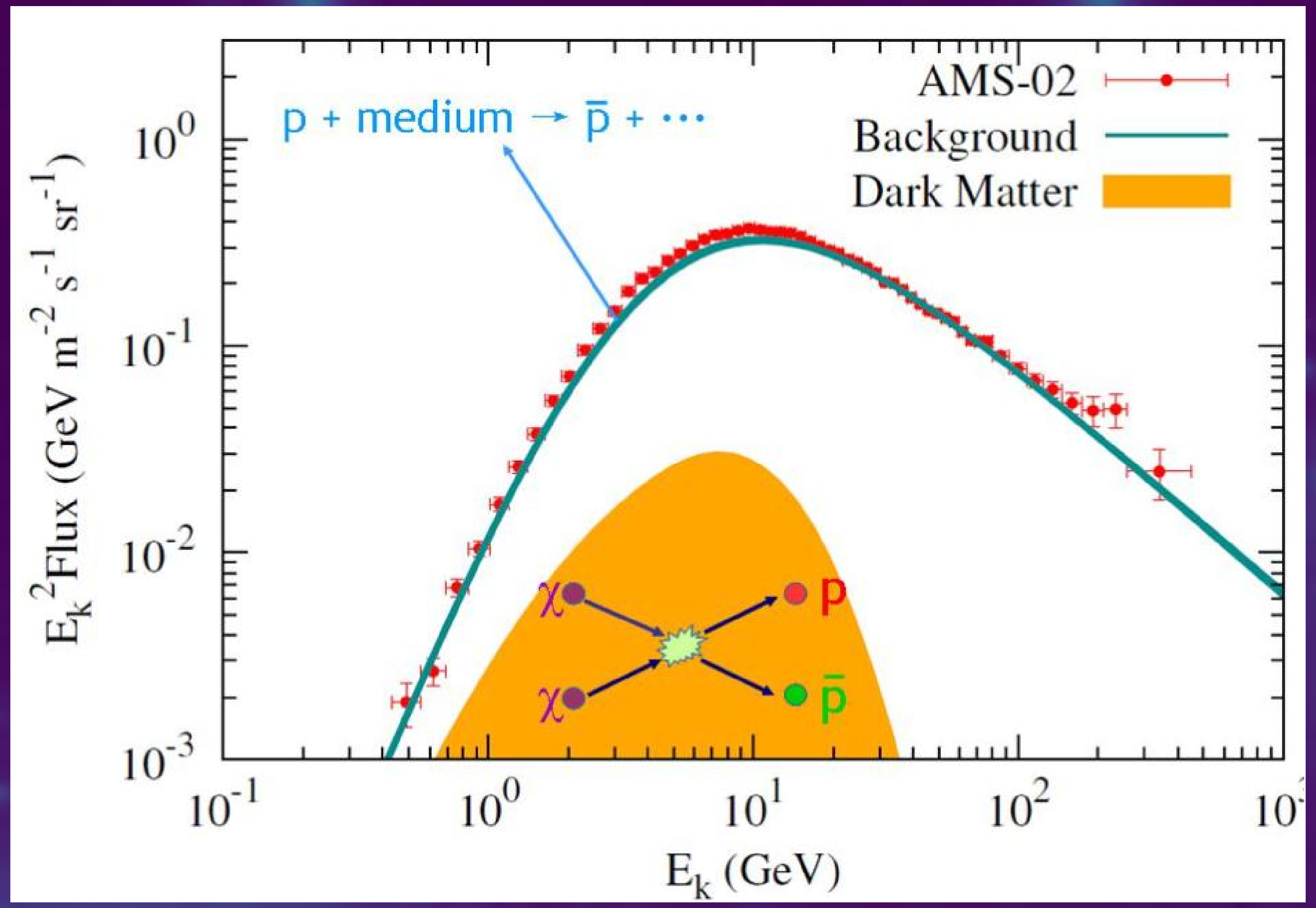
Dark Matter indirect detection (part II): sub-GeV Dark Matter

Yue-Lin Sming Tsai

(Purple Mountain Observatory)

2022 Summer School of Dark Matter and New Physics

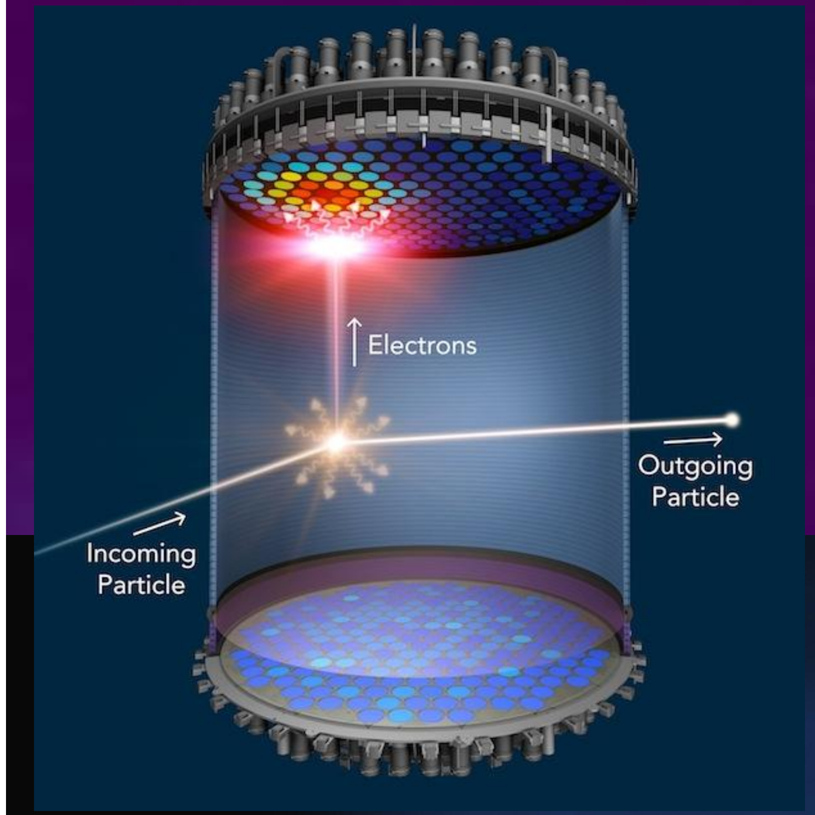
Dark Matter Simulation.

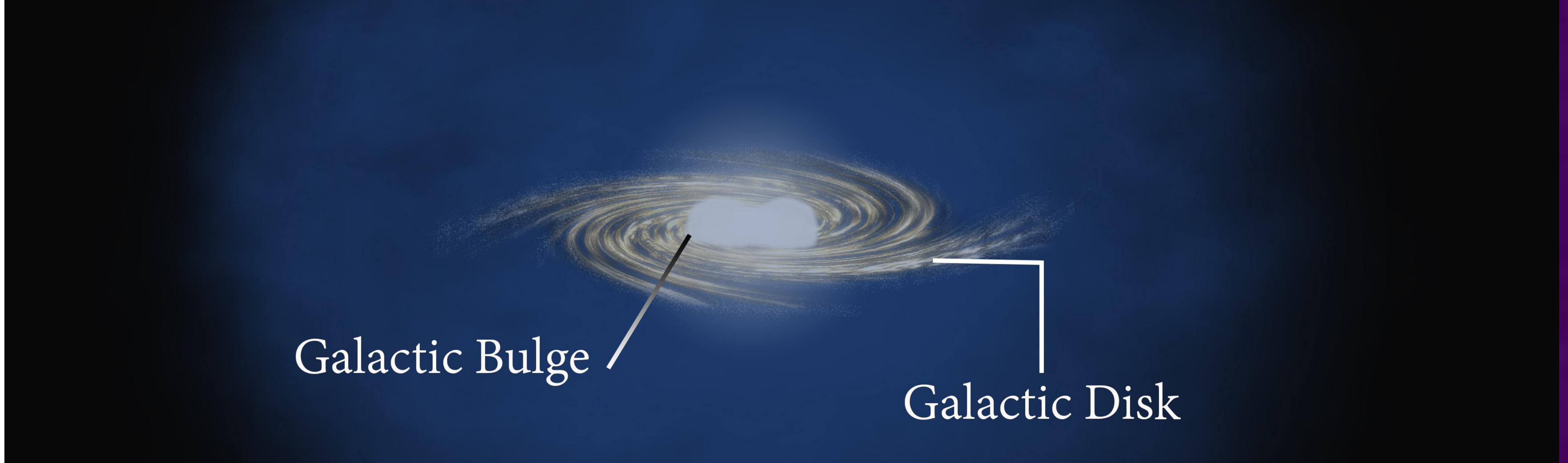


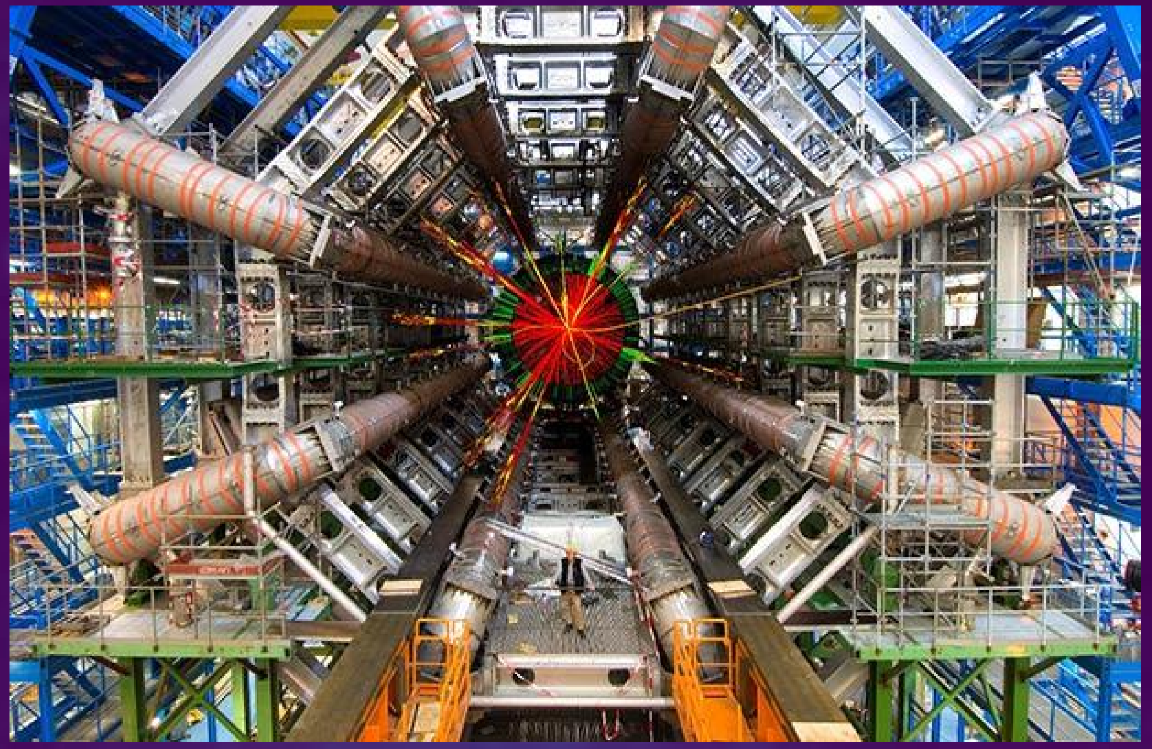
Dark Matter Cosmic Ray.

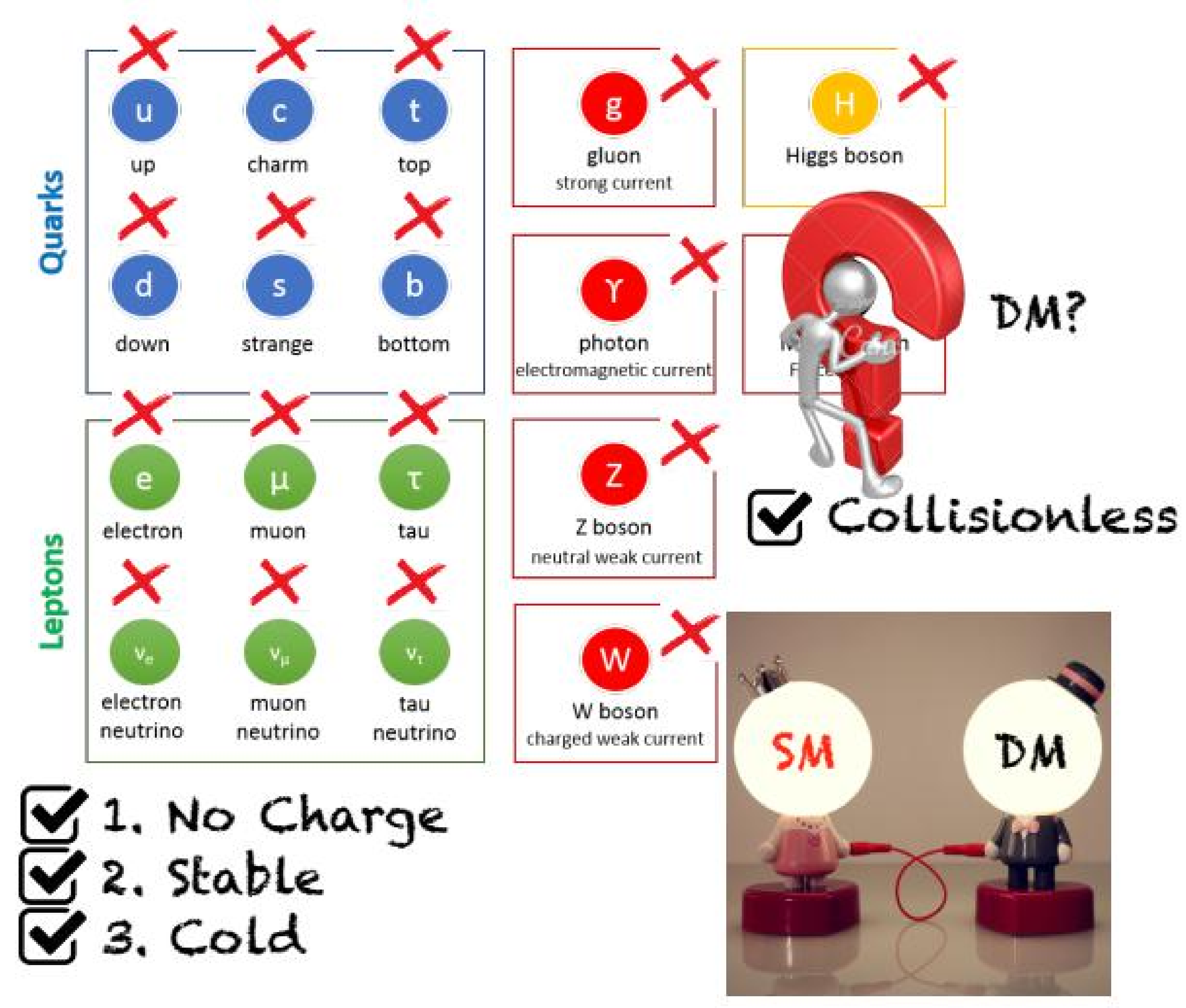
<u>Dark Matter search</u>:
underground detection,
Indirect detection,
Collider search,
Cosmology.

Dark Matter Model:
Minimal Dark Matter?
Supersymmetry?
Axion models?



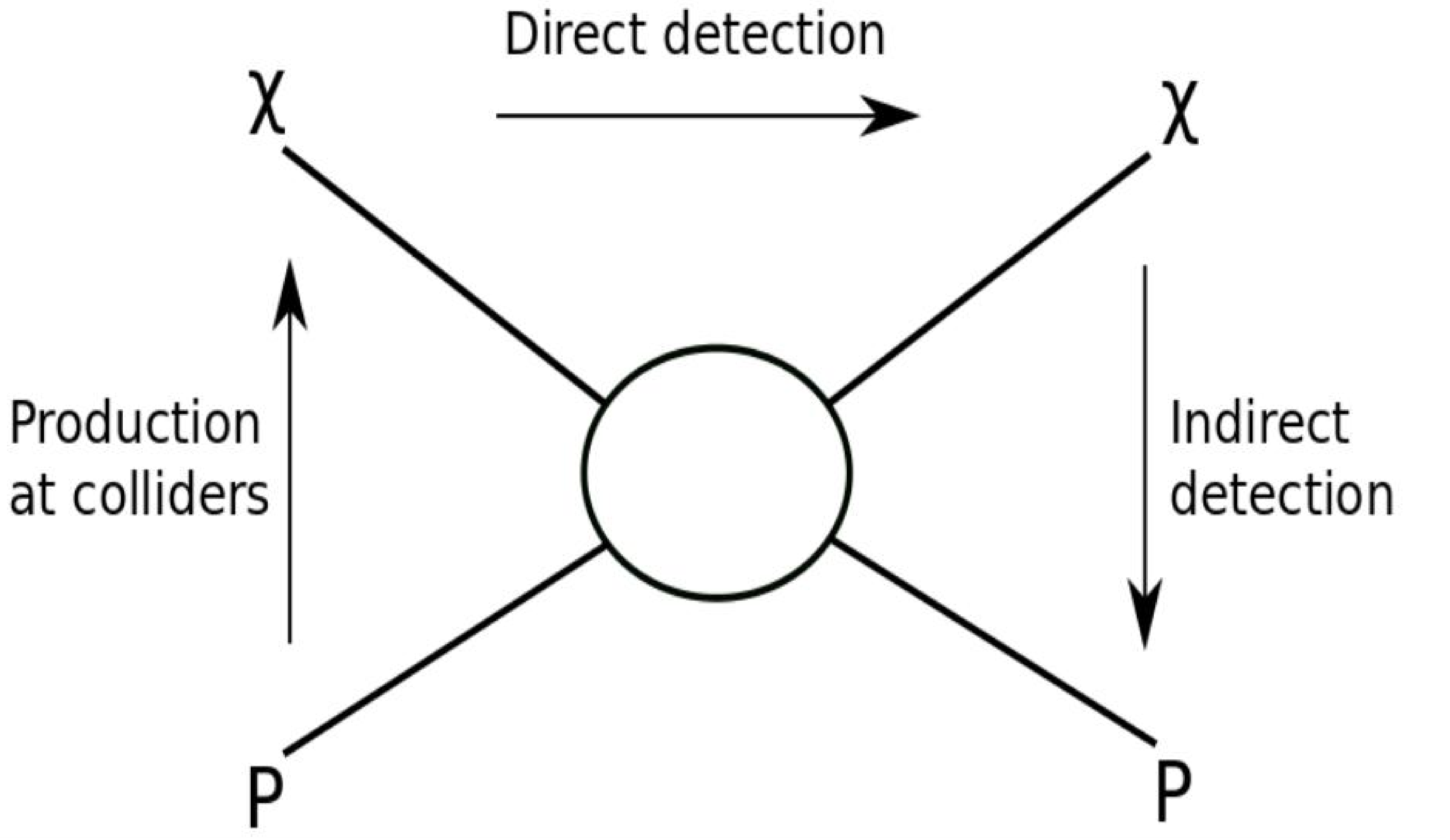


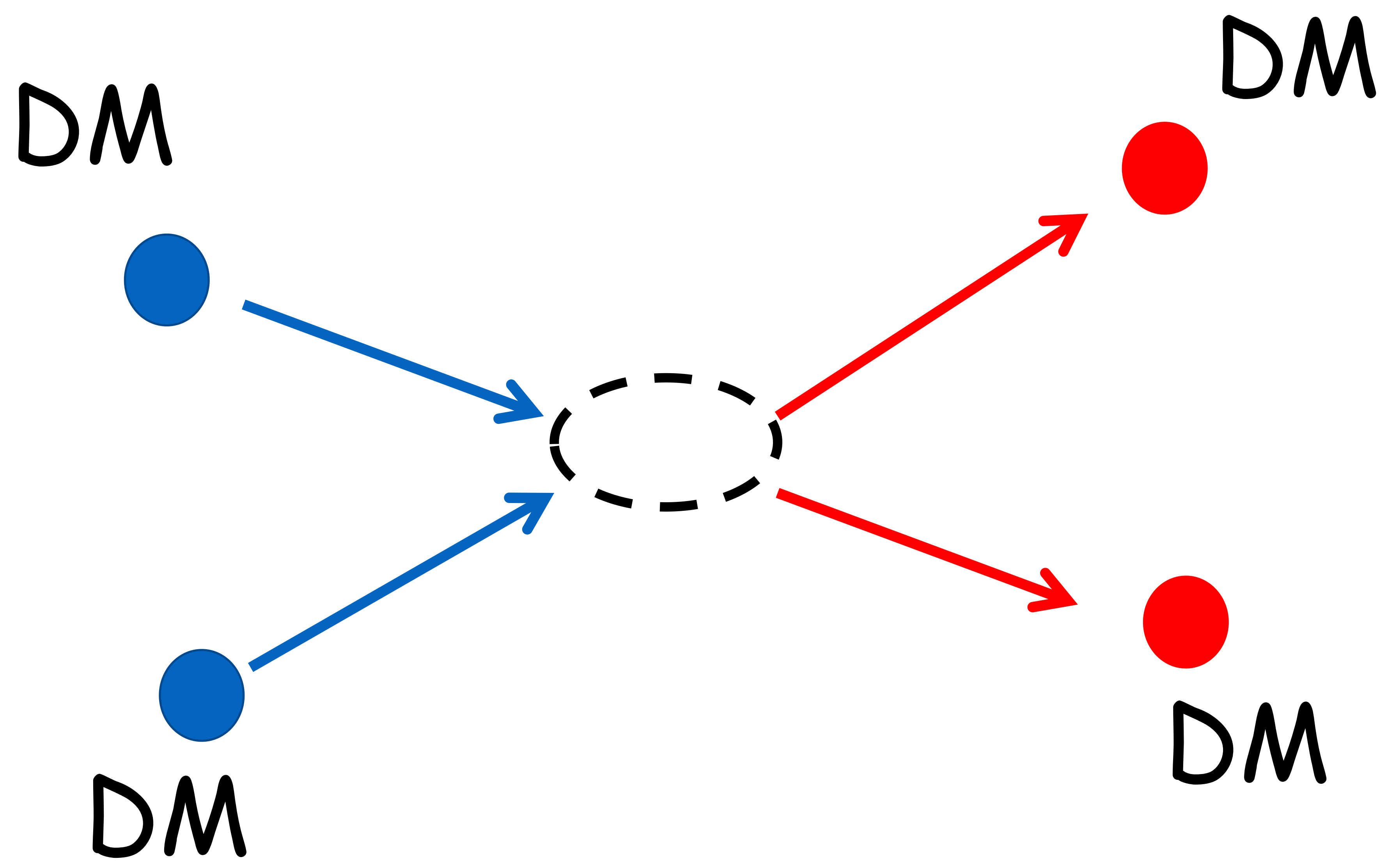




☑ Collisionless

☑ 1. No Charge
☑ 2. Stable
☑ 3. Cold





- We will focus on indirect detection for sub-GeV, especially for MeV-GeV DM.
- In the sub-GeV DM region, we define "DM ID" as detection of the indirect DM signals.

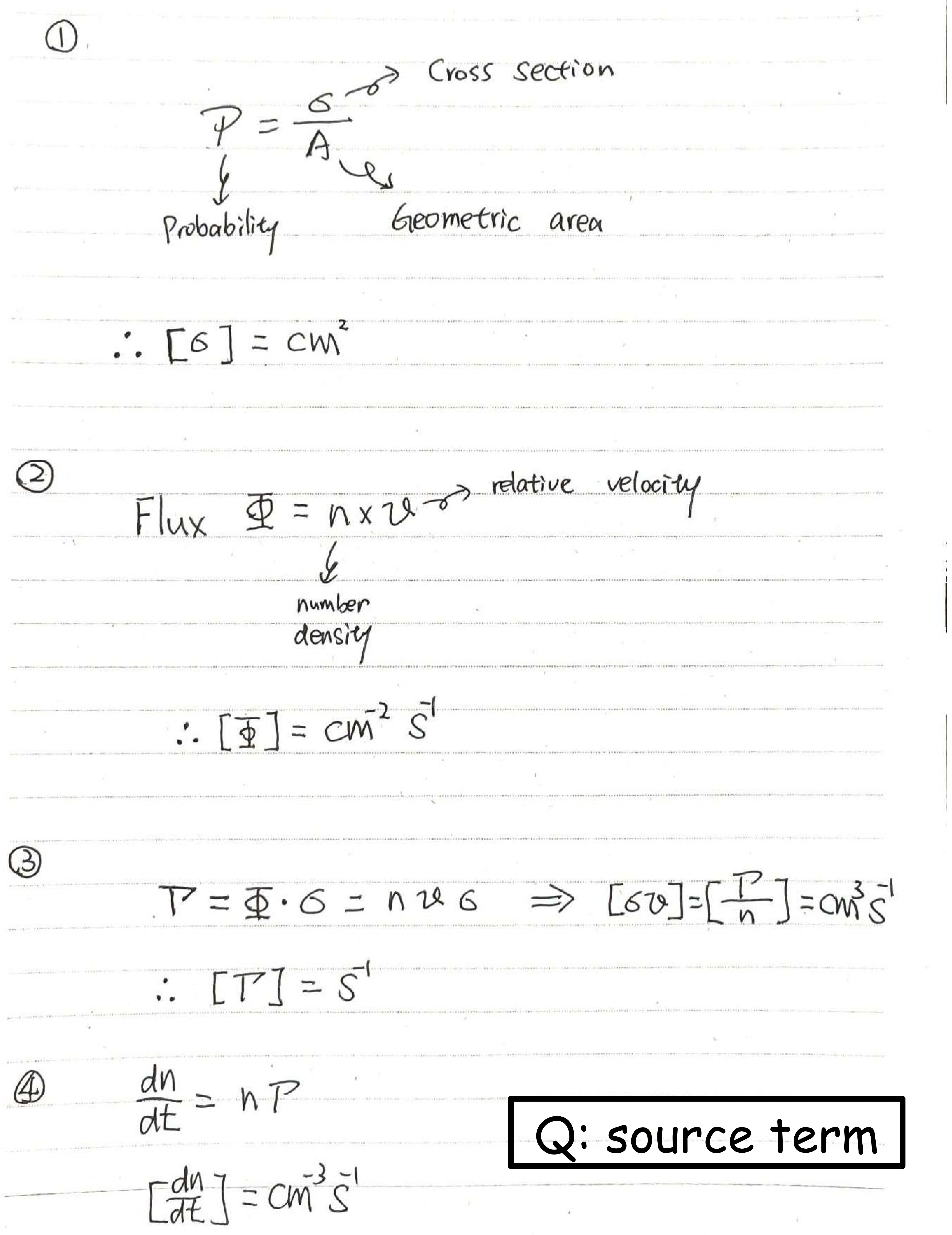
After freeze-out, why do we still believe that DM can annihilate to detectable signals?

Signal versus Background in spatial distribution and energy spectrum.

DM at	Role	Anomally	Exclusion
Colliders	missing energy, new BSM particles	LHC 750 GeV (gone)	new mass limit based on LHC, LEP, and so on.
Precision measurement	Propagator, new BSM particles	muon g-2 and W-boson (Fermilab)	new particles searches such as LHCb, Belle, Babar, etc.
Direct detection	Recoil energy, Annual modulation	DAMA, Cogent, XENON1T	XENON1T and PandaX
Cosmic Ray	Additional antimatter: positron, antiproton, neutrino	1. Positrons: PAMELA, Fermi, AMS02, DAMPE, and so on. 2. antiproton: AMS02. 3. neutrino: IceCube.	1. Positrons: AMS02+Voyage 2. antiproton: AMS02. 3. neutrino: IceCube.
Gamma ray (>400 MeV)	Energy spectrum spatial distribution	Fermi bubble and GCE	Fermi and HESS
X-ray (40 eV-0.4 MeV)	Energy spectrum spatial distribution	3.5 keV line: XMM-Newton, Chandra, Suzaku	Hitomi, Suzaku
Radio (< 4e-3 eV)	Energy spectrum spatial distribution	None	Green Bank
Cosmology	History of the Universe galaxy formation	Relic density, EDGES 21cm	PLANCK CMB, SARAS 21cm distortion

Summary of astroparticle observables?

- ❑ QM tells us that particle is point like.
- ❑ Flux is similar to the current in EM.
- ❑ For decaying DM, Gamma is 1/tau.
- ❑ mean free path lambda is 1/(n*sigma). [lambda]=cm
- ❑ lambda means how far does particle hit once with target.



①

Cross section

$$\underset{\text{Probability}}{\mathcal{P}} = \frac{\sigma}{A}$$

Geometric area

$$\therefore [\sigma] = cm^2$$

②

relative velocity

$$\text{Flux } \Phi = \underset{\text{number density}}{n} \times v$$

$$\therefore [\Phi] = cm^{-2}\, s^{-1}$$

③

$$\Gamma = \Phi \cdot \sigma = n v \sigma \Rightarrow [\sigma v] = \left[\frac{\Gamma}{n}\right] = cm^3 s^{-1}$$

$$\therefore [\Gamma] = s^{-1}$$

④

$$\frac{dn}{dt} = n\Gamma$$

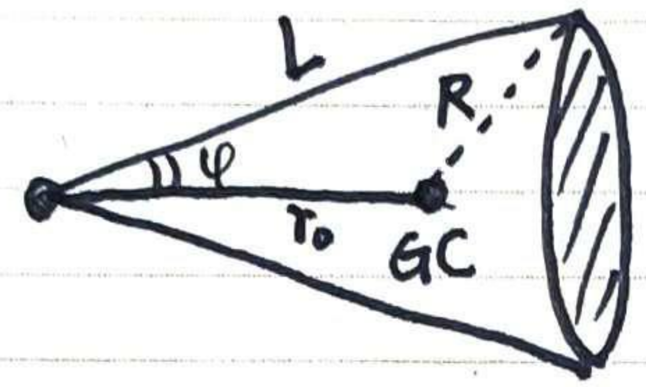
$$\left[\frac{dn}{dt}\right] = cm^{-3} s^{-1}$$

Q: source term

What is l.o.s.?

No.
Date.

l.o.s. = line of sight



$$\int_{l.o.s.} dL = \int \frac{dV}{r^2 d\Omega}$$

dV → Cone volume

$r^2 d\Omega$ → per solid angle

↙ flux decreasing with respect to r.

annihilation

$$J = \int_{l.o.s.} \rho^2 \, dL$$

Decay

$$D = \int_{l.o.s.} \rho \, dL$$

Date. / /

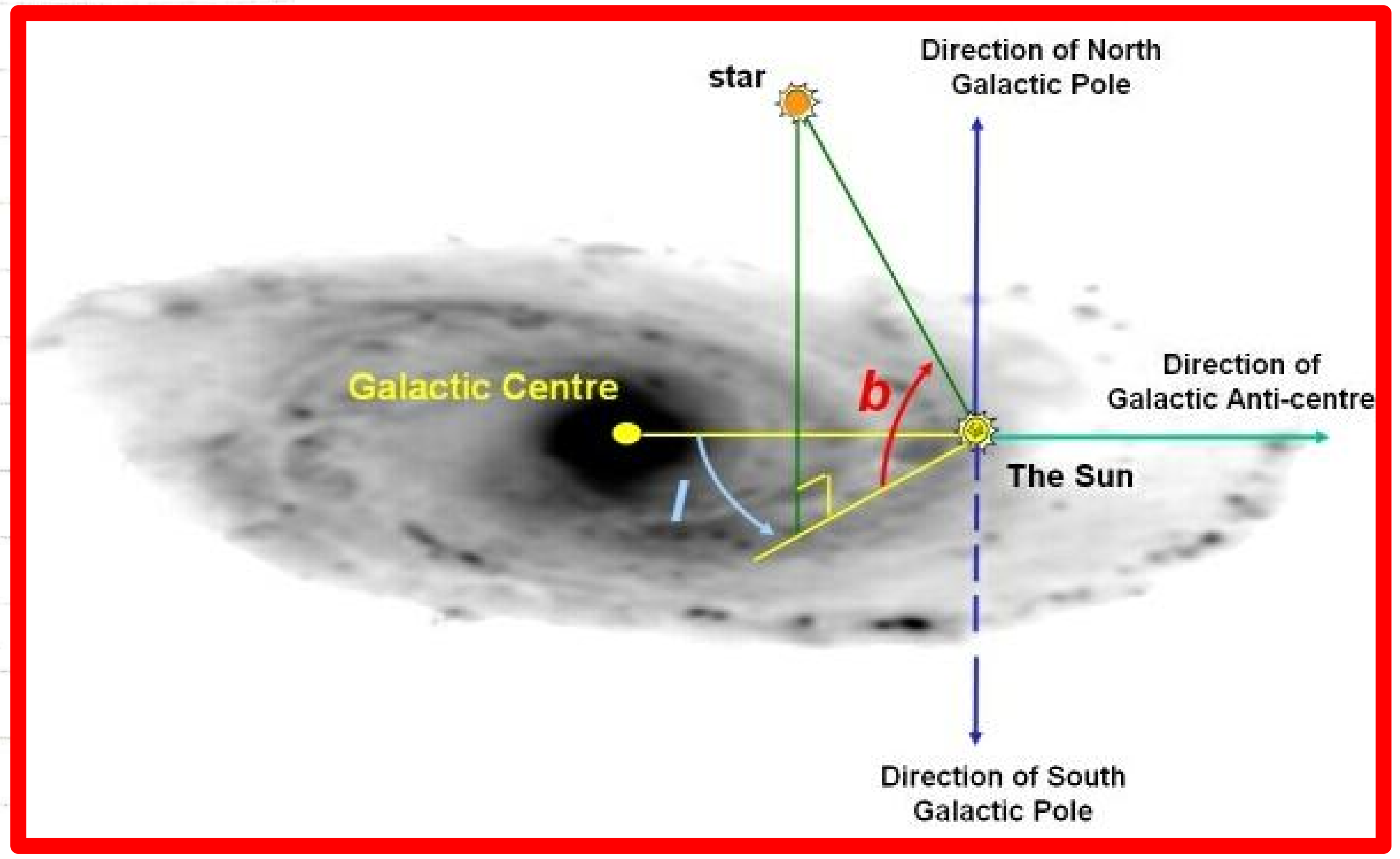
Coordinate transformation.

① Cone → GC coordinate

$$C_\varphi = \cos l \cos b$$

② $\vec{R} = \vec{L} - \vec{r_0}$

$$\Rightarrow R^2 = L^2 + r_0^2 - 2 L r_0 C_\varphi$$



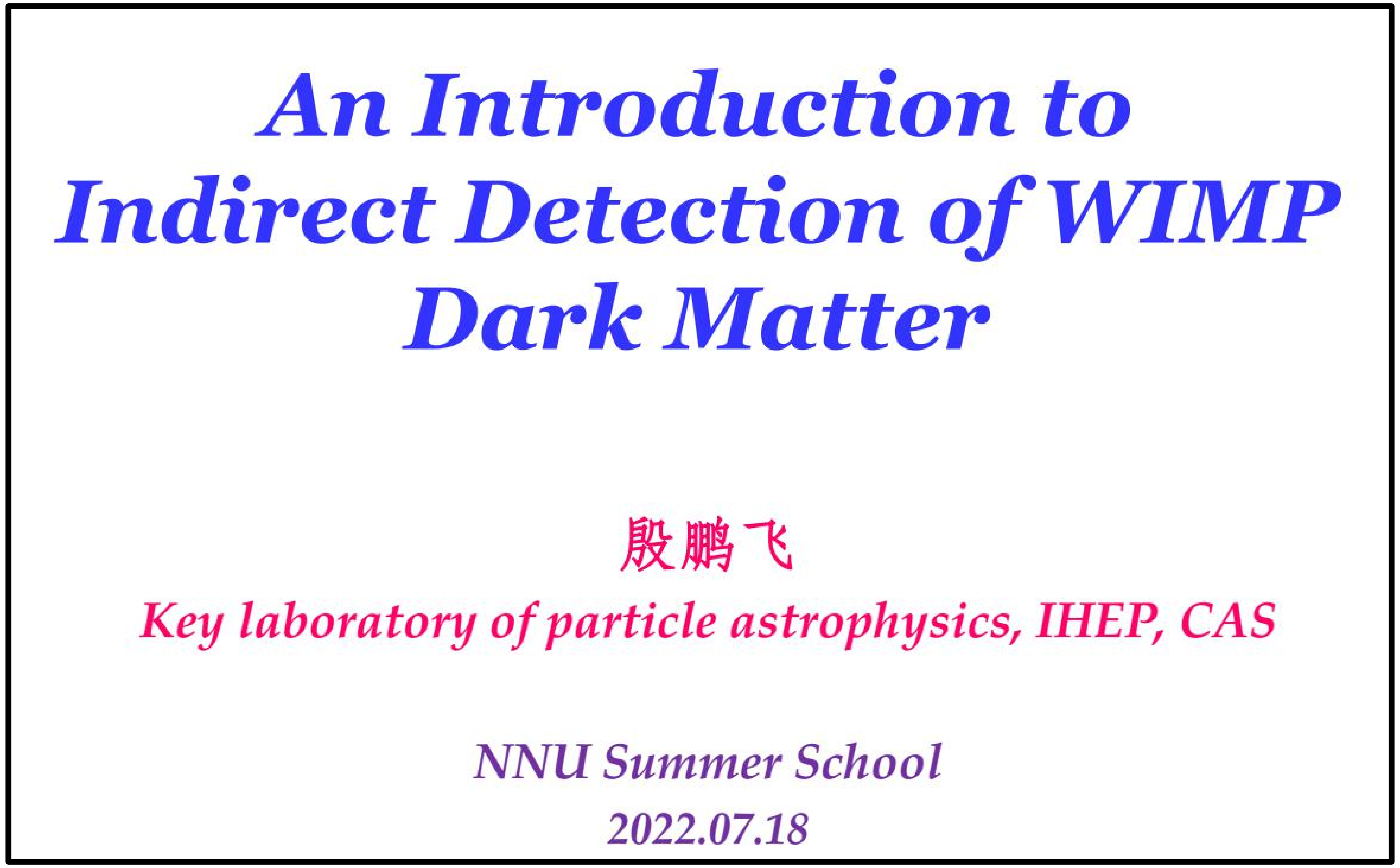
③ $\int_{C_\varphi}^{1} \int_{0}^{l_{max}} f(L) \times dL \times 2\pi \times dC_\varphi'$

- l_{max} is obtained from R_{MW}

$$R_{MW}^2 = l_{max}^2 + r_0^2 - 2 l_{max} r_0 C_\varphi$$

$$\Rightarrow l_{max} = r_0 C_\varphi + \sqrt{R_{MW}^2 - r_0^2 S_\varphi^2}$$

For WIMP DM indirect detection, we will not repeat it but refer it to the lecture given by Prof. Yin.



An Introduction to Indirect Detection of WIMP Dark Matter

殷鹏飞

Key laboratory of particle astrophysics, IHEP, CAS

NNU Summer School

2022.07.18

Outline

① History: from GeV to sub-GeV. (20 mins)

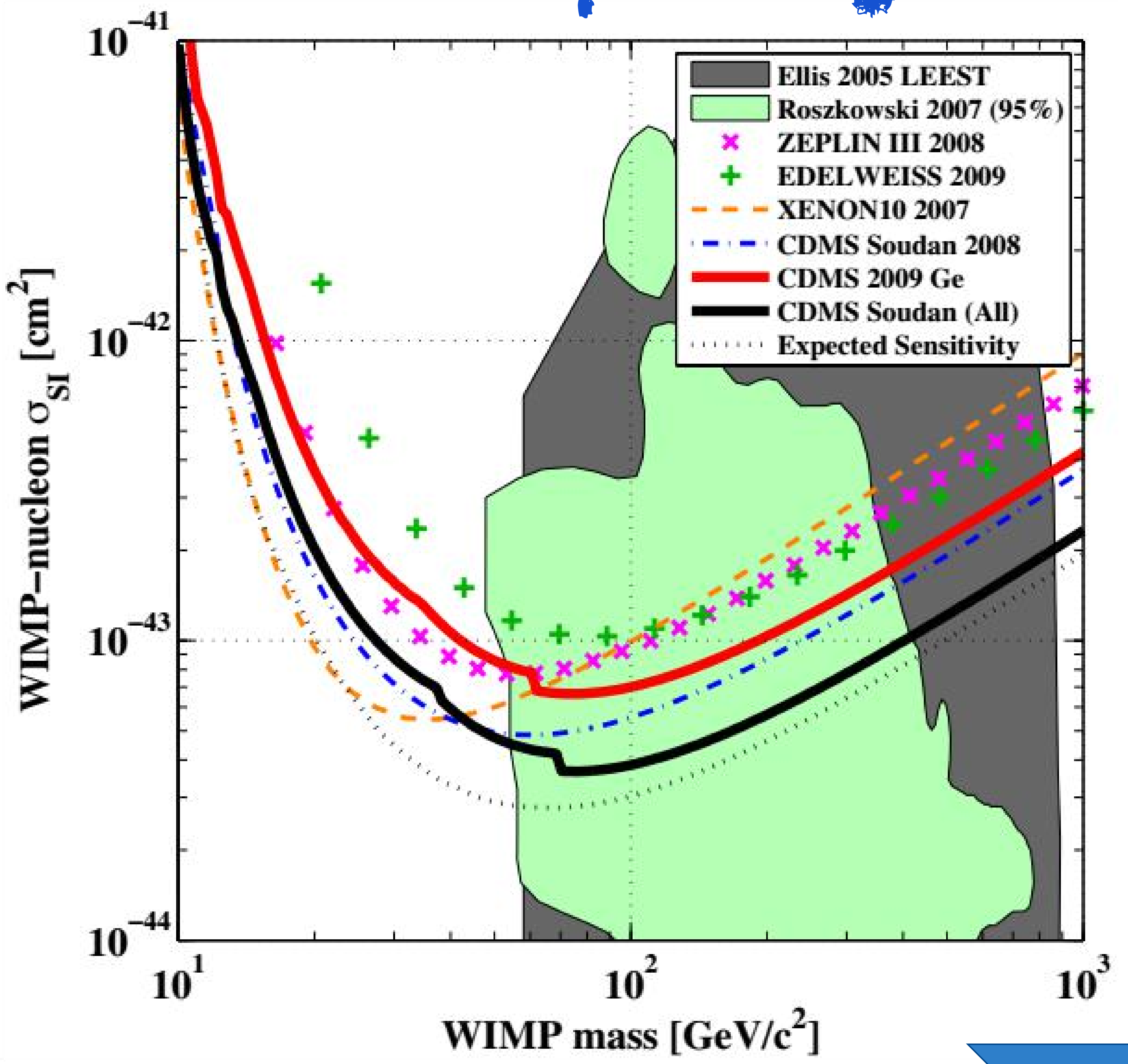
② Minimun Dark particle content. (25 mins)

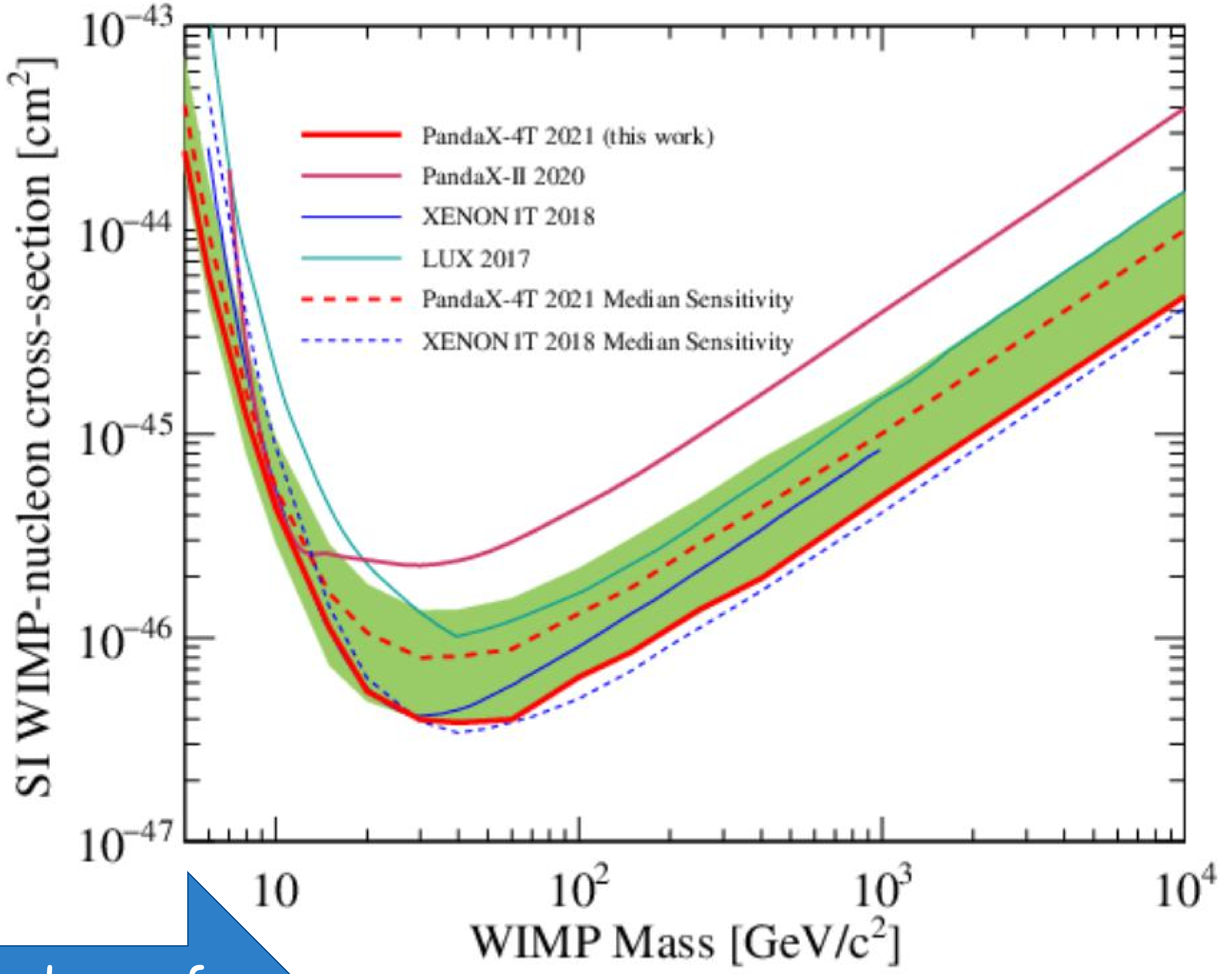
③ Possible indirect detections. (40 mins)

④ Indirect detection beyond MeV. (5 mins)

History: from GeV to sub-GeV.

