APCTP-TRP workshop

New era of dark matter research and direct detection experiments

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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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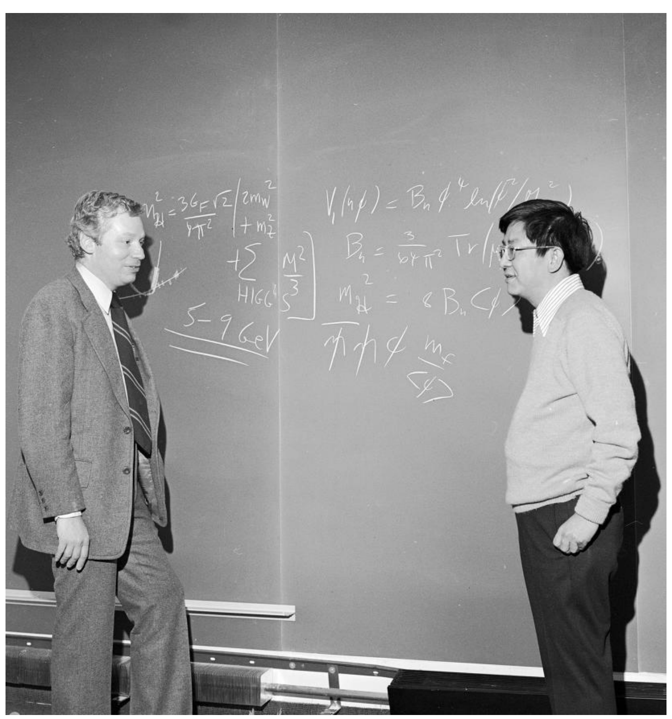
Preferred candidate so far was

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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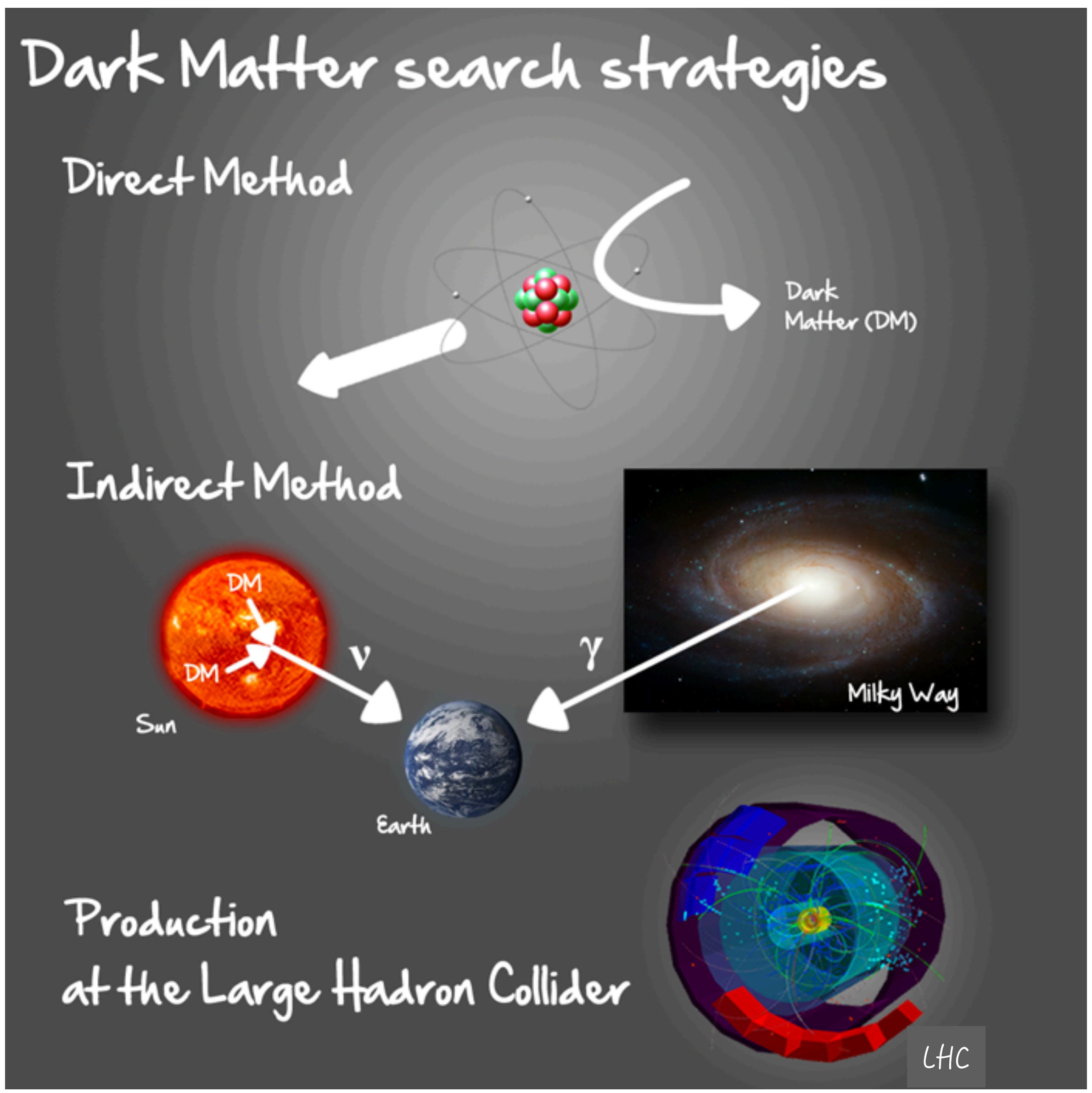

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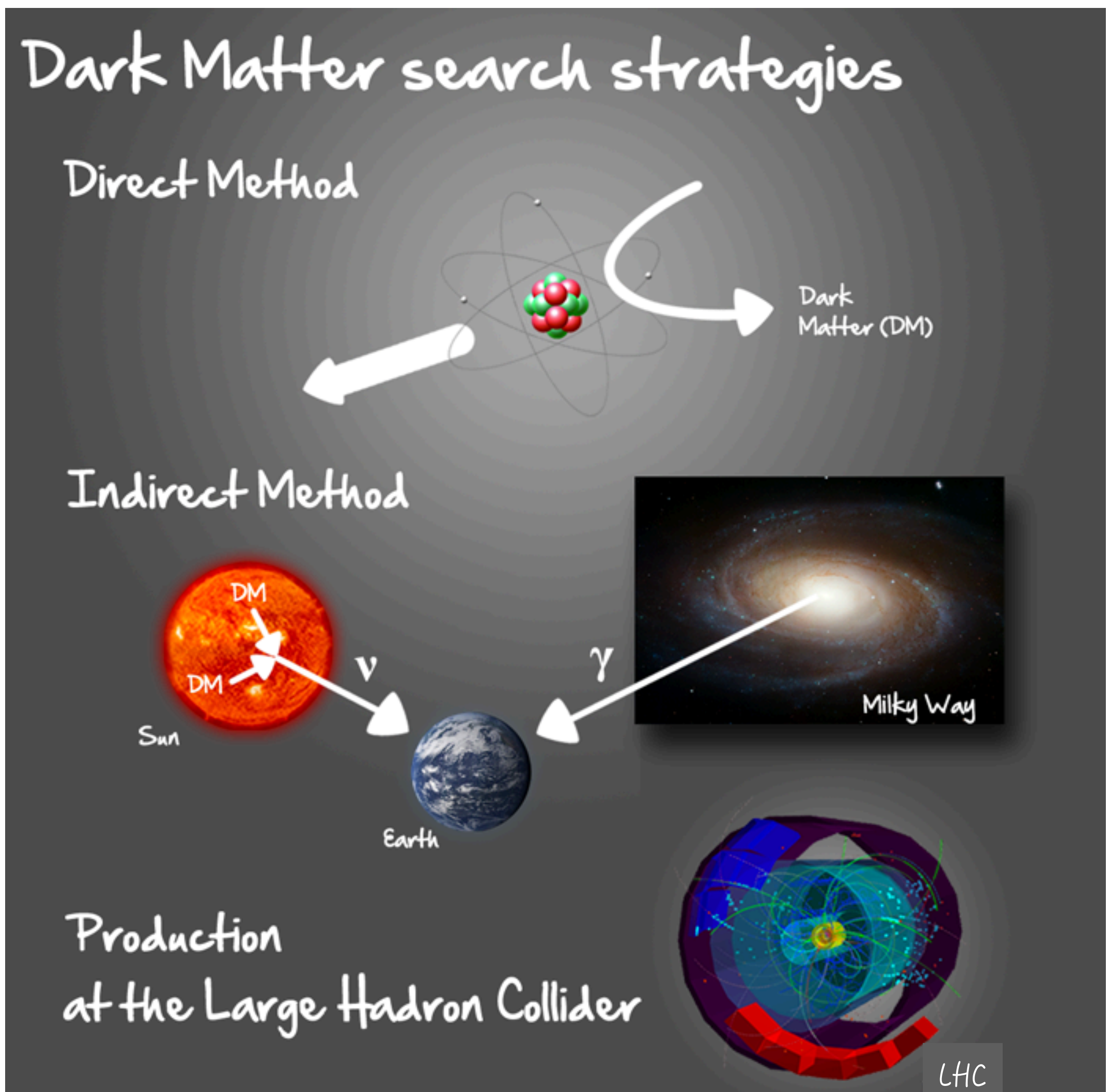
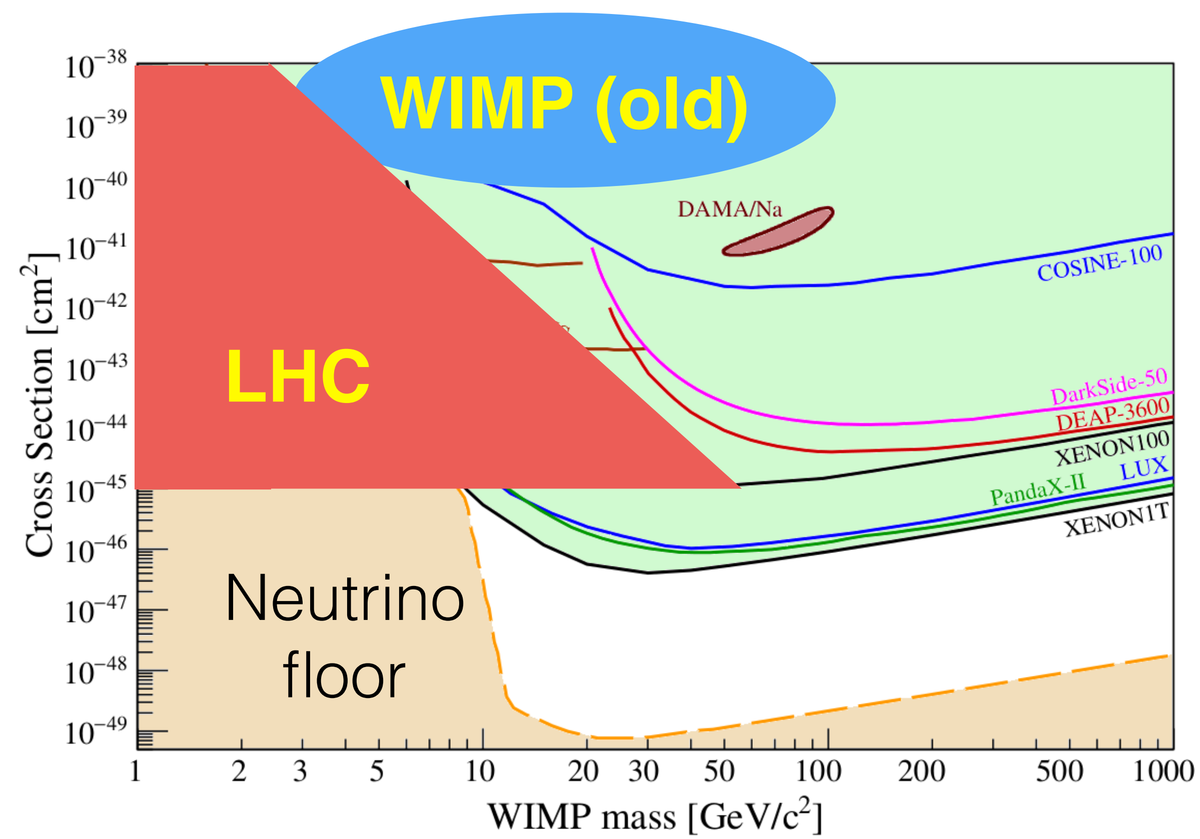
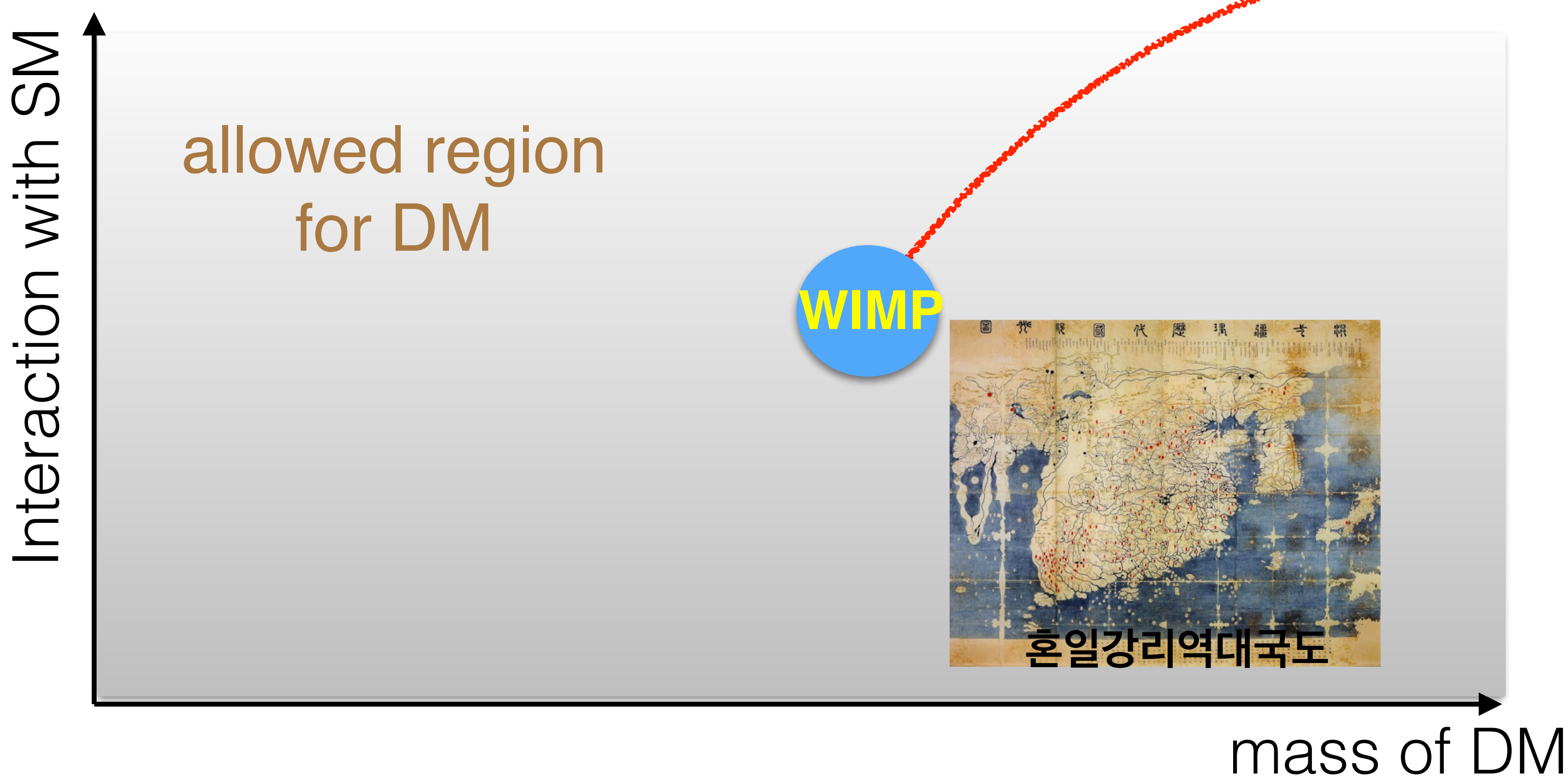


WIMP strongly constrained!

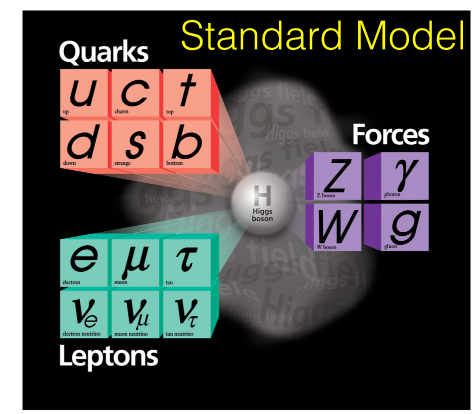


Dark World beyond WIMP

WIMP may be a theoretical bias.



- Small region
- Oversimplification compared to



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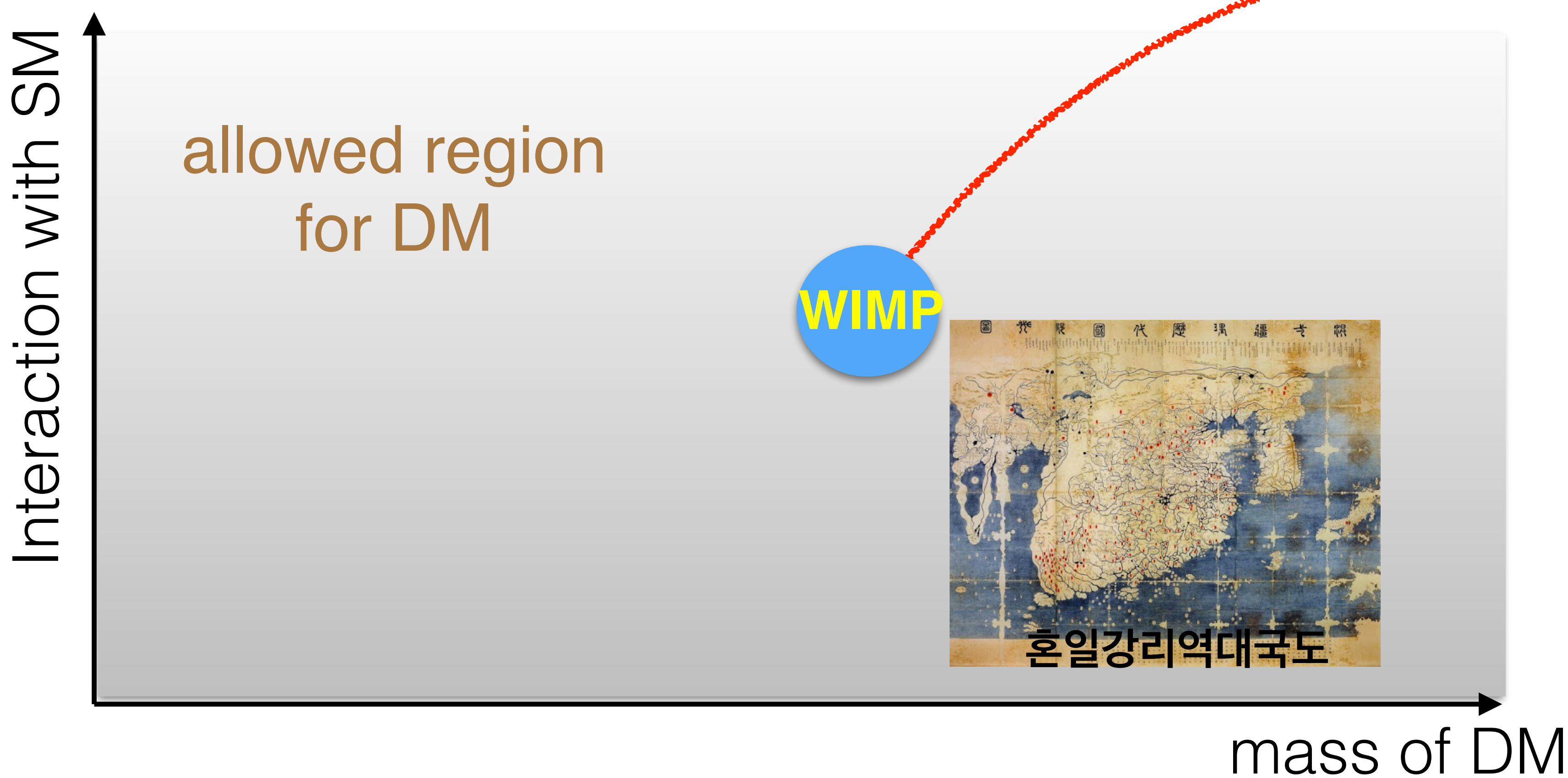

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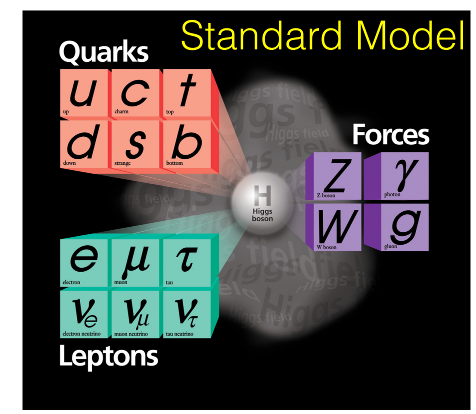

- Models with fast moving light DM are being focused recently.
  (including the light DM reflected by some energetic objects or emitted)

- Boosted Dark Matter (BDM) where the light DM is produced at the present universe by the <u>unique dark sector structure</u> is in the frontline.

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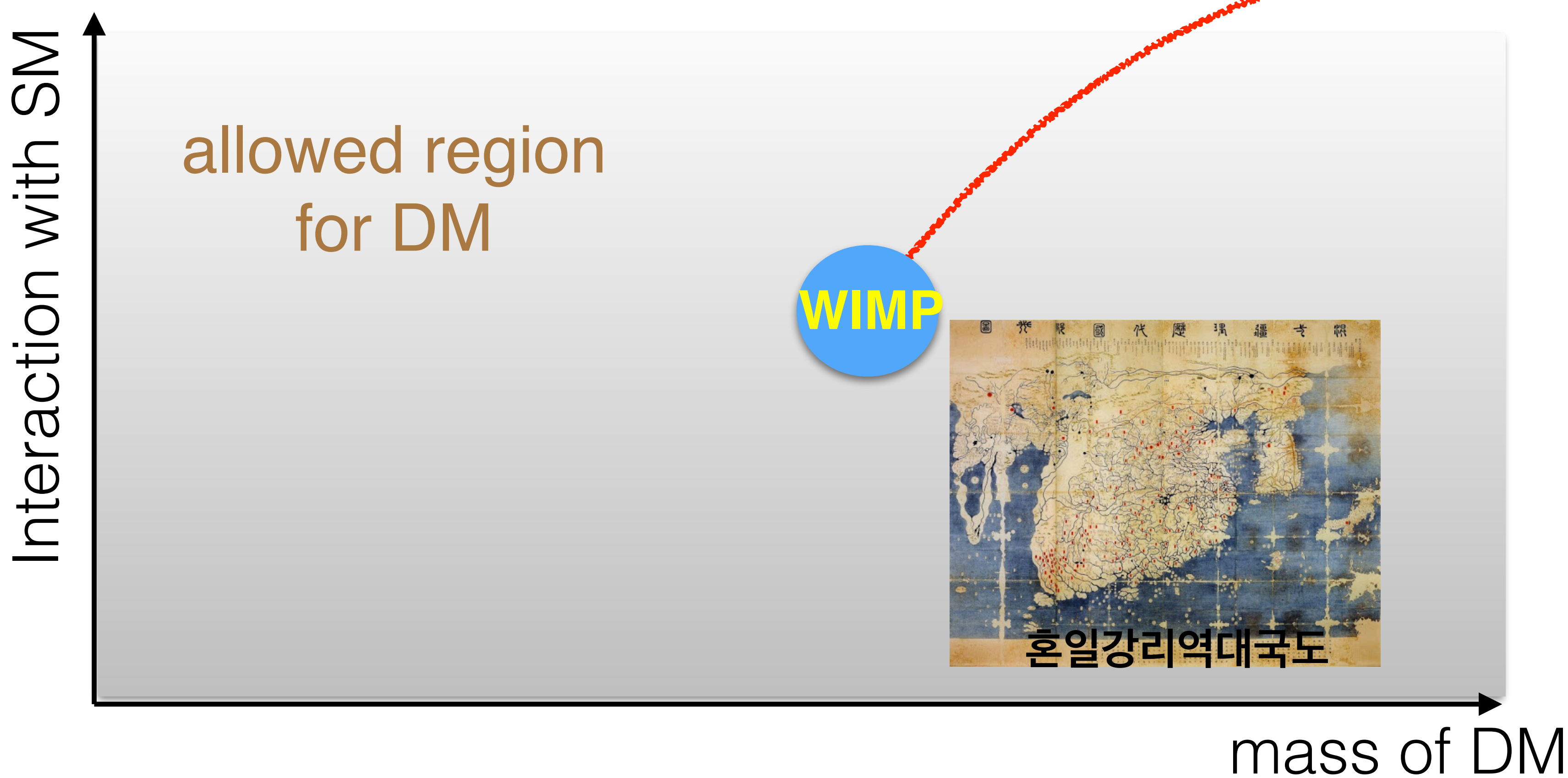

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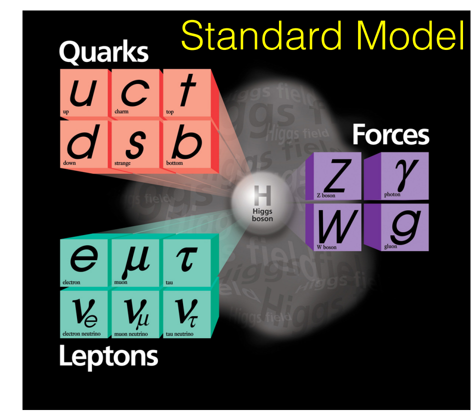

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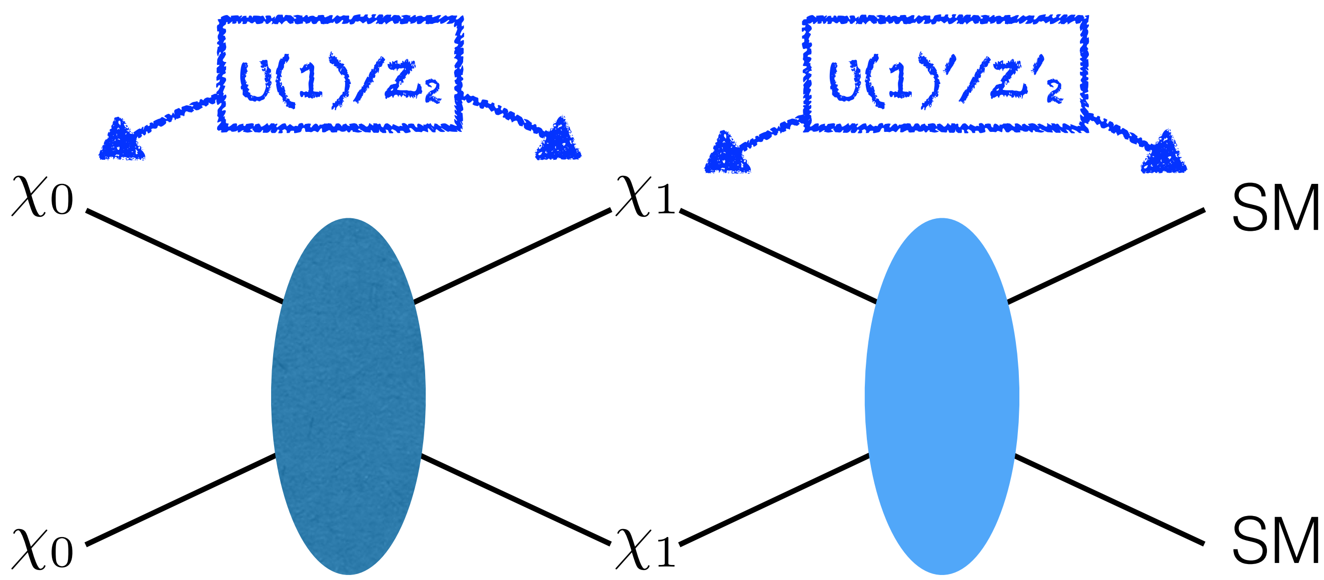
Multi-component Boosted DM (BDM)

