Dark Matter Transporting Mechanism Explaining Positron Excesses
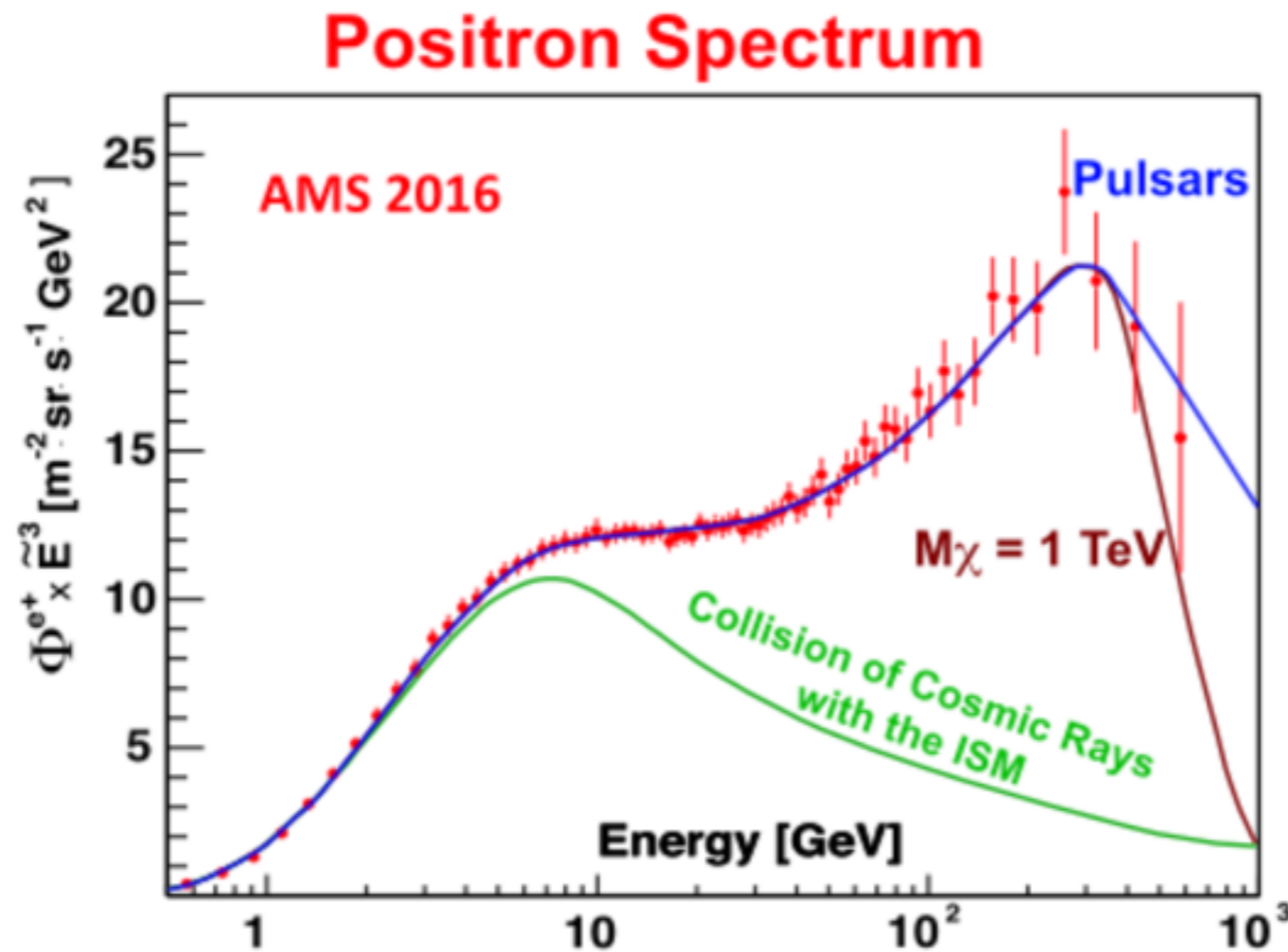
Seodong Shin

1702.02944 with Doojin Kim, Jong-Chul Park
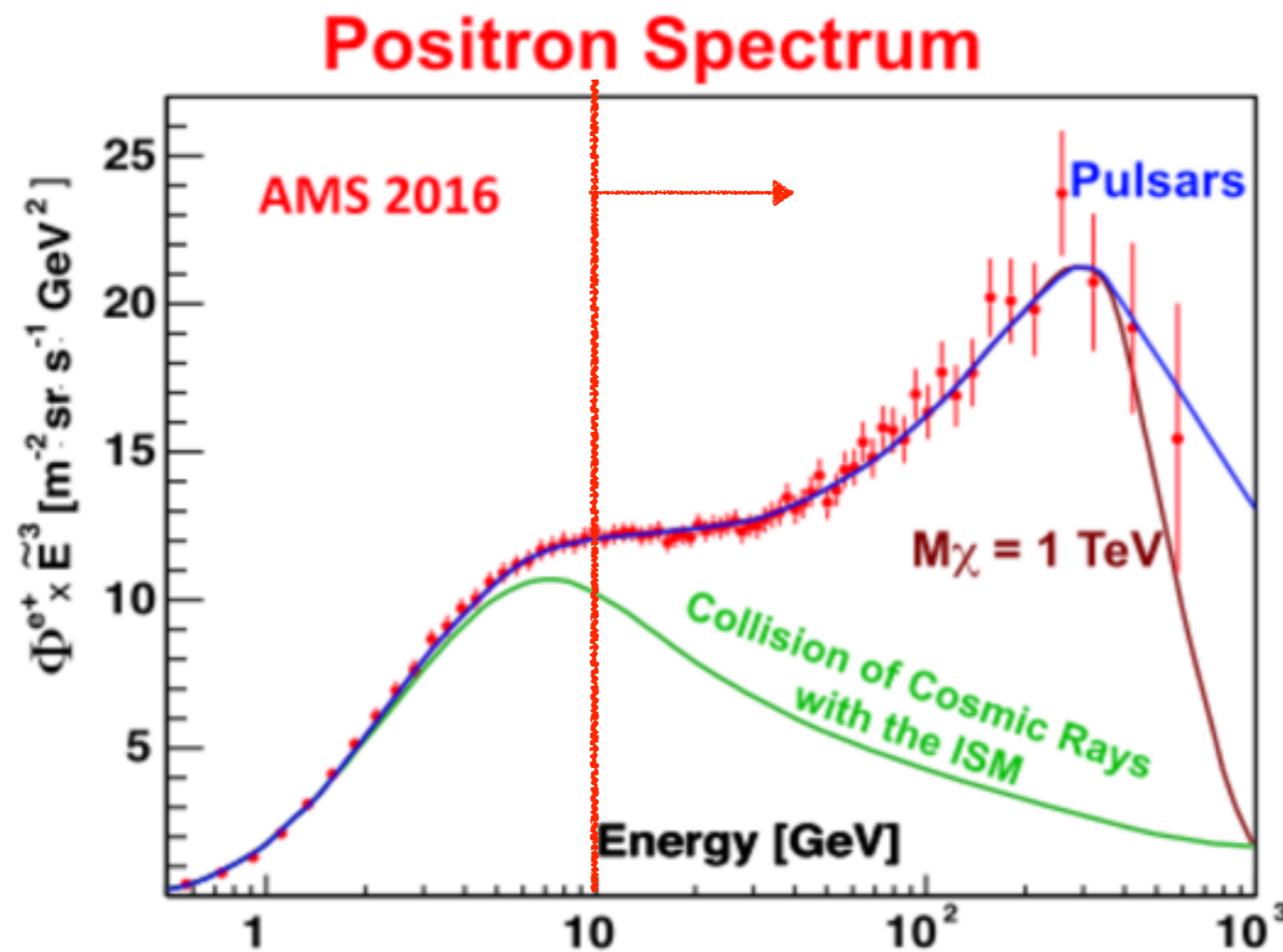
Cosmic-ray excesses: e$^+$

Cosmic-ray excesses: e⁺
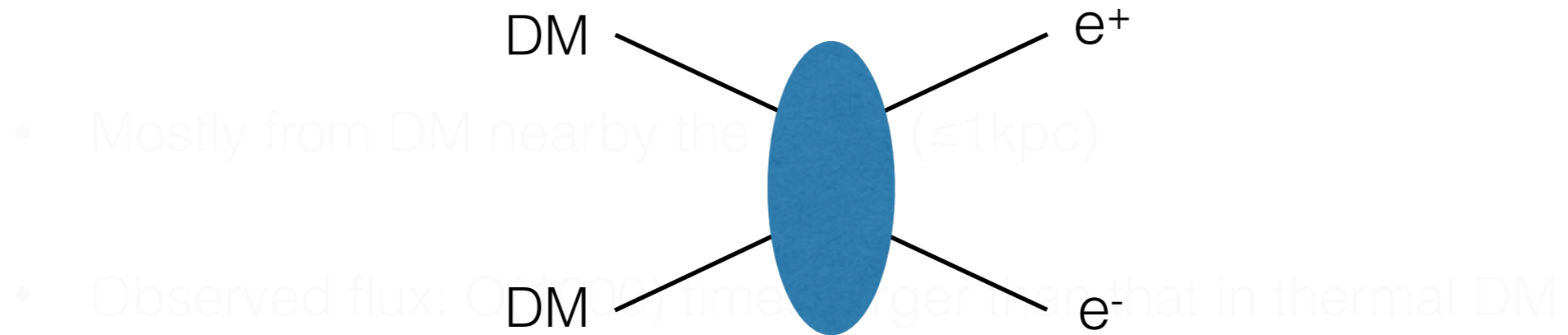
AMS-02 press release (Dec, 2016)
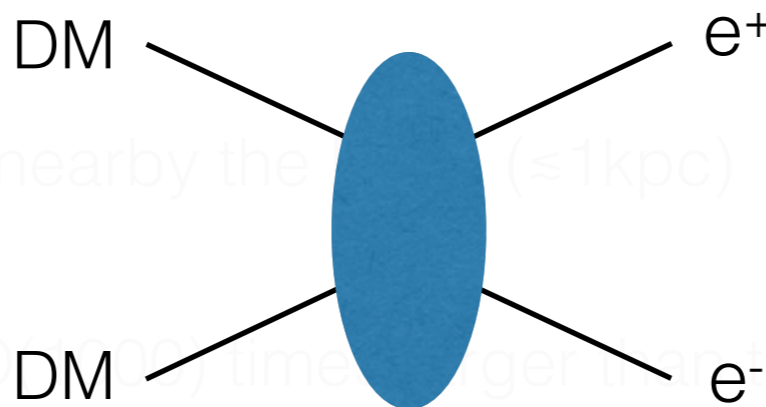

E > 10 GeV

- DM or Pulsars?
  Need more data

- Similar in old data of
  AMS-02 & PAMELA

e⁺ excess: DM annihilation?

Energy of e⁺: mass range of thermal DM

e⁺ excess: DM annihilation?

DM ⟍   ⟋ e⁺
      ⟍ ⬭ ⟋
      ⟋ ⬭ ⟍
DM ⟋   ⟍ e⁻

Energy of e⁺: mass range of thermal DM

DM density

GC

8.5 kpc

Figure by Doojin

e⁺ excess: DM annihilation?

- Mostly from DM nearby the Earth (≤1kpc): diffusion & E loss

- Observed flux: O(1000) times larger than that in thermal DM

$$\Phi \propto \rho^2 \langle \sigma v \rangle \text{ boosted}$$

GC

8.5 kpc
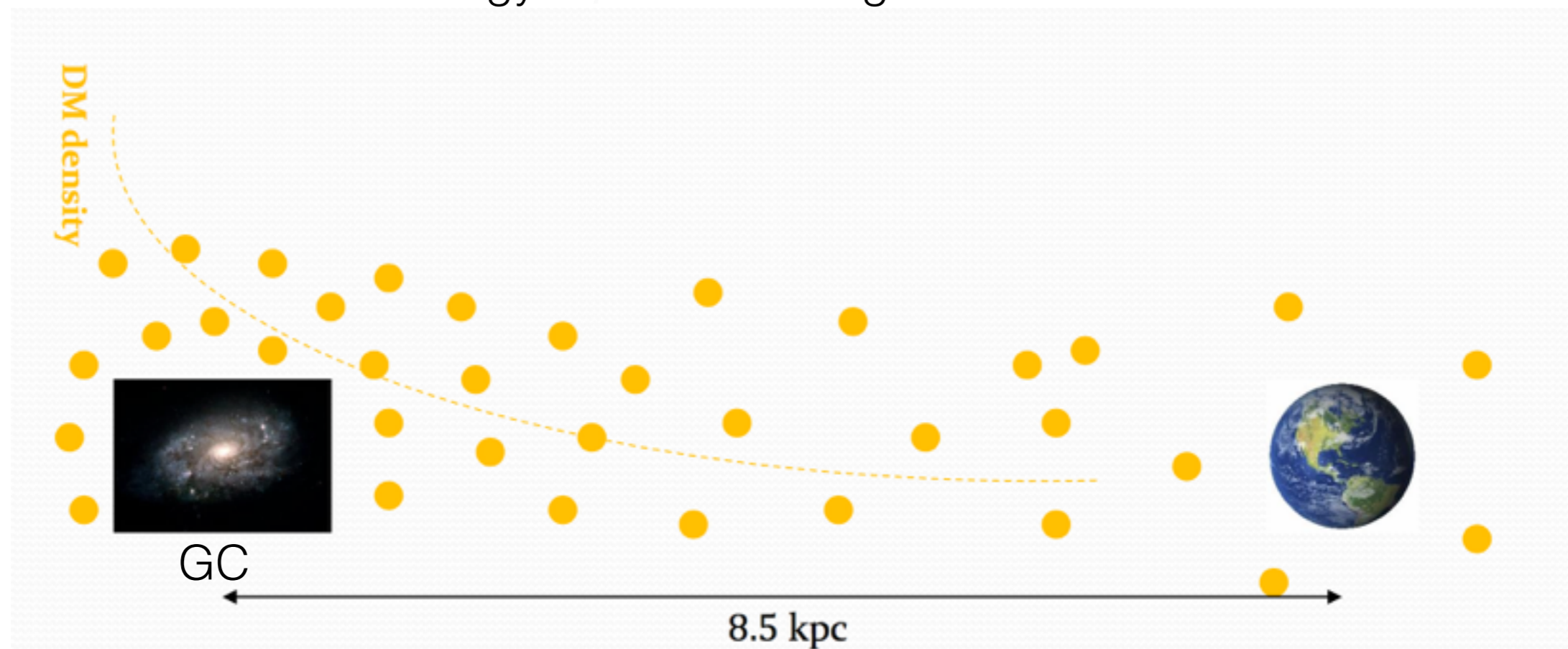
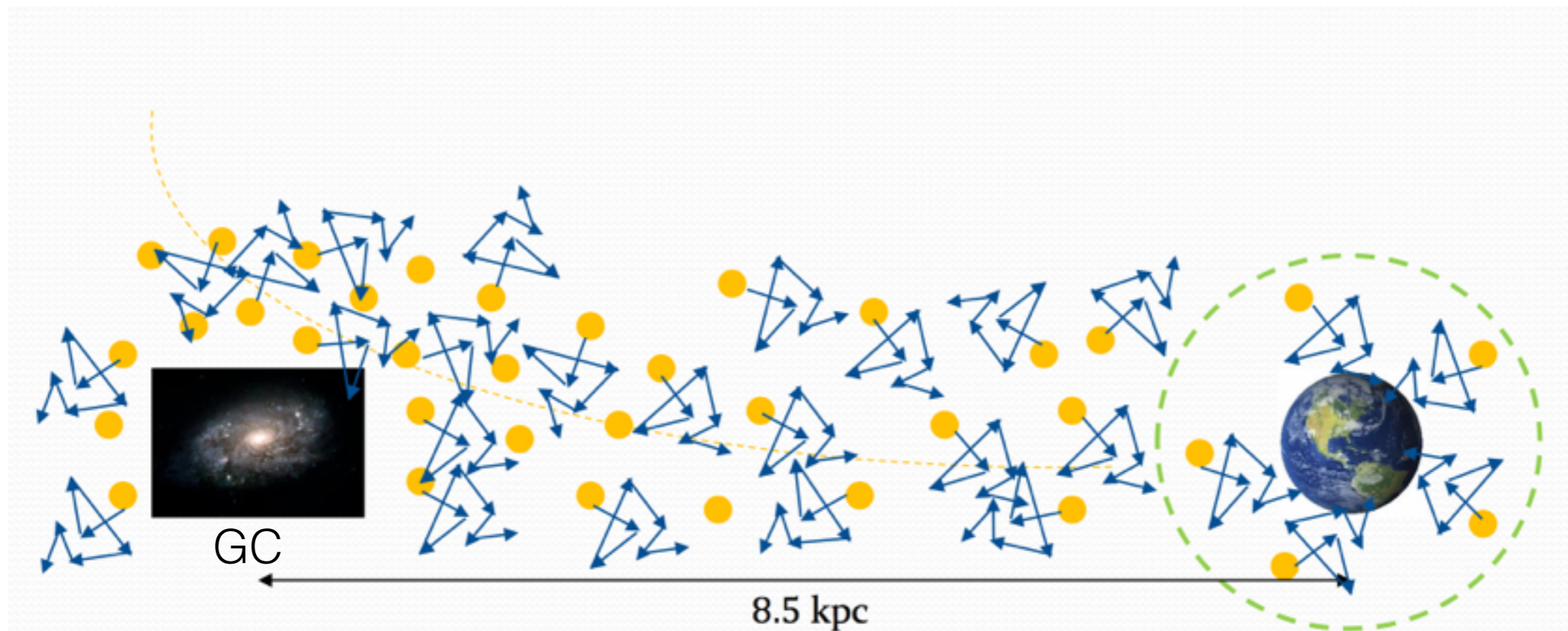# e⁺ excess: DM annihilation?

- Mostly from DM nearby the Earth (≲1kpc): diffusion & E loss

- Observed flux: $O(1000)$ times larger than that in thermal DM

  (s-wave dominant)

  $\Phi \propto \rho^2 \langle \sigma v \rangle$ need enhancement

e$^+$ excess: DM annihilation?

$\Phi \propto \rho^2 \langle \sigma v \rangle$ boosted $\quad \langle \sigma v \rangle \gg O(10^{-26} \text{ cm}^3/\text{s})$

e⁺ excess: DM annihilation?

$$\Phi \propto \rho^2 \langle \sigma v \rangle \text{ boosted} \quad \langle \sigma v \rangle \gg \mathcal{O}(10^{-26} \text{ cm}^3/\text{s})$$

e⁺ excess: DM annihilation?

$$\Phi \propto \rho^2 \boxed{\langle \sigma v \rangle} \text{ boosted} \qquad \langle \sigma v \rangle \gg O(10^{-26} \text{ cm}^3/\text{s})$$

- Sommerfeld enhancement of $\langle \sigma v \rangle$ as $1/v \rightarrow \langle \sigma v \rangle \gg \langle \sigma v \rangle_{\text{f.o.}}$

  Hisano, Matsumoto, Nojiri, 2002   Arkani-Hamed, Finkbeiner, Slatyer, Weiner, 2008

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e⁺ excess: DM annihilation?

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- Late decaying dark partner fits the relic density while

  $$\langle \sigma v \rangle \approx \langle \sigma v \rangle_{\text{f.o.}} \gg O(10^{-26} \text{ cm}^3/\text{s})$$

  Fairbairn, Zupan, 0810.4147

GC

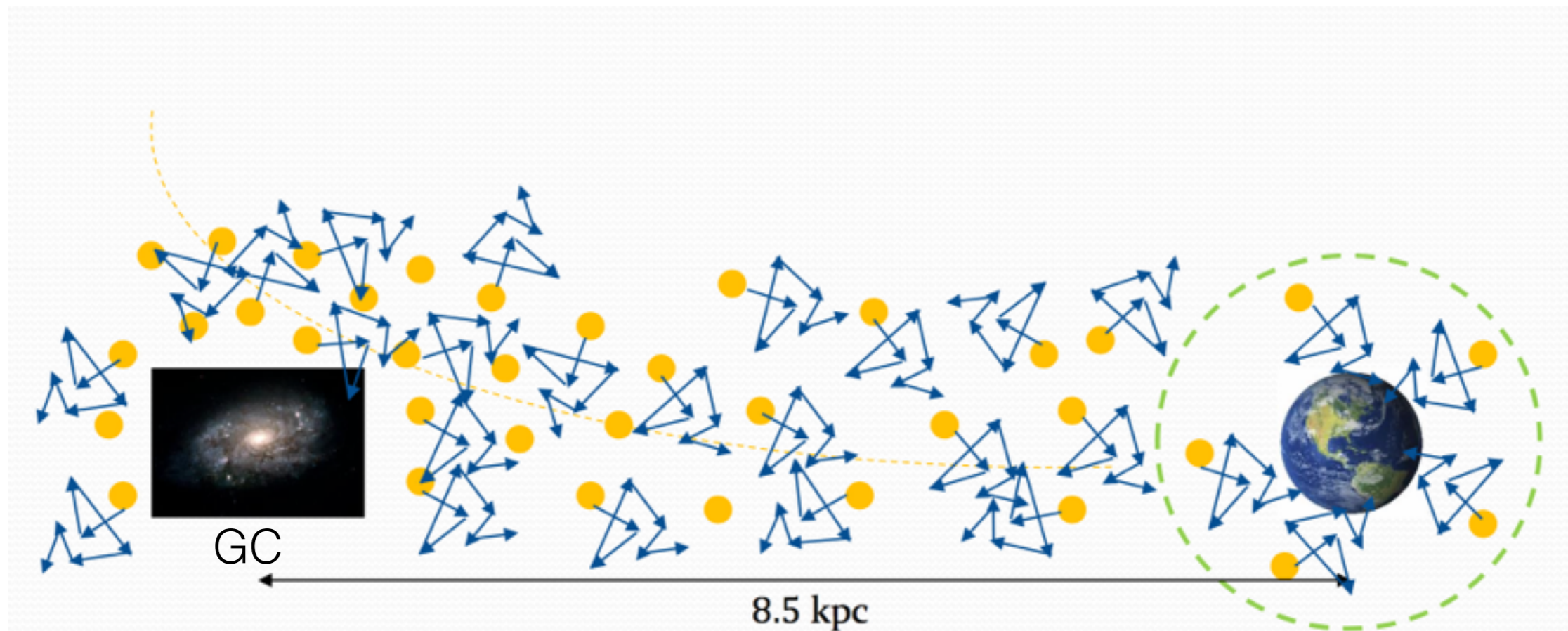8.5 kpc

e⁺ excess: DM annihilation?

$\Phi \propto \rho^2 \langle \sigma v \rangle$ boosted $\langle \sigma v \rangle \gg O(10^{-26}$ cm³/s$)$

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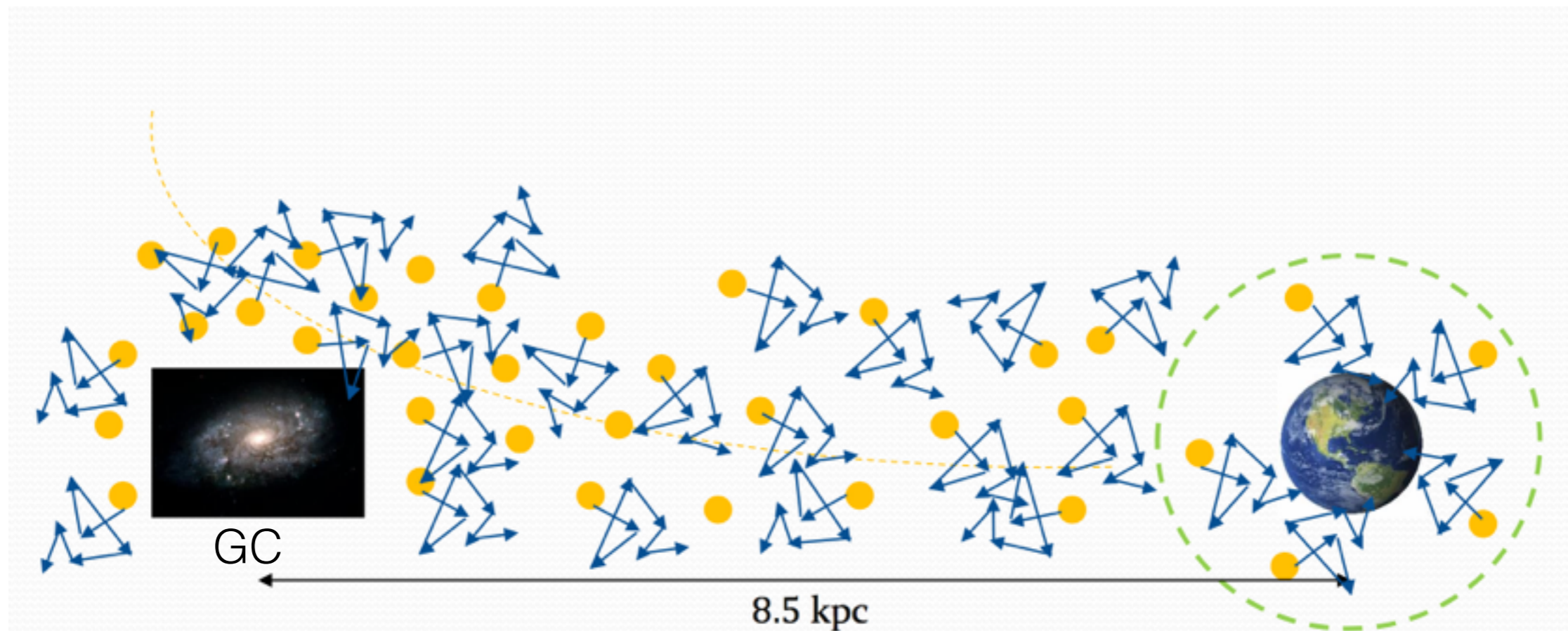 Hisano, Matsumoto, Nojiri, 2002   Arkani-Hamed, Finkbeiner, Slatyer, Weiner, 2008

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  Fairbairn, Zupan, 0810.4147

  BBN

  Large $\langle \sigma v \rangle$

  Strongly constrained from γ-ray data (dSphs, GC)
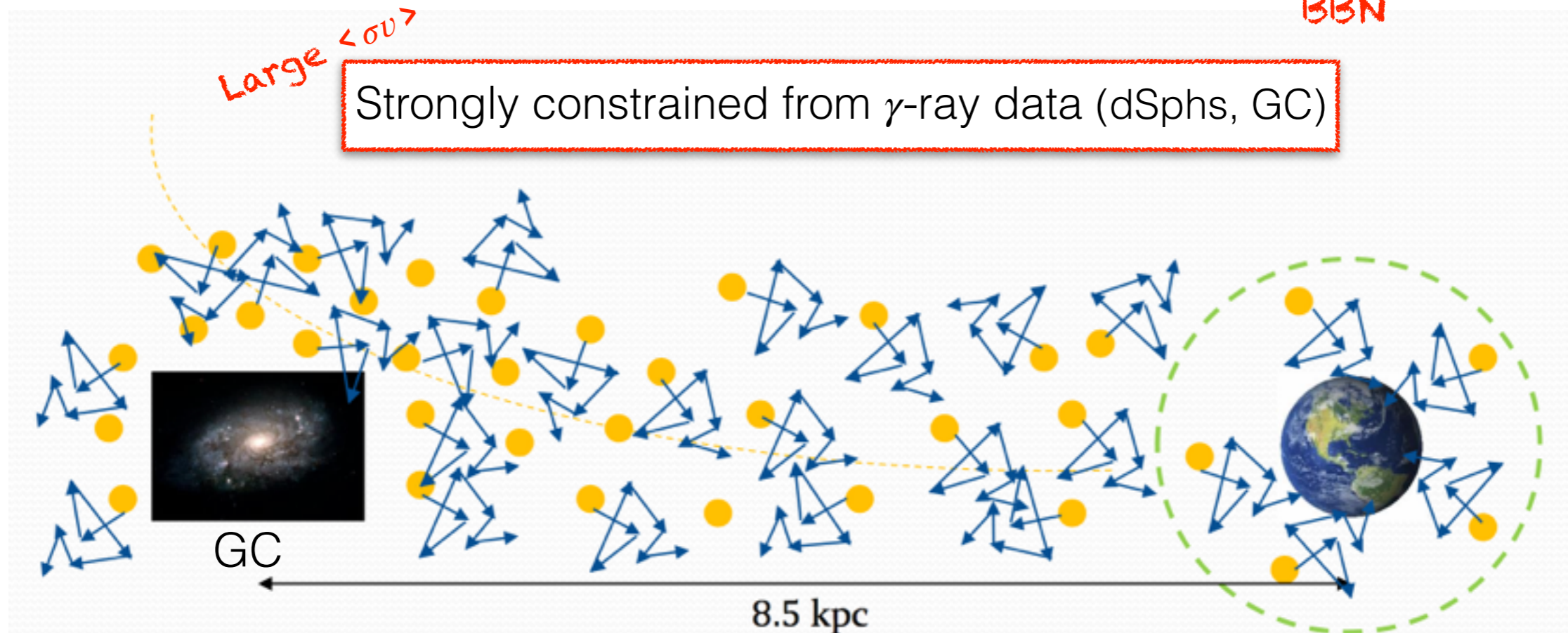
  GC

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e⁺ excess: DM annihilation?

$$\Phi \propto \rho^2 \langle \sigma v \rangle \text{ boosted}$$

- Locally clumpy DM

Some dense regions ~ ⊙ ?

GC

8.5 kpc
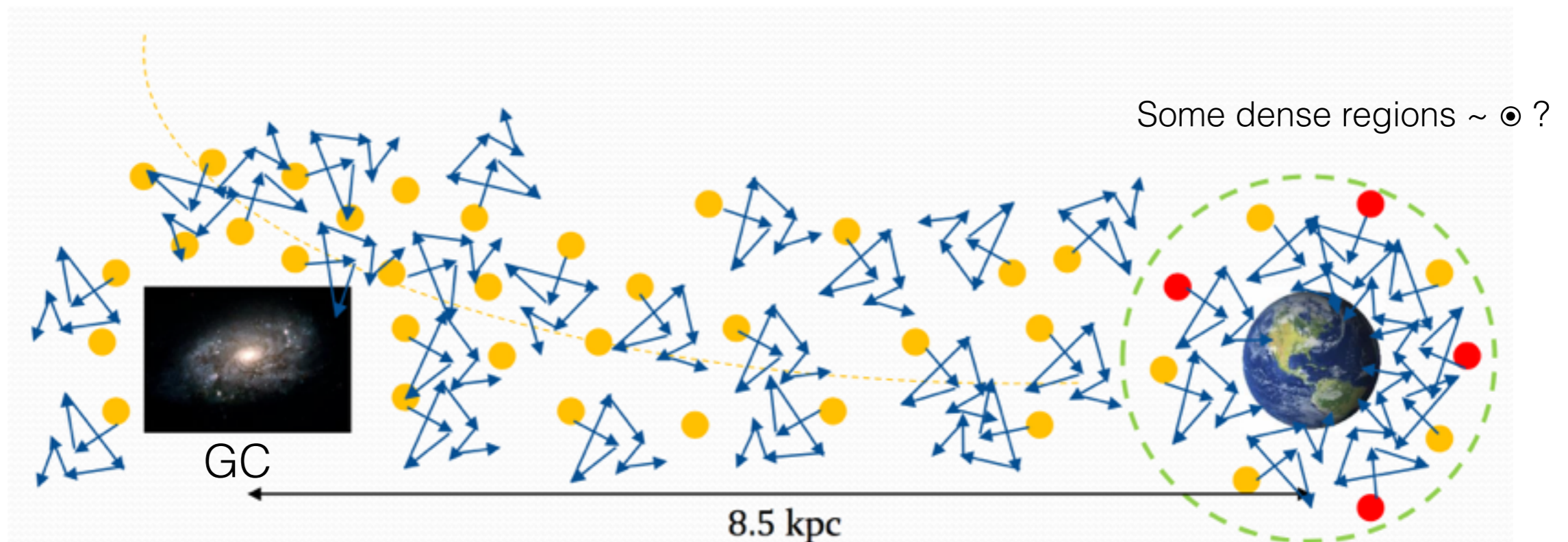
e⁺ excess: DM annihilation?

$$\Phi \propto \boxed{\rho^2} \langle \sigma v \rangle \text{ boosted}$$

- Locally clumpy DM

N-body simulation: ≲10 enhanced at most

Lavalle, Yuan, Maurin, Bi. 0709.3634

Some dense regions ~ ⊙ ?

GC

8.5 kpc
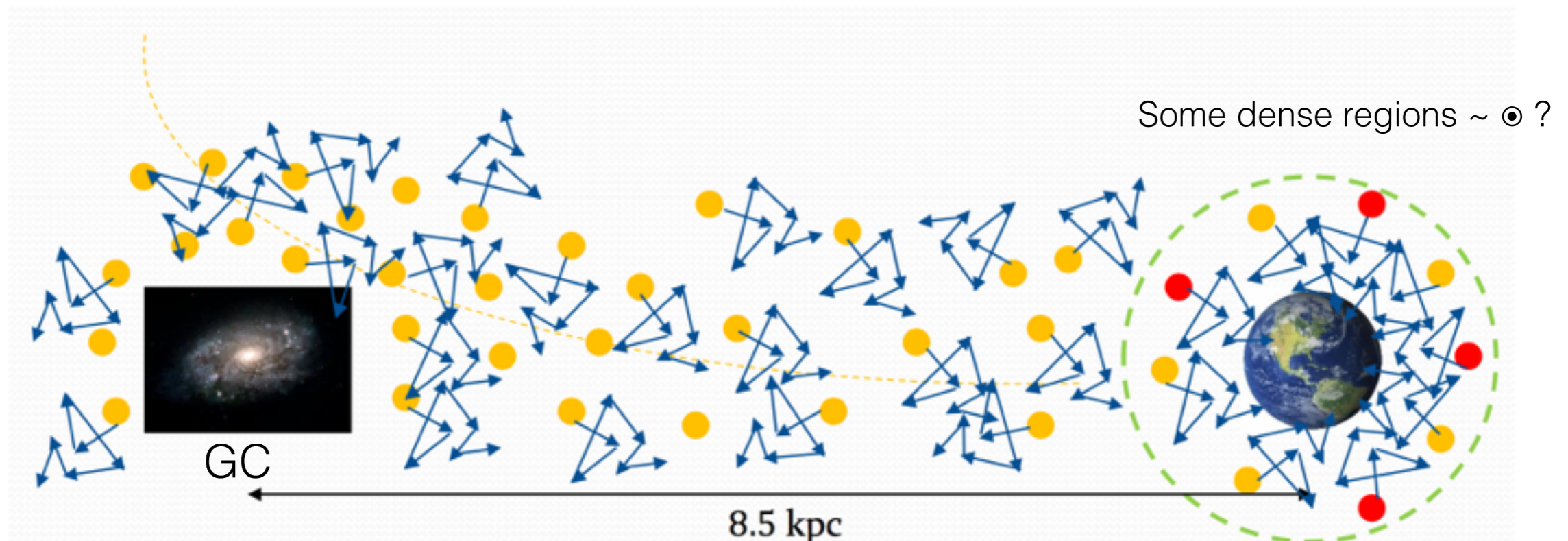
e+ excess: DM decay?

$\Phi \propto \rho\Gamma$: no boost factor needed for $\tau \sim 10^{26}$ sec

Chen, Takahashi, Yanagida, 0809.0792
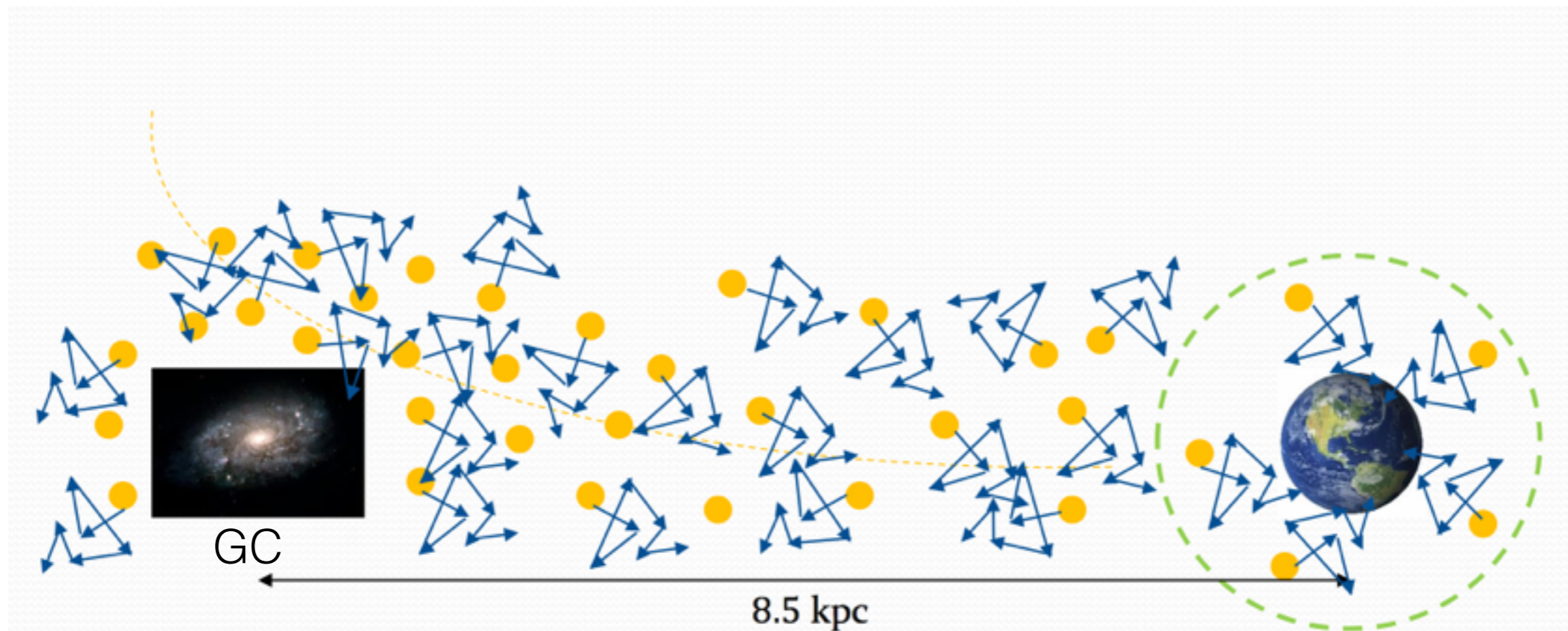
e⁺ excess: DM decay?