The rapidly improved DD limits





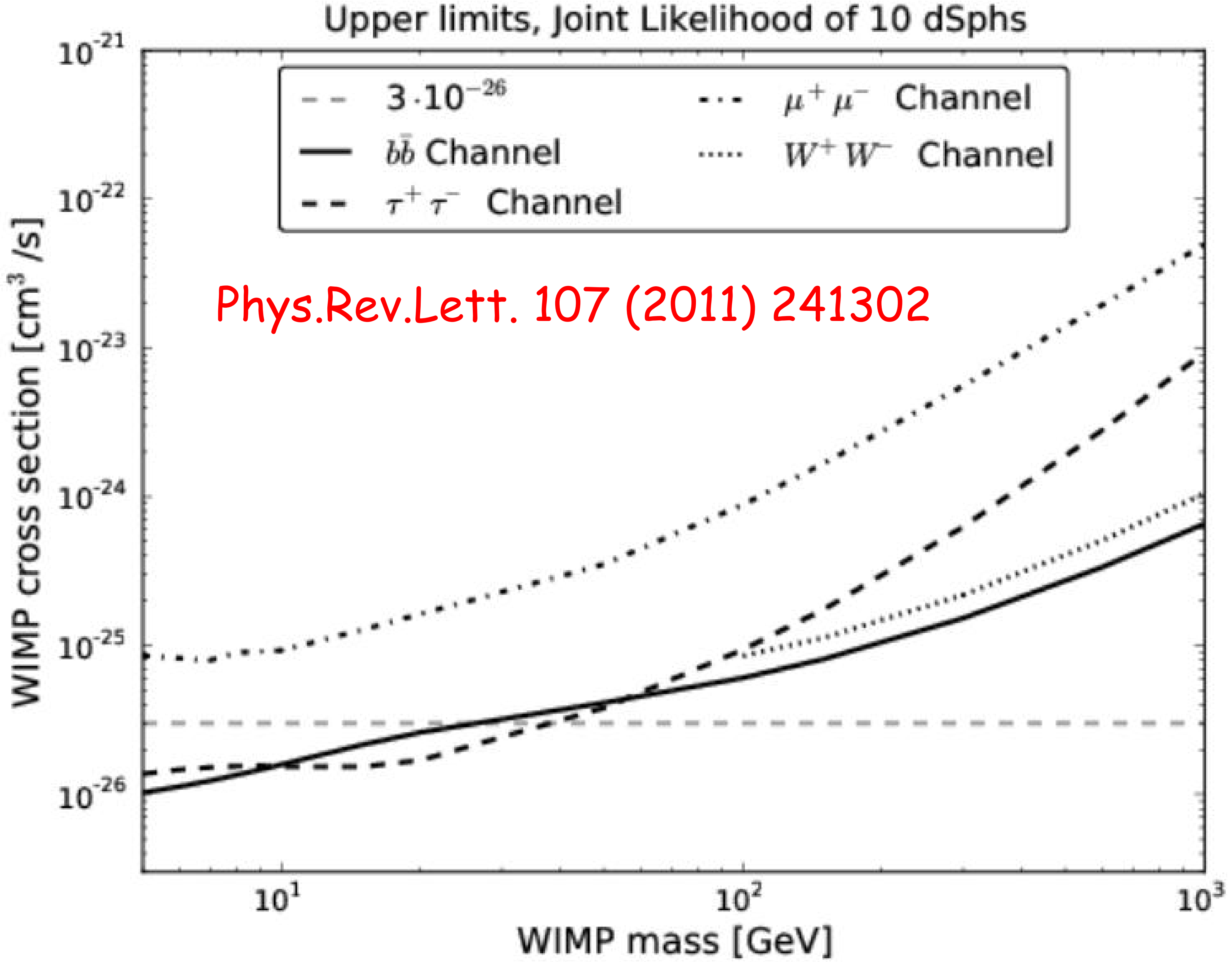
Before using XENON two phase technology...

3 orders of magnitude

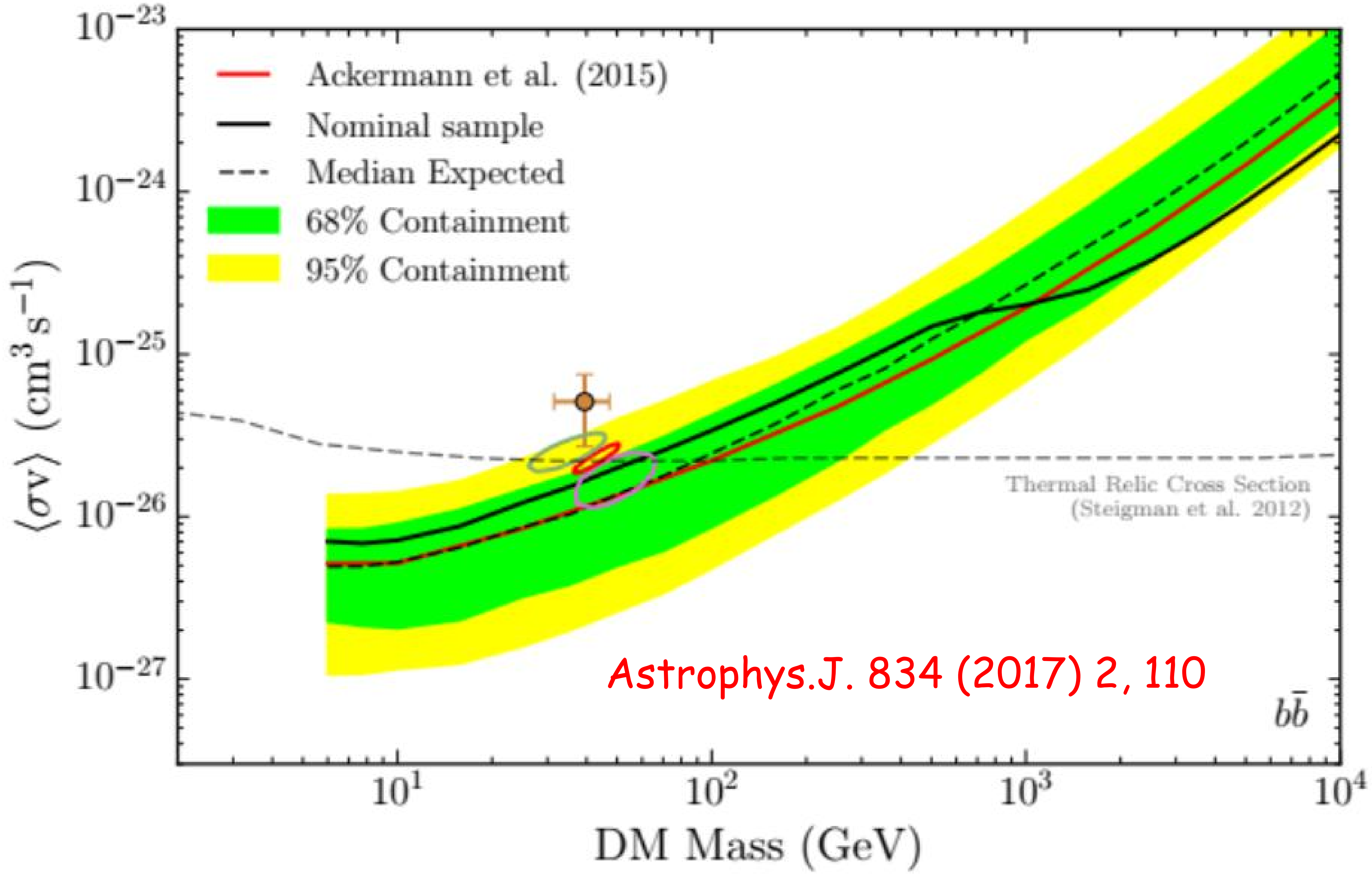
PandaX (2021), 12 years later.

ID: The Fermi gamma-ray limits

$$\boxed{\sigma v \approx \enclose{circle}{s} + p\,v^2 + \mathcal{O}(v^n)}$$


Upper limits, Joint Likelihood of 10 dSphs

Phys.Rev.Lett. 107 (2011) 241302


Astrophys.J. 834 (2017) 2, 110

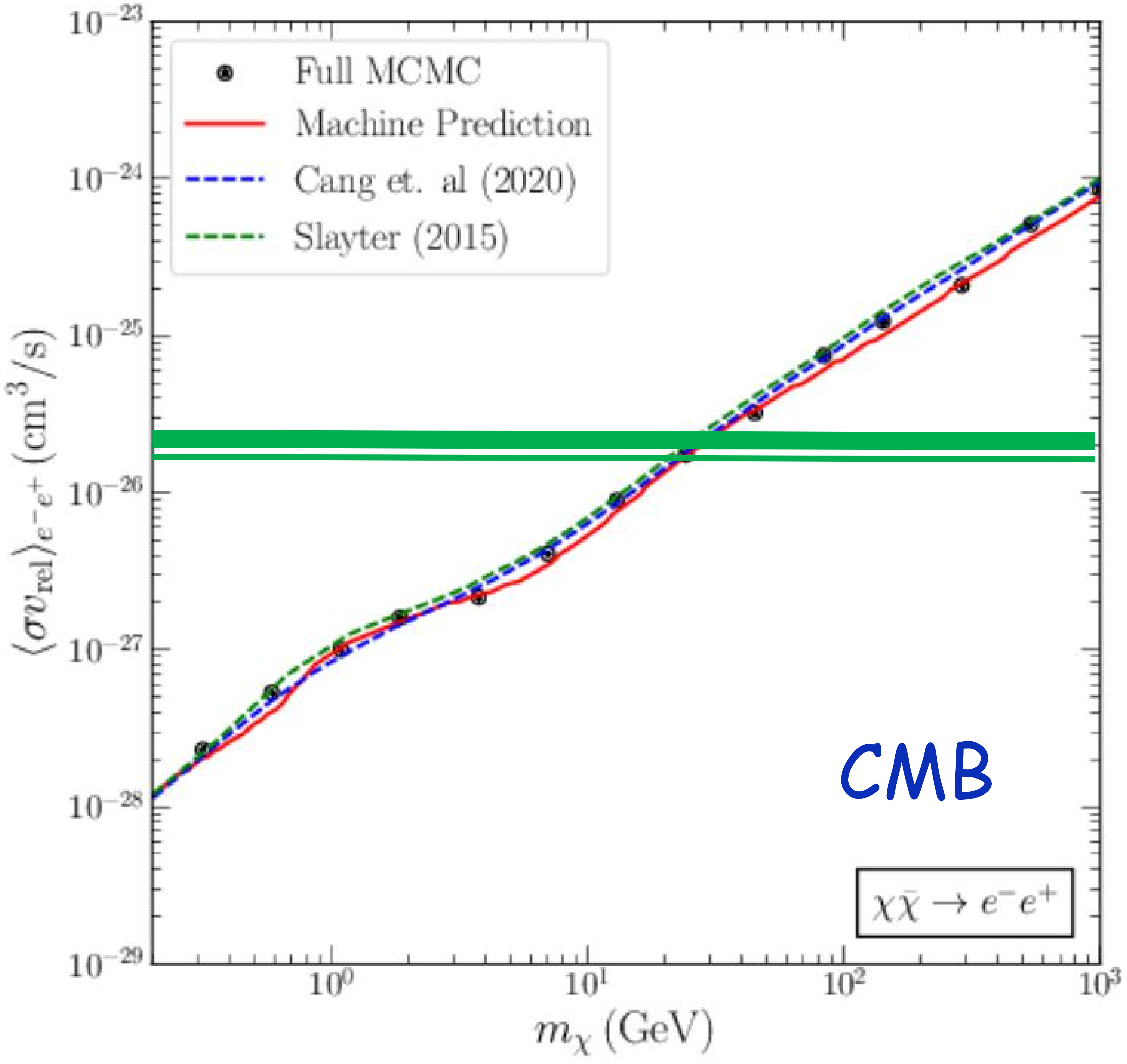
The first Fermi 10 dSphs result...

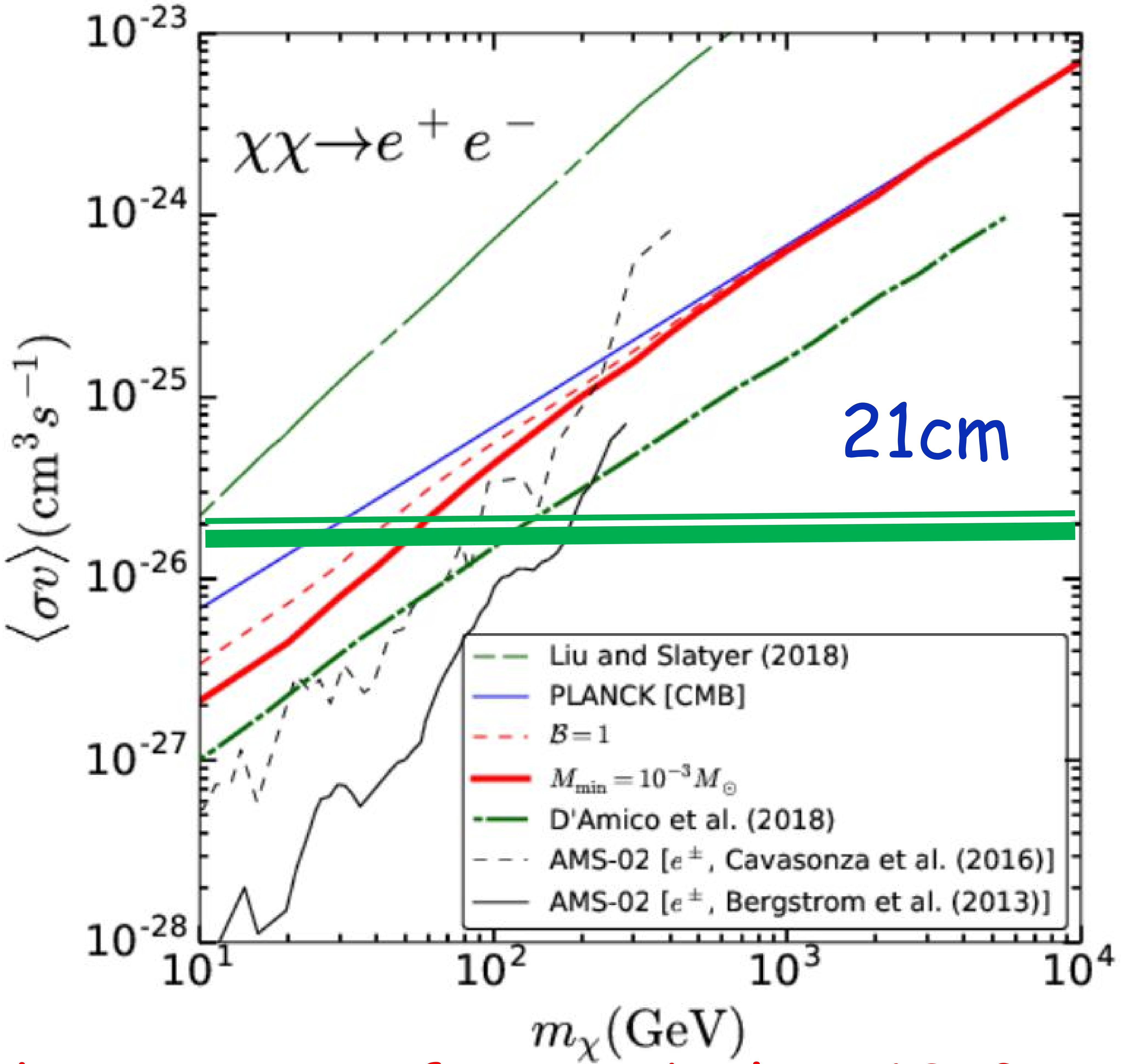
Only improved a few...

Fermi+DES, 45 dSphs.

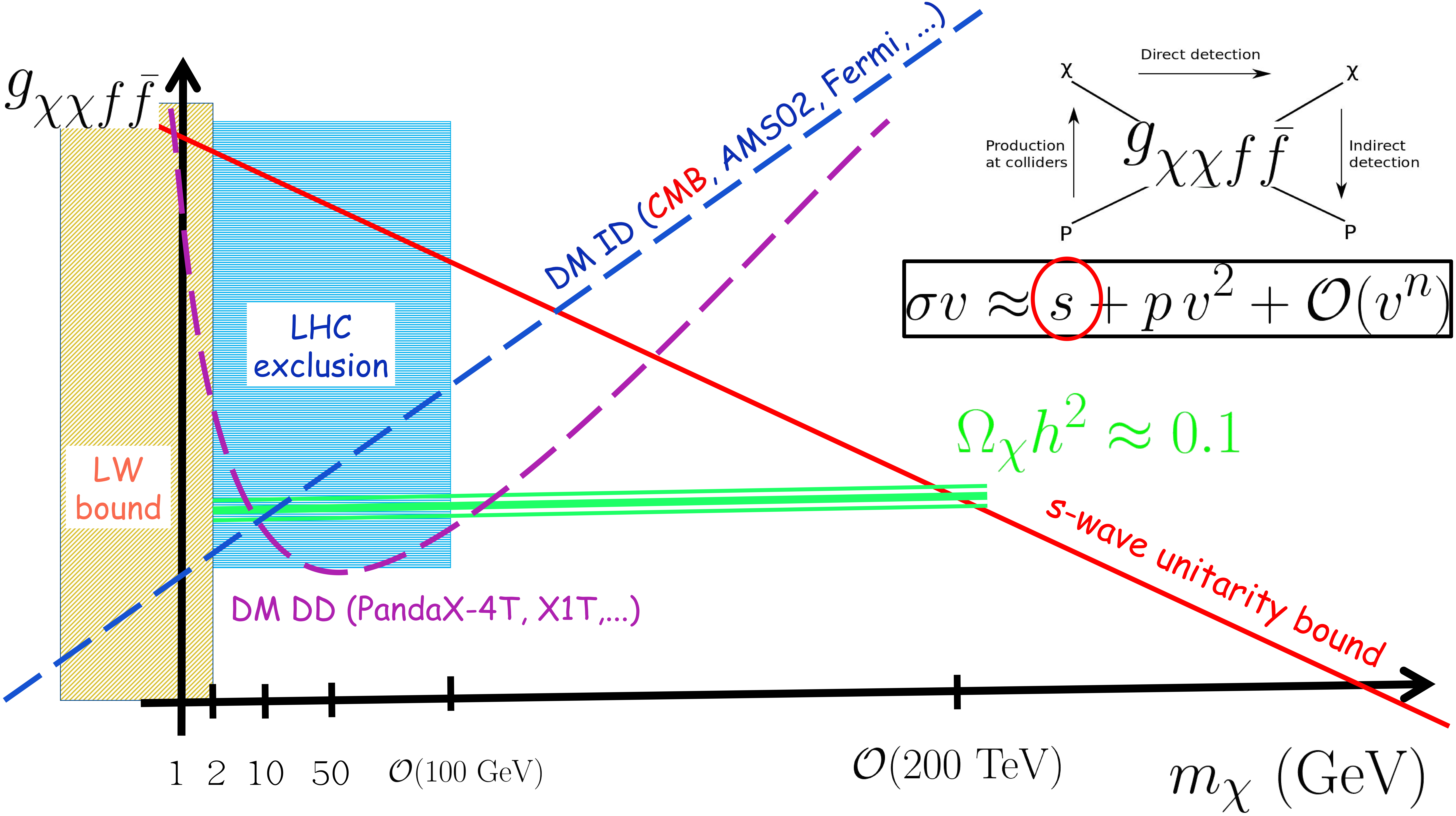
ID: CMB and 21 cm distortion

$$\boxed{\sigma v \approx s + p\,v^2 + \mathcal{O}(v^n)}$$

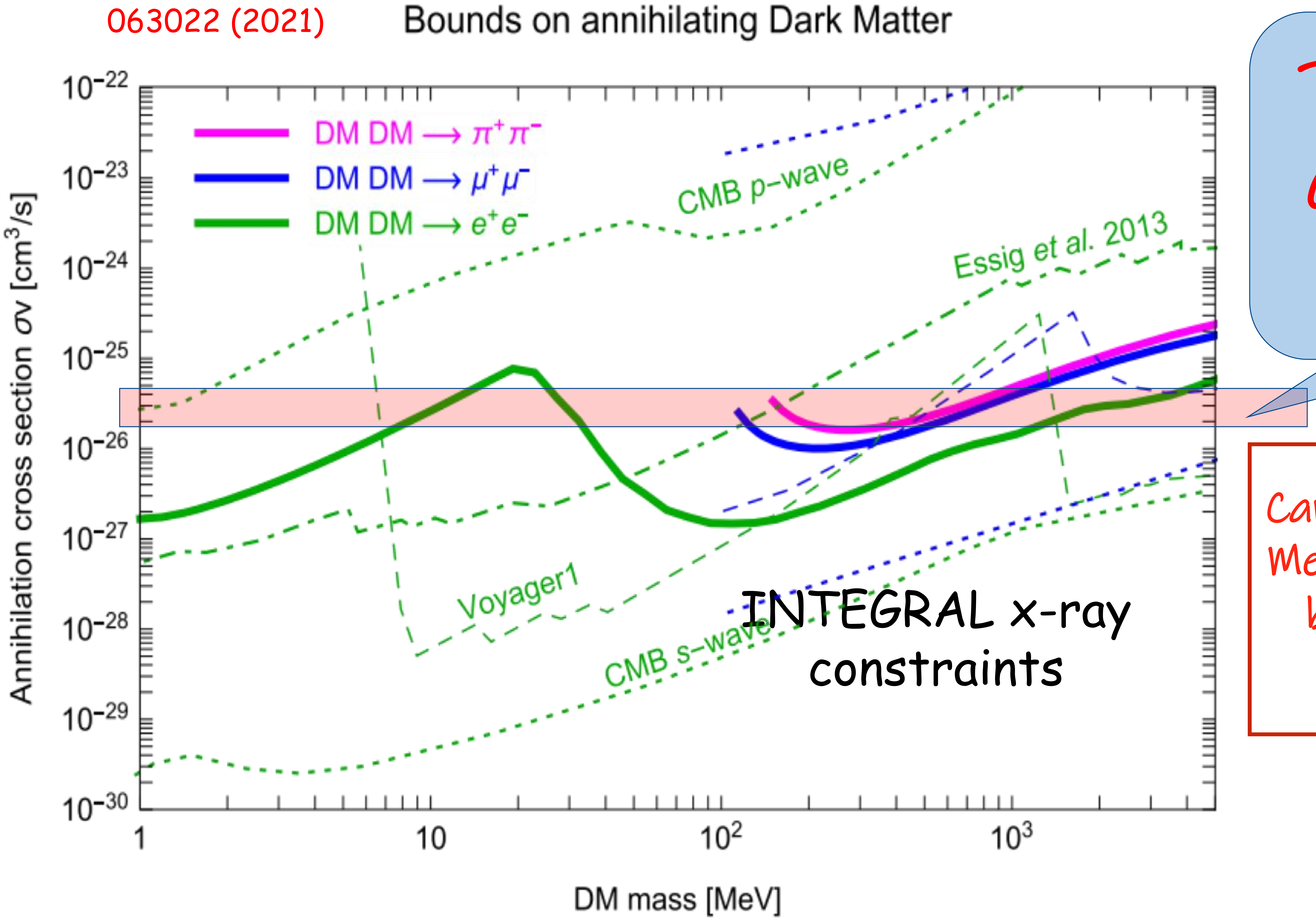




Pure s-wave (xx-> ee) is hard to survive for mx below 10 GeV.


$g_{\chi\chi f\bar{f}}$
DM ID (CMB, AMS02, Fermi, ...)
LHC exclusion
LW bound
DM DD (PandaX-4T, X1T,...)
$\Omega_\chi h^2 \approx 0.1$
s-wave unitarity bound
Direct detection
Production at colliders
Indirect detection
χ
χ
P
P
$g_{\chi\chi f\bar{f}}$
$\sigma v \approx s + p\, v^2 + \mathcal{O}(v^n)$
1
2
10
50
$\mathcal{O}(100\ \mathrm{GeV})$
$\mathcal{O}(200\ \mathrm{TeV})$
$m_\chi\ (\mathrm{GeV})$

PHYSICAL REVIEW D 103, 063022 (2021)



INTEGRAL x-ray constraints

Relic density cross section is excluded?

Can we find a DM signal in MeV gamma ray telescope but escape from CMB limits?.

Questions and strategies: toward the MeV Window.

※ Choices: higher energy or larger exposure? Alternatively, go to small DM mass!

※ LW bound. How could we escape from this limit?

※ Issues from s-wave.

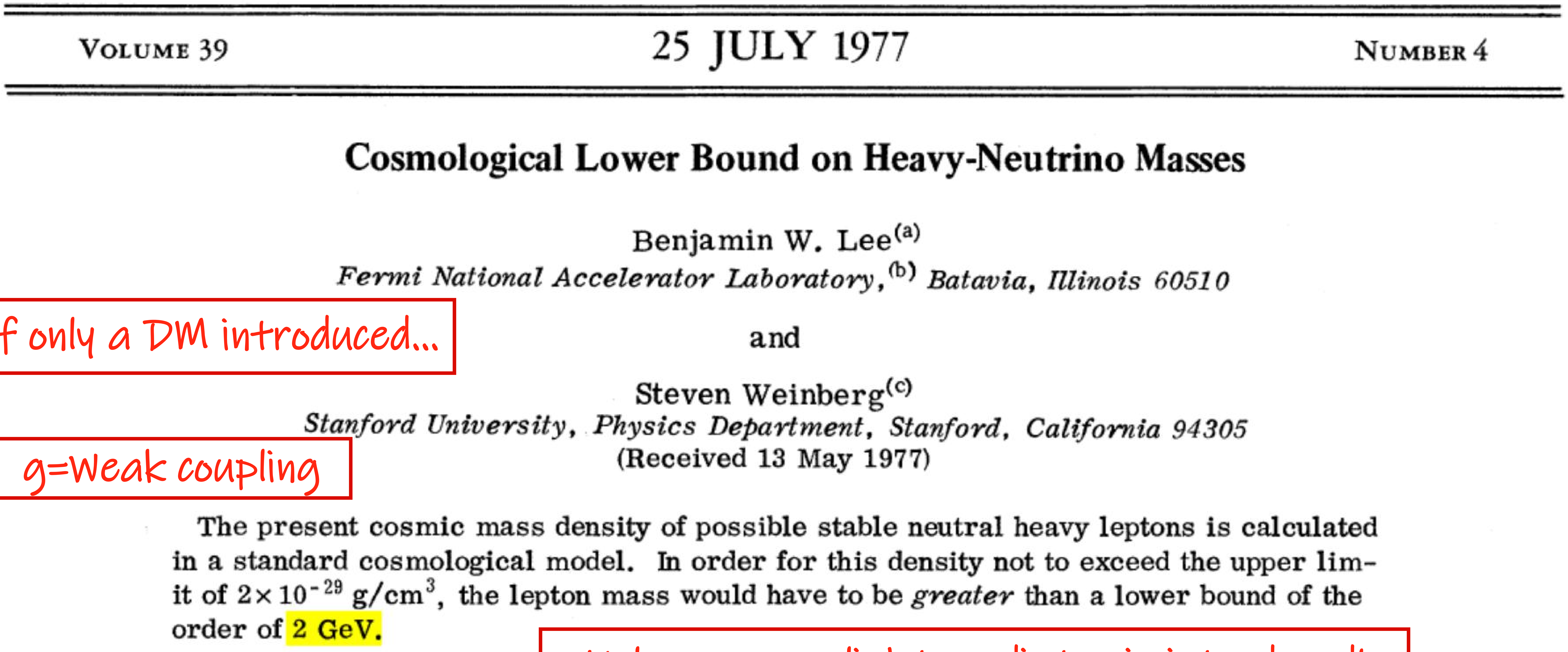
※ Important BBN constraints.

※ No good ID detectors for MeV-GeV DM. MeV-300 MeV gamma -ray telescopes are missing.

Minimun Dark particle content.

The Light DM mass region

Can we go to the region below GeV?



Volume 39 25 JULY 1977 Number 4

Cosmological Lower Bound on Heavy-Neutrino Masses

Benjamin W. Lee(a)
Fermi National Accelerator Laboratory,(b) Batavia, Illinois 60510

and

Steven Weinberg(c)
Stanford University, Physics Department, Stanford, California 94305
(Received 13 May 1977)

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.

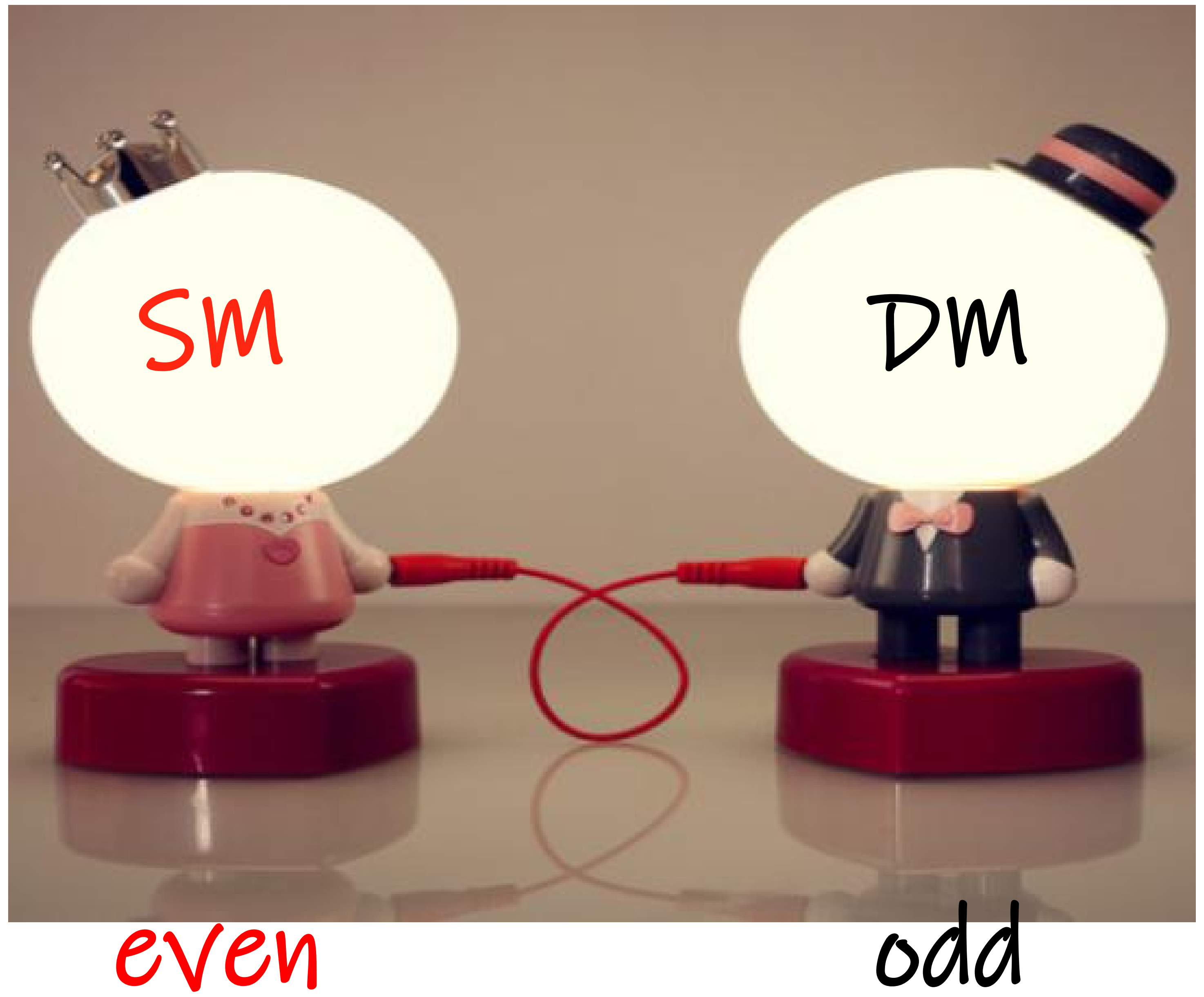
If only a DM introduced...

g=Weak coupling

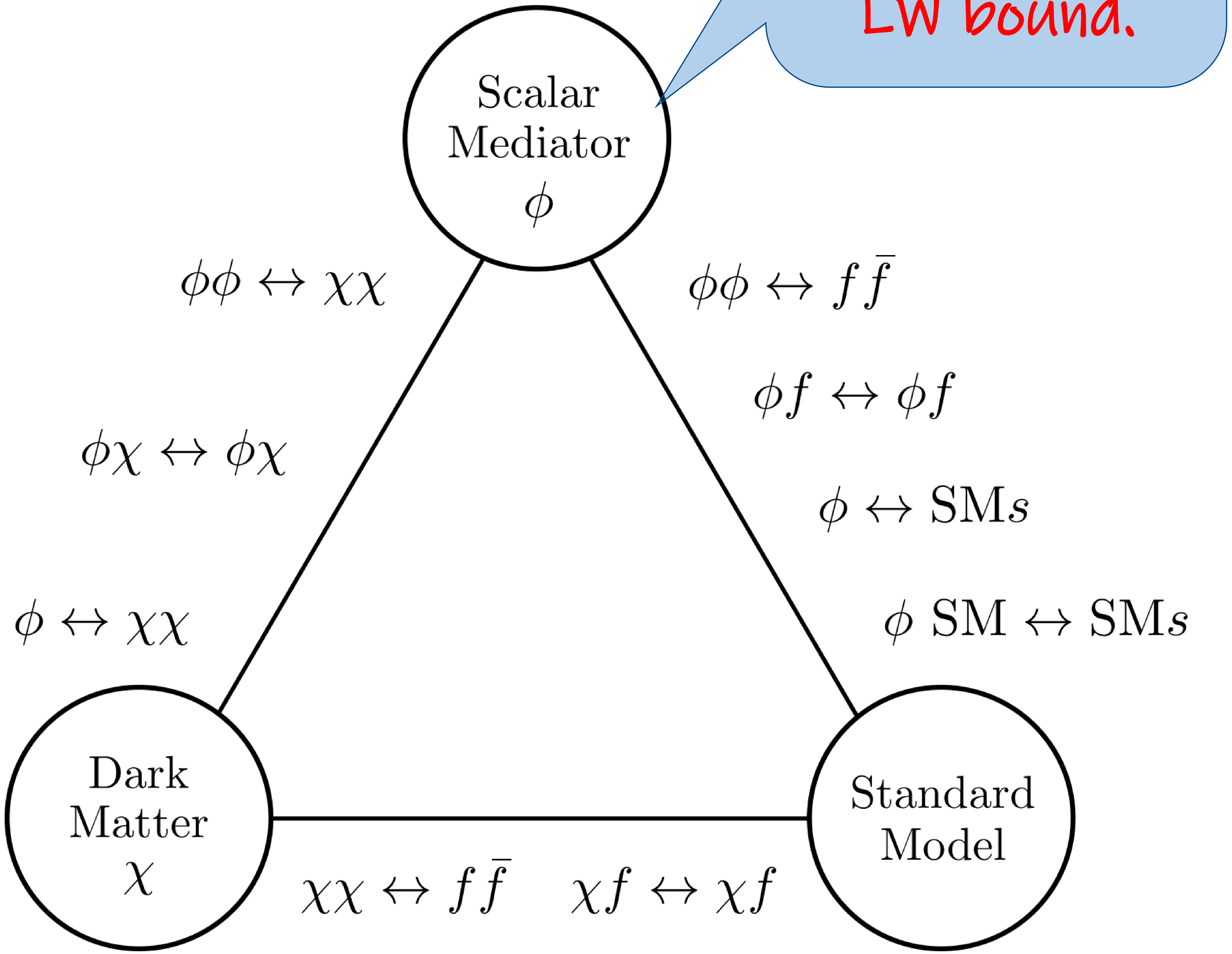
Unless, a new light mediator is introduced!

Minimum particle content

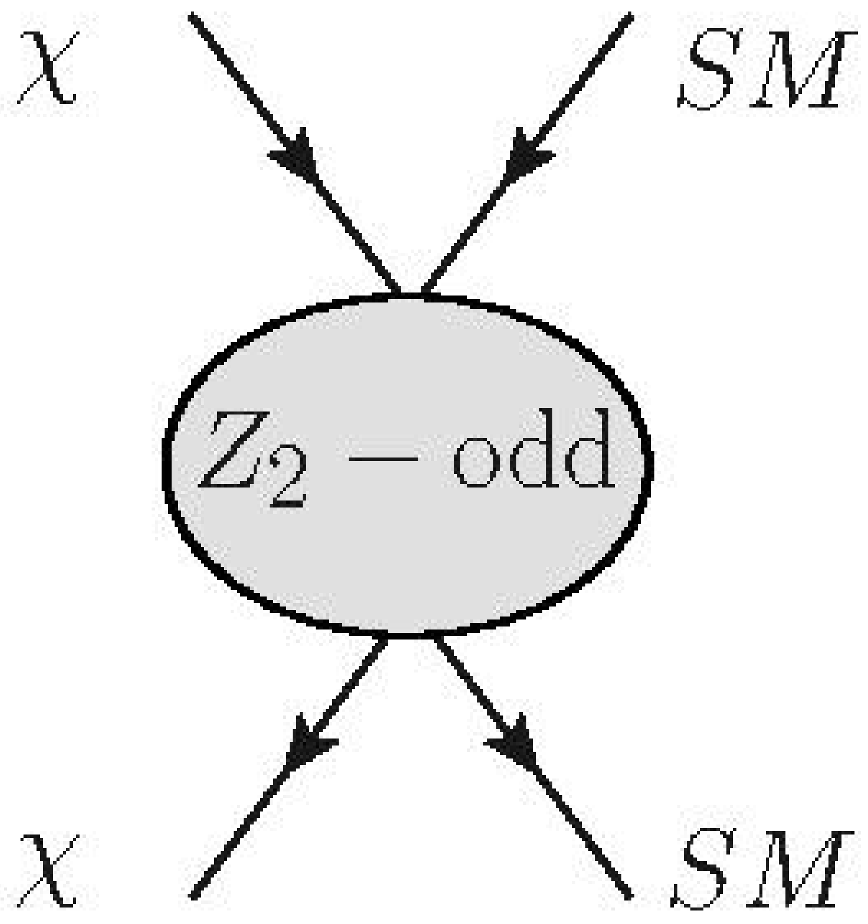
Need a new mediator to escape the LW bound.



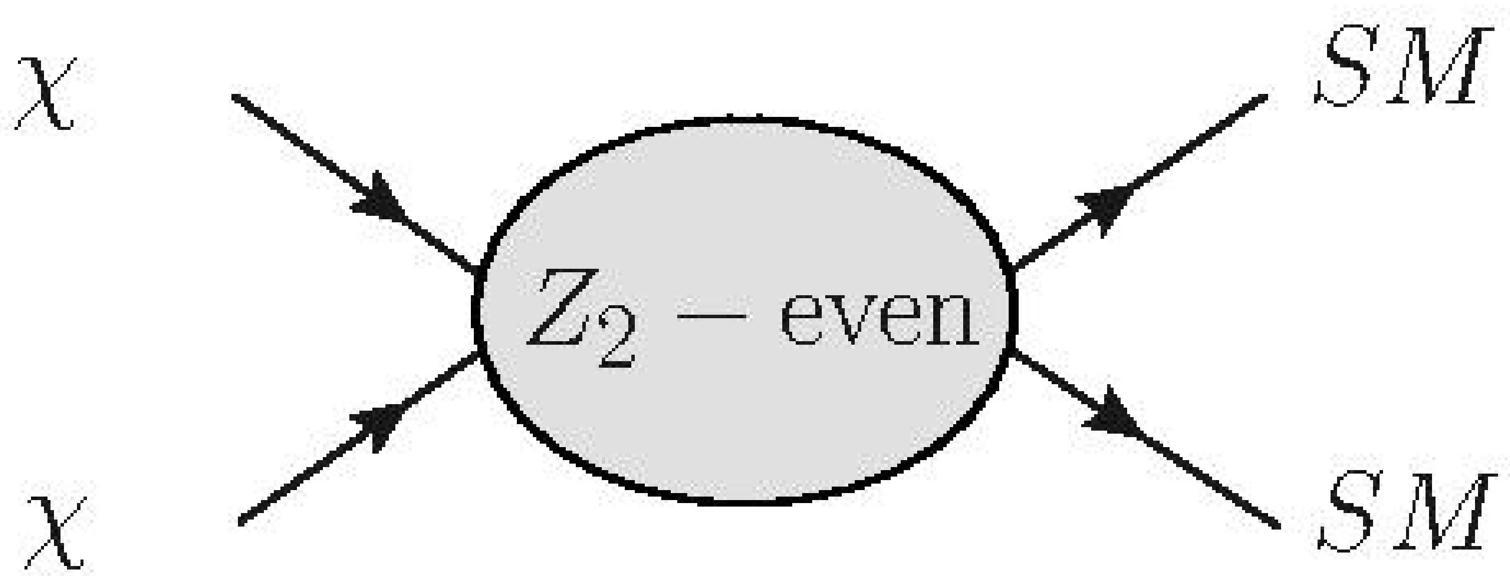
We can add two new particles, DM and MED!
(Only 2 particles)



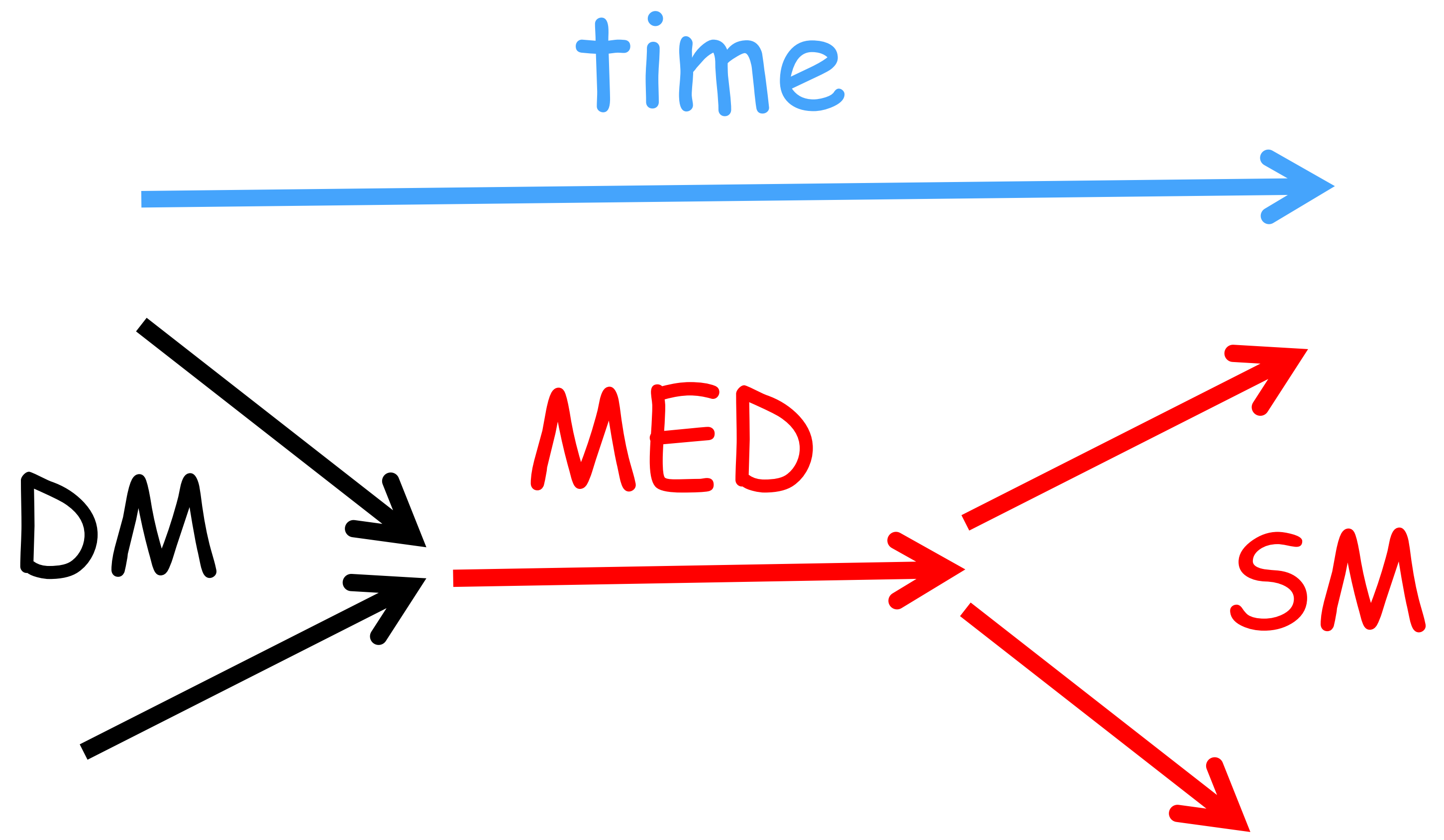
Simplicity and Light mediator



t-channel annihilation



s-channel annihilation



DM: Z2 = -1;

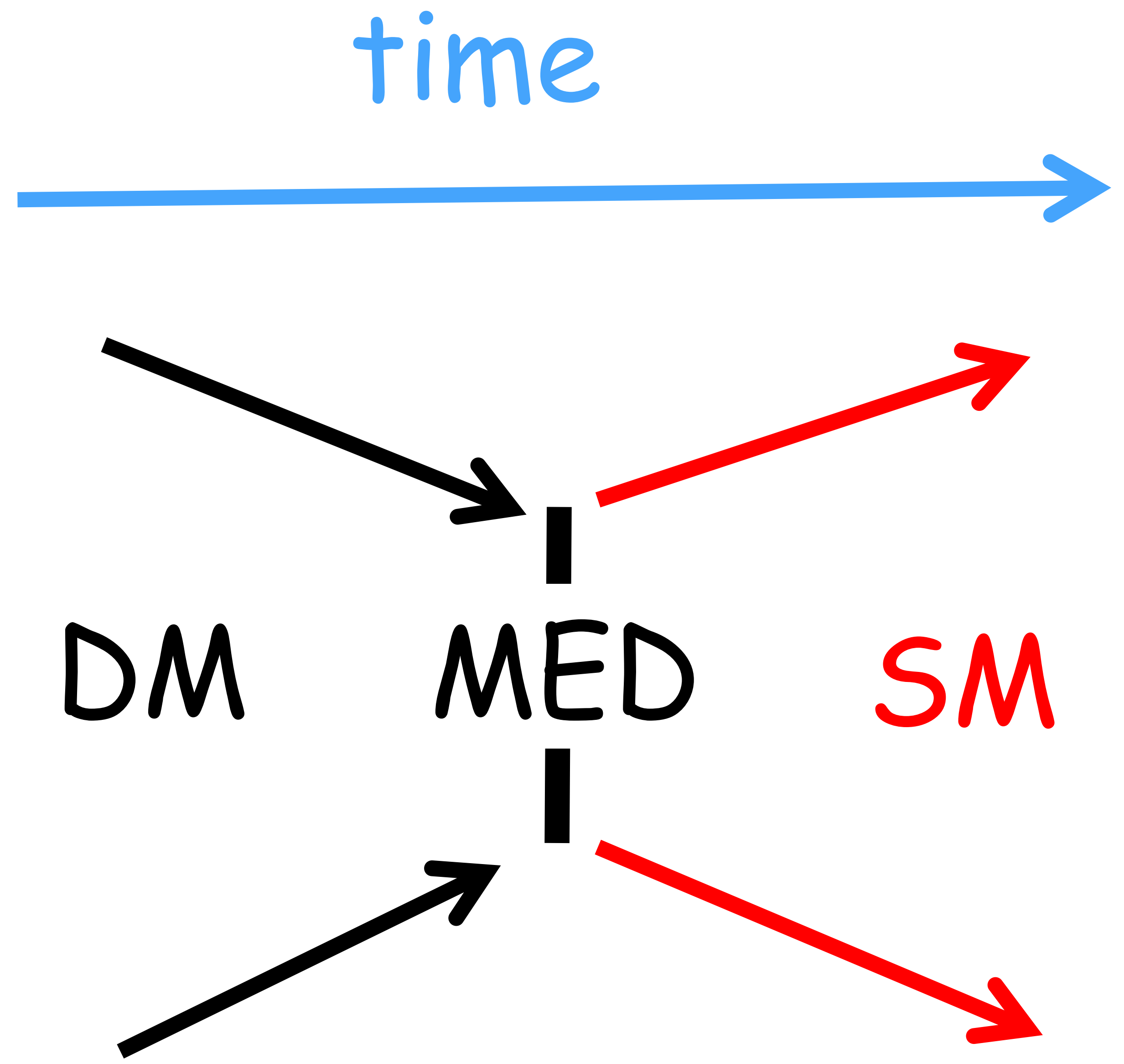
MED: Z2 = +1;

SM: Z2 = +1;

① Z_2 odd scalar mediator (like squark) + SM fermion. LEP mass limit for charged mediator is heavier than 100 GeV.

