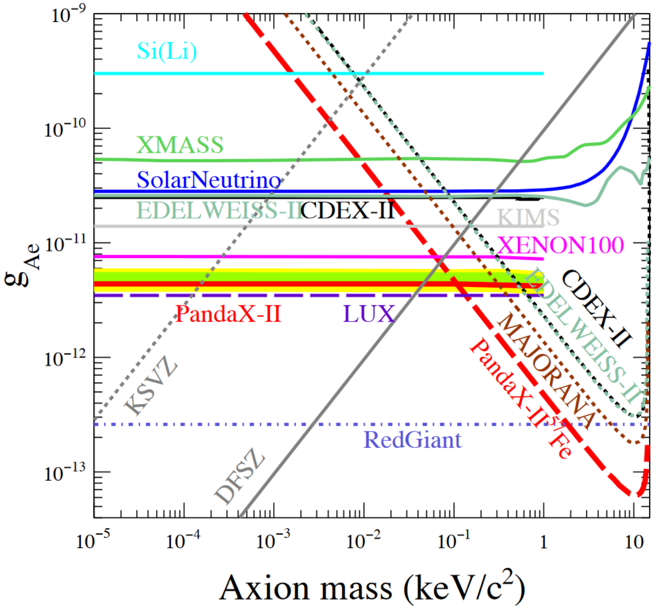
轴子最早为解决强CP破缺问题而引入

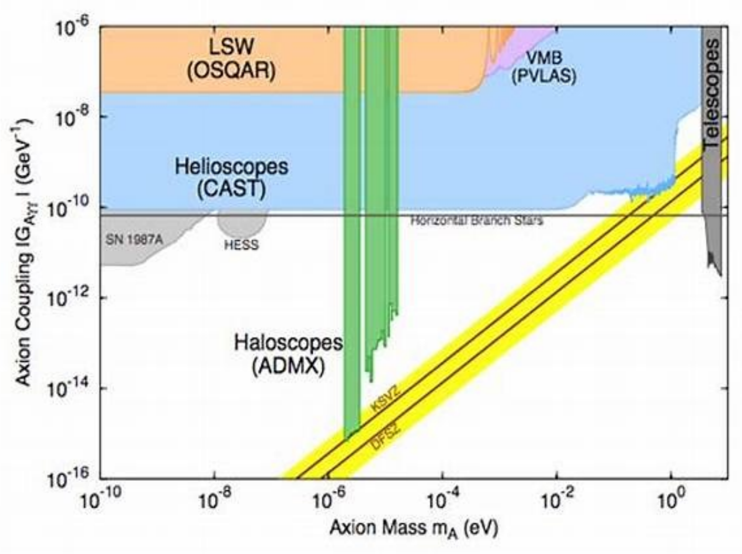
- 轴子与光子耦合
- 一些模型中轴子和电子耦合（DSFZ）
- 轴子可以是冷暗物质粒子，大量类轴子模型

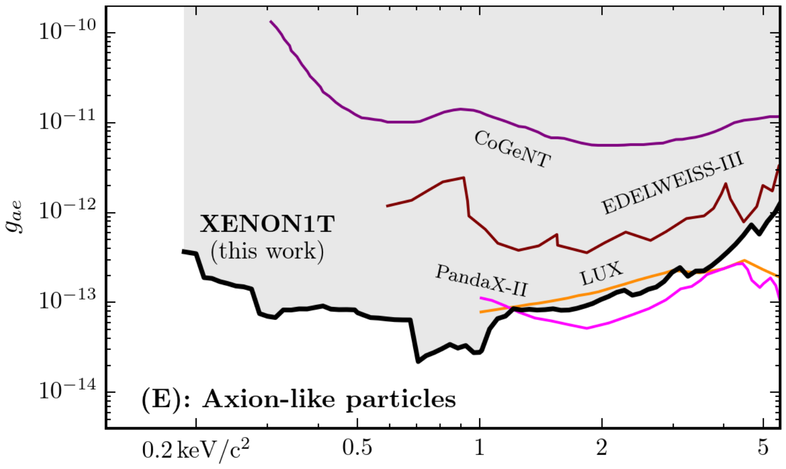




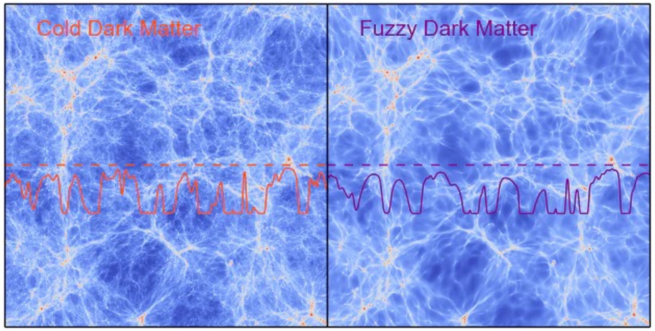
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 + \frac{1}{2}(\partial_\mu a\partial^\mu a - m^2a^2) + \frac{g_{a\gamma}}{4}aF_{\mu\nu}\tilde{F}^{\mu\nu},$$







Fuzzy DM



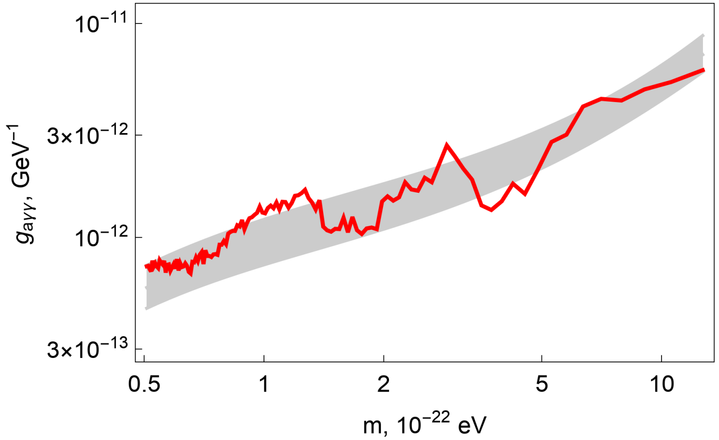
Fuzzy DM 能解决小尺度结构形成中的一些问题

I. Cusp-Core
II. Missing satellites
III. Too-big-to-fail

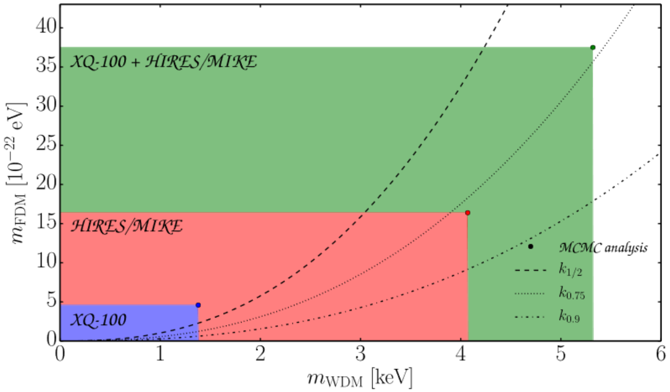
质量在 10^{-22} eV 附近的玻色子暗物质粒子（axion-like）

- □ 超冷玻色-爱因斯坦凝聚
- □ 改变电磁波传播极化
- □ 影响结构形成（Lyman-alpha）
- □ 影响引力波传播

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



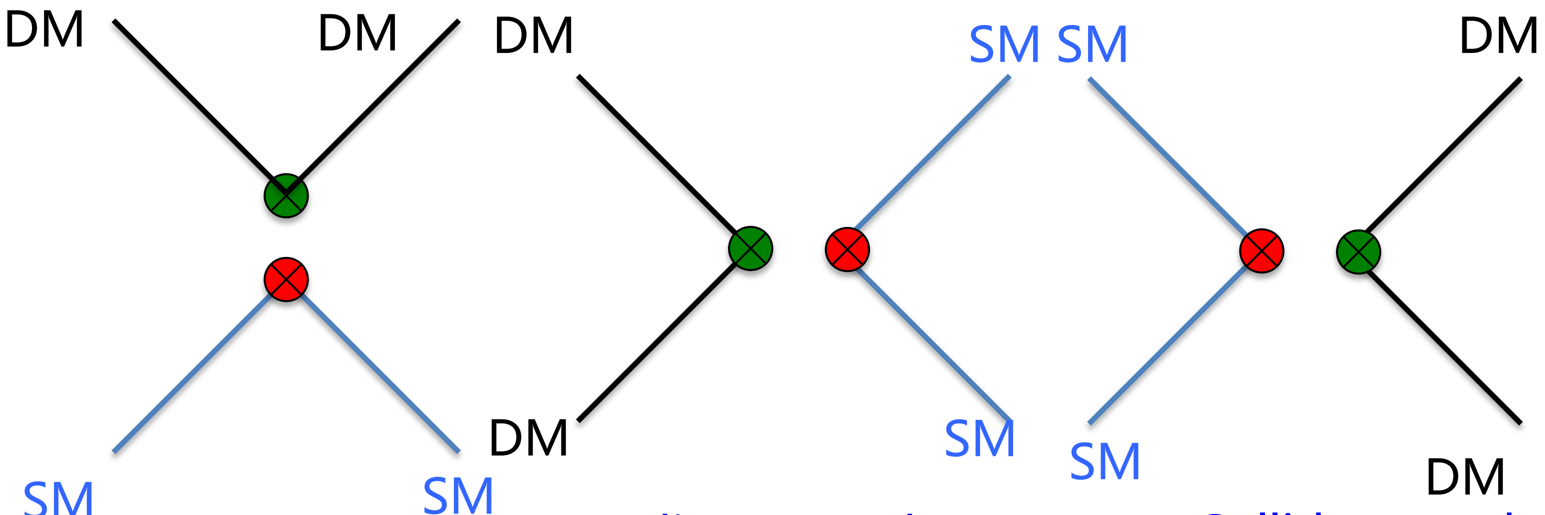
AGN radio 观测限制， M. Ivanov (2019)



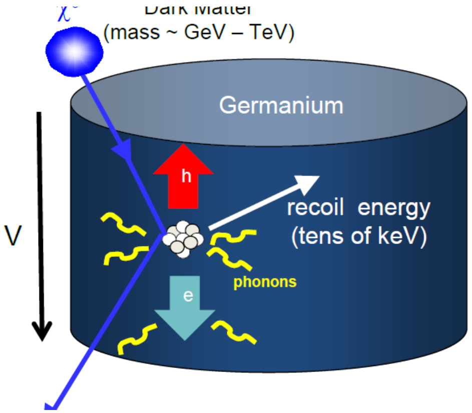
Lyman-alpha 观测, V. Irsic (2017)

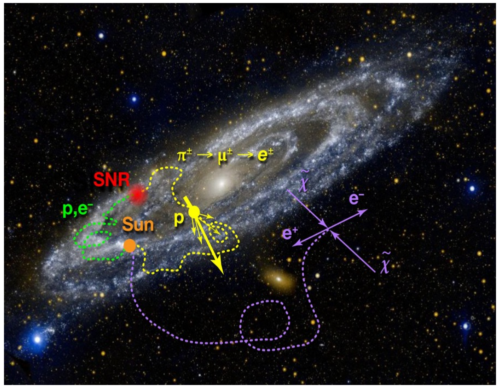
如何探测暗物质？

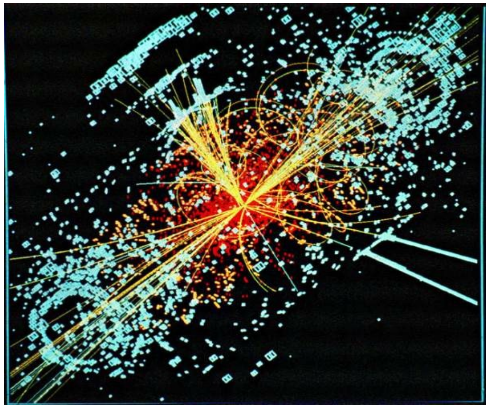
DM may interact with SM particles (weakly)



Direct searches Indirect searches Collider searches

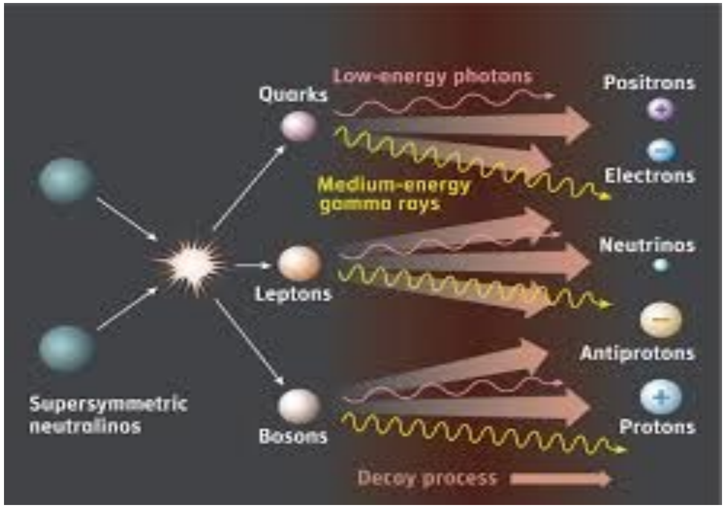


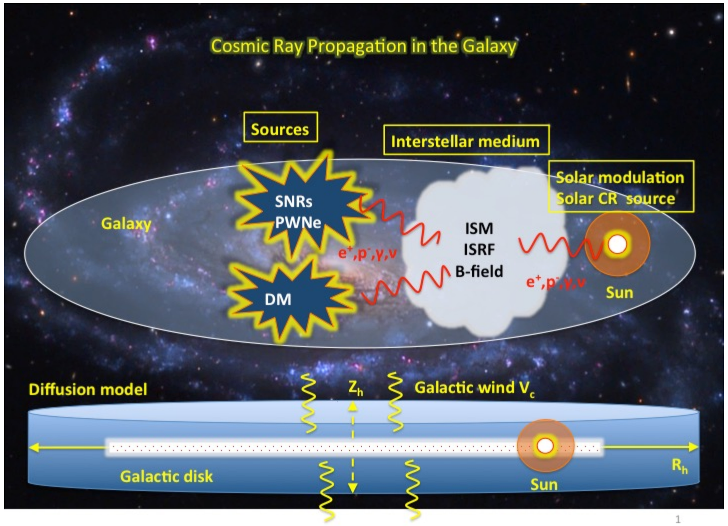




Connecting the three type of detections may not be straightforward

DM indirect detections





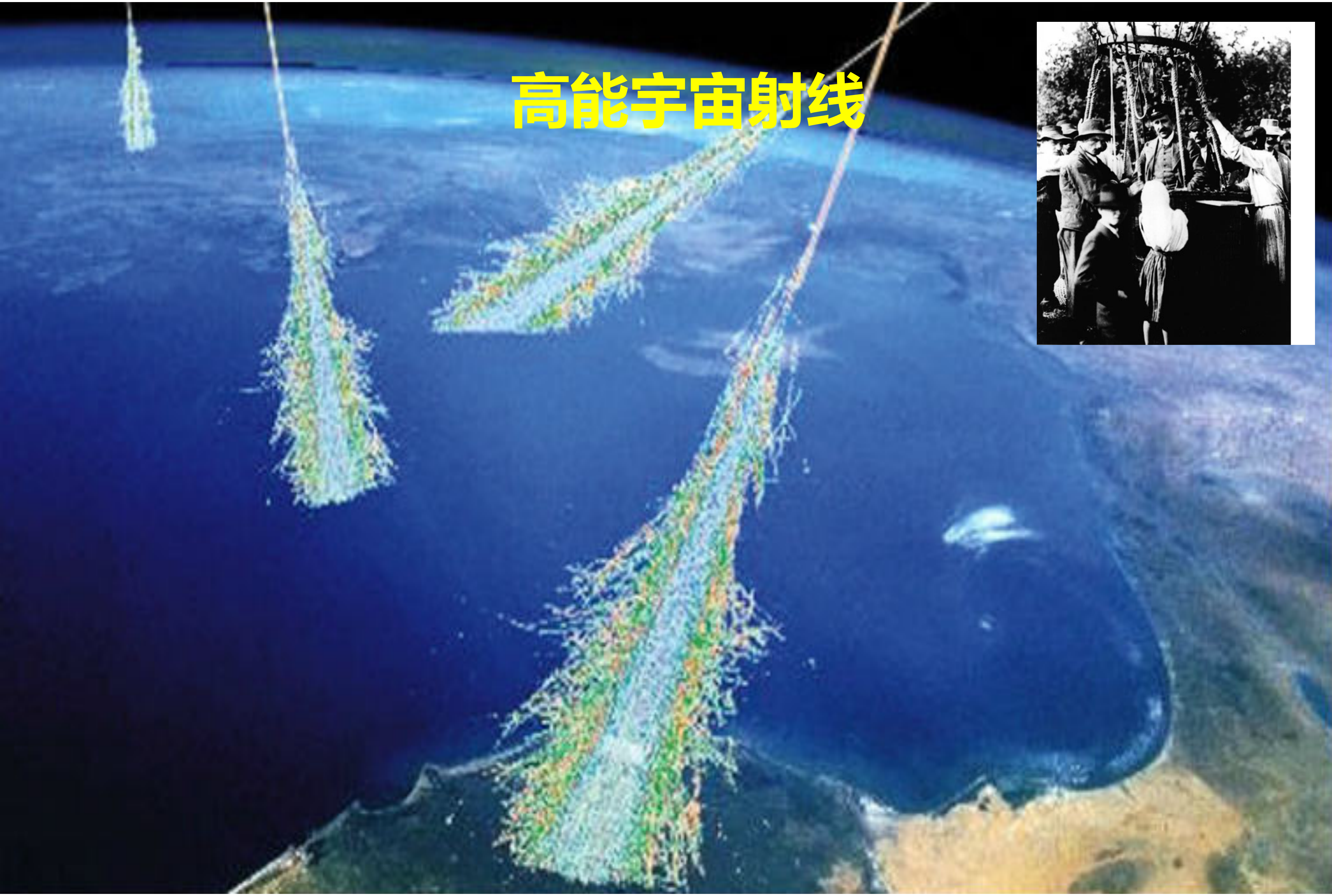
Advantages

- Probe DM annihilation, test the WIMP scenario
- Tiny signals enhanced by huge volume of the DM halo
- Many observables: CR leptons, hadrons, photons in multi-wave lengths. *Both* energy spectra and morphology
- Already place stringent constraints on DM

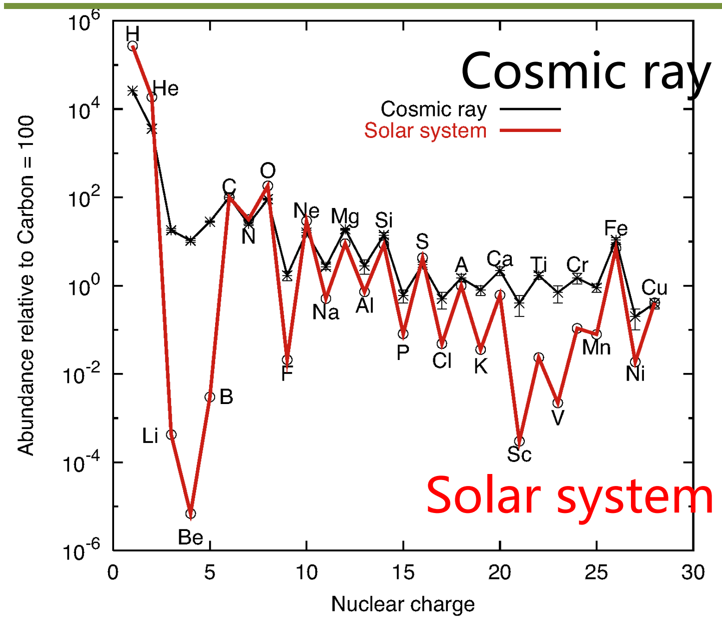
Difficulties

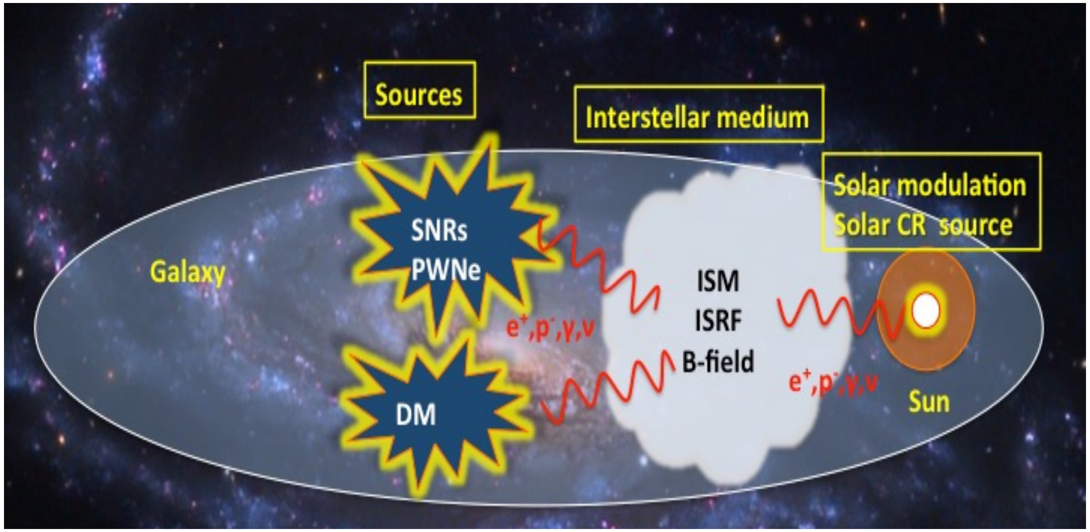
- Hard to distinguish DM "signal" from "background"
- Information lost of charged CRs (after propagation)
  - spectrum change du to E-dependent propagation,
  - convection, re-acceleration, E-loss
  - anisotropic source -->almost isotropic signals
- Significant uncertainties in theoretical predictions
  - models of CR propagation,
  - distributions of ISM,
  - interaction cross sections,
  - Solar modulation

高能宇宙射线



Introduction: propagation of CRs in the Galaxy



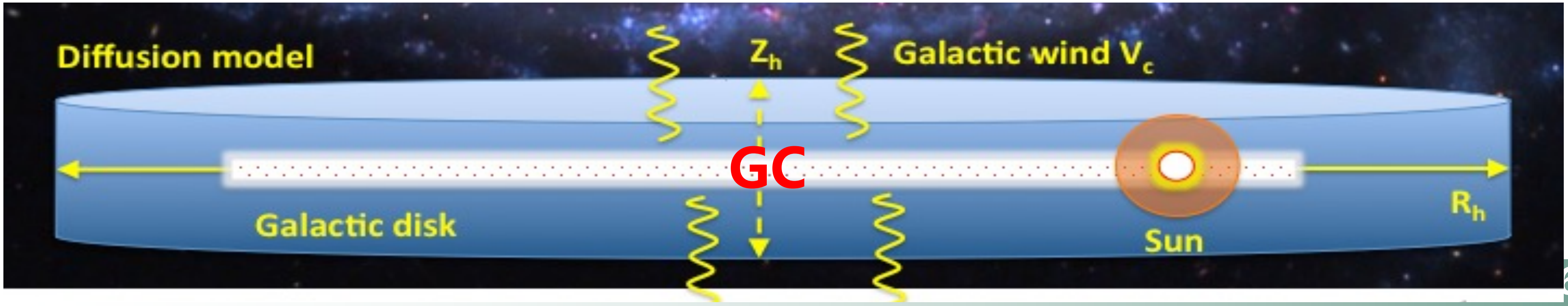


Source of CRs: SNRs, PWNe, AGNs, DM ...

