CERN-CKC 2021

Energetic Light Dark Matter and High Energy Electron Recoil in Direct Detection Experiments

Seodong Shin

전북대학교
JEONBUK NATIONAL UNIVERSITY

Gian Giudice, Doojin Kim, Jong-Chul Park, **SS**, PLB 780, 543 (2018), arXiv:1712.07126

Haider Alhazmi, Doojin Kim, KC Kong, Gopi Mohlabeng, Jong-Chul Park, **SS**,
JHEP 05, 055 (2021), arXiv: 2006.16252

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What is Dark Matter?

What particle is dark matter?

- Mass?
- (Non-gravitational) Interactions?

  DM - SM

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  DM - SM → i) Observation

  ii) Amount of DM

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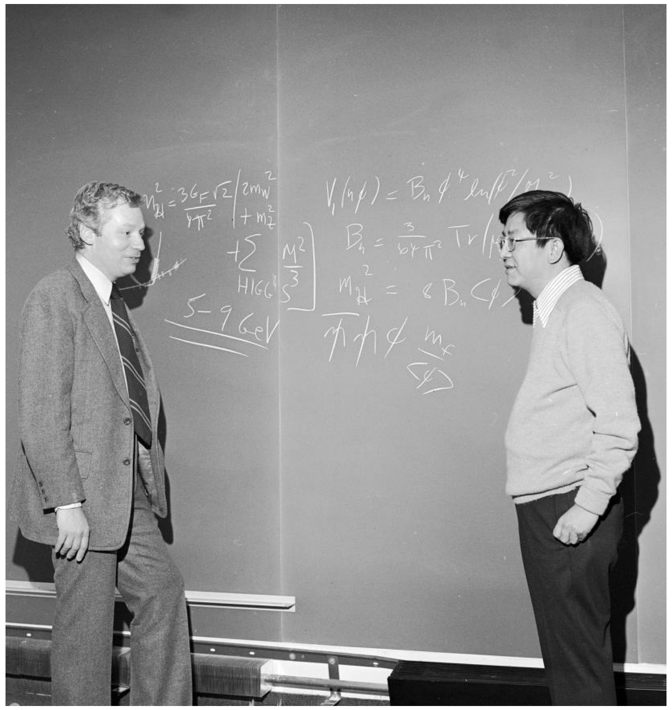
Preferred candidate so far was

Weakly Interacting Massive Particle (WIMP)



- Weak scale mass: O(1 ~ 100) × proton mass
- Weak interaction with the SM particles:
  about < 10^{-12} (in cross section) smaller than EM

Byproduct of many BSM theories for resolving the hierarchy problem

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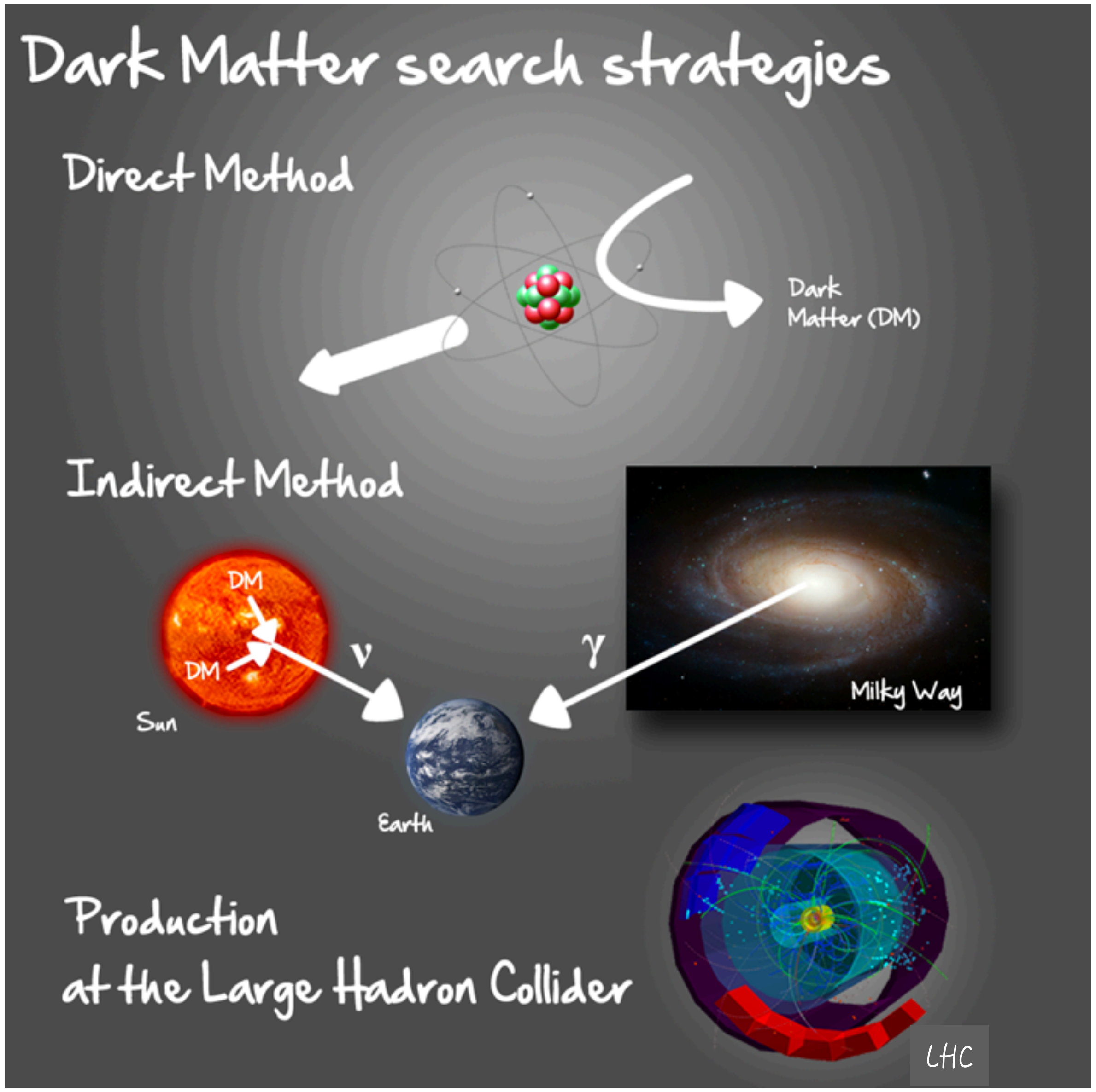

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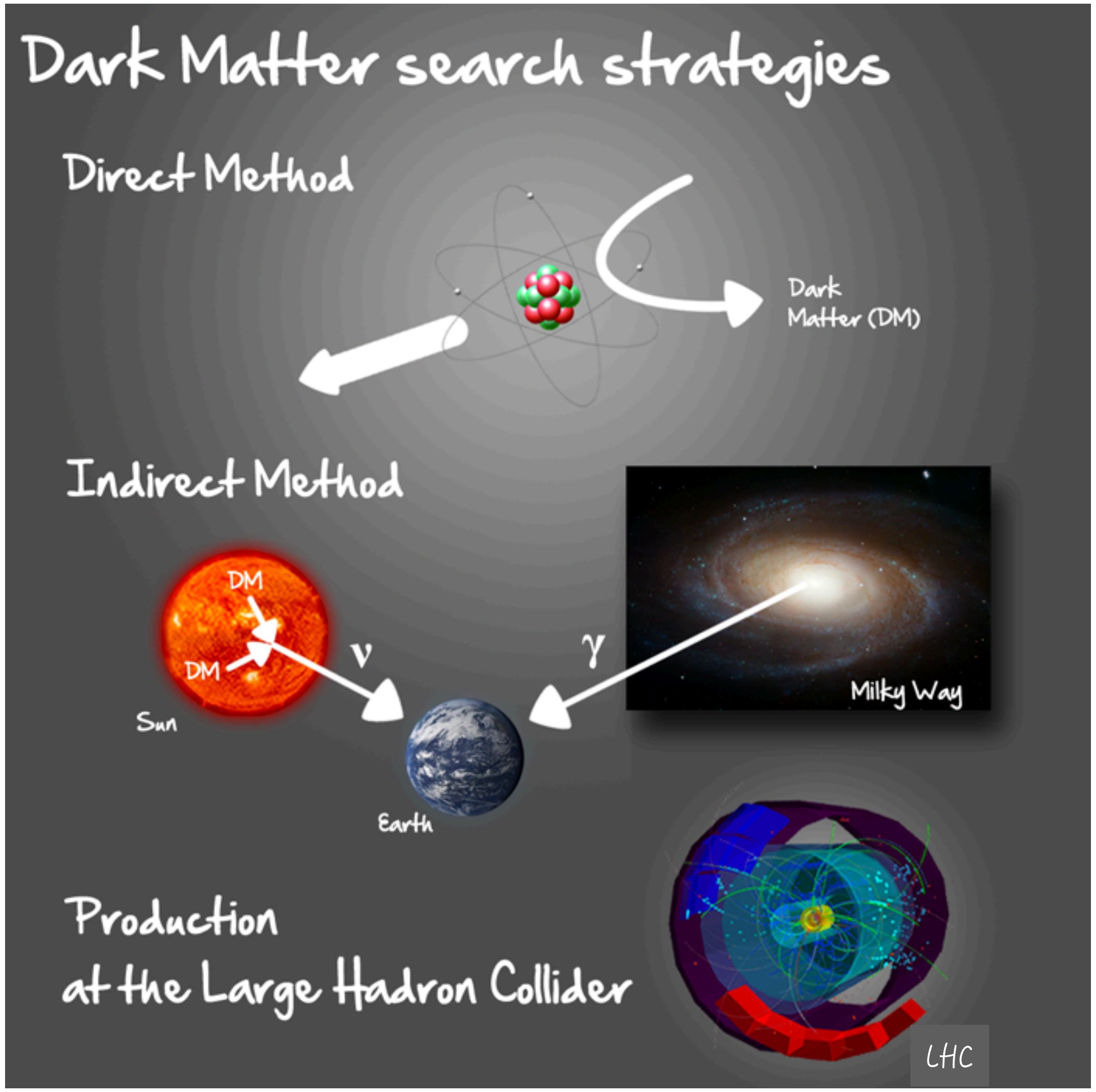
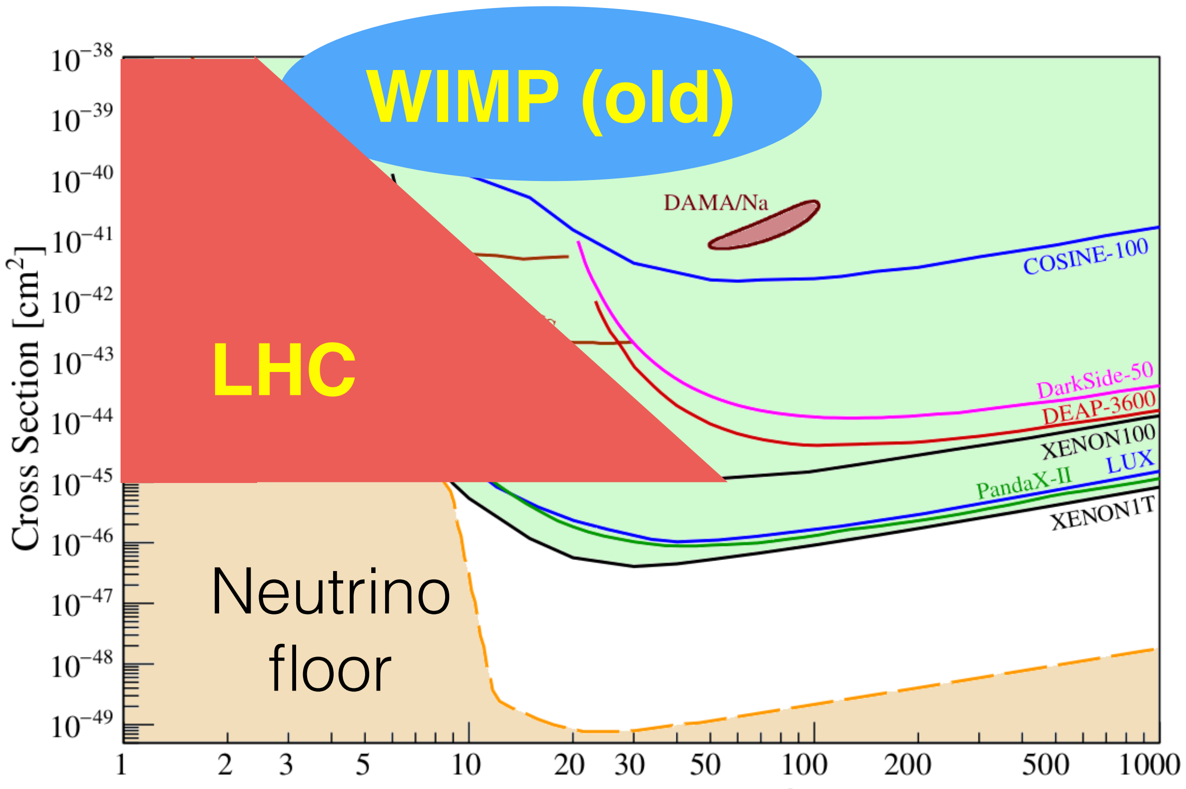


WIMP strongly constrained!



Schumann, 1903.03026

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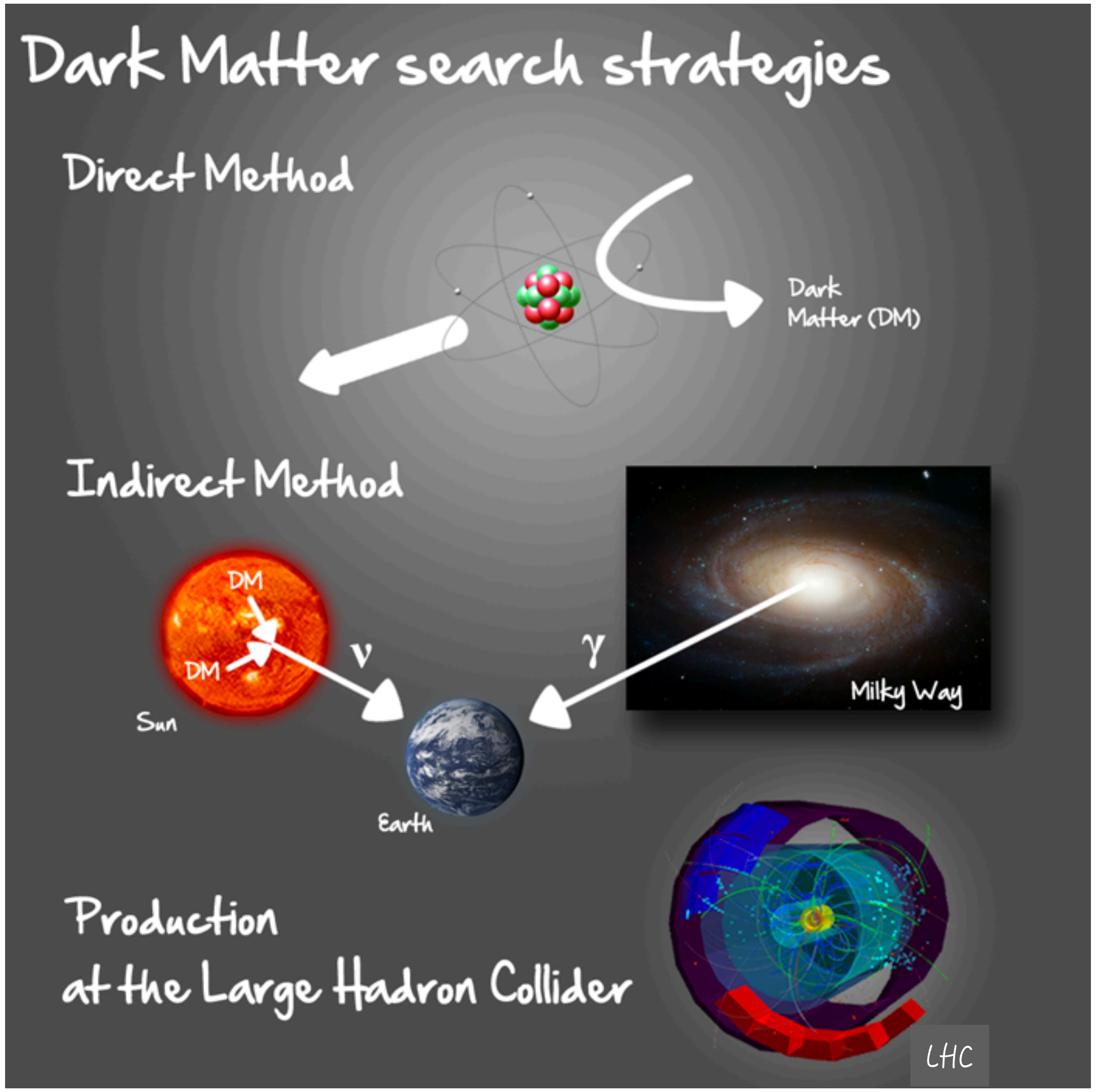

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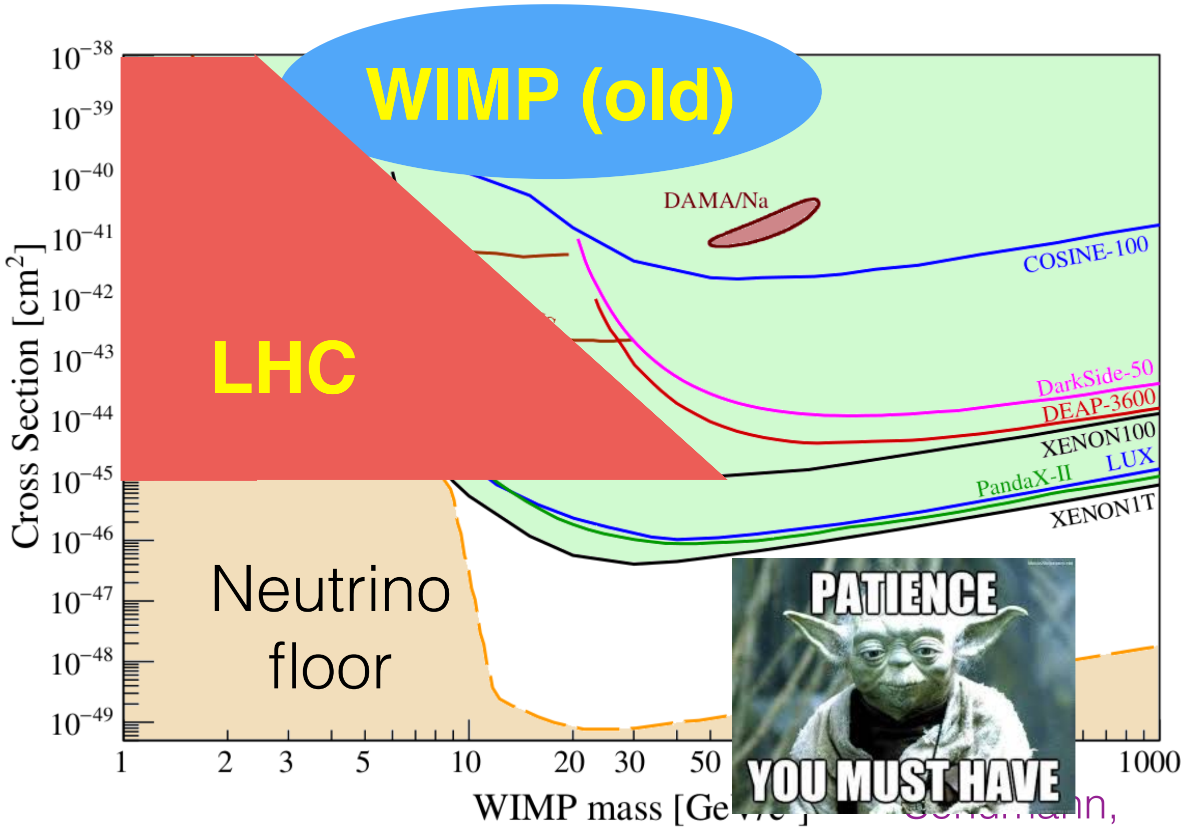

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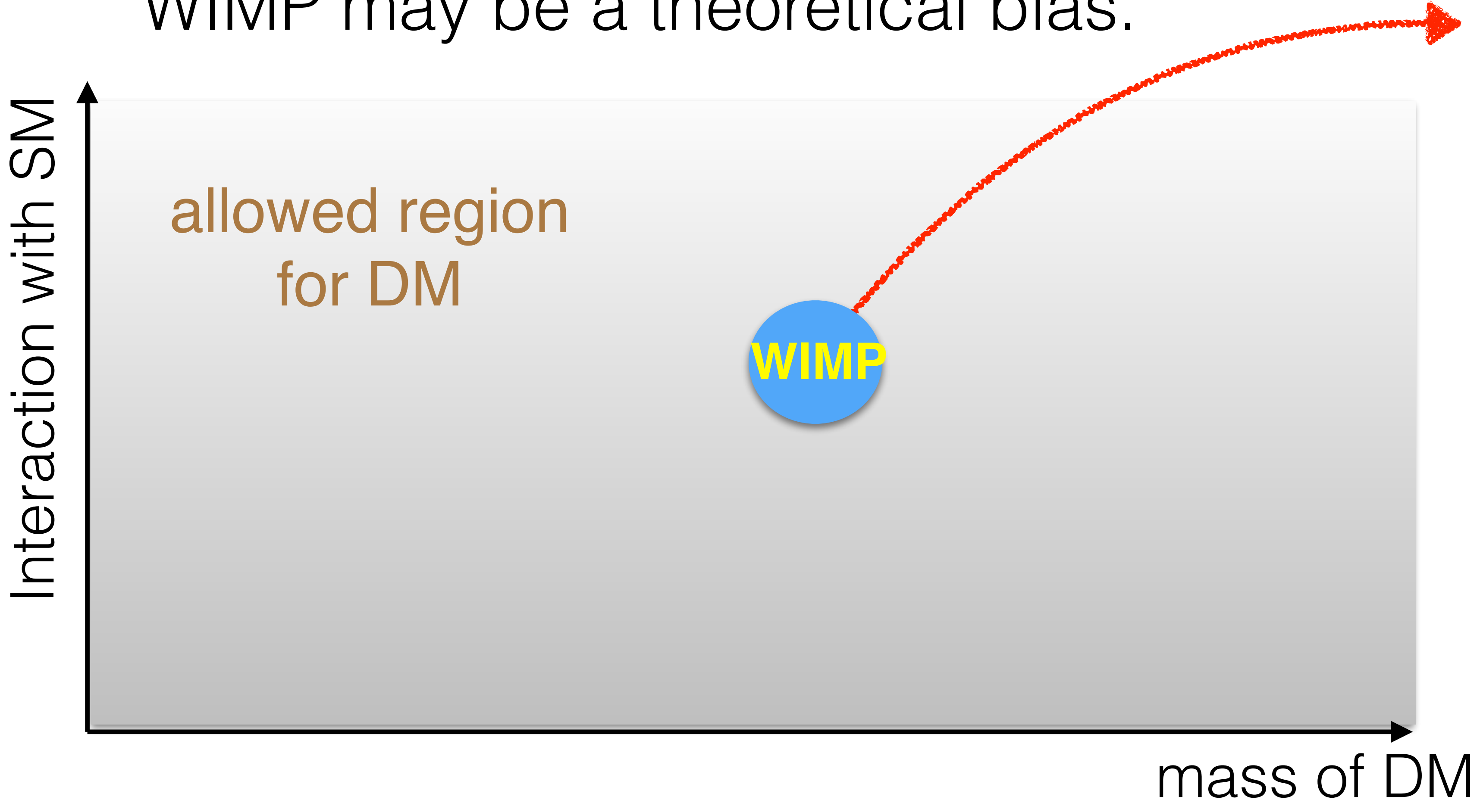
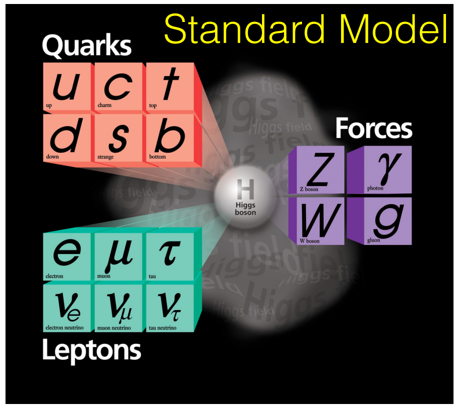
1903.03026

Dark World beyond WIMP

WIMP may be a theoretical bias.



- Small region
- Oversimplification compared to



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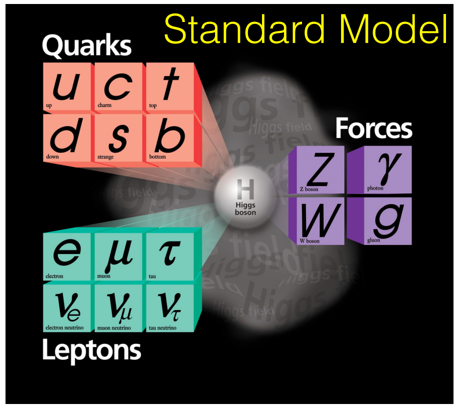

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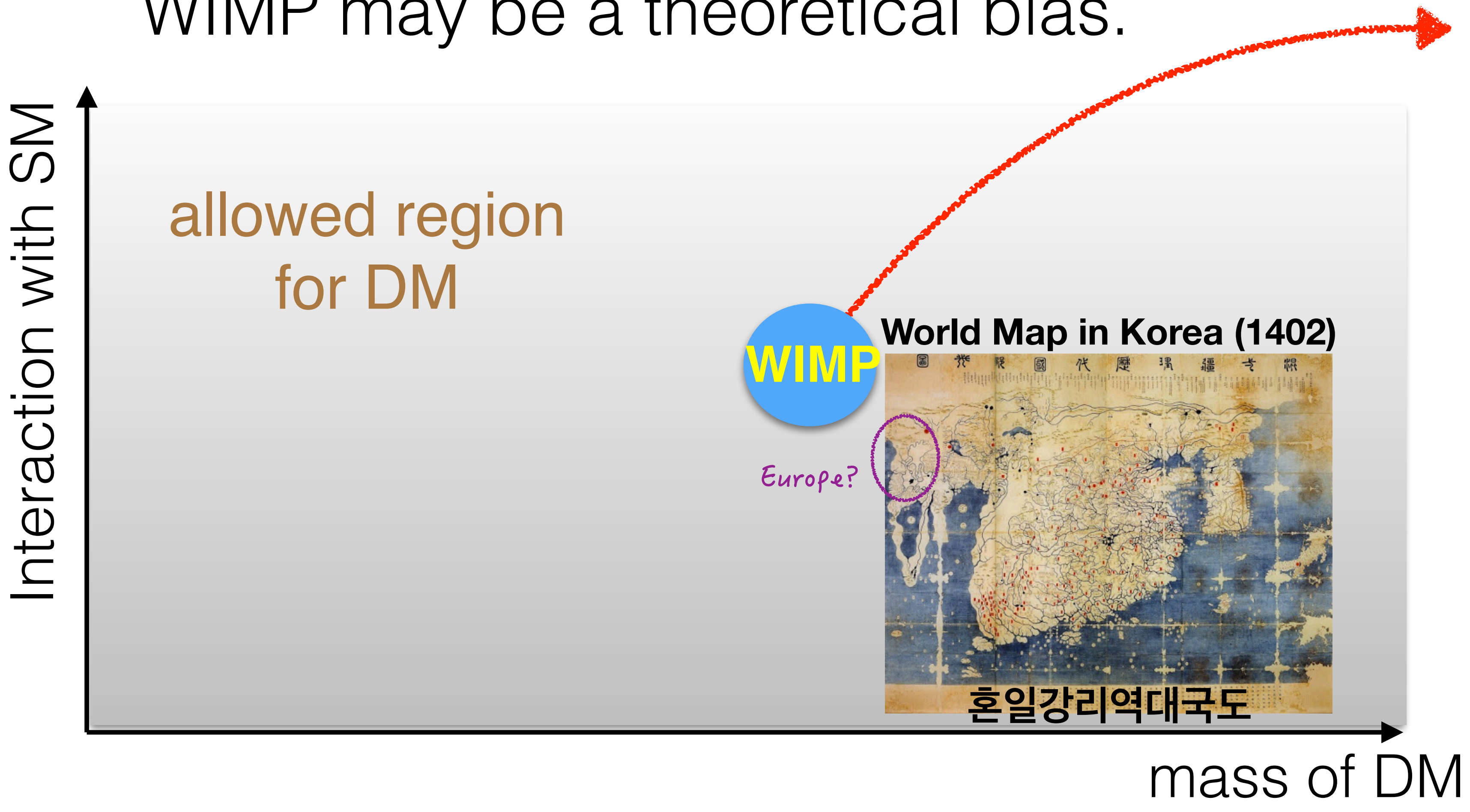

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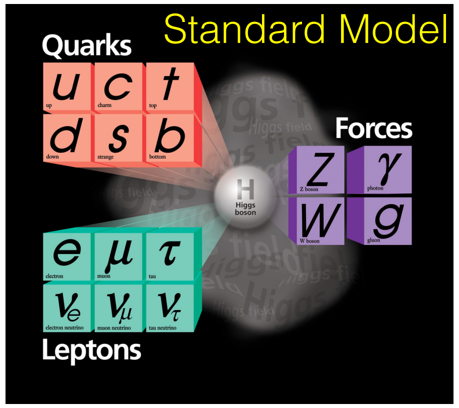

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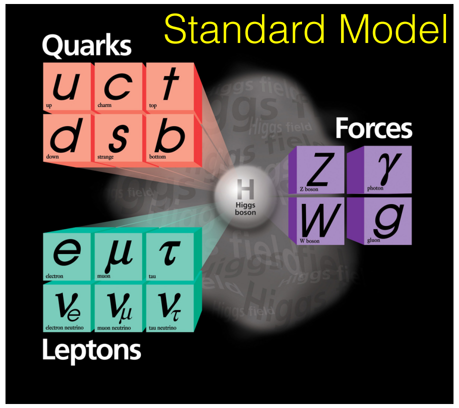

- Light Dark Matter is being actively considered as a dark sector candidate.

  (Both in a simplified model or UV model)

- Due to its mass, the interactions with electron target are being focused.

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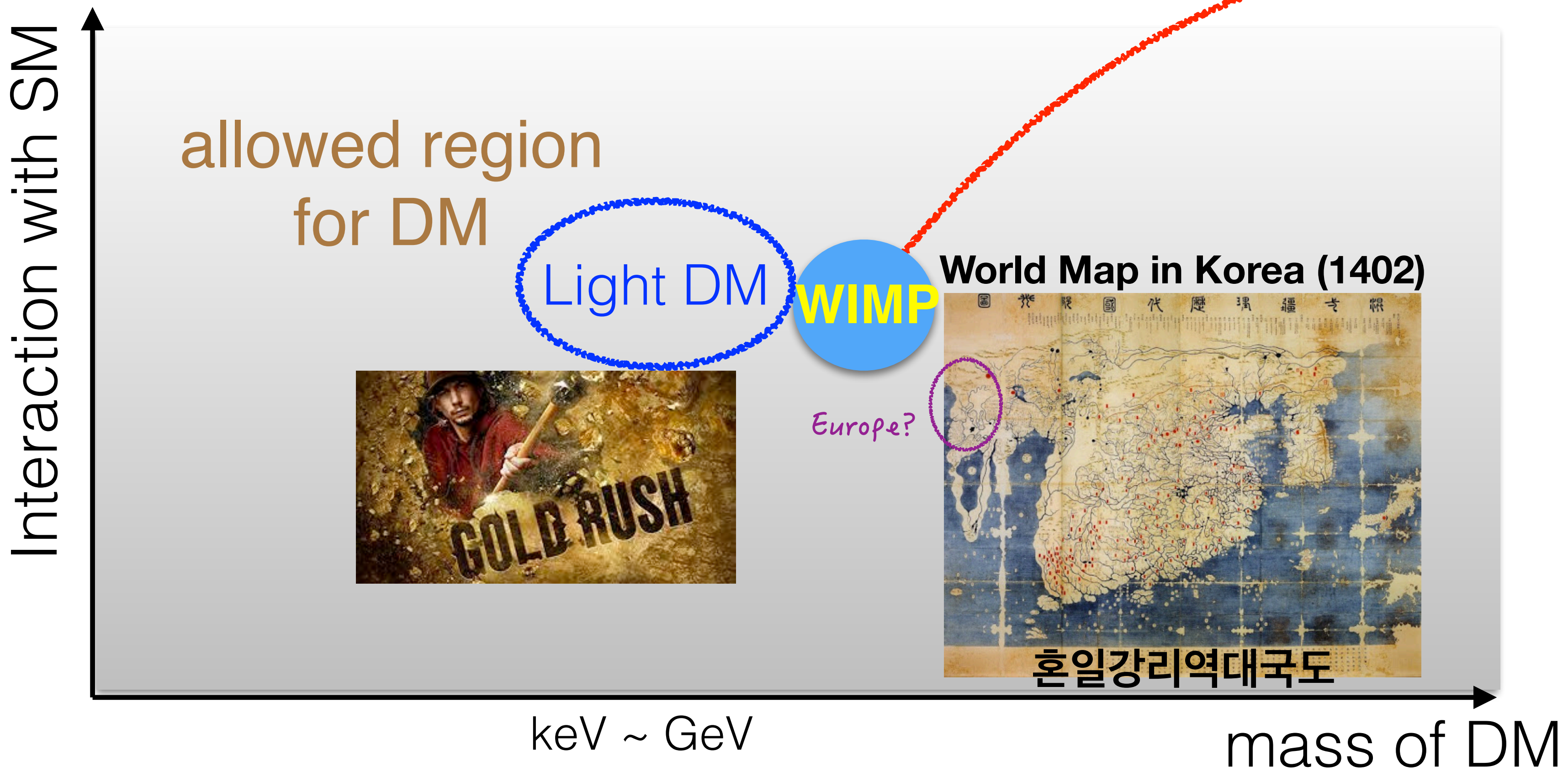

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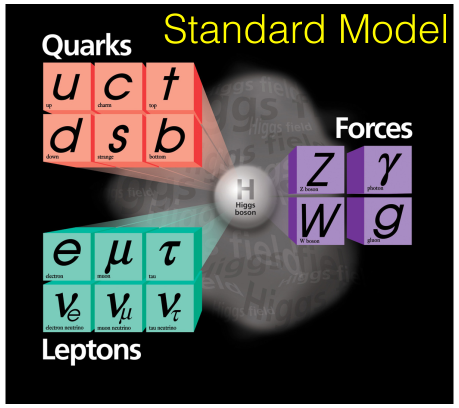

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  → Unlike WIMP (coherent scattering with nucleus)

Light Dark Matter recoiling electron

Where do we probe the LDM recoiling electron target?

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- Light WIMP (non-relativistic) at DM direct detection experiments: sometimes new devices are proposed.

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The electron target is in a bound state with a *typical* wavelength size of $R_{\rm Bohr} = 1/(\alpha m_e)$

The *typical* momentum of the electron is $k_e \simeq 1/R_{\rm Bohr} = \alpha m_e \longrightarrow v_e \simeq \alpha \lesssim 0.01$

The deposited energy by slowly moving DM (v ~ 10^{-3}) is mostly $\mathcal{O}$(eV) « keV ($E_{\rm th}$).