② Z_2 odd fermion mediator (like Chargino) + SM gauge boson. Invisible decay gives a severe limit.

Therefore, an MeV mediator of the the DM annihilation to SM pair CANNOT be Z_2-odd
(via t-channel).

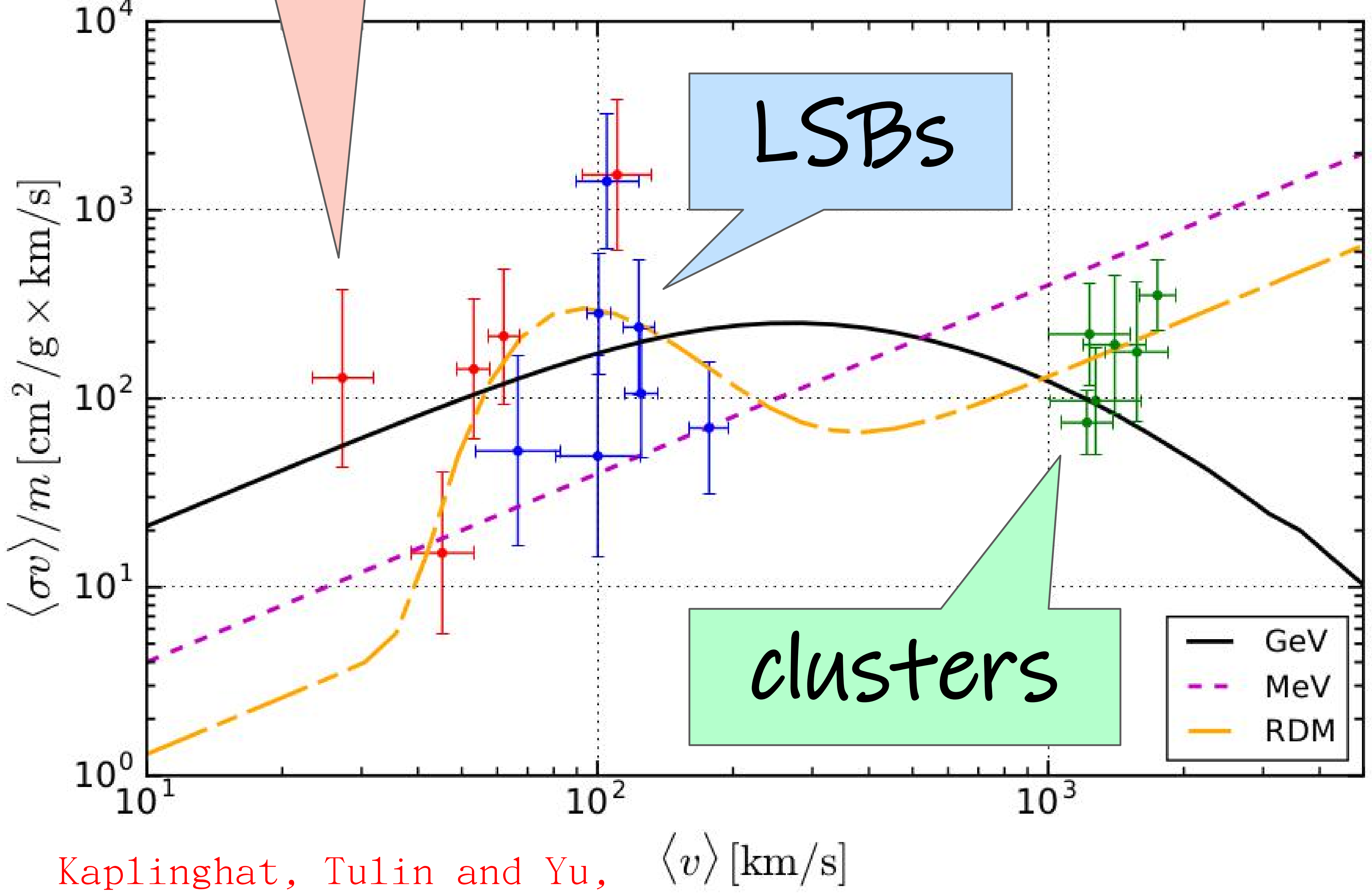


DM: Z2 = -1;
MED: Z2 = -1;
SM: Z2 = +1;

Only dark photon and dark Higgs can be the MeV mediator.

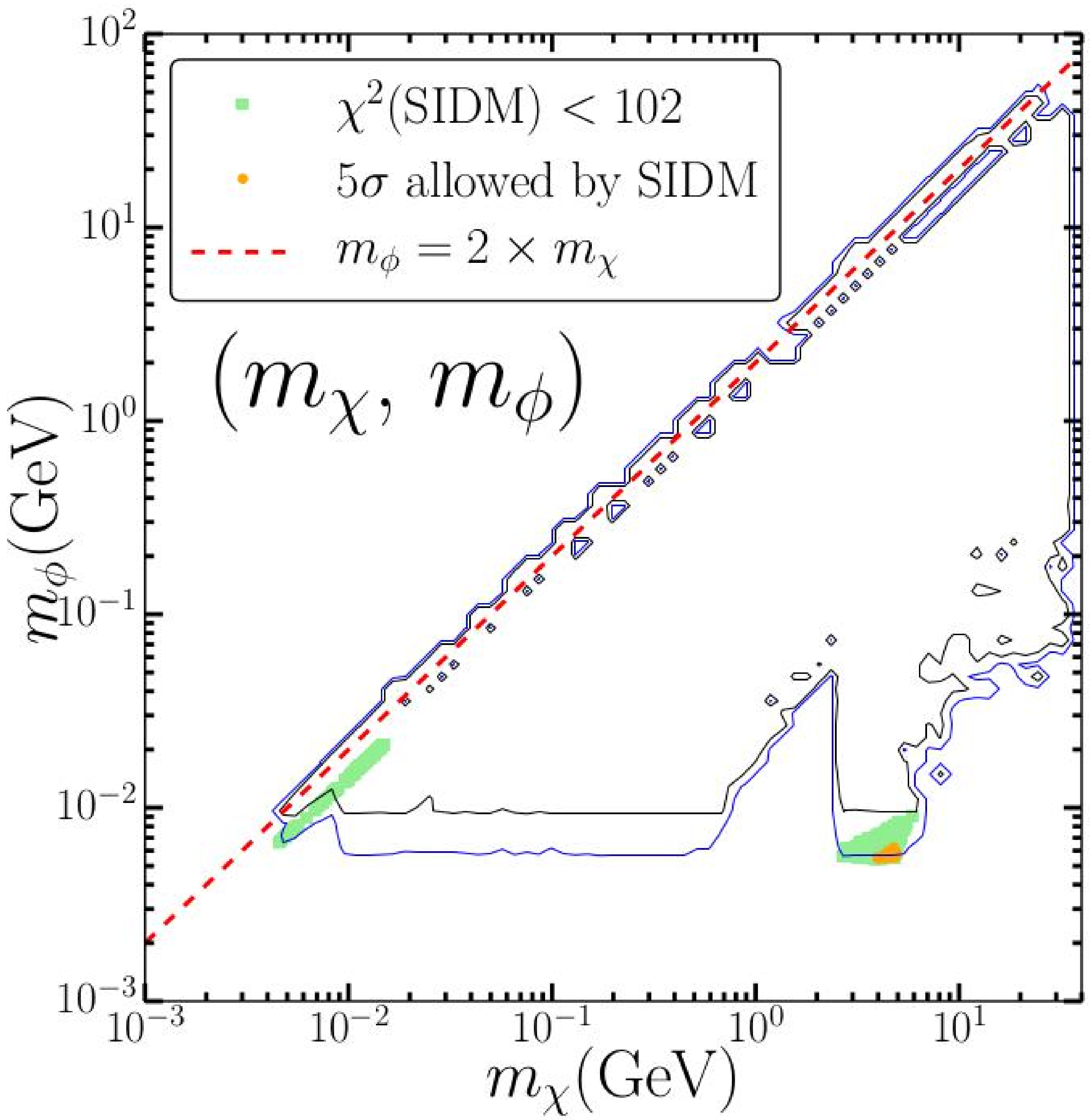
MeV Self-interacting dark matter

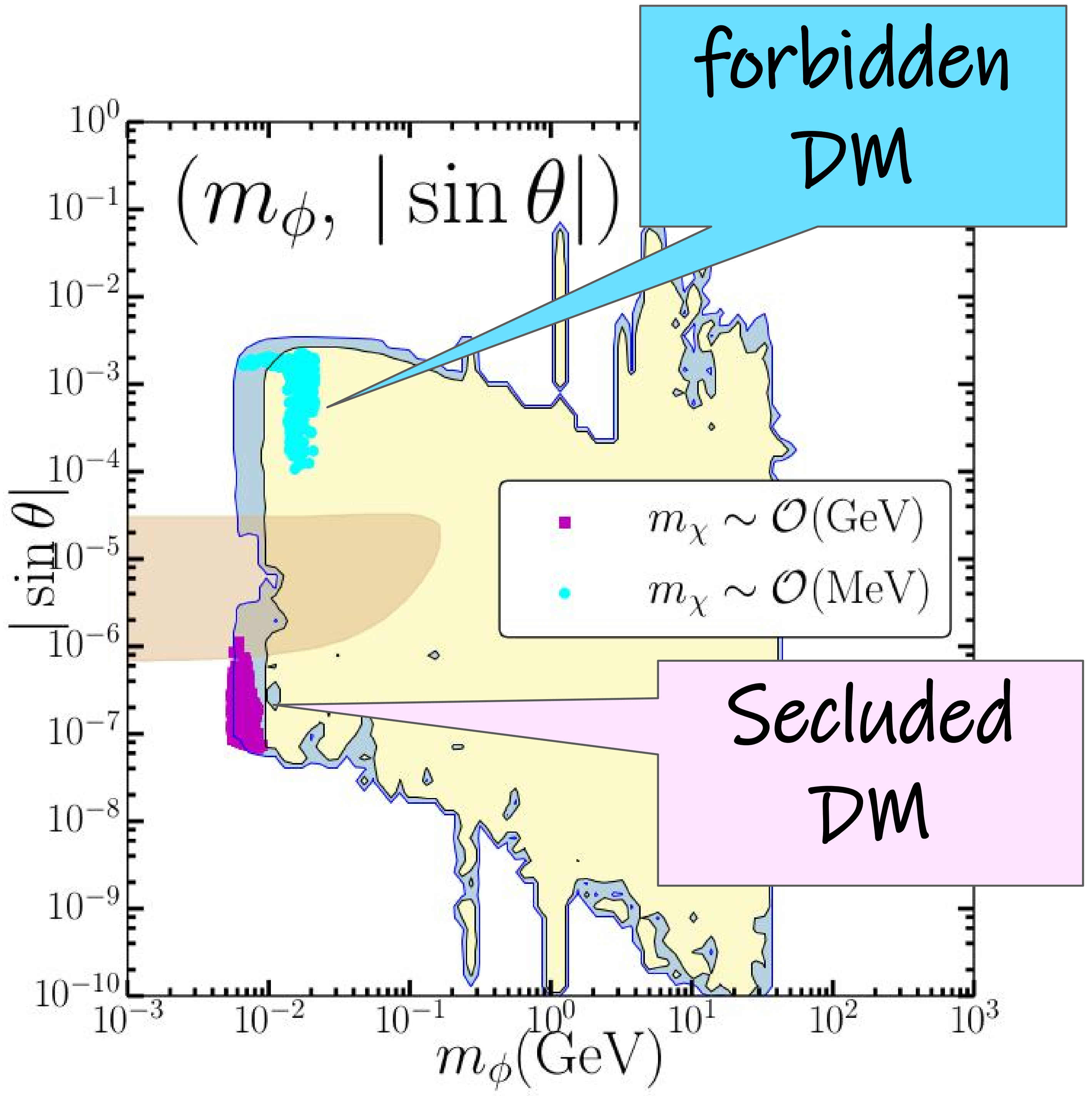
dwarfs



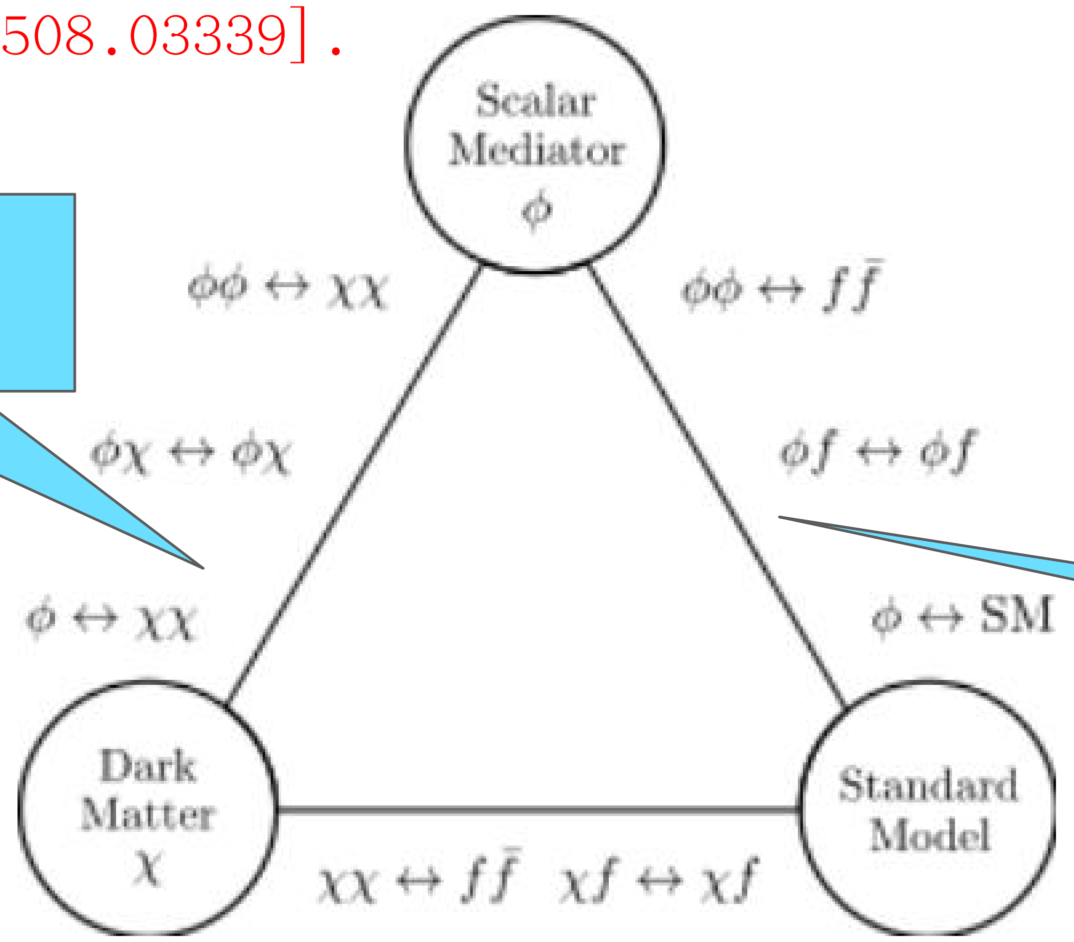
Kaplinghat, Tulin and Yu, Phys. Rev. Lett. **116**, no.4, 041302 (2016) [1508.03339].

Parameter space is finite.





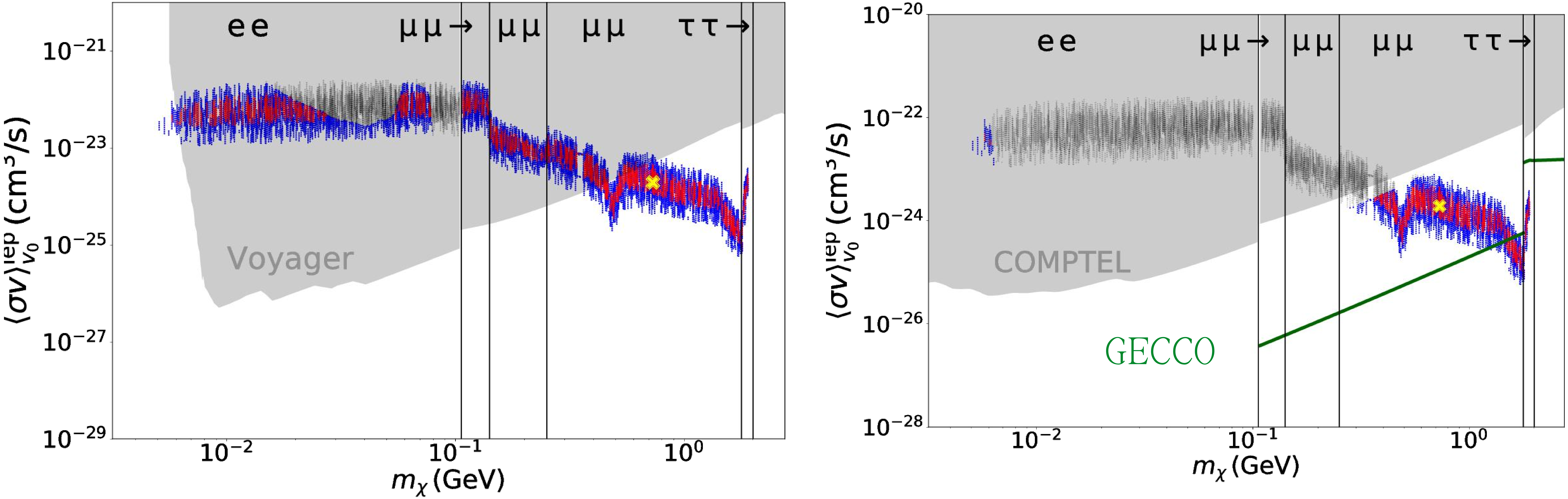
Strong.



Super Weak.

SIDM can be realized in this framework, but GeV DM can be soon tested by DM DD (LZ)!

MeV Self-interacting dark matter



Binder, Chakraborti,
Matsumoto and Watanabe
(2205.10149)

SIDM can be probed mostly in the futue with GECCO!
We will return to these experiments later.

How can we detect these corners?

◎DM might be too heavy or too light.
  -> Change the energy threshold.
  -> Indirectly search in the high luminosity experiments.

◎Coupling is tiny.
  -> Go beyond thermal DM paradigm and No WIMP miracle!
  -> Small mixing. Secluded or forbidden DM.

◎Two DM particles are mass degenerated.
  -> Coannihilation dominantes at the early time.
  -> Generate the heavy particle first.

本节小结 （Minimun Dark particle content）

◎为何需要同时引进暗物质与传播子？

◎分立对称性Z2的引入，Z2-odd不合适。

◎传播子只可能是暗光子跟暗希格斯。

◎MeV暗物质自动就有”强自相互作用”的特征。

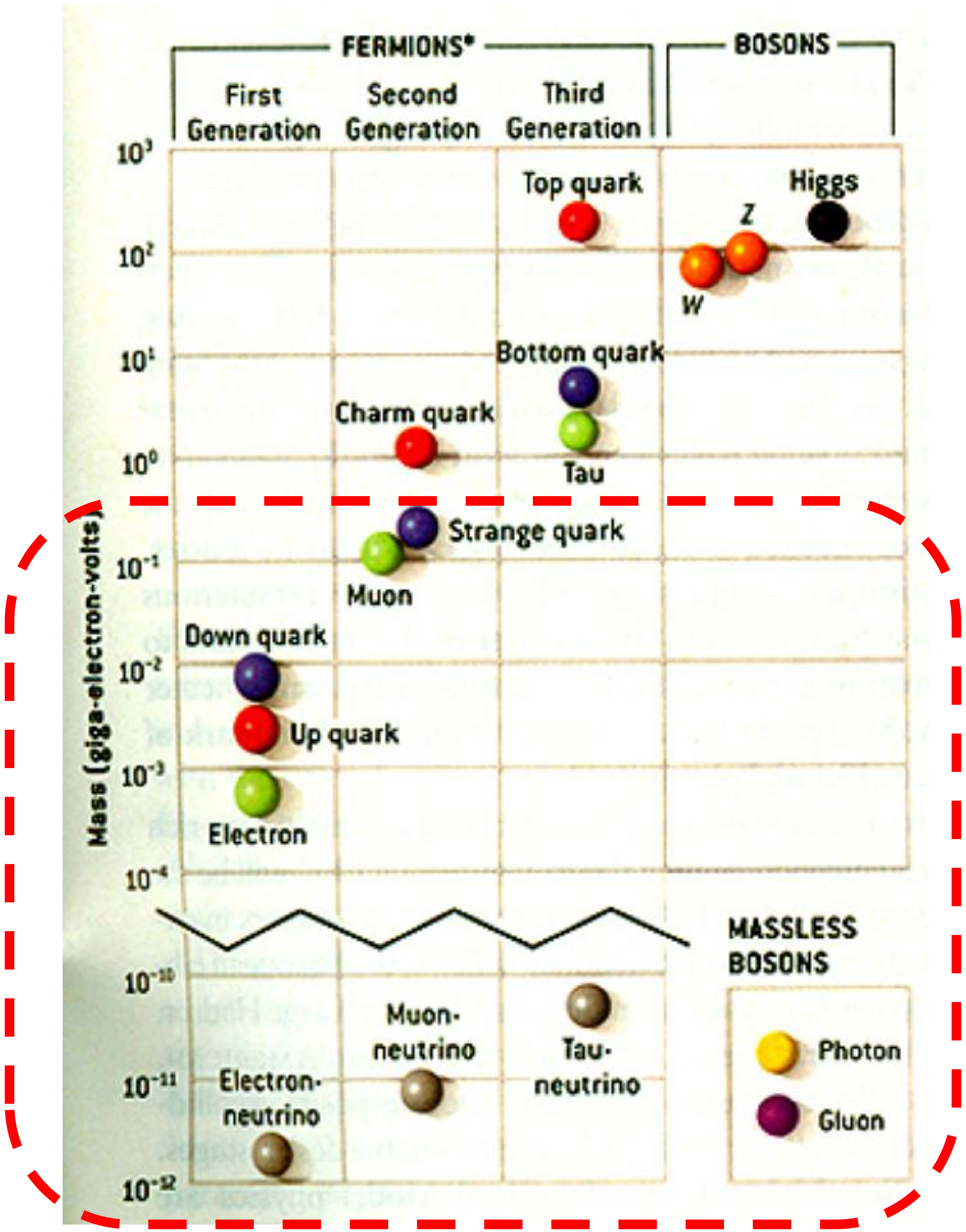
◎如果考虑用SIDM解释速度分布的问题，那未来间接探测会很强。

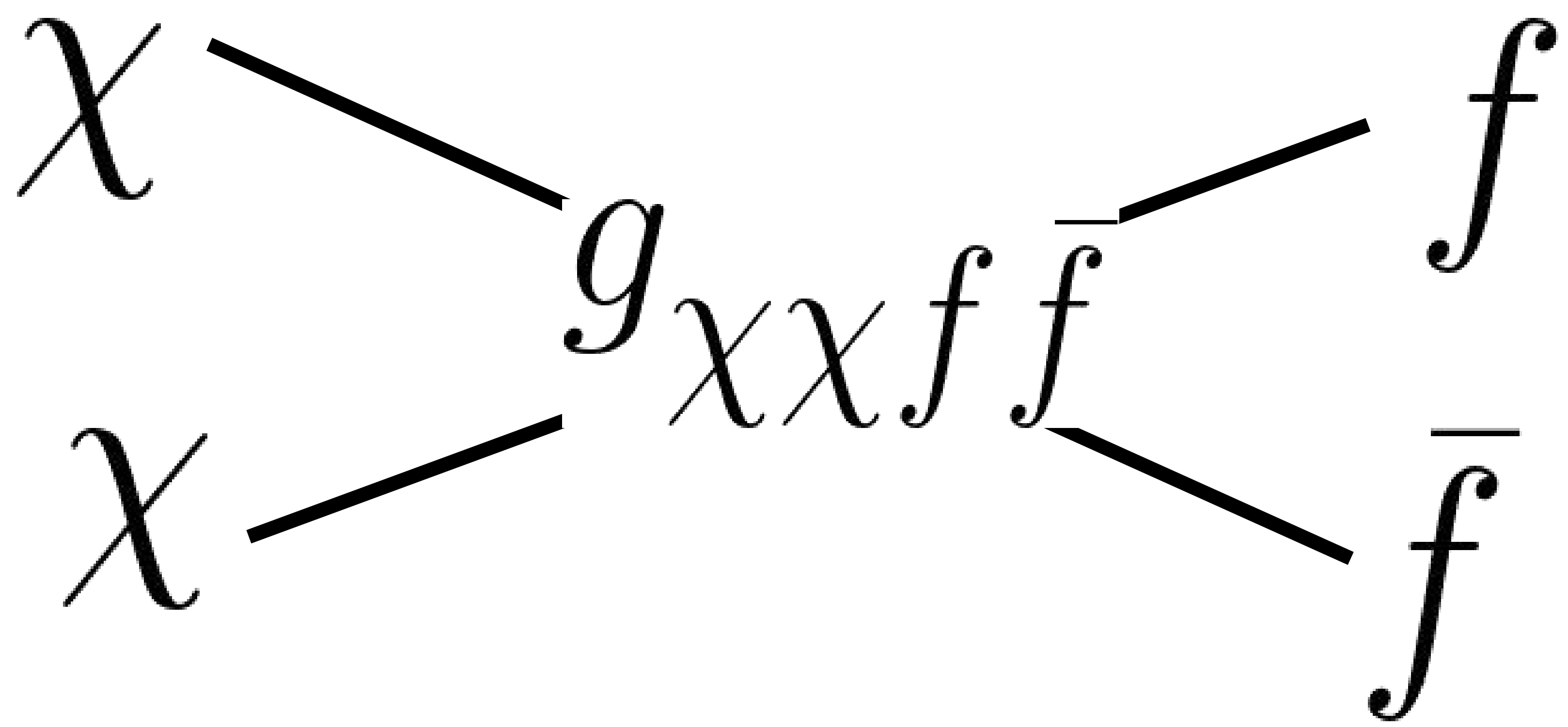
- photons (hard-X and gamma ray)
- Neutrinos
- Cosmic-ray (electron and CR boost DM)
- Cosmology (21 cm, CMB, and halo mass function)

Possible indirect detections.

Topic 1:

Hard X-ray, Gamma-ray and neutrino



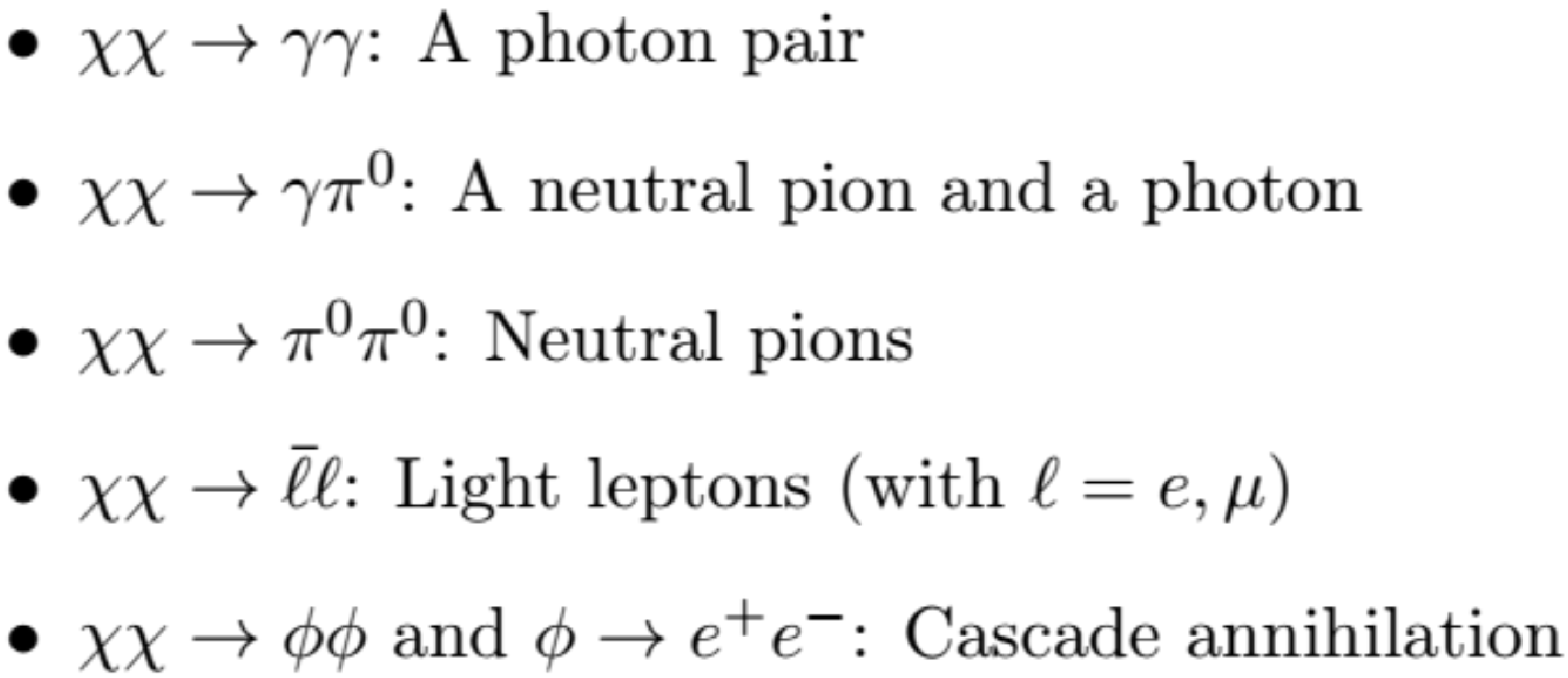


If DM is lighter than proton (< GeV), what are the possible final states?

-hadronic [pion, mesons...]

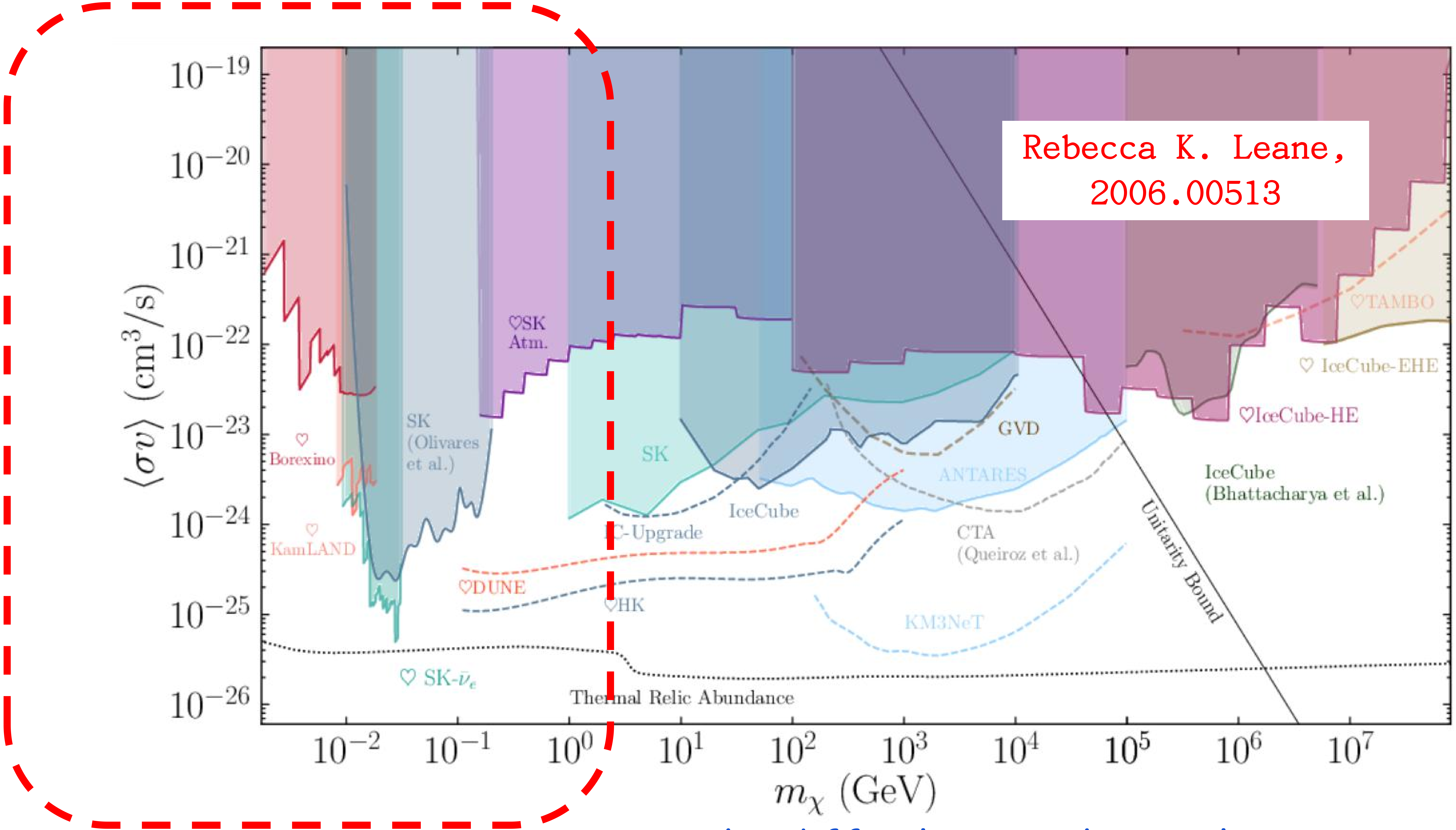
-leptonic [e, mu, nu]

New annihilation final state



- $\chi\chi \to \gamma\gamma$: A photon pair
- $\chi\chi \to \gamma\pi^0$: A neutral pion and a photon
- $\chi\chi \to \pi^0\pi^0$: Neutral pions
- $\chi\chi \to \bar{\ell}\ell$: Light leptons (with $\ell = e, \mu$)
- $\chi\chi \to \phi\phi$ and $\phi \to e^+e^-$: Cascade annihilation

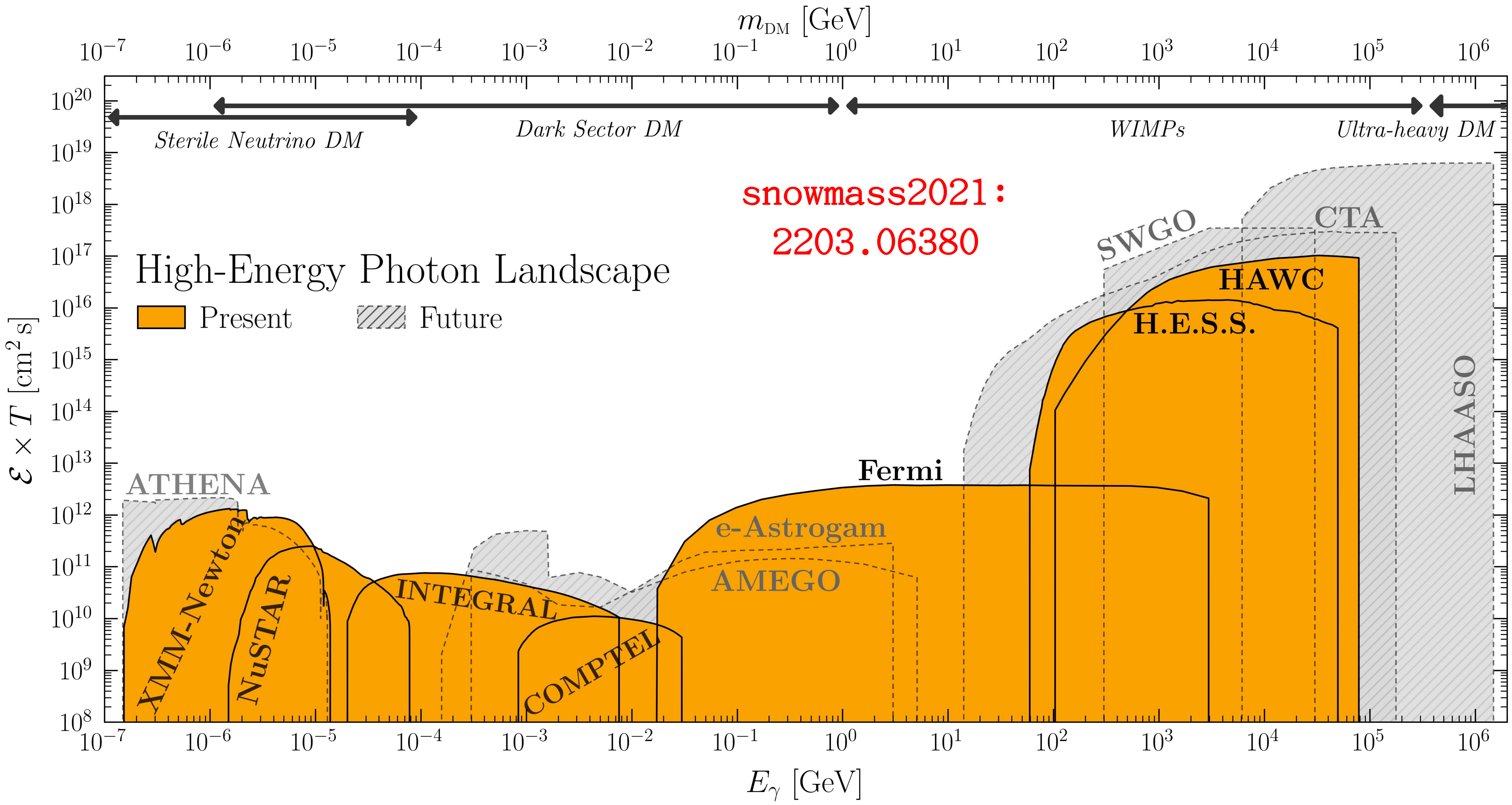
- chi chi to phi phi, then 4e, 4mu, or 4pi.
- New Hadronic final state.



Rebecca K. Leane,
2006.00513

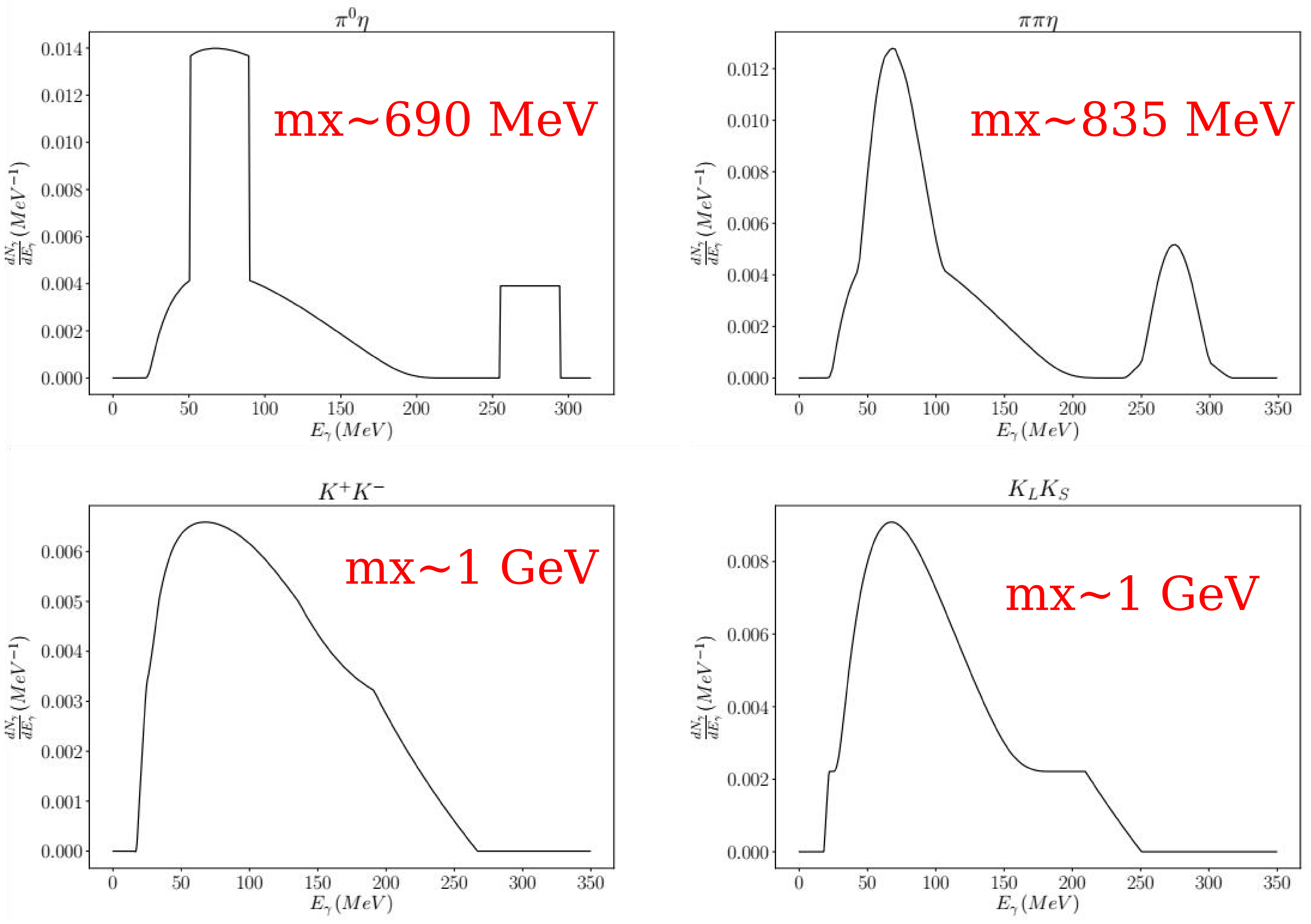
The difficulty is to have a large neutrino-neutrino-meditator coupling.

We have to move to freeze-in scenario.



$m_{\rm DM}$ [GeV]
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
Sterile Neutrino DM
Dark Sector DM
WIMPs
Ultra-heavy DM
snowmass2021:
2203.06380
High-Energy Photon Landscape
Present
Future
SWGO
CTA
HAWC
H.E.S.S.
LHAASO
Fermi
ATHENA
XMM-Newton
NuSTAR
INTEGRAL
COMPTEL
e-Astrogam
AMEGO
$\mathcal{E} \times T$ [cm^2 s]
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
E_γ [GeV]

Spectral Features in MeV Gamma Rays: hadronic final state.

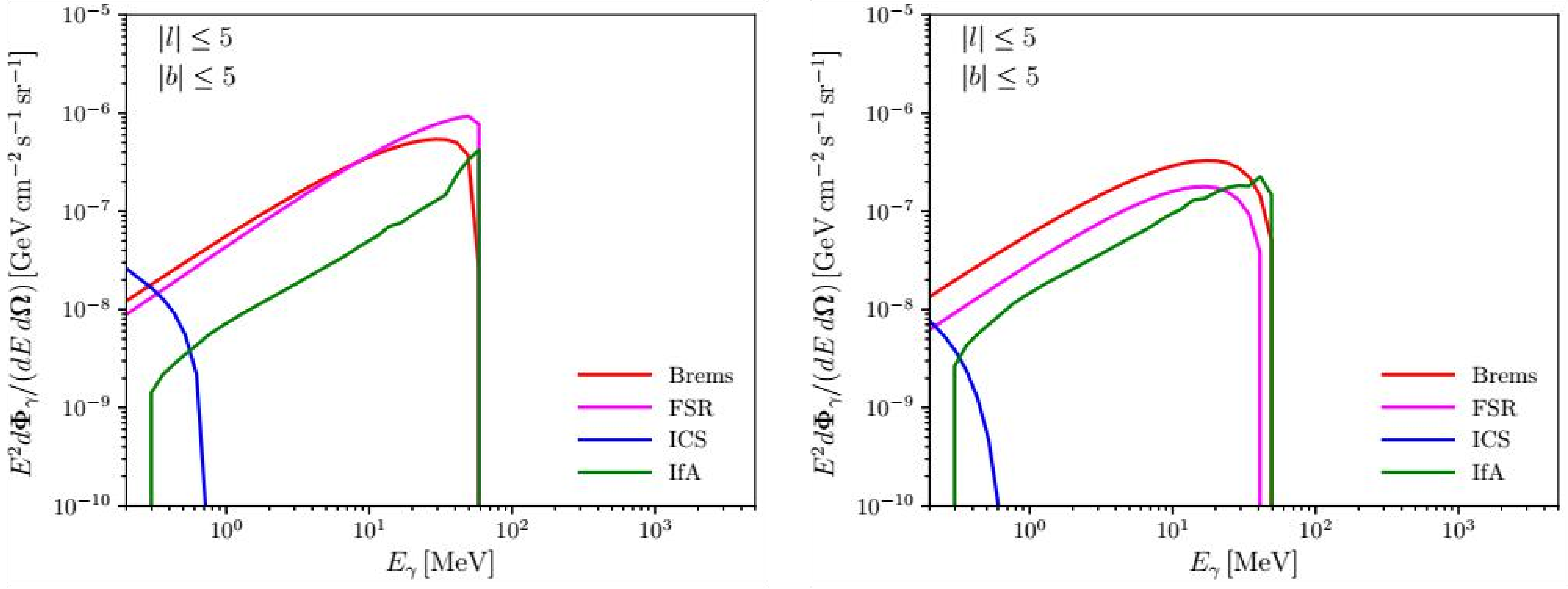


arXiv:2205.09356.
Similar study can be found in 1911.11147.

- Ths spectrum shape is very different with astrophsical.
- Good news is that the MeV gamma ray telescopes usually have a better resolution.