$\Phi \propto \rho\Gamma$: no boost factor needed for $\tau \sim 10^{26}$ sec

Chen, Takahashi, Yanagida, 0809.0792

Hard to avoid the bounds from γ-ray data (dSphs, GC)

Ando, Ishiwata, 1502.02007

Massari et al., 1503.07169

Liu, Bi, Lin, Yin, 1602.01012
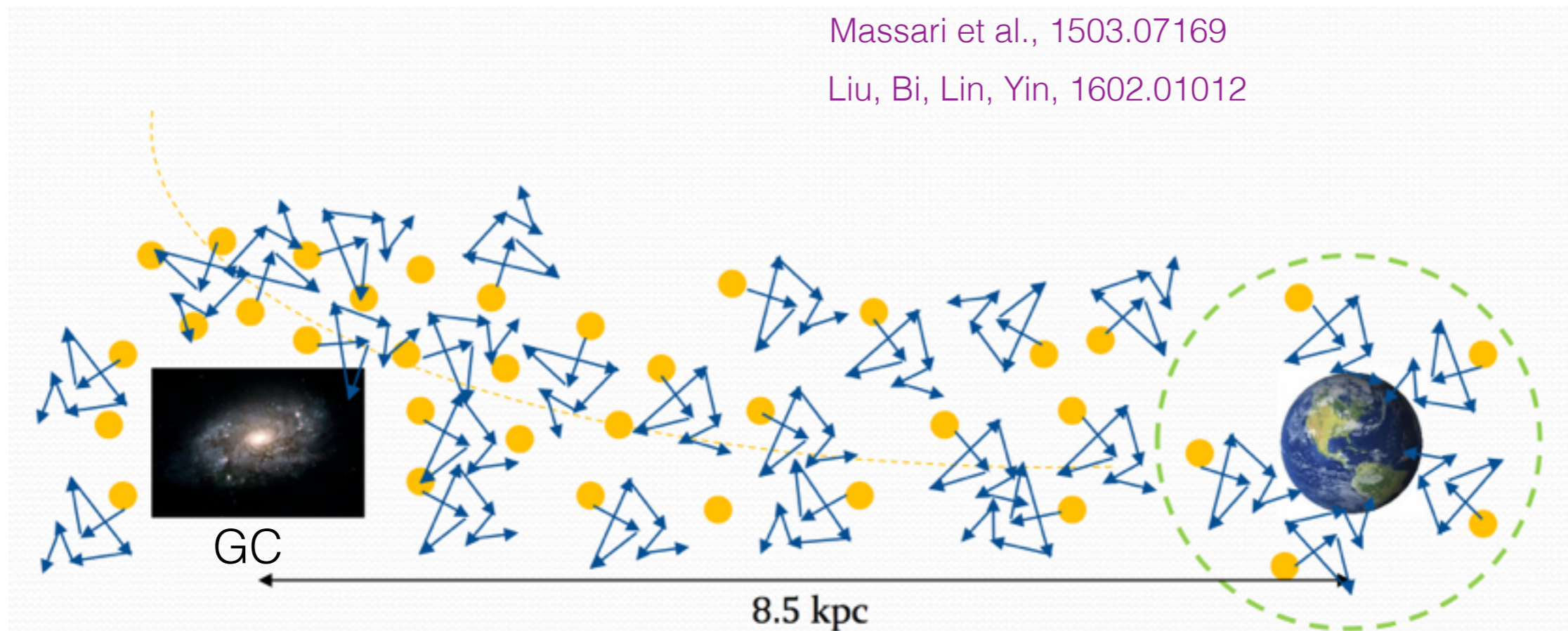
GC

8.5 kpc

Alternatives?

Non-thermal models? bounded from γ-ray data

Astrophysical sources like pulsars, SN remnants?

Hooper, Blasi, Serpico, 0810.1527   Hu et al., 0901.2520
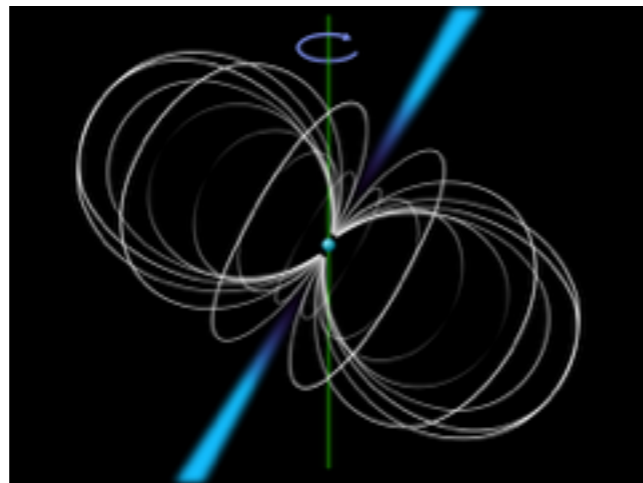
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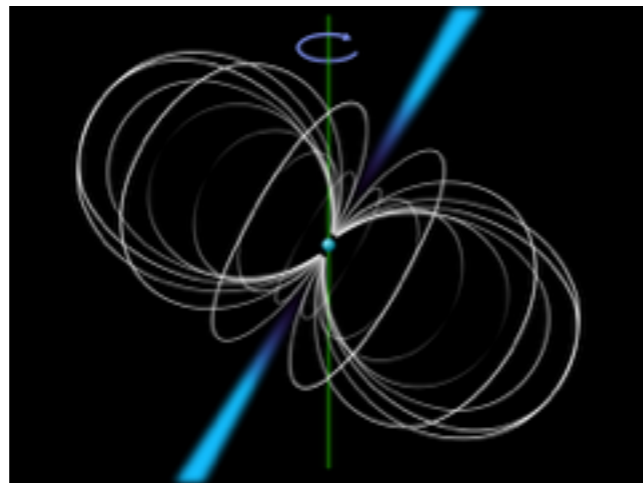
Not the END

High DM density at GC!!

Think about using the DM around Galactic Center
to explain cosmic-ray excesses

GC

8.5 kpc
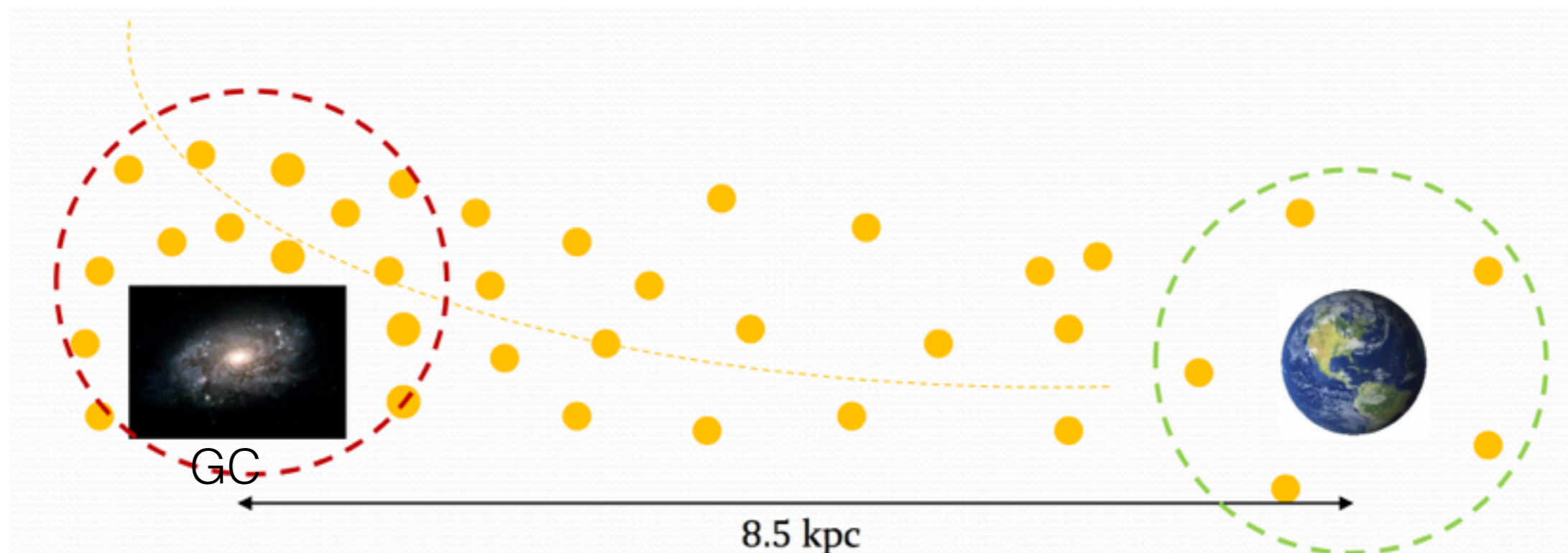
High DM density at GC!!

Think about using the DM around Galactic Center
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Kim, Park, **SS**, 1702.02944

BUT HOW??? charged particles don't reach to the Earth

GC

8.5 kpc
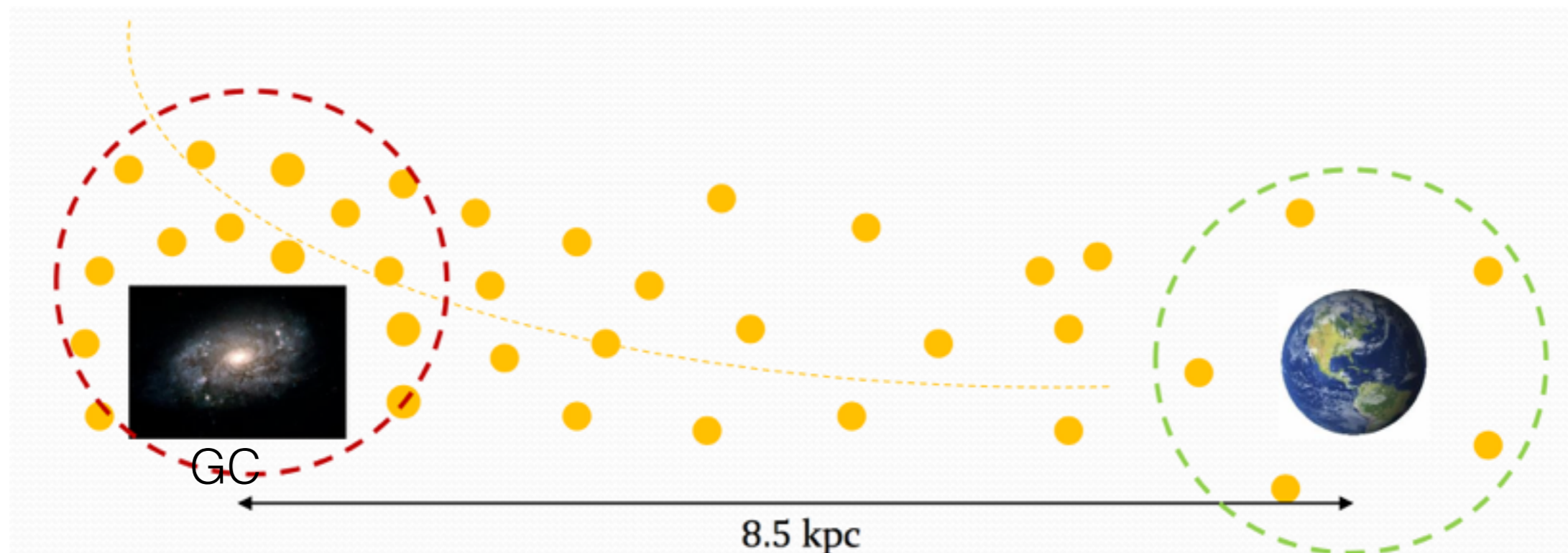
DM Transporting Mechanism

Think about using the DM around Galactic Center
to explain cosmic-ray excesses

Kim, Park, **SS**, 1702.02944

Effectively TRANSPORT DM: GC → Earth

GC

8.5 kpc

DM Transporting Mechanism

Non-minimal dark sector

- χ_h: heavier DM (dominant)

- ϕ: long-lived dark sector state

- : lighter DM (subdominant)

Galactic Center   Near the Earth

Kim, Park, **SS**, 1702.02944

GC

8.5 kpc

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Galactic Center   Near the Earth

Kim, Park, **SS**, 1702.02944

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Galactic Center   Near the Earth

Kim, Park, **SS**, 1702.02944

Transport

GC

8.5 kpc

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Galactic Center

Near the Earth

Kim, Park, **SS**, 1702.02944

Transport

GC

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Galactic Center   Near the Earth

Kim, Park, **SS**, 1702.02944

Example: boosted dark matter

Agashe, Cui, Necib, Thaler, 1405.7370

Assisted freeze-out
(Flux of relic χ_1: small)
non-relativistic

Belanger, Park, 1112.4491

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Galactic Center   Near the Earth

Kim, Park, **SS**, 1702.02944

Example: boosted dark matter with ϕ

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Galactic Center   **Near the Earth**
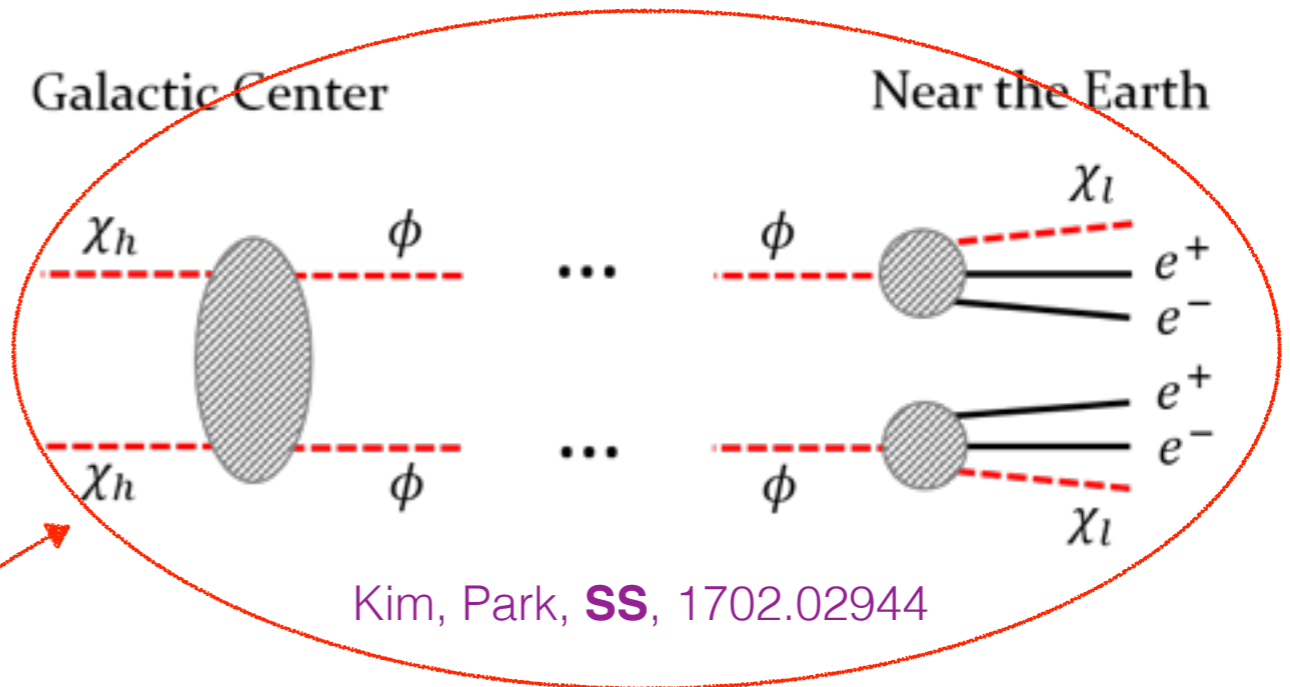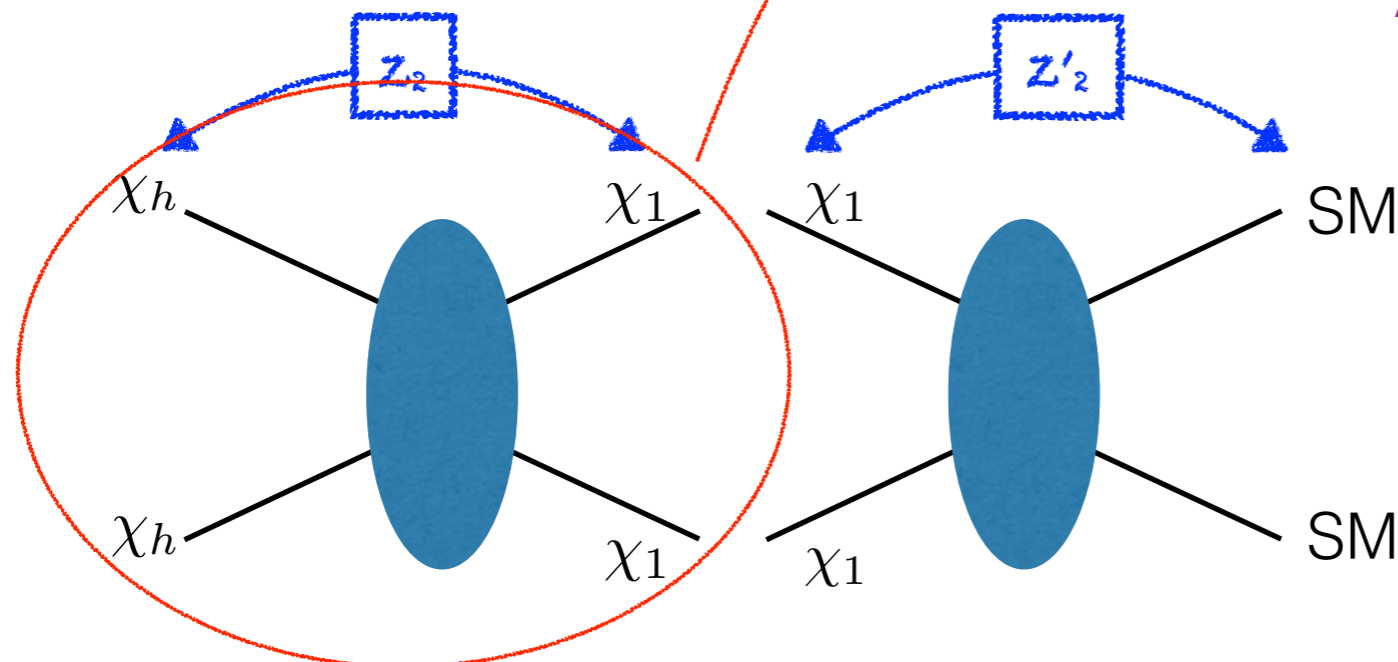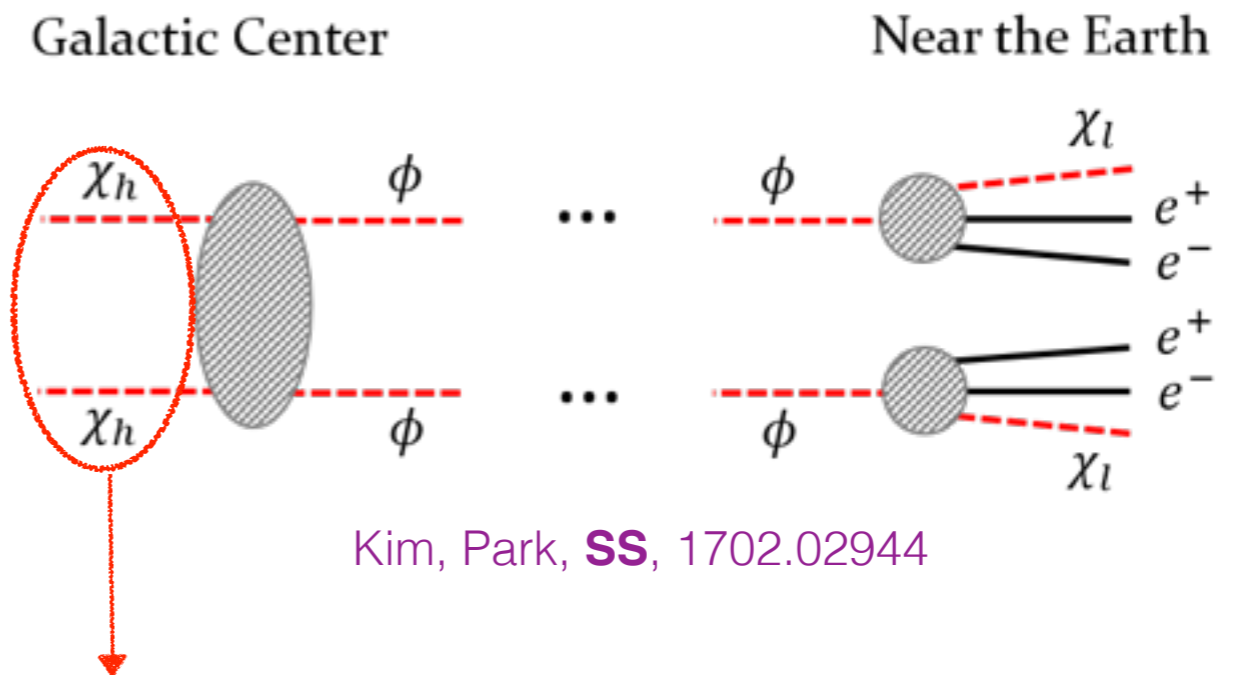
Kim, Park, **SS**, 1702.02944

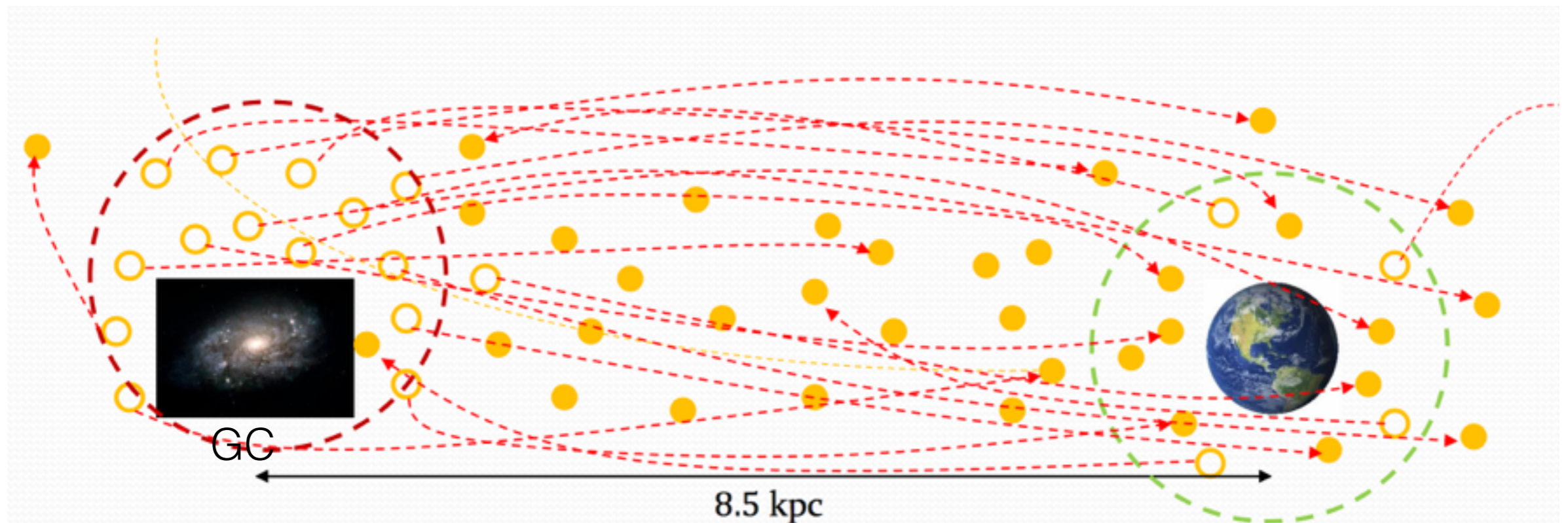Energy scale of the spectrum ~ 1 TeV (AMS-02)

DM Transporting Mechanism

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Galactic Center

Near the Earth

Kim, Park, **SS**, 1702.02944

Ballpark figure

GC to Earth ~ 8 kpc distance: 8×10^{11} sec for travel

DM Transporting Mechanism

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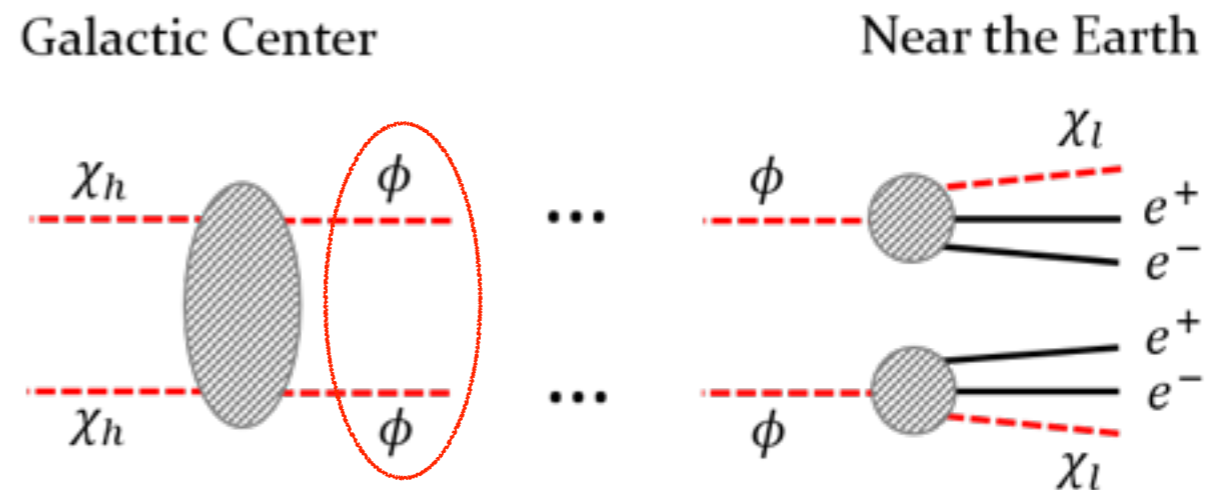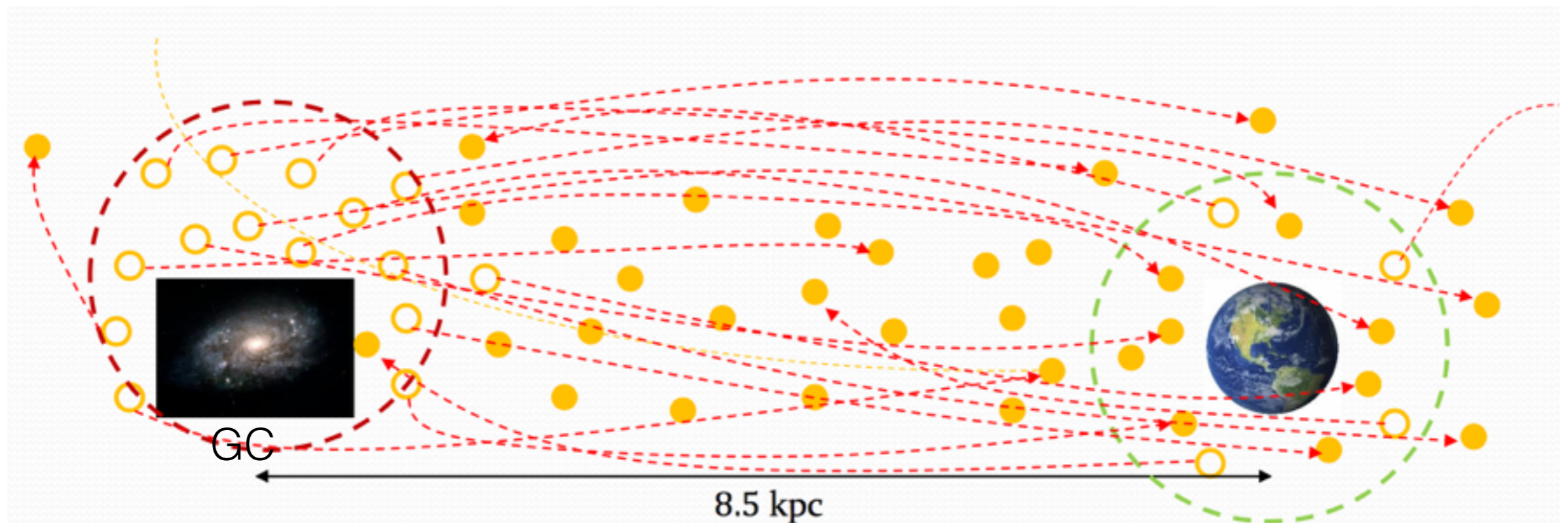
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Galactic Center

Near the Earth

Kim, Park, **SS**, 1702.02944

Ballpark figure

GC to Earth ~ 8 kpc distance: 8×10^{11} sec for travel

$\gamma_\phi \tau_\phi$

boost factor   life time at rest

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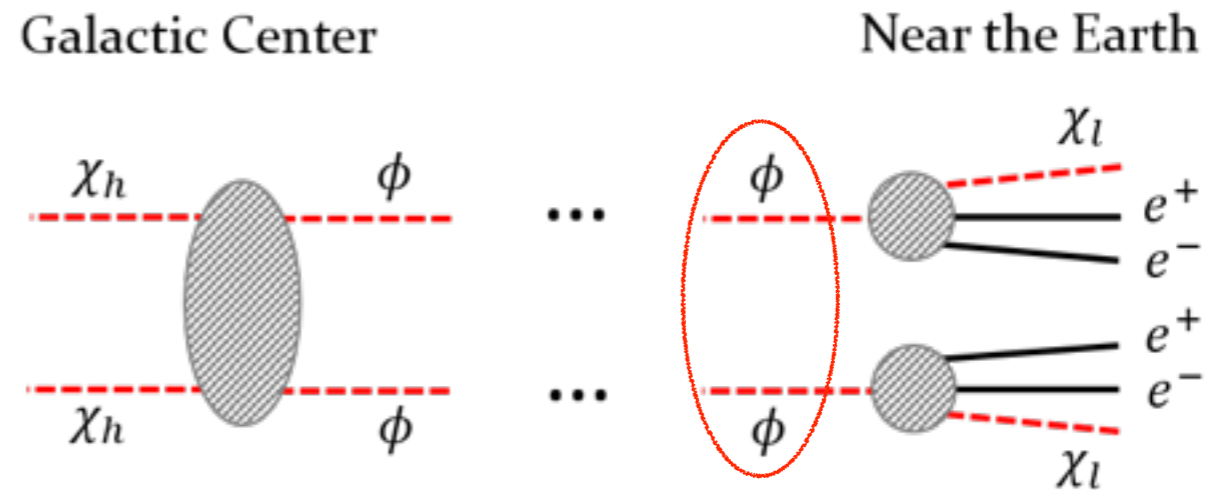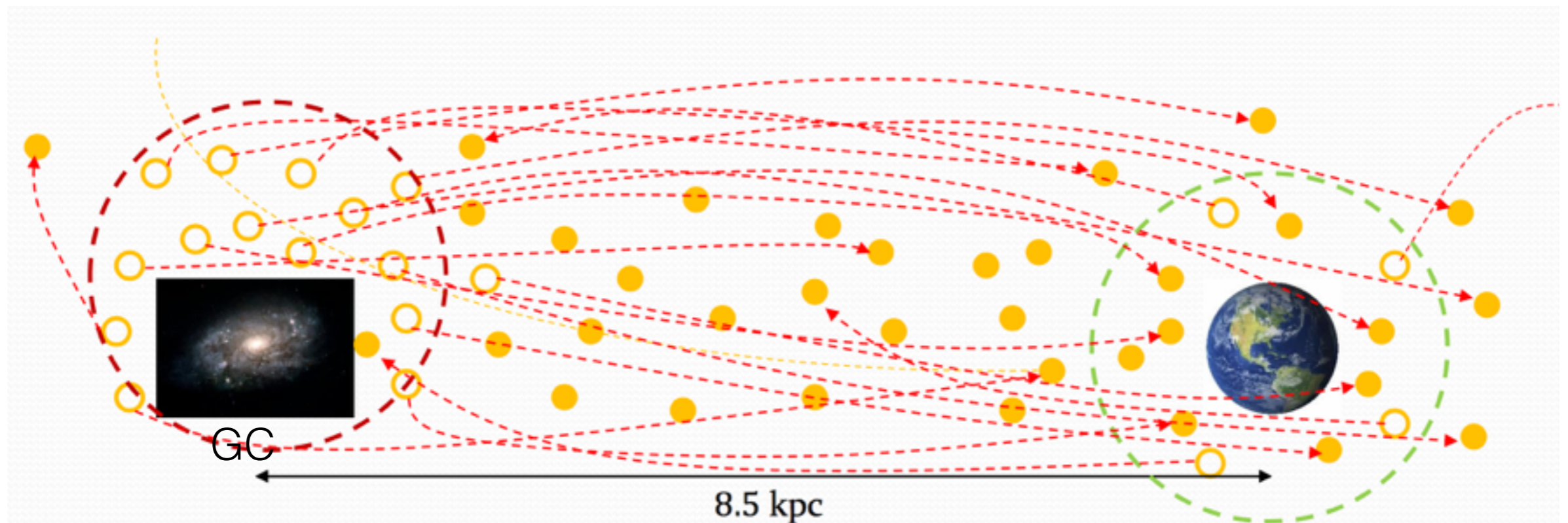
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Galactic Center

Near the Earth

Kim, Park, **SS**, 1702.02944

Ballpark figure

GC to Earth ~ 8 kpc distance: 8×10^{11} sec for travel

- CMB bound

$\gamma_\phi \tau_\phi$

boost factor   life time at rest

$\tau_\phi \lesssim 10^{12}$ sec

for $\rho_\phi \gtrsim 10^{-11} \, \rho_{CDM}$

- $m_\phi > 2 \, m_e$

- BBN bounds

DM Transporting Mechanism

Non-minimal dark sector

- χ_h: heavier DM (dominant)

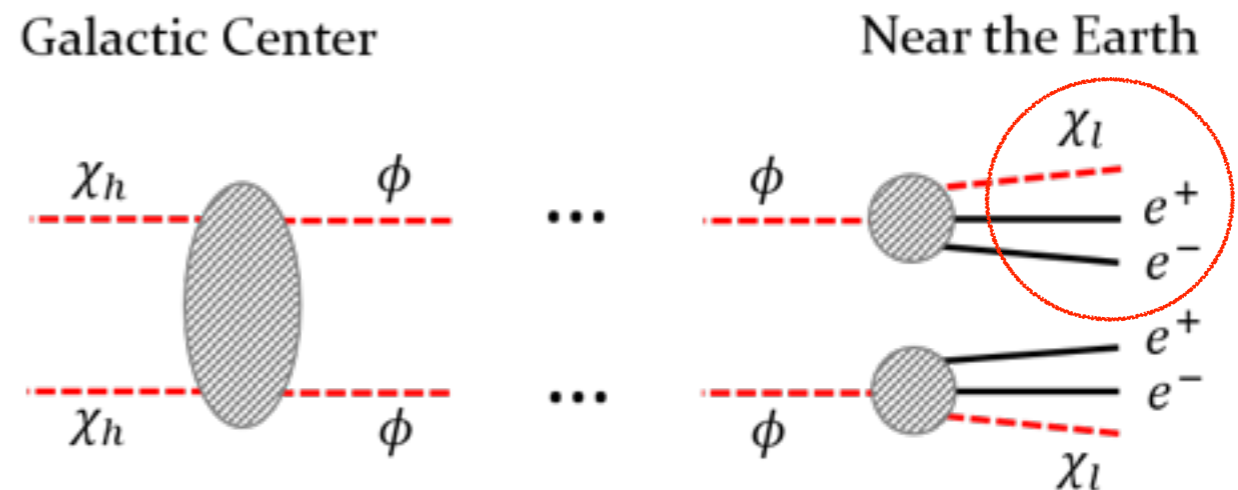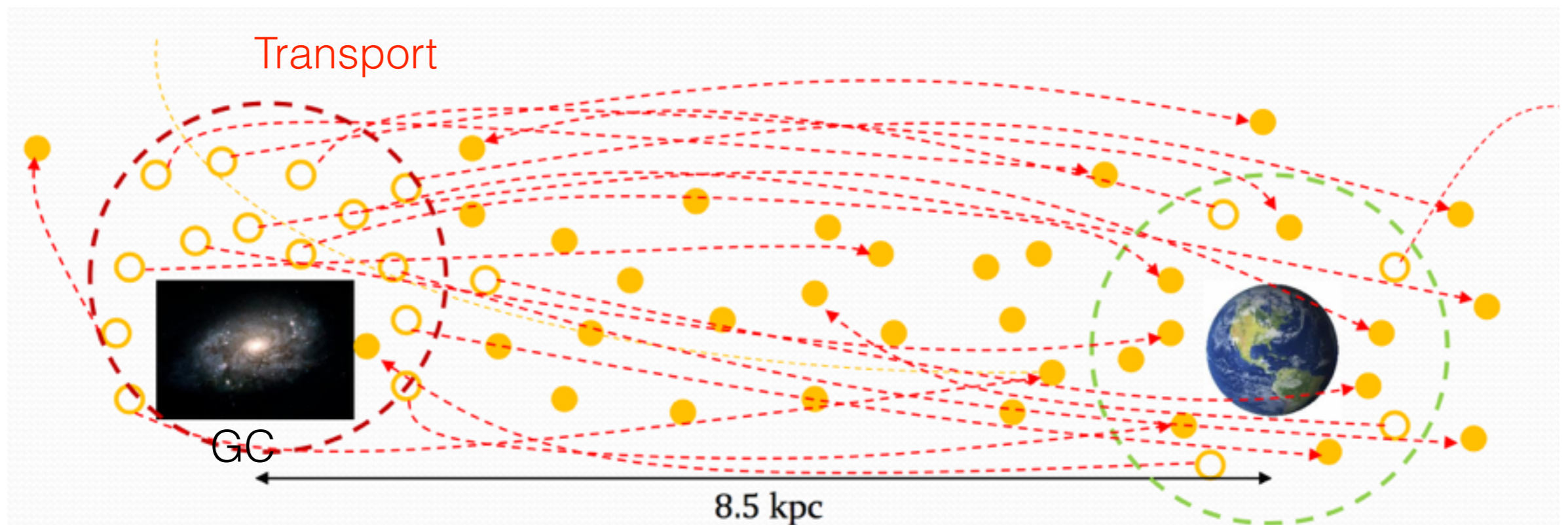- ϕ: long-lived dark sector state
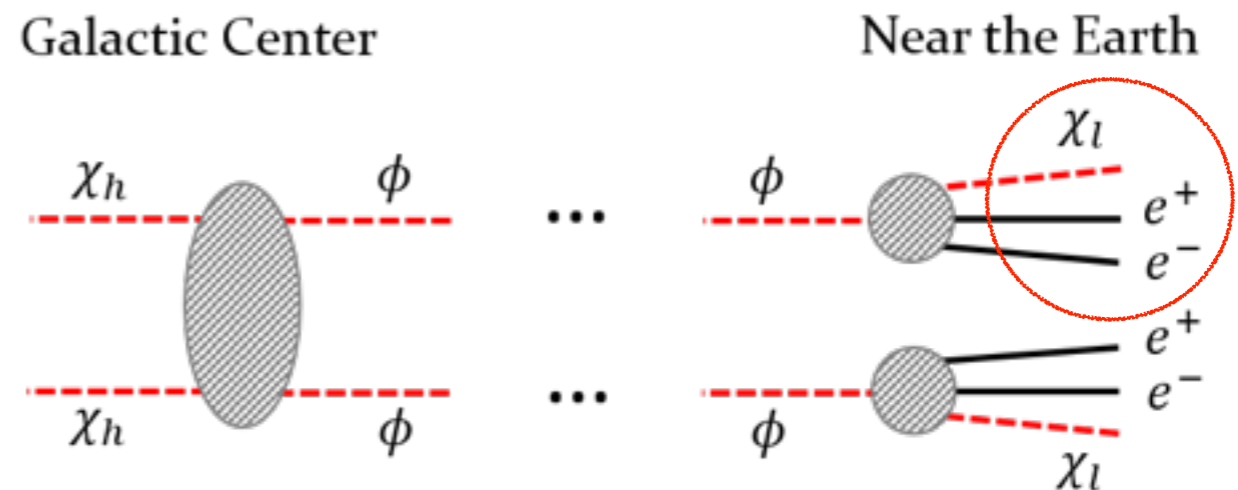
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Galactic Center   Near the Earth