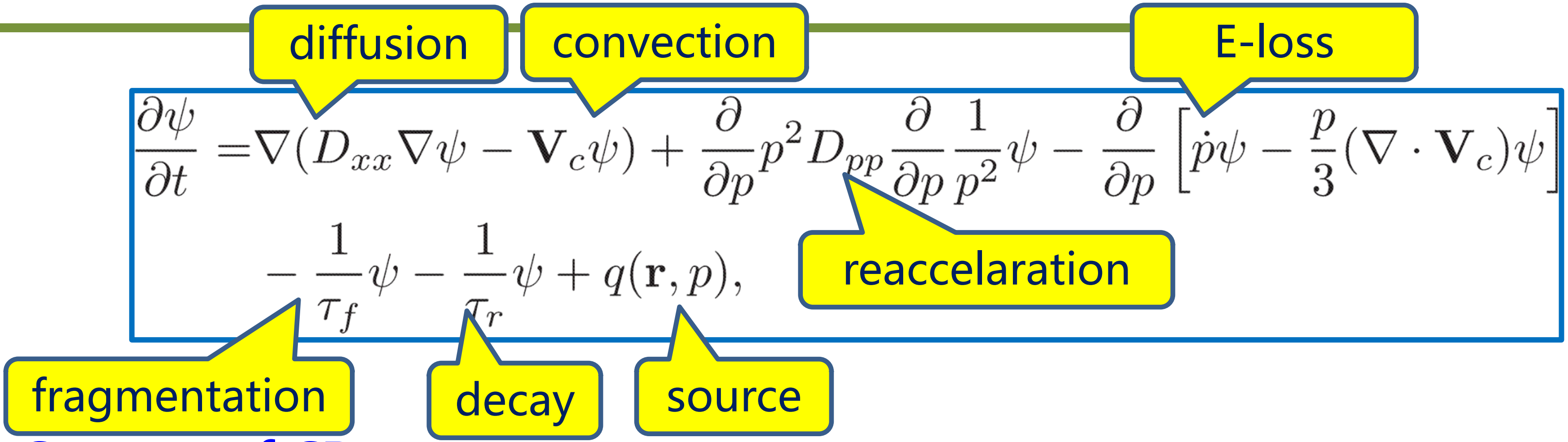
High B/C ratio: CRs trapped in the Galaxy for millions of years! (C+ H→ B+X)

Random magnetic fields: CRs move randomly in the Galaxy

Diffusion approximation: CR diffusion halo: R_h~20 kpc, Z_h~1-5 kpc with isotropic D_{xx}



Cosmic-ray transportation equation



$$\frac{\partial\psi}{\partial t} = \nabla(D_{xx}\nabla\psi - \mathbf{V}_c\psi) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\nabla\cdot\mathbf{V}_c)\psi\right] - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi + q(\mathbf{r},p),$$

Sources of CRs

- Primary sources from SNR, pulsars
- Primary sources from WIMP
- Secondary source from CR fragmentation

Processes in Propagation

- Diffusion (random B field)
- Convection (galactic wind)
- Reacceleration (turbulence)
- Energy loss: Ionization, IC, Synchrotron, bremsstrahlung
- Fragmentation (inelastic scattering)
- Radioactive decay (unstable species)

Solar modulation

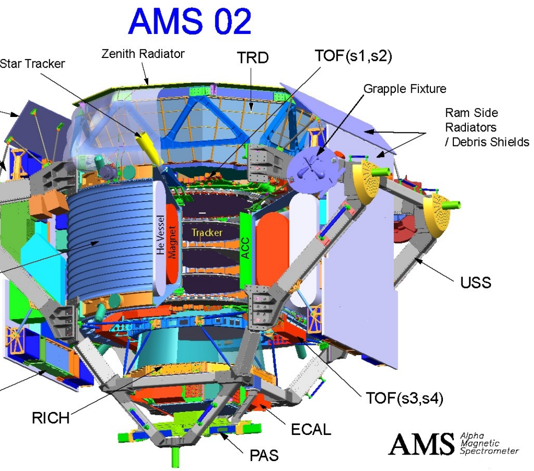
Uncertainties

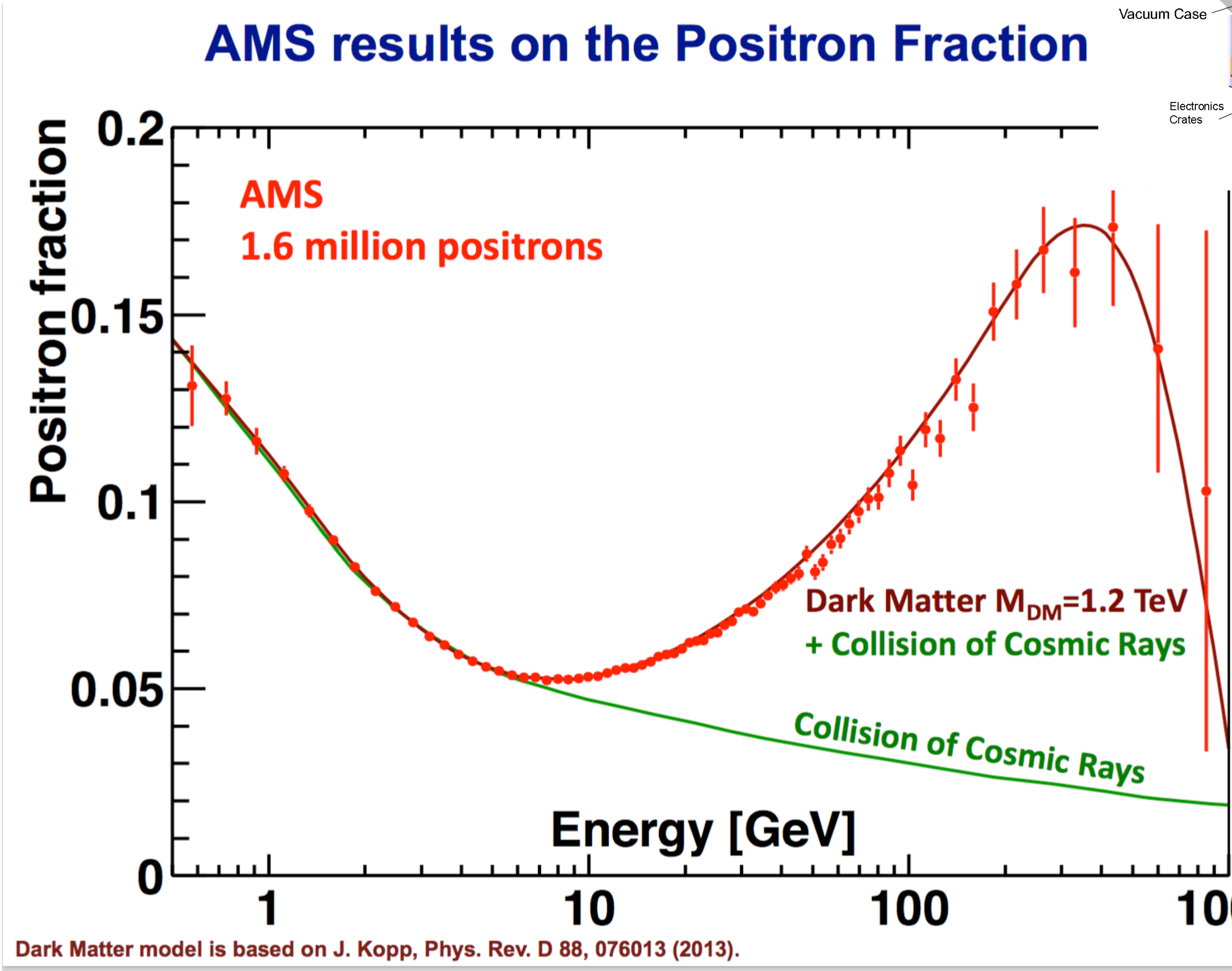
- Distribution of primary sources
- Parameters in the diffusion equatior
- Cross sections for nuclei fragmentat
- Distribution of B field
- Distribution of gas

Approaches

- Semi-analytical:two-zone diffusion r
- Numerical solution using realistic astrophysical data. GALPROP/Dragon code

宇宙正电子反常(PAMELA, AMS-02)

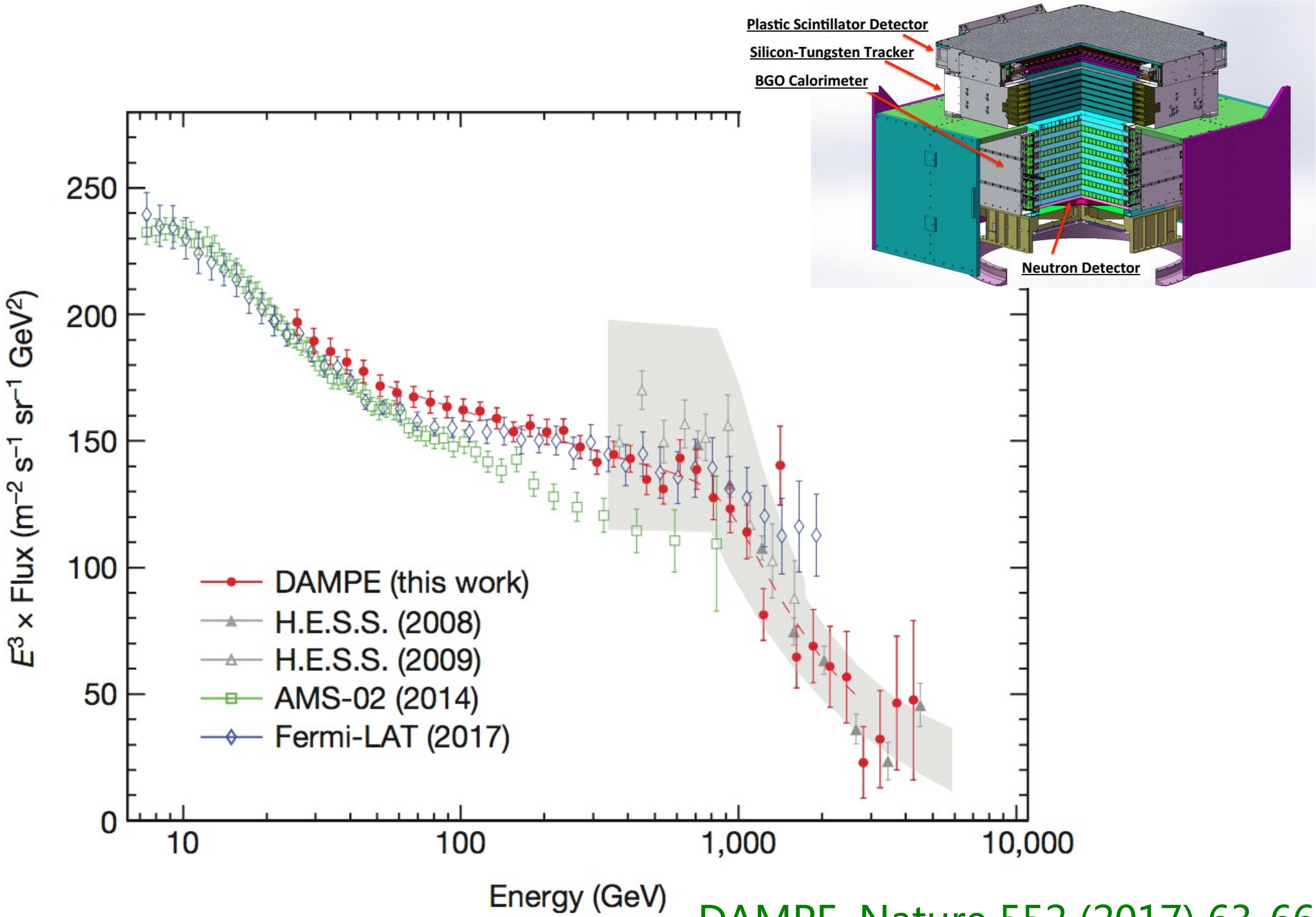




AMS results on the Positron Fraction

Dark Matter model is based on J. Kopp, Phys. Rev. D 88, 076013 (2013).

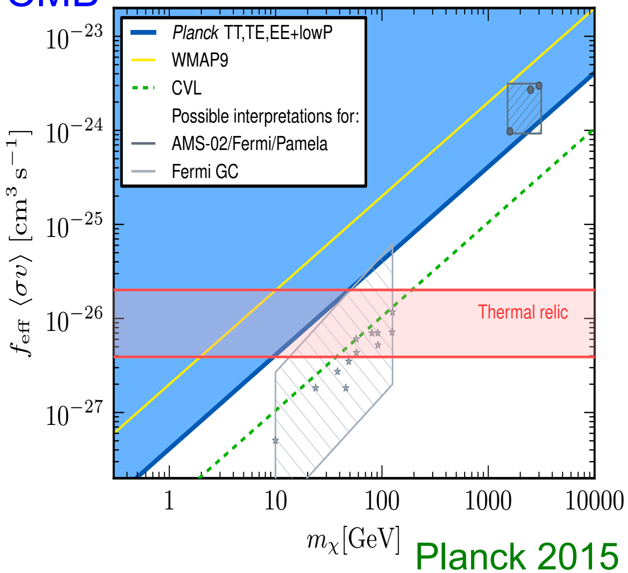
宇宙线电子能谱拐折与疑似超出



DAMPE, Nature 552 (2017) 63-66

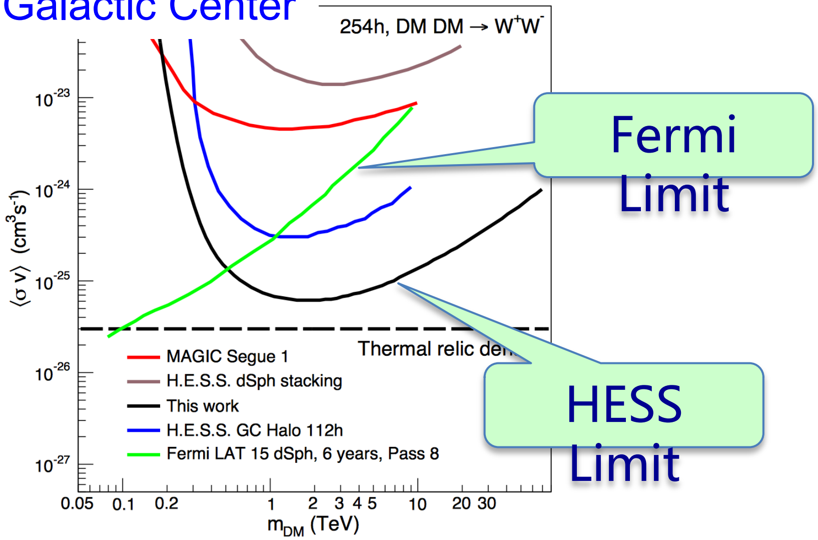
Stringent constraints on DM interpretations

CMB



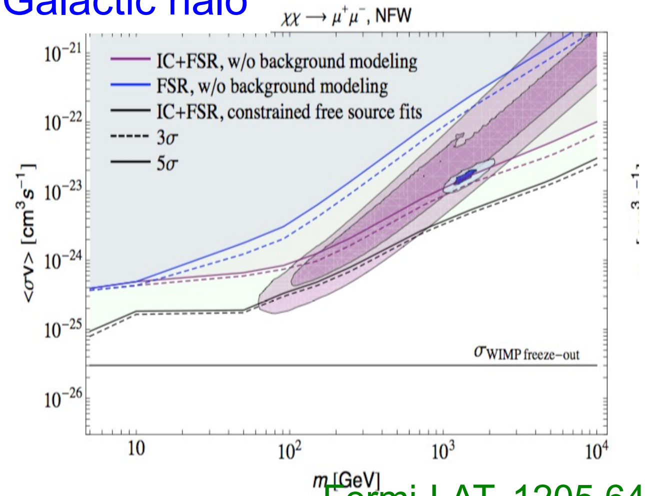
Planck 2015

Galactic Center



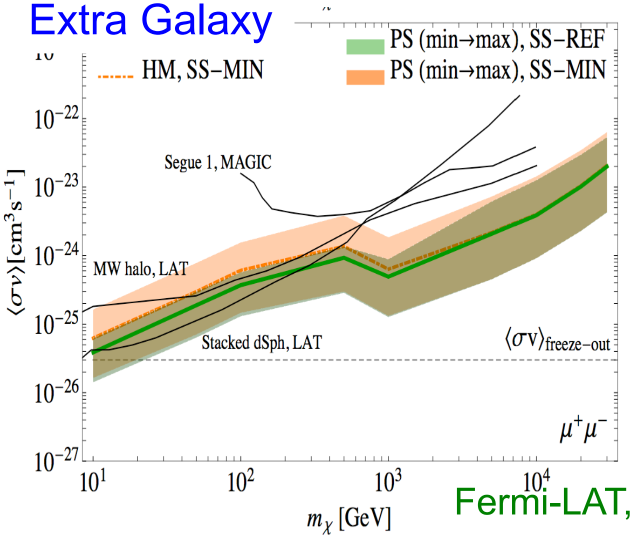
HESS 2016

Galactic halo



Fermi-LAT, 1205.6467

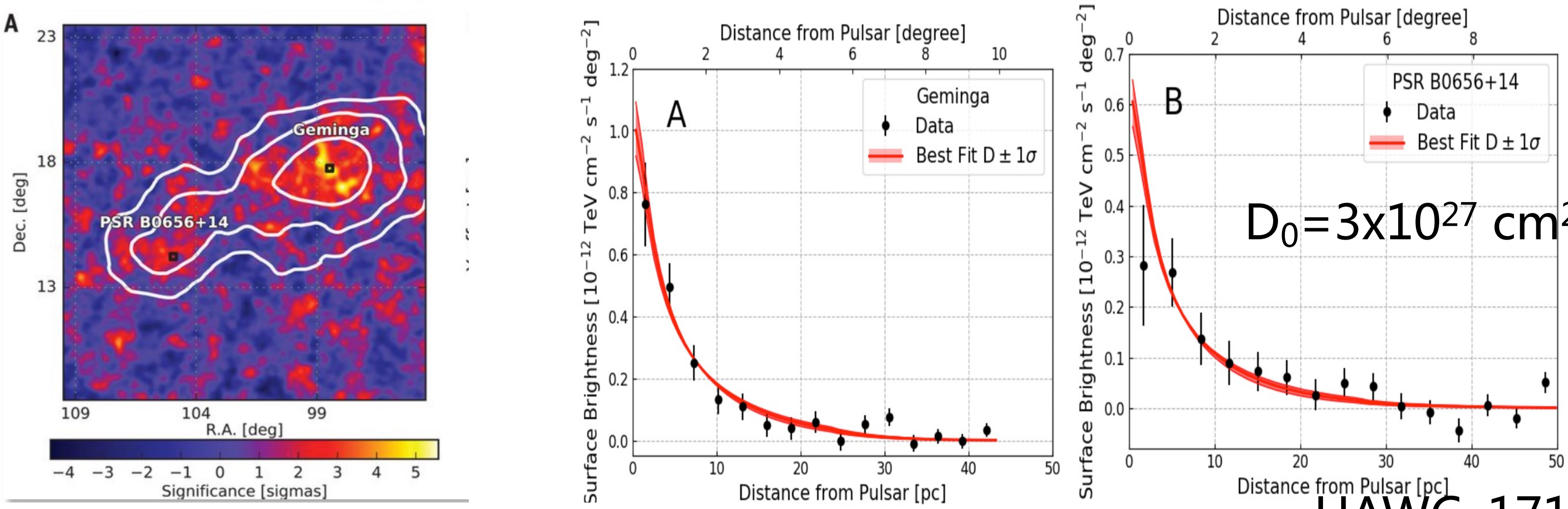
Extra Galaxy



Fermi-LAT, 1501.05464

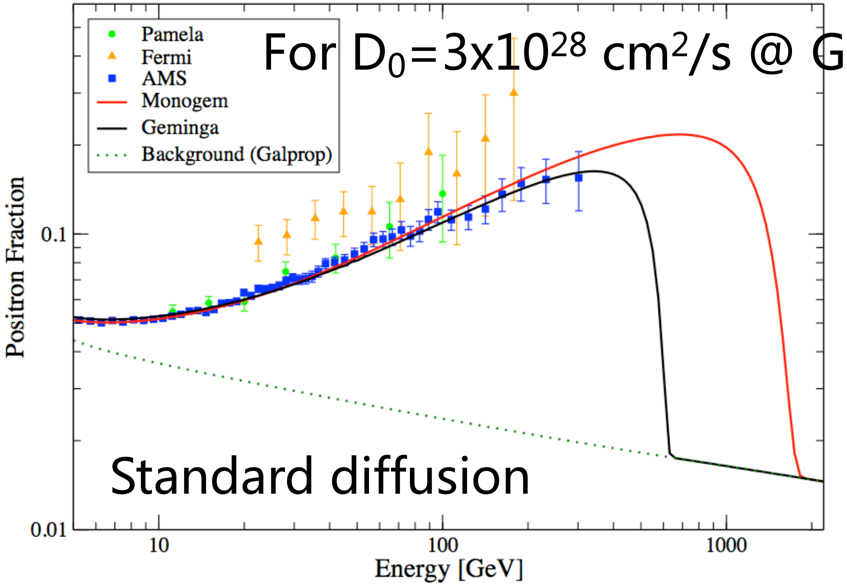
pulsar interpretations: challenges from the HAWC data

HAWC show upexpected slow diffusion of electrons from Geminga and PSR B065



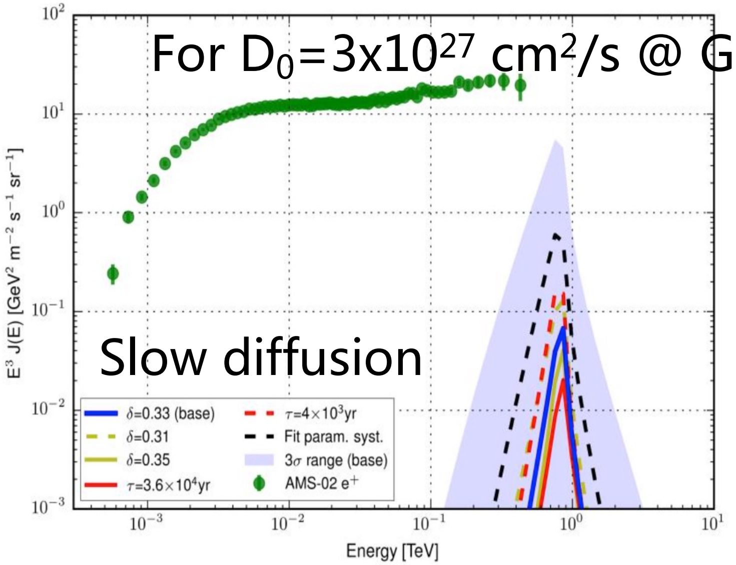
$D_0=3\text{x}10^{27}$ cm^2/s @ Ge

HAWC, 1711.06223



For $D_0=3\text{x}10^{28}$ cm^2/s @ GeV

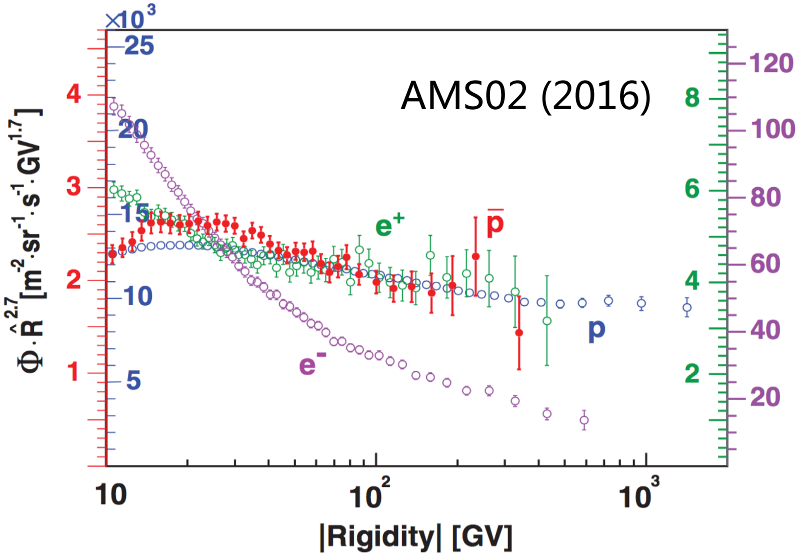
Standard diffusion



For $D_0=3\text{x}10^{27}$ cm^2/s @ GeV

Slow diffusion

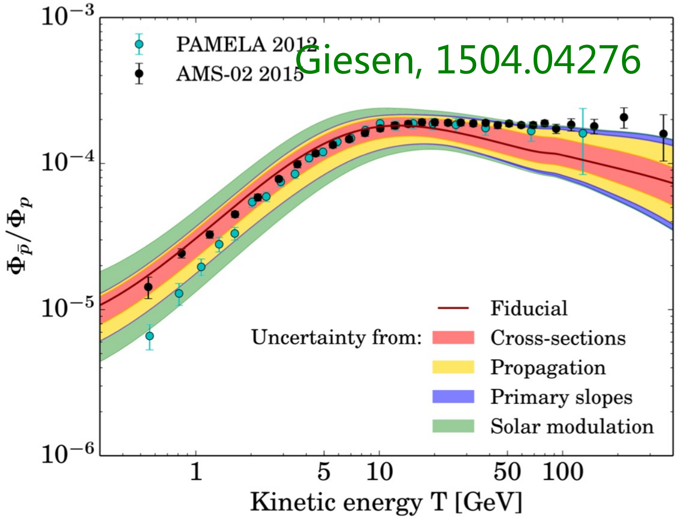
CR antiprotons



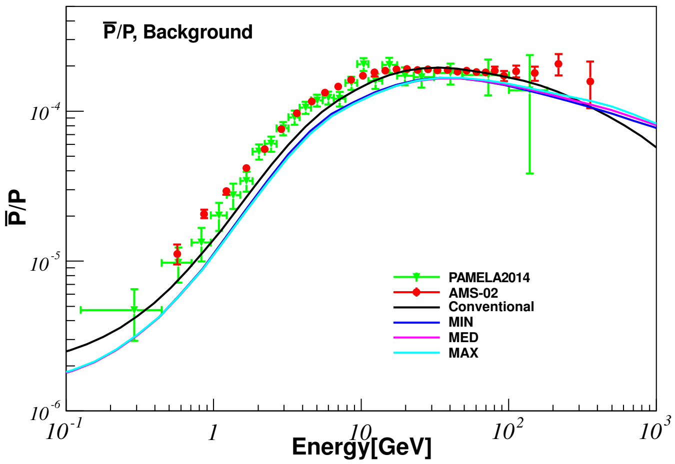
CR antiprotons

- 🟥 Pulsars unlikely to contribute
- Cooling is less important compared with that for electron
- SNRs still possible sources，but strongly correlated with proton spectrum.
- More sensitive to propagation parameters and DM profile

AMS-02 data roughly consistent with the background

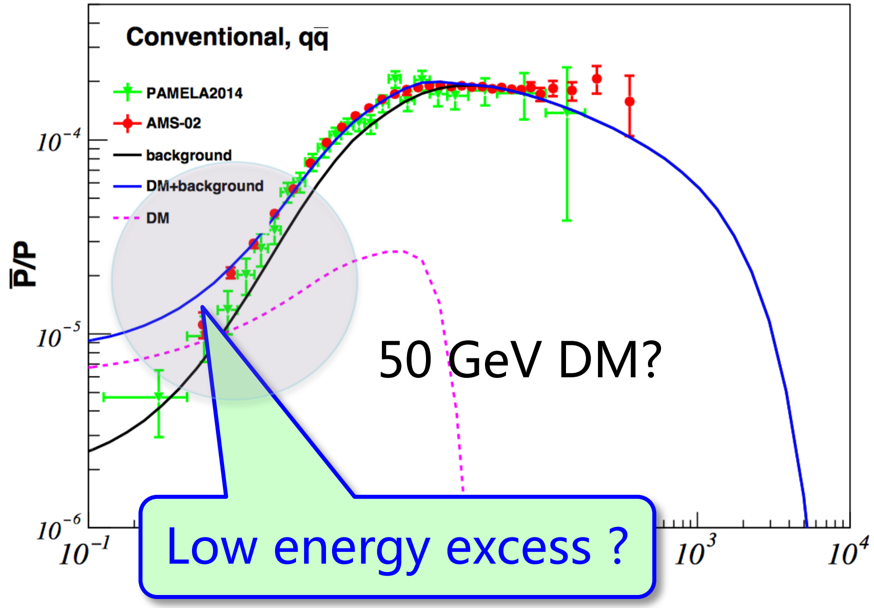


Giesen, 1504.04276



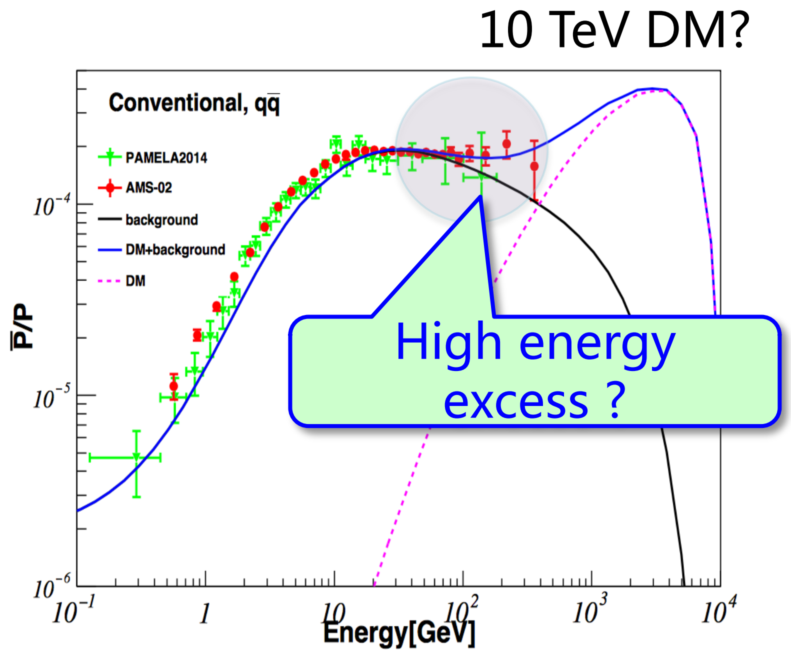
H.B.Jin, Y.L.Wu, YFZ, 1504.04601, PRD

Possible excesses and DM interpretations



50 GeV DM?

Low energy excess ?