χ_0: heavy, χ_1: light



Agashe, Cui, Necib, Thaler,1405.7370

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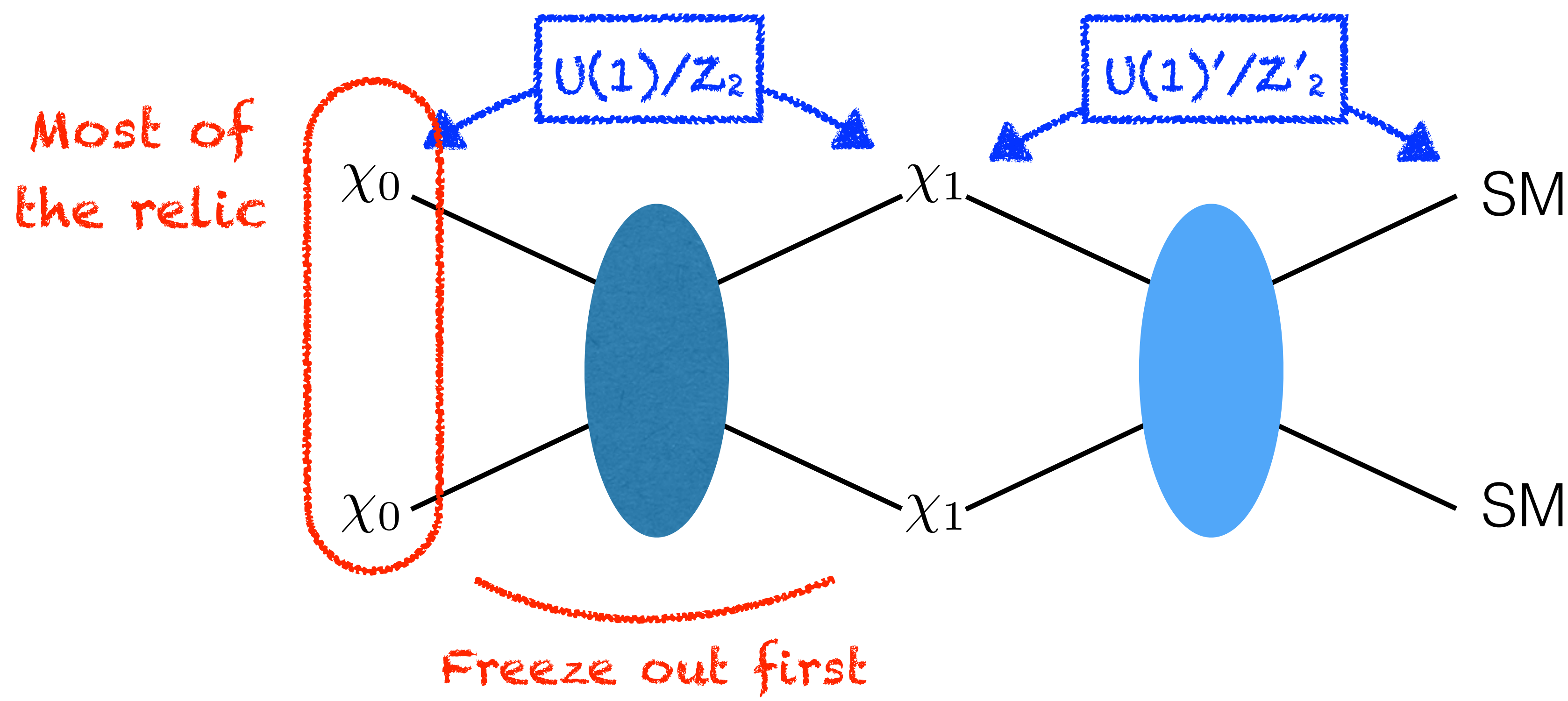

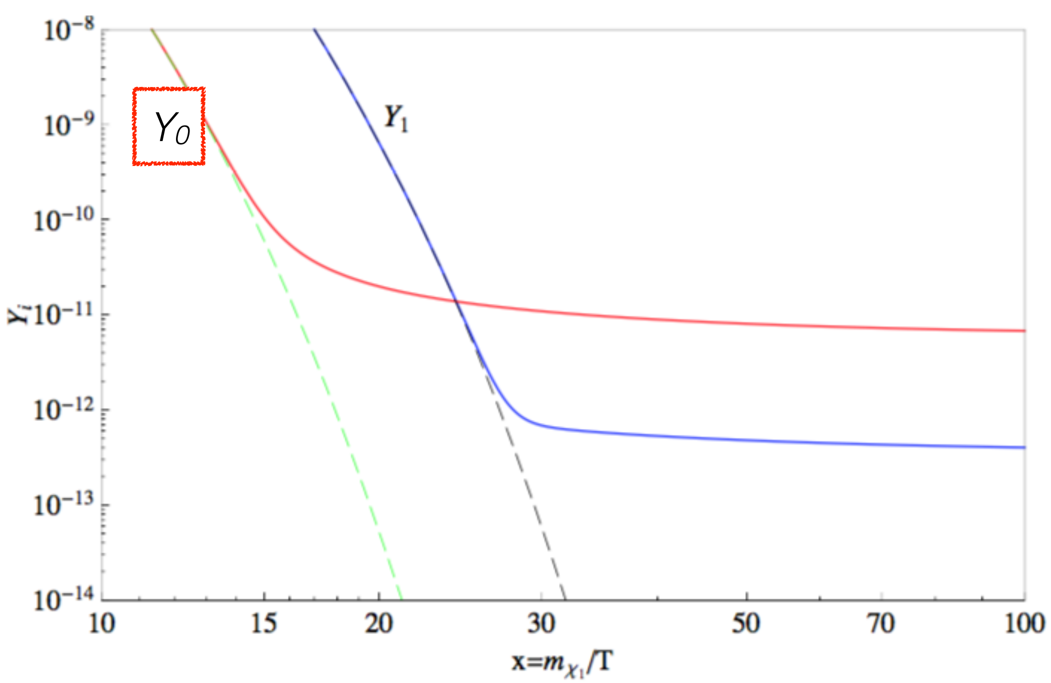

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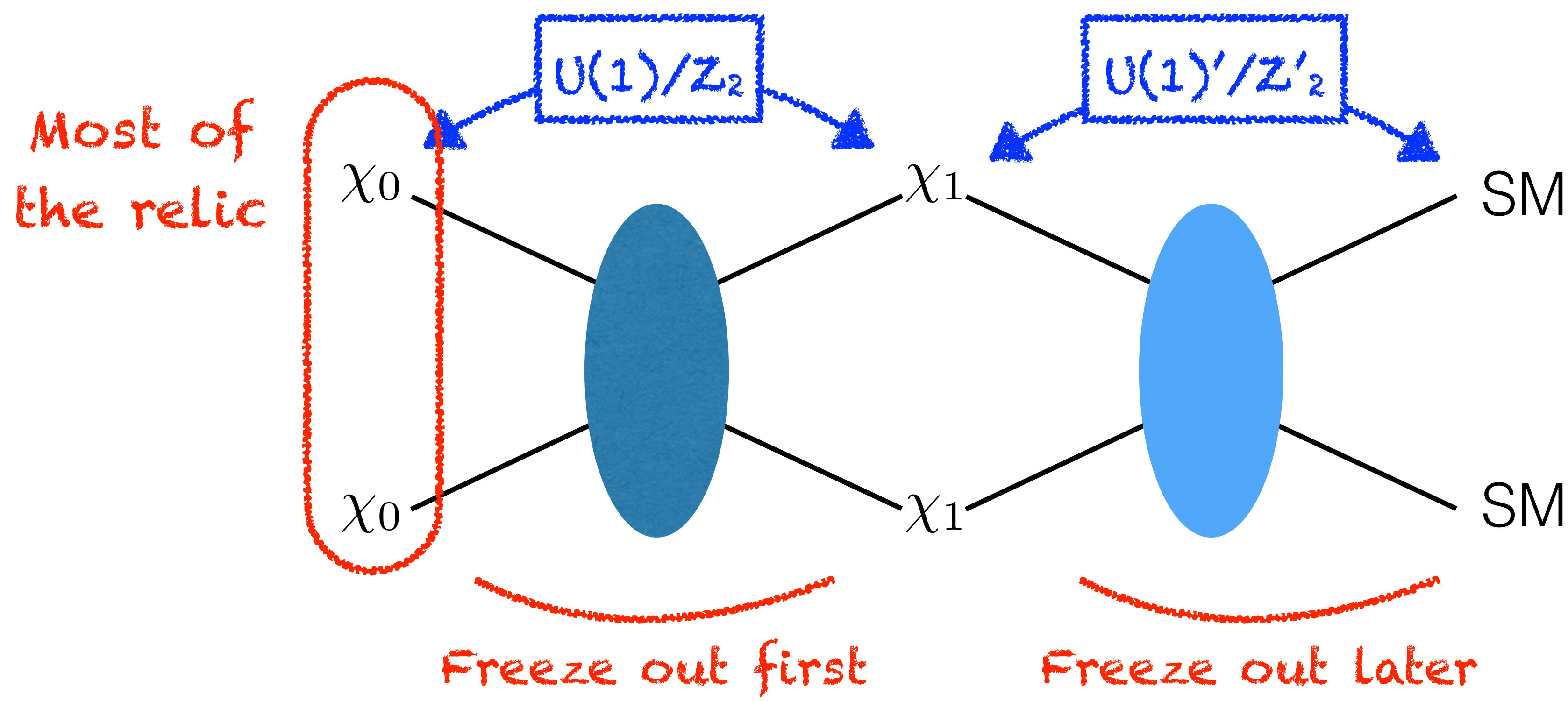
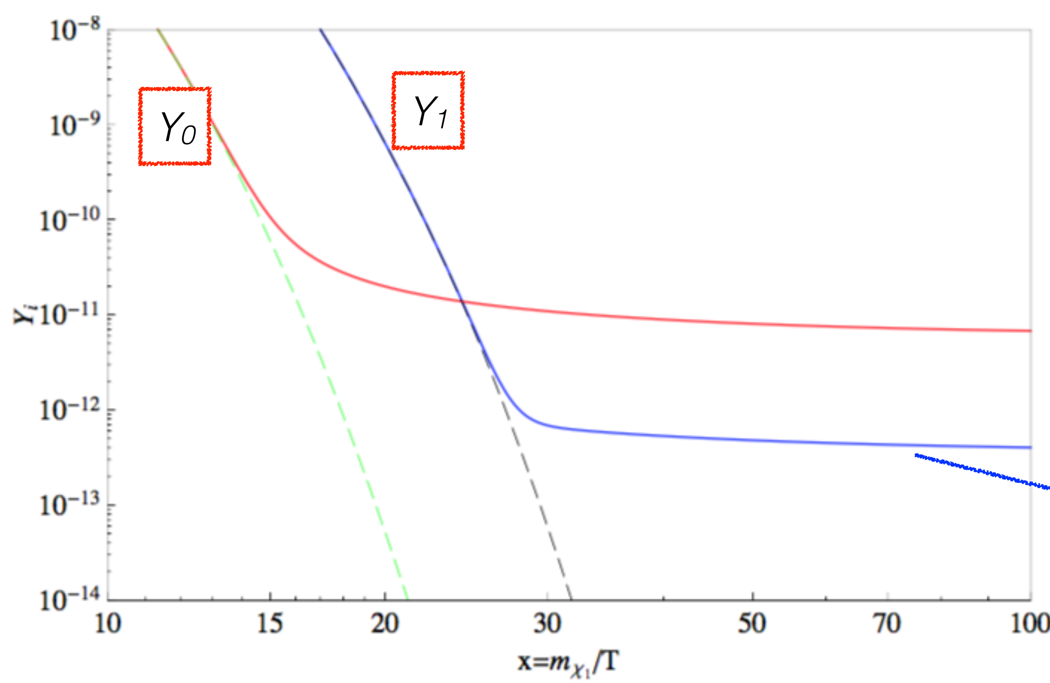




Agashe, Cui, Necib, Thaler,1405.7370

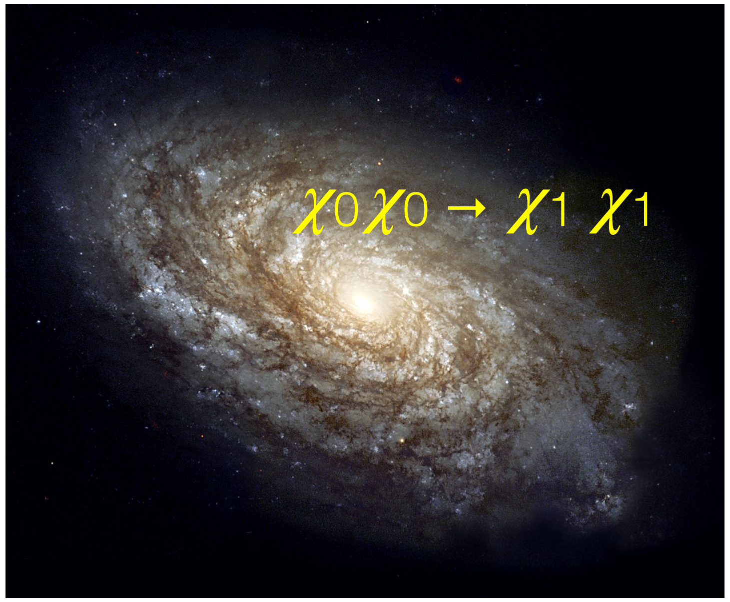
Belanger, Park, 1112.4491

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)

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

  ※ relic χ_1 is non-relativistic

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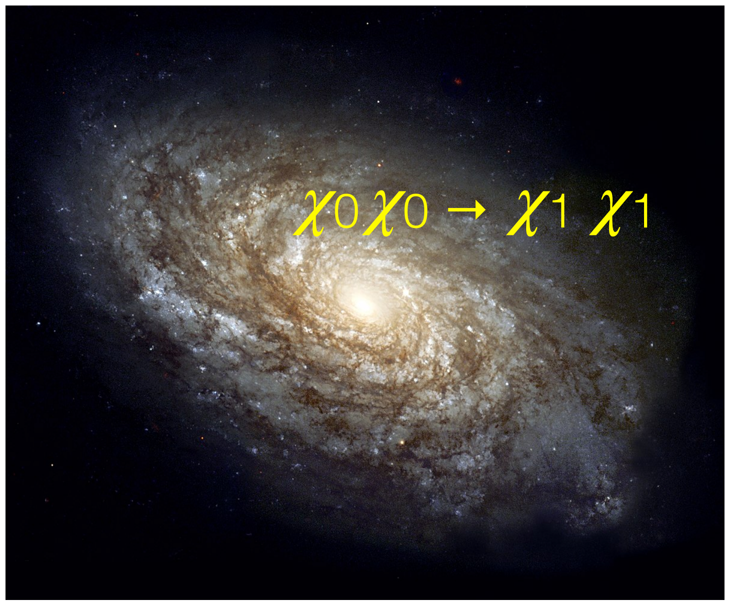

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(indirect detection of χ_0)

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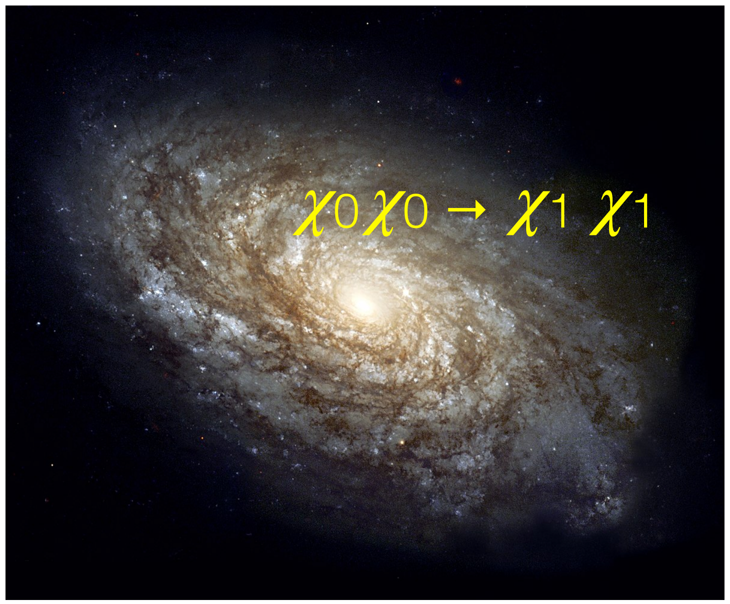

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$$\text{Flux of } \chi_1 \simeq 1.6 \times 10^{-8}\,\mathrm{cm}^{-2}\mathrm{s}^{-1} \times \left(\frac{\langle \sigma v \rangle_{0\to 1}}{5 \times 10^{-26}\,\mathrm{cm}^3\mathrm{s}^{-1}}\right) \times \left(\frac{100\,\mathrm{GeV}}{m_0}\right)^2$$

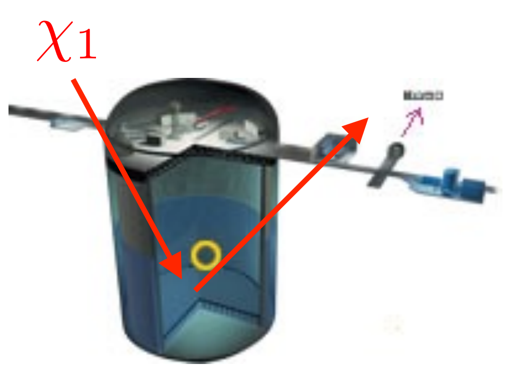
Assume: NFW

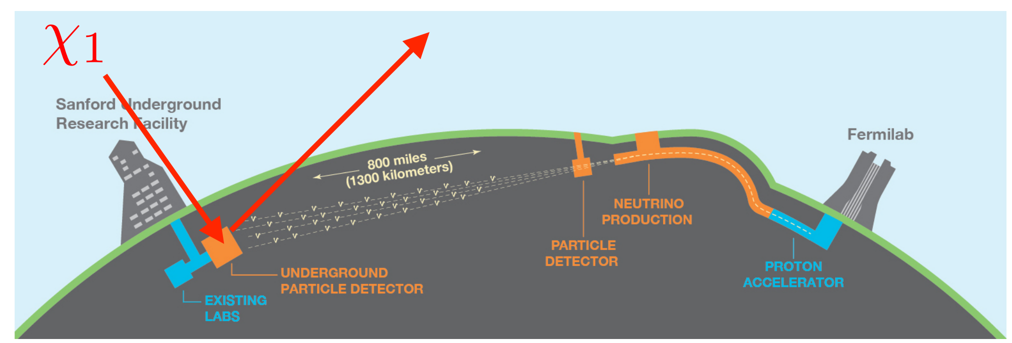
Fixed ~ 1 if s-channel annihilation dominates

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

Huge detector if $m_{\chi^0} \gtrsim O(10\ \text{GeV})$

Flux: small & Energy of χ_1: large ⟶ Large volume ν experiments





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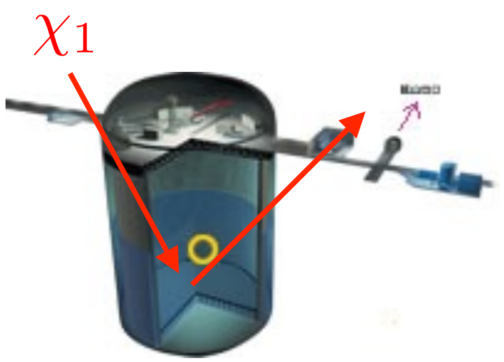

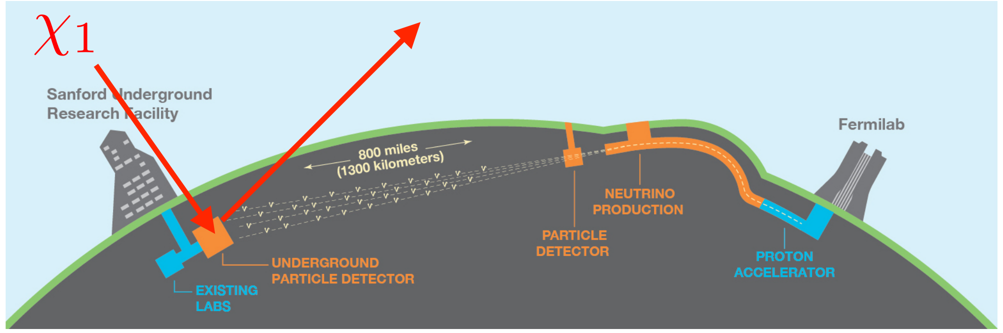

Subtraction of
major background (ν)

Important for all cosmogenic
BSM signals

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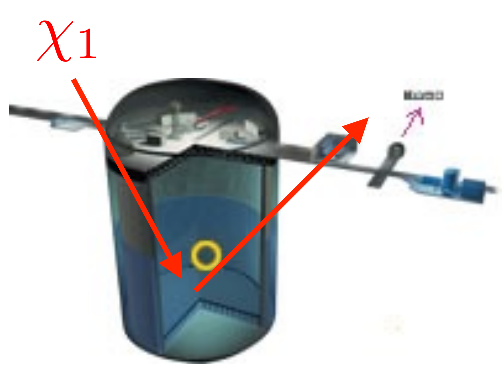

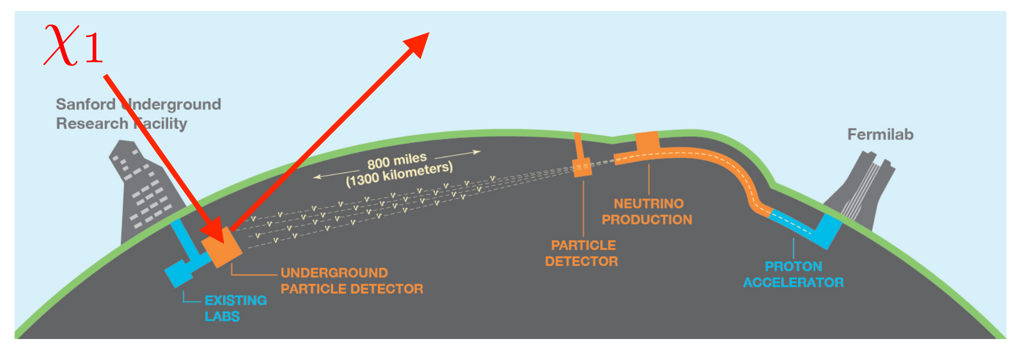

Subtraction of
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Important for all cosmogenic
BSM signals

- Directional information:
  e.g., GC, Sun, dSphs
- Signal with unique feature

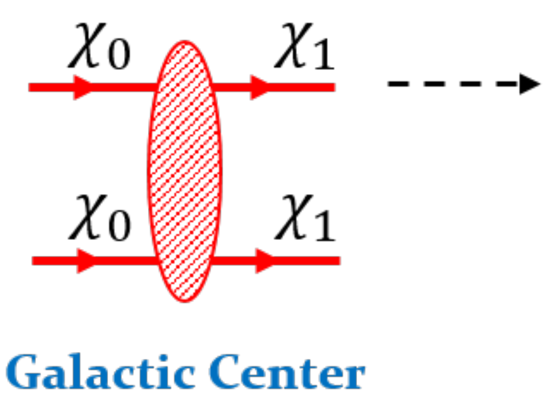
Open up novel possibilities of BDM search in many experiments

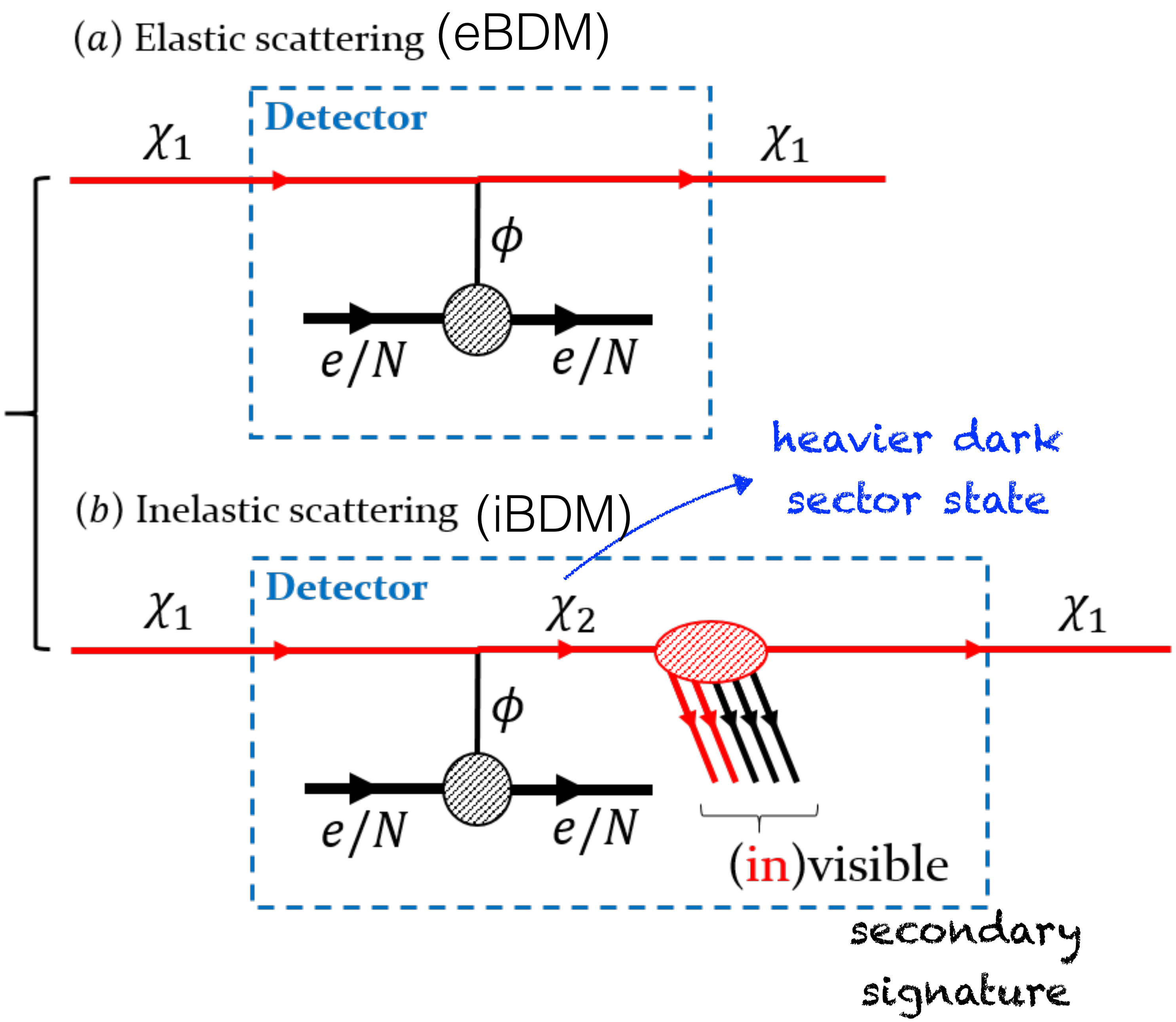
Inelastic BDM (iBDM)

χ_0: heavy DM

χ_1: light BDM

χ_2: excited state

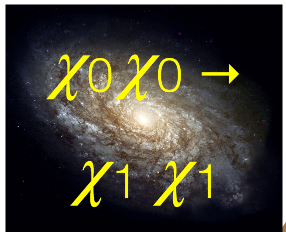




Kim, Park, **SS**, PRL 119, 161801 (2017)