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- Dark sector structure

Agashe, Cui, Necib, Thaler, JCAP 2014 Kim, Park, **SS**, PRL 2017

Kopp, Liu, Wang, JHEP 2015 Heurtier, Kim, Park, **SS**, PRD 2019

- Scattering with energetic background

Yin, 1809.08610 Ema, Sala, Sato, PRL 2019

Cappiello, Ng, Beacom, PRD 2019 Jho, Park, Park, Tseng, 2021

- Production in an astrophysical object providing large kinetic energy, e.g., SN

DeRocco, Graham, Kasen, Marques-Tavares, Rajendran, PRD 2019

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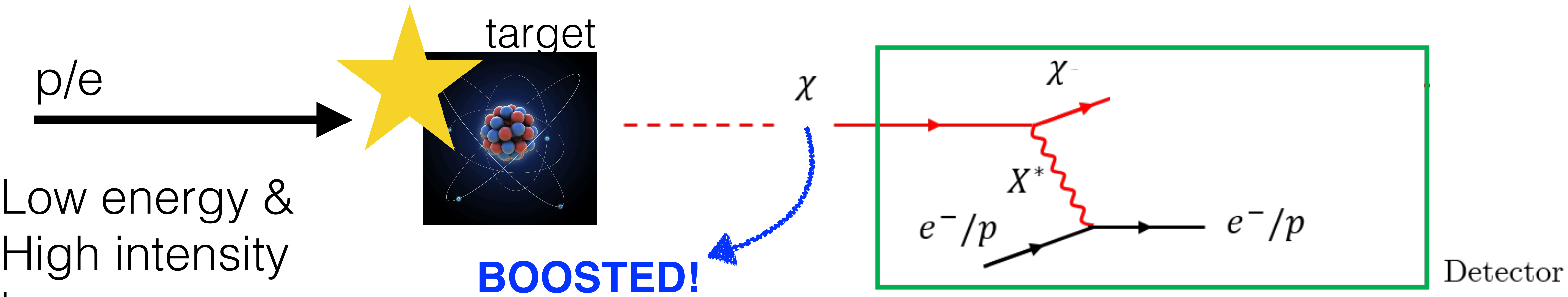

Low energy &
High intensity
beam

BOOSTED!
(beam E)

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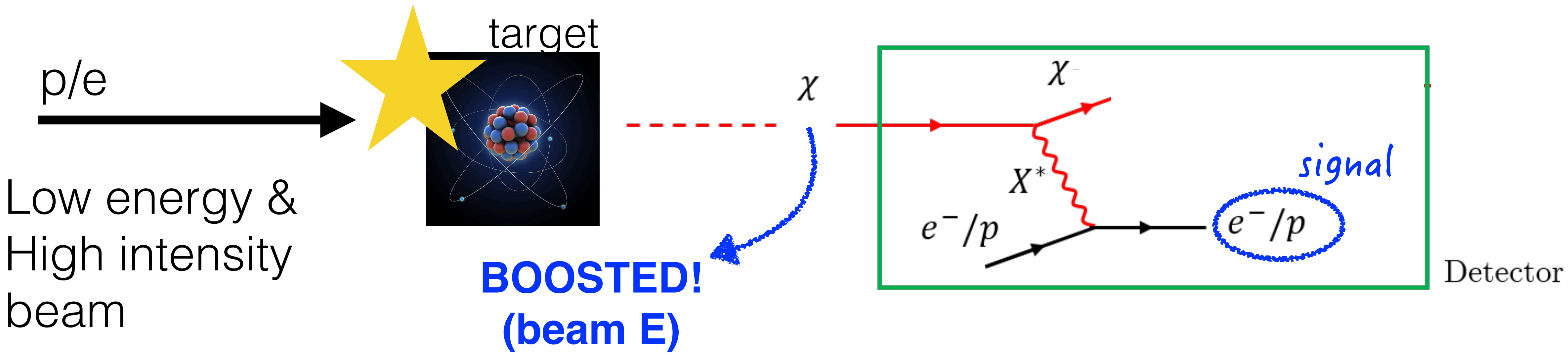

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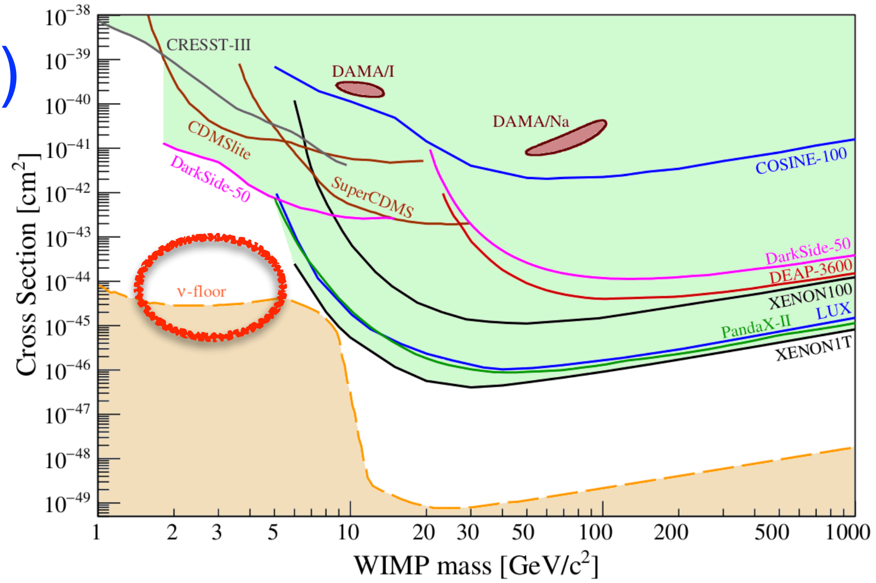
- COHERENT (Oak Ridge)
- Coherent Captain Mills (Los Alamos)
- JSNS^2 (J-PARC)



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3σ level mild **excess**
in 2018 CsI data
(4446 kg·day)

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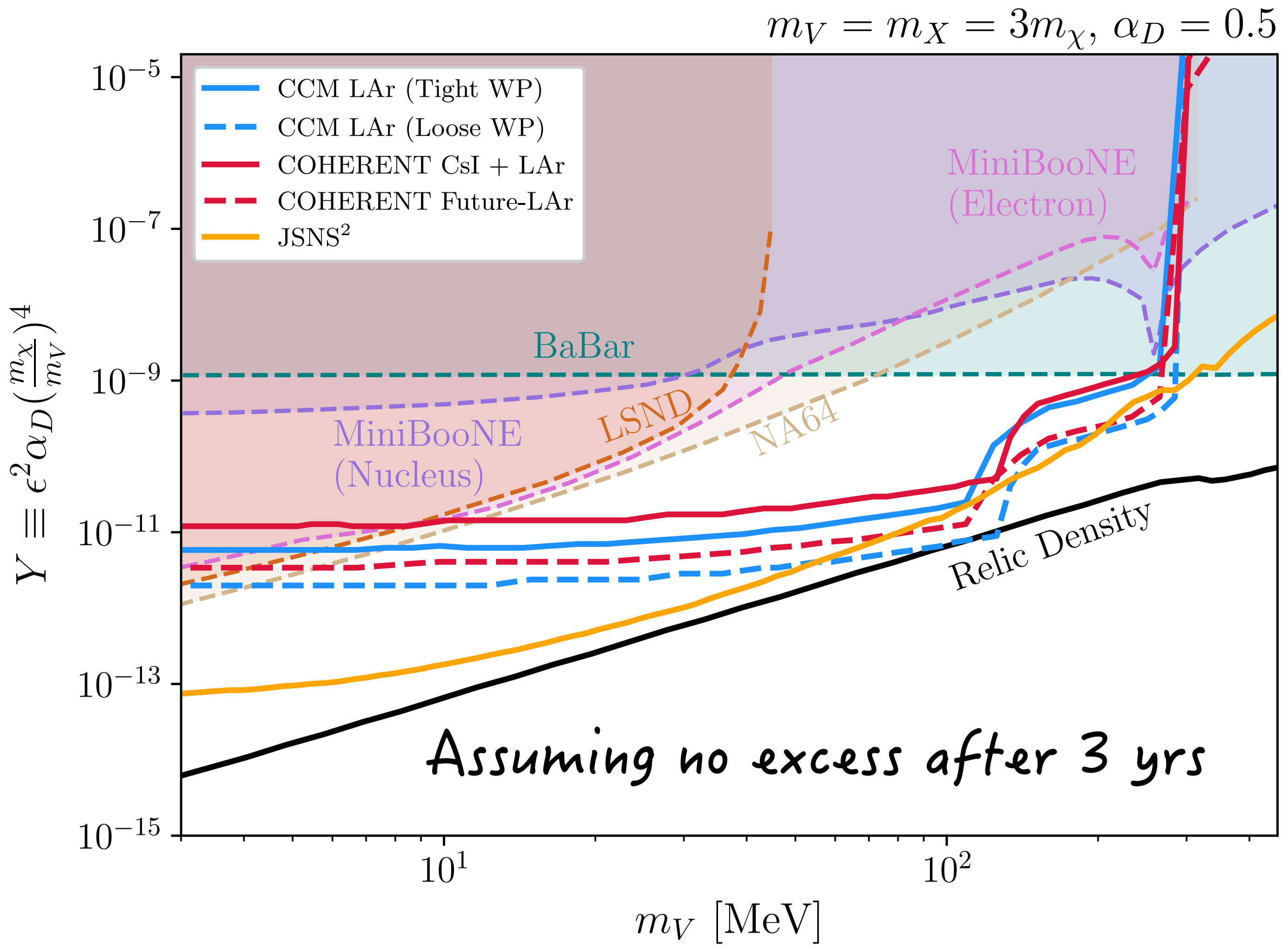

Assuming no excess after 3 yrs

- Light WII … riments:
  sometim

  Kopp, Niro, Schv … ysay, Sorensen, PRL 2012

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Nuclear recoil also possible

Giudice, Kim, Park, **SS**, PLB 780, 543 (2018)

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Contents

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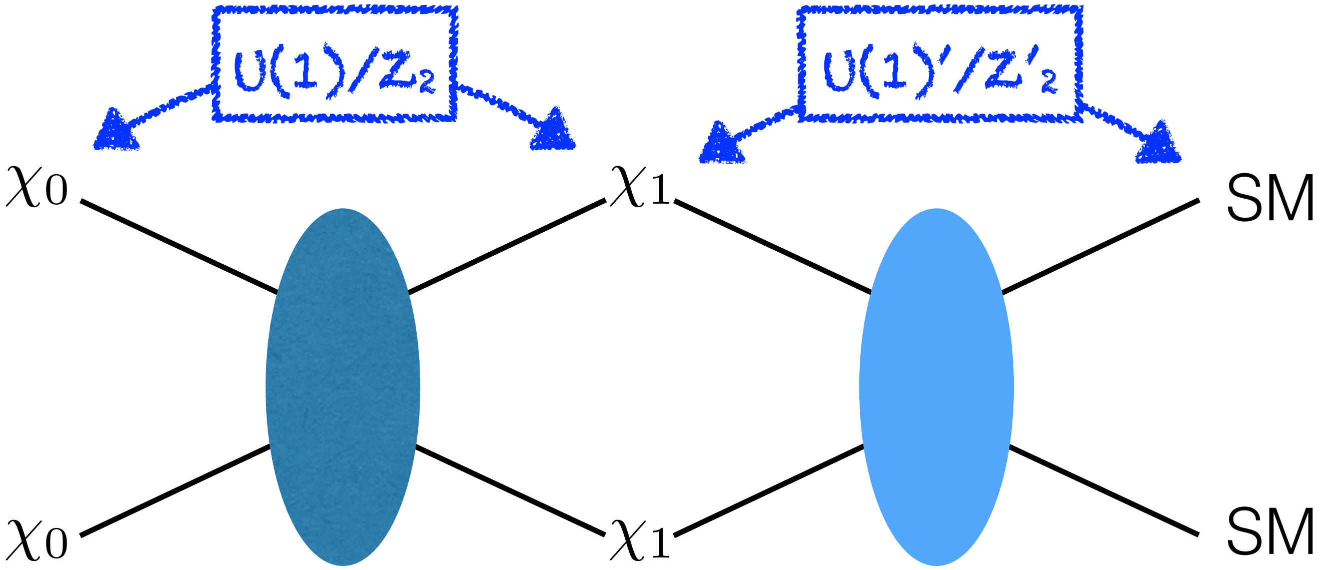
    - MeV scale e-recoil: Result in COSINE-100
    - keV scale e-recoil: XENON1T 2020

- Conclusions

Multi-component Boosted DM (BDM)

χ_0: heavy, χ_1: light



Agashe, Cui, Necib, Thaler,1405.7370

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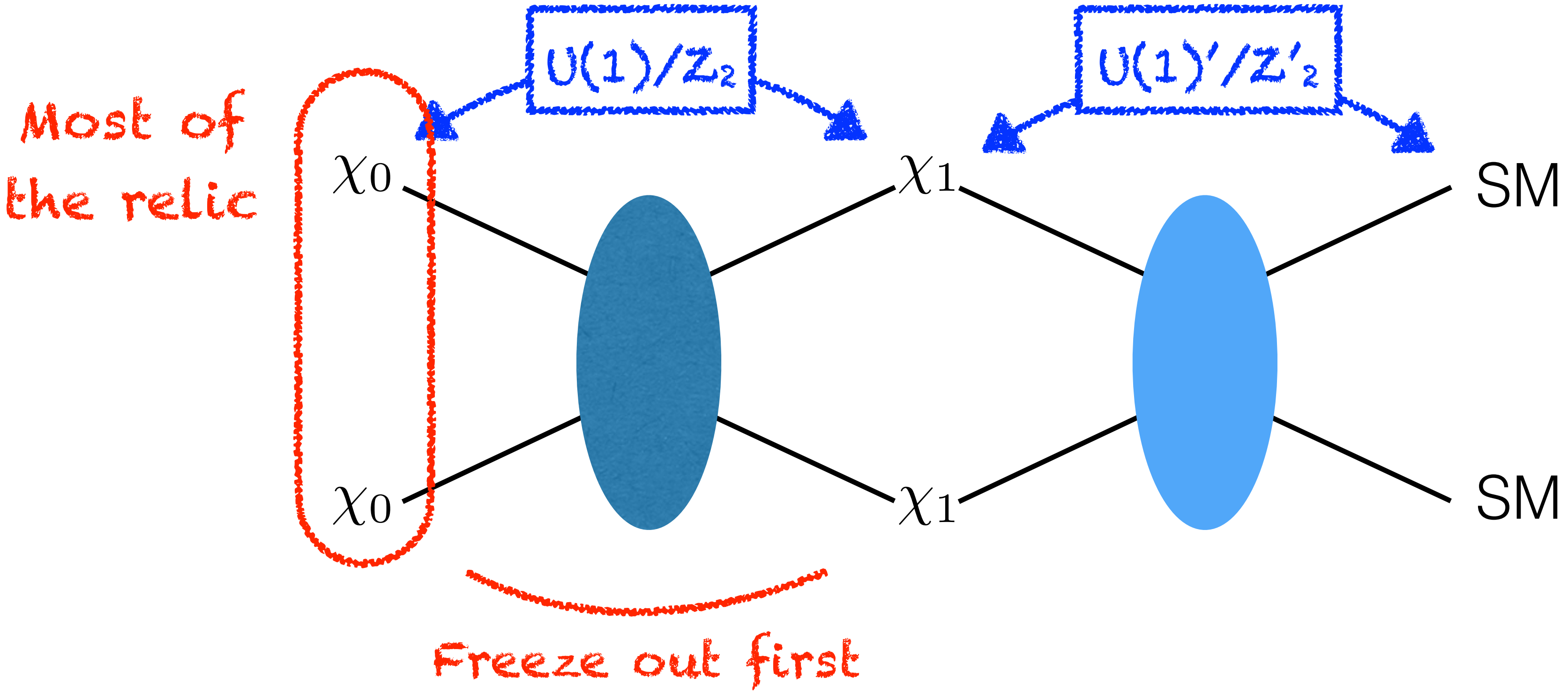
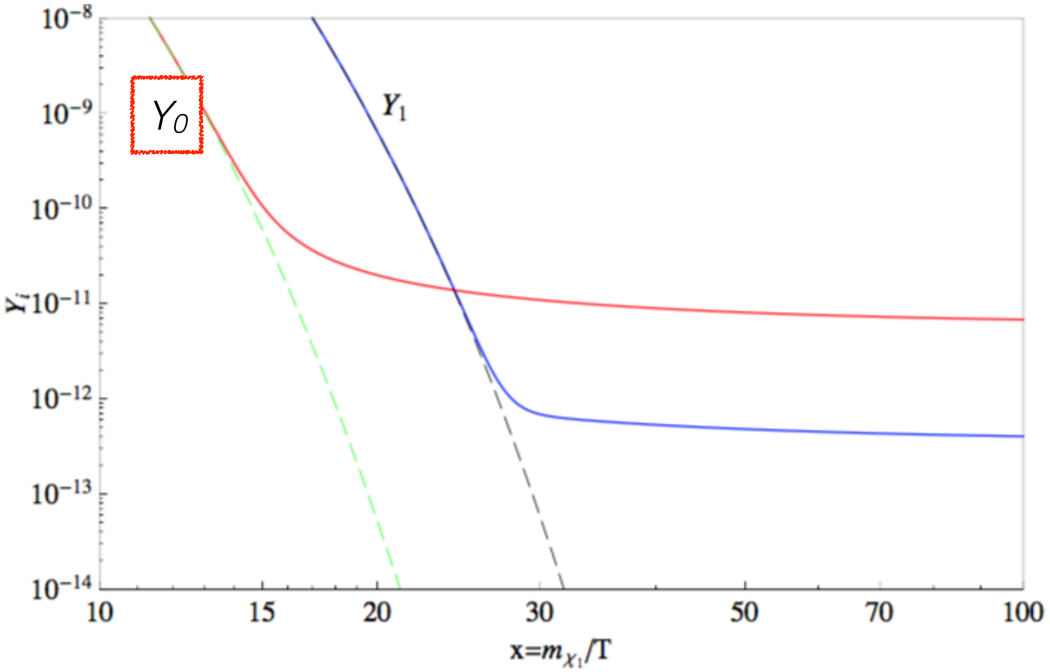


Most of the relic

Freeze out first



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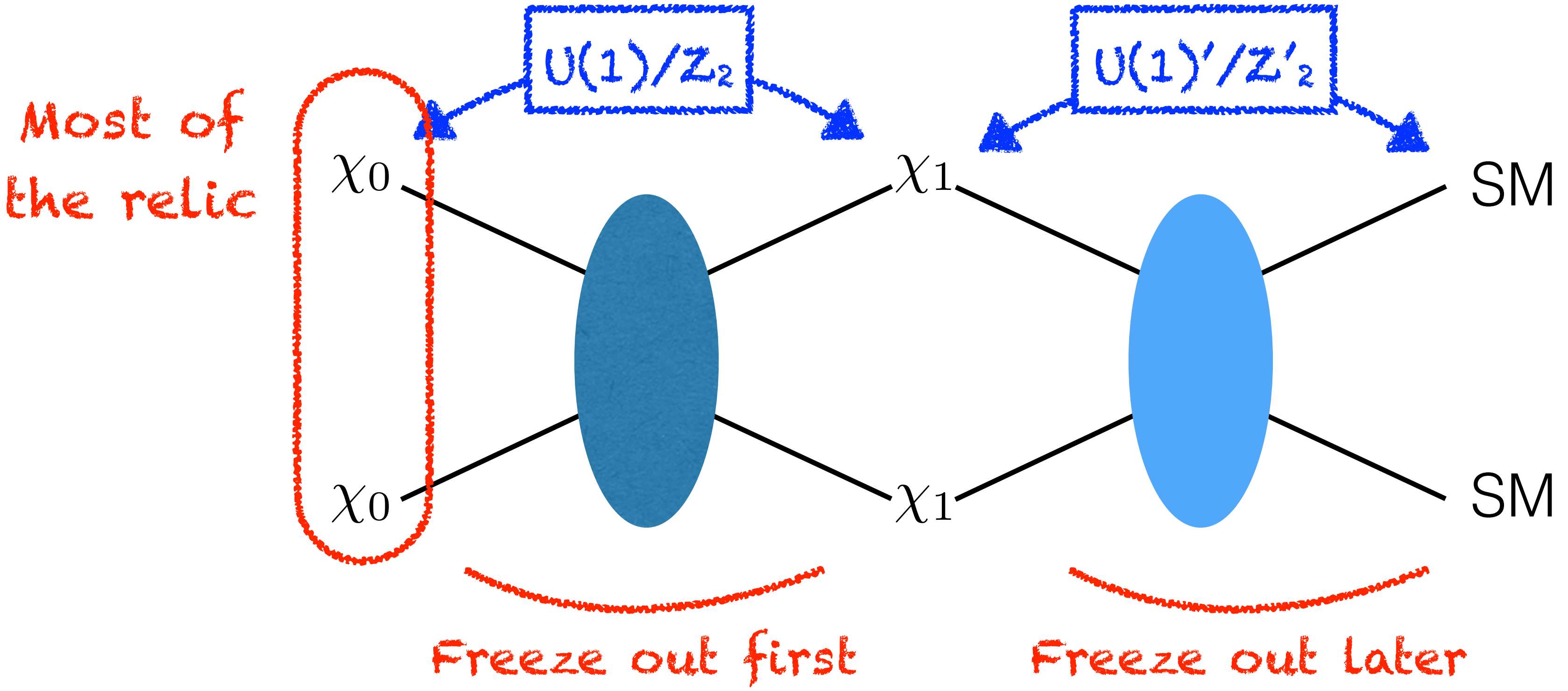
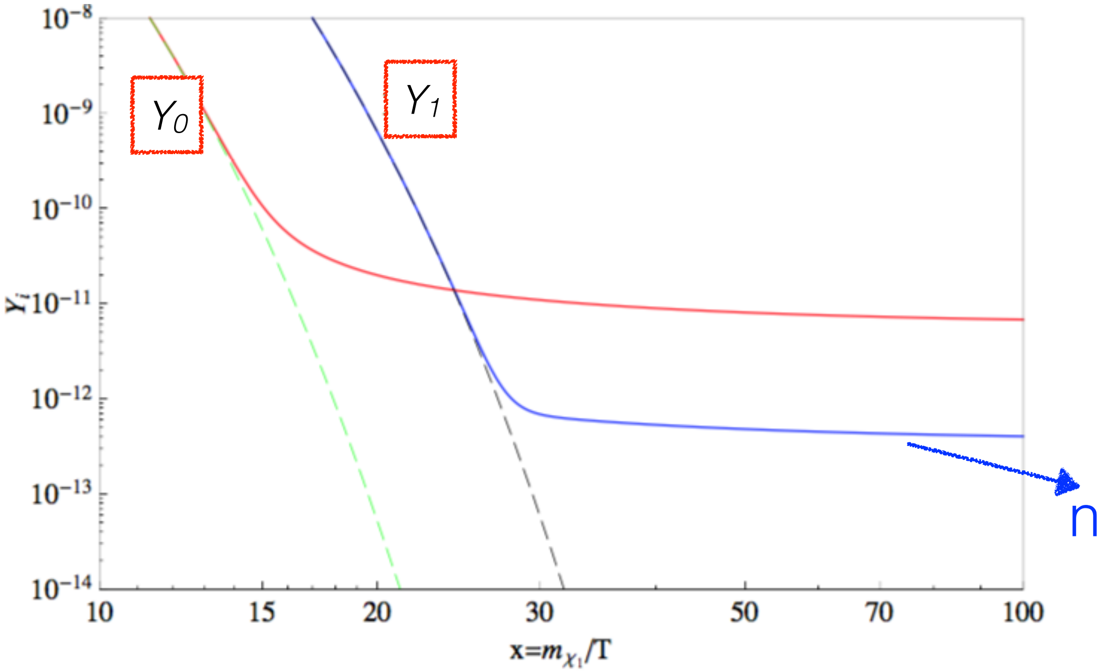


Most of the relic

Freeze out first

Freeze out later



Agashe, Cui, Necib, Thaler,1405.7370

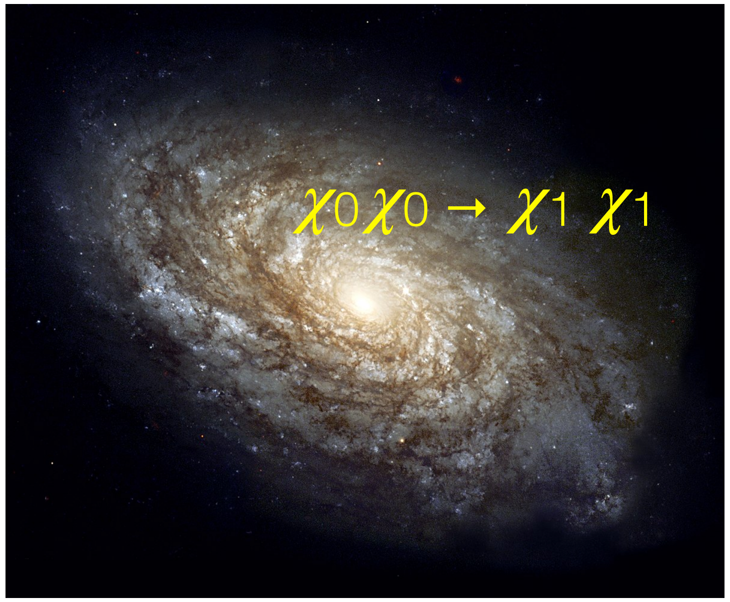
Belanger, Park, 1112.4491

Assisted freeze-out mechanism

non-relativistic relic χ_1 (negligible)

$Y_0 \gg Y_1$

Multi-component BDM



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  (GC, Sun, dSphs)

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  ※ relic χ_1 is non-relativistic

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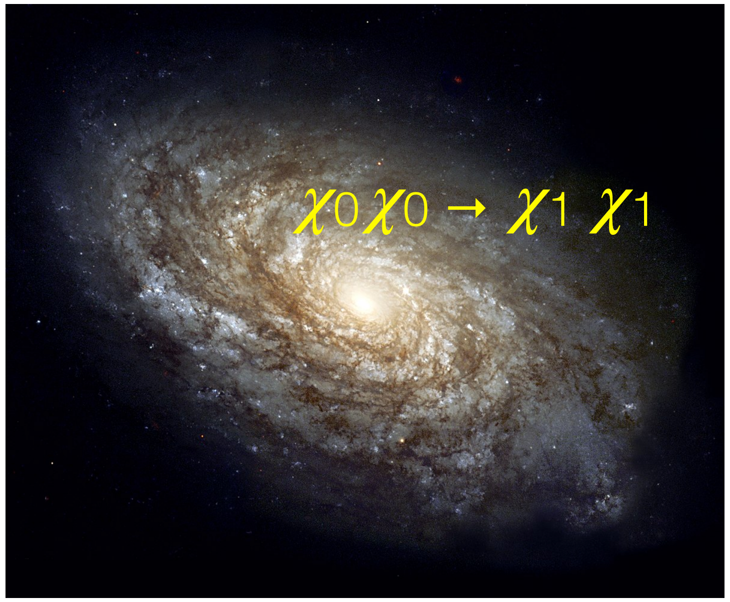

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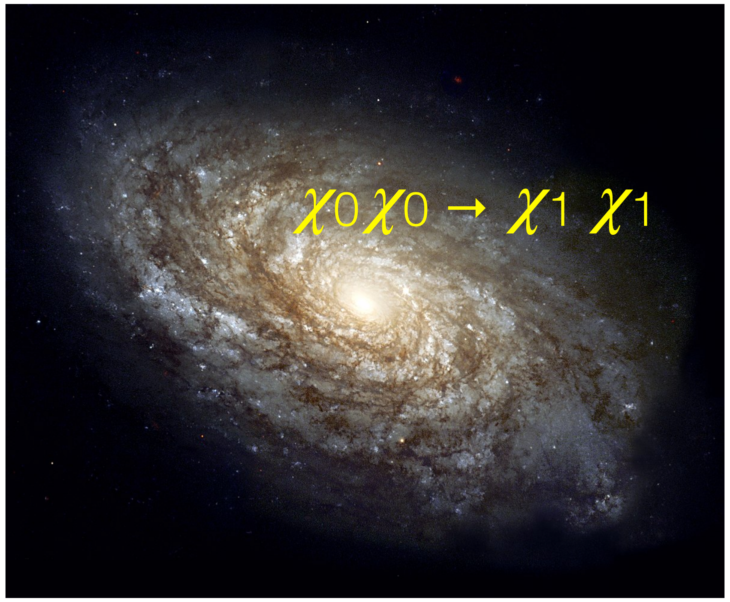

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(indirect detection of χ_0)

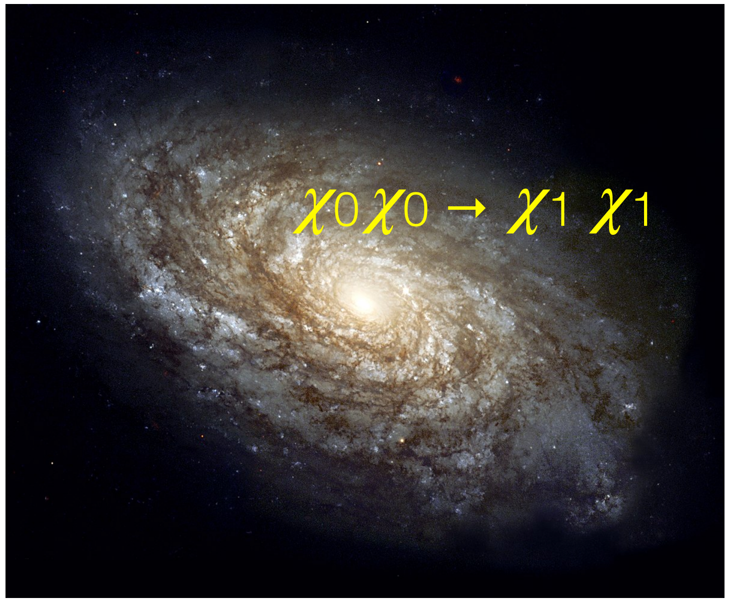
Flux of χ_1 $$\simeq 1.6 \times 10^{-8}\,\mathrm{cm}^{-2}\mathrm{s}^{-1} \times \left(\frac{\langle\sigma v\rangle_{0\rightarrow 1}}{5\times 10^{-26}\,\mathrm{cm}^3\mathrm{s}^{-1}}\right) \times \left(\frac{100\,\mathrm{GeV}}{m_0}\right)^2$$

Assume: NFW

Fixed ~ 1 if s-wave annihilation dominates

10,000 times smaller than the flux of atmospheric ν if m_0 ~ 100 GeV

Multi-component BDM



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※ relic χ_1 is non-relativistic

Observe χ_1 scattering off target with $E_1 > E_{th}$

(indirect detection of χ_0)

Flux of χ_1 $\simeq 1.6\times10^{-8}\,\mathrm{cm}^{-2}\mathrm{s}^{-1} \times \left(\frac{\langle\sigma v\rangle_{0\to1}}{5\times10^{-26}\,\mathrm{cm}^3\mathrm{s}^{-1}}\right) \times \left(\frac{100\,\mathrm{GeV}}{m_0}\right)^2$

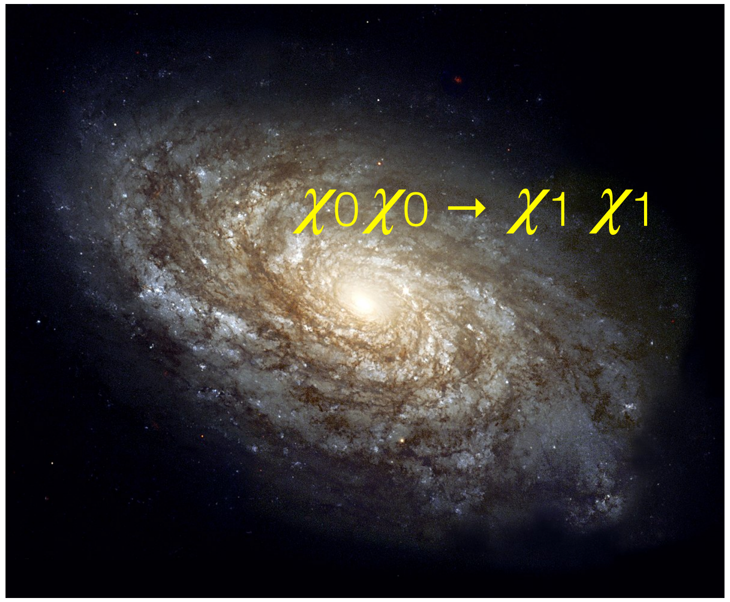
Assume: NFW

Fixed ~ 1 if s-wave annihilation dominates

10,000 times ~~smaller~~ than the flux of atmospheric **ν** if ~~m_0 ~ 100 GeV~~

larger **if $m_0 \lesssim 1$ GeV**

Multi-component BDM



- χ_0 : accumulated
  (GC, Sun, dSphs)

- $\chi_0\chi_0 \to \chi_1\ \chi_1$ (current universe) relativistic

※ relic χ_1 is non-relativistic

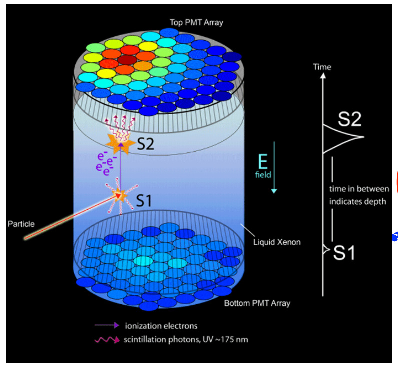
Observe χ_1 scattering off target with $E_1 > E_{th}$

(indirect detection of χ_0)

$$\text{Flux of } \chi_1 \simeq 1.6 \times 10^{-8}\,\mathrm{cm}^{-2}\mathrm{s}^{-1} \times \left(\frac{\langle\sigma v\rangle_{0\to1}}{5\times10^{-26}\,\mathrm{cm}^3\mathrm{s}^{-1}}\right) \times \left(\frac{100\,\mathrm{GeV}}{m_0}\right)^2$$

Assume: NFW

Fixed ~ 1 if s-wave annihilation dominates



0 times ~~smaller~~ than the flux of atmospheric ν if ~~m_0 ~ 100~~ GeV

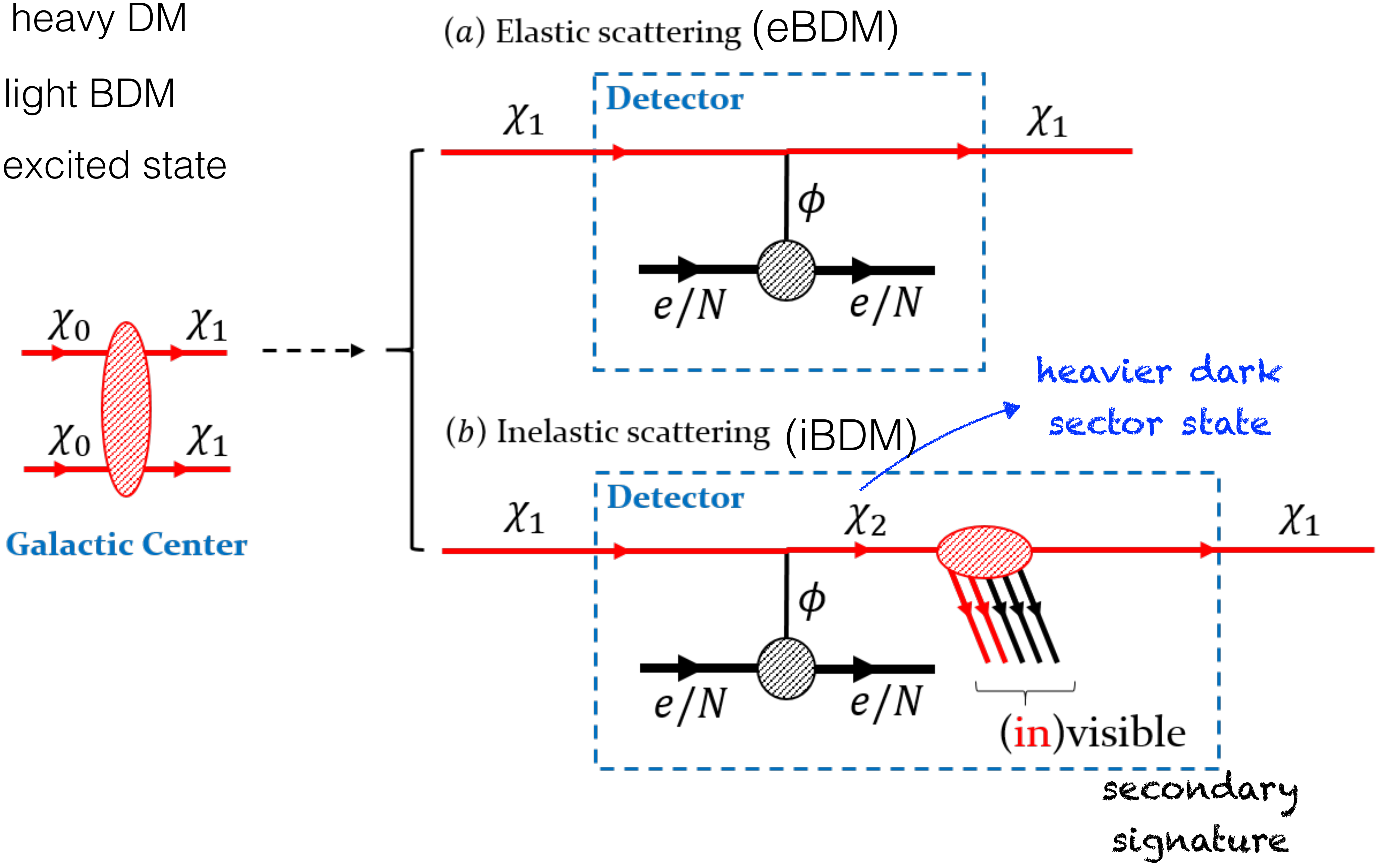
larger **if $m_0 \lesssim$ 1 GeV**

Inelastic BDM (iBDM)

