NEPLES 2019

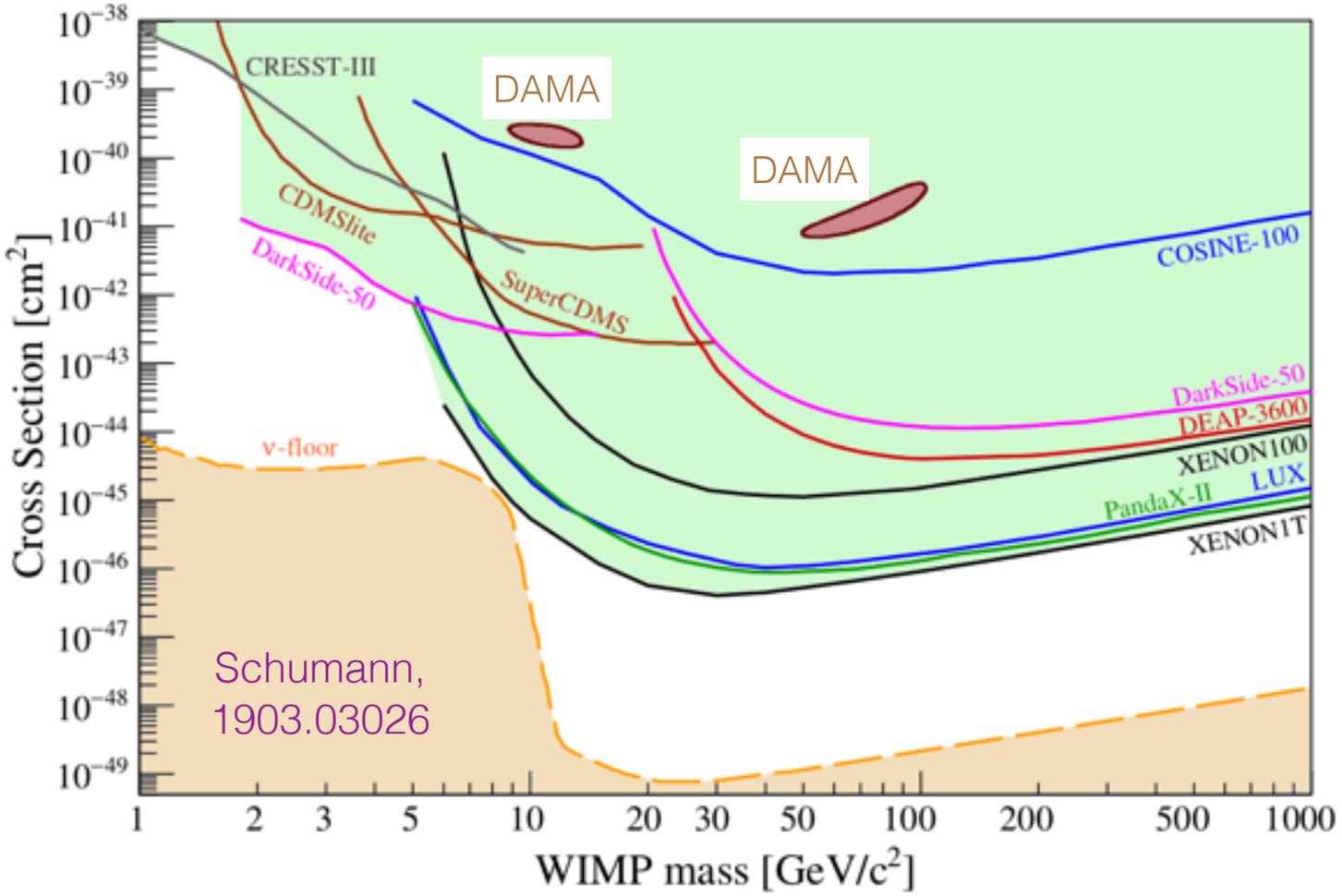
Inelastic Boosted Dark Matter (iBDM) at low energy scale experiments

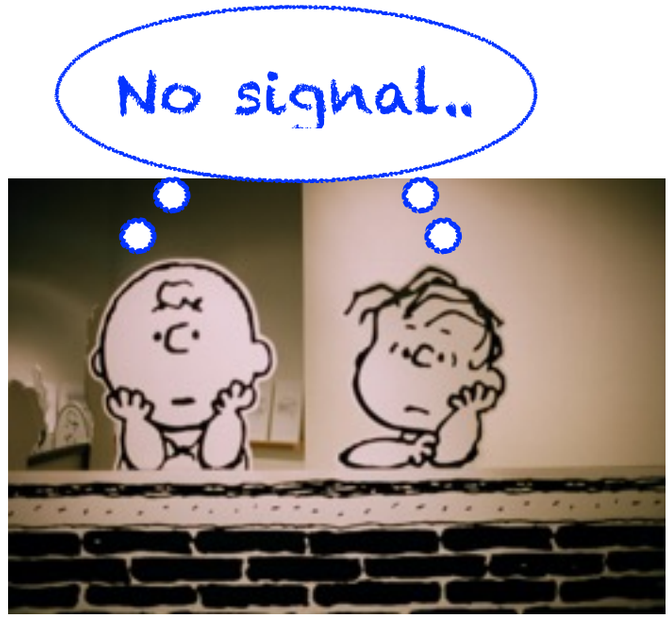
Seodong Shin

Bhaskar Dutta, Gian F. Giudice, Doojin Kim, Shu Liao, Kyoungchul Kong,
Pedro A. N. Machado, Jong-Chul Park, Louis Strigari

DUNE experimentalists: Chatterjee, De Roeck, Moghaddam, Whitehead, Yu

Dark World beyond WIMP





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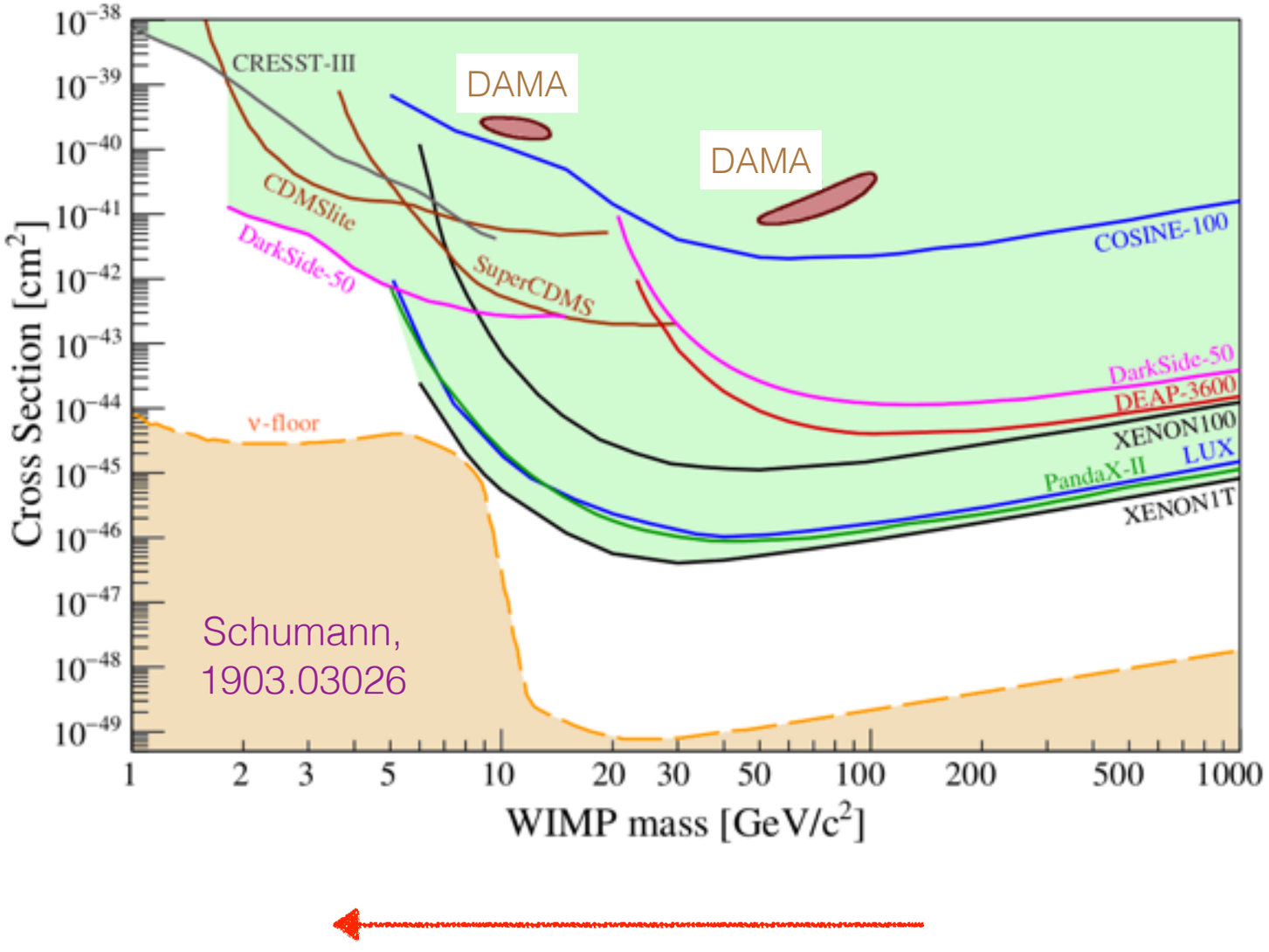
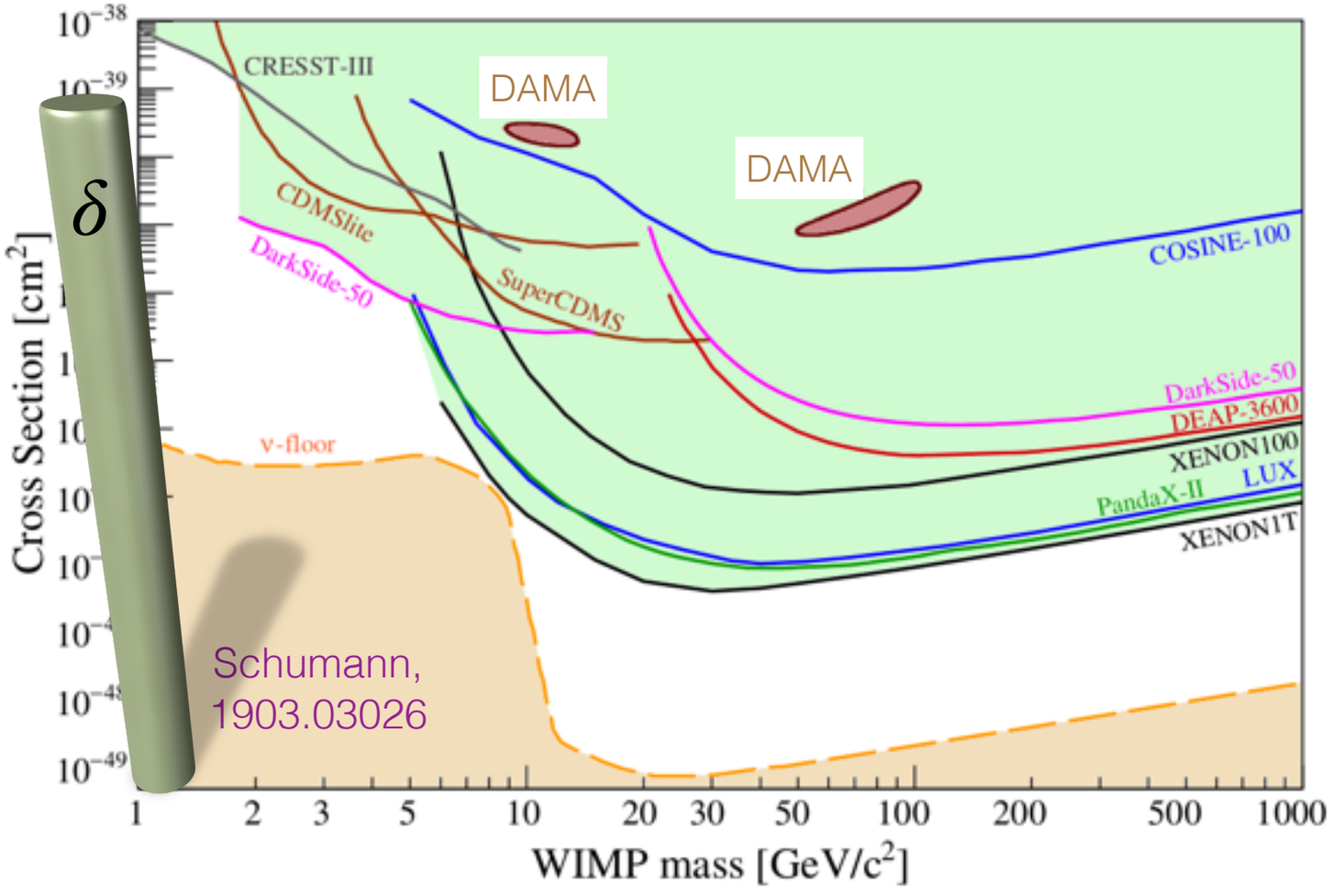


- Smaller couplings
- Lower mass
- Inelastic scattering (dark sector particles)

Dark World beyond WIMP



- Smaller couplings
- Lower mass
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Motivated by Paddy Fox's slides in Korea University, 2019