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

Signals inside a fiducial volume



iBDM

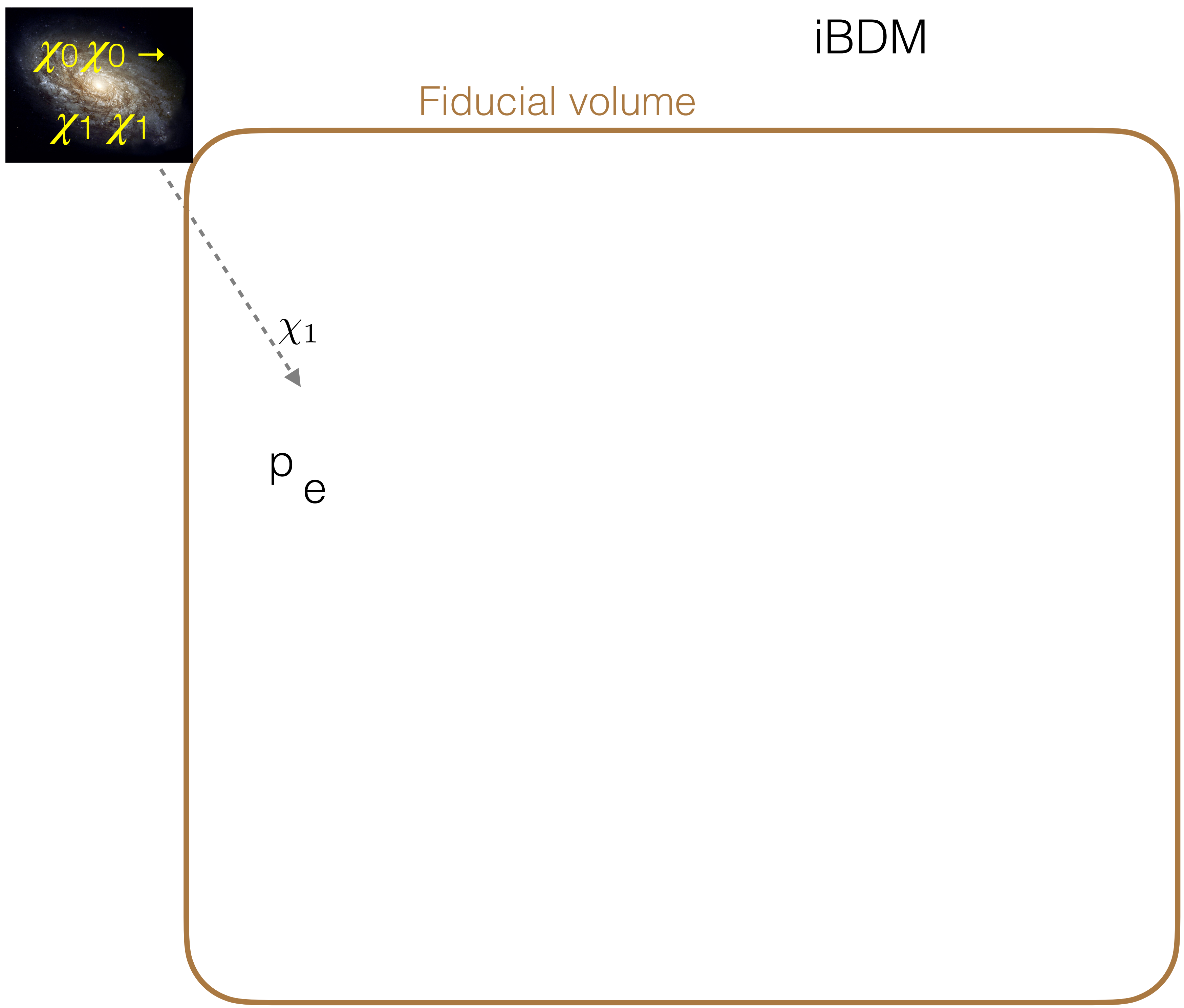
Fiducial volume

p e

χ_1: light BDM, χ_2: excited state

Signals inside a fiducial volume

iBDM



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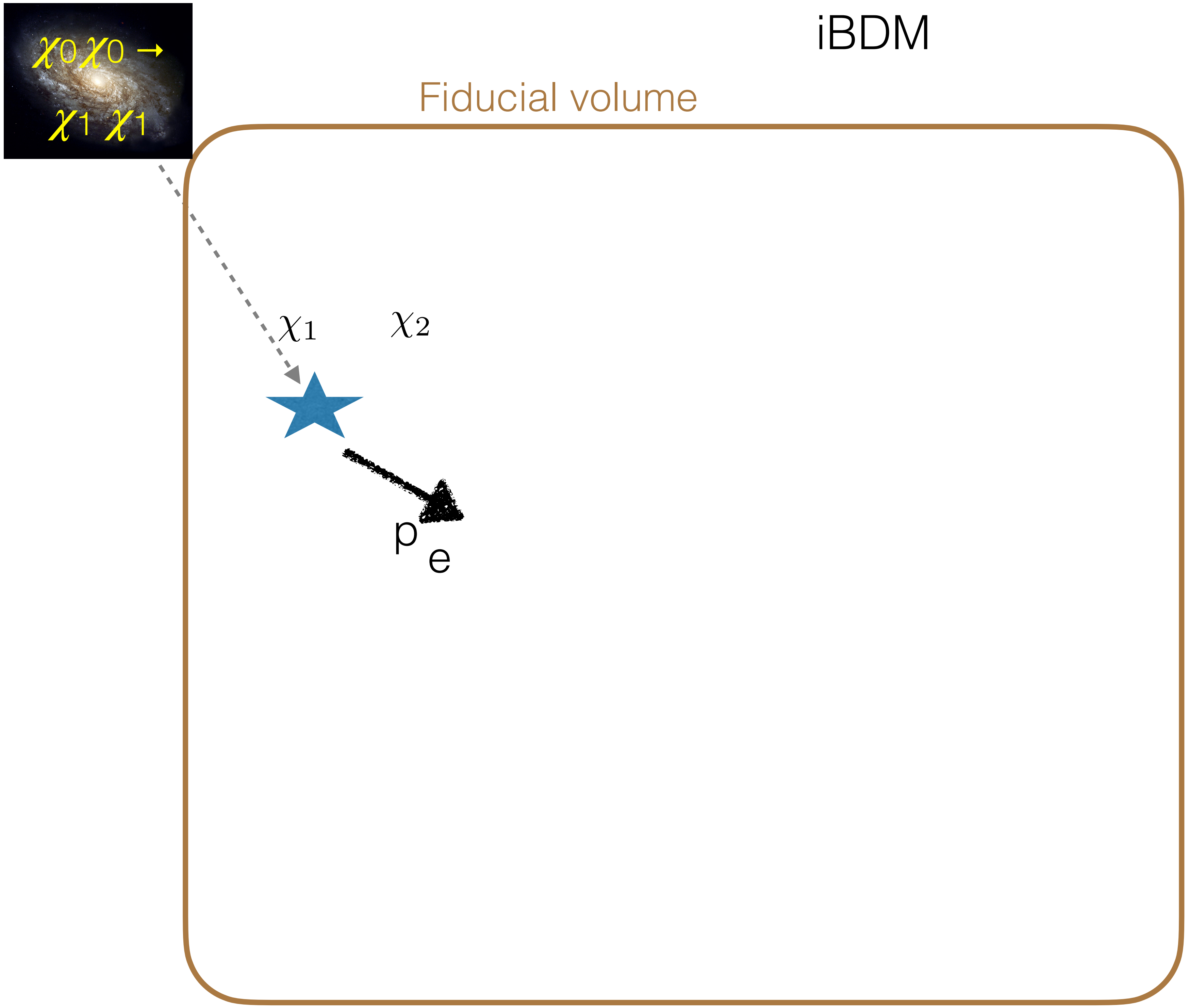

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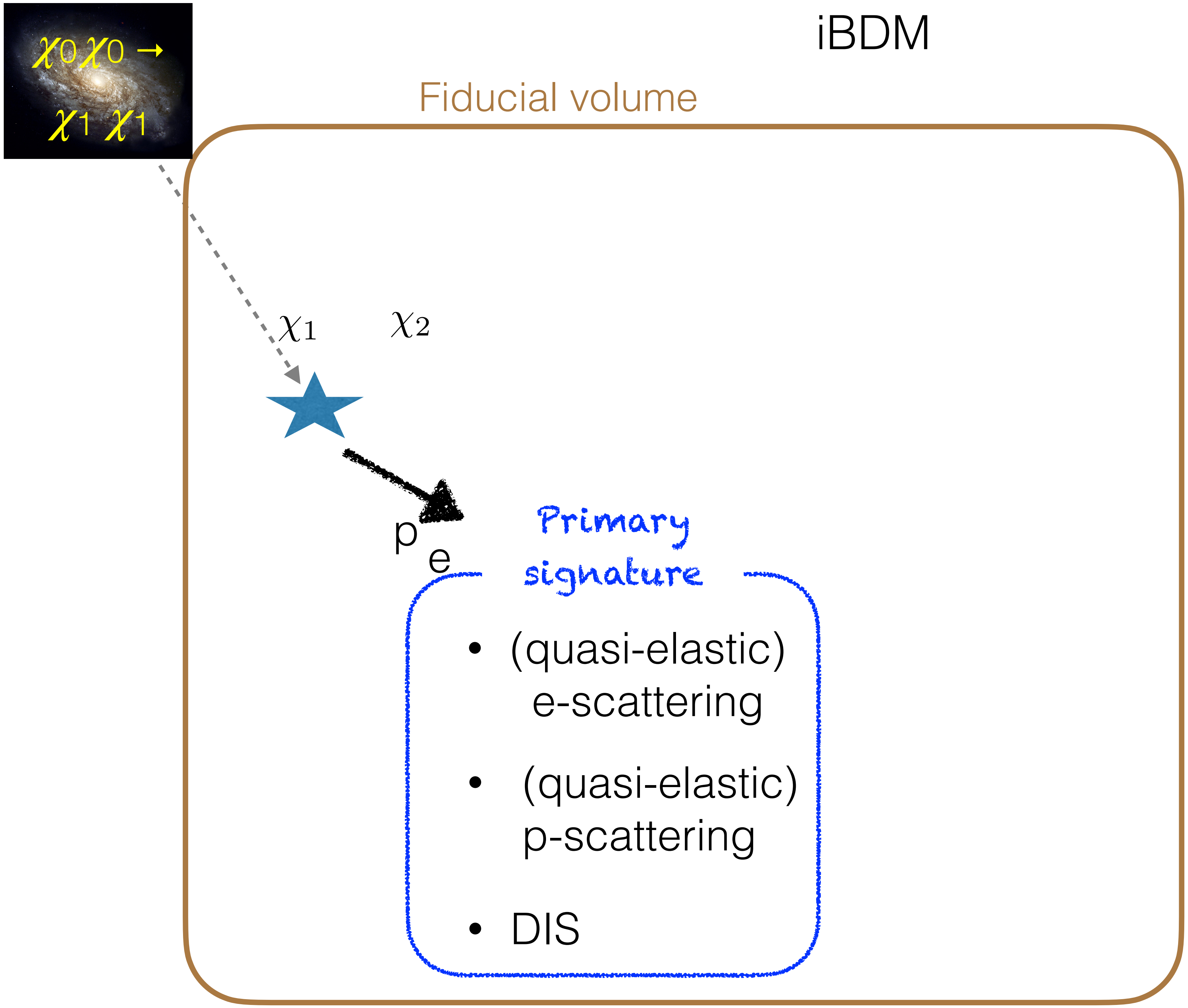

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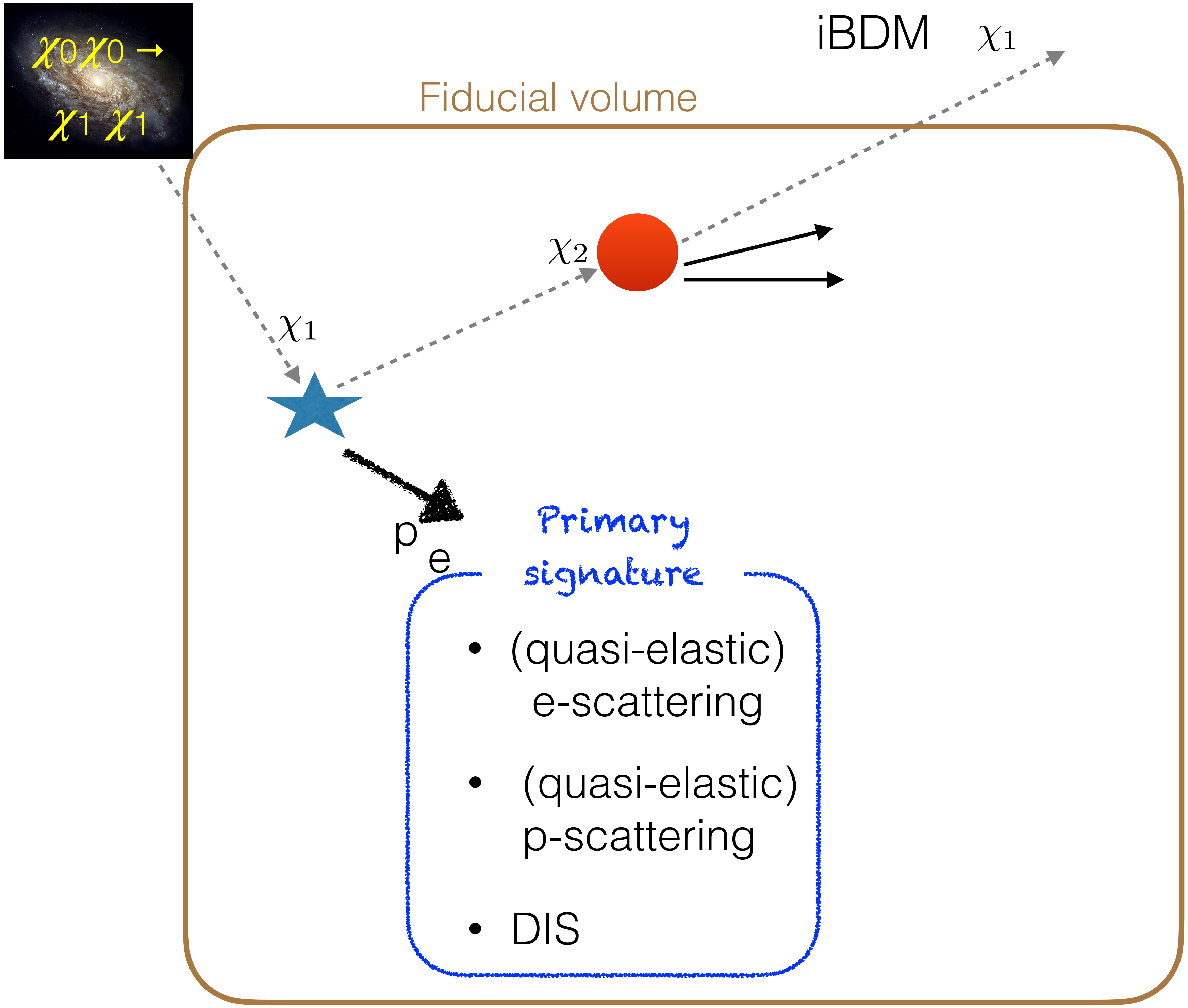

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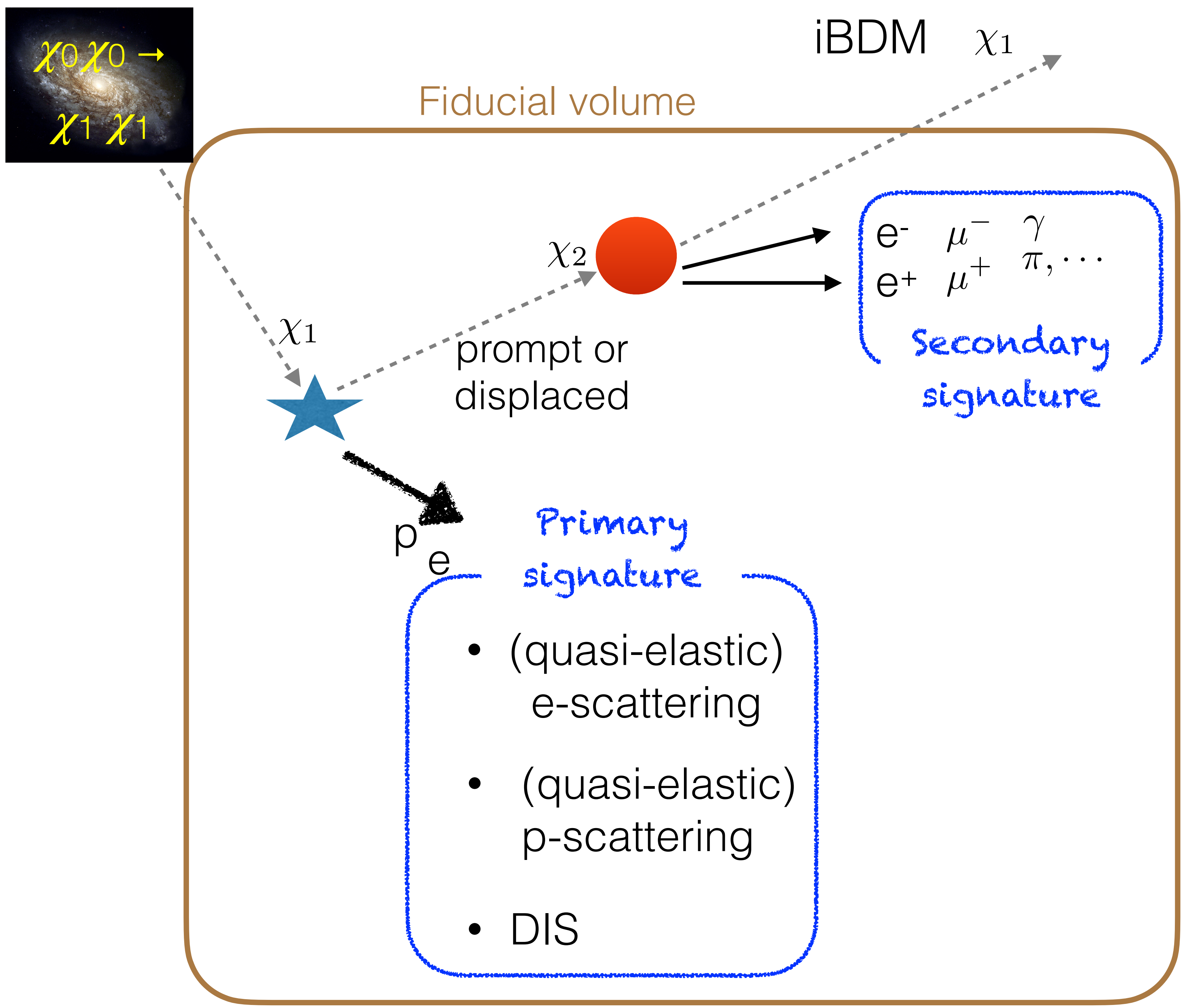

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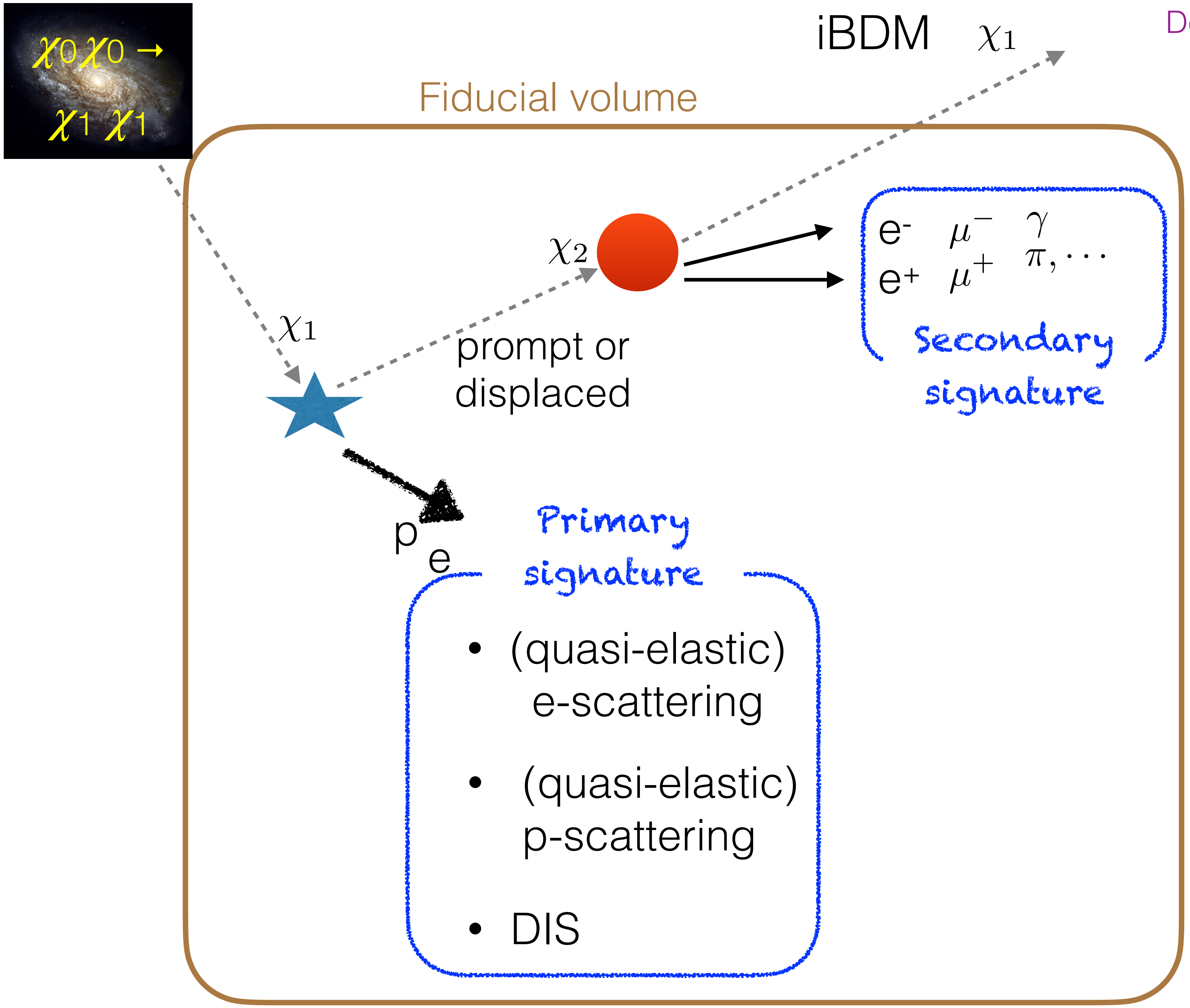
De Roeck, Kim, Moghaddam, Park, **SS**, Whitehead, 2005.08979

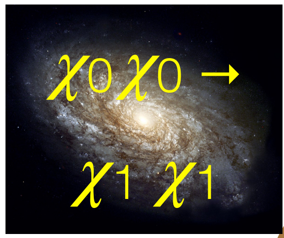


χ_1: light BDM, χ_2: excited state

- Tracks pop-up inside fiducial volume (reject the tracks extending outside the fiducial volume)
- Two signatures can be separated beyond the position and angular resolutions. (1cm for all and 1° for e, 5° for p)
- dE/dx for the merged e-recoil signal events

Zero - O(10) bkg. (conservative)

New method in eBDM search: darkstrahlung



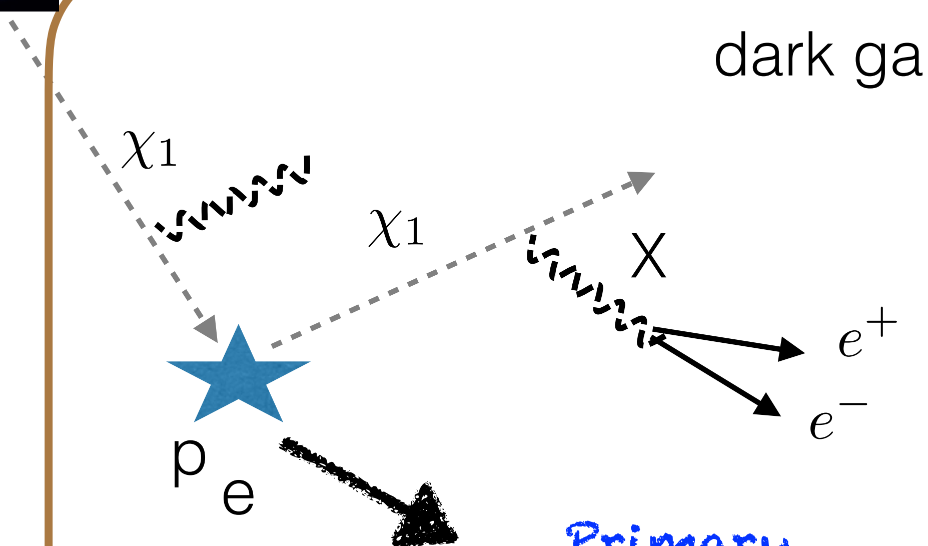
Kim, Park, **SS**, PRD2019, arXiv:1903.05087

eBDM: elastically scattering BDM

Fiducial volume

dark gauge boson scenario

NOT like ν



Secondary signature

Primary signature

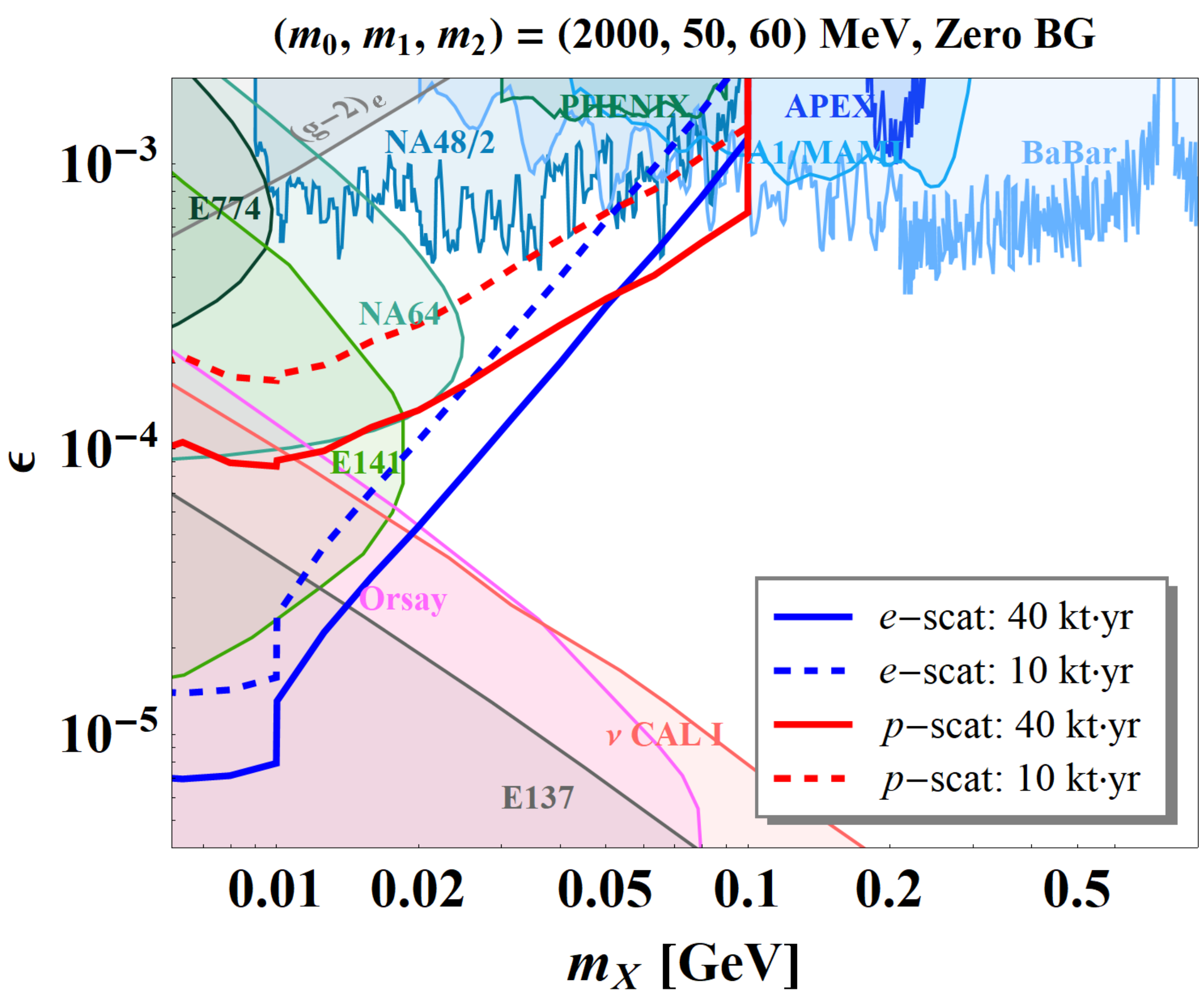
- (quasi-elastic) e-scattering
- (quasi-elastic) p-scattering
- DIS

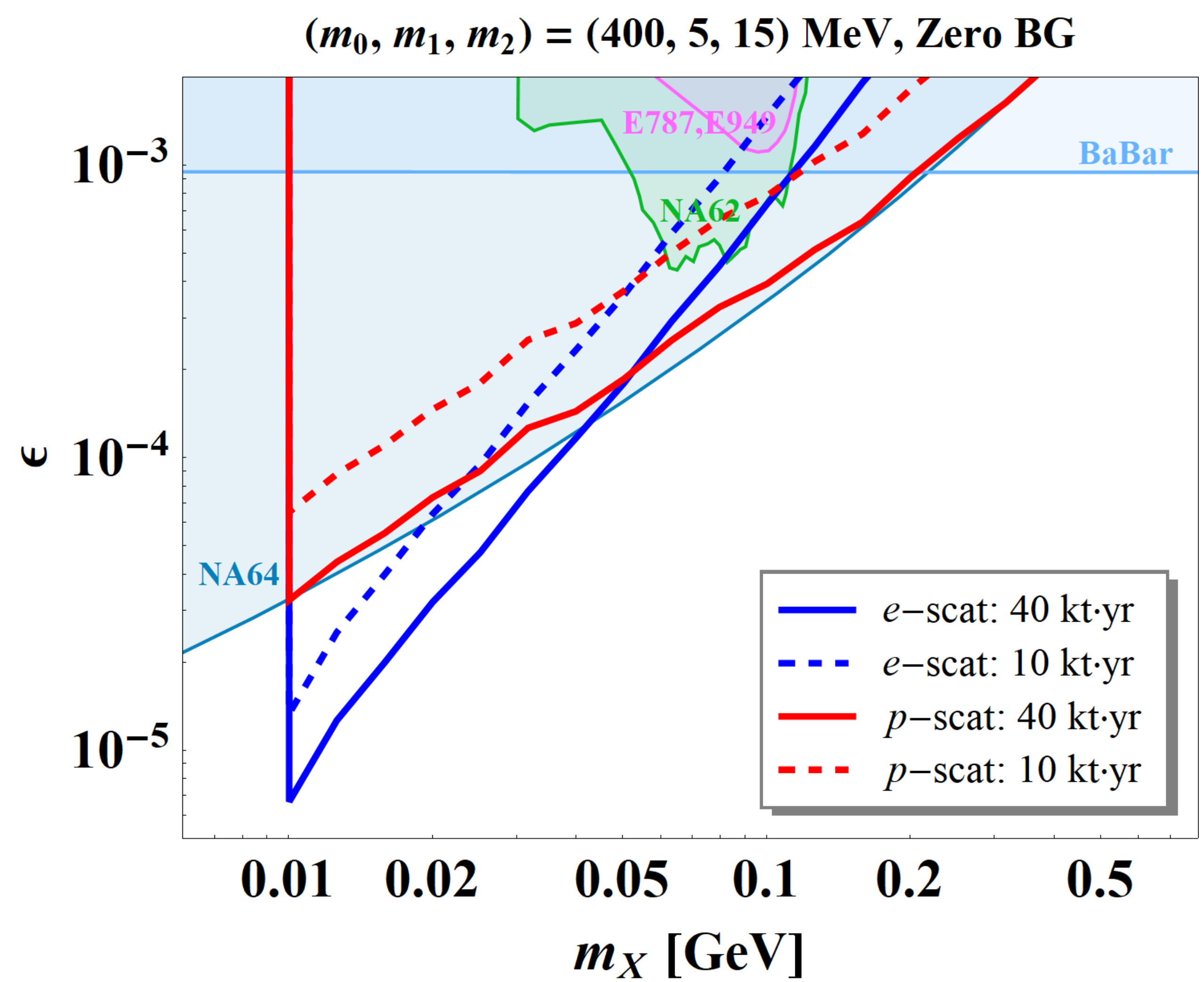
χ_1: light BDM

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

Experimental Sensitivities

DUNE





De Roeck, Kim, Moghaddam, Park, **SS**, Whitehead,2005.08979

Target experiments

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

- $m_{\chi^0} \gtrsim$ O(10 GeV): Large volume ν-experiments:

DUNE (TDR 2002.03005), SK (1711.05278, PRL 2018), HK/KNO, IceCube, ..

