Cosmic-Ray boosted DM and its effect on the DM-electron direct detection

Ding Ran

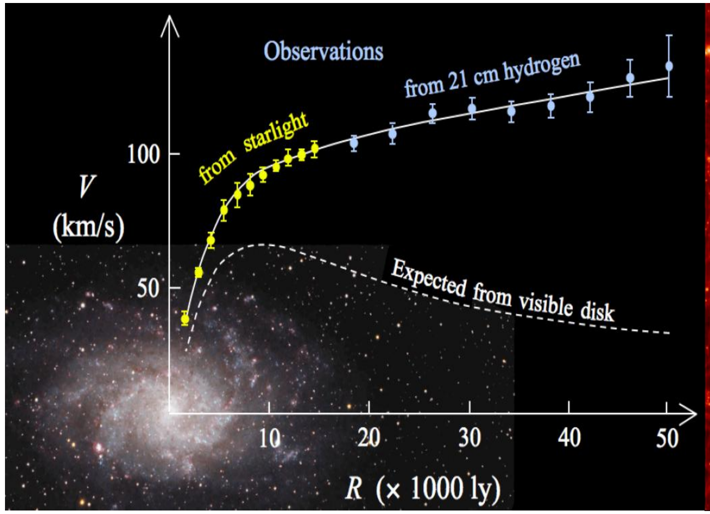
CHEP, PKU

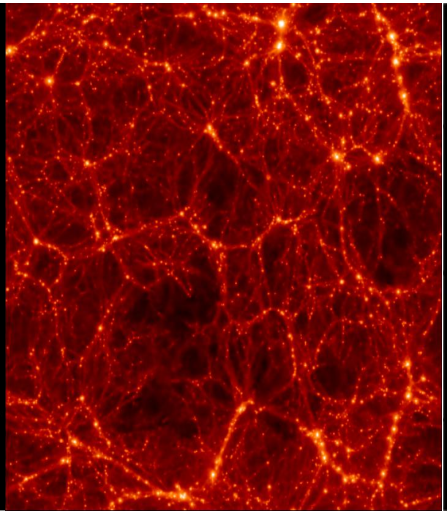
Collaborated with Xiang Qianfei & Cao Qinghong

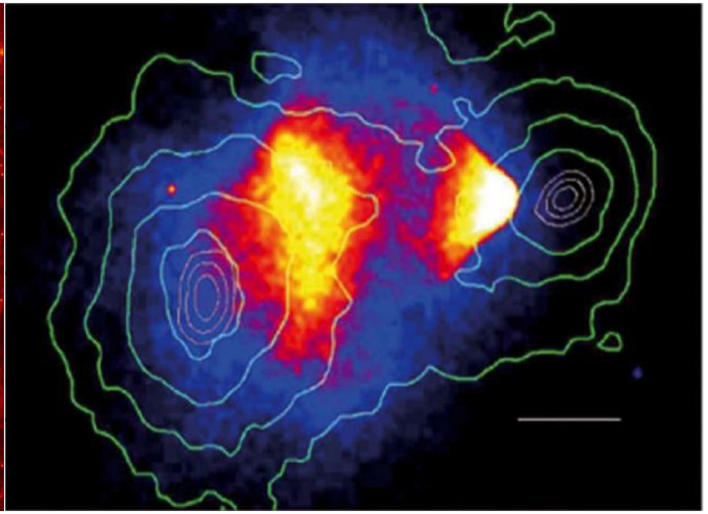
2nd TDLI Mini-Workshop on "New Physics at the Tera Scale"
2019.08.04

Evidences for DM

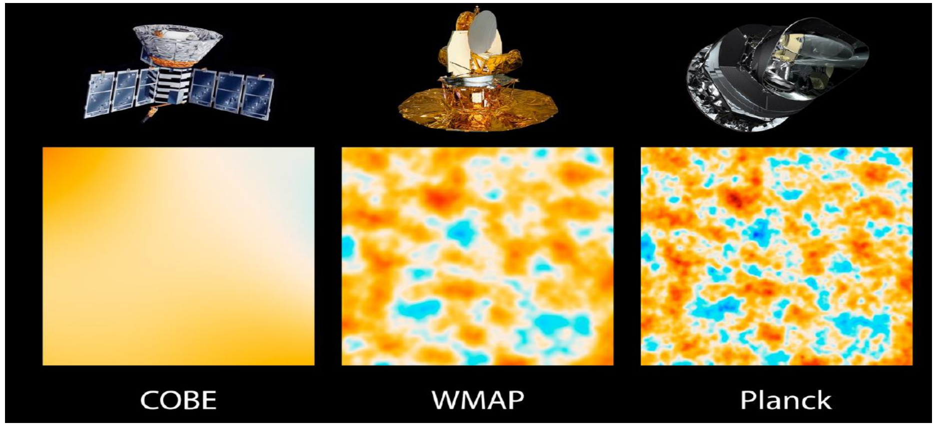
- Rotation curves
- LSS
- Bullet cluster