Searches for New Dark World

Low Energy experiments

- Accelerators (mostly C.O.M <10 GeV here) with high intensities

  B-factories, Fixed target experiments, Beam-dump, Neutrino experiments

Lots of talks in this workshop and the references such as

Batell, Pospelov, Ritz, 0906.5614

Bjorken, Essig, Schuster, Toro, 0906.0580

Searches for New Dark World

Low Energy experiments

- Accelerators (mostly C.O.M <10 GeV here) with high intensities

  B-factories, Fixed target experiments, Beam-dump, Neutrino experiments

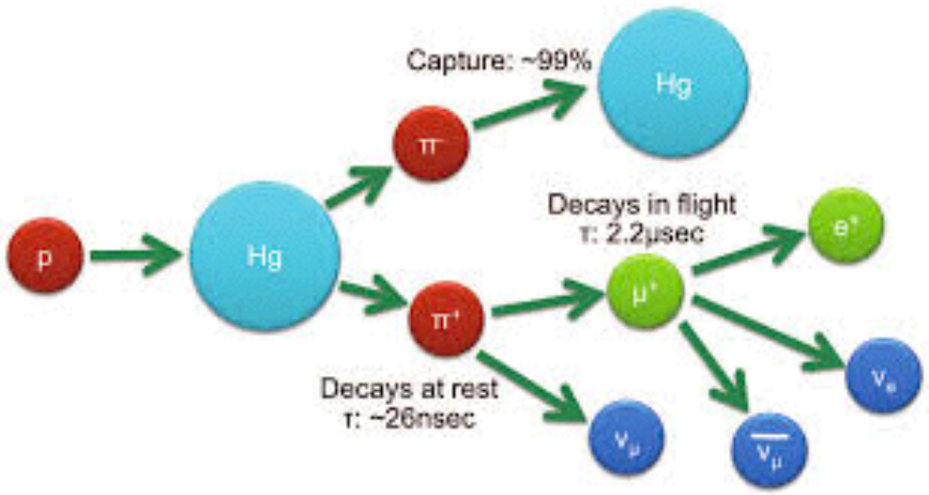
Even in neutrino experiments probing CEνNS (beam energy ≲ 1 GeV)

Dutta, Kim, Liao, Park, Shin, Strigari, 1906.10745 & in progress

deNiverville, Pospelov, Ritz, 1505.07805

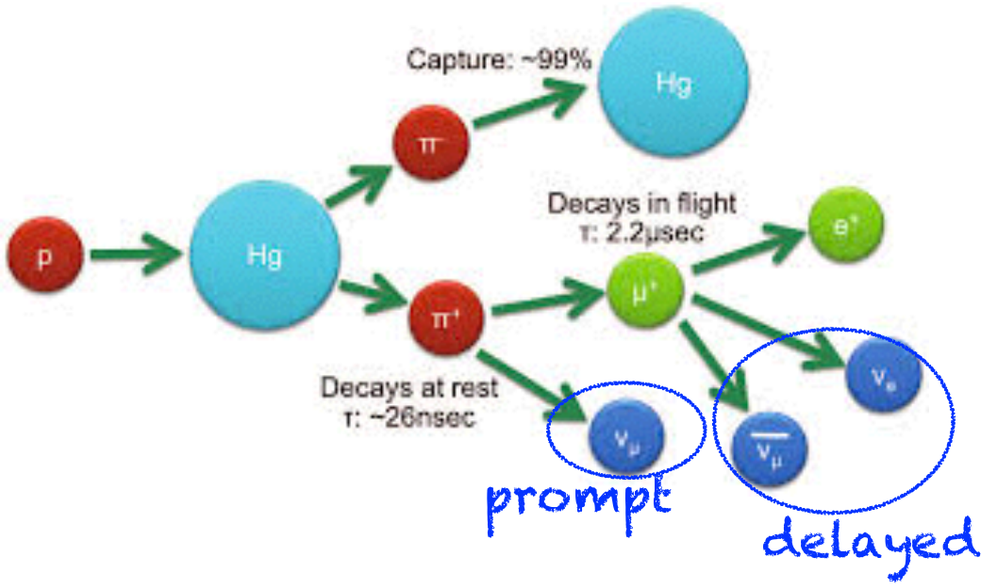
Ge, Shoemaker, 1710.10889

Searches for New Dark World



Talk by J. Yoo

Searches for New Dark World



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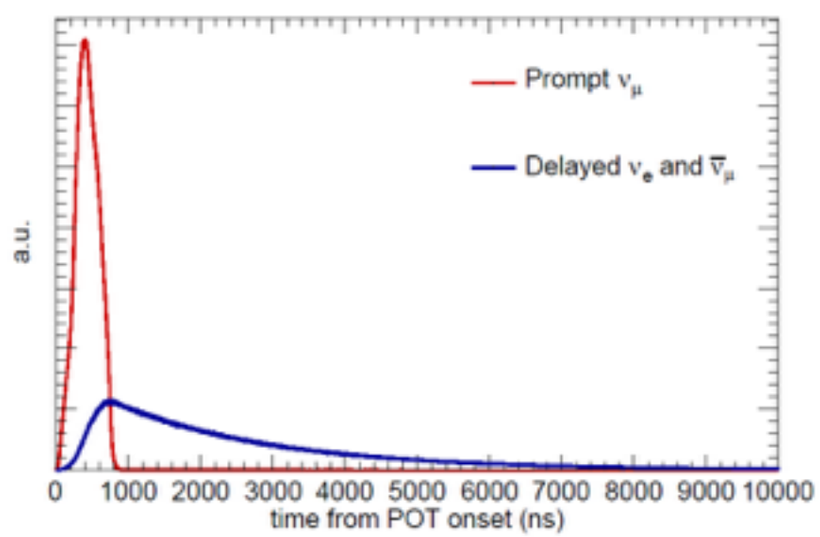
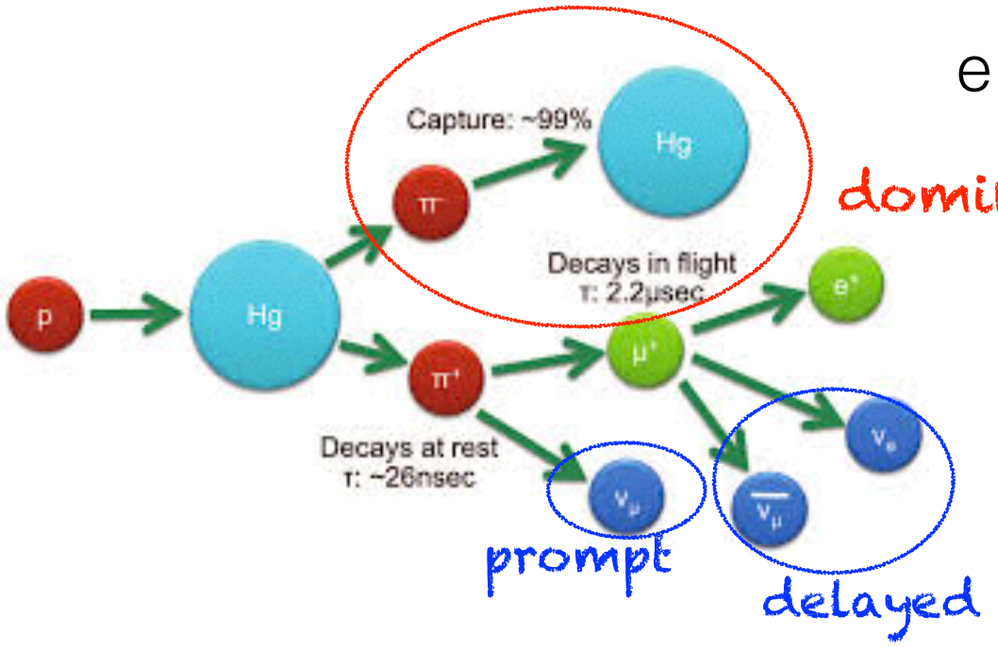
Timing information



beam arrival time

Searches for New Dark World



Talk by J. Yoo

Timing information

e.g., scenarios with dark photon (X)

dominant →

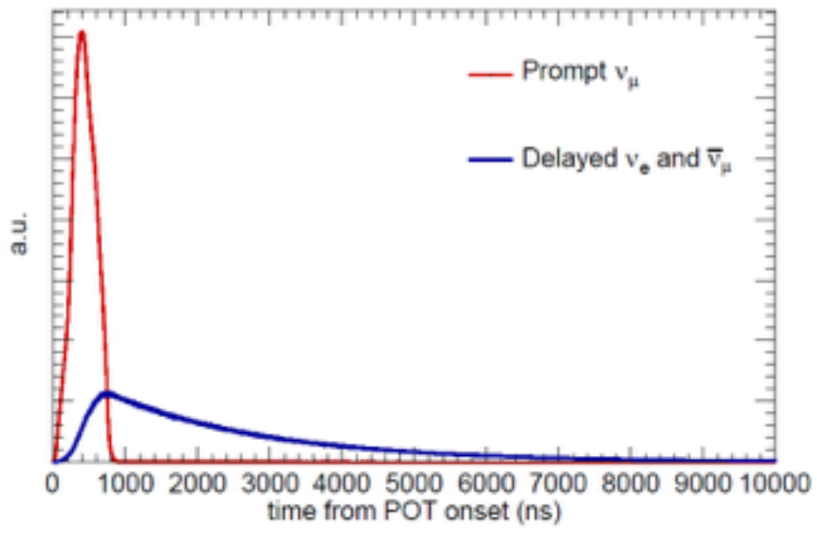
1. $\pi^- p \to X n \qquad X \to \chi\bar{\chi}$

2. $\pi^0 \to X\gamma$

Direct production
& subdominant

$\pi^+ n \to \pi^0 p$

$\pi^- p \to \pi^0 n$



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Dutta, Kim, Liao, Park, Shin, Strigari, 1906.10745 & in progress

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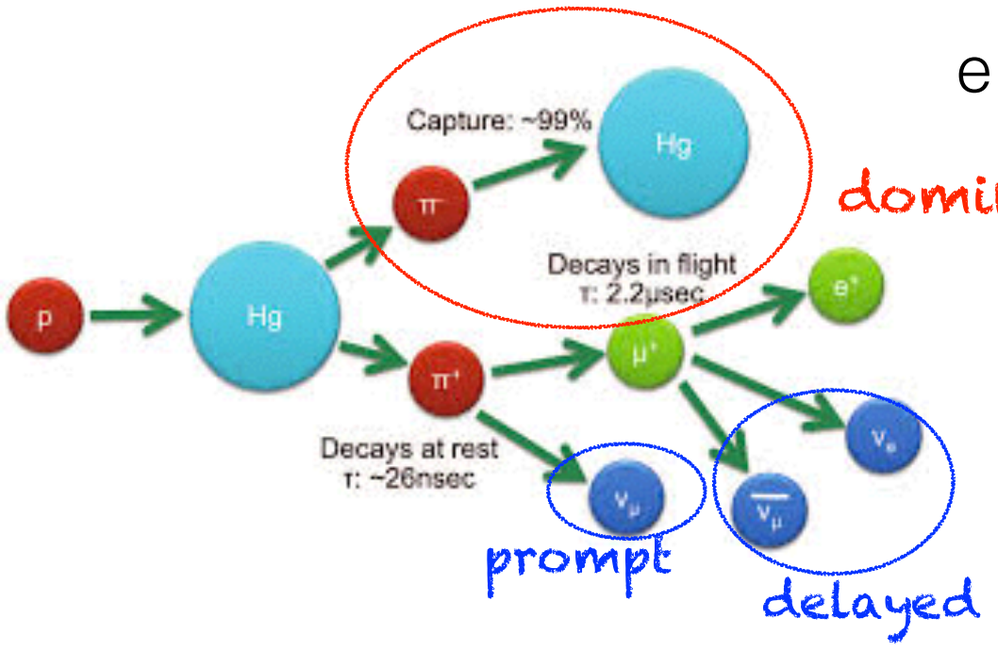

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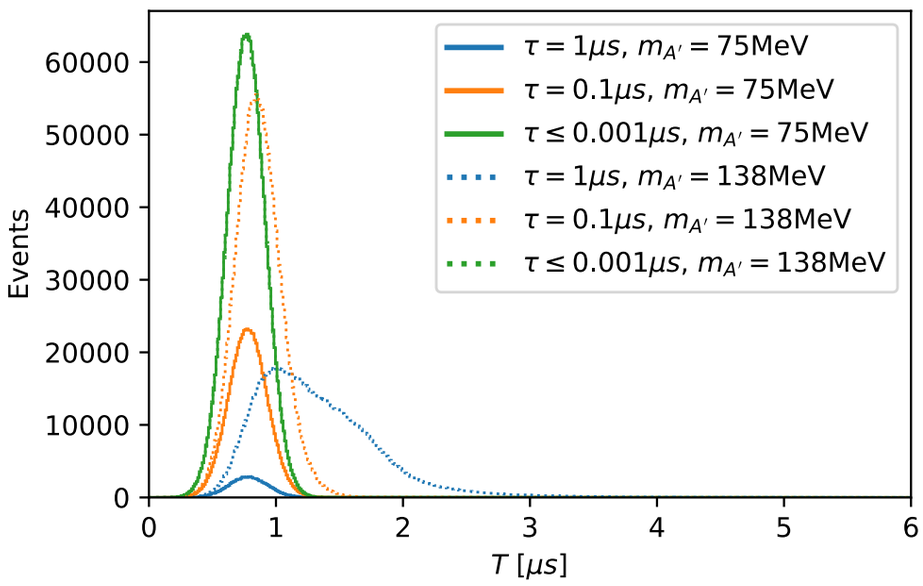

