Neutrino, dark matter, and new physics

TOKYO METROPOLITAN UNIVERSITY
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If you want to have further topics, let me know wen_at_tmu.ac.jp.
See also https://particletheory.fpark.tmu.ac.jp for the research topics.

@TGSW2024
30/9/2024

Plan

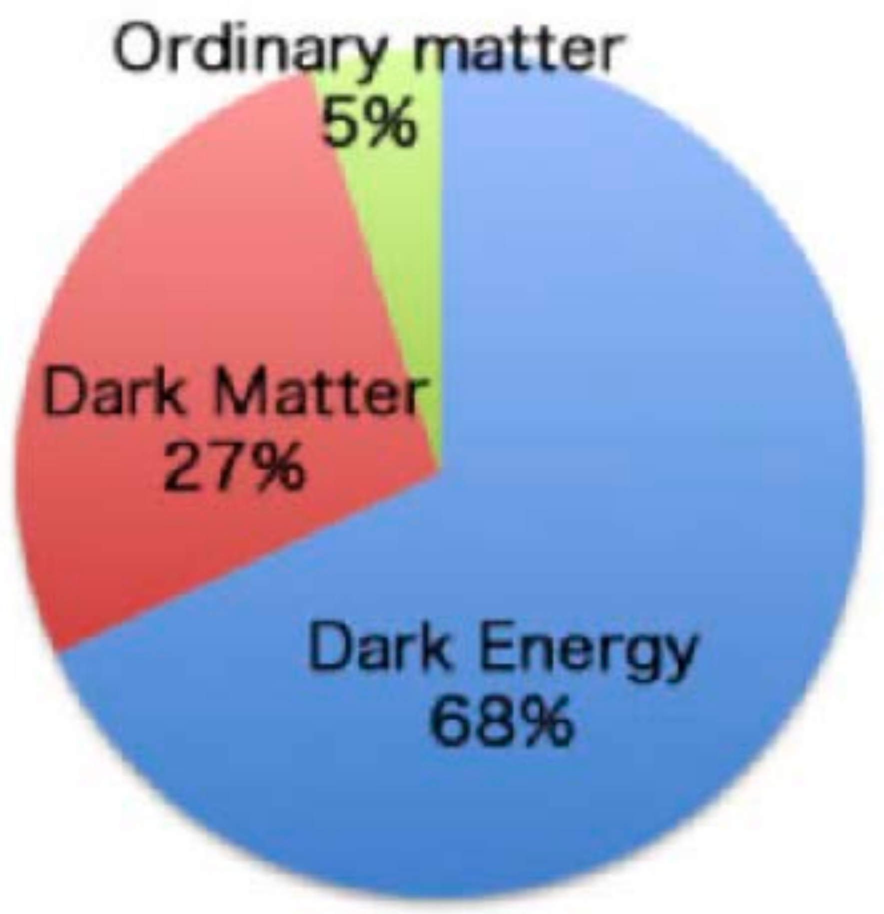
- 1. Introduction
- 2. WIMP DM and neutrinos.
- 3. DM longevity by neutrinos.
- 4. Conclusions

- 1. Introduction

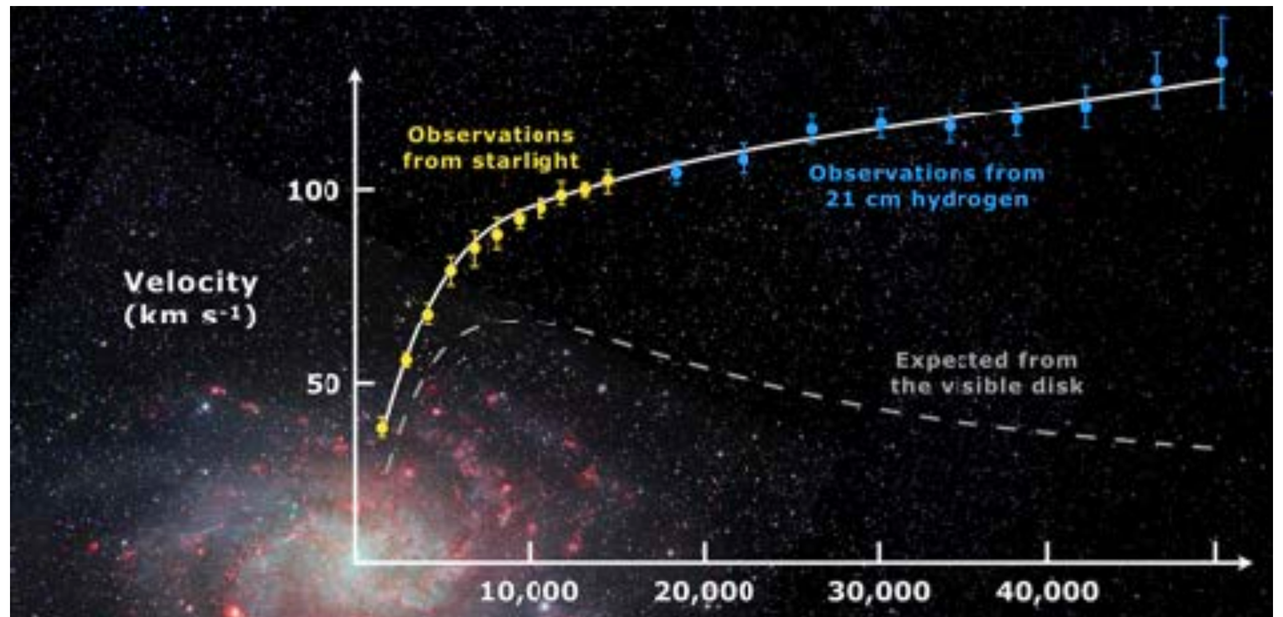
Dark matter (DM), long-standing mystery

What is DM? **Longevity**, Neutral, Cold, $\rho_{DM}/s \sim$ **eV**

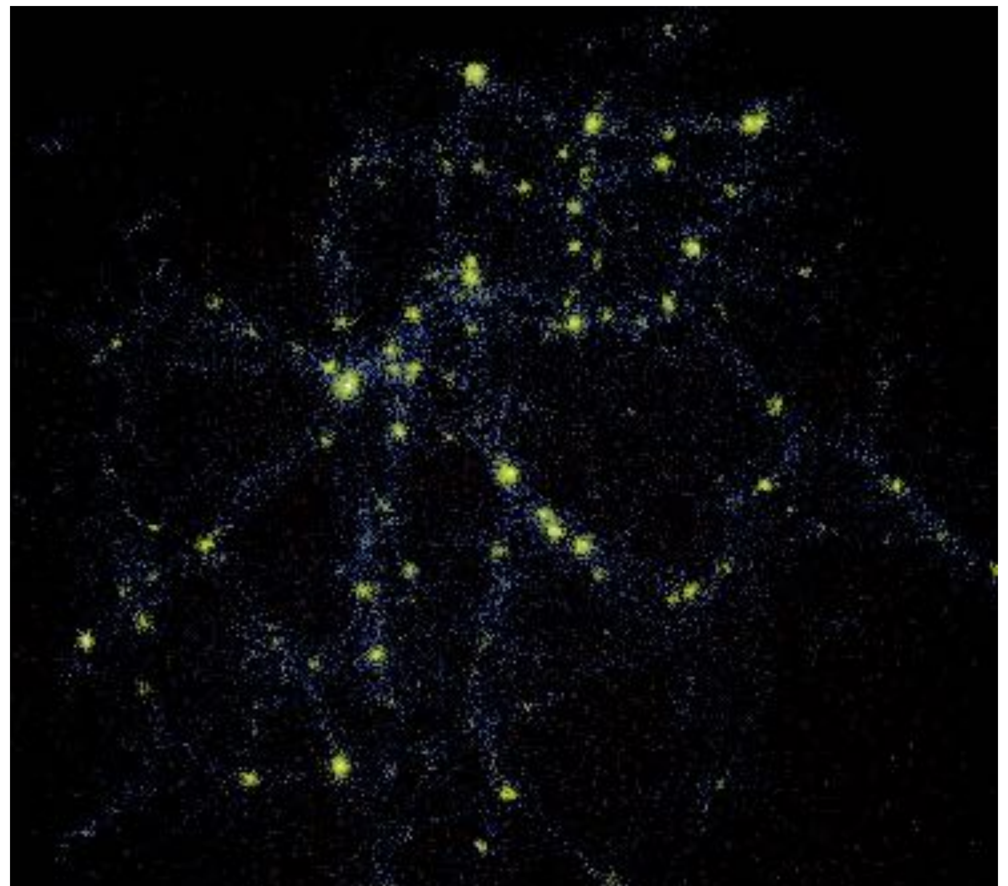
We do not know the particle property at all.



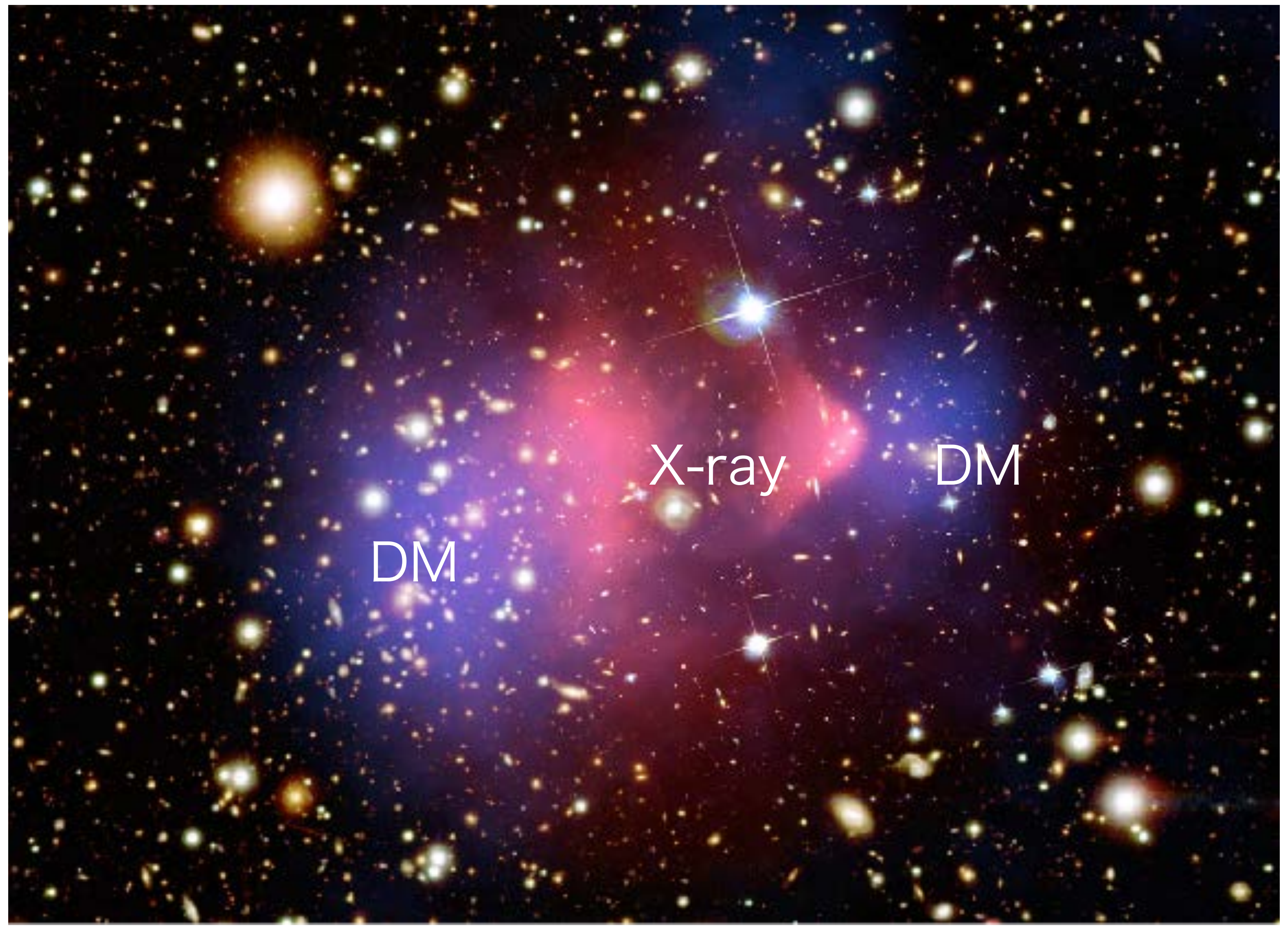
CMB data



Rotation curve



N-body simulation



Bullet cluster

Cosmic history and DM, ΛCDM model.

NASA / WMAP SCIENCE T

Cosmic history and DM, ΛCDM model.