Kim, Park, **SS**, 1702.02944

Ballpark figure

GC to Earth ~ 8 kpc distance: 8×10^{11} sec for travel

- CMB bound

$$\gamma_\phi \tau_\phi$$

- m_ϕ: > 2 m_e

boost factor   life time at rest

$$\gamma_\phi \lesssim 10^6 \qquad 10^6 \lesssim \tau_\phi \lesssim 10^{12} \, \text{sec}$$

practical maximum   for $\rho_\phi \gtrsim 10^{-11} \, \rho_{CDM}$

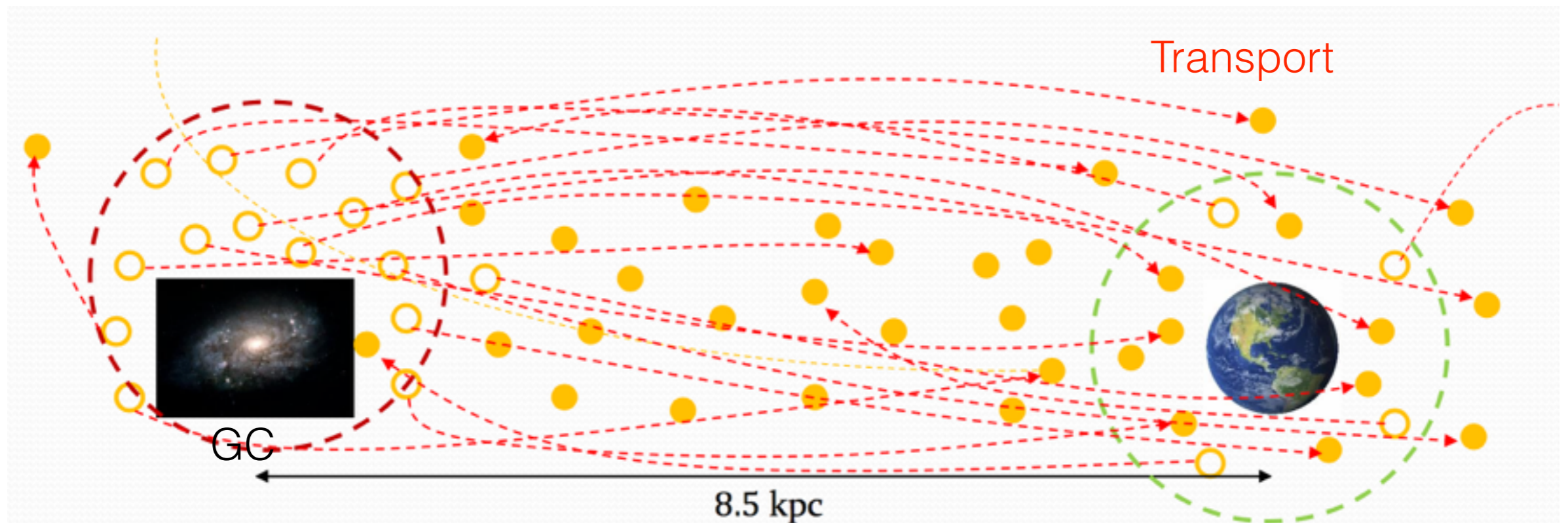$$m_{\chi_h} \sim 1 \, \text{TeV}$$

- BBN bounds

DM Transporting Mechanism

Non-minimal dark sector

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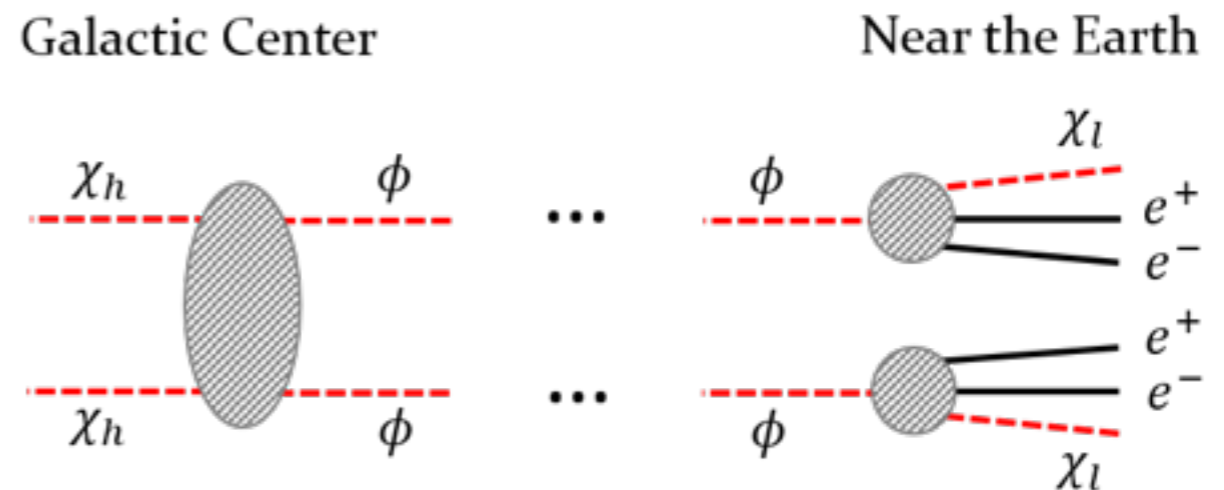- ϕ: long-lived dark sector state

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Galactic Center

Near the Earth

Kim, Park, **SS**, 1702.02944

Ballpark figure

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Galactic Center

Near the Earth

Kim, Park, **SS**, 1702.02944

Ballpark figure

GC to Earth ~ 8 kpc distance: 8×10^{11} sec for travel

- CMB bound

$$\gamma_\phi \tau_\phi$$

$$\gamma_\phi \sim 10^4 \, , \quad \tau_\phi \sim 10^8 \, \text{sec}$$

Good reference

- m_ϕ: $> 2\, m_e$

- BBN bounds

DM Transporting Mechanism

Non-minimal dark sector

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Galactic Center   **Near the Earth**

Kim, Park, **SS**, 1702.02944

Ballpark figure

GC to Earth ~ 8 kpc distance: 8×10^{11} sec for travel

- CMB bound

$\gamma_\phi \tau_\phi$

- m_ϕ: $> 2\, m_e$

$\gamma_\phi \sim 10^4 \,,\;\; \tau_\phi \sim 10^8 \,\mathrm{sec}$

Good reference

- BBN bound
  $(\rho_\phi / \rho_{\mathrm{CDM}}) \times (E(\gamma, e^\pm)/E_\phi) \lesssim 2 \times 10^{-5}$ (Relaxed: 10^{-2} for $\tau_\phi \sim 10^6 \,\mathrm{sec}$)
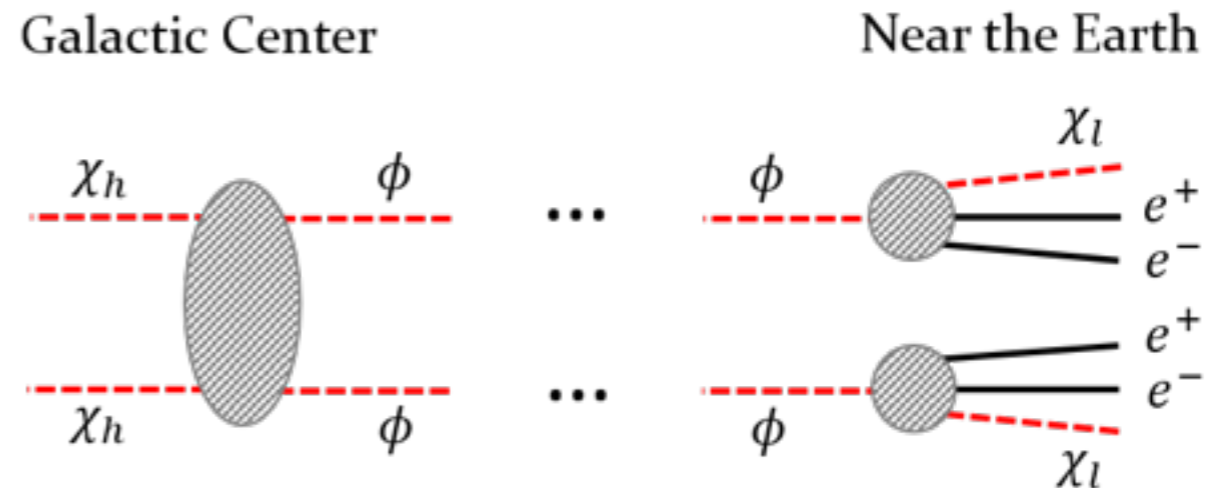
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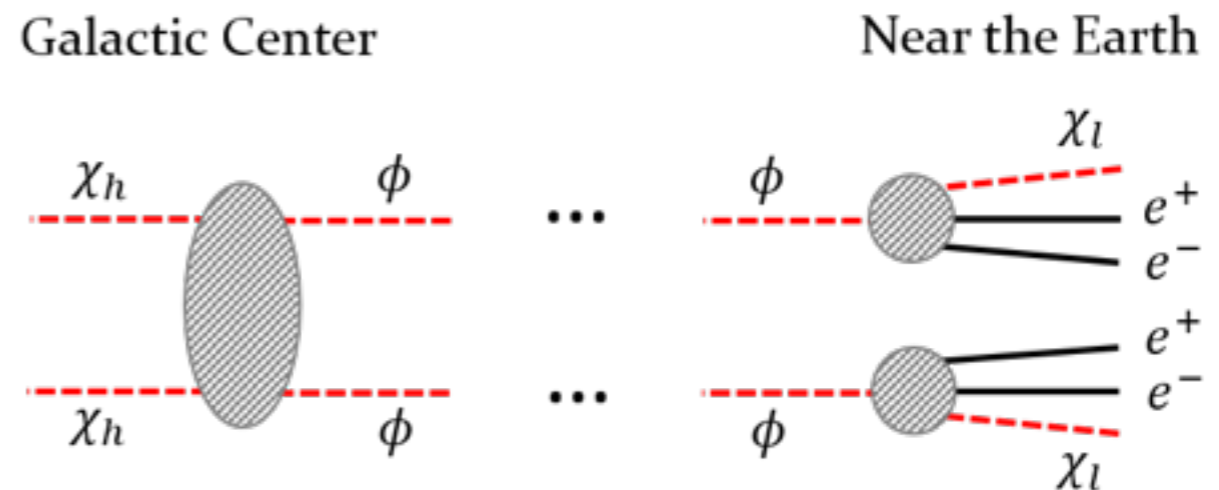
- χ_l: lighter DM (subdominant)

Galactic Center

Near the Earth

Kim, Park, **SS**, 1702.02944

Ballpark figure

GC to Earth ~ 8 kpc distance: 8×10^{11} sec for travel

- CMB bound

- m_ϕ: > 2 m_e

- BBN bound

$$(\rho_\phi/\rho_{\rm CDM}) \times (E(\gamma, e^\pm)/E_\phi) \lesssim 2 \times 10^{-5}$$

$$\frac{m_\phi n_\phi}{m_{\chi_h} n_{\chi_h}} \qquad \begin{array}{c} 2/3 \\ \text{(conservative)} \end{array}$$

DM Transporting Mechanism

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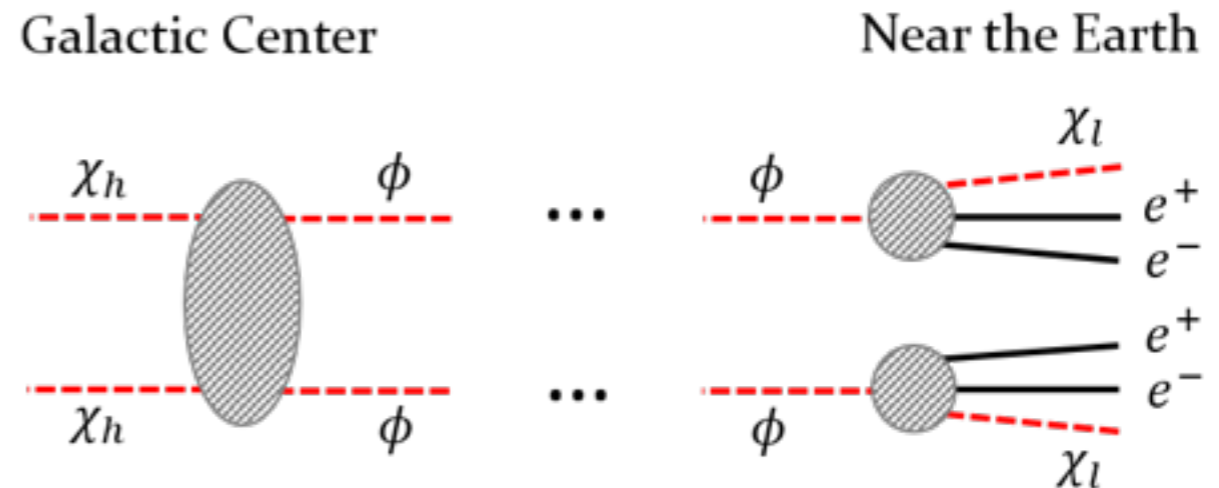- ϕ: long-lived dark sector state

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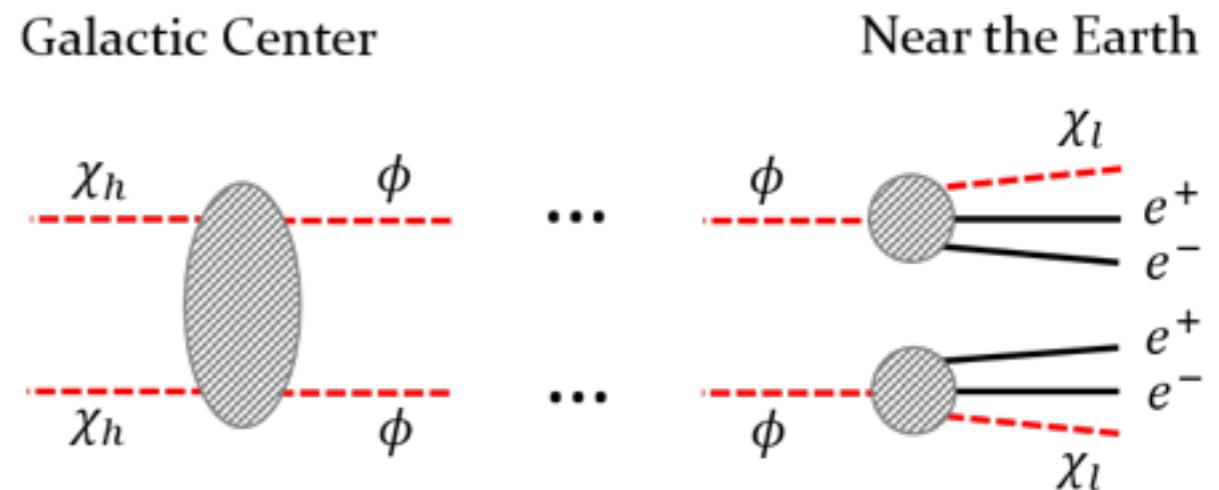
Kim, Park, **SS**, 1702.02944

Ballpark figure

GC to Earth ~ 8 kpc distance: 8×10^{11} sec for travel

- CMB bound

- m_ϕ: > 2 m_e

- BBN bound

$$m_\phi \lesssim 30\,\mathrm{MeV} \quad \text{for} \quad n_\phi \simeq n_{\chi_h}$$
$$m_\phi \text{ larger} \quad \text{for} \quad n_\phi \ll n_{\chi_h}$$

$\gamma_\phi \sim 10^4$, $\tau_\phi \sim 10^8$ sec

Still Good reference

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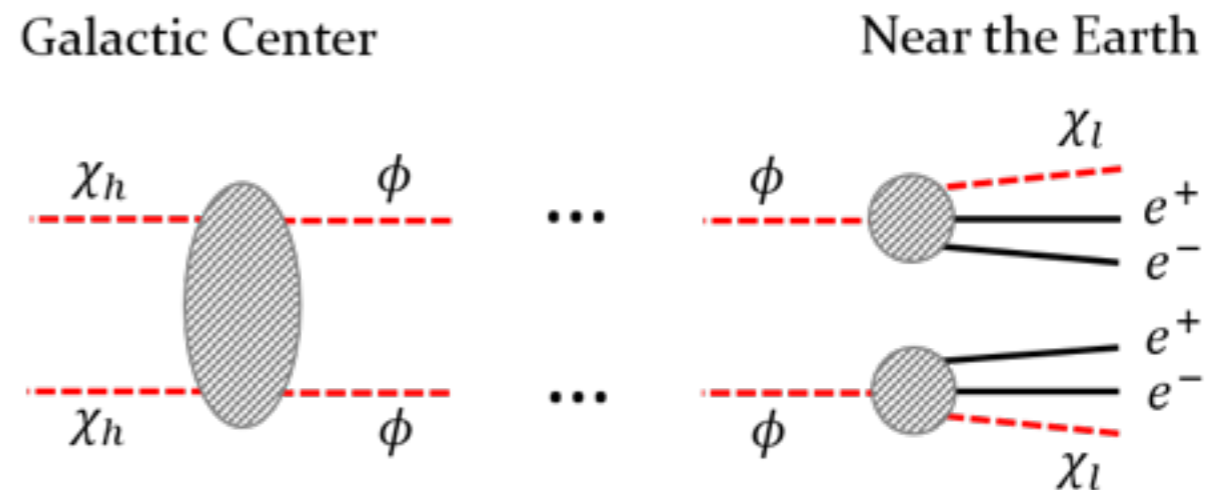
Kim, Park, **SS**, 1702.02944

Astrophysical constraints

- γ-rays from small region (dSphs, GC): ϕ decays far away from it

- $\bar{p}$ through EW gauge boson radiation: not strong for $m_{DM} \sim$ 1TeV

Cavasonza et al., 1612.06634   Giesen et al., 1504.04276

DM Transporting Mechanism

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Galactic Center ... **Near the Earth**
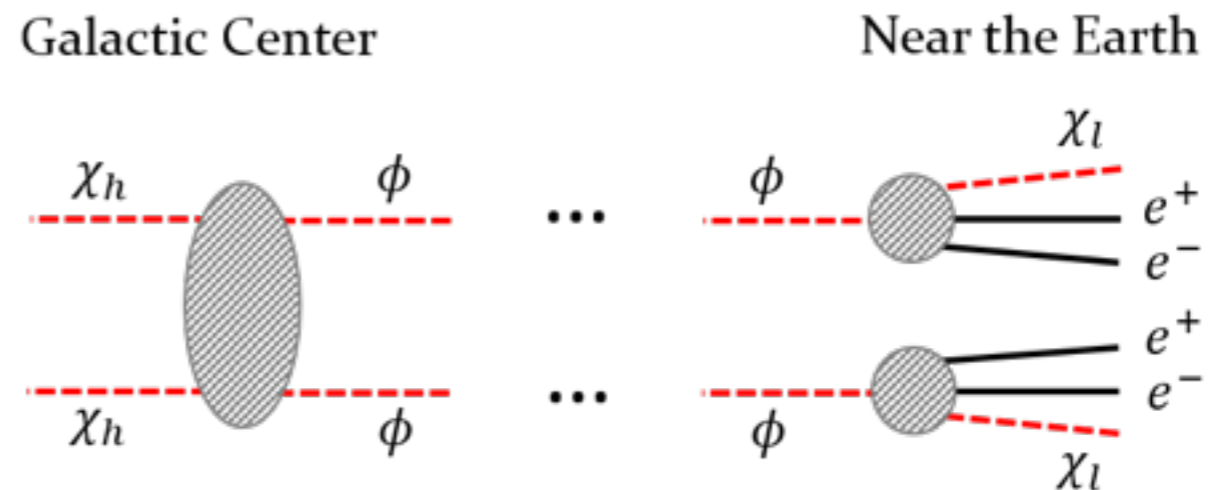
Kim, Park, **SS**, 1702.02944

Safe from various cosmological & astrophysical constraints!

e$^+$ spectrum calculation

Diffusion equation

$$\frac{\partial}{\partial t}f(\vec{x}, E) - \vec{\nabla} \cdot \left[K(\vec{x}, E)\vec{\nabla}f(\vec{x}, E)\right] - \frac{\partial}{\partial E}\left[b(\vec{x}, E)f(\vec{x}, E)\right] = Q(\vec{x}, E)$$

 diffusion energy loss source

$$\frac{d\Phi}{dE} = \frac{c}{4\pi}f$$

e⁺ spectrum calculation

Diffusion equation

$$\frac{\partial}{\partial t} f(\vec{x}, E) - \vec{\nabla} \cdot \left[K(\vec{x}, E) \vec{\nabla} f(\vec{x}, E) \right] - \frac{\partial}{\partial E} \left[b(\vec{x}, E) f(\vec{x}, E) \right] = Q(\vec{x}, E)$$

$$\underbrace{\qquad\qquad}_{\text{diffusion}} \qquad \underbrace{\qquad\qquad}_{\text{energy loss}} \quad \underbrace{\quad}_{\text{source}}$$

$$\frac{d\Phi}{dE} = \frac{c}{4\pi} f$$

Decay of φ

$$Q(\vec{x}, E) = n_\phi(\vec{x}) \, \Gamma_\phi^{\text{lab}} \, \frac{dN}{dE}$$

$$\Gamma_\phi^{\text{lab}} = \Gamma_\phi / \gamma_\phi$$

e⁺ spectrum calculation

Diffusion equation

$$\frac{\partial}{\partial t} f(\vec{x}, E) - \vec{\nabla} \cdot \left[K(\vec{x}, E) \vec{\nabla} f(\vec{x}, E) \right] - \frac{\partial}{\partial E} \left[b(\vec{x}, E) f(\vec{x}, E) \right] = Q(\vec{x}, E)$$

diffusion   energy loss source

$$\frac{d\Phi}{dE} = \frac{c}{4\pi} f$$

Decay of φ

Annihilation of $\chi_h \chi_h \to \phi\phi$

$$Q(\vec{x}, E) = n_\phi(\vec{x}) \, \Gamma_\phi^{\text{lab}} \, \frac{dN}{dE}$$

$$\Gamma_\phi^{\text{lab}} = \Gamma_\phi / \gamma_\phi$$

$$\frac{d\Phi_\phi(\vec{x})}{d\Omega_{x_*} dE_\phi} = \left(\frac{1}{2} \right) \cdot \frac{1}{4\pi} \int_{\text{l.o.s}} ds_{x_*} \frac{n_{\chi_h}^2(\vec{y})}{2} \langle \sigma v \rangle_{\chi_h \chi_h \to \phi\phi} \times e^{-\frac{|\vec{x} - \vec{y}|}{c} \Gamma_\phi^{\text{lab}}} \frac{dN_\phi}{dE_\phi}$$

$$\Phi_\phi = n_\phi \cdot v_\phi$$

like photon spectrum
+
ϕ decay factor in propagation
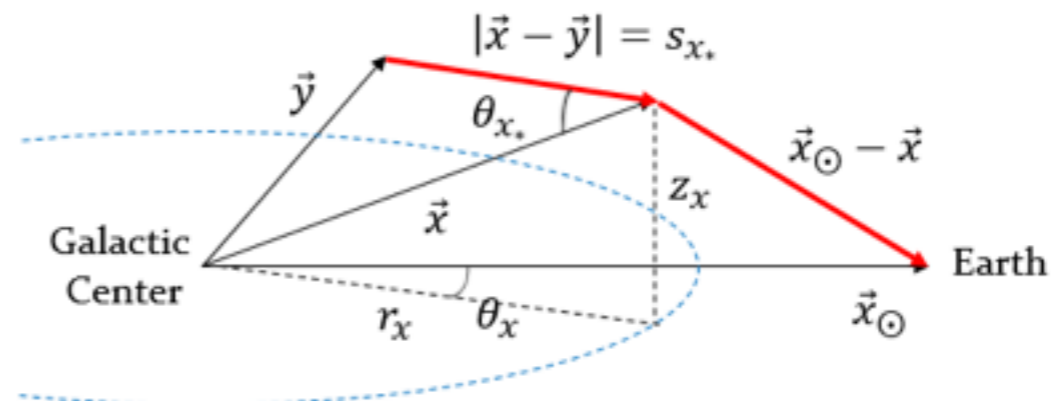
e$^+$ spectrum calculation

$$\frac{d\Phi_\phi(\vec{x})}{d\Omega_{x_*} dE_\phi} = \left(\frac{1}{2}\right) \cdot \frac{1}{4\pi} \int_{\text{l.o.s}} ds_{x_*} \frac{n_{\chi_h}^2(\vec{y})}{2} \langle \sigma v \rangle_{\chi_h \chi_h \to \phi\phi} \times e^{-\frac{|\vec{x}-\vec{y}|}{c}\Gamma_\phi^{\text{lab}}} \frac{dN_\phi}{dE_\phi}$$

$$\Phi_\phi = n_\phi \cdot v_\phi$$

DM density

$$\frac{dN_\phi}{dE_\phi} = 2 \cdot \delta(E_\phi - m_{\chi_h})$$

$$y^2 = r_x^2 + z_x^2 + s_{x_*}^2 - 2\sqrt{r_x^2 + z_x^2}\, s_{x_*} \cos\theta_{x_*}$$

Usual halo of χ_h: only **O**(1) enhancement (small flux)

e⁺ spectrum calculation

$$\frac{d\Phi_\phi(\vec{x})}{d\Omega_{x_*} dE_\phi} = \left(\frac{1}{2}\right) \cdot \frac{1}{4\pi} \int_{\text{l.o.s}} ds_{x_*} \frac{n_{\chi_h}^2(\vec{y})}{2} \langle \sigma v \rangle_{\chi_h \chi_h \to \phi\phi} \times e^{-\frac{|\vec{x}-\vec{y}|}{c} \Gamma_\phi^{\text{lab}}} \frac{dN_\phi}{dE_\phi}$$

$$\Phi_\phi = n_\phi \cdot v_\phi$$

DM density

$$\frac{dN_\phi}{dE_\phi} = 2 \cdot \delta(E_\phi - m_{\chi_h})$$

$$y^2 = r_x^2 + z_x^2 + s_{x_*}^2 - 2\sqrt{r_x^2 + z_x^2}\, s_{x_*} \cos\theta_{x_*}$$

Usual halo of χ_h: only $O(1)$ enhancement (small flux)

- Large uncertainty of DM density nearby the GC

- Simple toy model

$$\rho_{\chi_h}(y) = \begin{cases} \rho_0 \frac{(y/y_s)^{-1}}{(1+y/y_s)^2} \equiv \rho_{\text{NFW}}(y) & \text{for } y \geq y_C \\ \mathcal{N} \times \rho_{\text{NFW}}(y_C) & \text{for } y < y_C \end{cases},$$

density scaling factor

core size

e⁺ spectrum calculation

Best fit in the fitting parameter scan y_C & N

$m_{\chi_h} = 1040$ GeV, $R = 0.2$, $\Gamma_\phi^{lab} = 10^{-12}\ s^{-1}$

$y_C = 0.5 \to 0.001$ kpc

$\mathcal{N} = 277 \to 5900$

- AMS 2016
- MED
- MAX
- MIN

$E_{e^+}^3 \Phi_{e^+}$ [GeV$^2 m^{-2} s^{-1} sr^{-1}$]

E_{e^+} [GeV]

$R = m_{\chi_l}/m_\phi$
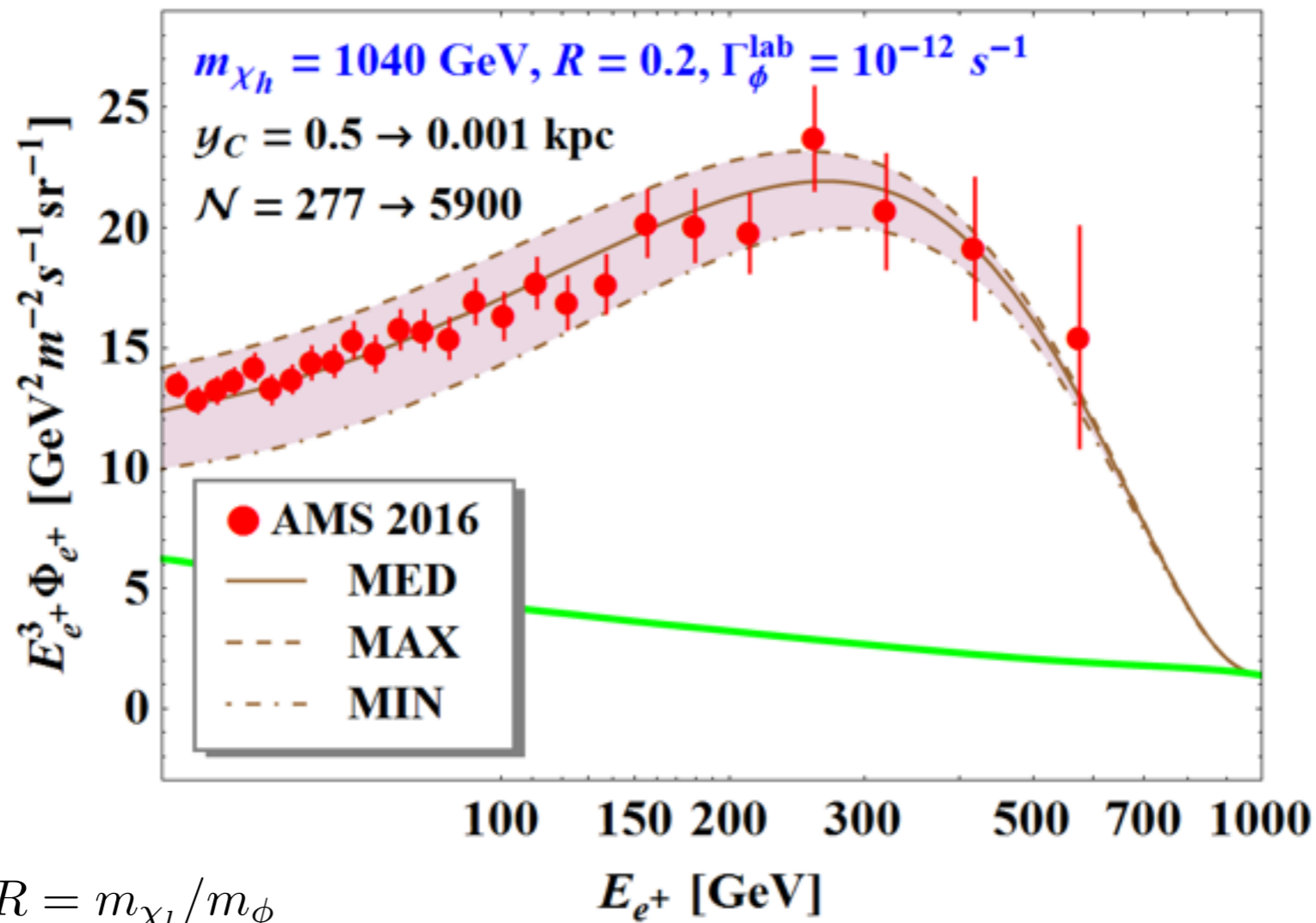
$$\frac{dN}{dE} \sim \frac{m_{\chi_h} - E}{m_{\chi_h}} + R^2 \log \left[R^2 \left(\frac{m_{\chi_h} - E}{m_{\chi_h}} \right)^{-1} \right] \quad \text{for} \quad m_{\chi_h} \gg m_\phi \gg m_{\chi_l}$$

e⁺ spectrum calculation

Changing the mass parameters
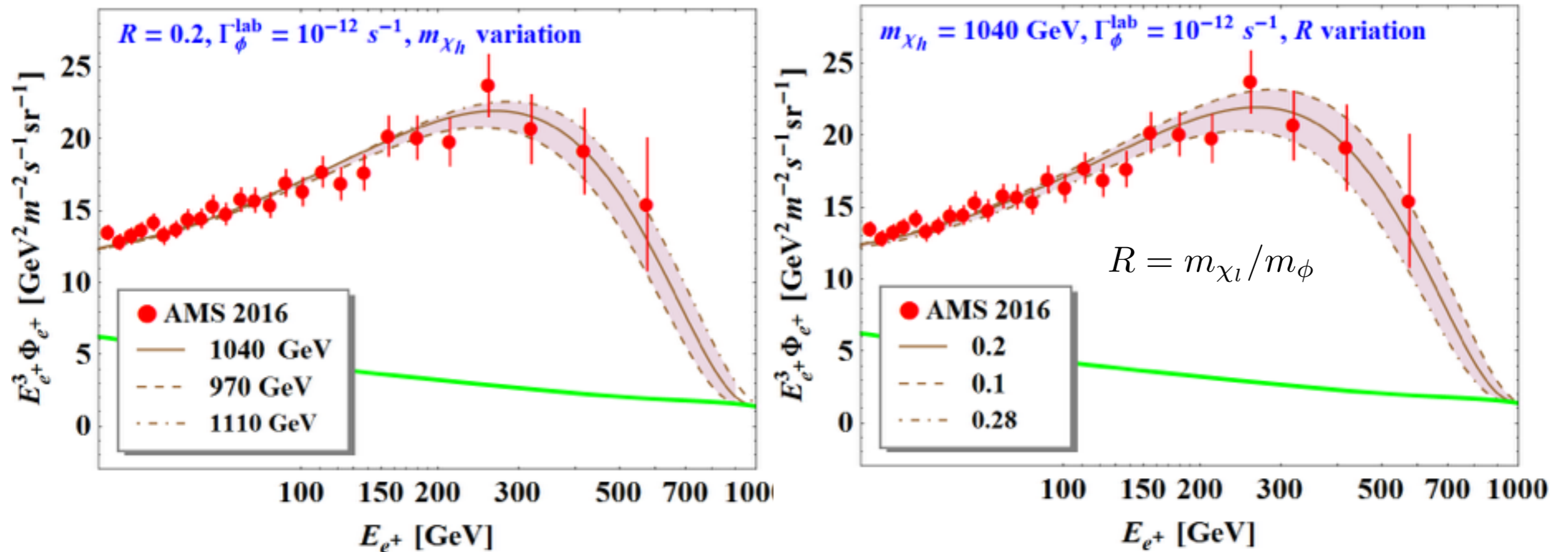
- e⁺ takes larger energy for heavier & smaller R

- Need more detailed data

Conclusions

- Effectively transporting DM by long-lived dark sector particle:
  Huge flux of cosmic-rays ~ $r_\odot$

- Reference: e^+ excess from AMS-02 (fit very well)

- Basically applied to any kind of cosmic-ray excesses

- Future work: model construction, γ-ray from the whole sky,
  anisotropy of the spectrum (level of pulsars?)

Back up

Back up

Positron Fraction
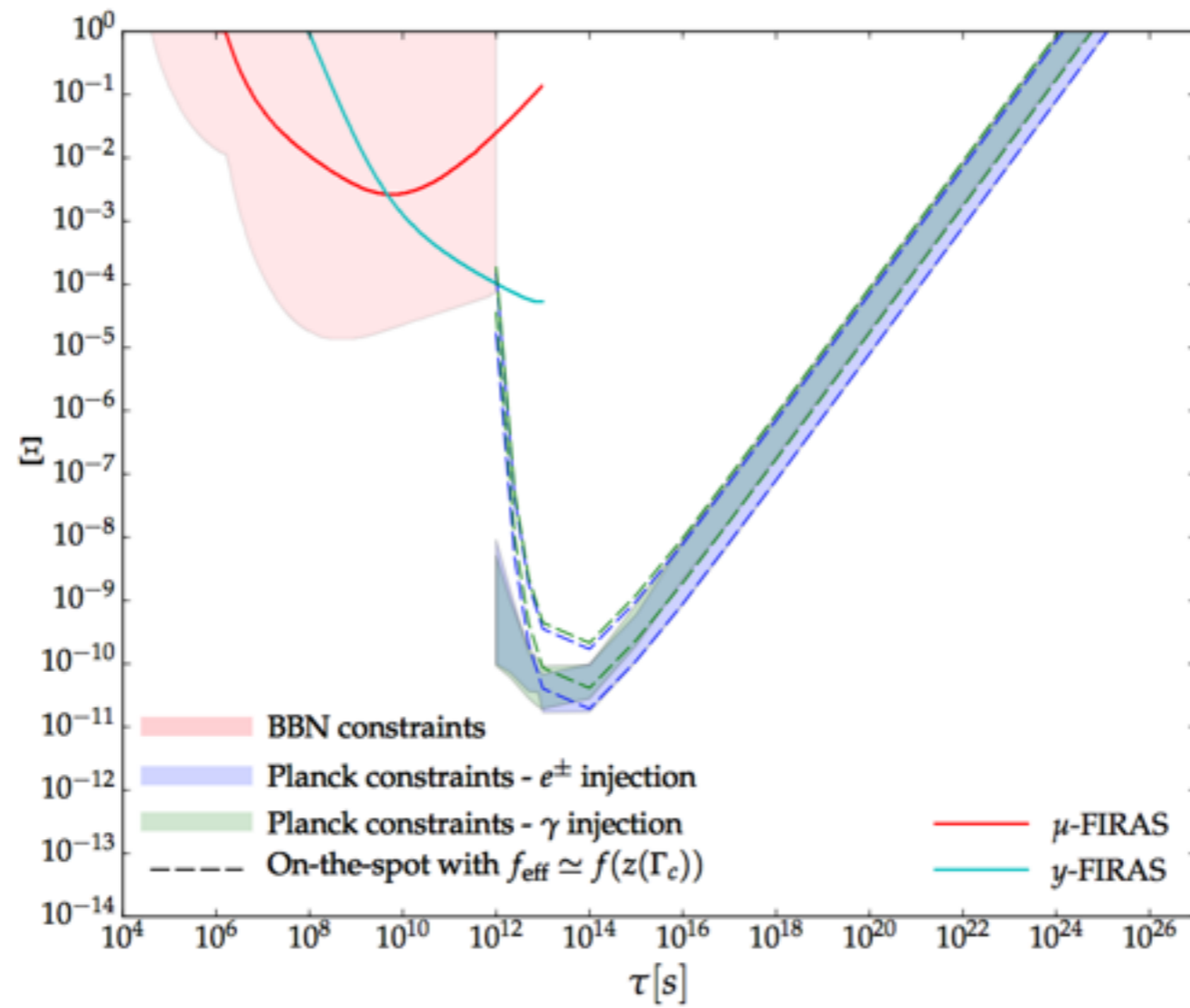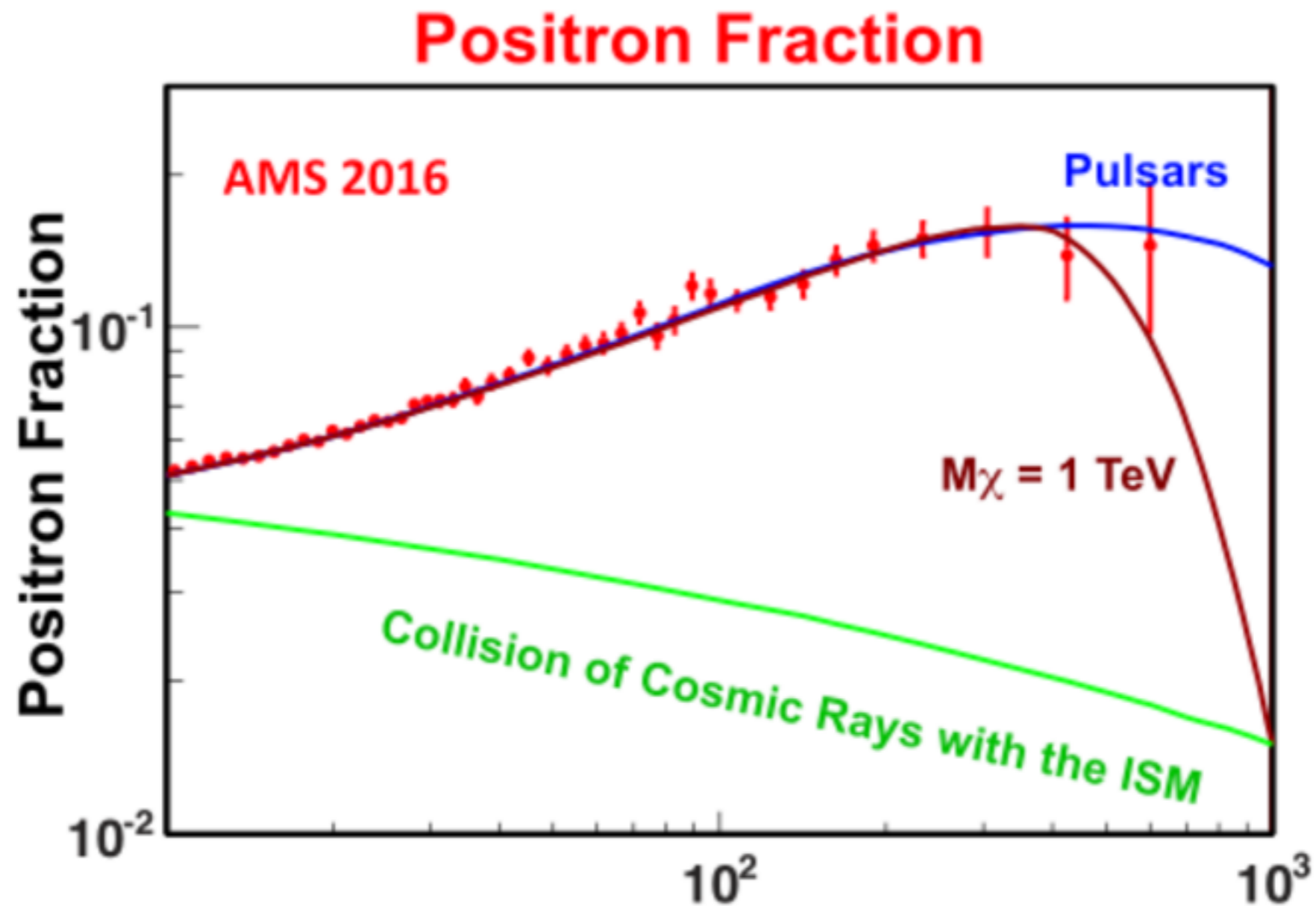
Back up