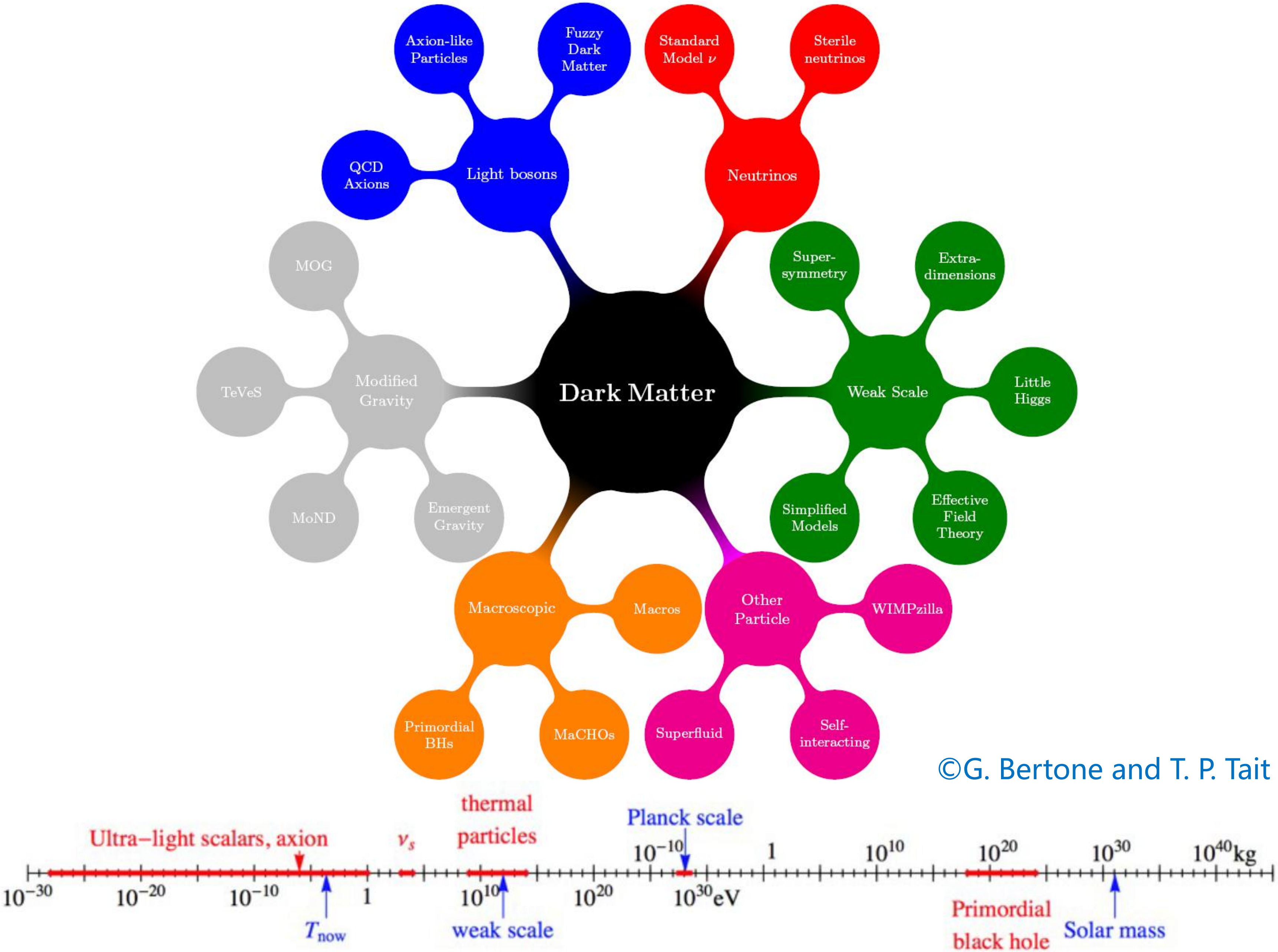




- CMB



Dark sector candidates



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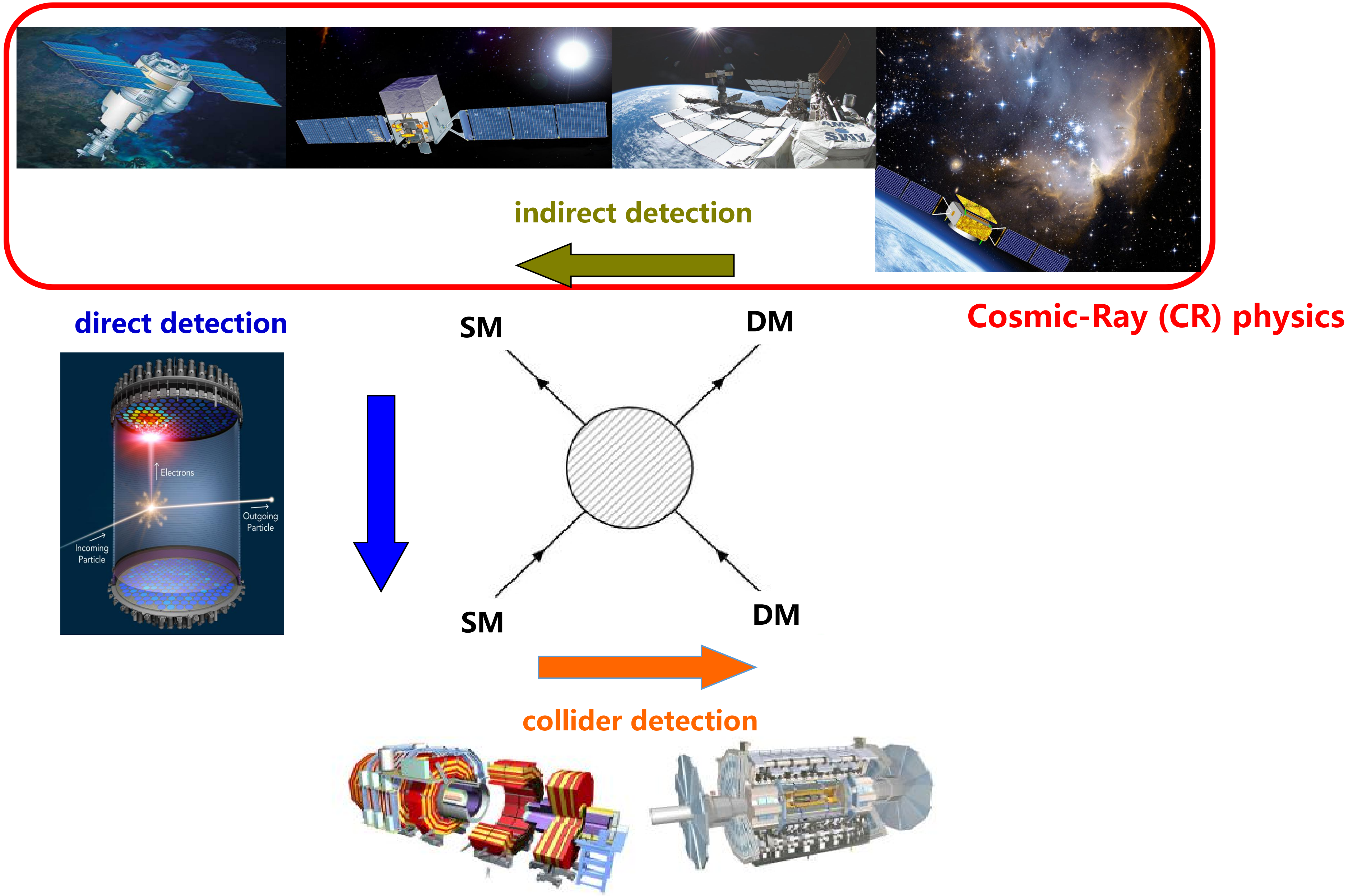
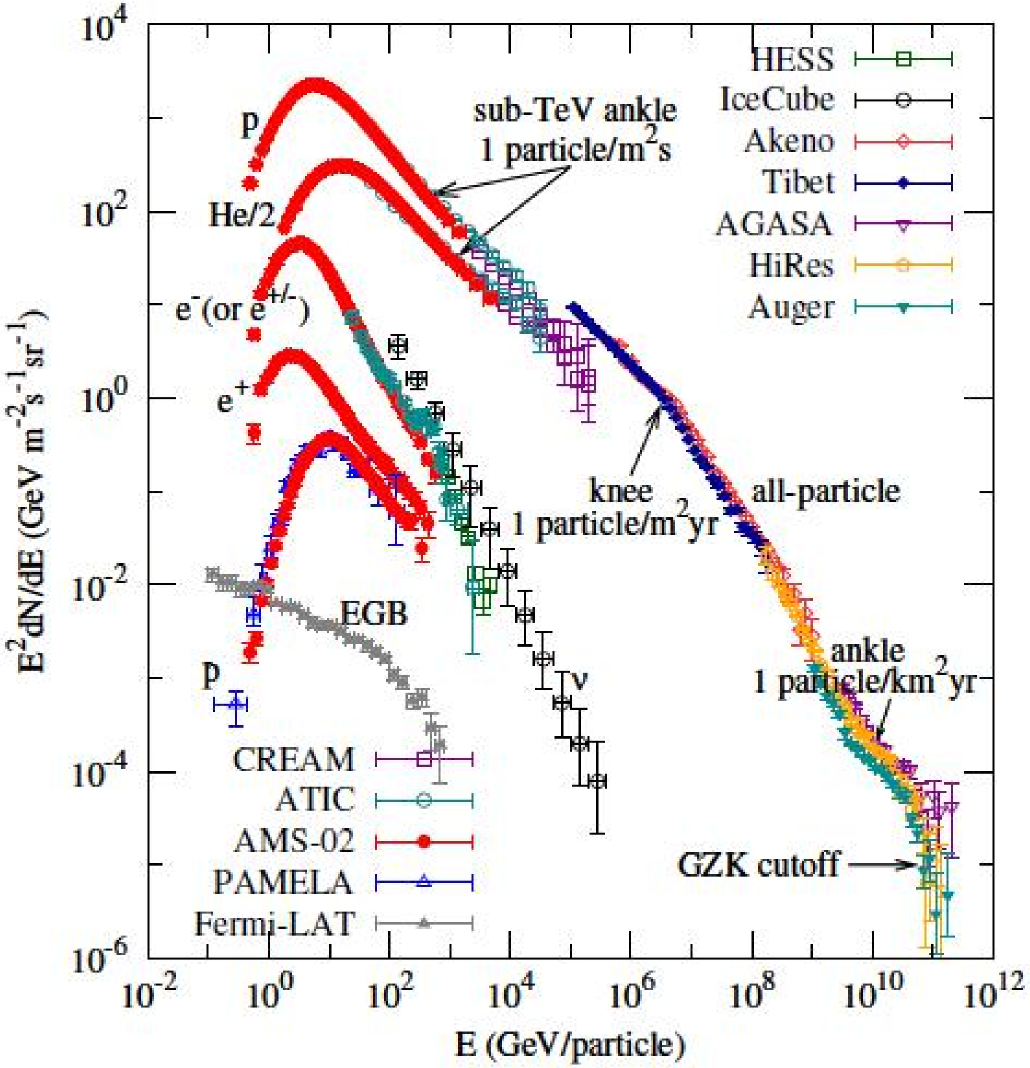
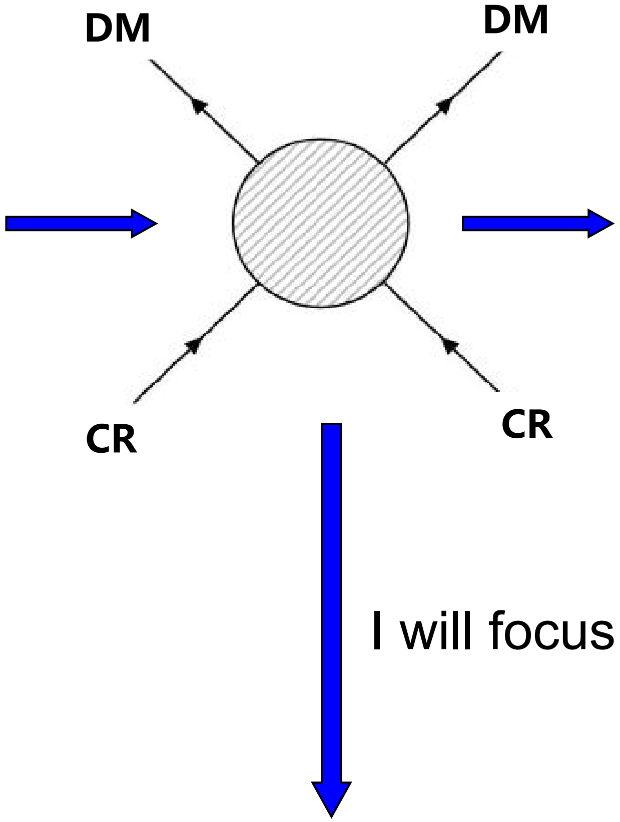
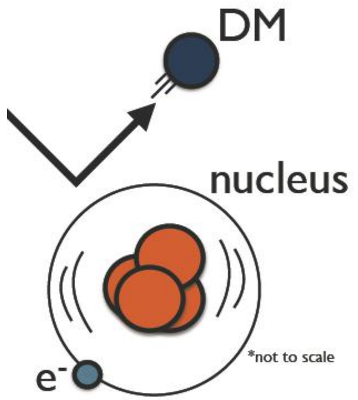

indirect detection
direct detection
SM
DM
Cosmic-Ray (CR) physics
Electrons
Outgoing Particle
Incoming Particle
SM
DM
collider detection