10 TeV DM?

High energy excess ?

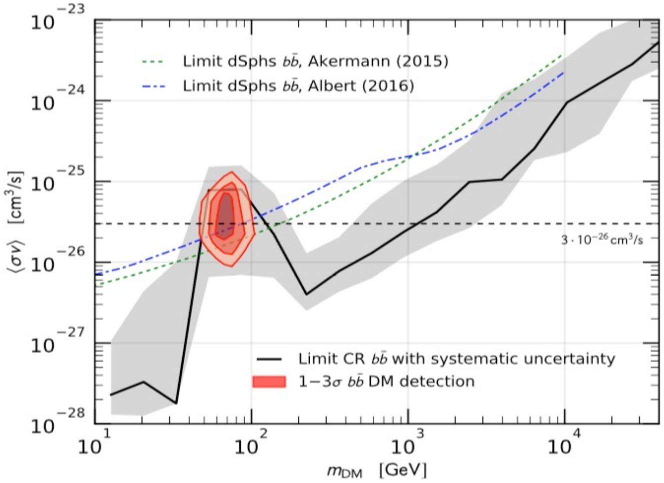
H.B.Jin, Y.L.Wu, YFZ arXiv:1504.04601, PRD

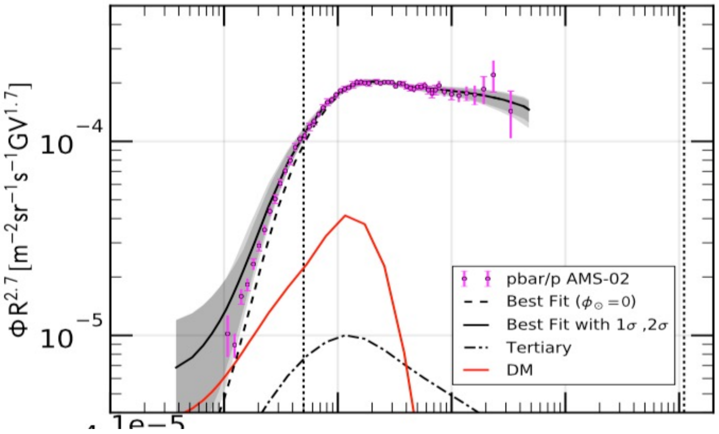
Low energy excess: 40-50 GeV DM to 2b, thermal cross section, consistent with GC
High energy excess: 10 TeV DM annihilation into 2W, 2b, boost factor ~10-100

Giesen, 1504.04276; Ibe 1504.05554;
Hamaguchi, 1404.05937; Lin, 1504.07230
Chen, 1504.07848; Chen,1505.00134

antiproton “excess”: low-energy region

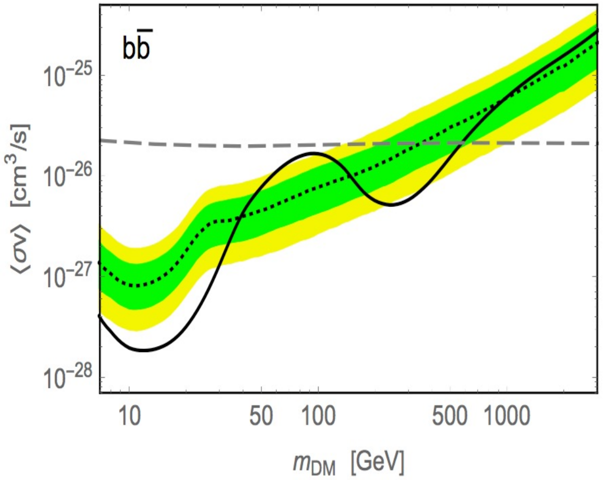
a 4σ excess ?

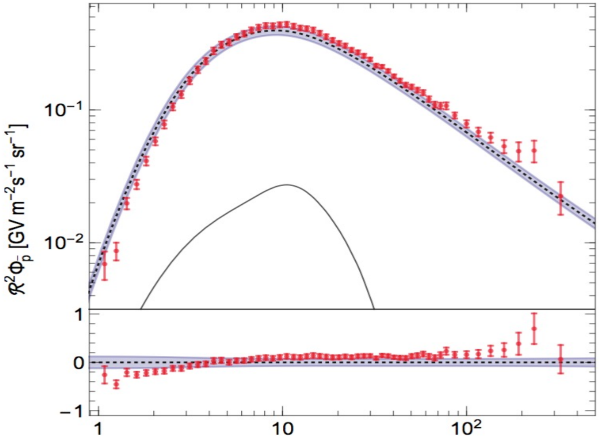




Cuoco, et al, 1610.03071
Cui, et al, 1610.03840

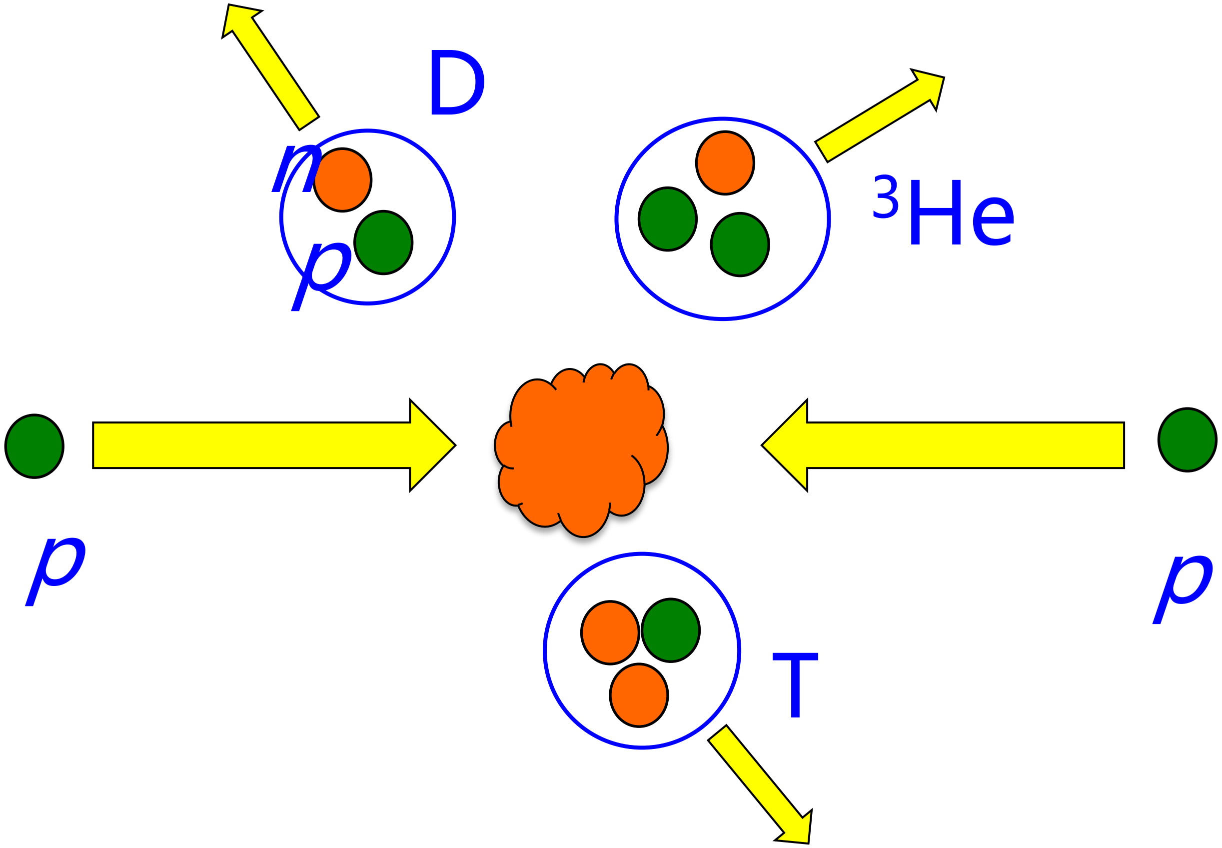
Reduce to 2.2σ (global 1.1σ) after including uncertainties in hadronic cross sections





Reinert, Winker, 1712.00002

heavy CR anti-nuclei



production threshold: 17m_p (antideuteron), 31m_p (antihelium)

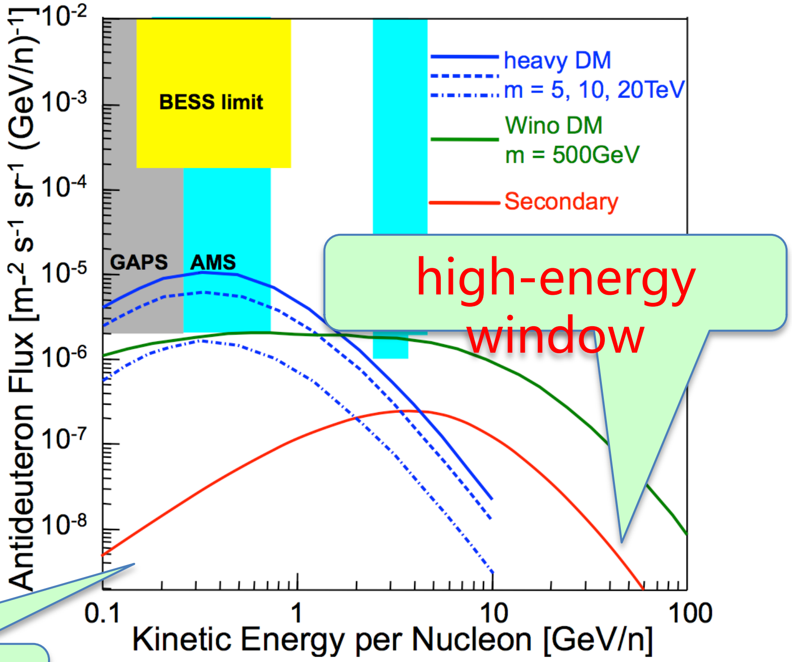
heavy anti-nuclei

Spectra feature of secondary anti-nuclei

- Highly boosted after production
  - production threshold: $17m_p$ (antideuteron), $31m_p$ (antihelium)
  - low binding energy → less energy loss
  - leave a low-energy window (<GeV) for exotic contributions
- Low production rate towards high energ
  - fast falling of primary CRs $\sim E^{-2.7}$
  - leave a high-energy window (>100 GeV
  - exotic contributions

Major source of uncertainties

- DM profiles (NFW, Einasto, Isothermal, ..
- CR propagation models (MIN, MED, MA
- Models for anti-nuclei formation
  - potential models
  - coalescence models
  - thermal models



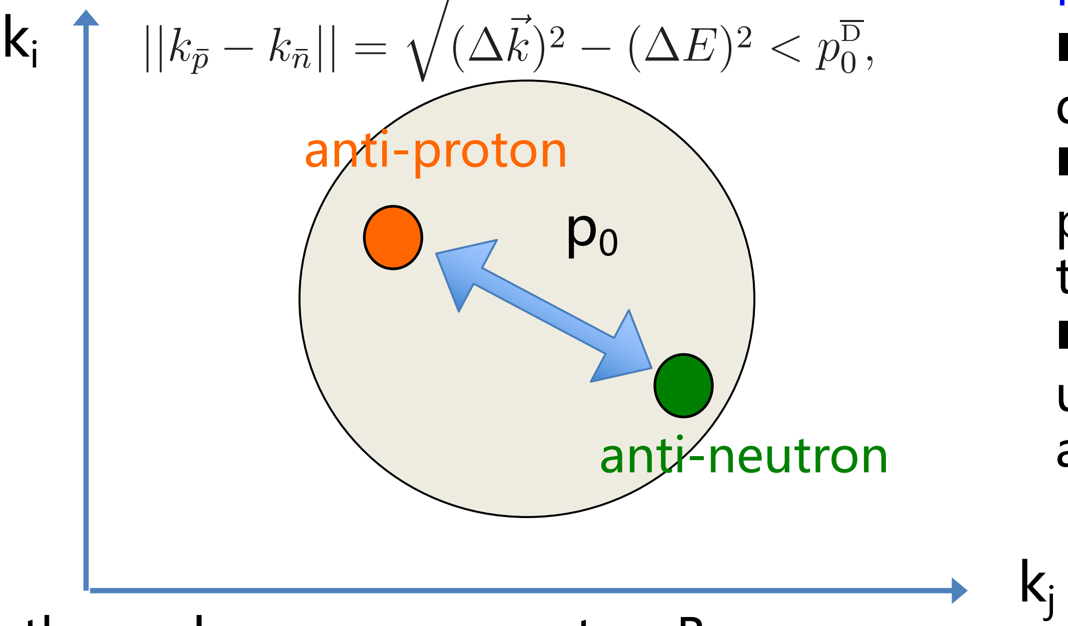
Low-energy window

Aramaki, etal, 1505.07785

Formation of heavy nuclei: the coalescence model

The coalescence condition:
relative momenta must be small enough

The coalescence model: A=2 case



$$||k_{\bar{p}} - k_{\bar{n}}|| = \sqrt{(\Delta\vec{k})^2 - (\Delta E)^2} < p_0^{\bar{D}},$$

Main features

- ■phase-space model, no dynamics
- ■ extremely simple (only one parameter p_0), but describe with the data very well
- ■ coalescence rate ~ $p_0^{3(A-1)}$, uncertainty in p_0 can be amplified

the coalescence parameters B_A

$$E_A \frac{d^3N_A}{dp_A^3} = B_A \left(E_p \frac{d^3N_p}{dp_p^3} \right)^Z \left(E_n \frac{d^3N_n}{dp_n^3} \right)^N, \vec{p}_p = \vec{p}_n = \vec{p}_A/A$$

model prediction (assuming no correlations):

$$\frac{dN_{\bar{d}}}{dT_{\bar{d}}} = \frac{p_0^3}{6} \frac{m_{\bar{d}}}{m_{\bar{n}} m_{\bar{p}}} \frac{1}{\sqrt{T_{\bar{d}}^2 + 2m_{\bar{d}}T_{\bar{d}}}} \frac{dN_{\bar{n}}}{dT_{\bar{n}}} \frac{dN_{\bar{p}}}{dT_{\bar{p}}},$$

Formation of heavy anti-nuclei: the coalescence model

The coalescence model

- no dynamics (phase-space mo
- only one parameter p_0
- coalescence rate ~ $p_0^{(2A-1)}$

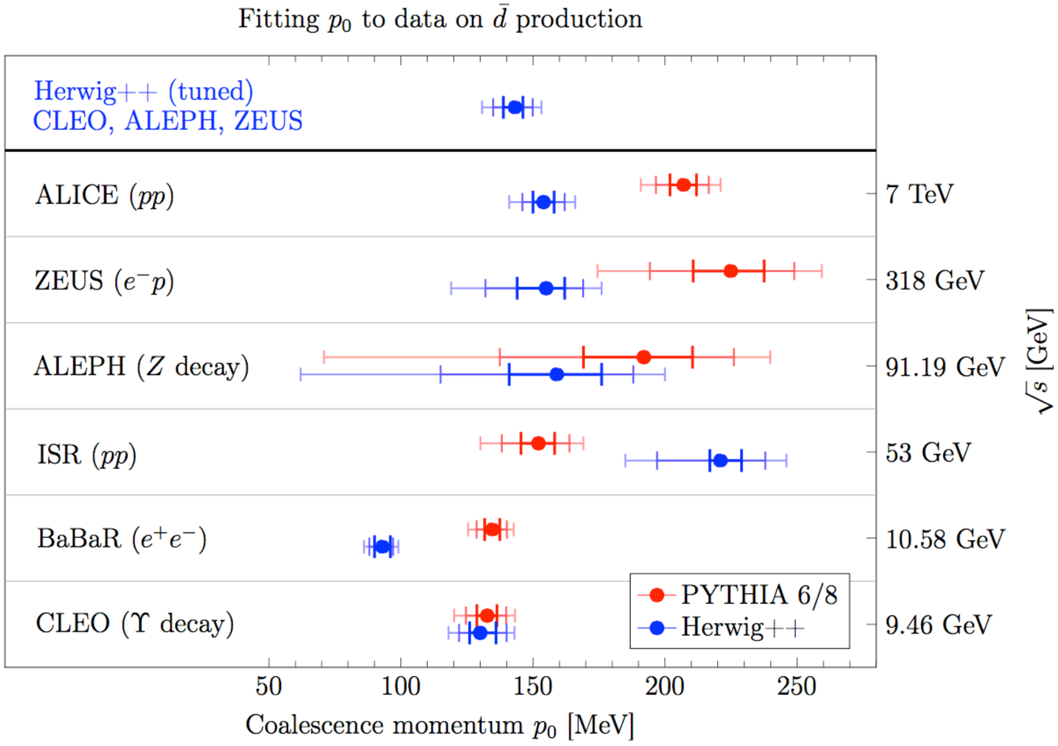
The case of anti-deuteron

$$||k_{\bar{p}} - k_{\bar{n}}|| = \sqrt{(\Delta\vec{k})^2 - (\Delta E)^2} < p_0^{\bar{D}},$$

Energy spectrum of anti-deuteror

$$\frac{dN_{\bar{d}}}{dT_{\bar{d}}} = \frac{p_0^3}{6}\,\frac{m_{\bar{d}}}{m_{\bar{n}}m_{\bar{p}}}\,\frac{1}{\sqrt{T_{\bar{d}}^2 + 2m_{\bar{d}}T_{\bar{d}}}}\,\frac{dN_{\bar{n}}}{dT_{\bar{n}}}\,\frac{dN_{\bar{p}}}{dT_{\bar{p}}}$$

Determination of p^0 for anti-deuteron



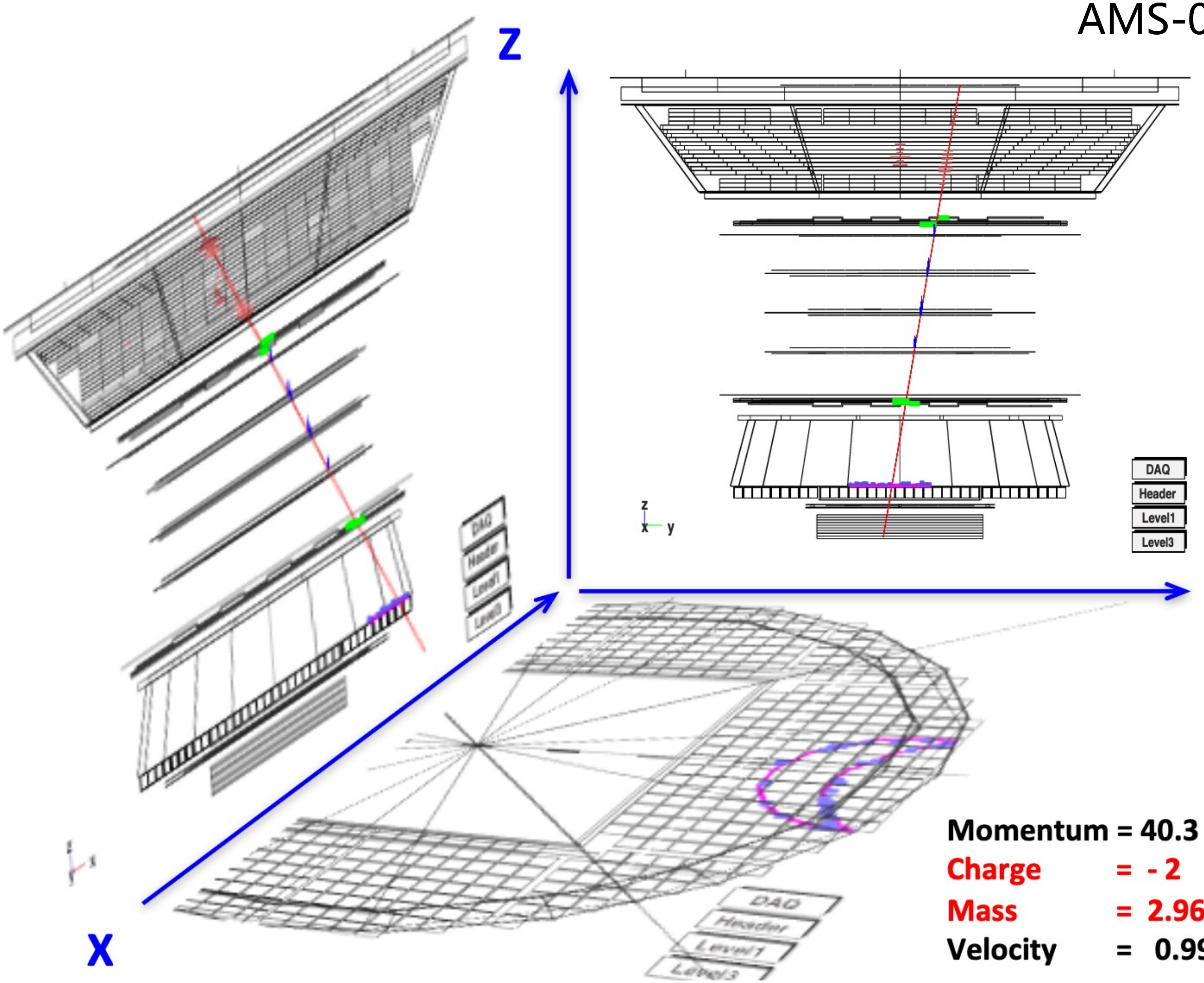
Aramaki, etal, 1505.07785

The case of anti-helium

- Use the relation between nucl $p_{0A}^{\overline{\mathrm{He}}} = \langle p_0^{\mathrm{He}}/p_0^{\mathrm{D}}\rangle\, p_0^{\bar{\mathrm{D}}} = 1.28\, p_0^{\bar{\mathrm{D}}} = 0.246 \pm 0.038$ GeV.
- Use binding energy: $p_{0B}^{\overline{\mathrm{He}}} = \sqrt{E_b^{\overline{^3\mathrm{He}}}/E_b^{\bar{\mathrm{D}}}}\; p_0^{\bar{\mathrm{D}}} = 0.357 \pm 0.059$ GeV.
- Use Exp. data (e.g. ALICE, but energy scale is too high)