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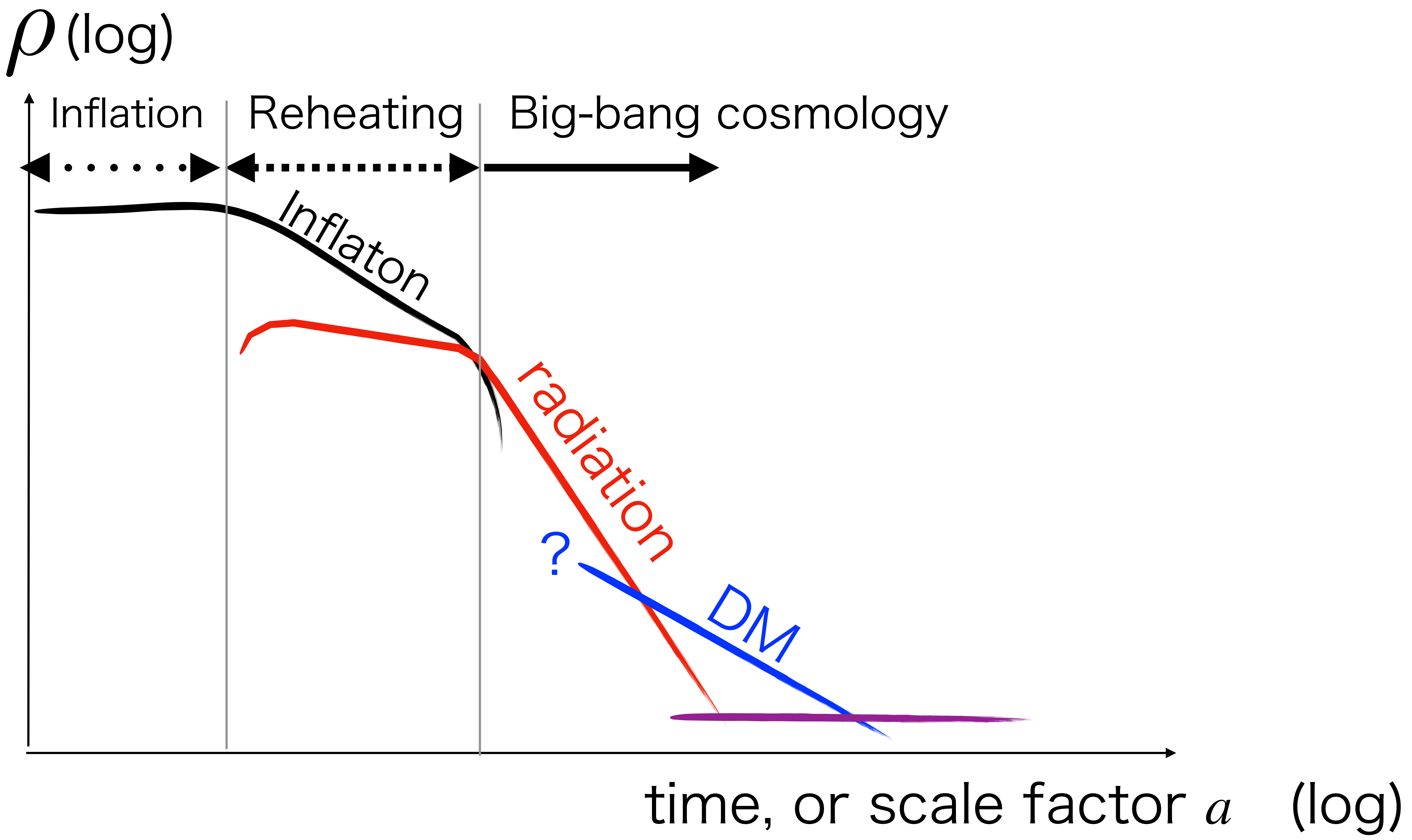

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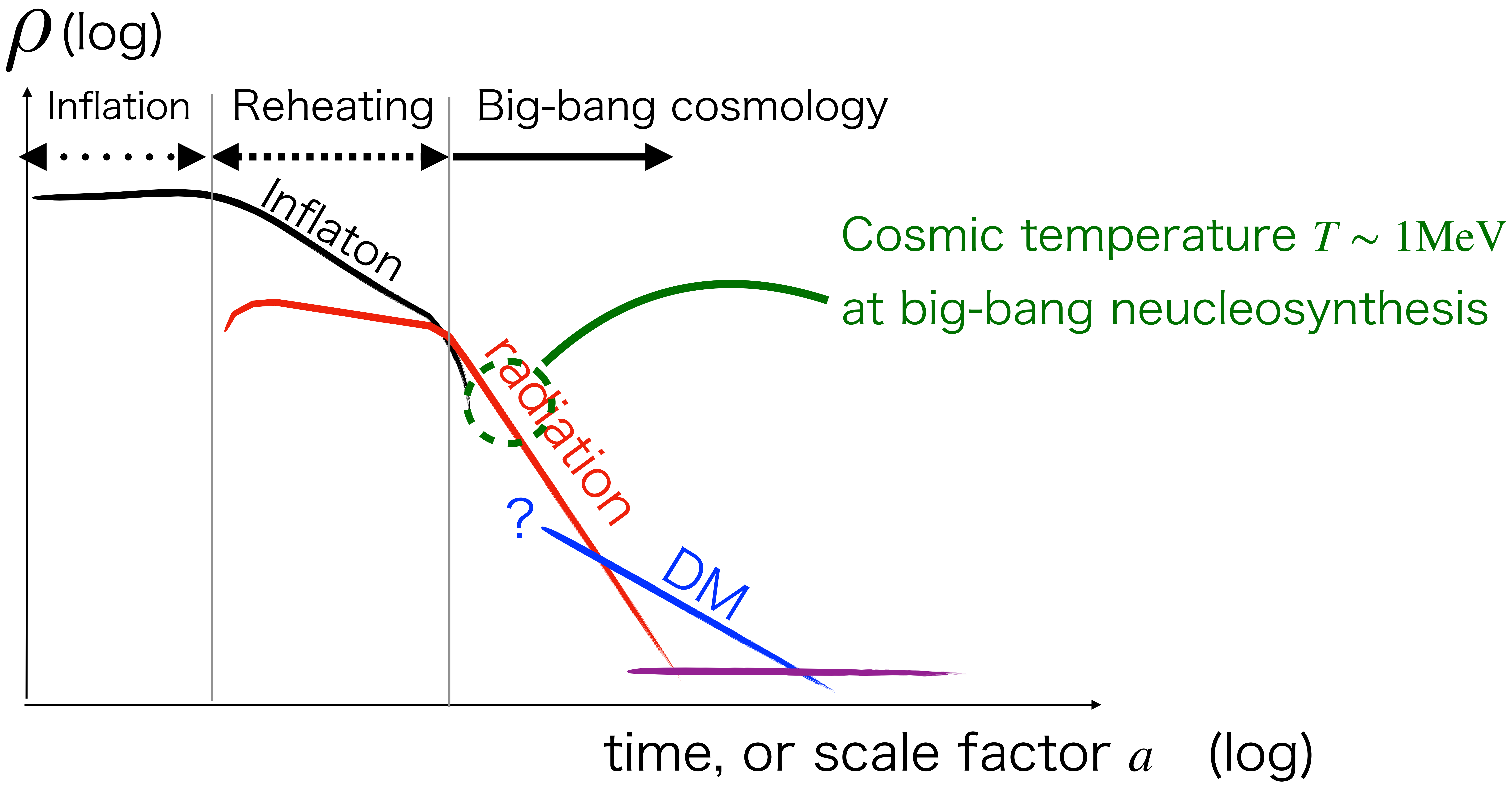

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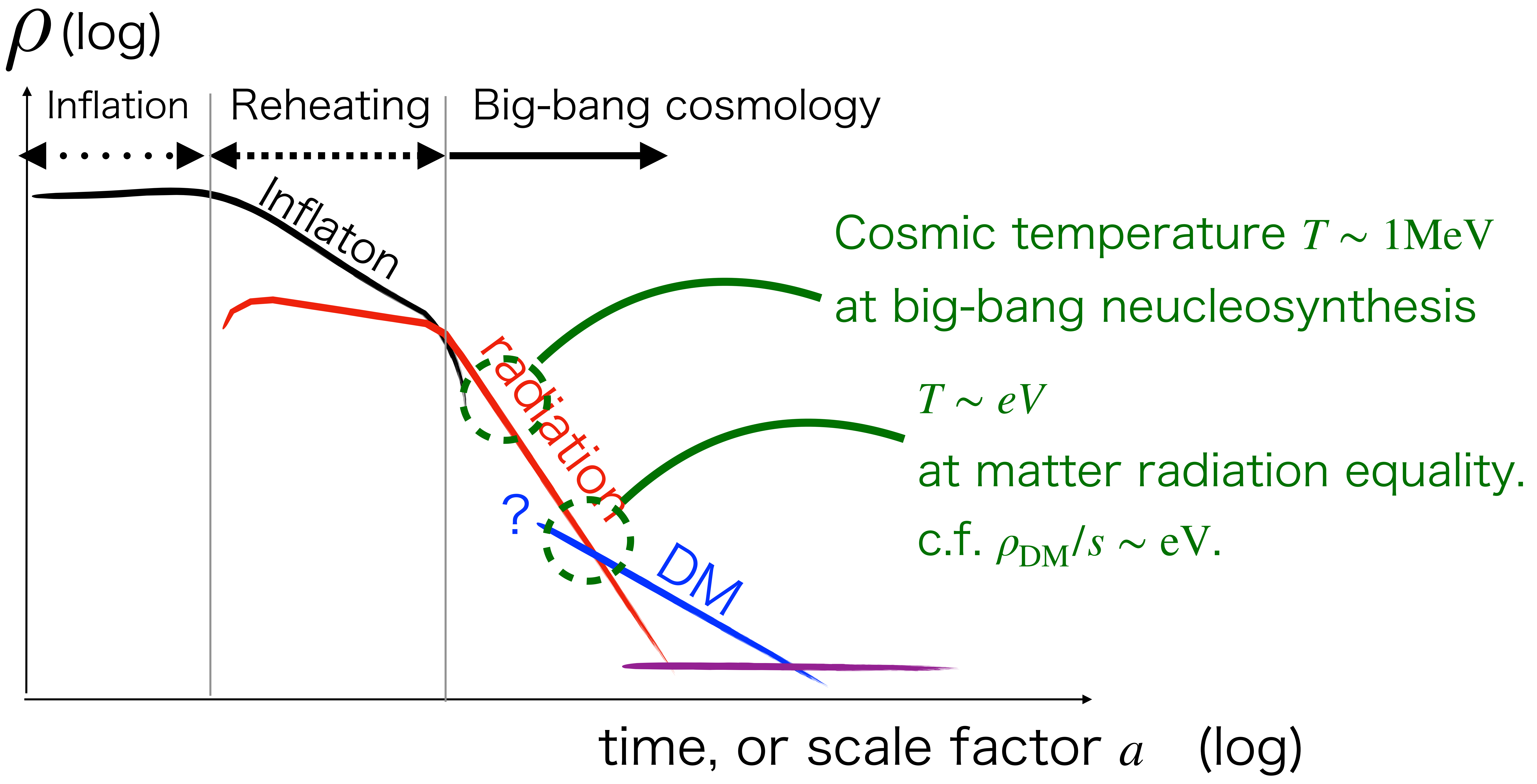
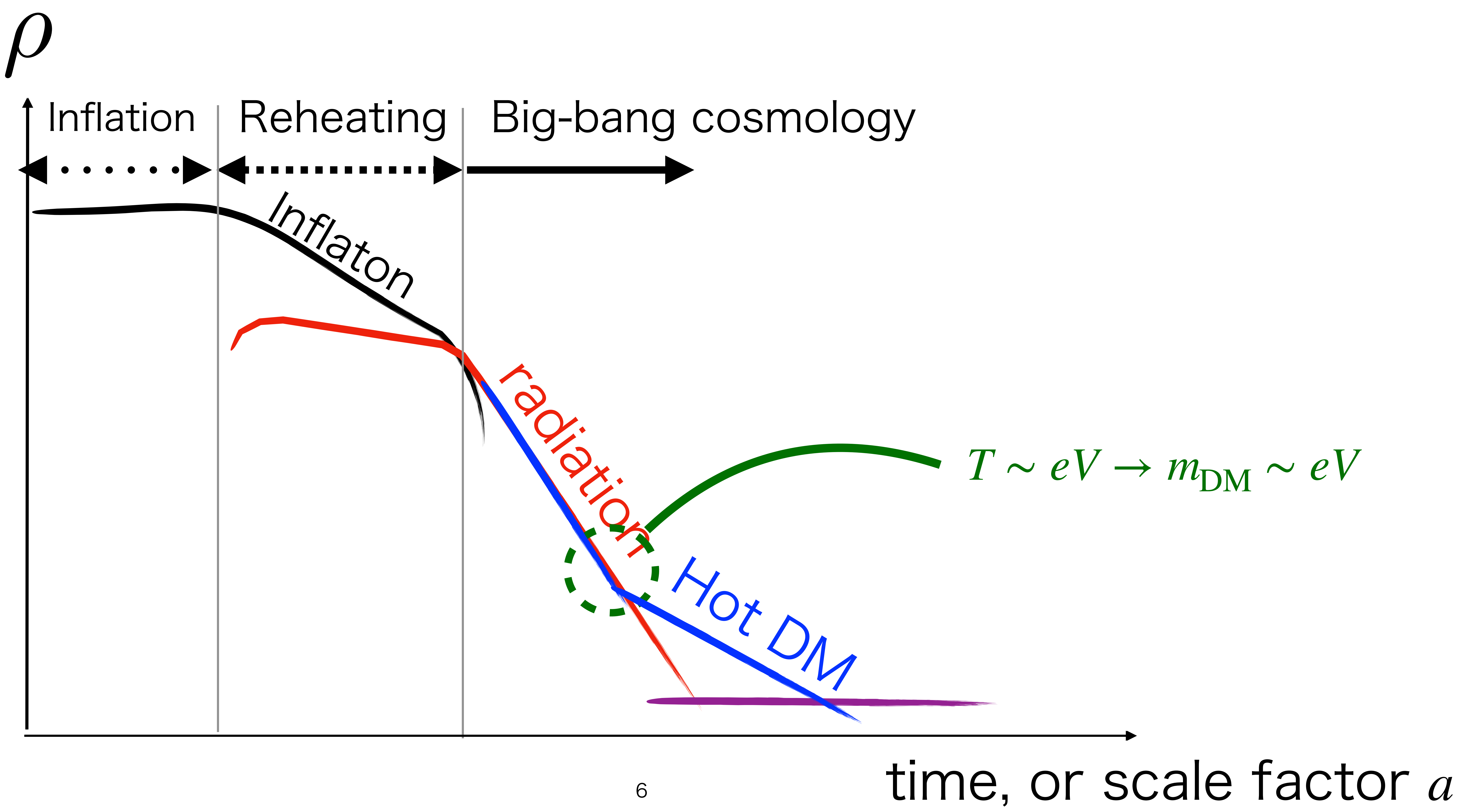