AMS-02 future

+
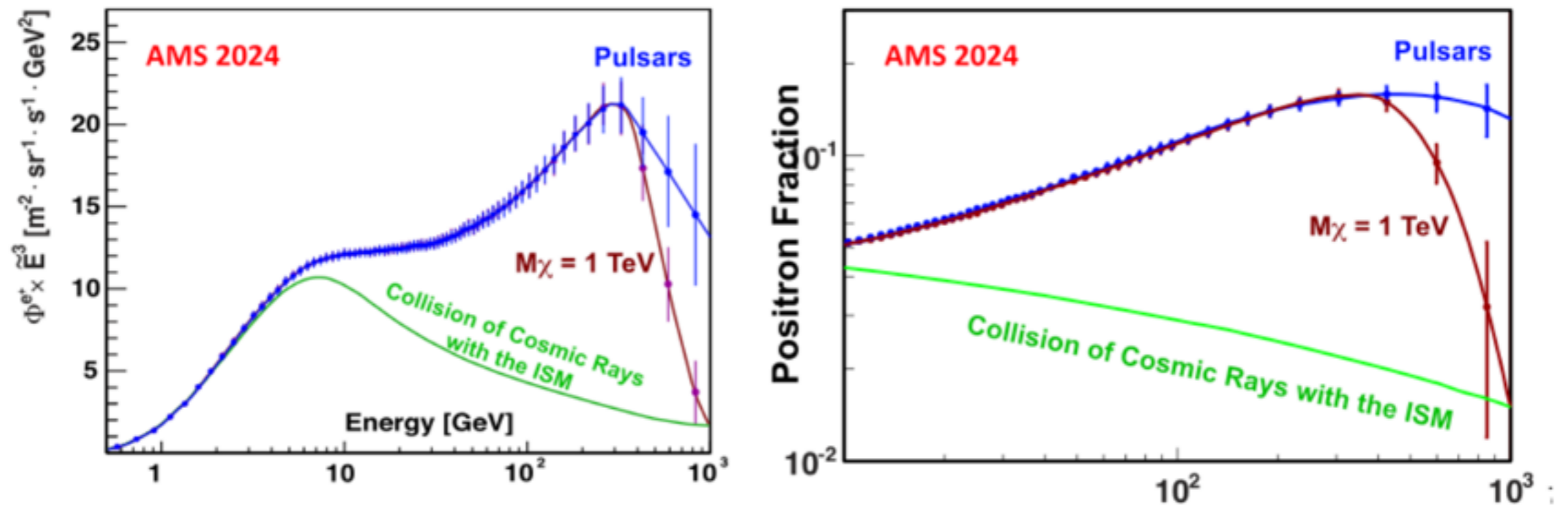
Spectrum Isotropy

Back up

Late decaying dark partner

keeps the relic density
for $m_1 = 1$ TeV
$Y = Y_2 + Y_1 =$ const.
after freeze-out

$m_1 = 1 \, \text{TeV}$

$m_2 = 2 \, \text{TeV}$

$\Gamma_2 = 10^{-24} \, \text{GeV}$
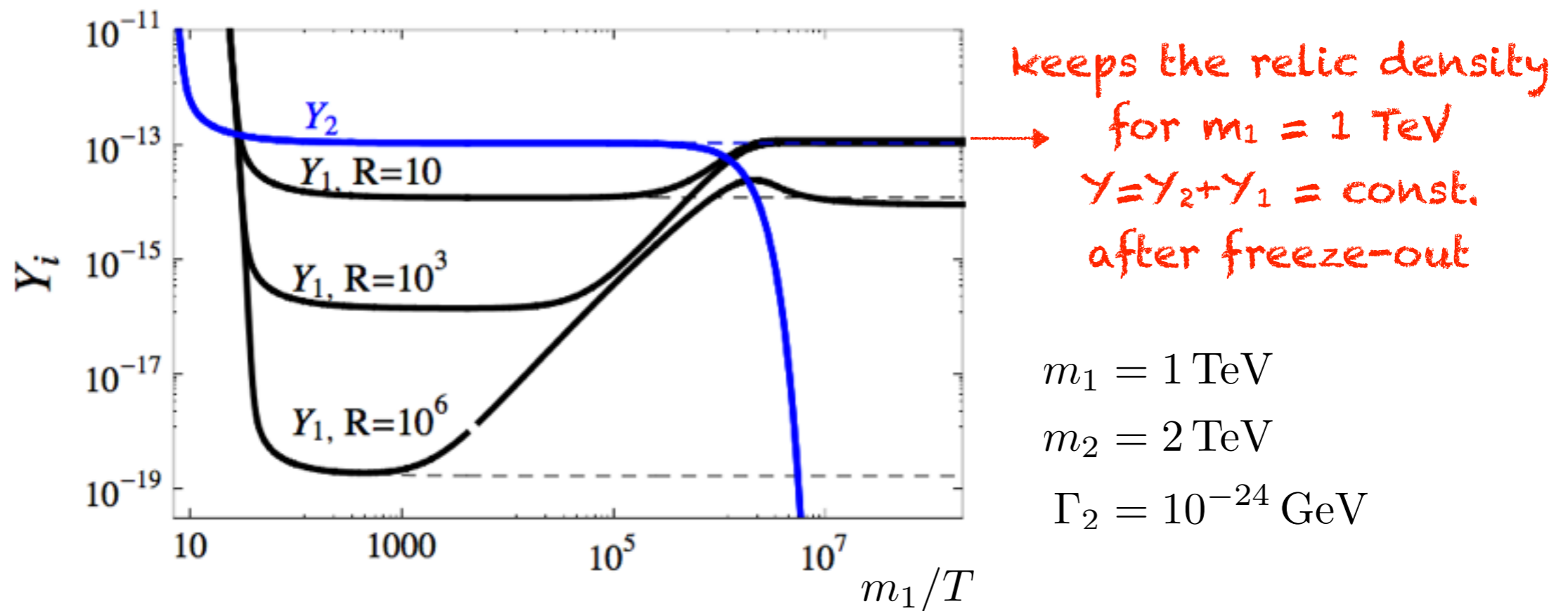
$mY \sim 4 \times 10^{-10} \, \text{GeV}$

Back up

Φ increase by dN/dE instead of $\rho^2 \langle \sigma v \rangle$?

Φ basically depends on $n^2 = (\rho/m)^2$

For example, cascade decays can increase dN/dE but decrease flux by increasing m to fit the data

Back up

EW gauge boson radiation

Cavasonza et al., 1612.06634

Giesen et al., 1504.04276
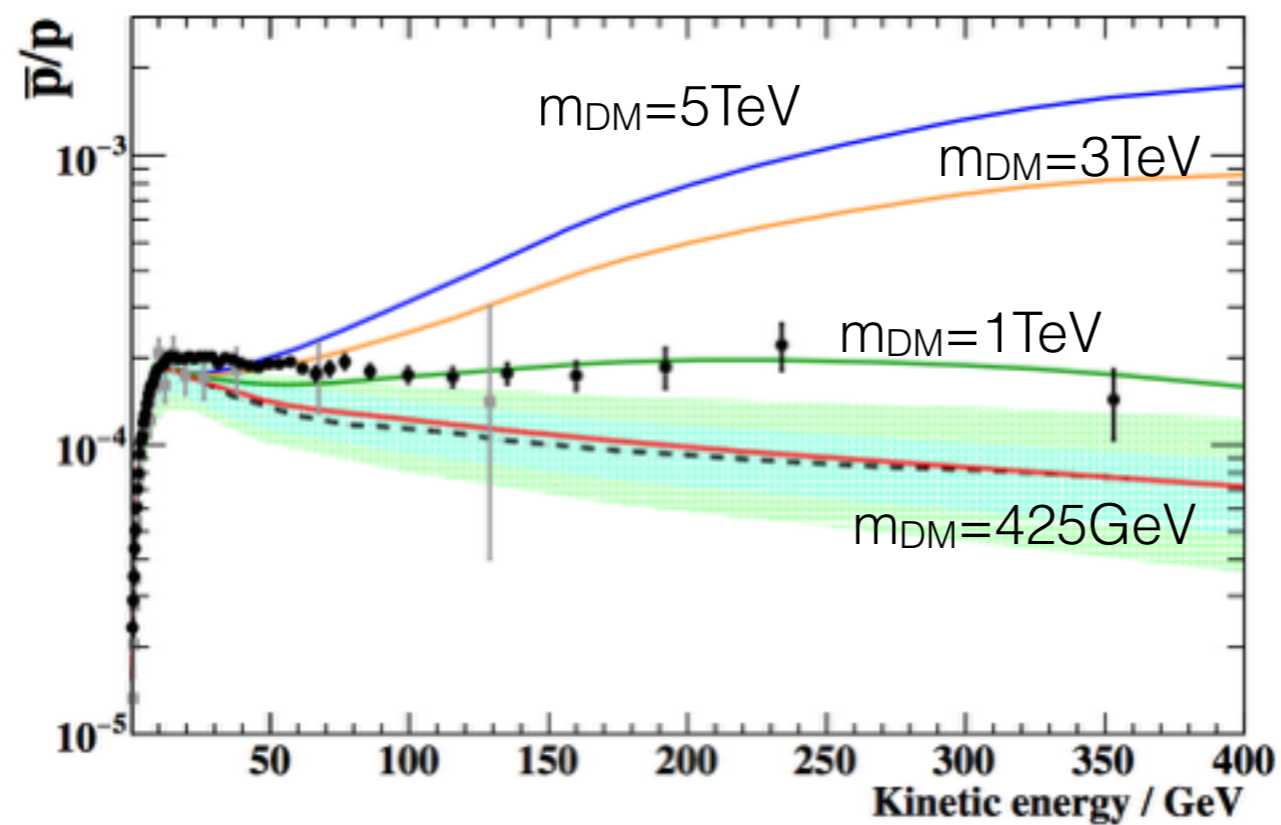
Black: AMS-02, Gray: PAMELA
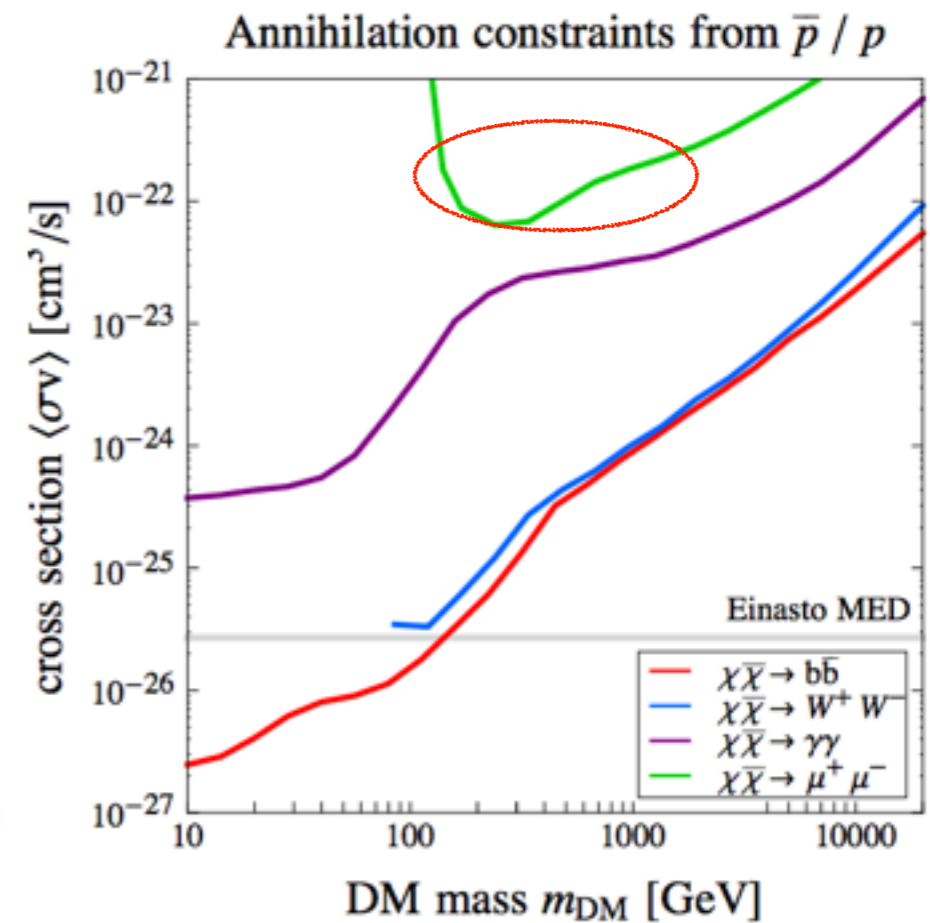
10^{-22} cm³/s level upper bound

While we leave the detailed calculation for future [37], our (rough) assessment finds that $\rho_\phi/\rho_{\rm DM} \lesssim 10^{-5}$ for $m_{\chi_h} = 1$ TeV, $m_\phi = 0.5$ GeV, and $m_{\chi_l} = 0.1$ GeV in a dark $U(1)_X$ scenario. Note again that this parameter choice provides the best fit as displayed in the left panel of FIG. 3.

Back up

Liu, Bi, Lin, Yin, 1602.01012

Back up

Ilten, Thaler, Williams, Xue, 1509.06765

Back up

Essig et al., 1311.0029

Back up

Super-K (2012)

$$\pi^+ \to \quad \mu^+ \quad + \nu + \mu$$
$$\qquad \quad \hookrightarrow e^+ + \nu_e + \overline{\nu}_\mu$$
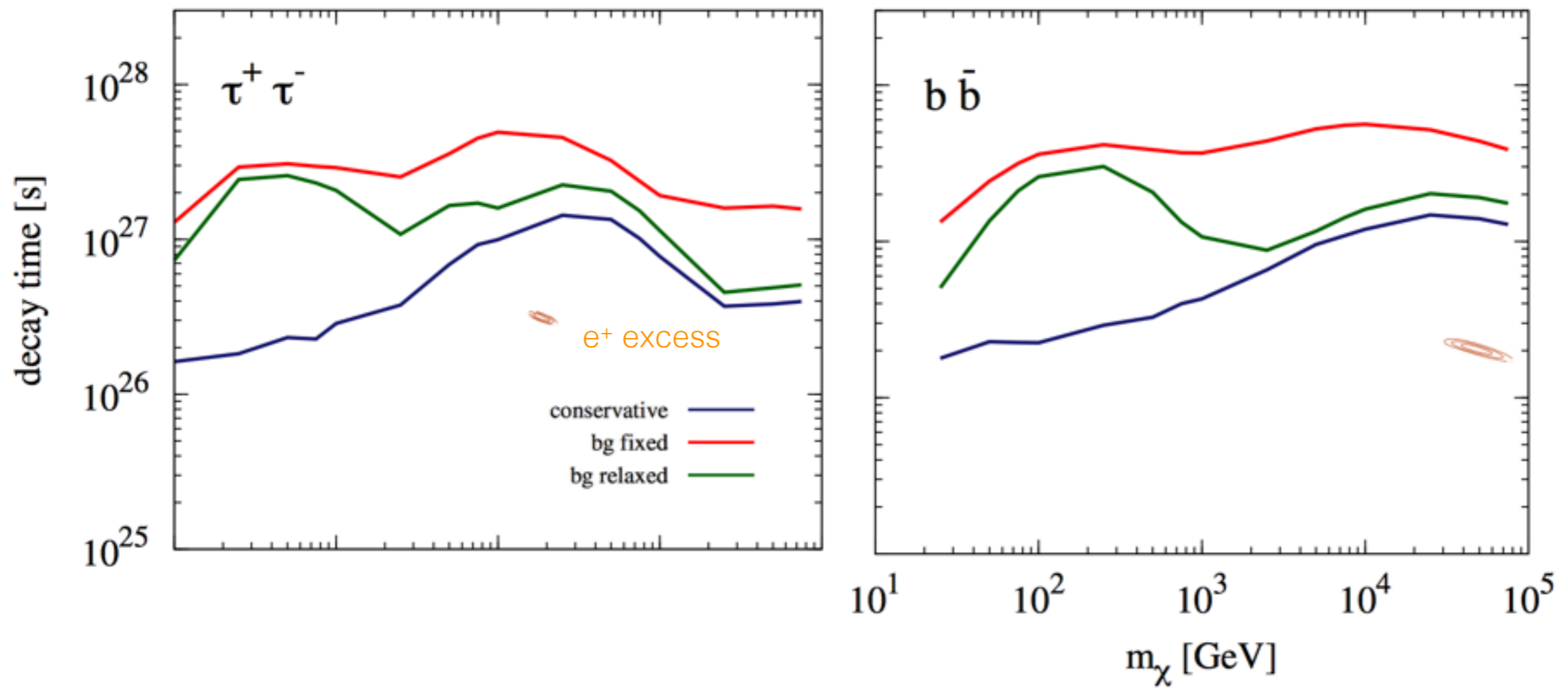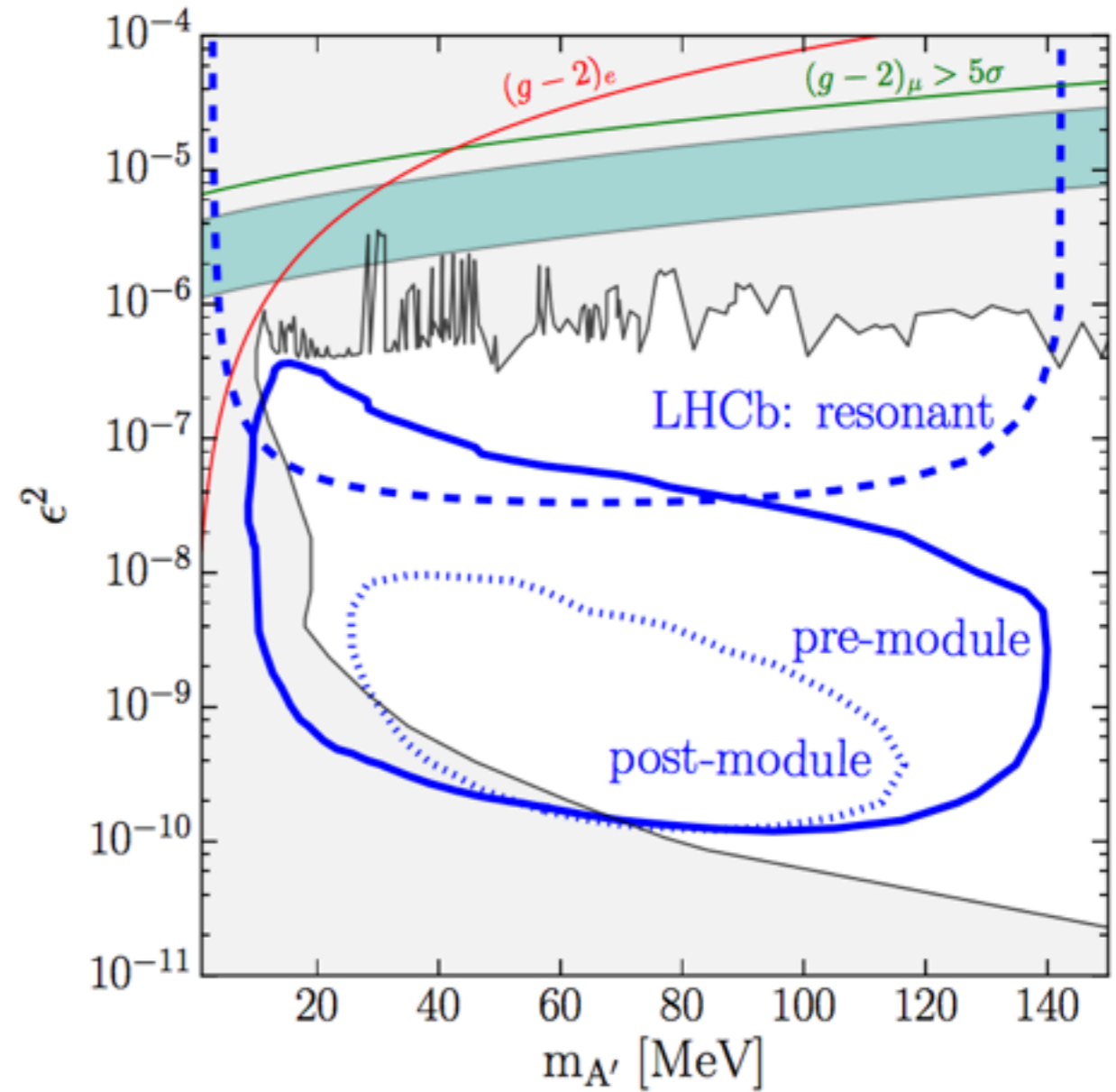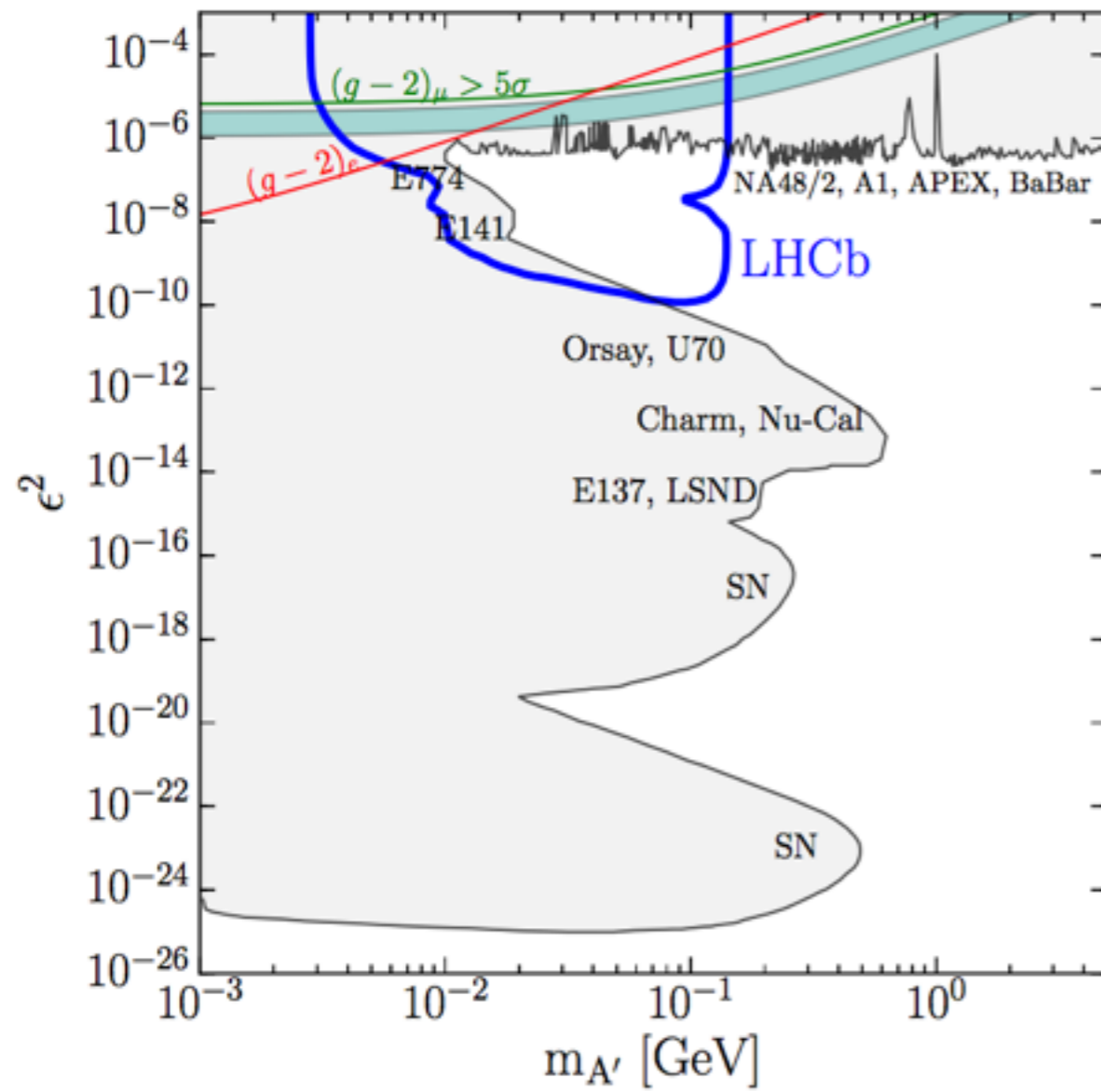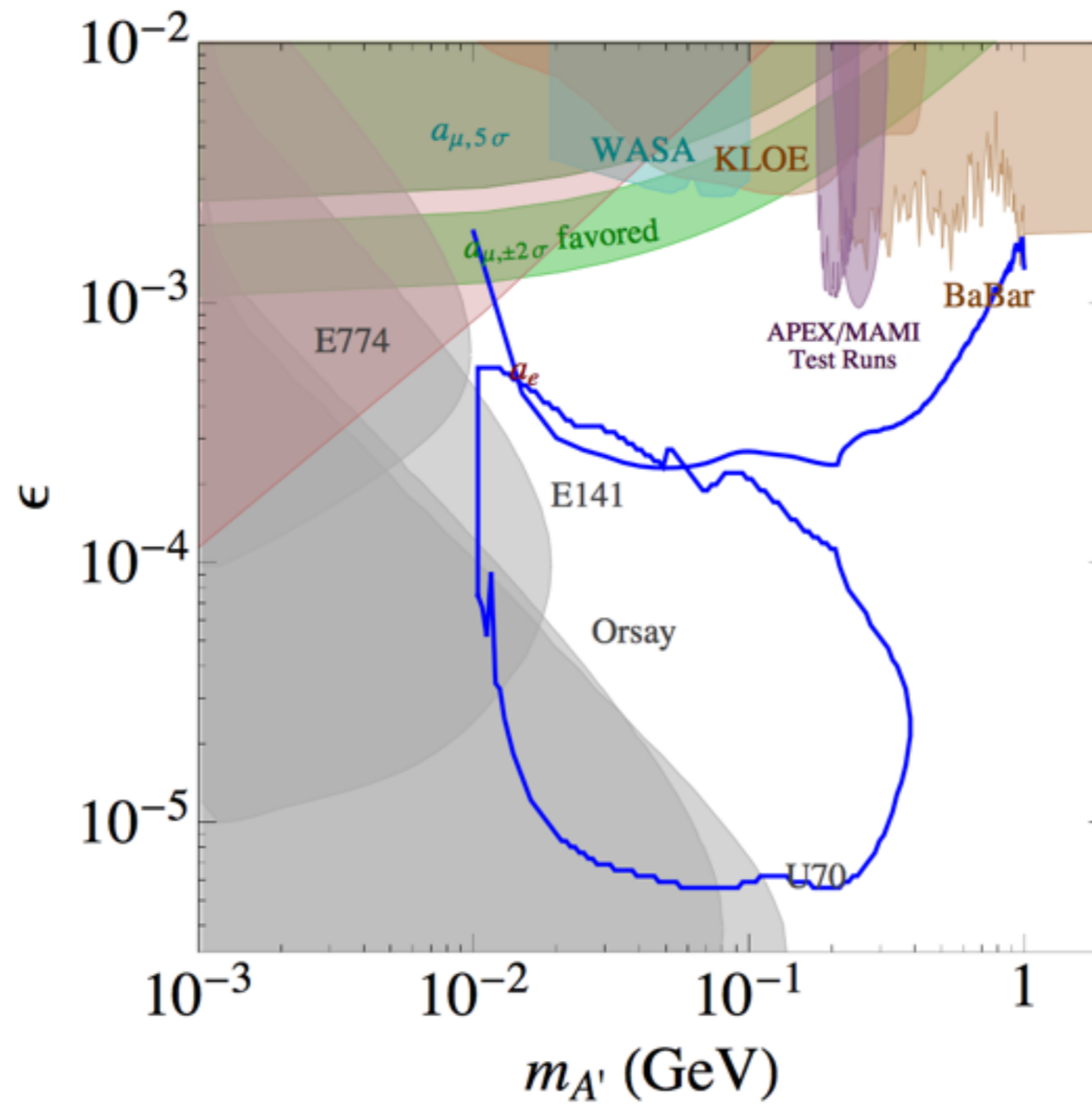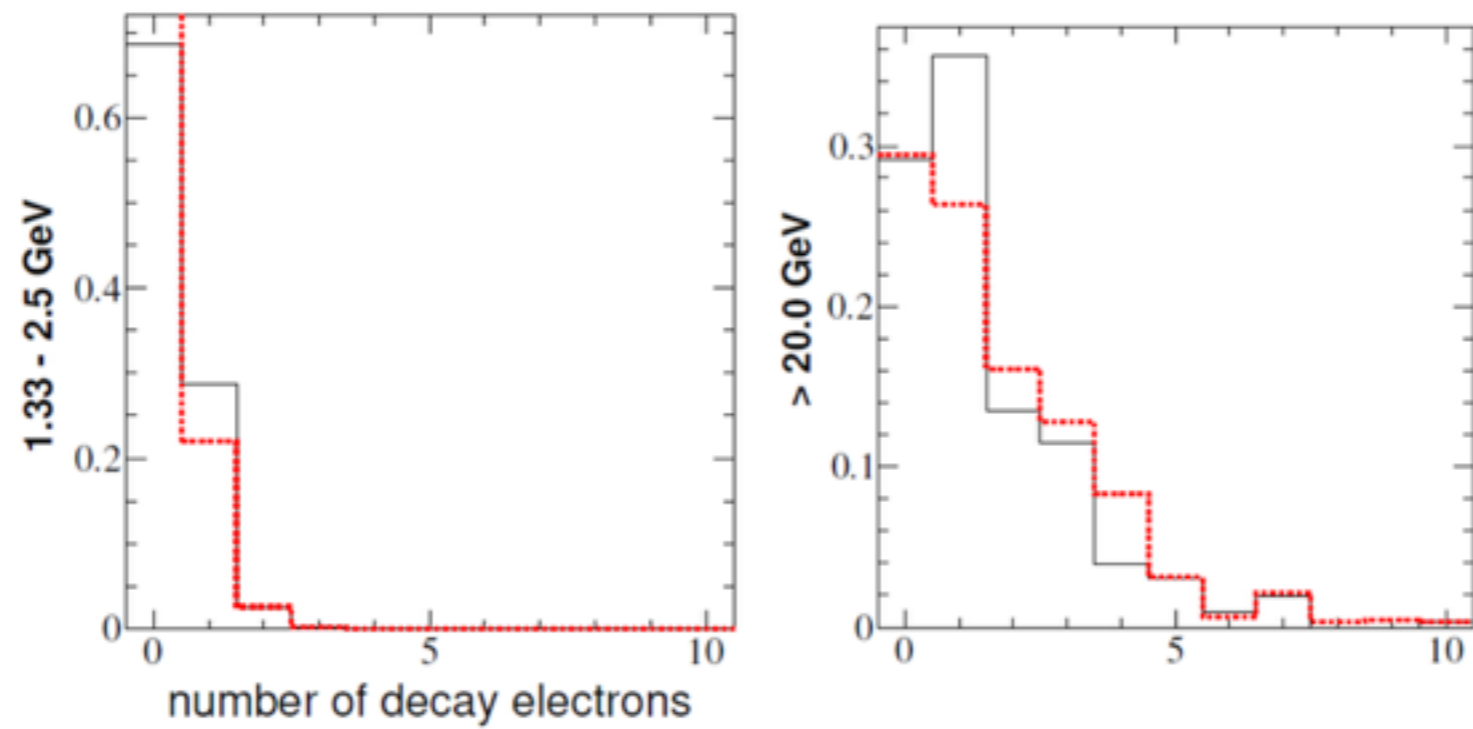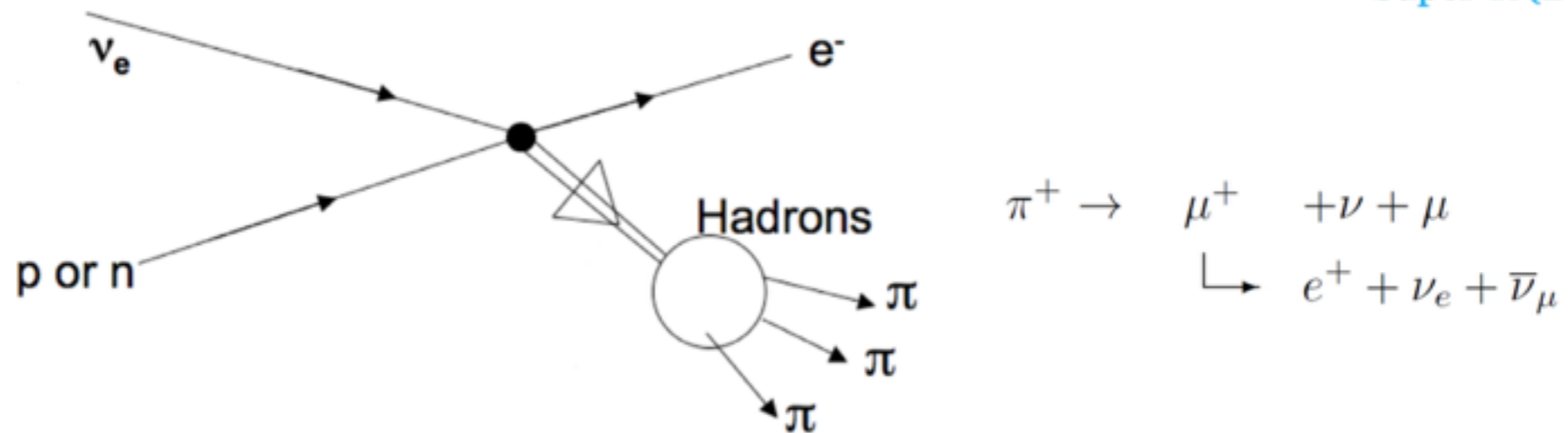
Back up

Flux of atmospheric neutrino
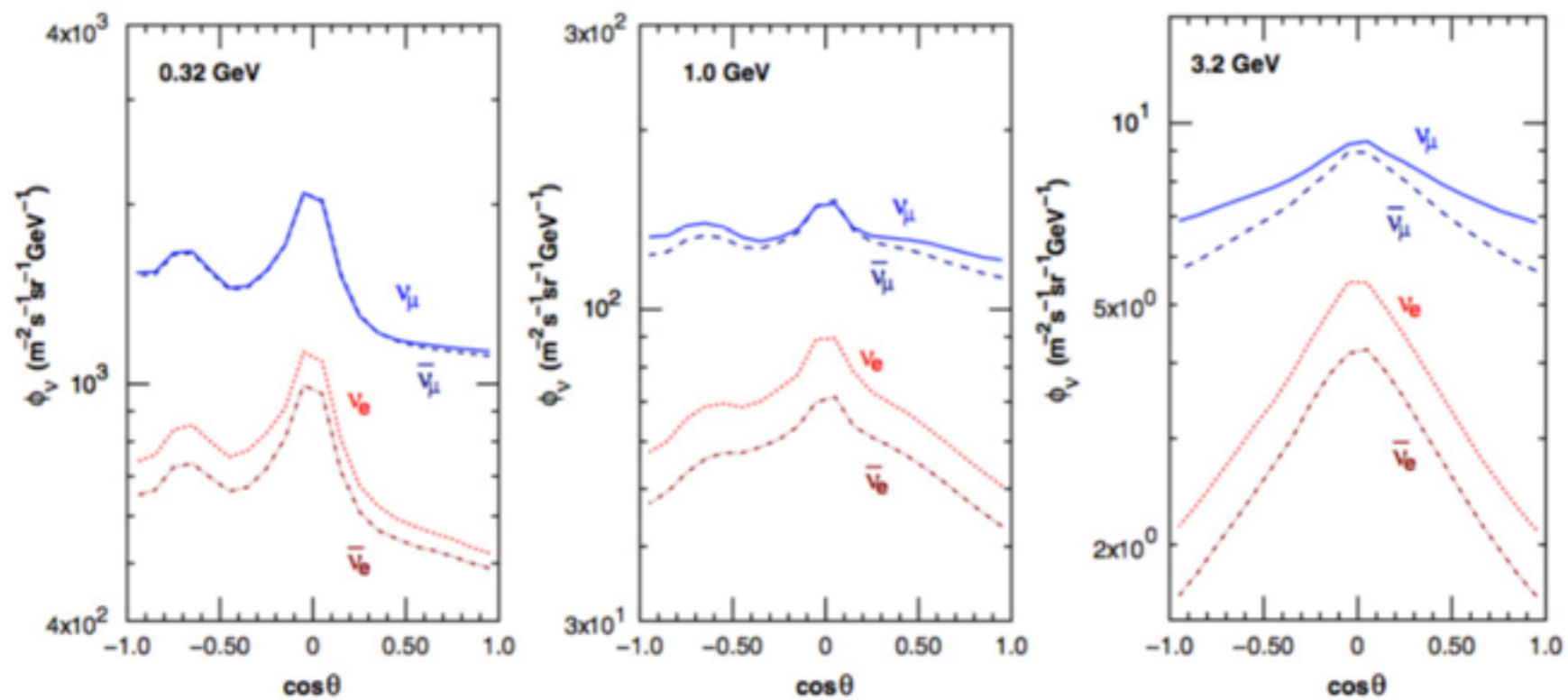
θ: zenith angle

Energetic neutrino ~ 10^{-4} cm^{-2} s^{-1}

Back up

Sub-Sample	SK-I	SK-II	SK-III	SK-IV	Total		ν_eCC	ν_μCC	NC
			Livetime (days)						
FC and PC	1489	799	518	1993	4799				
UPMU	1646	828	636	1993	5103				
			Number of Events					Interaction [%]	
FC e-like									
sub-GeV single-ring	3288 (3104.7)	1745 (1632.8)	1209 (1100.7)	4251 (4072.8)	10493	(9911.0)	94.1	1.5	4.4
multi-GeV single-ring	856 (842.8)	396 (443.7)	274 (299.5)	1060 (1080.0)	2586	(2666.0)	86.3	3.2	10.5
multi-GeV multi-ring	449 (470.1)	267 (252.1)	140 (161.9)	634 (654.9)	1490	(1539.0)	73.0	7.6	19.4
FC μ-like									
sub-GeV single-ring	3184 (3235.6)	1684 (1731.8)	1139 (1152.0)	4379 (4394.7)	10386	(10514.0)	0.9	94.2	4.9
multi-GeV single-ring	712 (795.4)	400 (423.9)	238 (273.9)	989 (1051.5)	2339	(2544.7)	0.4	99.1	0.5
multi-GeV multi-ring	603 (656.5)	337 (343.8)	228 (237.9)	863 (927.8)	2031	(2166.0)	3.4	90.5	6.1
PC									
stop	143 (145.3)	77 (73.2)	54 (53.3)	237 (229.0)	511	(500.8)	12.7	81.7	5.6
thru	759 (783.8)	350 (383.0)	290 (308.8)	1093 (1146.7)	2492	(2622.3)	0.8	98.2	1.0
UPMU									
stop	432.0 (433.7)	206.4 (215.7)	193.7 (168.3)	492.7 (504.1)	1324.8	(1321.8)	1.0	97.7	1.3
non-showering	1564.4 (1352.4)	726.3 (697.5)	612.9 (504.1)	1960.7 (1690.3)	4864.3	(4244.4)	0.2	99.4	0.3
showering	271.7 (291.6)	110.1 (107.0)	110.0 (126.0)	350.1 (274.4)	841.9	(799.0)	0.1	99.8	0.1

x 0.1 or smaller

Back up

Sub-Sample	SK-I		SK-II		SK-III		SK-IV		Total		Interaction [%]		
					Livetime (days)						ν_eCC	ν_μCC	NC
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x 0.1 or smaller