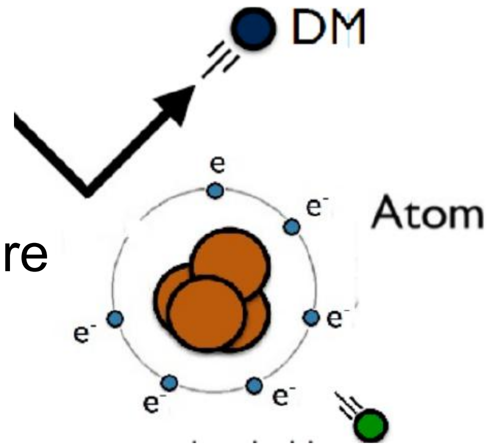


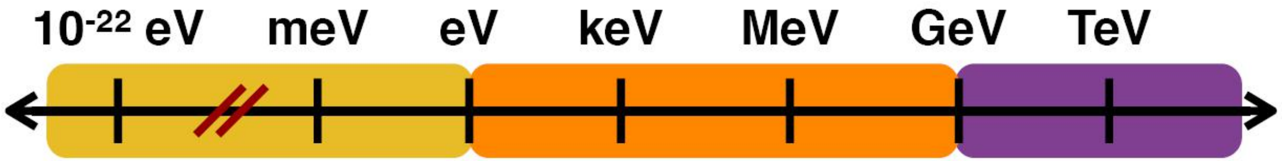
I will focus here

DM-nucleon scattering



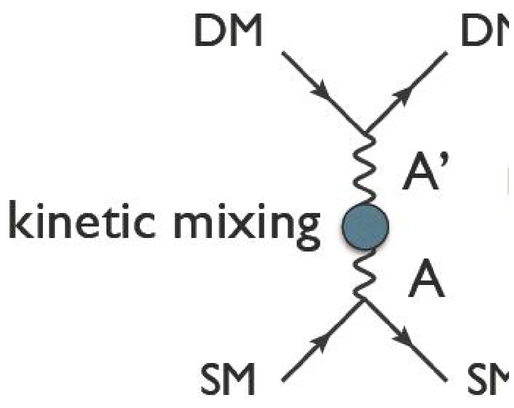
DM-electron scattering

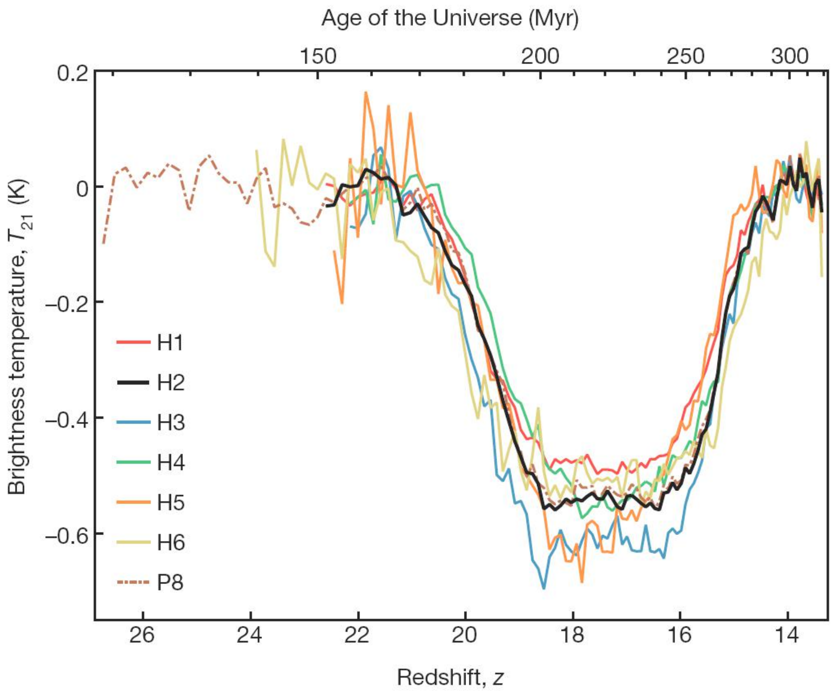


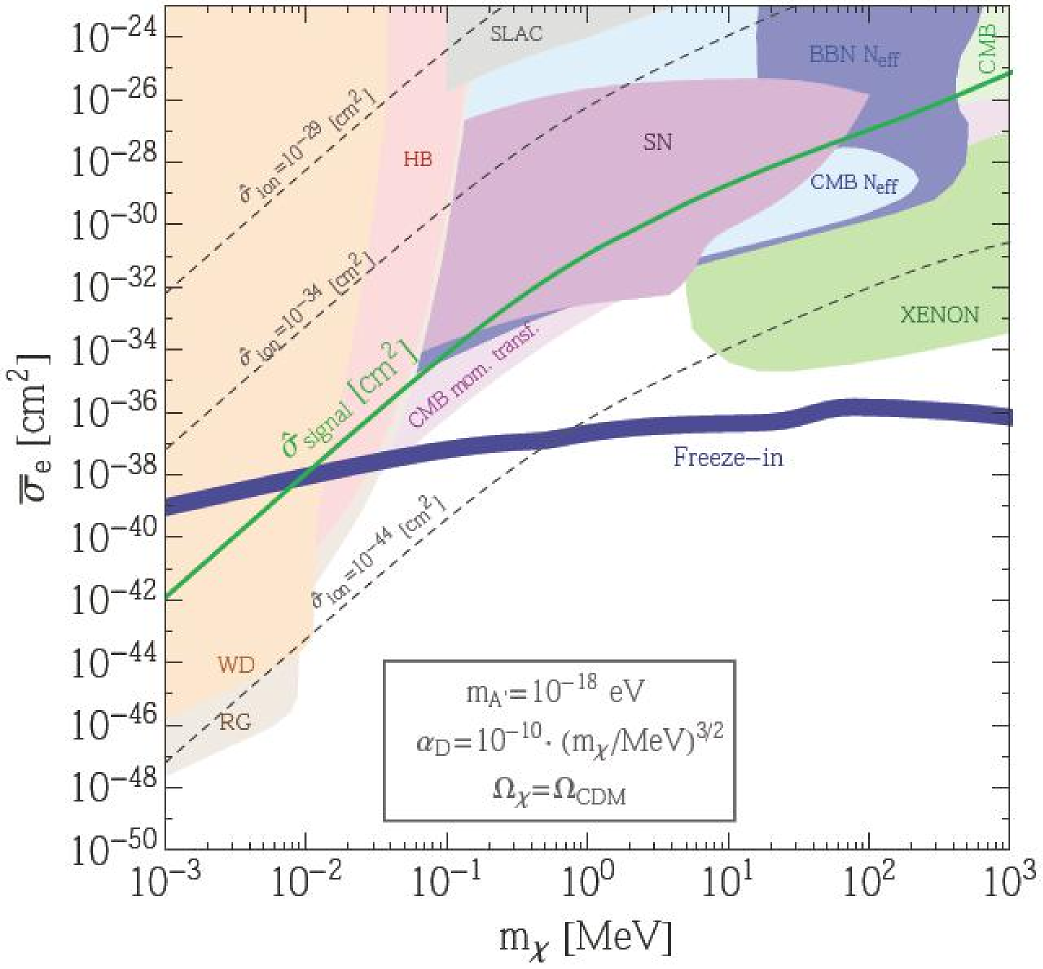


Theoretical motivation of light DM