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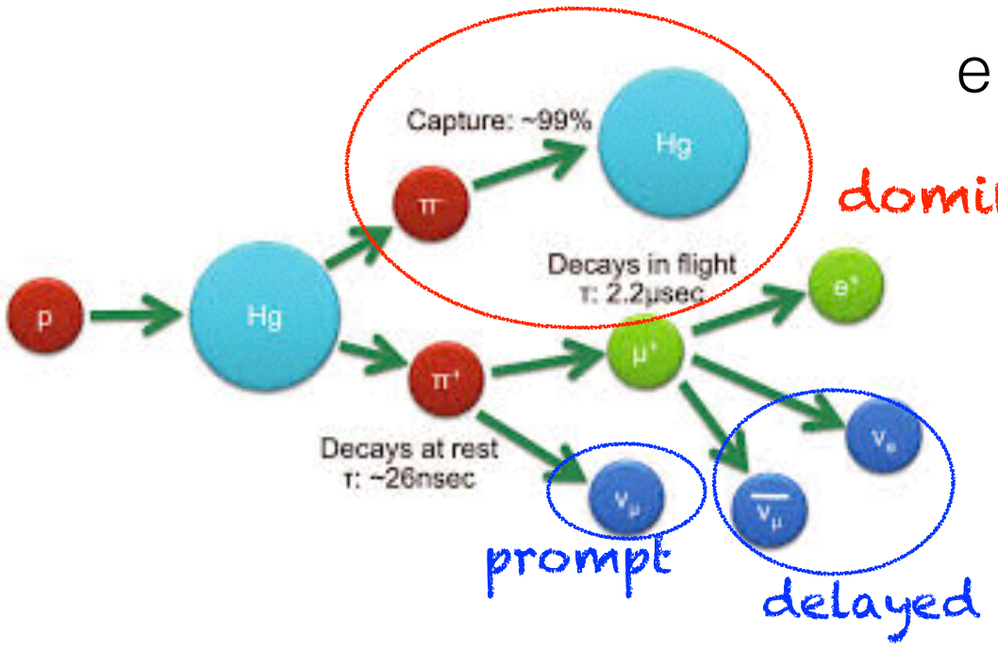

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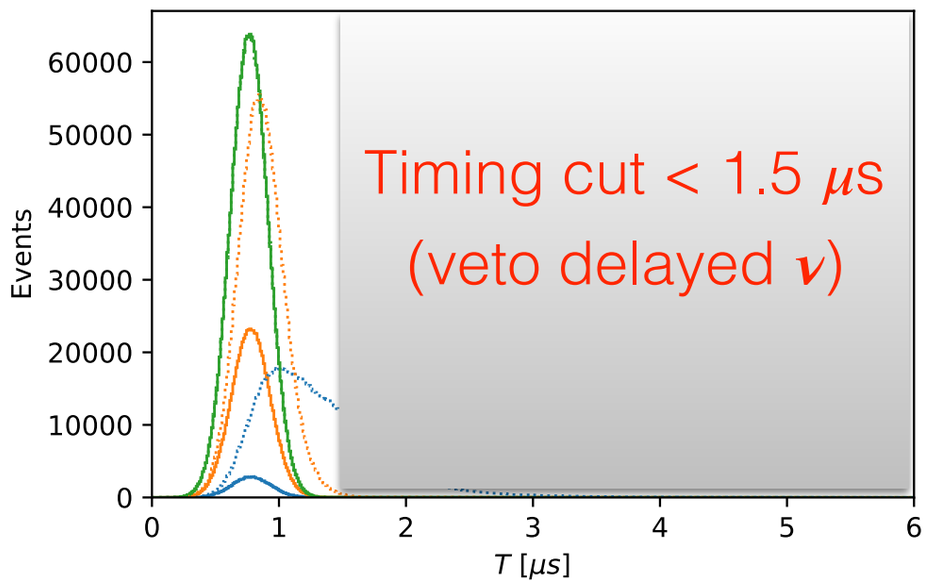

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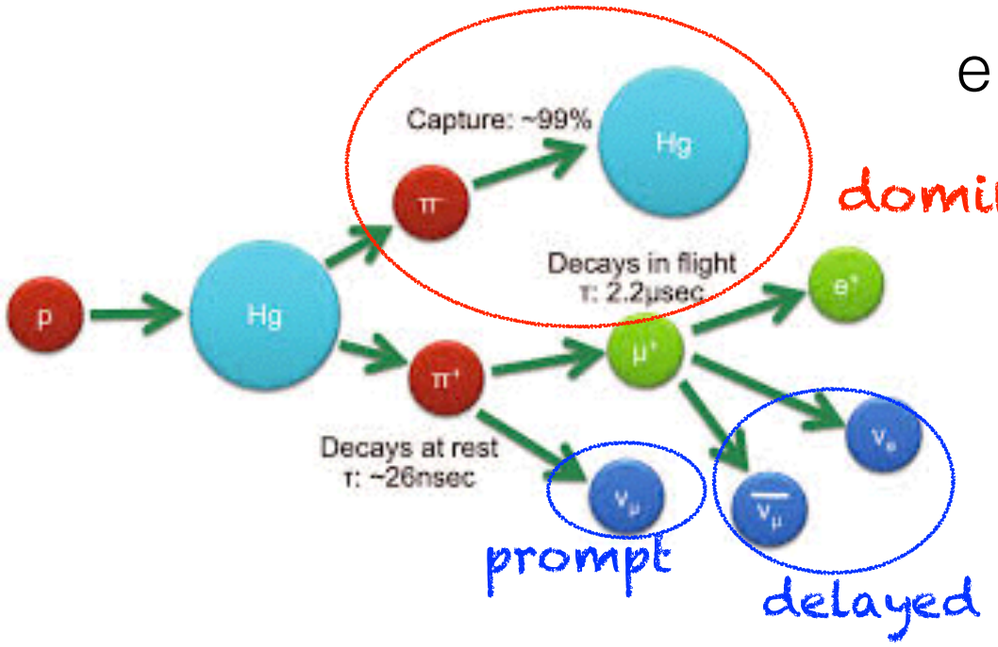

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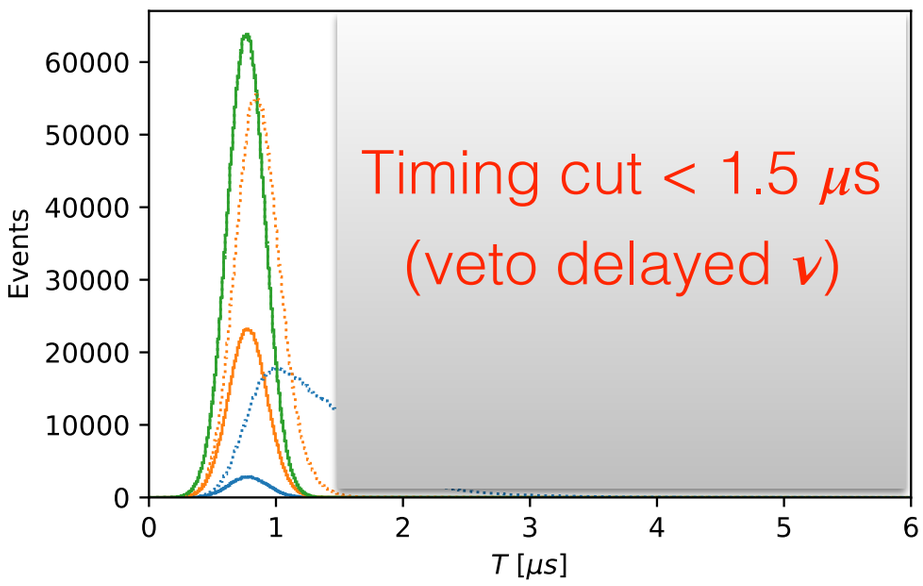

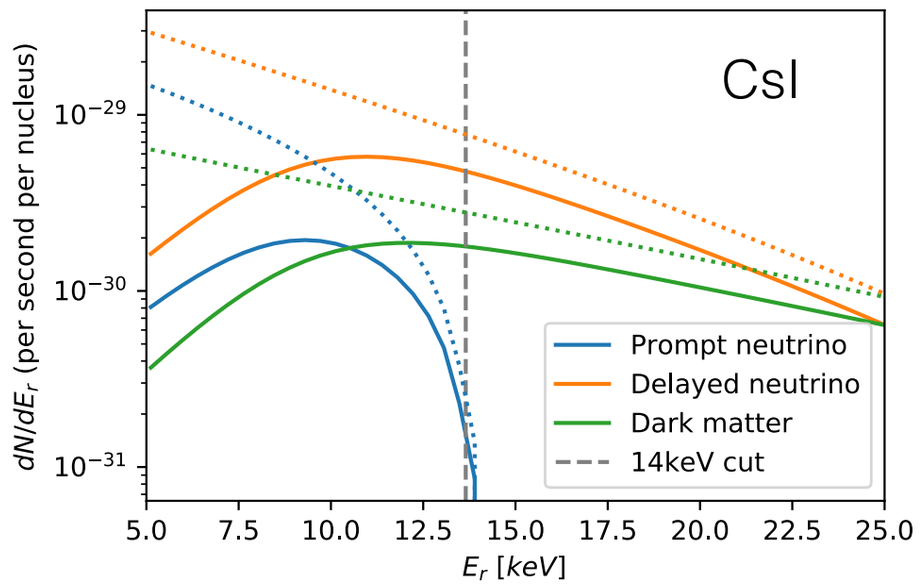

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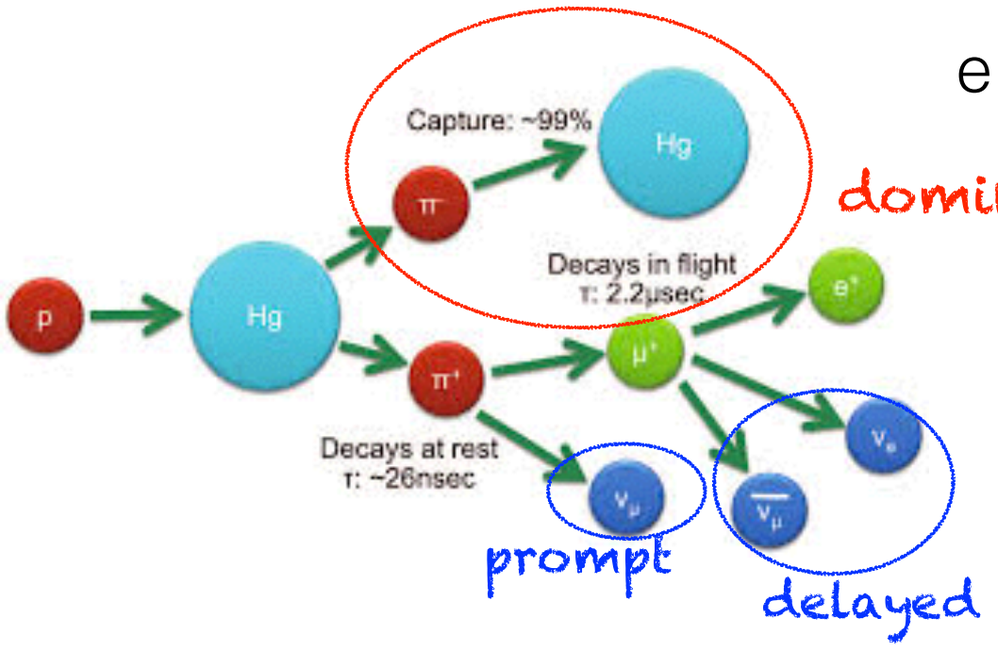

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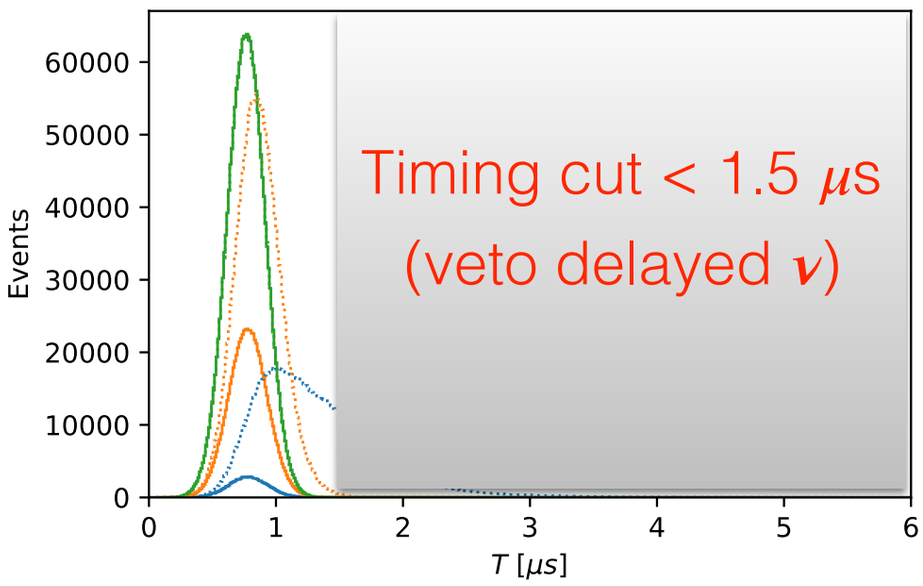
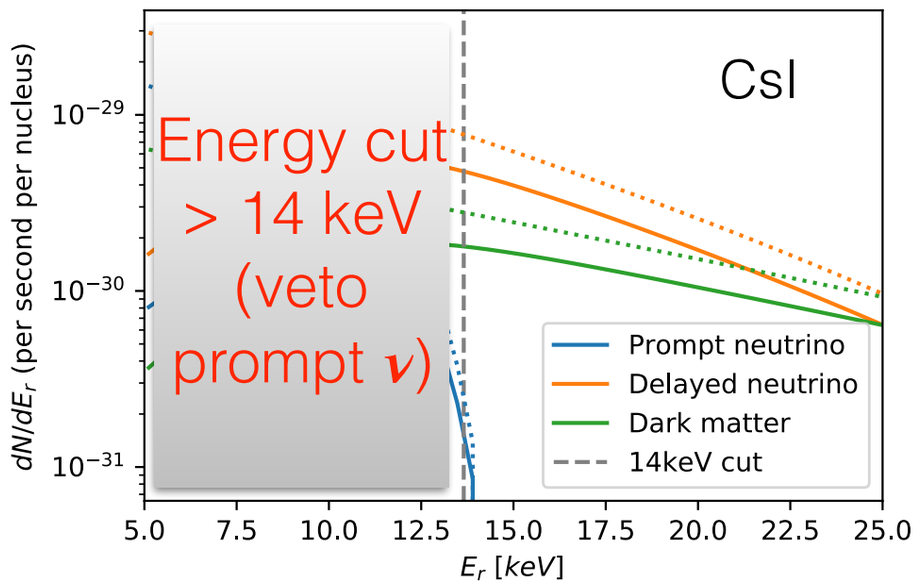