χ_0: heavy DM

χ_1: light BDM

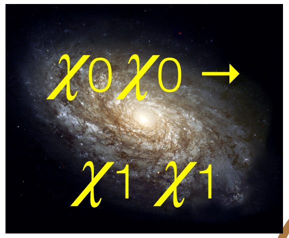
χ_2: excited state

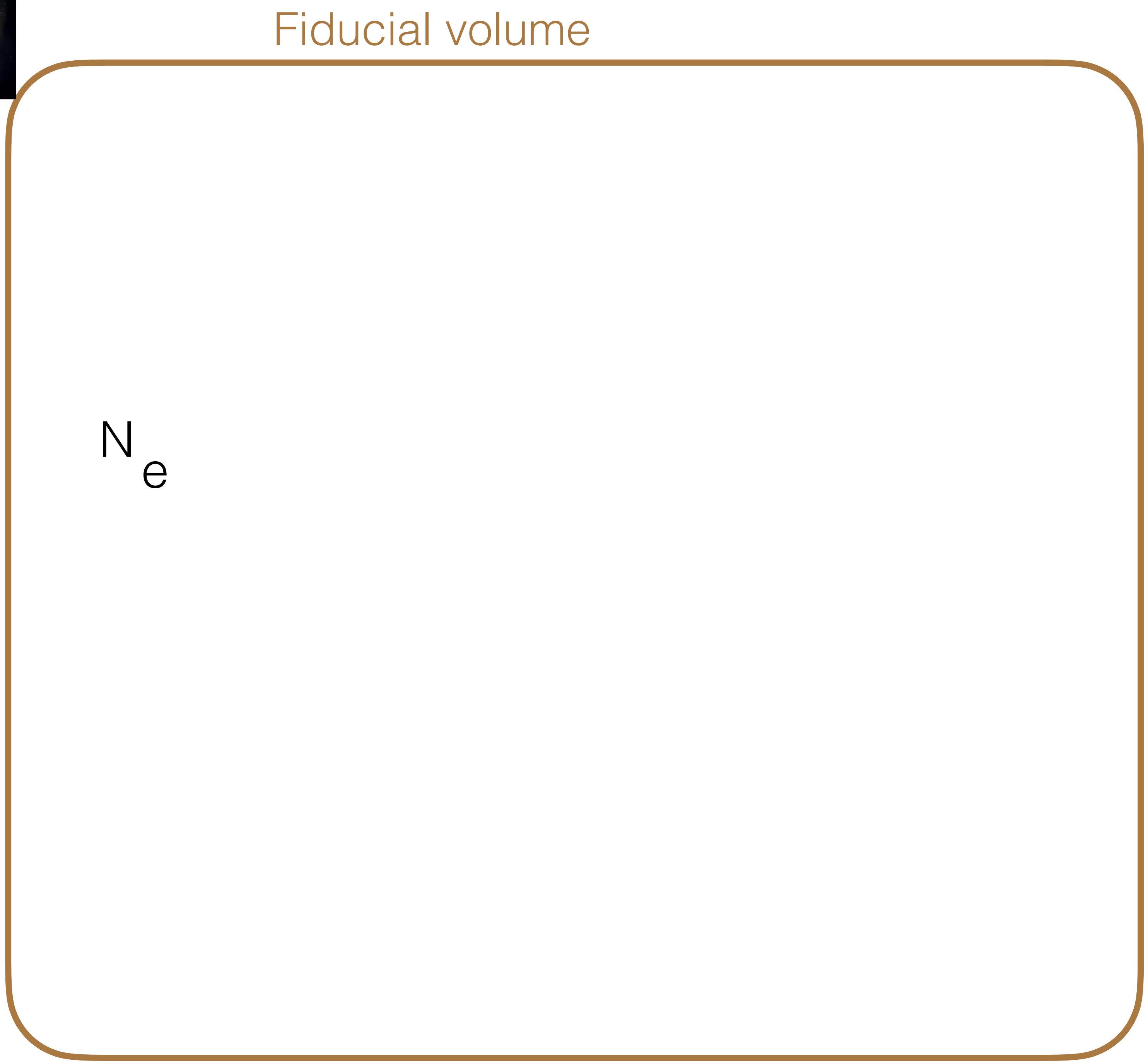


Kim, Park, **SS**, PRL 119, 161801 (2017)

Giudice, Kim, Park, **SS**, PLB 780, 543 (2018)

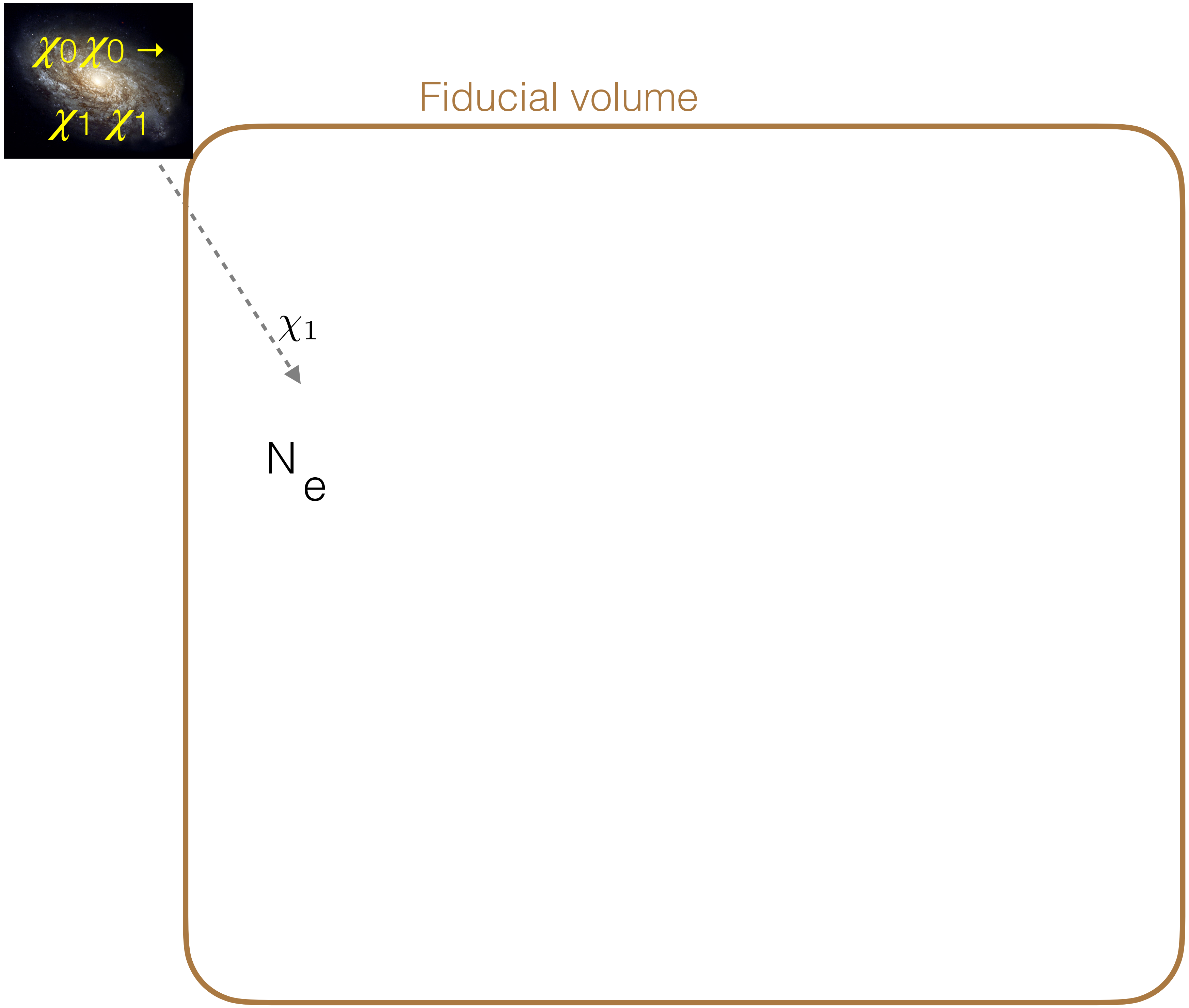
Signals inside a fiducial volume





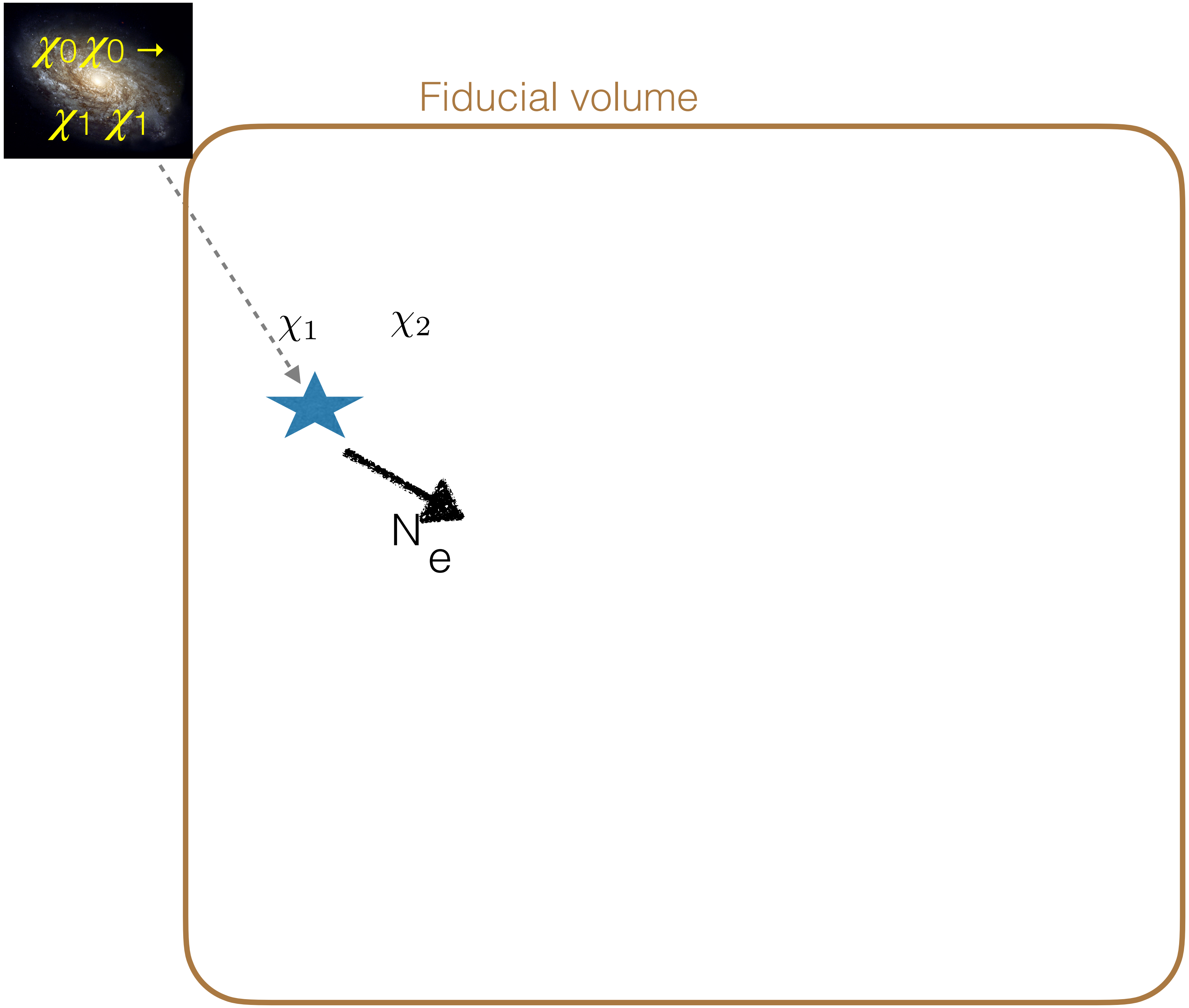
χ_1: light BDM, χ_2: excited state

Signals inside a fiducial volume



χ_1: light BDM, χ_2: excited state

Signals inside a fiducial volume



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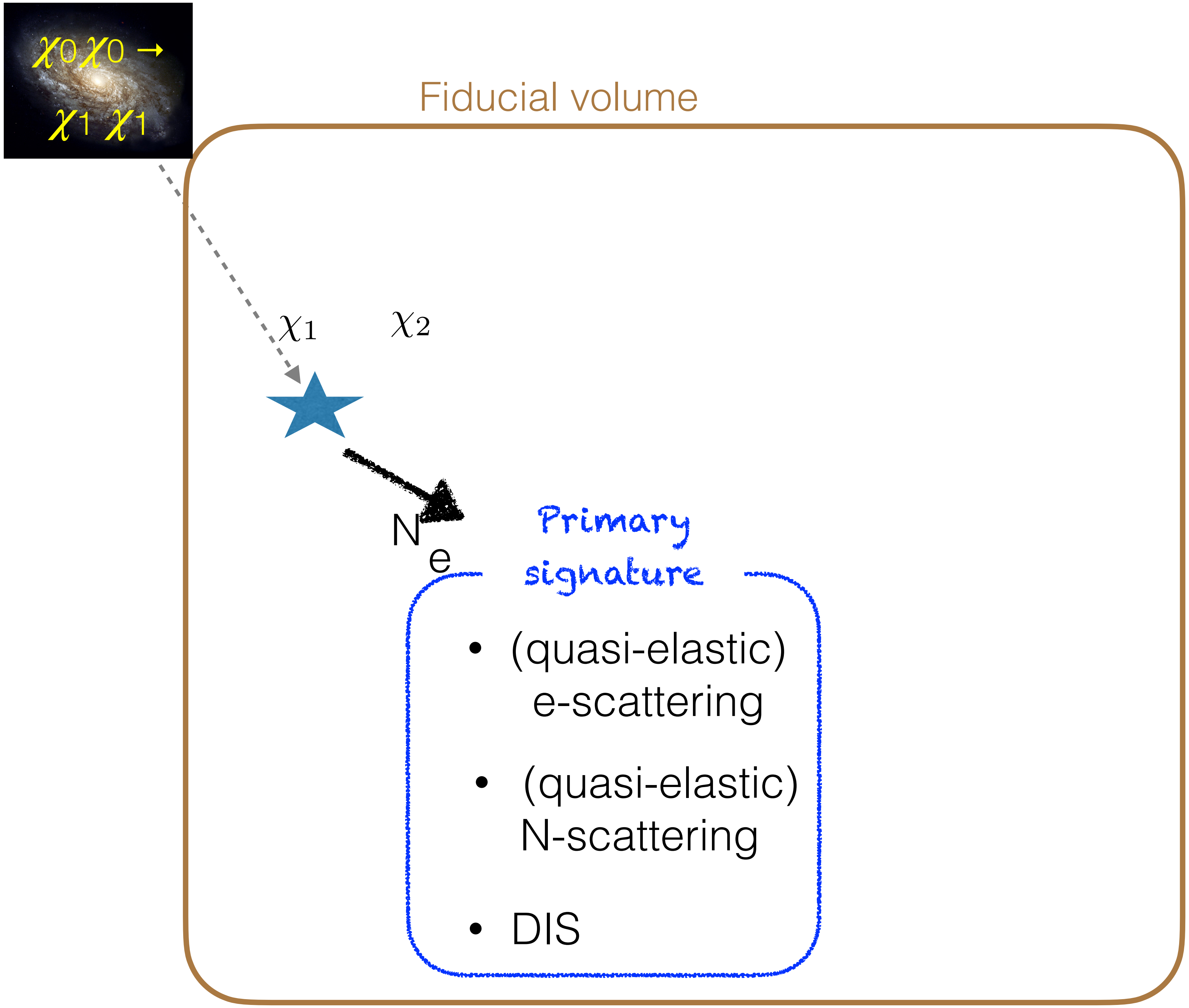
Signals inside a fiducial volume

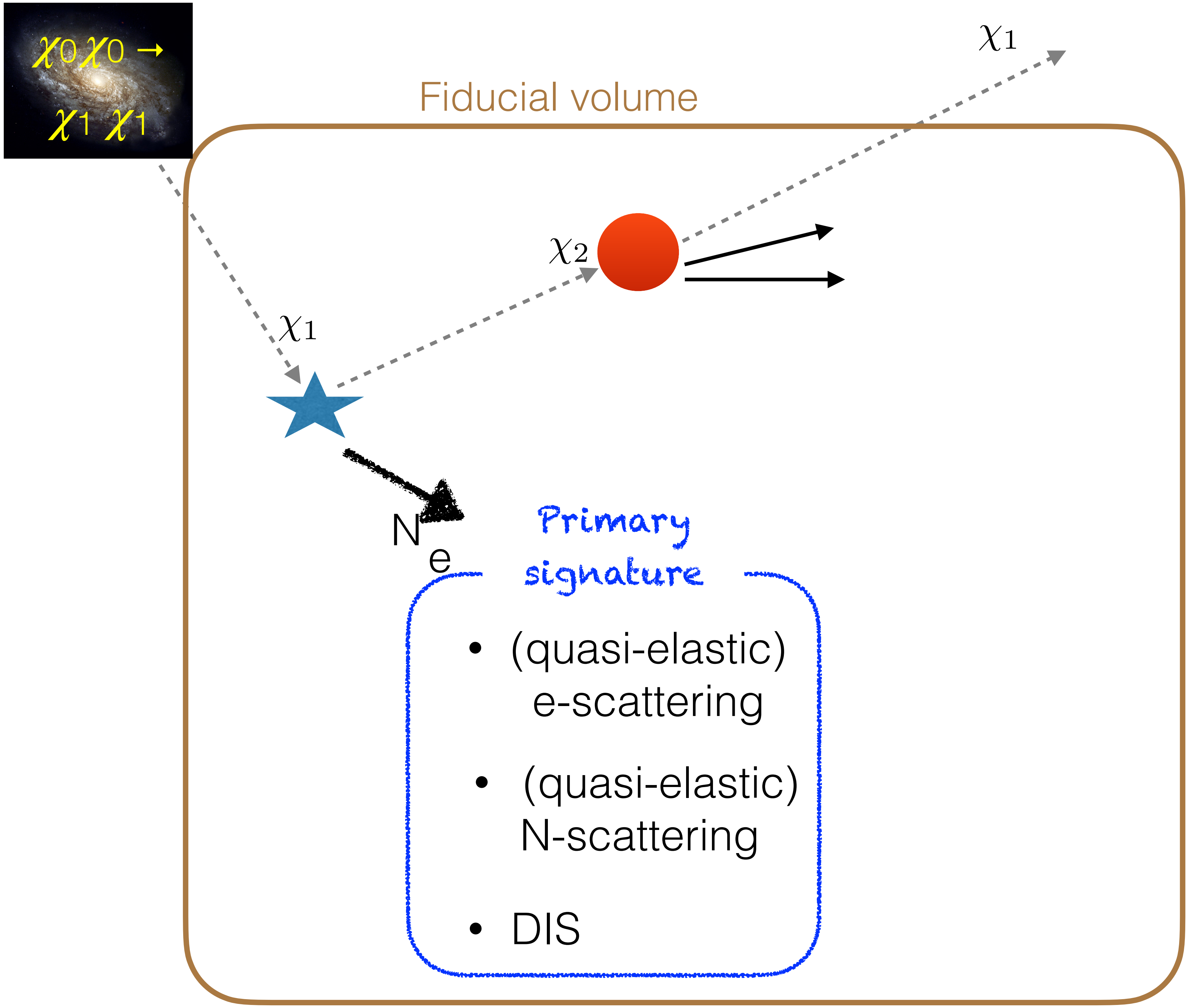


Primary signature

- (quasi-elastic) e-scattering
- (quasi-elastic) N-scattering
- DIS

χ_1: light BDM, χ_2: excited state

Signals inside a fiducial volume



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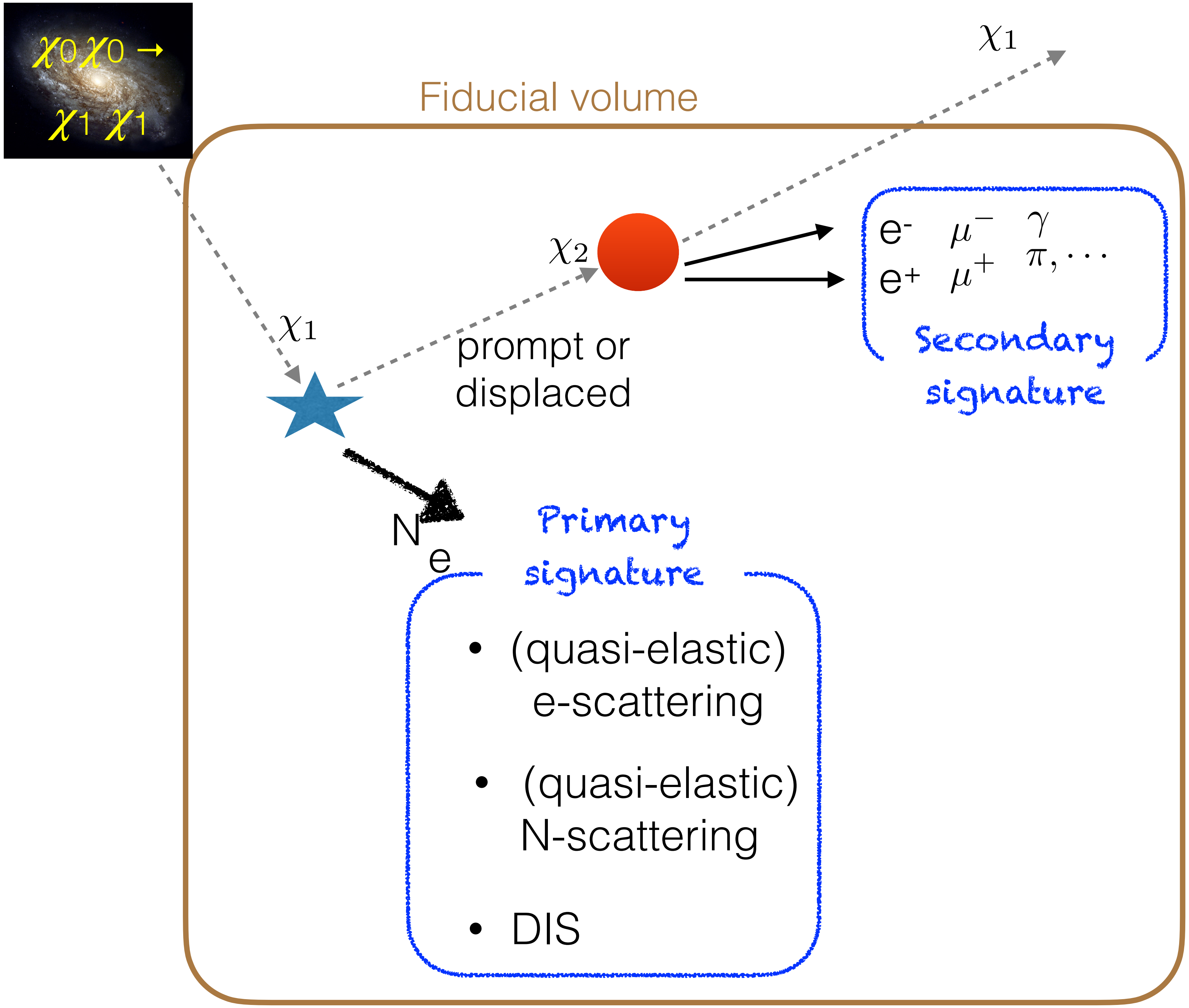
Signals inside a fiducial volume



prompt or displaced

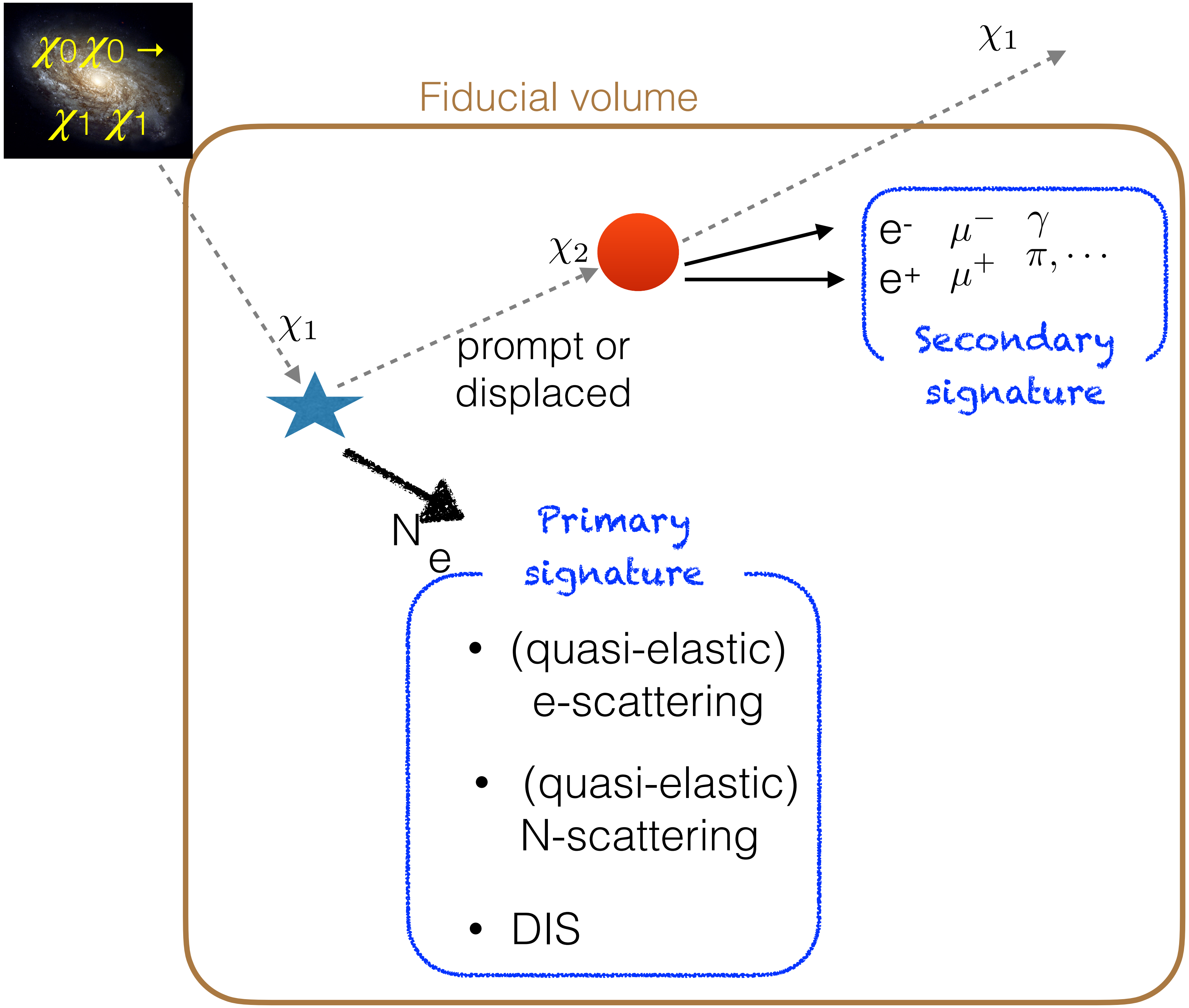
Secondary signature

Primary signature

- (quasi-elastic) e-scattering
- (quasi-elastic) N-scattering
- DIS

χ_1: light BDM, χ_2: excited state

Signals inside a fiducial volume



$\chi_0 \chi_0 \rightarrow \chi_1 \chi_1$

Fiducial volume

χ_1

χ_2

χ_1

prompt or displaced

N

e

e^- μ^- γ

e^+ μ^+ $\pi, \cdots$

Secondary signature

Primary signature

- (quasi-elastic) e-scattering
- (quasi-elastic) N-scattering
- DIS

χ_1: light BDM, χ_2: excited state

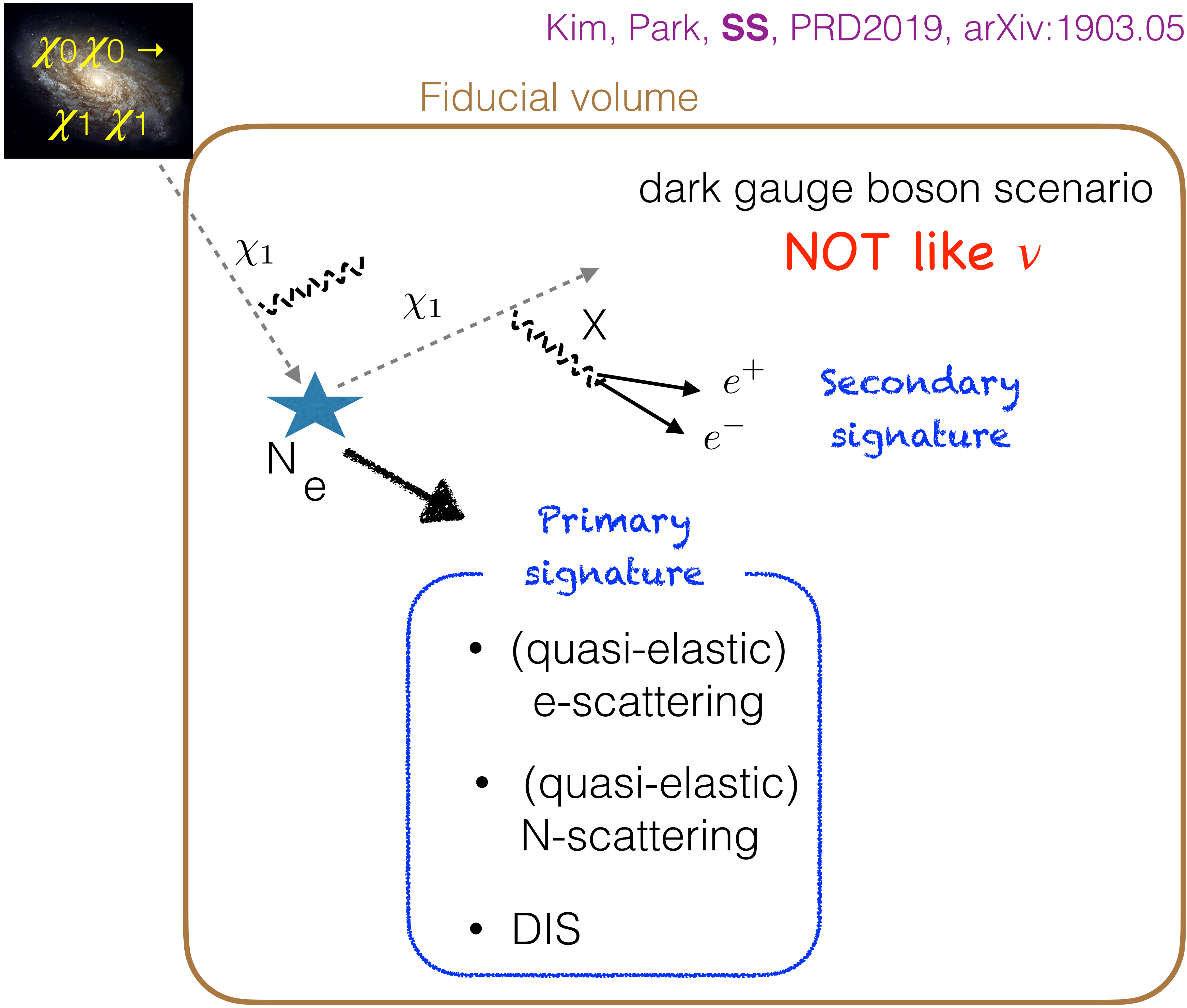
- For iBDM, two signatures can be separated beyond the position and angular resolutions.

Zero bkg. (conservative)

- For eBDM, energy deposit in e-recoil signatures is larger than what is expected by light WIMP.

New method in eBDM search: darkstrahlung

Kim, Park, **SS**, PRD2019, arXiv:1903.05087



- (quasi-elastic) e-scattering
- (quasi-elastic) N-scattering
- DIS

χ_1: light BDM

2nd signature in the elastic scattering

- Different from WIMP → ν ν
- NLO but O(10-20%) of LO possible (impossible for beam produced DM)
- Efficient for large N_{BG} (cosmogenic BSM signal)

Contents

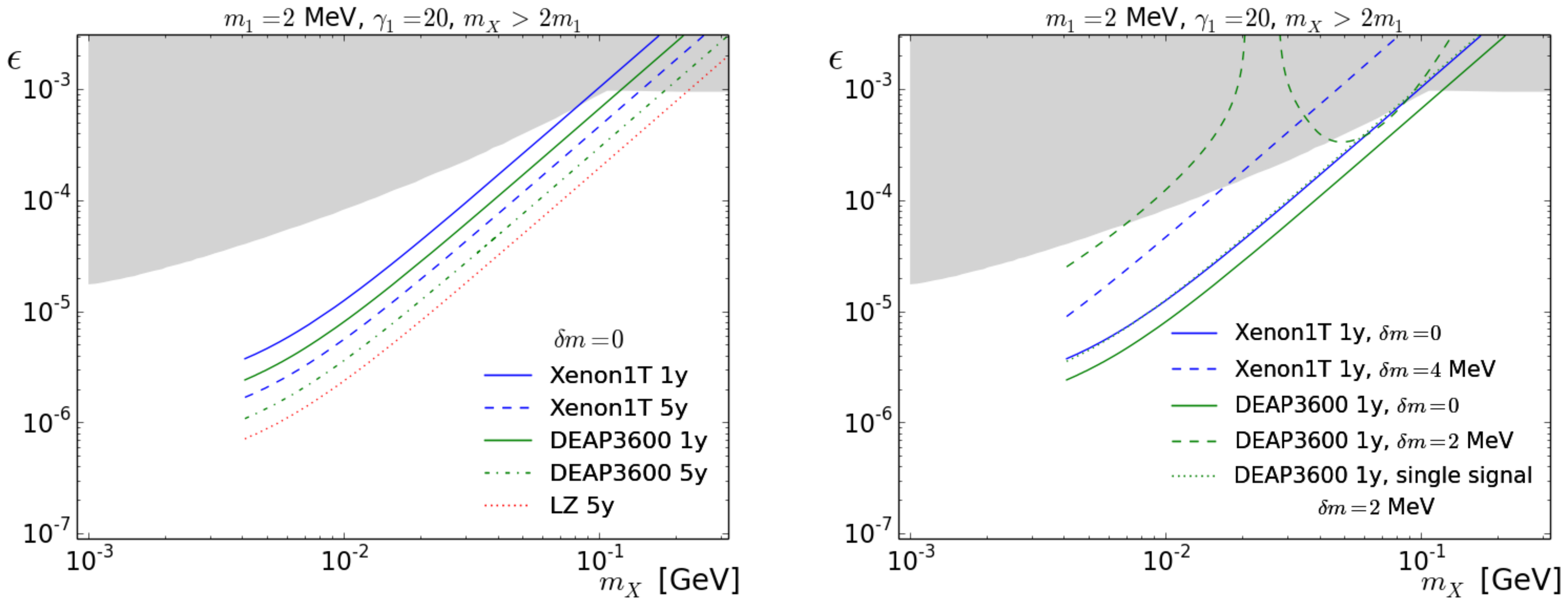
- Introduction
  - Dark World beyond WIMP
  - Light DM recoiling electron target

- Boosted dark matter (BDM) and the signatures
  - Multi-component BDM
  - Inelastic BDM (iBDM)

- High energetic electron recoils by BDM
  - MeV scale e-recoil: Result in COSINE-100
  - keV scale e-recoil: XENON1T 2020

- Conclusions

MeV scale e-recoil by BDM



Giudice, Kim, Park, **SS**, PLB 780, 543 (2018)

- Various direct detection experiments can have good enough sensitivities: e.g., in a dark photon scenario: $\chi_{1(2)}$ - e

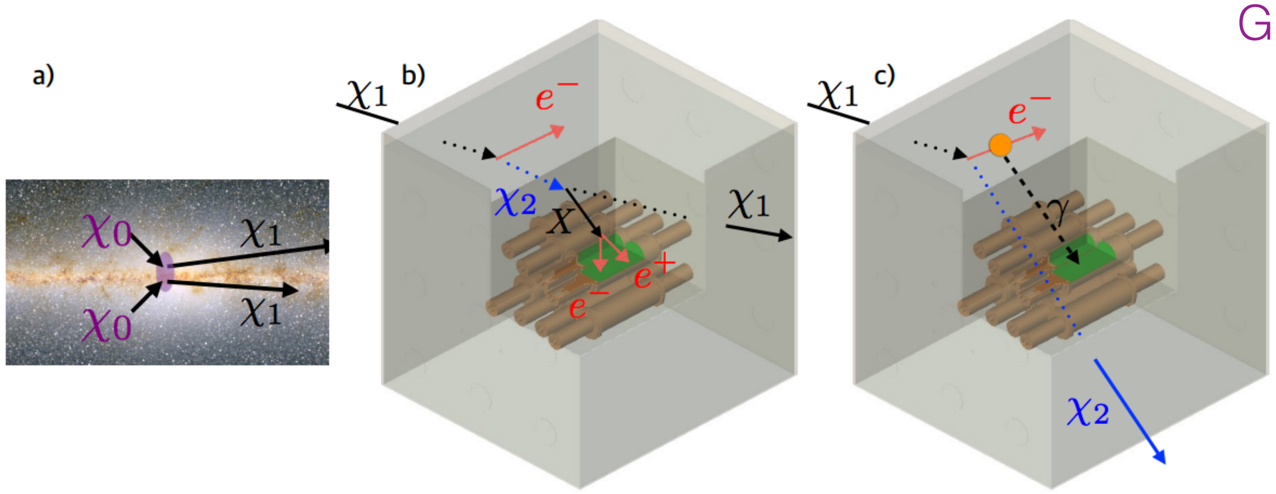
- Experimental details (position/angle/energy resolutions) are crucial in determining the sensitivities.