- $m_{\chi^0} \lesssim$ O(1 GeV):

1. Moderate volume ν-experiments:

ProtoDUNE — Chatterjee, De Roeck, Kim, Moghaddam, Park, **SS**, Whitehead, Yu, 1803.03264, PRD 98, 075027 (2018)

SBNP — Kim, Kong, Park, **SS**, 1804.07302, JHEP 1808, 155 (2018)

2. Ton-scale DM direct detection experiments:

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

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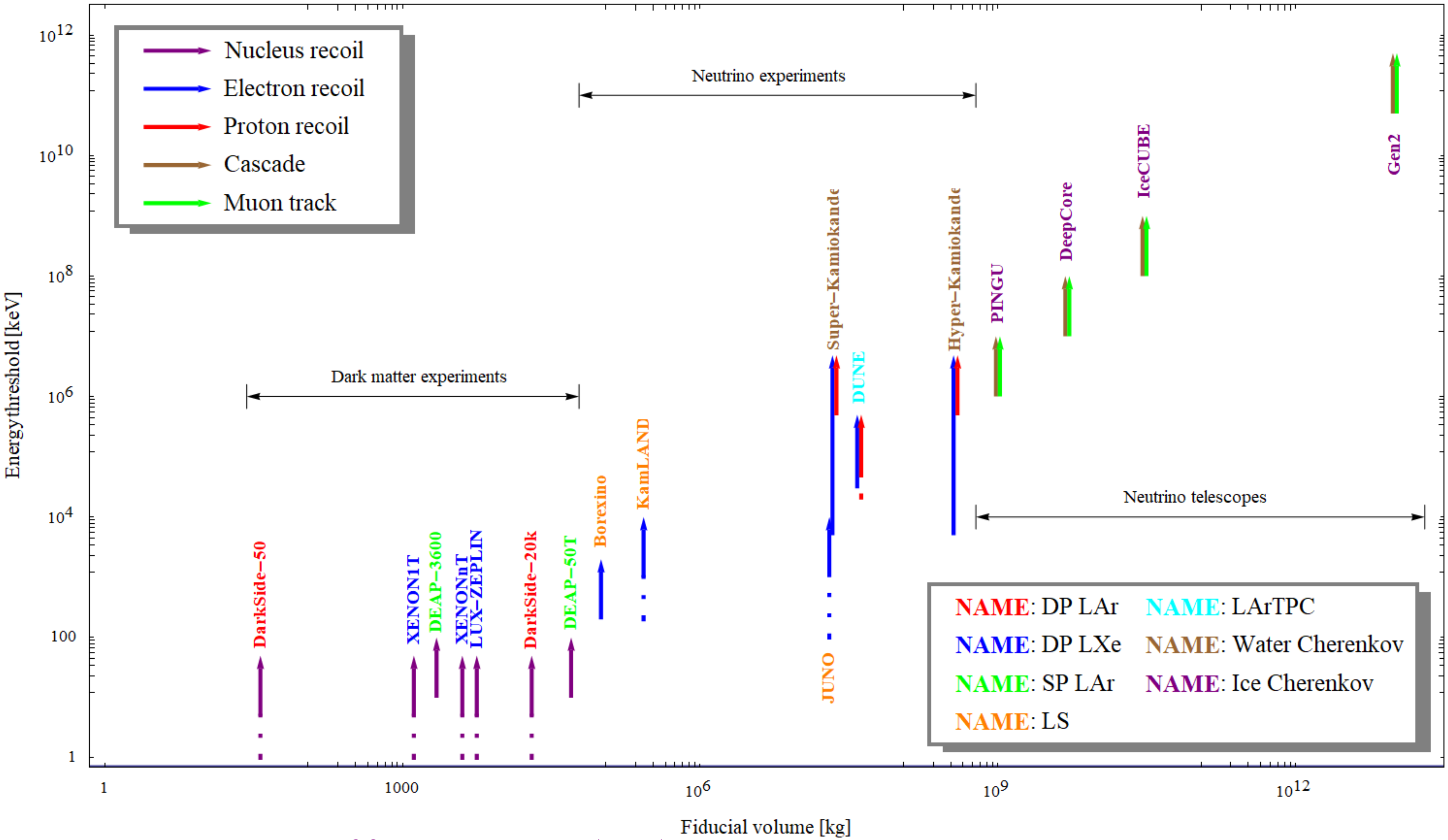
First proposal of high e-recoil in DM direct detection exp. such as XENON1T

Search for BDM



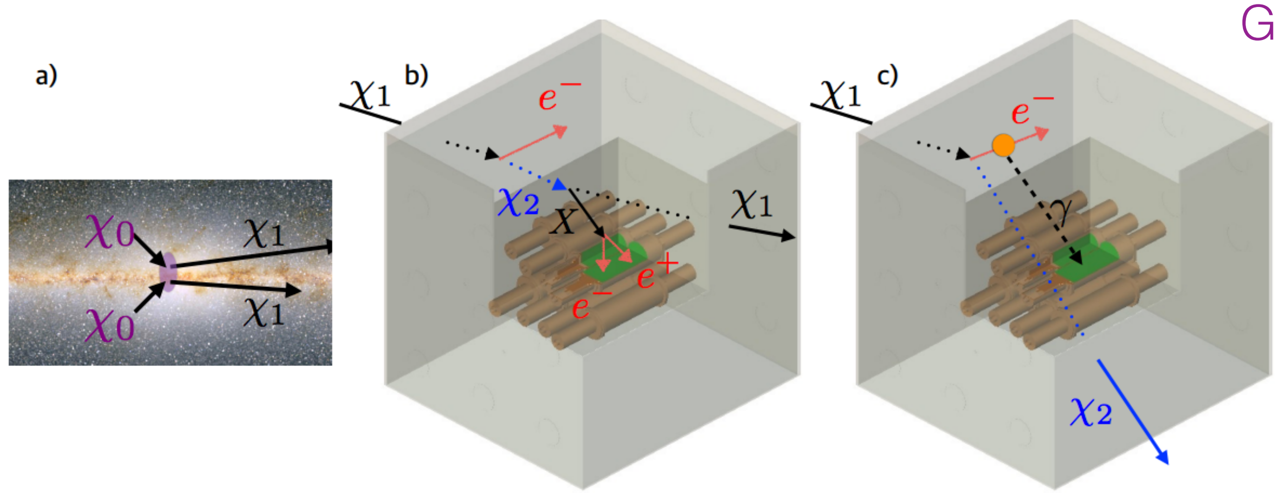
Kim, Machado, Park, **SS**, JHEP 2007, 057 (2020)

COSINE-100 result

COSINE-100, PRL 2019

Based on theoretical study

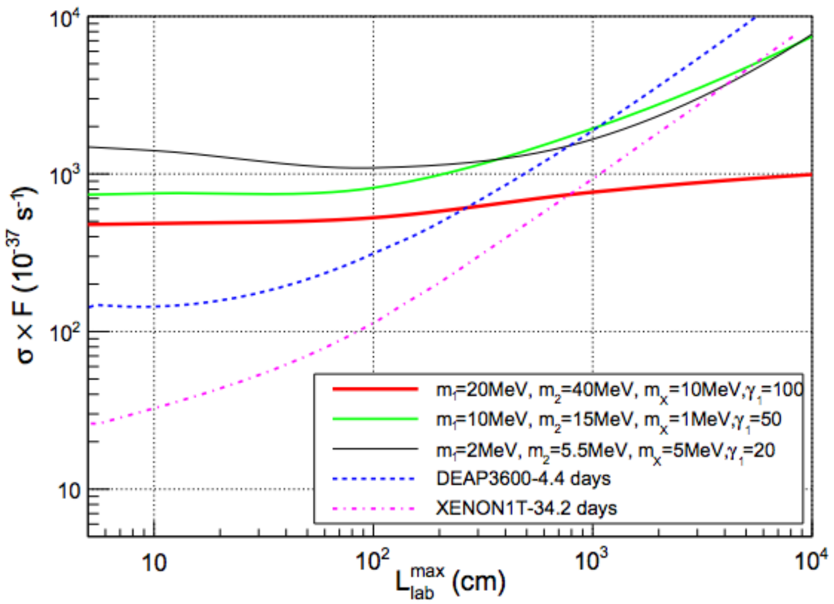
Giudice, Kim, Park, **SS**, PLB 780, 543 (2018)

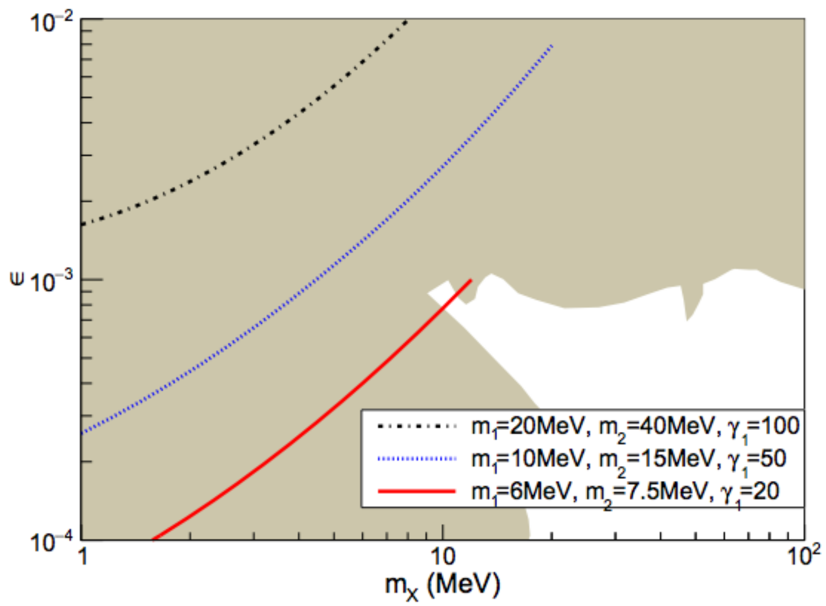


106kg array of 8 ultra-pure NaI(Tl) crystals immersed in an active veto detector

2200L of liquid scintillator (~ 2 ton)

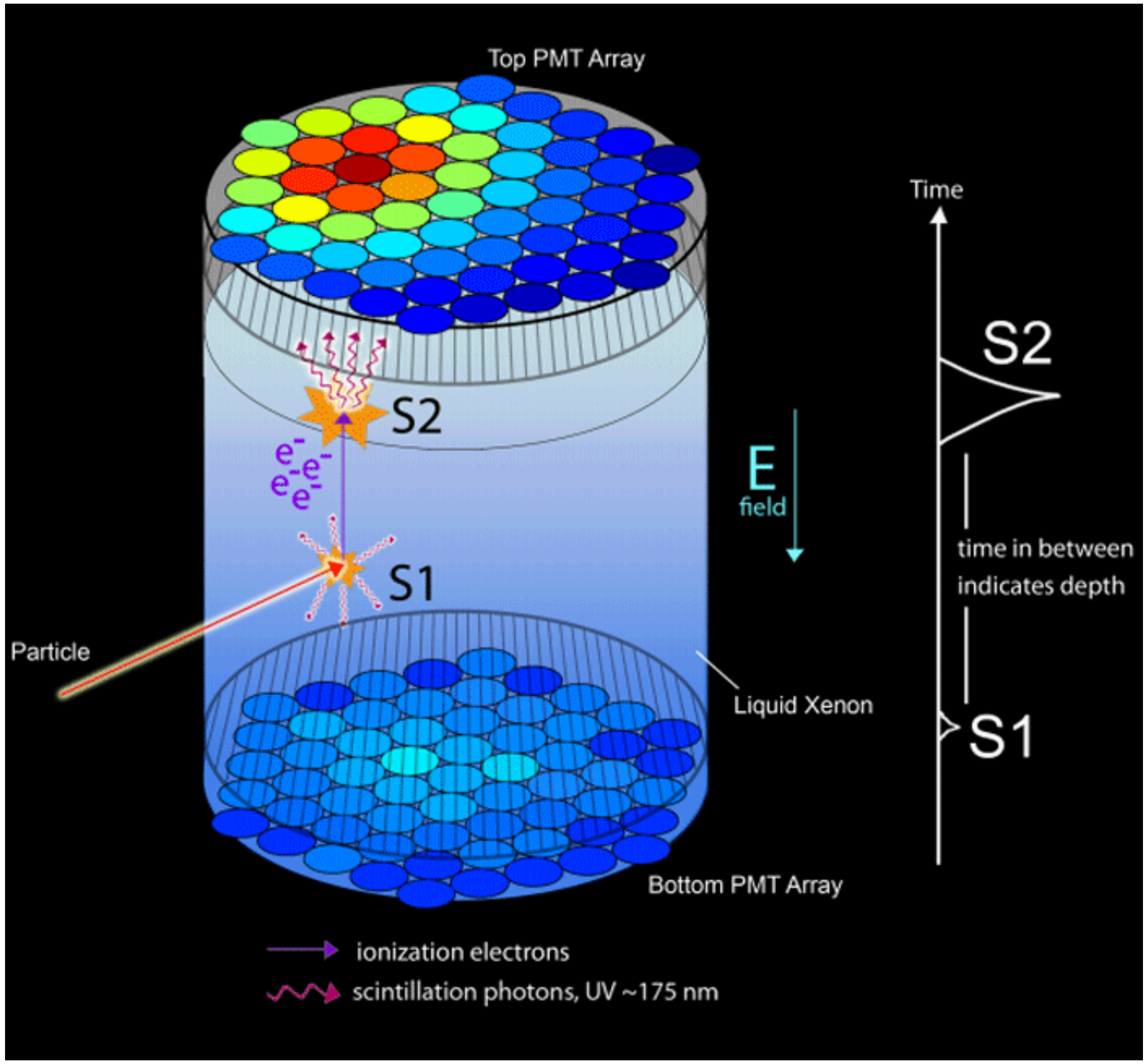
Observed: 21 events, Background expected: 16.4 ± 2.1

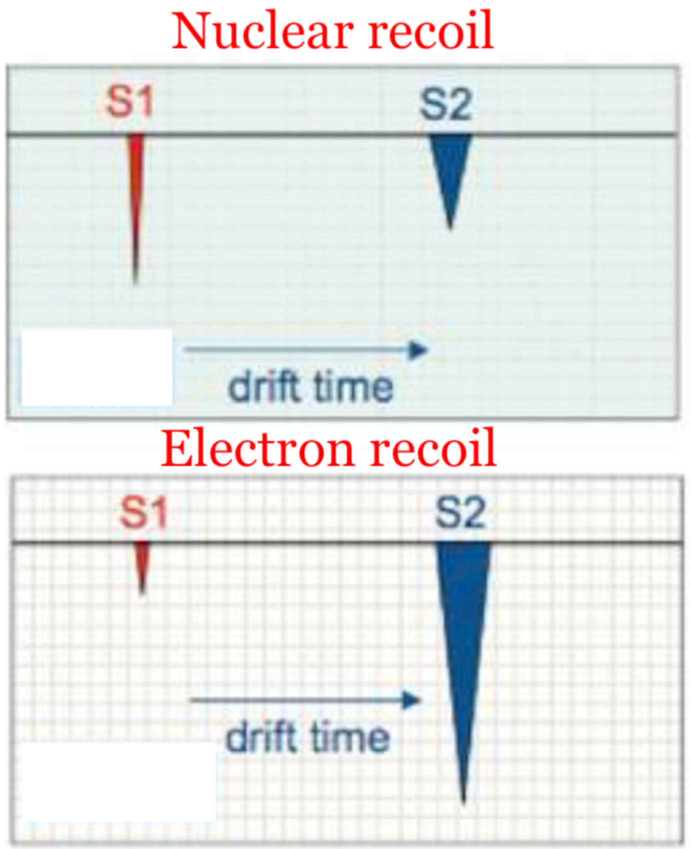




XENON detectors

XENON1T, NT, LUX-ZEPLIN, PANDA, …





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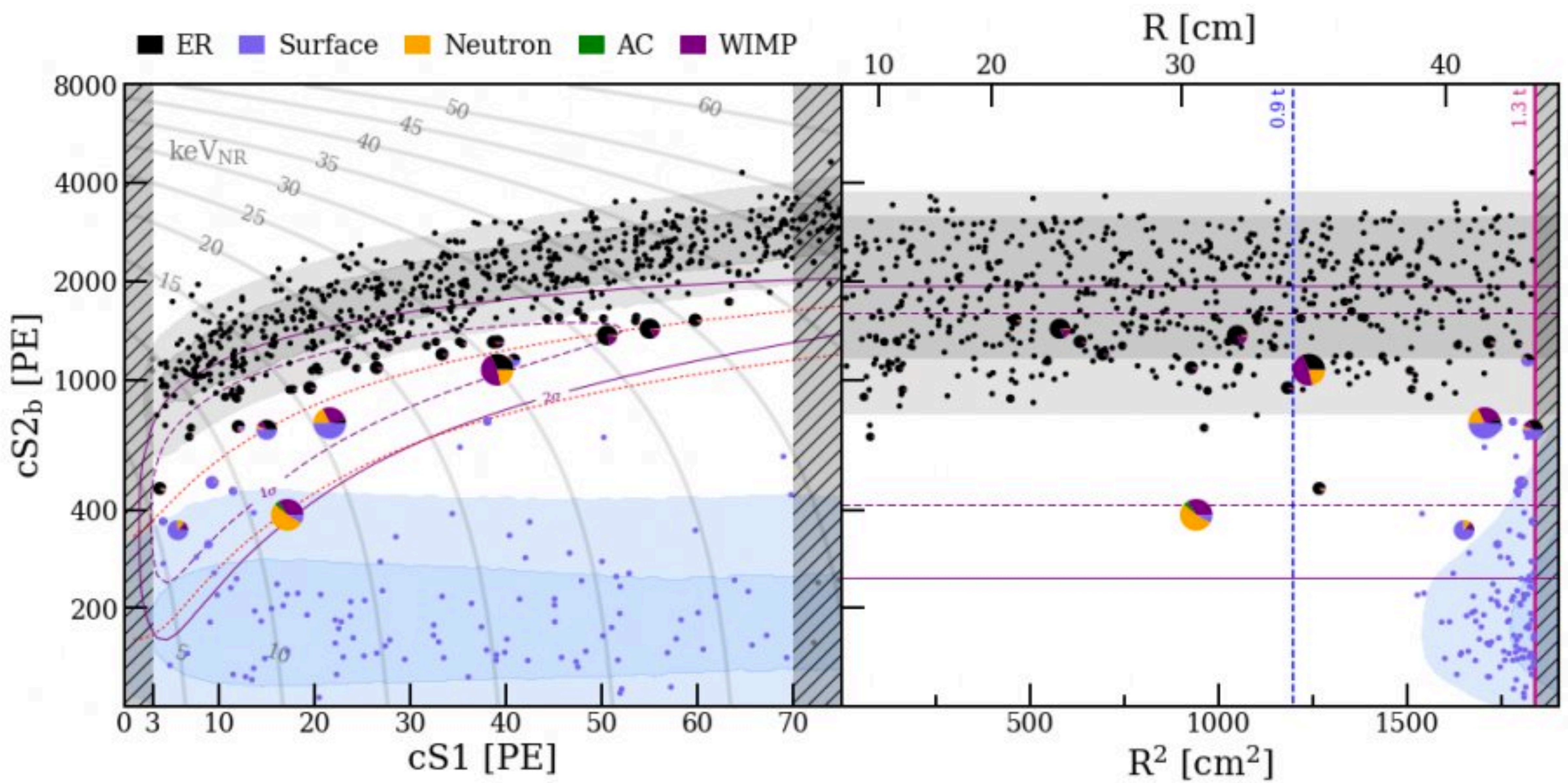
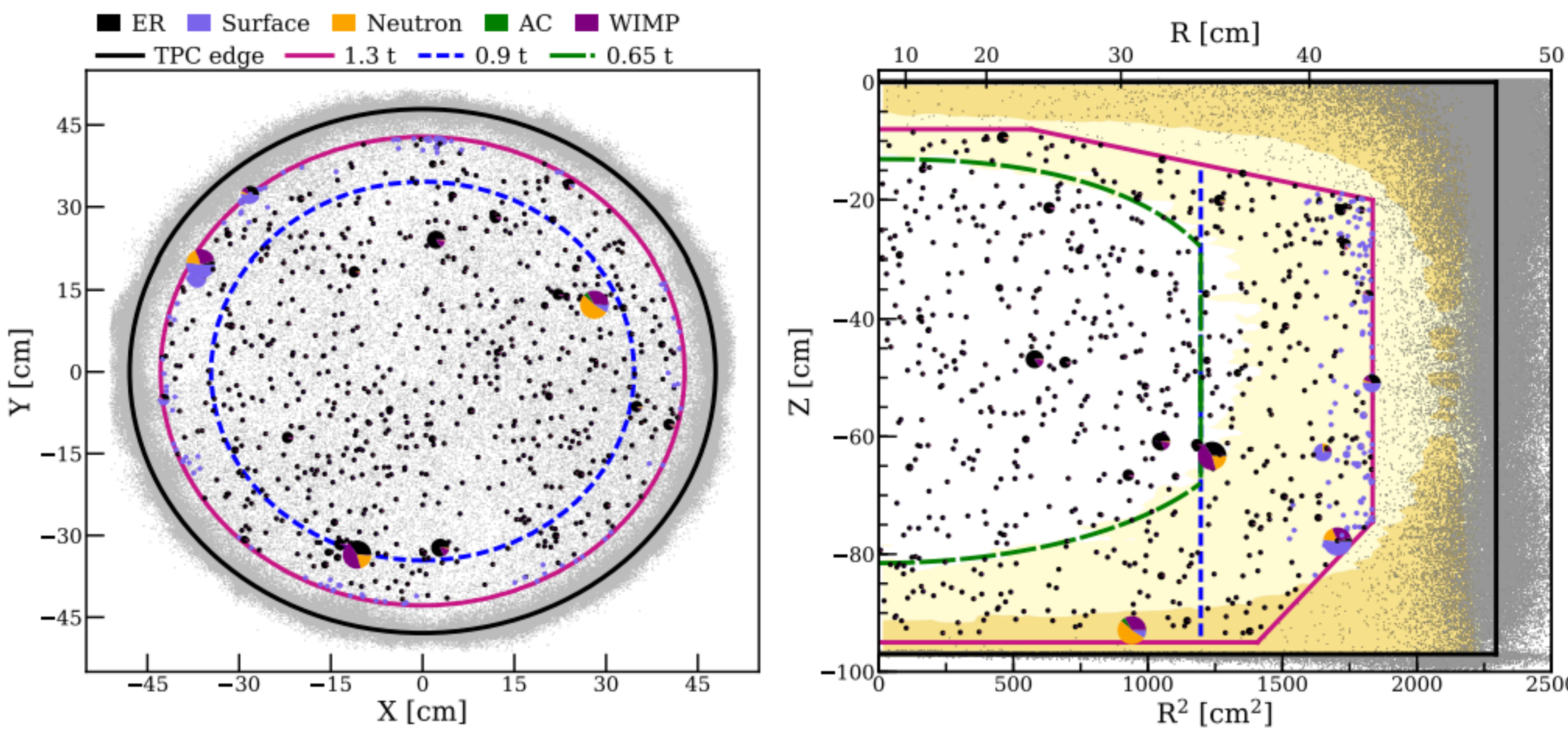


XENON1T, 1805.12562

Neutrons include cosmogenic neutrons and radiogenic neutrons from detector materials.

AC: Artificial Coincidence, an artificial background from detector effects

XENON detectors

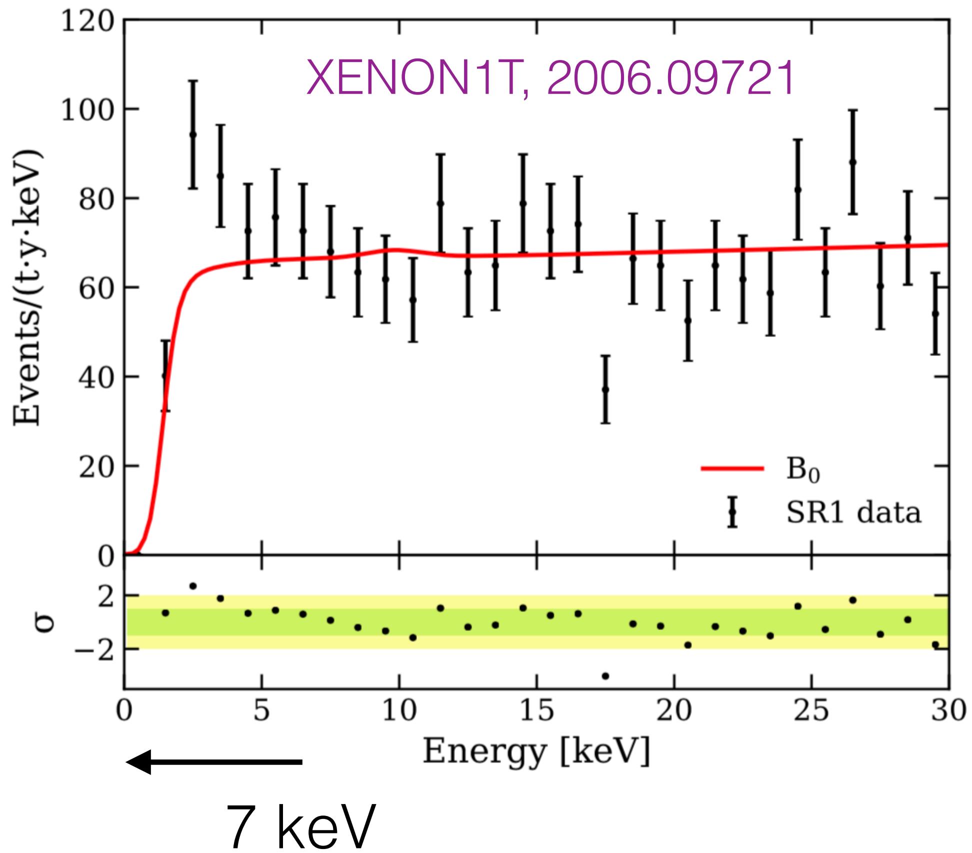


XENON1T, 1805.12562

XENON1T 2020

0.65 ton·year

76 ± 2(stat) events exceeding background expectation



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- Solar axion, neutrino MDM ~3σ ?
- Dark Matter recoil?