Hot DM paradigm (-1984)



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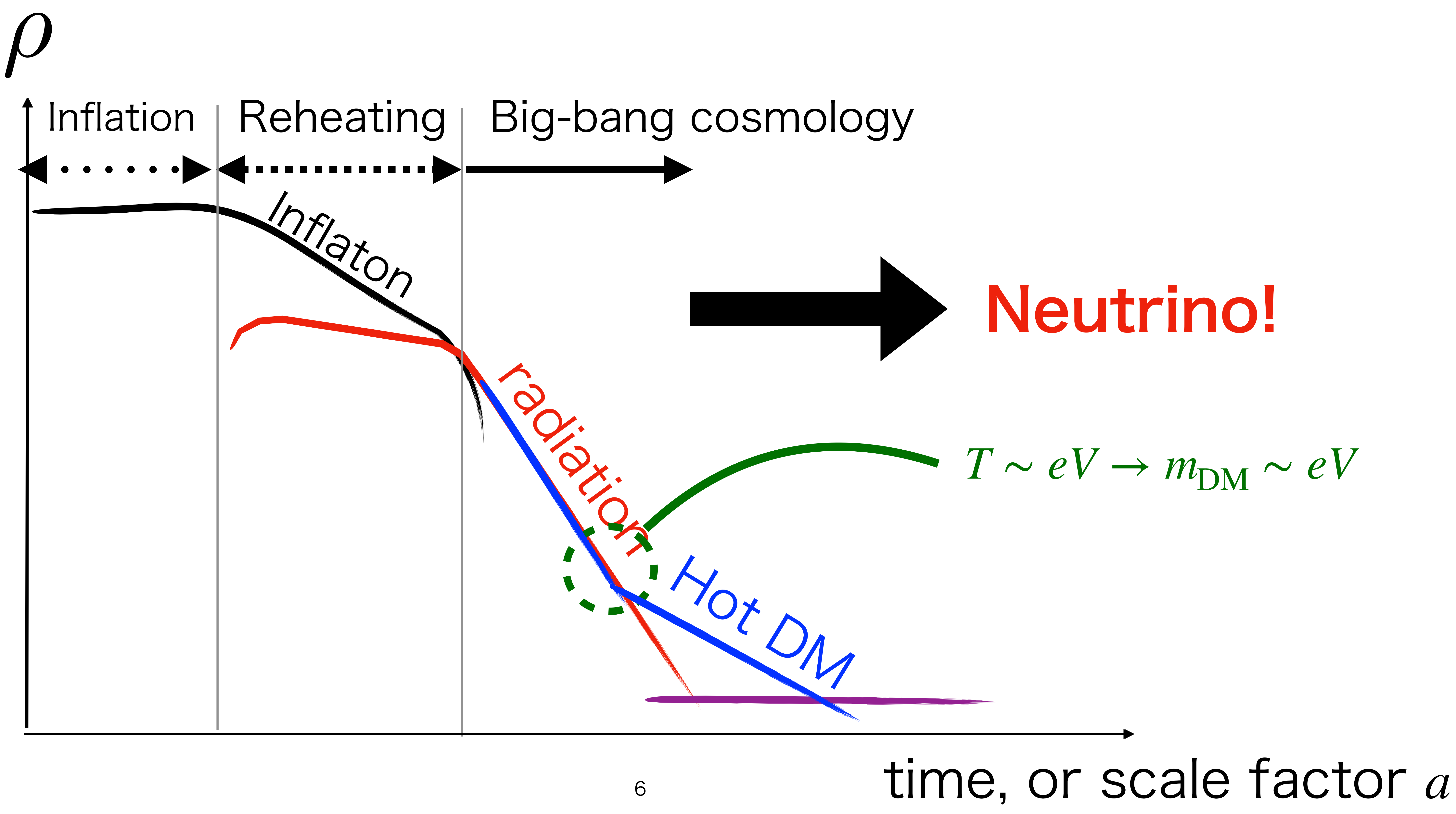
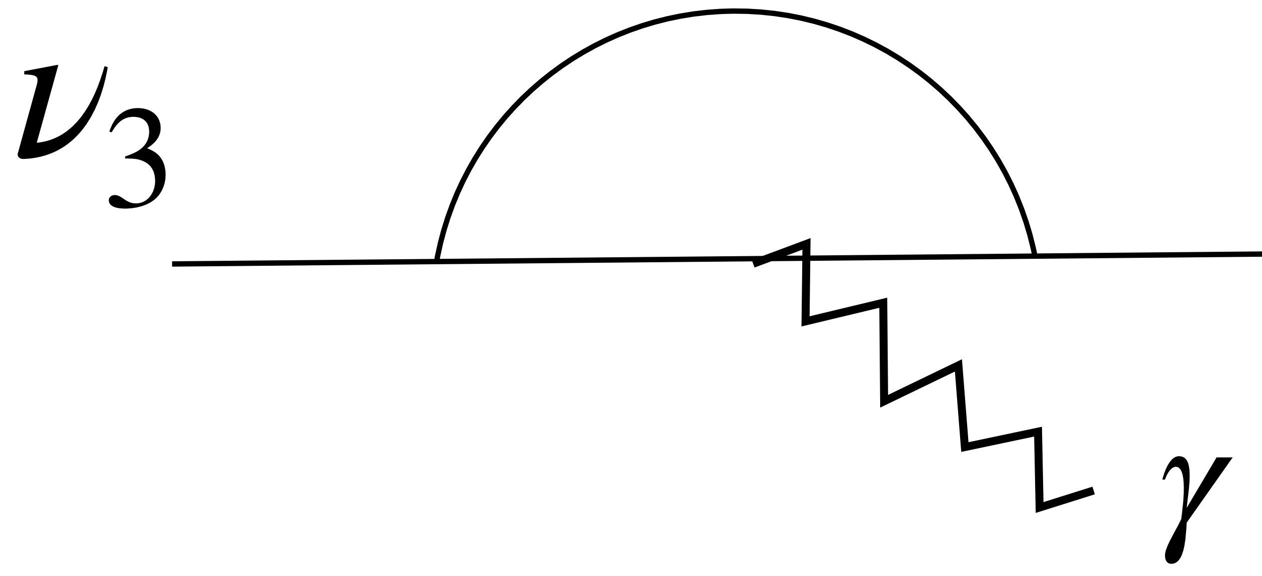


Neutrino!

Property of Weak Interaction

- 'Weak' only for reaction with low kinematical energy



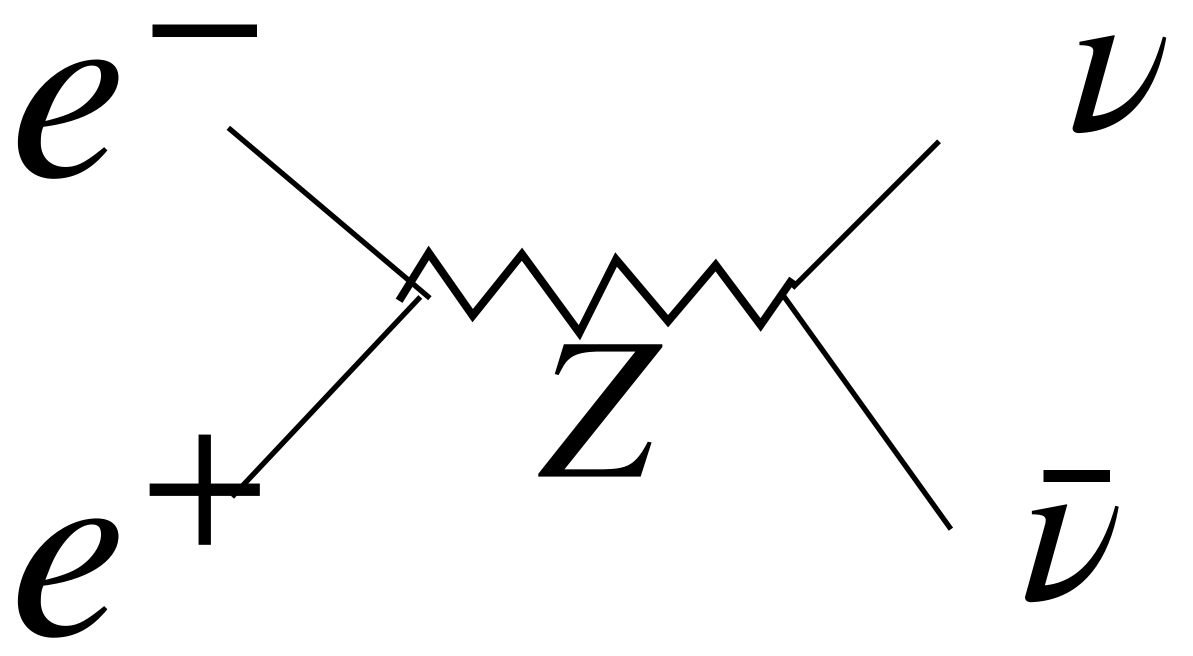
$$\Gamma_{\rm decay} \sim \kappa G_F^2 m_{\nu_3}^5 \sim \frac{1}{10^{35} yr}\left(\frac{m_\nu}{1{\rm eV}}\right)^5,$$

$$\kappa \sim \frac{e^2}{(4\pi)^5}\frac{m_\tau^4}{m_W^4}$$ (Phase space suppression neglected.)

c.f. age of Universe $13.8 \times 10^9 yr$

- This depends on the new physics giving mass to neutrinos and the lifetime may be shorter.

- Not 'weak' at high energy,



$$\Gamma_{\rm prod} \sim \frac{1}{4\pi} G_F^2 T^5 \sim \frac{1}{1{\rm ms}}\left(\frac{T}{10{\rm MeV}}\right)^5$$

c.f. BBN begins from $\sim 1{\rm s}\ with\ T \sim 10 MeV$

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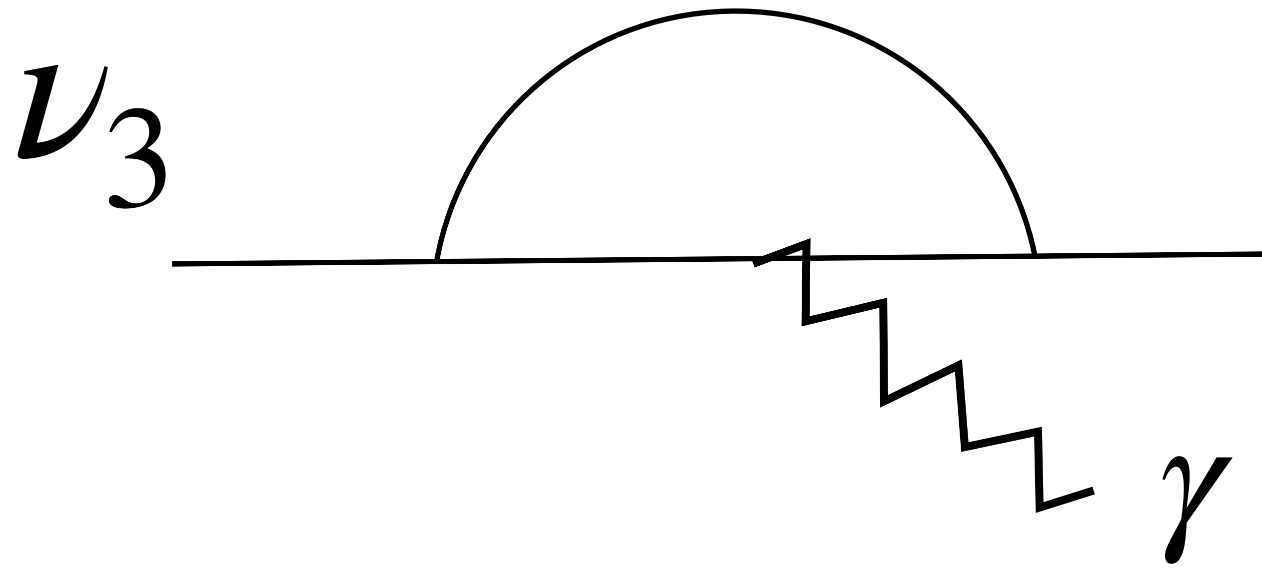