COSINE-100 result

COSINE-100, PRL 2019

Based on theoretical study

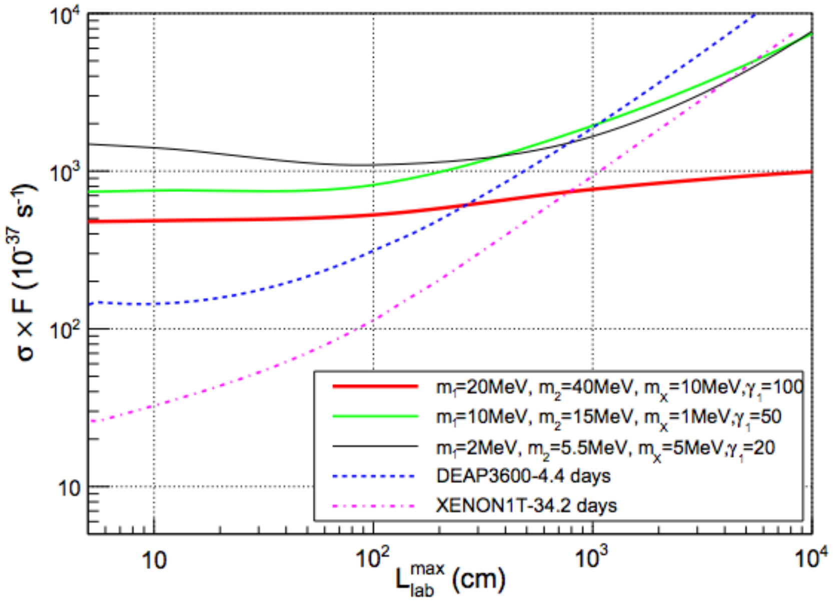
Giudice, Kim, Park, **SS**, PLB 780, 543 (2018)

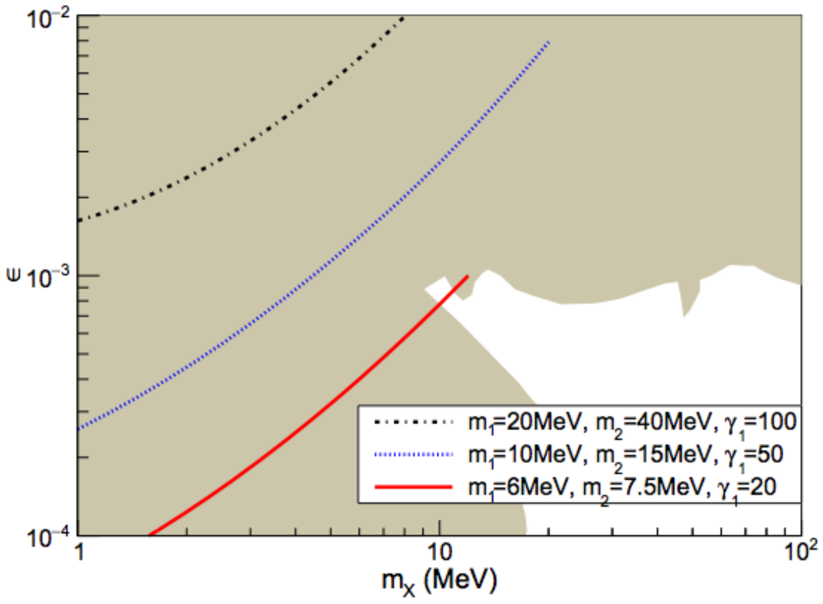


2200L of liquid scintillator
(~ 2 ton)

106kg array of 8 ultra-pure NaI(Tl) crystals
immersed in an active veto detector

Observed: 21 events, Background expected: 16.4 ± 2.1

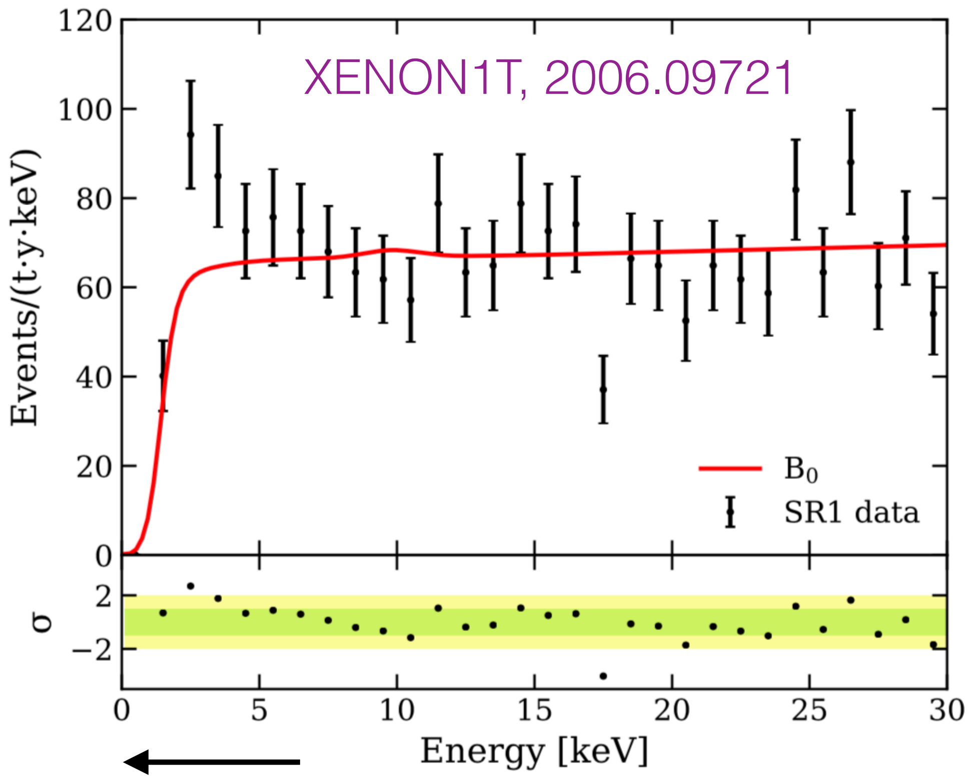




keV scale e-recoil: XENON1T 2020

0.65 ton·year

76 ± 2(stat) events exceeding background expectation



XENON1T, 2006.09721

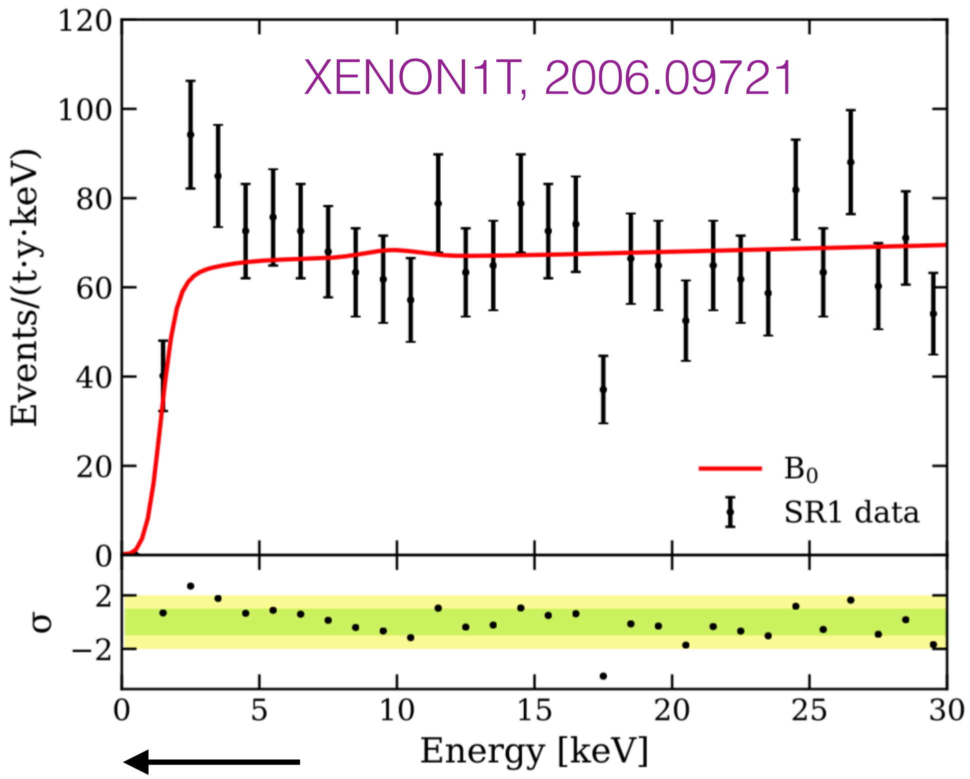
7 keV

- Background? Tritium, Ar37 decays (most probable?)
- Solar axion, neutrino MDM ~3σ ?
- Dark Matter recoil?

keV scale e-recoil: XENON1T 2020

0.65 ton·year

76 ± 2(stat) events exceeding background expectation



7 keV

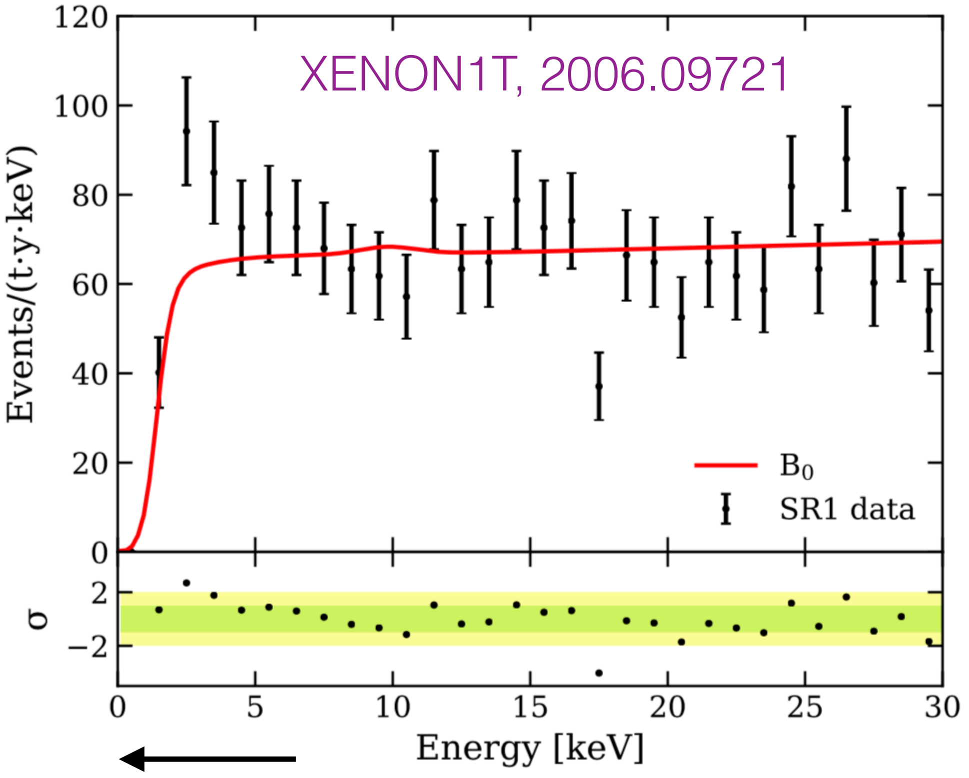
- Background? Tritium, Ar37 decays (most probable?)
- Solar axion, neutrino MDM ~3σ ?
- Dark Matter recoil?

- No nuclear recoil signals

- Too high energy *e*-recoil for WIMP or WIMP-like light DM

keV scale e-recoil: XENON1T 2020

0.65 ton·year 76 ± 2(stat) events exceeding background expectation



7 keV

Fast-moving light DM

- Background? Tritium, Ar37 decays (most probable?)
- Solar axion, neutrino MDM ~3σ ?
- Dark Matter recoil?

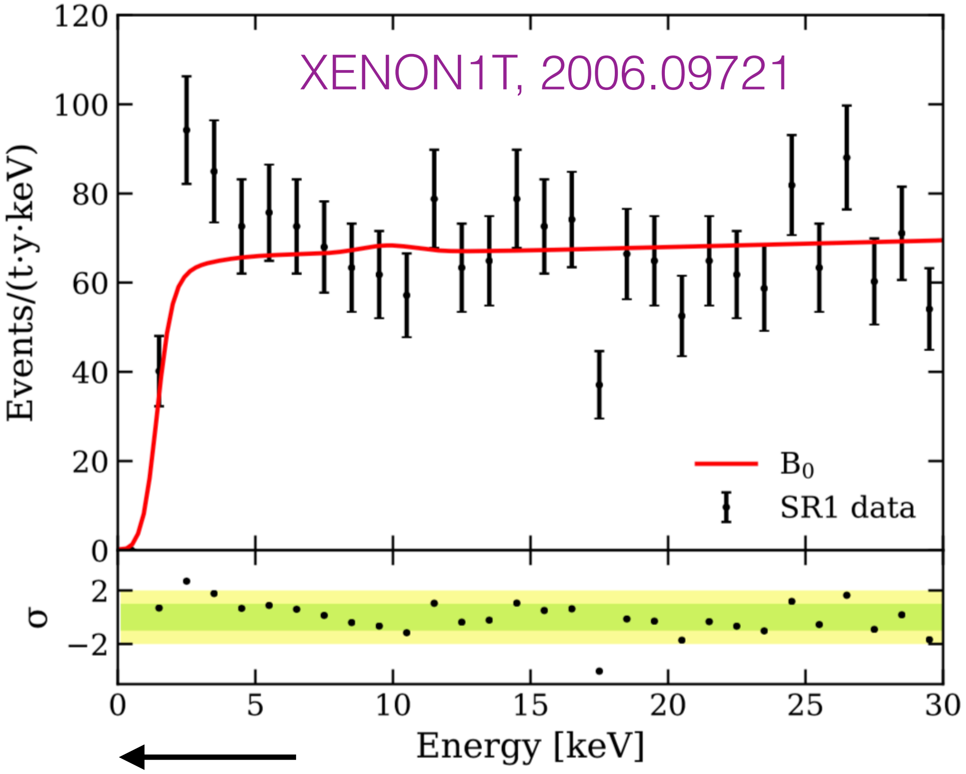
- No nuclear recoil signals

- Too high energy *e*-recoil for WIMP or WIMP-like light DM

keV scale e-recoil: XENON1T 2020

0.65 ton·year

76 ± 2(stat) events exceeding background expectation



7 keV

- Background? Tritium, Ar37 decays (most probable?)
- Solar axion, neutrino MDM ~3σ ?
- Dark Matter recoil?

- No nuclear recoil signals

- Too high energy *e*-recoil for WIMP or WIMP-like light DM

Fast-moving light DM

See also

- Light DM absorption
- Inelastic (exothermic) DM

Parameter fit of XENON1T 2020

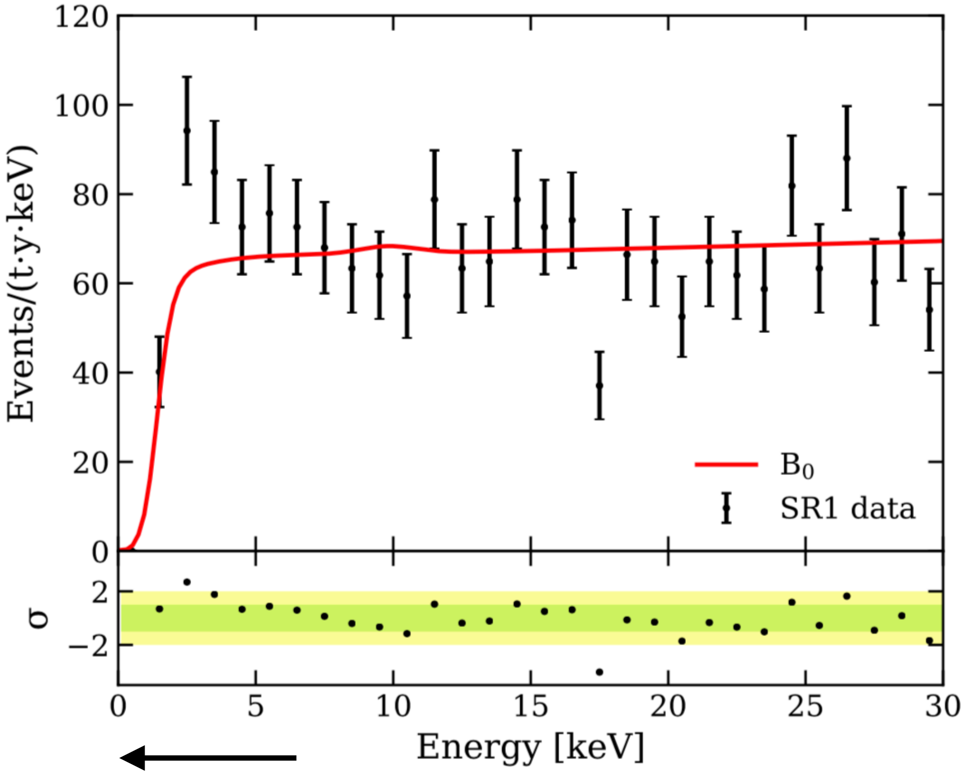
Not so simple task

- Large number of events: large cross section with the material of Earth (deflected and loose energy)

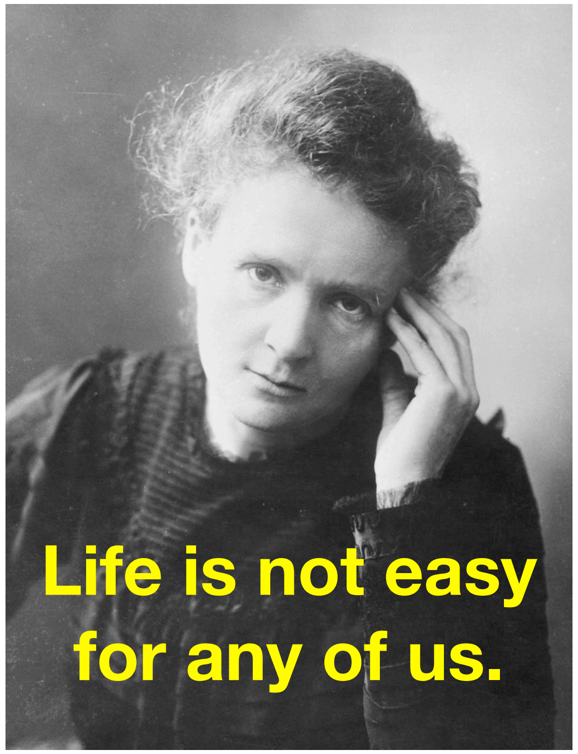
- A narrow range of 2 keV ≤ E_R ≤ 7 keV is preferred.

- The binding energy of electrons in Xe is not negligible. (for E_R ~ keV)

More difficult than MeV case

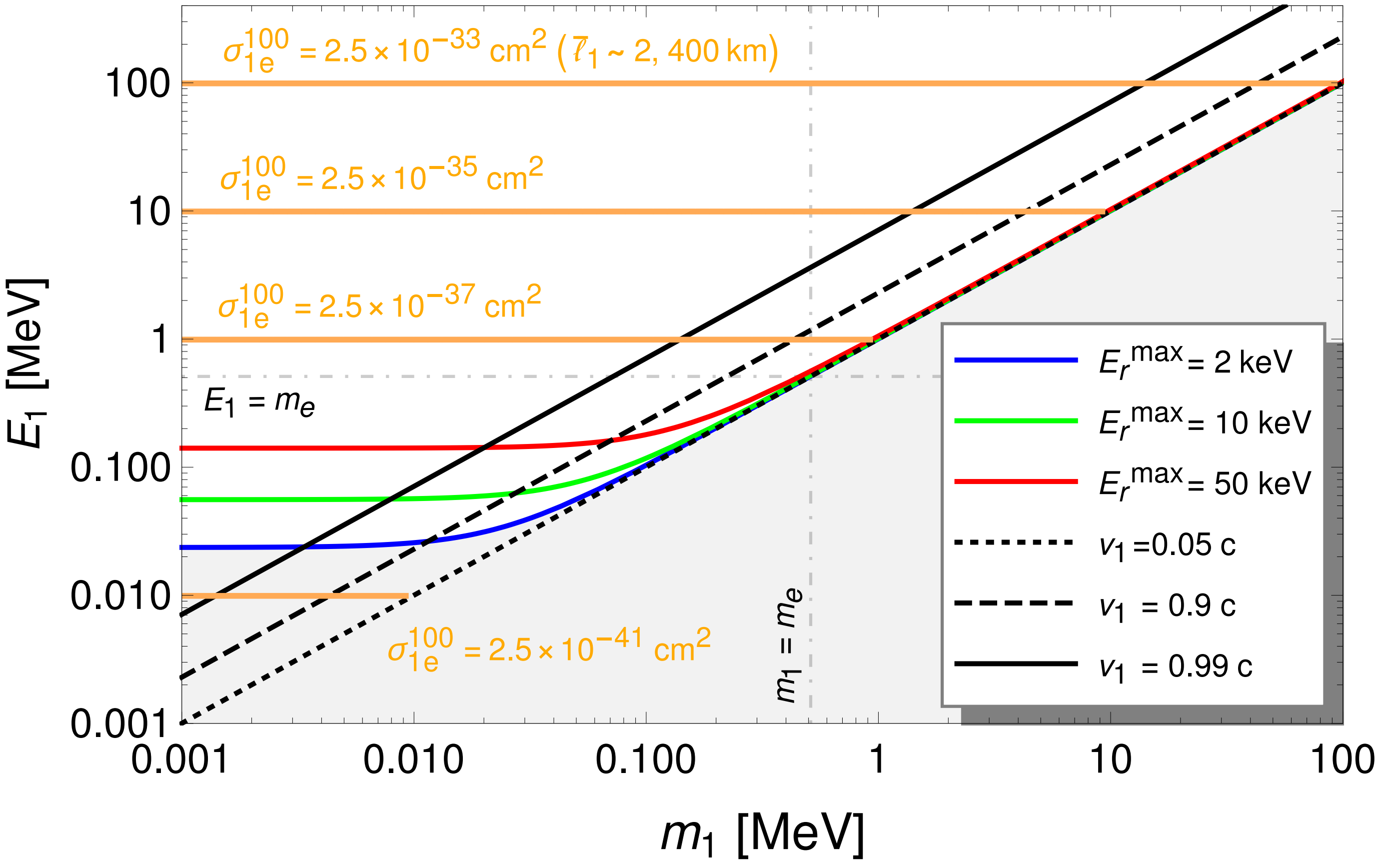


7 keV



Parameter fit of XENON1T 2020

Alhazmi, Kim, Kong, Mohlabeng,
Park, **SS**, JHEP 05, 055 (2021),
arXiv: 2006.16252



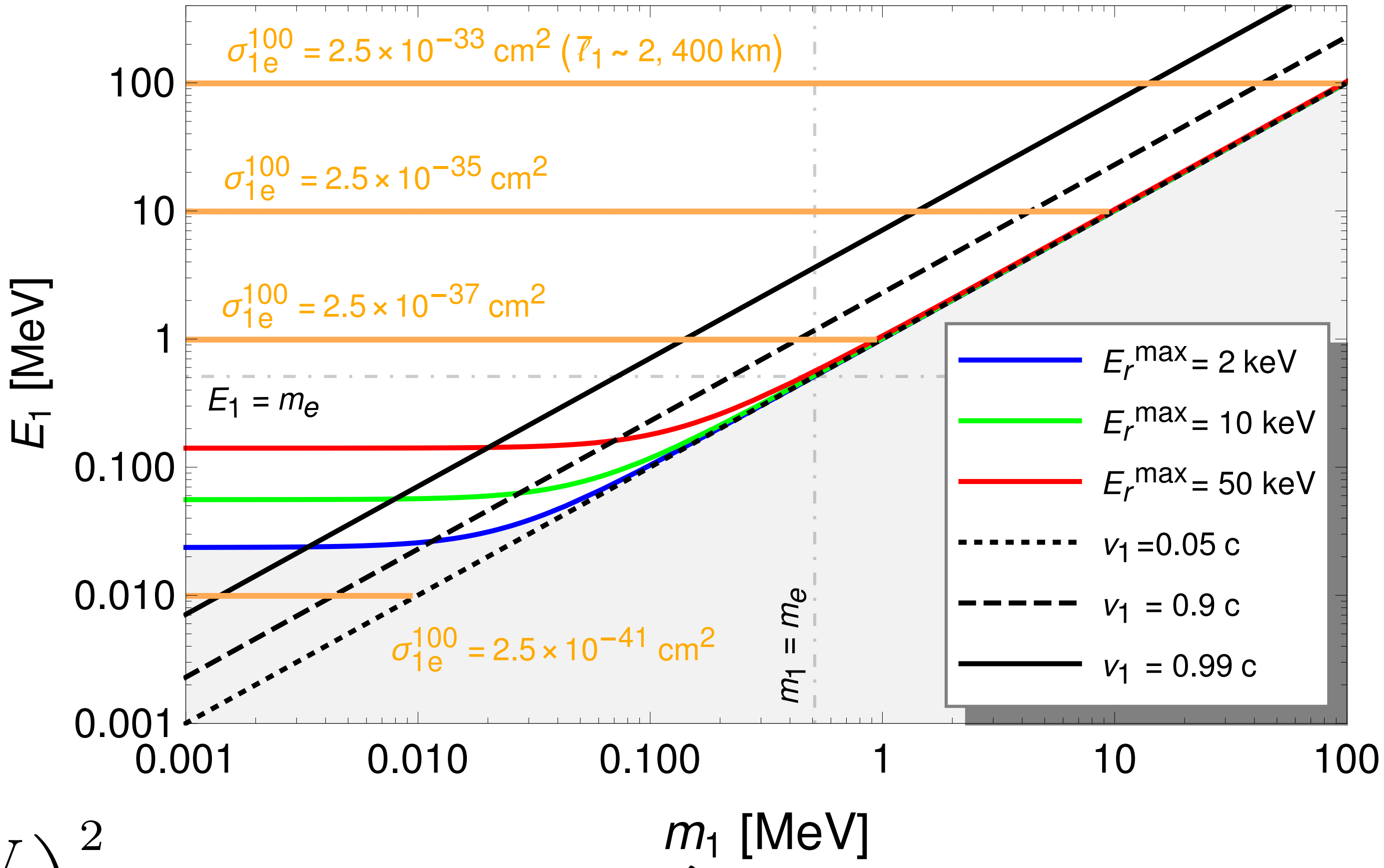
Energy of the incoming BDM

Mass of BDM

Parameter fit of XENON1T 2020

Alhazmi, Kim, Kong, Mohlabeng, Park, **SS**, JHEP 05, 055 (2021), arXiv: 2006.16252

Energy of the incoming BDM



Mass of BDM

Two-component BDM from GC

$$\mathcal{F}_1 = 1.6\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

$$\times \left(\frac{\langle \sigma_{0\to 1} v\rangle}{5\times 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}\right)\left(\frac{10\,\mathrm{MeV}}{m_0}\right)^2$$

First approximation

$$N_{\rm sig} = \mathcal{F}_1 \sigma_{1e} N_{e,\,\rm tot}^{\rm eff} t_{\rm exp}$$

χ_1 - e (fiducial) scattering cross section

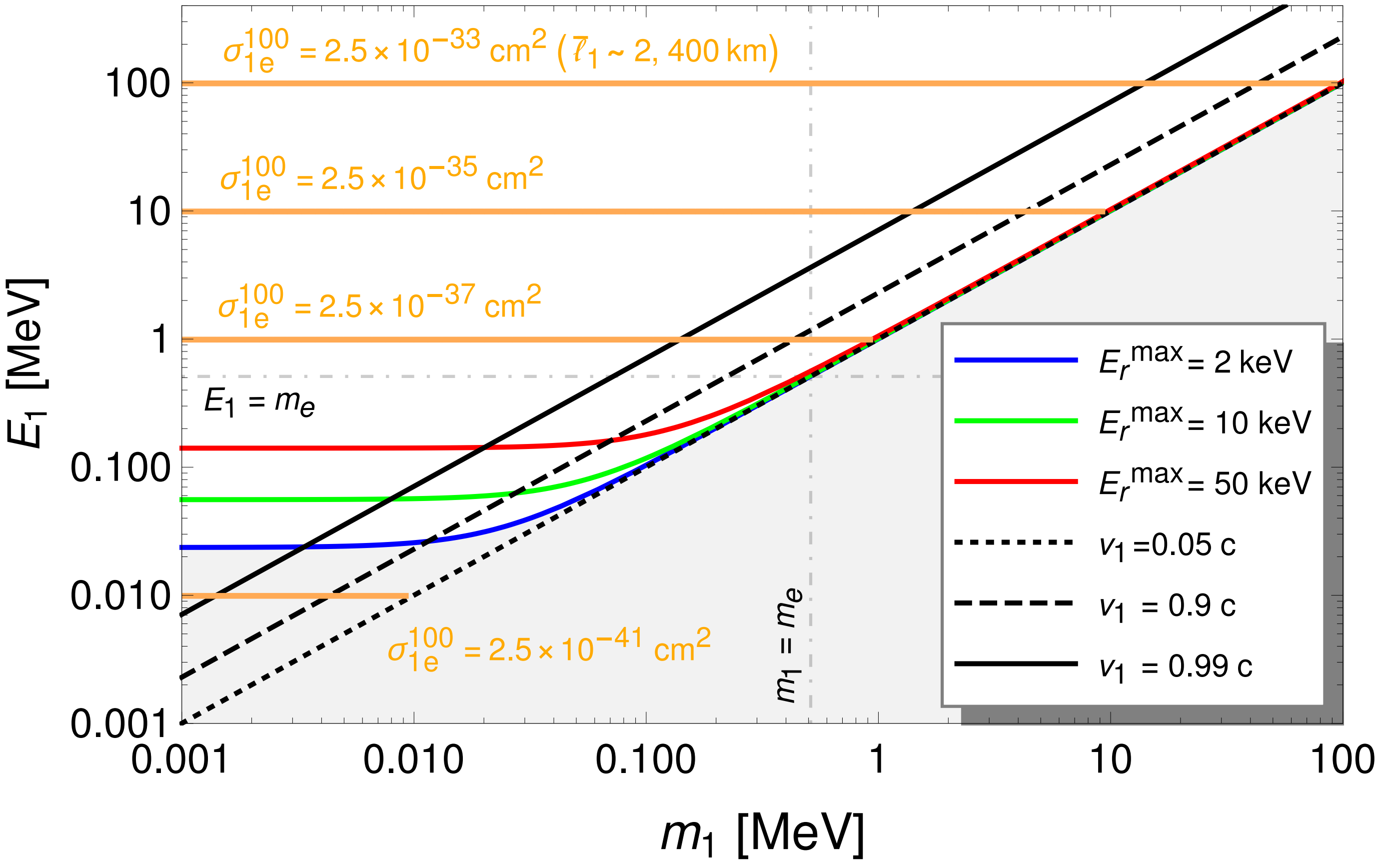
Number of effective target electrons in the fiducial volume

Total exposure time

Parameter fit of XENON1T 2020

Alhazmi, Kim, Kong, Mohlabeng,
Park, **SS**, JHEP 05, 055 (2021),
arXiv: 2006.16252

Energy of
the incoming BDM



Mass of BDM

$$E_r^{\max} = \frac{2m_e p_1^2}{s} = \frac{E_1^2 - m_1^2}{m_1^2 + m_e^2 + 2m_e E_1}$$

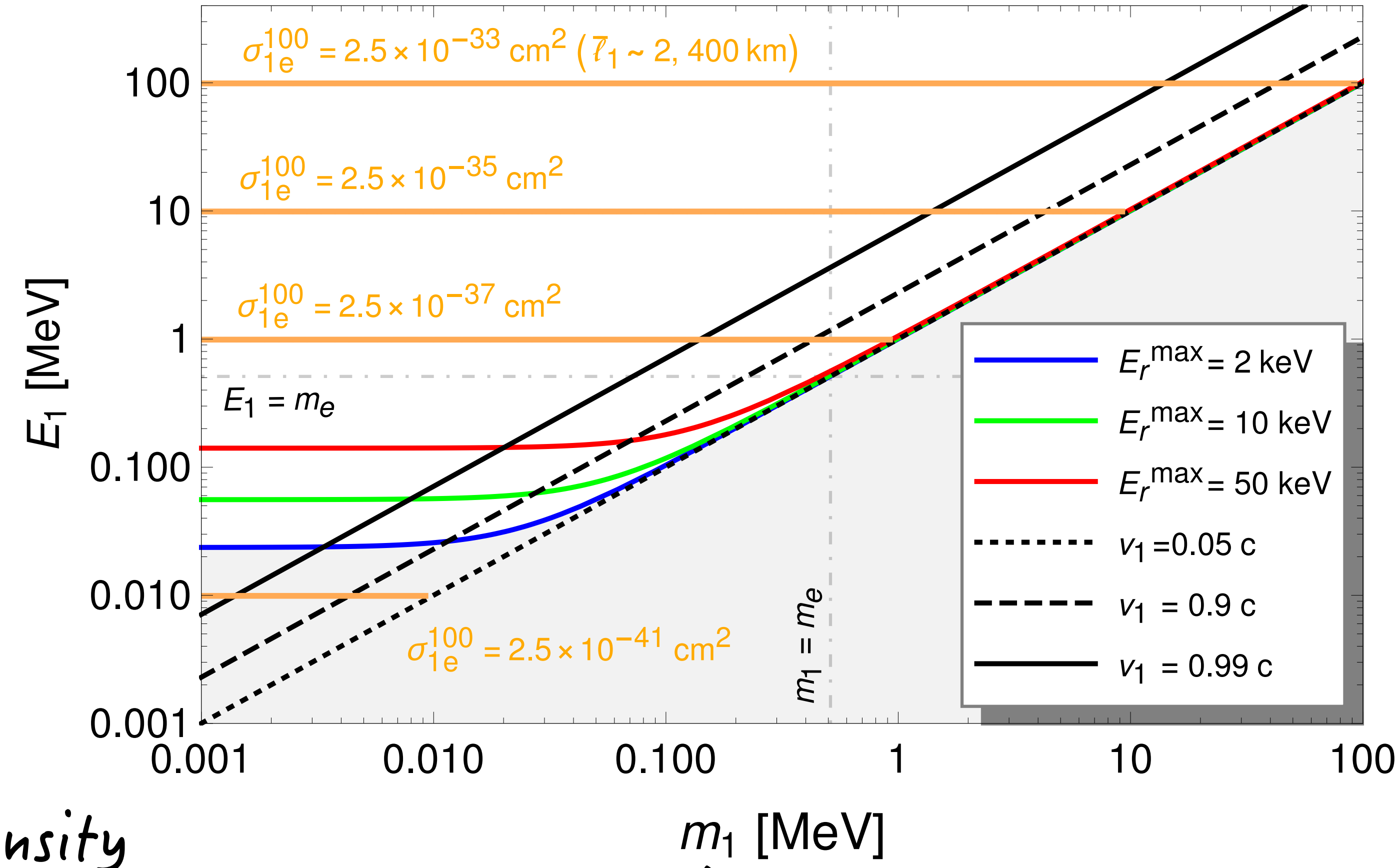
- The maximum E_R of electrons scattered by BDM ≥ 2 keV (non-shaded). This is **model independently** given as above.

- $E_1 \gtrsim 20$ keV is preferred (depending on m_1).

Parameter fit of XENON1T 2020

Alhazmi, Kim, Kong, Mohlabeng, Park, **SS**, JHEP 05, 055 (2021), arXiv: 2006.16252

Energy of the incoming BDM



$$\bar{\ell}_1 \sim \frac{1}{\langle n_e \rangle \sigma_{1e}}$$

Mean e-number density along the χ_1 propagation line.