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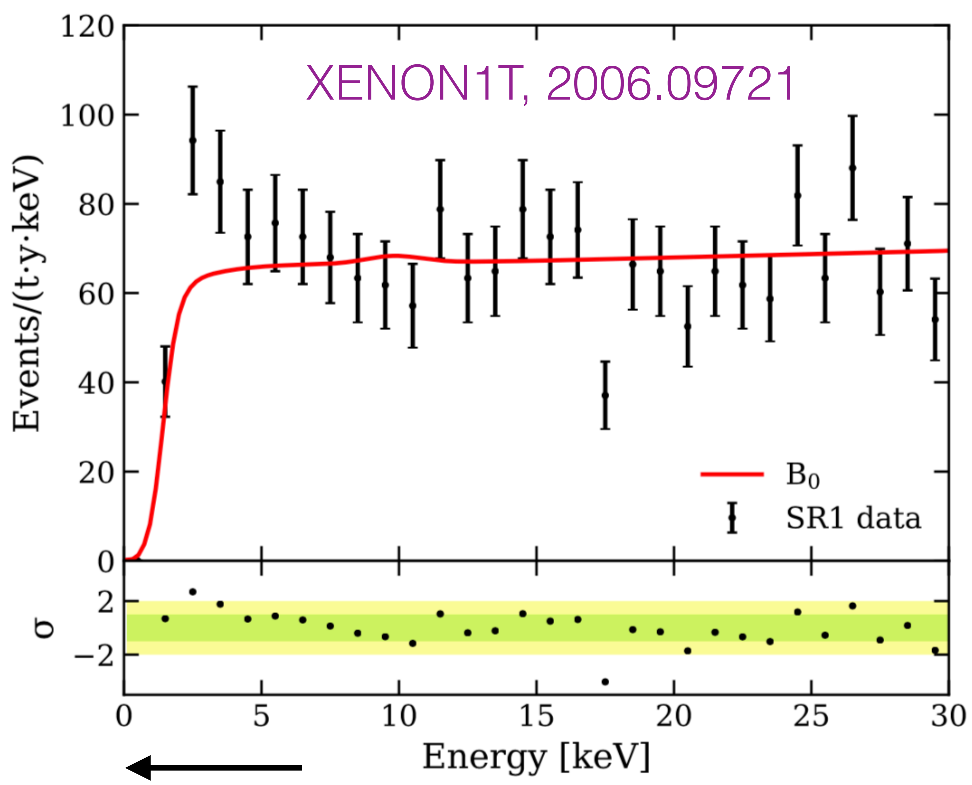

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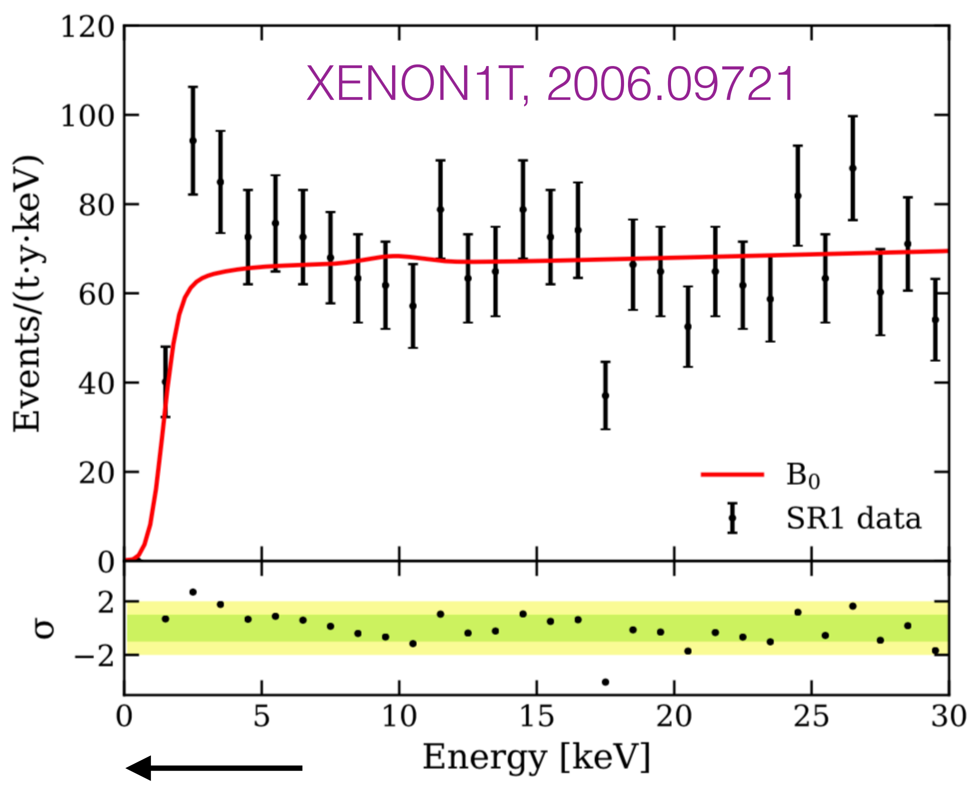

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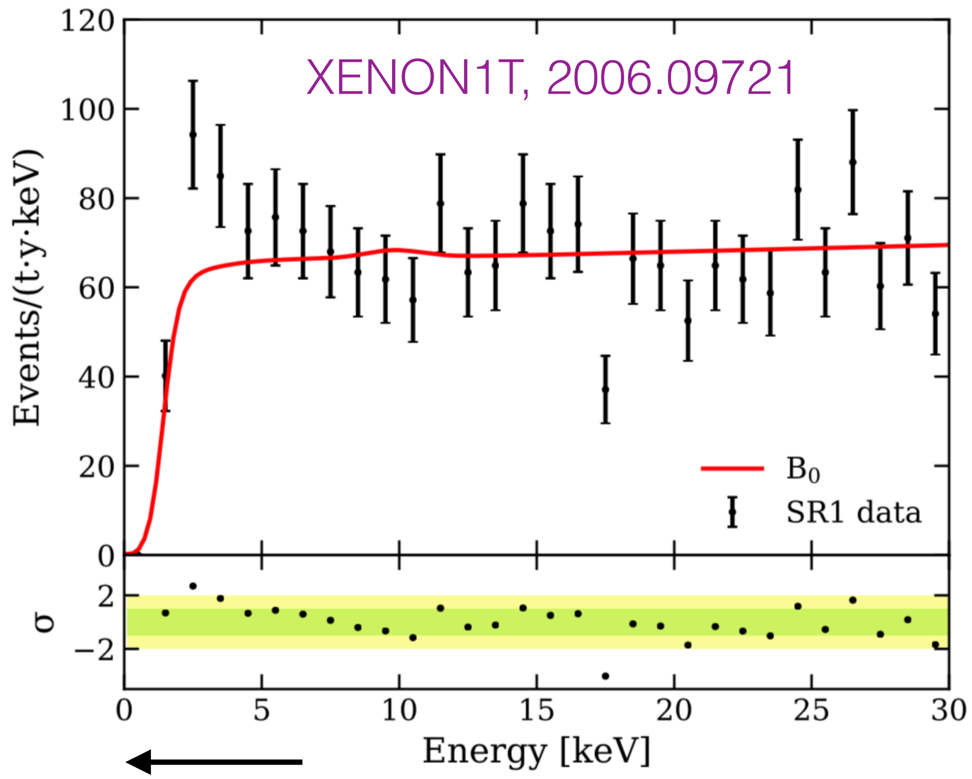
The electron target is in a bound state with a typical wavelength size of $R_{\rm Bohr} = 1/(\alpha m_e)$

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 at most $\mathcal{O}$(eV) « keV.

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

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

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

The deposited energy by slowly moving DM (v ~ 10^{-3}) is at most $\mathcal{O}$(eV) ≪ keV.

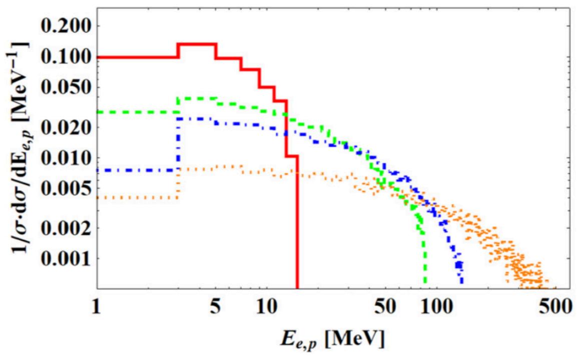
XENON1T 2020

The first proposal of searching for high energy *e*-recoil by fast-moving light DM

Inelastic Boosted Dark Matter at direct detection experiments

Gian F. Giudice [a,*], Doojin Kim [a,*], Jong-Chul Park [b,*], Seodong Shin [c,d,*]

Theoretical Physics Department, CERN, Geneva, Switzerland
Department of Physics, Chungnam National University, Daejeon 34134, Republic of Korea
Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, USA
Department of Physics & IPAP, Yonsei University, Seoul 03722, Republic of Korea



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

	m_1	m_2	m_X	γ_1	ϵ
ref1 (red solid)	2	5.5	5	20	4.5×10^{-5}
ref2 (green dashed)	3	8.5	7	50	6×10^{-5}
ref3 (blue dot-dashed)	20	35	11	50	7×10^{-4}
ref4 (orange dotted)	20	40	15	100	6×10^{-4}

But the reference parameters were different at that time. E_R ~ MeV

Probably, the U. Chicago group misunderstood that the model cannot explain their preliminary results. :(

XENON1T 2020

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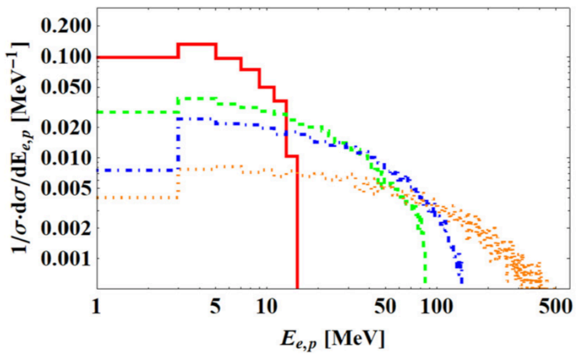

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Probably, the U. Chicago group misunderstood that the model cannot explain their preliminary results. :(

Regardless of the reliability of the excess, further analyses are useful in the sense that

1. XENON-NT can consider our reference models in confirming the excess.

2. we can provide guidelines to future ton-scale experiments, e.g., DarkSide, COSINE-200, in searching for fast-moving DM signals.

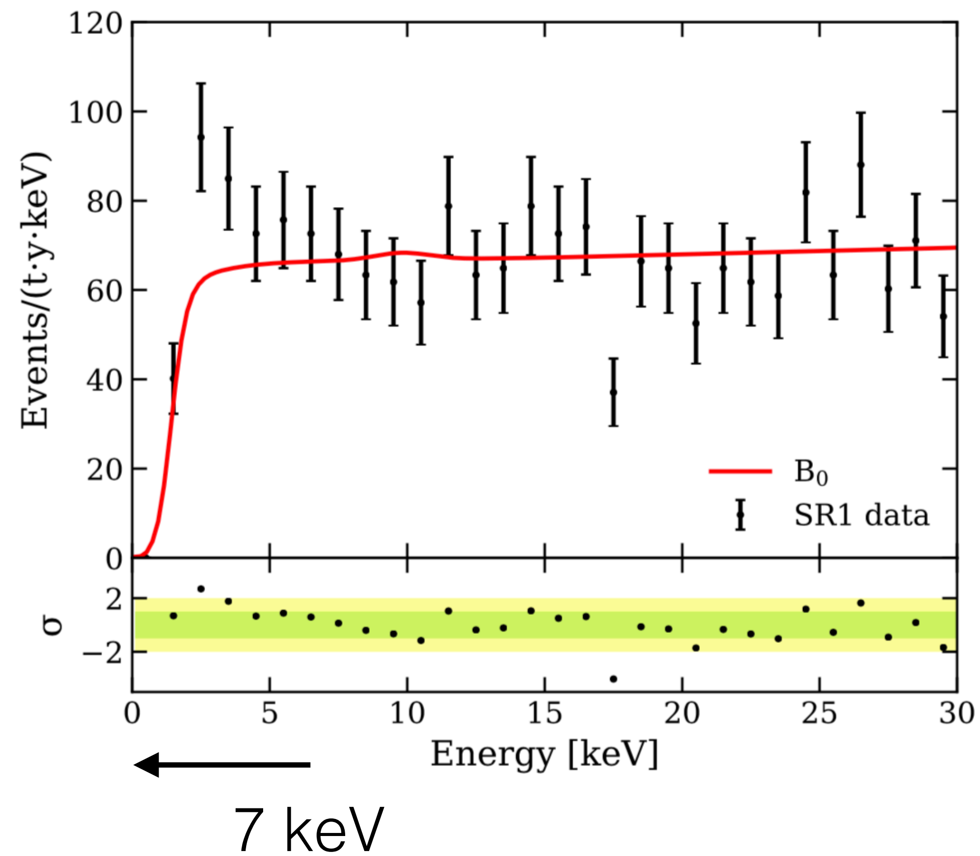
Favored parameter region

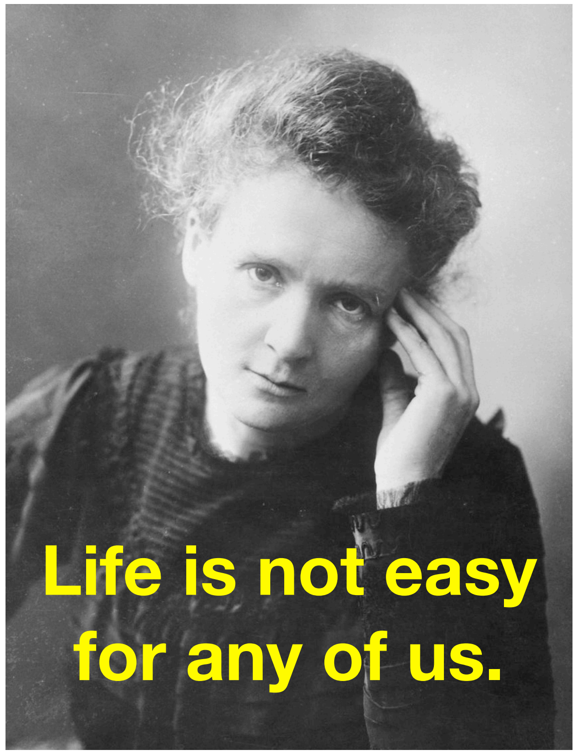
Not so simple task (some authors had to update their original papers)

- 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)

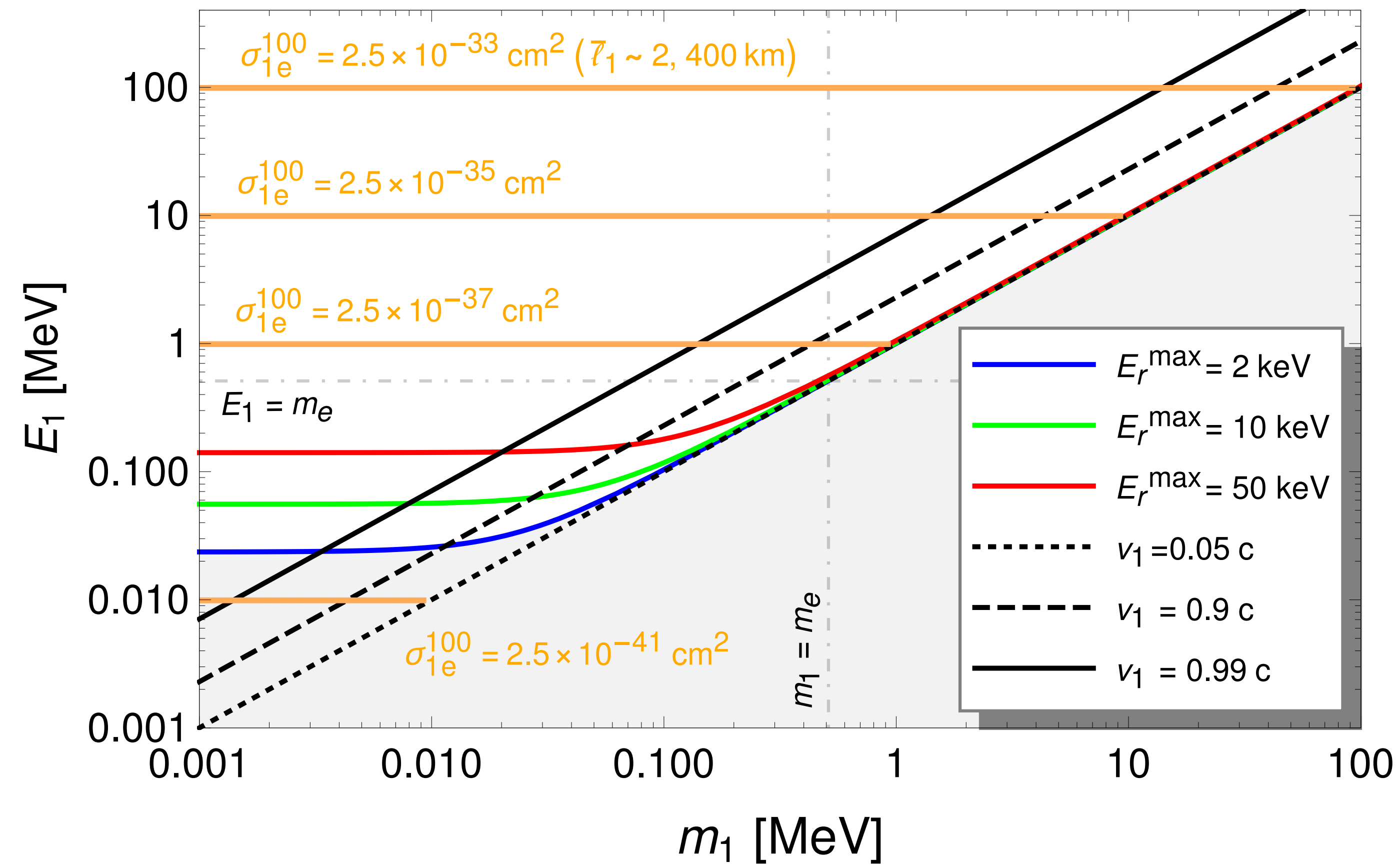




Favored parameter region

Alhazmi, Kim, Kong, Mohlabeng, Park, **SS**, arXiv: 2006.16252

Energy of the incoming BDM



Mass of BDM

Favored parameter region

Alhazmi, Kim, Kong, Mohlabeng, Park, **SS**, arXiv: 2006.16252

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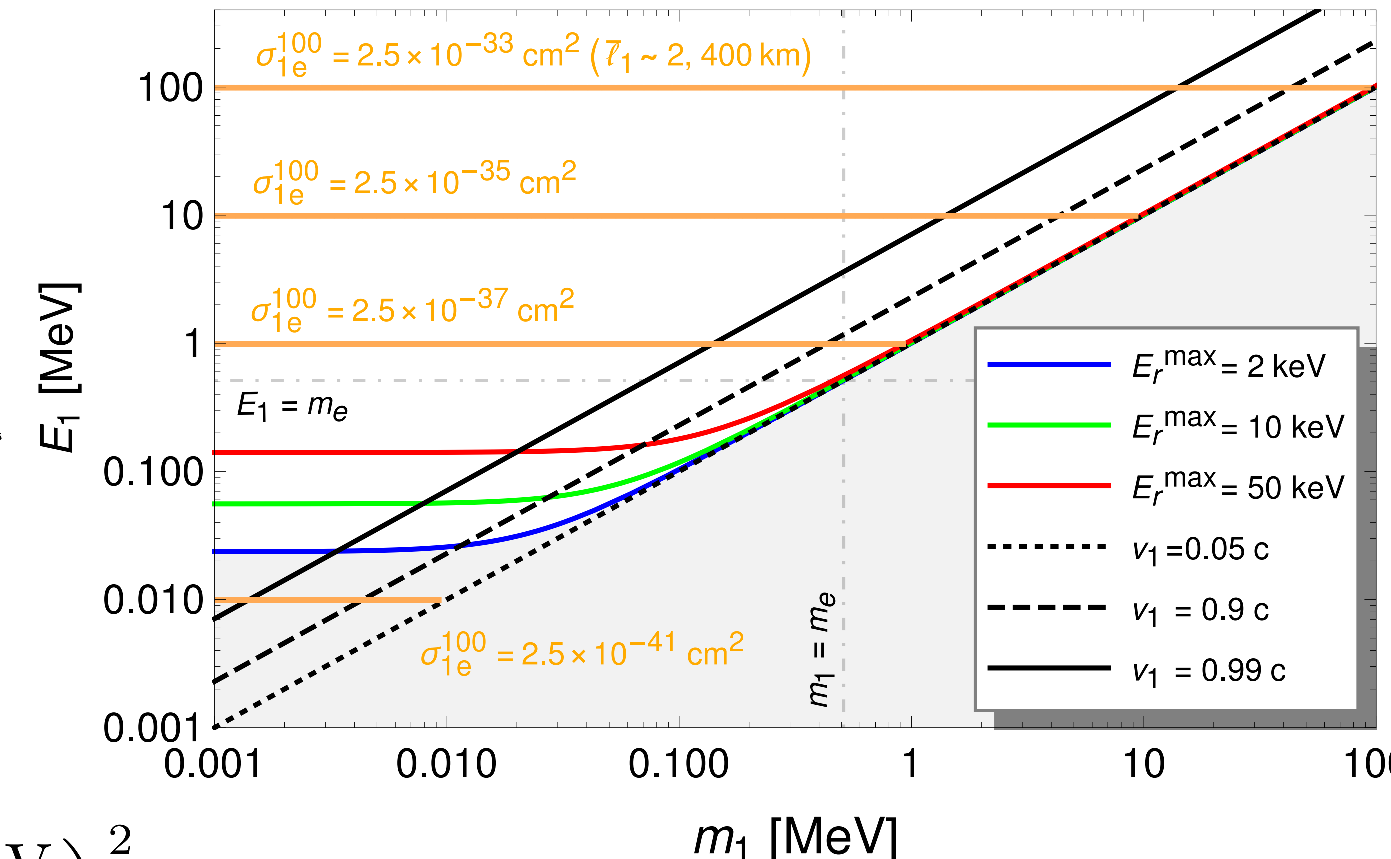


Mass of BDM

Two-component BDM from GC

$$\mathcal{F}_1 = 1.6\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1} \times \left(\frac{\langle\sigma_{0\to1}v\rangle}{5\times10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}\right)\left(\frac{10\,\mathrm{MeV}}{m_0}\right)^2$$

$$N_{\mathrm{sig}} = \mathcal{F}_1 \sigma_{1e} N_e^{\mathrm{eff}} t_{\mathrm{exp}}$$

Total exposure time

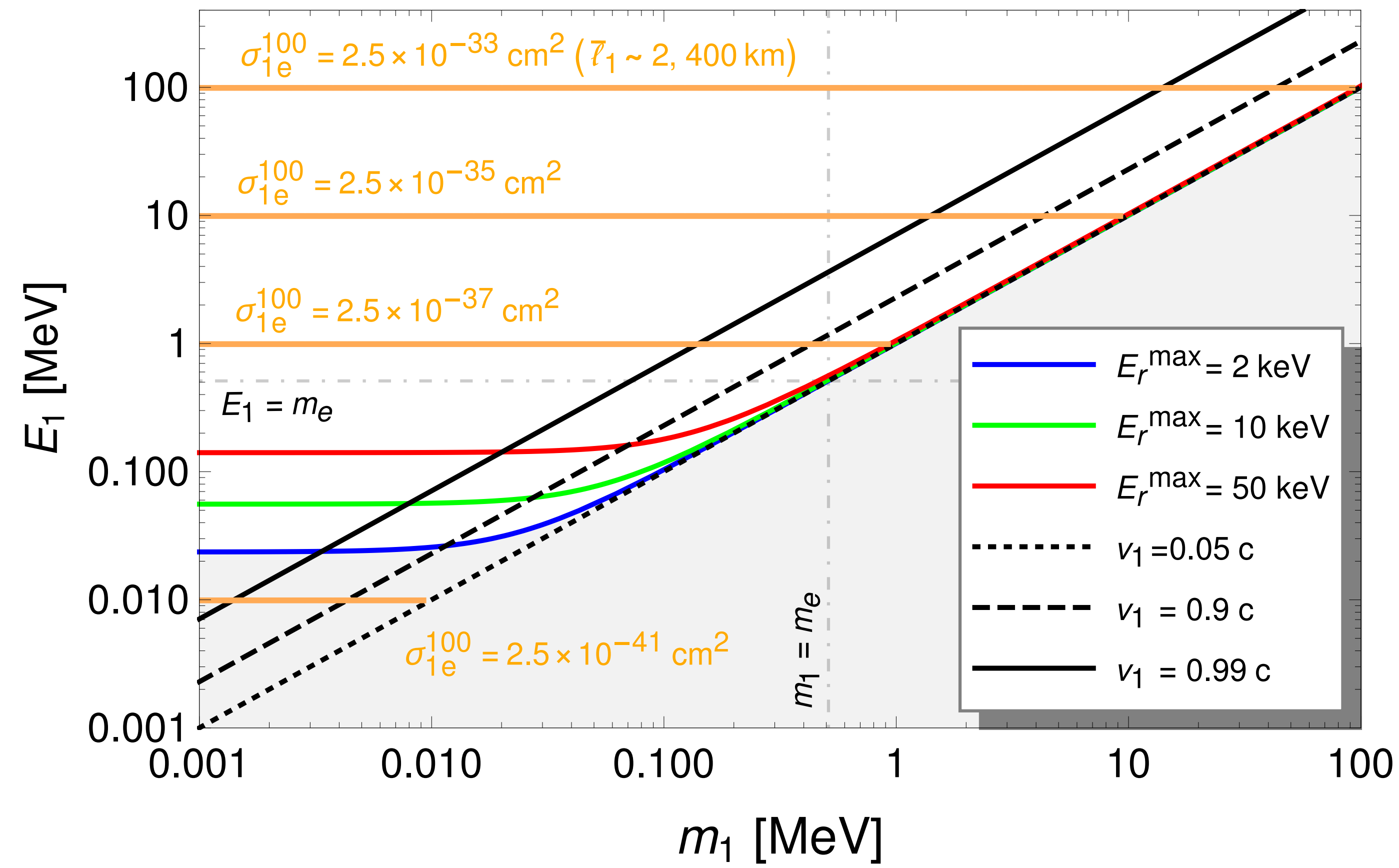
χ_1 - e (fiducial) scattering cross section

Number of effective target electrons in the fiducial volume

Favored parameter region

Alhazmi, Kim, Kong, Mohlabeng, Park, **SS**, arXiv: 2006.16252

Energy of the incoming BDM



Mass of BDM

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

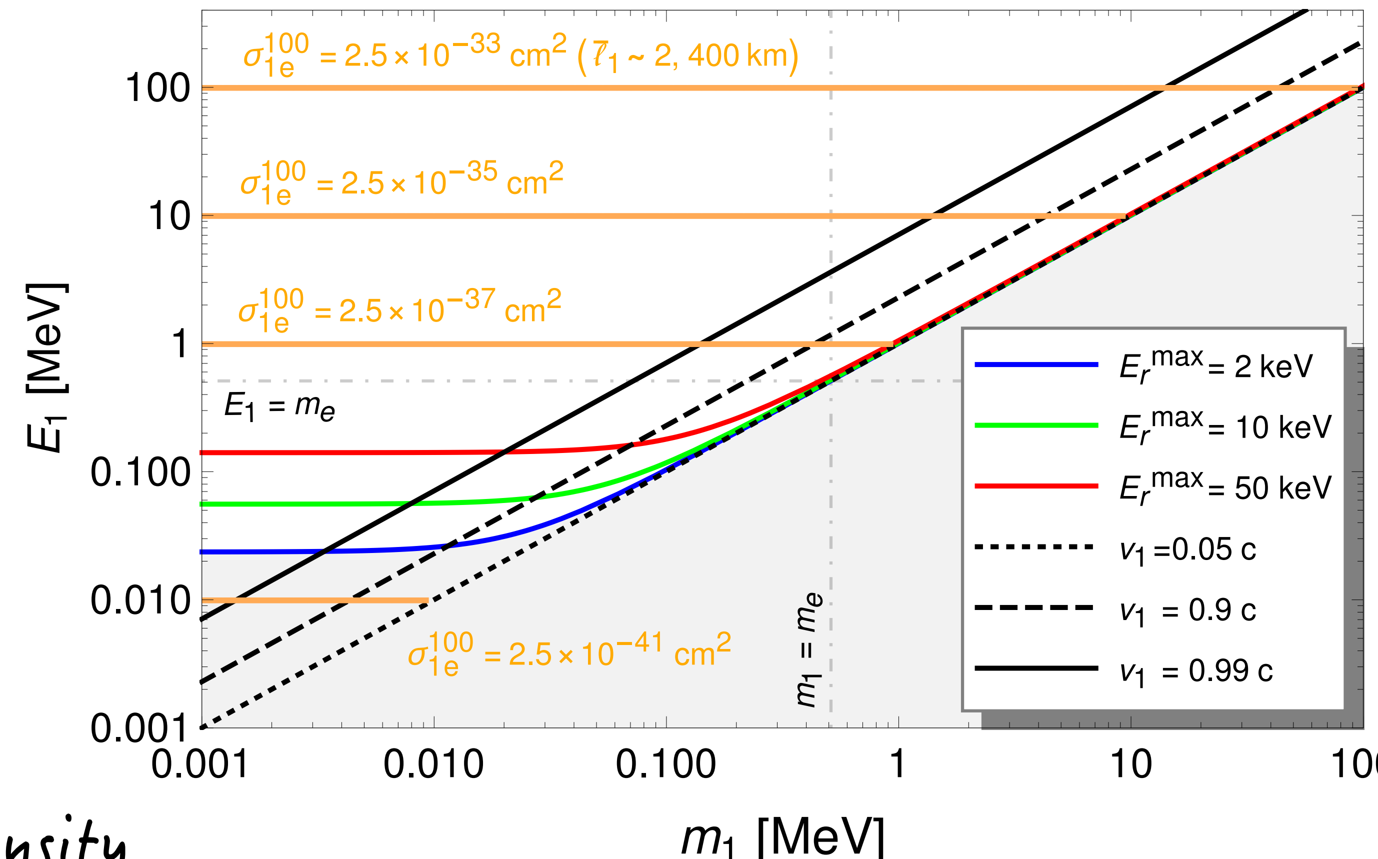
- The maximum E_R of electrons scattered by BDM ≥ 2 keV (non-shaded). This is **model independently** given as above.