- Hidden Photon Mediator

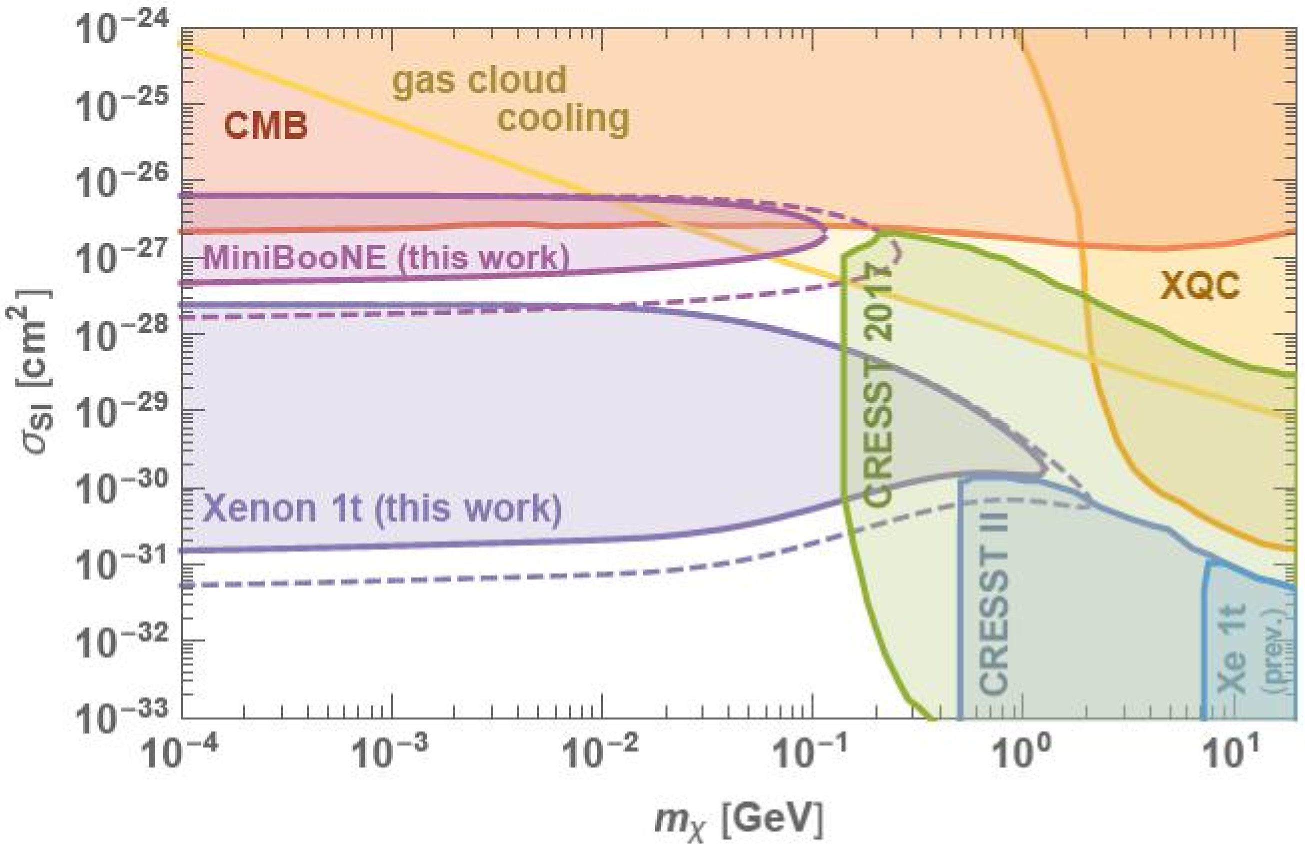






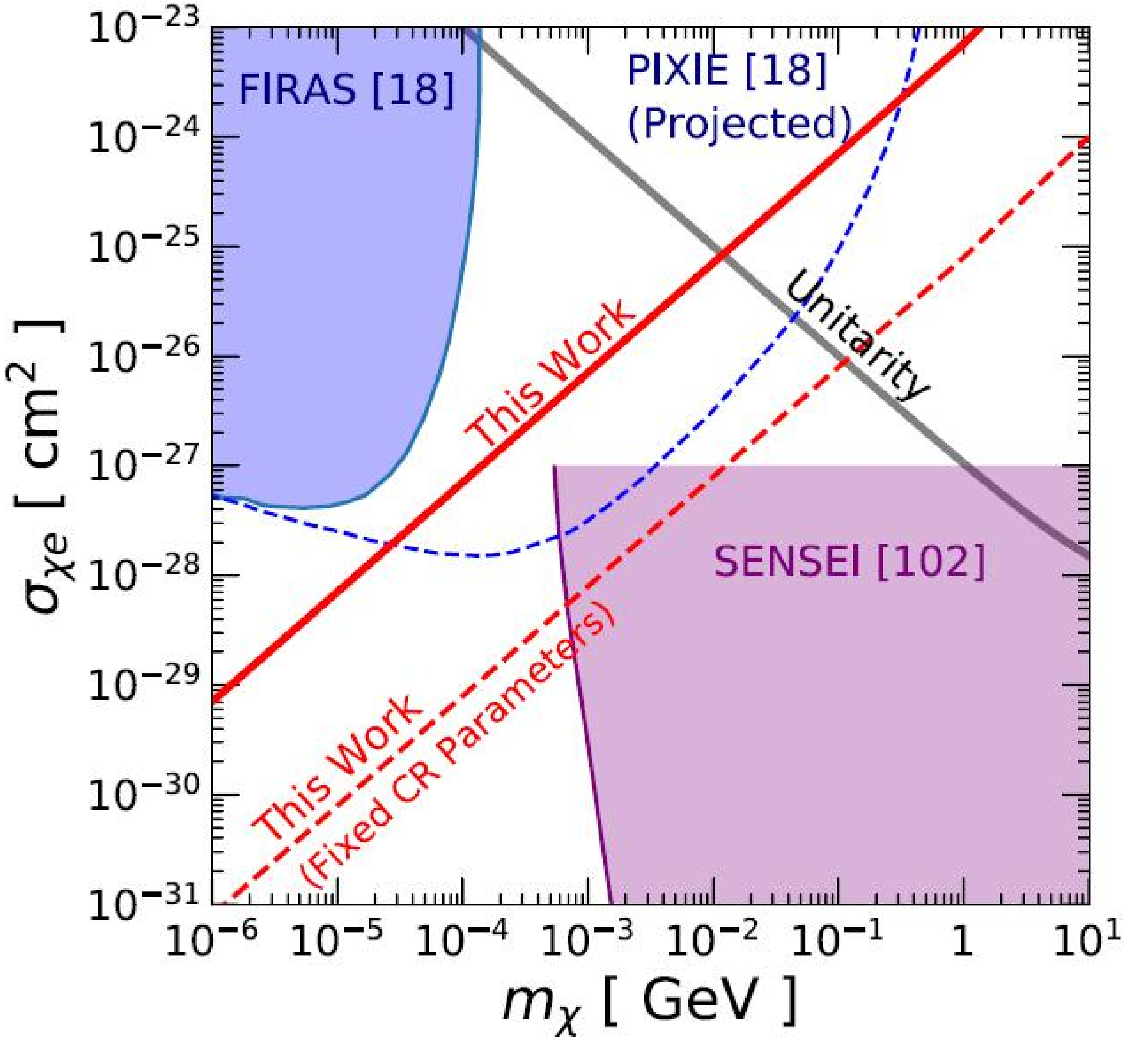
Limits from DM-nucleon direct detection

T. Bringmann and M. Pospelov, arXiv:1810.10543



Reverse Direct Detection

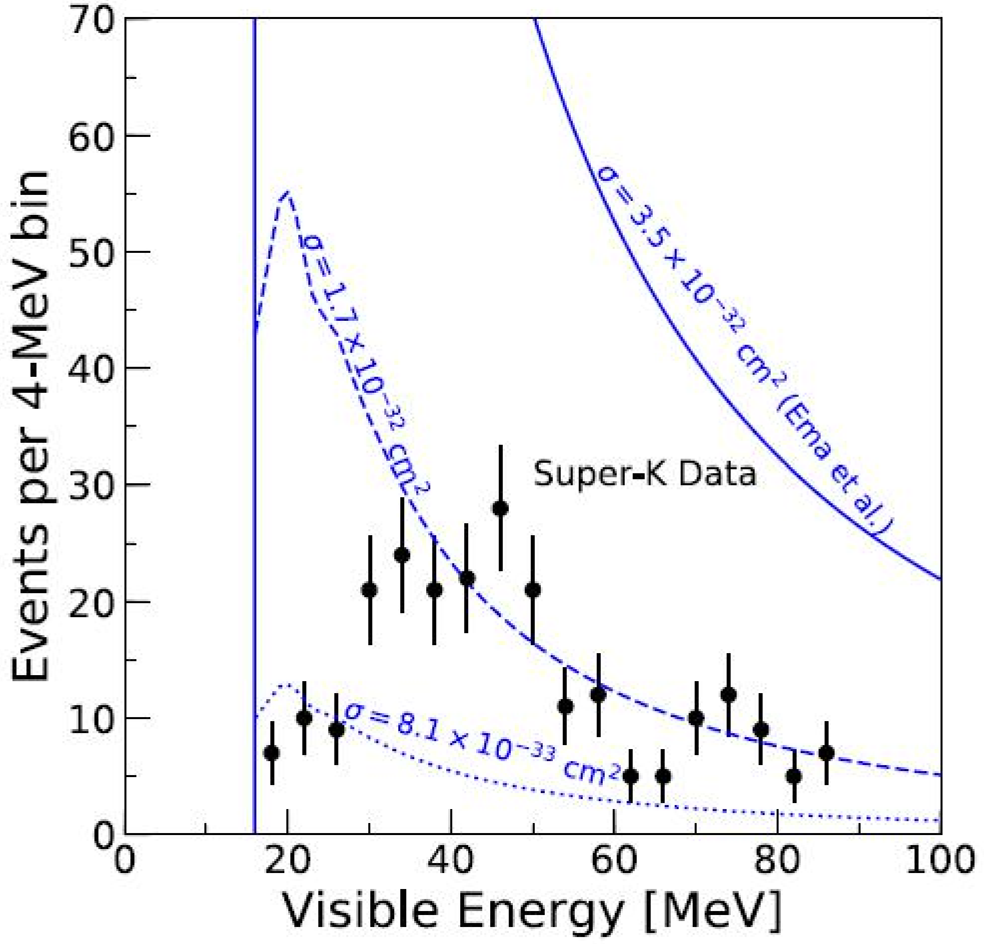
C. V. Cappiello, K. C. Y. Ng and J. F. Beacom, arXiv:1810.07705