Dutta, Kim, Liao, Park, Shin, Strigari, 1906.10745 & in progress

Searches for New Dark World

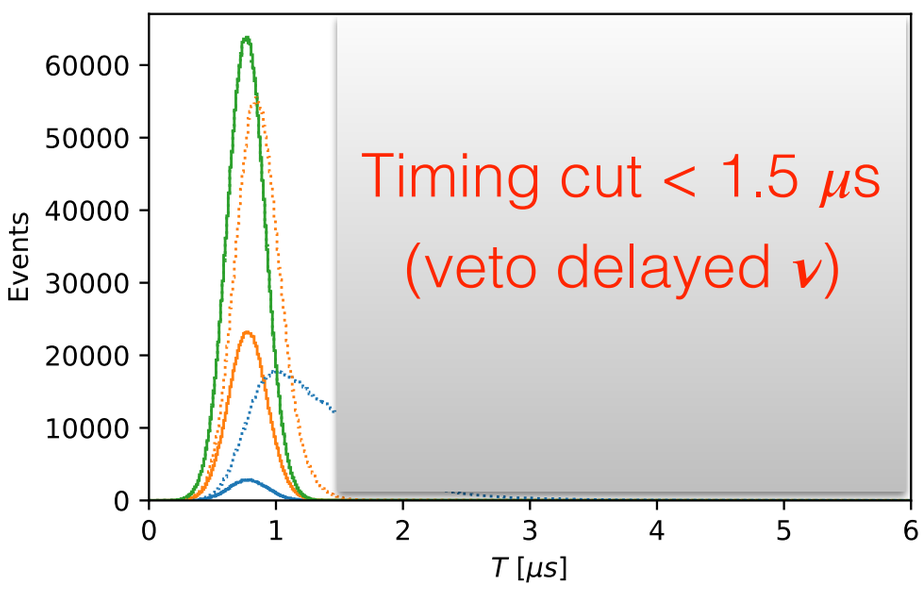
Data from COHERENT measurement (CsI): 1803.09183

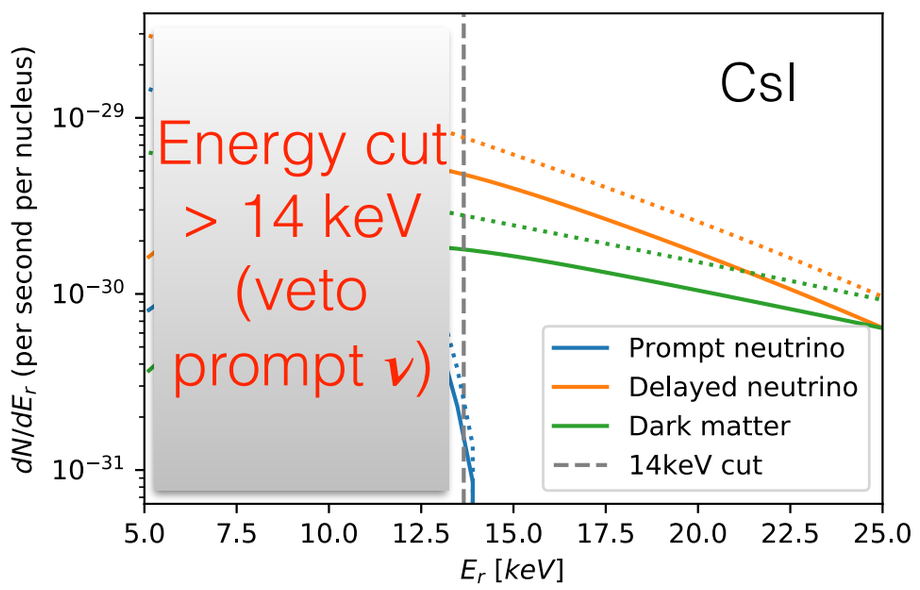
Observed events: 97 (E_r < 28 keV)

Steady-state background: 49

Delayed neutrino: 19

Beam related neutron: 3





Dutta, Kim, Liao, Park, Shin, Strigari, 1906.10745 & in progress

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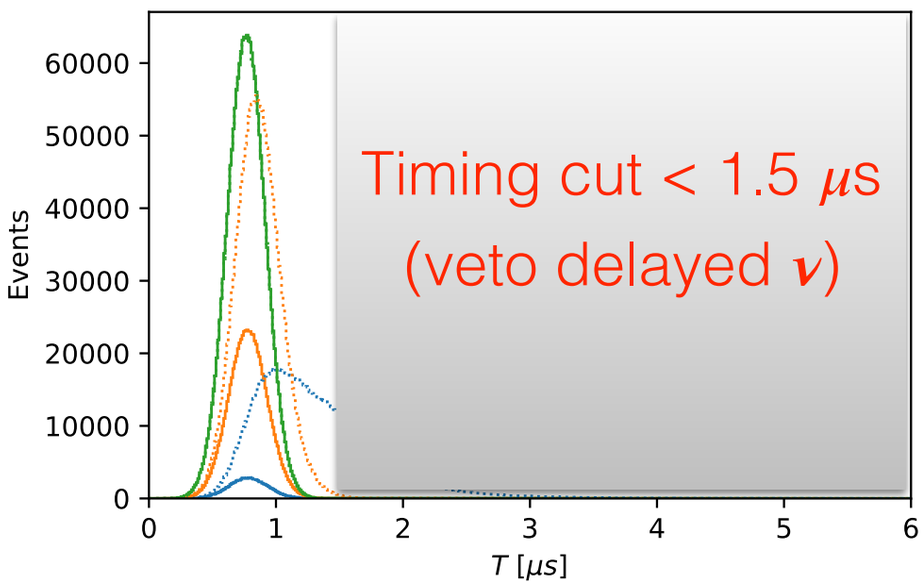
Beam related neutron: 3

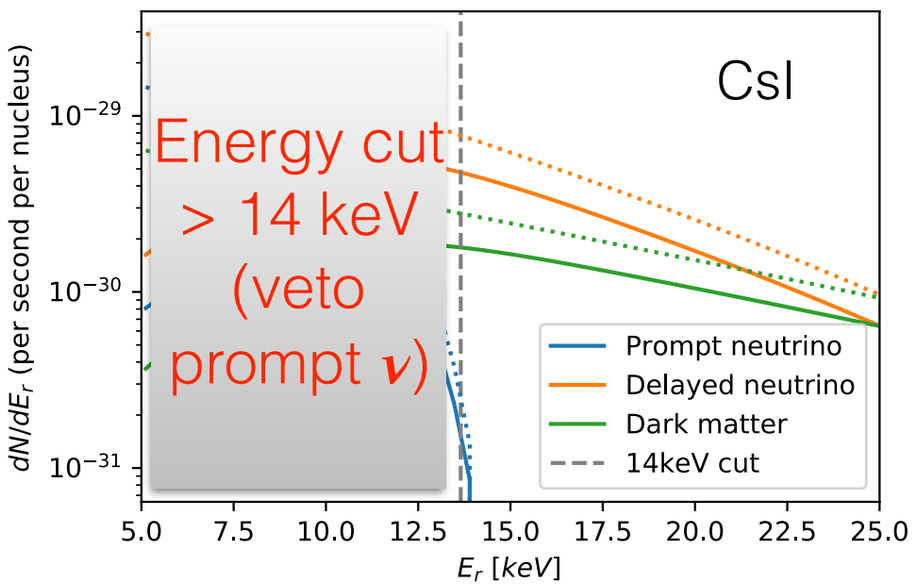
DM?

Excess: 26

2.4σ for R_n = 4.7fm

3σ for R_n = 5.5fm





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Low Energy experiments

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  B-factories, Fixed target experiments, Beam-dump, Neutrino experiments

- Accelerated in the universe

Energetic DM scenarios

- 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

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- Boosted Dark Matter: DM boosted by the dark sector structure
  (not from scattering with the energetic SM particles)

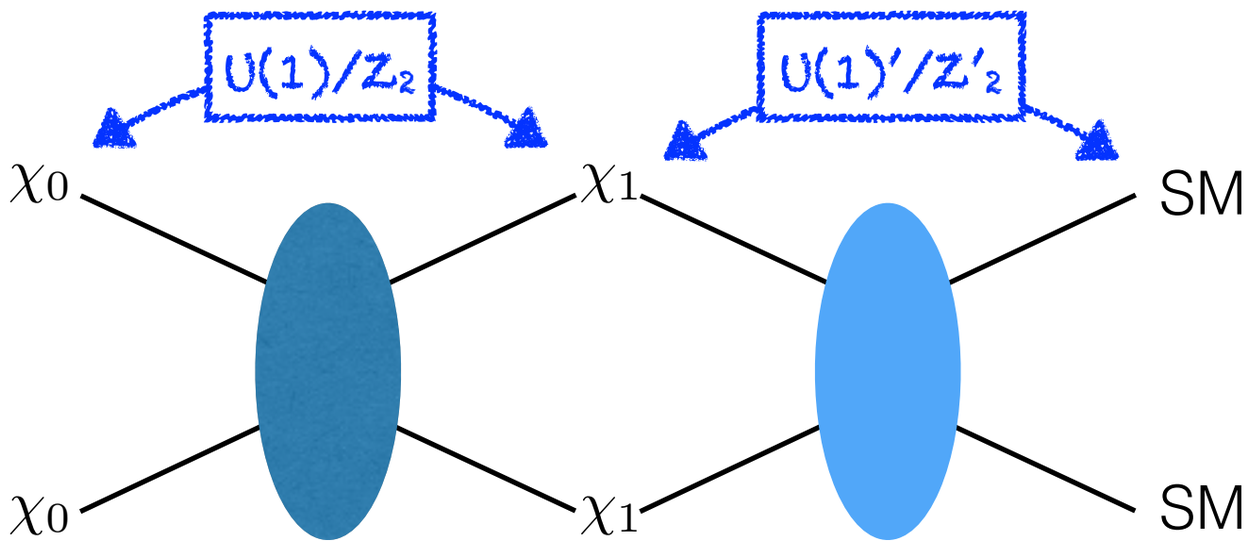
  Agashe, Cui, Necib, Thaler,1405.7370 Kim, Park, **SS**, 1612.06867, PRL 119, 161801 (2017)

  Giudice, Kim, Park, **SS**, 1712.07126, PLB 780, 543 (2018)

  + ...

Multi-component Boosted DM (BDM)

χ_0: heavy, χ_1: light



Agashe, Cui, Necib, Thaler,1405.7370

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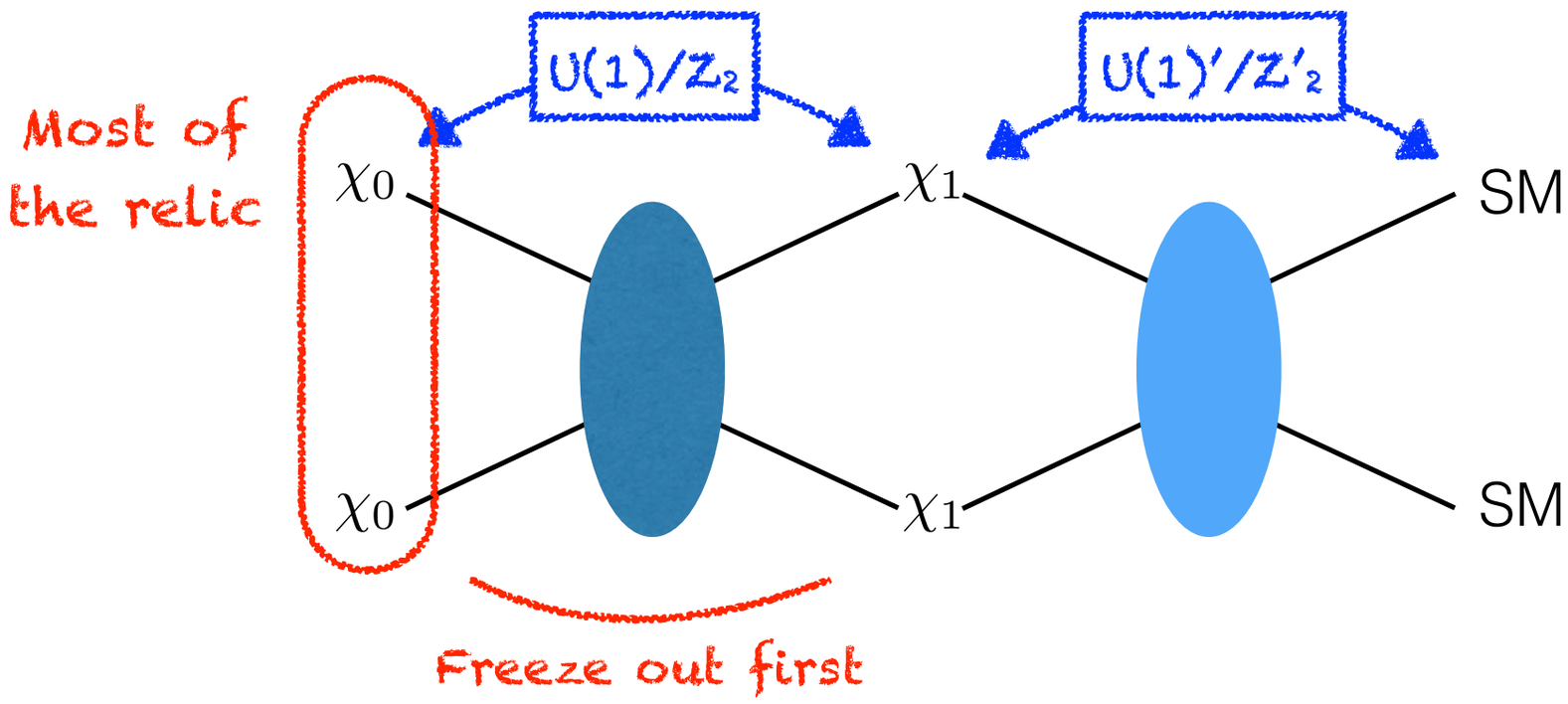