Back up

- **Collider as a heavy-state probe**
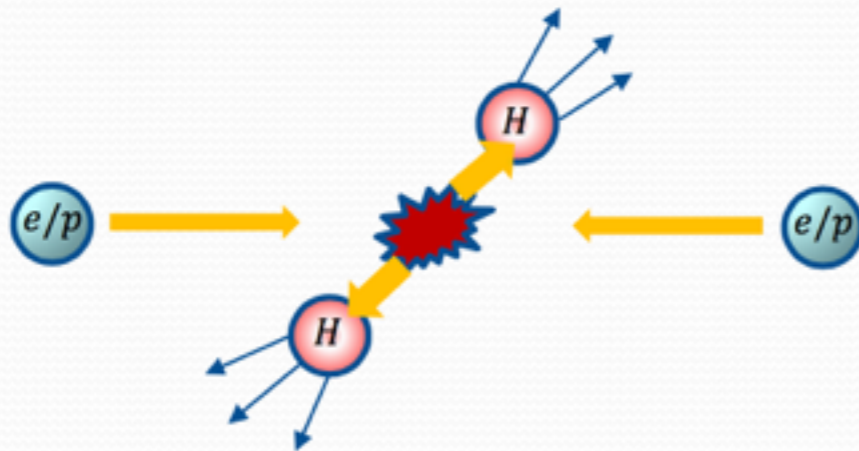
Conventional colliders

- Head-on collision of light SM-sector (stable) particles
- to produce heavier states
- and study resulting phenomenology
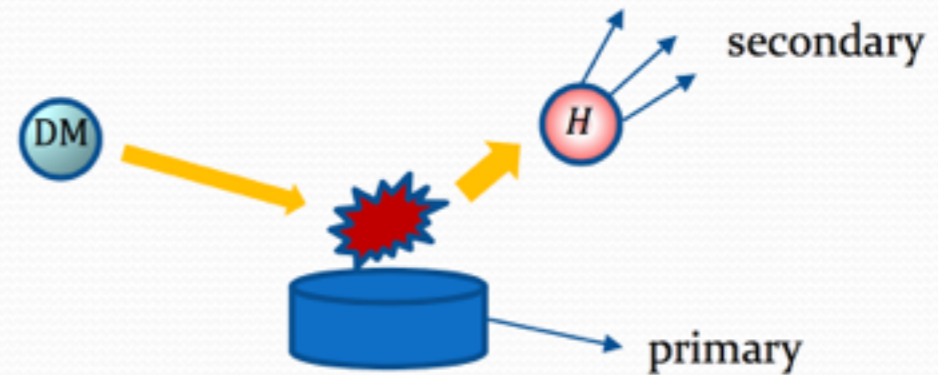
Dark matter colliders

- Collision of light dark-sector (stable) particles onto a target
- to produce heavier dark-sector states
- and study resulting phenomenology

Back up

SHiP as a Hidden Sector Detector

● **Detection**

☐ $pp \rightarrow H +$ others, $H \rightarrow A'^*\gamma \rightarrow \chi_B\chi_B\gamma / H \rightarrow A'^*\gamma \rightarrow \chi_B X\gamma /$

$H \rightarrow A'^*\gamma \rightarrow XX\gamma$

☐ $pp \rightarrow A'^* \rightarrow \chi_B\chi_B, \chi_B X, XX$

☐ Etc.
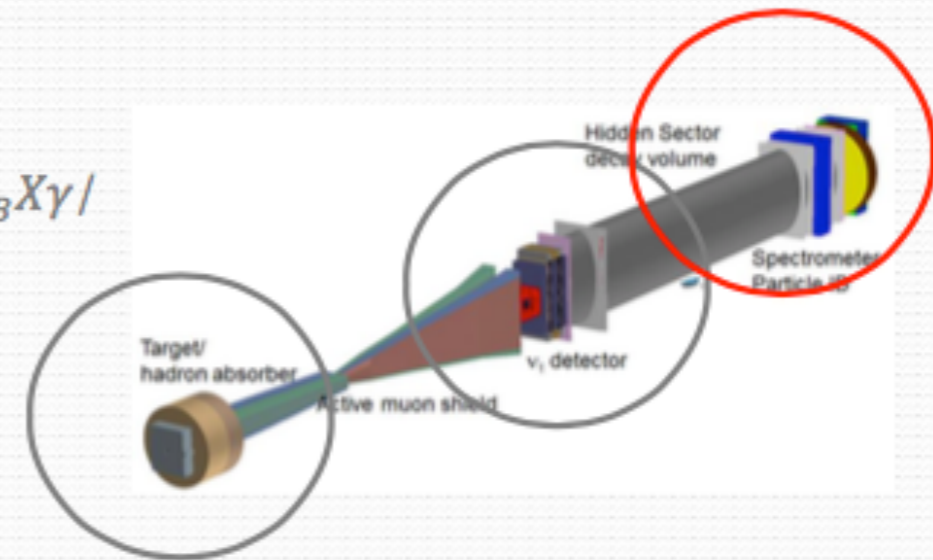
☐ $\chi_B + \nu_\tau$ detector $\rightarrow X +$ recoil e/p

❖ Prompt scenario: $X \rightarrow \chi_B A', A' \rightarrow e^+e^-$ at ν_τ

detector, **3 (hopefully) resolvable** objects

❖ "Long-lived" scenario: 1) $X \rightarrow \chi_B A'^* \rightarrow \chi_B e^+e^-$ 2) $X \rightarrow \chi_B A', \dots \dots, A' \rightarrow e^+e^-$,

detection of electron/positron at the calorimeter complex $\rightarrow$ **3 resolvable** objects

Back up

SHiP

Production of χ_1: collide (tau) neutrino detector

Assisted freeze-out: χ_1 - SM interaction does not have to be larger than the weak scale because ann. cross section ~ 1/m^2

Search of Dark Matter
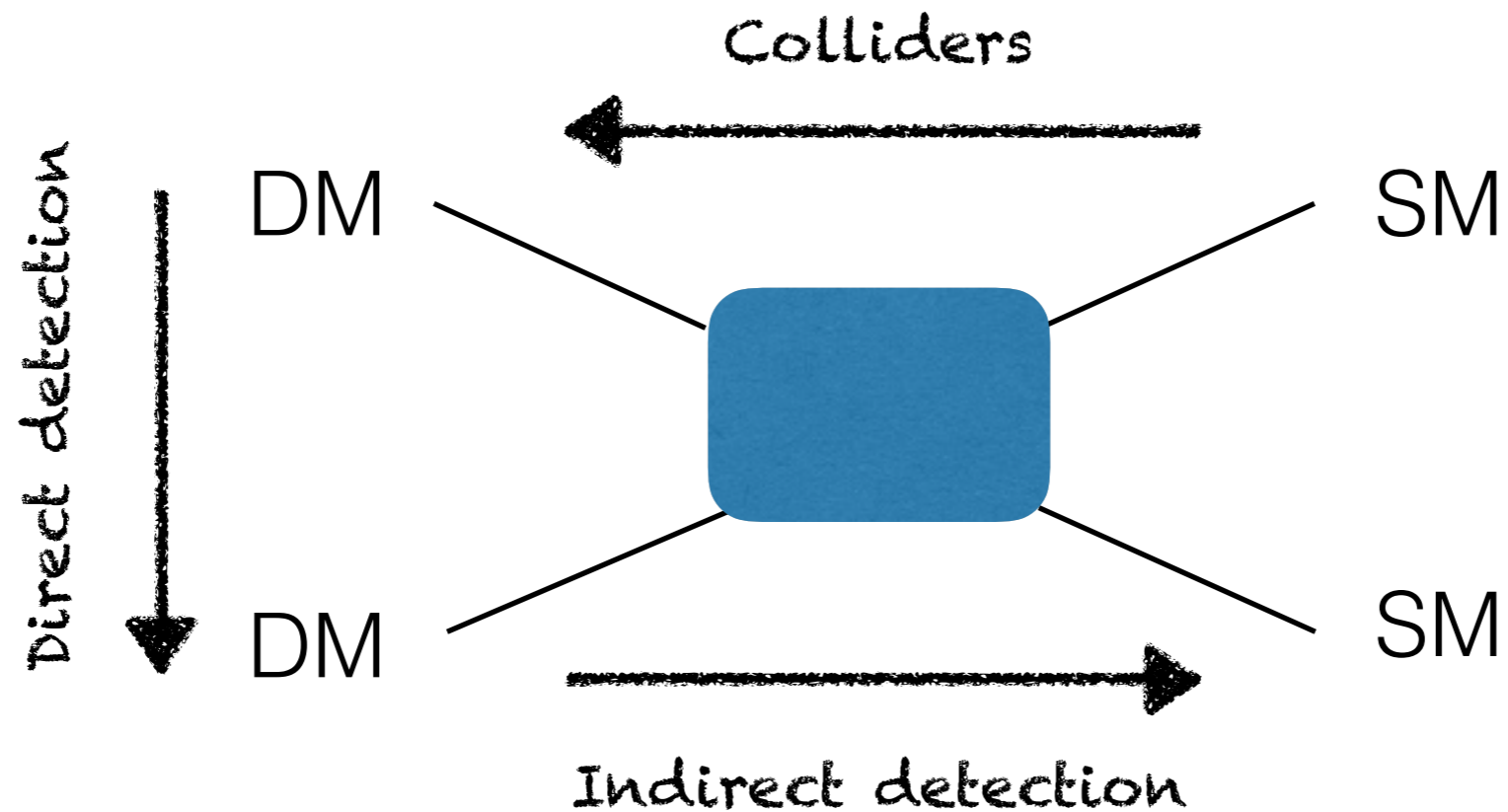
Popular figure shown everywhere for the search of WIMP

Search of Dark Matter

Non-relativistic scattering of WIMP

Colliders

DM — SM

DM — SM

Direct detection

Indirect detection
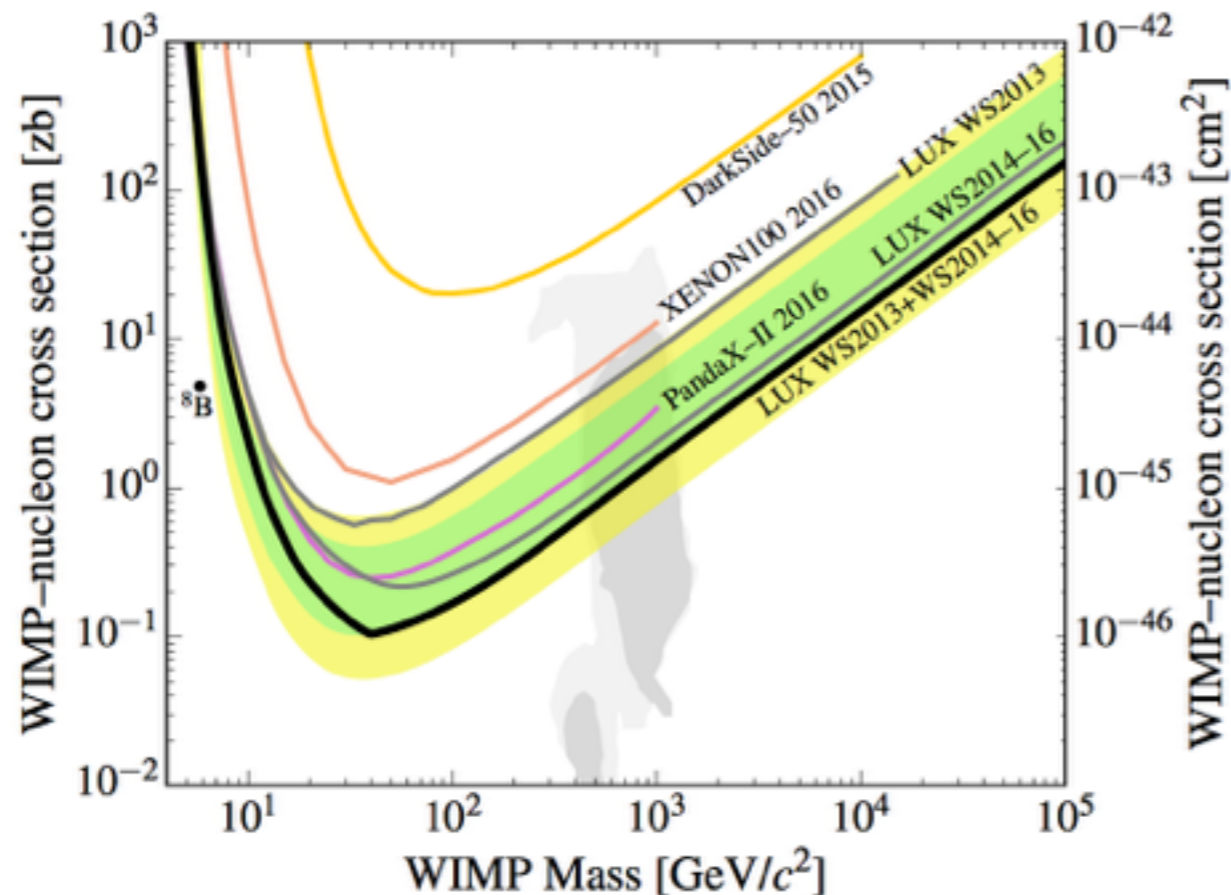
Touch down a part of neutrino floor soon!!!

LUX 2016
1608.07648

Search of Dark Matter

Strong bounds too (mono-X)

Colliders
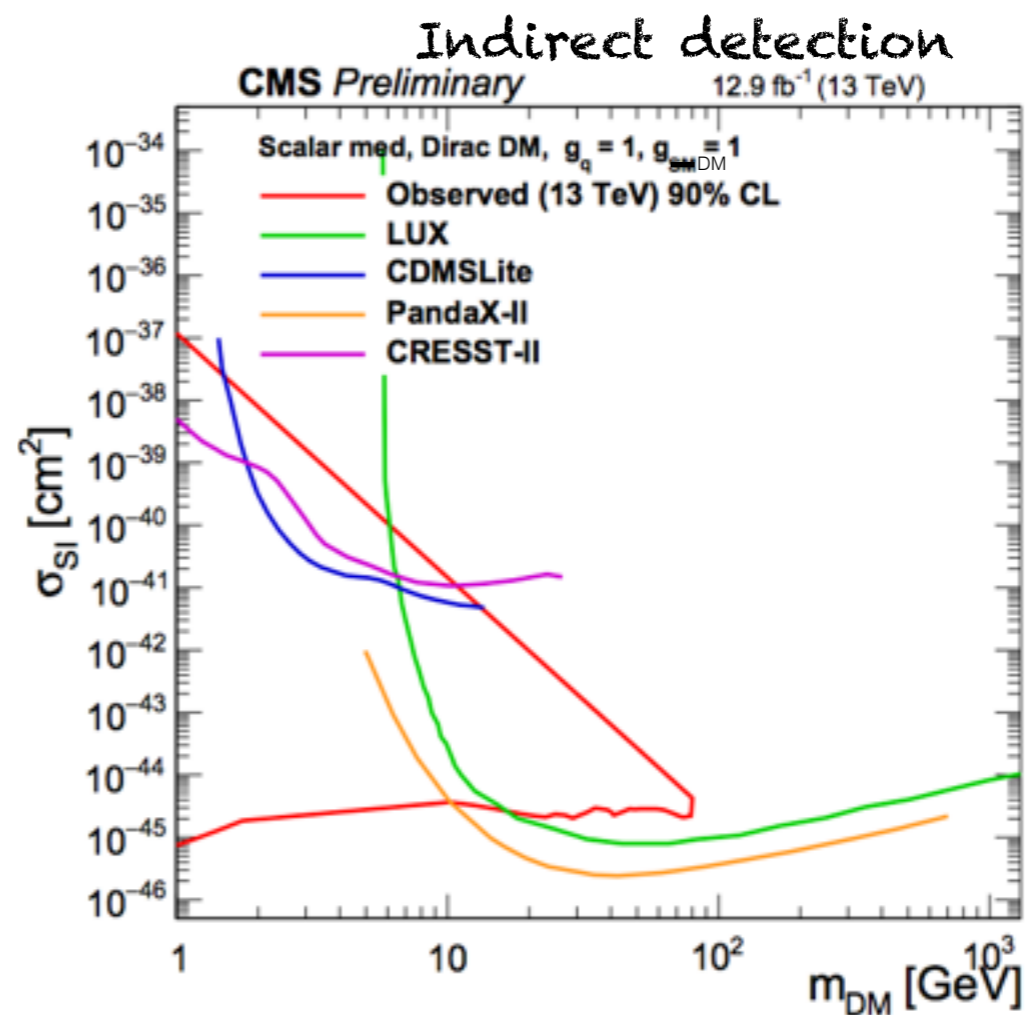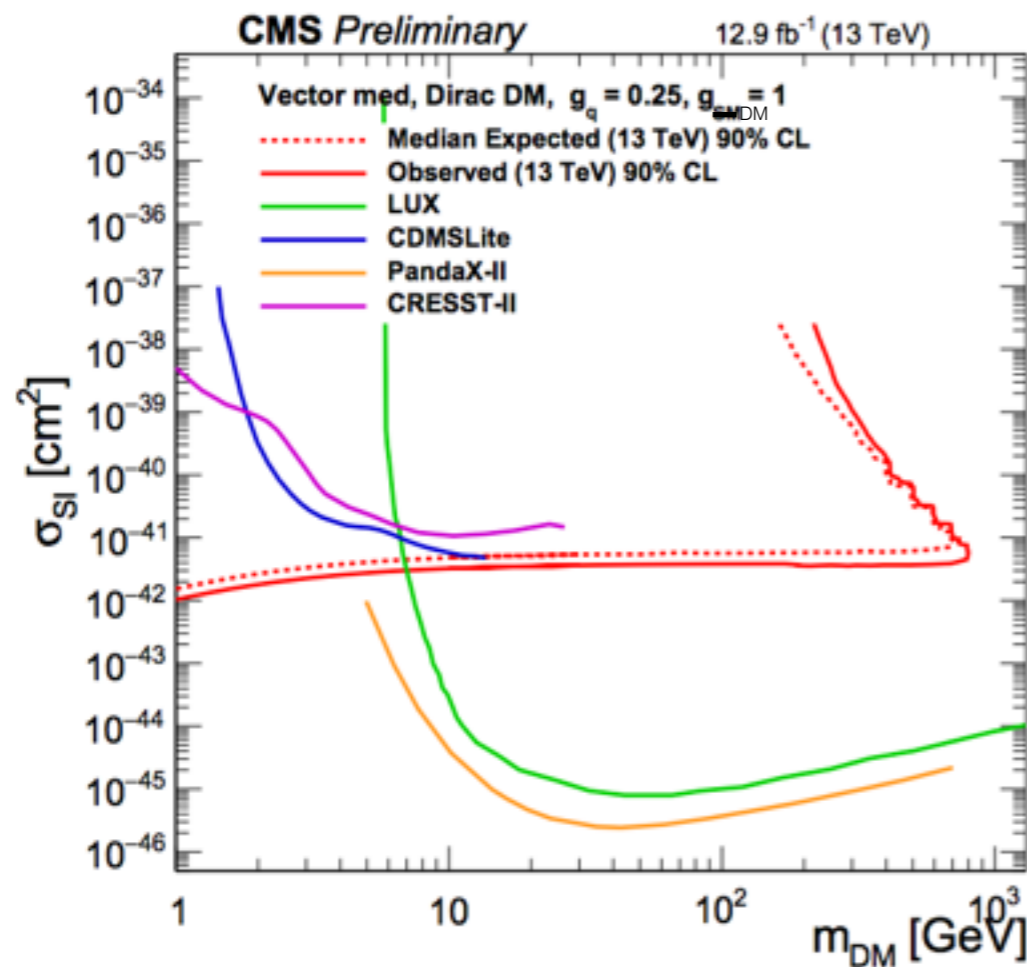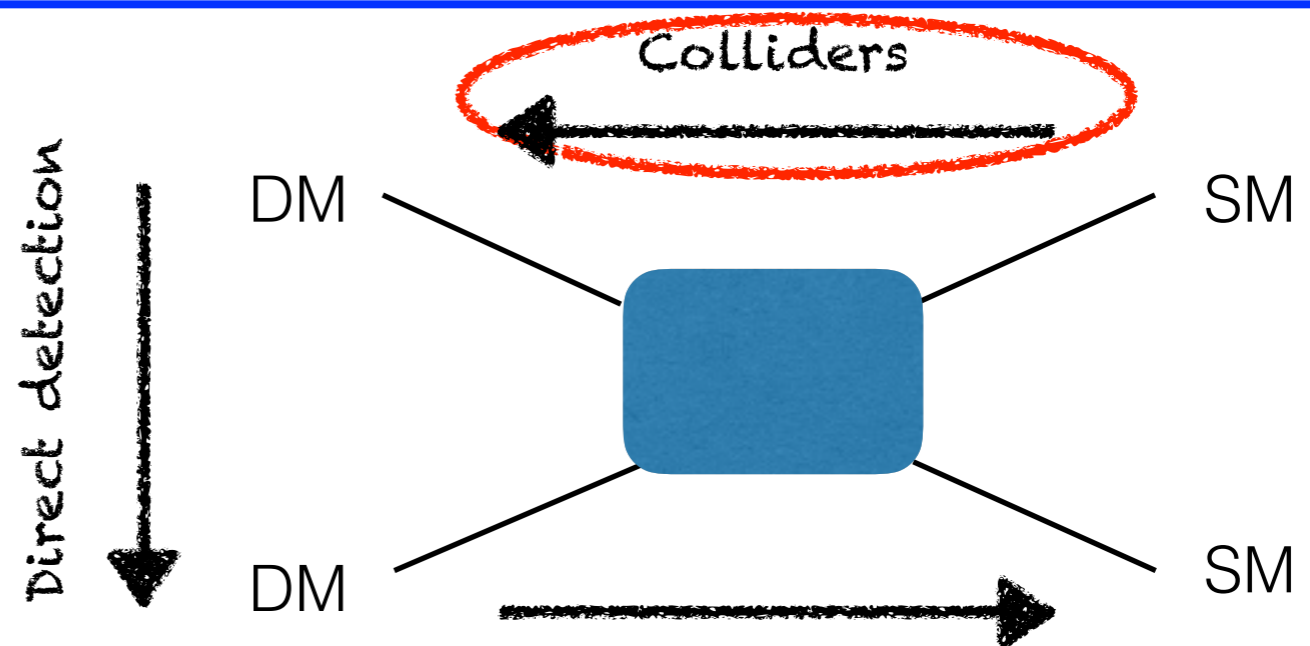
Direct detection

DM — SM

DM — SM

Indirect detection

CMS, EXO-16-037-pas

CMS *Preliminary*   12.9 fb⁻¹ (13 TeV)

Vector med, Dirac DM, g_q = 0.25, g_{DM} = 1
- Median Expected (13 TeV) 90% CL
- Observed (13 TeV) 90% CL
- LUX
- CDMSLite
- PandaX-II
- CRESST-II

σ_{SI} [cm²]

m_{DM} [GeV]

CMS *Preliminary*   12.9 fb⁻¹ (13 TeV)

Scalar med, Dirac DM, g_q = 1, g_{DM} = 1
- Observed (13 TeV) 90% CL
- LUX
- CDMSLite
- PandaX-II
- CRESST-II

σ_{SI} [cm²]

m_{DM} [GeV]

Search of Dark Matter

Some (strong) bounds

- γ-rays from dSphs

- Antiproton ratios

Colliders

DM   SM

Direct detection

DM   SM

Indirect detection
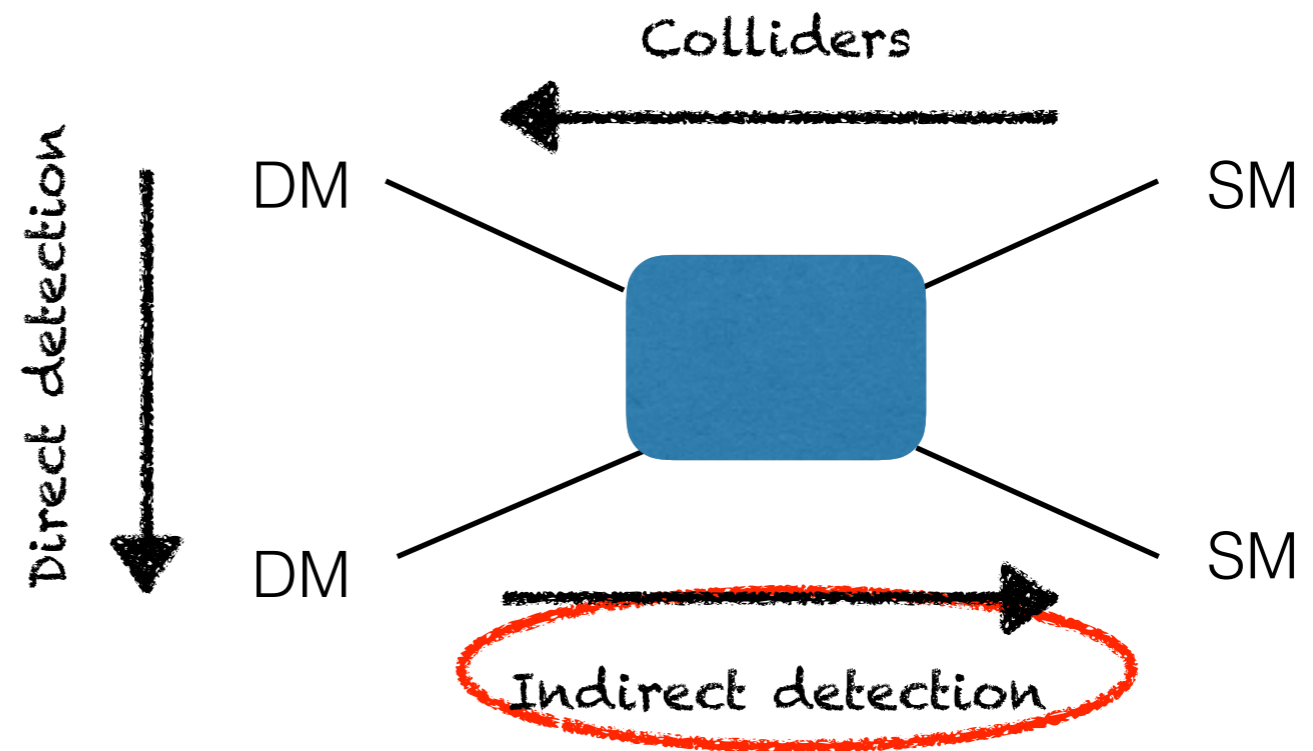
but some hints as well (although bkg. is not fully understood)

- γ-rays from the galactic center

- Positron ratio

- Neutrino signals

Search of Dark Matter
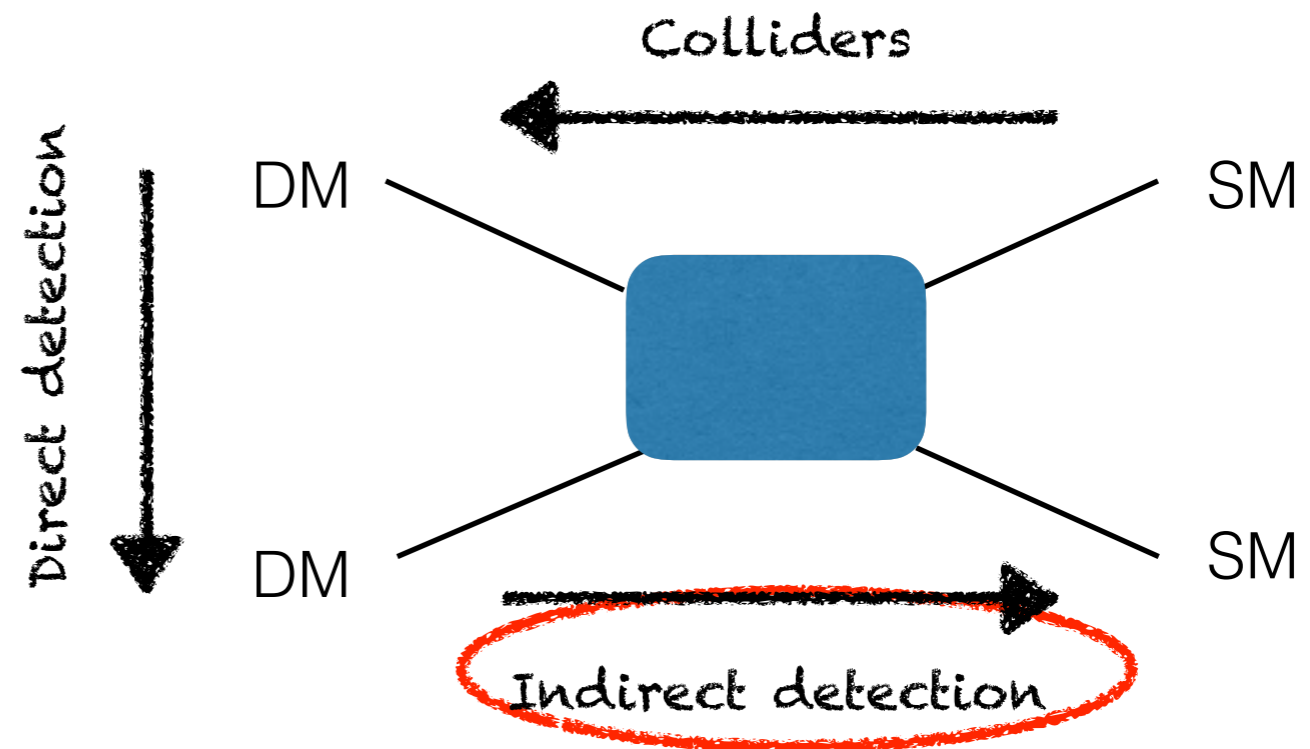
Some (strong) bounds

- γ-rays from dSphs

- Antiproton ratios

Colliders

DM ——— SM

DM ——— SM

Direct detection

Indirect detection

but some hints as well (although bkg. is not fully understood)

- γ-rays from the galactic center

- Positron ratio

- Neutrino signals

DM signal not sensitive to direct detection & colliders

Secluded Dark Matter?

Secluded set-up

Huh, Kim, Park, Park, 0711.3528

Pospelov, Ritz, Voloshin, 0711.4866

Kim, **SS**, 0901.2609

 & many others……
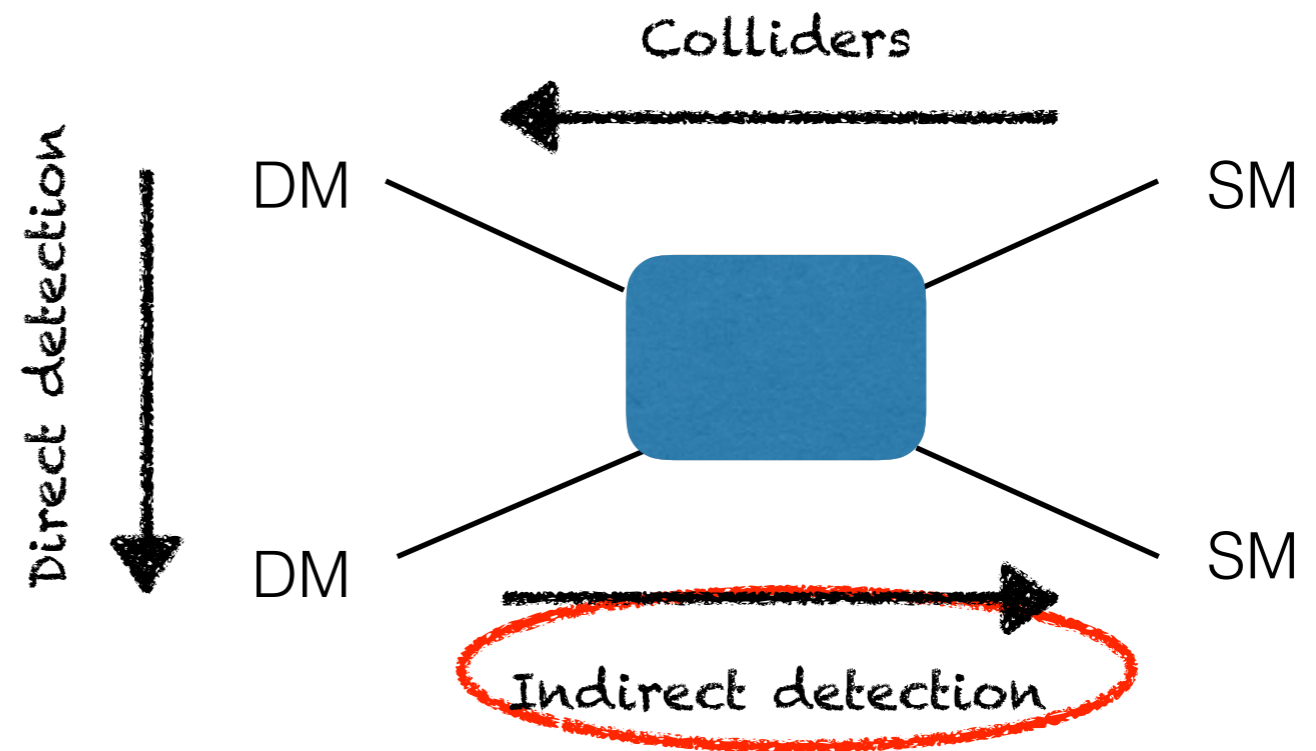
- Size of DM interaction with SM is small:
     avoid strong bounds from direct detection & colliders

- Processes for the relic/ID are separated from DD or collider:
     with more particles in the dark sector

Kim, **SS**, 0901.2609   Kim, Lee, **SS**, 0803.2932

Search of Secluded Dark Matter

How do you search such a hidden DM?

- Indirect detection can be a key guide:
  provide reference parameters for the searches in colliders & DD

- Relativistic scattering of DM with a target

O(GeV) broad γ-ray excess
from the galactic center

(Fermi-LAT)

→
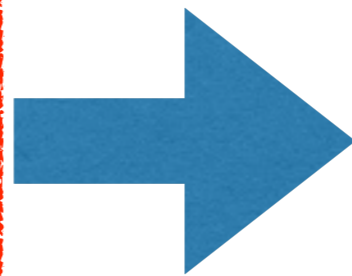
Consistent parameters in
famous WIMP models

Kim, Lee, Park, **SS**, 1601.05089

& many others……

Search of Secluded Dark Matter

How do you search such a hidden DM?

- Indirect detection can be a key guide:
    provide reference parameters for the searches in colliders & DD
    Kim, Lee, Park, **SS**, 1601.05089

- Relativistic scattering of DM with a target

Search of Secluded Dark Matter

How do you search such a hidden DM?