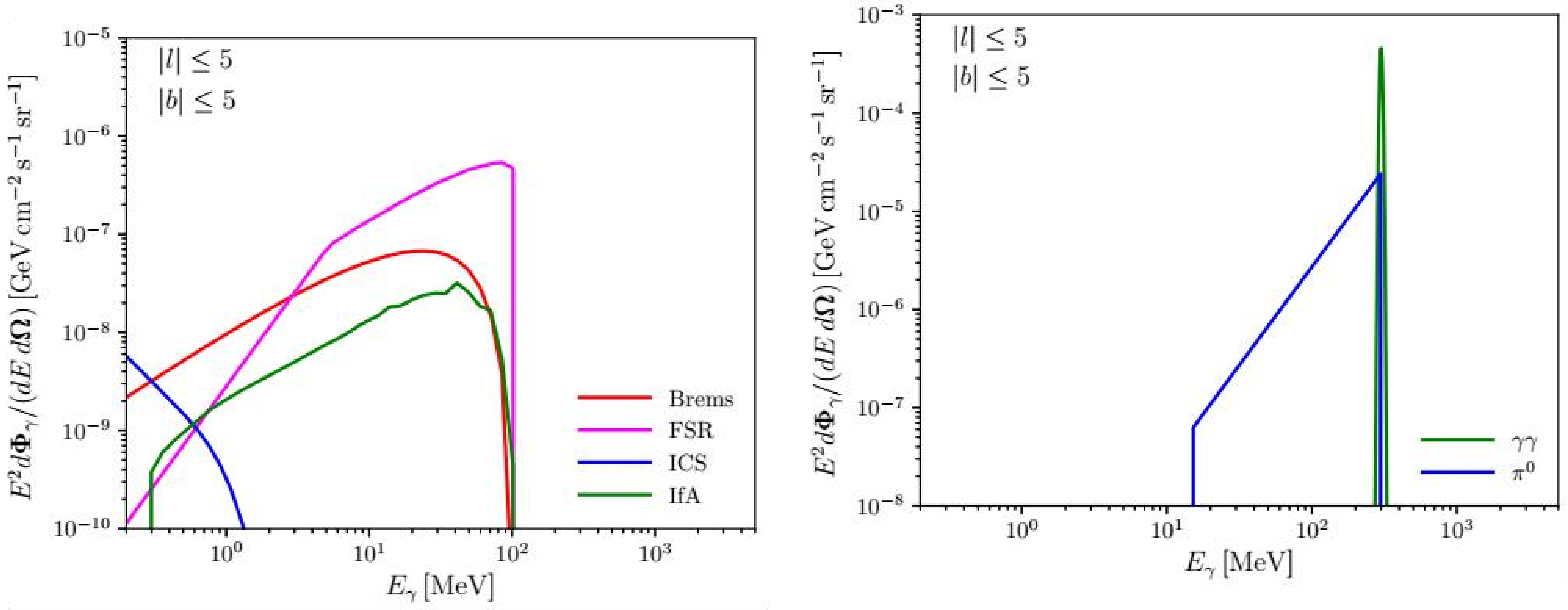
Charged pion mass~140 MeV.
Neutral pion mass ~135 MeV.
eta ~548 MeV.
charged Kaon~ 494 MeV.

Energy spectrum: new annihilation final state



(a) Spectrum for $\chi\chi \to e^+e^-$ and $m_\chi = 60\,\text{MeV}$.

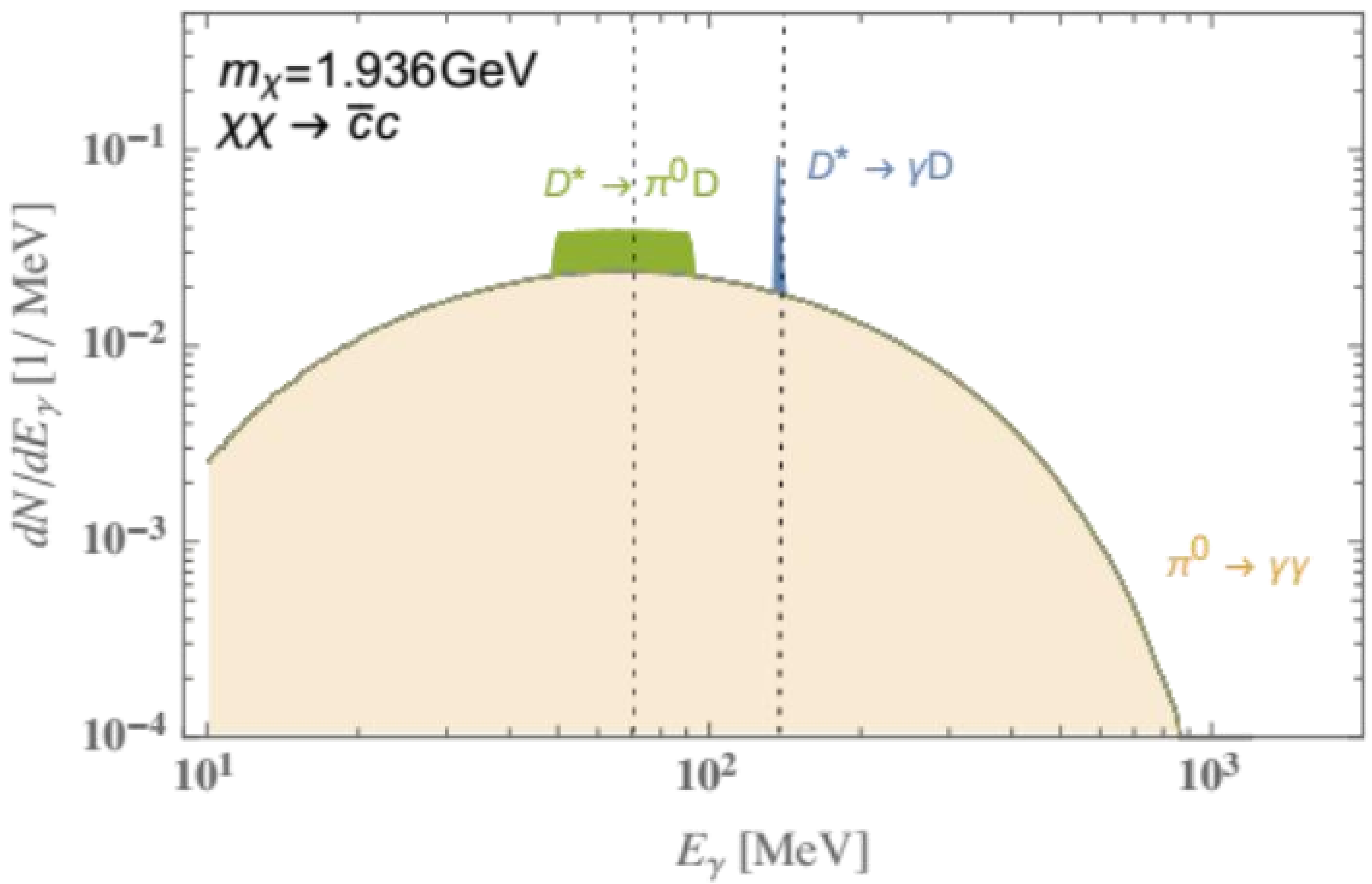
(b) Spectrum for $\chi\chi \to \phi\phi \to e^+e^-e^+e^-$, $m_\chi = 60\,\text{MeV}$ and $m_\phi = 5\,\text{MeV}$.



(c) Spectrum for $\chi\chi \to \mu^+\mu^-$ and $m_\chi = 110\,\text{MeV}$.

(d) Spectrum for $\chi\chi \to \pi^0\gamma$ and $m_\chi = 300\,\text{MeV}$. The width of the line is set to 2% to ease the eye.

R. Bartels, D. Gaggero. and C. Weniger (2017).



T. Bringmann, A. Galea, A. Hryczuk, and C. Weniger (2017)
1610.04613

DM annihilation energy spectrum

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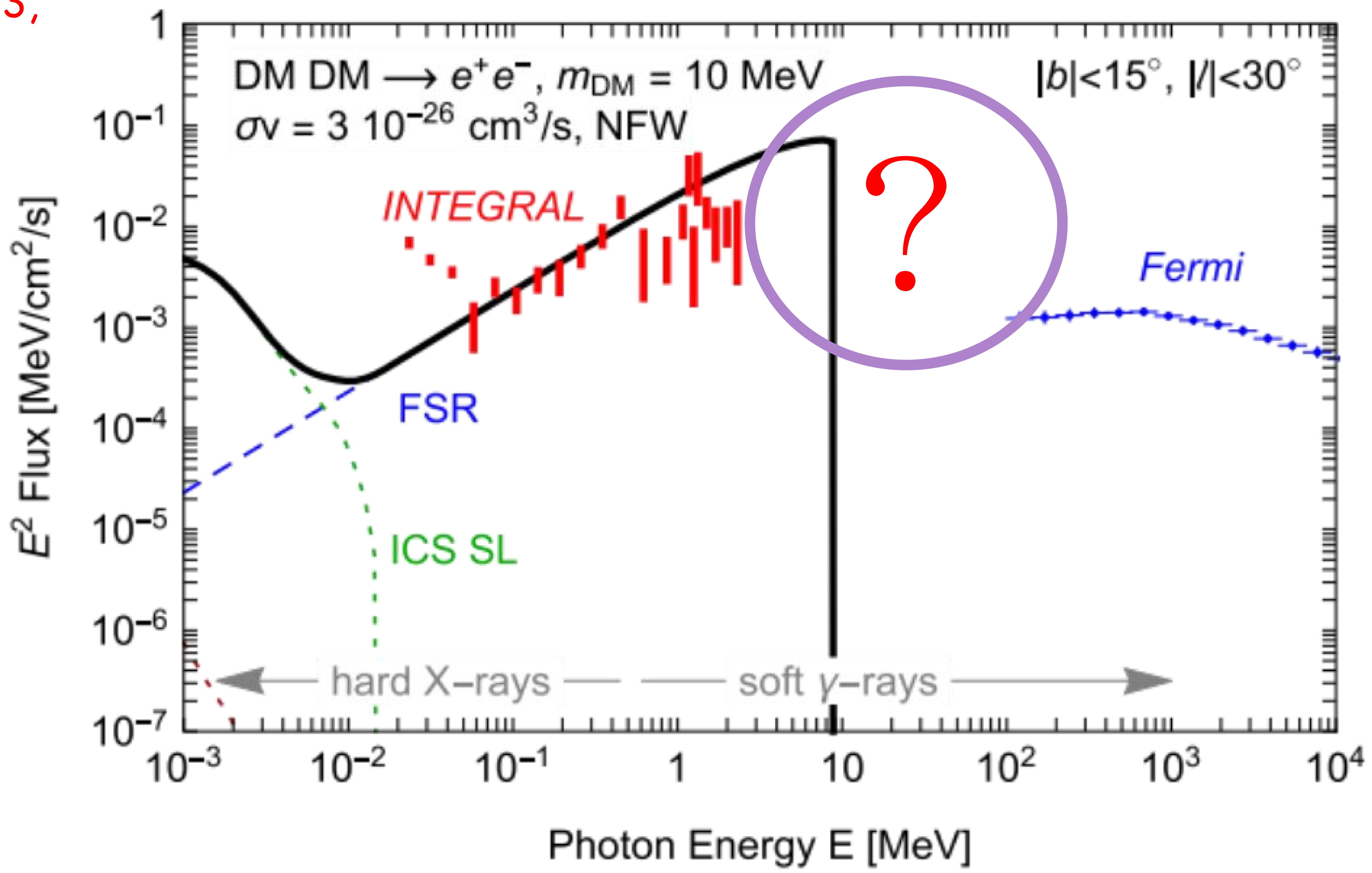


- Leptonic final state spectra are also very sharp.
- No data between INTEGRAL and Fermi!

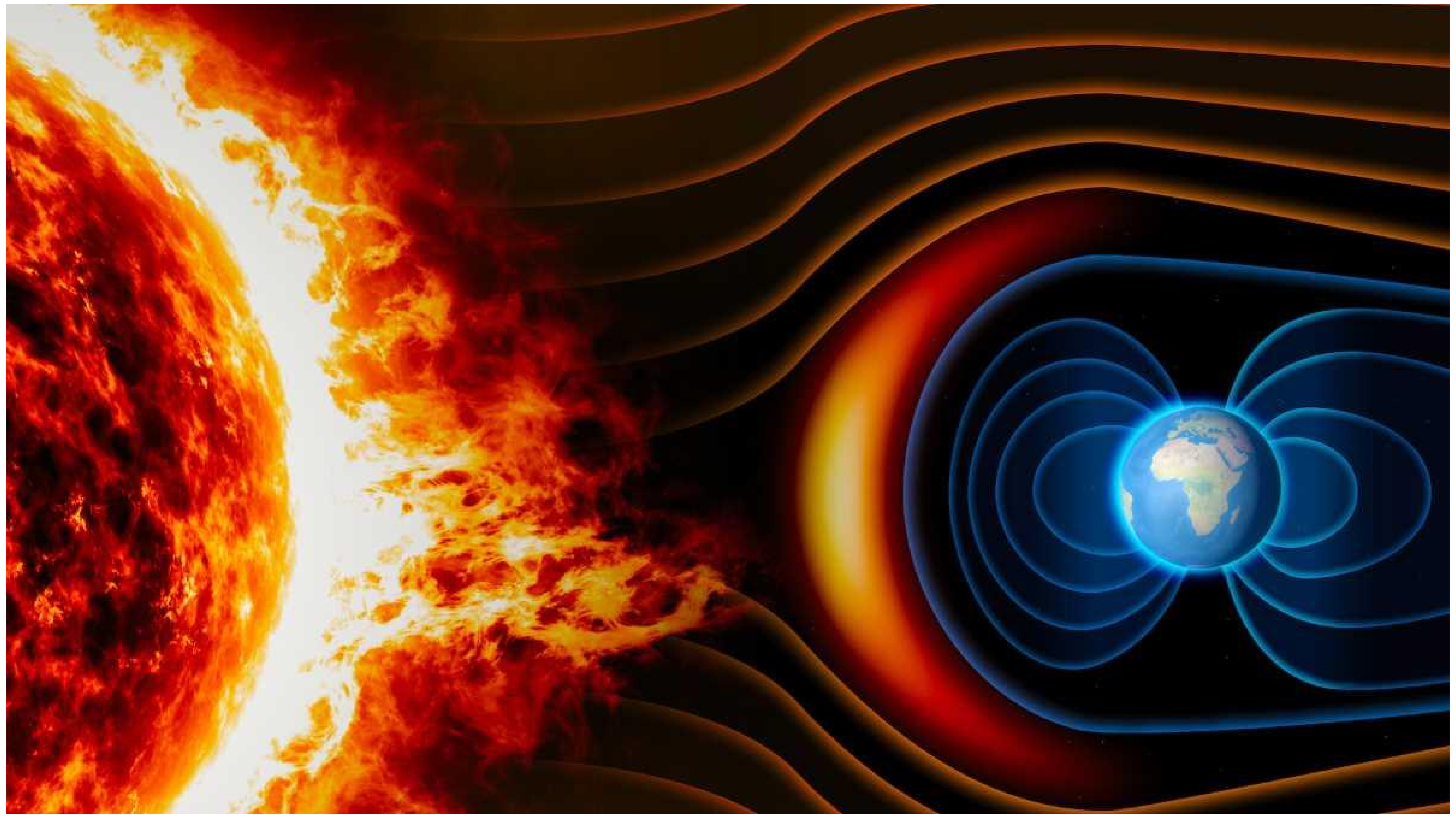
MeV Gamma ray telescopes

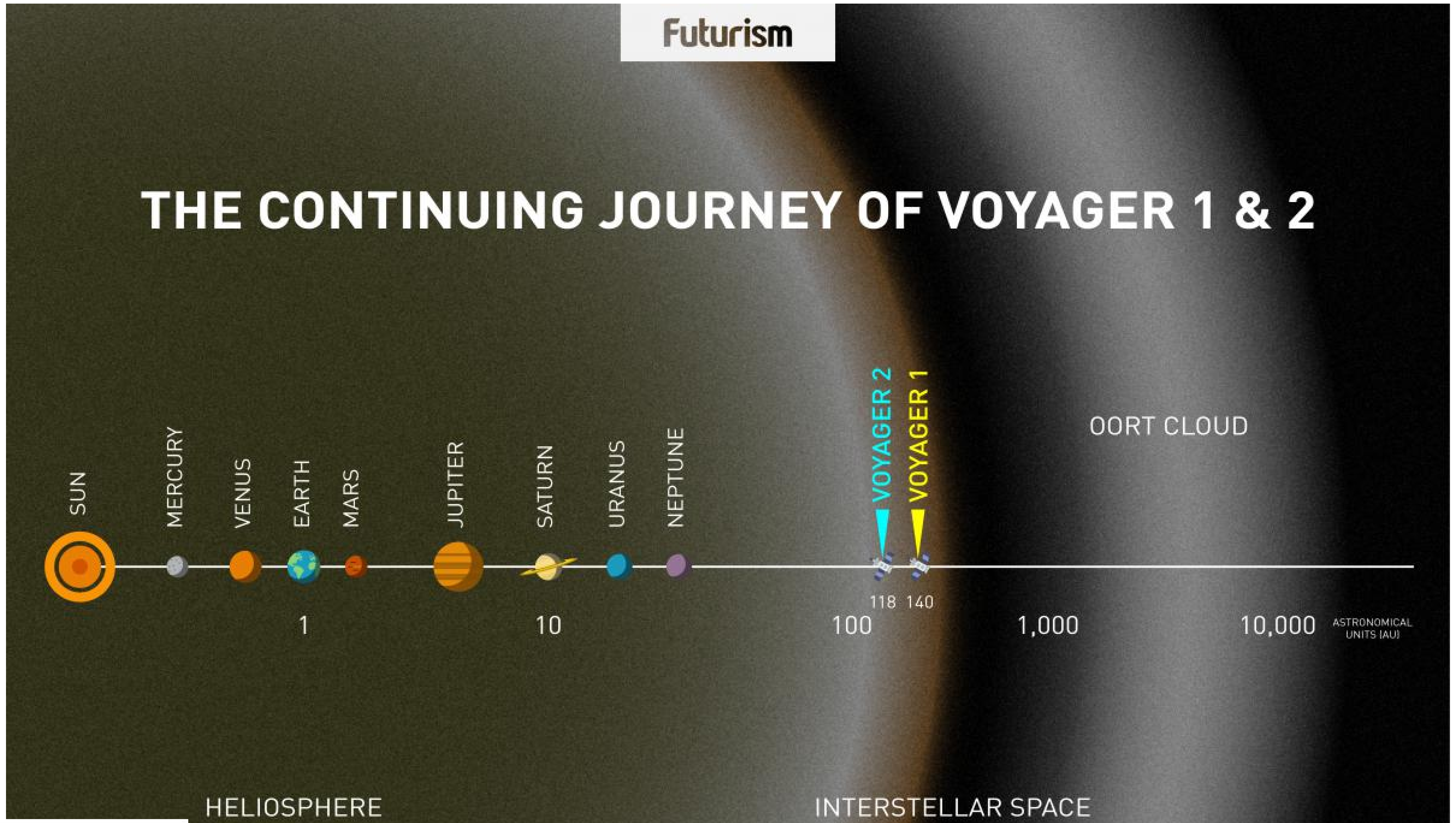
Telescope	Status	Energy Range	Reference
INTEGRAL	On 2002 October 17	15 keV to 10 MeV	0801.2086 1107.0200
e-ASTROGAM	2029	0.3 MeV to 3 GeV	1711.01265
COSI	2025	0.2 MeV to 5 MeV	2109.10403
GECCO	?	0.1 MeV to 8 MeV	2112.07190
AMEGO	?	0.2 MeV to 10 GeV	1907.07558
VLAST	?	100 MeV to 20 TeV	chinaXiv:202203.00033V2

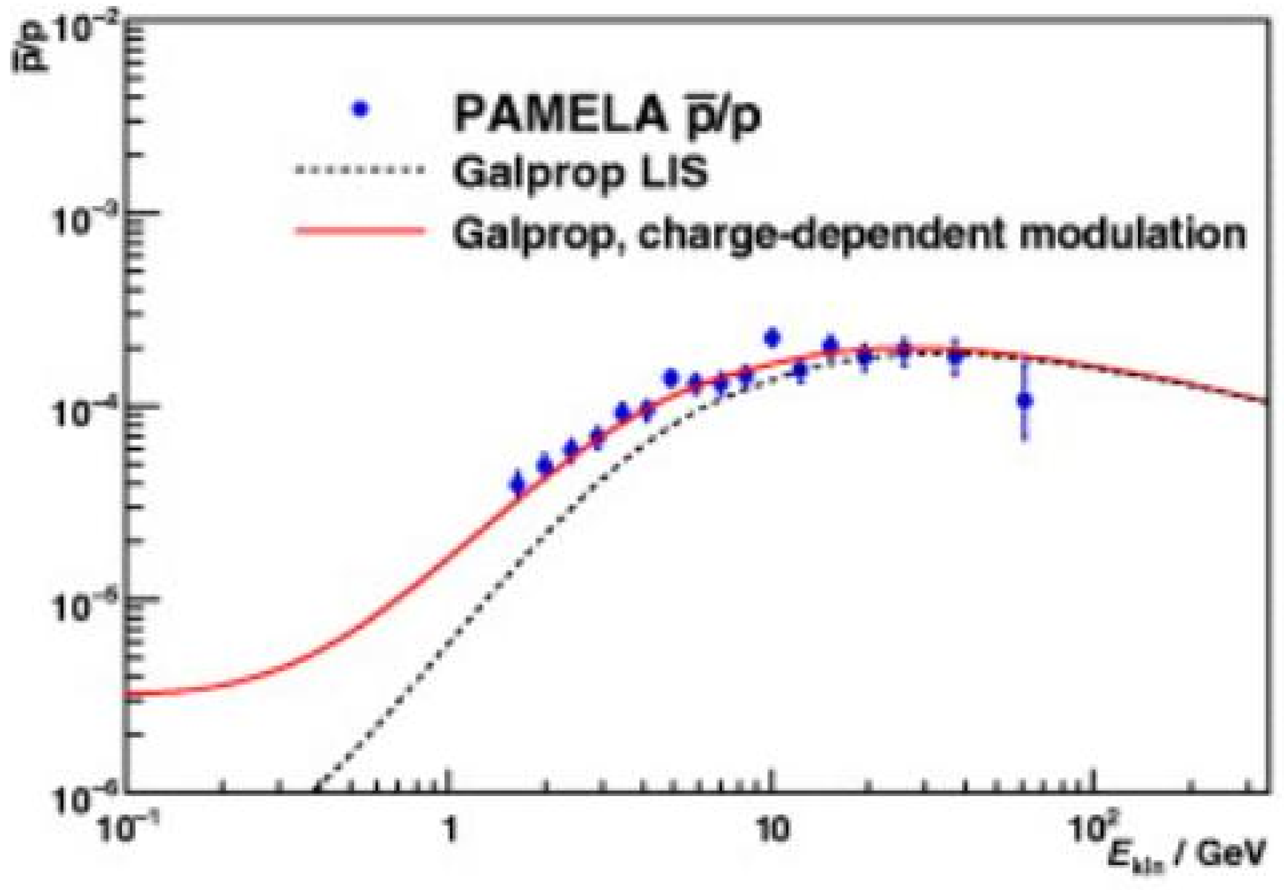
Topic 2: Cosmology and cosmic ray: two most strigent ID limits

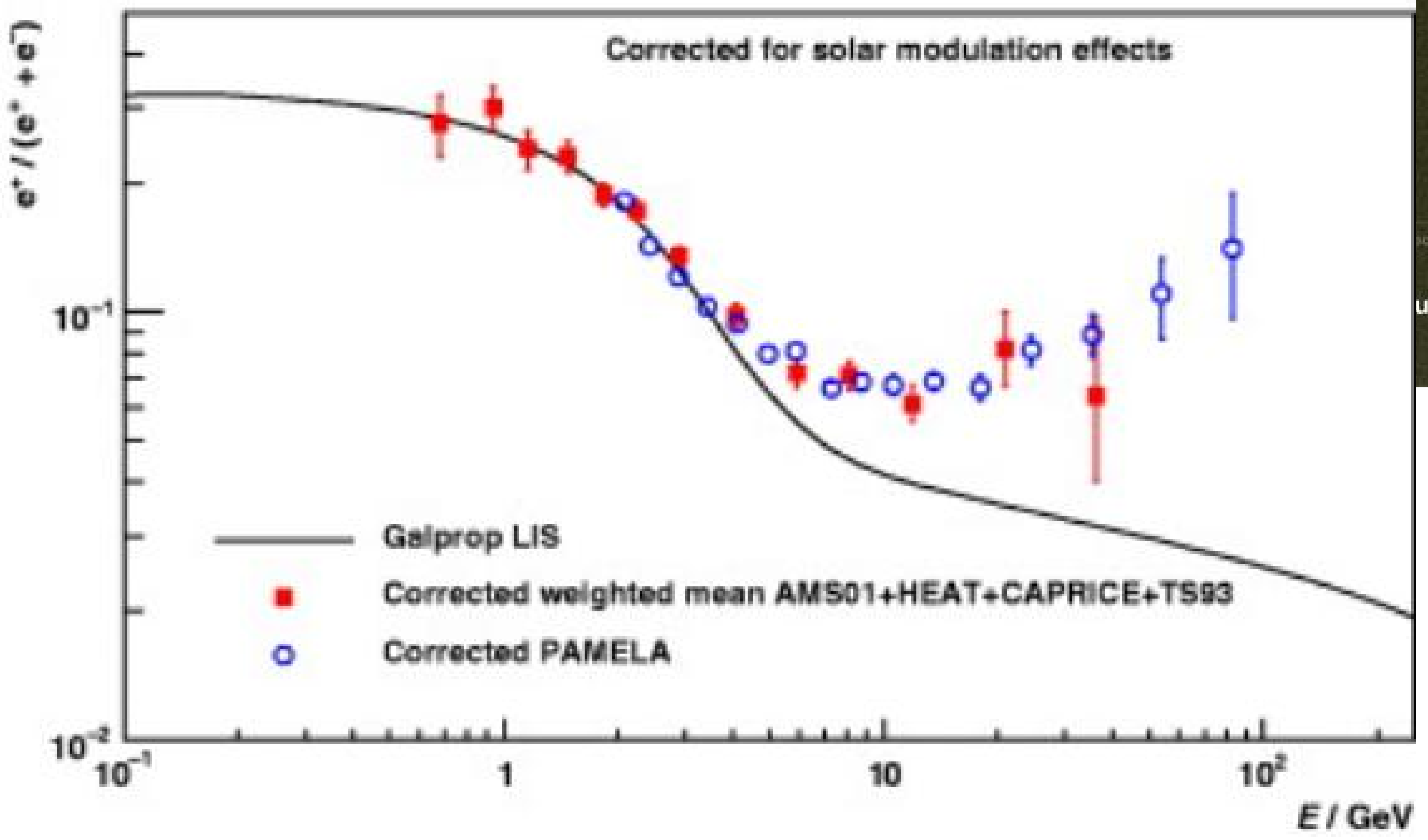
Dark matter freeze-out	?	?	?
Neutrino decoupling	1 s	6×10^9	1 MeV
Electron-positron annihilation	6 s	2×10^9	500 keV
Big Bang nucleosynthesis	3 min	4×10^8	100 keV
Matter-radiation equality	60 kyr	3400	0.75 eV
Recombination	260–380 kyr	1100–1400	0.26–0.33 eV
Photon decoupling	380 kyr	1000–1200	0.23–0.28 eV
Reionization	100–400 Myr	11–30	2.6–7.0 meV
Present	now	$0<z<2$	$v \sim 10^{-3}$ c

The DM cosmic ray spectra for MeV scale





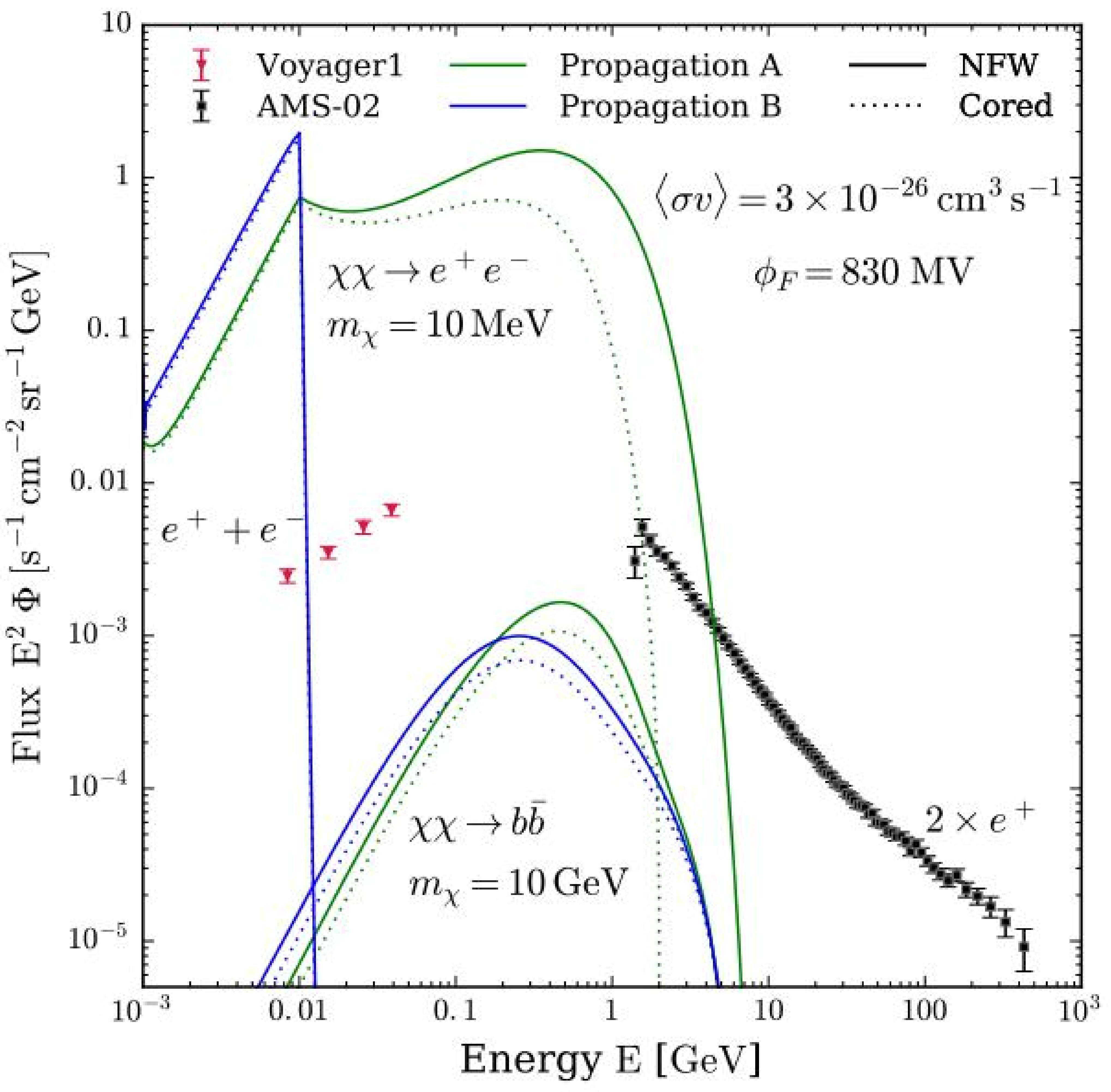




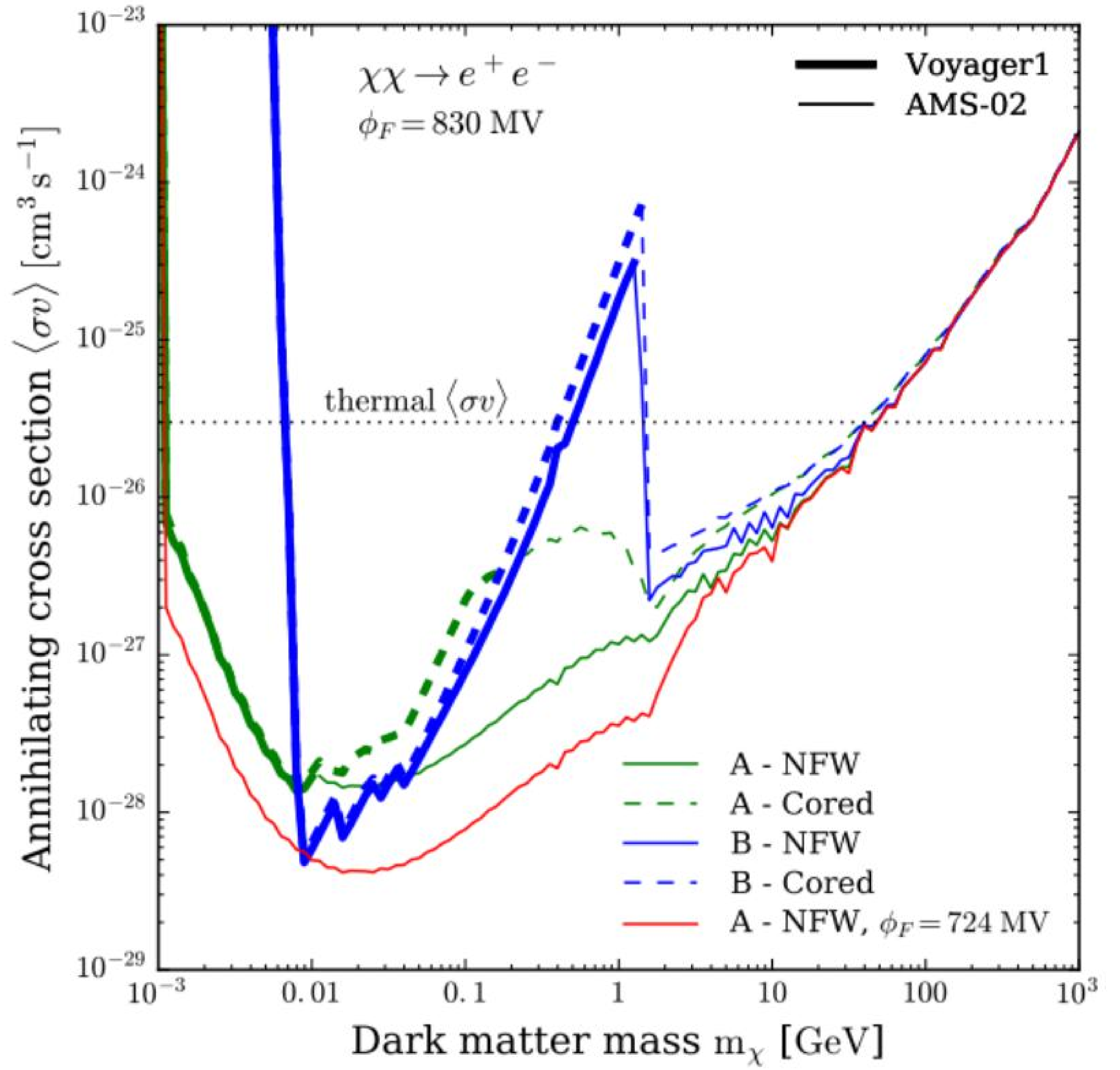
Beischer et. al. (2009)

Solar modulation can significantly change MeV DM indirect detection!

The DM cosmic ray spectra for MeV scale

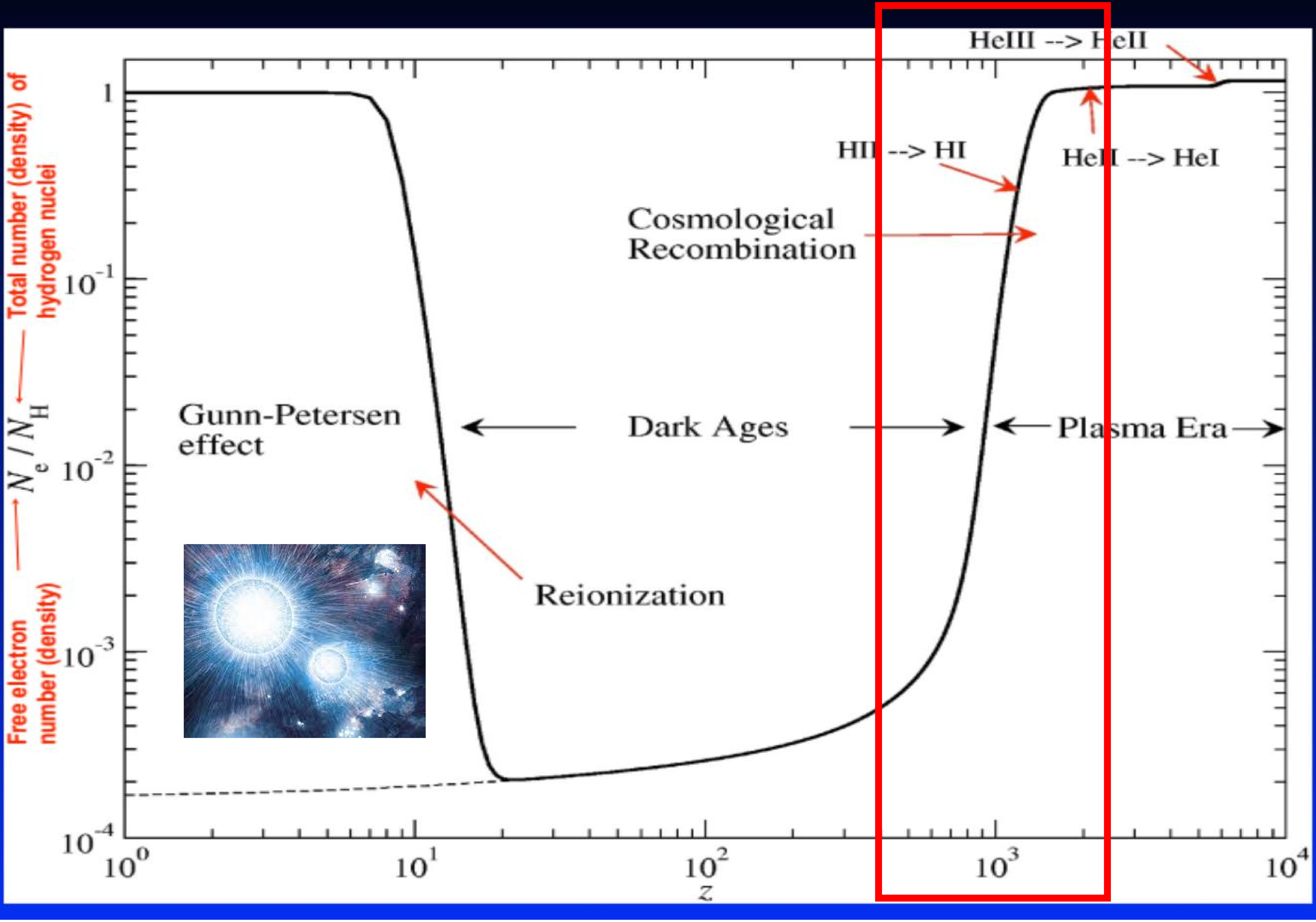


Phys.Rev.Lett. 119 (2017) 2, 021103
[1612.07698]



1e-28 cm3 s-1 for 10 MeV DM!

Sketch of the Cosmic Ionization History



- **at redshifts higher than ~10^4 Universe → *fully ionized***
- **$z \geq 10^4$ → *free electron fraction* $N_e/N_H \sim 1.16$** (Helium has 2 electrons and abundance ~ 8%)
- **HeIII → HeII recombination at z~6000**
- **HeII → HeI recombination at z~2000**
- **HII → HI recombination at z~1000**

Credit: Jens Chluba
CosmoTools 2018

CMB power spectrum distortion for MeV DM

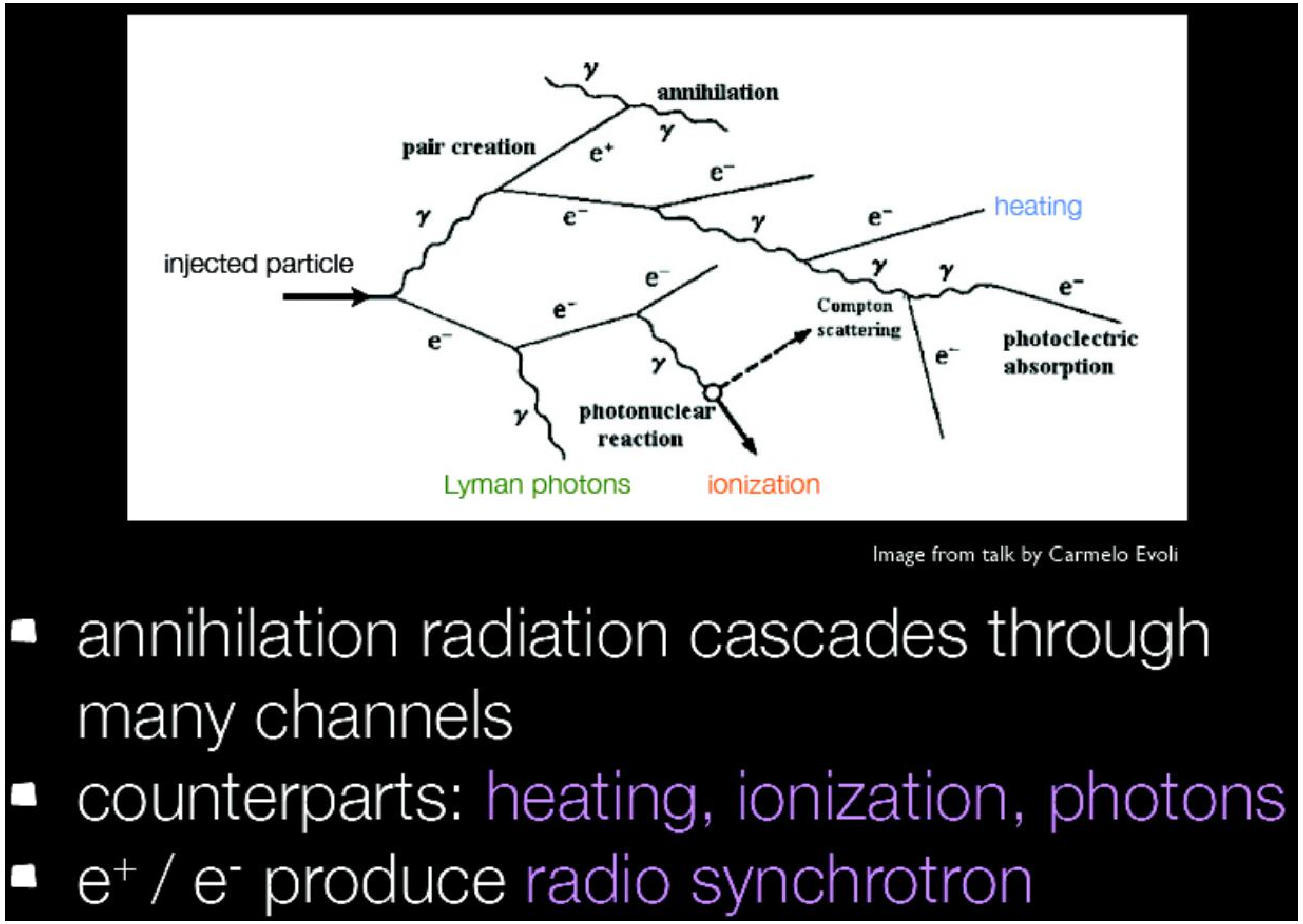
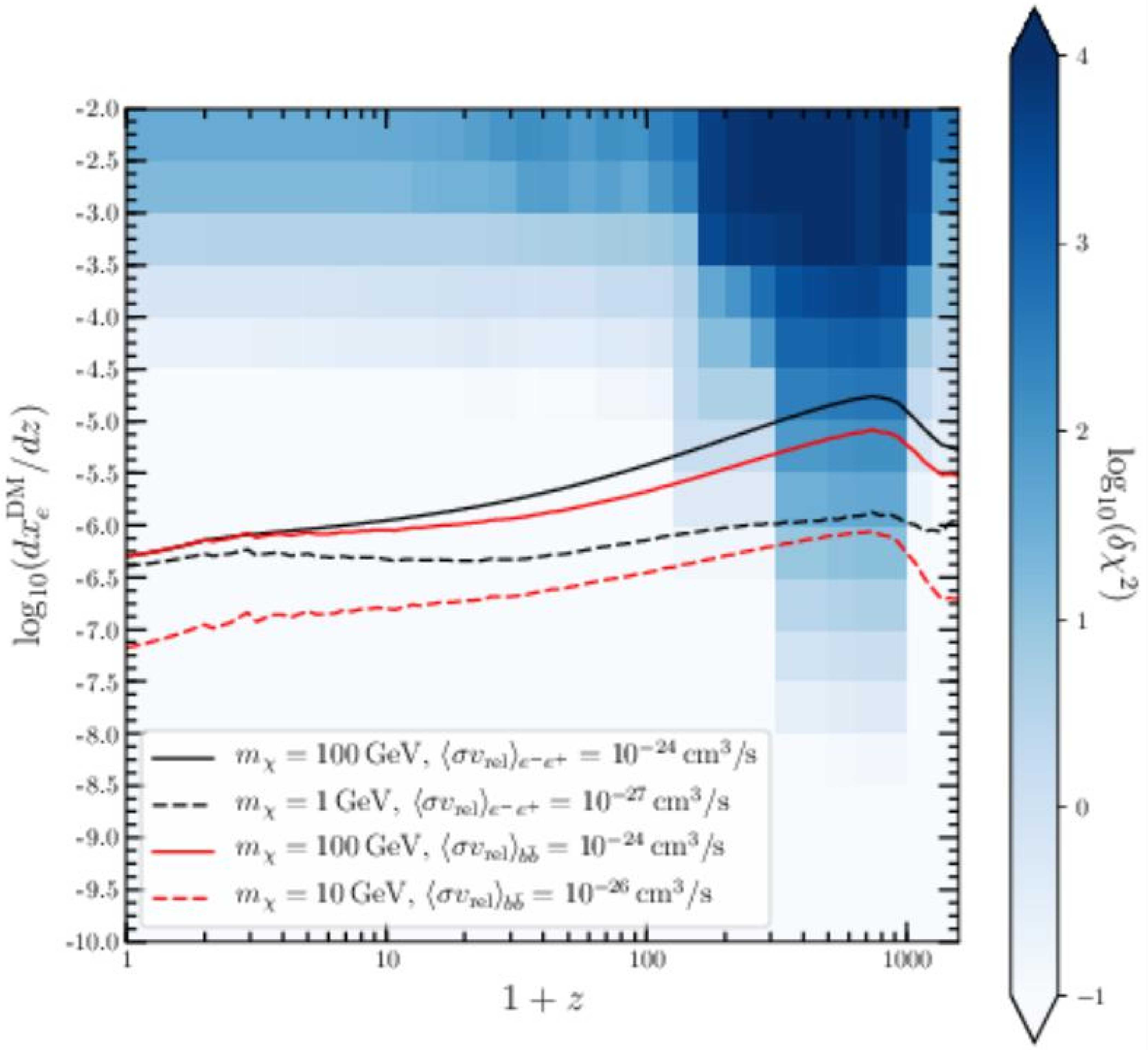


Image from talk by Carmelo Evoli

- annihilation radiation cascades through many channels
- counterparts: heating, ionization, photons
- e^+ / e^- produce radio synchrotron

$$\frac{d\chi^F_{i,h}(m_\chi,z,z')}{dz} = \int dE\, \frac{E}{m_\chi}\left[2\frac{dN^F_e}{dE}\frac{d\chi^e_{i,h}(E,z,z')}{dz} + \frac{dN^F_\gamma}{dE}\frac{d\chi^\gamma_{i,h}(E,z,z')}{dz}\right].$$

CMB power spectrum distortion for MeV DM



Planck 2018 data (TT, TE, and EE), and lensing power spectrum.