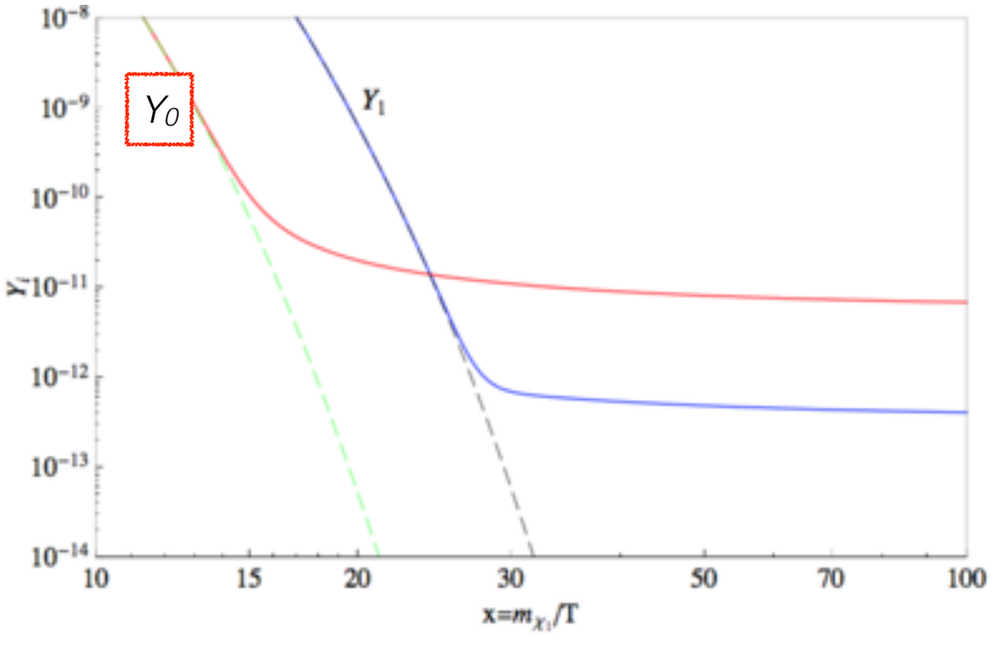

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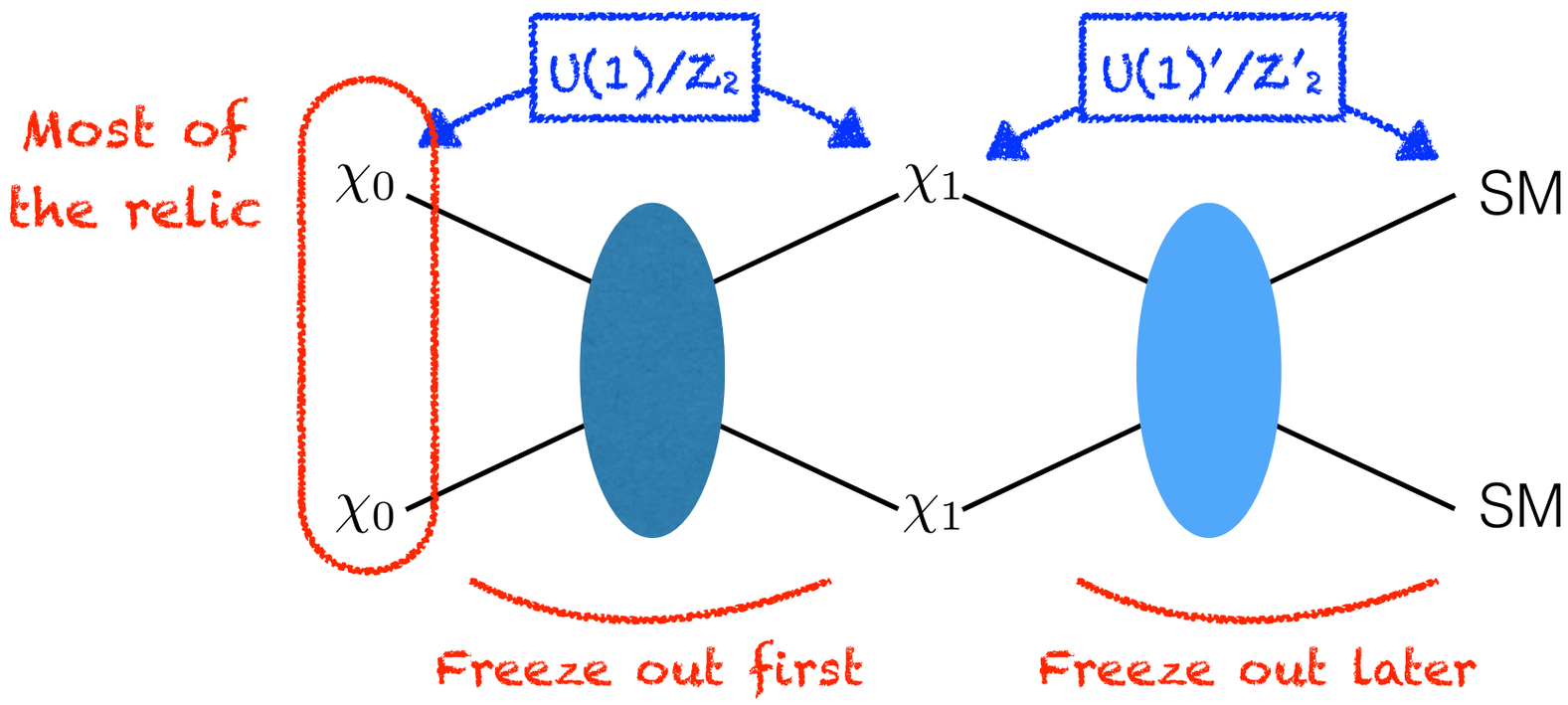

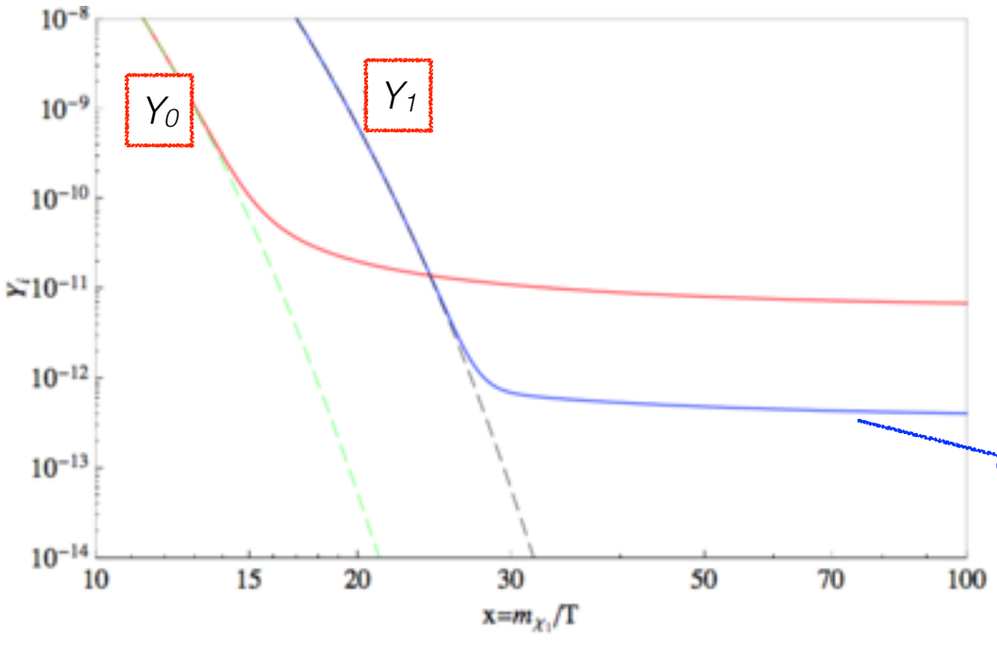

Agashe, Cui, Necib, Thaler,1405.7370

Belanger, Park, 1112.4491

Assisted freeze-out mechanism

non-relativistic relic χ_1 (negligible)

$Y_0 \gg Y_1$

Multi-component BDM

- χ_0 : gravitationally WIMP accumulated
  (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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Observe χ_1 scattering off target with $E_1 > E_{th}$

(indirect detection of χ_0)

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Flux of χ_1 $\simeq 1.6 \times 10^{-8}\,\mathrm{cm}^{-2}\mathrm{s}^{-1} \times \left(\dfrac{\langle\sigma v\rangle_{0\to1}}{5\times10^{-26}\,\mathrm{cm}^3\mathrm{s}^{-1}}\right) \times \left(\dfrac{100\,\mathrm{GeV}}{m_0}\right)^2$

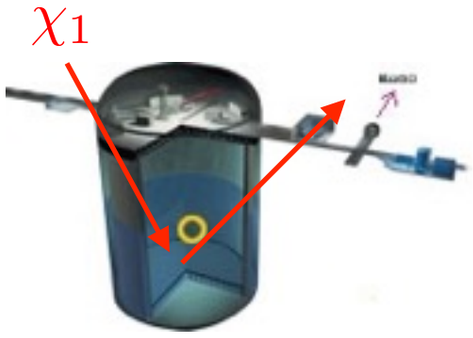
Assume: NFW

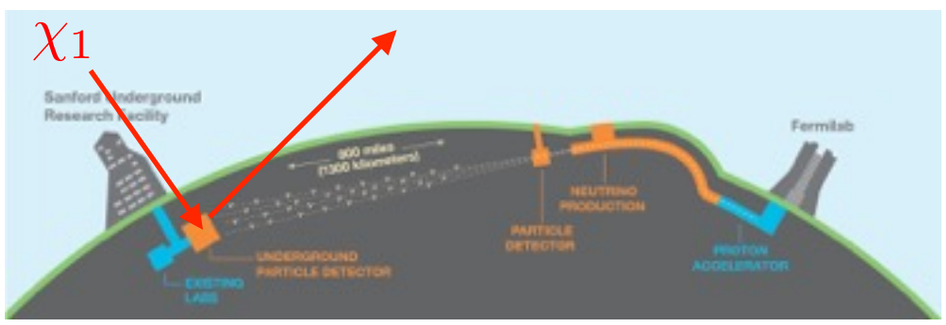
Fixed ~ 1 if s-channel annihilation dominates

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

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

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





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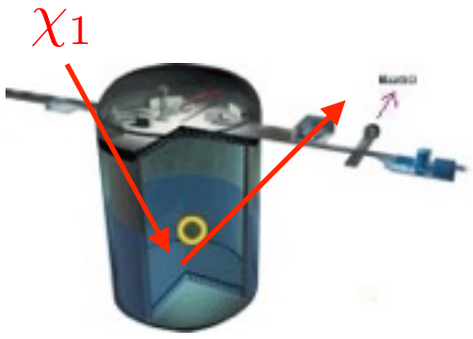

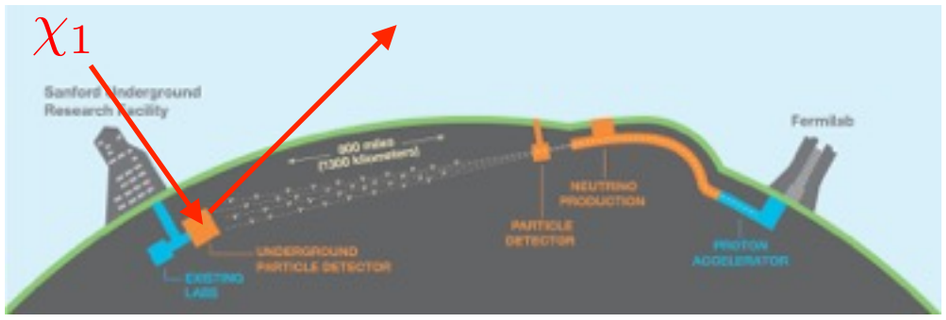

Subtraction of
major background (ν)

Important for all cosmogenic
BSM signals

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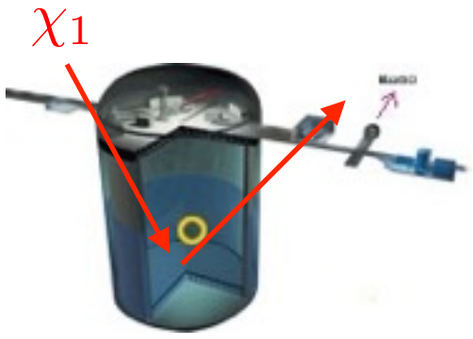
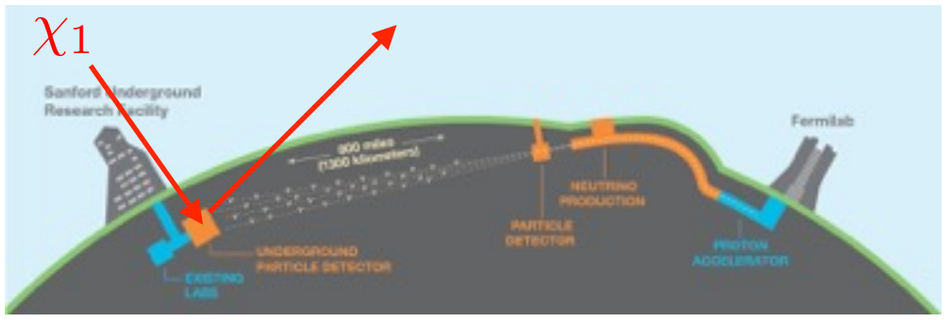




Subtraction of
major background (ν)