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

Favored parameter region

Alhazmi, Kim, Kong, Mohlabeng, Park, **SS**, arXiv: 2006.16252

Energy of the incoming BDM



Mass of BDM

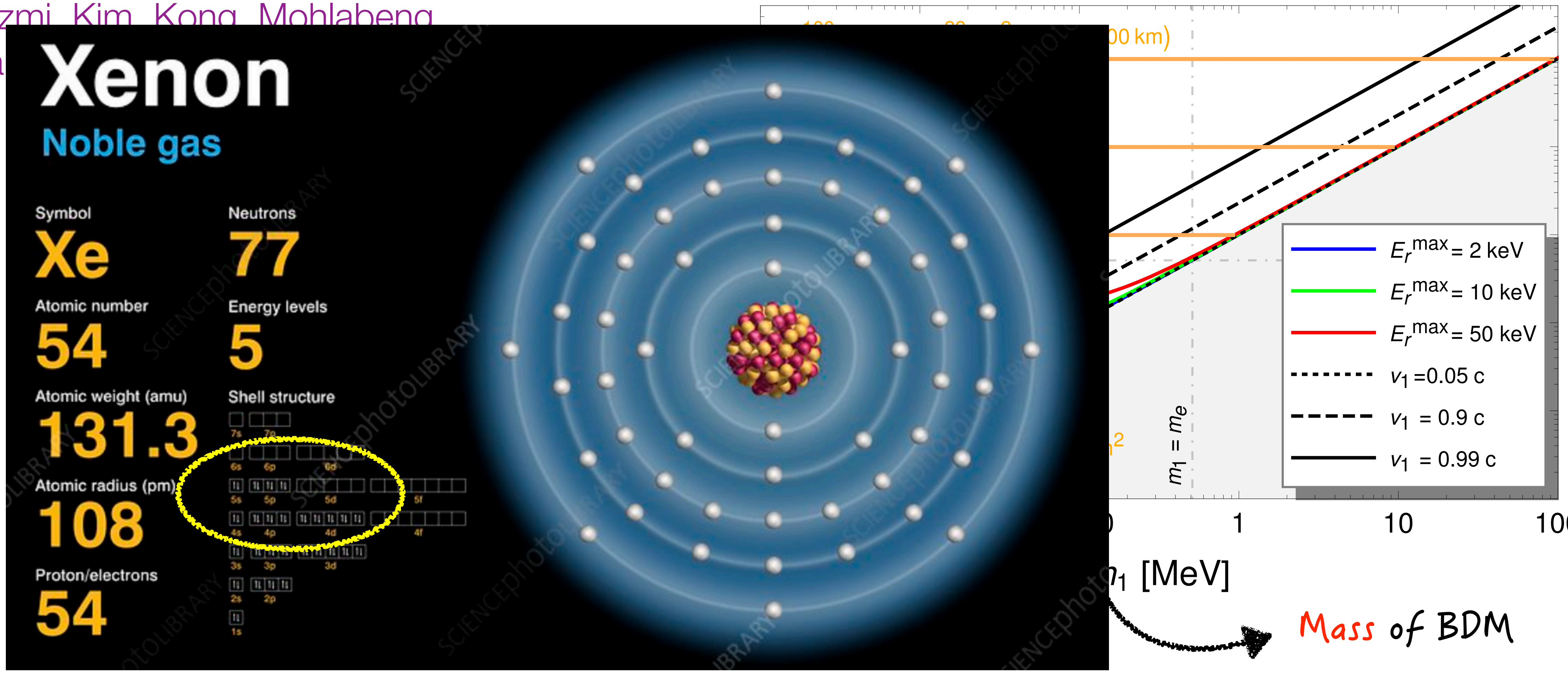
$$\bar{\ell}_1 \sim \frac{1}{\langle n_e \rangle \sigma_{1e}}$$

Mean e-number density along the χ_1 propagation line.

- The values of (fiducial) cross section σ_{1e} giving N_{sig} = 100 are shown, assuming $N_e^{\text{eff}} = 26$ (will be discussed in the next slide).
- 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)

Favored parameter region

Alhazmi, Kim, Kong, Mohlabeng
Pa

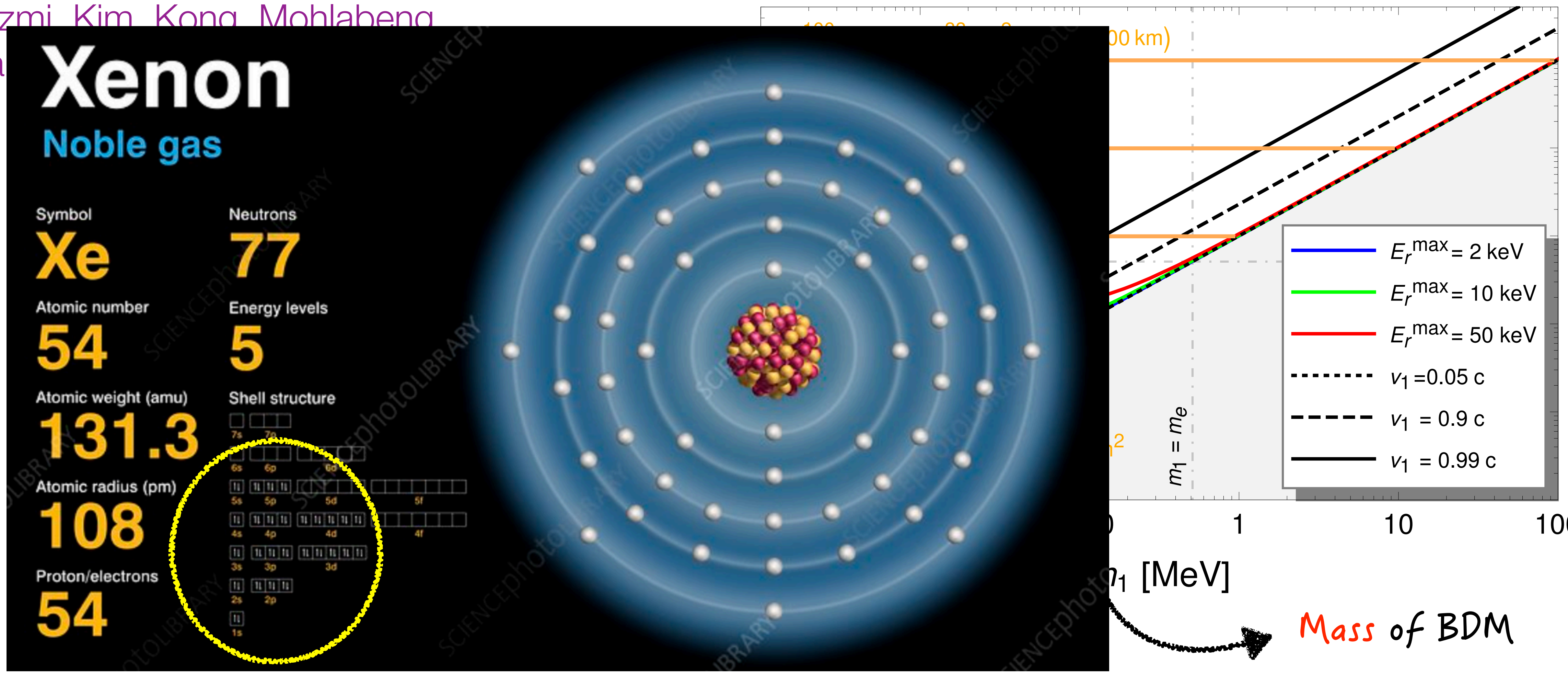


- The value of $N_e^{\mathrm{eff}} = 26$ is from naively considering the O-shell (outermost, 8) and the N-shell (18, binding energy ≲ 213 eV ~10% of the energy resolution).

- In practice, we need to consider ionization form factor from all the shells. (Do not significantly change the results but it depends on E_1 and mediators.)

Favored parameter region

Alhazmi, Kim, Kong, Mohlabeng
Pa



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Preliminary Work in progress with Alhazmi, Kim, Kong, Mohlabeng, Park, **SS**

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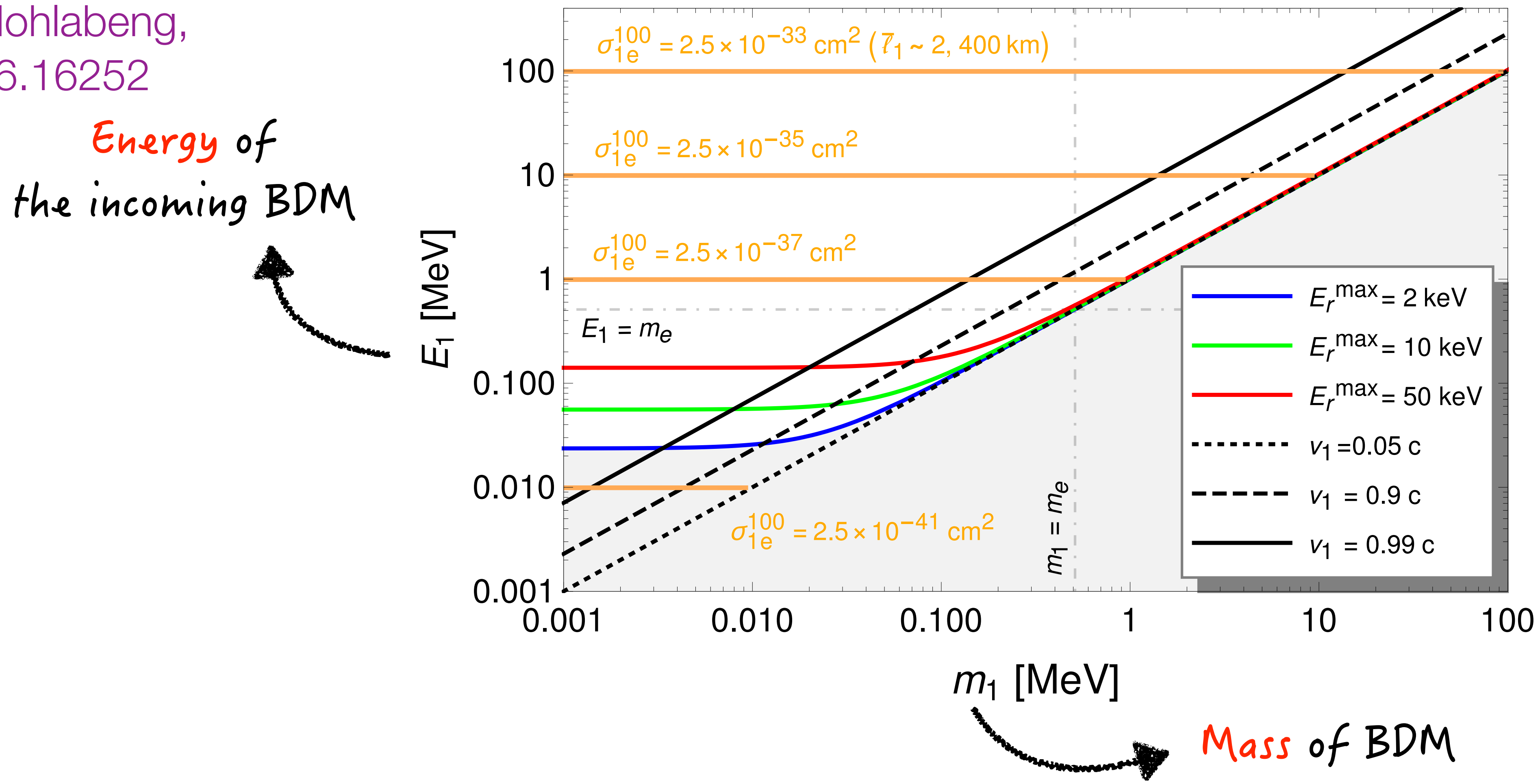
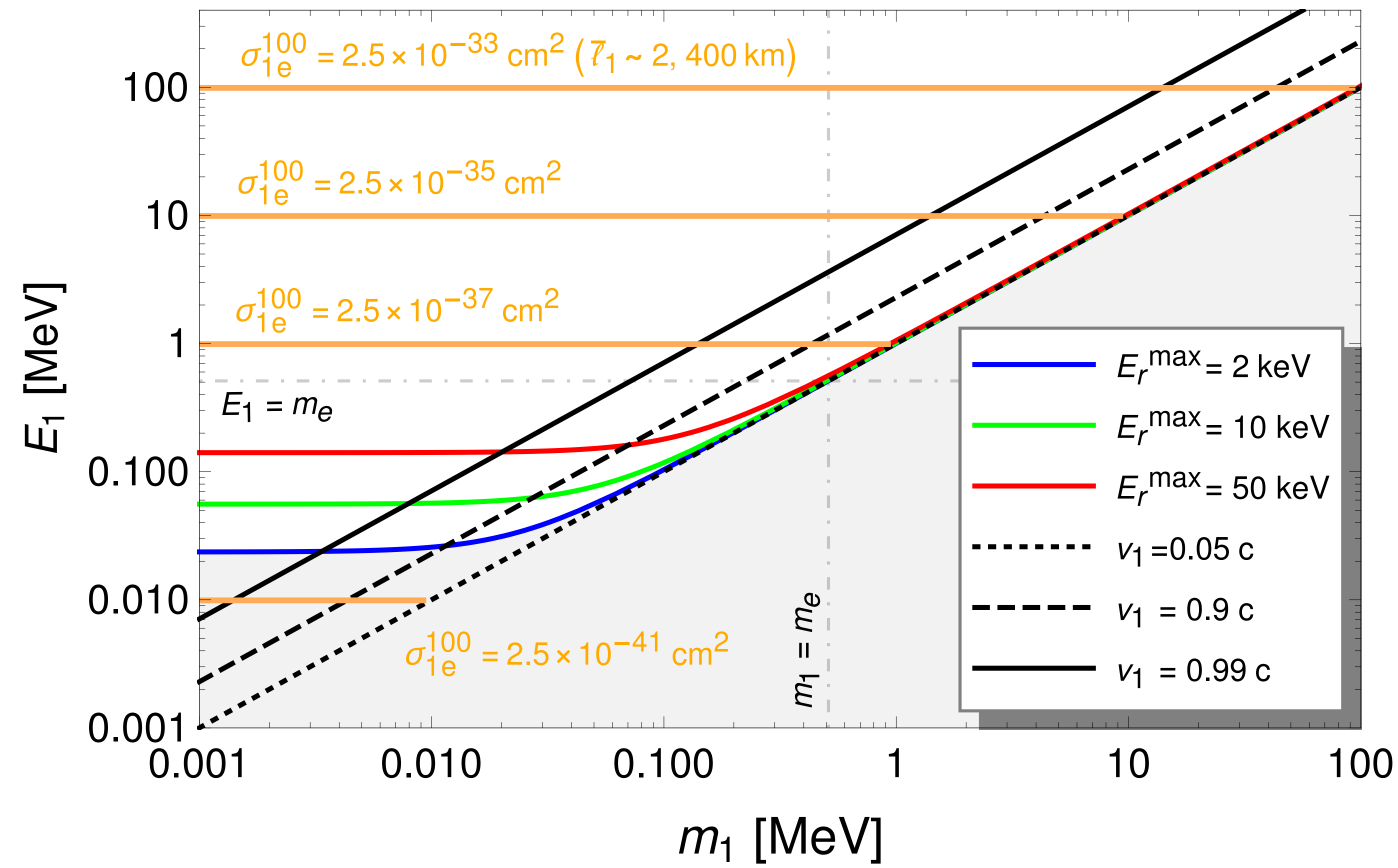
Alhazmi, Kim, Kong, Mohlabeng,
Park, **SS**, arXiv: 2006.16252



- 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).

Dependence on mediators

mediator	DM
V	F
V	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.

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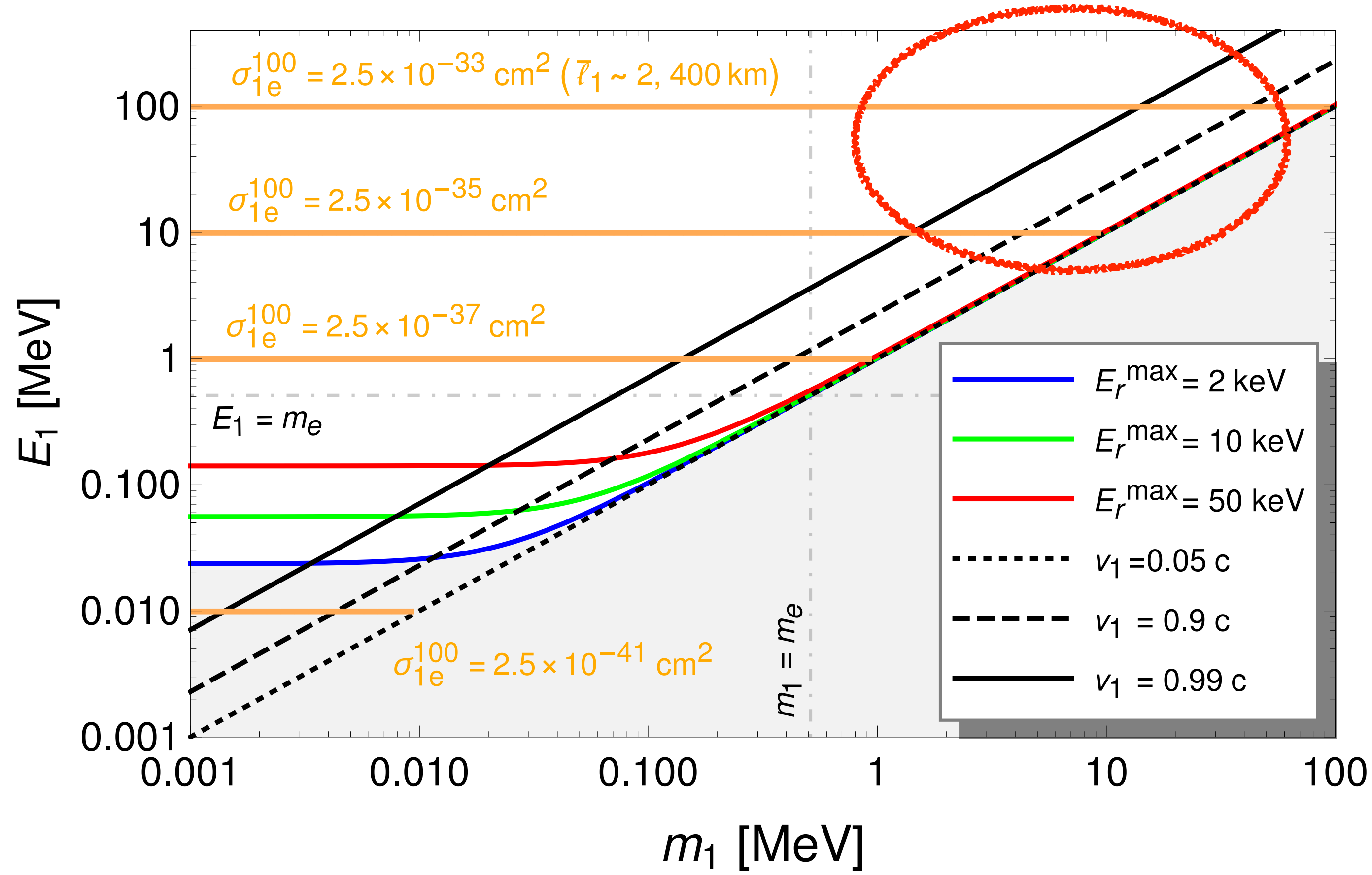

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(i) $E_1 \approx m_1 \gg m_e\,, \quad m_i \gg m_e$

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

Dependence on mediators

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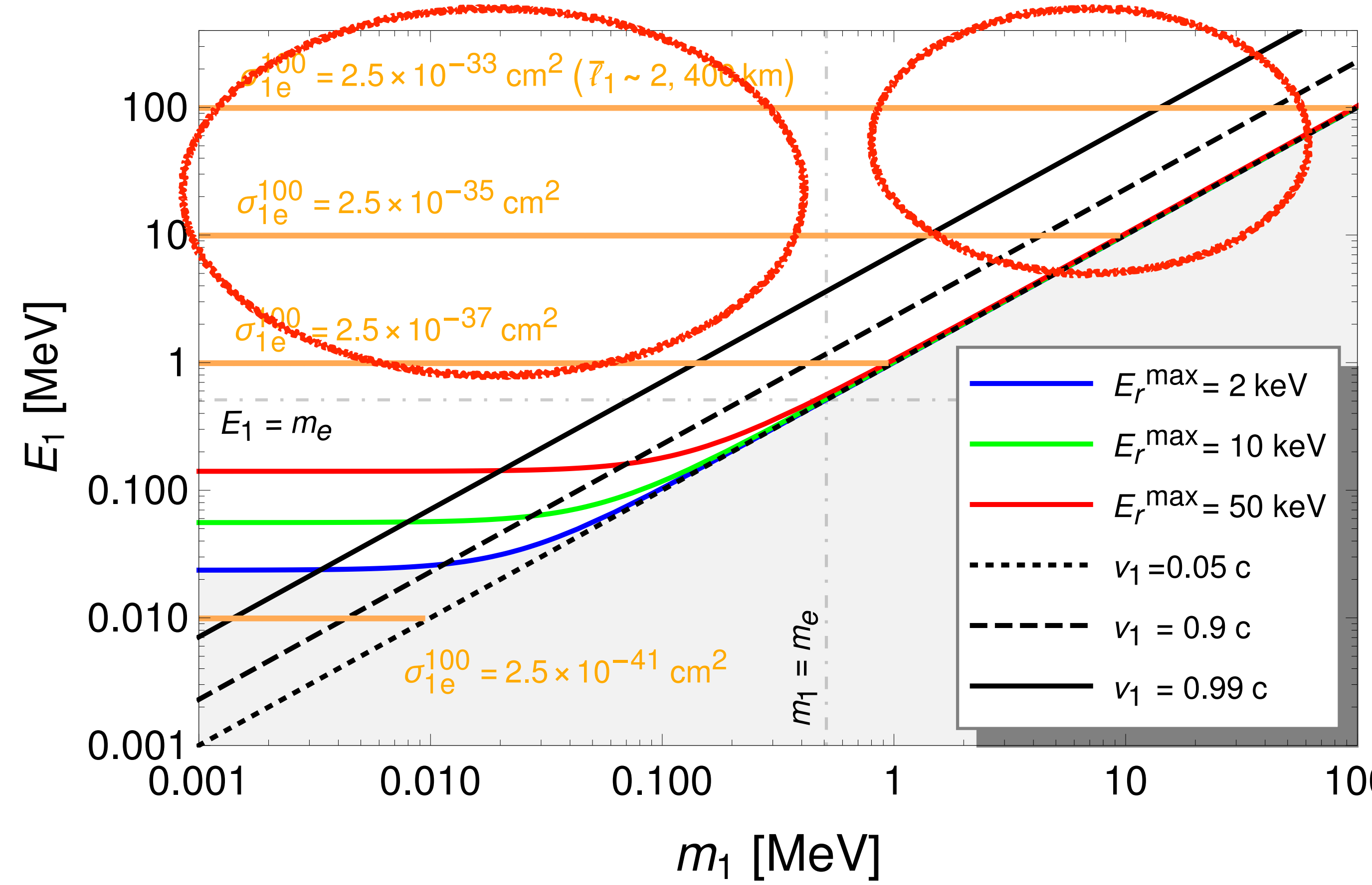
P	F
P	S
S	F
S	S



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

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

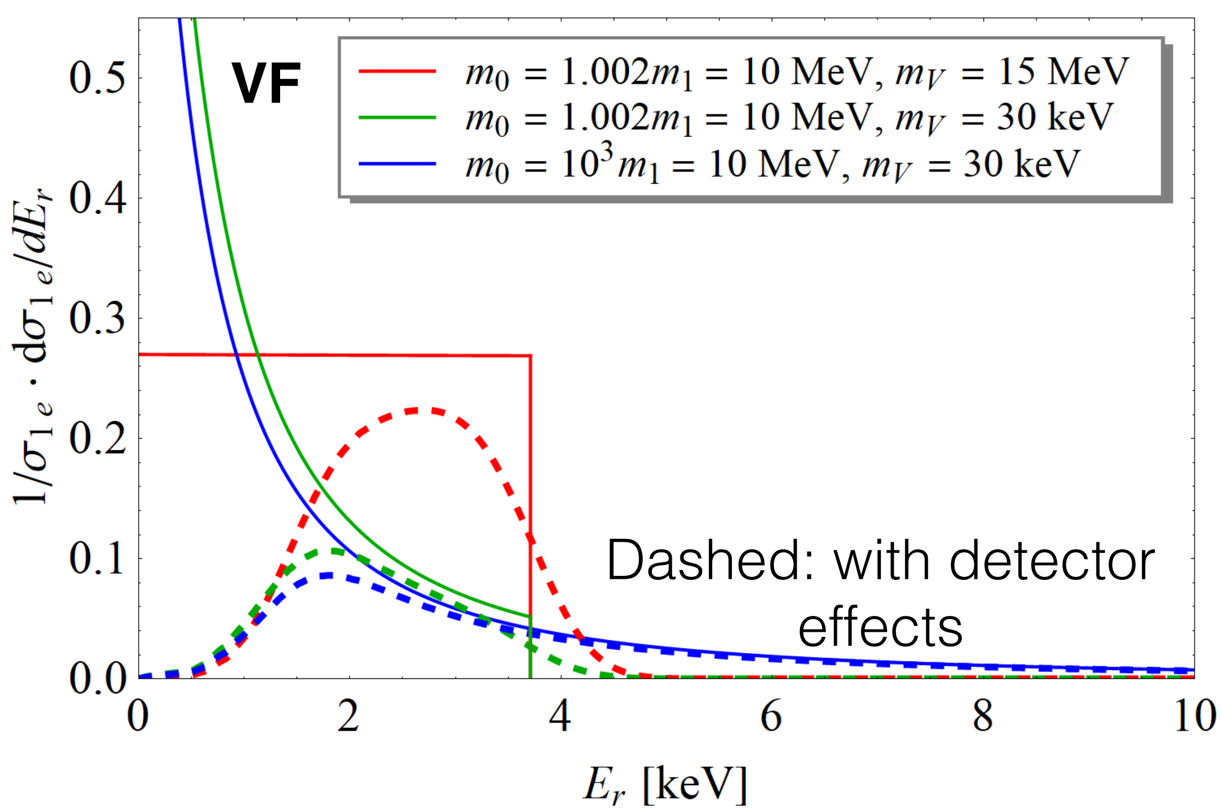
Dependence on mediators

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

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	$(g_e^\phi\bar{e}e + g_\varphi^\phi m_1\varphi^*\varphi)\phi$	$8m_em_1^2(E_r + 2m_e)$

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) $\frac{d\sigma_{1e}}{dE_r} \propto \frac{m_e E_1^2}{(2m_eE_r + m_V^2)^2}$



Dependence on mediators

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

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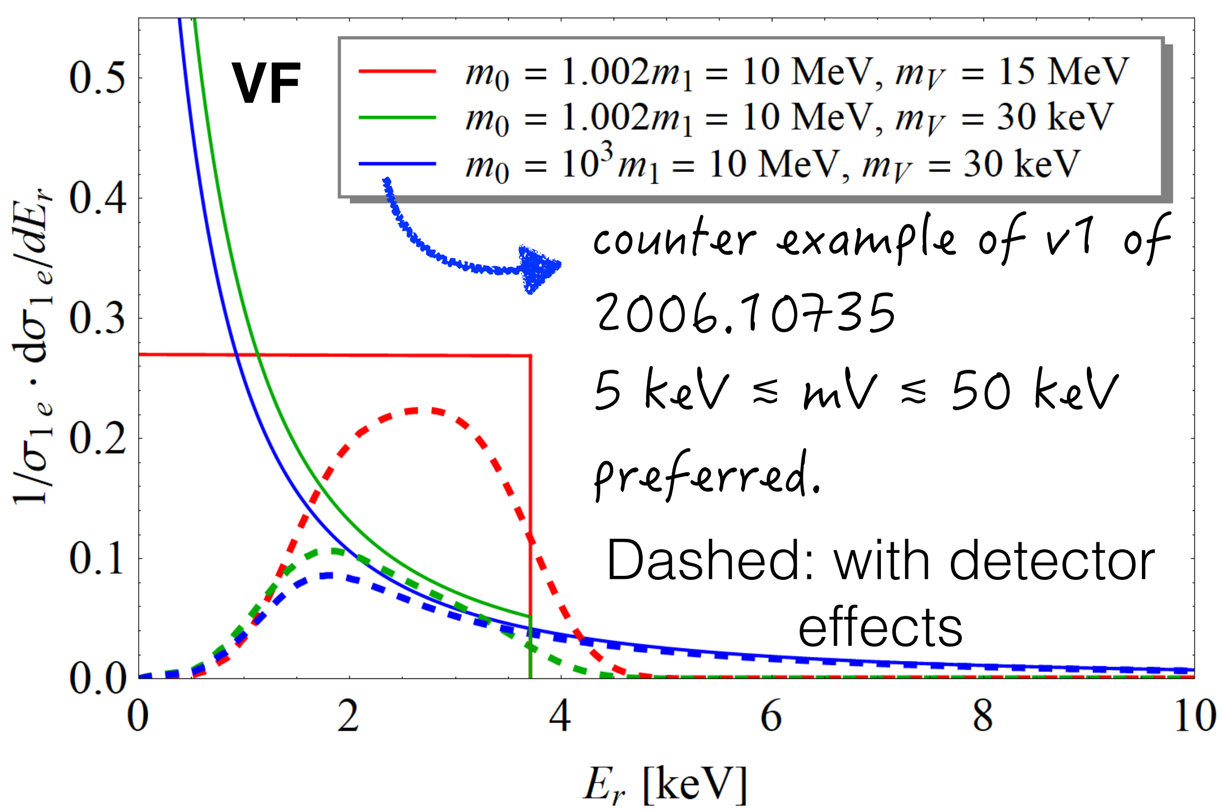