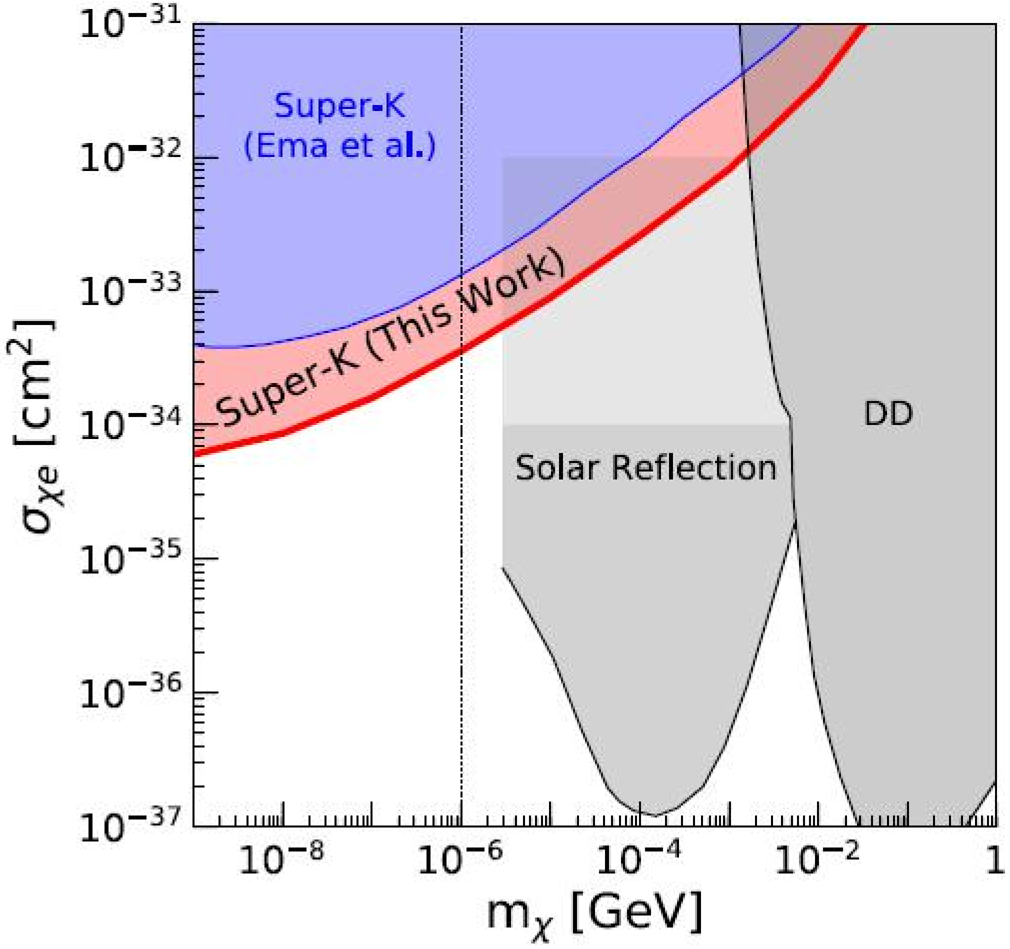


Limits from Neutrino Experiments

Y. Ema, F. Sala and R. Sato, arXiv:1811.00520

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





Calculation framework

Flux of CR electrons

↓

Flux of DM boosted by CR electrons

↓

Spectrum of electron recoil energy in xenon

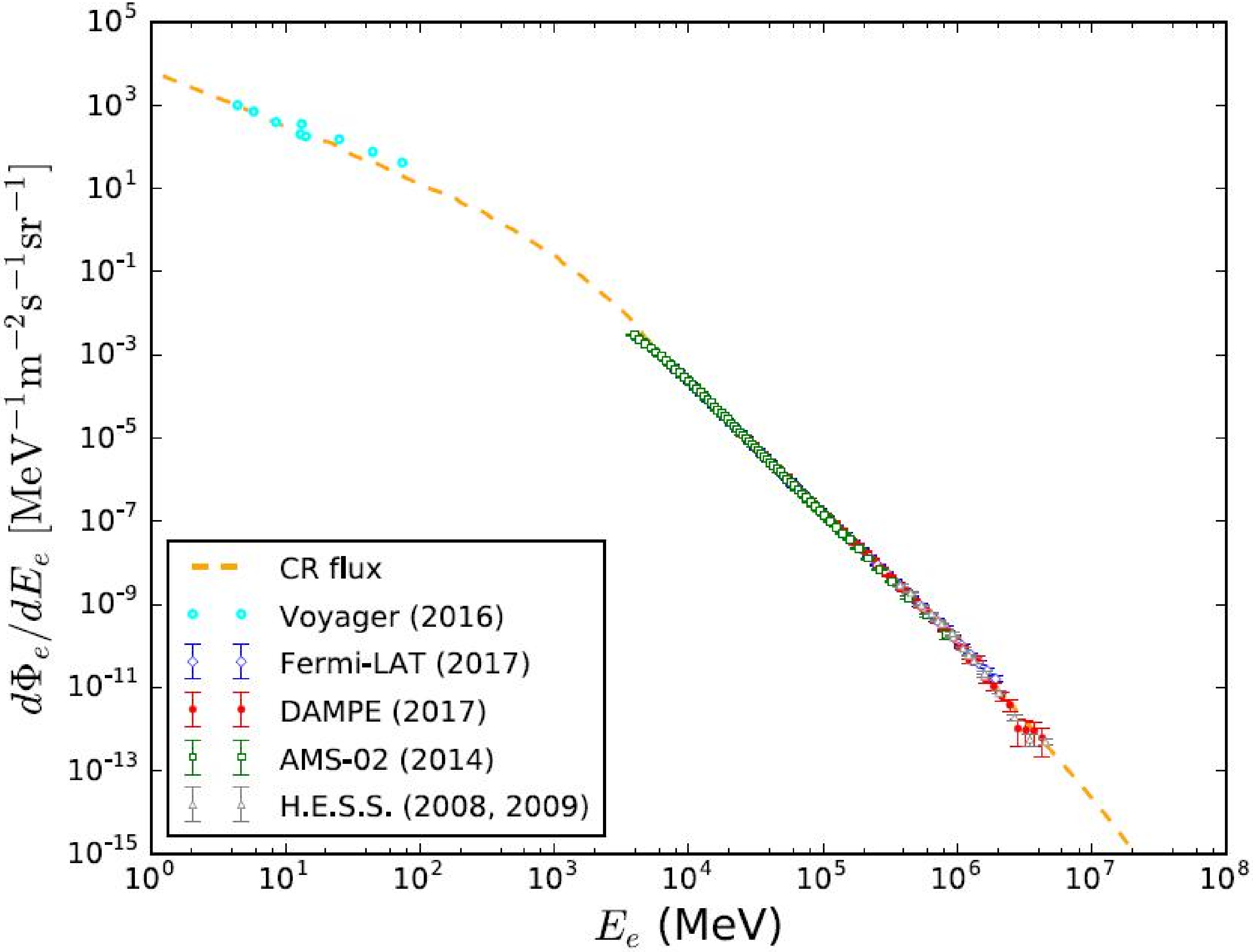
↓

Spectrum of photoelectrons (PE) in xenon

↓

Limit on the DM-electron scattering cross section

Flux of CR electrons

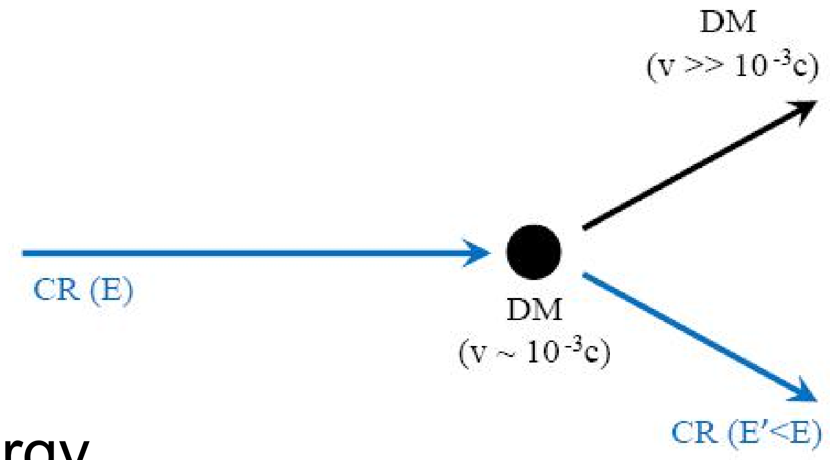


Flux of DM boosted by CR electrons

- Kinematics of DM-CR scattering

$$T_\chi^{\max} = \frac{2m_\chi T_{\rm CR}(T_{\rm CR} + 2m_{\rm CR})}{(m_{\rm CR} + m_\chi)^2 + 2T_{\rm CR}m_\chi}$$

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



- Differential flux at Earth in terms of the CR energy

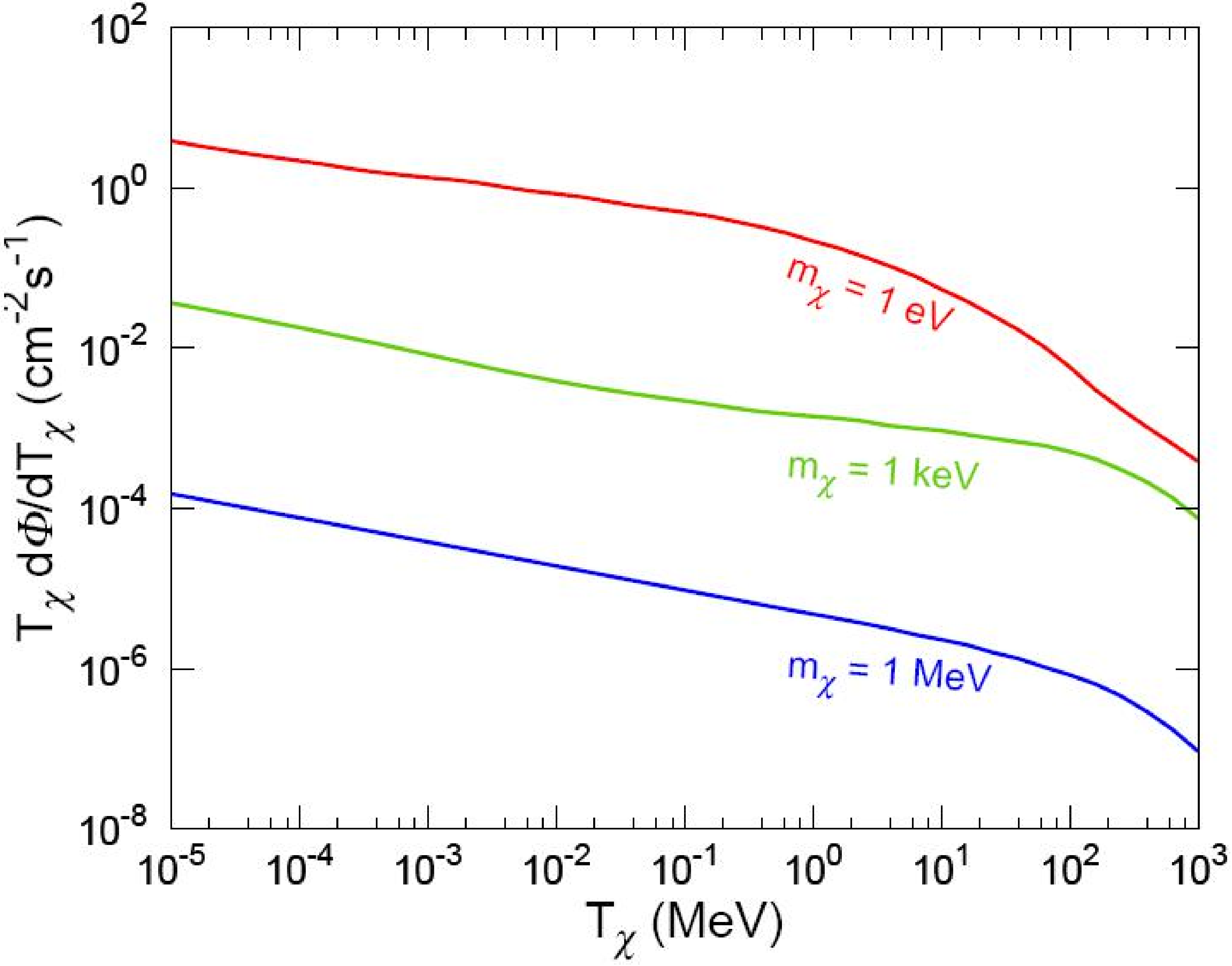
$$\frac{d\Phi_\chi}{dT_i} = \int \frac{d\Omega}{4\pi}\int_{l.o.s} dl \sigma_{\chi i}\frac{\rho_\chi}{m_\chi}\frac{d\Phi_i}{dT_i} \equiv \sigma_{\chi i}\frac{\rho_\chi}{m_\chi}\frac{d\Phi_i}{dT_i}D_{\rm eff}$$

line-of-sight integration out to 10 kpc $D_{\rm eff} = 8.02\,{\rm kpc}$

- Convert into a DM energy spectrum

$$\frac{d\Phi_\chi}{dT_\chi} = \int_0^\infty dT_i \frac{d\Phi_i}{dT_i}\frac{1}{T_\chi^{\max}(T_i)}\Theta\left[T_\chi^{\max}(T_i) - T_\chi\right]$$