AMS-02 antihelium-3 candidate events

AMS-02 （2016）



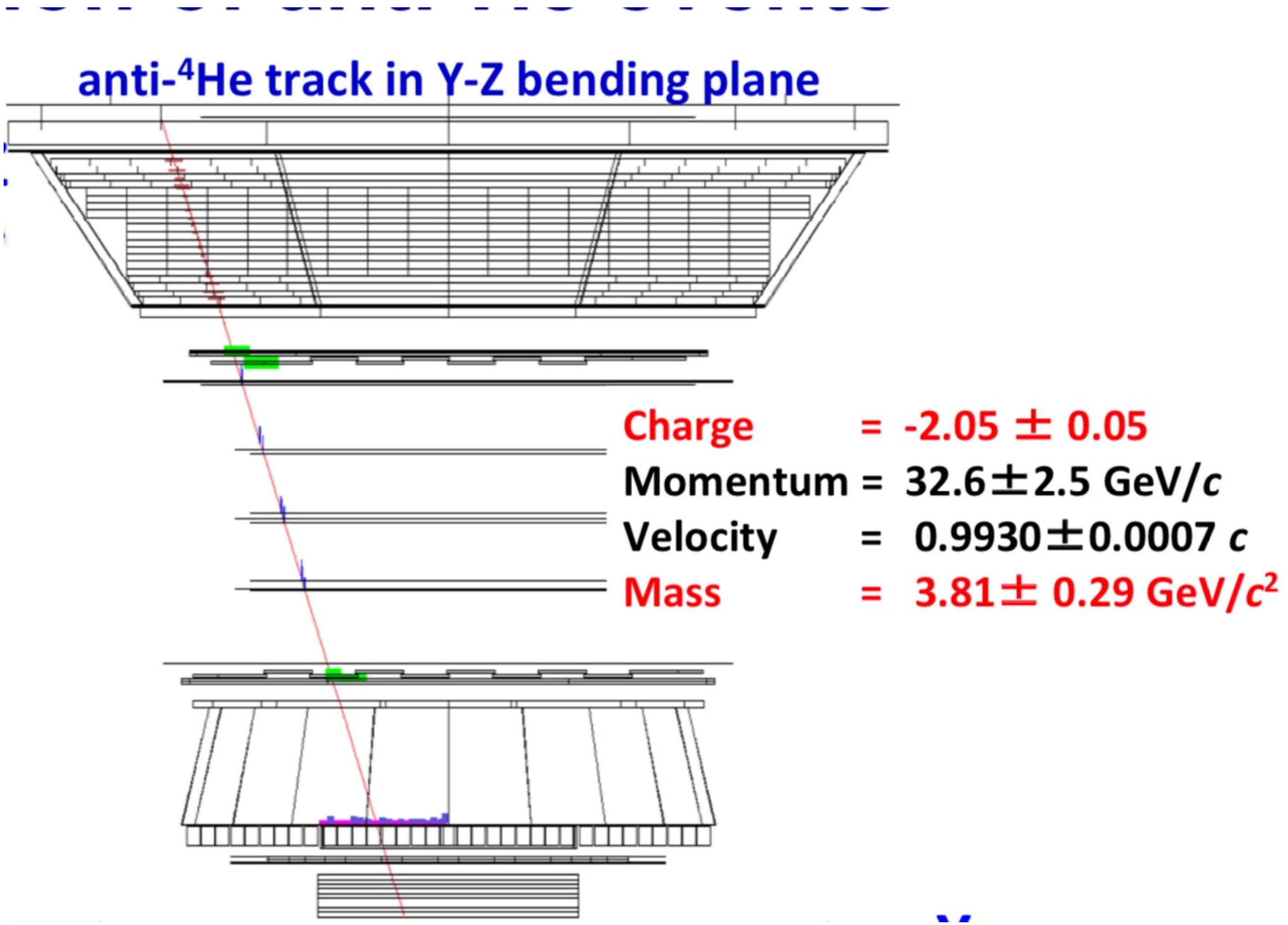
Momentum = **40.3 ±2.9 GeV/*c***

Charge = **- 2**

Mass = **2.96±0.33 GeV/c^2**

Velocity = **0.9973±0.0005 *c***

AMS-02 antihelium-4 candidate events



anti-^{4}He track in Y-Z bending plane

Charge = -2.05 ± 0.05

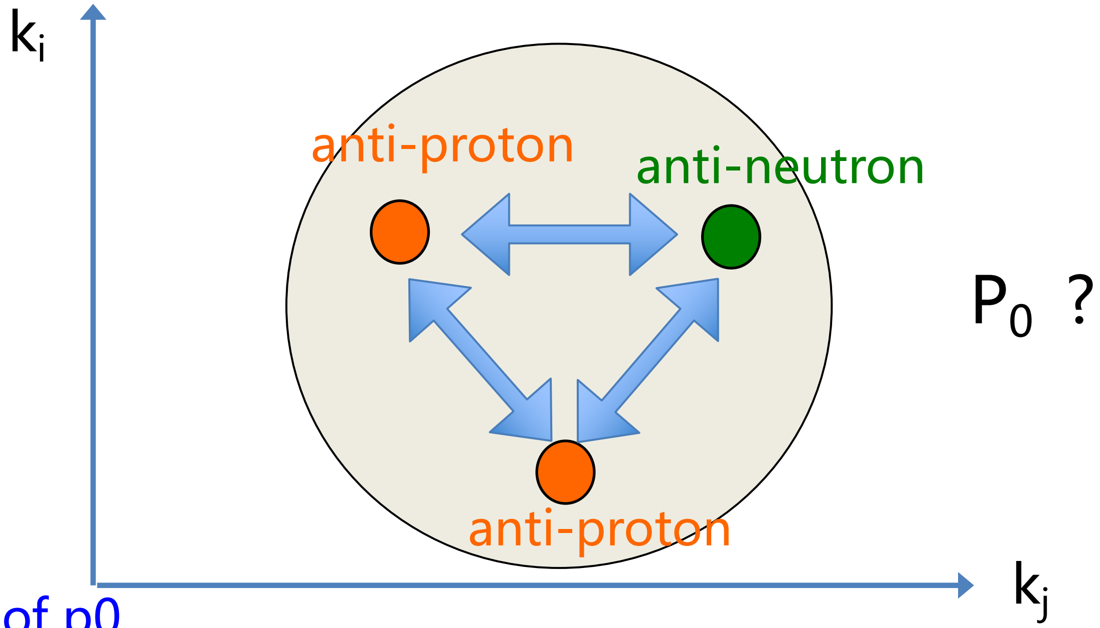
Momentum = 32.6±2.5 GeV/*c*

Velocity = 0.9930±0.0007 *c*

Mass = 3.81± 0.29 GeV/c^2

The case of anti-helium

The coalescence model: A=3 case (antijhelium)



Definitions of p0

- minimal circle

$$d_{\mathrm{circ}} = \frac{l_1 l_2 l_3}{\sqrt{(l_1+l_2+l_3)(-l_1+l_2+l_3)(l_1-l_2+l_3)(l_1+l_2-l_3)}} < p_0^{\overline{\mathrm{He}}}.$$

- absolute difference for each relative momenta

$$||k_i - k_j|| < p_0^{\overline{\mathrm{He}}}, \qquad (i \neq j).$$

Coalescence momentum of anti-Helium

Indirect approaches

- Use the relation between nucl

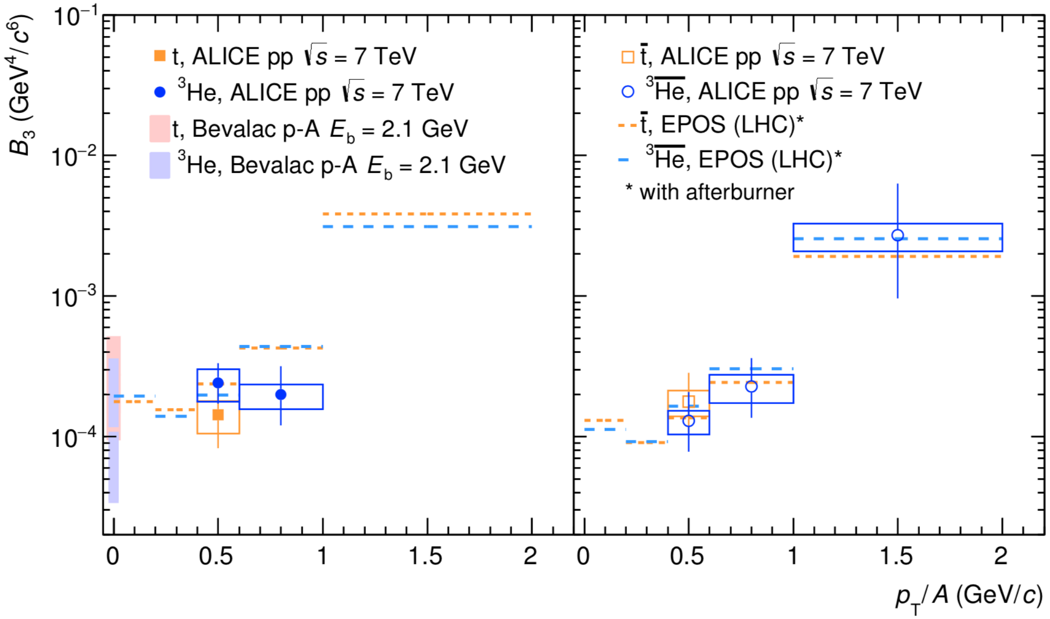
$$p_{0A}^{\overline{\mathrm{He}}} = \langle p_0^{\mathrm{He}}/p_0^{\mathrm{D}}\rangle\, p_0^{\bar{\mathrm{D}}} = 1.28\, p_0^{\bar{\mathrm{D}}} = 0.246 \pm 0.038\ \mathrm{GeV}.$$

- Use binding energy:

$$p_{0B}^{\overline{\mathrm{He}}} = \sqrt{E_b^{3\overline{\mathrm{He}}}/E_b^{\bar{\mathrm{D}}}}\, p_0^{\bar{\mathrm{D}}} = 0.357 \pm 0.059\ \mathrm{GeV}.$$

Direct approaches

- Use Exp. data (e.g. ALICE, STAR)



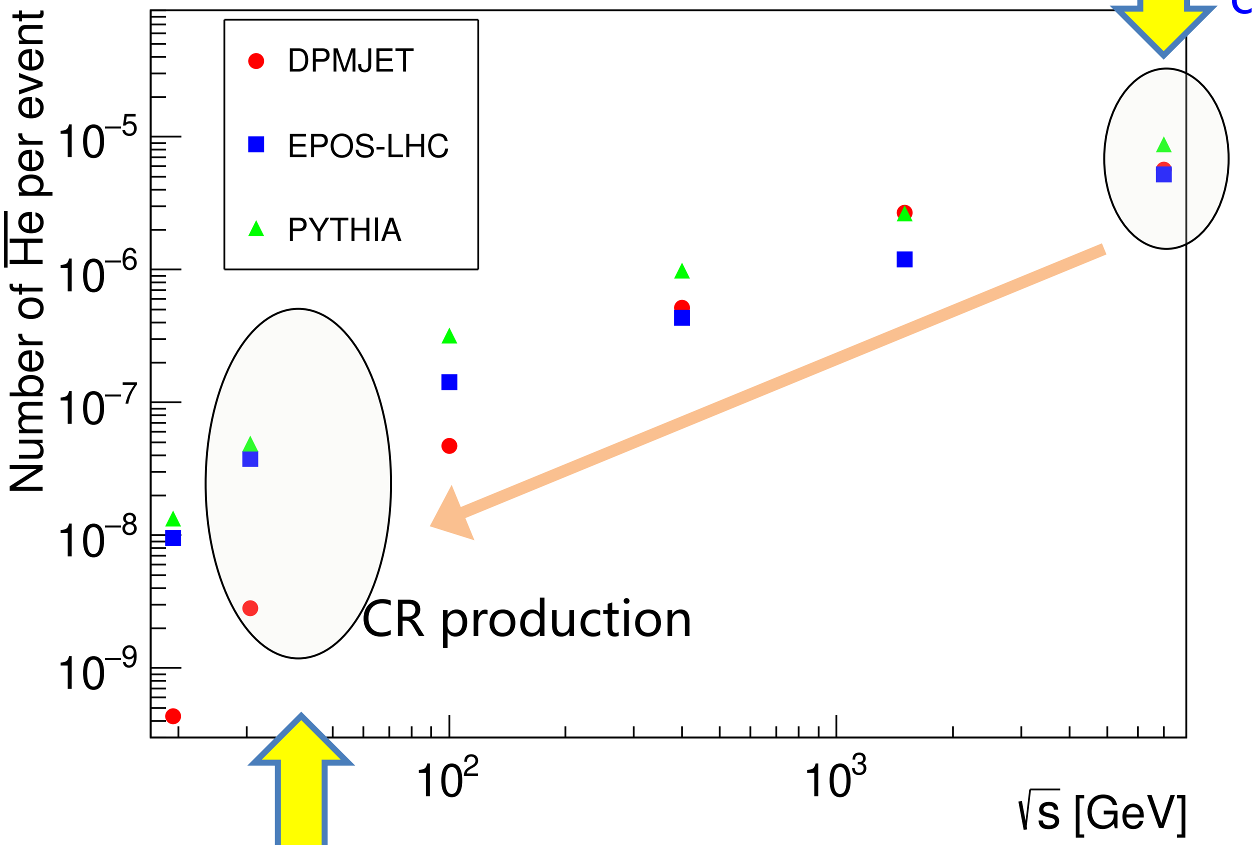
ALICE, 1709.08522 (assuming rate ~ $(p_0)^6$)

Significant uncertainties arise when extrapolating to low energies

ALICE data is for E_{cm}=7 TeV, to high for CR anti-helium production

E_{cm} =7 TeV

collider production

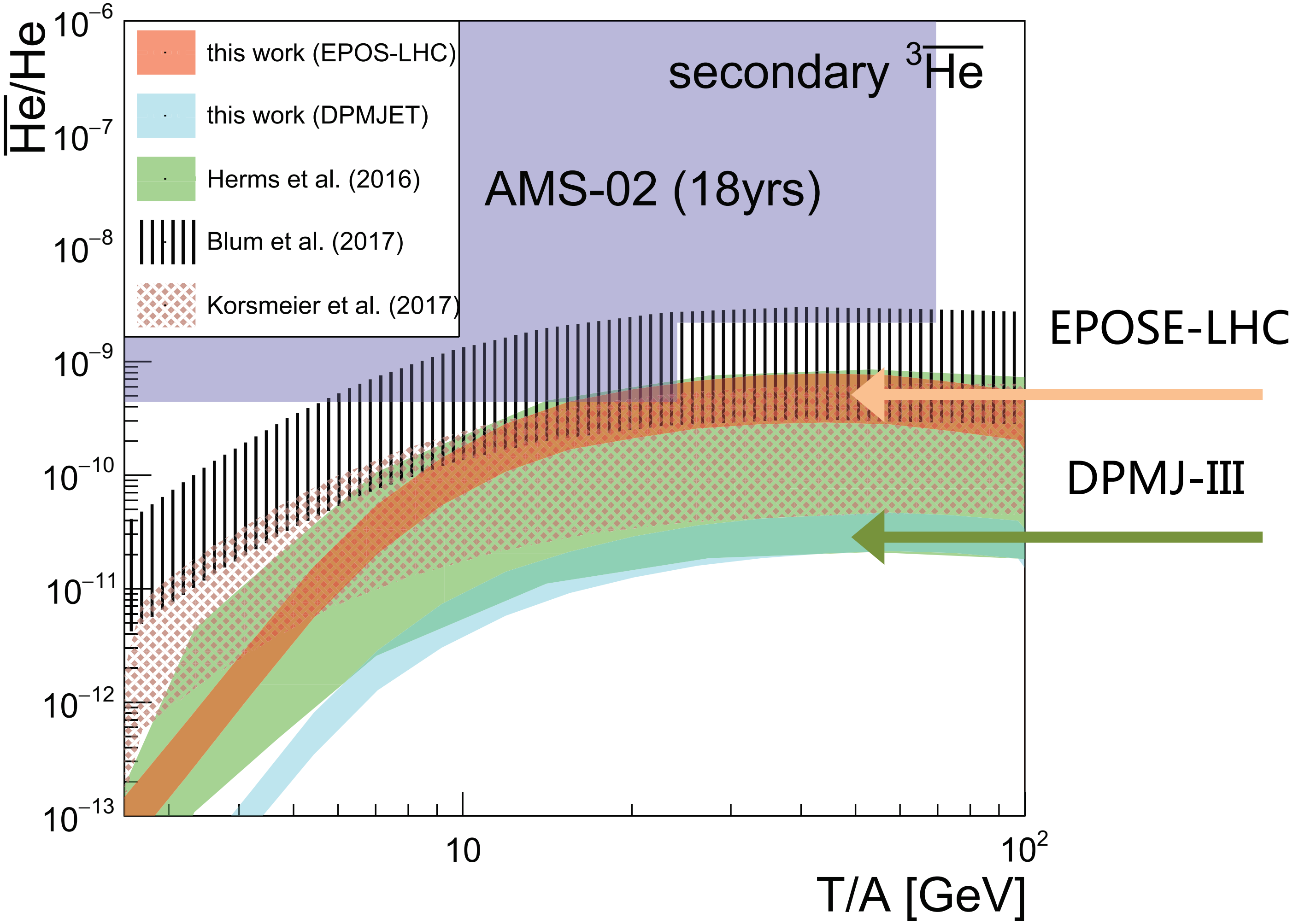


CR production

E_{cm} ~ 50 GeV

energy scale relevant to CR anti-helium production

Predicted secondary backgrounds

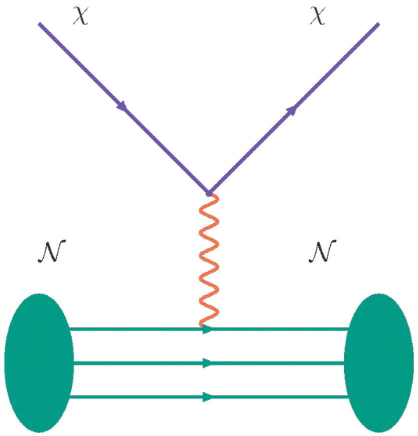


EPOSE-LHC

DPMJ-III

Y.C. Ding, N. Li, C.C.Wei, Y.L.Wu, YFZ, 1808.03612, JCAP

暗物质直接探测



散射截面.

$$R = N_T \left(\frac{\rho_0}{m_\chi}\right) \frac{m_A \sigma_0}{2\mu_A^2} \int F^2(E_R)\, dE_R \int_{v_{min}}^{v_{esc}} d^3v \frac{f(v)}{v} ,$$

局域暗物质密度

核子形状因子
暗物质形状因子

暗物质局域速度分布

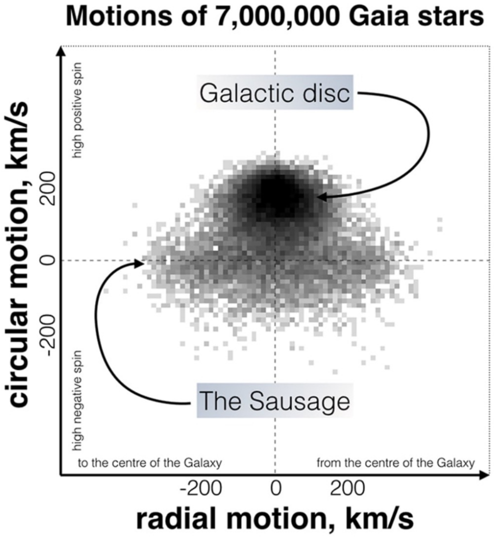
Theoretical assumptions commonly adopted

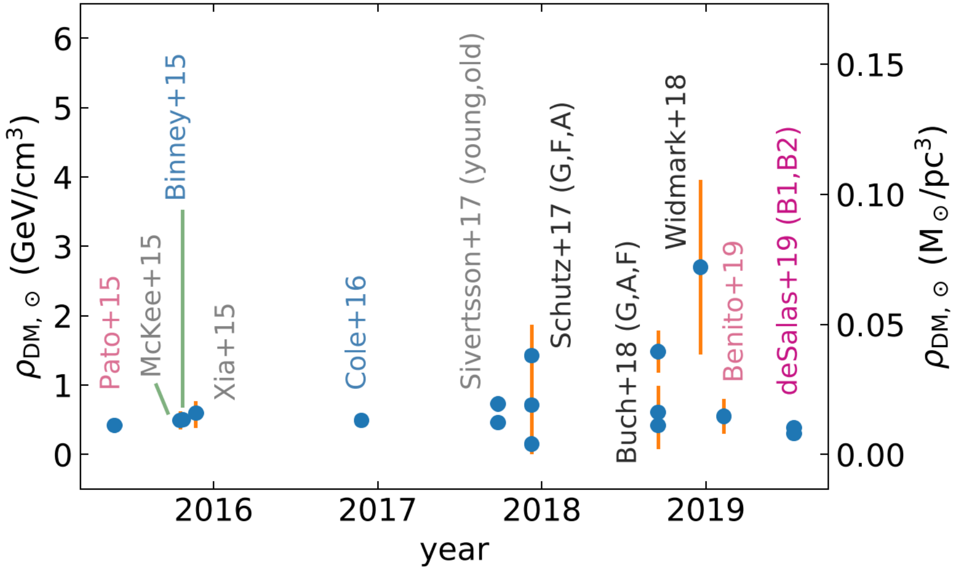
- Velocity distribution of halo DM (Maxwellian-Boltzmann ? Eddington’s formula)
- Smooth local DM energy density (rho=0.2-0.7 GeV/cm^3)
- Form factors (Helm etc.)
- Contact interactions (heavy mediator, no q^2 and v-dependences)
- Elastic scatterings
- Isospin-conserving interactions (for SI cross-section)

DM local velocity distribution

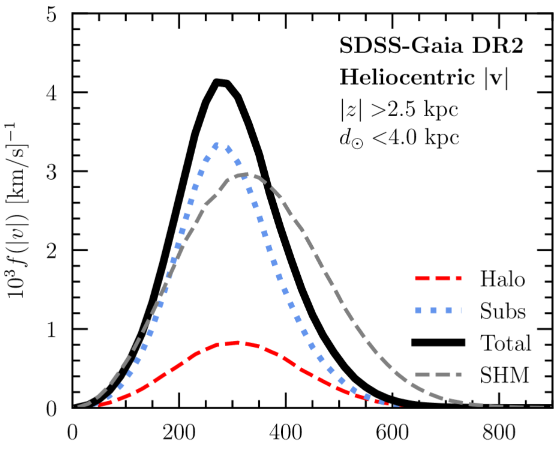
Gaia, SDSS 等一批新数据出现

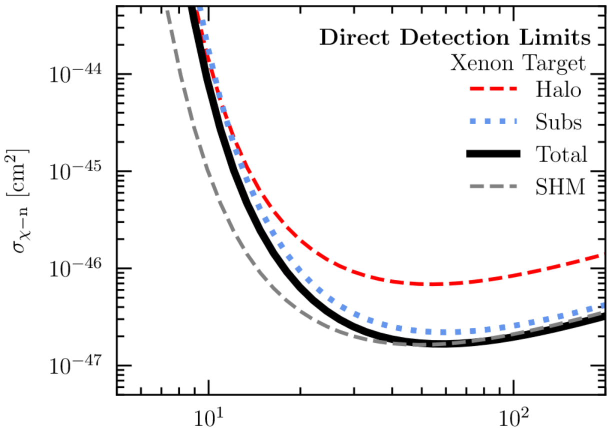
- ☐ 暗物质密度 0.3-0.4 GeV/cm3
- ☐ 子结构 Gaia-Sausage