Mass of BDM

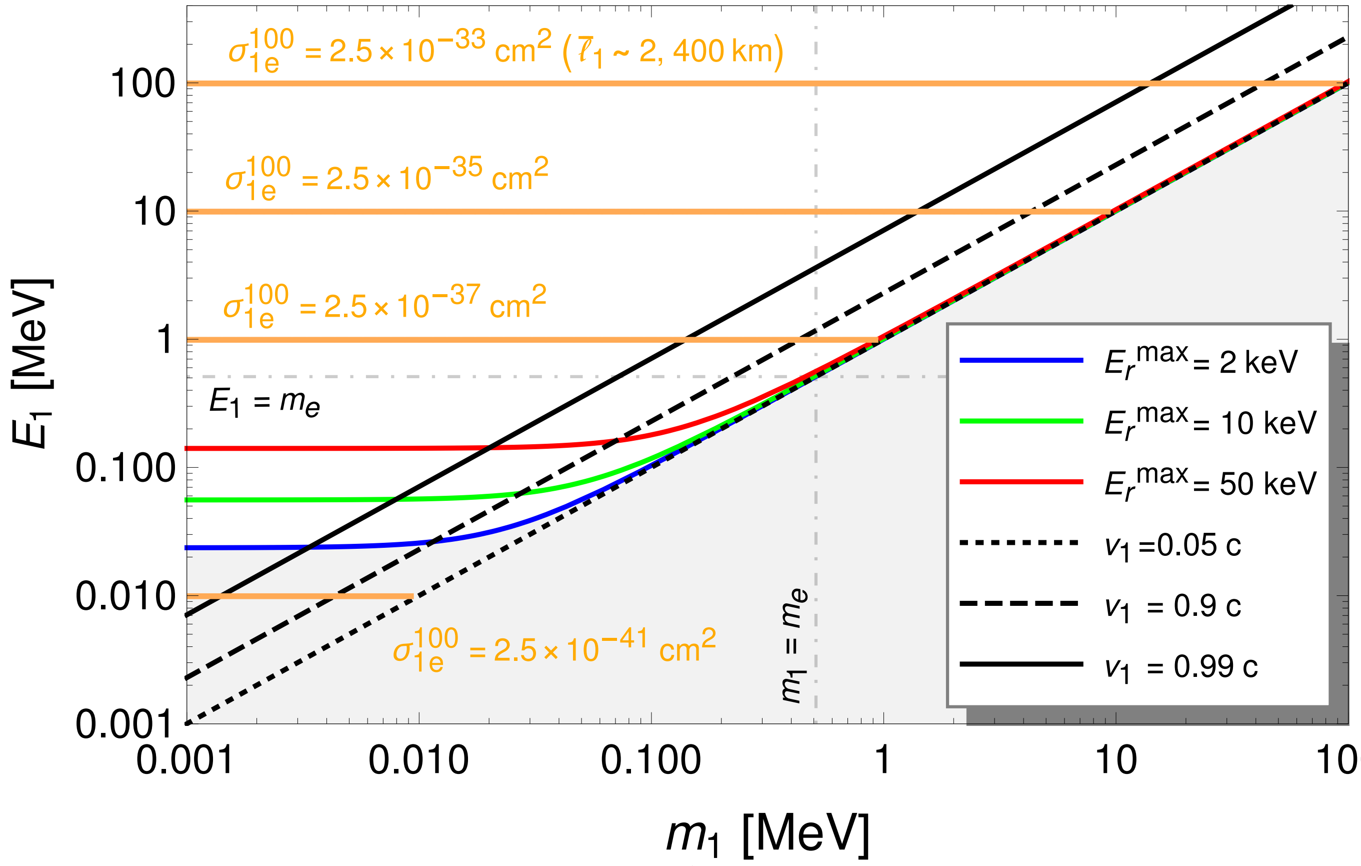
- The values of (fiducial) cross section σ_{1e} giving N_{sig} = 100 are shown, assuming $N_e^{\text{eff}} = 18$ (will be discussed later). $N_{e,\text{tot}}^{\text{eff}} = 4.59 \times 10^{27} N_e^{\text{eff}}$ for 1 ton of liquid Xe

- To avoid the Earth attenuation, the mean free path ≳ $\mathcal{O}$(1000 km) is preferred. (at least larger than the depth of XENON1T ~ 1.6 km)

Parameter fit of XENON1T 2020

Alhazmi, Kim, Kong, Mohlabeng,
Park, **SS**, JHEP 05, 055 (2021),
arXiv: 2006.16252

Energy of
the incoming BDM



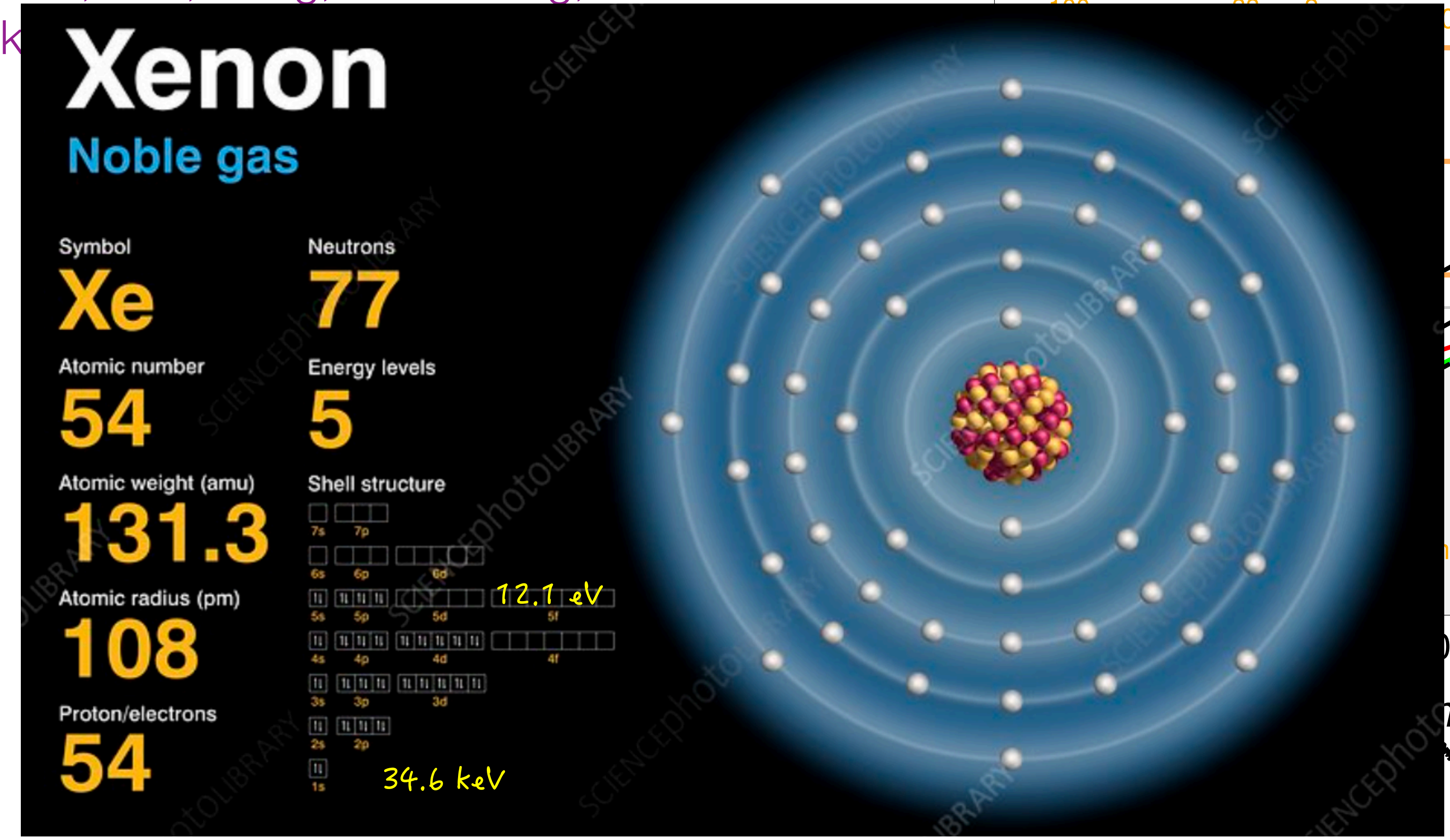
Mass of BDM

- The velocity of BDM, v_1, can be close to c in a wide range of parameter space ($\gg 0.1c$ is also preferred).

- Shade regions and the black lines are model independent while the orange lines are applied for conventional BDM (but readily applicable).

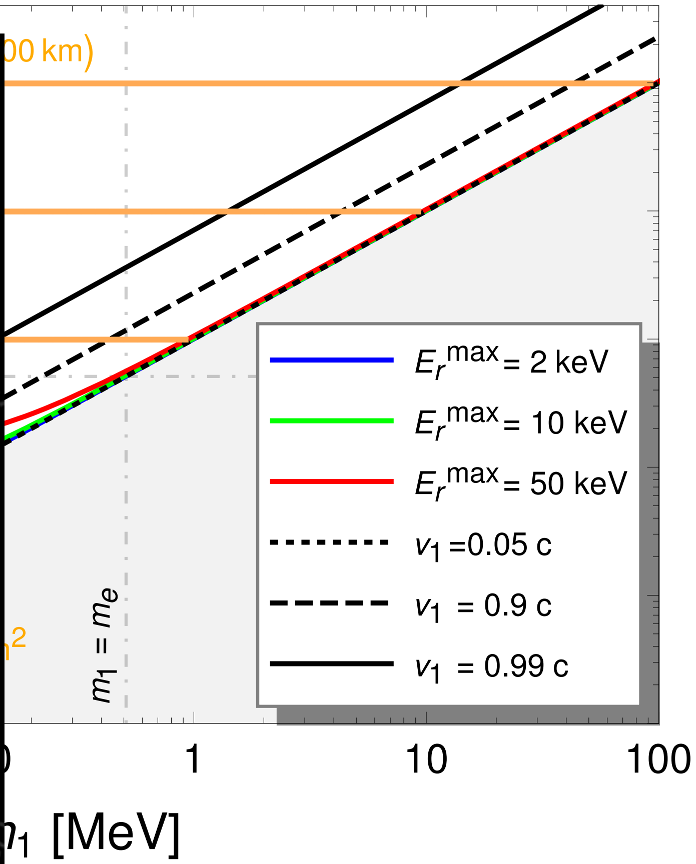
Parameter fit of XENON1T 2020

Alhazmi, Kim, Kong, Mohlabeng,
Park



12.1 eV

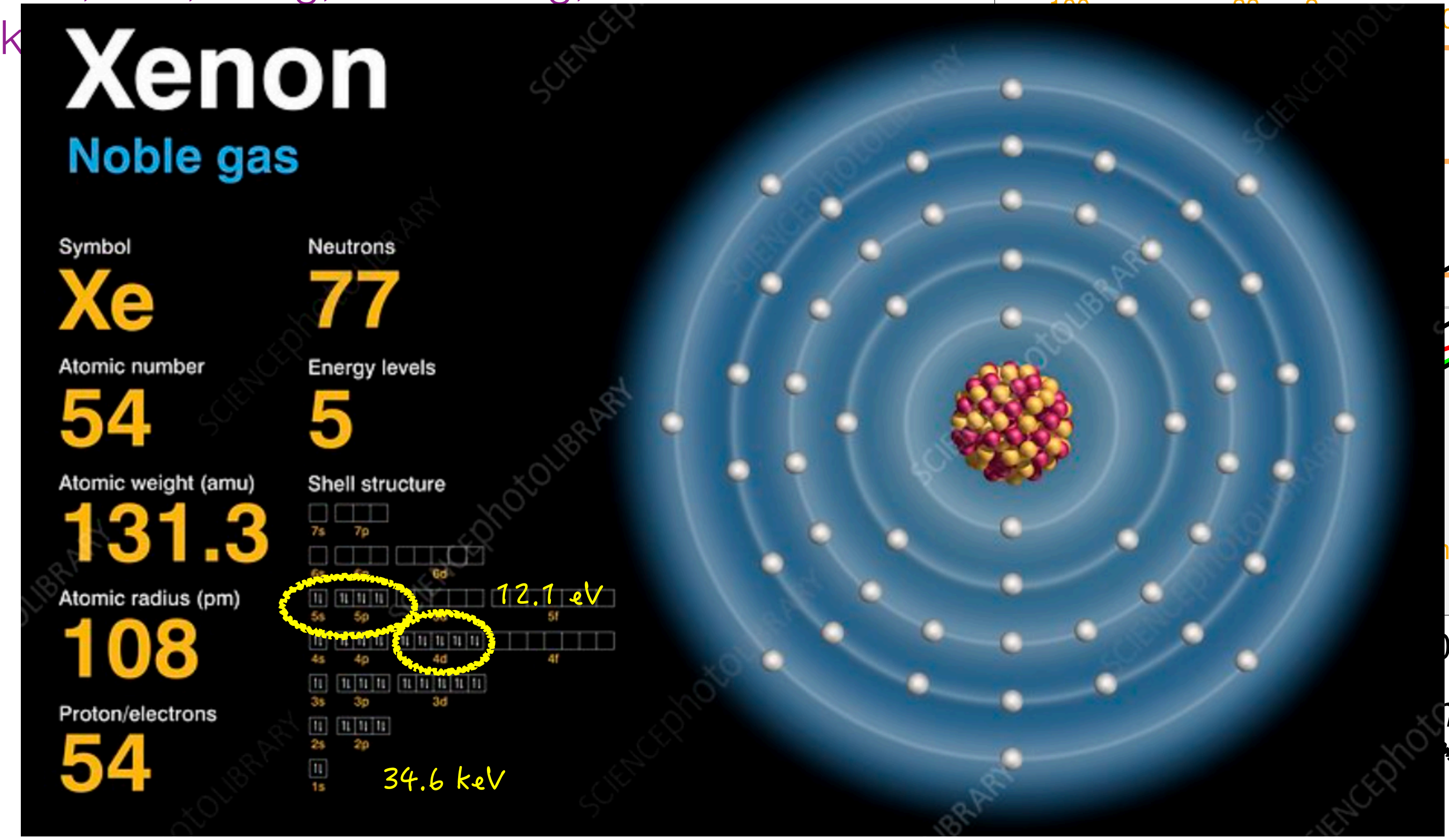
34.6 keV

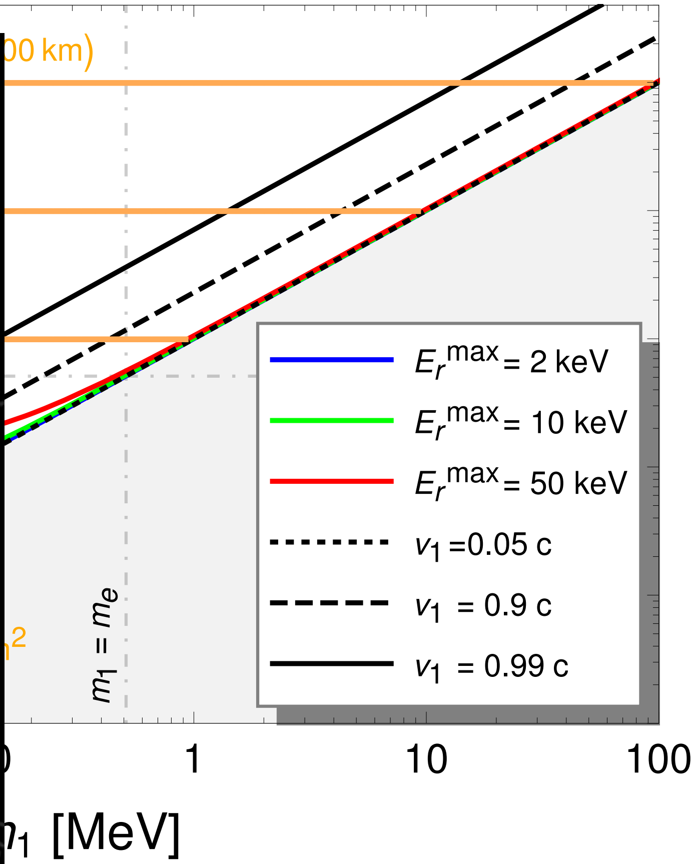


Mass of BDM

Parameter fit of XENON1T 2020

Alhazmi, Kim, Kong, Mohlabeng,
Park



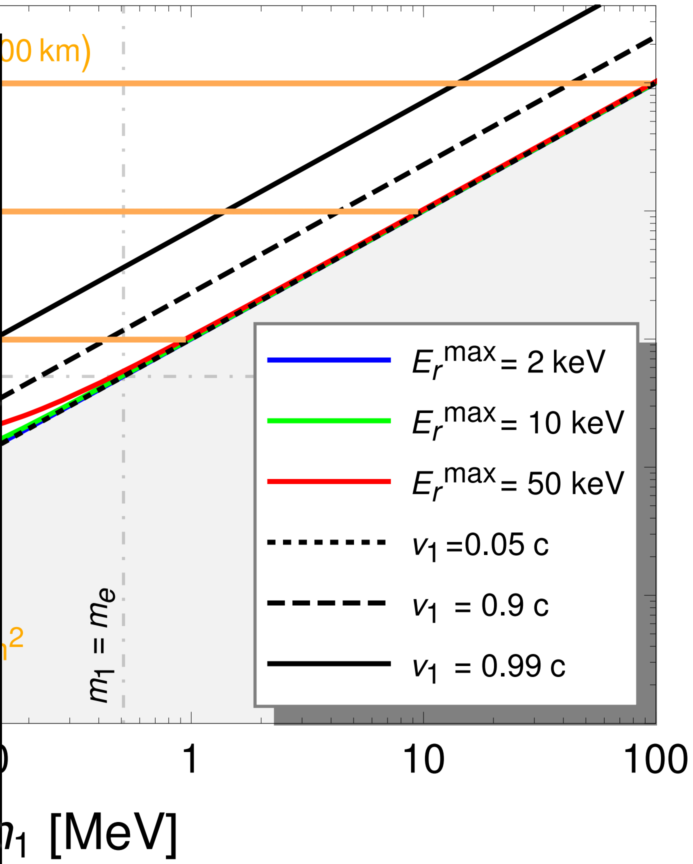


Mass of BDM

- The value of $N_e^{\rm eff} = 18$ is used from naively considering the 3 outermost shells (5p,5s,4d).
- The largest binding energy ≲ 76 eV ~17% of the energy resolution (450 eV): induce ≲ 5% uncertainty in estimating 2-3 keV energy deposition.

Parameter fit of XENON1T 2020

Alhazmi, Kim, Kong, Mohlabeng,
Park



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Parameter fit of XENON1T 2020

Alhazmi, Kim, Kong, Mohlabeng,
Park

Mass of BDM

- Atomic Ionization Form Factor: Likelihood that a given momentum transfer results in a particular E_R.

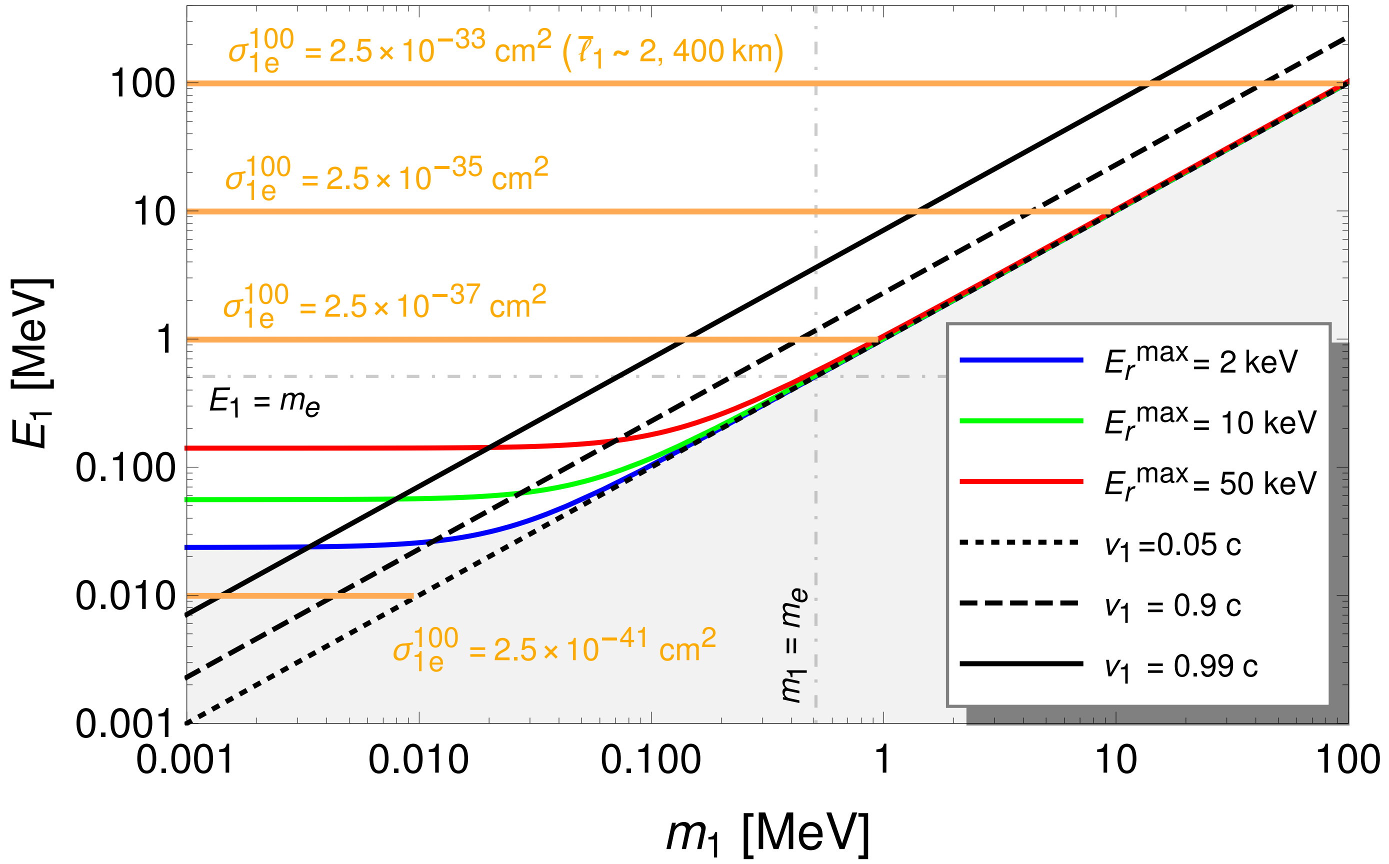
Essig, Mardon, Volansky, PRD2012 Lee, Lisanti, Mishra-Sharma, Safdi, PRD 2015

- The incoming light BDM is relativistic & the electron velocities in the inner shell can be large: Relativistic approach needed (for large q).

Roberts, Dzuba, Flambaum, Pospelov, Stadnik, PRD 2016 Work in progress with Alhazmi, Kim, Kong, Mohlabeng, Park,

Dependence on mediators

mediator	DM
V	F
V	S
A	S
P	F
P	S
S	F
S	S



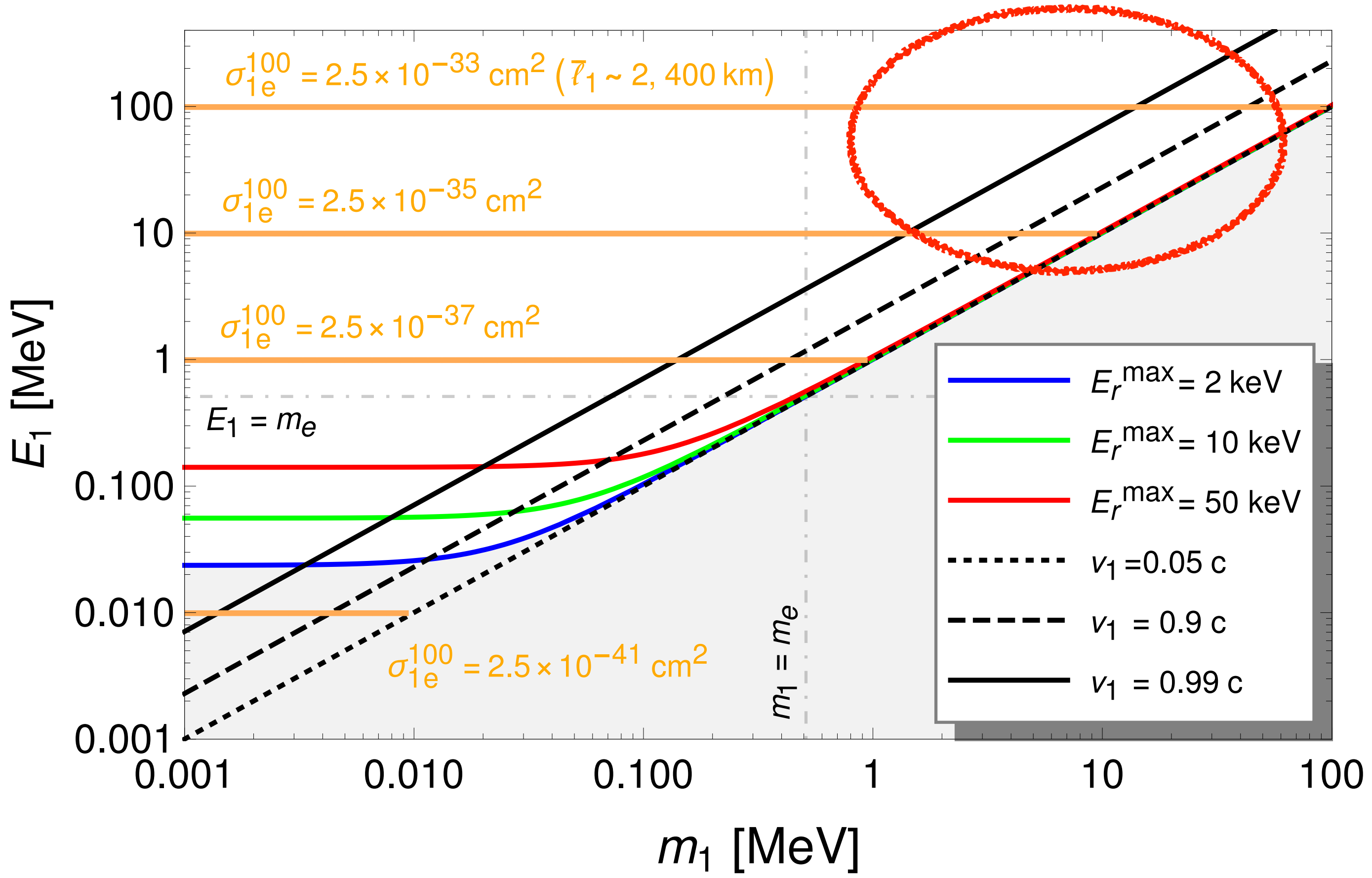
- The scales of mass and coupling parameters preferred by the excess depend on the type of the mediators.

- We analyze the shape of the spectrum for various types of mediators (vector:V, pseudoscalar: P, scalar: S) and DM (fermion: F, scalar: S).

- Three reference parameter regions are chosen.

Dependence on mediators

mediator	DM
V	F
V	S
A	S
P	F
P	S
S	F
S	S



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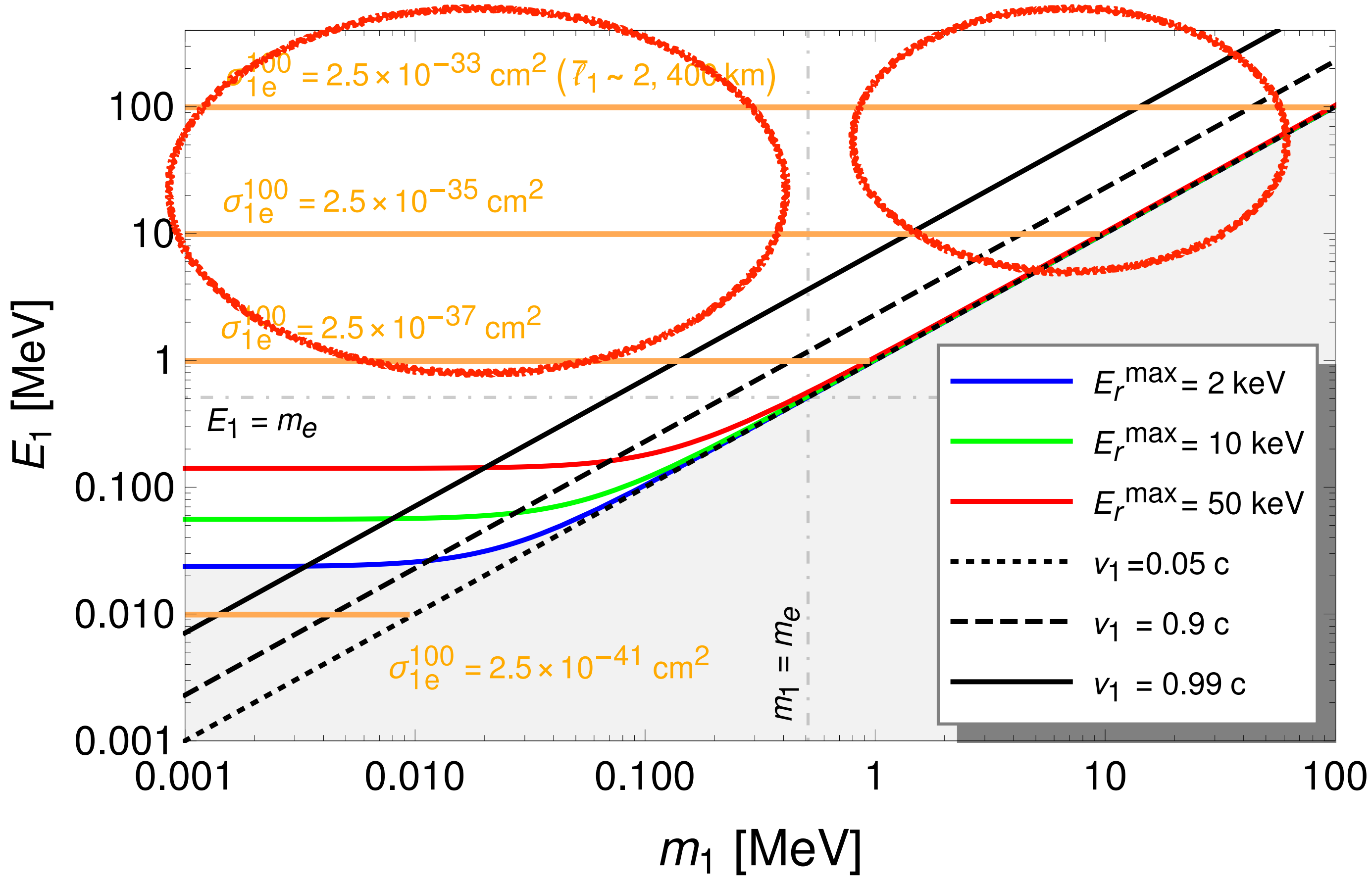
(i) $E_1 \approx m_1 \gg m_e\,, \quad m_i \gg m_e$

(ii) $E_1 \approx m_1 \gg m_e\,, \quad m_i < m_e$

Dependence on mediators

mediator	DM
V	F
V	S
A	S
P	F
P	S
S	F
S	S



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(i) $E_1 \approx m_1 \gg m_e\,, \quad m_i \gg m_e$

(ii) $E_1 \approx m_1 \gg m_e\,, \quad m_i < m_e$

(iii) $E_1 \gg m_e > m_1, \quad m_i < m_e$

- Three reference parameter regions are chosen.

Dependence on mediators

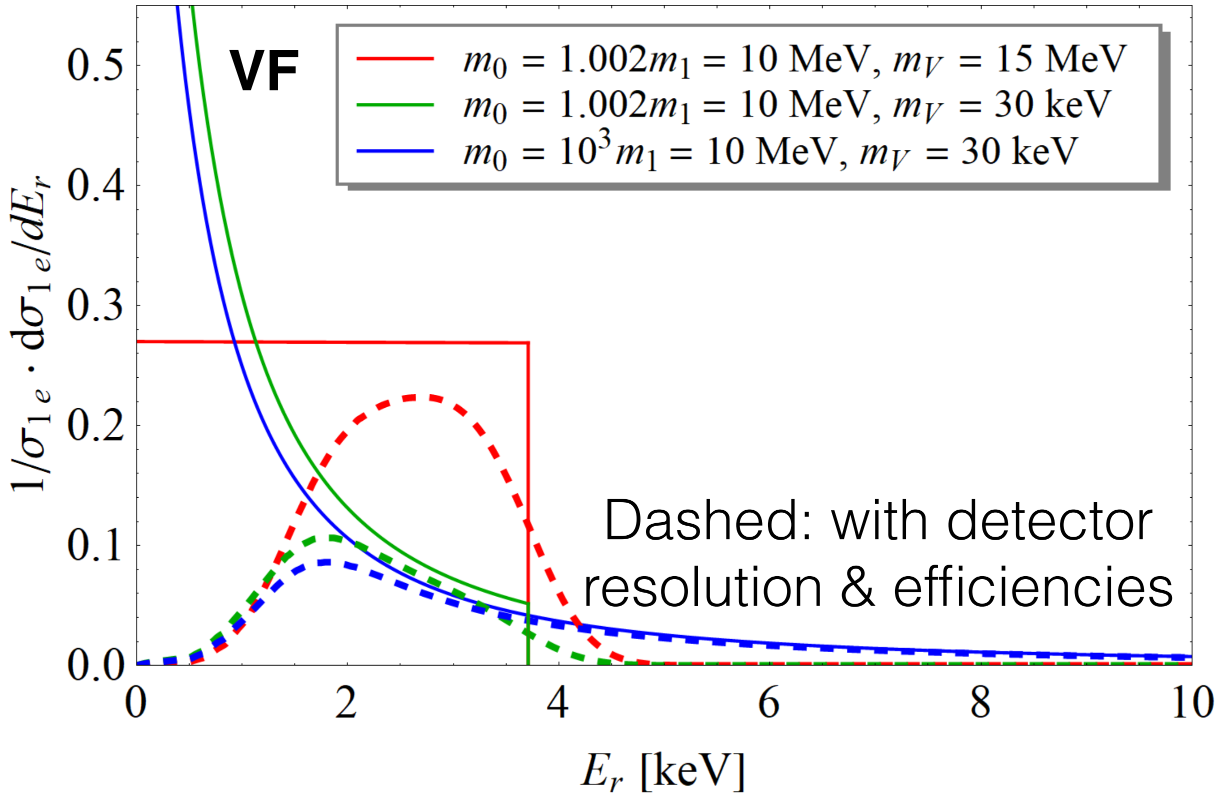
$$\frac{d\sigma_{1e}}{dE_r} = \frac{(g^i_j g^i_e)^2}{8\pi\lambda(s, m_e^2, m_1^2)(2m_e E_r + m_i^2)^2}|\bar{\mathcal{A}}|^2$$

without detector resolution and efficiency

Case	Mediator	Dark matter	$\mathcal{L}_{\rm int}$	$\overline{\lvert\mathcal{A}\rvert}^2$
VF	V_μ	χ_1	$(g_e^V \bar{e}\gamma^\mu e + g_\chi^V \bar{\chi}_1\gamma^\mu\chi_1)V_\mu$	$8m_e\left\{m_e(2E_1^2 - 2E_1E_r + E_r^2) - (m_e^2 + m_1^2)E_r\right\}$
VS	V_μ	φ_1	$(g_e^V \bar{e}\gamma^\mu e + g_\varphi^V \varphi_1^*\partial^\mu\varphi_1 + \text{h.c.})V_\mu$	$8m_e\left\{2m_eE_1(E_1 - E_r) - m_1^2E_r\right\}$
PF	a	χ_1	$(ig_e^a\bar{e}\gamma^5 e + ig_\chi^a\bar{\chi}_1\gamma^5\chi_1)a$	$4m_e^2E_r^2$
PS	a	φ_1	$(ig_e^a\bar{e}\gamma^5 e + ig_\varphi^a m_1\varphi^*\varphi)a$	$8m_em_1^2E_r$
SF	ϕ	χ_1	$(g_e^\phi\bar{e}e + g_\chi^\phi\bar{\chi}_1\chi_1)\phi$	$4m_e(E_r + 2m_e)(2m_1^2 + m_eE_r)$
SS	ϕ	φ_1	$(g_e^\phi\bar{e}e + g_\varphi^\phi m_1\varphi^*\varphi)\phi$	$8m_em_1^2(E_r + 2m_e)$

DM form factor (in q)

VF (i) $\frac{d\sigma_{1e}}{dE_r} \propto \frac{m_e m_1^2}{m_V^4}$ (ii) $\frac{d\sigma_{1e}}{dE_r} \propto \frac{m_e m_1^2}{(2m_eE_r + m_V^2)^2}$ (iii) $\frac{d\sigma_{1e}}{dE_r} \propto \frac{m_e E_1^2}{(2m_eE_r + m_V^2)^2}$



Dashed: with detector resolution & efficiencies

Dependence on mediators

$$\frac{d\sigma_{1e}}{dE_r} = \frac{(g^i_j g^i_e)^2}{8\pi\lambda(s, m_e^2, m_1^2)(2m_e E_r + m_i^2)^2} |\bar{\mathcal{A}}|^2$$

without detector resolution and efficiency

Case	Mediator	Dark matter	$\mathcal{L}_{\text{int}}$	$\overline{\lvert\mathcal{A}\rvert}^2$
VF	V_μ	χ_1	$(g_e^V \bar{e}\gamma^\mu e + g_\chi^V \bar{\chi}_1\gamma^\mu\chi_1)V_\mu$	$8m_e\left\{m_e(2E_1^2 - 2E_1E_r + E_r^2) - (m_e^2 + m_1^2)E_r\right\}$
VS	V_μ	φ_1	$(g_e^V \bar{e}\gamma^\mu e + g_\varphi^V \varphi_1^*\partial^\mu\varphi_1 + \text{h.c.})V_\mu$	$8m_e\left\{2m_eE_1(E_1 - E_r) - m_1^2E_r\right\}$
PF	a	χ_1	$(ig_e^a\bar{e}\gamma^5 e + ig_\chi^a\bar{\chi}_1\gamma^5\chi_1)a$	$4m_e^2E_r^2$
PS	a	φ_1	$(ig_e^a\bar{e}\gamma^5 e + ig_\varphi^a m_1\varphi^*\varphi)a$	$8m_e m_1^2 E_r$
SF	ϕ	χ_1	$(g_e^\phi\bar{e}e + g_\chi^\phi\bar{\chi}_1\chi_1)\phi$	$4m_e(E_r + 2m_e)(2m_1^2 + m_eE_r)$
SS	ϕ	φ_1	$(g_e^\phi\bar{e}e + g_\varphi^\phi m_1\varphi^*\varphi)\phi$	$8m_e m_1^2(E_r + 2m_e)$

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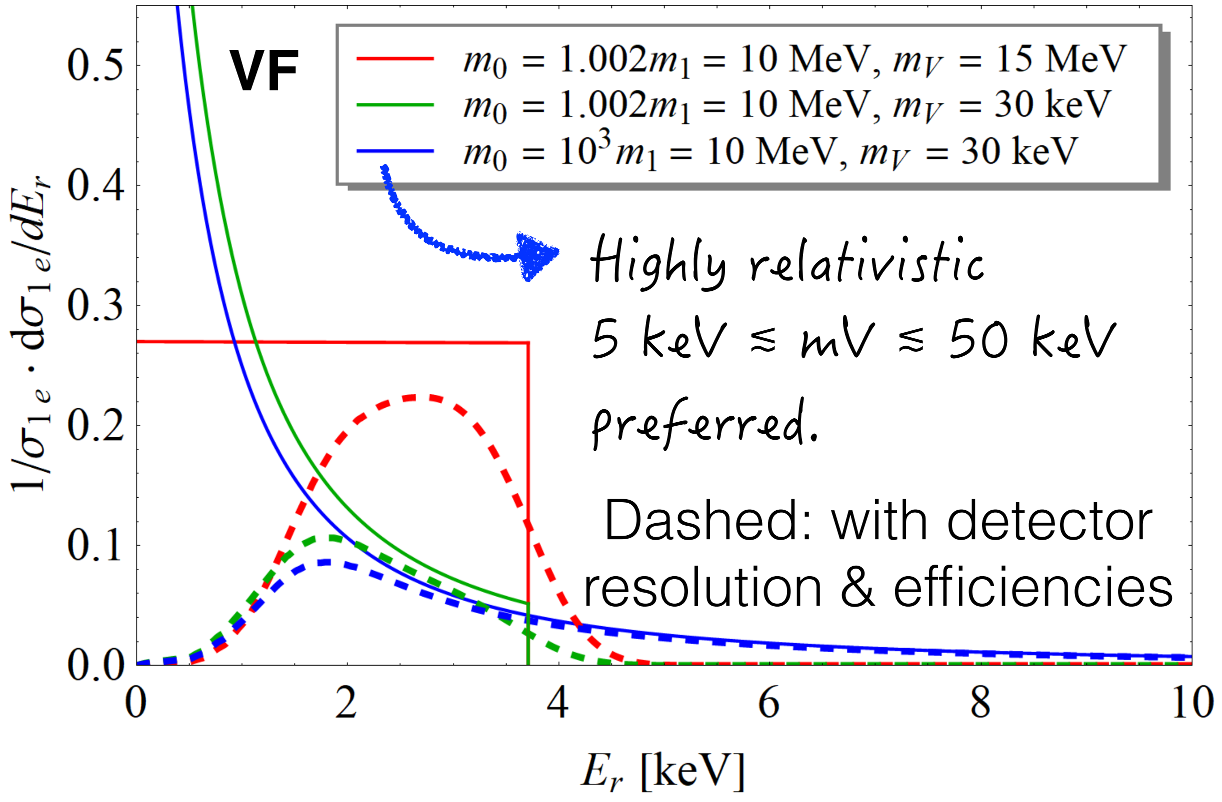

Highly relativistic $5 \text{ keV} \lesssim mV \lesssim 50 \text{ keV}$ preferred.