Important for all cosmogenic
BSM signals

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

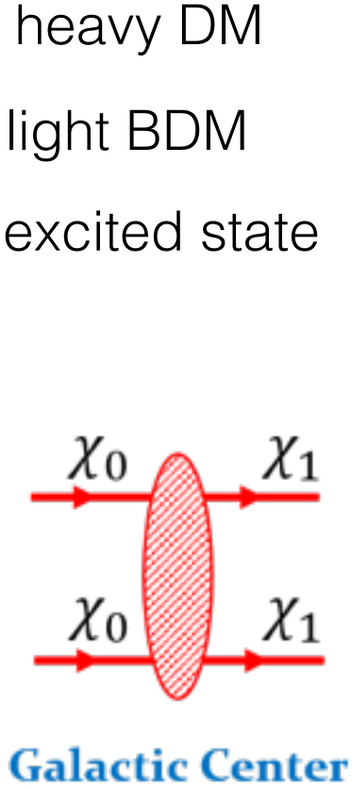
Open up novel possibilities of BDM search in many experiments

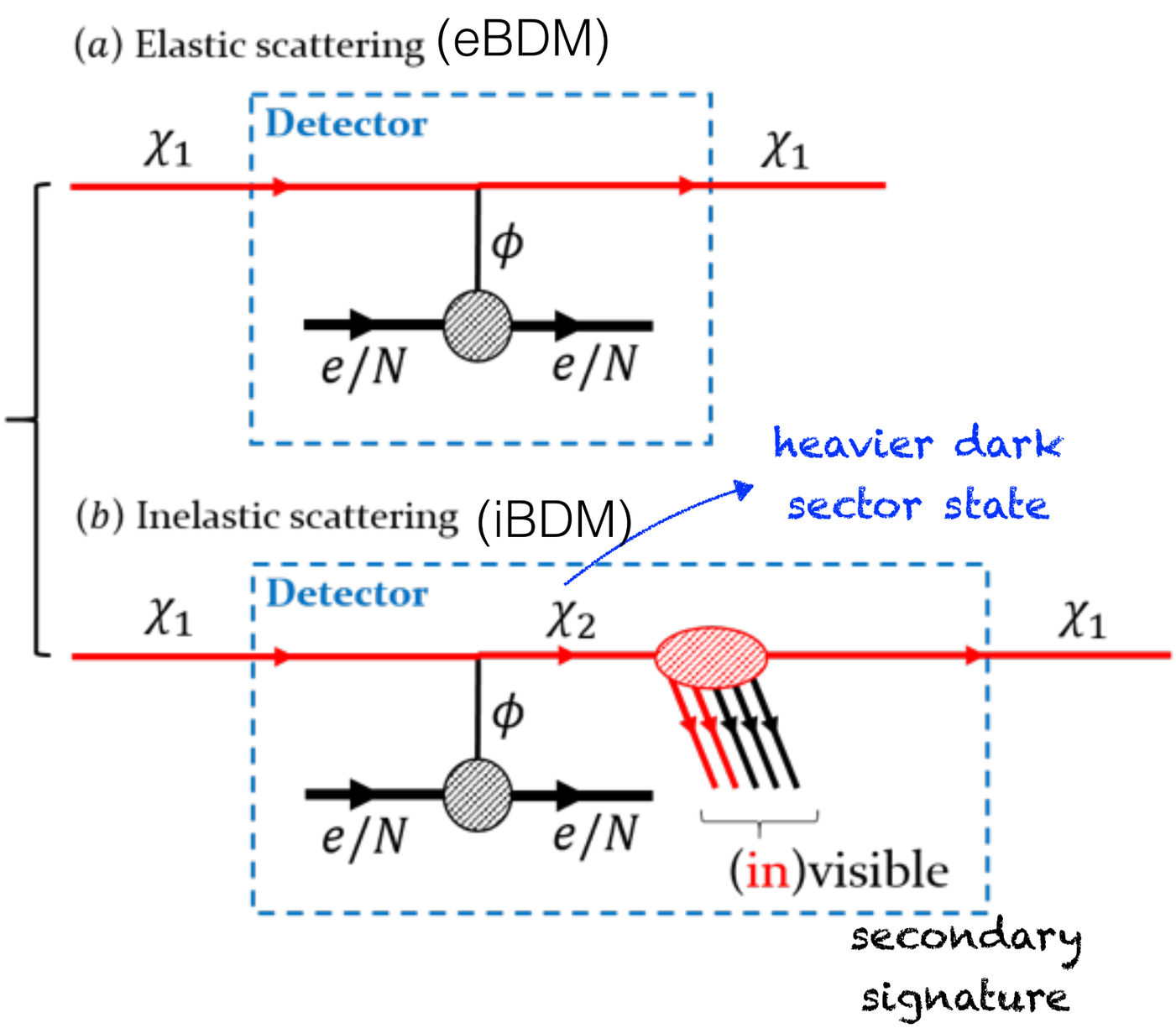
Inelastic BDM (iBDM)

χ_0: heavy DM

χ_1: light BDM

χ_2: excited state

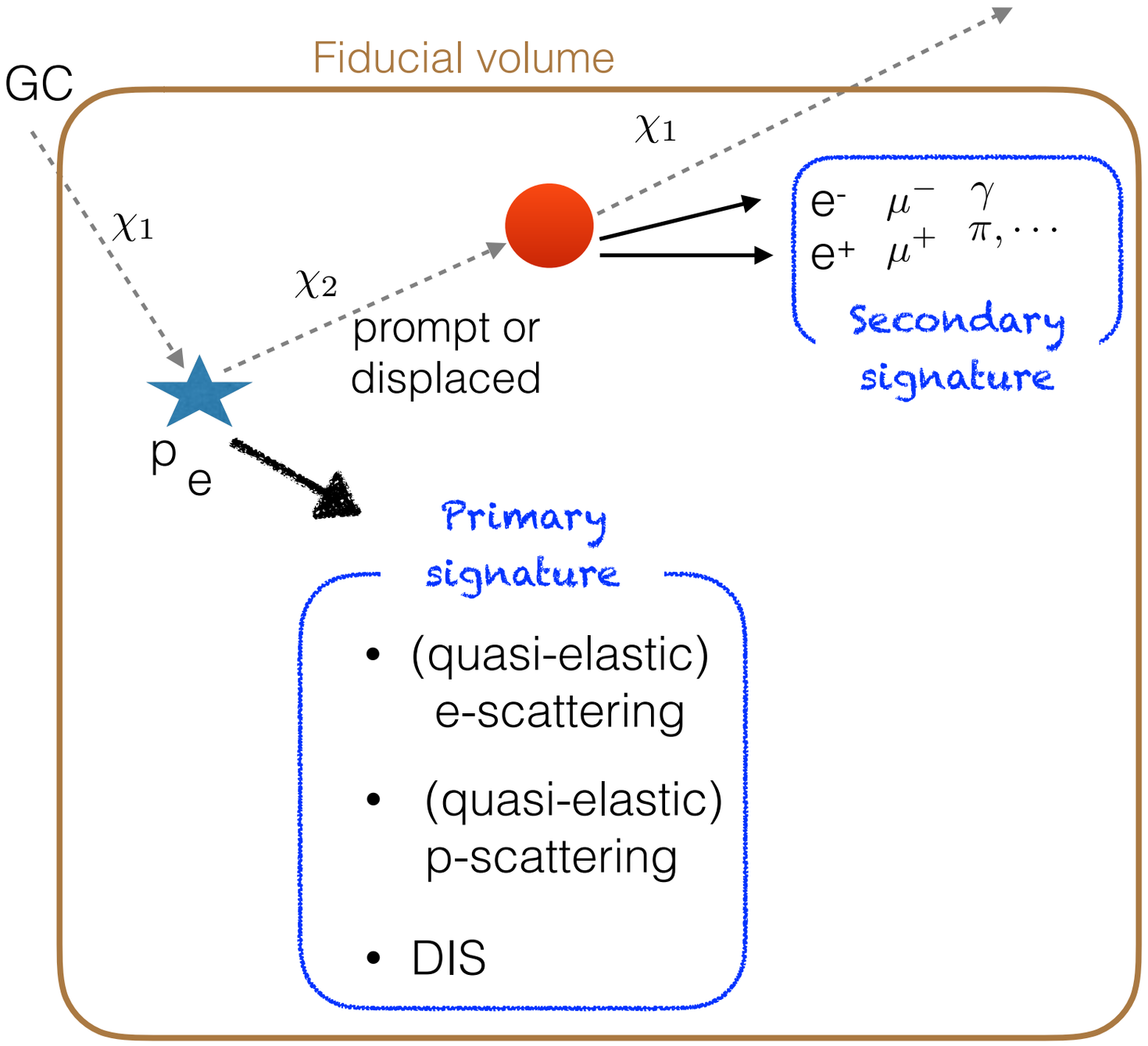




Kim, Park, **SS**, PRL 119, 161801 (2017)

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

Signals inside a fiducial volume



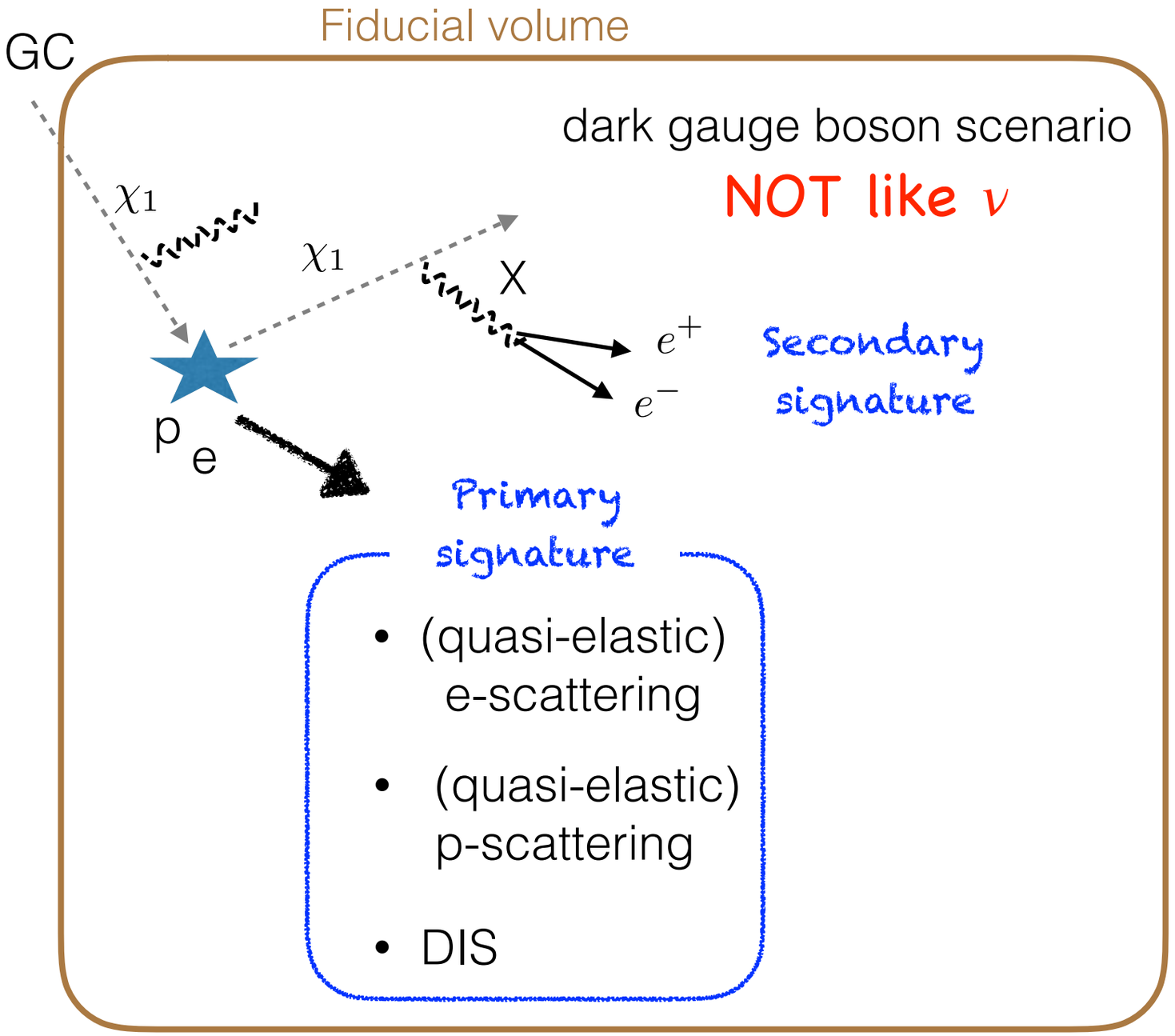
iBDM

- Tracks pop-up inside fiducial volume
- Track observation & time correlation can reject bkg.