- ☐ 暗物质速度分布
- ☐ 对直接探测的影响

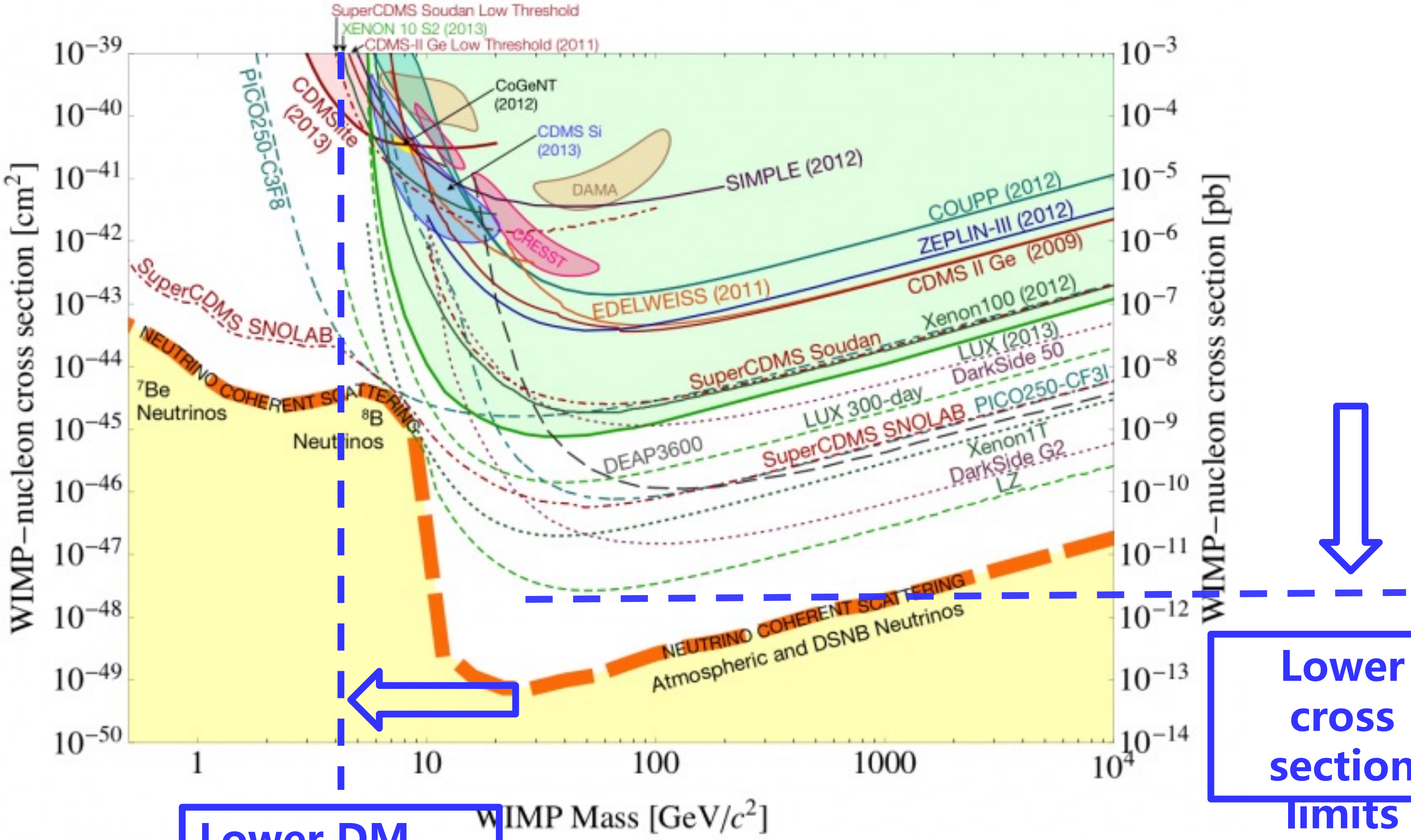




子结构内暗物质的运动速度更低→ 更弱的散射截面limit

L. Necib, et al,1807.0251

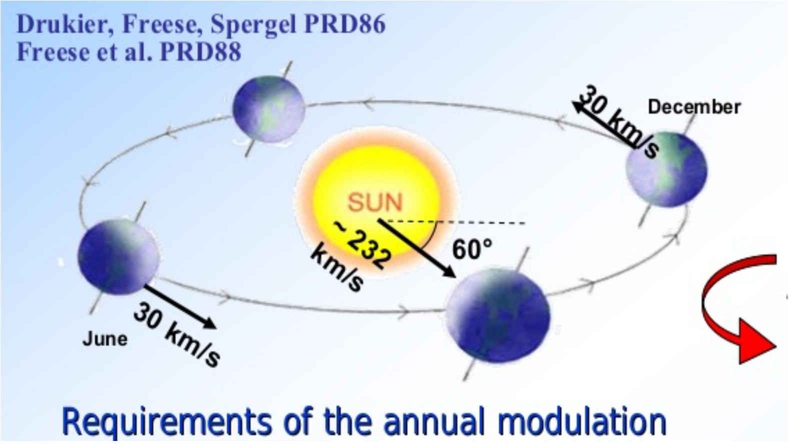
Two frontiers of dark matter direct detection experiments



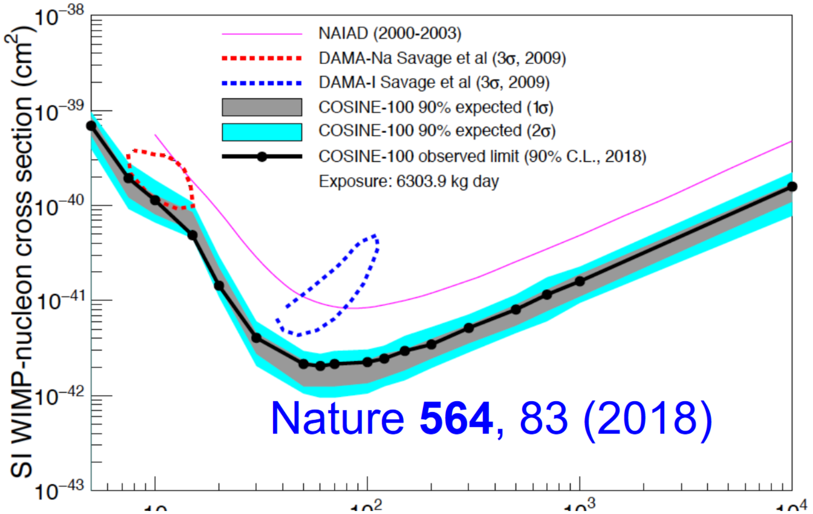
Lower DM mass

Lower cross section limits

DAMA vs. COSINE



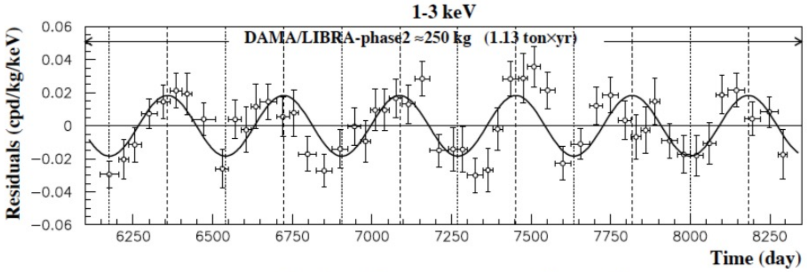
Requirements of the annual modulation



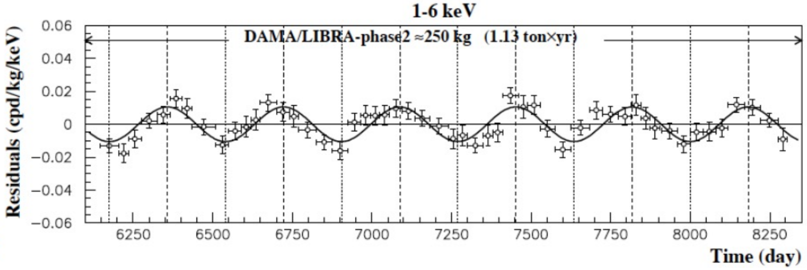
Nature **564**, 83 (2018)

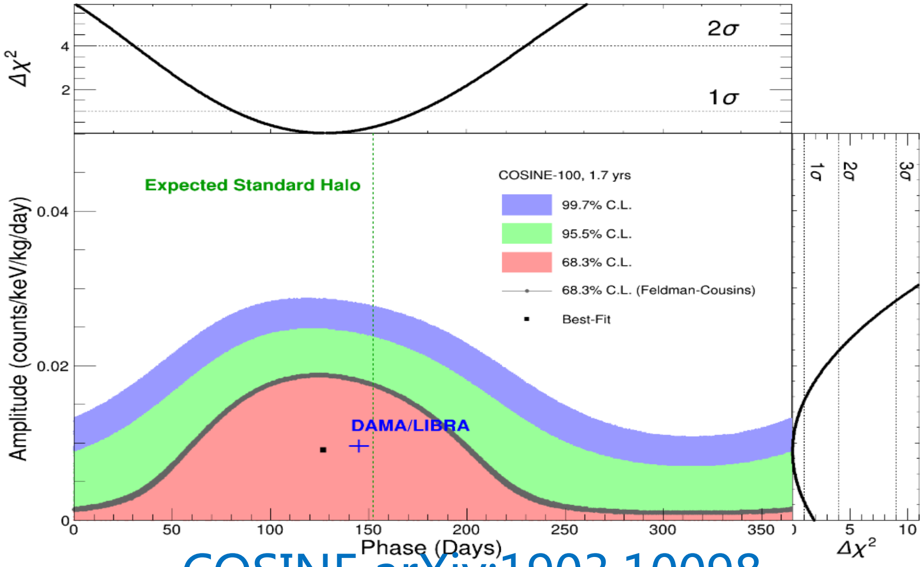
arXiv:1805.10486

Energy (k



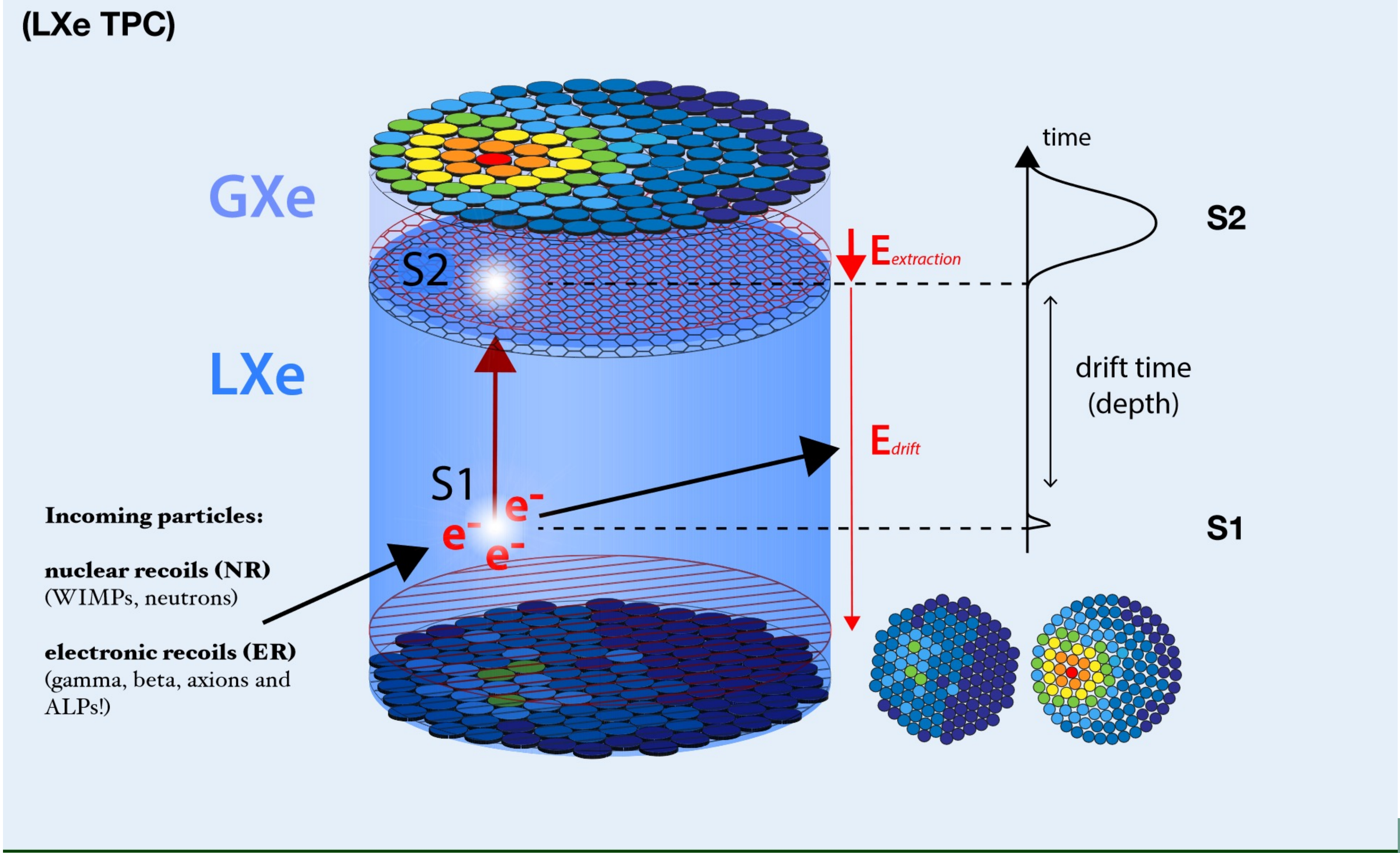
Modulation amplitude





COSINE arXiv:1903.10098

The Xenon-1T experiment



Incoming particles:

nuclear recoils (NR)
(WIMPs, neutrons)

electronic recoils (ER)
(gamma, beta, axions and ALPs!)

Response of the LXe

- Total number of quantum for given T_N

$$N_q = N_{ex} + N_i = \mathrm{Bino}(T_N/W, L)$$

work function $W = 13.8$ eV.

- The Linderhard factor

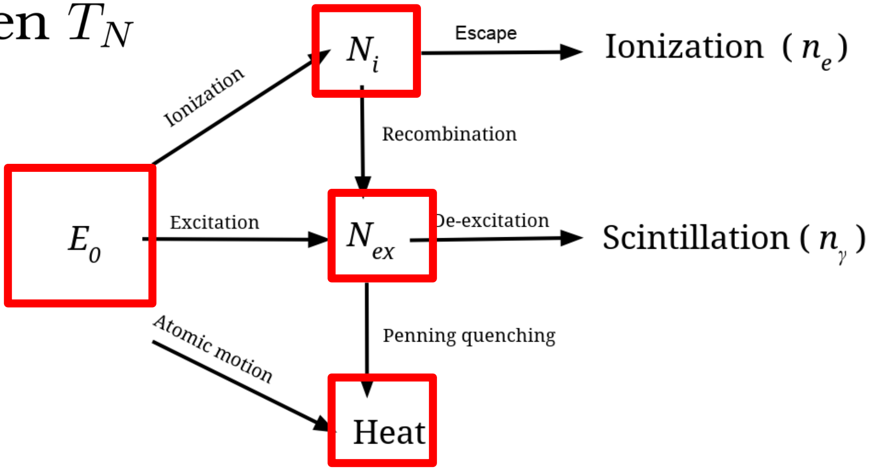
$$L = \frac{kg(\epsilon)}{1 + kg(\epsilon)}$$

- Number of ion

$$N_i = \mathrm{Bino}(N_q, 1/(1 + \langle N_{ex}/N_i \rangle))$$
$$N_{ex} = N_q - N_i$$

- Number of electrons and photons

$$N_e = \mathrm{Bino}(N_i, 1 - r)$$
$$N_\gamma = N_{ex} + N_i - N_e$$



E_0

Ionization

Excitation

Atomic motion

N_i

Escape

Ionization (n_e)

Recombination

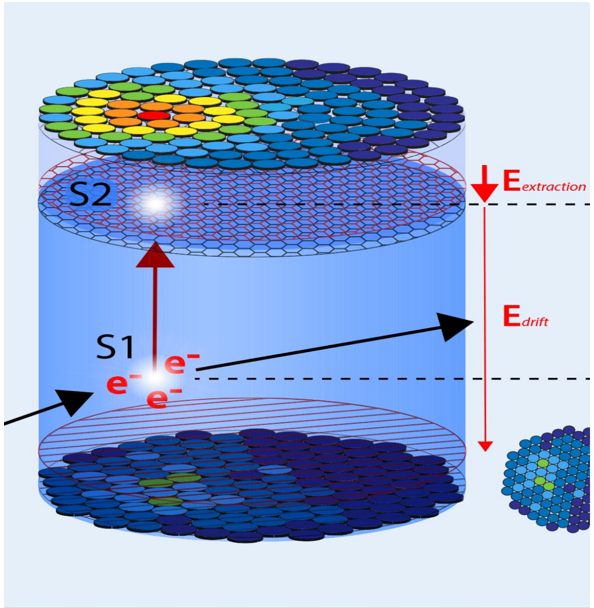
N_{ex}

De-excitation

Scintillation (n_γ)

Penning quenching

Heat



S1 and S2 signals

Thomas-Imel box model for recombination factor *r*

$$\langle r \rangle = 1 - \frac{\ln(1 + N_i \varsigma/4)}{N_i \varsigma/4}$$

averaged signal numbers

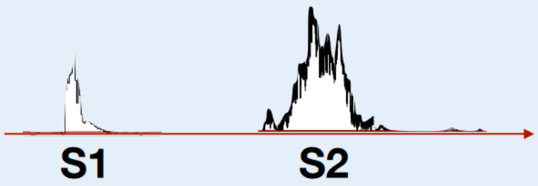
$$\frac{\langle N_\gamma \rangle}{T_N} = \frac{L}{W} \cdot \frac{\langle r \rangle + \langle N_{\rm ex}/N_i \rangle}{1 + \langle N_{\rm ex}/N_i \rangle},$$

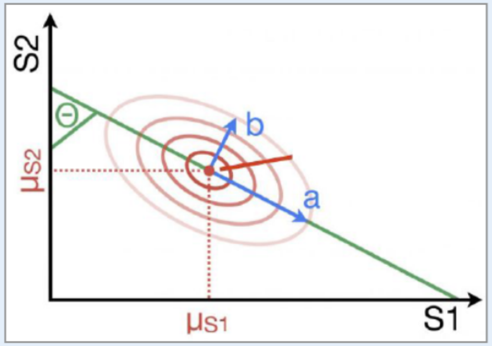
$$\frac{\langle N_e \rangle}{T_N} = \frac{L}{W} \cdot \frac{1 - \langle r \rangle}{1 + \langle N_{\rm ex}/N_i \rangle}.$$

signals are converted into PEs at PMTs

- gain factors for S1 and S2: $g_1(x, y, z)$ and $g_2(x, y)$
- gain factors for spatially corrected signals: cS1 and cS2$_{\rm b}$: g_1 and g_2

S1/S2 signals and recoil energy



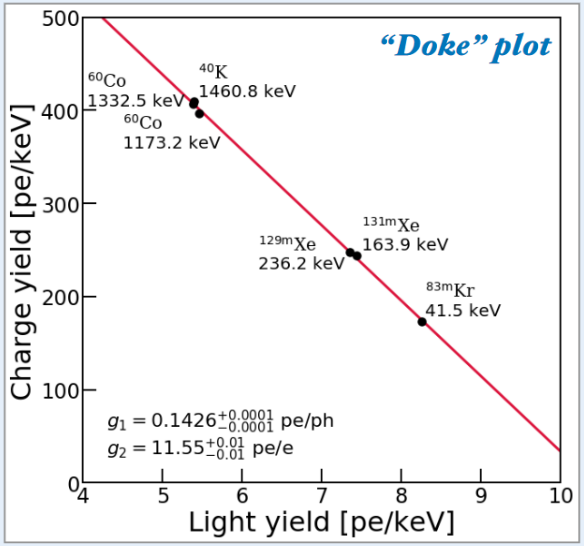


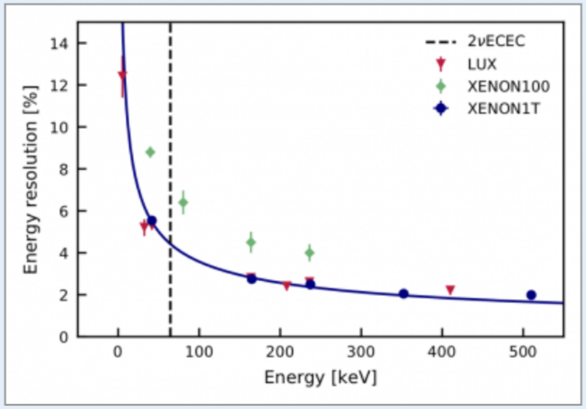
$$E = (N_{ph} + N_e) \cdot W = \left(\frac{S1}{g1} + \frac{S2}{g2}\right) \cdot W$$

where W = 13.7 eV/quanta

g1 and g2: detector-specific gain constants extract g1/g2 from calibration data, use it to reconstruct energy of each event

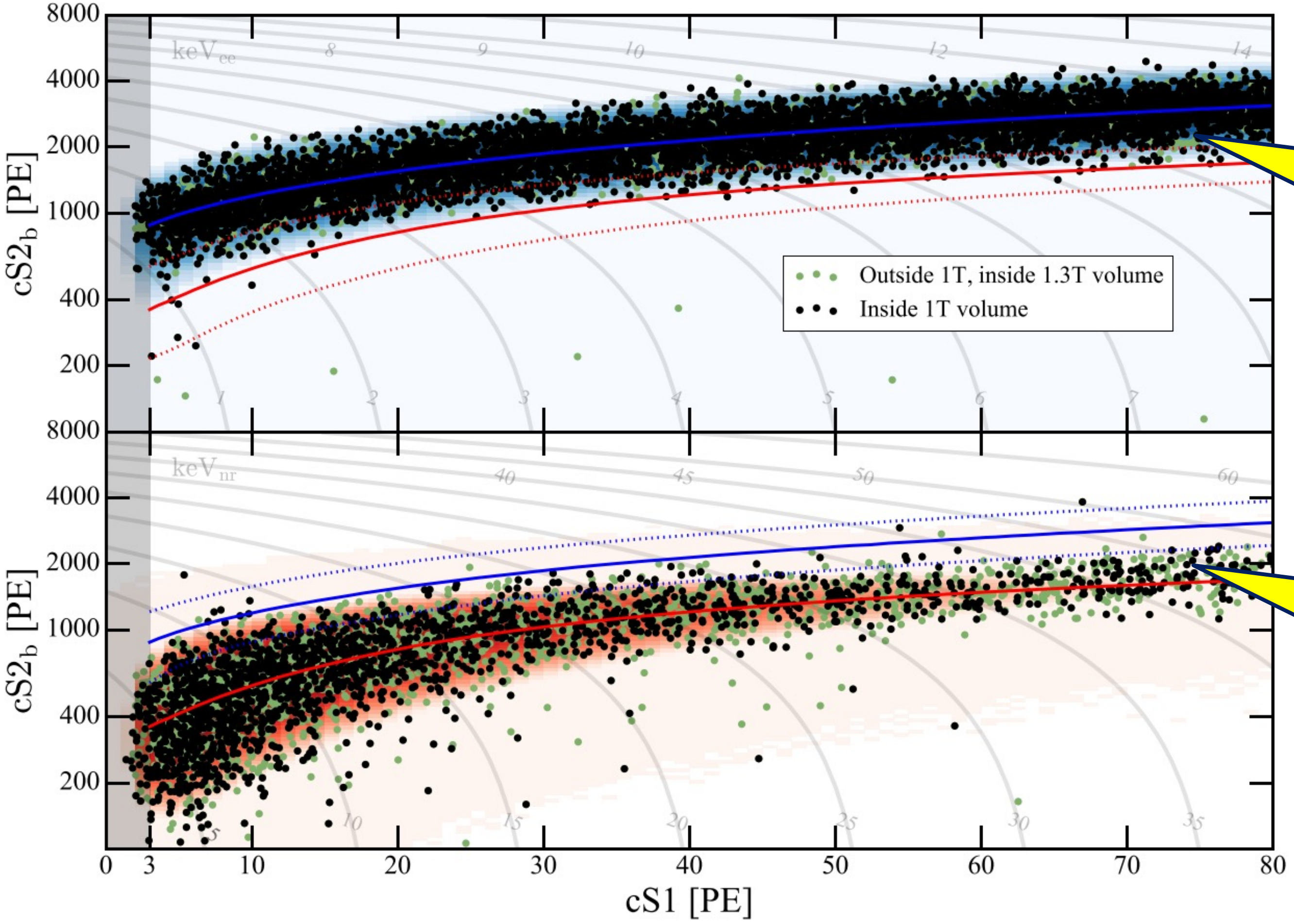
Combined Energy Scale





Nuclear vs. electronic recoil

^{220}Rn generator



Electronic recoil

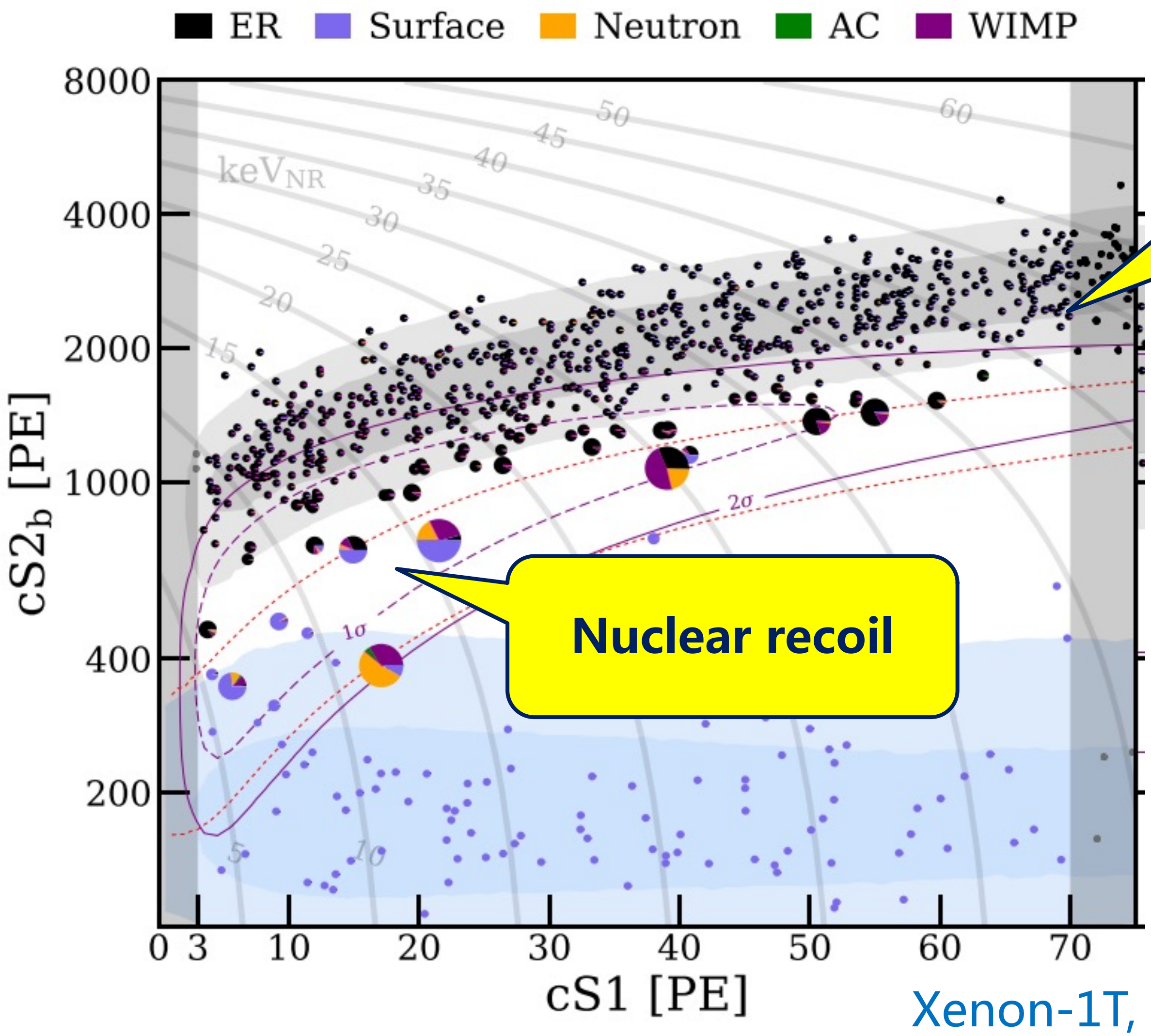
Nuclear recoil

neutron generator

Xenon-1T, arXiv:1906.04717

Xenon-1T one-tone year results: nuclear recoil

ROI (4.9—40.9 keVnr)