→ **Super long-lived**

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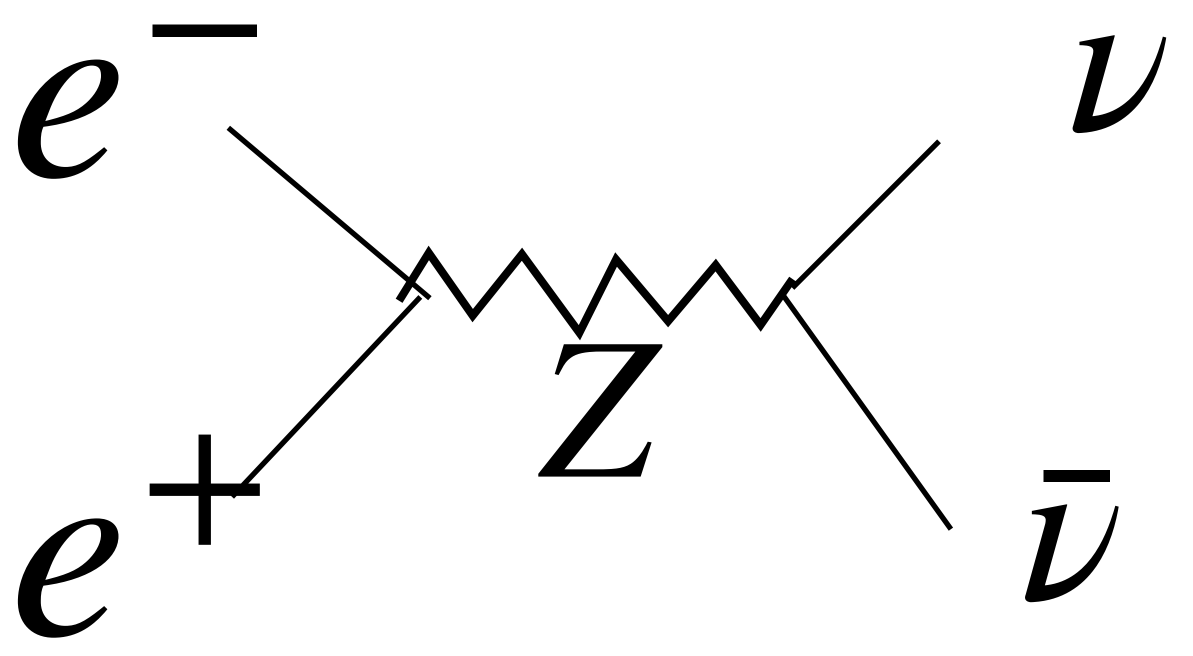

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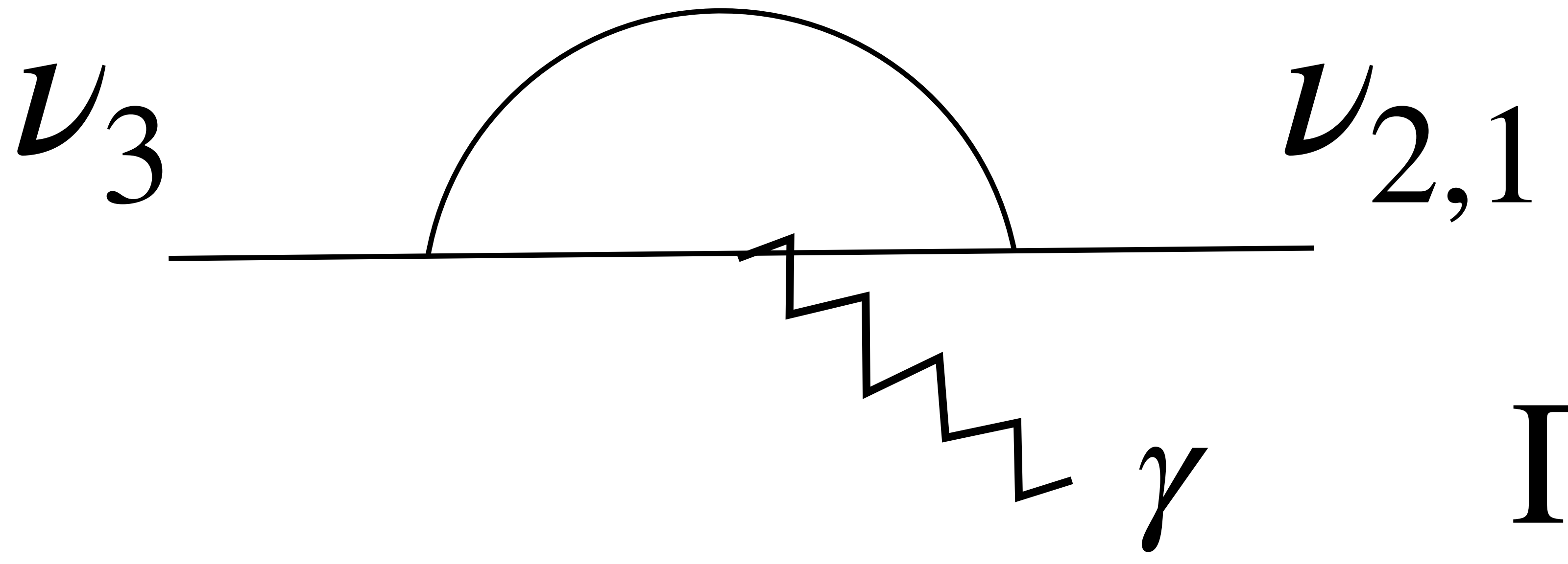

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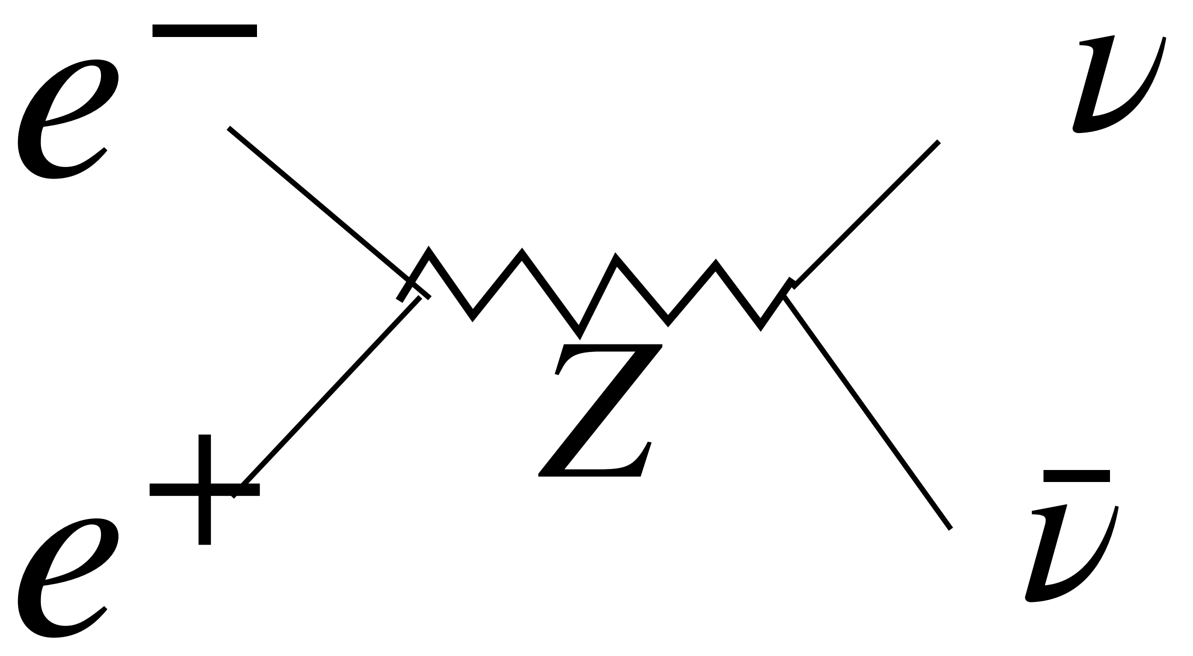
→ **Thermal equilibrium in the early Universe**



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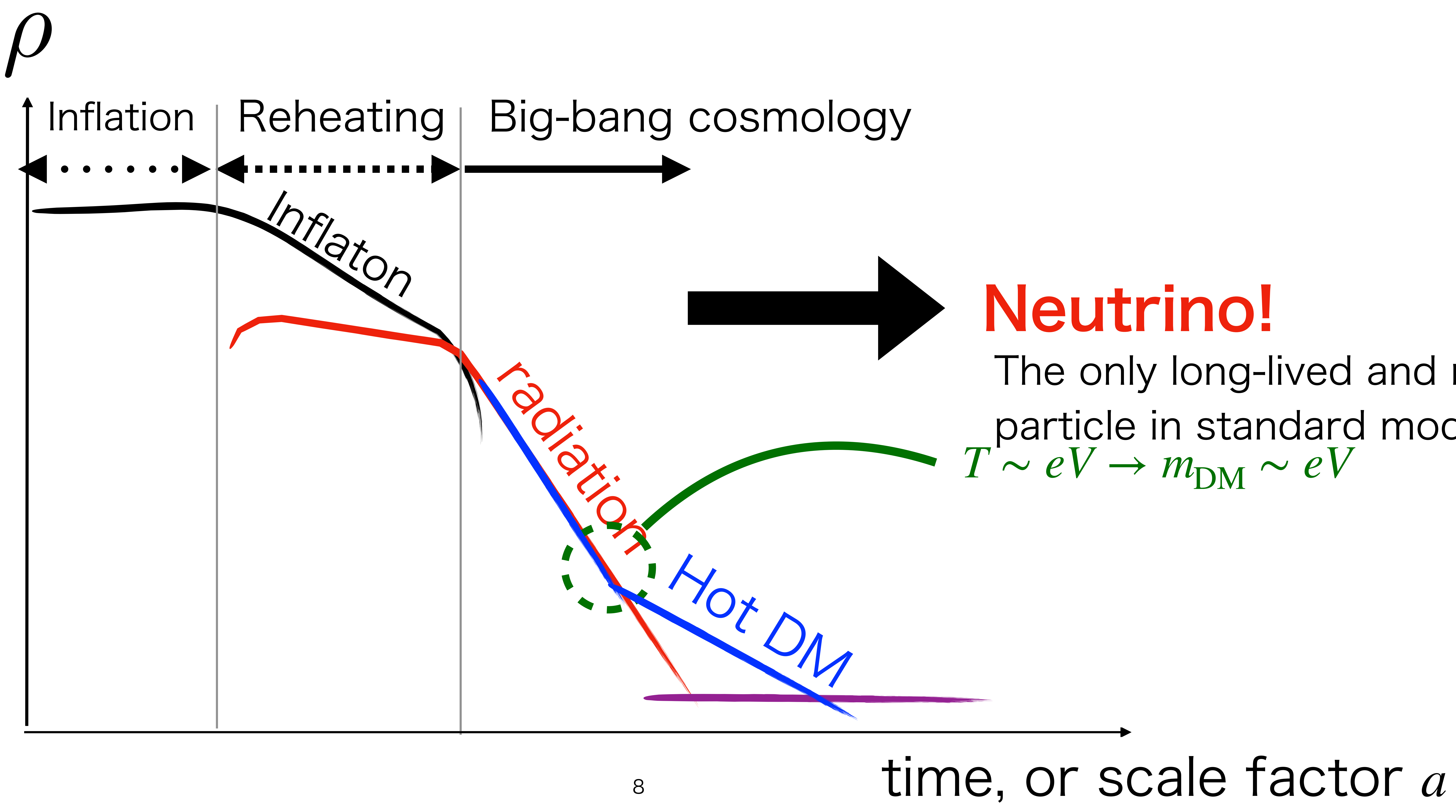


Neutrino!

The only long-lived and neutral particle in standard model.