Flux of DM boosted by CR electrons

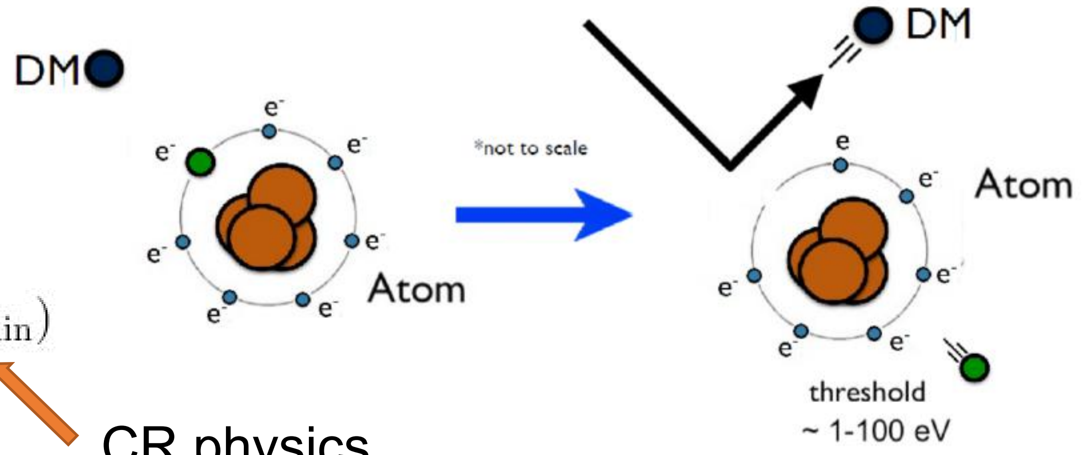


Spectrum of electron recoil energy in xenon

- Differential scattering rate

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

$$\chi(p) + e(k) \to \chi(p') + e(k')$$



particle physics

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

CR physics

solid state physics

$$\eta\,(E_{\min}) = \int_{\rm DM} \frac{m_\chi^2}{p_\chi E_\chi} = \frac{1}{\rho_\chi}\int_{E_{\min}} dE_\chi \frac{m_\chi^2}{p_\chi E_\chi}\frac{d\Phi_\chi}{dE_\chi}$$

In non-relativstic limit

$$\eta\,(v_{\min}) = \int_{DM} \frac{m_\chi^2}{m_\chi^2 v} = \int_{DM} \frac{1}{v}$$

boosted DM energy spectrum

$$p_\chi^{\min} = \frac{q}{2\,(1-\Delta E_e^2/q^2)}\left(1 - \frac{\Delta E_e^2}{q^2} \pm \frac{\Delta E_e}{q}\sqrt{\left(1-\frac{\Delta E_e^2}{q^2}\right)\left(1+\frac{4m_\chi^2}{q^2}-\frac{\Delta E_e^2}{q^2}\right)}\right)$$

Spectrum of electron recoil energy in xenon

- Ionization from factor
  - outgoing electron as a free plane wave.

$$|f_{ion}^{nl}(k',q)|^2 = \frac{2k'^3}{(2\pi)^3} \sum_{\substack{nlm,\\ n'l'm'}} |\langle n'l'm'|e^{iq\chi}|nlm\rangle|^2$$

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

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

- Roothaan Hartree Fock (RHF) method

$$\chi_{nl}(p) = 4\pi i^l \int dr r^2 R_{nl}(r) j_l(pr)$$

  - Radial wave functions: linear combination of Slater type orbitals

C. F. Bunge, J. A. Barrientos and A. V. Bunge (1993)

$$R_{nl}(r) = \sum_k C_{nlk} \frac{(2Z_{lk})^{n_{lk}+1/2}}{a_0^{3/2}\sqrt{(2n_{lk})!}} (r/a_0)^{n_{lk}-1} \exp\left(-\frac{Z_{lk} r}{a_0}\right)$$

  - Analytical expression

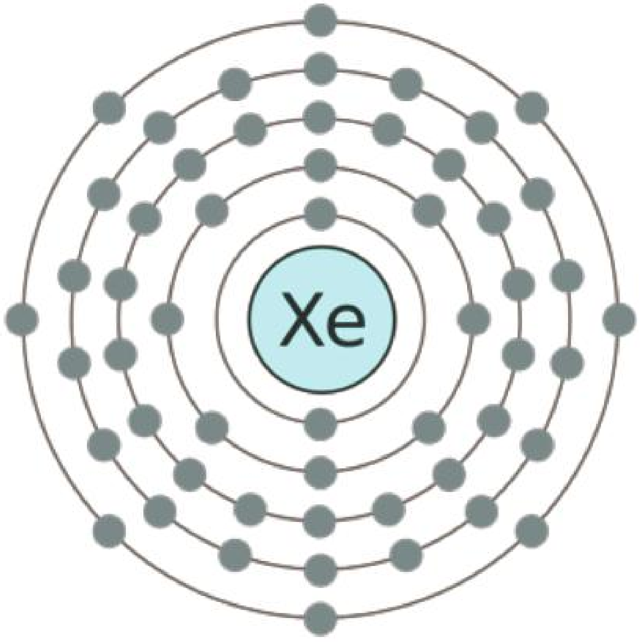
J. Kopp, V. Niro, T. Schwetz and J. Zupan, arXiv:0907.3159

$$\chi_{nl}(p) = \sum_k C_{nlk} 2^{n_{lk}-1} \left(\frac{2\pi a_0}{Z_{lk}}\right)^{3/2} \left(\frac{ipa_0}{Z_{lk}}\right)^l \frac{\Gamma(n_{lk}+l+2)}{\Gamma(l+\frac{3}{2})\sqrt{(2n_{lk})!}}$$

$$\times {}_2F_1\left[\frac{1}{2}(n_{lk}+l+2), \frac{1}{2}(n_{lk}+l+3), l+\frac{3}{2}, -\left(\frac{pa_0}{Z_{lk}}\right)^2\right]$$

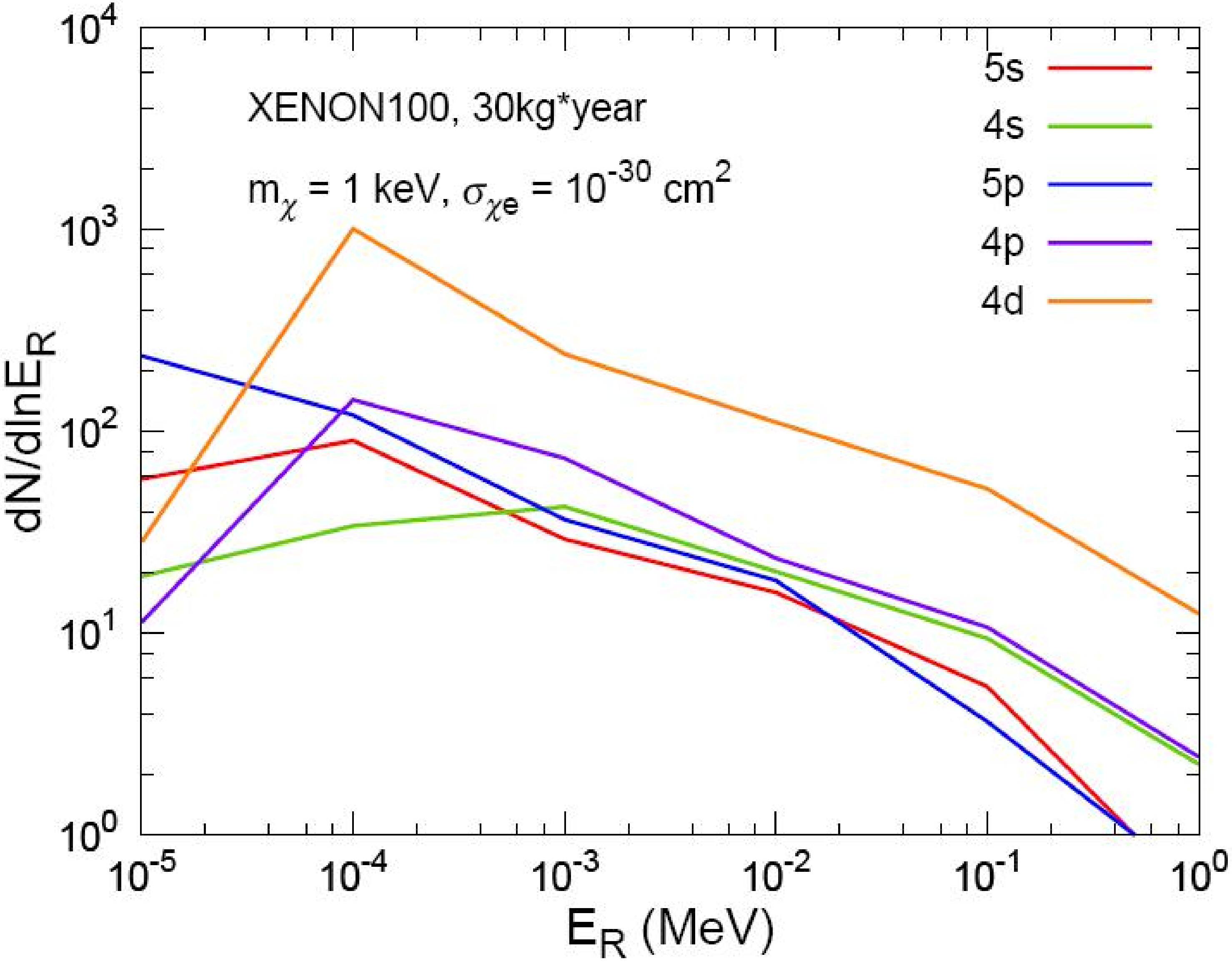
Spectrum of electron recoil energy in xenon

$$\frac{dR_{ion}}{d\ln E_R} = N_T \frac{\rho_\chi}{m_\chi} \frac{d\langle \sigma_{ion}^{nl} v \rangle}{d\ln E_R}$$