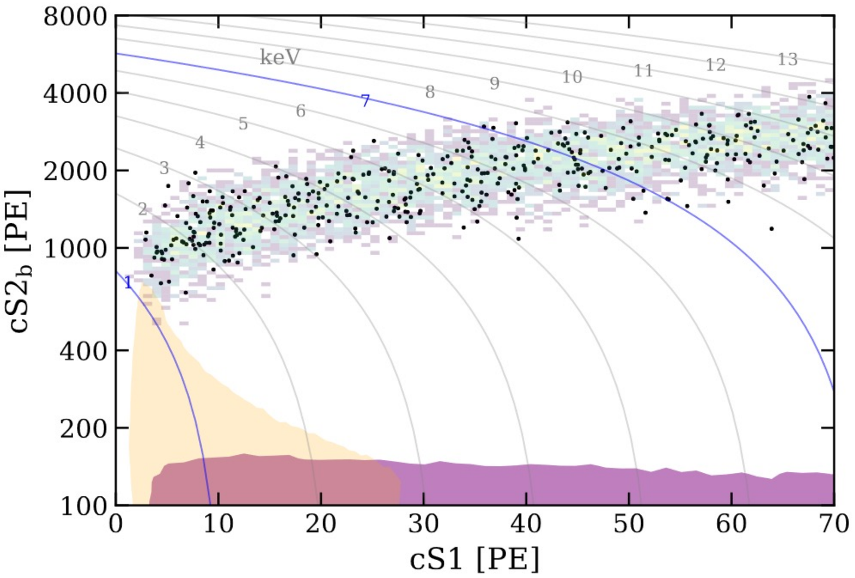


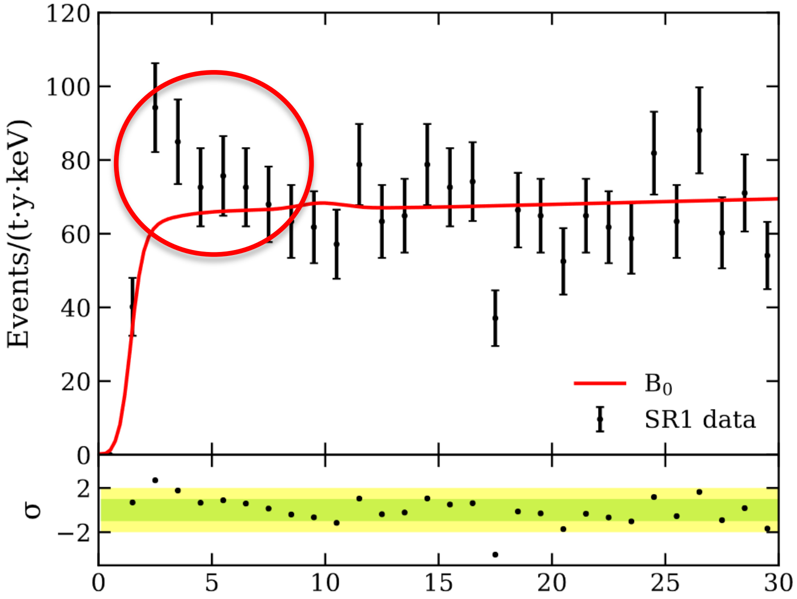
Electronic recoil

Nuclear recoil

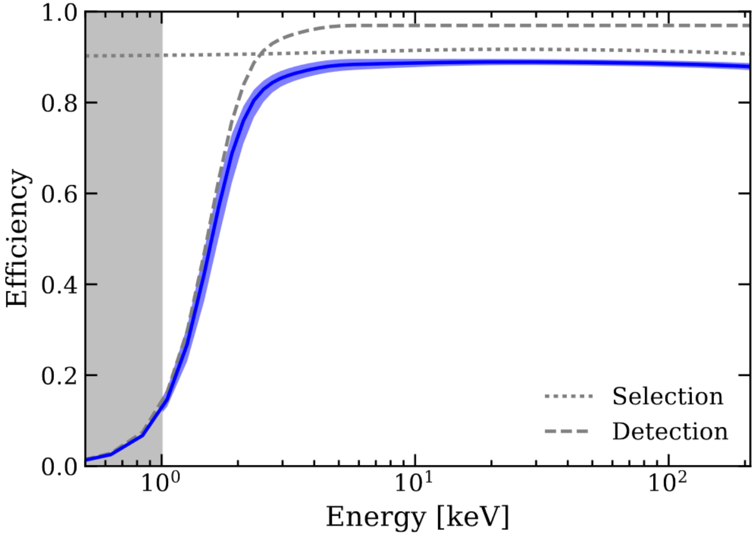
Xenon-1T, arXiv:1805.12562

Xenon-1T electronic excess ?



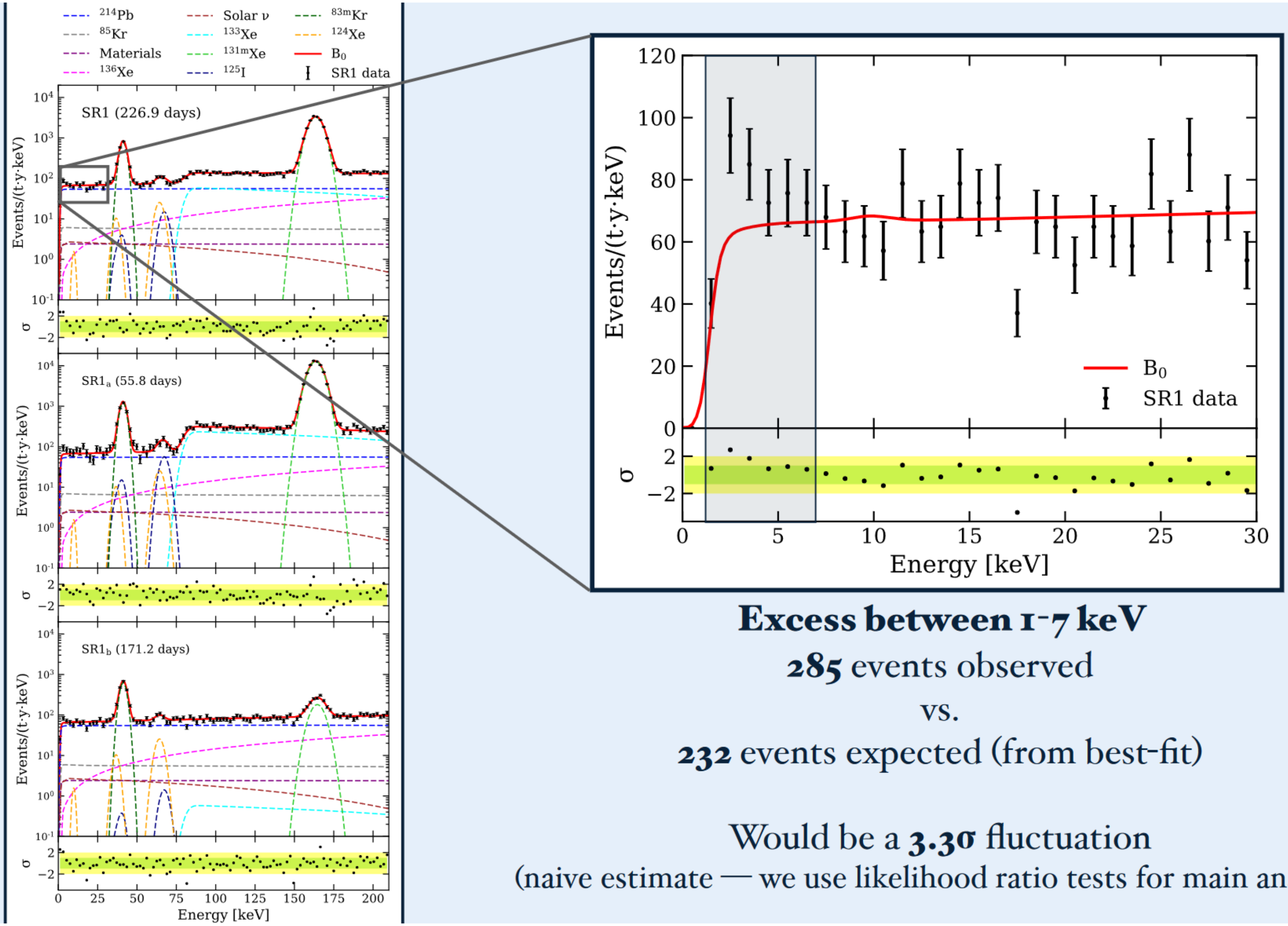


EXPO: 0.65 tone-yr, SR1 (226.9 days)
ROI: (1—210 keV)
Background:
76 events/(tonne yr keV) in 1-30 keV
Excess: (1-7 keV)
Total events 285
Background events 232+-15



Xenon-1T, arXiv:2006.09721

Signals vs. Backgrounds



Excess between 1-7 keV

285 events observed

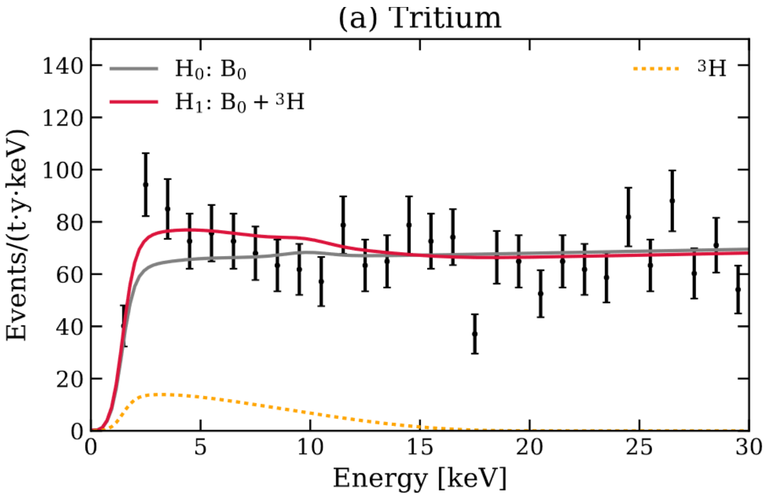
vs.

232 events expected (from best-fit)

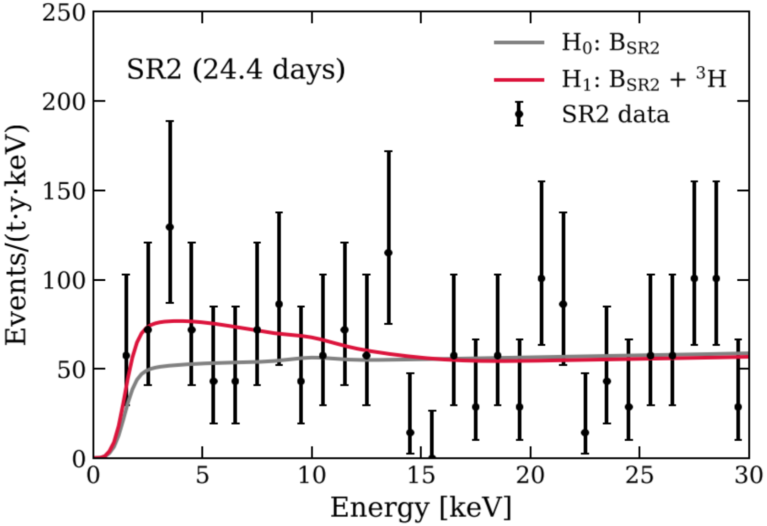
Would be a **3.3σ** fluctuation

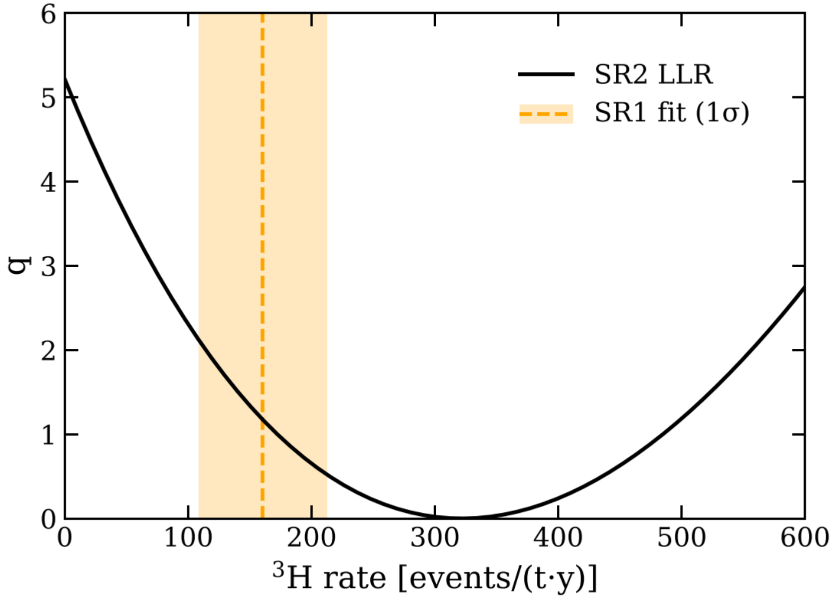
(naive estimate — we use likelihood ratio tests for main analysis)

Tritium background (H_2/HT) ?



- Tritium favored at 3.2 sigma 159 events/t.yr
- ^3H/Xe expected to be removed from Xe purification system
- ^3H/Xe from exposure to CR is estimated
- H_2O/HTO extremely small
- H_2/HT NOT QUANTIFIED !!





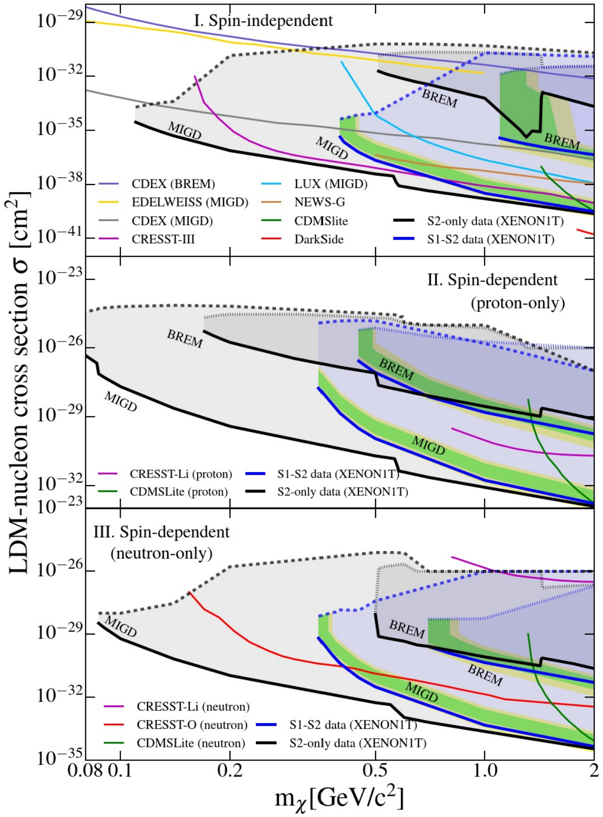
暗物质探测实验上探测轻暗物质

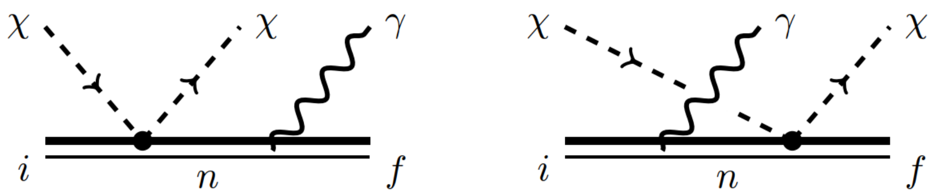
实验探测轻暗物质（小于GeV）的困难

- ❑ 典型直接探测实验的阈值： O(keV)
- ❑ 本地暗物质最大速度（逃逸速度）：500 km/s

e.g. 1 GeV 暗物质与100 GeV核子弹性散射，最大反冲能只有0.06 keV

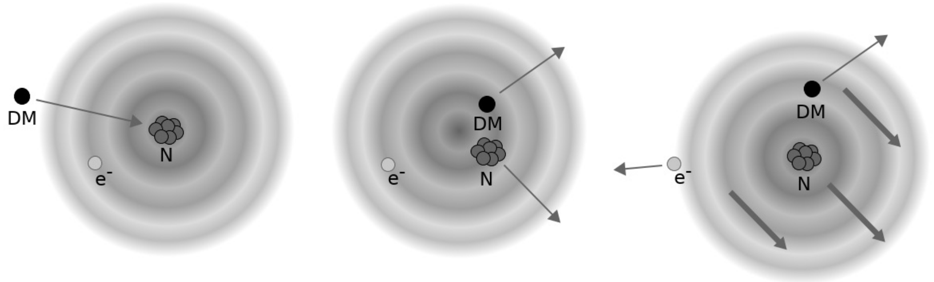
利用非弹性散射（原子激发、电离）过程的光子、电子信号





光子末态辐射

Kouvaris, et al (2016)

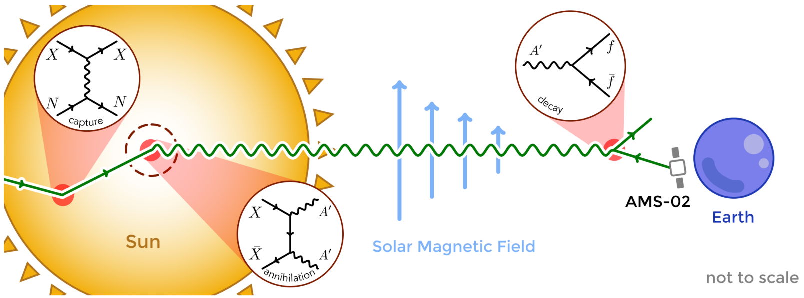


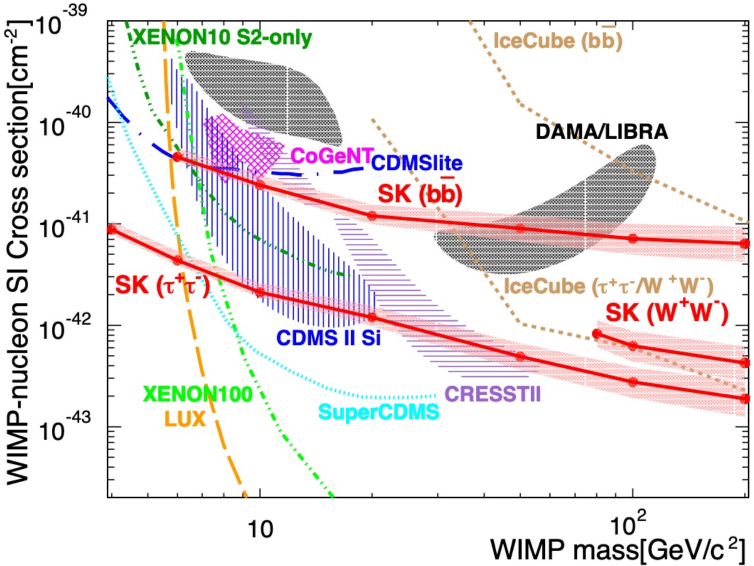
Migdal 效应

Ibe, et al (2017)

测量范围扩大到sub-GeV

Probing DM-proton scattering through DM annihilation





SuperK, arXiv:1503.04858

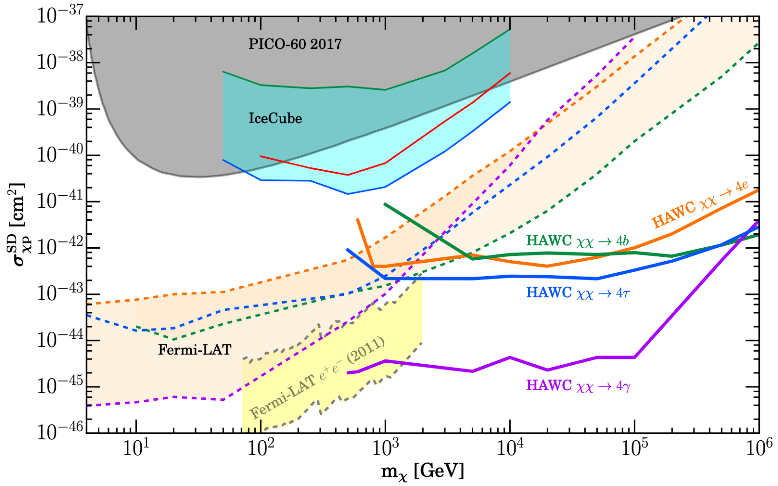
Anihilation → Scattering

❑ DM-nucleus scattering lead to DM capture

❑ capture and annihilation reach

$$\dot{N}_X = C_{\mathrm{cap}} + C_{\mathrm{self}} N_X - C_{\mathrm{ann}} N_X^2 \ ,$$

$$N_X = \sqrt{\frac{C_{\mathrm{cap}}}{C_{\mathrm{ann}}}} \tanh \frac{t}{\tau}$$



HAWC, arXiv: 1808.05624

Observables

❑ direct escape: neutrinos

❑ through mediators: electrons/positrons

Constraints

$\sigma < 10^{-43}\,\mathrm{cm}^2$ @ 100 GeV ($2\chi \to 2\tau$) Super-K

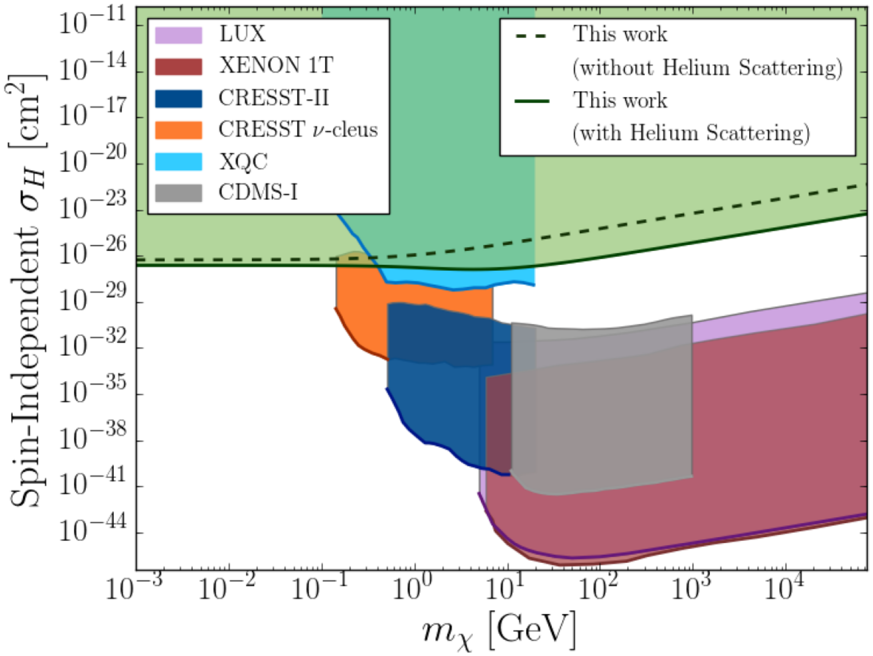
$\sigma < 10^{-45}\,\mathrm{cm}^2$ @ 1 TeV ($2\chi \to 2\varphi \to 4Y$) HWAC