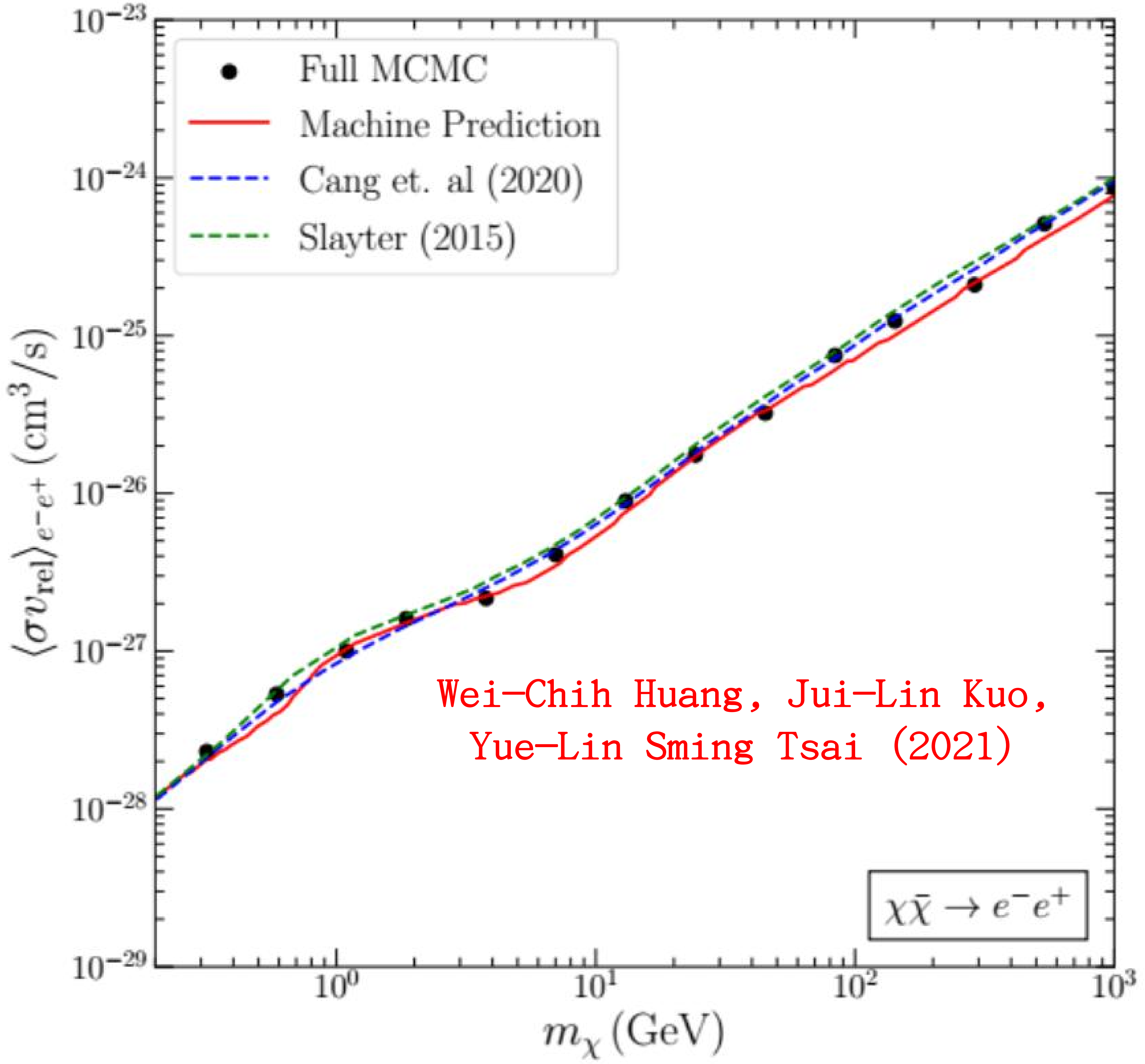
$$-\left[\frac{dx_e^{\rm DM}}{dz}\right]_{s\text{-wave}} = \sum_F {\rm Br}_F \int_z \frac{dz'}{H(z')(1+z')} \frac{n_\chi^2(z')\langle\sigma v_{\rm rel}\rangle}{2n_{\rm H}(z')} \frac{m_\chi}{E_{\rm RY}} \frac{d\chi_i^F(m_\chi,z,z')}{dz},$$

$$-\left[\frac{dT_g^{\rm DM}}{dz}\right]_{s\text{-wave}} = \sum_F {\rm Br}_F \int_z \frac{dz'}{H(z')(1+z')} \frac{n_\chi^2(z')\langle\sigma v_{\rm rel}\rangle}{3n_{\rm H}(z')} m_\chi \frac{d\chi_h^F(m_\chi,z,z')}{dz},$$

$$\left[\frac{dx_e^{\rm DM}}{dz}\right]_i = \begin{cases} \mathcal{N}_{\rm DM}, & \text{if } \; z_i \le z \le z_{i+1}, \\ 0, & \text{else.} \end{cases}$$

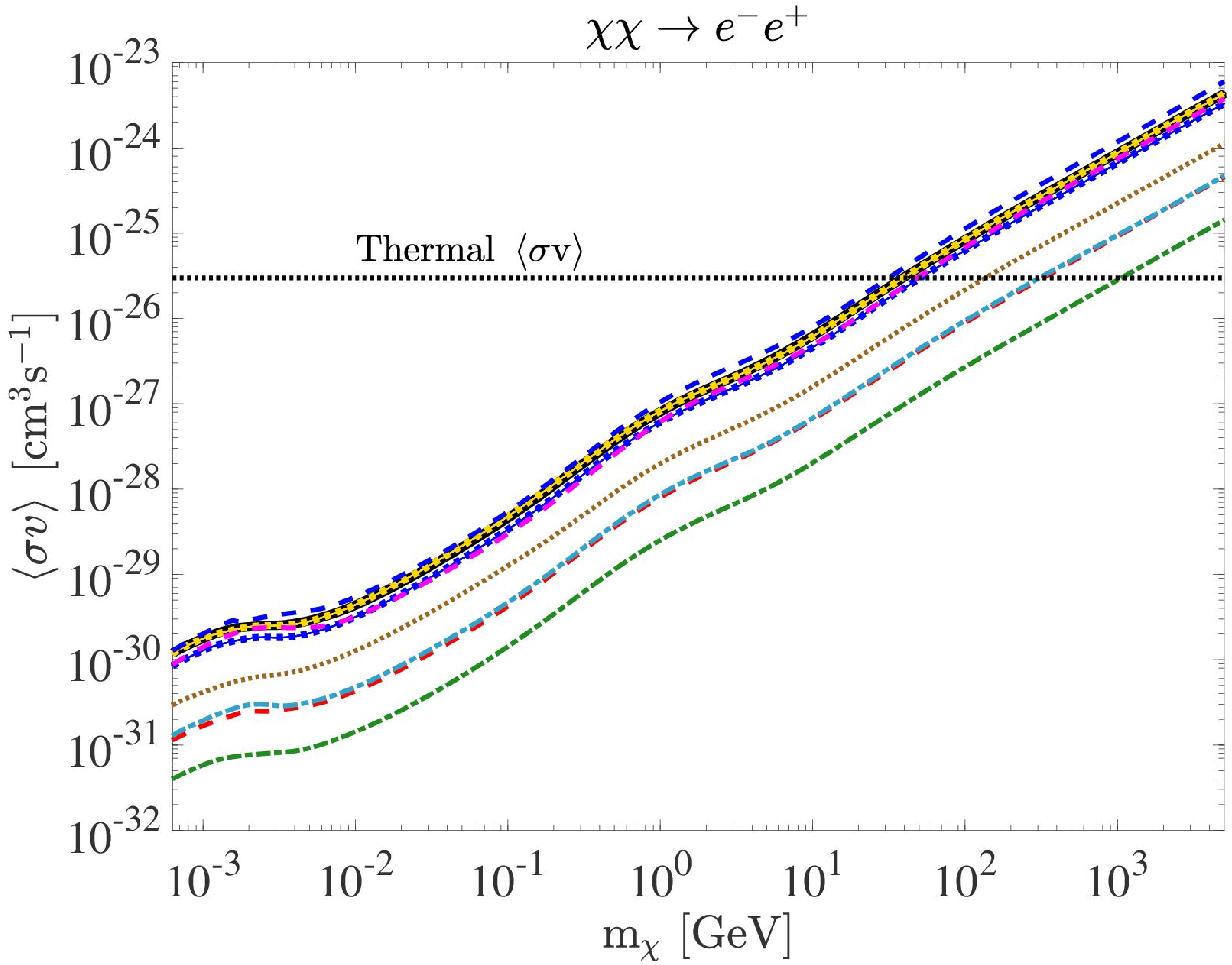
We can see Planck data is sensitive to Z~600.

CMB power spectrum distortion for MeV DM



Wei-Chih Huang, Jui-Lin Kuo, Yue-Lin Sming Tsai (2021)

Junsong Cang, Yu Gao, Yin-Zhe Ma (2020)



1e-30 cm3 s-1 for 10 MeV DM!

DM velocities at CMB and present?

$$\frac{T_\gamma^{\rm CMB}}{T_\gamma^{\rm FO}} = \frac{1+z_c}{1+z_F}$$

$$T_\chi^{\rm CMB} = \frac{(T_\gamma^{\rm CMB})^2}{T_\chi^{\rm FO}}$$

Diamanti, Lopez-Honorez, Mena, Palomares-Ruiz and Vincent,
JCAP **02**, 017 (2014)
[arXiv:1308.2578].

$$\frac{T_\chi^{\rm CMB}}{T_\chi^{\rm FO}} = \left[\frac{1+z_c}{1+z_F}\right]^2$$

$$= \frac{x_F}{m_\chi} \times (T_\gamma^{\rm CMB})^2$$

For a DM with mass around 0.1 GeV and its freeze-out temperature is around 5 MeV, then the DM velocity at z=600 is 1e-8 c.
However, the later nonlinear effect from gravitational acceleration boosts DM to 1e-3c.

DM velocities at CMB and present?

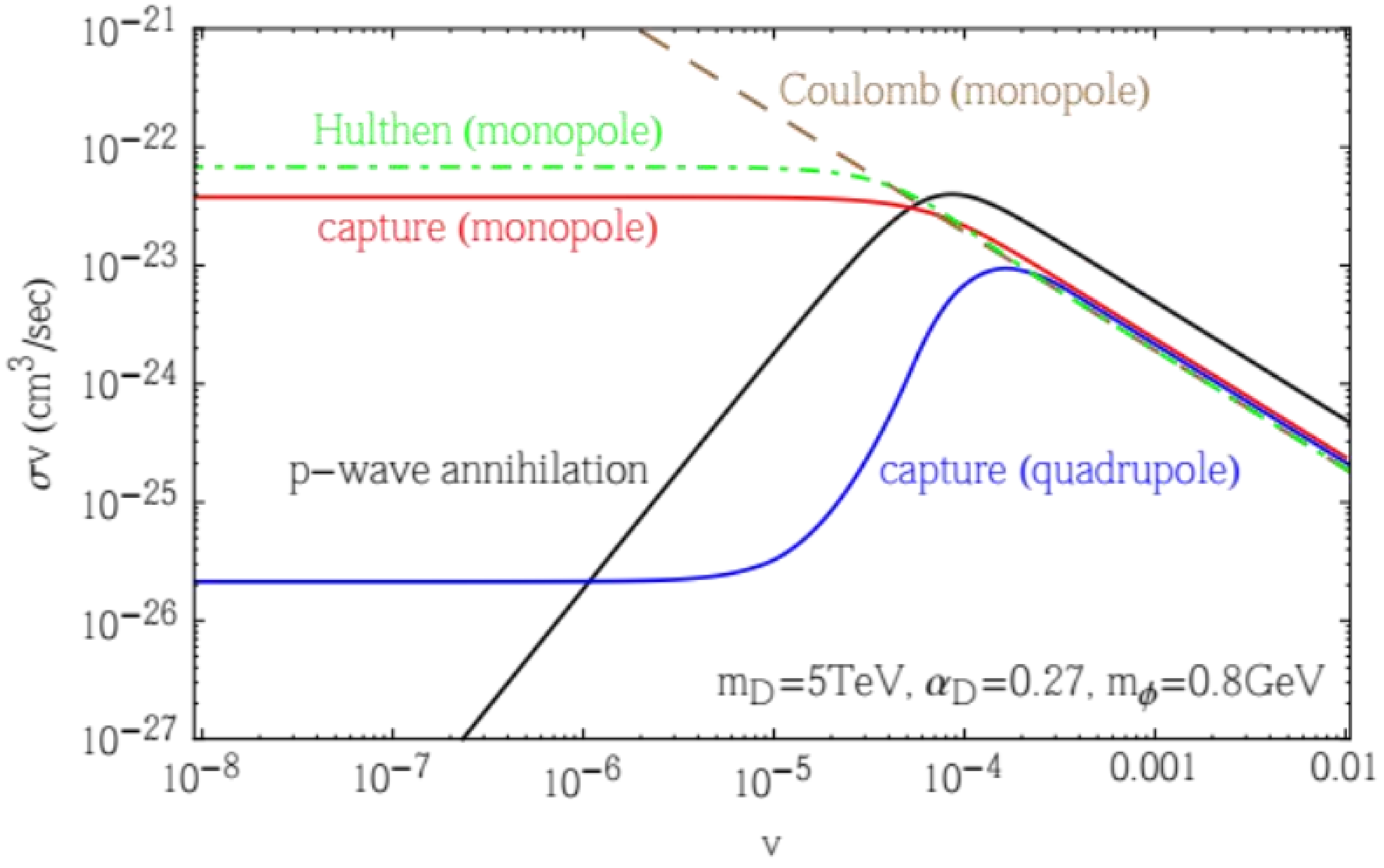
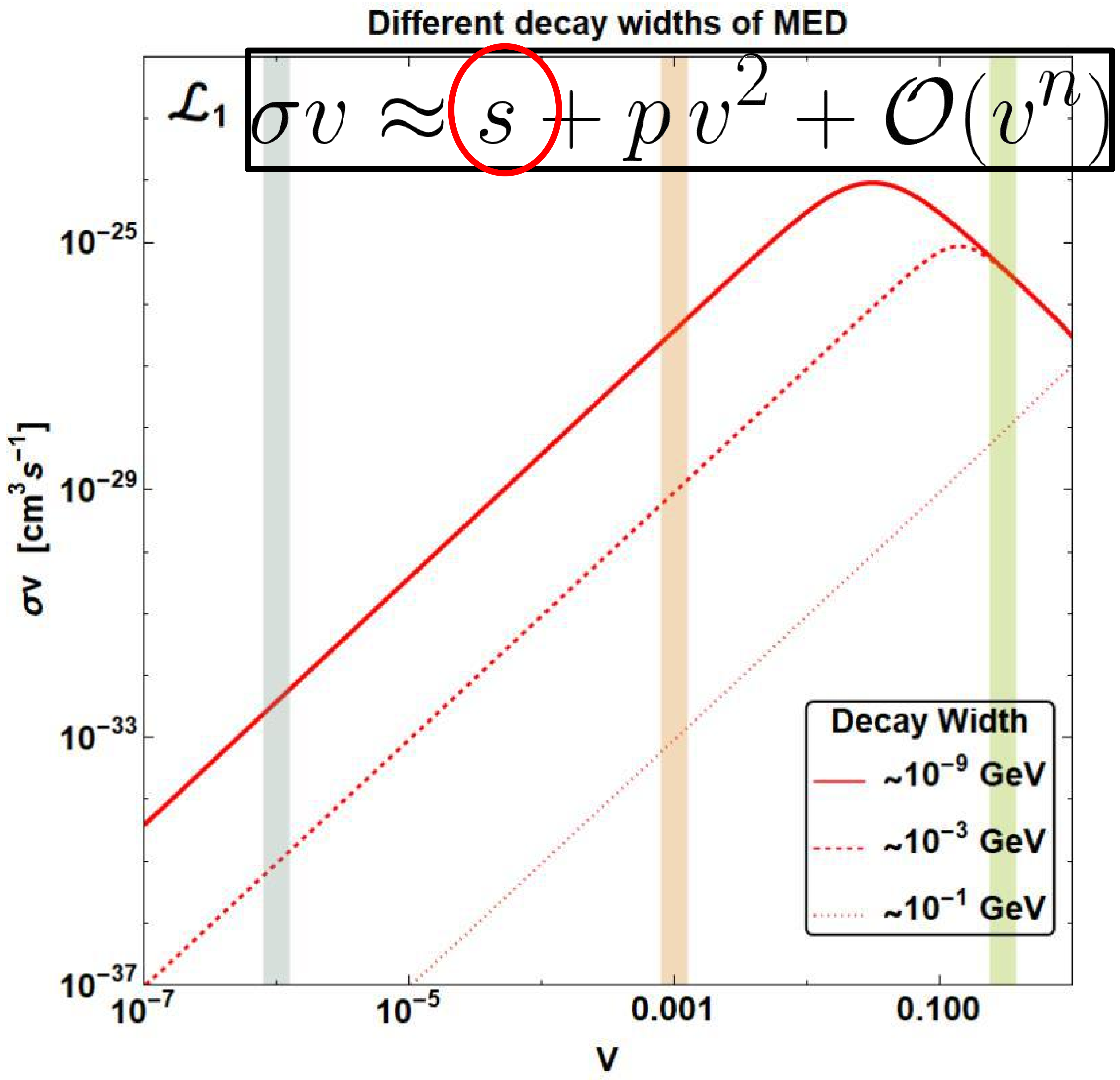


FIG. 1: DM relative velocity dependence in various cross sections. The black curve is the p-wave direct annihilation cross section for $\chi\bar{\chi} \to \phi\phi$. The red curve is the $(\chi\bar{\chi})$ bound state formation cross section via monopole transition, evaluated numerically using Eqs. (4) and (5). The blue curve stands for quadrupole transition counterpart. The brown line is the monopole transition cross section in the Coulomb limit, while the green curve is based on the Hulthén potential which gives a quite good approximation to the realistic Yukawa potential.

Haipeng An, Mark B. Wise, and Yue Zhang
(1606.02305)



$$\sigma v \approx \boxed{s} + p\,v^2 + \mathcal{O}(v^n)$$

Topic 3: 21 Cosmology

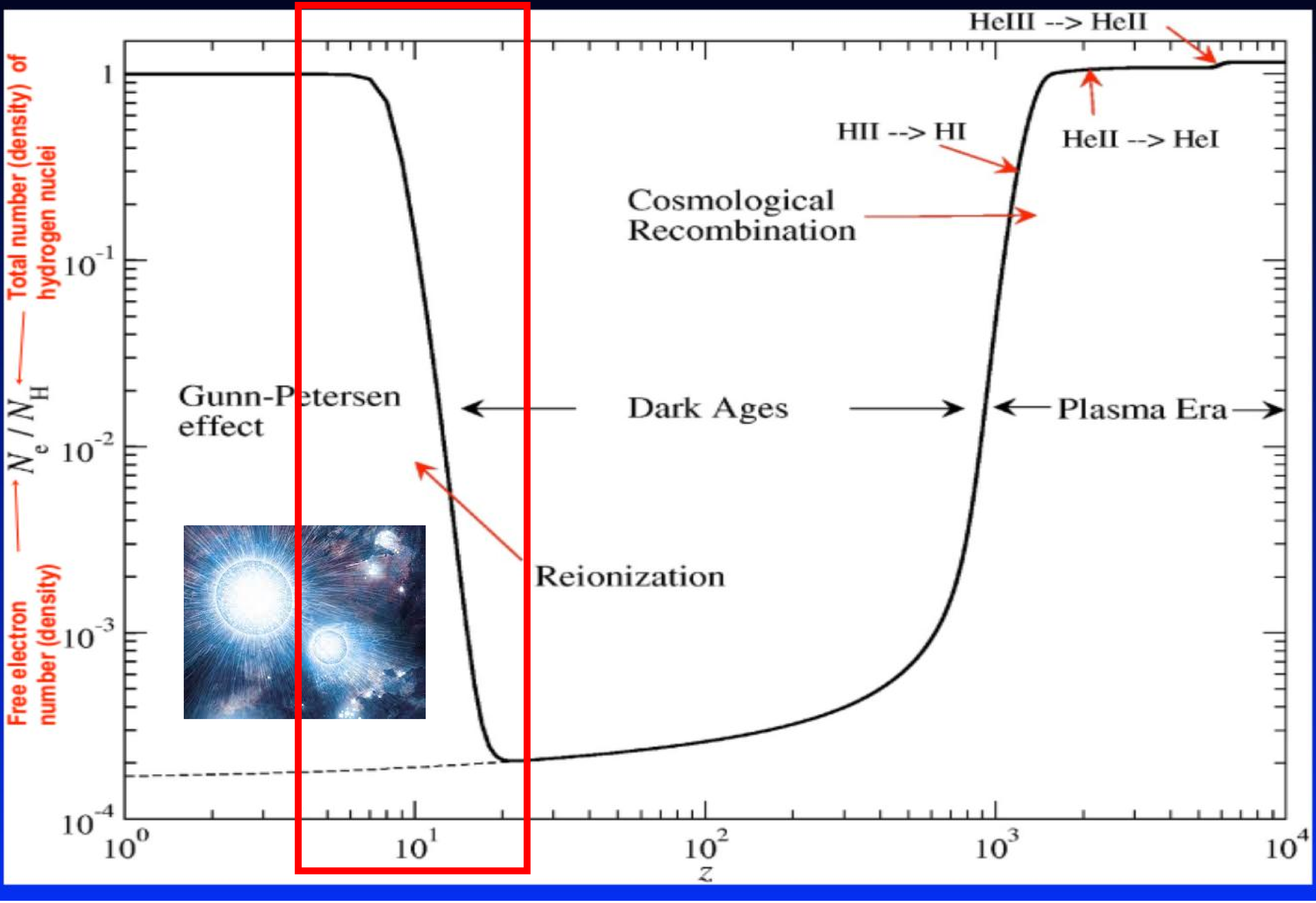
EDGES

Nature 555 (2018) 7694, 67-70

SARAS 3

Nature Astron. **6**, no.5, 607-617 (2022)

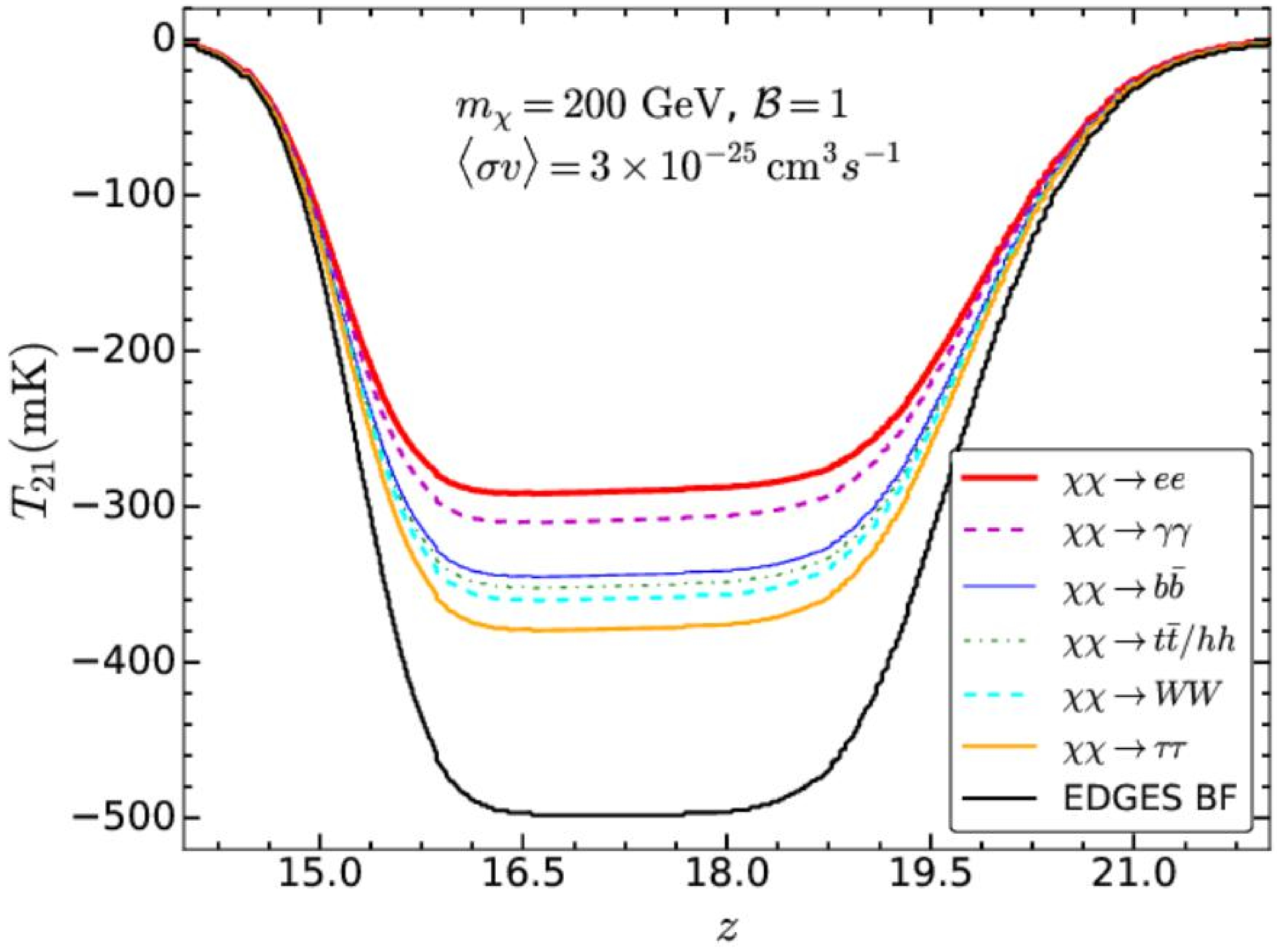
Sketch of the Cosmic Ionization History



- at redshifts higher than ~10^4 Universe → *fully ionized*
- **z ≥ 10^4 →** *free electron fraction* N_e/N_H **~ 1.16** (Helium has 2 electrons and abundance ~ 8%)
- **HeIII → HeII recombination at z~6000**
- **HeII → HeI recombination at z~2000**
- **HII → HI recombination at z~1000**

Credit: Jens Chluba
CosmoTools 2018

EDGES 21 cm



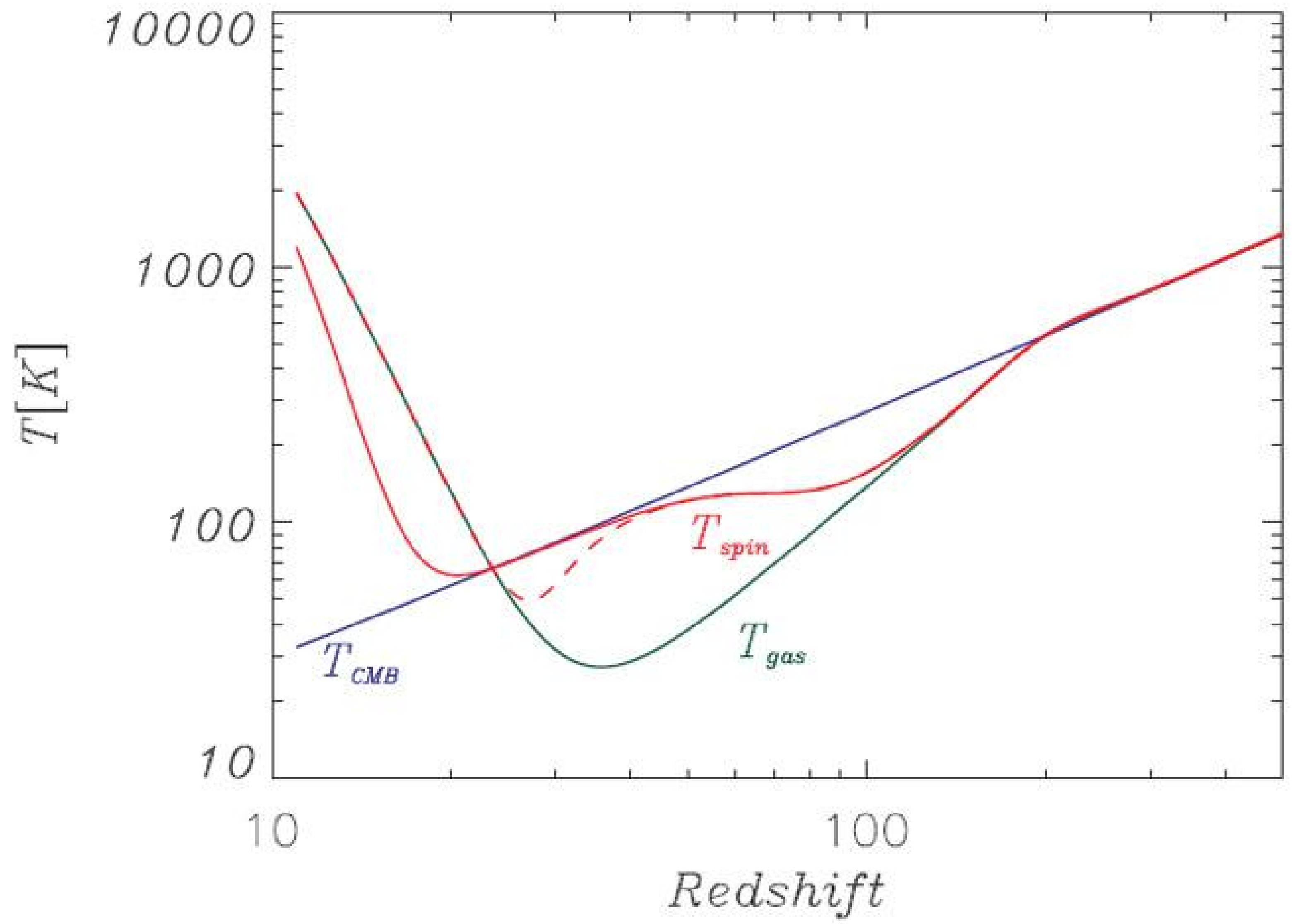
EDGES has recently measured an absorption feature for 21-cm emission [9]. At the redshift $z = 17.2$, the temperature T_{21} at 99% confidence level (C.L.) is reported by

$$T_{21}^{\rm EDGES} = -500^{+200}_{-500}\,{\rm mK}, \tag{1}$$

where the errors $^{+200}_{-500}$ mK present the systematic uncertainties.

On the other hand, the theoretical prediction is given by

$$T_{21}(z) \simeq 23\,{\rm mK}\left[1 - \frac{T_\gamma(z)}{T_s(z)}\right]\left(\frac{\Omega_b h^2}{0.02}\right)\left(\frac{0.15}{\Omega_m h^2}\right)\sqrt{\frac{1+z}{10}}\,x_{HI}, \tag{2}$$



21 cm brightness temperature and Spin temperature

@ 21 cm brightness temperature:

$$T_{21}(z) \simeq 23\mathrm{mK}\left[1-\frac{T_\gamma(z)}{T_s(z)}\right]\left(\frac{\Omega_b h^2}{0.02}\right)\left(\frac{0.15}{\Omega_m h^2}\right)\sqrt{\frac{1+z}{10}}\,x_{HI}$$

@ Spin temperature:

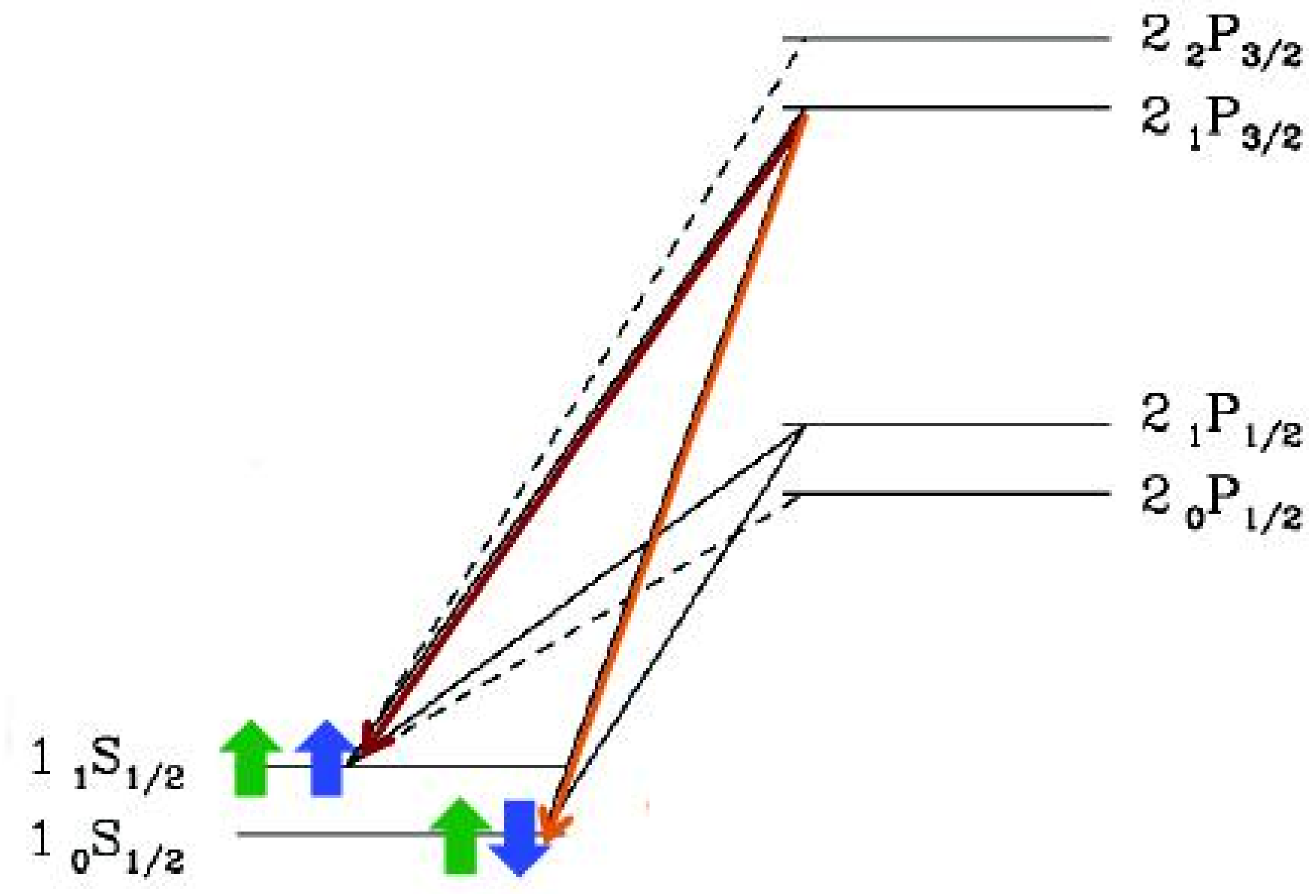
Color temperature of ambient Ly-α radiation

Gas temperature

$$T_S^{-1} = \frac{T_\gamma^{-1}+x_\alpha T_\alpha^{-1}+x_c T_K^{-1}}{1+x_\alpha+x_c}$$

Gas collision pumping efficiency

Ly-α pumping efficiency

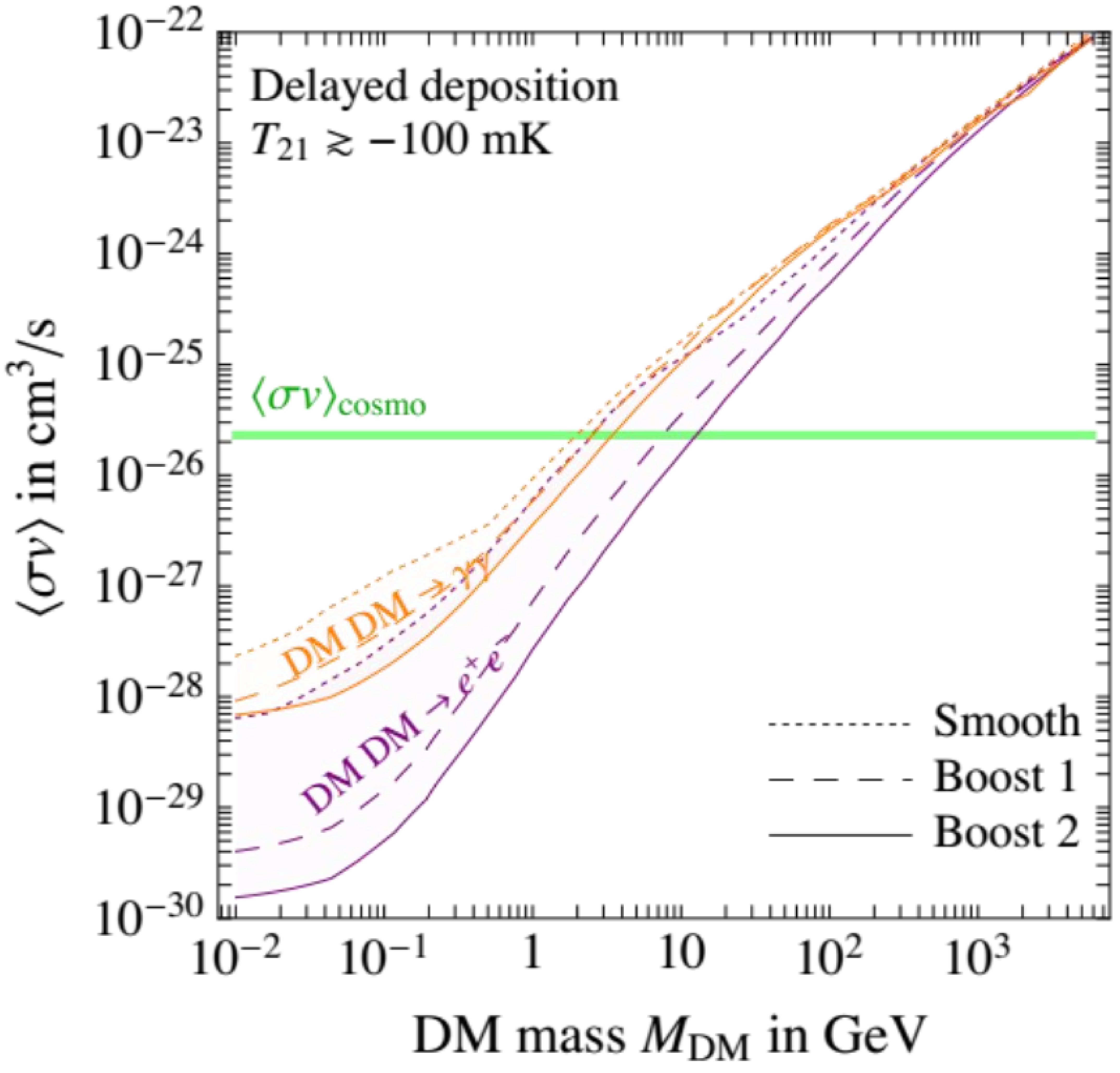


Wouthuysen-Field effect

Electron spin redistribution: $\frac{n_u}{n_l}=\frac{g_u}{g_l}\exp\left(-\frac{\Delta E_{\ 21cm}}{k_b T_s}\right)$

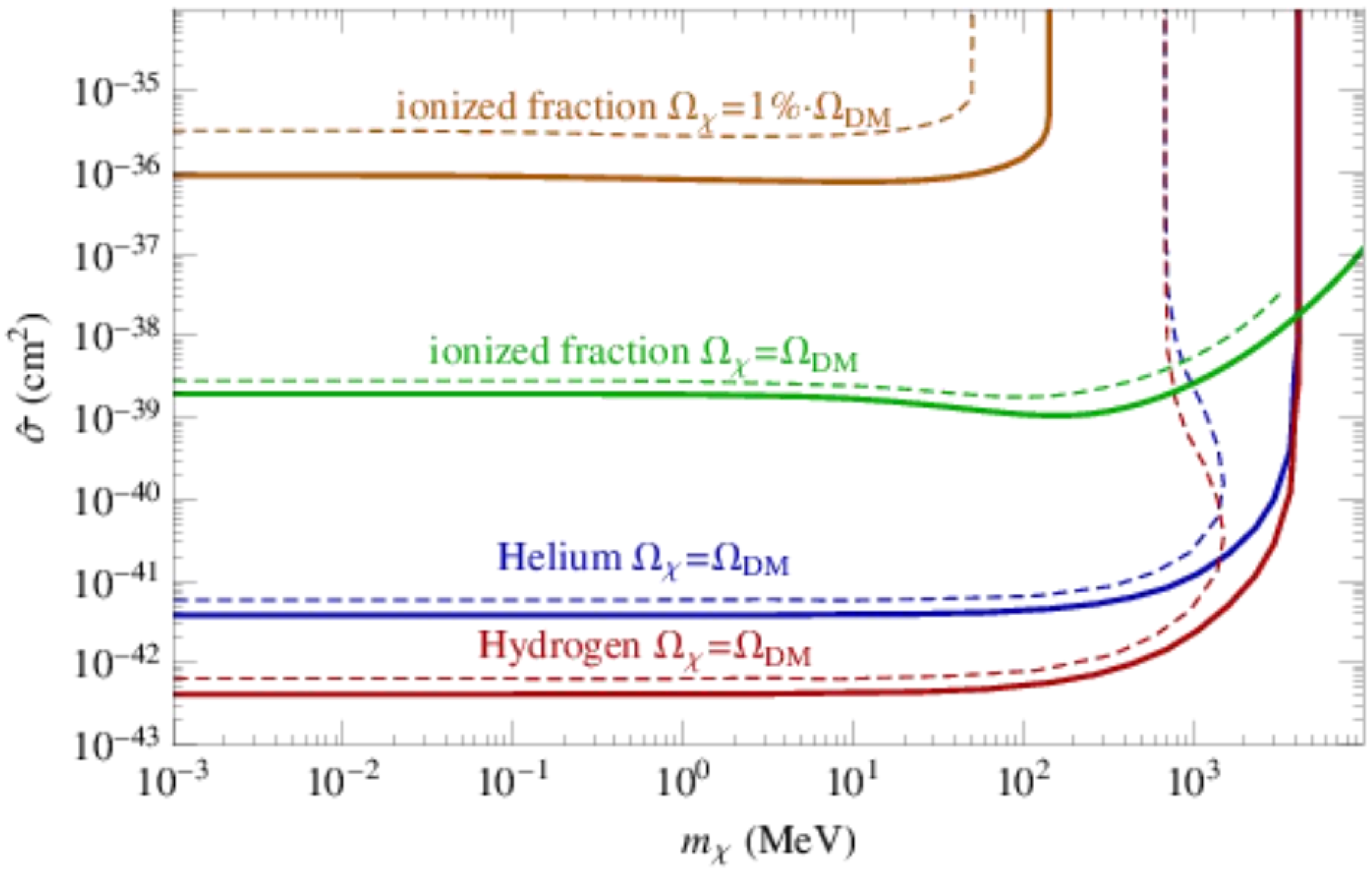
EDGES 21 cm

Guido D'Amico, Paolo Panci,
Alessandro Strumia (1803.03629)

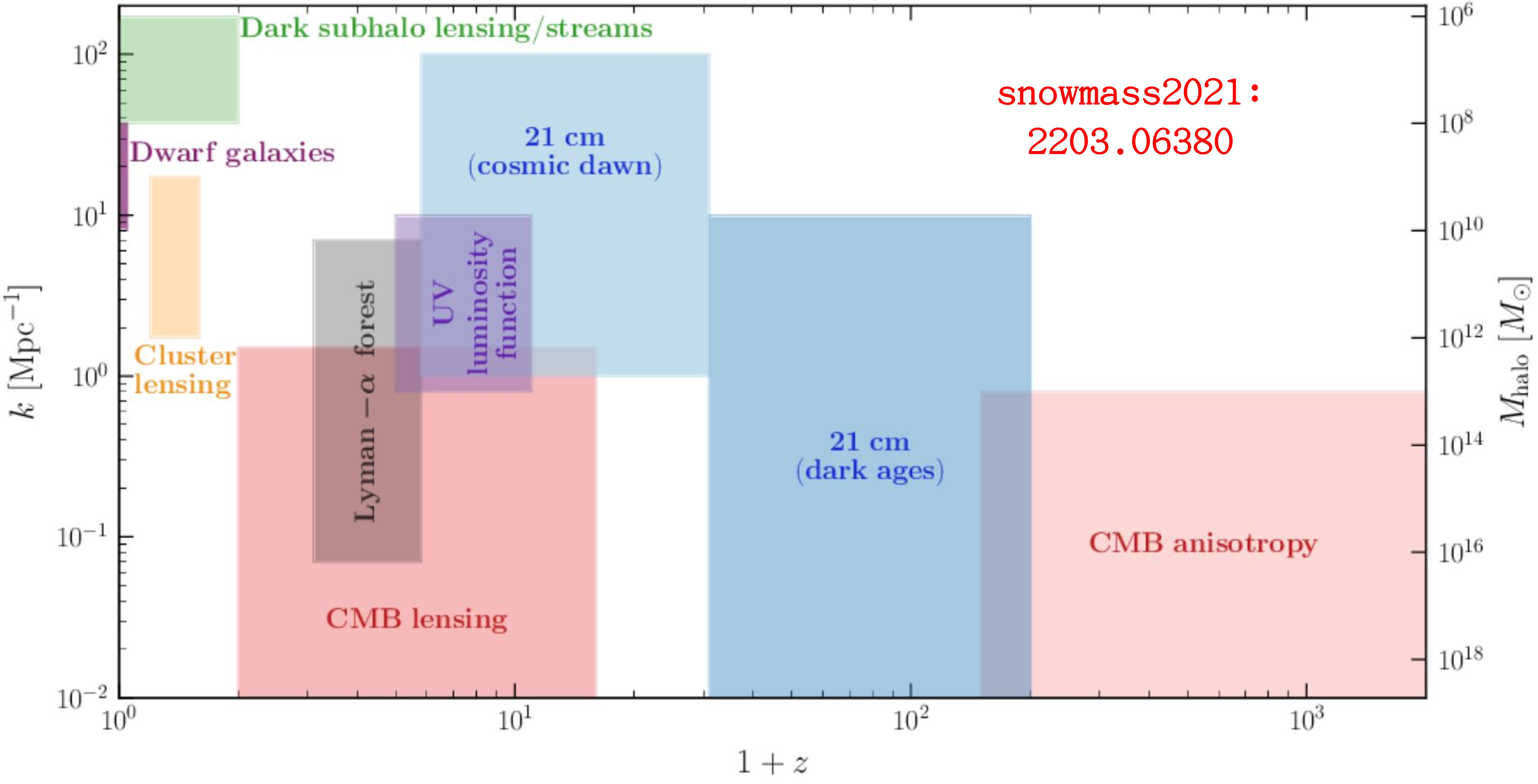


1e-30 cm3 s-1 for 10 MeV DM!