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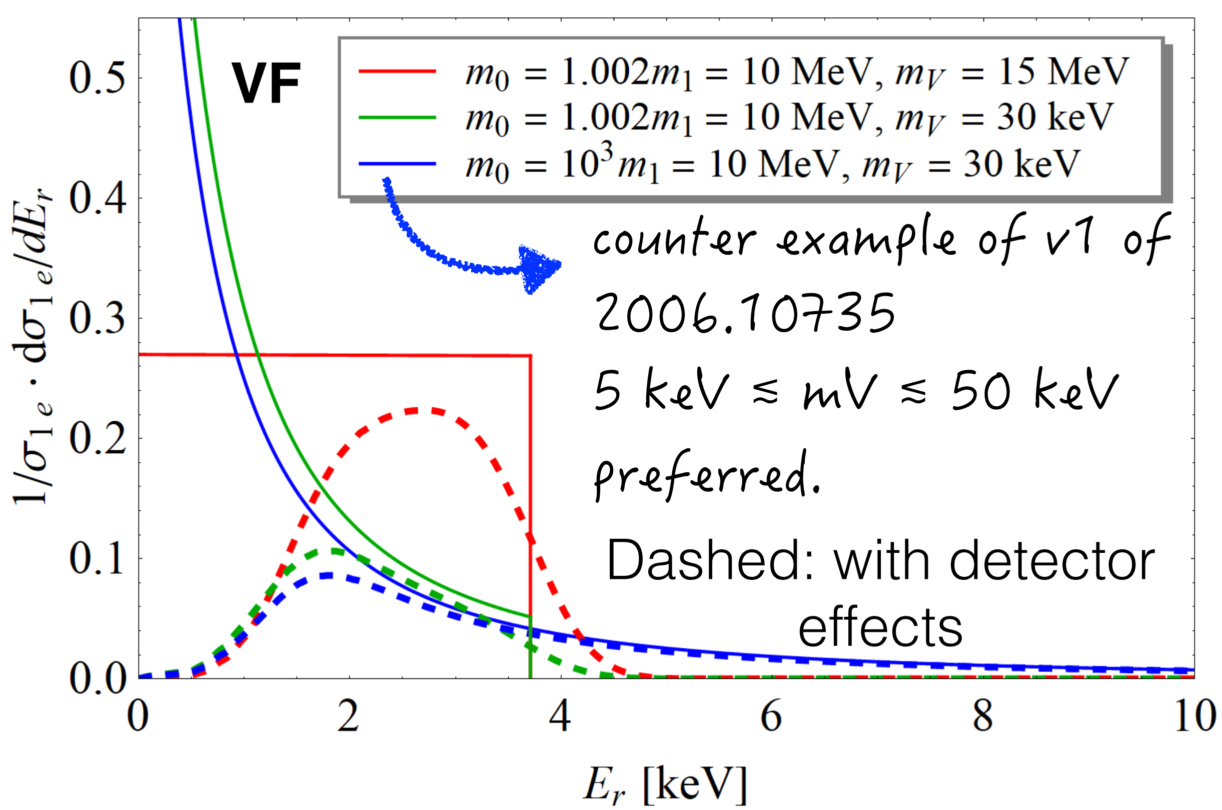

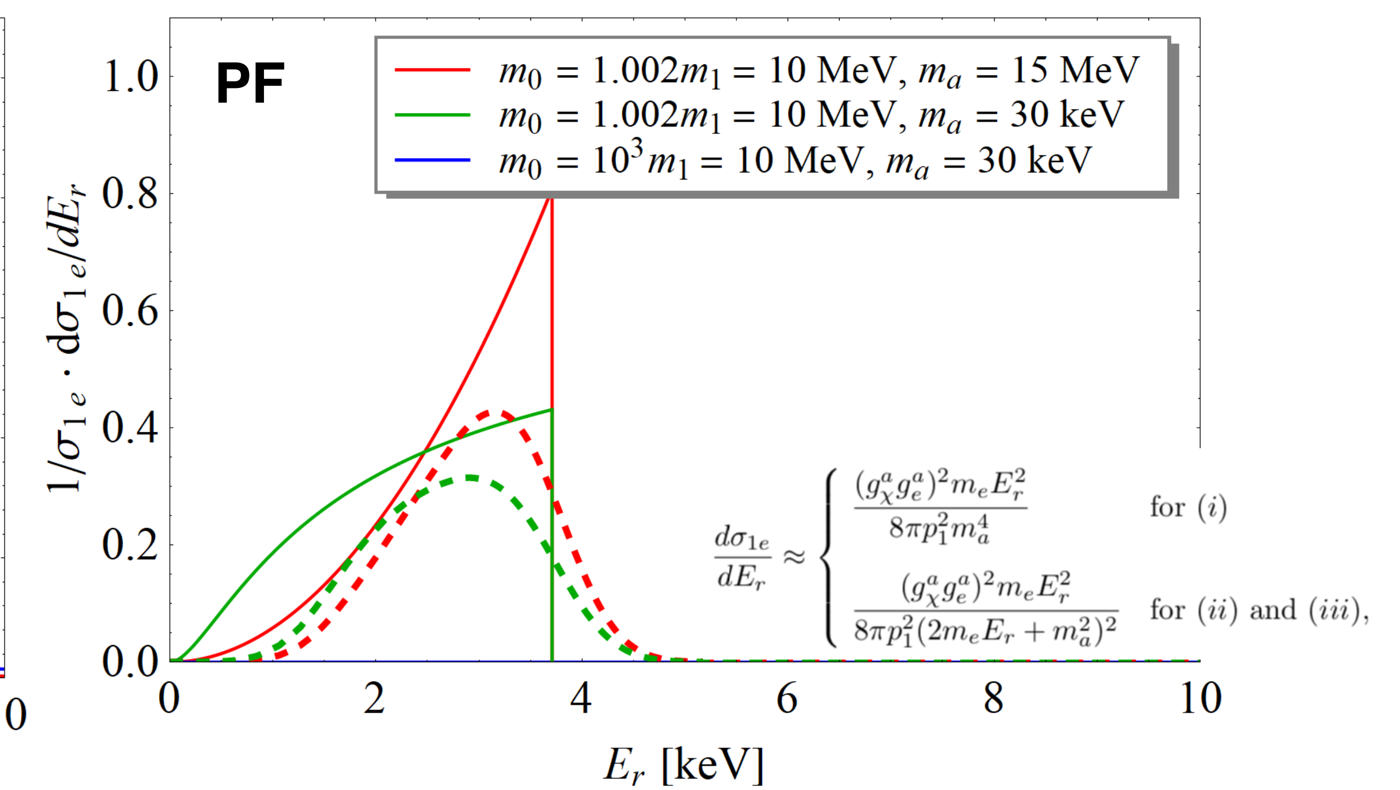

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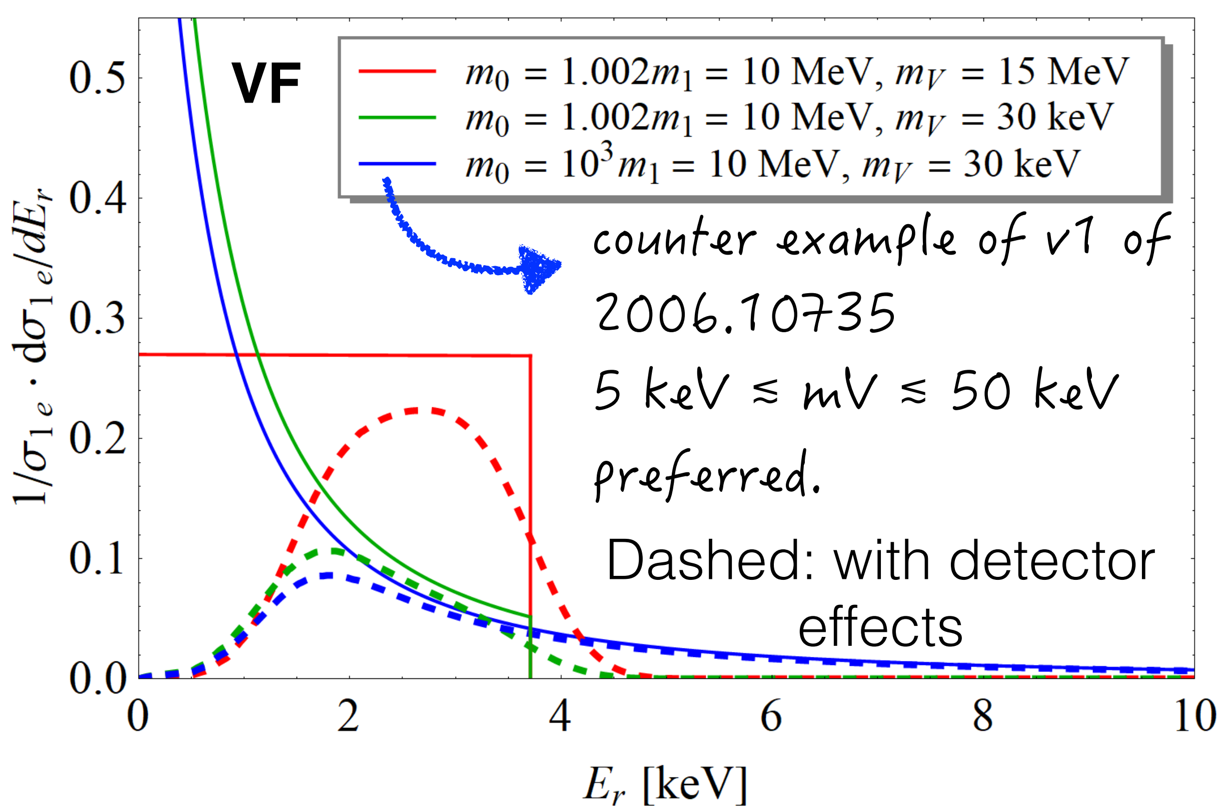
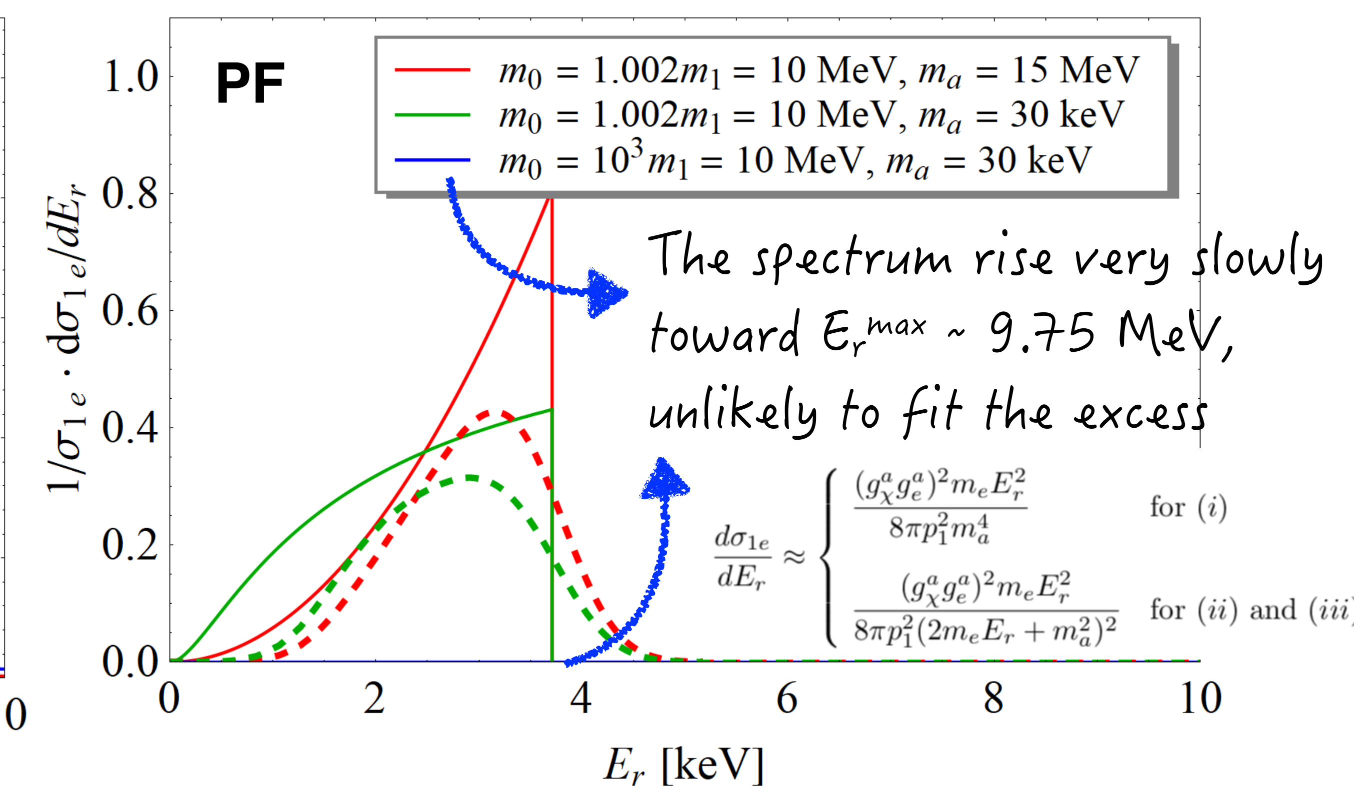
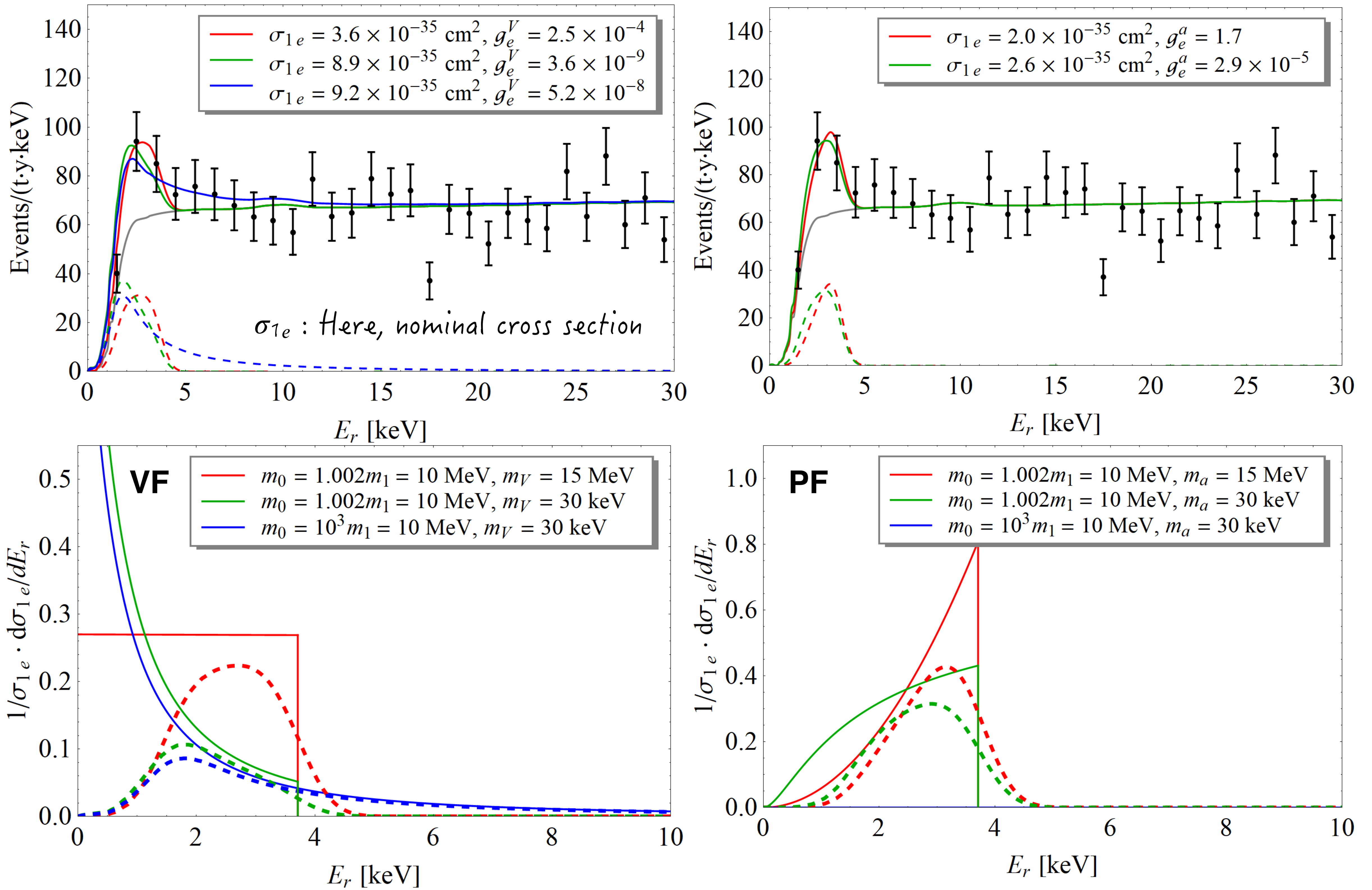




Fit to the excess



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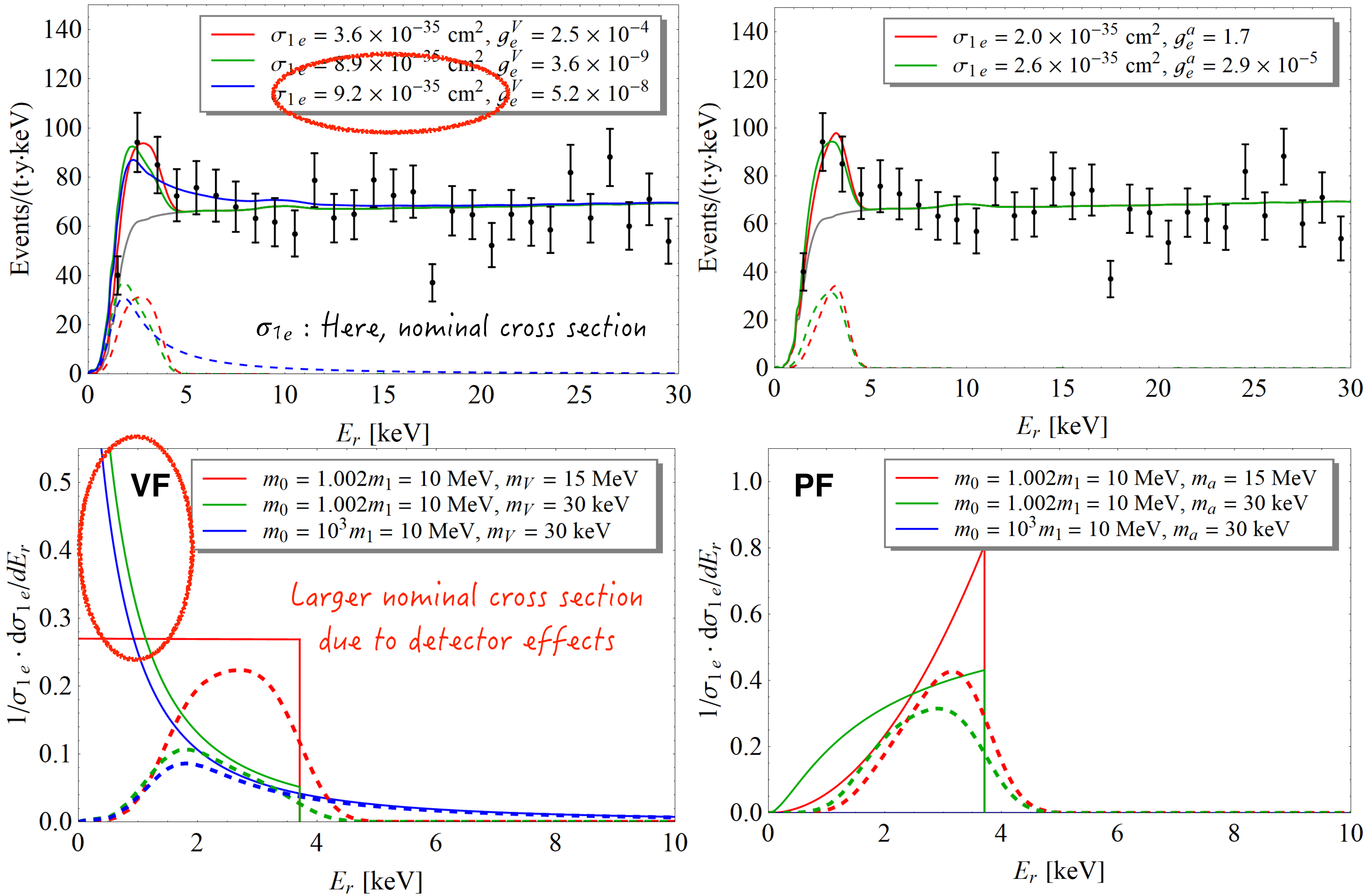
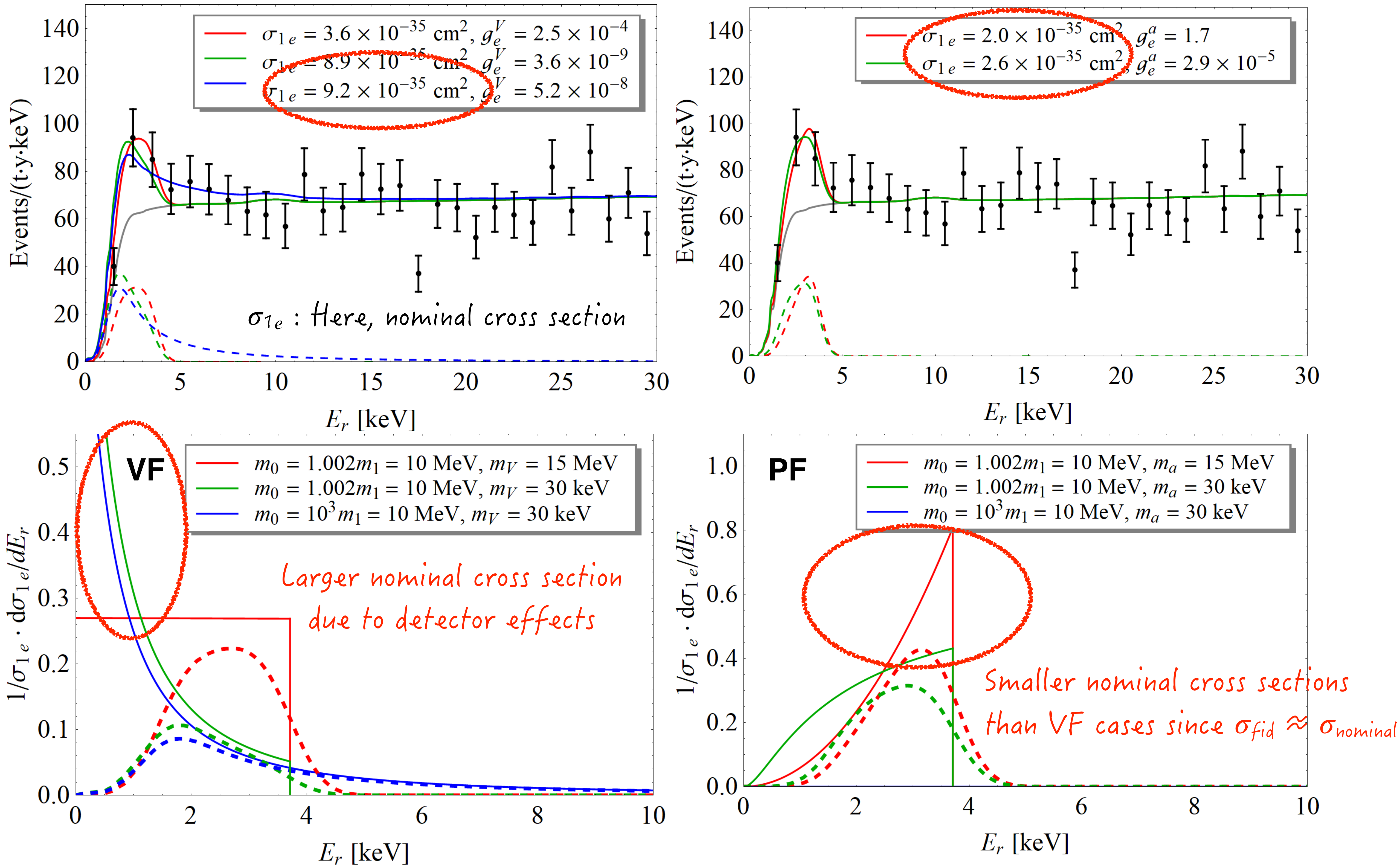
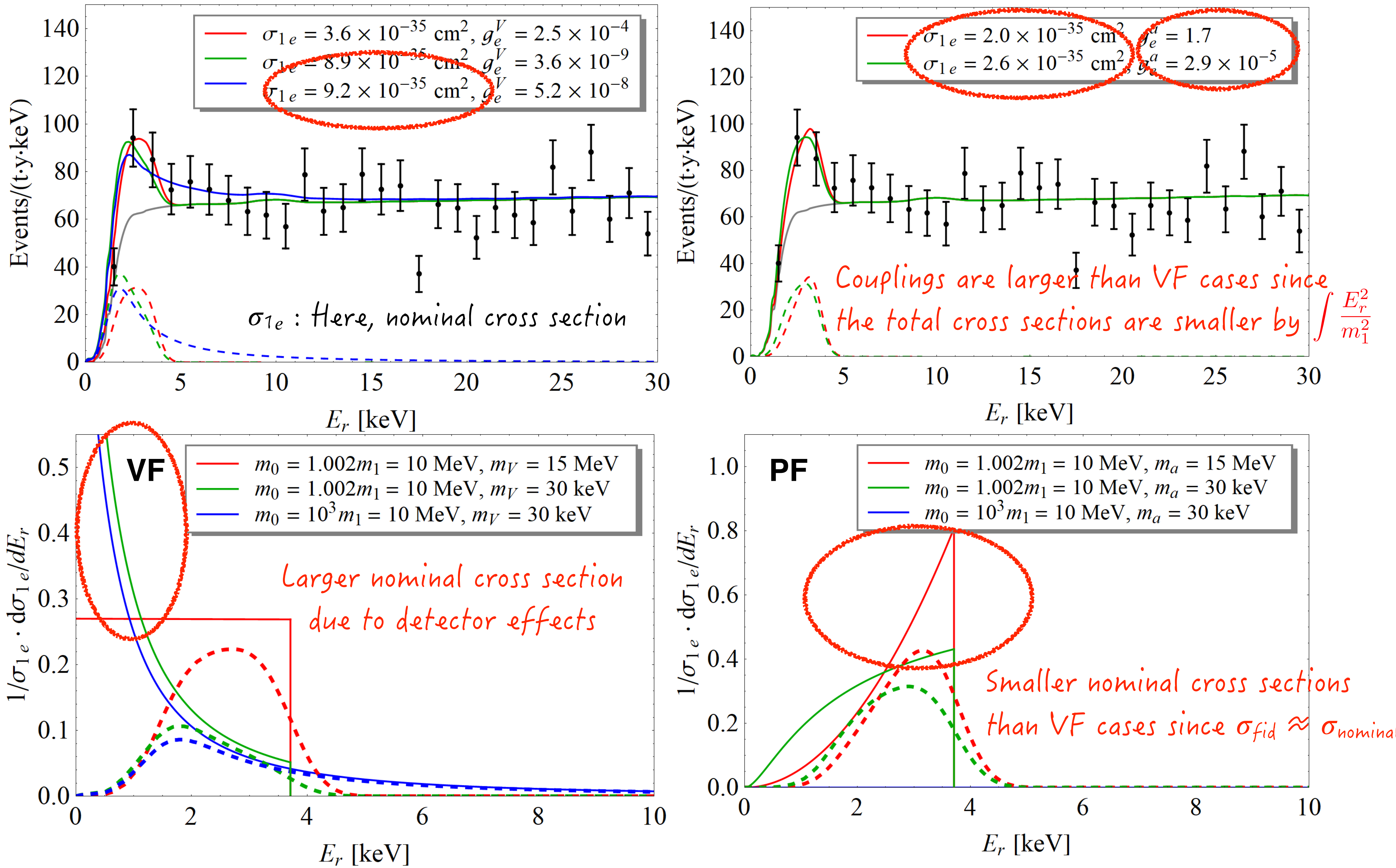


Fit to the excess



Fit to the excess



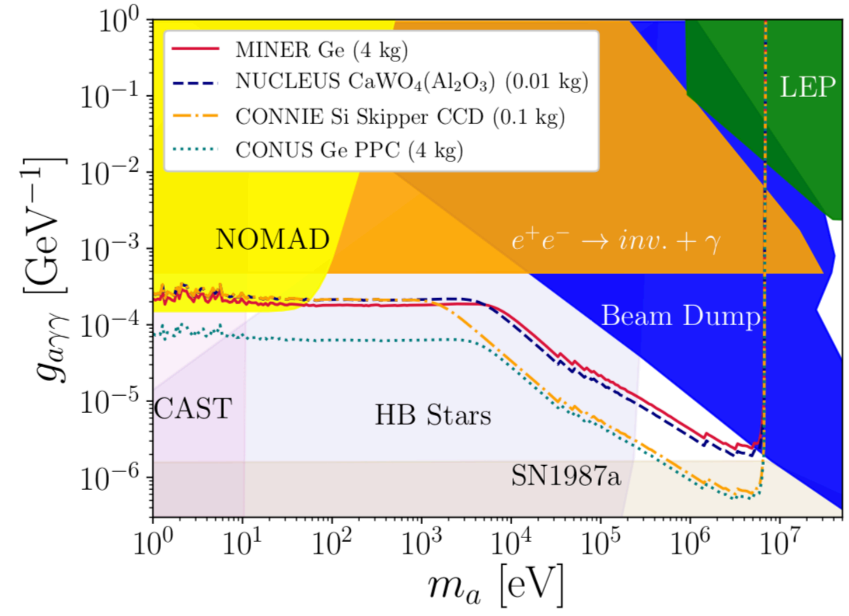
Fit to the excess

	Region (i)	Region (ii)	Region (iii)
$\gamma_{\rm BDM}$	≈ 1	≈ 1	$\gg 1$
VF	✔(flat)	✓(falling)	✓(falling)
VS	✔(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?