Q: Is DM neutrino？

Neutrino's status

-Constraint from Tritium β decay

$$T_2 \to {}^3\mathrm{HeT}^+ + e^- + \bar{\nu}_e$$

The KATRIN Collaboration. 2022

neutrino mass $\lesssim 1\mathrm{eV}$

-Neutrinoless double β decay

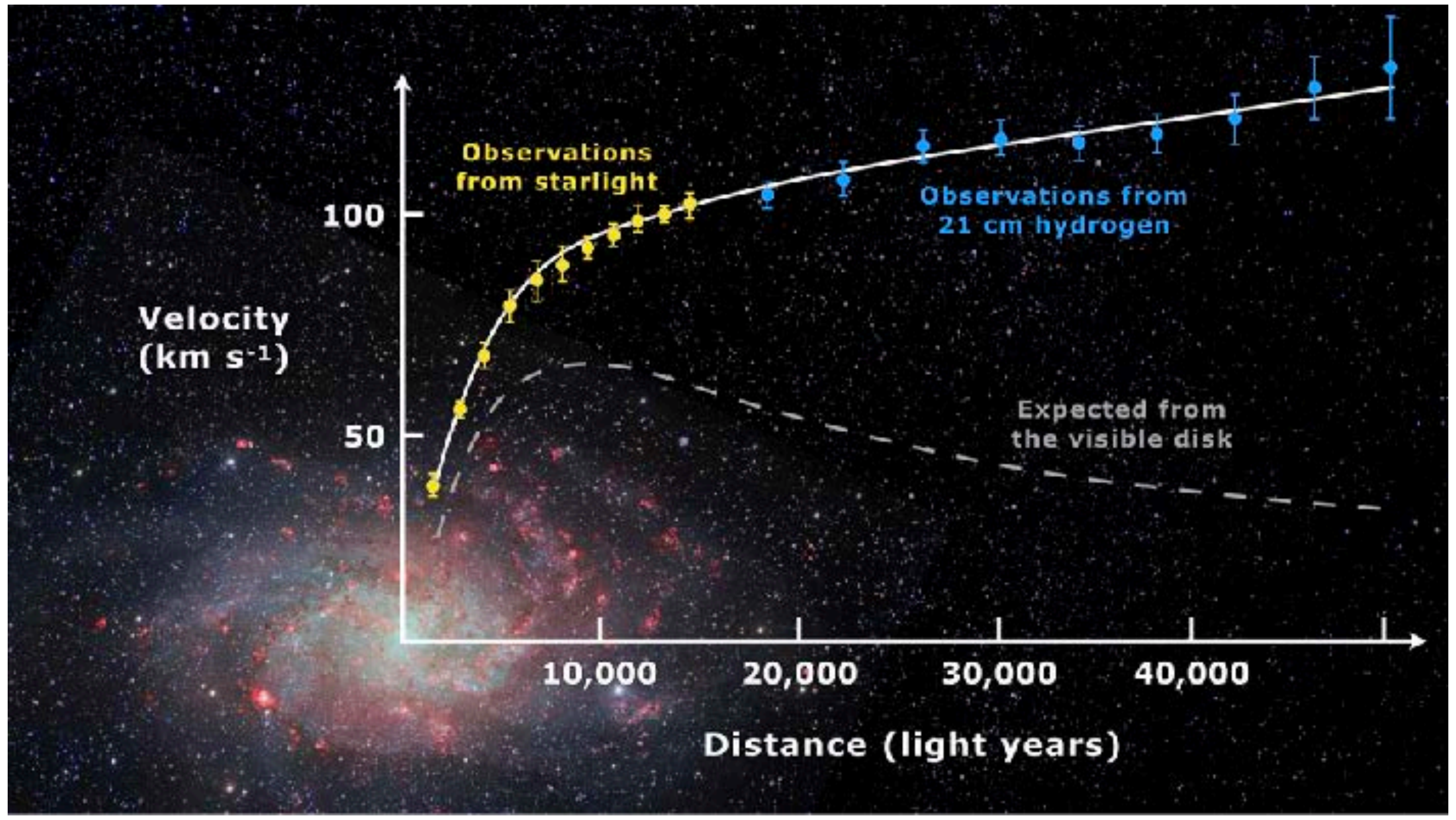
KamLAND-Zen Collaboration,
Phys.Rev.Lett. 130 (2023) 5, 051801

(Majorana)Neutrino mass $\lesssim 0.1\mathrm{eV}$

Neutrino mass $\lesssim 1\mathrm{eV}$

If neutrino is the DM

Pauli Exclusion Principle



∵Neutrino cannot be too many in the galaxy

(Tremaine & Gunn 1979).

Neutrino mass $\gtrsim 100\mathrm{eV}$

This is also a constraint for generic fermionic DM

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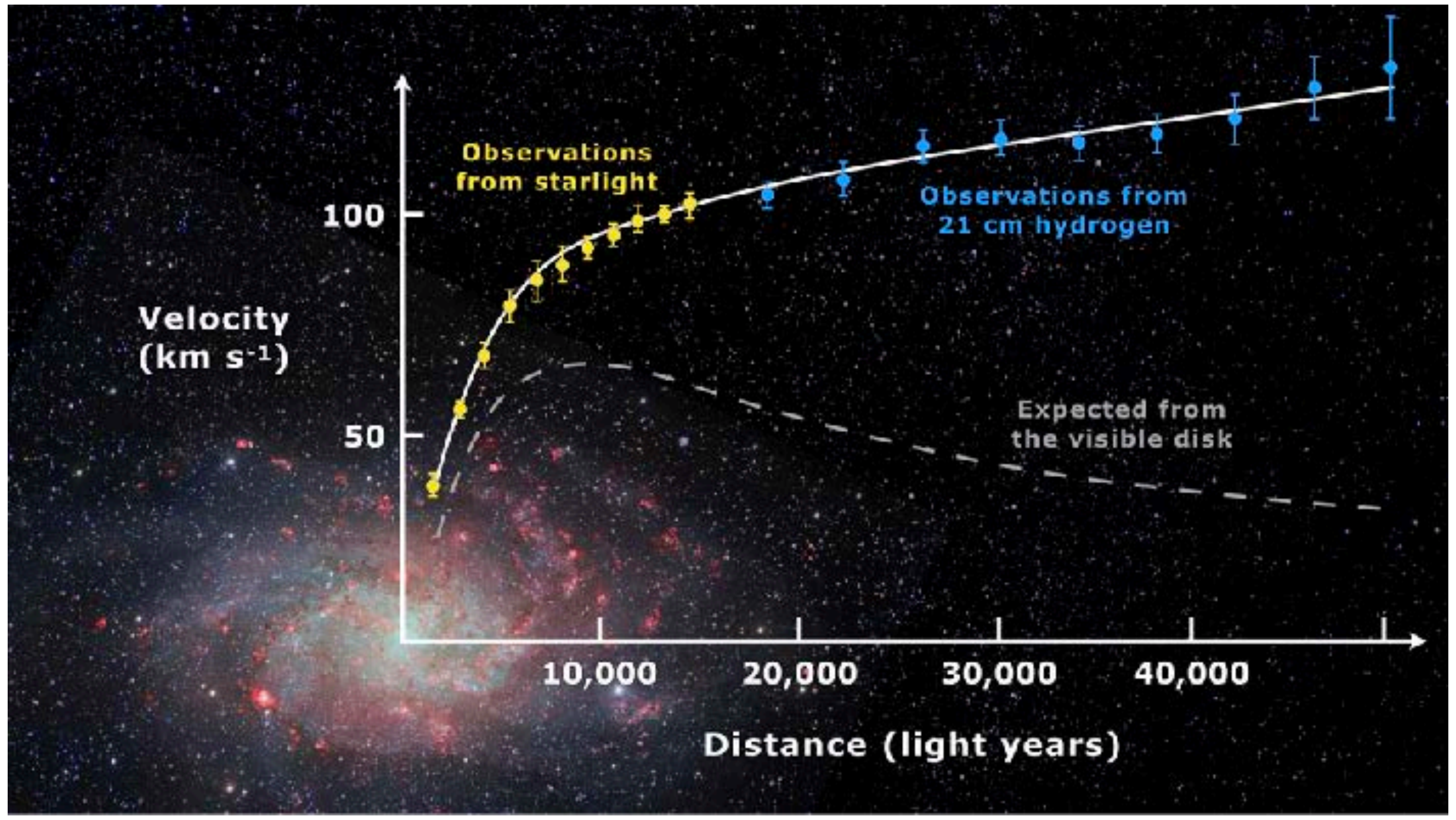

$\because$Neutrino cannot be too many in the galaxy

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Contradict

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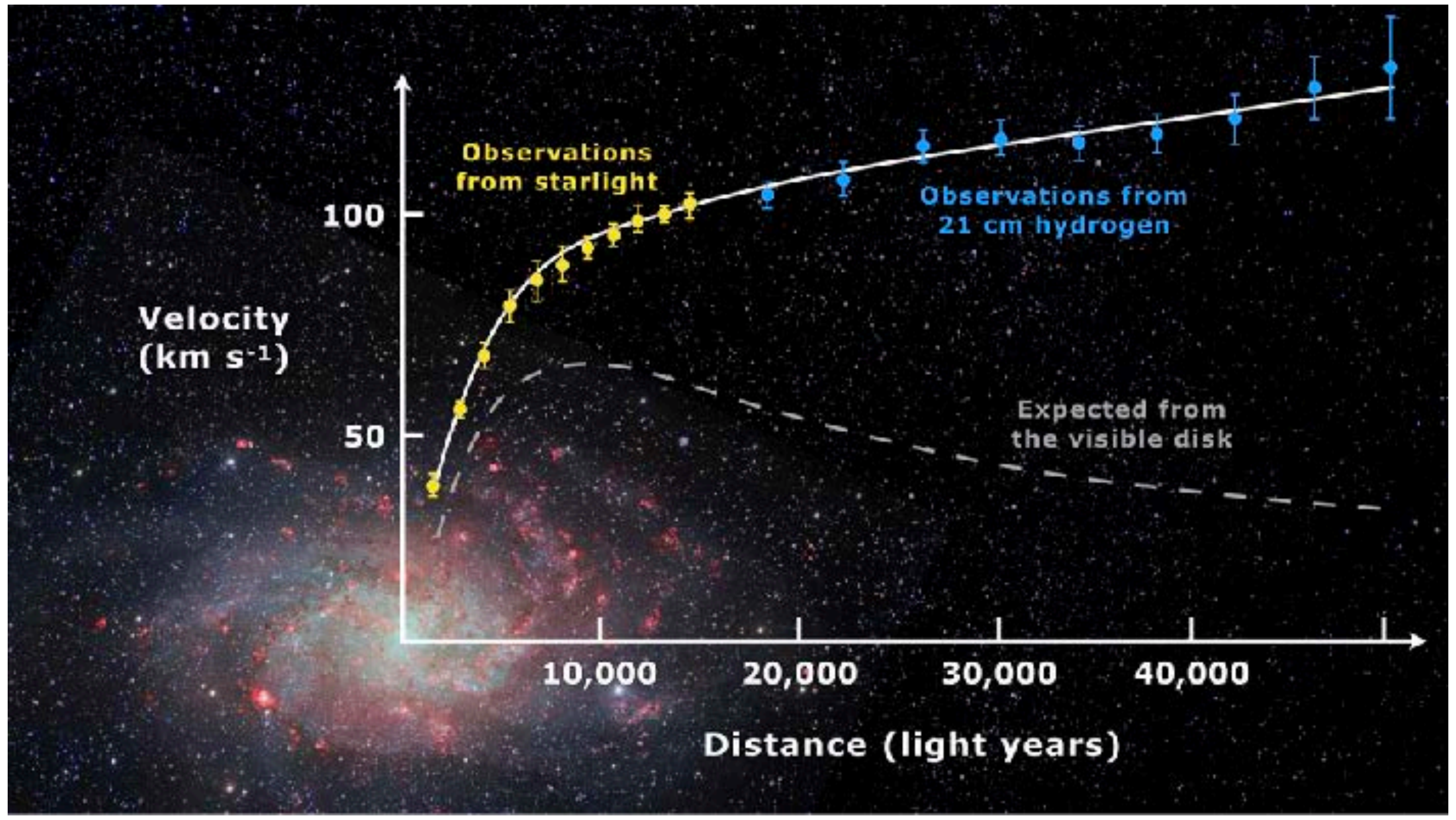

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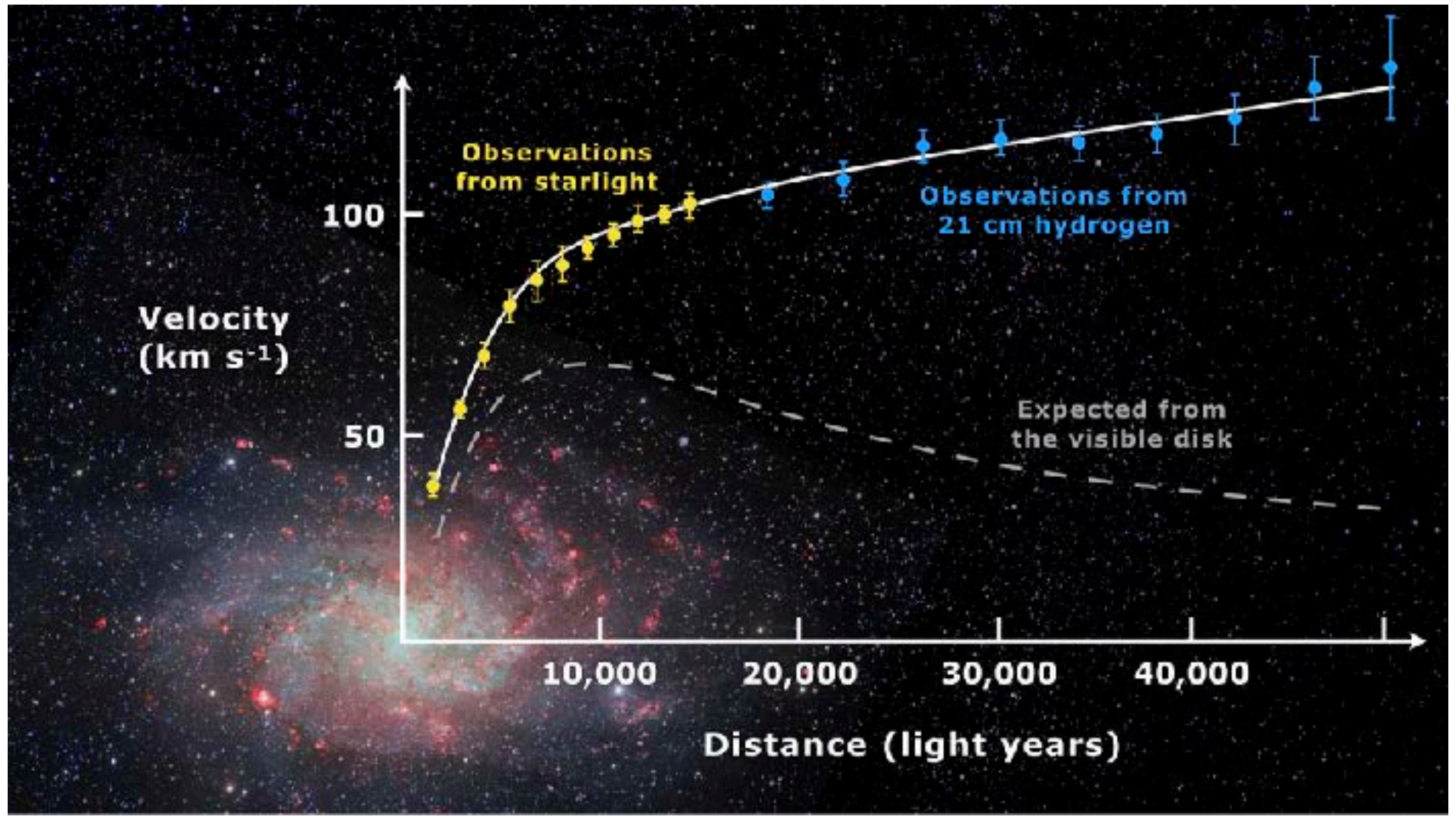

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This no-go theorem does not rely early cosmology and thus super robust.