Rennan Barkana, Nadav Joseph Outmezguine,
Diego Redigolo, Tomer Volansky (1803.03091)



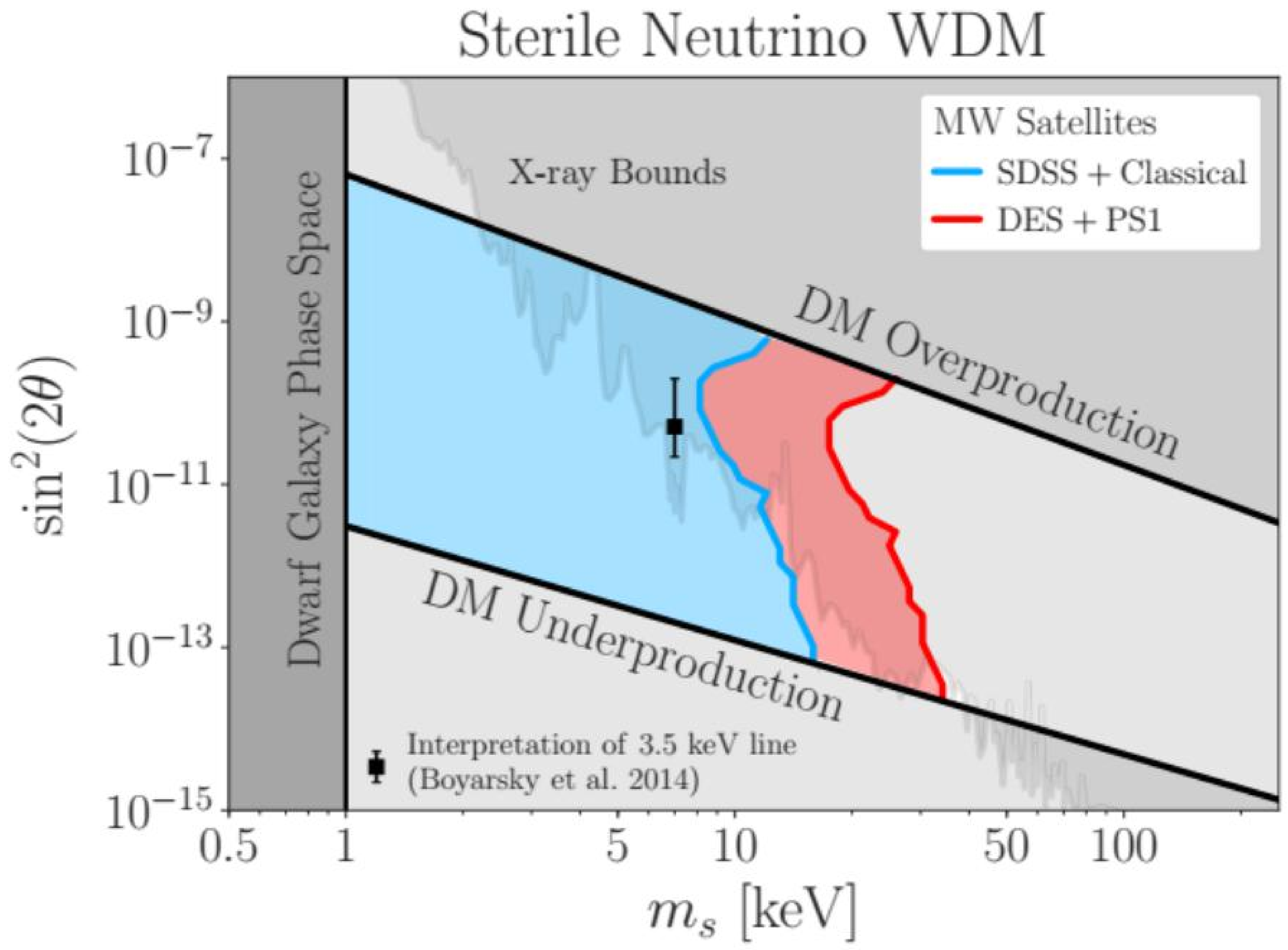
Constraints on scattering cross section!

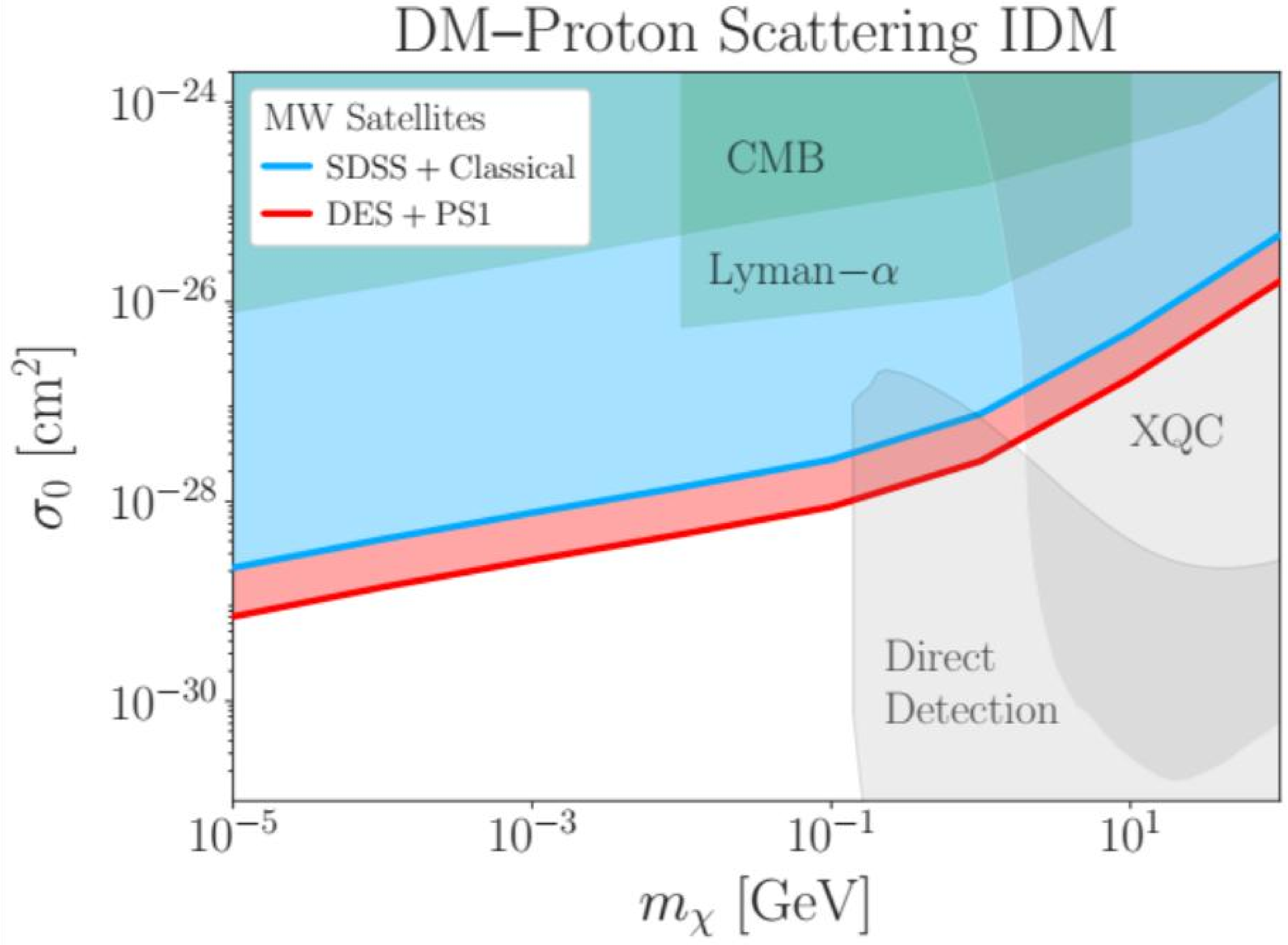


snowmass2021:
2203.06380

Topic 4: halo mass function

E. O. Nadler et al. [DES],
``Milky Way Satellite Census. III. Constraints on Dark Matter Properties from Observations of Milky Way Satellite Galaxies,''
Phys. Rev. Lett. 126 (2021), 091101
[arXiv:2008.00022].





Topic 5: CR boosted DM (see Prof. 王雯宇's lecture)

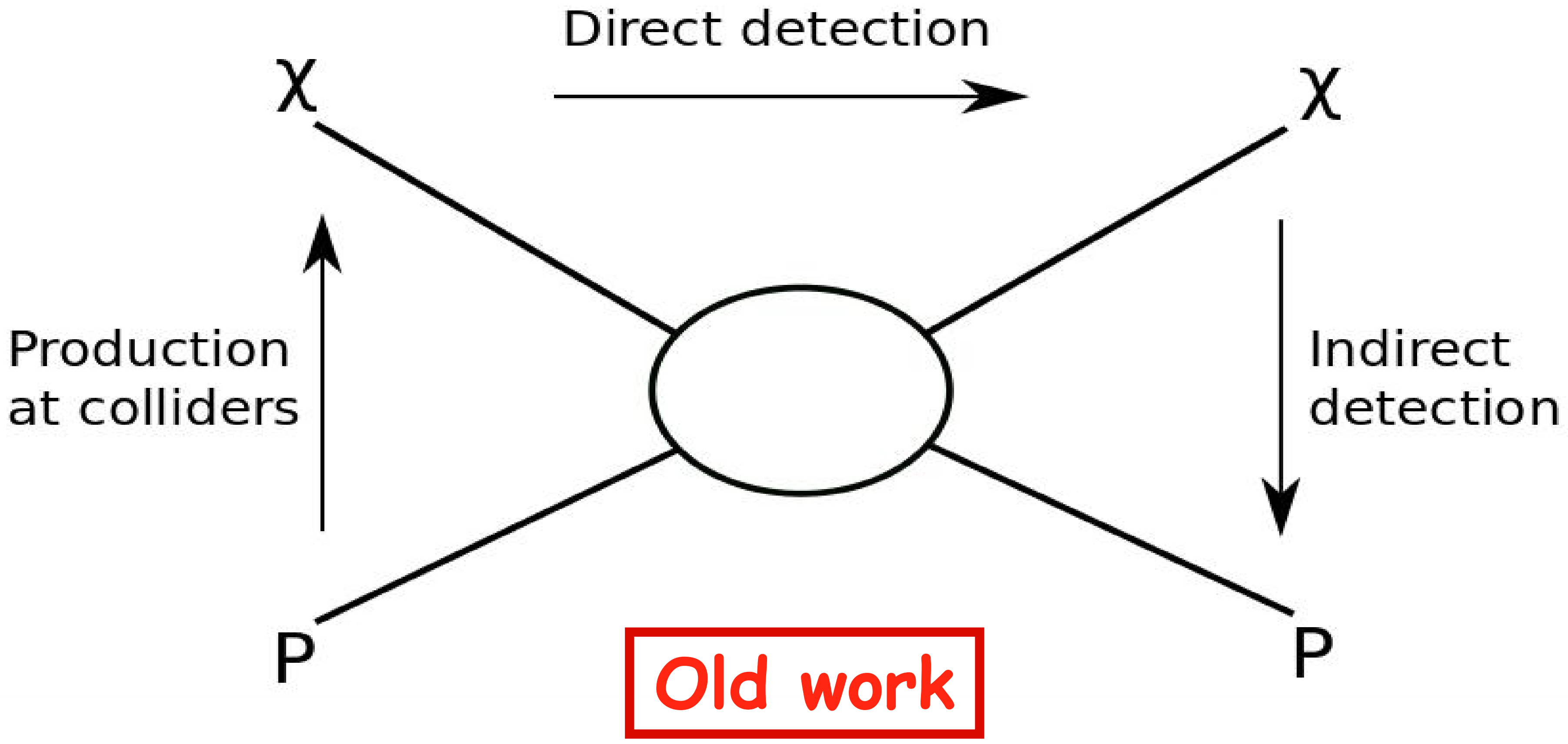
DM-CR elastic and inelastic scattering

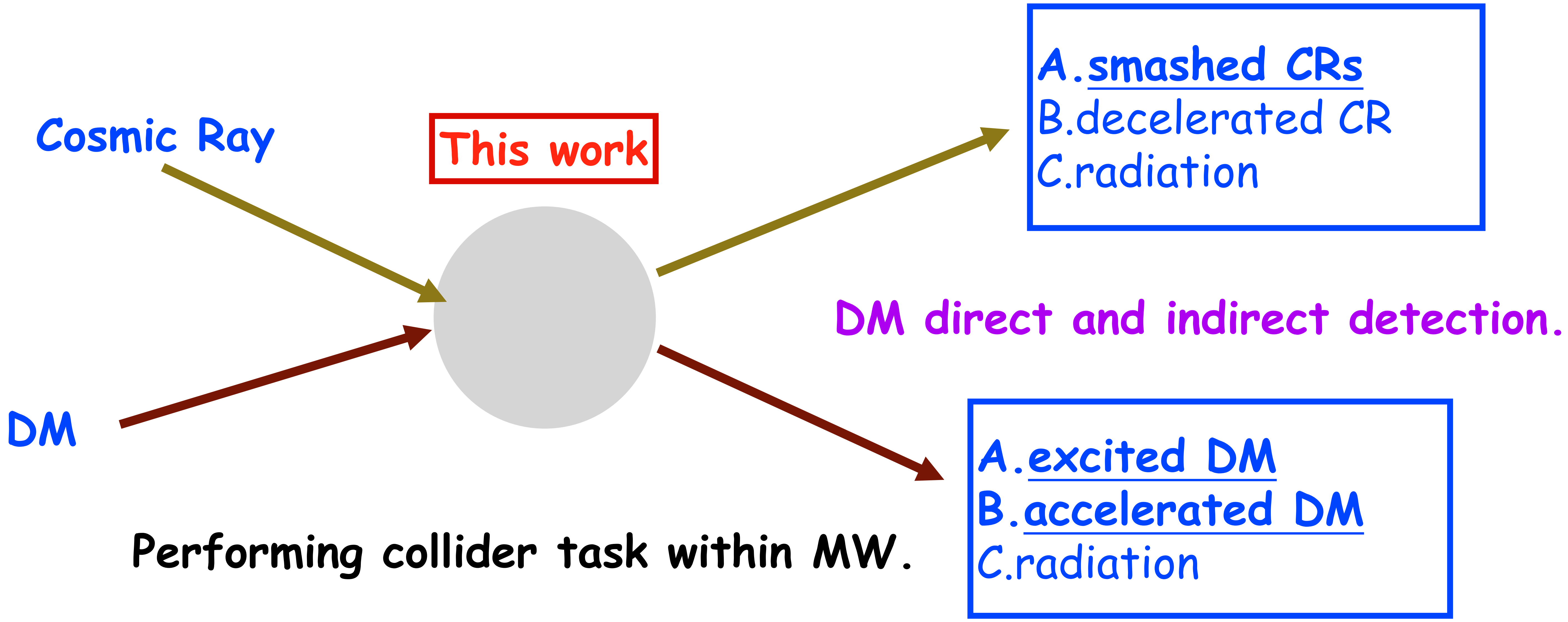
※We are facing the neutrino floor in underground detectors.（Can we use the same data for MeV DM?）

※No buget for buliding new high energy and luminosity collider. (How can we measure the mass, coupling, and spin of DM?)

※Sub-GeV DM can be accerlated by CRs. (Can this be a solution of above two questions?)

※Usually, the classical DM measurements (DD, ID, collider) are based on three processes. (Can we just use one process?)





A.smashed CRs
B.decelerated CR
C.radiation

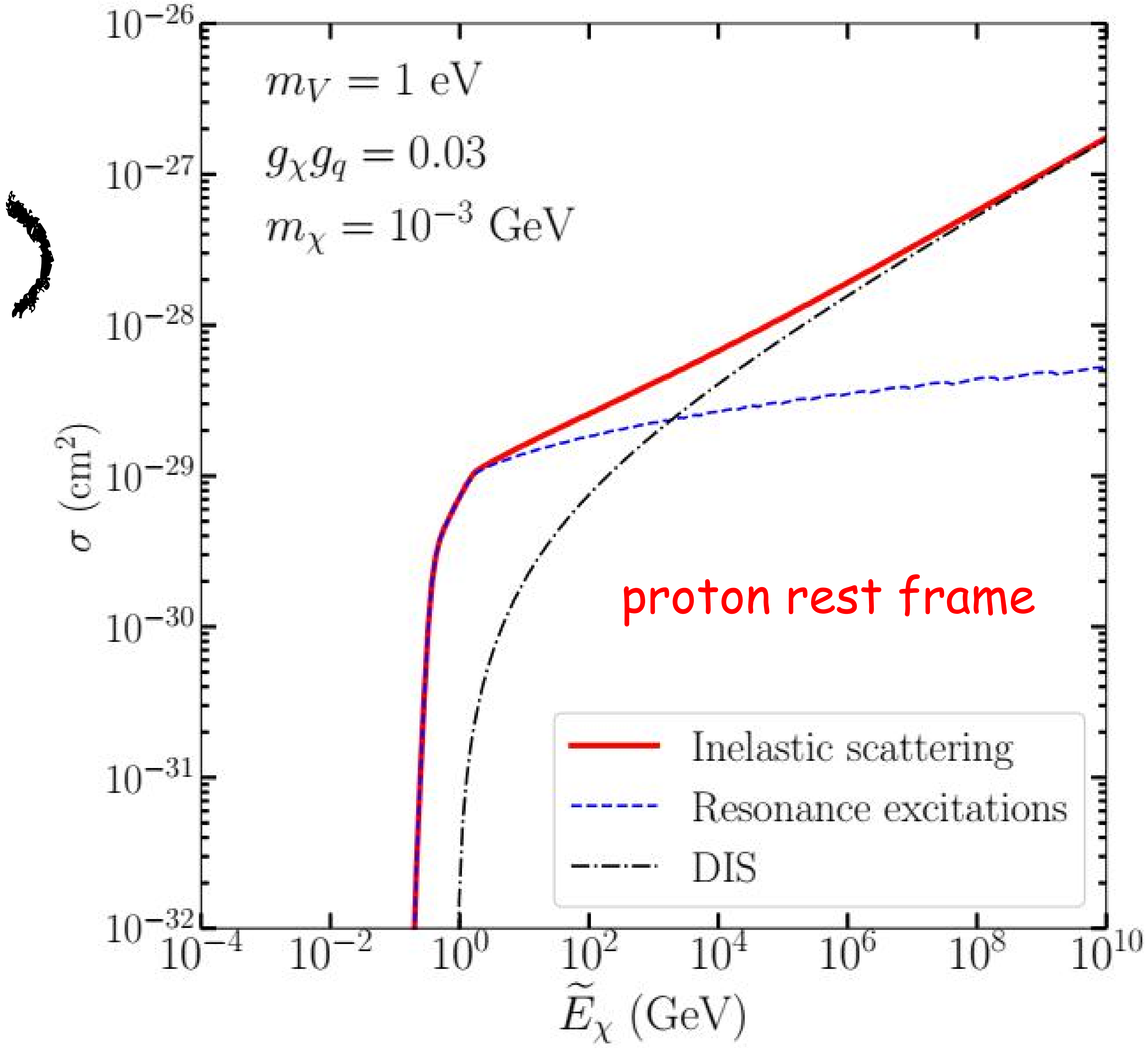
DM direct and indirect detection.

A.excited DM
B.accelerated DM
C.radiation

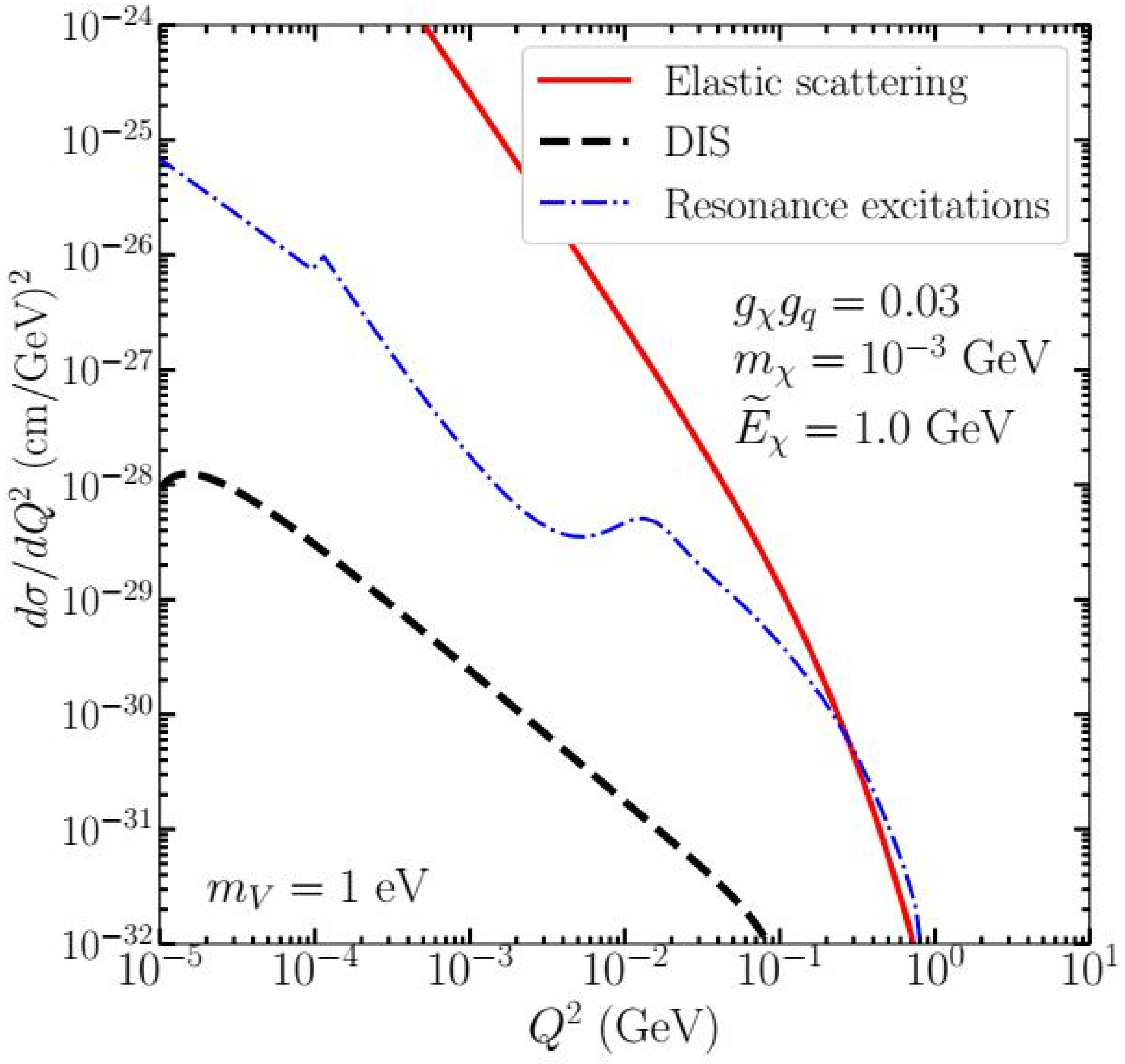
Performing collider task within MW.

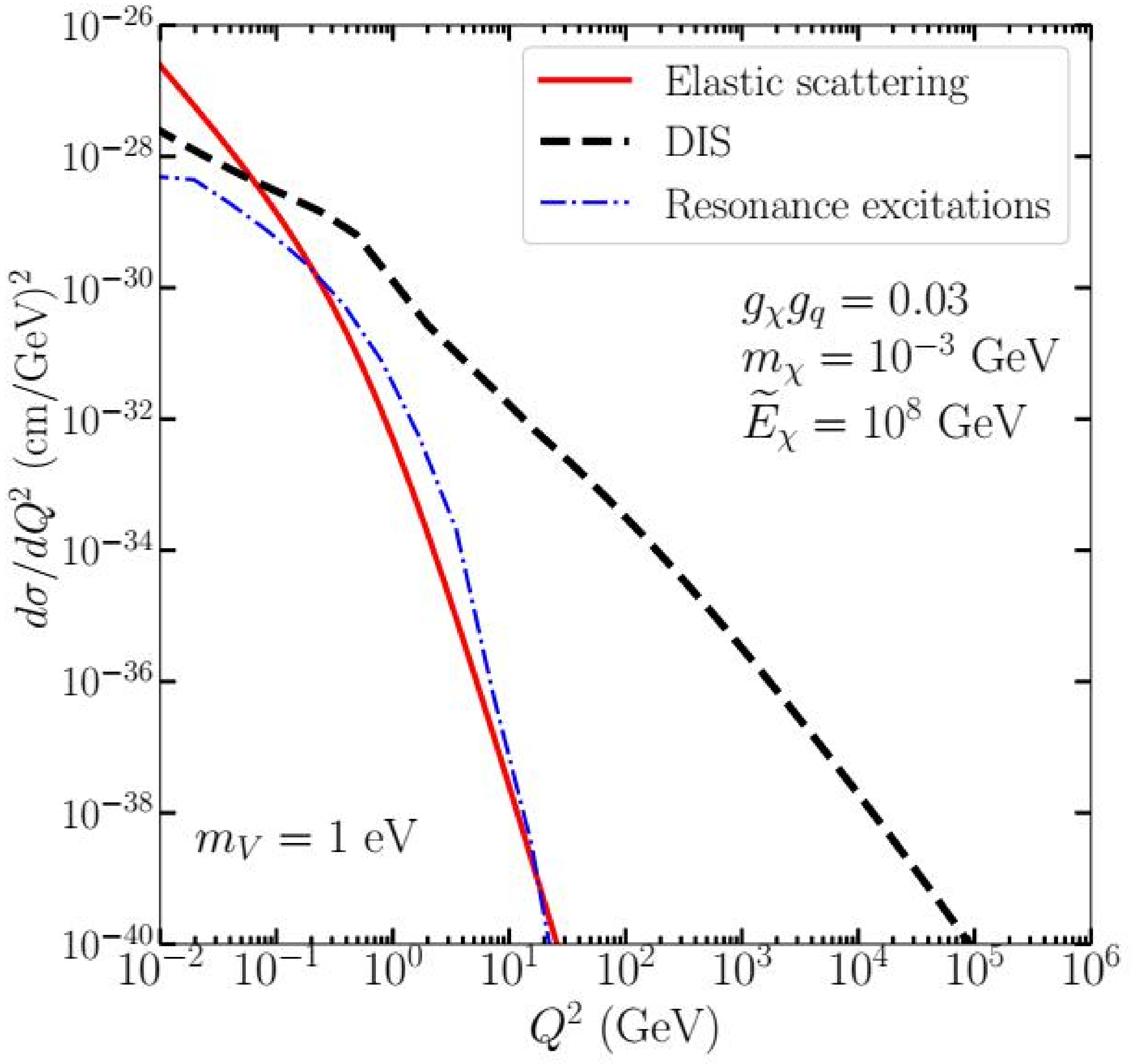
Inelastic scattering (Delta resonance and DIS)

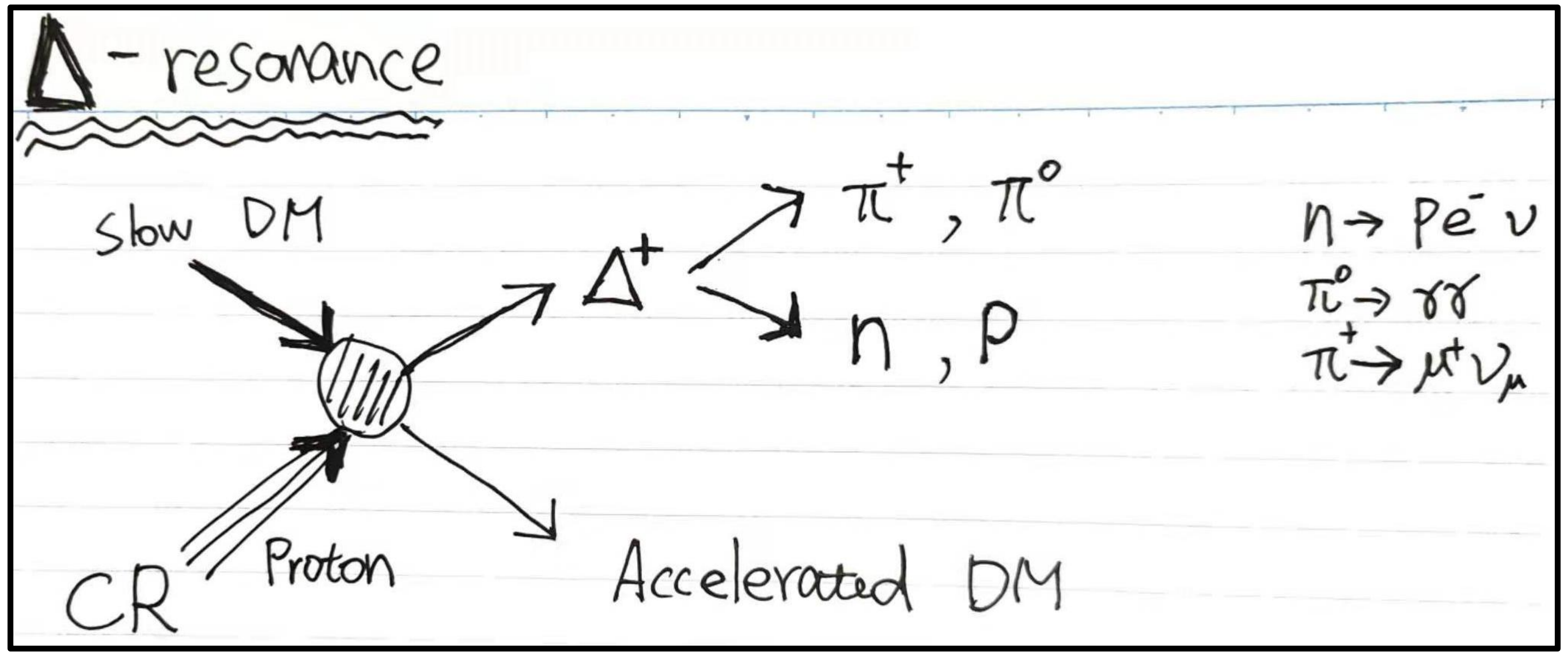
$$\chi + p \to \chi + X \to \chi + \text{hadronic showers} + \gamma\text{-rays} + \text{neutrinos.}$$



proton rest frame





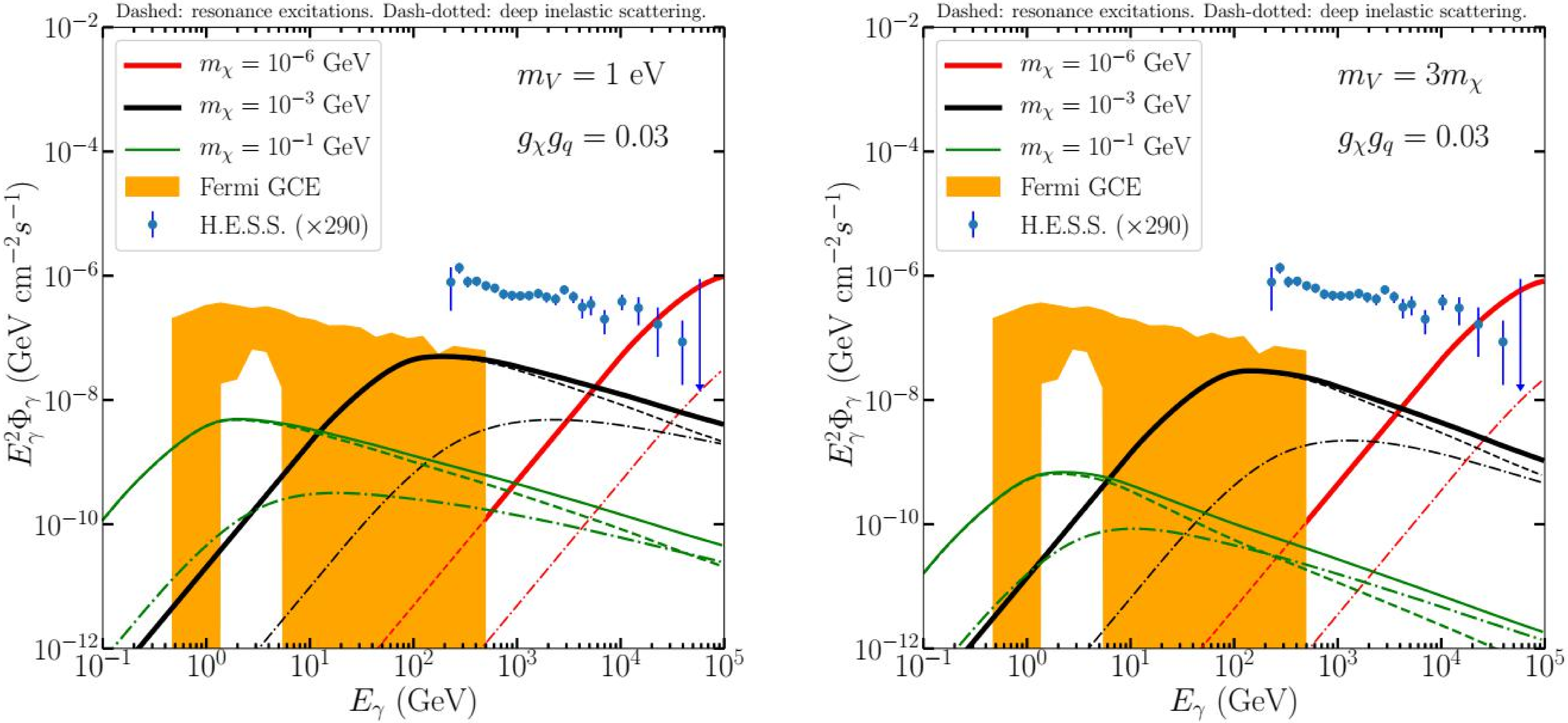


The scattering cross section and energy distribution must be model dependent.

Gamma ray and neutrino produced by DM-CR inelastic scattering.

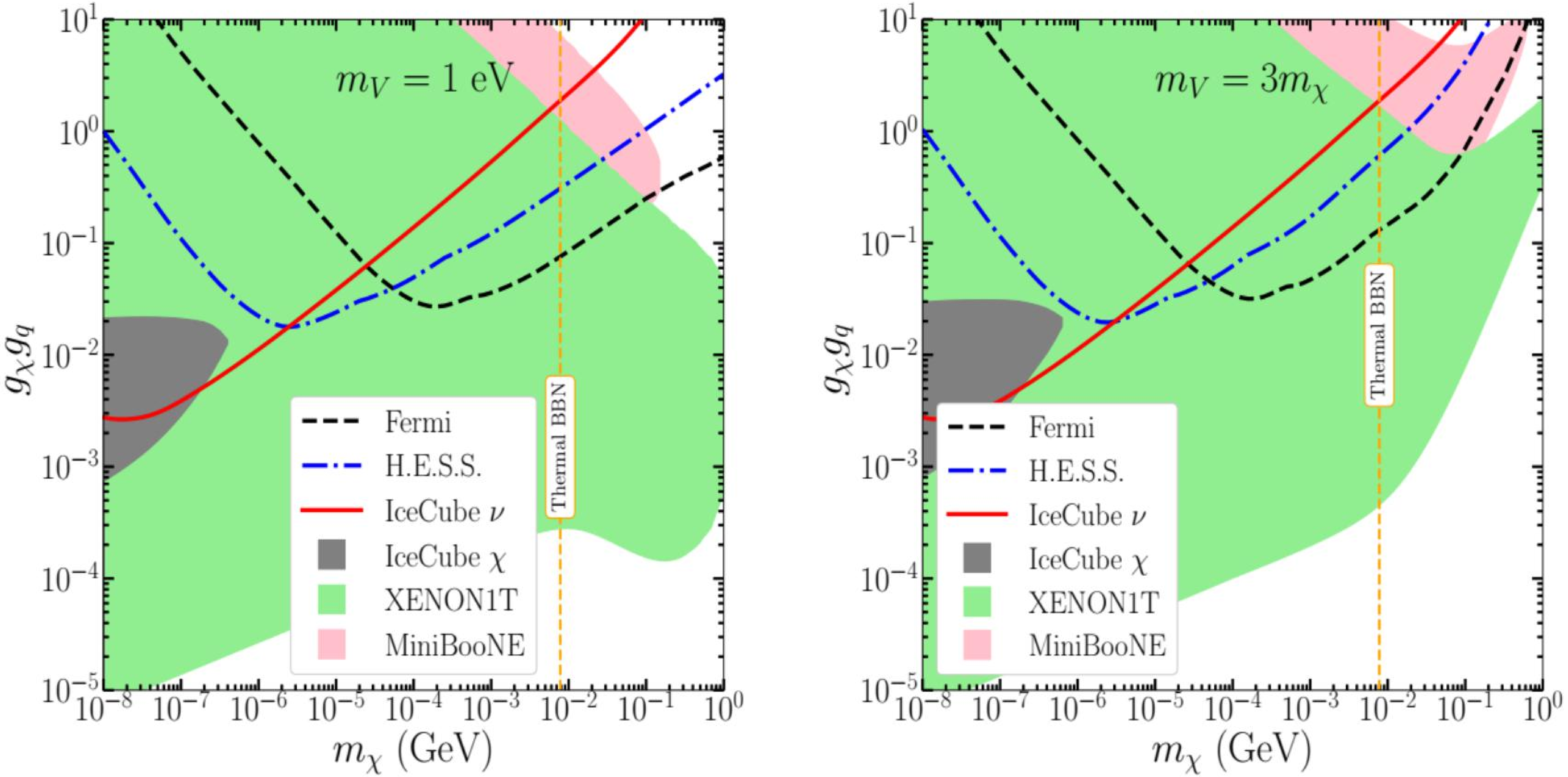
$$\phi_{\gamma,\nu}(E_{\gamma,\nu},\Omega) = \int_{\rm l.o.s.} d\ell \int dE_p \frac{\rho_\chi(r)}{m_\chi}\phi_p(E_p) \int d\nu dQ^2 \times \frac{d^2\sigma_{\rm inel}}{d\nu dQ^2} \times \frac{dN_{\gamma,\nu}(E_p, E_{\gamma,\nu}, \nu, Q^2)}{dE_{\gamma,\nu}}$$

At Gamma ray telescope, the resonance contribution is more important.



Difference with unual ID: Fermi probes the heavy DM region while HESS probes the light DM.

Limits from DM-CR inelastic scattering.



Topic 6: Multi-frequency analysis: SKA

Multi-frequency analysis

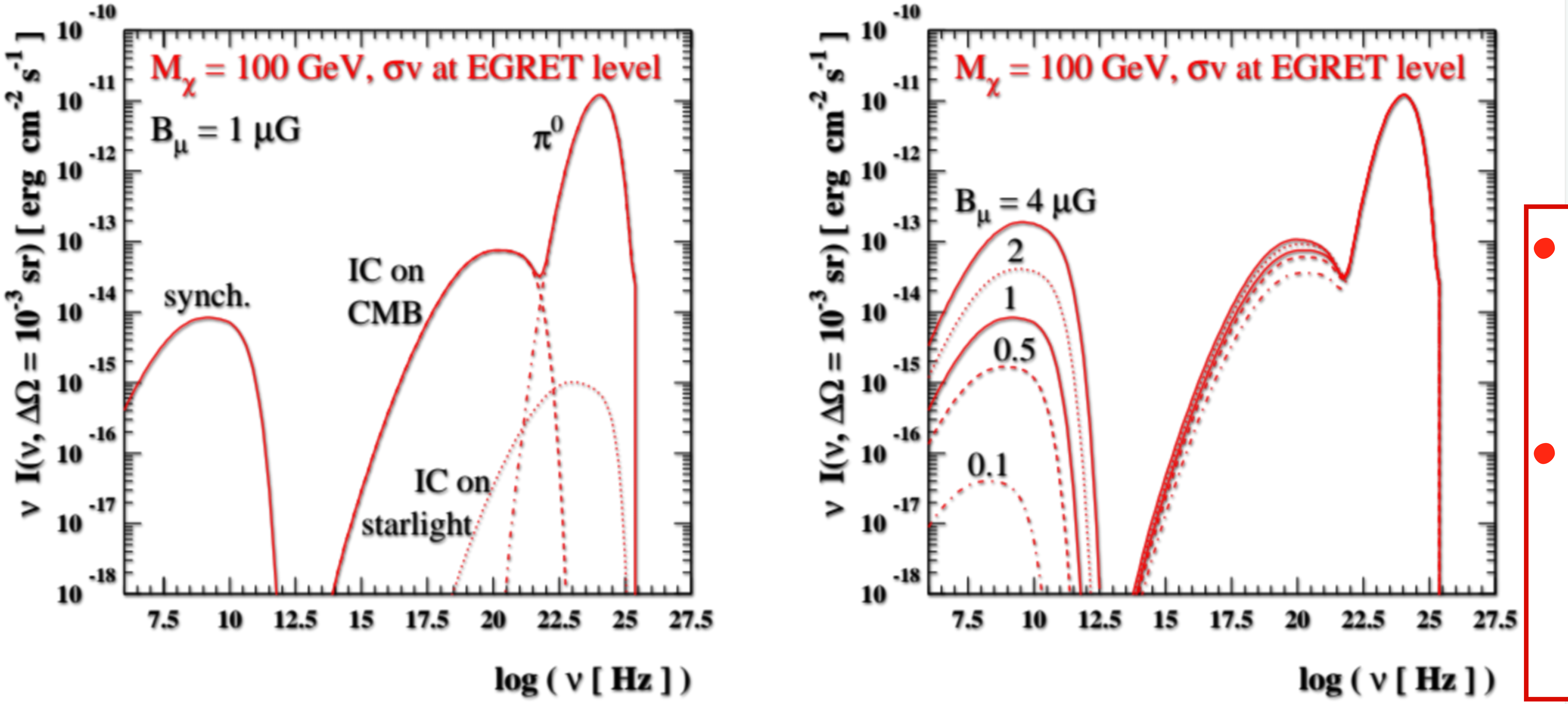


Figure 1: Left. The Draco dSph multi-wavelength spectrum for a 100 GeV WIMP annihilating into $b\bar{b}$. Right. The effect of varying the magnetic field strength on the Draco multi-wavelength spectrum for a 100 GeV WIMP annihilating into $b\bar{b}$. The WIMP pair annihilation rate has been tuned as to give a γ-ray signal at the level of the EGRET measured flux upper limit (from Colafrancesco et al. 2007).

1e15 Hz ~ 4.14 eV.