χ_1: light BDM, χ_2: excited state

New method in eBDM search: darkstrahlung

Kim, Park, **SS**, 1903.05087



χ_1: light BDM

eBDM: elastically scattering BDM

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

Target experiments

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

Assume: NFW

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

  DUNE (TDR coming up), 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)

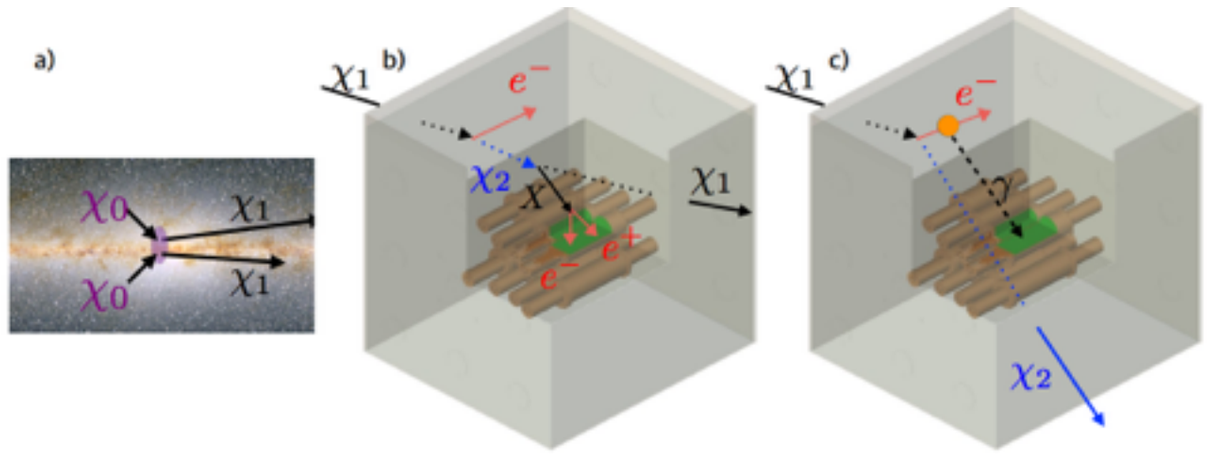
  2. Ton-scale DM direct detection experiments:

  COSINE-100 — 1811.09344 (PRL 2019)

  Talk by C. Ha

COSINE-100 result

COSINE-100, 1811.09344



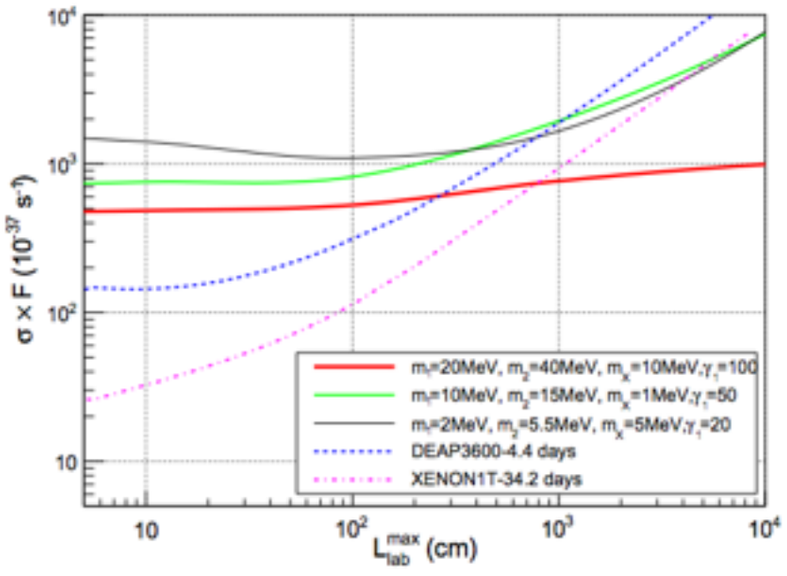
Based on theoretical study

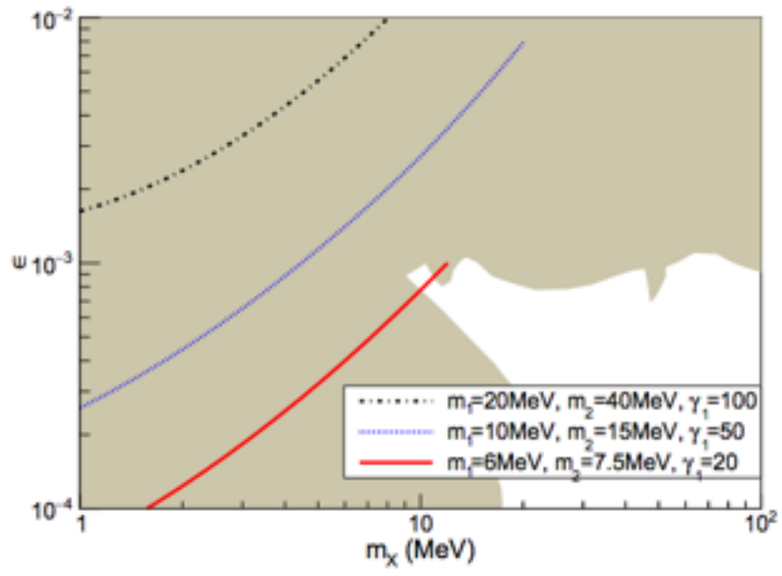
Giudice, Kim, Park, **SS**, 1712.07126

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





Conclusions

- Dark World beyond WIMP is now in attention.

- Accelerators: B-factories, fixed target experiments, …

  Timing & Energy cut ⇒ 3σ level excess at COHERENT

- Accelerated in the universe: energetic DM scenarios

  (inelastic) Boosted Dark Matter

- Probes in various current & future experiments:

  Large or moderate volume ν-experiments,

  DM direct detection experiments,

  Novel understanding of energetic signals, e.g., ANITA

  Heurtier, Kim, Park, **SS**, 1905.13223, PRD 100, 055004 (2019)

Backup: sensitivity

$$N_{\text{sig}} = \sigma_e \cdot \mathcal{F} \cdot A \cdot t_{\text{exp}} \cdot N_T$$

- σ_e: scattering cross section between χ_1 and (target) electron
- $\mathcal{F}$: flux of incoming (boosted) χ_1
- A: acceptance (detector geometry, only for iBDM)
- t_{exp}: exposure time
- N_T: total number of target (e,p,n)

) Fixed for a given experiment

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) Fixed for a given experiment

Both primary and secondary inside the fiducial volume

- Function of decay length of χ_2 (event generation assuming cumulatively isotopic flux of χ_1)
- Conservatively, we calculate the maximum mean decay length in the laboratory frame for each parameter set

Backup: sensitivity

$$N_{\text{sig}} = \sigma_e \cdot \mathcal{F} \cdot A \cdot t_{\text{exp}} \cdot N_T$$

σ^{fid} or σ^{vis}

- σ_e: scattering cross section between χ_1 and (target) electron
- $\mathcal{F}$: flux of incoming (boosted) χ_1
- A: acceptance (detector geometry, only for iBDM)
- t_{exp}: exposure time
- N_T: total number of target (e,p,n)

with signal efficiency

Fixed for a given experiment

Both primary and secondary inside the fiducial volume

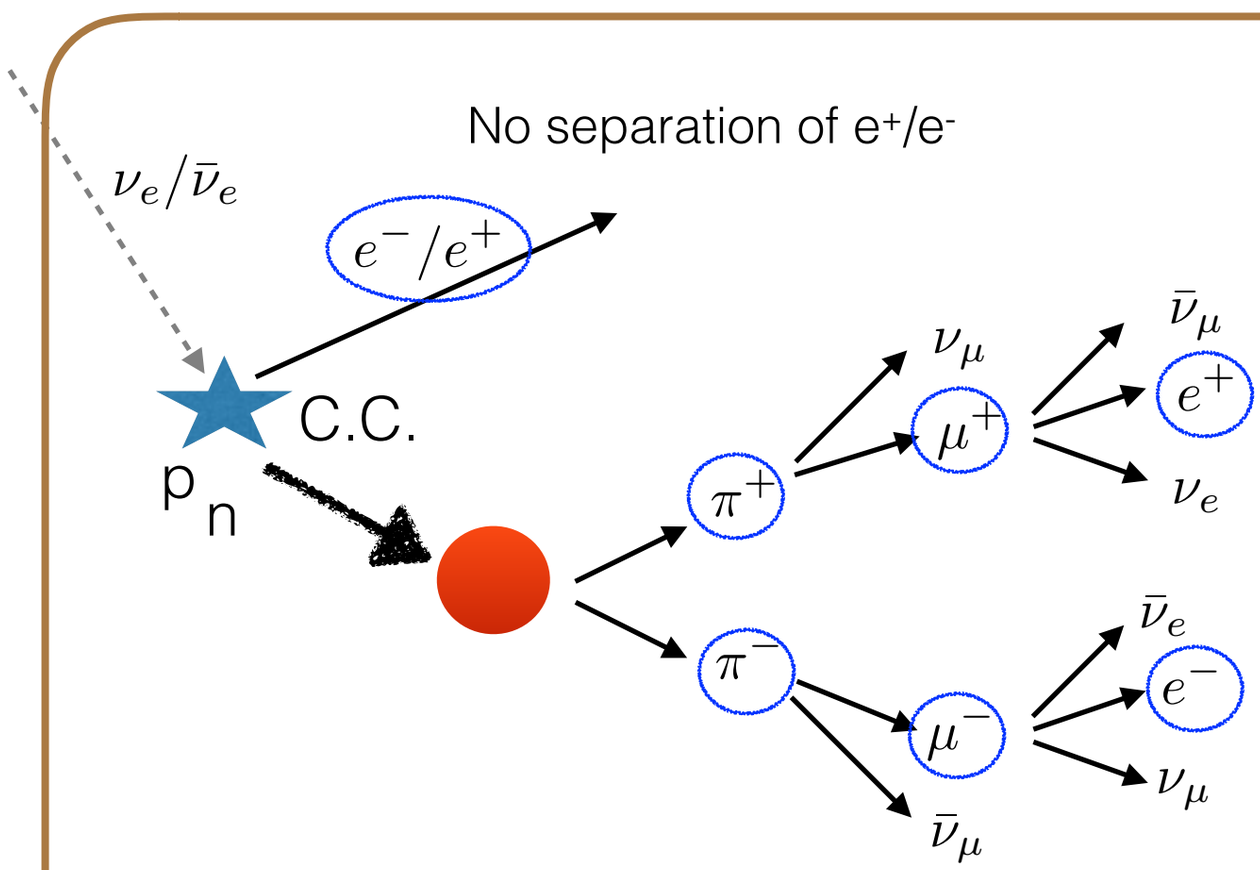
- Function of decay length of χ_2 (event generation assuming cumulatively isotopic flux of χ_1)
- Conservatively, we calculate the maximum mean decay length in the laboratory frame for each parameter set

Background candidate: underground

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

Work in progress

Fiducial volume



480/yr/40kt $\times$ [Track-based PID (e from π) Timing information etc..] < 1 DUNE

χ_1: light BDM, χ_2: excited state

- Other subdominant bkg. negligible

  N.C. events (smaller)