- Just `hot dark matter' does not mean an exclusion. See WY 2301.08735.

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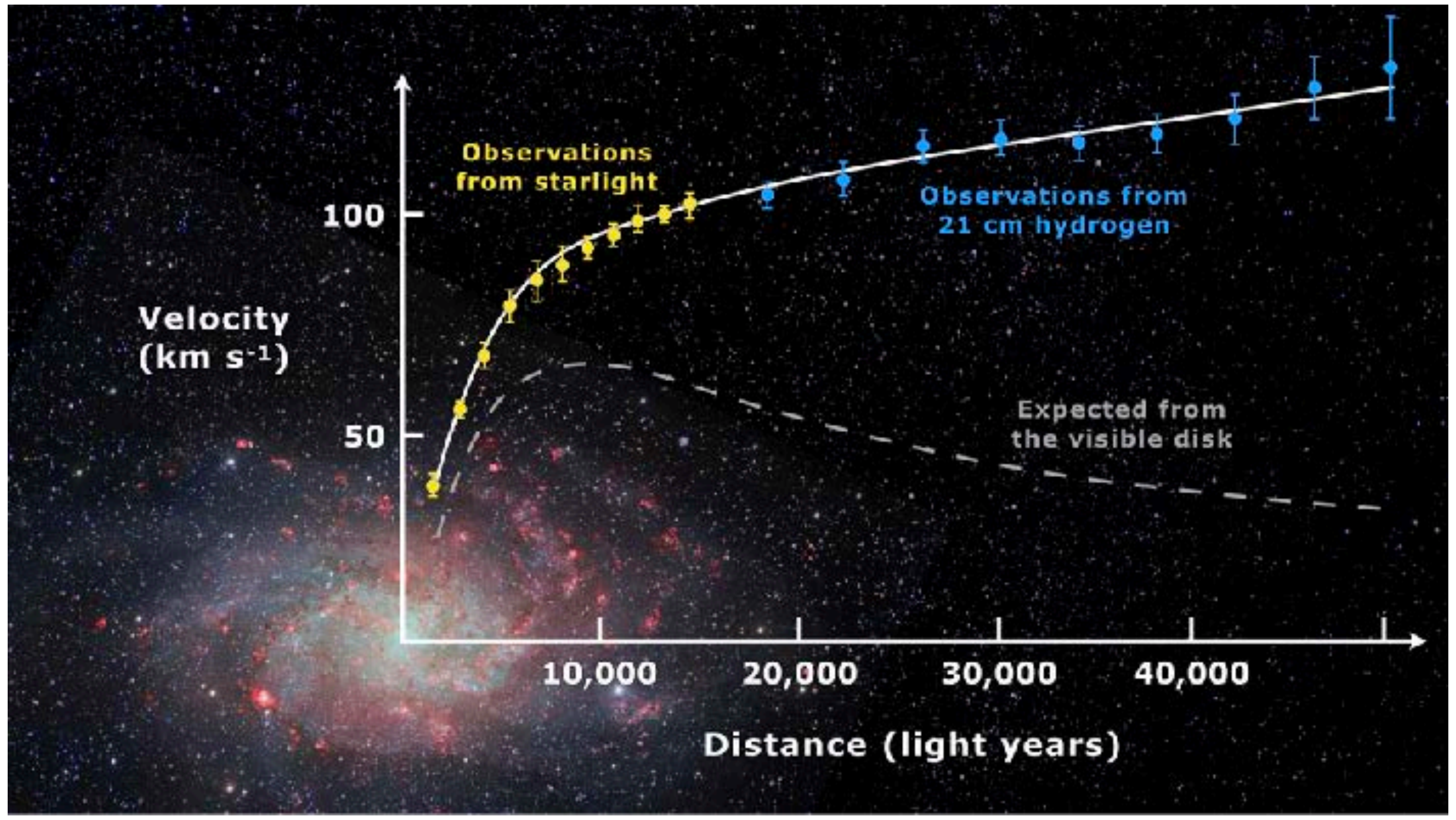

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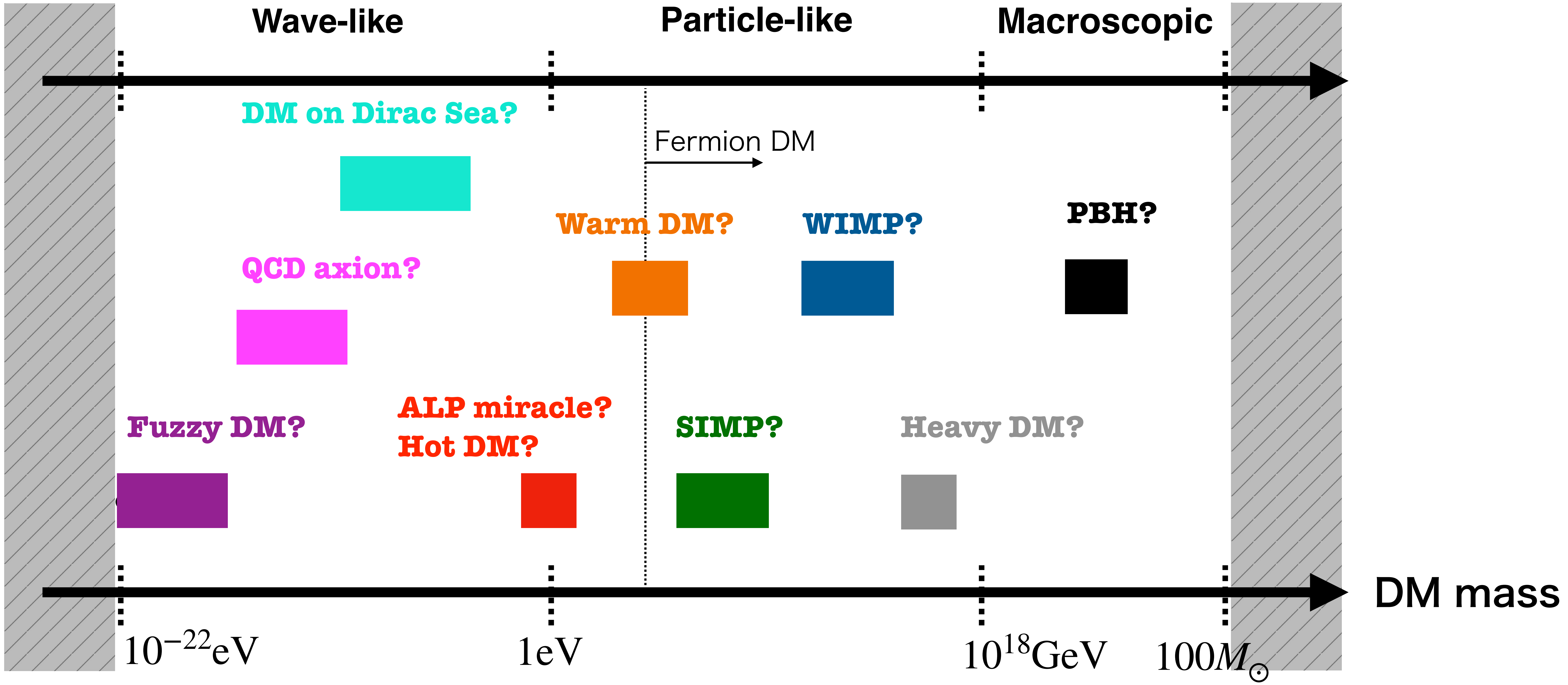
- What is DM?
- What roles do neutrinos play?

Dark matter (DM) and particle property

What is DM? Long lived, Neutral, Cold, $\rho_{\rm DM}/s \sim$ eV

We do not know the particle property at all.



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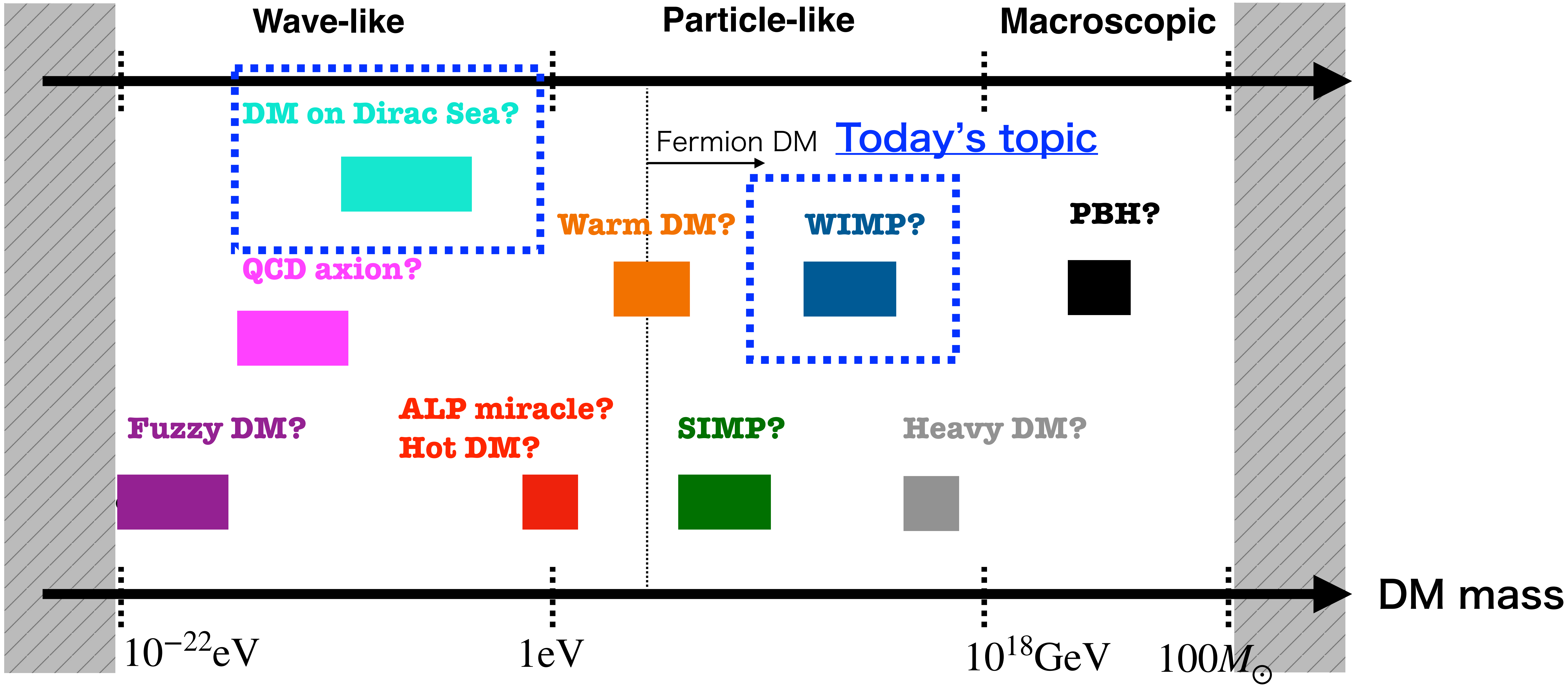
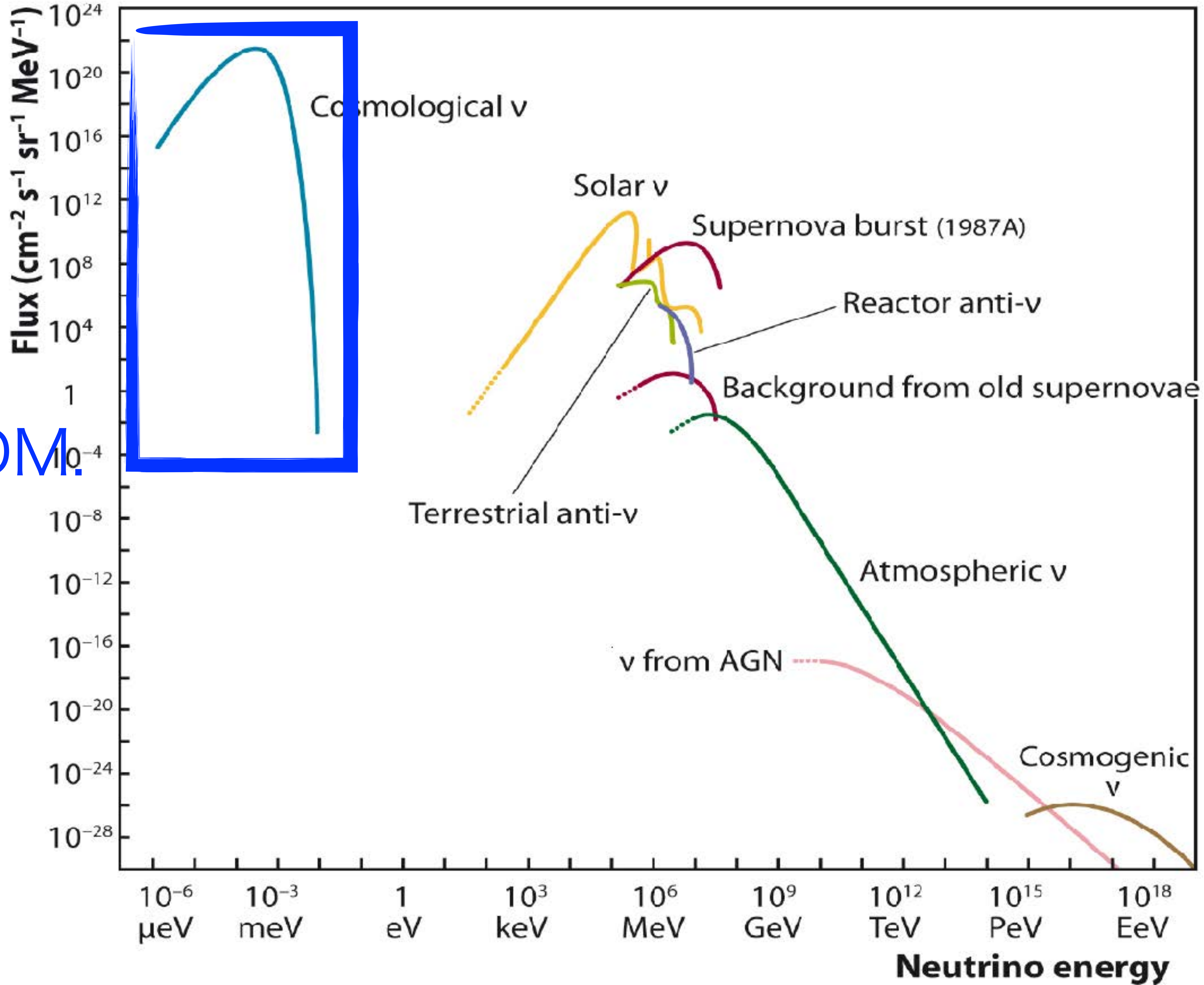