Dashed: with detector resolution & efficiencies

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without detector resolution and efficiency

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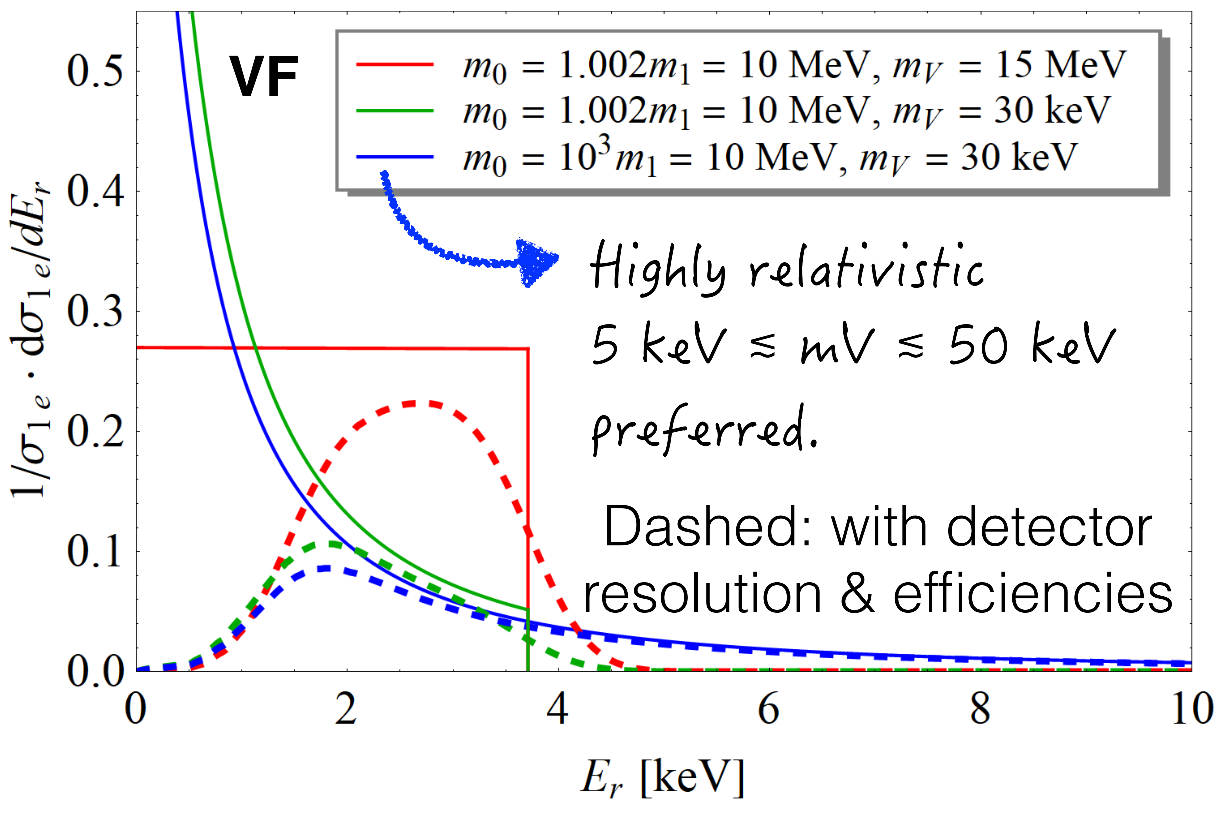
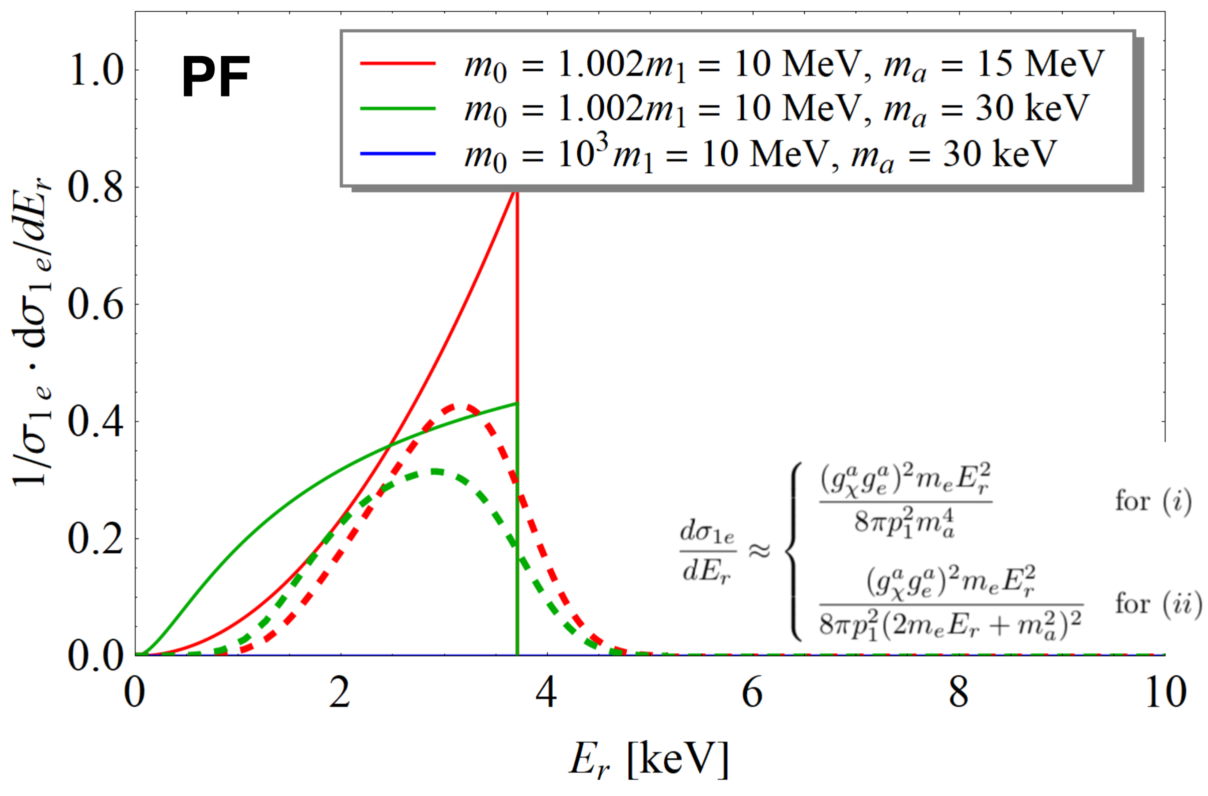


Highly relativistic
5 keV ≲ mV ≲ 50 keV
preferred.

Dashed: with detector resolution & efficiencies



$$\frac{d\sigma_{1e}}{dE_r} \approx \begin{cases} \dfrac{(g_\chi^a g_e^a)^2 m_e E_r^2}{8\pi p_1^2 m_a^4} & \text{for } (i) \\ \dfrac{(g_\chi^a g_e^a)^2 m_e E_r^2}{8\pi p_1^2(2m_eE_r+m_a^2)^2} & \text{for } (ii) \text{ and } (iii), \end{cases}$$

Dependence on mediators

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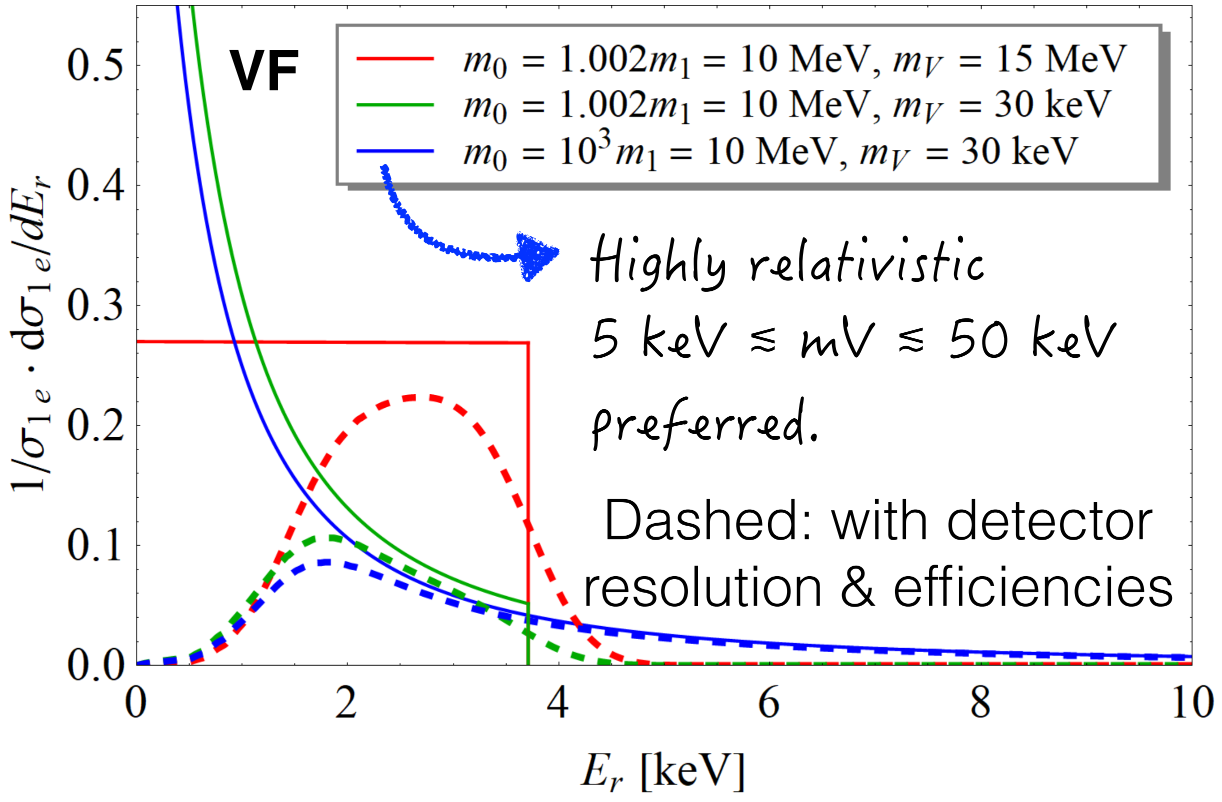

Highly relativistic 5 keV ≲ mV ≲ 50 keV preferred.

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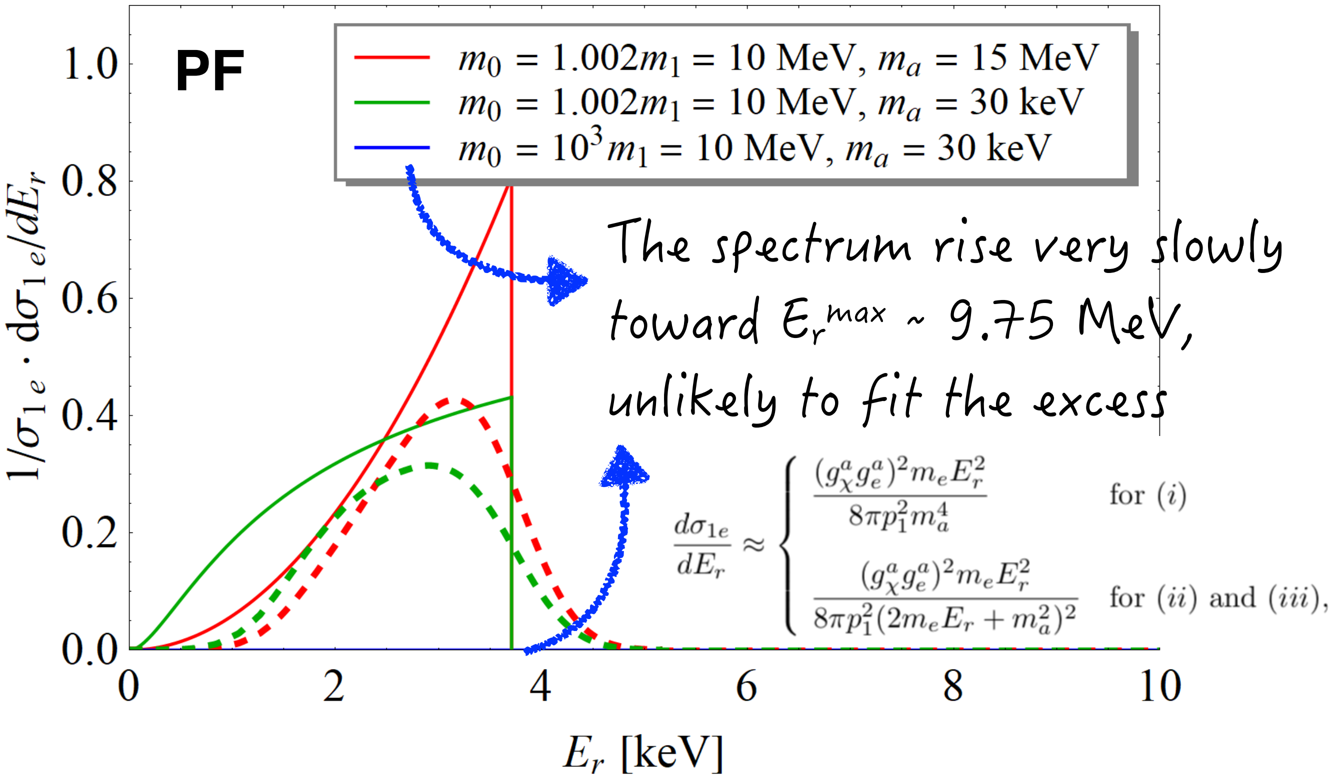
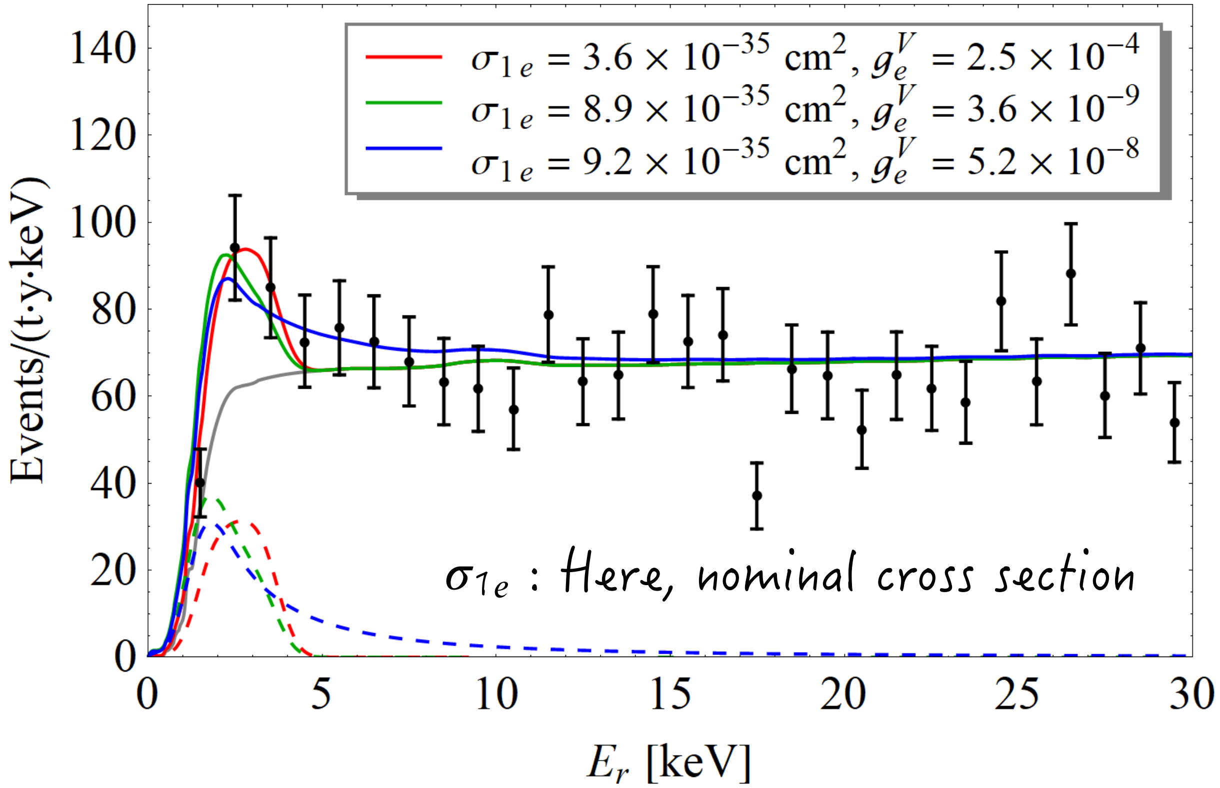


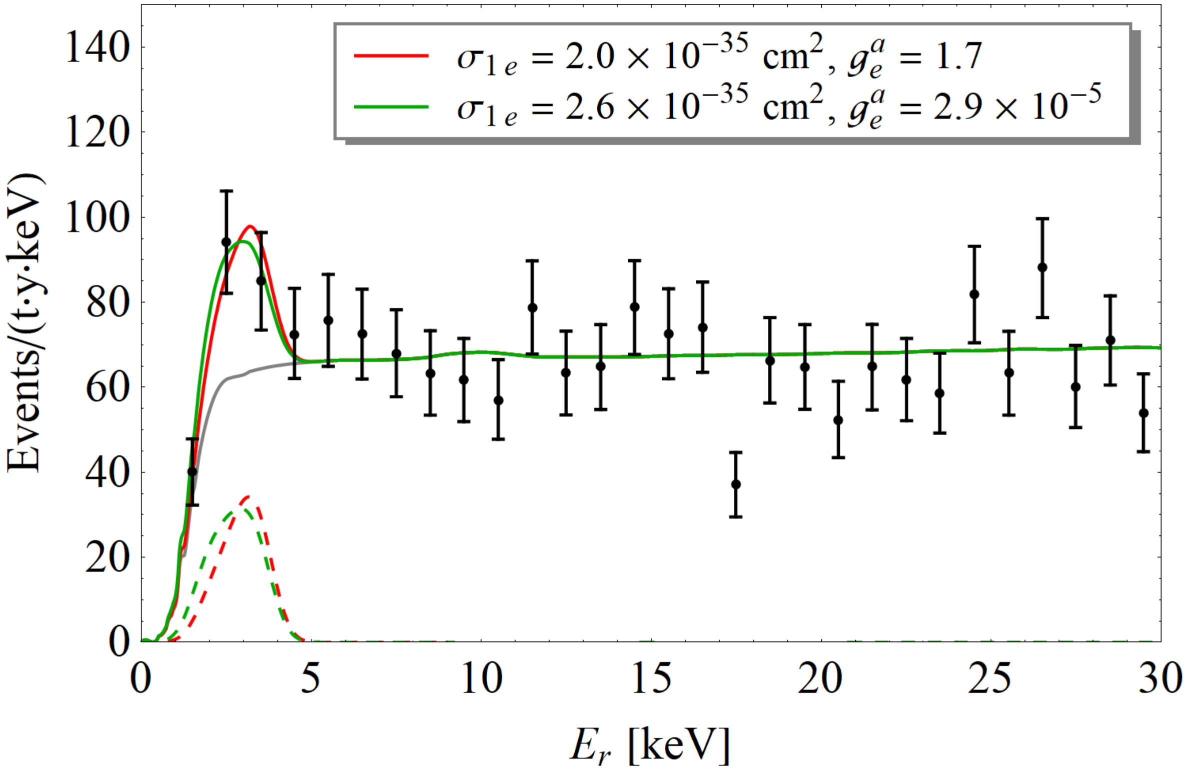
The spectrum rise very slowly toward E_r^{max} ~ 9.75 MeV, unlikely to fit the excess

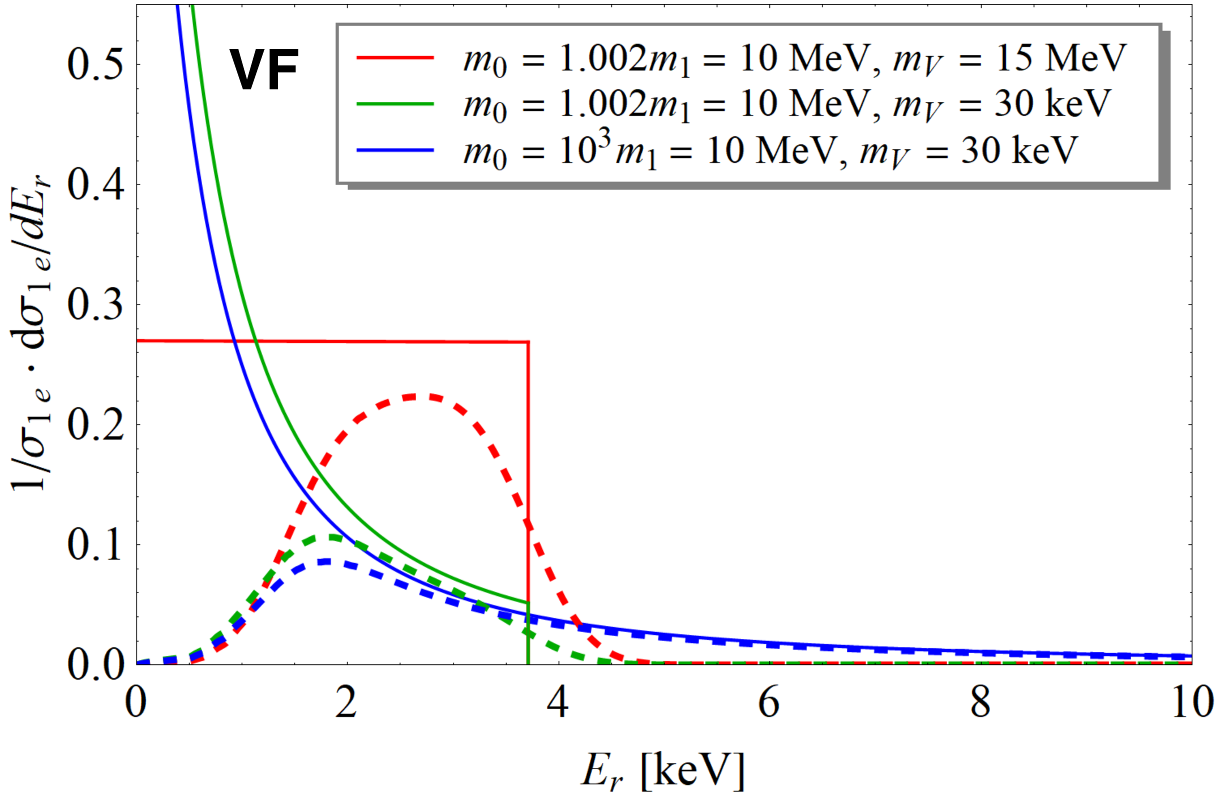
$$\frac{d\sigma_{1e}}{dE_r} \approx \begin{cases} \frac{(g_\chi^a g_e^a)^2 m_e E_r^2}{8\pi p_1^2 m_a^4} & \text{for } (i) \\ \frac{(g_\chi^a g_e^a)^2 m_e E_r^2}{8\pi p_1^2 (2m_eE_r + m_a^2)^2} & \text{for } (ii) \text{ and } (iii), \end{cases}$$

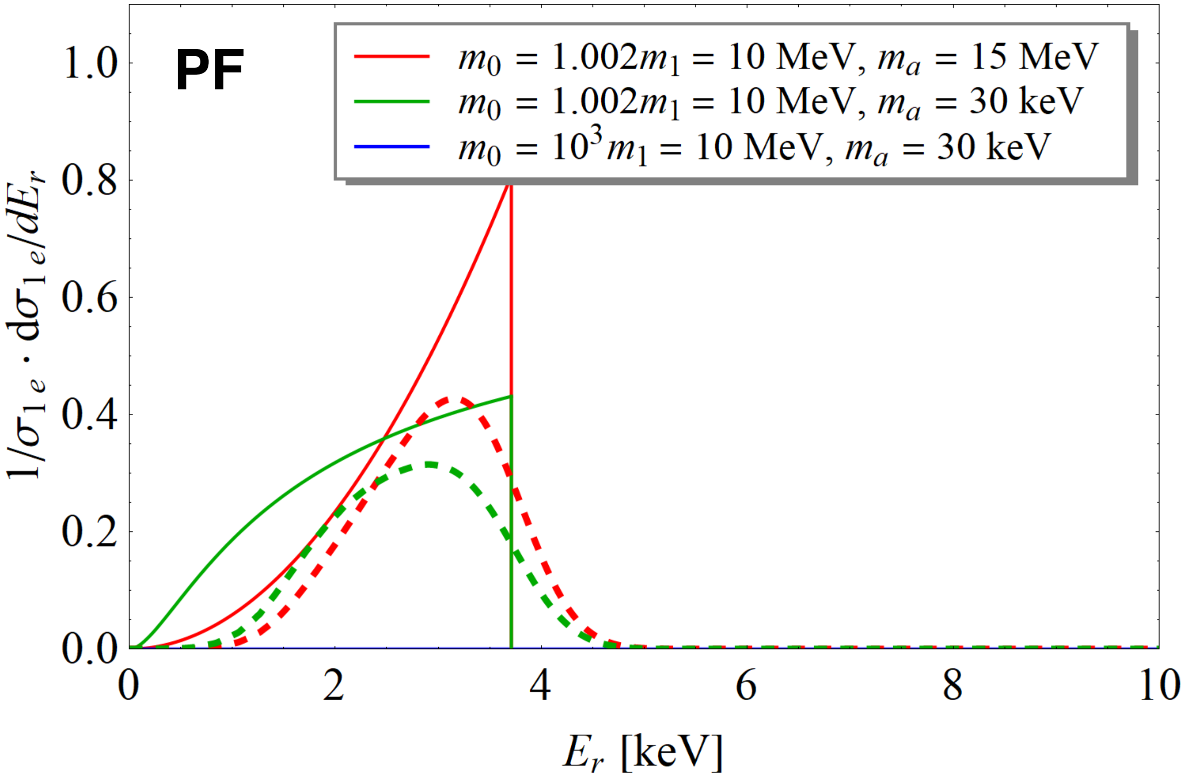
Fit to the excess



σ_{1e} : Here, nominal cross section







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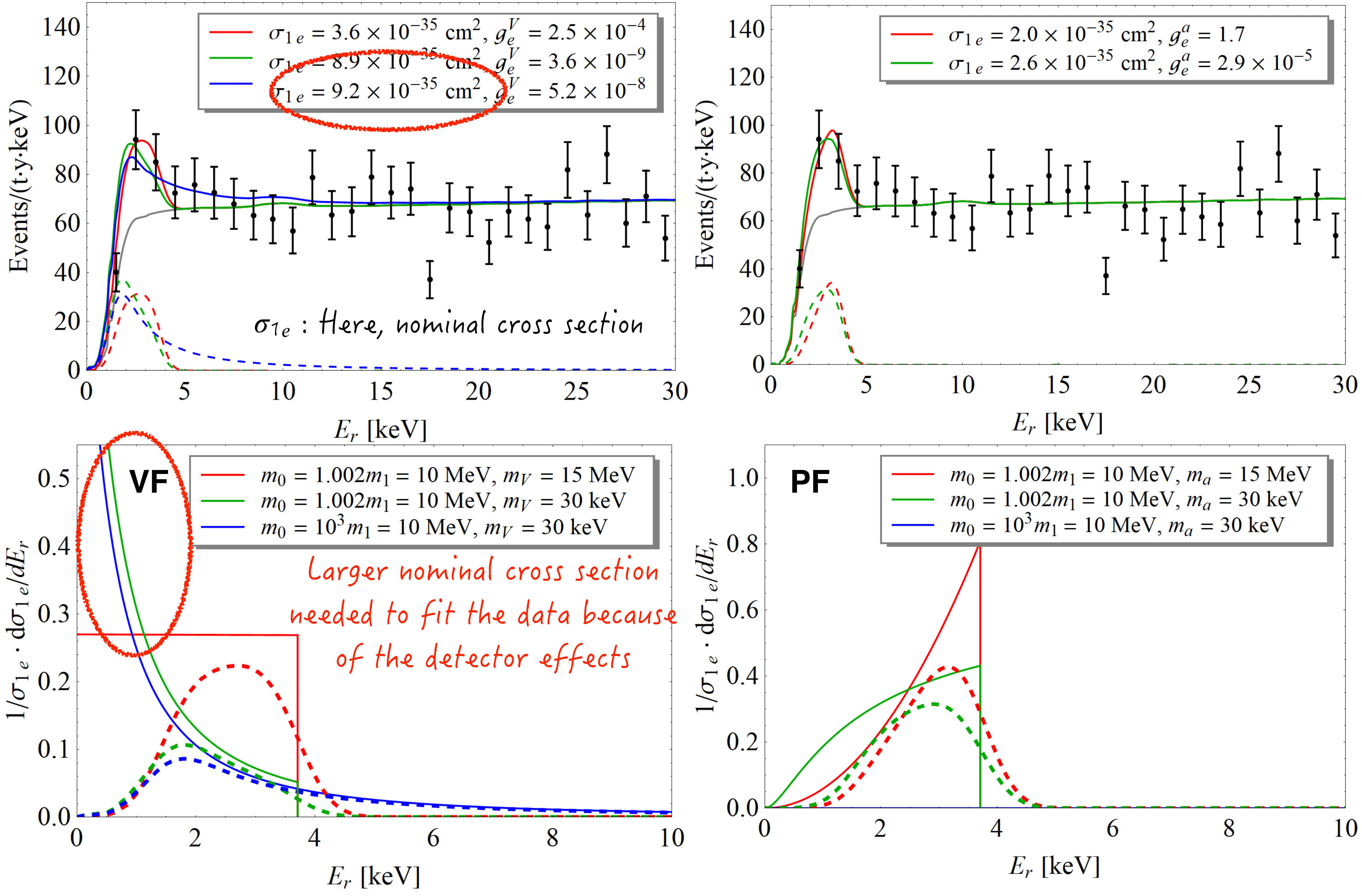

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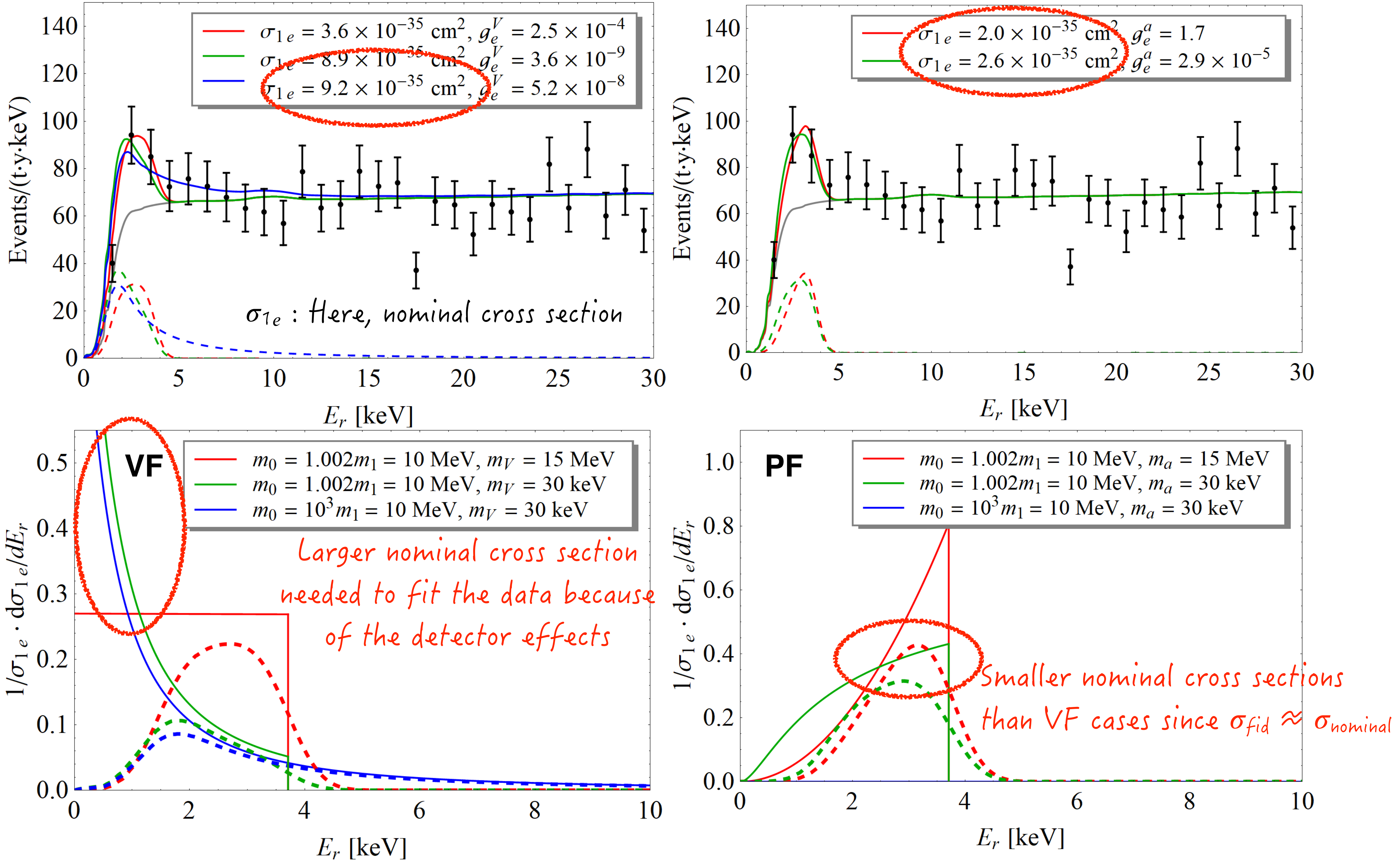
Larger nominal cross section needed to fit the data because of the detector effects

Fit to the excess



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Smaller nominal cross sections than VF cases since $\sigma_{fid} \approx \sigma_{nominal}$

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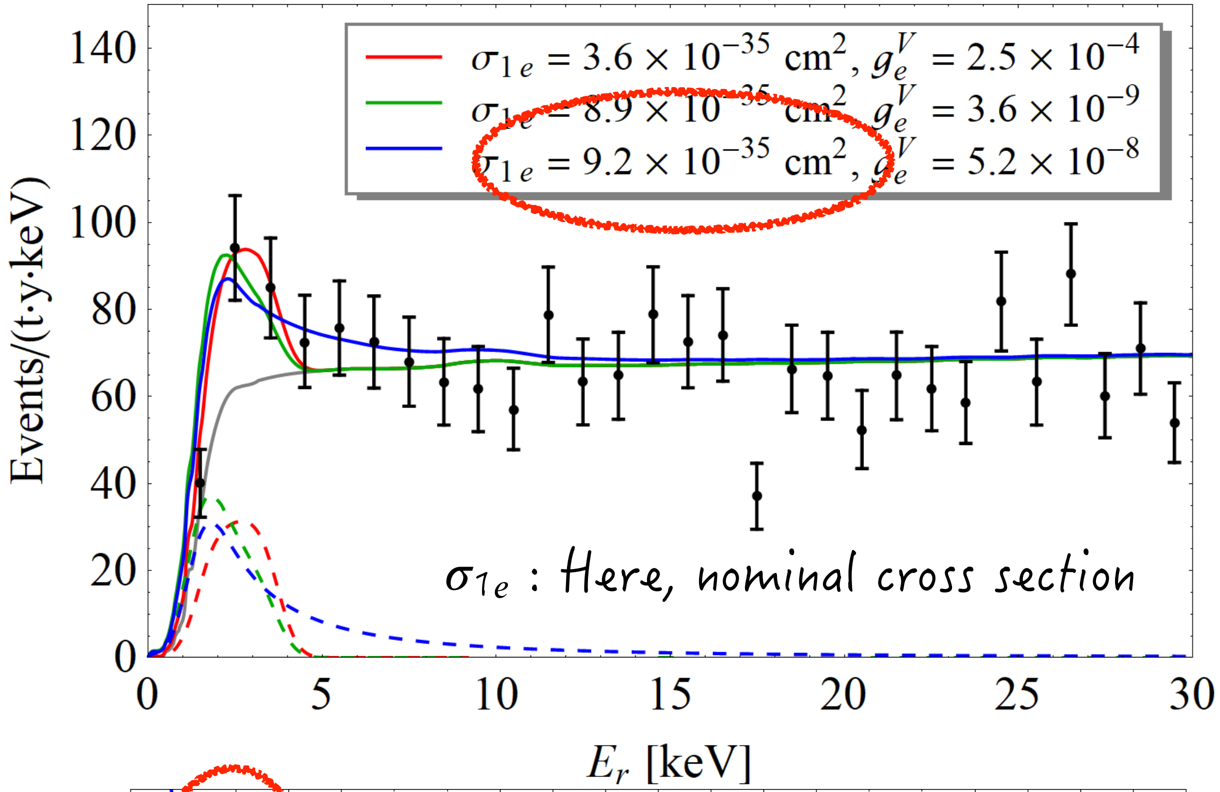