- Indirect detection can be a key guide:
  provide reference parameters for the searches in colliders & DD

  Kim, Lee, Park, **SS**, 1601.05089

- Relativistic scattering of DM with a target

  - Some components of DM are relativistic: boosted DM

    Agashe, Cui, Necib, Thaler, 1405.7370
    Kong, Mohlaberg, Park, 1411.6632

  - (Light) DM is produced in fixed target experiments

    Bjorken, Essig, Schuster, Toro, 0906.0580
    Batell, Pospelov, Ritz, 0906.5614

Boosted DM
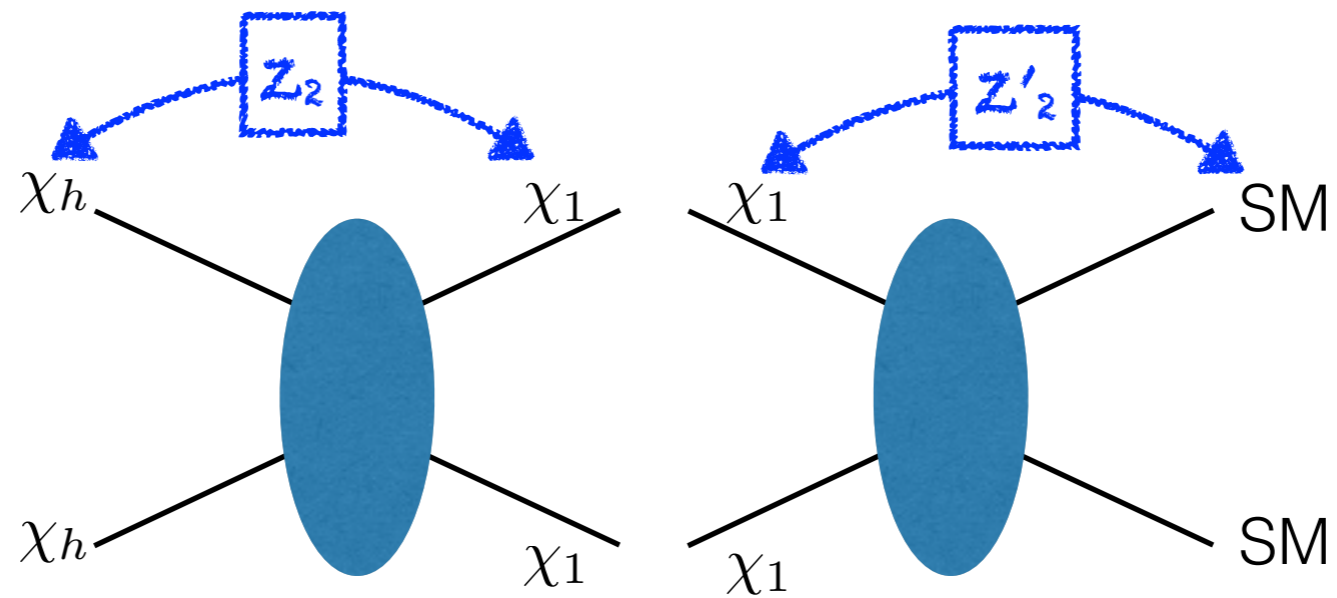
Minimal model example

Belanger, Park, 1112.4491

Agashe, Cui, Necib, Thaler, 1405.7370

Boosted DM

Minimal model example

Most of the relic

Freeze out first

Z_2 Z'_2

χ_h χ_1 χ_1 SM

χ_h χ_1 χ_1 SM

Y_h Y_1

$x = m_{\chi_1}/T$

Belanger, Park, 1112.4491

Agashe, Cui, Necib, Thaler, 1405.7370

Boosted DM

Minimal model example

Most of the relic

Z_2

χ_h χ_1

χ_h χ_1

Freeze out first

Z'_2

χ_1 SM

χ_1 SM

Freeze out later

Y_h

Y_1
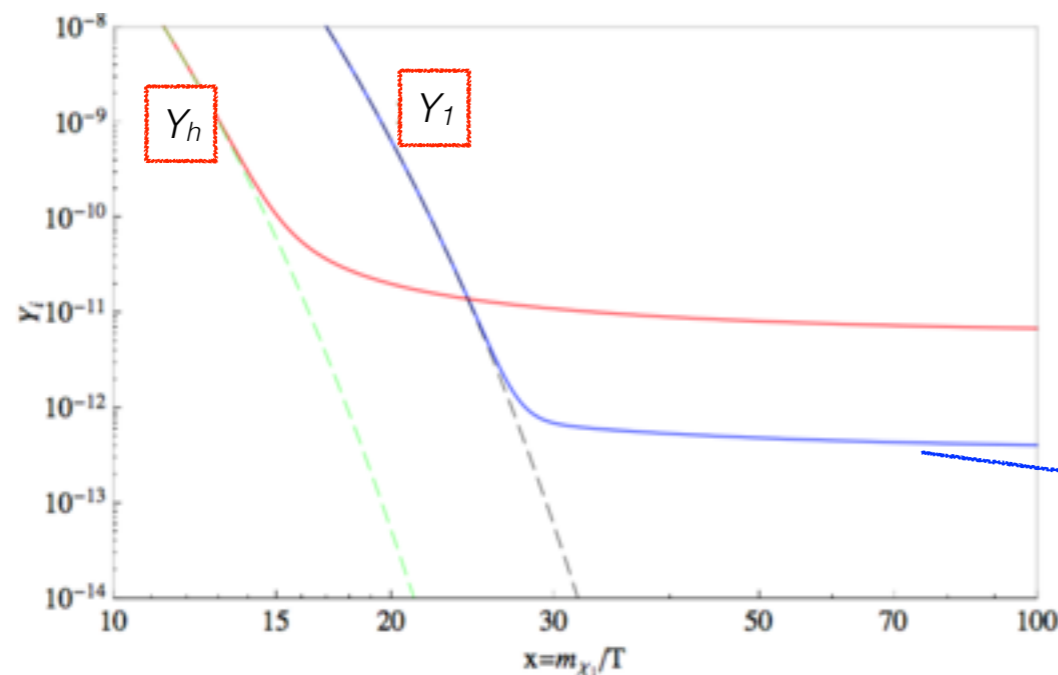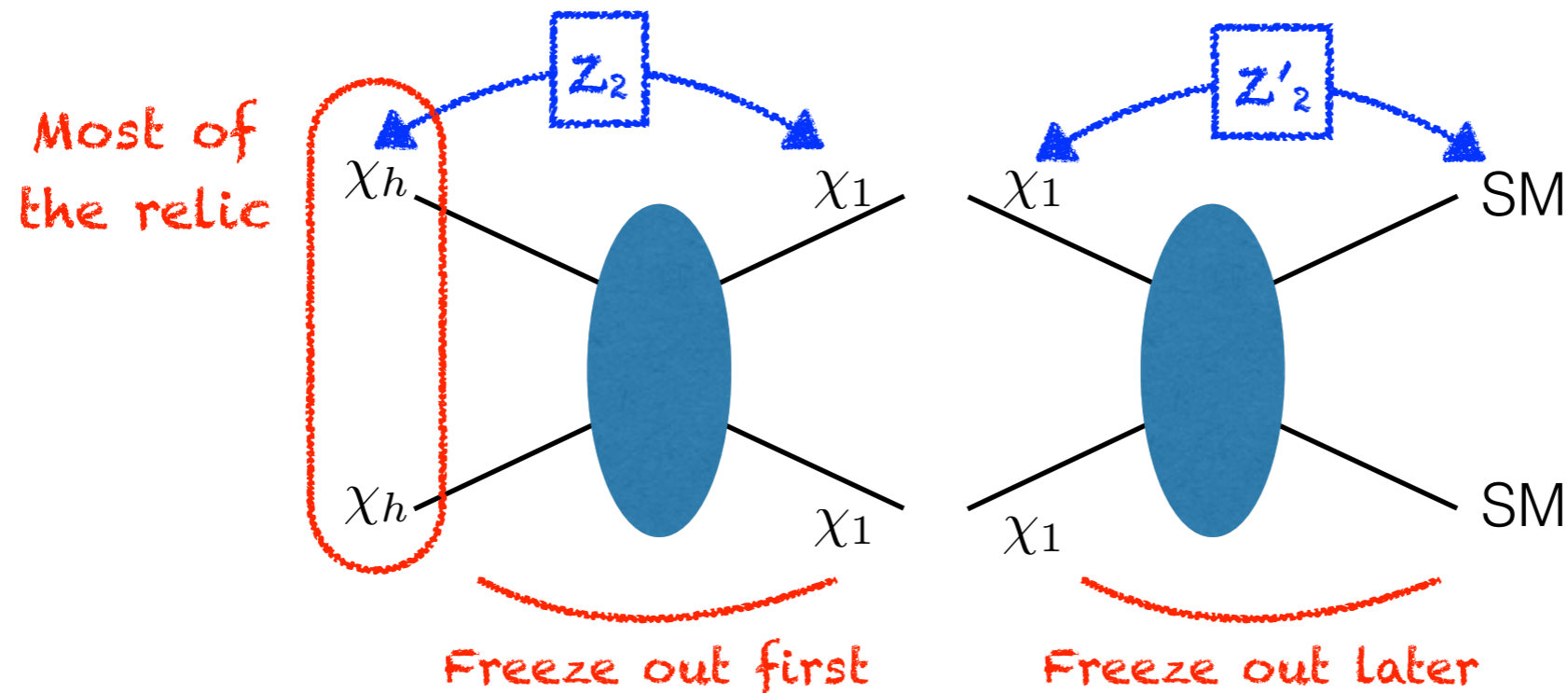
Belanger, Park, 1112.4491

Agashe, Cui, Necib, Thaler, 1405.7370

Assisted freeze-out

(Flux of relic χ_1: small)

non-relativistic

Detection of boosted DM

Dominant relic χ_h: but do not directly interact with SM

$\downarrow$

through χ_1

- $\chi_h \chi_h \rightarrow \chi_1 \chi_1$ (current universe) relativistic: need a huge detector ∵ flux small

$$m_{\chi_h} \gtrsim \mathcal{O}(10\,\text{GeV})$$

Super (& Hyper)
Kamiokande
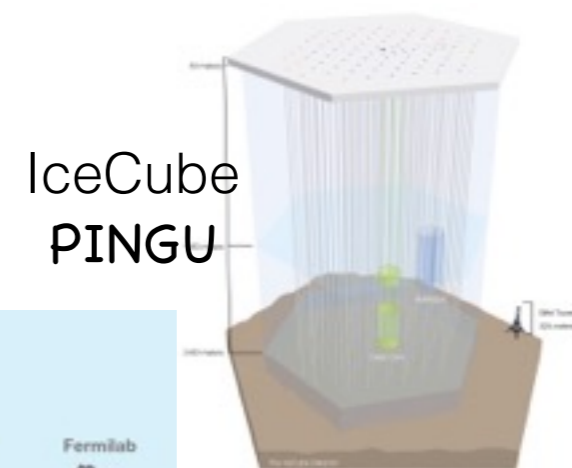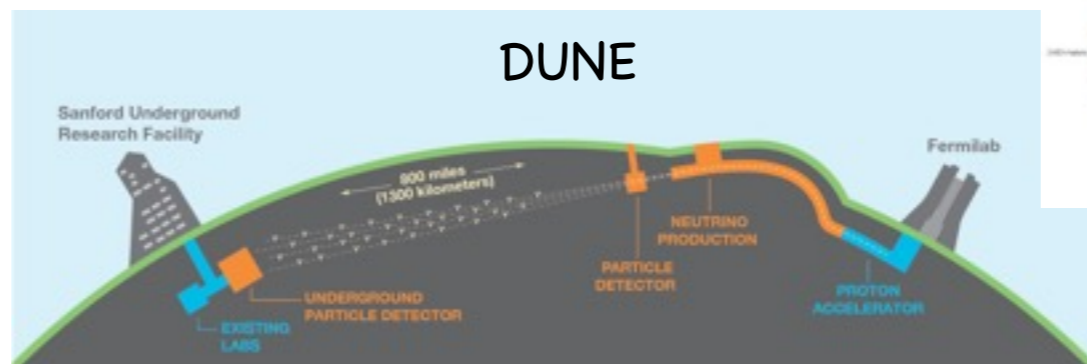
DUNE

IceCube
PINGU

Detection of boosted DM

Dominant relic χ_h: but do not directly interact with SM

$\downarrow$

through χ_1

- $\chi_h \chi_h \to \chi_1 \chi_1$ (current universe) relativistic: need a huge detector $\because$ flux small

$$m_{\chi_h} \gtrsim \mathcal{O}(10\,\text{GeV})$$

	Volume [Mt]	E_e^{thres} [GeV]	E_p^{thres} [GeV]	θ_e^{res}	θ_p^{res}
Super-K	0.0224	0.01	1.07	$3°$	$3°$
Hyper-K	0.56	0.01	1.07	$3°$	$3°$
DUNE	0.04	0.03	0.05	$1°$	$5°$

better

Detection of boosted DM

Dominant relic χ_h: but do not directly interact with SM

$\downarrow$

through χ_1

- $\chi_h \chi_h \rightarrow \chi_1 \chi_1$ (current universe) relativistic: need a huge detector ∵ flux small

- Fixed target experiments relativistic: high intensity increases flux

Fixed-Target Experiments

Particle Beam
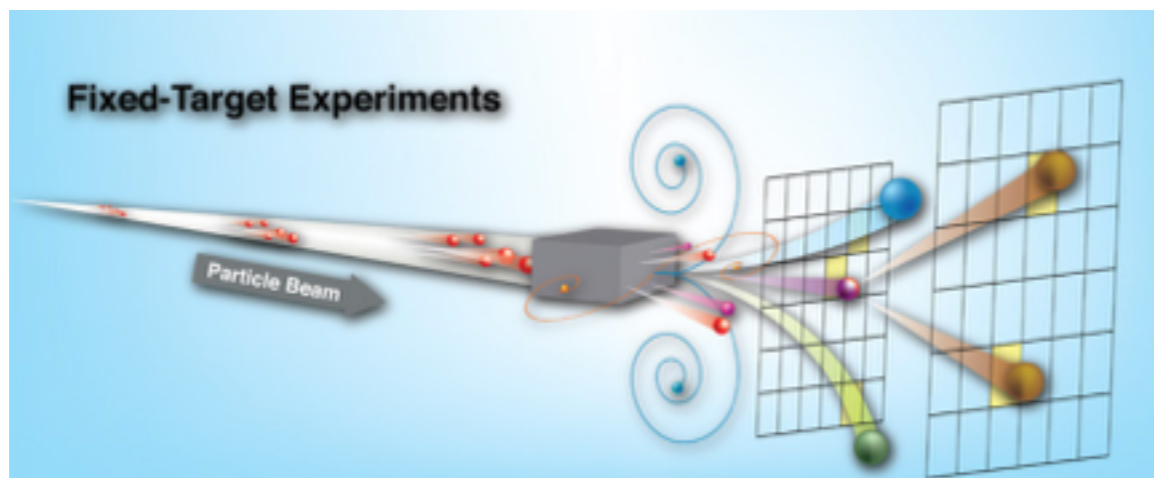
Not have to be a BDM

Signal observations in both cases

Counting N_{events} over the expected background

neutrino

Super interesting but not easy
to confirm the signals over ν

Signal observations in both cases

Counting N_{events} over the expected background
neutrino

Super interesting but not easy
to confirm the signals over ν

Modification of minimal models make them promising

- From Sun: a small coupling of χ_h - SM or self-interaction of χ_h

  Berger, Cui, Zhao, 1410.2246   Kong, Mohlaberg, Park, 1411.6632
  Alhazmi, Kong, Mohlaberg, Park, 1611.09866

- More complicated dark sector (just like SM?): extraordinary signal

  Kim, Park, **SS**, 1612.06867

Cascade process in detection of DM

Cascade signal of relativistic DM
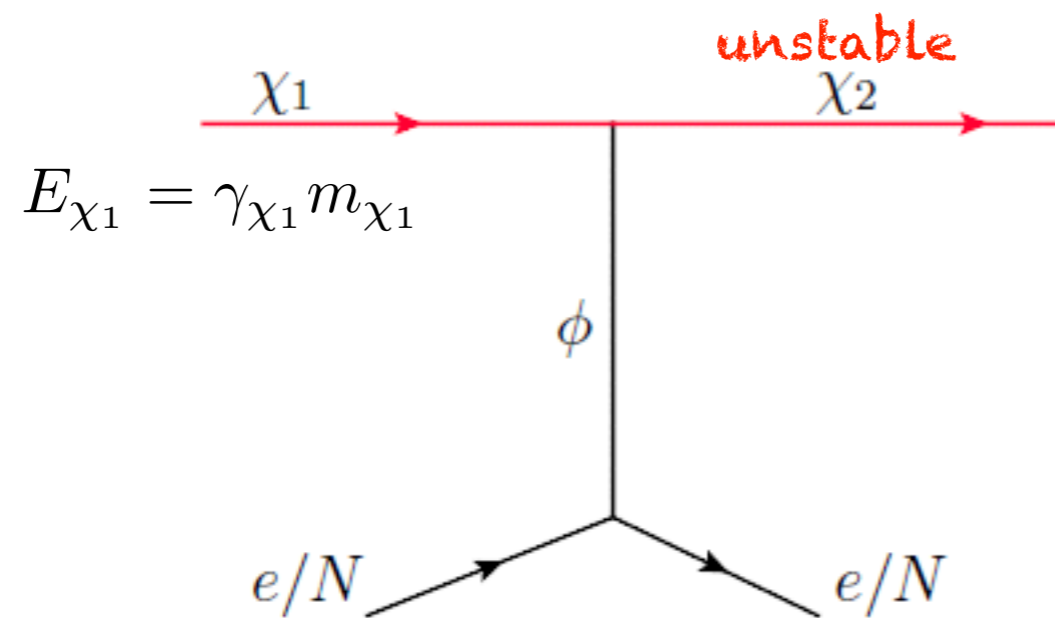
$$E_{\chi_1} = \gamma_{\chi_1} m_{\chi_1}$$

- Heavier (unstable) dark partner χ_2: $m_{\chi_2} > m_{\chi_1}$

- Mediator ϕ: not specified but assume either spin 0 or 1

Cascade signal of relativistic DM

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Cascade signal of relativistic DM

$$E_{\chi_1} = \gamma_{\chi_1} m_{\chi_1}$$

unstable χ_2

(in)visible

Secondary: unique
(avoid ν bkg.)
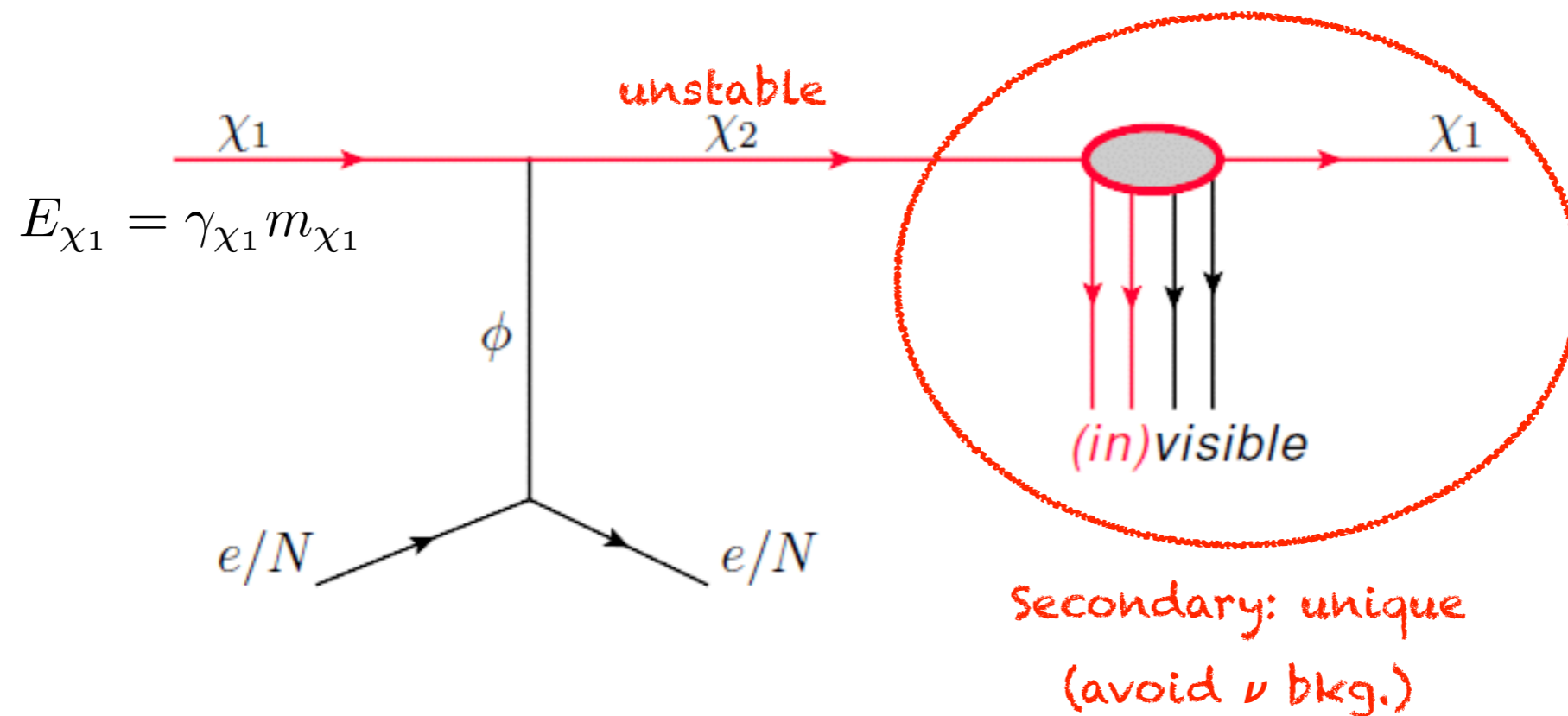
- Heavier (unstable) dark partner χ_2: $m_{\chi_2} > m_{\chi_1}$

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Cascade signal of relativistic DM

$$E_{\chi_1} = \gamma_{\chi_1} m_{\chi_1}$$

unstable χ_2

χ_1 χ_1

ϕ

e/N e/N

(in)visible
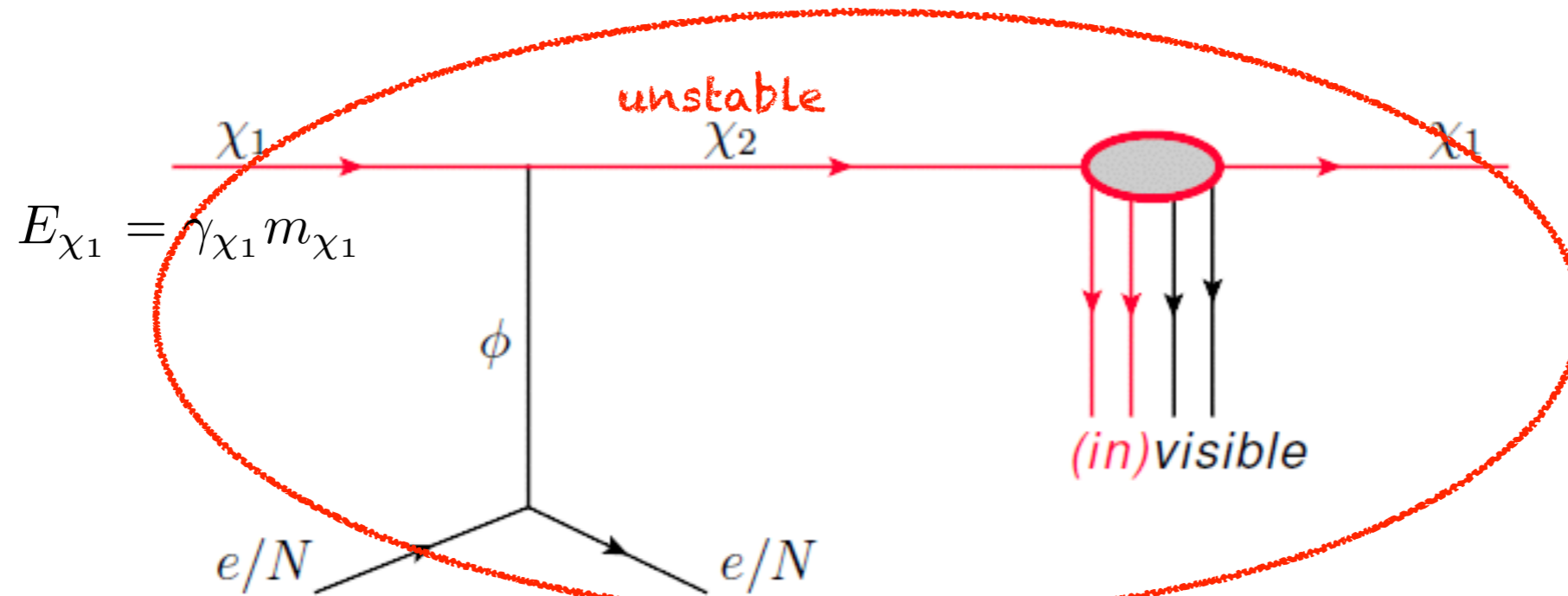
Colliders events?
1. Fixed target experiments
2. Usual p/e colliders

secondary

primary
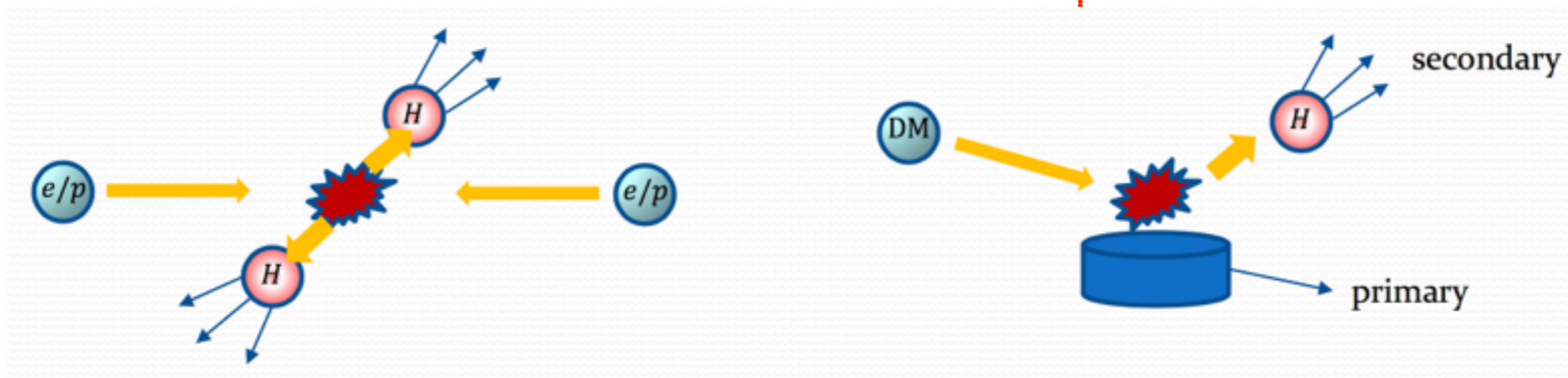
- Secondary (or more) process by χ_2: cascade signal (collider?)

Cascade signal of relativistic DM
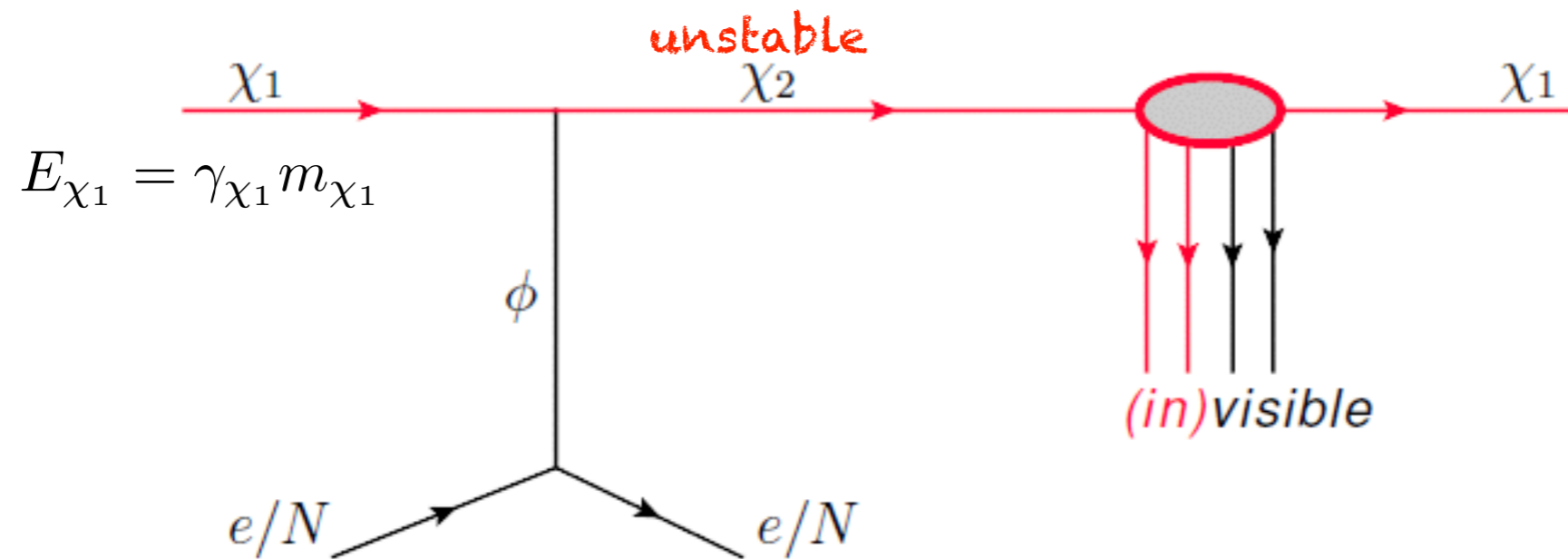
- Focus on the detection prospects in huge neutrino detectors in this talk

- Fixed target experiments: future work

Detection prospects

Energy spectrum
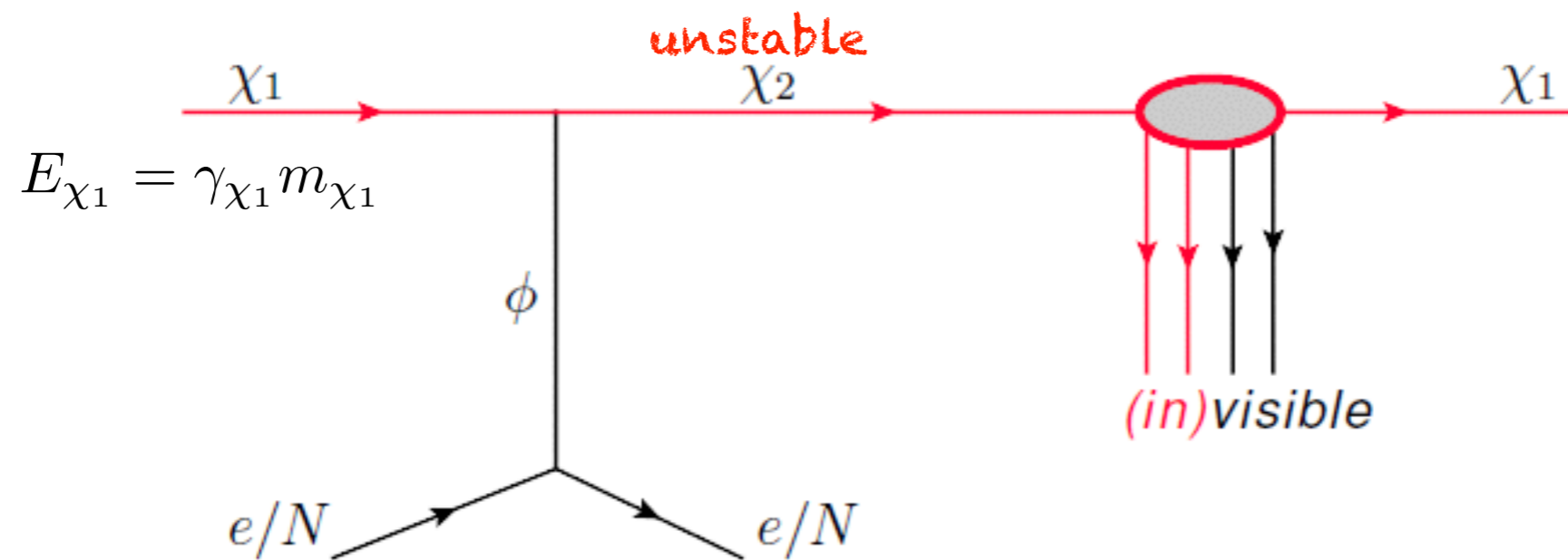
$$E_{\chi_1} = \gamma_{\chi_1} m_{\chi_1}$$

- Everything is relativistic: need large energy to have χ_2 (large γ_{χ_1})

- Electron scattering with one vector mediator: light DM with huge γ_{χ_1}

Energy spectrum: e-scattering

$$E_{\chi_1} = \gamma_{\chi_1} m_{\chi_1}$$

unstable

χ_1 χ_2 χ_1

ϕ

ϕ

e/N e/N

ϕ energy spectrum: electron target
- - - $m_{\chi_1} = 0.4$, $m_{\chi_2} = 0.5$, $m_\phi = 0.06$, $\gamma_{\chi_1} = 250$
—— $m_{\chi_1} = 0.1$, $m_{\chi_2} = 0.14$, $m_\phi = 0.04$, $\gamma_{\chi_1} = 200$

Highly boosted

$1/\sigma \cdot d\sigma/dE_\phi$

E_ϕ [GeV] in lab frame

- Everything is relativistic: need large energy to have χ_2 (large γ_{χ_1})

- Electron scattering with one vector mediator: light DM with huge γ_{χ_1}

Energy spectrum: e-scattering

unstable

χ_1 χ_2

ϕ

e/N e/N

primary scattering

Electron recoil spectrum

- - - $m_{\chi_1} = 0.4, m_{\chi_2} = 0.5, m_\phi = 0.06, \gamma_{\chi_1} = 250$

—— $m_{\chi_1} = 0.1, m_{\chi_2} = 0.14, m_\phi = 0.03, \gamma_{\chi_1} = 200$

$1/\sigma \cdot d\sigma/dp_e$

p_e [GeV]   in lab frame
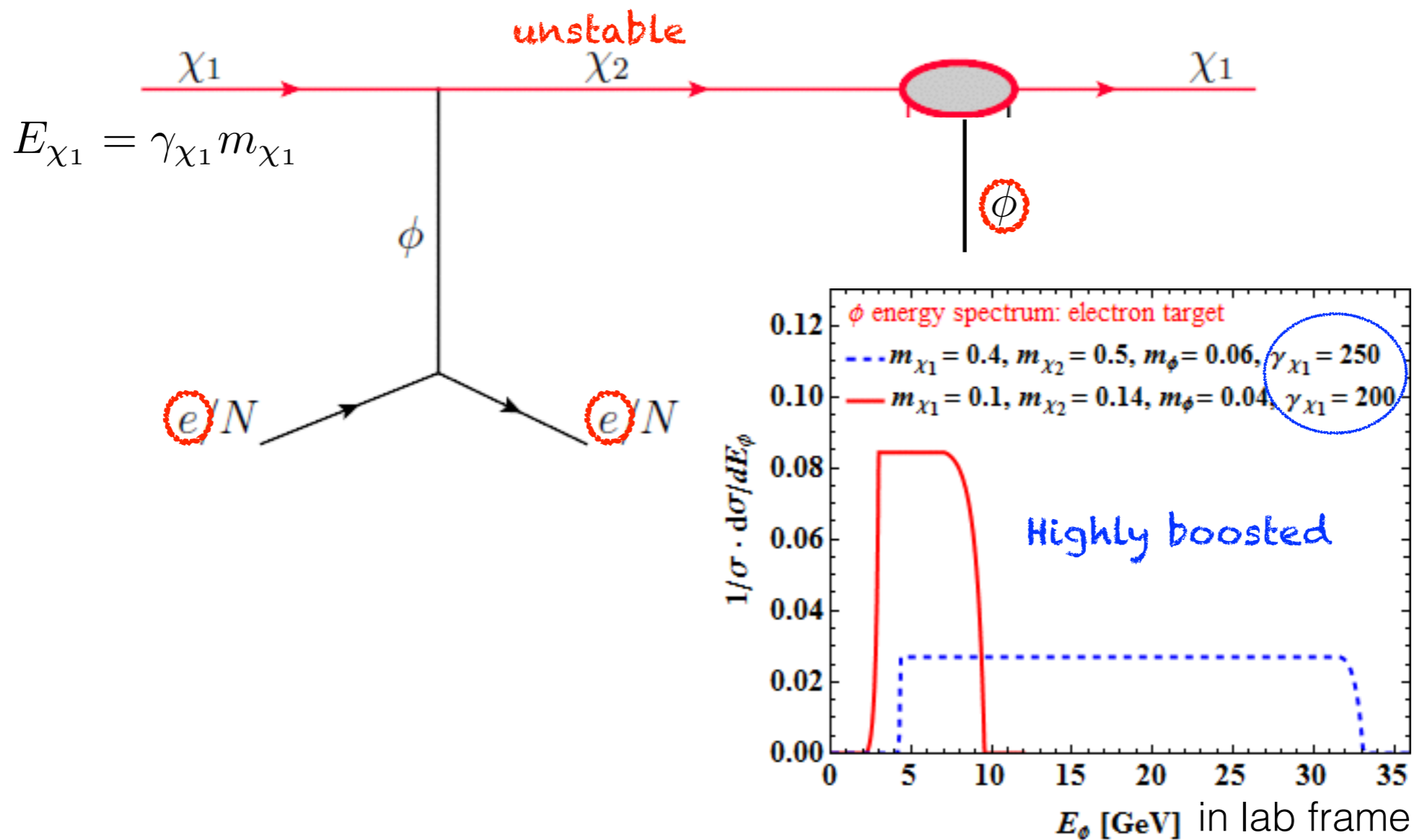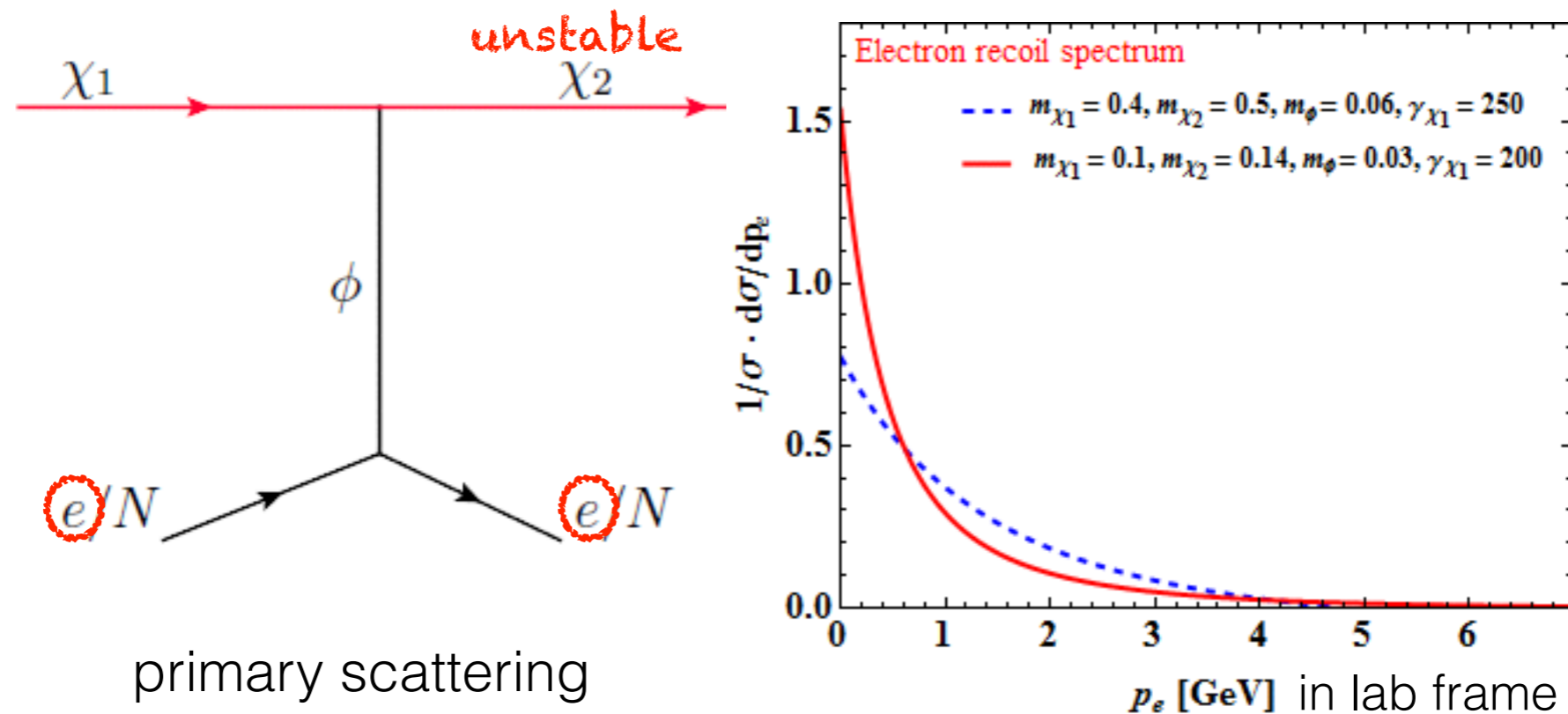
e-scattering preferred over p-scattering

- Primary scattering cross section large when <u>momentum transfer small</u>

- <u>E_{th} low</u> for e-scattering but high for p-scattering (Cherenkov detectors)