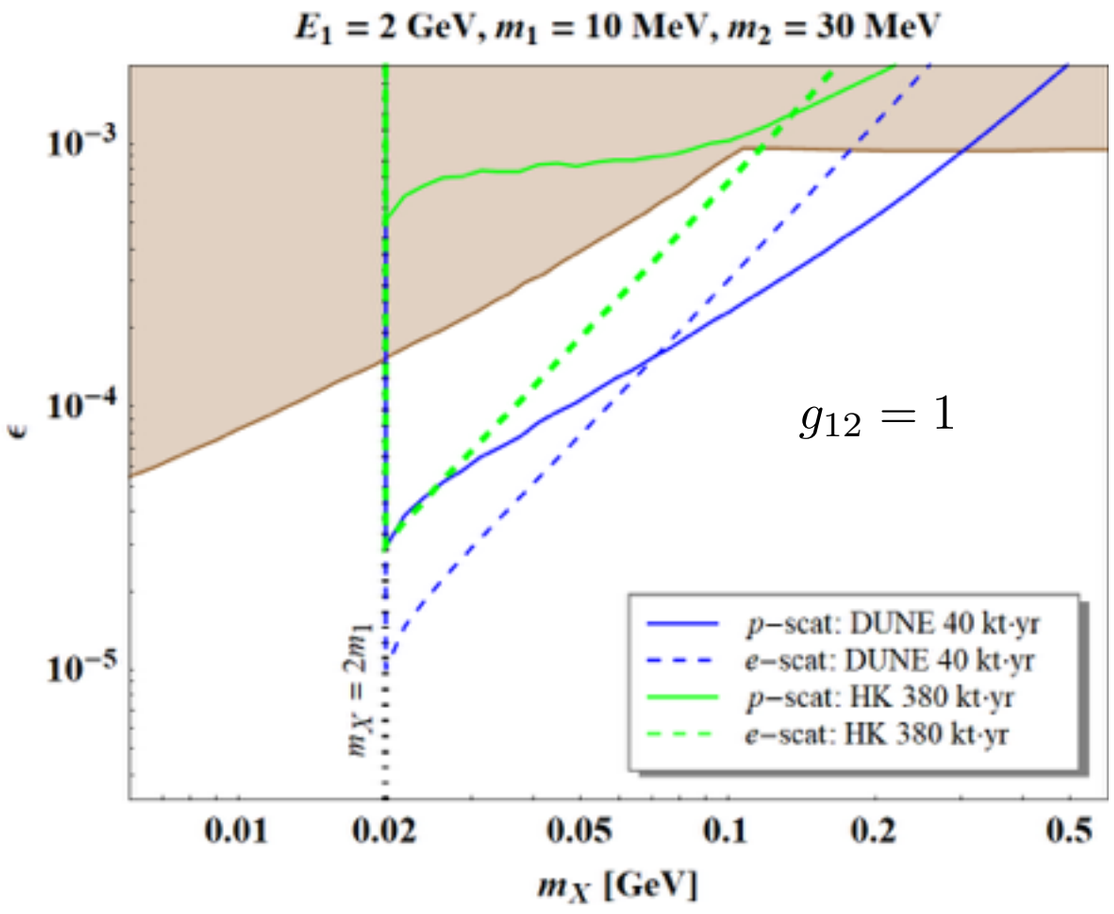
  ν_μ: accompanying μ

  ν_τ: too small flux

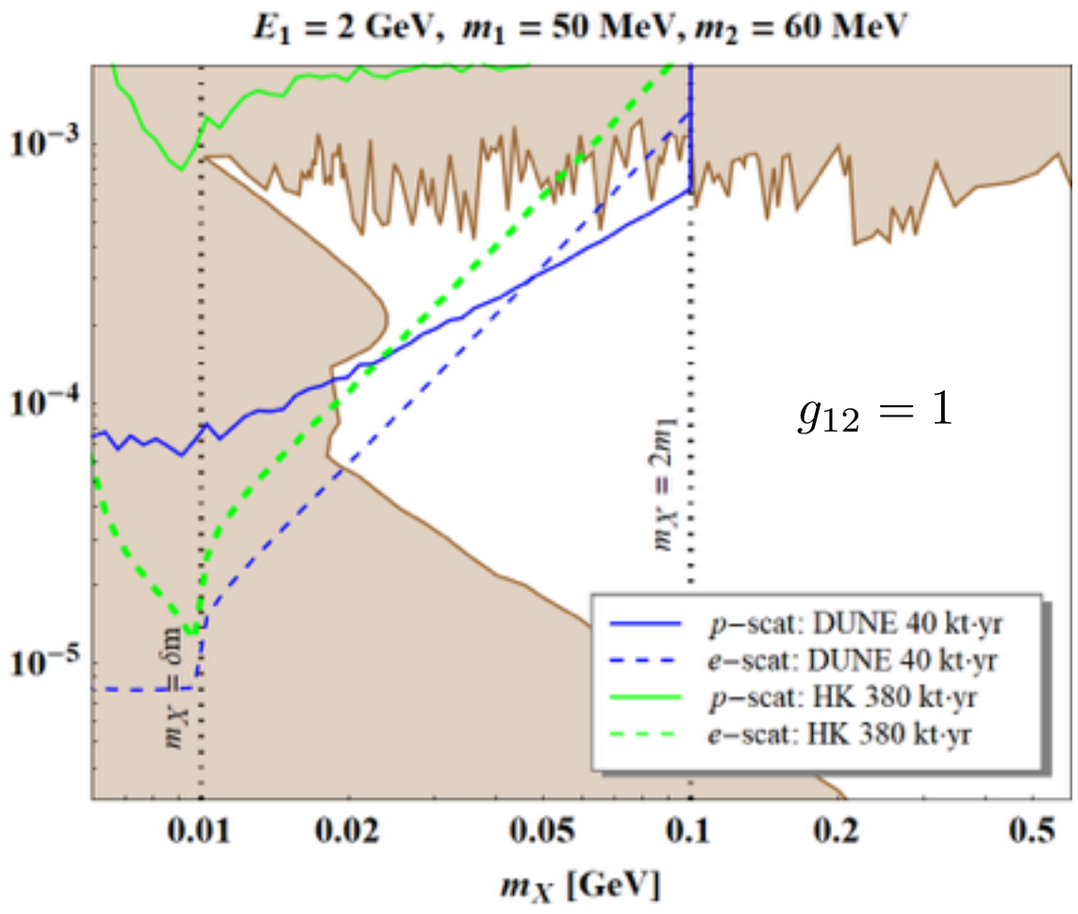
- Zero-bkg. is easily achievable

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

Backup: Sensitivities at DUNE vs HK



$m_X > 2m_1$ $\quad \chi_2 \to X^* \chi_1 \to e^+ e^- \chi_1$



$m_X < 2m_1$ $\quad \chi_2 \to X^{(*)} \chi_1 \to e^+ e^- \chi_1$

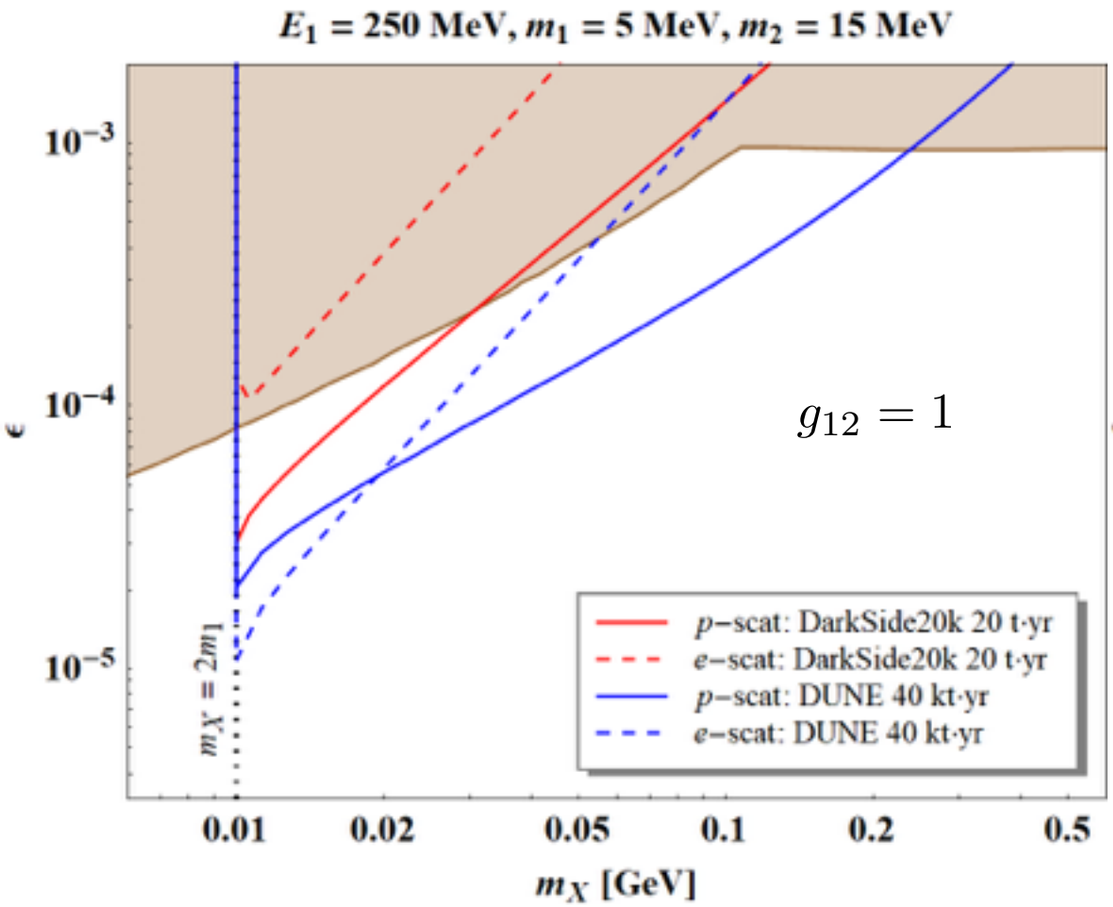
- DUNE preferred parameter region over HK although the size is 1/10 (lower E_{th}, better resolution)

Better for larger E_1

- Difference is huge for p-scattering

Kim, Machado, Park, **SS**, To appear soon

Backup: Sensitivities at DUNE vs DarkSide



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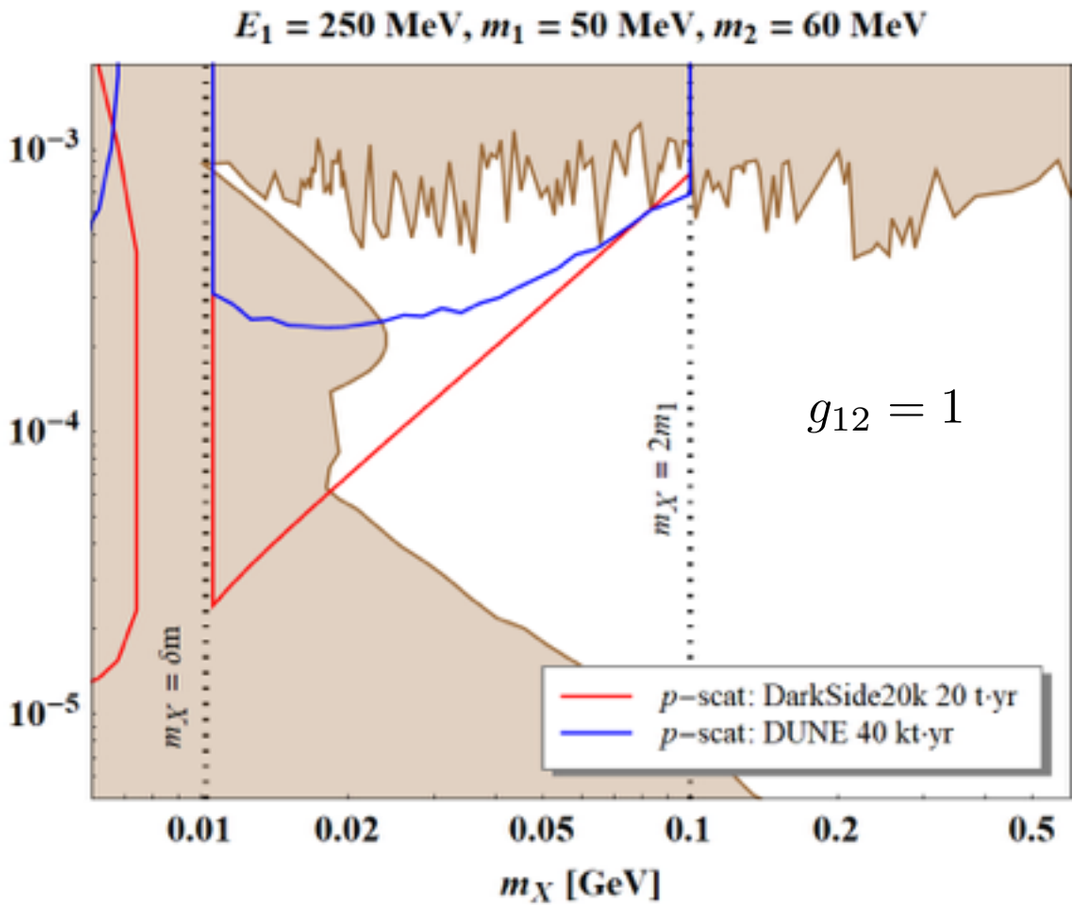
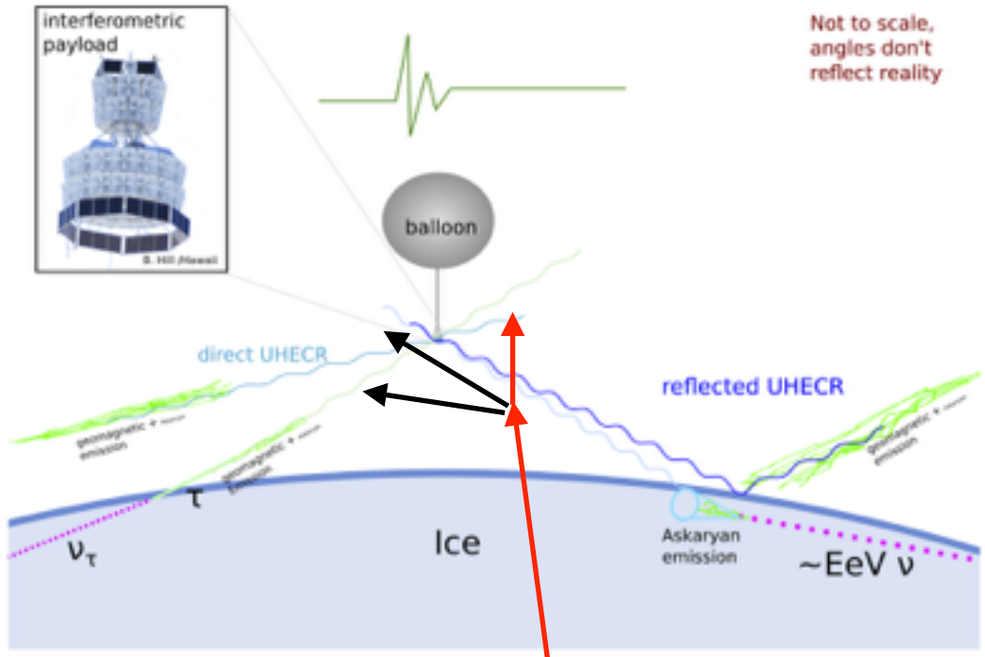
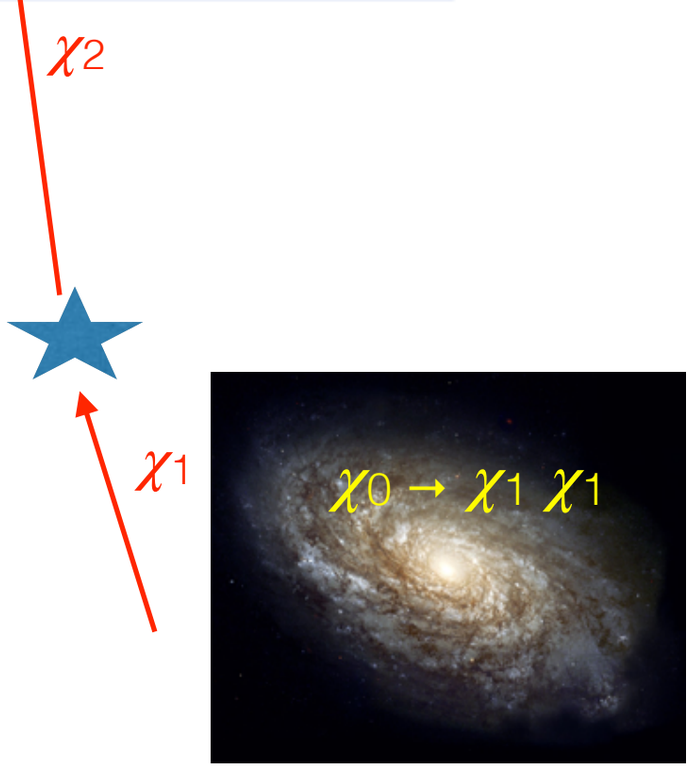


$m_X < 2m_1$ $\quad \chi_2 \to X^{(*)} \chi_1 \to e^+ e^- \chi_1$

- e-scattering gets larger more rapidly than p-scattering as decreasing m_X
- DarkSide-20k sensitive for smaller m_X (longer decay length: identify two signals)
- DarkSide-20k can be competitive over DUNE when E_1 and m_X is small (E_{th})

Backup: Higher Energy?





Heurtier, Kim, Park, **SS**, 1905.13223,
PRD 100, 055004 (2019)