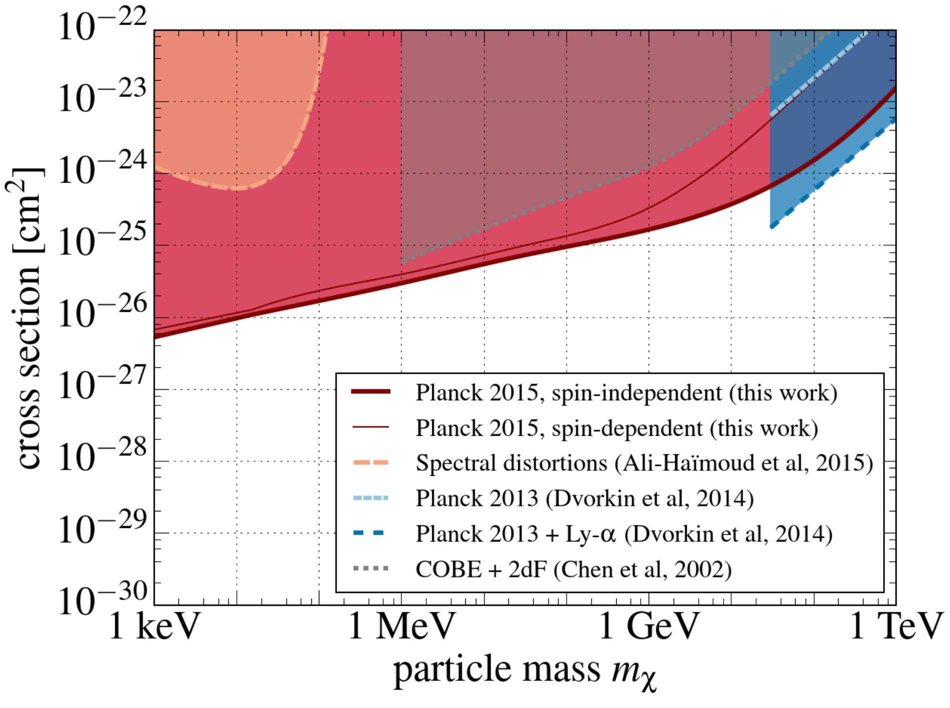
DM-proton scattering in the Universe: CMB

Consequence of DM-proton scattering 400000 yrs ago

- Distortion of CMB spectrum
- Suppression of small sale structure (drag force)

Constraints: $\sigma < 10^{-27}\ \mathrm{cm}^2$ @ 1 keV

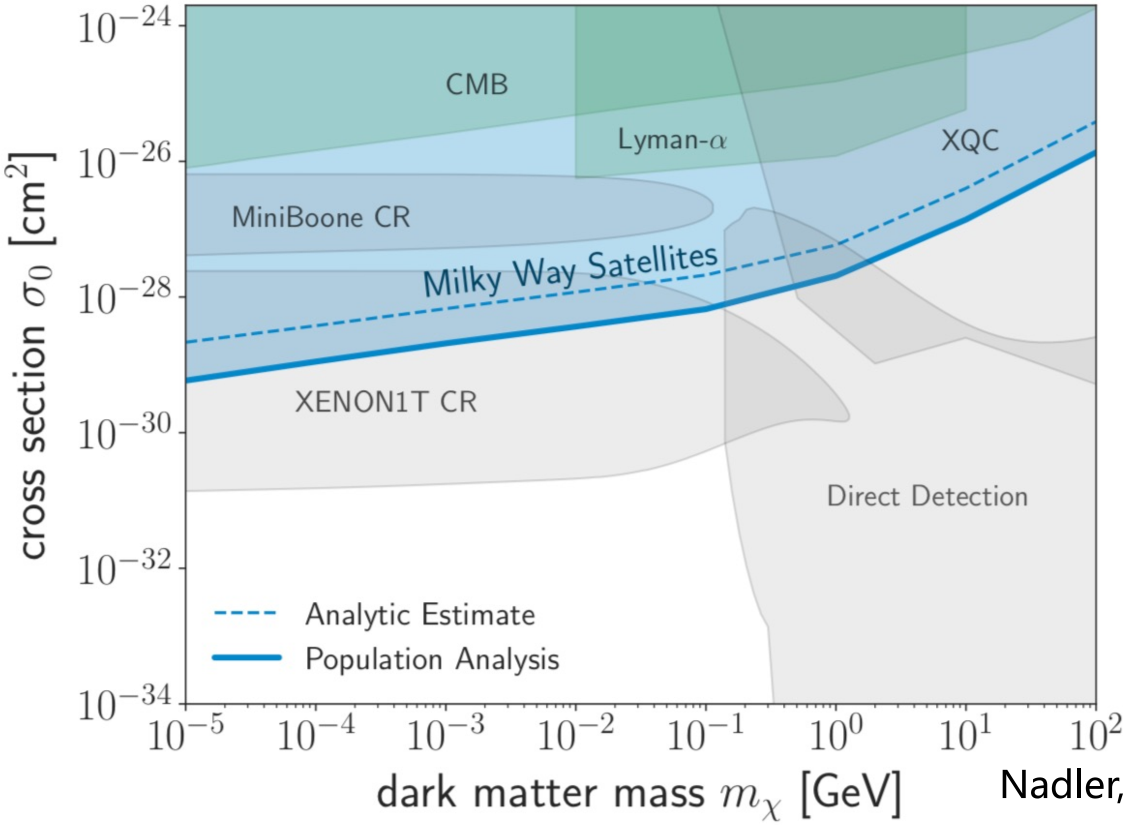




Gluscevic & Boddy, arXiv:1712.07133

DM-proton scattering in the Universe: Structure formation

DM-proton scattering damp structure perturbation
Distribution of dwarf satellite galaxies is modified
$\sigma < 6\text{x}10^{-30}\,\text{cm}^2$ @ 10 keV, ($<10^{-27}\,\text{cm}^2$ @ 10 GeV)
The upper limits scale with DM mass as $m^{1/4}$ for m <<1 GeV



Nadler, et al., arXiv:1904.10000
DES, arXiv:2008.00022

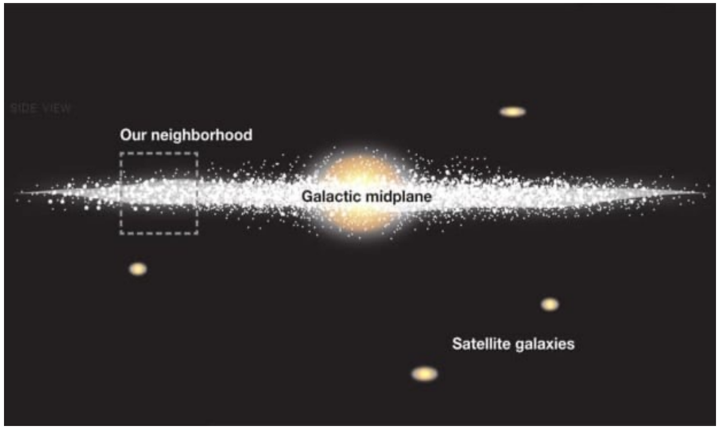
DM-proton scattering in galaxies: Gas cooling

DM above KeV has a temperature higher than the coldest atomic gas

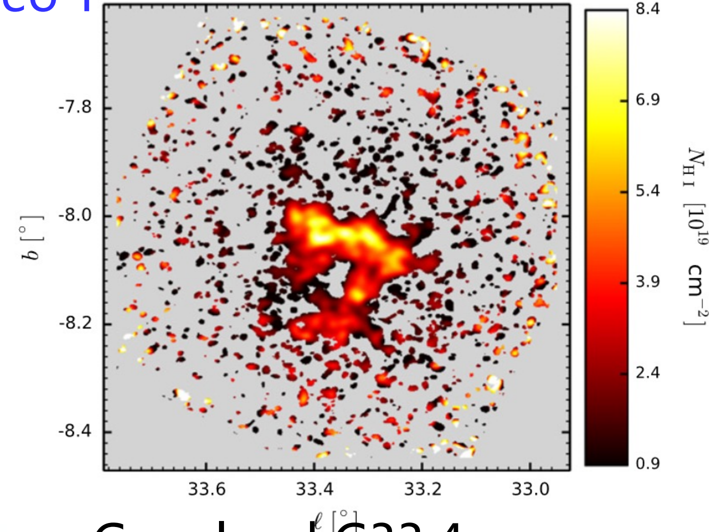
$$T_x \sim m_x v_x^2 \simeq 10^4\ \mathrm{K}\left(\frac{m_x}{\mathrm{MeV}}\right)\left(\frac{v_x}{10^{-3}}\right)^2,$$

DM-proton scattering heat the gas and change its cooling rate

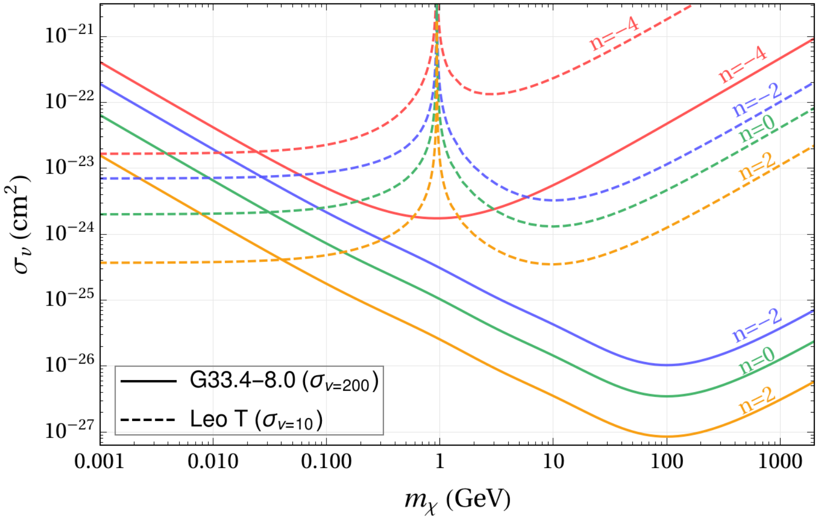
$\sigma < 10^{-(23\text{-}25)}$ cm^2 for a large mass range 10^{-23} eV -- 10^{-10} eV from dwarf galaxy Leo T



dwarf galaxies



Gas cloud G33.4-



Wadeker & Farrar, arXiv:1903.12

CR-DM scattering: CR spectrum distortion

CRs will hit halo DM before escape if

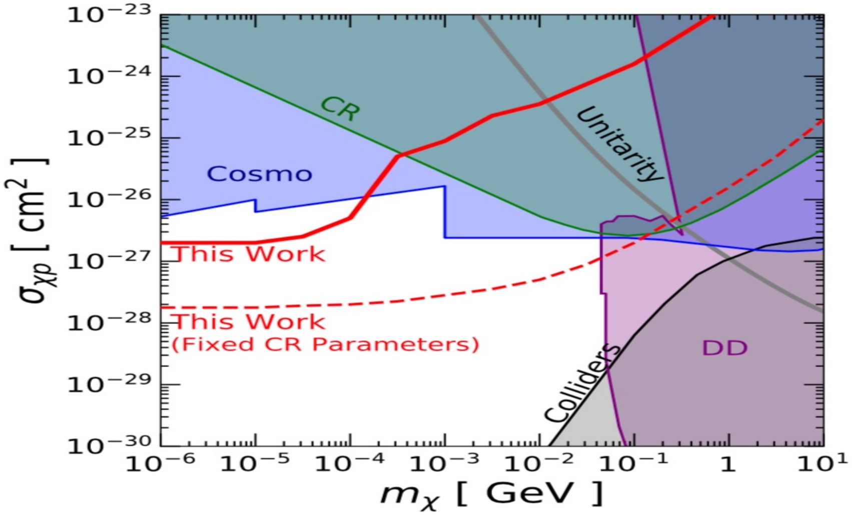
$$\sigma_{1-\mathrm{int}} \sim 2\times 10^{-31}\,\mathrm{cm}^2 \left(\frac{m_\chi}{\mathrm{keV}}\right)\left(\frac{E}{10\,\mathrm{GeV}}\right)^{\delta} .$$

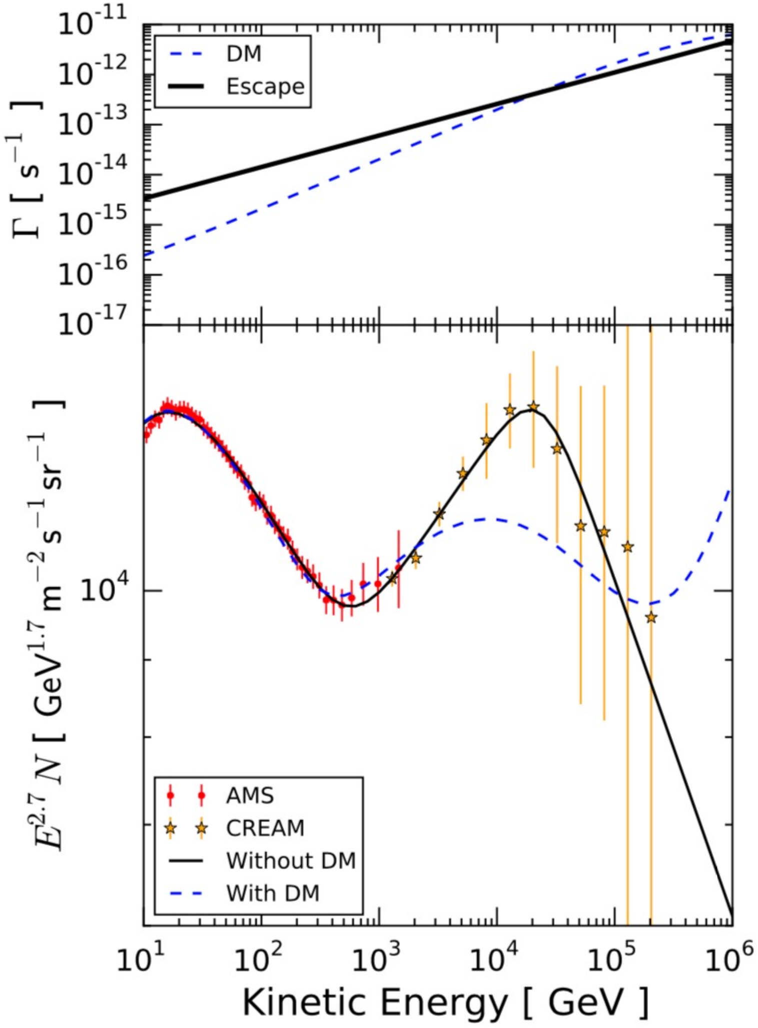
CRs will loss most of the energy if

$$\sigma^{\chi p}_{\mathrm{loss}} \sim 2\times 10^{-26}\left(\frac{E}{10\,\mathrm{GeV}}\right)^{\delta-1}\mathrm{cm}^2 ,$$

Constraints

$\sigma < 10^{-(27-28)}\,\mathrm{cm}^2$ @keV





Cappiello, et al. arXiv:1810.07705

CR-DM inelastic scattering: gamma-ray production

Inelastic process : χp→ χΔ → χp Y

CR propagation in the extended halo

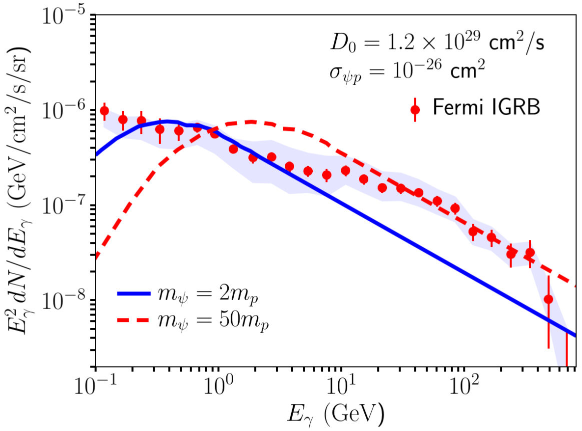
$$0 = \vec{\nabla} \cdot [D(E_p)\vec{\nabla}\frac{dN_p}{dE_p}(\vec{x},t,E_p)] + Q(\vec{x},t,E_p),$$

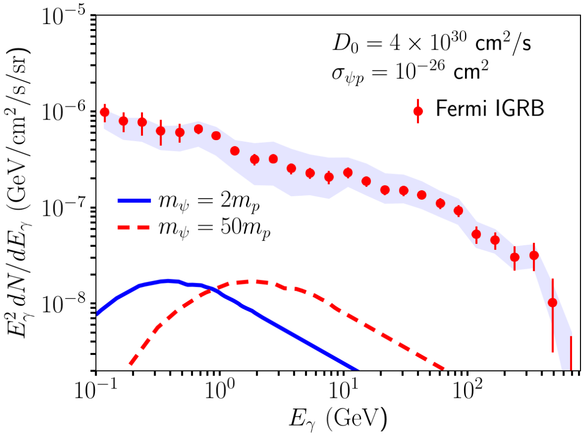
Lorimer profile of sources

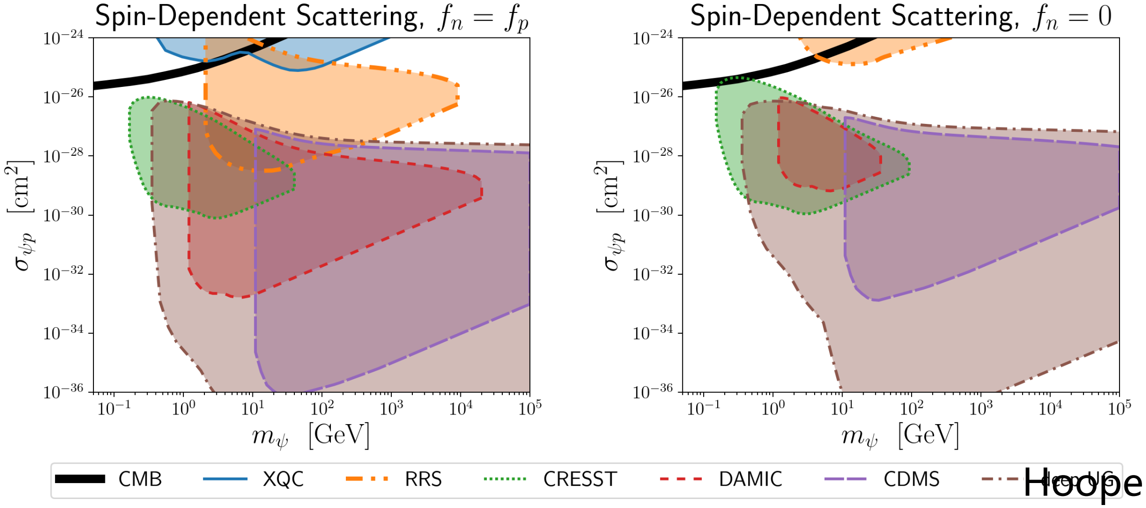
$$Q(R,t,E_p) = Q_0\, E_p^{-2.4}\, R^{2.35}\, \exp(-R/1.528\,\mathrm{kpc})\, f(t), \tag{5}$$

Results depend on the diffusion coefficient

σ < 10^{-26} cm^2 @100 MeV







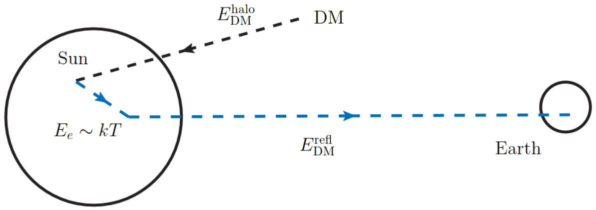
Hooper& McDemott, arXiv:1802.03025

暗物质探测实验上探测轻暗物质

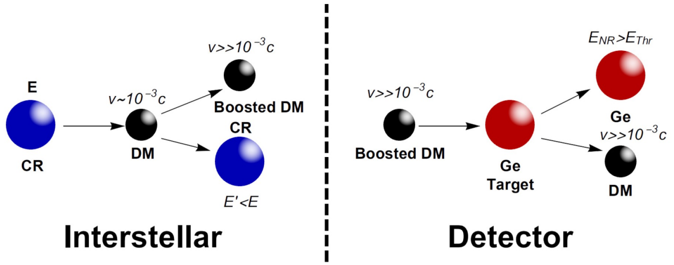
直接探测的逆过程：核子、电子撞击暗物质粒子（同样的截面）

□ 暗物质粒子被加速，获得很大动能，轻易突破阈值限制

□ 核子（电子）亦损失能量，带来可观测效



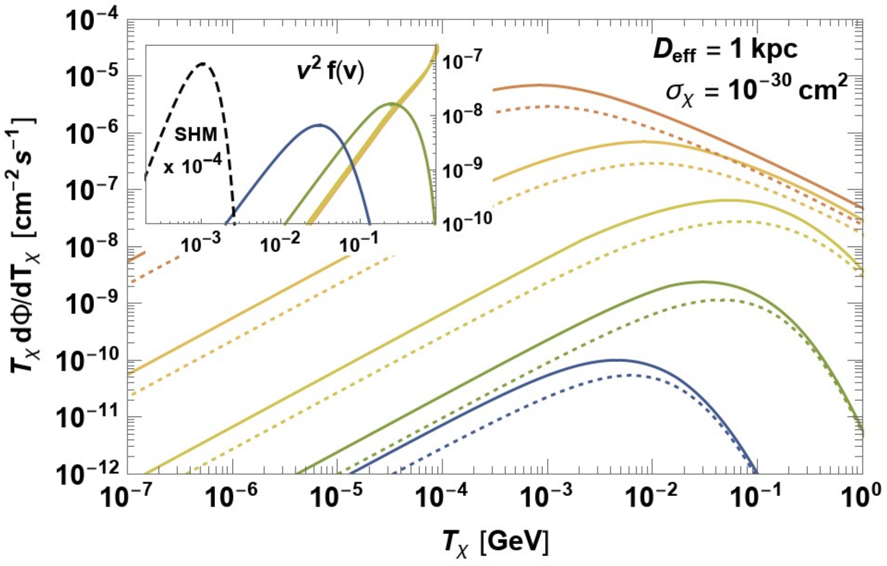
An, et al, 1708.03642.



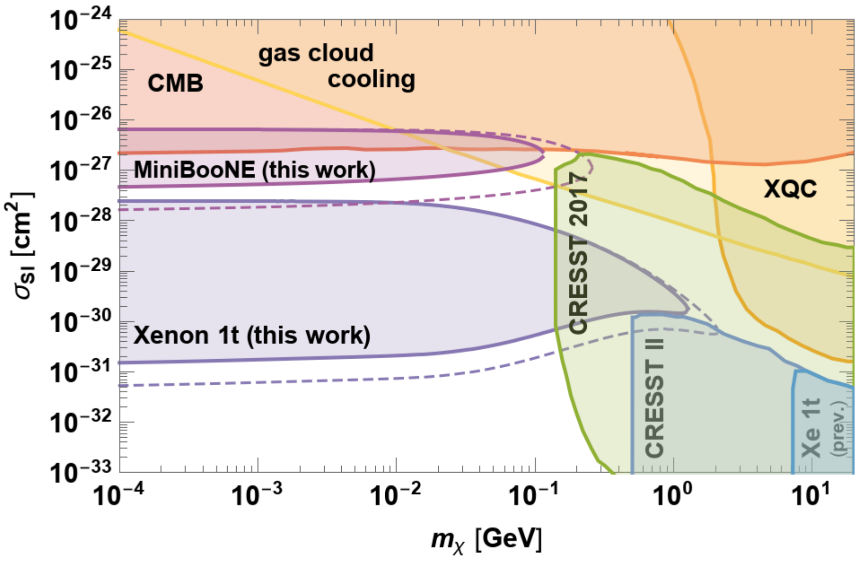
Y. Ema, et al, 1811.00520

Wang, Wu, Yang, Zhou, Zhu, 1912.09904

Ge, Liu, Yuan, Zhou, 2005.09480



Bringmann, et al 810.10543



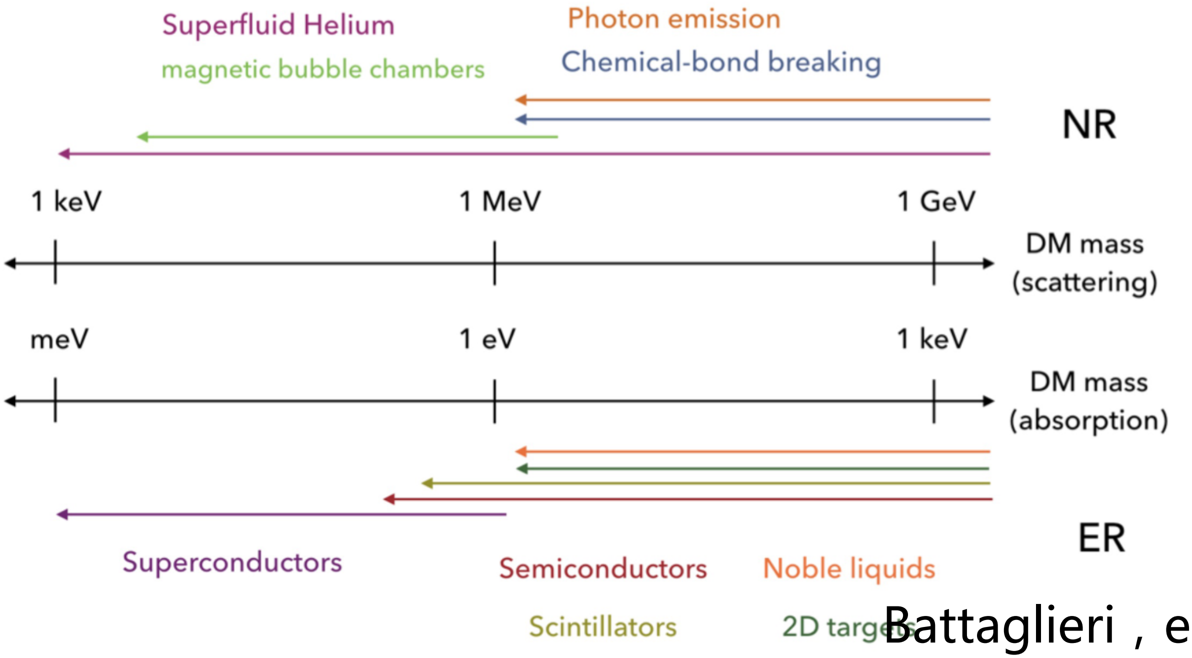
Direct detection: the future ?