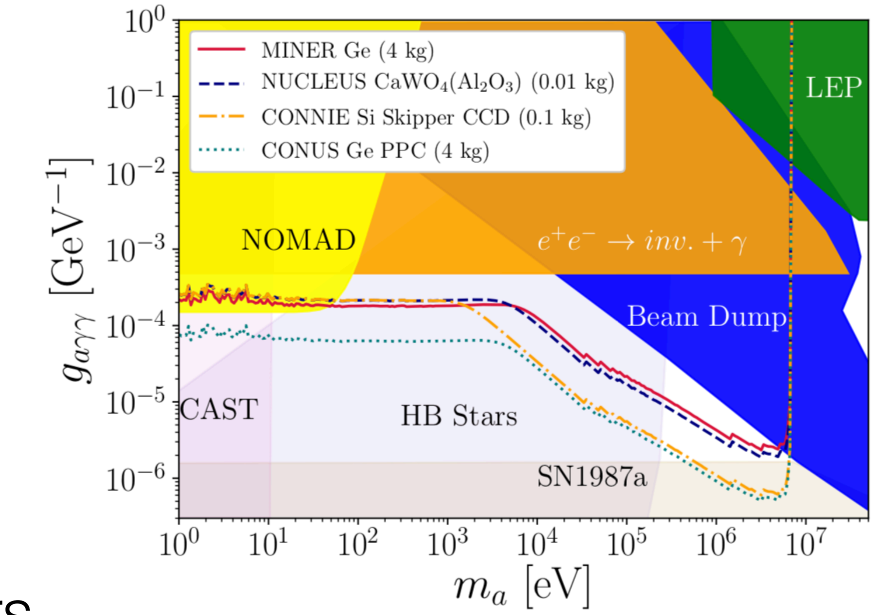
Dent et al., PRL 2020

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.



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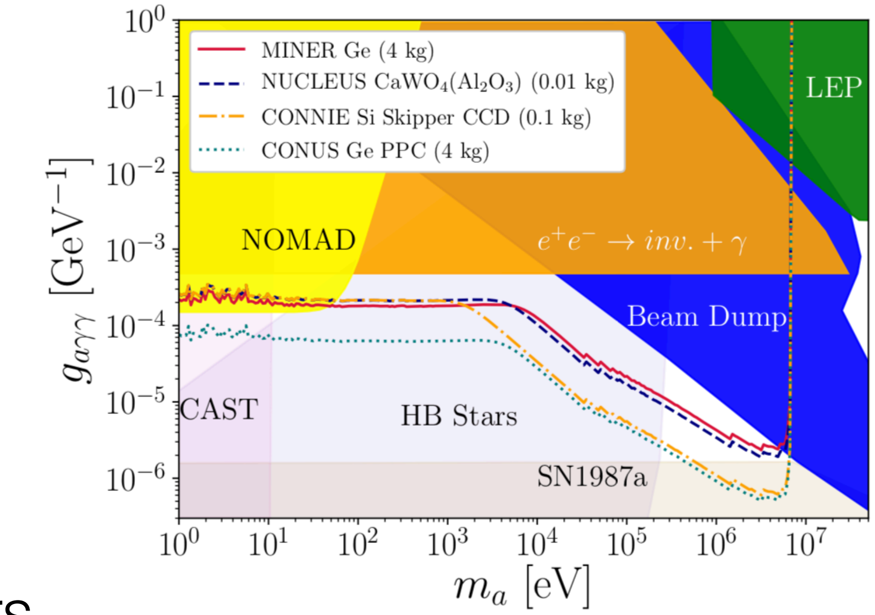

Dent et al., PRL 2020

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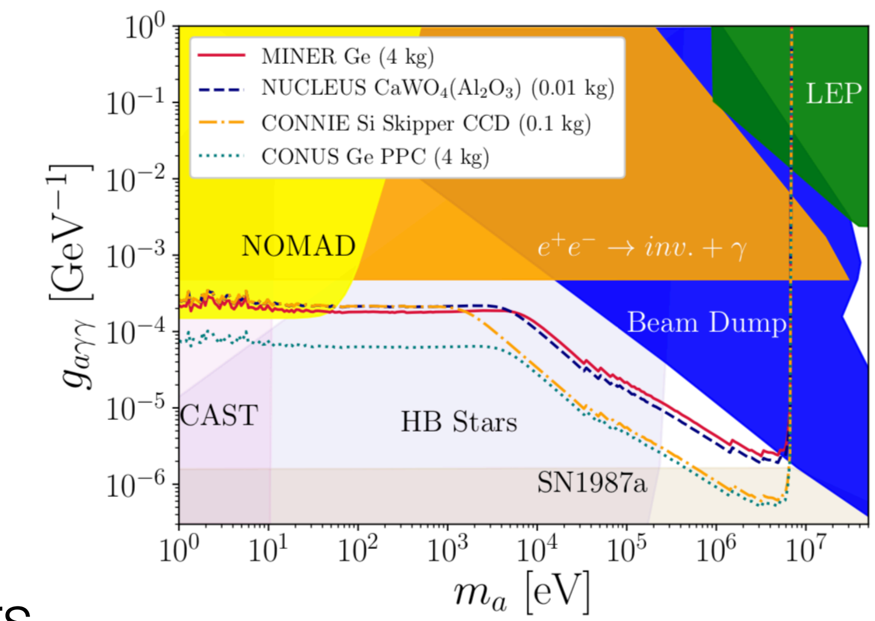

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Dent et al., PRL 2020

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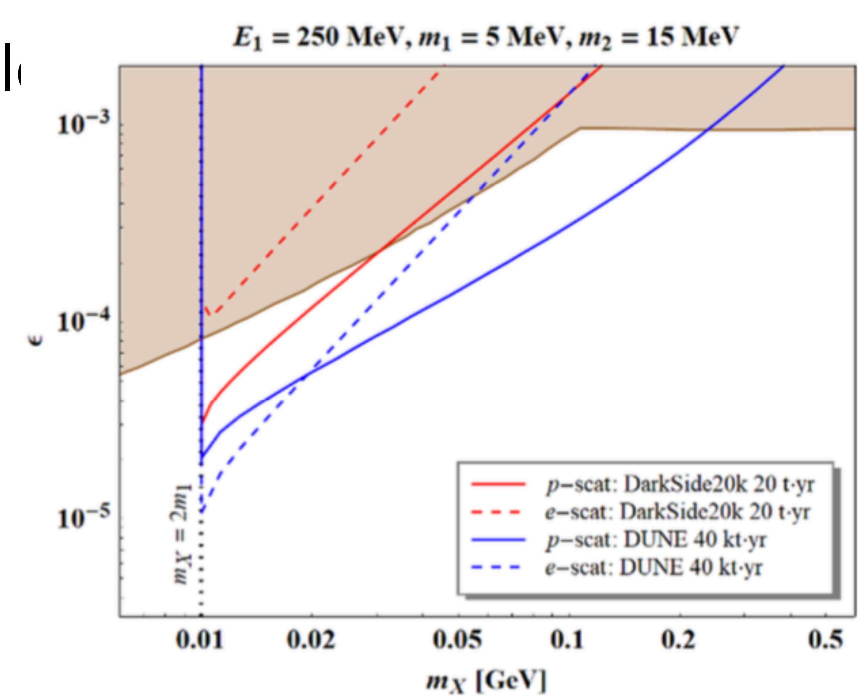


  - Complimentary searches are possible.

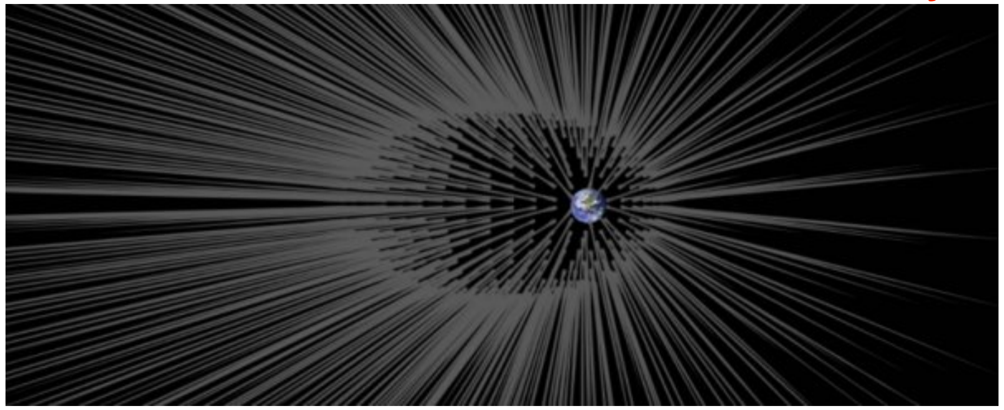
Kim, Machado, Park, **SS**, JHEP 2007, 057 (2020)

Conclusions

- The XENON1T excess can be a smoking gun signal of Dark World beyond WIMP: fast moving DM, e.g., Boosted Dark Matter.
- The dedicated analyses will be helpful in future studies in XENON-NT, DarkSide, COSINE-200, …
- Fitting the excess with BDM is nontrivial (large cross section, mean free path, a narrow range of E_R, binding energy of the electron).
- We found a wide range of BDM parameter region that can fit the excess including $v \sim c$ and $m_1 < m_e$ for various mediator masses.
- The scales of mass and couplings preferred by the excess relies on the type of mediator (further studies for more reference models needed).
- Our method is general, and hence readily applicable to the interpretation of observed data in the DM direct detection experiments.

Energetic dark matter from the Universe

WIMP wind ~ O(100 km/s)



≫ 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

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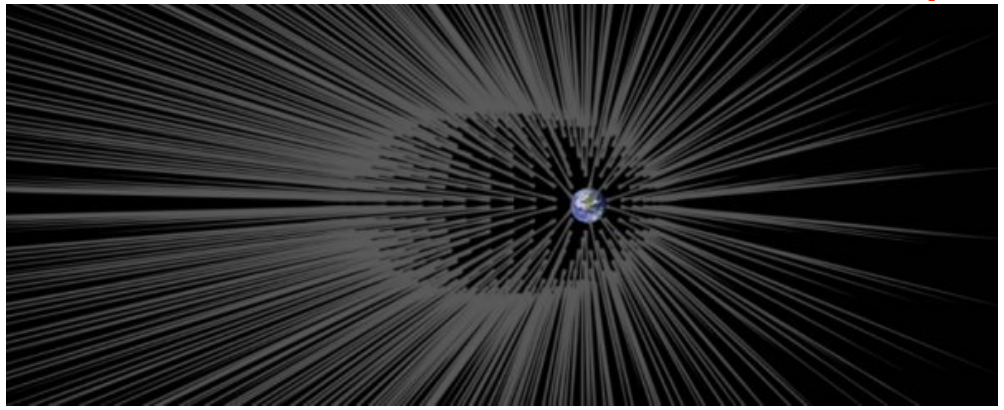

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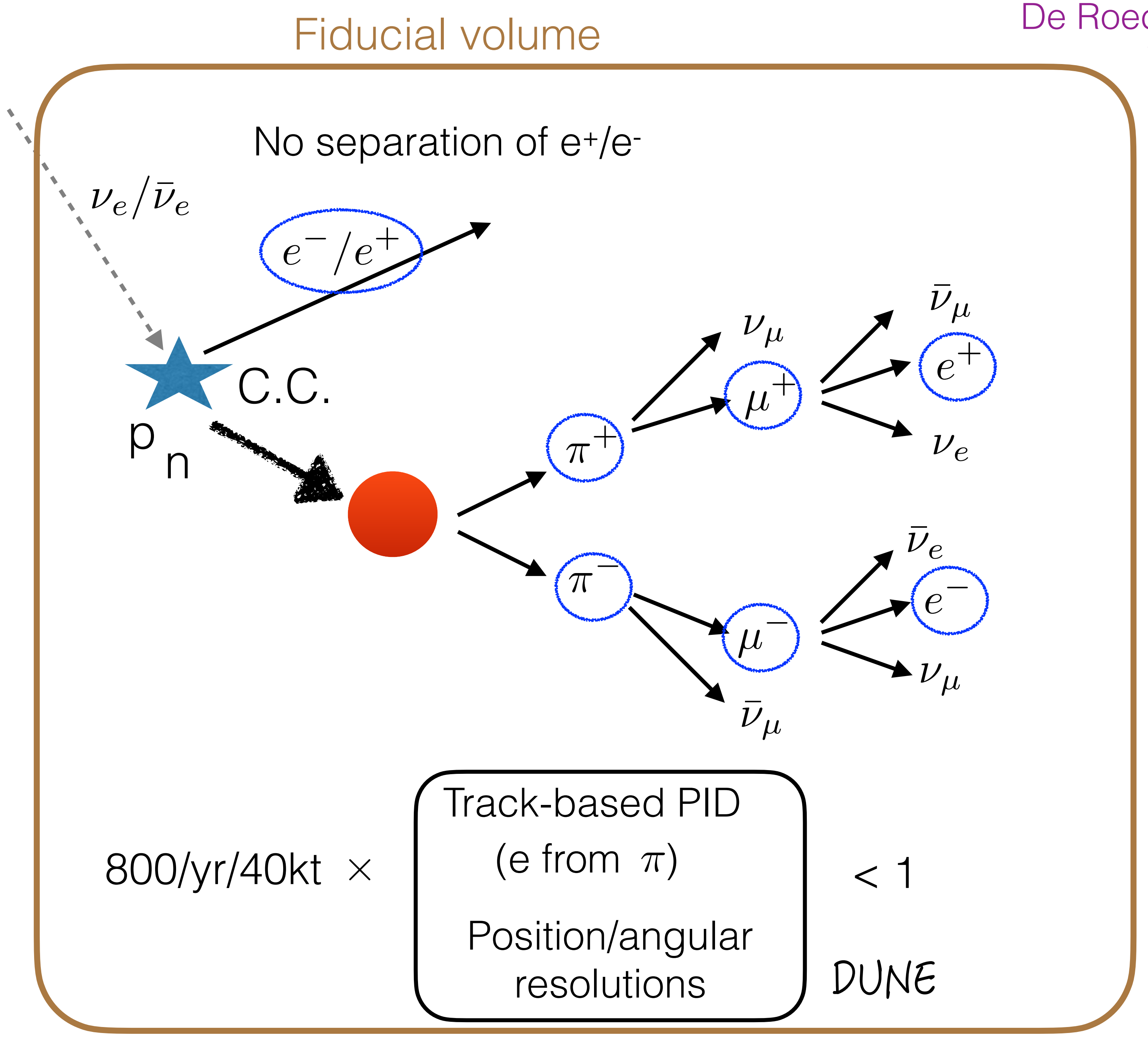
- Boosted Dark Matter: DM boosted by the dark sector structure

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

Backup: Background candidate

e.g., primary: e-scattering, secondary $e^+ e^-$ iBDM

De Roeck, Kim, Moghaddam, Park, **SS**, Whitehead, 2005.08979



χ_1: light BDM, χ_2: excited state

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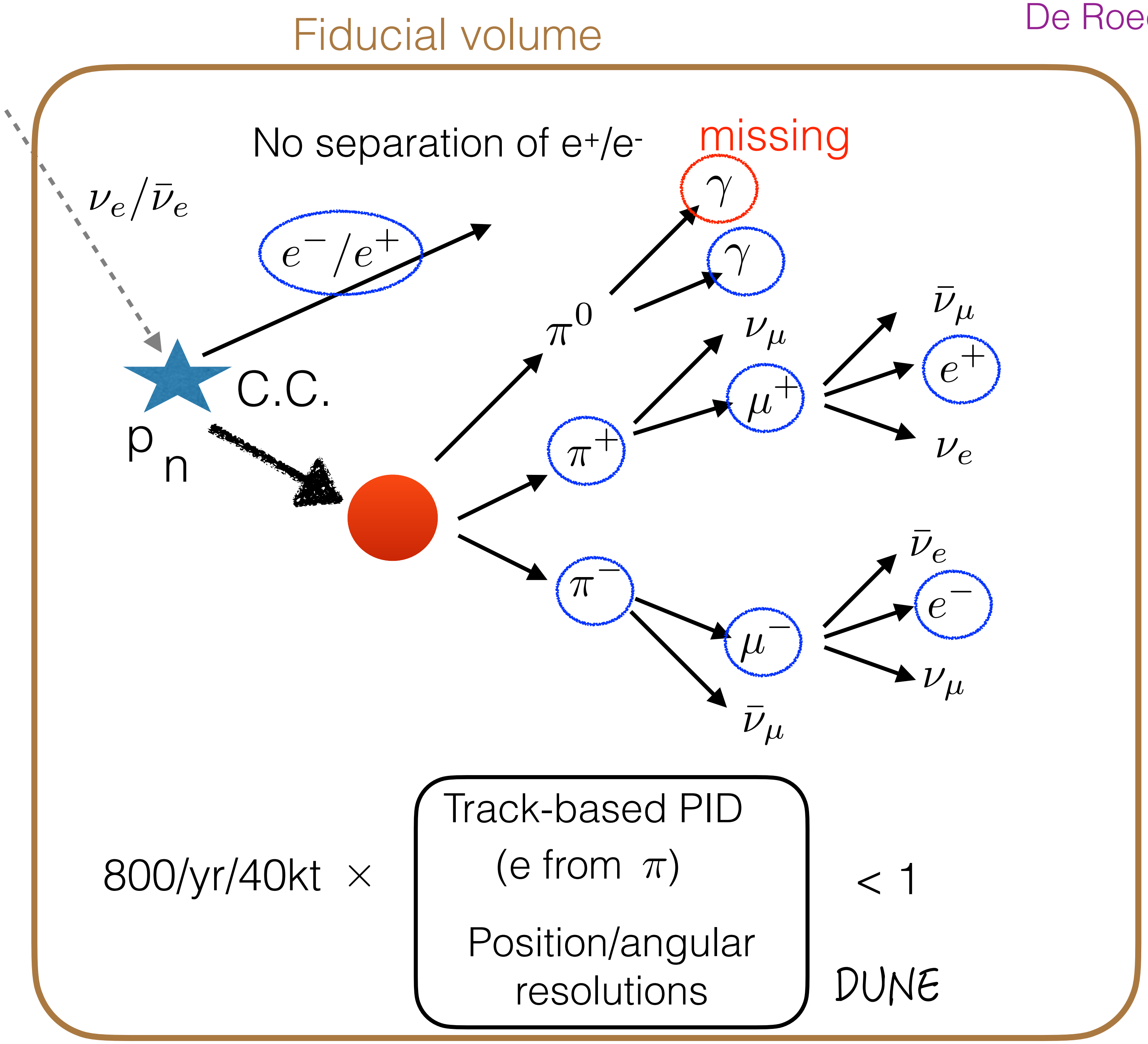

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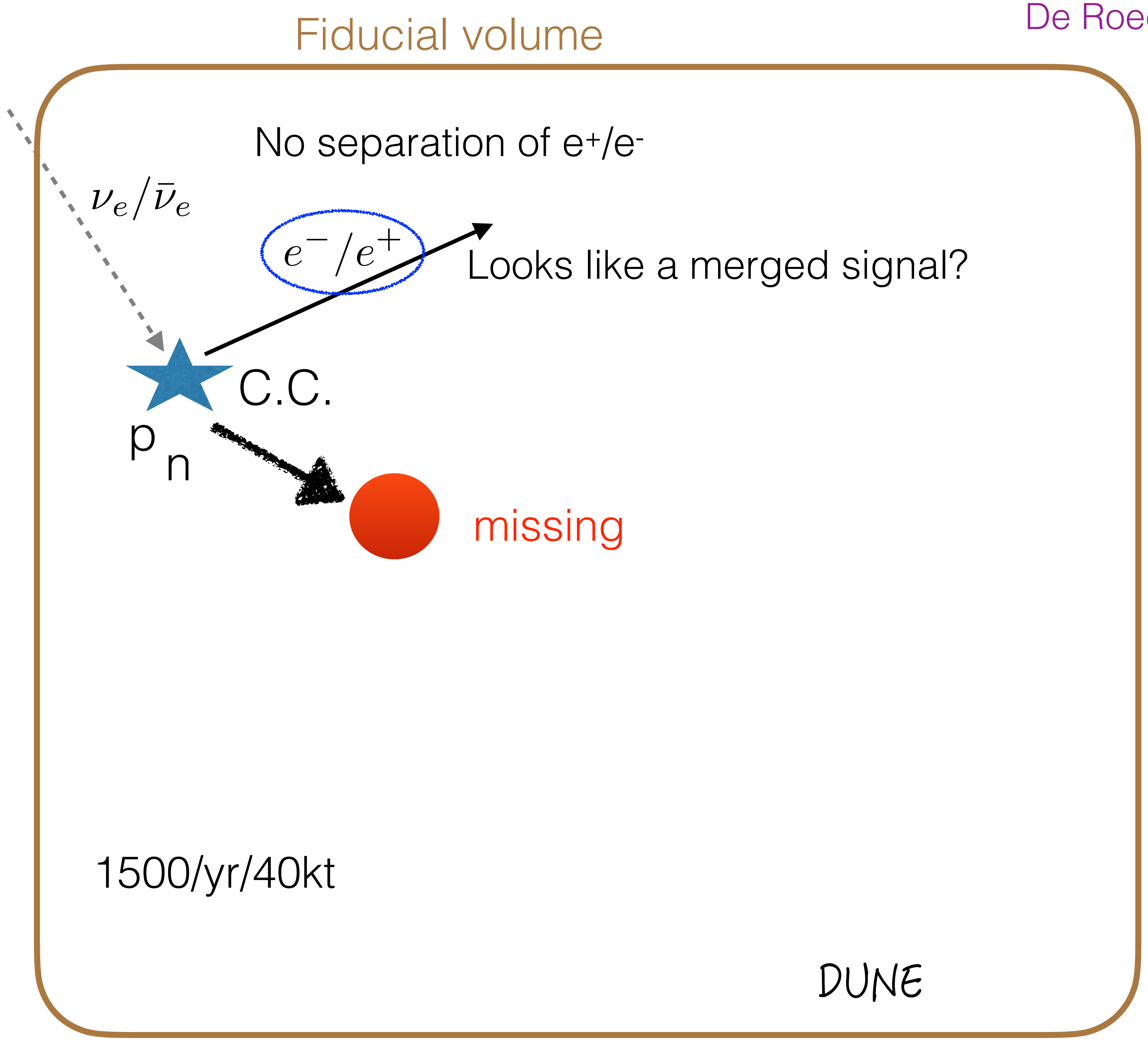

μ

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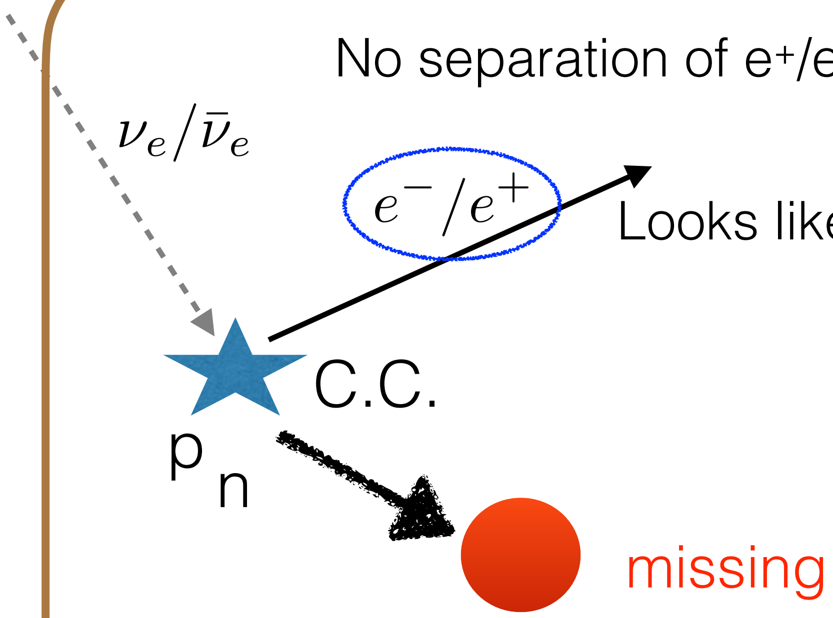
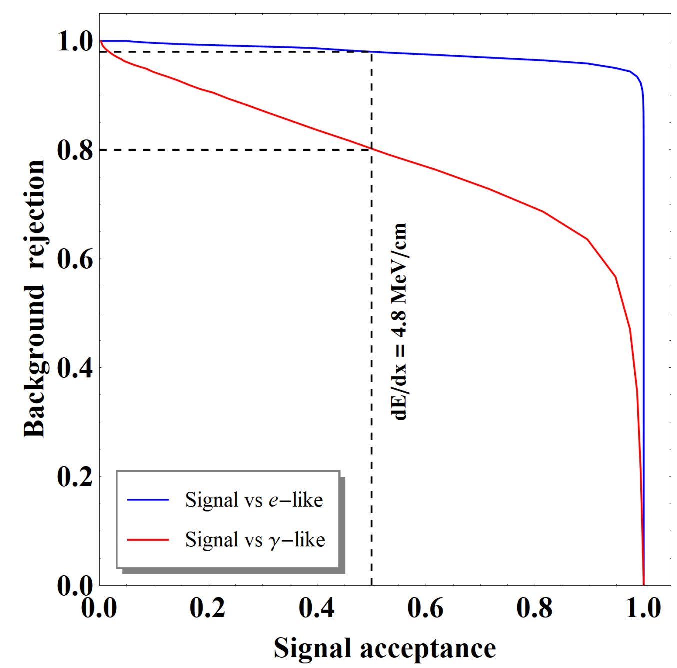
De Roeck, Kim, Moghaddam, Park, **SS**, Whitehead, 2005.08979

Fiducial volume

No separation of e^+/e^-



Looks like a merged signal?



1500/yr/40kt × dE/dx comparison with a merged signal

Very conservative $\lesssim O(10)$

DUNE

μ

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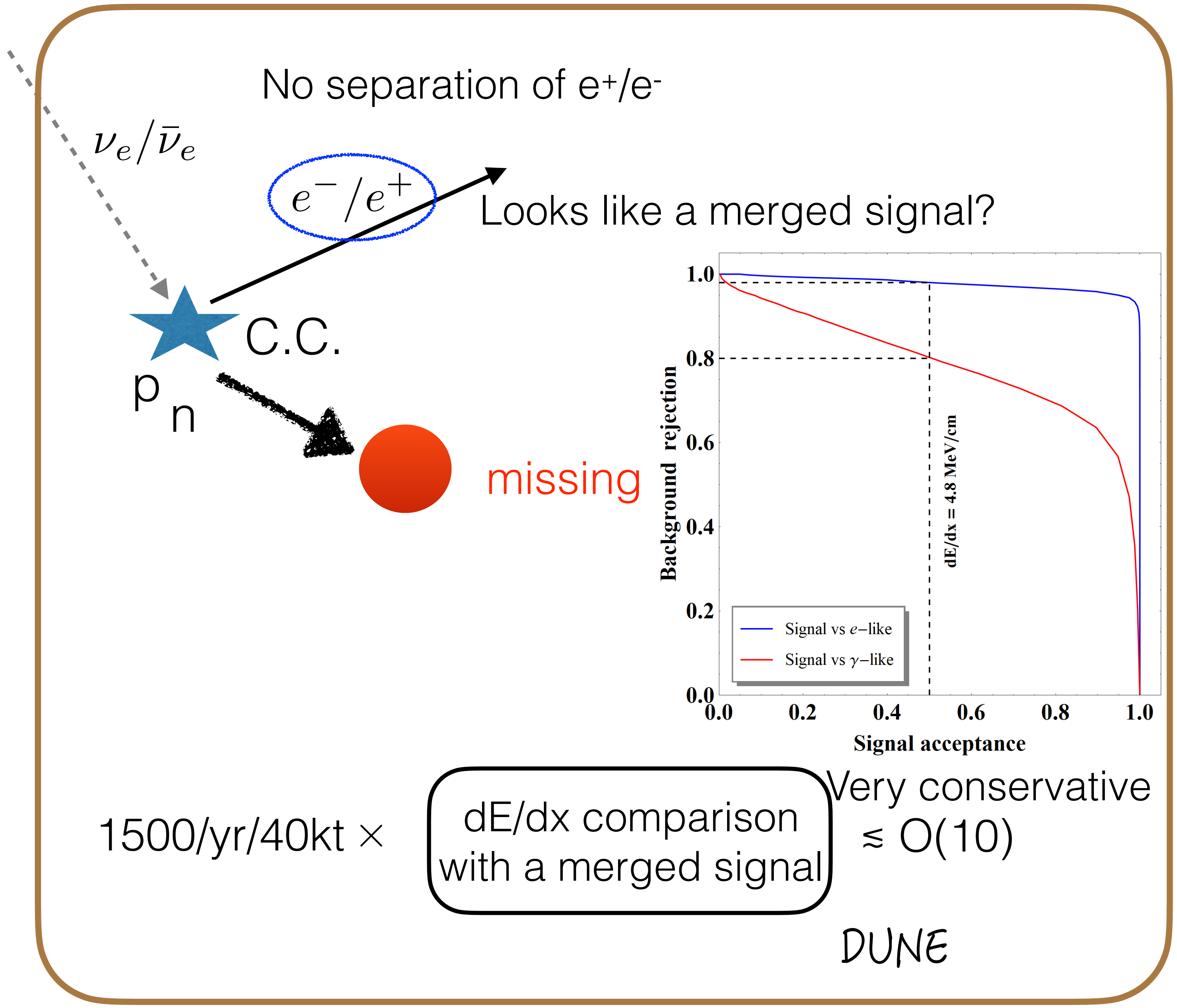

χ_1: light BDM, χ_2: excited state

- Other subdominant bkg. negligible

  N.C. events (smaller)

  ν_μ: accompanying μ

  ν_τ: too small flux

  Comic-ray: flux & PID

- Zero-bkg. is easily achievable

- (quasi-elastic) proton scattering: less bkg.