- IC and Sync are located at different frequency.
- When magnetic field strength increasing, spectrum is also enhanced.

astro-ph/0607073

Thompson/Compton Scattering

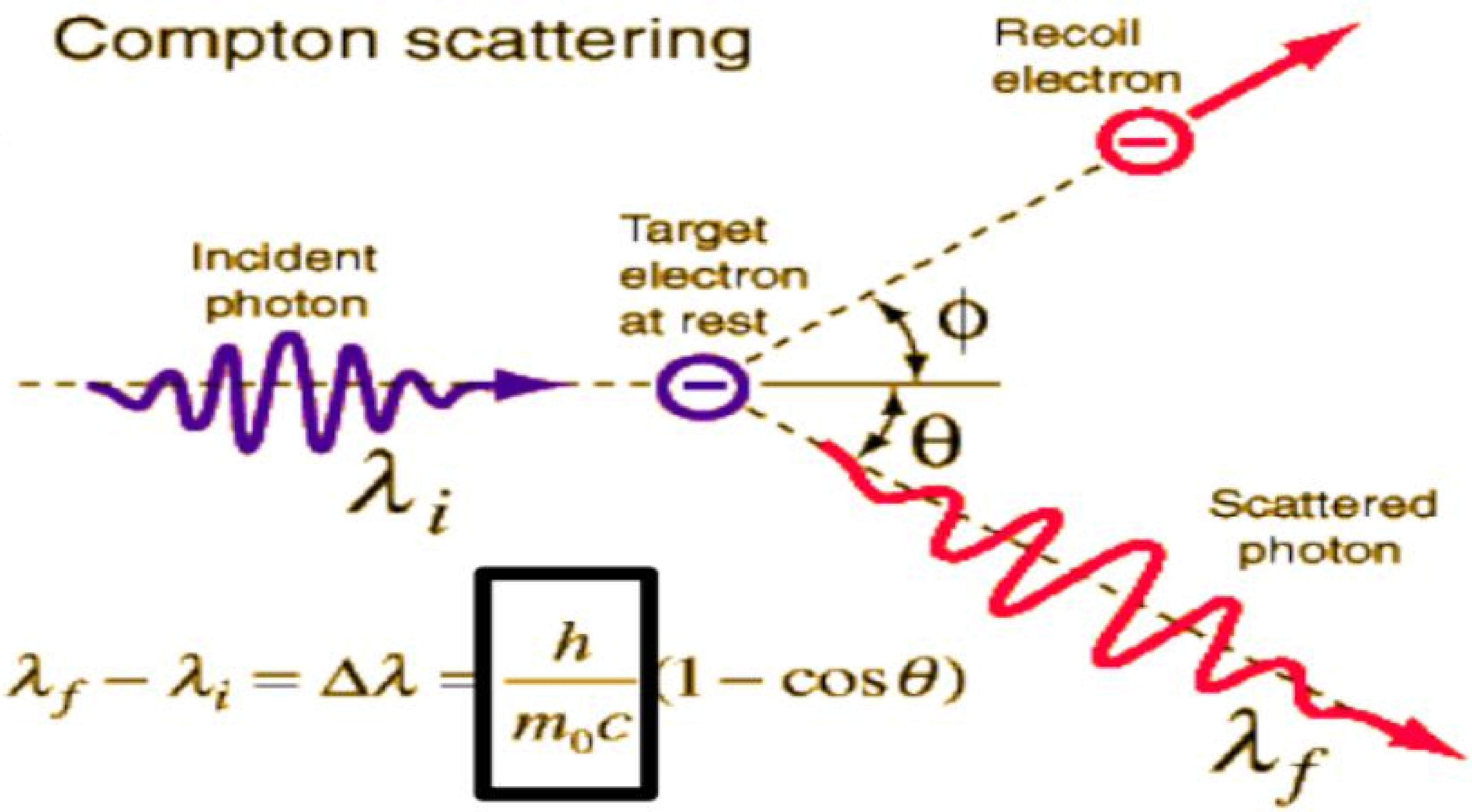
Longair Ch 9.2-9.6 (9.1in next lecture,9.4.3 not covered)RB Ch 3.8

- Thomson scattering: elastic scattering of low-energy photons from low-energy electrons, with cross-section $\sigma_T = (8\pi/3)(e^2/m_e c^2) = 6.65\times10^{-25}$ cm^2

- Compton scattering: low-energy photon inelastically scatters off non-relativistic electron, ***photon loses energy***

- Inverse Compton scattering: low-energy photon inelastically scatters off relativistic electron, ***photon gains energy in observer rest frame***

Compton Wavelength $= h/m_e c = 0.00243$ nm for an electron



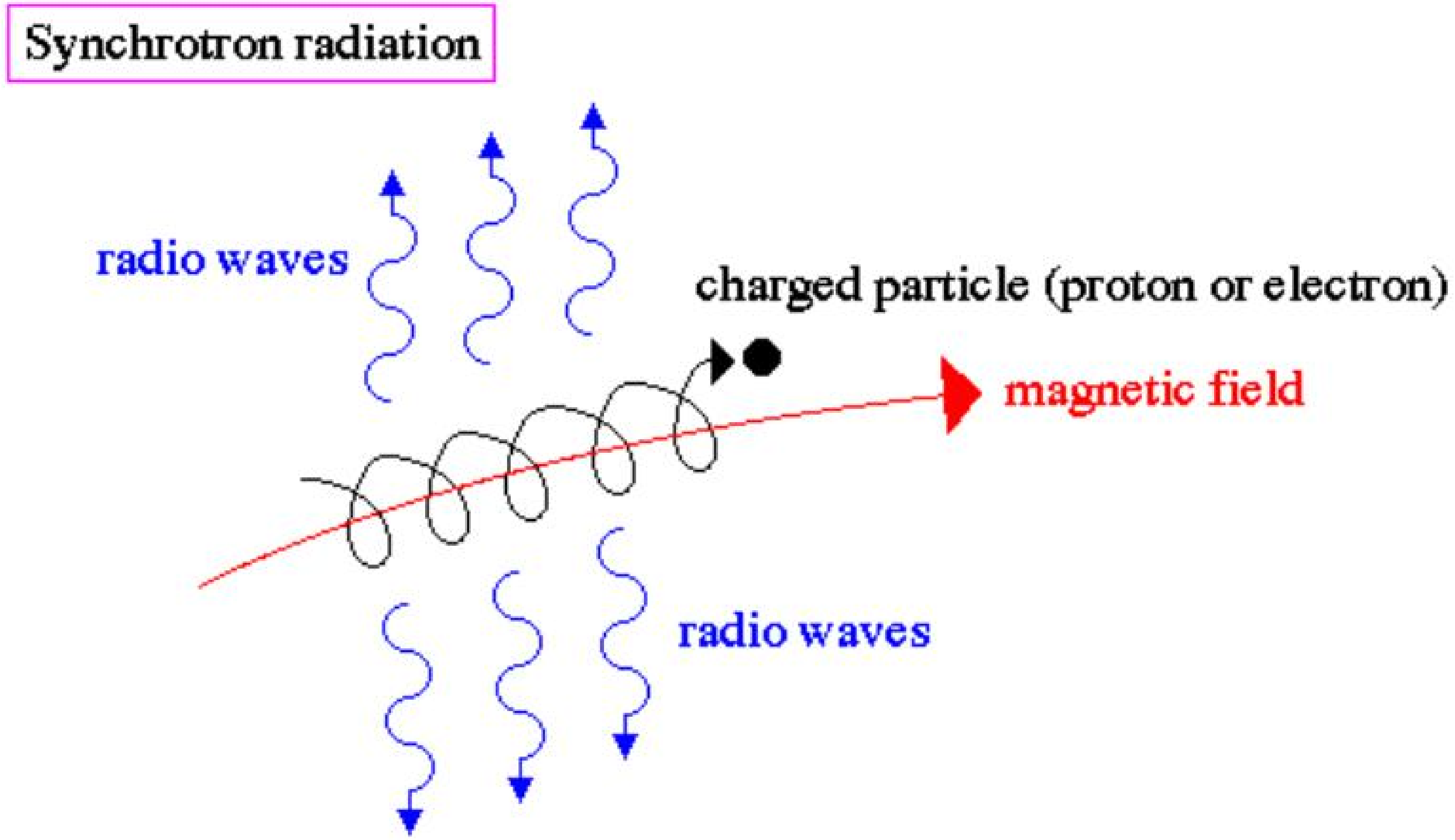
$$\lambda_f - \lambda_i = \Delta\lambda = \boxed{\frac{h}{m_0 c}}(1-\cos\theta)$$

Whether the photon gives energy to the electron or vice versa

http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/compton.html

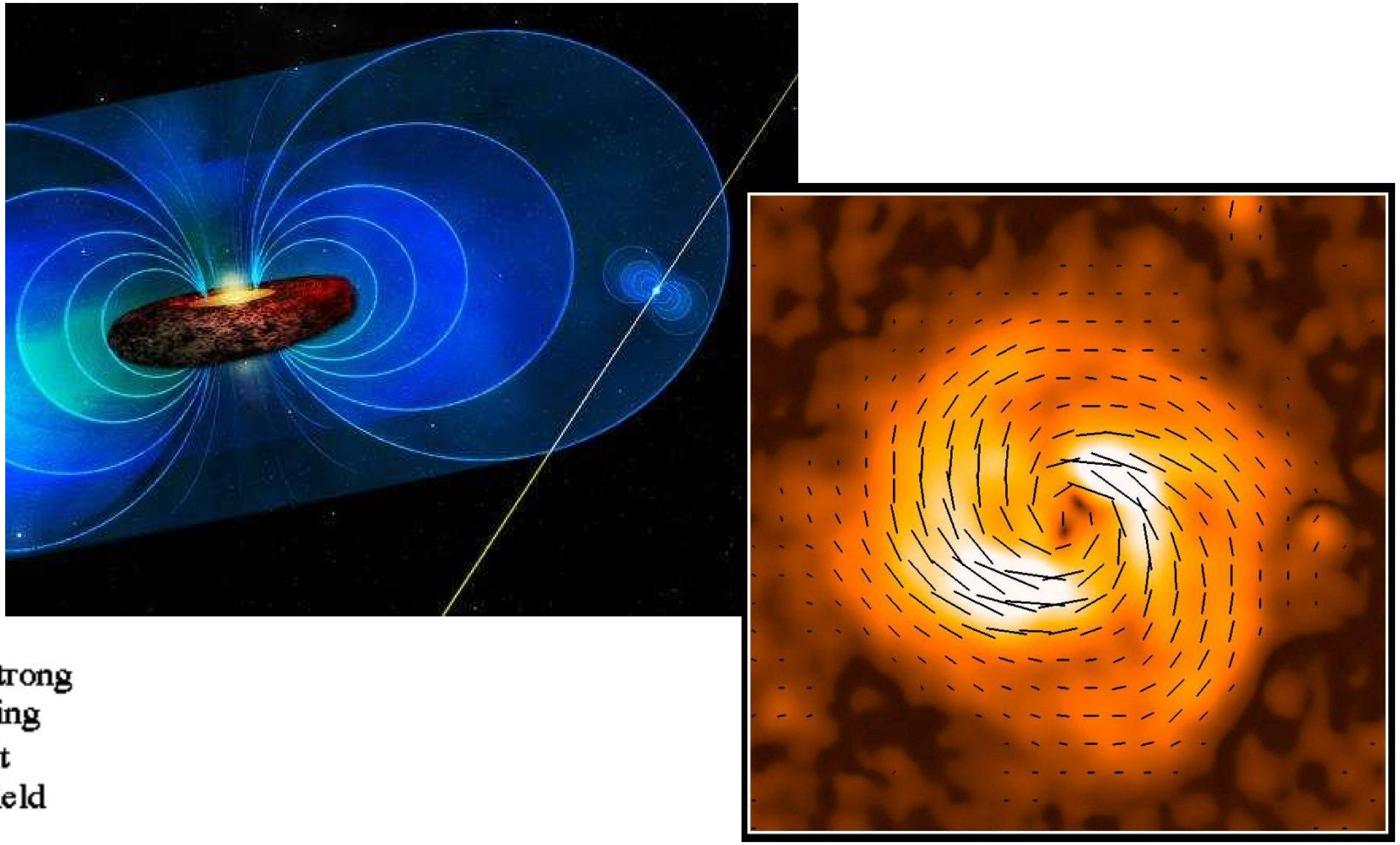
ICs= fast electrons + low energy photon.

Synchrotron radiation



Excerpt from the Encyclopedia Britannica

synchrontron radiation occurs when a charged particle encounters a strong magnetic field – the particle is accelerated along a spiral path following the magnetic field and emitting radio waves in the process – the result is a distinct radio signature that reveals the strength of the magnetic field



Electrons traveling inside galaxy can radiate synchrotron!

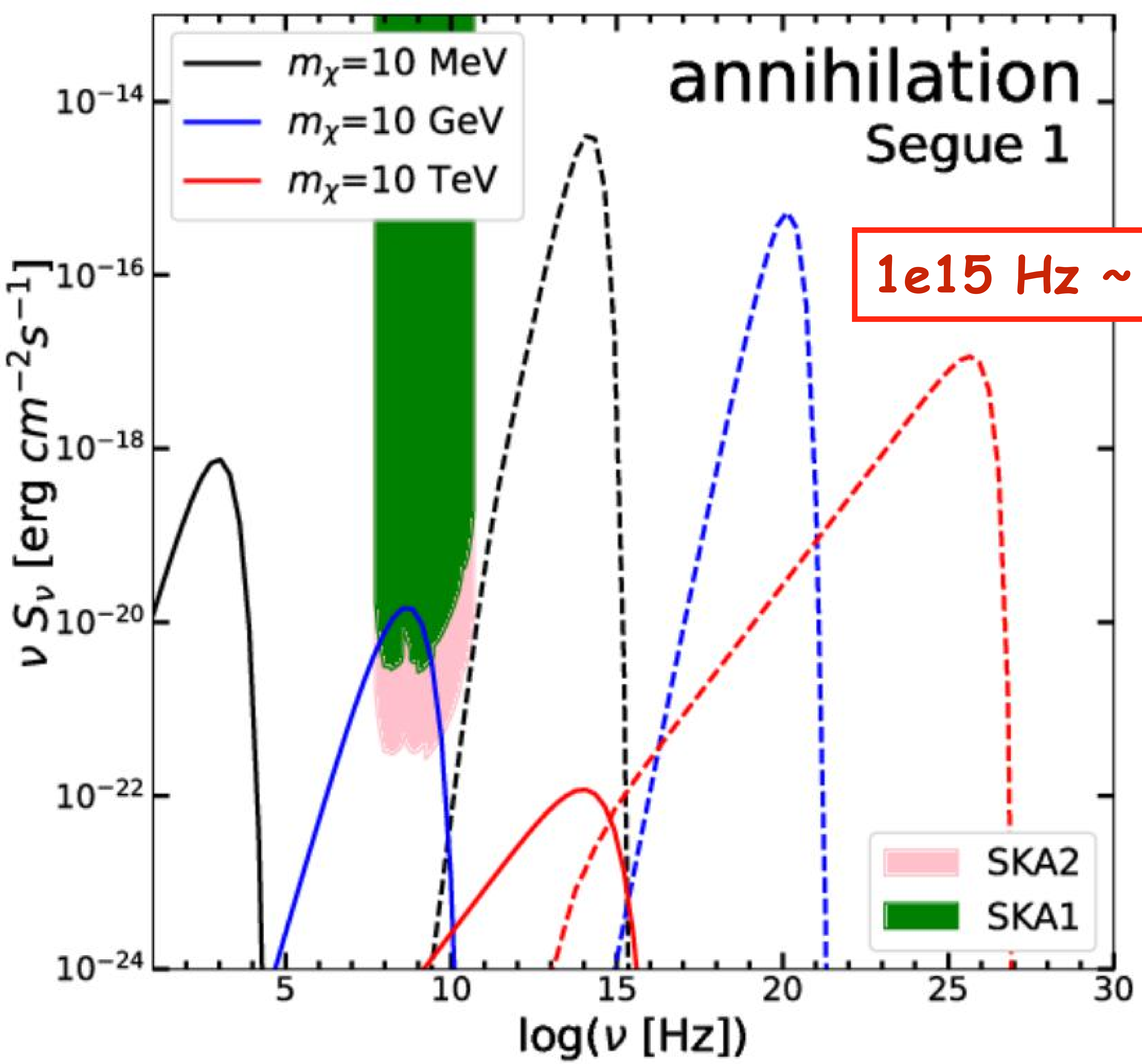
$$B(r) = B_0 \exp(-r/r_c), \tag{10}$$

where B_0 is the magnetic field strength and $r_c = 0.22$ kpc is the core radius of Draco.

Future SKA senstivity to DM annihilation

Z. Chen, Y.-L.S. Tsai, Q. Yuan (2105.00776)

Dashed: Inverse Compton, Solid : Synchrotron



1e15 Hz ~ 4.14 eV.

CMB photon peaks at 160.23 GHz ~6.6e-4 eV.

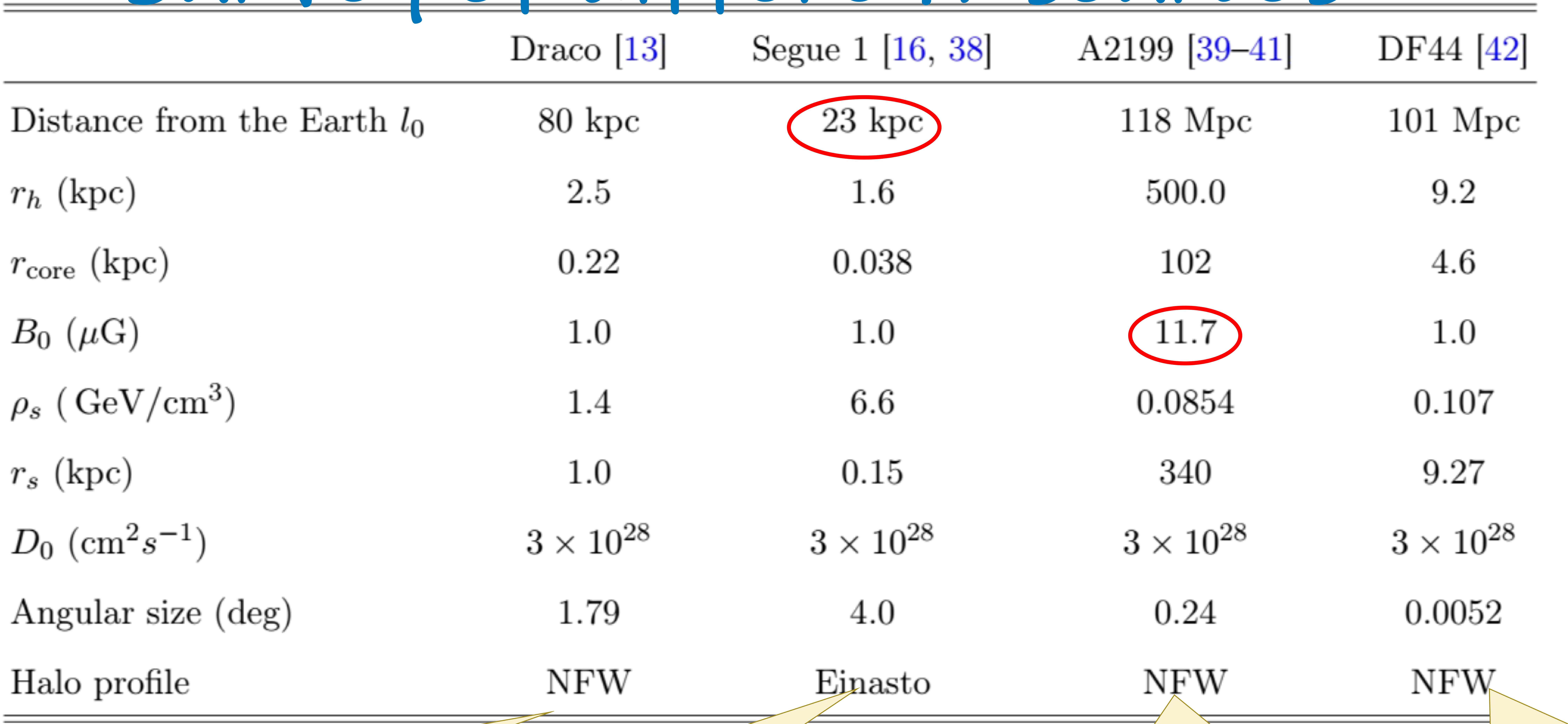
$$-\nabla\left[D(E,\mathbf{r})\nabla\frac{\partial n_e}{\partial E}\right]-\frac{\partial}{\partial E}\left[b(E,\mathbf{r})\frac{\partial n_e}{\partial E}\right]=Q(E,\mathbf{r}),$$

$$Q_e(E,r)=\begin{cases}\frac{1}{2}\left[\frac{\rho(r)}{m_\chi}\right]^2\langle\sigma v\rangle\frac{dN_e}{dE} & \text{for DM annihilation,}\\ \frac{\rho(r)}{m_\chi}\times\frac{1}{\tau}\times\frac{dN_e}{dE} & \text{for DM decay.}\end{cases}$$

$$S_\nu(\nu)=\int d\Omega\int_{l.o.s.}\frac{dl}{4\pi}\int_E^{m_\chi}2dE\times(\mathcal{P}_{IC}+\mathcal{P}_{syn})\times\frac{\partial n_e}{\partial E}.$$

- ※ Segue 1 is a closer dSphs to the Earth and the annihilation channel here is xx->ee.
- ※ DM with mx<GeV can be detected by synchrotron but MeV DM can be detected by inverse compoton.
- ※ Heavier DM contributes lower fluxes, see the source term.
- ※ D is diffusion coefficent, D ~ lambda* velocity.

Survey of different sources



	Draco [13]	Segue 1 [16, 38]	A2199 [39–41]	DF44 [42]
Distance from the Earth l_0	80 kpc	23 kpc	118 Mpc	101 Mpc
r_h (kpc)	2.5	1.6	500.0	9.2
r_{core} (kpc)	0.22	0.038	102	4.6
B_0 (μG)	1.0	1.0	11.7	1.0
ρ_s (GeV/cm^3)	1.4	6.6	0.0854	0.107
r_s (kpc)	1.0	0.15	340	9.27
D_0 (cm$^2 s^{-1}$)	3×10^{28}	3×10^{28}	3×10^{28}	3×10^{28}
Angular size (deg)	1.79	4.0	0.24	0.0052
Halo profile	NFW	Einasto	NFW	NFW

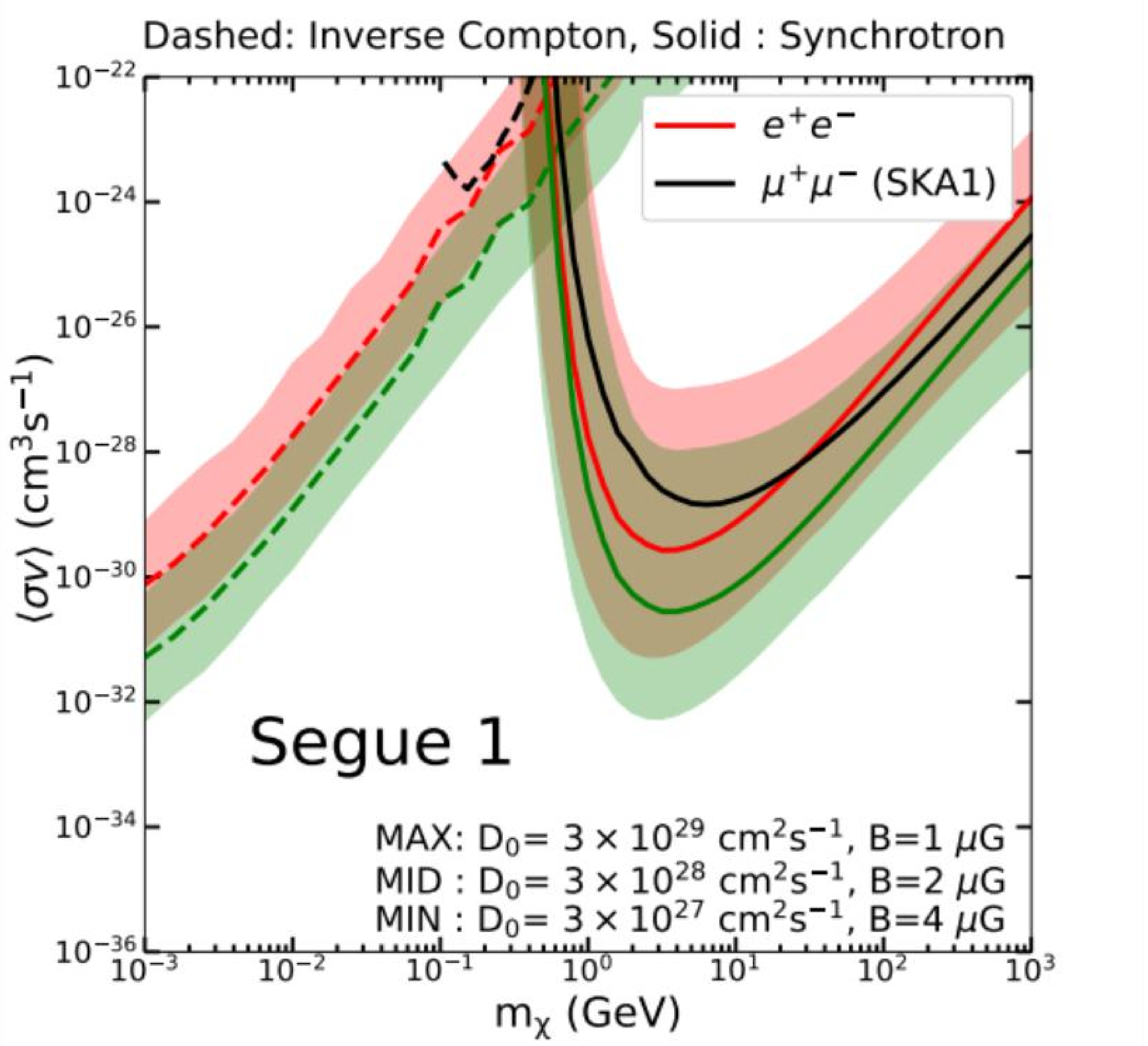
classic one

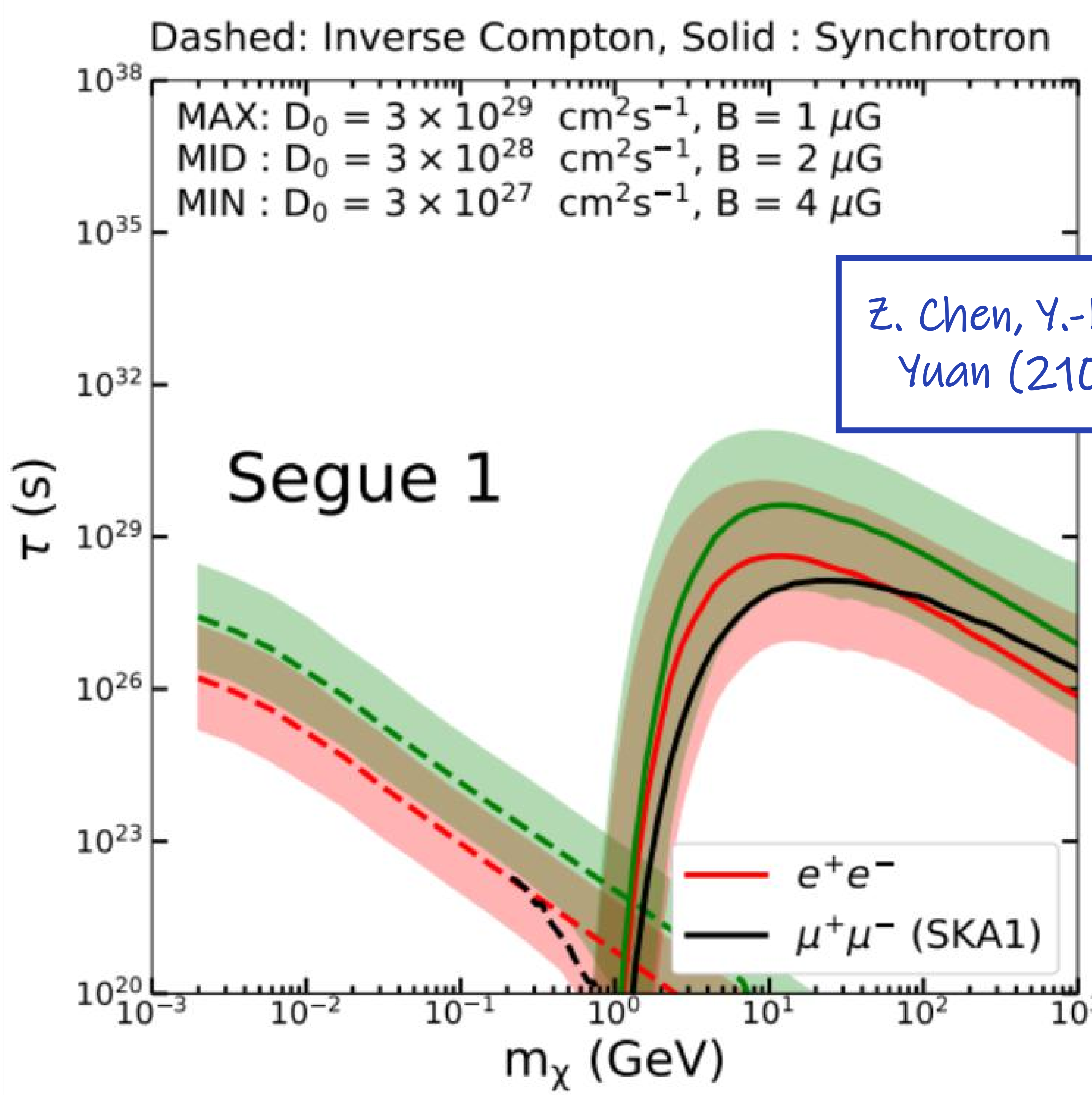
Closest one

radio-poor cluster

DM rich ultra-diffuse galaxy

Future SKA senstivity to DM annihilation and decay: Segue 1

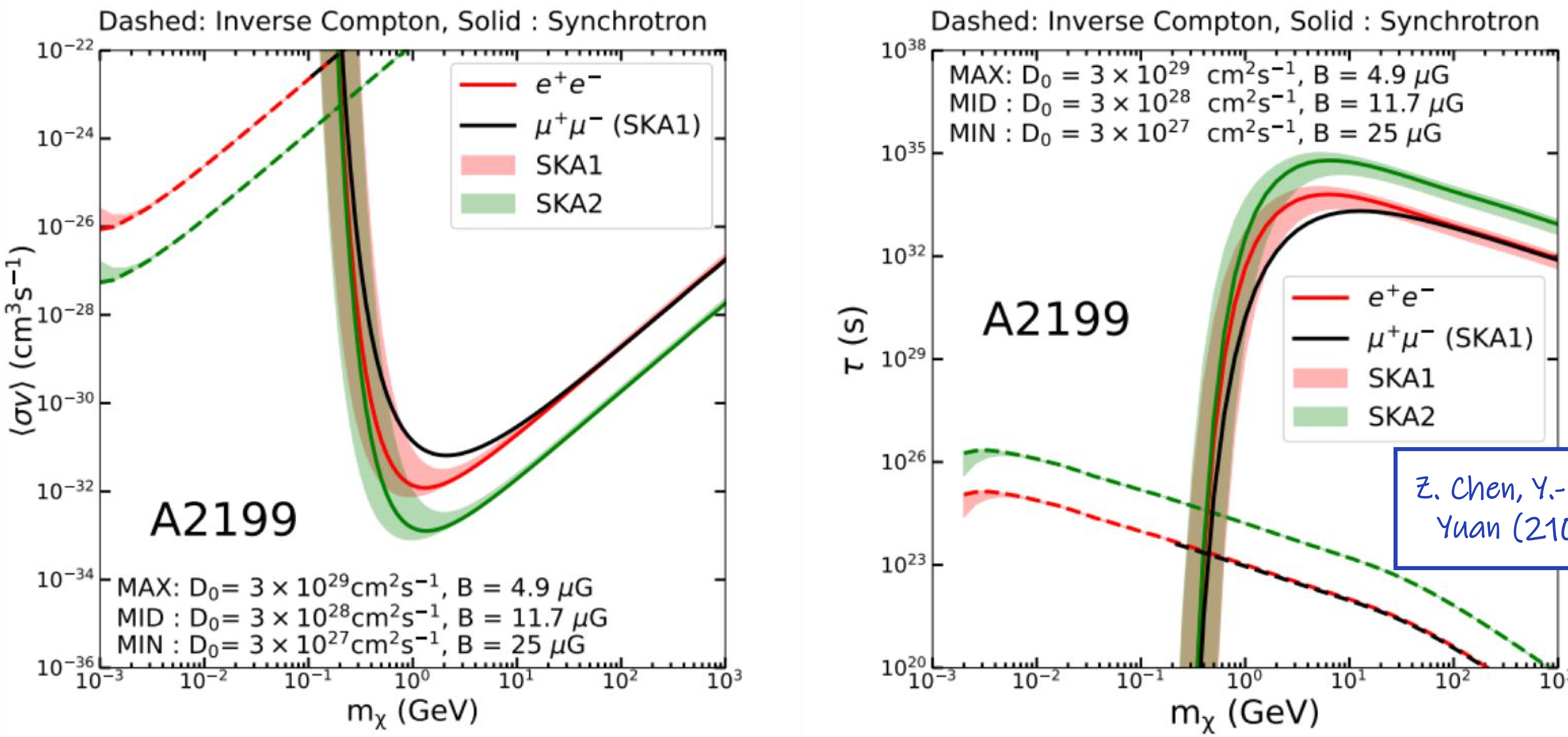




Z. Chen, Y.-L.S. Tsai, Q. Yuan (2105.00776)

ICS from Segue 1 and synchrotron from Ophiuchus provide the most strigent limits.

Future SKA senstivity to DM annihilation and decay: A2199



Z. Chen, Y.-L.S. Tsai, Q. Yuan (2105.00776)

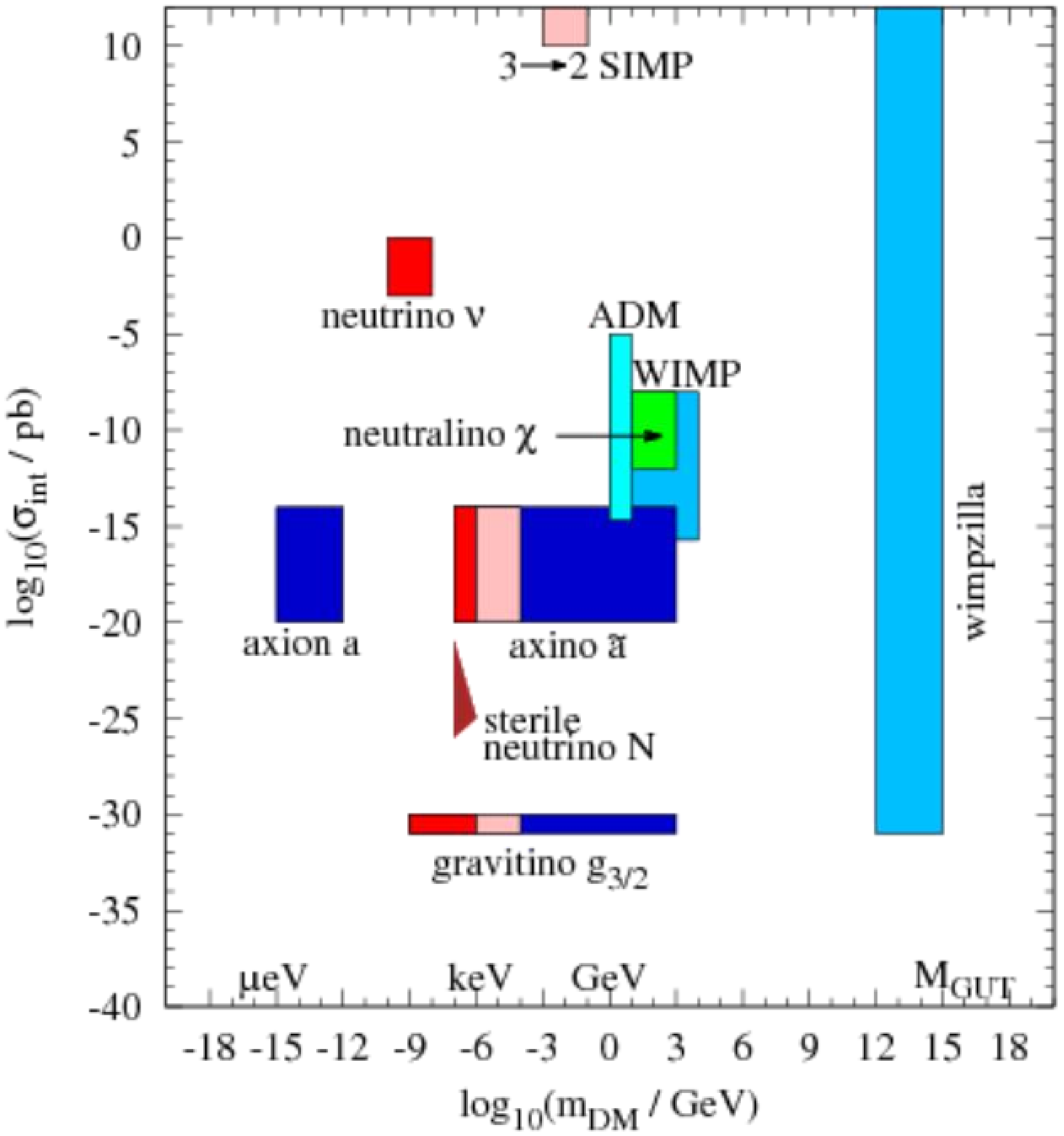
A2199 halo size "rh" is much larger than the one of Segue 1 (the mean free path of electron are similar).

Hence, the uncertainties of A2199 is smaller than Segue 1.

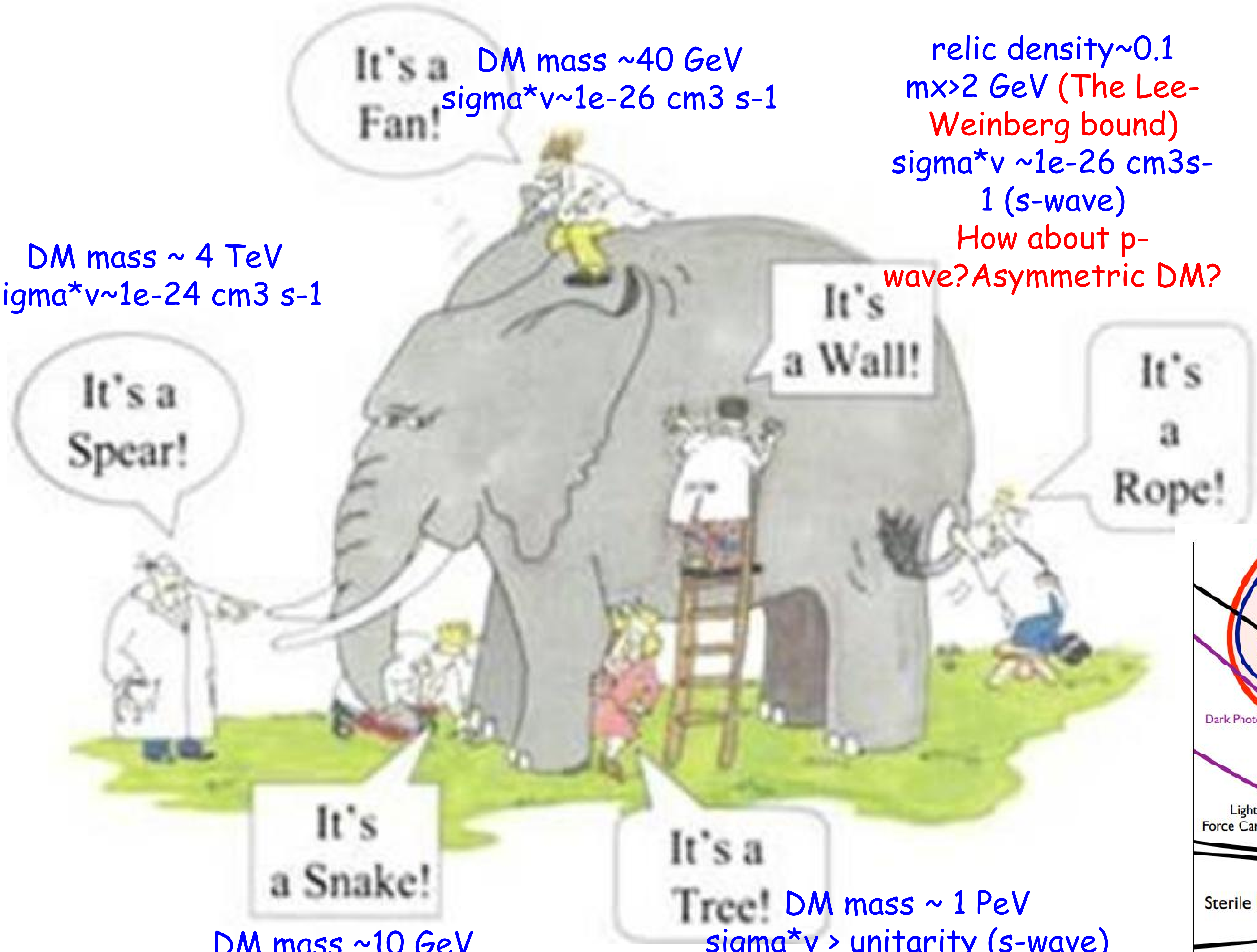
Indirect detection beyond MeV.

Beyond MeV DM indetection.

轴子专题（杨峤立）
量子精密测量探测暗物质（舒菁）
引力波探测暗物质（赵悦）
天文探测暗物质粒子（袁强）



关于sub-GeV暗物质的细节请见以上老师的课程。



DM mass ~40 GeV
sigma*v~1e-26 cm3 s-1

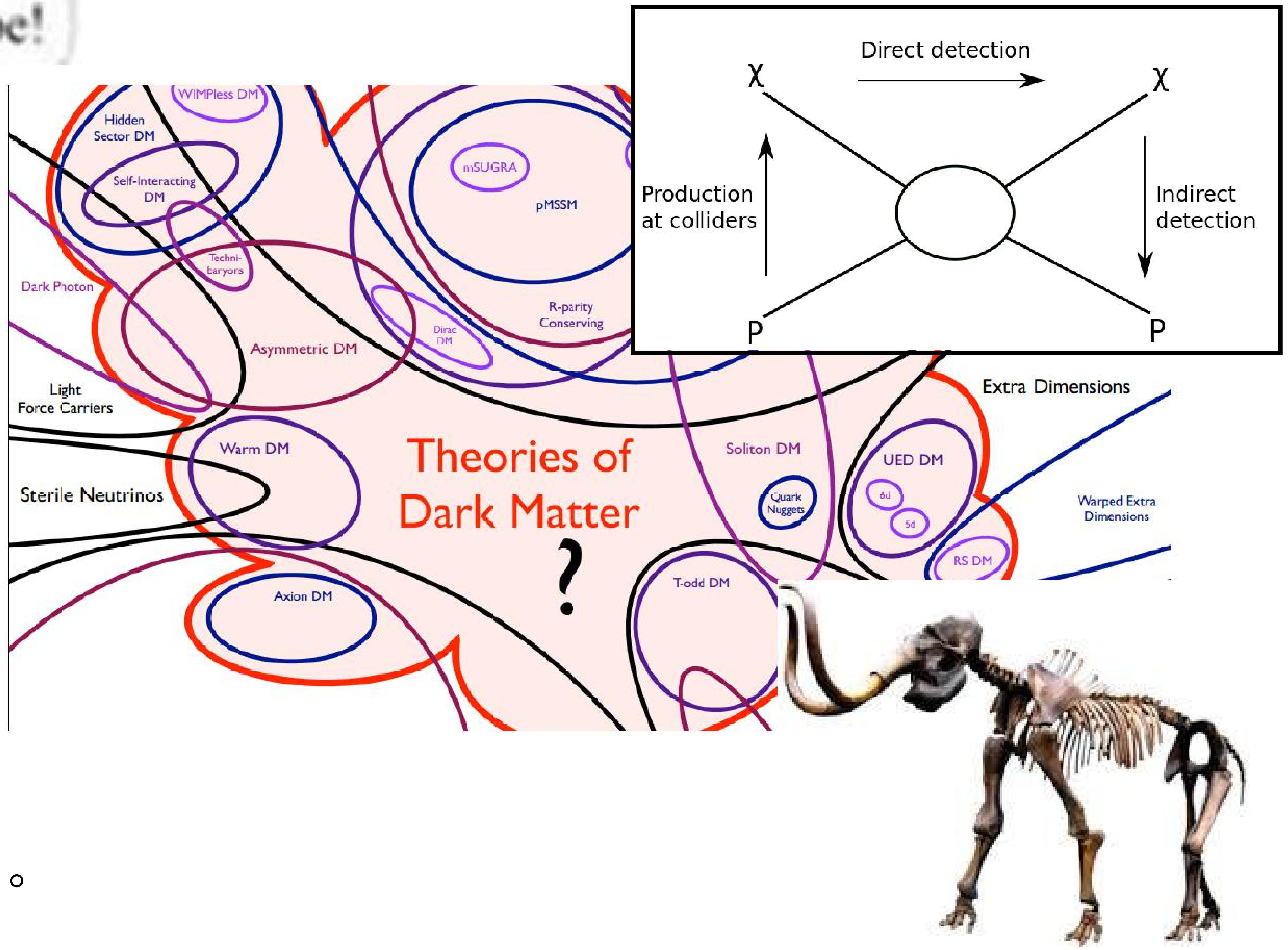
relic density~0.1
mx>2 GeV (The Lee-Weinberg bound)
sigma*v ~1e-26 cm3s-1 (s-wave)
How about p-wave?Asymmetric DM?

DM mass ~ 4 TeV
sigma*v~1e-24 cm3 s-1

DM mass ~10 GeV
sigsip~1e-4 pb

DM mass ~ 1 PeV
sigma*v > unitarity (s-wave)
How about p-wave?

DM still leaves a lot unknown:
- Spin
- Electroweak charge
- Real/Majorana or Complex/Dirac



暗物质物理将迎向最重要的几年。
将会决定WIMP或是研究方向大转向。
当我们只能摸象，每一片资讯都是很重要的。

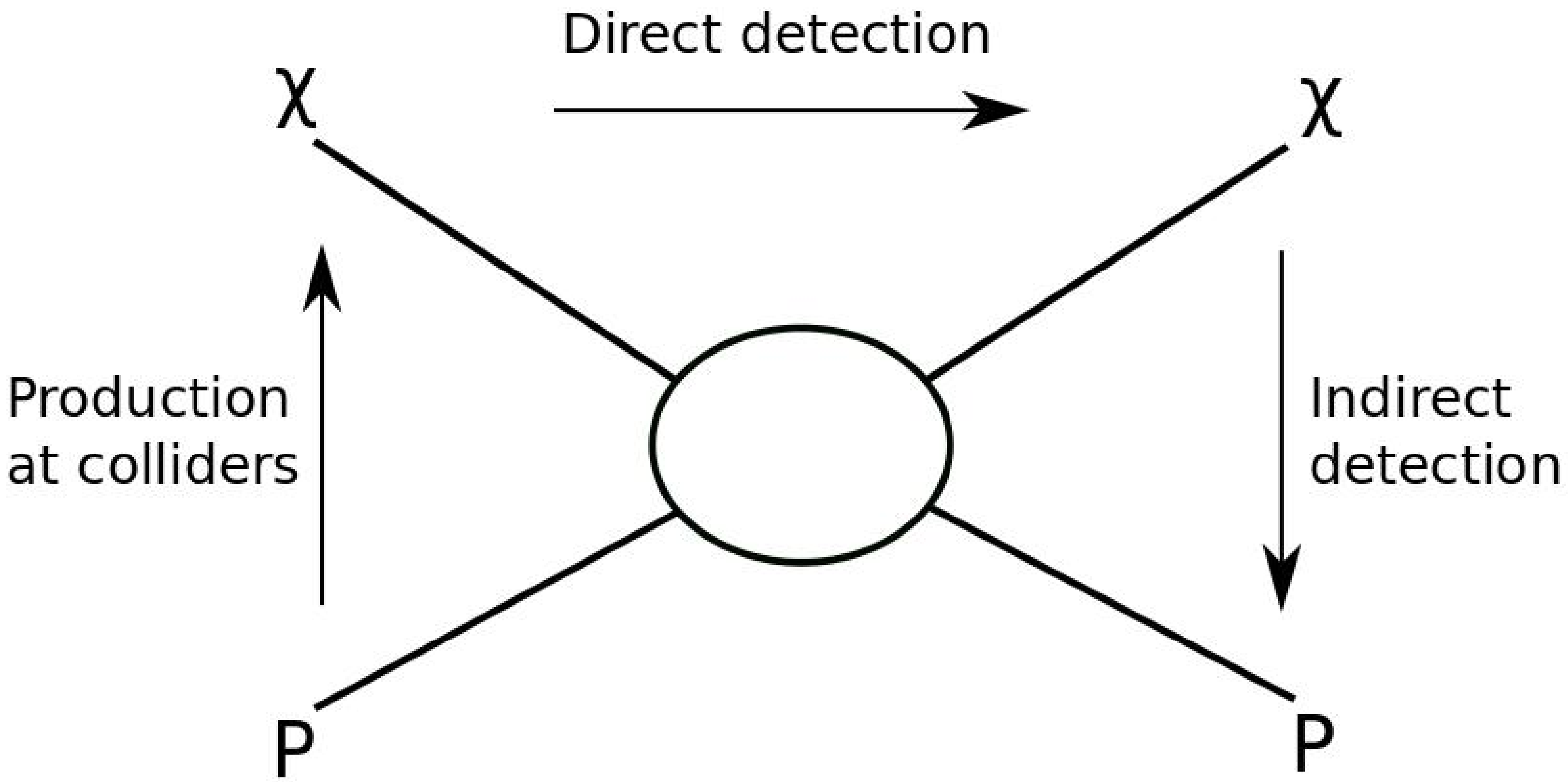
原创 杨振宁最后一战：美国花350亿做不到，中国砸1000亿就能成功吗?