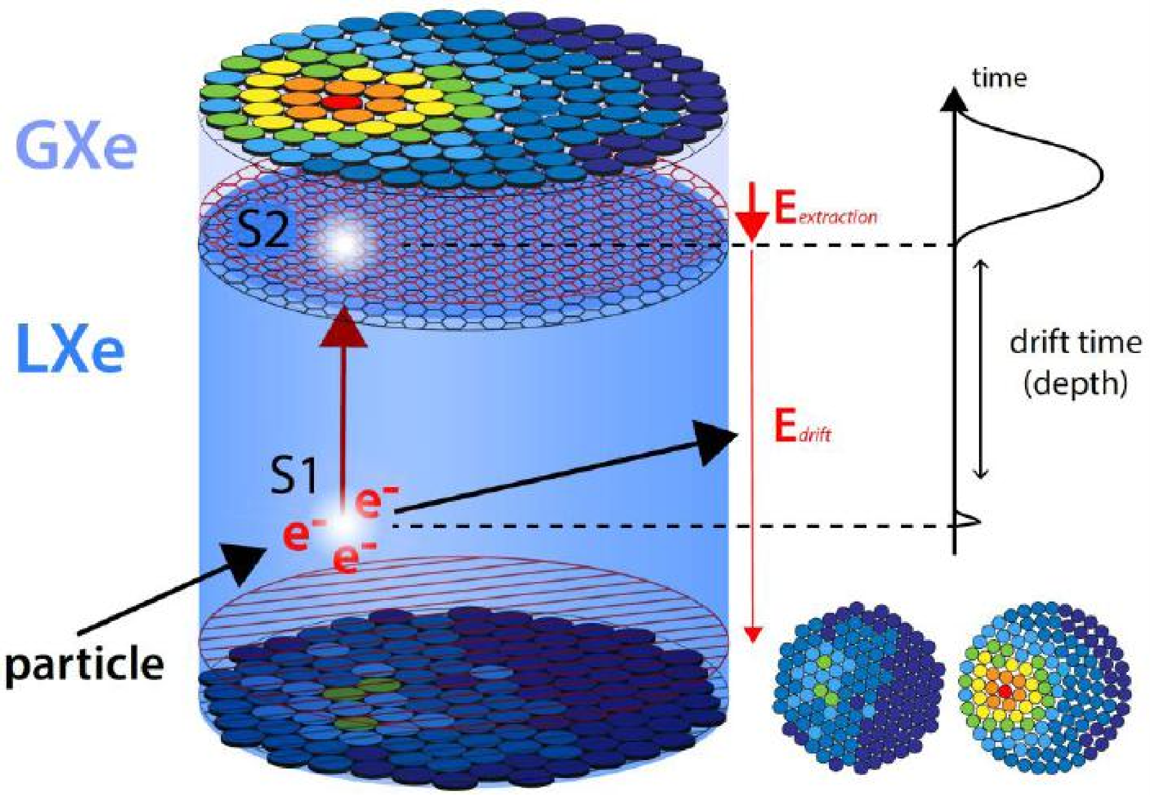
Electron configuration:

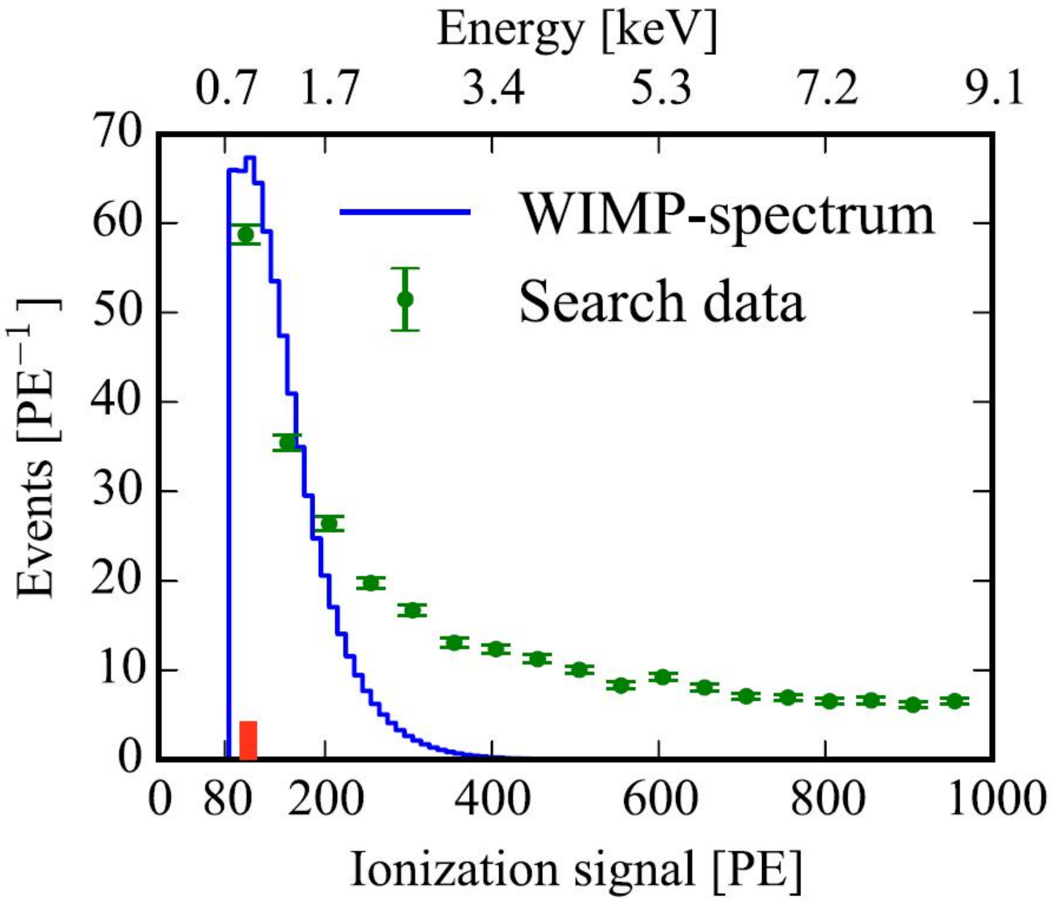
[Ar] 3d10 4s2 4p6 4d10 5s2 5p6



Spectrum of photoelectrons (PE) in xenon

- S1 light signal:Prompt scintillation photons
- S2 Charge signal: Secondary scintillation photons from electroluminescence in Gxe due to drifted electrons





Spectrum of photoelectrons (PE) in xenon

- Event rate for Si responses

$$\frac{dR}{dS_i} = \int dE_R\, P(S_i|E_R) \frac{dR_{ion}}{d\ln E_R}$$

- Probability to produce S2 for given recoil energy

$$P(n_e|\langle n_e\rangle) = \mathrm{binom}(n_e|N_Q, f_e)$$

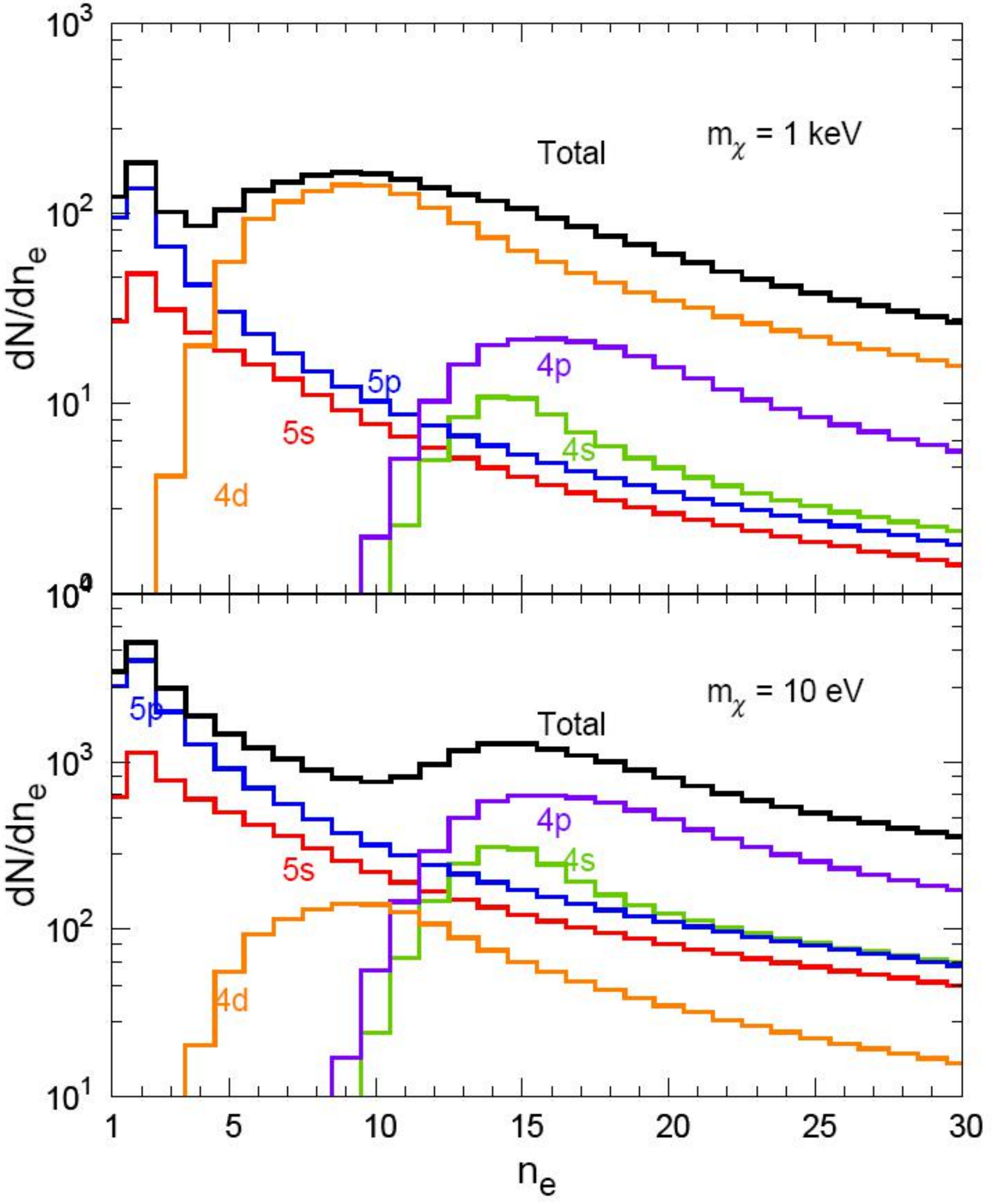
$$N_Q = n_e + n_\gamma = N_i + N_{\mathrm{ex}}$$