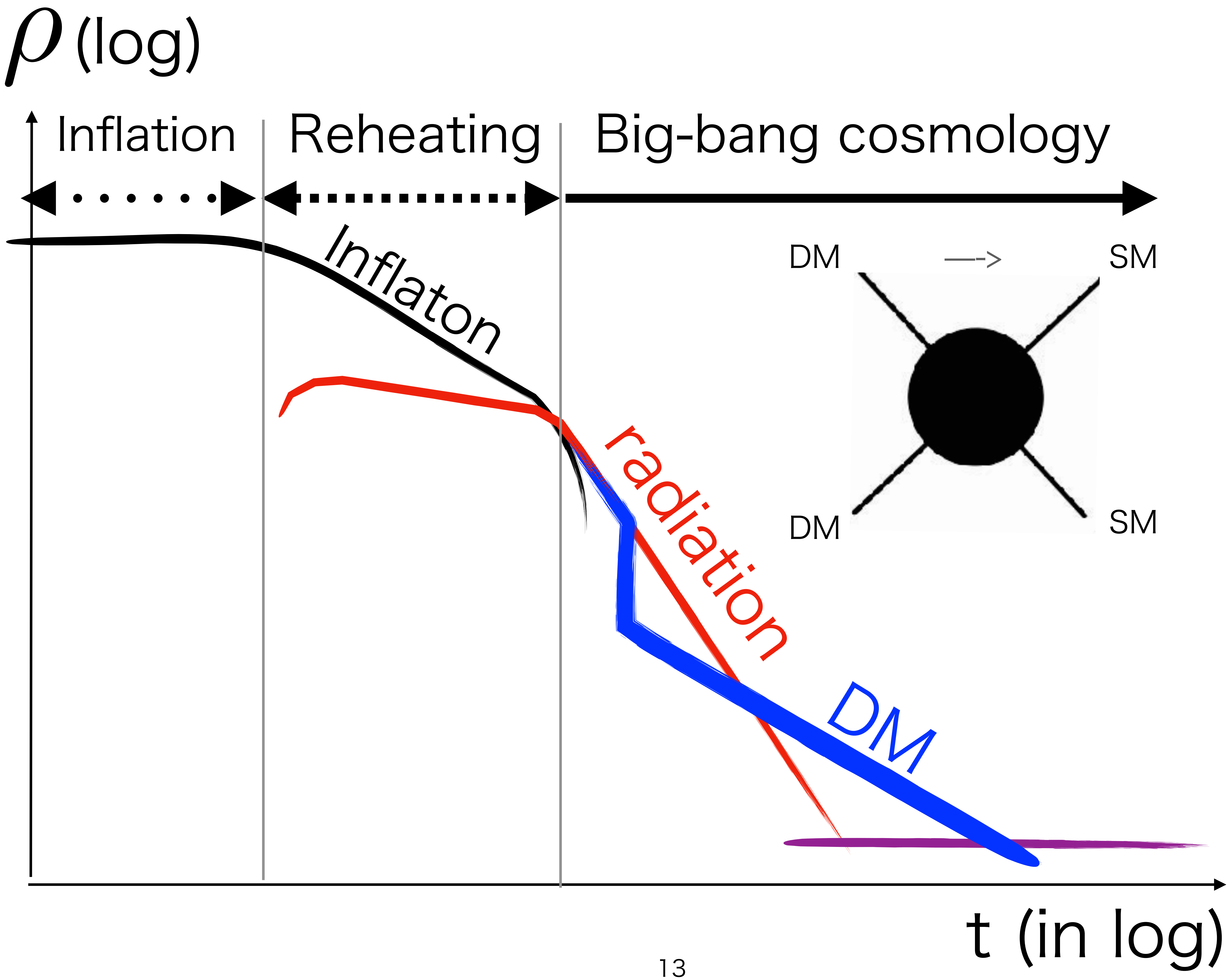
Since neutrino mass $\ll 1eV$, it composes Cosmic Neutino Background($C\nu B$)



$C\nu B$

- Robust Prediction of ΛCDM.
- CMB data suggests it, but not dicovered yet.
- Not dominant DM.

2. Weakly Interacting Massive Particle (WIMP) and Neutrinos



$$\rho_{DM}/s = m_{\rm DM} n_{\rm DM}/s \sim eV$$

n_{DM}/s ↘ m_{DM} ↗

WIMP has been populary studied over 40years.

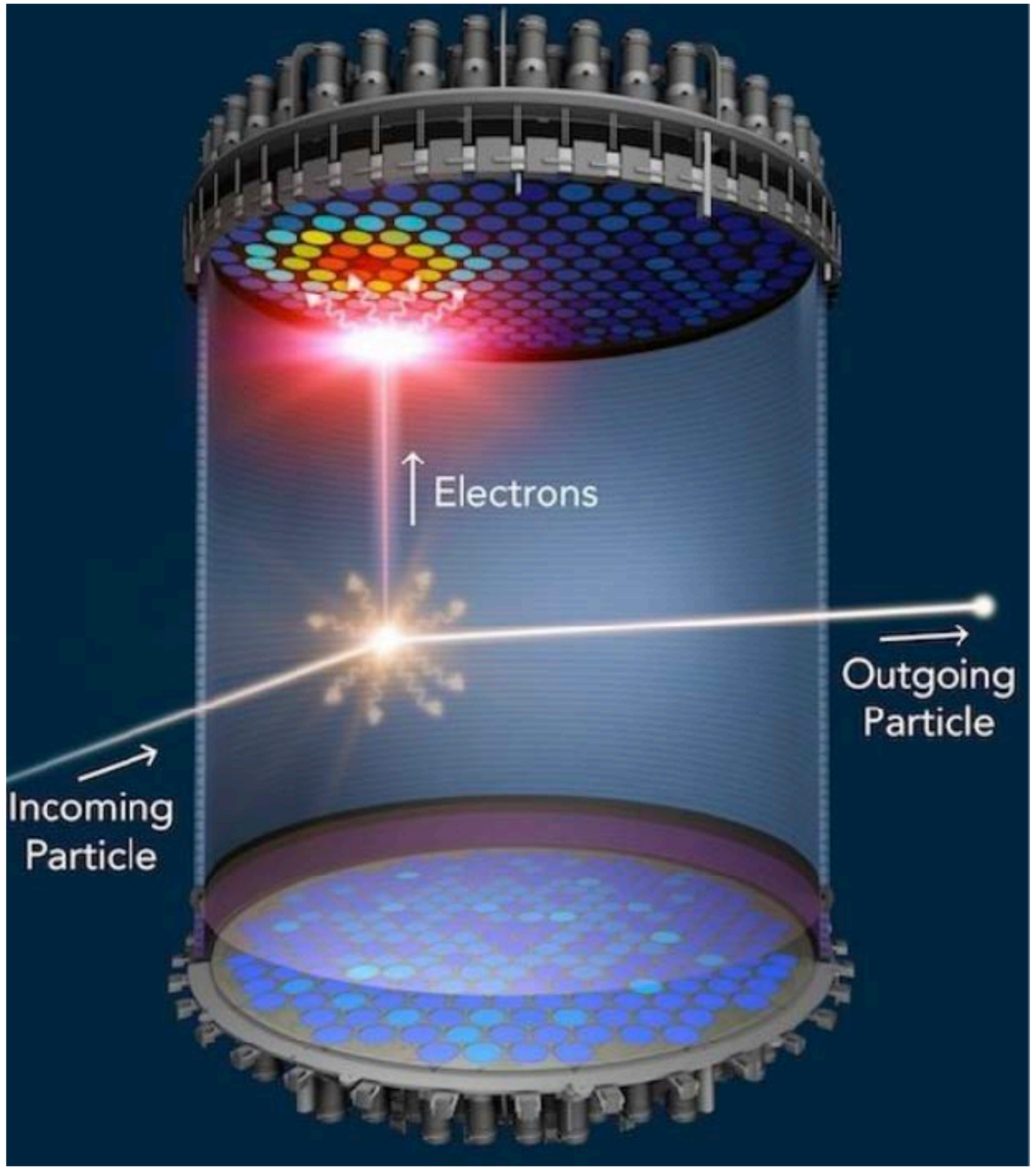
$$\Omega_{\mathrm{DM}} \sim 30\,\% \frac{\langle v_{\mathrm{rel}}\sigma\rangle^{-1}}{(20\mathrm{TeV})^2}$$

$$\sigma \sim 10^{-36} cm^2$$

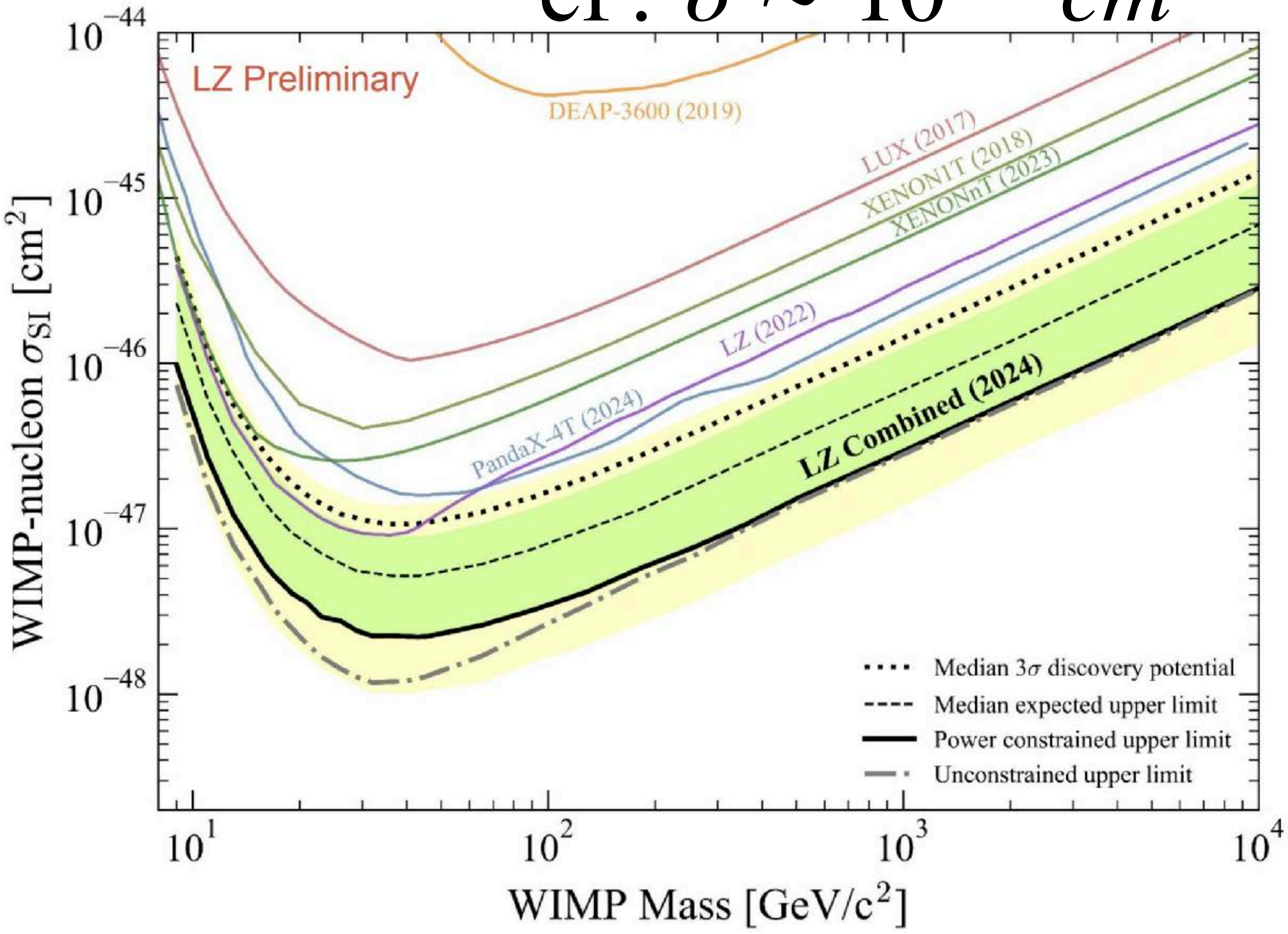
- Many extensions of the standard model, supersymmetric extension, extra dimension, composite Higgs, etc., predict particles with this crosssection.