新方案 (低阈值)

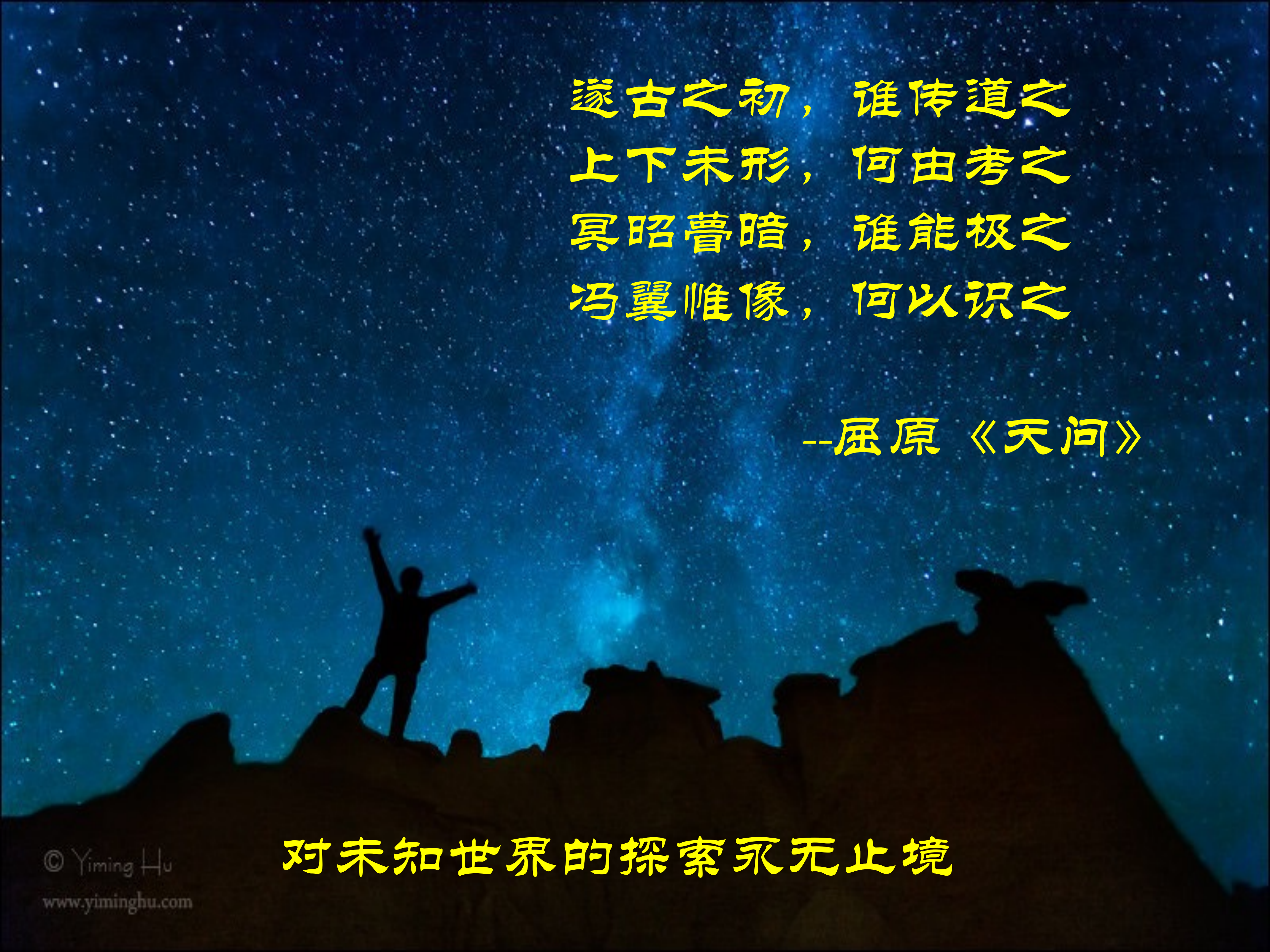
- 液氦超流体(Suprfluid helium)：量子蒸发
- 化学键破缺（chemical-Bond breaking）：分子瓦解，晶体缺陷
- 分子自旋态反转(spin-flip avalanches)（magnetic bubble chambers, Zeeman效应,）

新技术

- CCD 探测器 (SENSEI, DAMIC-1K)
- 核子反冲方向性测量（CYGNUS HD-10）



Battaglieri，et al, arXiv:1707.04591



遂古之初，谁传道之
上下未形，何由考之
冥昭瞢暗，谁能极之
冯翼惟像，何以识之

--屈原《天问》

对未知世界的探索永无止境

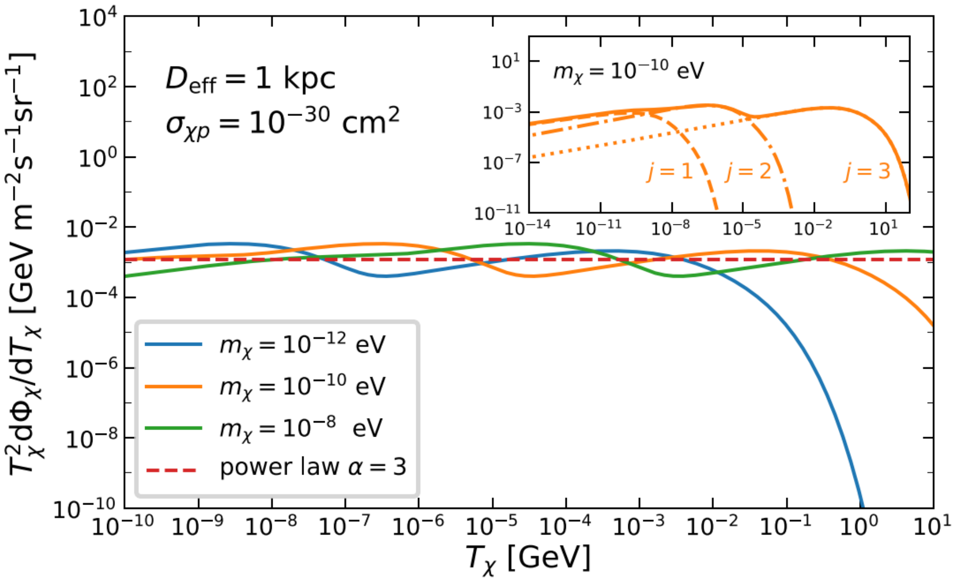
BACKUPS

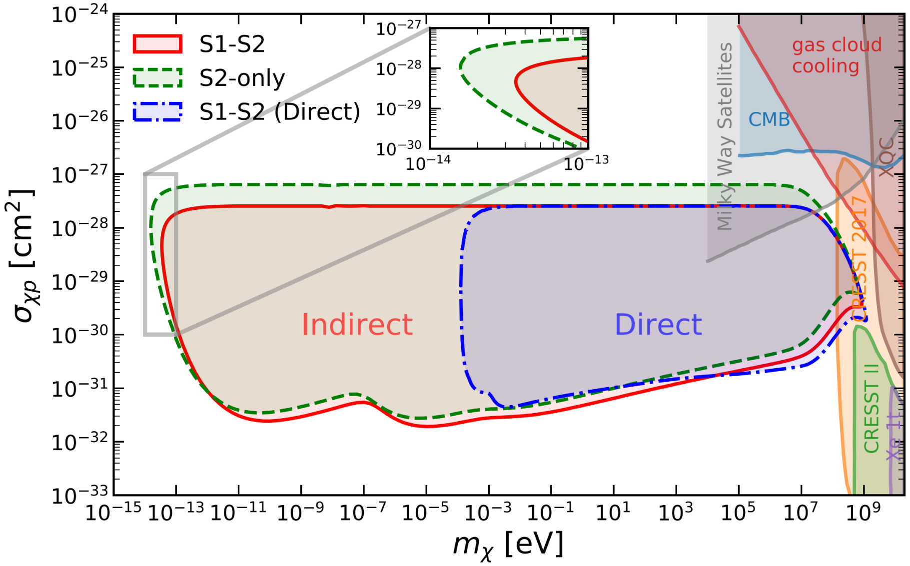
暗物质探测实验上探测超轻暗物质

超高能高能宇宙线（UHECR）：来自宇宙中最高能的加速器（supernova， AGN）

- 加速能力取决于宇宙线能谱硬度，硬度高于 E^{-3} 幂律能谱可加速超轻的暗物质
- 观测表明宇宙线能谱十分接近 E^{-3}（尤其是“膝”区以上）
- 宇宙线加速机制最终受制于 GZK 截断 ：10^{20} eV
- 可限制 10^{-14} eV 质量的暗物质， 比当前限制拓展10^{10} 倍！

Xu, Xia, YFZ, 2009.00353





(迄今为止) 所有支持暗物质存在的证据都来自引力效应研究

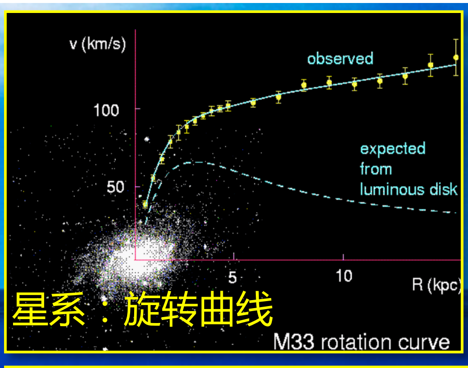
常规重子物质
（占物质总量15%）

暗物质
（占物质总量85%）

大量观测证据：
空间各种尺度（Galaxy，Cluster，Cosmic）
宇宙不同时期（BBN，CMB，Today），

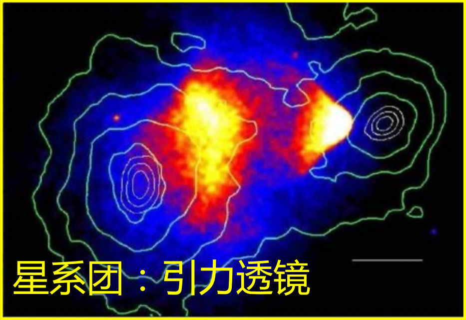
大量理论研究：星系形成，N-体数值模拟

暗物质是什么？如何起源？是否可探测（非引力作用）？

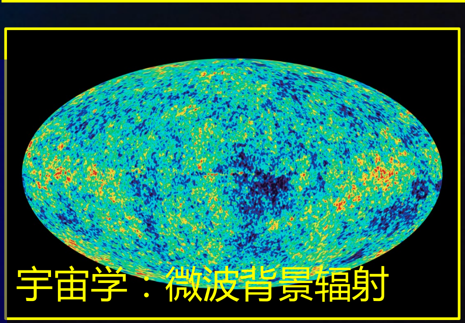


星系：旋转曲线

M33 rotation curve



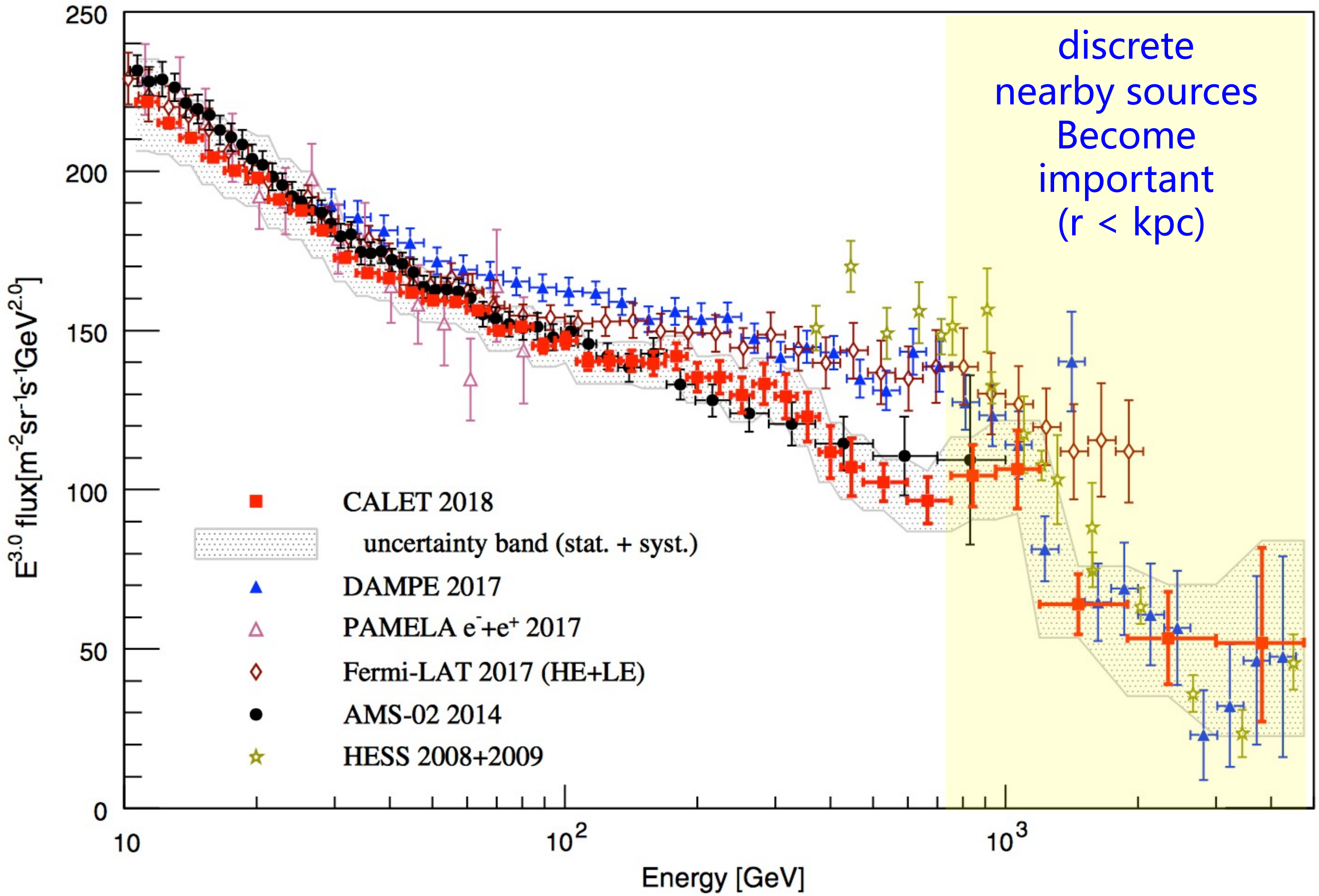
星系团：引力透镜



宇宙学：微波背景辐射

CR primary: all electron flux

Fermi-LAT, AMS-02, CALET, DAMPE, HESS. not in full agreement

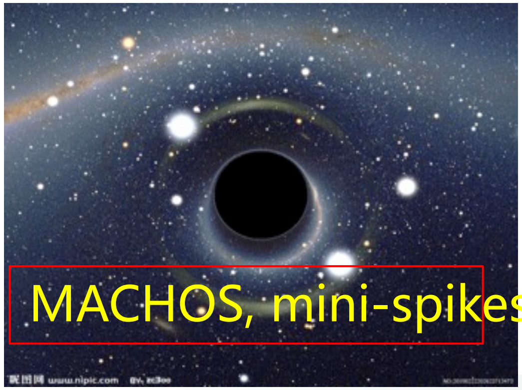


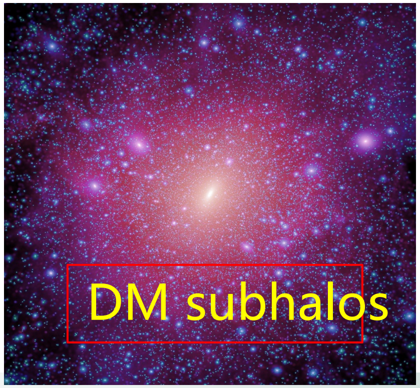
discrete
nearby sources
Become
important
(r < kpc)

The origin of a sharp electron structure

- Burst-like sources (astrophysical sources): spectrum-shrinking
  PWNe, SNRs
- Continuous sources (DM-like sources): spectrum-broadening
  - *Point-like sources*
    Mini-spikes around IMBH — Bertone, etal, astro-ph/0509565
    Ultra Compact mini halos (UCMH), — Scott, Sivertsson 0908.4082
    Dissipative DM, — Agrawal, Randall 1706.04195
  - *Extended sources*
    DM subhalos (suggested by N-body simulations)
    Smooth Galactic DM halo

Discrete nearby sources may reveal themselves through structures in CRE flux


MACHOS, mini-spikes


DM subhalos


Pulsar Wind Nebula


Supernova Remn

1) Spectrum broadening (for continuous sources)

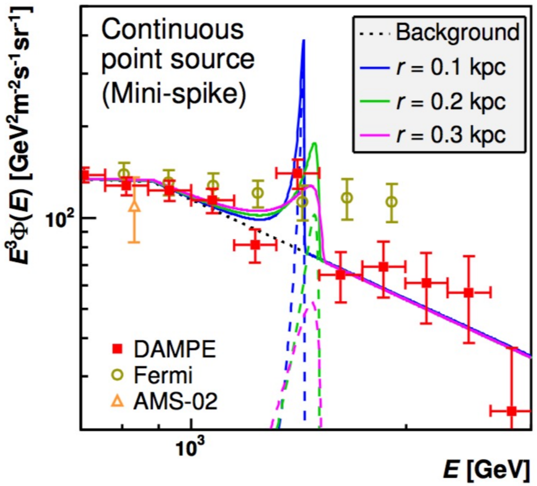
Continuous sources inevitably expand

Injection spectrum

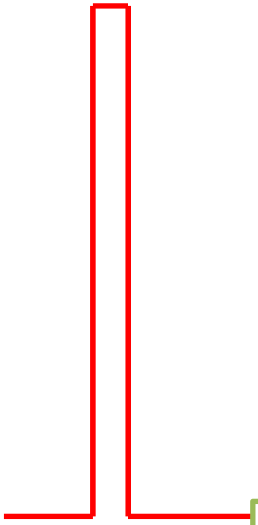
$$Q(r,E) \approx Q_0 \delta(E - E_0) \delta^{(3)}(\mathbf{r})$$

Spectrum broadening

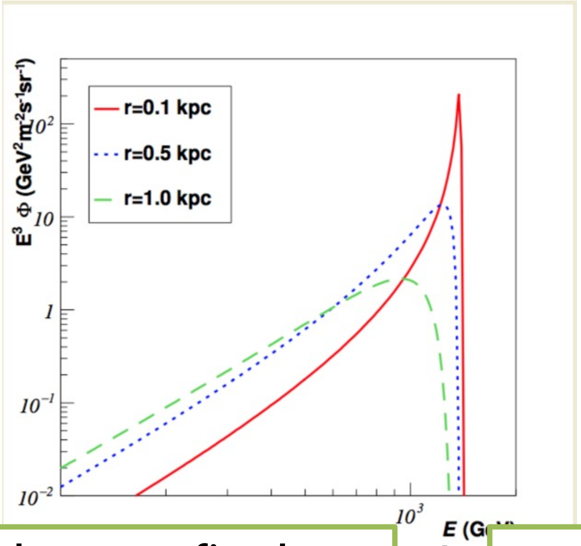
$$f(r,E) = \frac{Q_0 E^{-2}}{\pi^{3/2} b_0 r_d^3(E)} \exp\left(-\frac{r^2}{r_d^2(E)}\right)$$



before

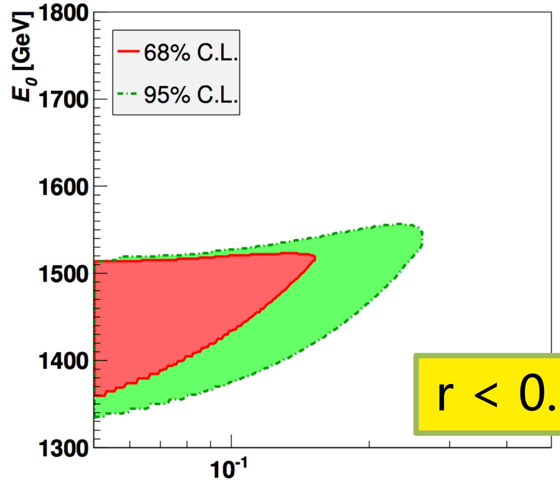


after



Only e+e- final states!

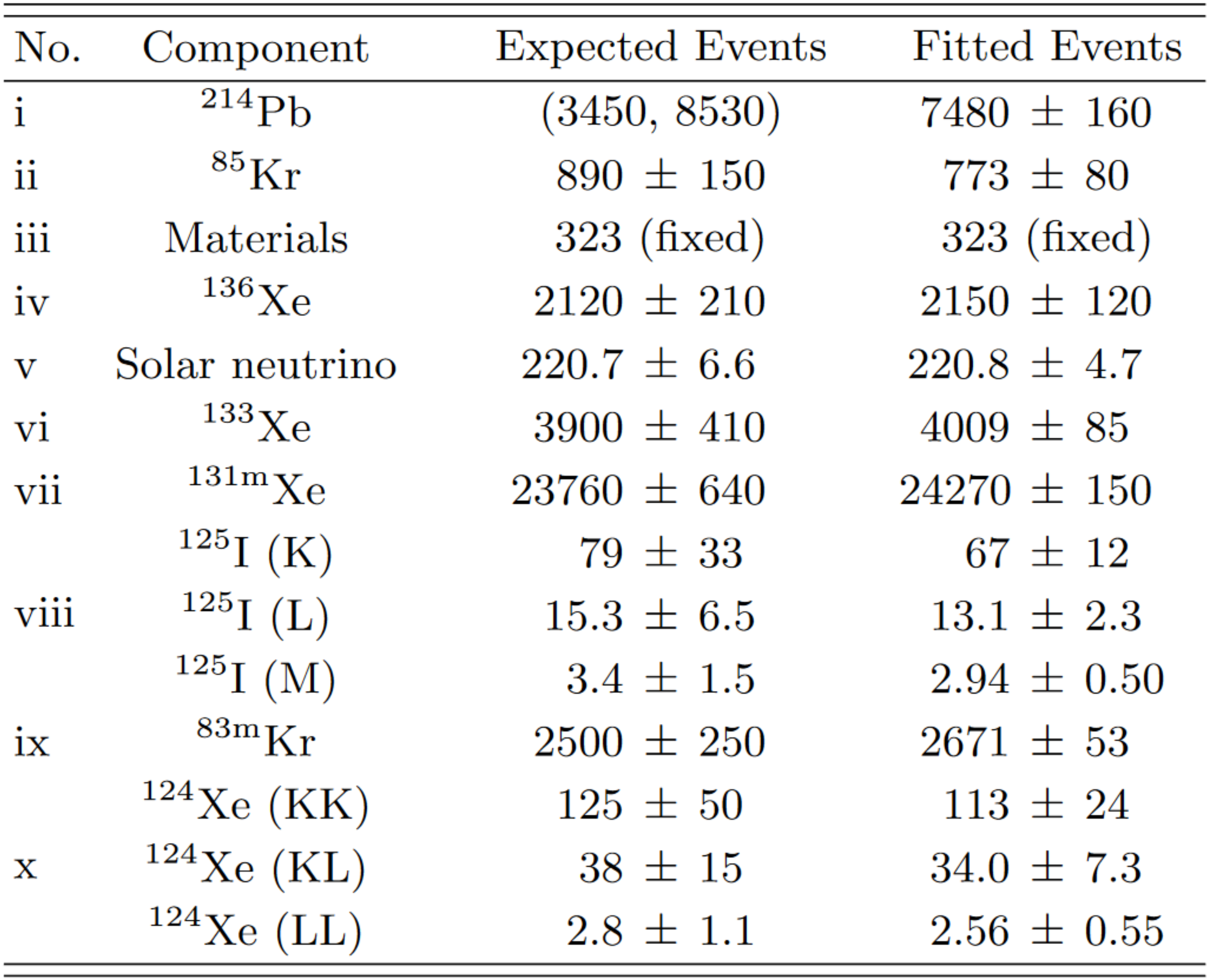
Width determines distance !



r < 0.3 kpc

X.J.Huang, W.H.Zhang, Y.L.Wu, YFZ, arXiv:1712.00005

Sources of backgrounds for electronic recoil



No.	Component	Expected Events	Fitted Events
i	^{214}Pb	(3450, 8530)	7480 ± 160
ii	^{85}Kr	890 ± 150	773 ± 80
iii	Materials	323 (fixed)	323 (fixed)
iv	^{136}Xe	2120 ± 210	2150 ± 120
v	Solar neutrino	220.7 ± 6.6	220.8 ± 4.7
vi	^{133}Xe	3900 ± 410	4009 ± 85
vii	$^{131\mathrm{m}}$Xe	23760 ± 640	24270 ± 150
viii	^{125}I (K)	79 ± 33	67 ± 12
	^{125}I (L)	15.3 ± 6.5	13.1 ± 2.3
	^{125}I (M)	3.4 ± 1.5	2.94 ± 0.50
ix	$^{83\mathrm{m}}$Kr	2500 ± 250	2671 ± 53
x	^{124}Xe (KK)	125 ± 50	113 ± 24
	^{124}Xe (KL)	38 ± 15	34.0 ± 7.3
	^{124}Xe (LL)	2.8 ± 1.1	2.56 ± 0.55

Cosmic rays (aurora borealis)

极光

人面蛇身，赤色，身长千里，钟山之神也。 《山海经》