  Kamiokande

- Proton scattering is suppressed by atomic form factor

e-scattering: highly collimated

unstable

χ_1 χ_2 χ_1

highly collimated

ϕ

ϕ

e/N e/N

in lab frame

red line: angle target - χ_2

$m_{\chi_1} = 0.1,\ m_{\chi_2} = 0.14,\ m_\phi = 0.03,\ \gamma_{\chi_1} = 200$

Opening angle [degree]

p_e [GeV] in lab frame

e-scattering: highly collimated

χ_1 unstable χ_2 χ_1

highly collimated

ϕ

in lab frame

red line: angle target - χ_2

$m_{\chi_1} = 0.1,\ m_{\chi_2} = 0.14,\ m_\phi = 0.03,\ \gamma_{\chi_1} = 200$
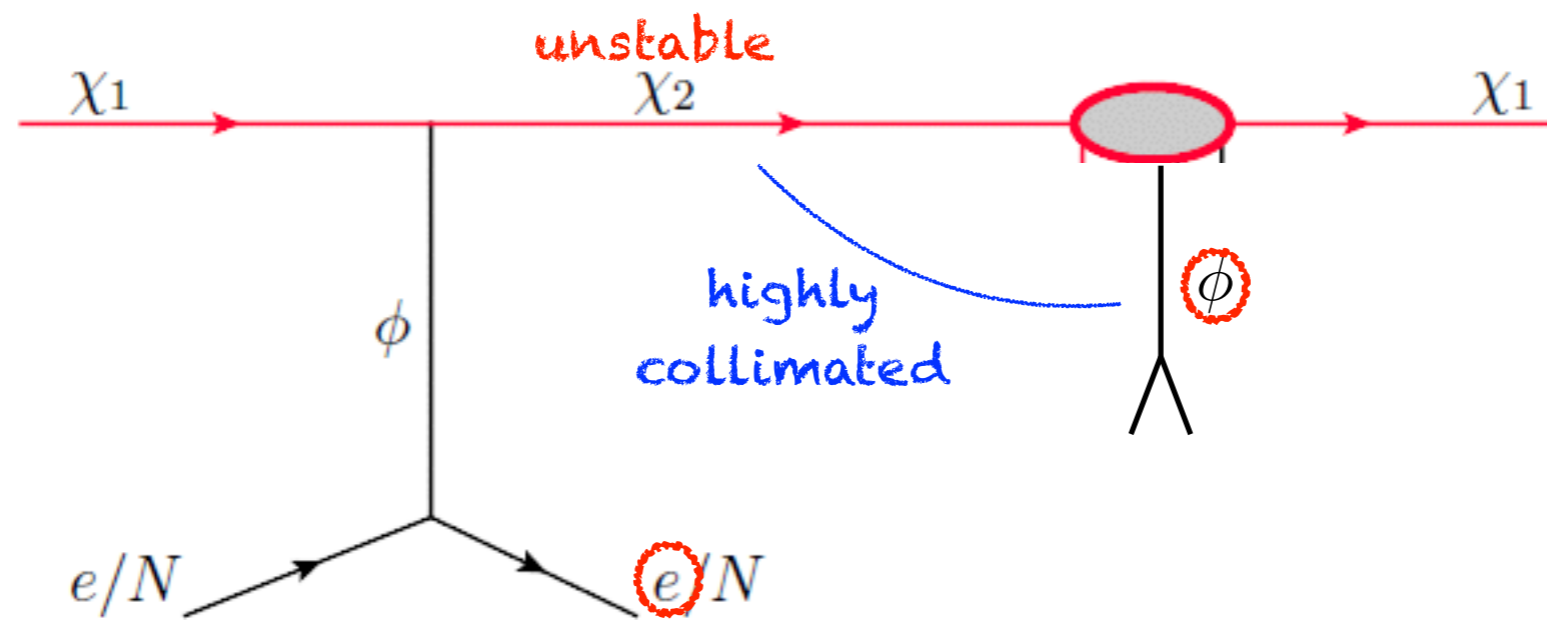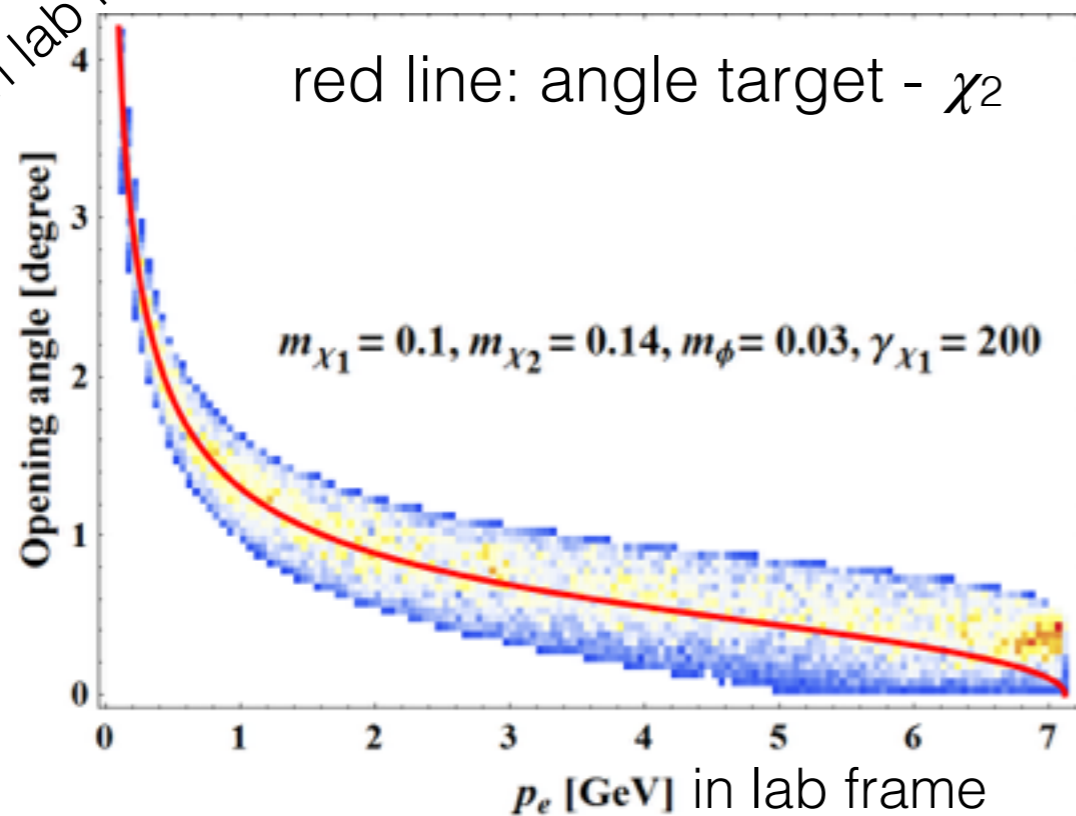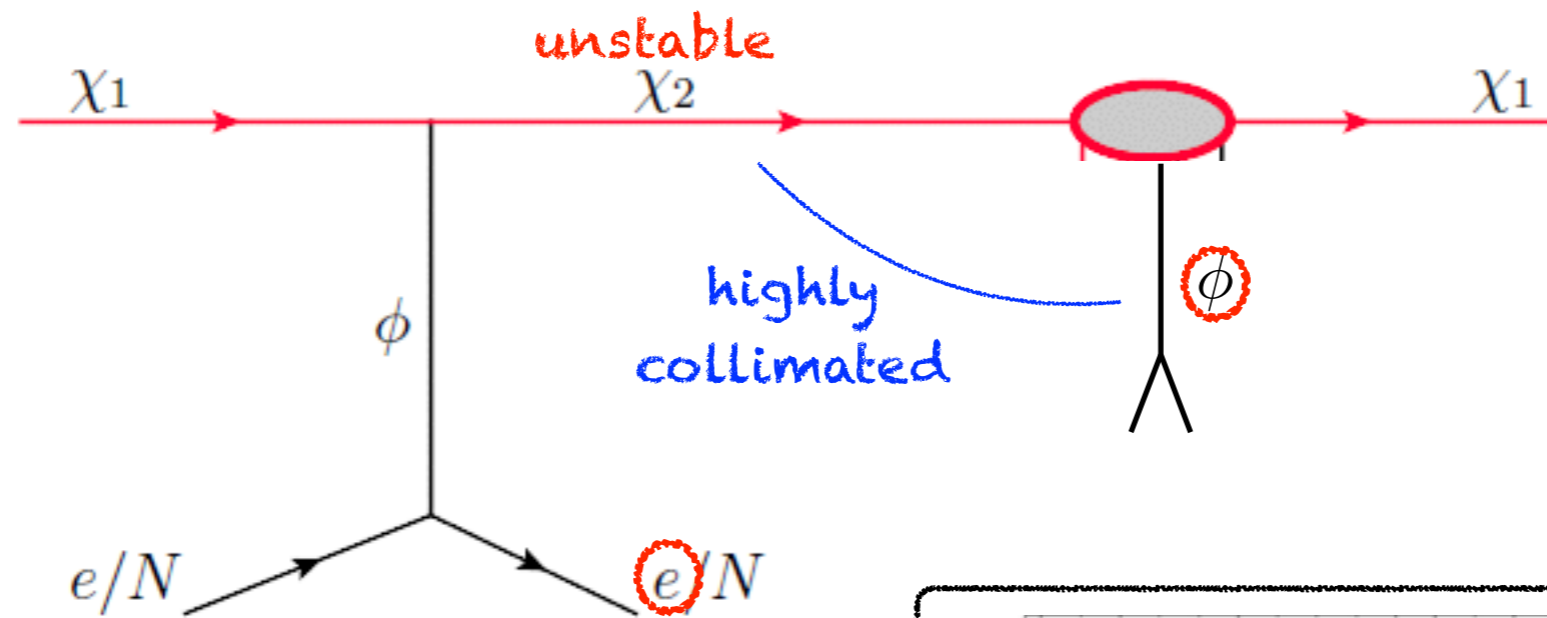
p_e [GeV] in lab frame
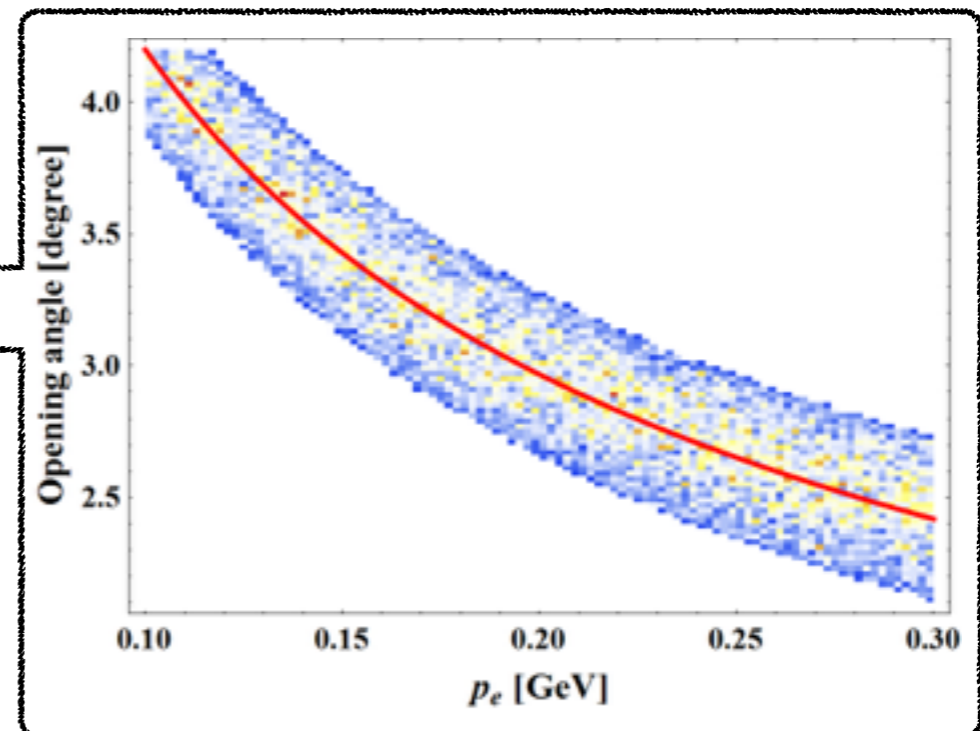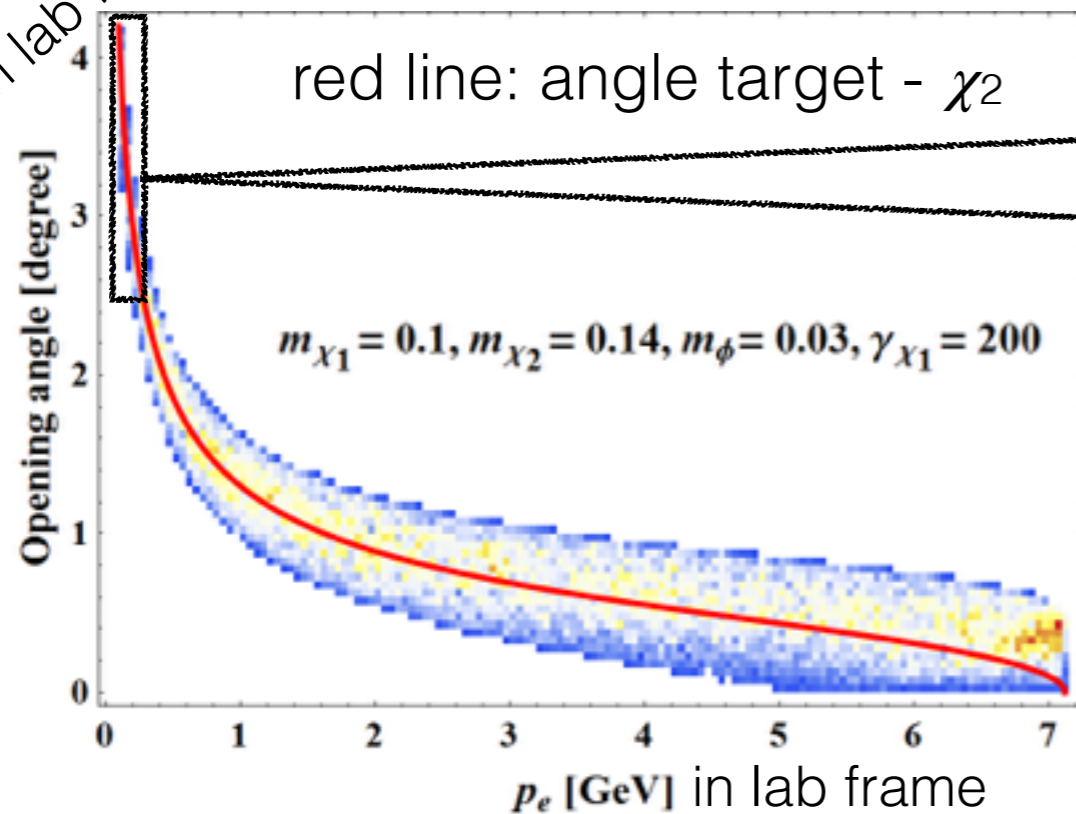
Angular resolution 3° ? **two signals!**
(drops for smaller p_e)

e-scattering: highly collimated

Assume ϕ decays to $e^+ e^-$
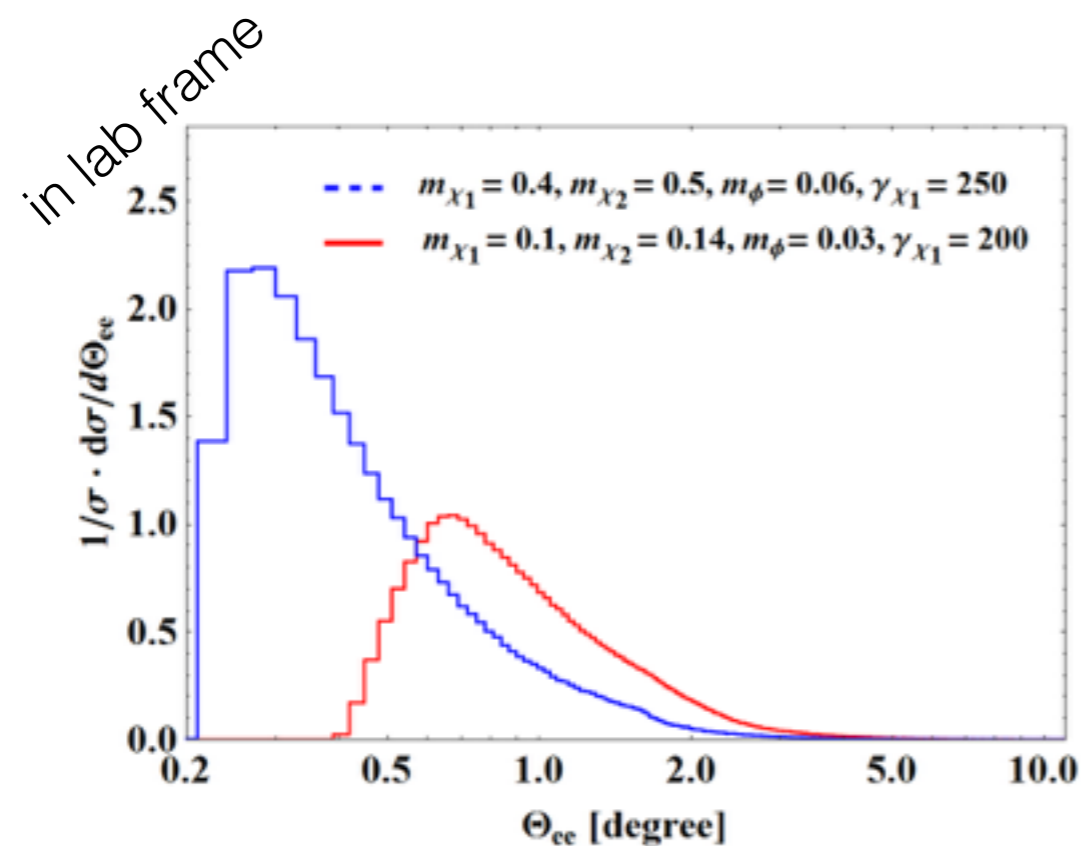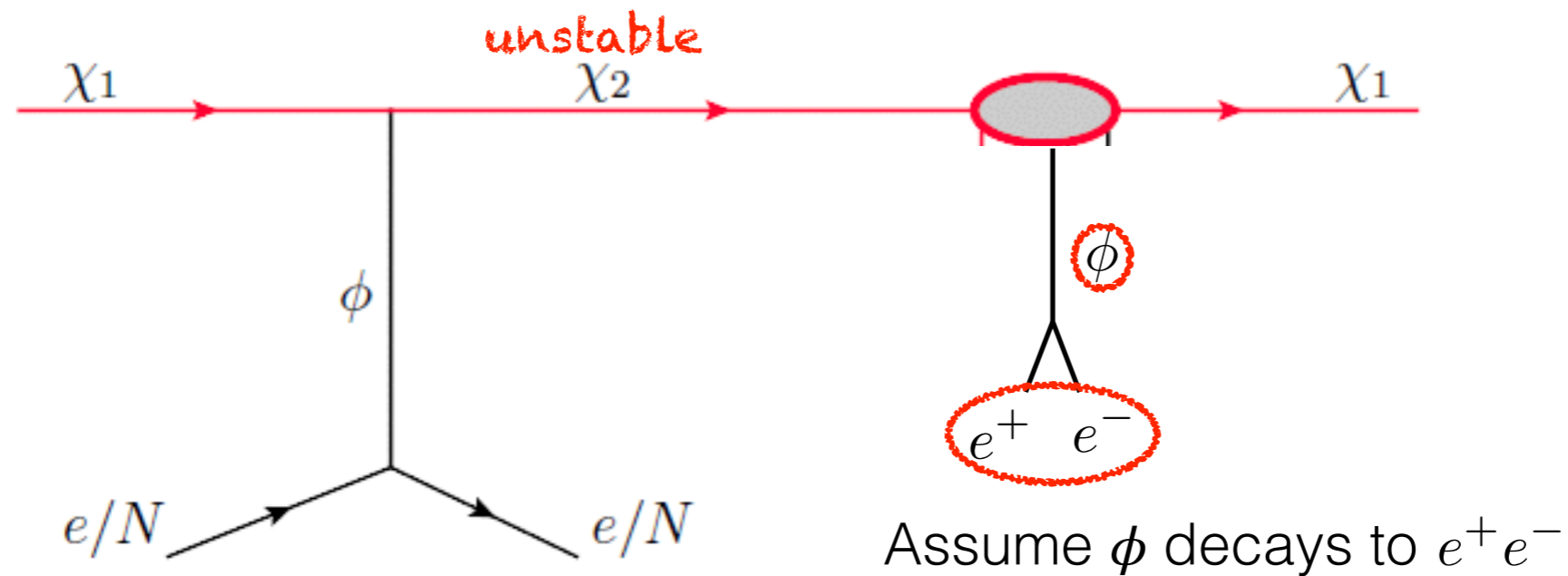
Mostly < 1.5°

e-scattering: highly collimated

Assume ϕ decays to $e^+ e^-$

in lab frame

$m_{\chi_1} = 0.1, \; m_{\chi_2} = 0.14, \; m_\phi = 0.03, \; \gamma_{\chi_1} = 200$
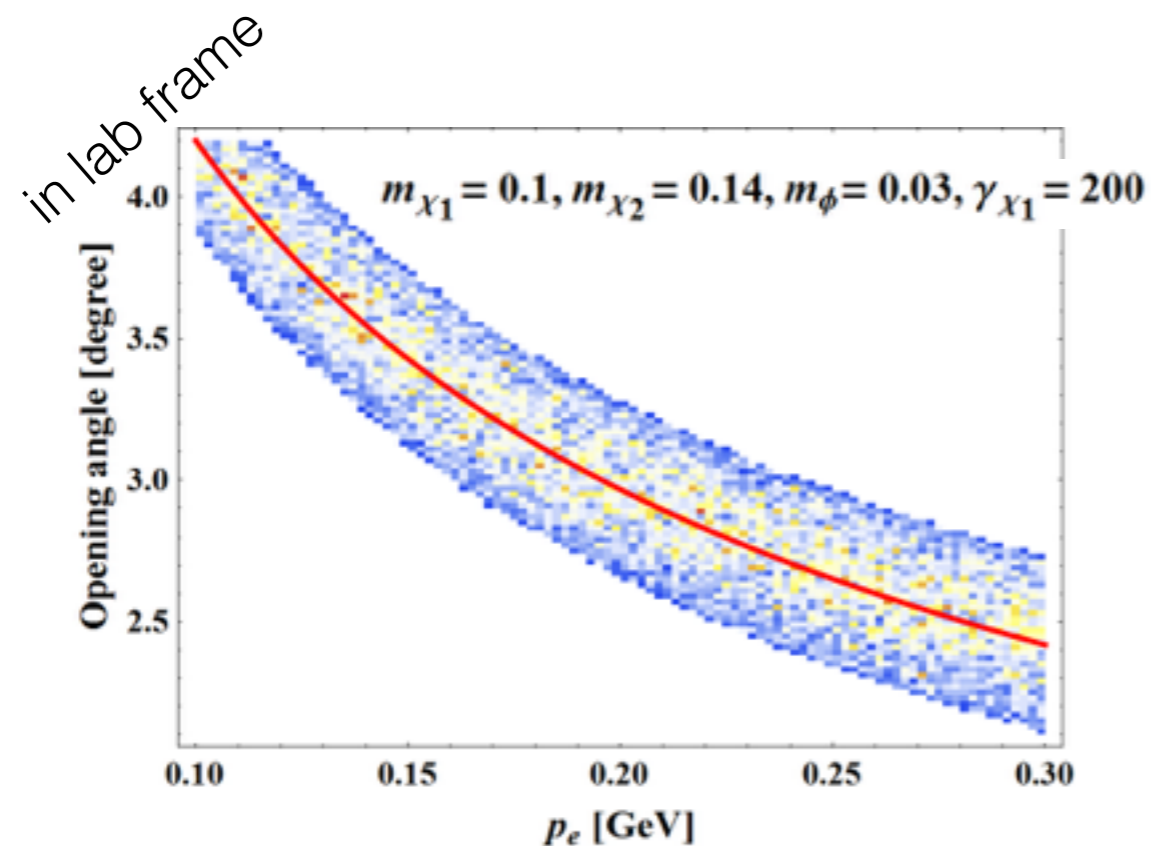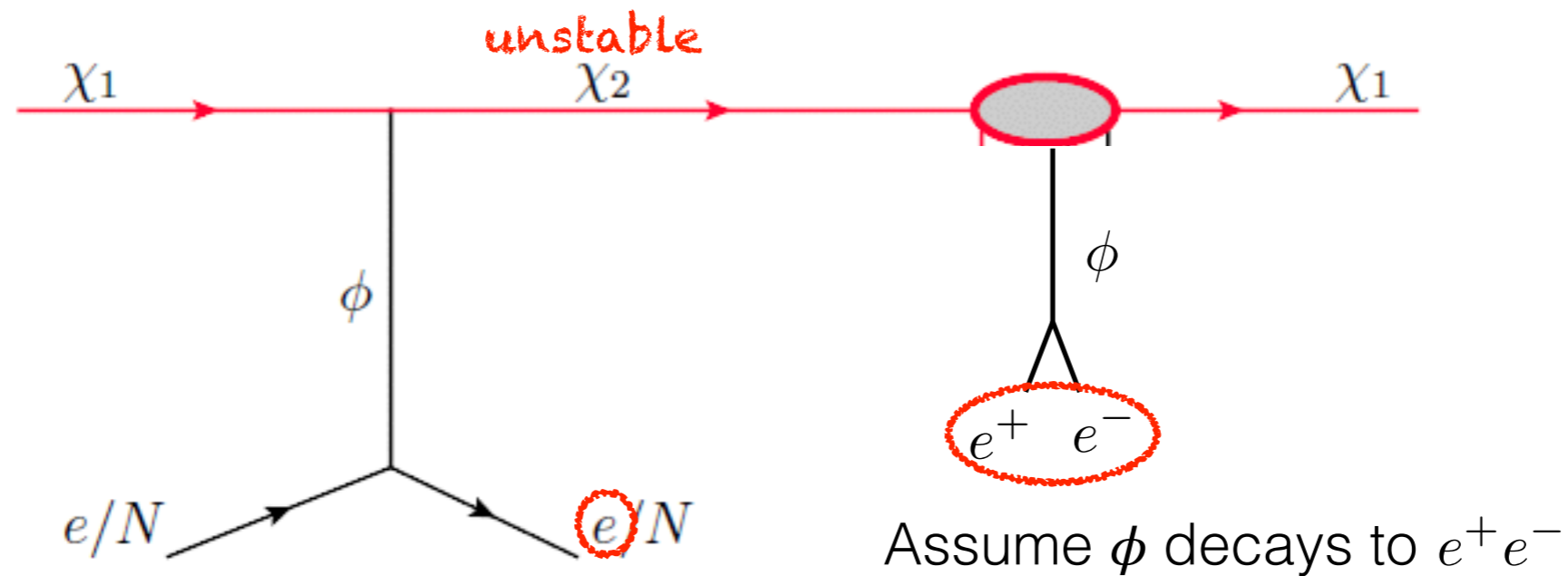
High chance to observe
two separate signals!!

in an experiment with
angular resolution ~ 3°
for primary p_e: 0.1 - 0.3 GeV

e-scattering: detection prospects

unstable

χ_1 χ_2 χ_1

ϕ vector

ϕ

e^+ e^-

e/N e/N

Assume ϕ decays to $e^+ e^-$
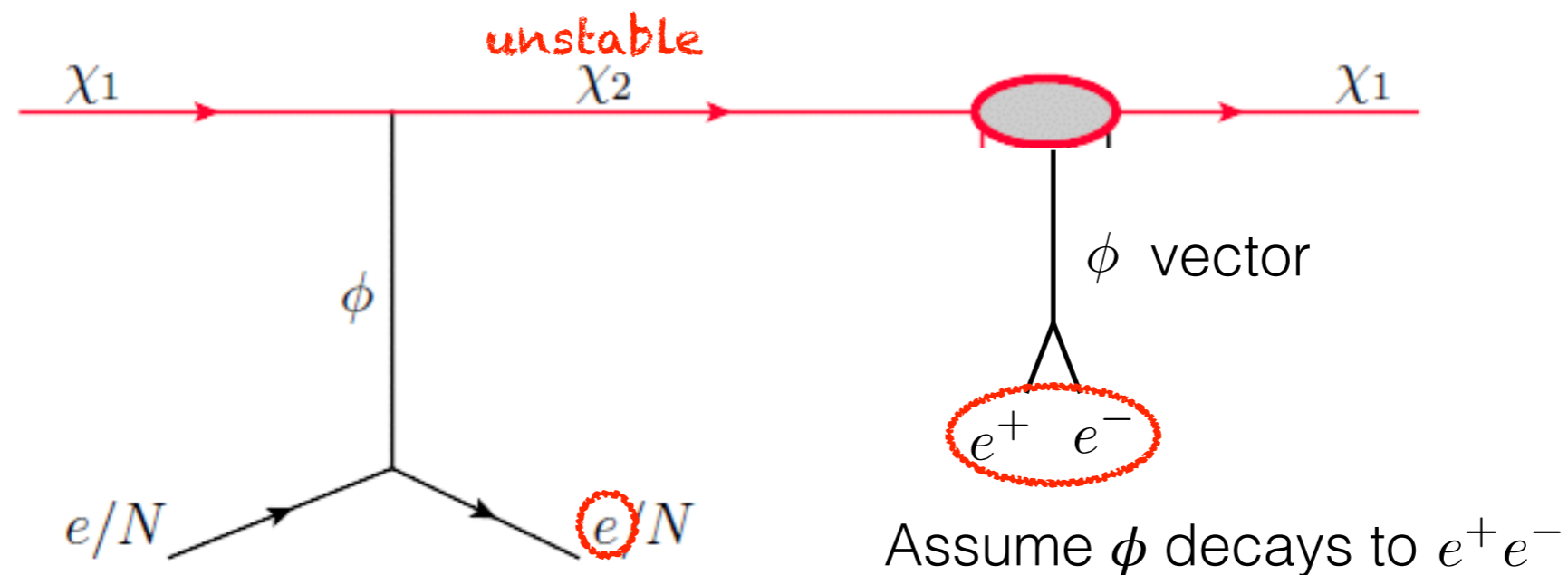
Super/Hyper-K & DUNE can do it!

	Volume [Mt]	E_e^{thres} [GeV]	E_p^{thres} [GeV]	θ_e^{res}	θ_p^{res}
Super-K	0.0224	0.01	1.07	3°	3°
Hyper-K	0.56	0.01	1.07	3°	3°
DUNE	0.04	0.03	0.05	1°	5°

even better

e-scattering: detection prospects

Assume ϕ decays to $e^+ e^-$

	Volume [Mt]	E_e[GeV]	E_p^{thres} [GeV]	θ_e^{res}	θ_p^{res}
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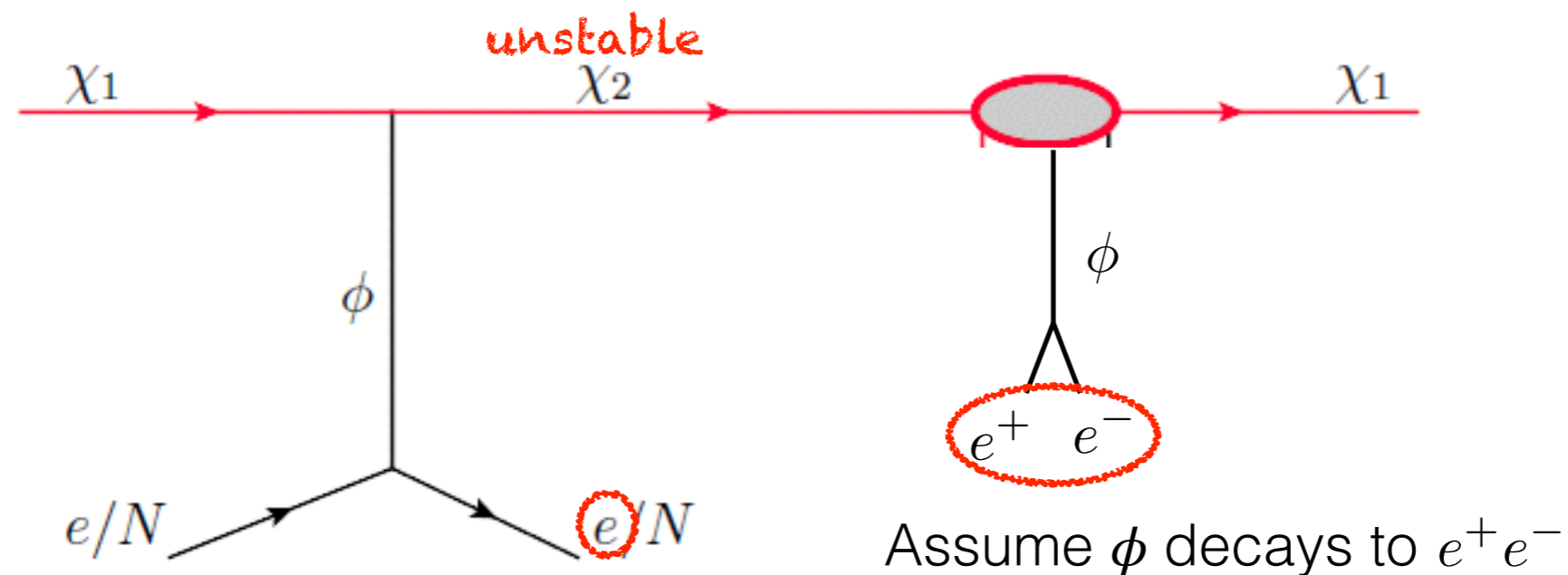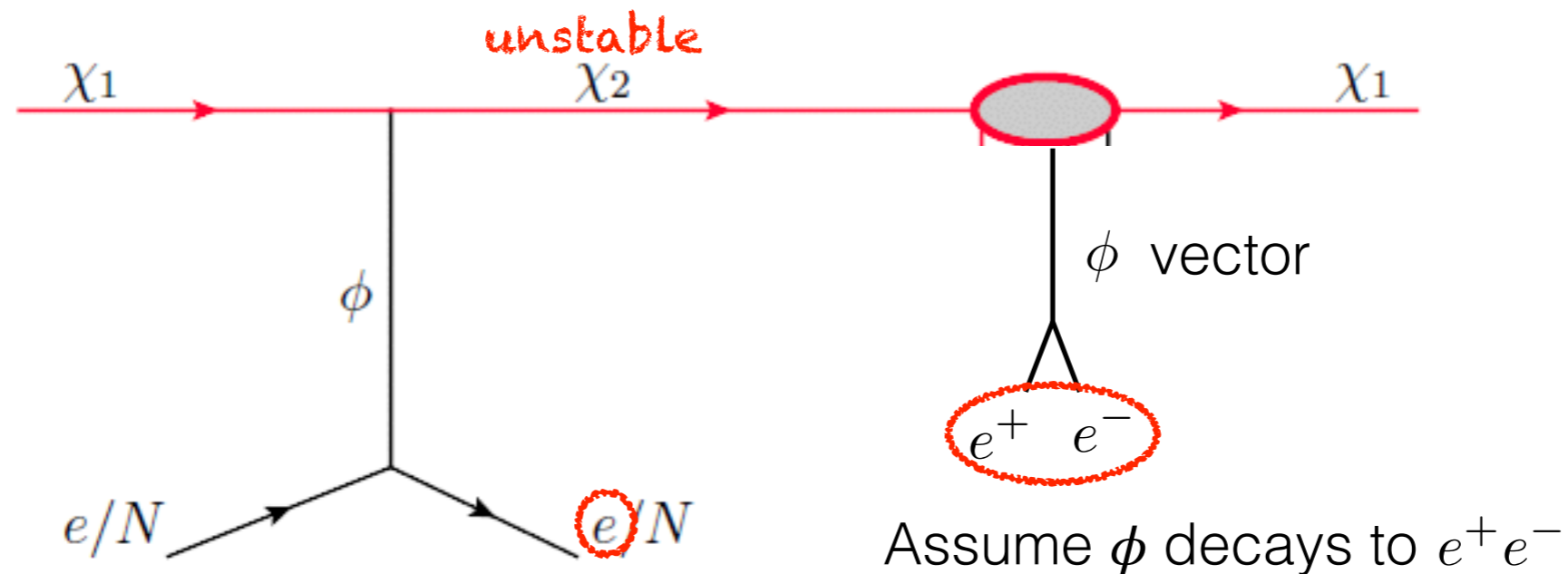
effective for E > E_th

We need good res.

e-scattering: sensitivities on flux

unstable

χ_1 χ_2 χ_1

ϕ vector

ϕ

e/N e/N

e^+ e^-

Assume ϕ decays to $e^+ e^-$

$m_{\chi_1} = 0.1,\ m_{\chi_2} = 0.14,\ m_\phi = 0.03,\ \gamma_{\chi_1} = 200$ $g_{12} = 0.5,\ \epsilon = 0.0003$

toy model $\mathcal{L}_X \supset -\dfrac{\epsilon}{2} F_{\mu\nu} X^{\mu\nu} + g_{12} \bar{\chi}_2 \gamma^\mu \chi_1 X_\mu + h.c.$

Experiments	$\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Super-K 4799 days	7.1×10^{-7}
Hyper-K 1 year	3.7×10^{-7}
Hyper-K 4799 days	2.8×10^{-8}
DUNE 1 year	9.0×10^{-7}
DUNE 4799 days	6.9×10^{-8}

Assume no bkg.   4799 days ≈13.6 yr

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our process sensitive

Remind, in a <u>minimal BDM</u>, flux over the whole sky
$\mathcal{O}(10^{-7}\,\mathrm{cm^{-2} s^{-1}})$

Promising example!