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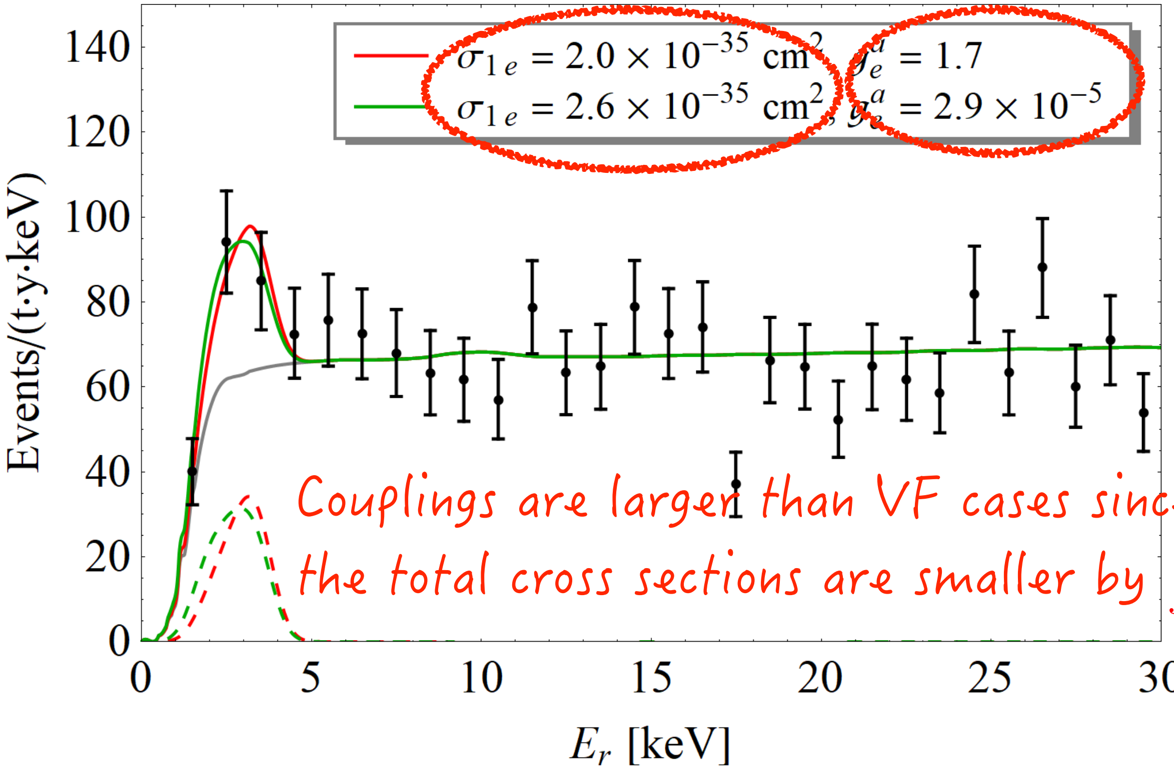
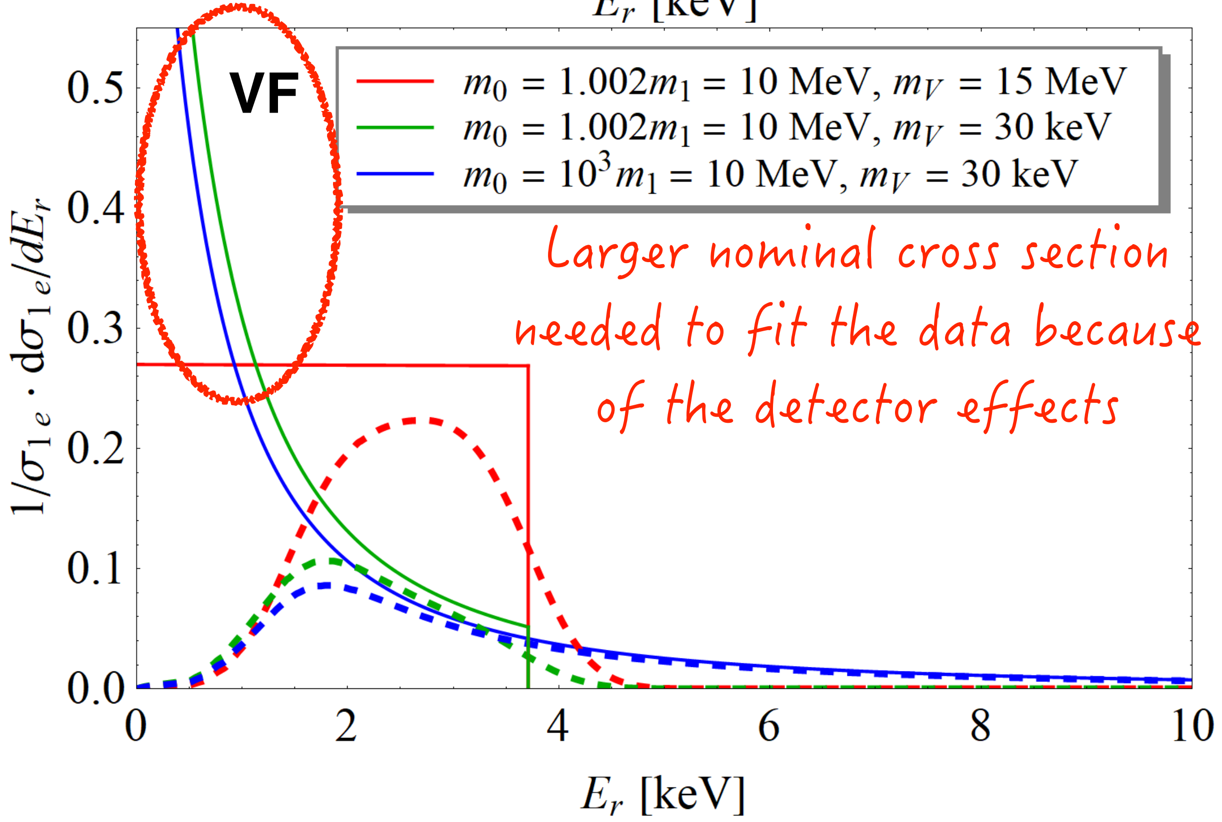


Couplings are larger than VF cases since the total cross sections are smaller by $\int \frac{E_r^2}{m_1^2}$



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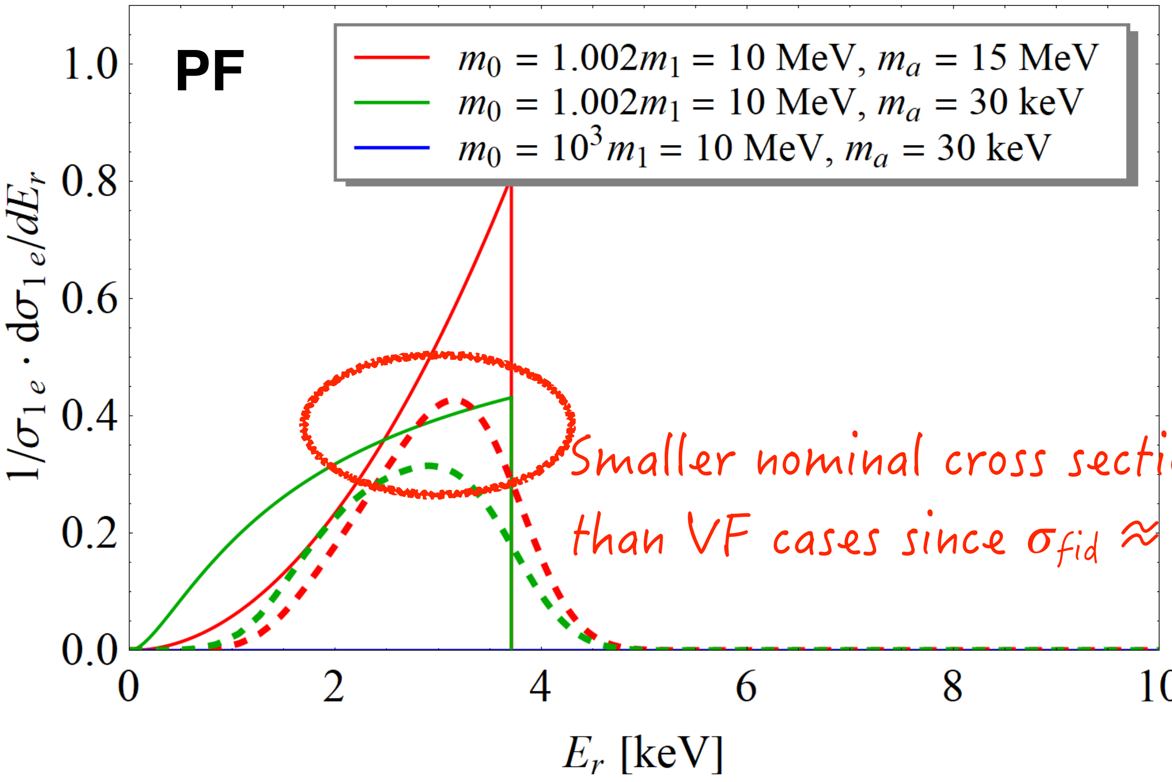

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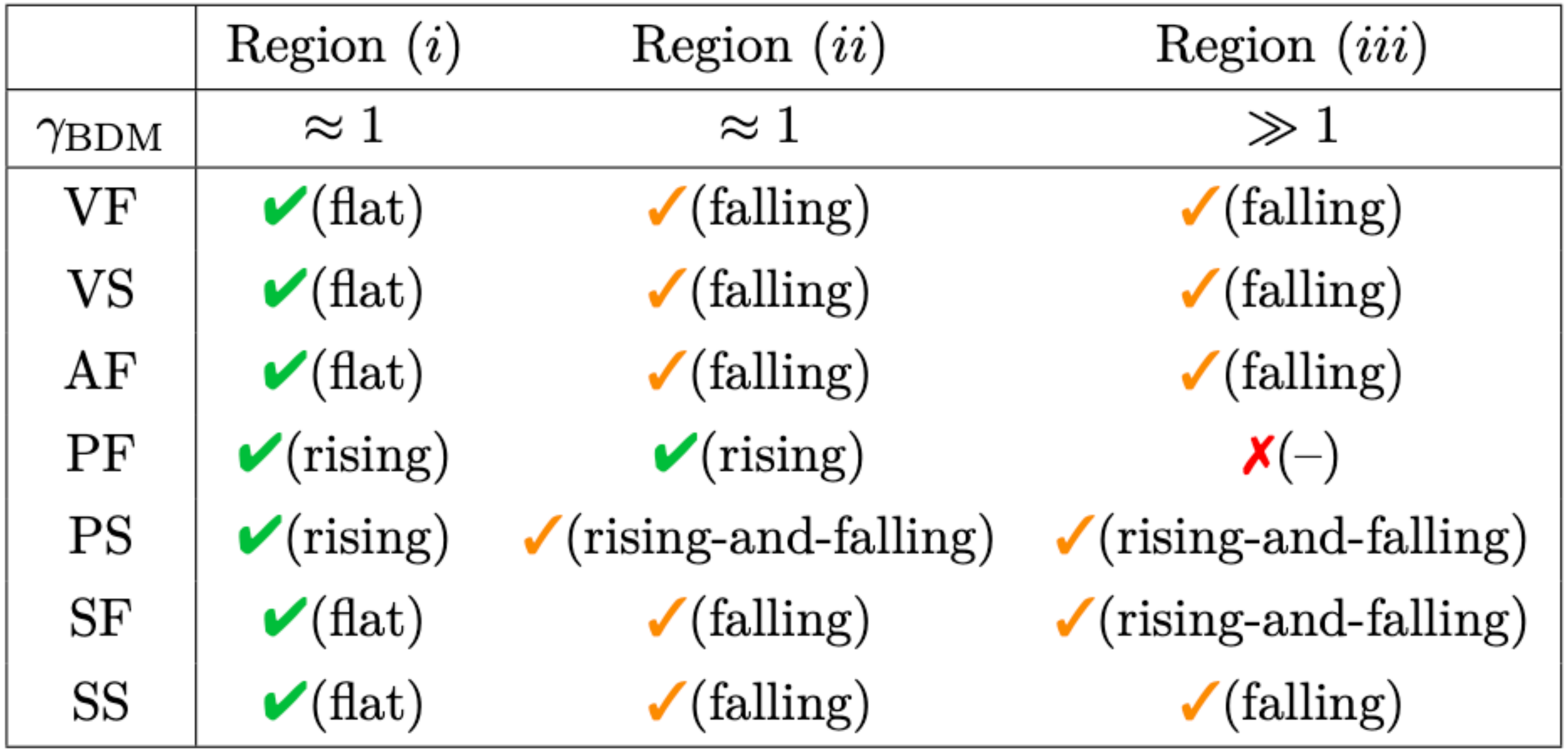


	Region (i)	Region (ii)	Region (iii)
$\gamma_{\rm BDM}$	≈ 1	≈ 1	$\gg 1$
VF	✔(flat)	✓(falling)	✓(falling)
VS	✔(flat)	✓(falling)	✓(falling)
AF	✔(flat)	✓(falling)	✓(falling)
PF	✔(rising)	✔(rising)	✘(–)
PS	✔(rising)	✓(rising-and-falling)	✓(rising-and-falling)
SF	✔(flat)	✓(falling)	✓(rising-and-falling)
SS	✔(flat)	✓(falling)	✓(falling)

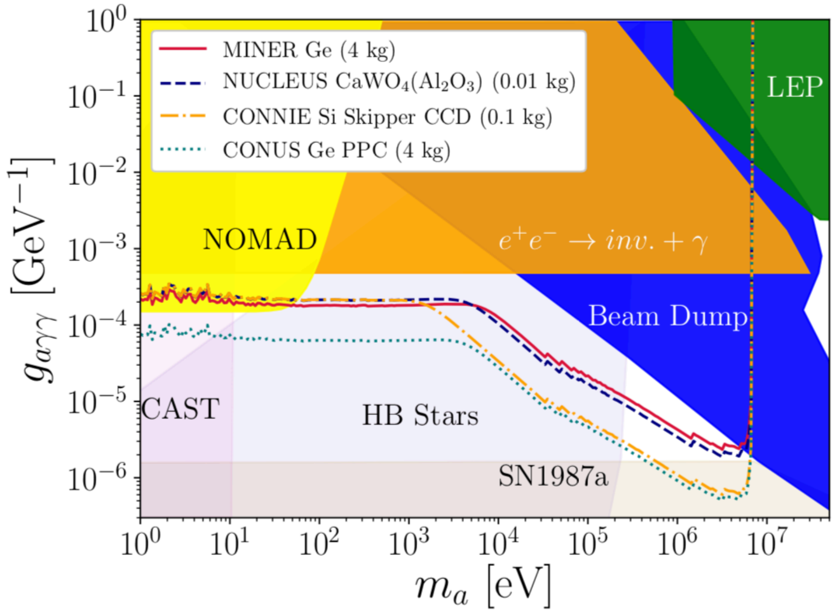
- ✔: One can find mass spectra to reproduce XENON1T excess and satisfy the conditions of the associated regions.

- ✓: A certain range of mediator mass may not reproduce the XENON1T excess.

- ✘: It is generally hard to find a mass spectrum to explain the excess.

Further discussions

- Bounds from accelerators, astrophysical and cosmological observations?



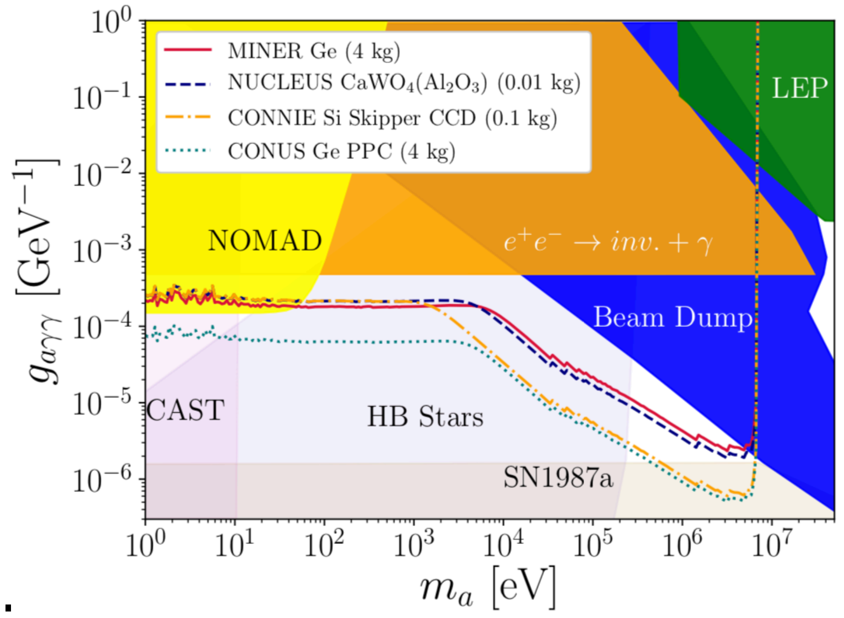
Dent et al., PRL 2020

Further discussions

- Bounds from accelerators, astrophysical and cosmological observations?

- If the coupling constant and the mass parameter have effective dependence upon environmental conditions of astrophysical objects such as temperature and matter density, the limits can be relaxed by several orders of magnitude.

- Some regions can be probed in future accelerators.



Dent et al., PRL 2020

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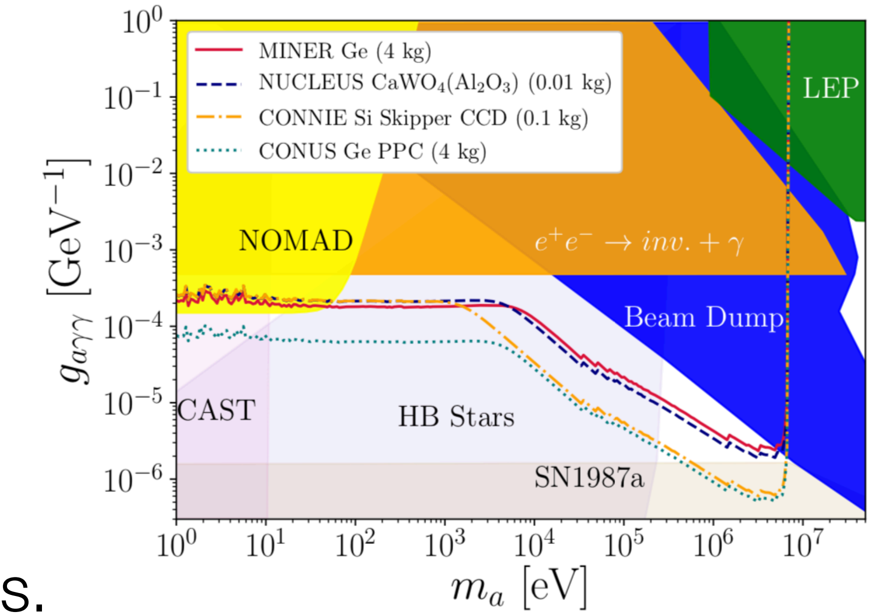

Dent et al., PRL 2020

- Nuclear scattering can occur when E_1 increases over $\mathcal{O}$(10 MeV).

  (reference parameters do not induce nuclear scattering due to kinematics)

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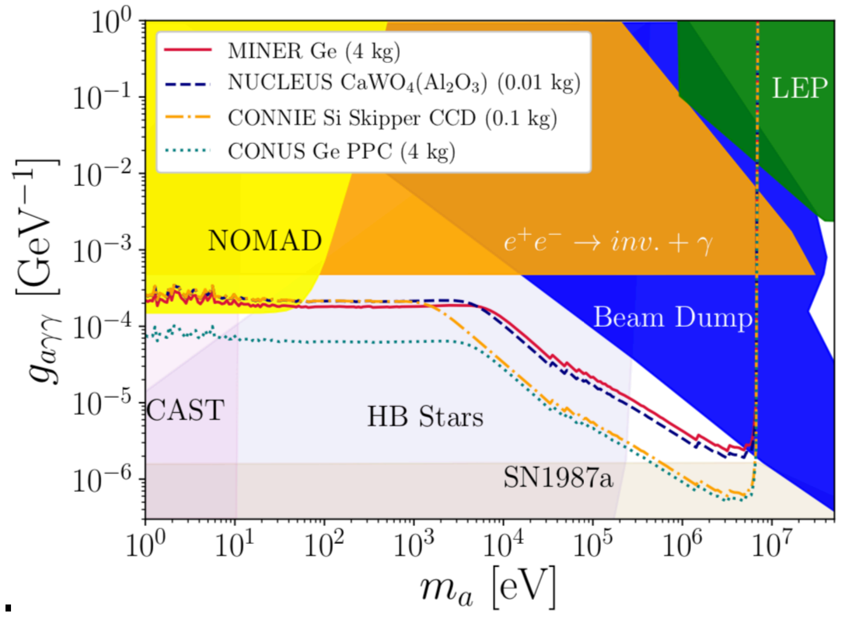

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Dent et al., PRL 2020

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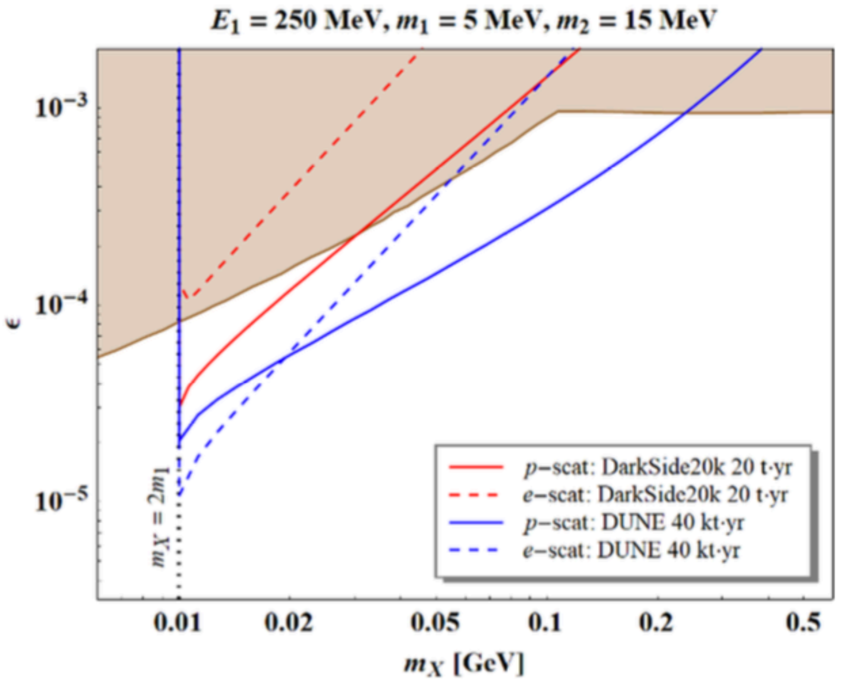


- Complimentary searches are possible.

Kim, Machado, Park, **SS**, JHEP 2007, 057 (2020)

Conclusions

- Light dark matter is being considered as a promising example of dark sector beyond WIMP.

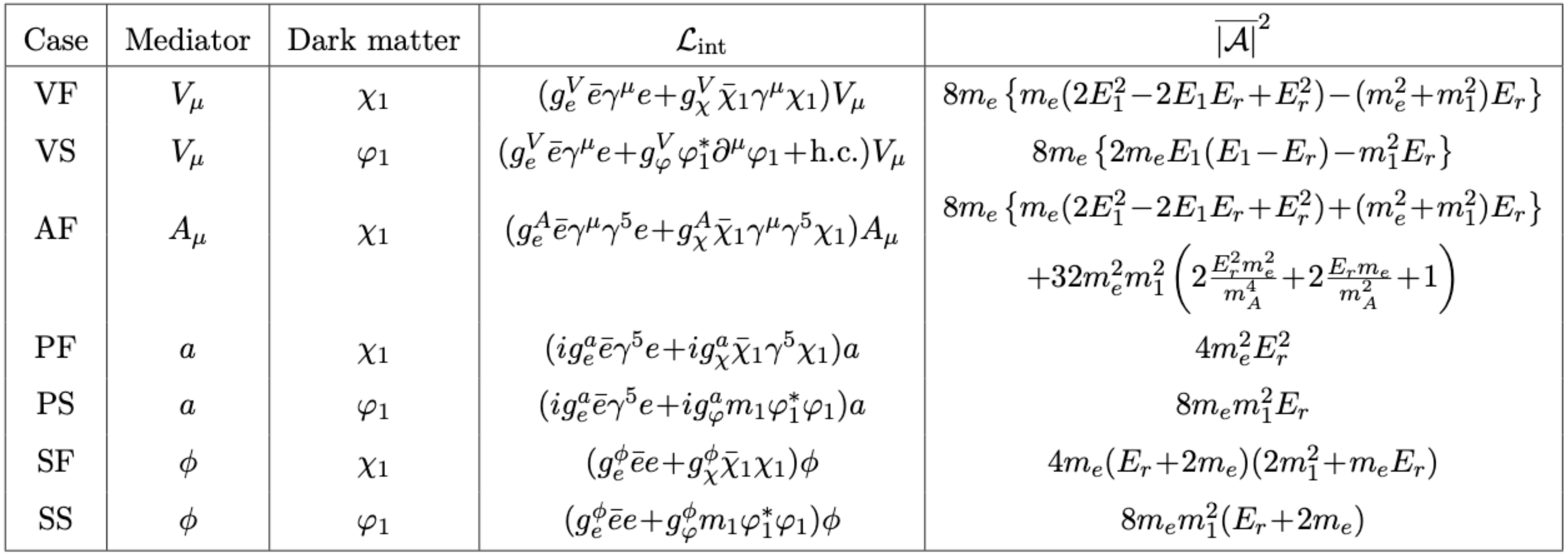
- Due to kinematics, there are tons of experimental program searching for its electron recoil signals: mostly $E_R \sim \mathcal{O}$(eV) for non-relativistic light DM.

- Energetic light dark matter boosted in the universe (not just BDM) can leave high energy (> keV) electron recoil signals in DM direct detection experiments: Byproduct of the existing or planned experiments, e.g., COSINE-100.

- Dedicated analysis for the case with keV scale electron recoil needs more careful considerations of the binding potential of the electrons: XENON1T.

- Future direct detection experiments can give more hints to light DM!

Backup



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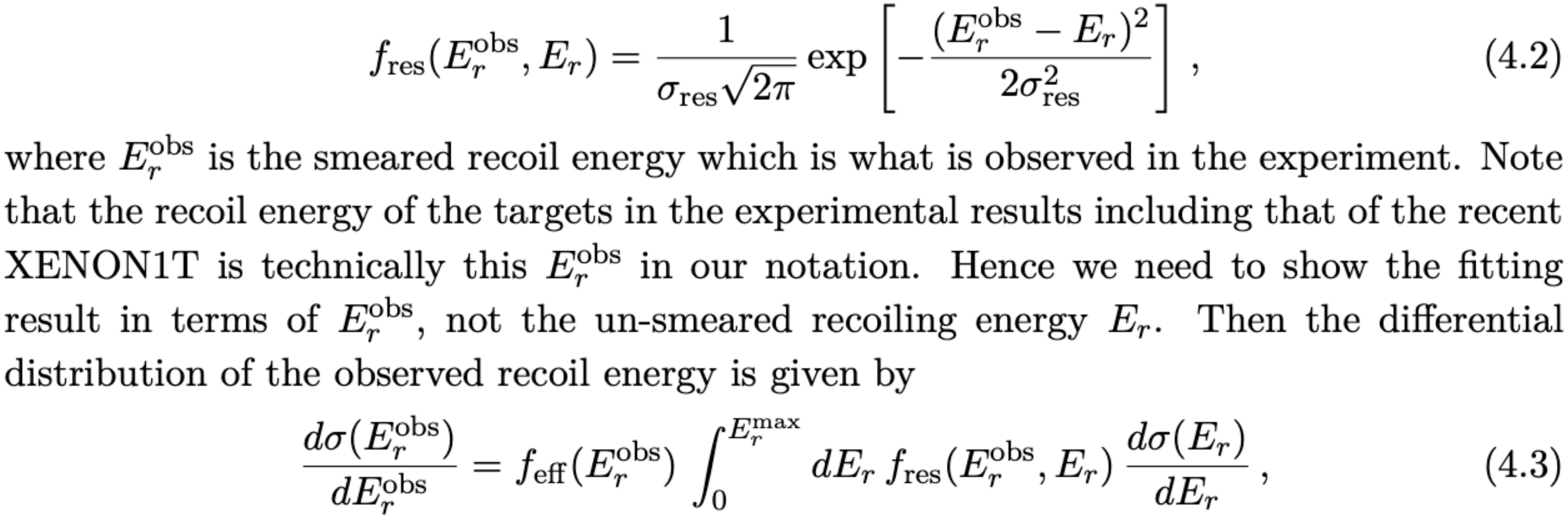
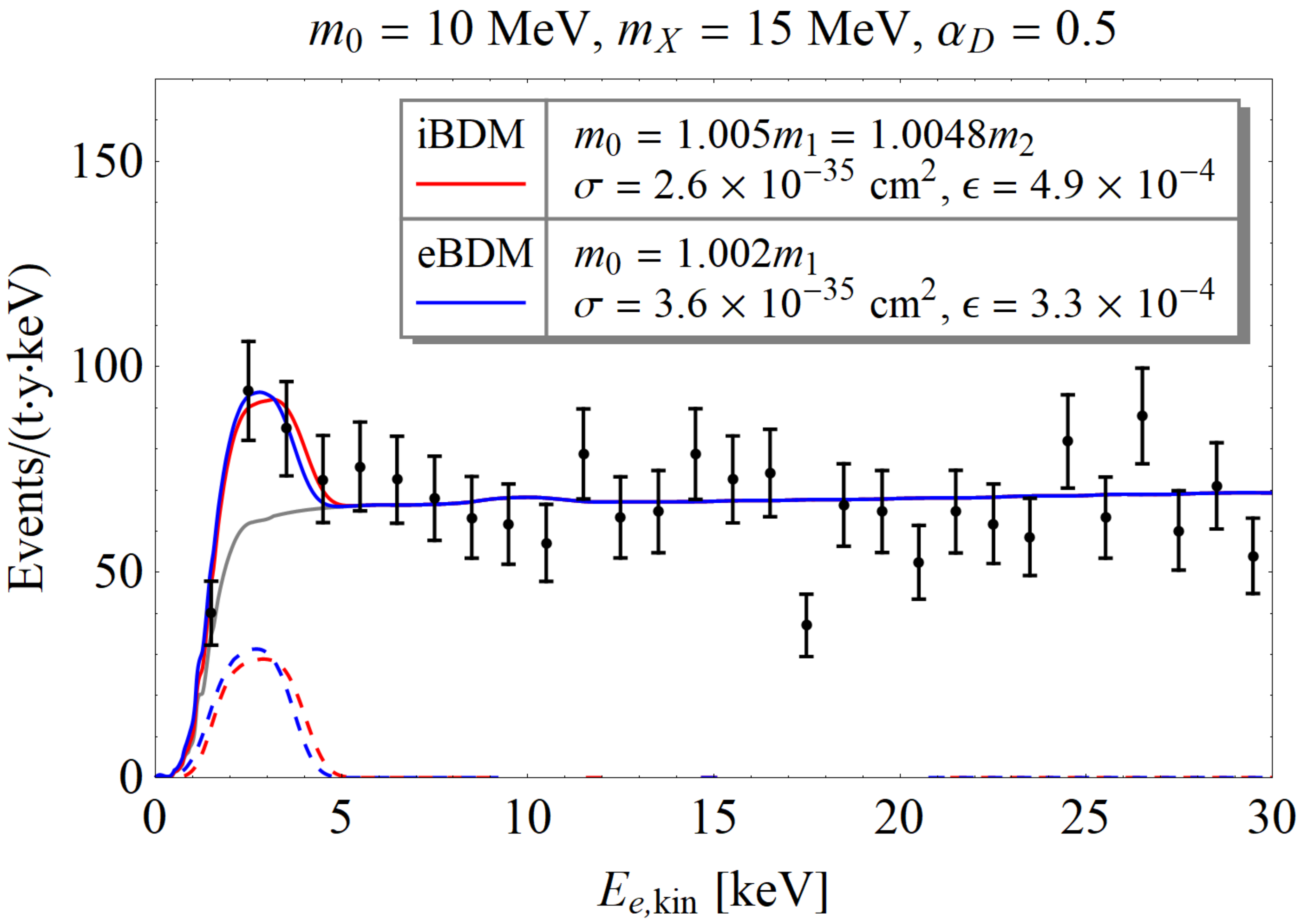


$$f_{\text{res}}(E_r^{\text{obs}}, E_r) = \frac{1}{\sigma_{\text{res}}\sqrt{2\pi}}\exp\left[-\frac{(E_r^{\text{obs}}-E_r)^2}{2\sigma_{\text{res}}^2}\right], \tag{4.2}$$

where E_r^{obs} is the smeared recoil energy which is what is observed in the experiment. Note that the recoil energy of the targets in the experimental results including that of the recent XENON1T is technically this E_r^{obs} in our notation. Hence we need to show the fitting result in terms of E_r^{obs}, not the un-smeared recoiling energy E_r. Then the differential distribution of the observed recoil energy is given by

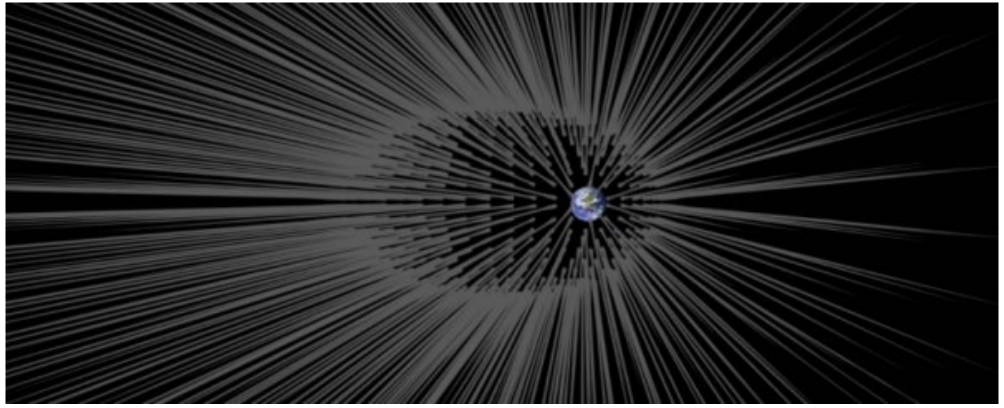
$$\frac{d\sigma(E_r^{\text{obs}})}{dE_r^{\text{obs}}} = f_{\text{eff}}(E_r^{\text{obs}})\int_0^{E_r^{\max}} dE_r\, f_{\text{res}}(E_r^{\text{obs}}, E_r)\,\frac{d\sigma(E_r)}{dE_r}, \tag{4.3}$$

Backup: iBDM fit



Backup: various BDM scenarios

~~WIMP wind ~ O(100 km/s)~~ $\gg$ O(100 km/s)



in promising theories beyond WIMP

- Anti-DM from DM-induced nucleon decay in the Sun

  Huang, Zhao, 1312.0011

- Solar reflection: light DM scattered with hot solar nuclei or electrons

  An, Pospelov, Pradler, Ritz, 1708.03642 Emken, Kouvaris, Nielsen, 1709.06573

- Energetic cosmic-ray induced light DM

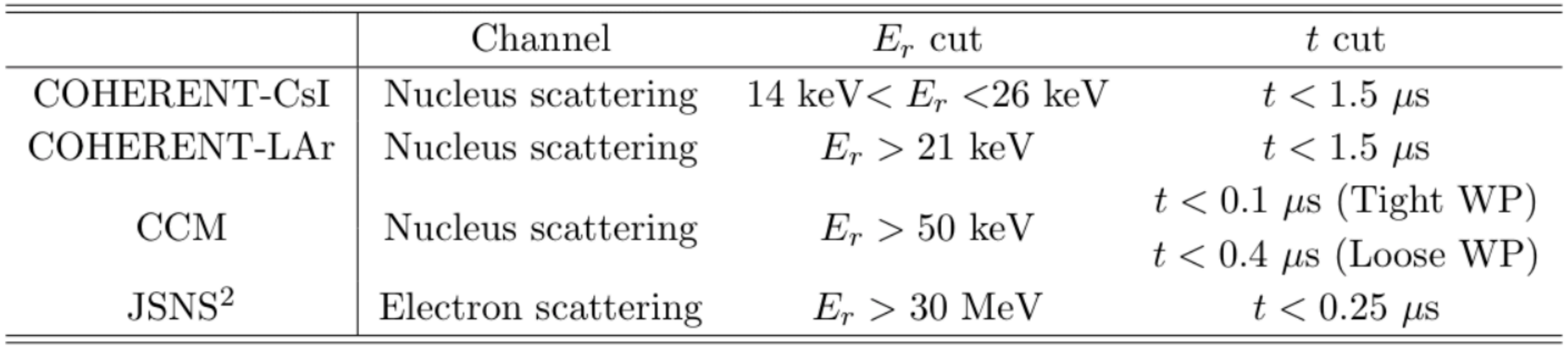
  Bringmann, Pospelov, 1810.10543 Yin, 1809.08610 Ema, Sala, Sato, 1811.00520