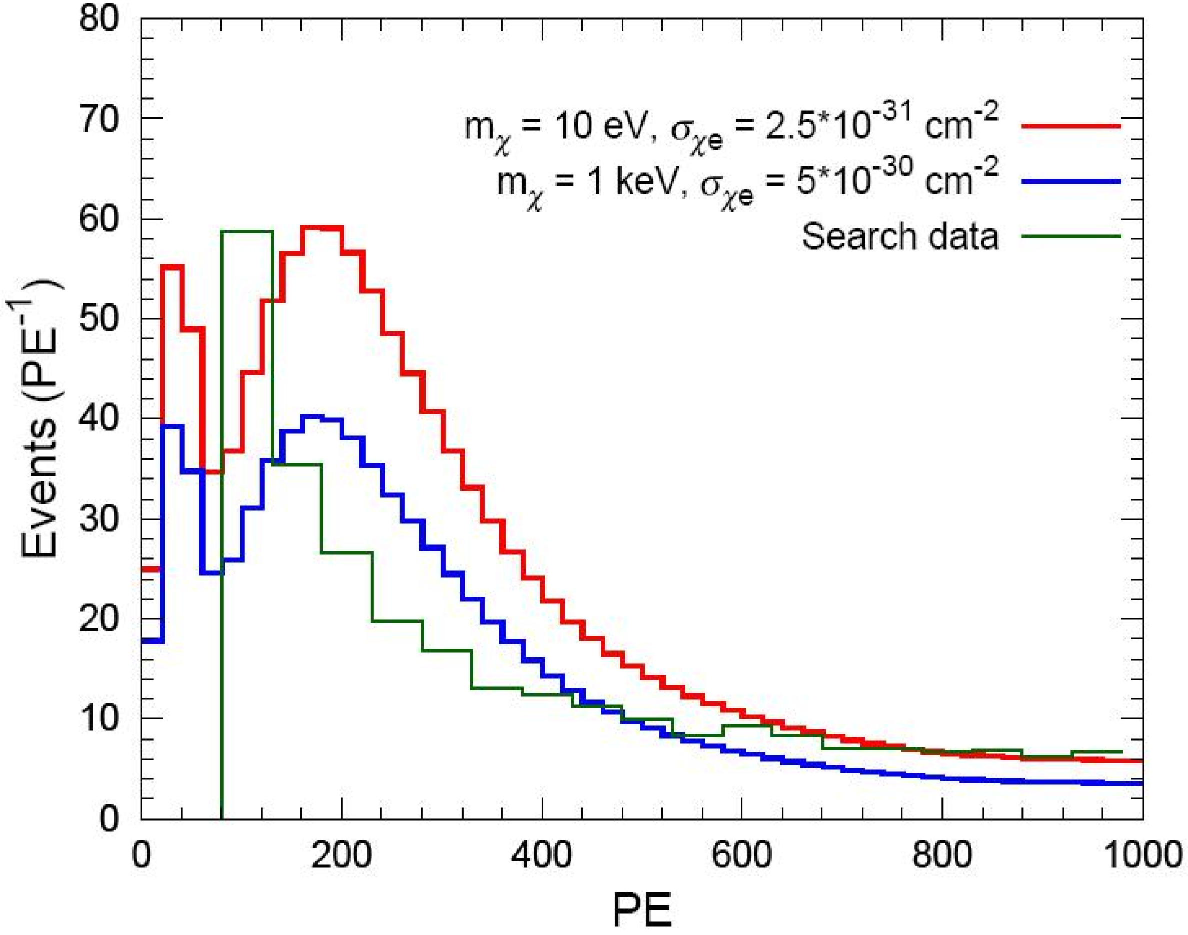
$$f_e = (1 - f_R)(1 + N_{\mathrm{ex}}/N_i)^{-1} \approx 0.83$$

$$P(n_e^{\mathrm{surv}}|n_e) \approx 1, \quad P(S2|n_e^{\mathrm{surv}}) = \mathrm{gauss}(S2|n_e^{\mathrm{surv}},\ \sigma_{S2})$$

$$P(S2|E_R) = \sum_{n_e^{\mathrm{surv}}} \sum_{n_e} P(S2|n_e^{\mathrm{surv}}) P(n_e^{\mathrm{surv}}|n_e) P(n_e|\langle n_e\rangle)$$

Spectrum of photoelectrons (PE) in xenon

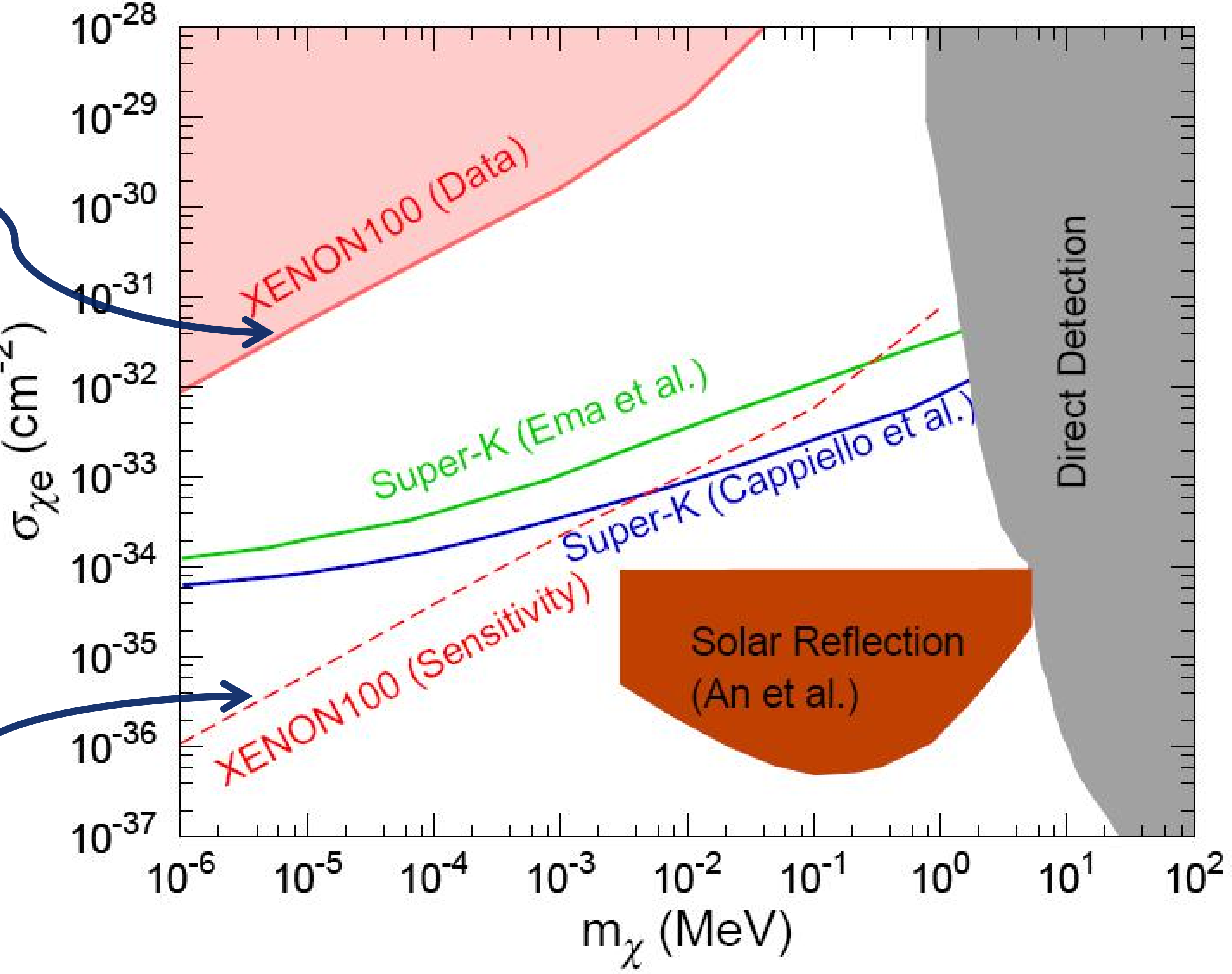




Limit on the DM-electron scattering cross section

$$\frac{dR}{dS_i} = \int dE_R \, P(S_i|E_R) \frac{dR_{ion}}{d\ln E_R}$$

$$\left.\frac{dR}{dS_i}\right|_{\rm satu} \simeq \int_{E_R > {\rm KeV}} dE_R \frac{dR_{ion}}{d\ln E_R}$$



谢谢大家