2019-12-13 02:39

杨振宁，中国一代传奇物理学家，科学界认为他的成就远胜于霍金，甚至是可以比肩爱因斯坦的存在，他于1957年获诺贝尔物理学奖，在粒子物理学、统计力学和凝聚态物理等领域作出了里程碑性贡献。

然而就是这样一位令无数国人为之骄傲的科学家院士，却竭尽全力阻止我国在一科技领域反超西方、领跑全球。从此，外界对他的评论开始出现两极分化，这么多年也依旧争论不休。

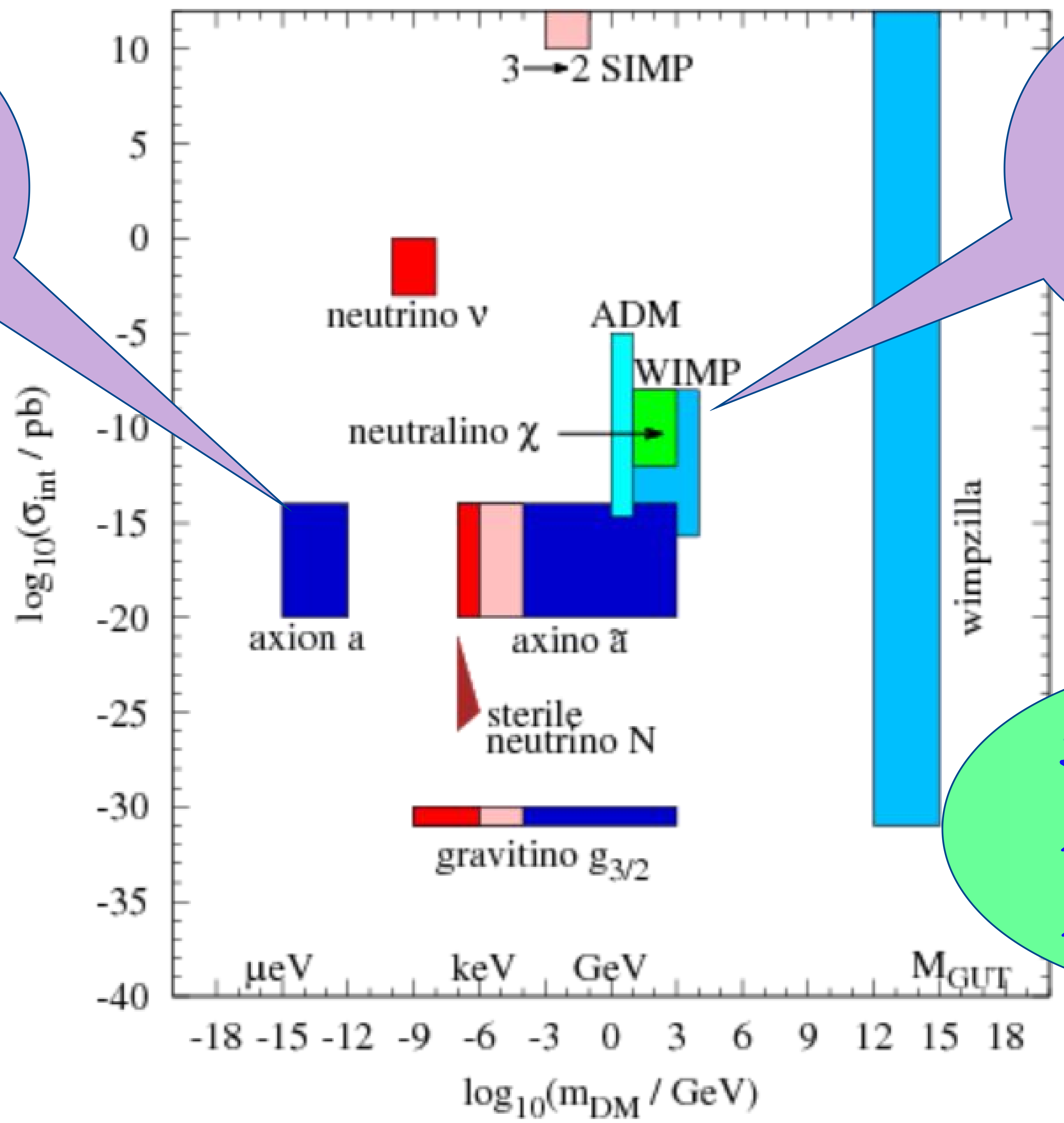
美国下马，日本拖延，杨振宁竭力反对，中国要不要花300多亿干这事？



未来的考量：没有对撞机后我们该怎么了解暗物质粒子特性？

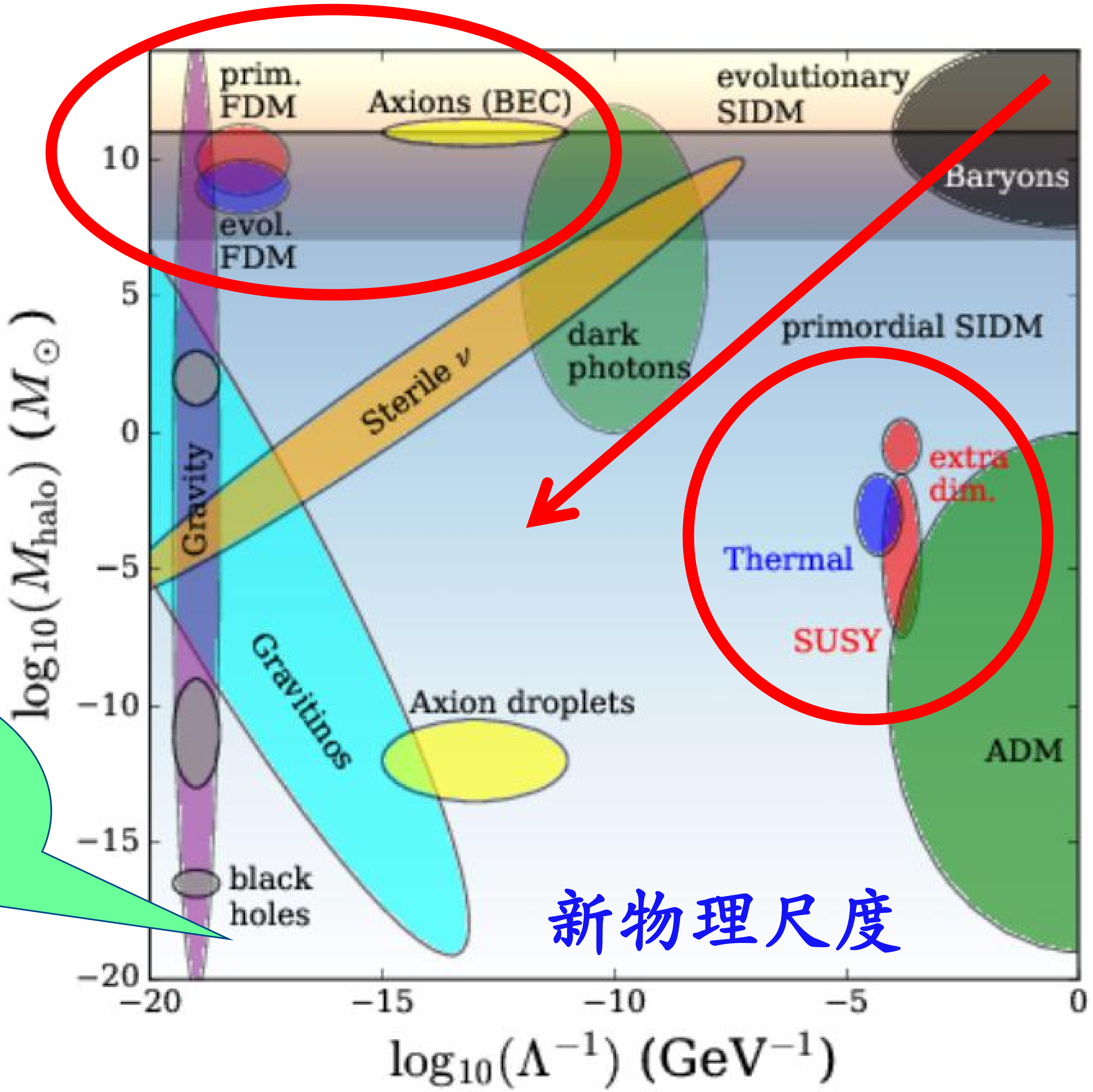
暗物质现状

质量最小



动机最强

此方向逼进只能利用引力探测法。



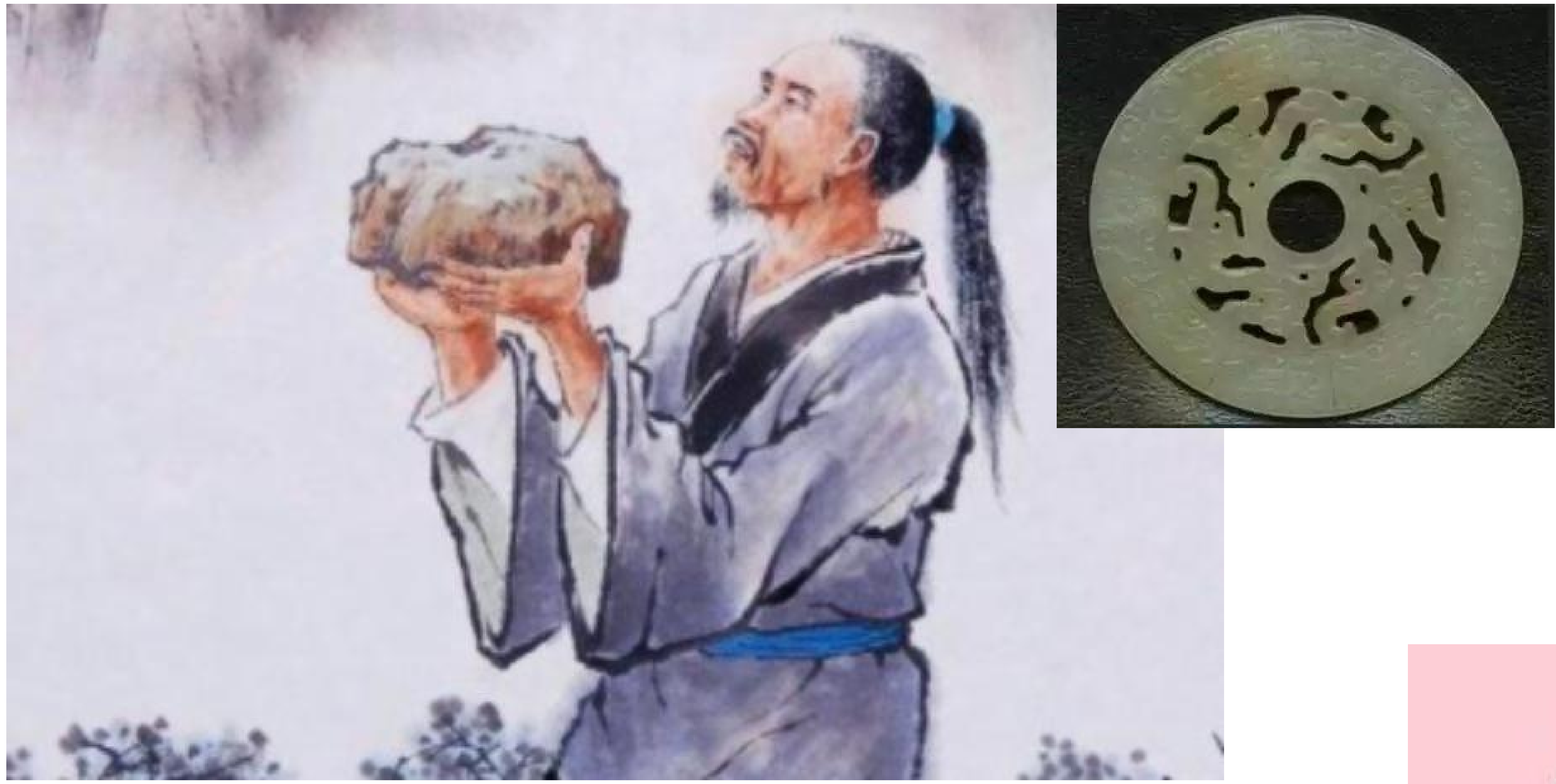
新物理尺度

天文尺度

质量范围40数量级，作用力范围40量级！！！

我们的策略：用不同的探测法进行围捕。

Dark Matter and Mr He's Jade



《韩非子·和氏》记载：楚人和氏得玉璞楚山中，奉而献之厉王。厉王使玉人相之，玉人曰："石也。"王以和为诳，而刖其左足。及厉王薨，武王即位。和又奉其璞而献之武王。武王使人相之，有曰："石也。"王又以和为诳，而刖其右足。武王薨，文王即位，和乃抱其璞而哭于楚山之下，三日三夜，泣尽而继之以血。王闻之，使人问其故，曰："天下刖者多矣，子奚哭之悲也？"和曰："吾非悲刖也，悲夫宝玉而视之石也，忠贞之士而名之以诳，此吾所以悲也。"王乃使玉人理其璞，果得宝焉，遂命曰"和氏璧"。

We do not loss our feet but only time and efforts. We can do it with more efficient ways.

卞和

SJTU & Science 125 (Physics):

10. What is dark matter?

Top 10 scientific mysteries for the 21st century

① The meaning of quantum entanglement.
② Does intelligent life exist elsewhere?
③ Quantum gravity
④ The nature of time
⑤ Are there extra dimensions of space?
⑥ Genes, cancer and luck
⑦ How to measure evidence
⑧ What is the nature of the dark energy that drives cosmic acceleration?
⑨ What is the identity of the dark matter?
⑩ How did life originate?

www.sciencenews.org

Questions for the New Century (Physics of the Universe report, https://www.nsf.gov)
Q1: What is Dark Matter?
Q2: What is the Nature of Dark Energy?
Q3: How Did the Universe Begin?

Science 125 anniversary:

1. What Is the Universe Made Of?

SJTU & Science 125 (Astronomy):

8. What is the universe made of?

Summary

☐ MeV DM (WIMP-like?) is a new window to be probed.

☐ The parameter space is finite.

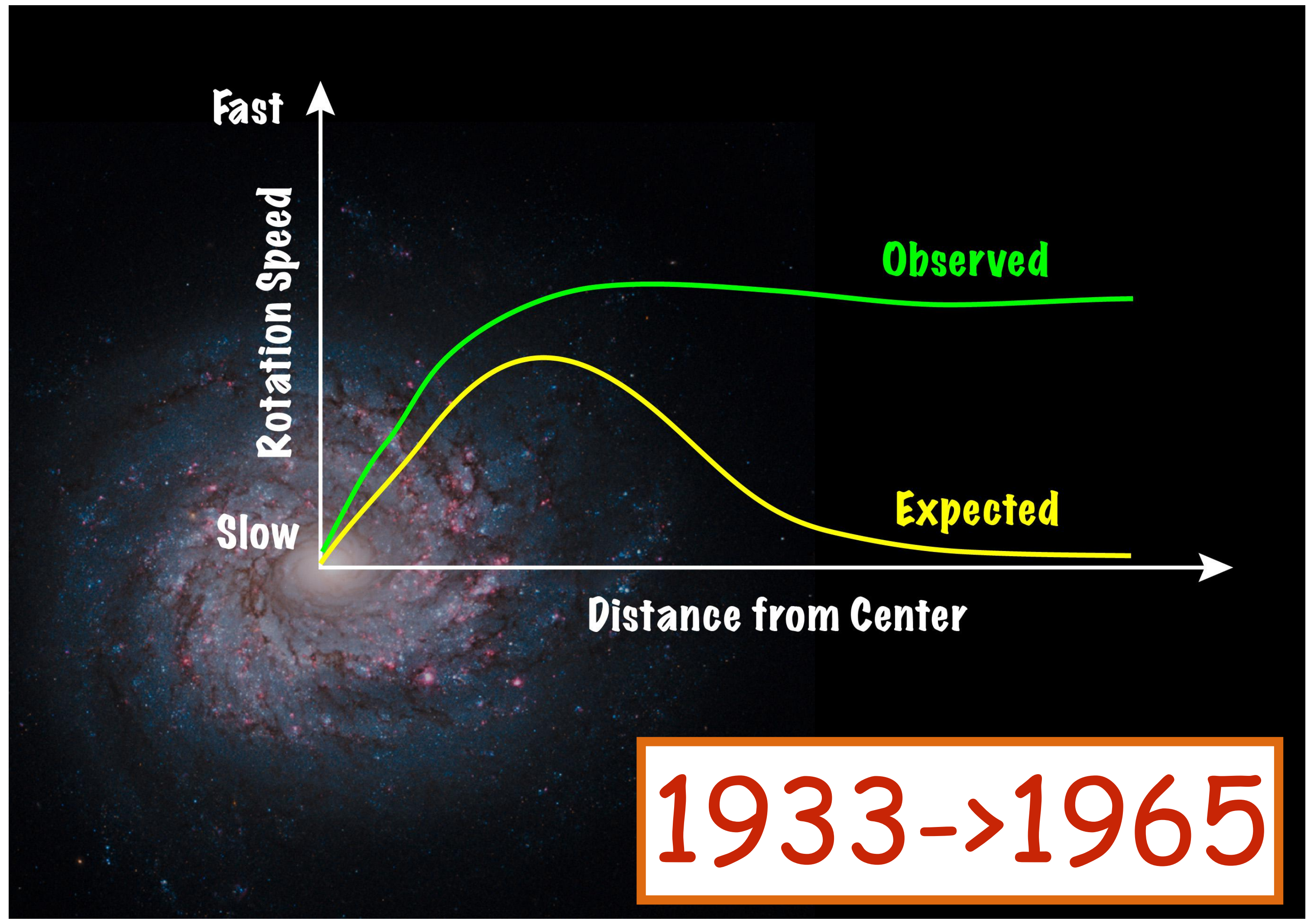
☐ Future indirect detection: CMB, future cosmological constraints, MeV gamma-ray telescopes, and ratio telescopes can be powerful.

☐ The cross section could not solely be s-wave if agrees with relic and CMB.

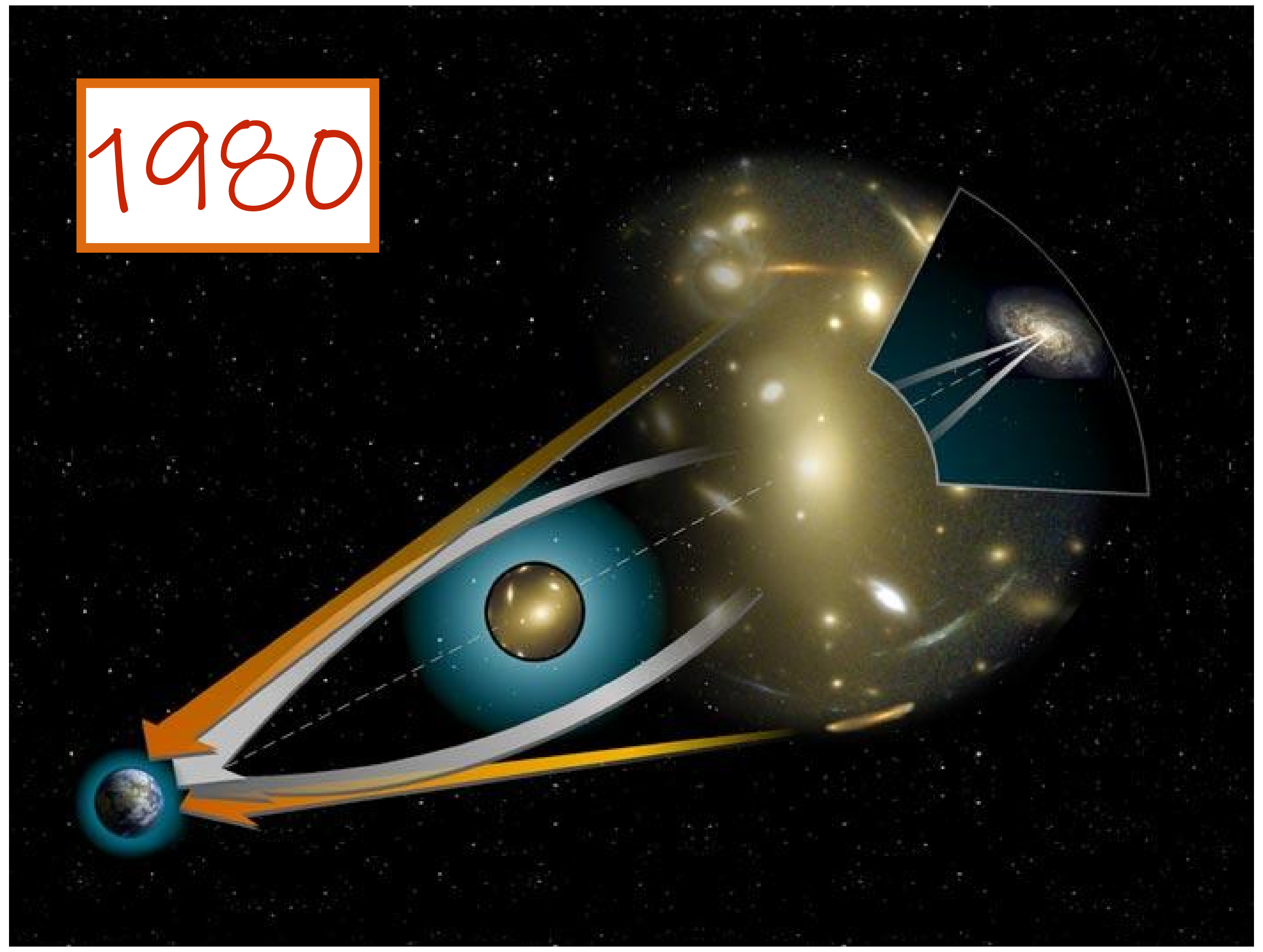
☐ Ratio, X-ray, and soft gamma-ray telescopes may provide a new approach to probe this WIMP-like DM.

Thank you.

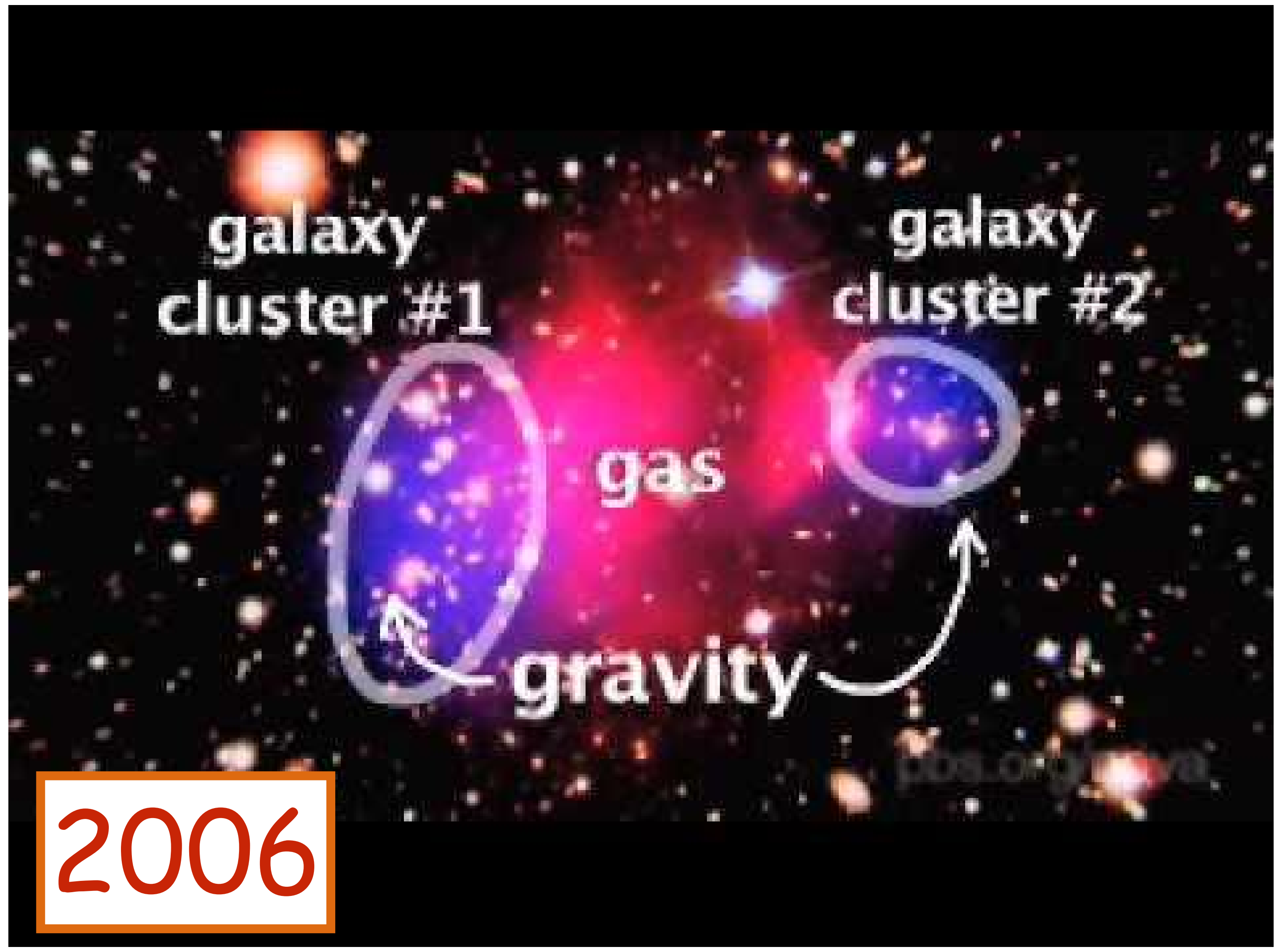
Dark Matter



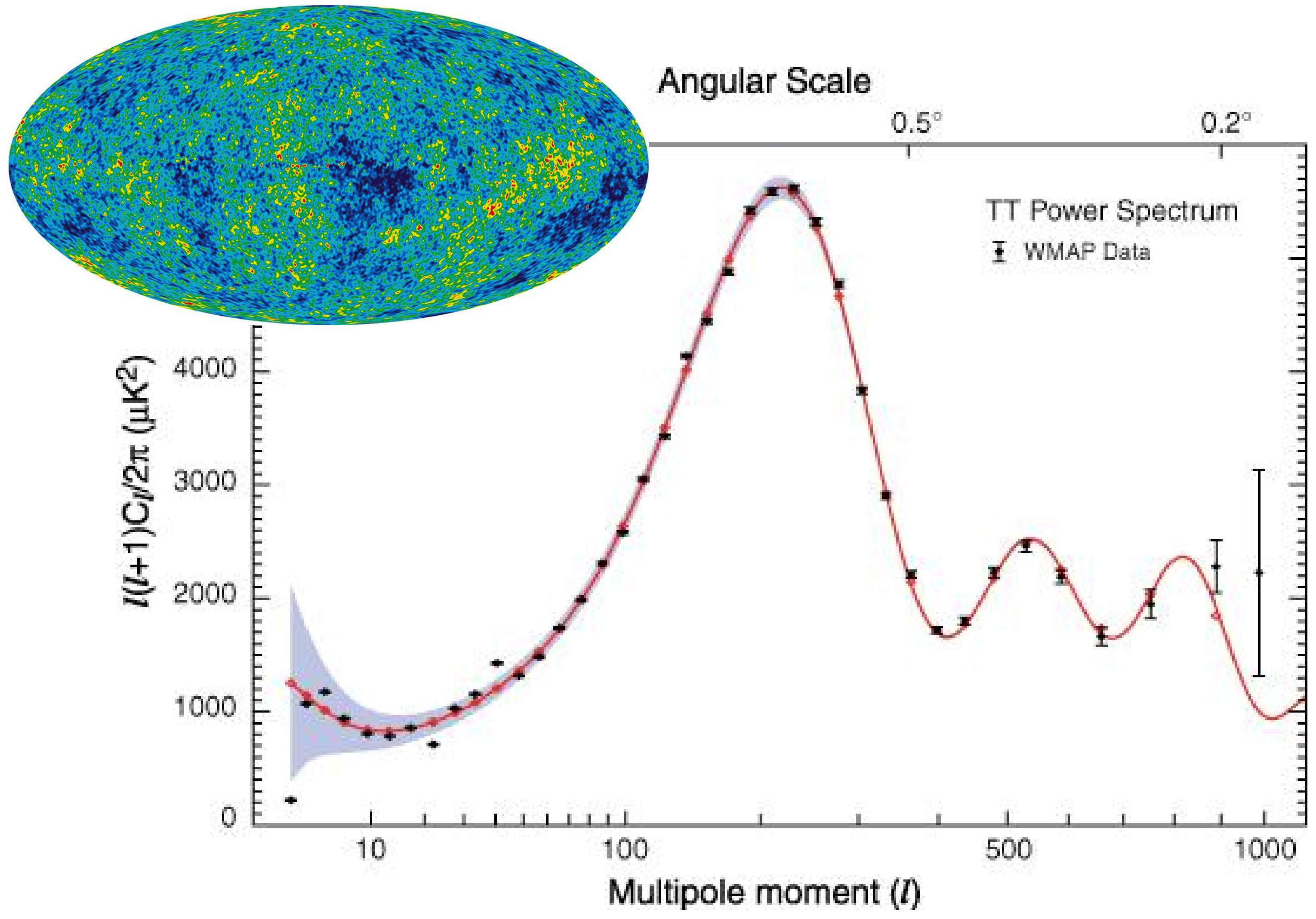
1933->1965

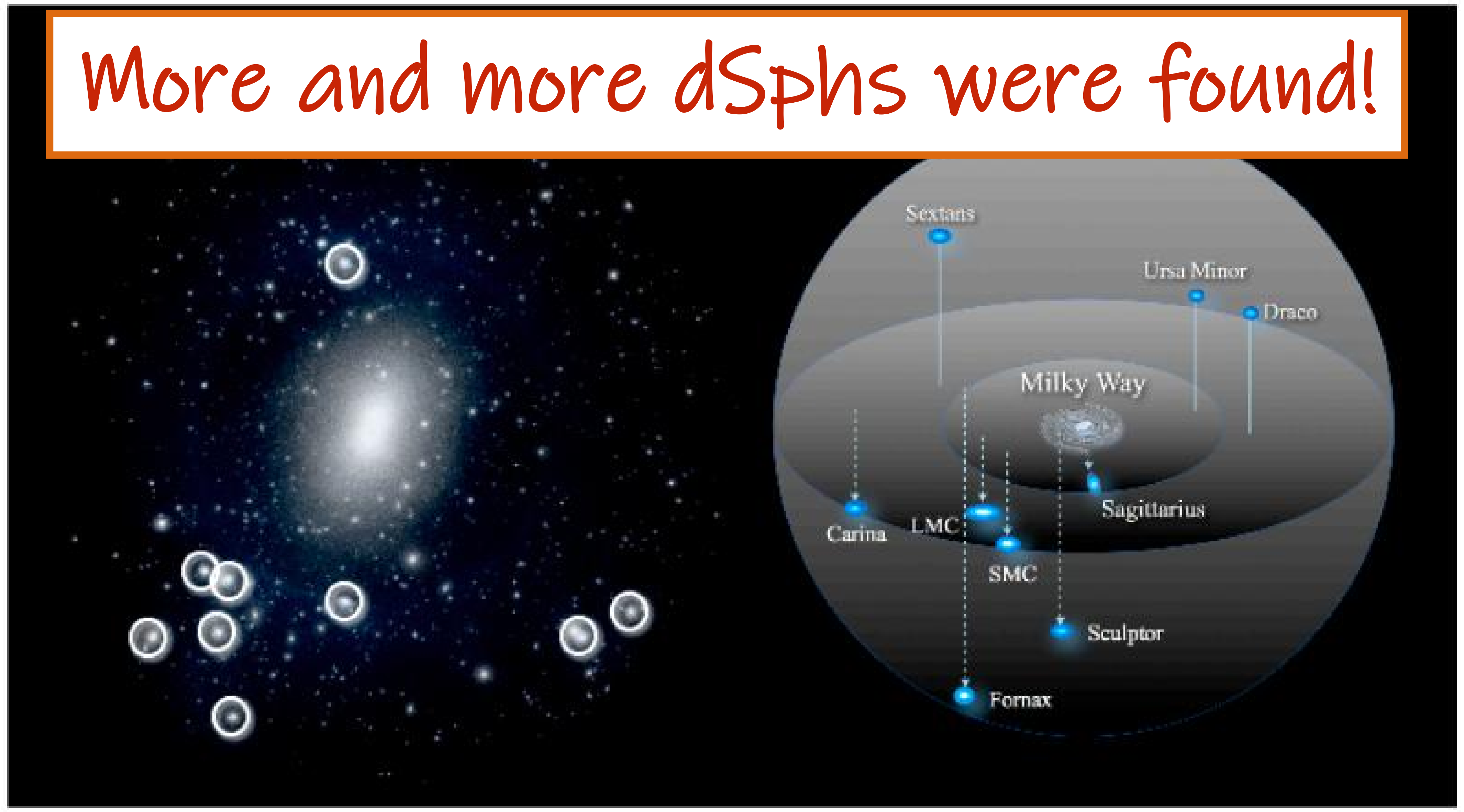


1980



2006





More and more dSphs were found!

It will be difficult to explain the universe without DM assumption.

Basic and minimum Lagrangian

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{2}\bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \frac{1}{2}(\partial\Phi)^2 - \frac{c_s}{2}\Phi\bar{\chi}\chi - \frac{c_p}{2}\Phi\bar{\chi}i\gamma_5\chi - V(\Phi,H),$$

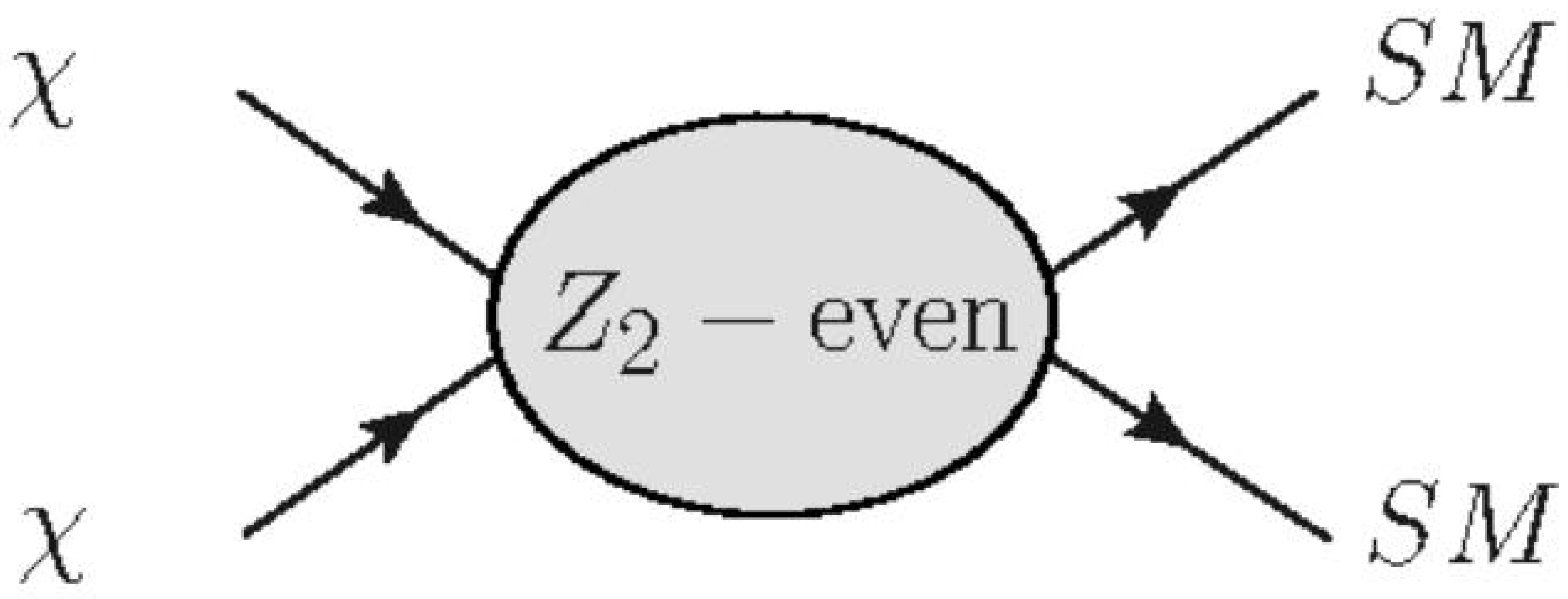
Majorana DM

SM singlet scalar

pseudo-scalar interaction

Scalar interaction

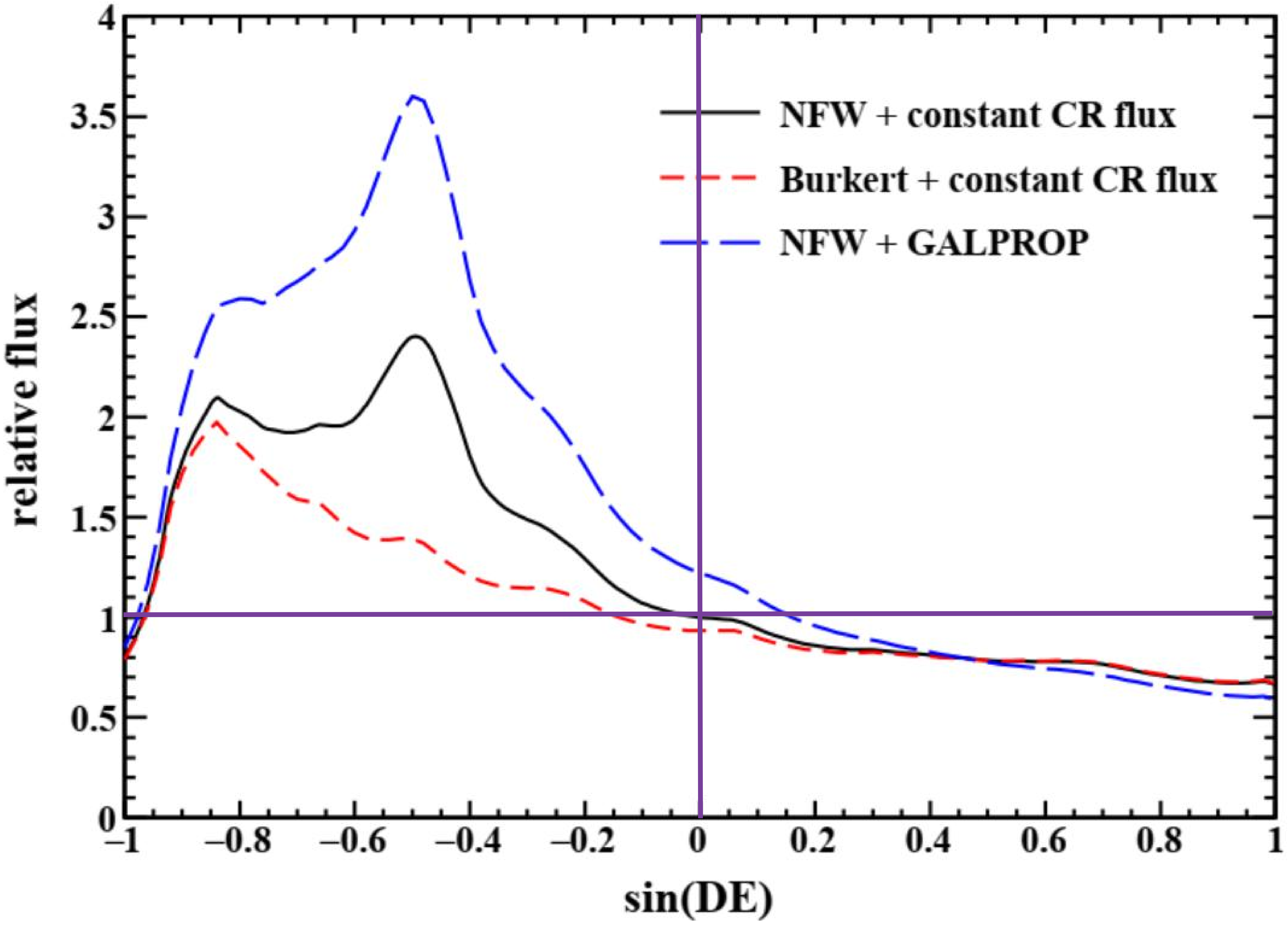
Mixing between New mediator and SM Higgs.



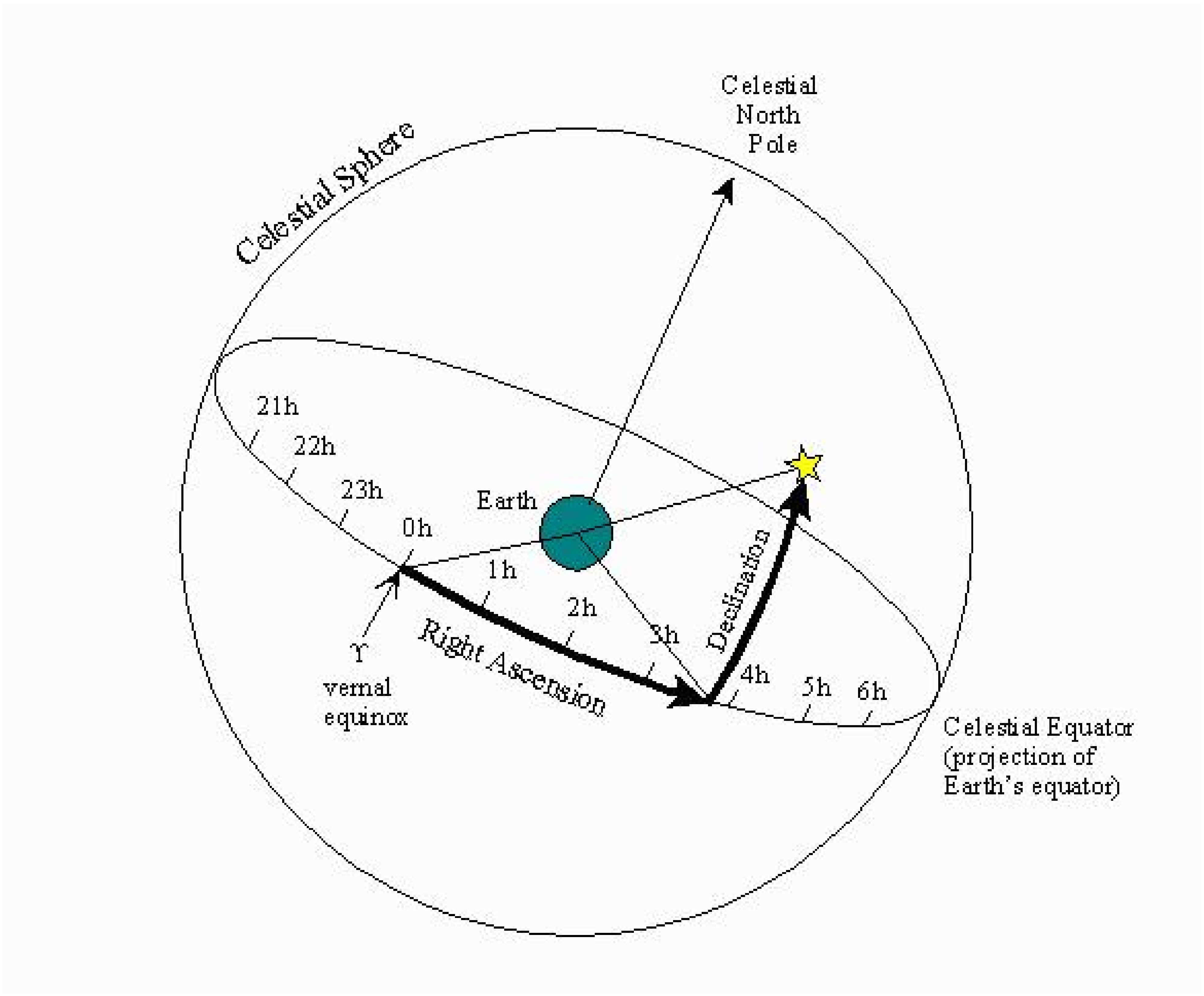
$$\mathscr{L}_{\rm int} \supset -\frac{\cos\theta}{2}(c_s\phi\bar{\chi}\chi + c_p\phi\bar{\chi}i\gamma_5\chi) + \frac{\sin\theta}{2}(c_s h\bar{\chi}\chi + c_p h\bar{\chi}i\gamma_5\chi).$$

A minimum setup:
one SM singlet Majorana DM + one SM singlet scalar mediator.

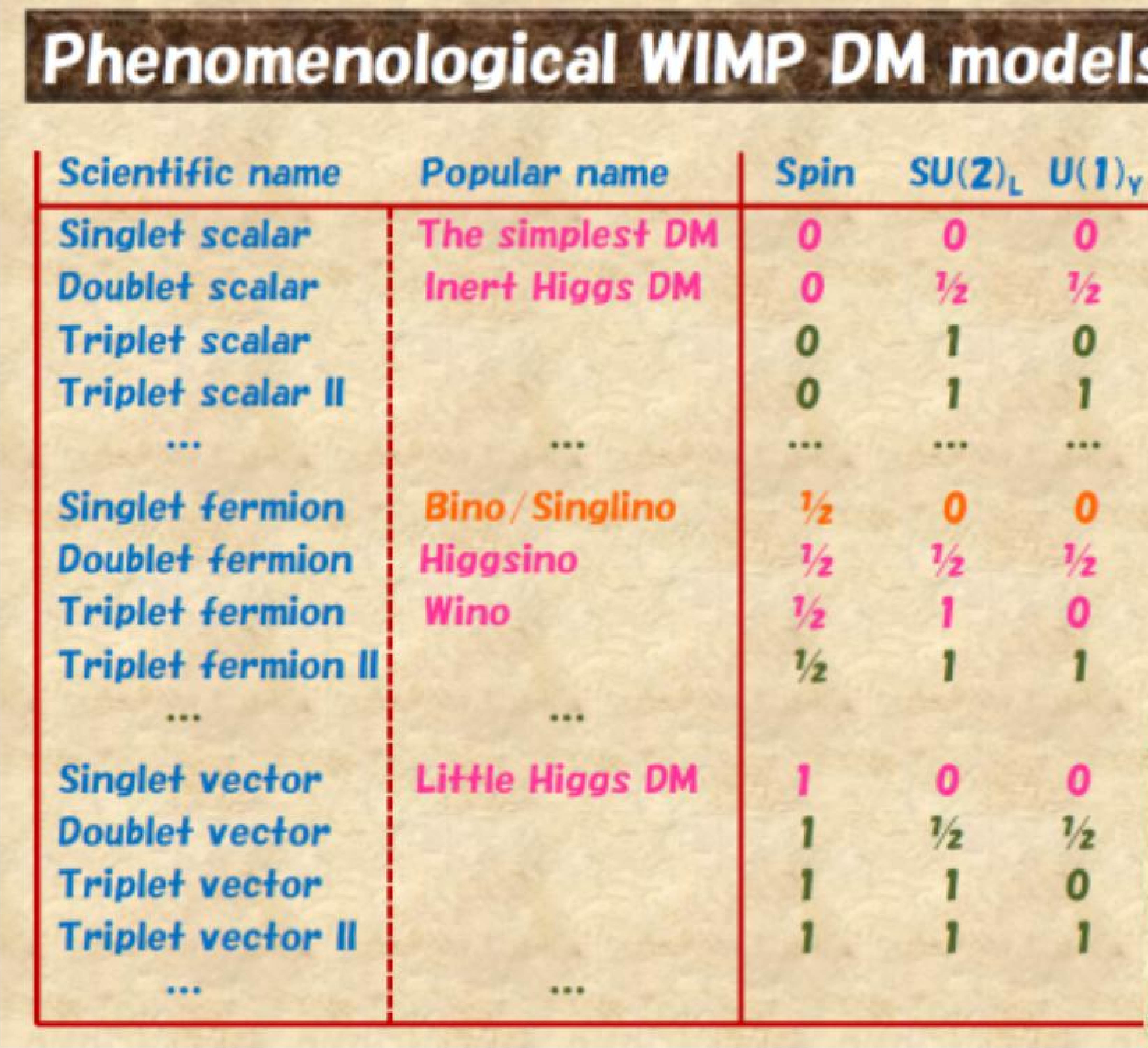
Total DM spatial spatial distribution



$$\phi^{\rm MW}_{\chi,\rm DE} = \int_0^{2\pi} d{\rm RA}\ \phi^{\rm MW}_\chi(T_\chi, \Omega)$$



The propagation uncertainties do not affect the result much.



Phenomenological WIMP DM models

Scientific name	Popular name	Spin	$SU(2)_L$	$U(1)_Y$
Singlet scalar	The simplest DM	0	0	0
Doublet scalar	Inert Higgs DM	0	½	½
Triplet scalar		0	1	0
Triplet scalar II		0	1	1
…	…	…	…	…
Singlet fermion	Bino/Singlino	½	0	0
Doublet fermion	Higgsino	½	½	½
Triplet fermion	Wino	½	1	0
Triplet fermion II		½	1	1
…	…			
Singlet vector	Little Higgs DM	1	0	0
Doublet vector		1	½	½
Triplet vector		1	1	0
Triplet vector II		1	1	1
…	…			

Credit: Shigeki Matsumoto

DM still leaves a lot unknown:

- ✓ Spin
- ✓ Electroweak charge
- ✓ Real/Majorana or Complex/Dirac