  Cappiello, Beacom, 1906.11283 Cappiello, Ng, Beacom, 1810.07705

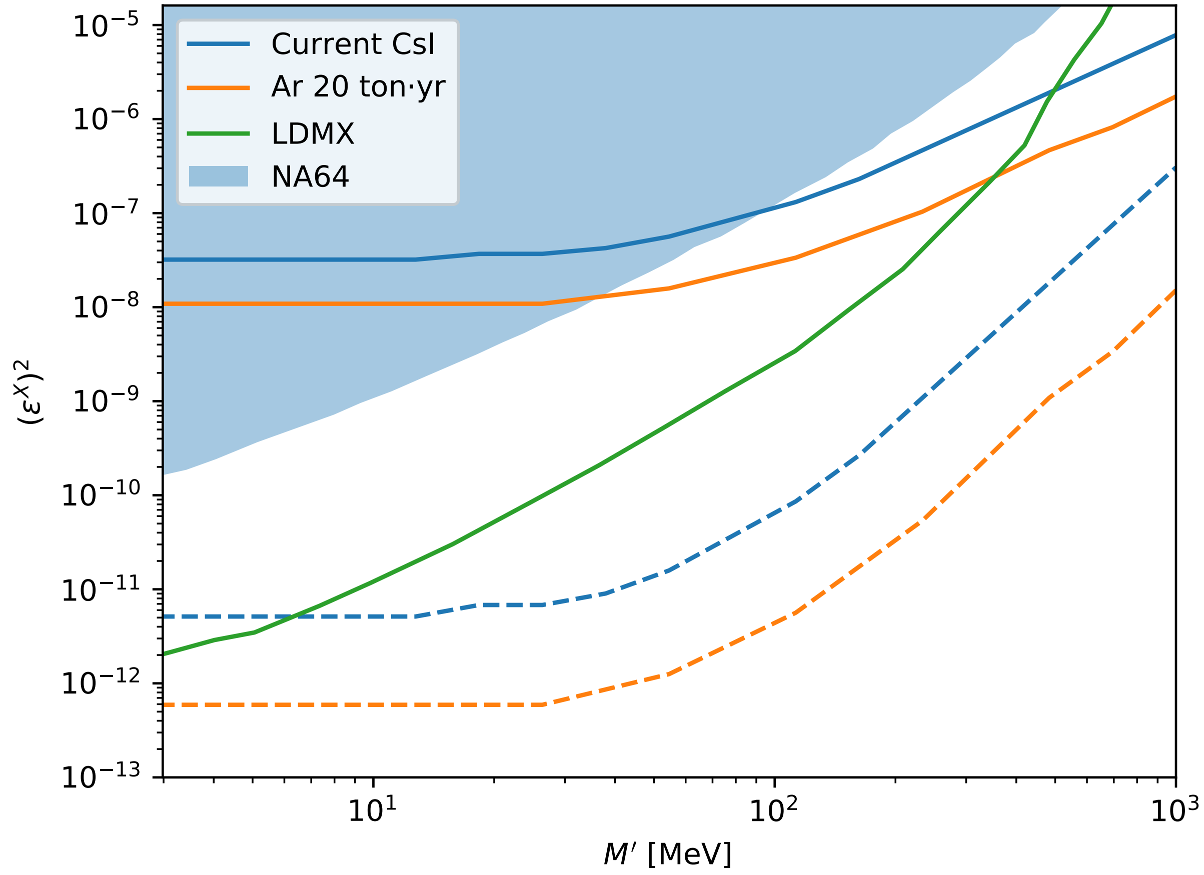
- Boosted Dark Matter: DM boosted by the dark sector structure

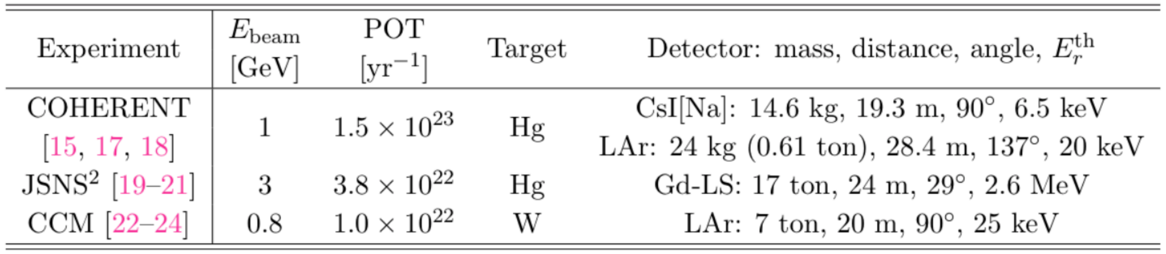
  from 2014 (not from scattering with the energetic SM particles)

Backup: COHERENT



	Channel	E_r cut	t cut
COHERENT-CsI	Nucleus scattering	14 keV< E_r <26 keV	$t < 1.5$ μs
COHERENT-LAr	Nucleus scattering	$E_r > 21$ keV	$t < 1.5$ μs
CCM	Nucleus scattering	$E_r > 50$ keV	$t < 0.1$ μs (Tight WP) $t < 0.4$ μs (Loose WP)
JSNS^2	Electron scattering	$E_r > 30$ MeV	$t < 0.25$ μs

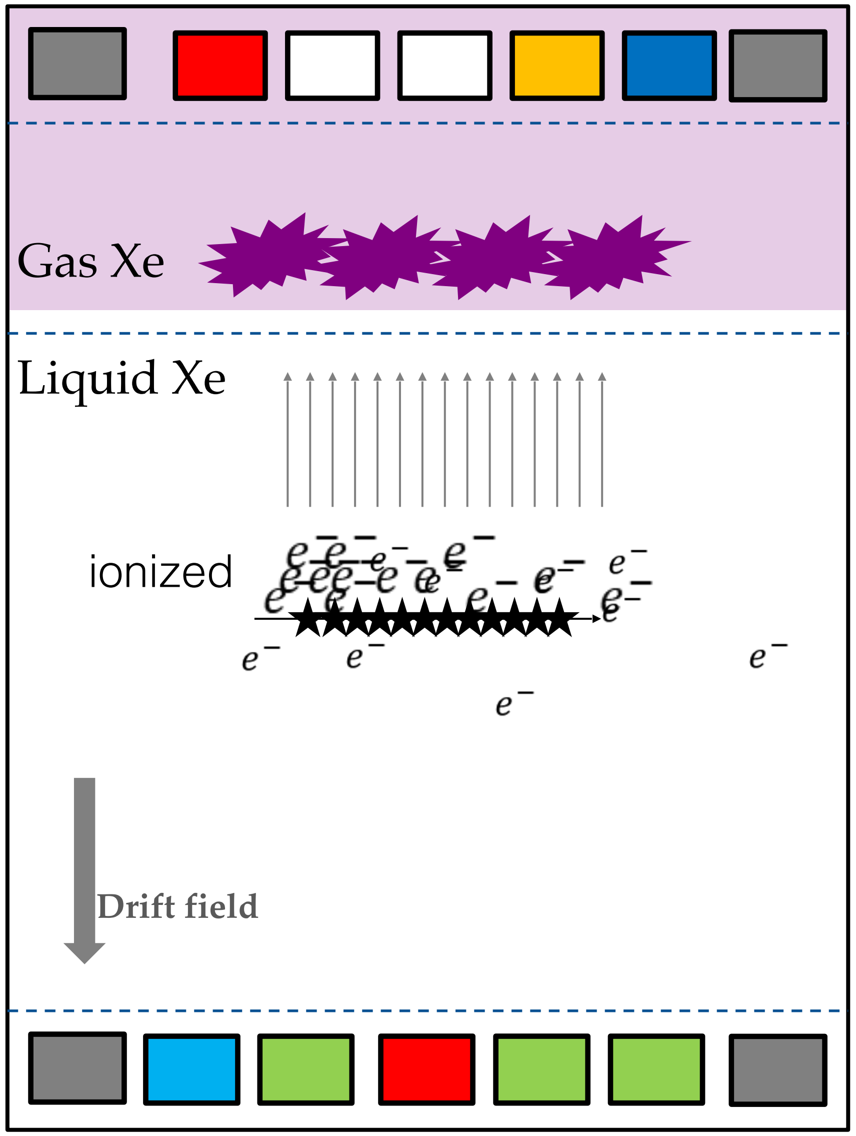




Experiment	$E_{\rm beam}$ [GeV]	POT [yr^{-1}]	Target	Detector: mass, distance, angle, $E_r^{\rm th}$
COHERENT [15, 17, 18]	1	1.5×10^{23}	Hg	CsI[Na]: 14.6 kg, 19.3 m, 90°, 6.5 keV LAr: 24 kg (0.61 ton), 28.4 m, 137°, 20 keV
JSNS^2 [19–21]	3	3.8×10^{22}	Hg	Gd-LS: 17 ton, 24 m, 29°, 2.6 MeV
CCM [22–24]	0.8	1.0×10^{22}	W	LAr: 7 ton, 20 m, 90°, 25 keV

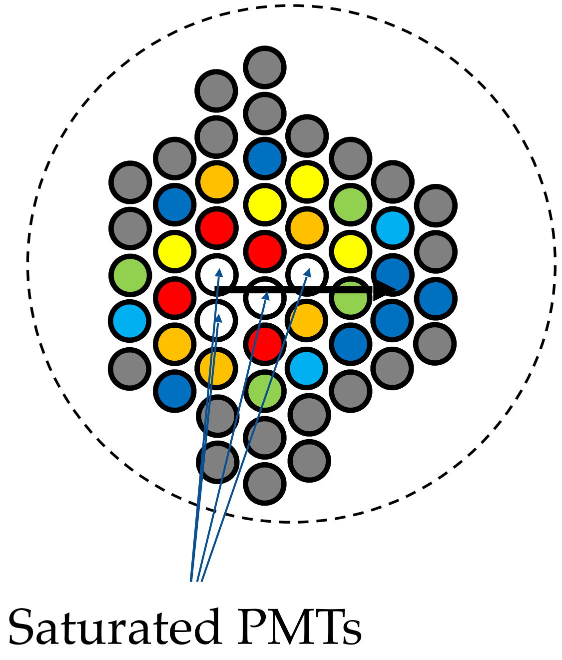
Backup: expected pattern

XENONT1T or LZ



- Simultaneous charging of PMTs (some of them saturated)

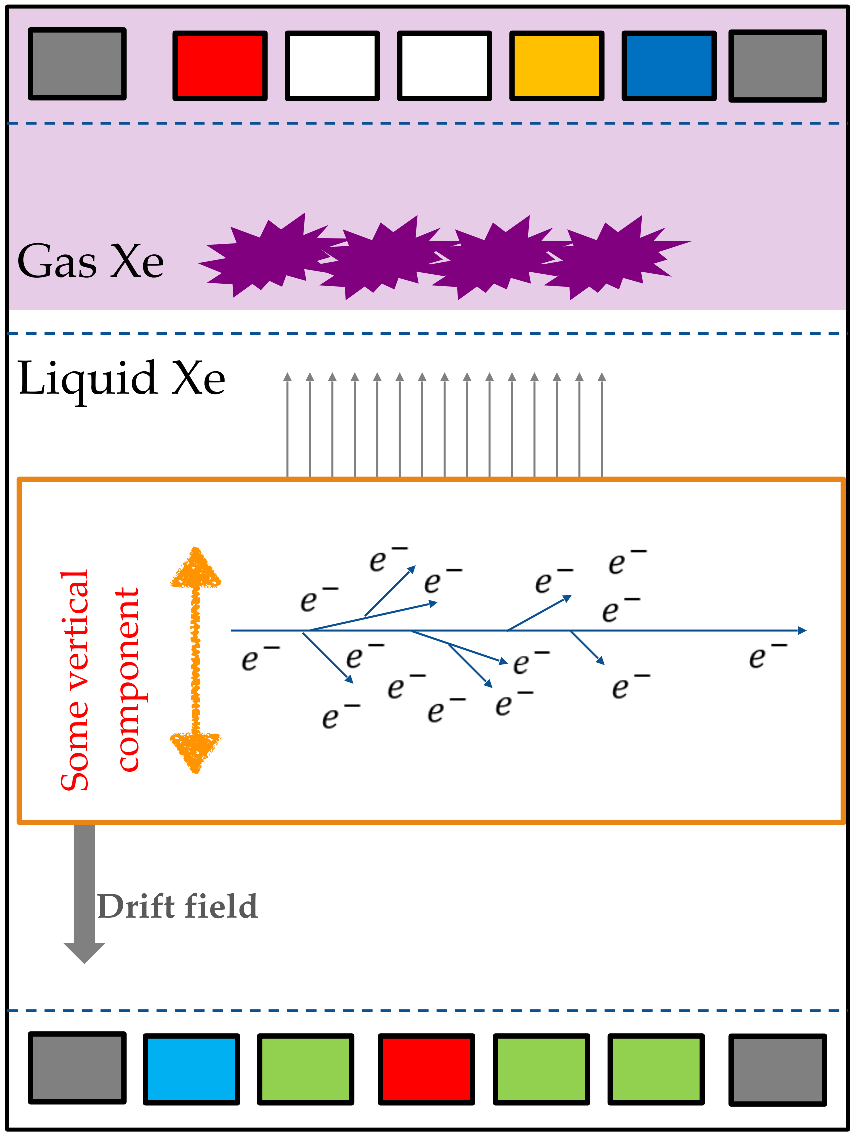
- Identification of a lengthy track



- Track/energy reconstruction from likelihood analysis with unsaturated PMTs

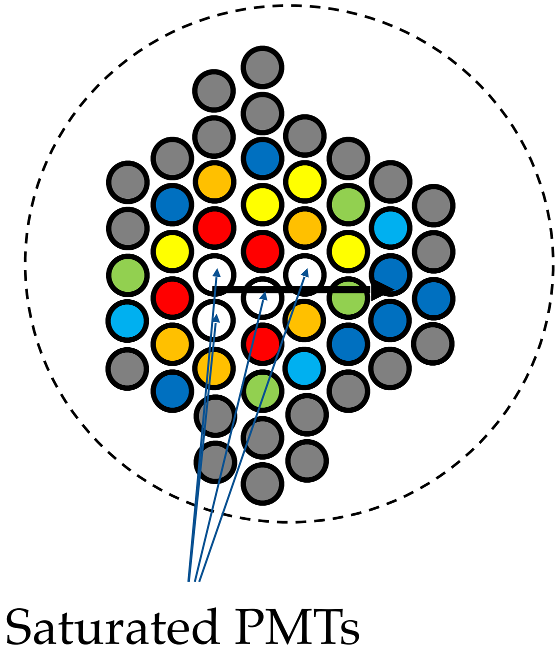
Backup: expected pattern

XENONT1T or LZ



- Simultaneous charging of PMTs (some of them saturated)

- Identification of a lengthy track

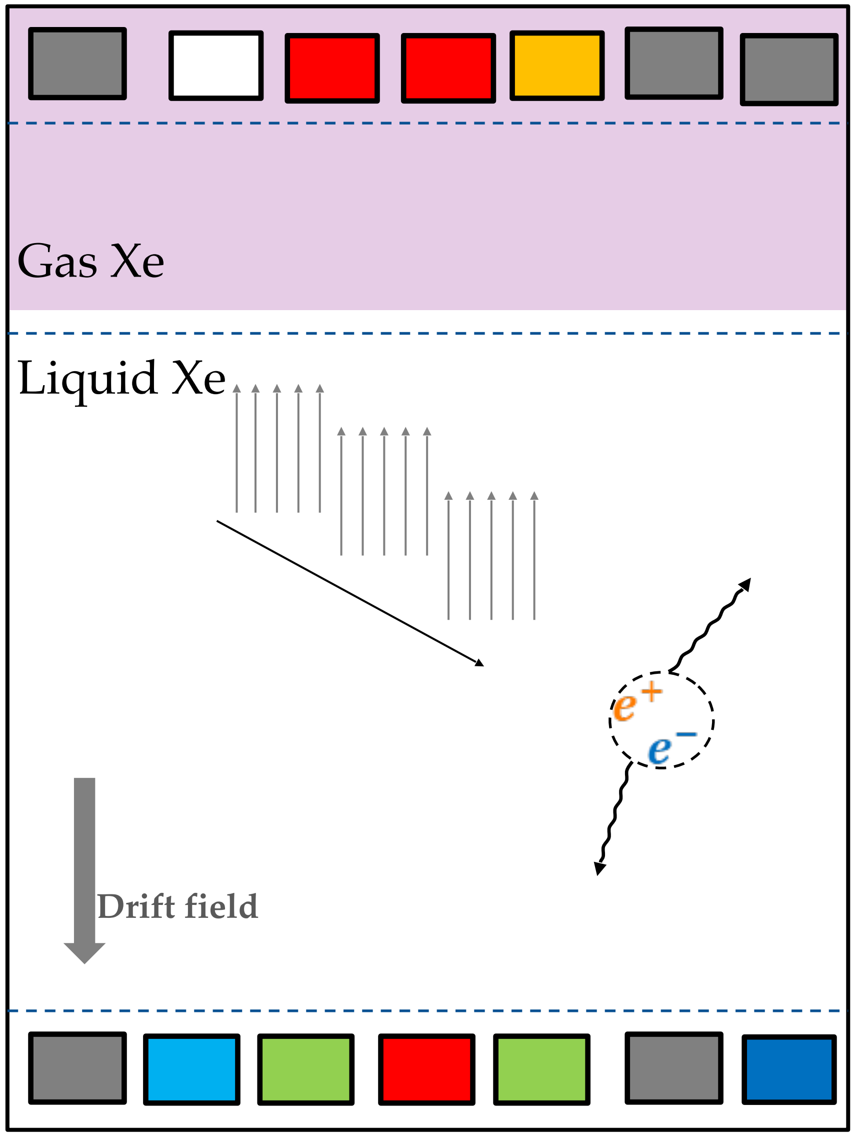


- Track/energy reconstruction from likelihood analysis with unsaturated PMTs

- Additional flickering pattern from secondary collisions?

Backup: expected pattern

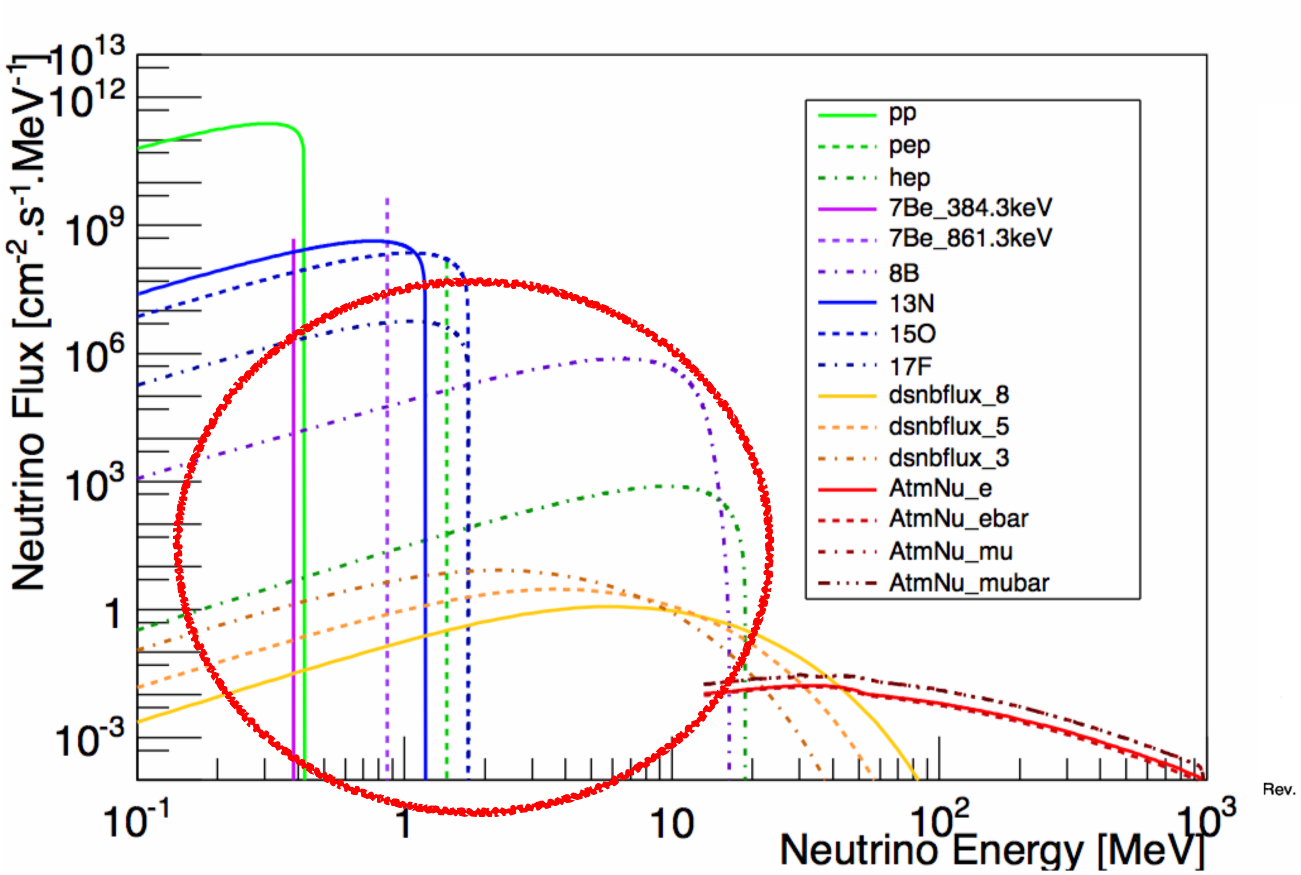
Characteristic feature in Bragg peak



- Two 511keV γ-rays
- Region isolated from primary vertex

Backup: Possible backgrounds?

- Displaced vertex: No → Promising!
- Elastic/prompt decay: solar neutrino? Energy cut!



1307.5458

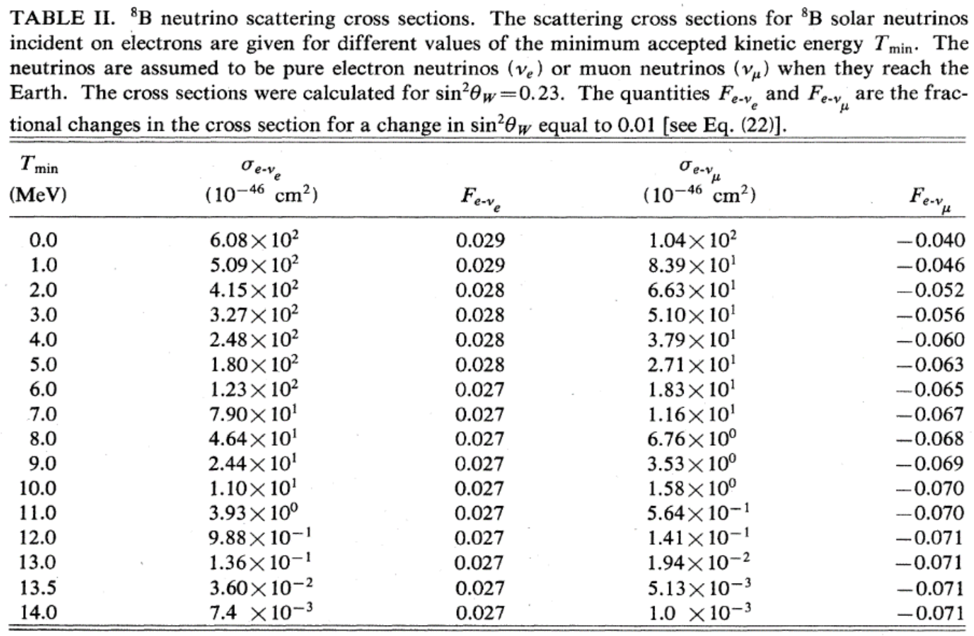


TABLE II. ^{8}B neutrino scattering cross sections. The scattering cross sections for ^{8}B solar neutrinos incident on electrons are given for different values of the minimum accepted kinetic energy $T_{\min}$. The neutrinos are assumed to be pure electron neutrinos (ν_e) or muon neutrinos (ν_μ) when they reach the Earth. The cross sections were calculated for $\sin^2\theta_W = 0.23$. The quantities $F_{e\text{-}\nu_e}$ and $F_{e\text{-}\nu_\mu}$ are the fractional changes in the cross section for a change in $\sin^2\theta_W$ equal to 0.01 [see Eq. (22)].

$T_{\min}$ (MeV)	$\sigma_{e\text{-}\nu_e}$ (10^{-46} cm^2)	$F_{e\text{-}\nu_e}$	$\sigma_{e\text{-}\nu_\mu}$ (10^{-46} cm^2)	$F_{e\text{-}\nu_\mu}$
0.0	6.08×10^{2}	0.029	1.04×10^{2}	-0.040
1.0	5.09×10^{2}	0.029	8.39×10^{1}	-0.046
2.0	4.15×10^{2}	0.028	6.63×10^{1}	-0.052
3.0	3.27×10^{2}	0.028	5.10×10^{1}	-0.056
4.0	2.48×10^{2}	0.028	3.79×10^{1}	-0.060
5.0	1.80×10^{2}	0.028	2.71×10^{1}	-0.063
6.0	1.23×10^{2}	0.027	1.83×10^{1}	-0.065
7.0	7.90×10^{1}	0.027	1.16×10^{1}	-0.067
8.0	4.64×10^{1}	0.027	6.76×10^{0}	-0.068
9.0	2.44×10^{1}	0.027	3.53×10^{0}	-0.069
10.0	1.10×10^{1}	0.027	1.58×10^{0}	-0.070
11.0	3.93×10^{0}	0.027	5.64×10^{-1}	-0.070
12.0	9.88×10^{-1}	0.027	1.41×10^{-1}	-0.071
13.0	1.36×10^{-1}	0.027	1.94×10^{-2}	-0.071
13.5	3.60×10^{-2}	0.027	5.13×10^{-3}	-0.071
14.0	$7.4\ \times10^{-3}$	0.027	$1.0\ \times10^{-3}$	-0.071

Rev. Mod. Phys., Vol. 59, No. 2, April 1987

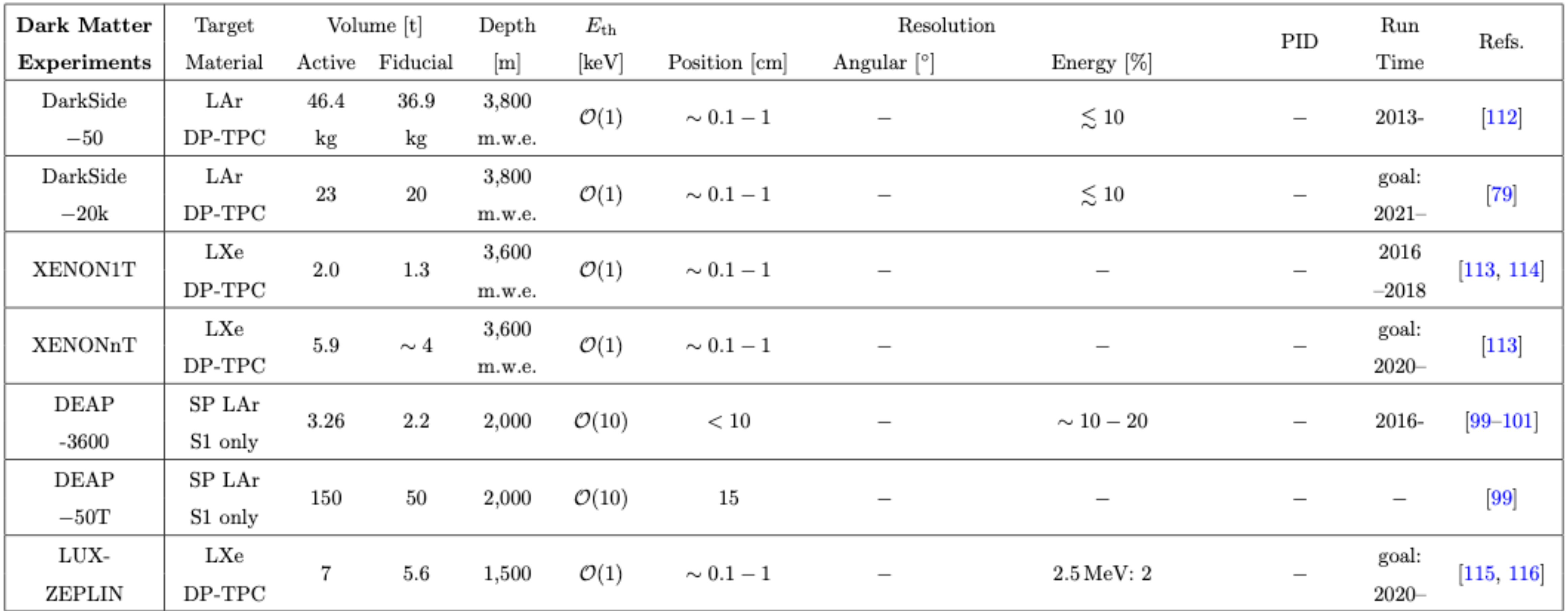
0.1 events at LZ-5y with E_e > 10 MeV cut

Backup: Detector comparison

Xenon1T	Borexino (solar ν)	COSINE-100, CUORE (array-type)
Ton size	100 ton size	Sub-ton size
Good angular/ position resolutions	Bad angular/position resolutions	Better in identifying displaced vertices
Less background (prompt/elastic)	More background (prompt/elastic)	No background (small size)
Lower energy range	Higher energy range 0.2MeV	Lower energy range
Smaller m_1 and E_1 Displaced vertex Post-discovery analysis	Larger m_1 and E_1	“Long” displaced vertex

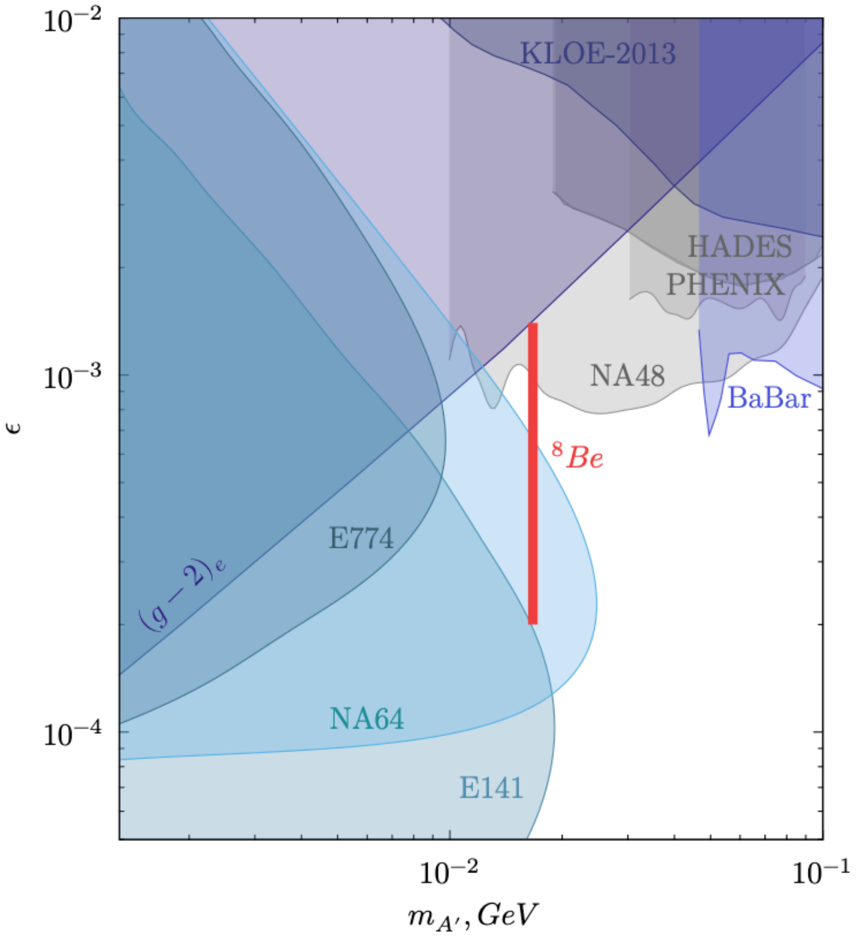
Backup: DM experiments

Kim, Machado, Park, **SS**, JHEP 2007, 057 (2020)

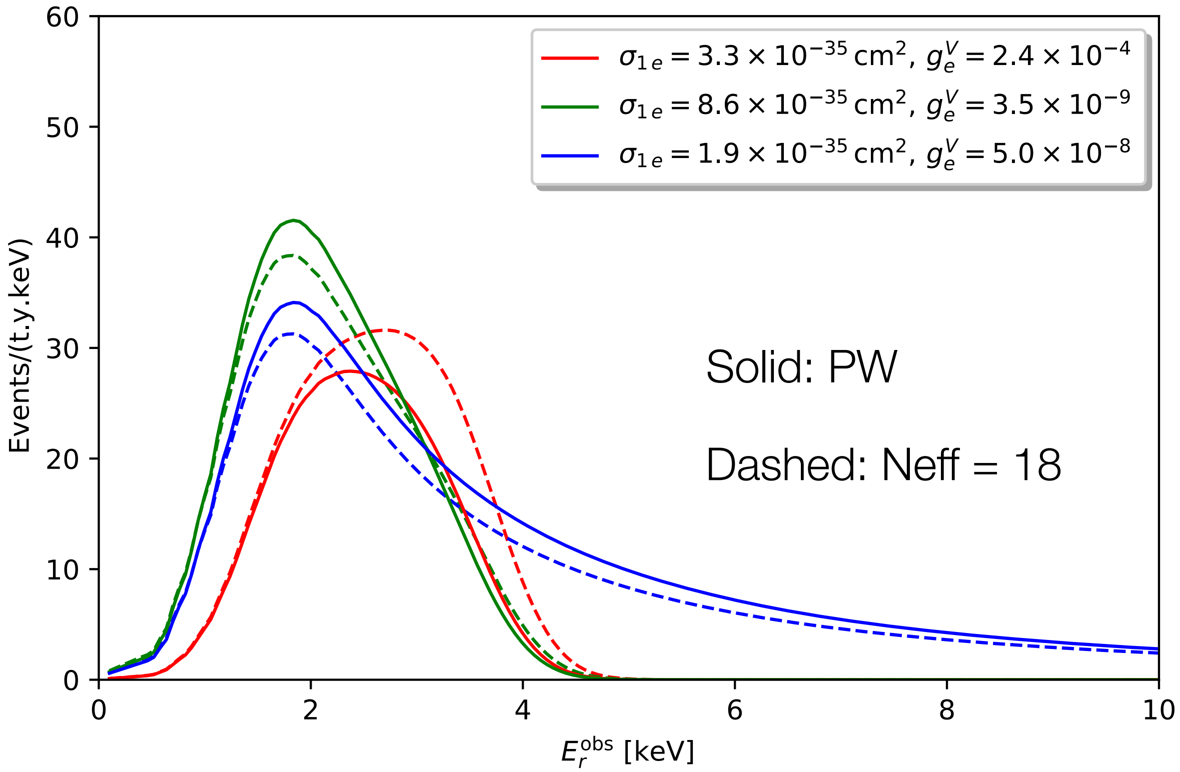


Dark Matter	Target	Volume [t]		Depth	E_{th}		Resolution		PID	Run	Refs.
Experiments	Material	Active	Fiducial	[m]	[keV]	Position [cm]	Angular [°]	Energy [%]		Time	
DarkSide –50	LAr DP-TPC	46.4 kg	36.9 kg	3,800 m.w.e.	$\mathcal{O}(1)$	$\sim 0.1 - 1$	–	$\lesssim 10$	–	2013-	[112]
DarkSide –20k	LAr DP-TPC	23	20	3,800 m.w.e.	$\mathcal{O}(1)$	$\sim 0.1 - 1$	–	$\lesssim 10$	–	goal: 2021–	[79]
XENON1T	LXe DP-TPC	2.0	1.3	3,600 m.w.e.	$\mathcal{O}(1)$	$\sim 0.1 - 1$	–	–	–	2016 –2018	[113, 114]
XENONnT	LXe DP-TPC	5.9	~ 4	3,600 m.w.e.	$\mathcal{O}(1)$	$\sim 0.1 - 1$	–	–	–	goal: 2020–	[113]
DEAP -3600	SP LAr S1 only	3.26	2.2	2,000	$\mathcal{O}(10)$	< 10	–	$\sim 10 - 20$	–	2016-	[99–101]
DEAP –50T	SP LAr S1 only	150	50	2,000	$\mathcal{O}(10)$	15	–	–	–	–	[99]
LUX-ZEPLIN	LXe DP-TPC	7	5.6	1,500	$\mathcal{O}(1)$	$\sim 0.1 - 1$	–	2.5 MeV: 2	–	goal: 2020–	[115, 116]

Backup: constraints & comparisons



NA64, arXiv:1912.11389



Solid: PW

Dashed: Neff = 18