Assume no bkg.   4799 days ≈13.6 yr

p-scattering: energy spectrum

p-scattering NOT preferred over e-scattering (Cherenkov)

- Primary scattering cross section large when <u>momentum transfer small</u>

- E_{th} high for proton scattering (for Cherenkov)

- Proton scattering is suppressed by atomic form factor

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p-scattering: energy spectrum

p-scattering NOT preferred over e-scattering (Cherenkov)

- Primary scattering cross section large when <u>momentum transfer small</u>

- E_{th} high for proton scattering (for Cherenkov)

- Suppression by atomic form factor: <u>not so severe for p_p < 2 GeV</u>

p-scattering: energy spectrum
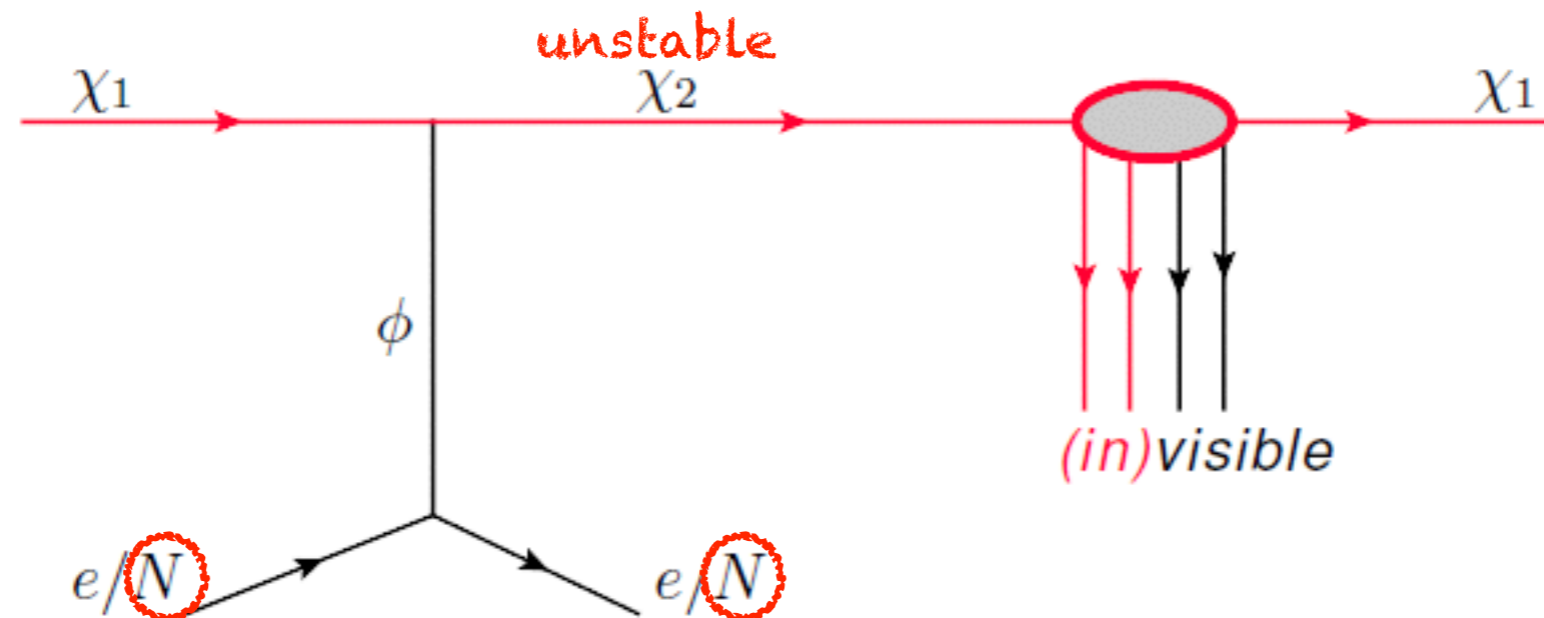
However, the cascade process is still unique

- E_{th} low for proton scattering for liquid Ar detectors (DUNE: E_{th} 50 MeV)

- Separation of two signals are more promising than e-scattering

p-scattering: energy spectrum
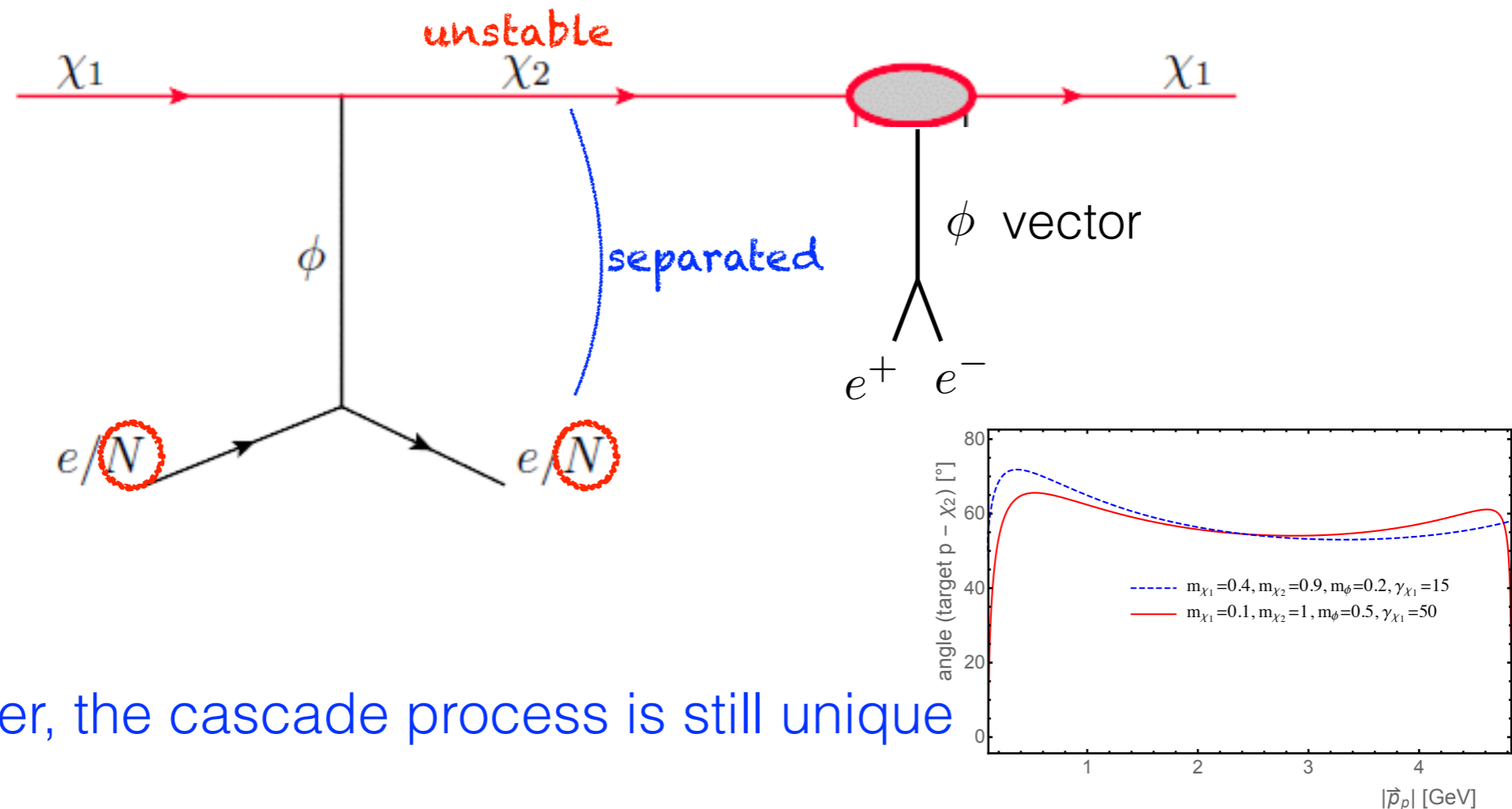
However, the cascade process is still unique

- E_{th} low for proton scattering for liquid Ar detectors (DUNE: E_{th} 50 MeV)

- Separation of two signals super good & **3 visible objects**

p-scattering: sensitivities on flux

unstable

χ_1 χ_2 χ_1

ϕ

e/N e/N

ϕ vector

e^+ e^-

Assume ϕ decays to $e^+ e^-$
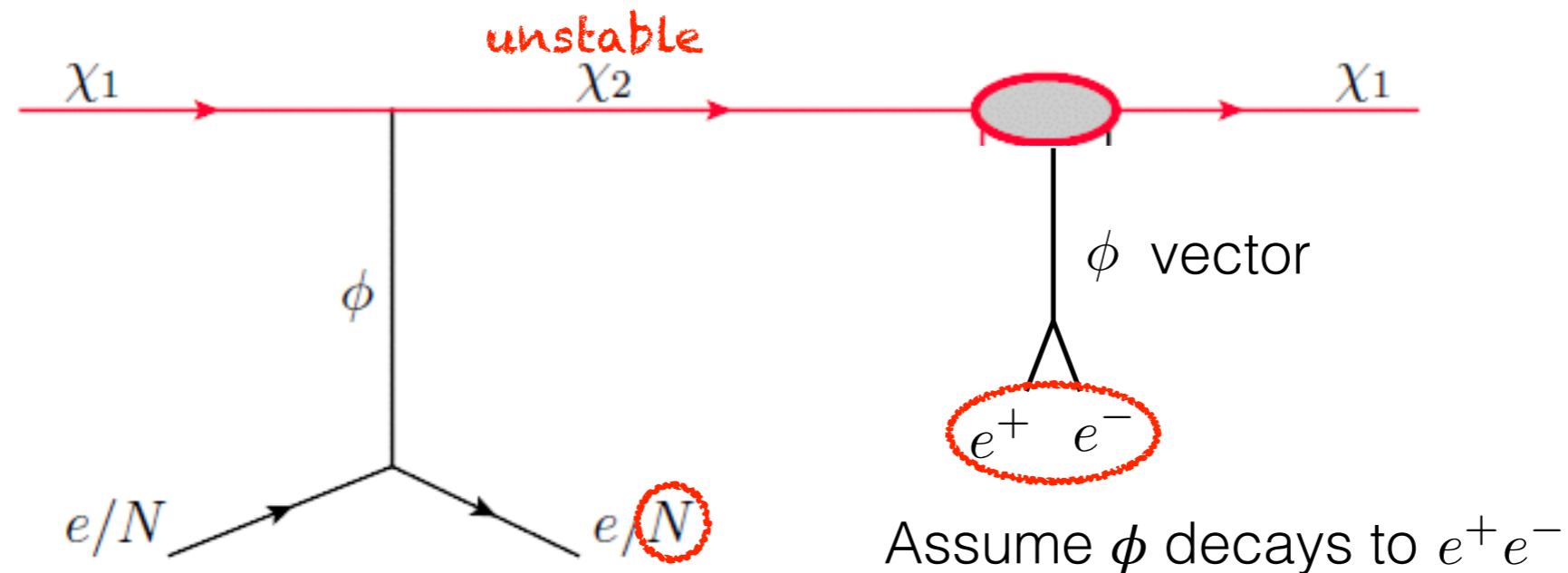
Flux can be higher in non-minimal BDM model
or fixed target experiments

toy model
$g_{12} = 0.5, \; \epsilon = 0.0003$

Exp.	Run time	e-ref.1	e-ref.2	p-ref.1	p-ref.2
SK	13.6 yr	170	7.1	3500	5200
HK	1 yr	88	3.7	1900	2800
HK	13.6 yr	6.7	0.28	140	210
DUNE	1 yr	190	9.0	150	1600
DUNE	13.6 yr	14	0.69	11	120

less sensitive than e

Assume no bkg.   unit: $10^{-7} \mathrm{cm}^{-2} \mathrm{s}^{-1}$
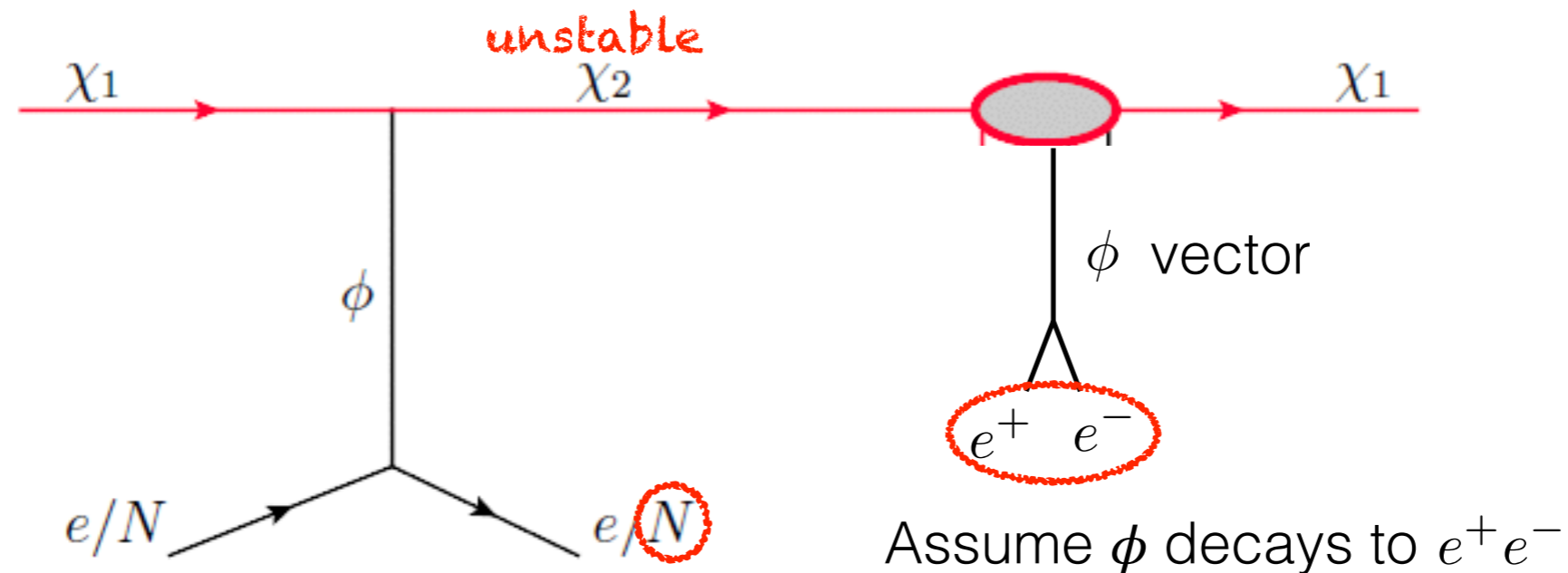
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DUNE	13.6 yr	14	0.69	11	120

13.6 yr of HK improves
the sensitivity

Assume no bkg.

unit: $10^{-7}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
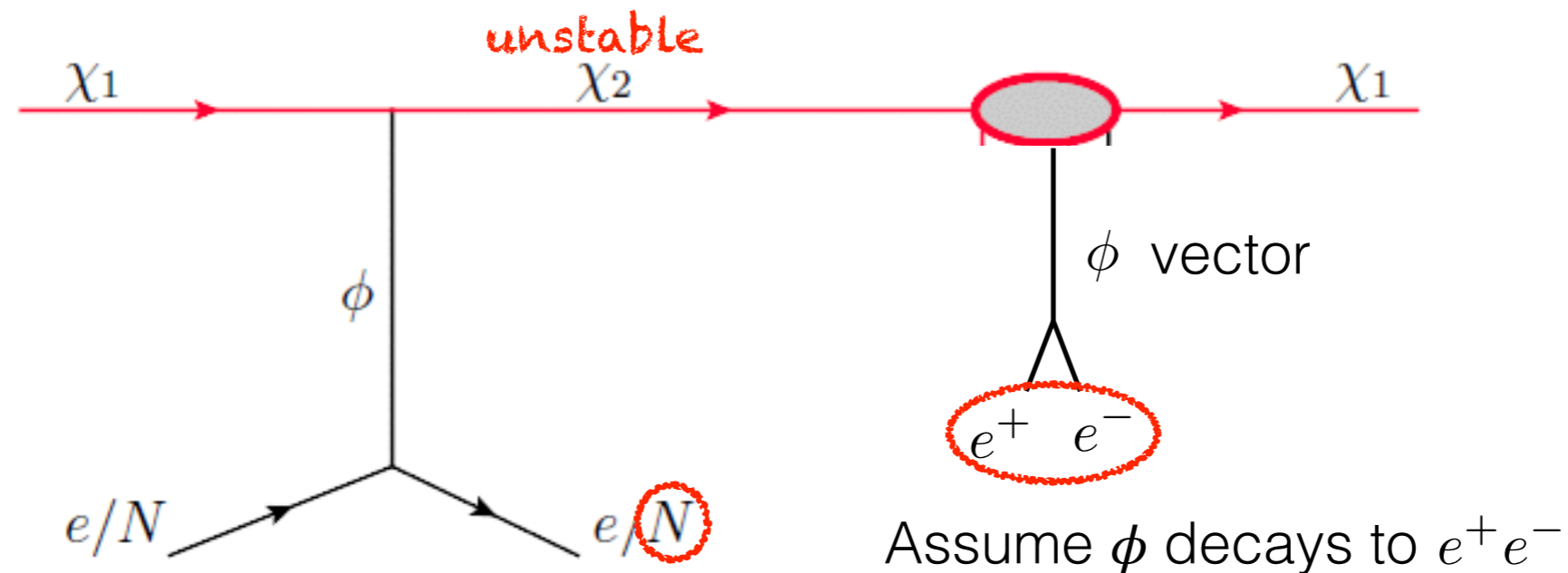
p-scattering: sensitivities on flux

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DUNE	13.6 yr	14	0.69	11	120

Remarkable
improvement
in DUNE!!!

Promising
(3 simultaneous signals)

Assume no bkg.

unit: $10^{-7} \mathrm{cm}^{-2} \mathrm{s}^{-1}$

Really background free?

Background may be negligible (dedicated analysis needed)

- Not energetic muon $\mu \to e \nu_e \nu_\mu$ (e + ℓ), cut out by requiring E > 0.1 GeV

- $n\nu_\tau \to p\tau \to p\ell\nu_\ell \nu_\tau$ (p + ℓ), cut out by requiring 3 visible objects

- $n\nu_e \to pe \to 3e + \dots$ by hadronized p (or just by NC), ring shape & energy

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Kim, Park, **SS**, Work in progress

Cherenkov light detectors (Kamiokande)

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- $n\nu_e \to pe \to 3e + \dots$ by hadronized p (or just by NC): ring shape & energy

Our signal (e-scattering)	Hadronized background
Primary signal (clean): 0.1 - 0.3 GeV	e from CC (clean): higher E
Secondary signal (vague): higher E	e from p/n (vague): lower E

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+ Number of events of p(n) $\to$ (2)e small

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Secondary signal (vague): higher E	e from p/n (vague): lower E

+ Number of events of p(n) → (2)e small + directionality (GC)?

Really background free?

Background may be negligible (dedicated analysis needed)

Ionization from the charged track (DUNE)

- Not energetic muon $\mu \rightarrow e \nu_e \nu_\mu$ (e + ℓ): cut out by requiring E > 0.1 GeV

- $n\nu_\tau \rightarrow p\tau \rightarrow p\ell\nu_\ell \nu_\tau$ (p + ℓ): cut out by requiring 3 visible objects

- $n\nu_e \rightarrow pe \rightarrow 3e + \ldots$ by hadronized p (or just by NC): shower can be seen

Maybe DUNE can separate all possible backgrounds

Detection prospects: DM collider

- Non-minimal dark sector (χ_2): cascade process

- Analyzed in current & future huge ν detectors:
  Super-K, Hyper-K, DUNE

pros

cons

e-scattering
• E_{th} low in Cherenkov light detectors (high σ)
• Sensitive with small flux
• Separation of two signals not easy (good for low p_e)

cons

pros

p-scattering
• E_{th} high in Cherenkov light detectors (low σ)
• Need large flux
• Separation of two signals & 3 visible objects: promising

Detection prospects: DM collider

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- Analyzed in current & future huge ν detectors:
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DUNE

p-scattering

cons

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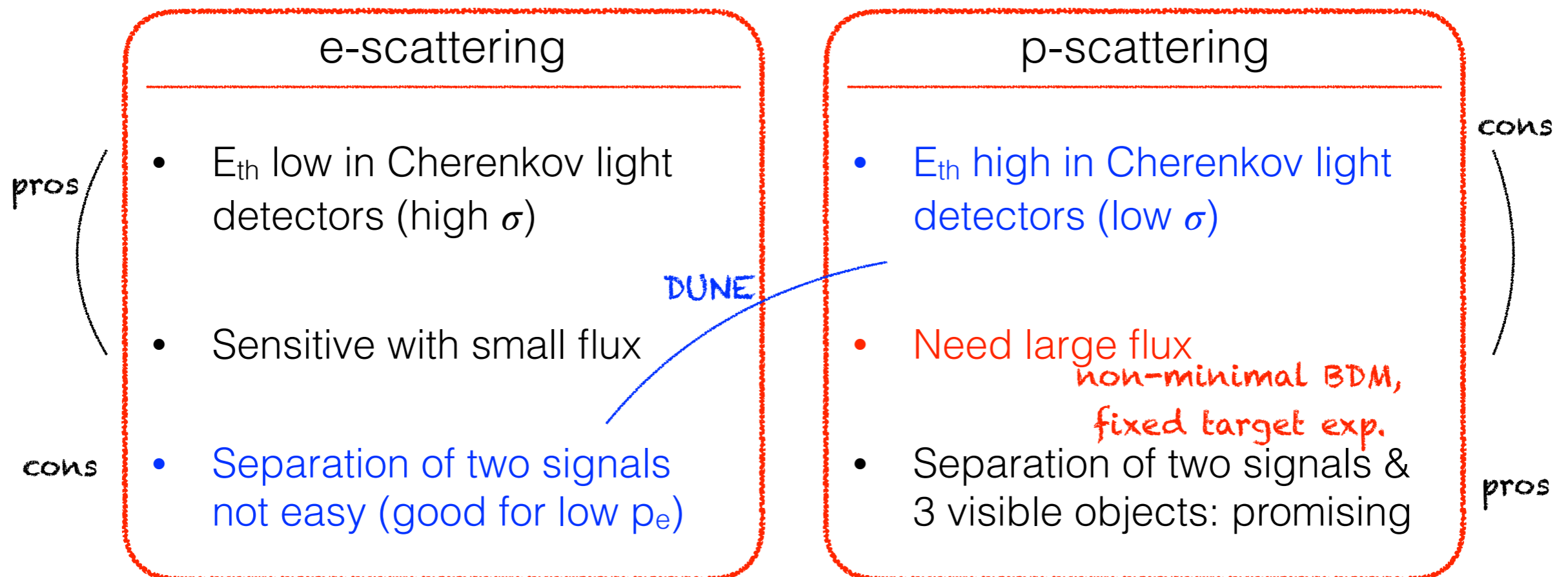
Detection prospects: DM collider

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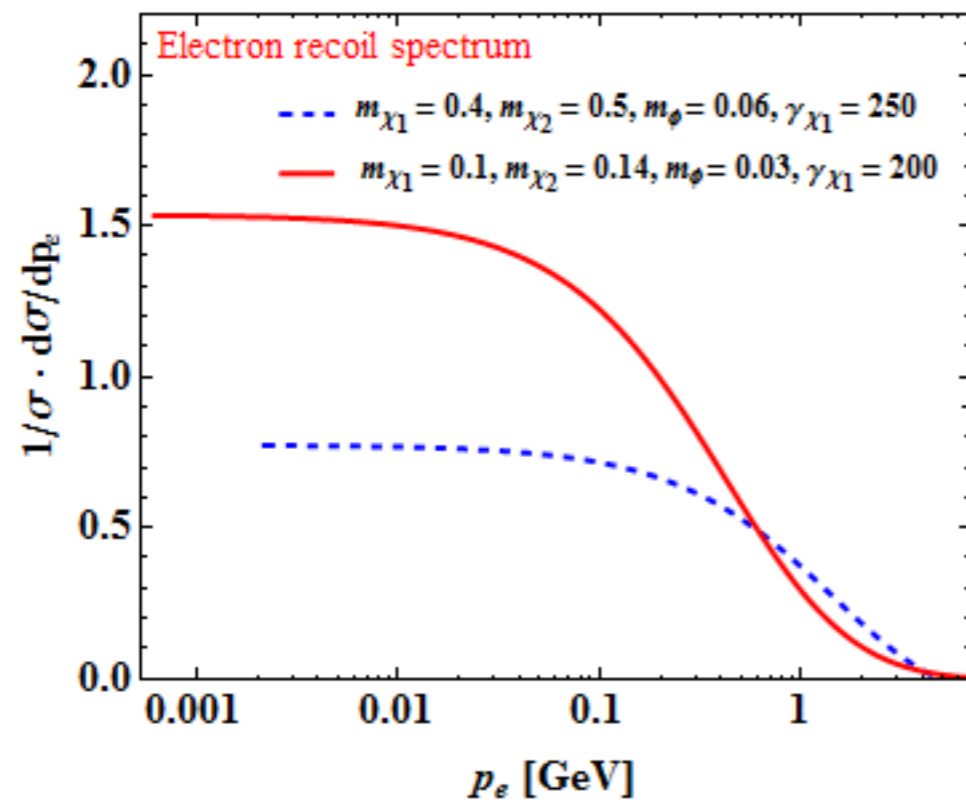- Analyzed in current & future huge ν detectors:
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pros

cons

e-scattering

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DUNE

p-scattering

- E_{th} high in Cherenkov light detectors (low σ)

- Need large flux

  non-minimal BDM, fixed target exp.

- Separation of two signals & 3 visible objects: promising

cons

pros

Back up

Electron recoil spectrum

$m_{\chi_1} = 0.4,\ m_{\chi_2} = 0.5,\ m_\phi = 0.06,\ \gamma_{\chi_1} = 250$

$m_{\chi_1} = 0.1,\ m_{\chi_2} = 0.14,\ m_\phi = 0.03,\ \gamma_{\chi_1} = 200$

Back up

BDM from the Sun: roughly O(1000) enhancement
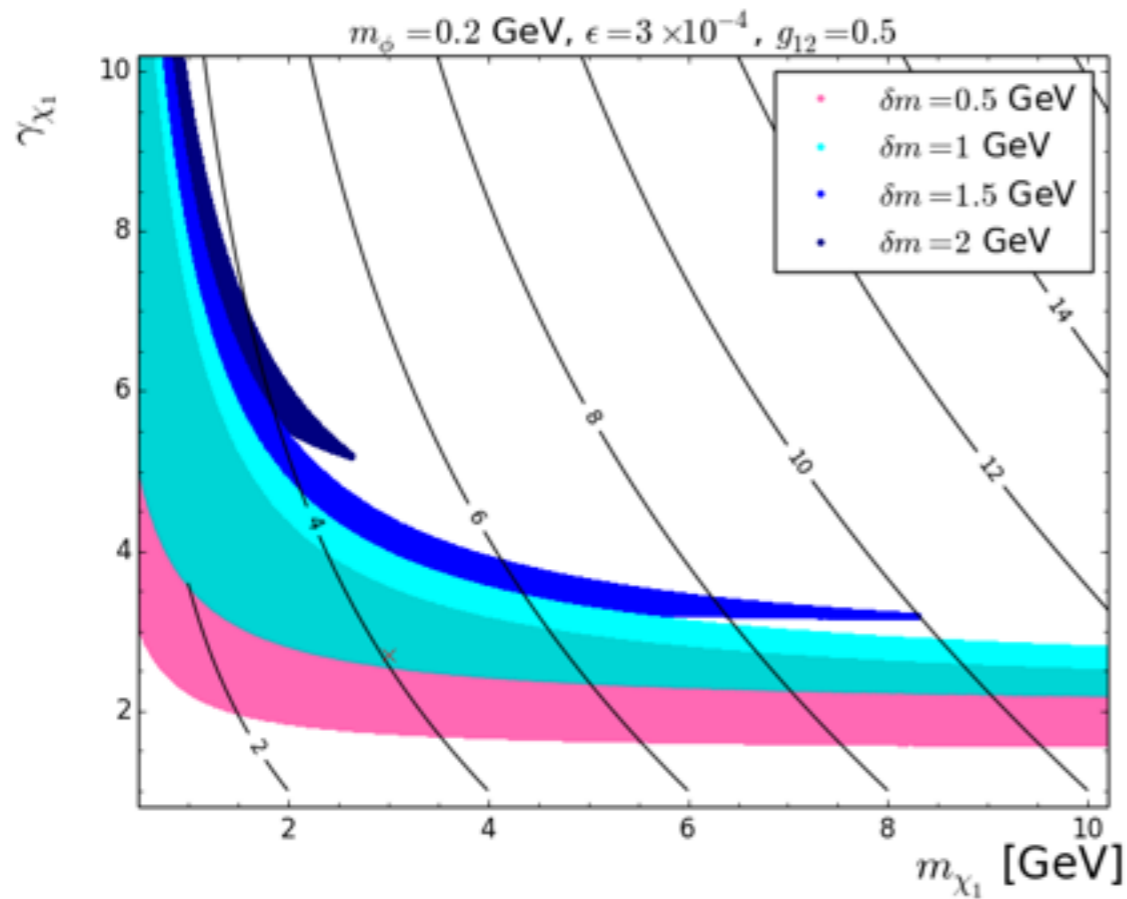for $m_{\chi h} \sim 10$ GeV

following eq. (3.1) of 1410.2246

Capture rate proportional to $m_{\chi h}^{-2}$

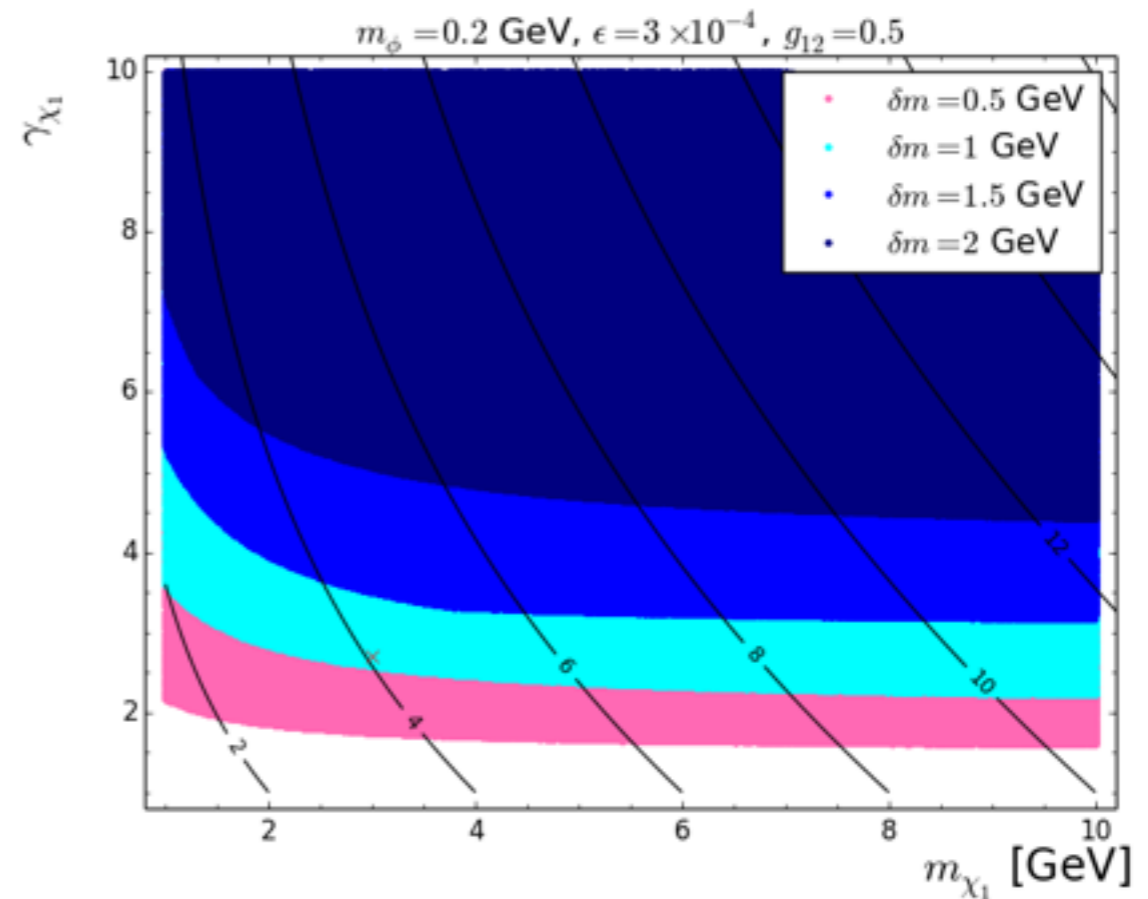Flux $= 10^{-6} \times \sigma_{DD} \times m_{\chi h}^{-2}$

$$\Phi \sim 10^{-6} \times \left(\frac{\sigma_{DD}}{10^{-42}\,\mathrm{cm}^2} \right) \times \left(\frac{100\,\mathrm{GeV}}{m_{\chi h}} \right)^2$$

p-scattering: possible search area
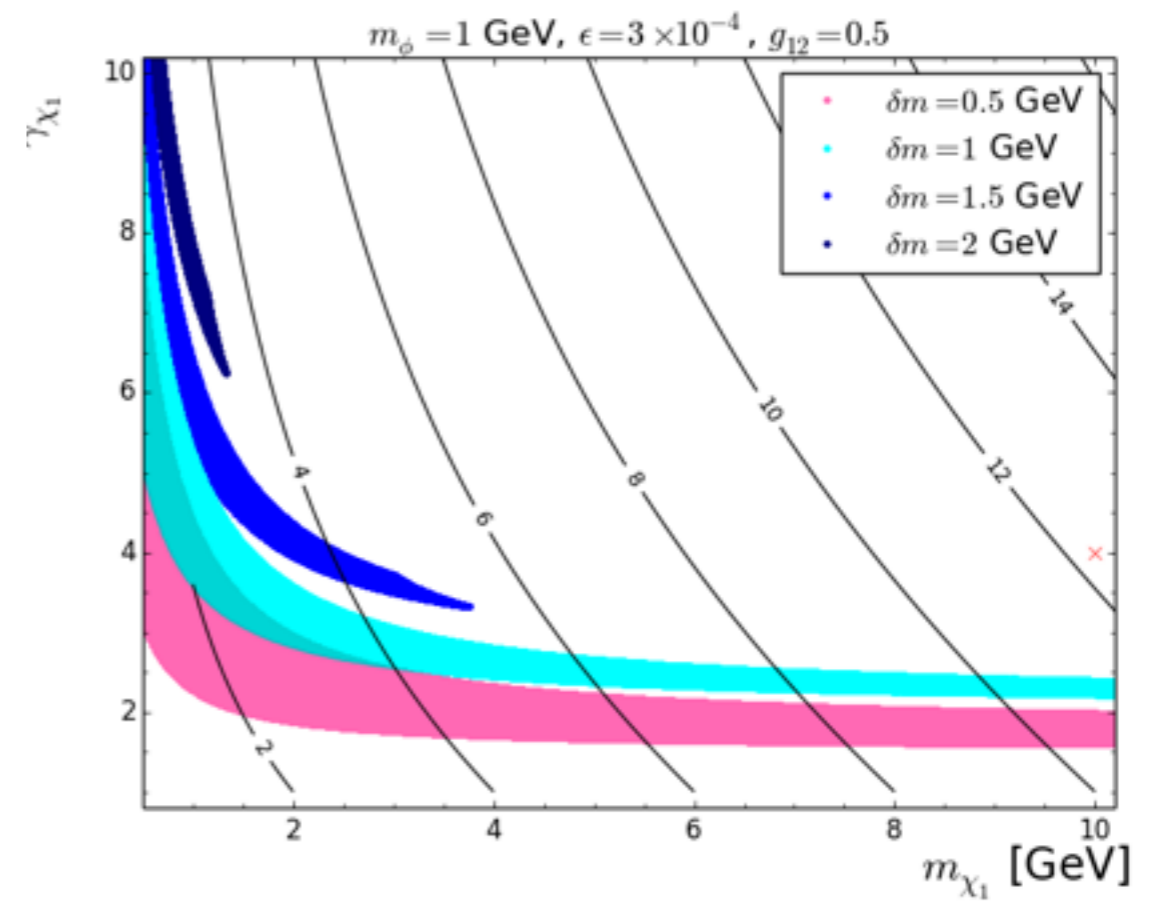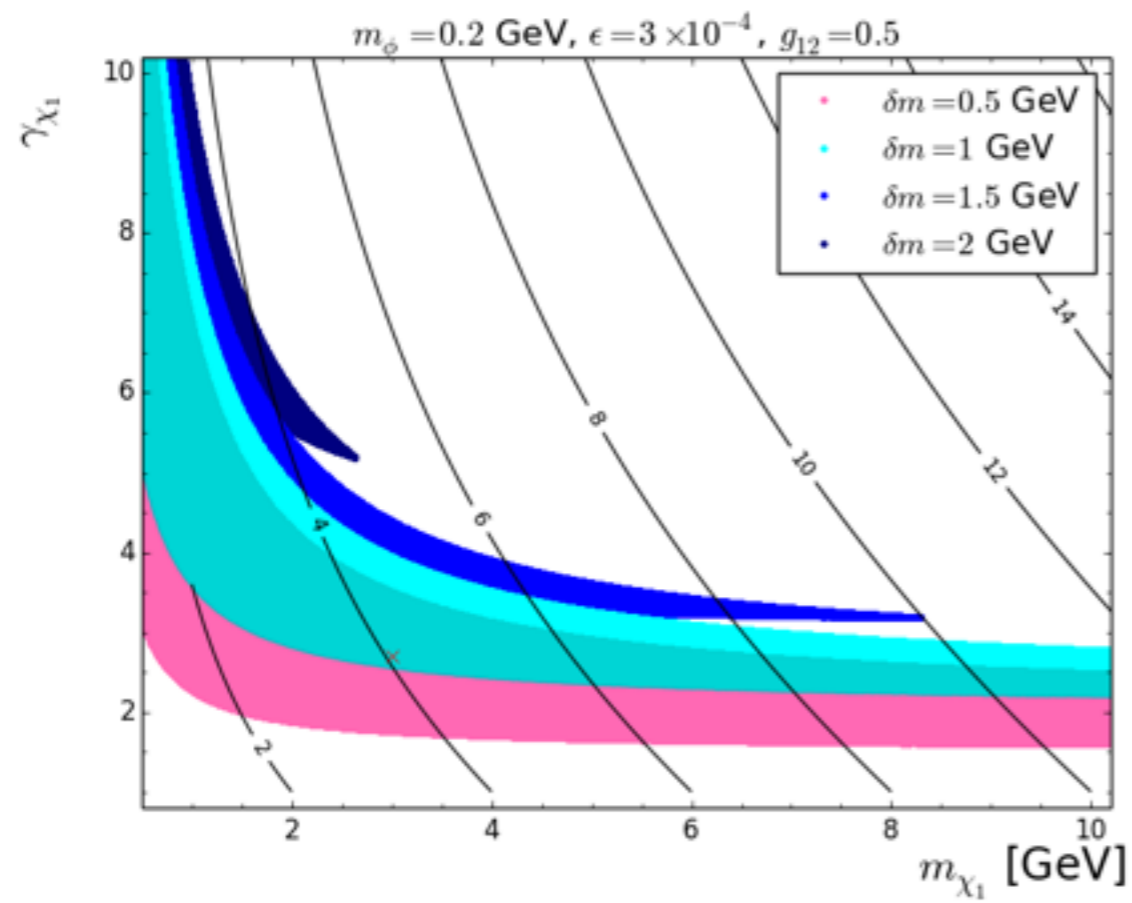
Region of elastic scattering p_p: [E_{th}, 1.8 GeV]

Kamiokande

DUNE

Back up

Singlet Fermionic Dark Matter

DM: singlet Dirac fermion

$$\psi$$

SM particles

$$f, W, Z, \cdots$$

singlet scalar   Higgs

$$S \longleftrightarrow H$$

mixing

$$h_2 \qquad\qquad h_1$$
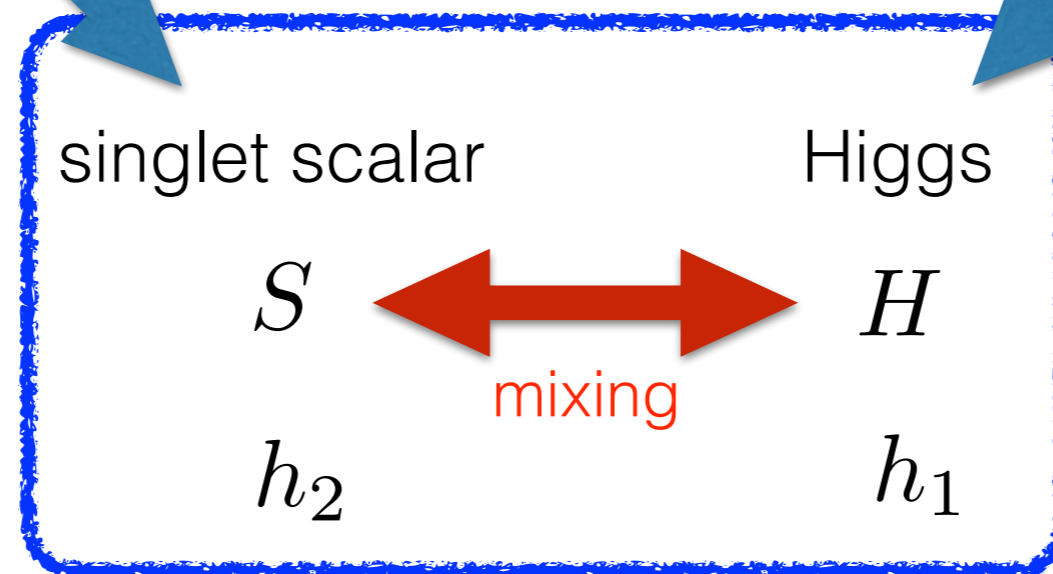
Y.G. Kim, K.Y. Lee, **SS**, JHEP 0805, 100 [arXiv:0803.2932]

A renormalizable Higgs portal WIMP model

(induce bunch of phenomenological studies: exotic decay, …)

Secluded SFDM

Secluded set-up by Kim, Lee, Park, **SS**, 1601.05089

- Small mixing angle: Higgs measurements at the LHC
  & null results in direct detection

- Pseudoscalar int. in the dark sector: p-wave in t-channel WIMP-SM recoil
  s-wave in s-channel

Lopez-Honorez, Schwetz, Zupan, 1203.2064

Fedderke, Chen, Kolb, Wang, 1404.2283

$$-\mathcal{L}_{\text{int}}^{\text{dark}} = g_S \cos\xi \, s\bar{\psi}\psi + g_S \sin\xi \, s\bar{\psi}i\gamma^5\psi,$$

Secluded SFDM for the γ-ray excess

Our starting point

- DM annihilation (not denying other possibilities)

- Apply the result by Calore et al., 1409.0042, 1411.4647: syst. & stat. error

- Assume a generalized NFW profile allowing the uncertainties in the astrophysical factor $\bar{J}$ with scaling [0.17, 5.3] and $\gamma = 1.2$

  Calore, Cholis, McCabe, Weniger, 1411.4647

$$\rho(r) = \rho_s \frac{(r/r_s)^{-\gamma}}{(1 + r/r_s)^{3-\gamma}}$$

$$\frac{dN}{dE} = \frac{\bar{J}}{16\pi m_\chi^2} \sum_f \langle \sigma v \rangle_f \frac{dN_\gamma^f}{dE}$$

$$\bar{J} = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} \int_{\text{l.o.s}} \rho^2(r(s, \psi))\, ds\, d\Omega.$$

Secluded SFDM for the γ-ray excess

Analysis process

- Unavoidable bounds: Higgs measurements, $\bar{p}$ ratios, γ-rays from dSphs.

- GeV level excess is best-fitted by changing $\bar{J}$ while fixing the relic density as observed (how we avoid the astrophysical bounds)

- Check the pure (dark sector) pseudoscalar case first (sinξ=1). If not good, allow the scalar interaction.

Best-fitted for $\psi\bar{\psi} \to b\bar{b}, \, h_i h_j$ as model independent

$$i,j = 1,2$$ searches expected

But some subtleties exist