Current status: Direct Detection Experiment provides a super strong bound.

$cf.\ \sigma \sim 10^{-36} cm^2$

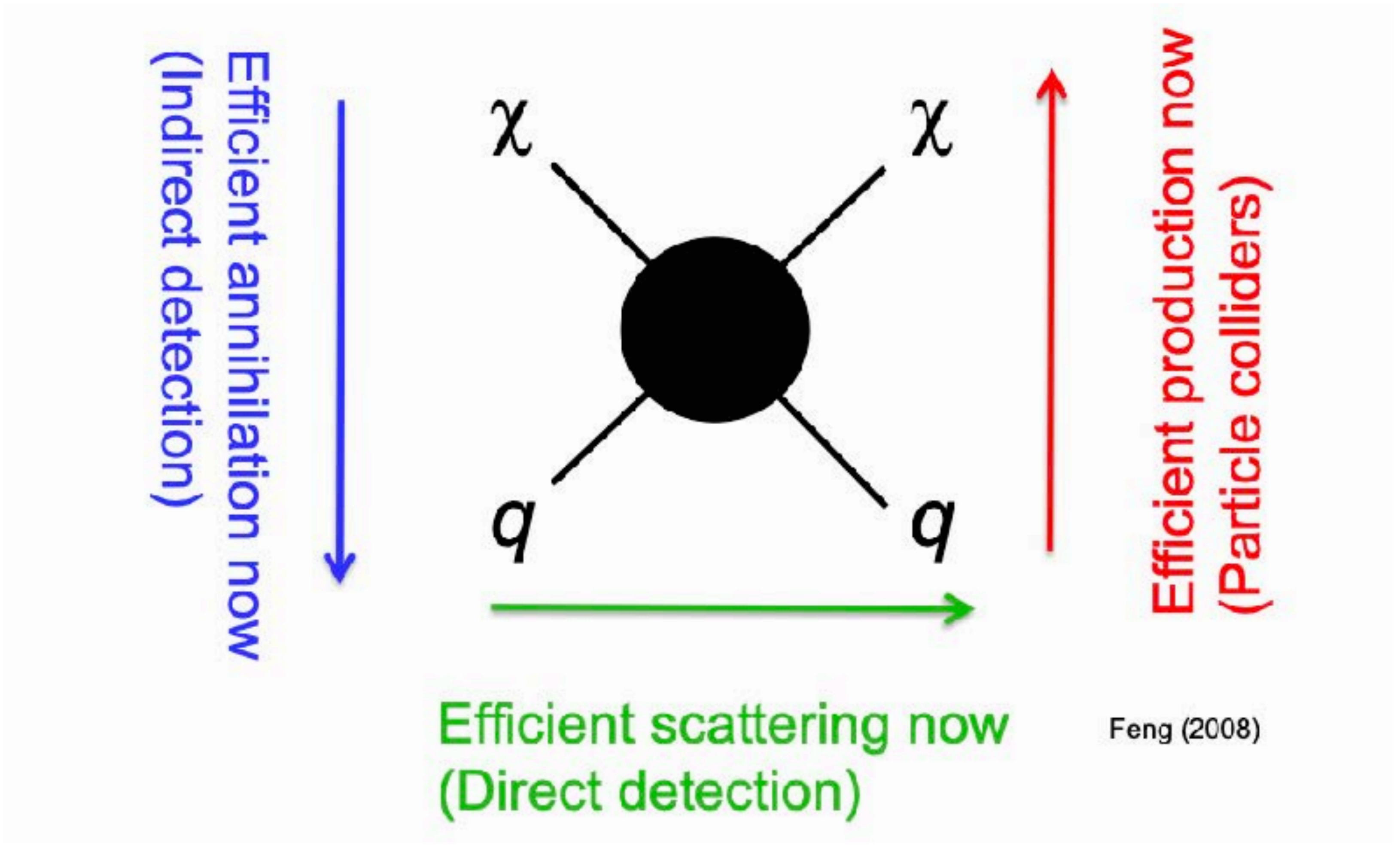


LBNL



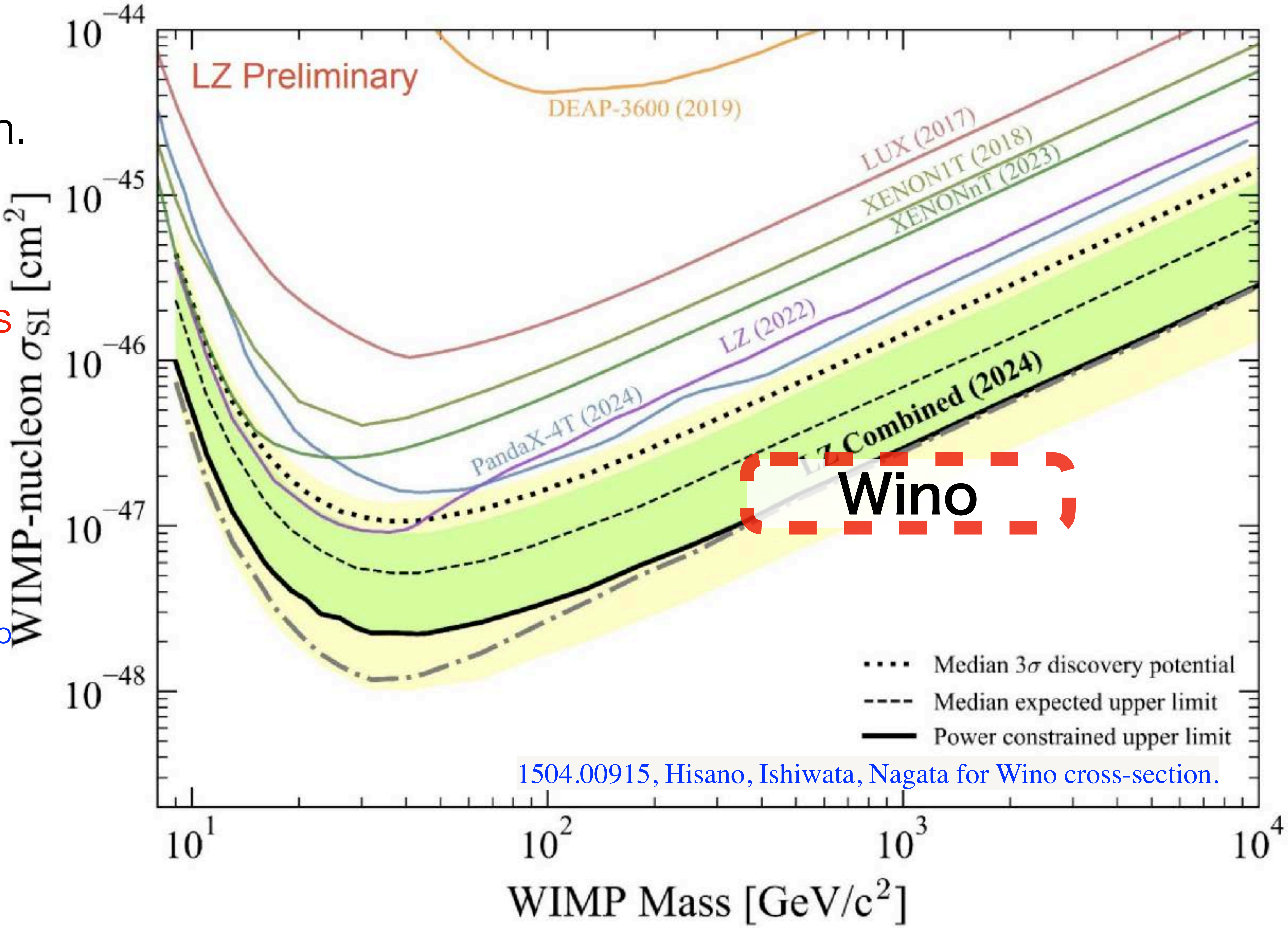
What does the exclusion limit of the direct detection experiment imply?

- 1. Very different interaction rate for scattering and annihilation
- 2. Light WIMP
- 3. Not WIMP



Example of the 1st possibility: Wino DM

- Wino is a superpartner of SU(2) Triplet Majorana fermion.
- In early Universe, annihilation is via gauge interaction, while in present Universe scattering is suppressed due to EWSB.
- A cosmologically-safe model with Yukawa coupling unification. WY, Yokozaki, 1607.05705, Yanagida, WY, Yokozaki, 1801.05785, (see also WY, 2104.03259 for muon g-2 anomaly)



The 2nd Possibility: smaller mass than GeV

How to probe it?

Light neutrino portal DM and
detecting light WIMP boosted by cosmic-ray

WY, 1809.08610

Light neutrino portal DM

$\mathscr{L} \supset \bar{\nu}_\tau(\phi\psi)$ with DM mass < GeV

ϕ, ψ are new Z_2 charged particles, one of which is DM.

- Why this? BSM must exist in neutrino sector for neutrino mass.

It is consistent with the current status of WIMP search.

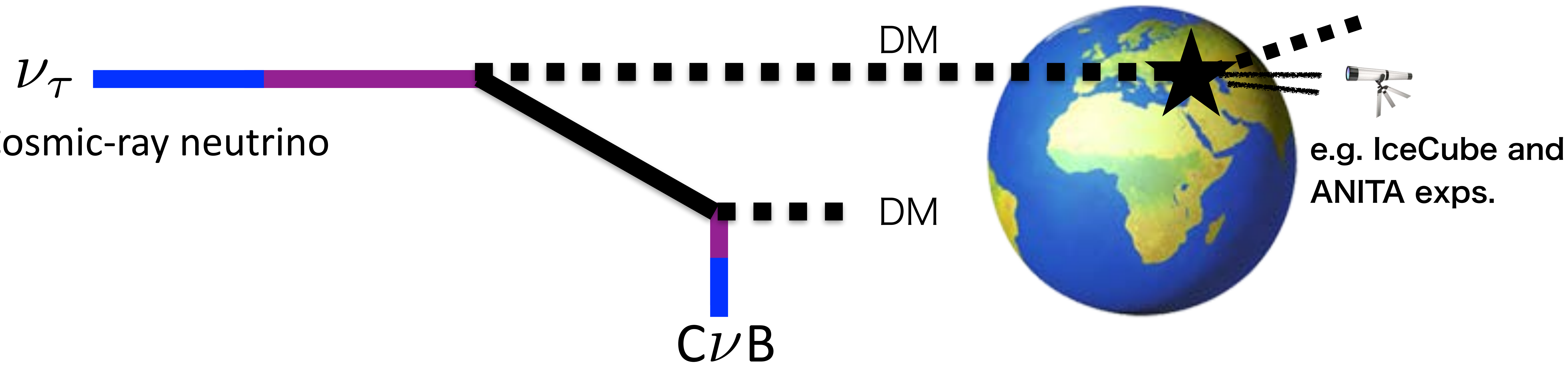
- Alleviated direct detection bound. $\because$ small recoil energy.
- Alleviated indirect detection bound. $\because \mathrm{DMDM} \to \tau\bar{\tau}$ is kinematically forbidden.
- Interestingly, $\mathrm{DMDM} \to \bar{\nu}\nu$ can be probed at neutrino detectors such **as Super-Kamiokande, Borexino, DUNE, and Hyper-Kamiokande.**

Campo et al, 1711.05283, Blennow et al, 1903.00006

Light WIMP DM can be boosted by cosmic-ray and detected, a la direct detection

WY, 1809.08610
(see also Cappiello, Ng, and Beacom, 1810.07705; Bringmann and Pospelov 1810.10543;
Ema, Sala, and Sato,1811.00520 etc for subsequent studies.)

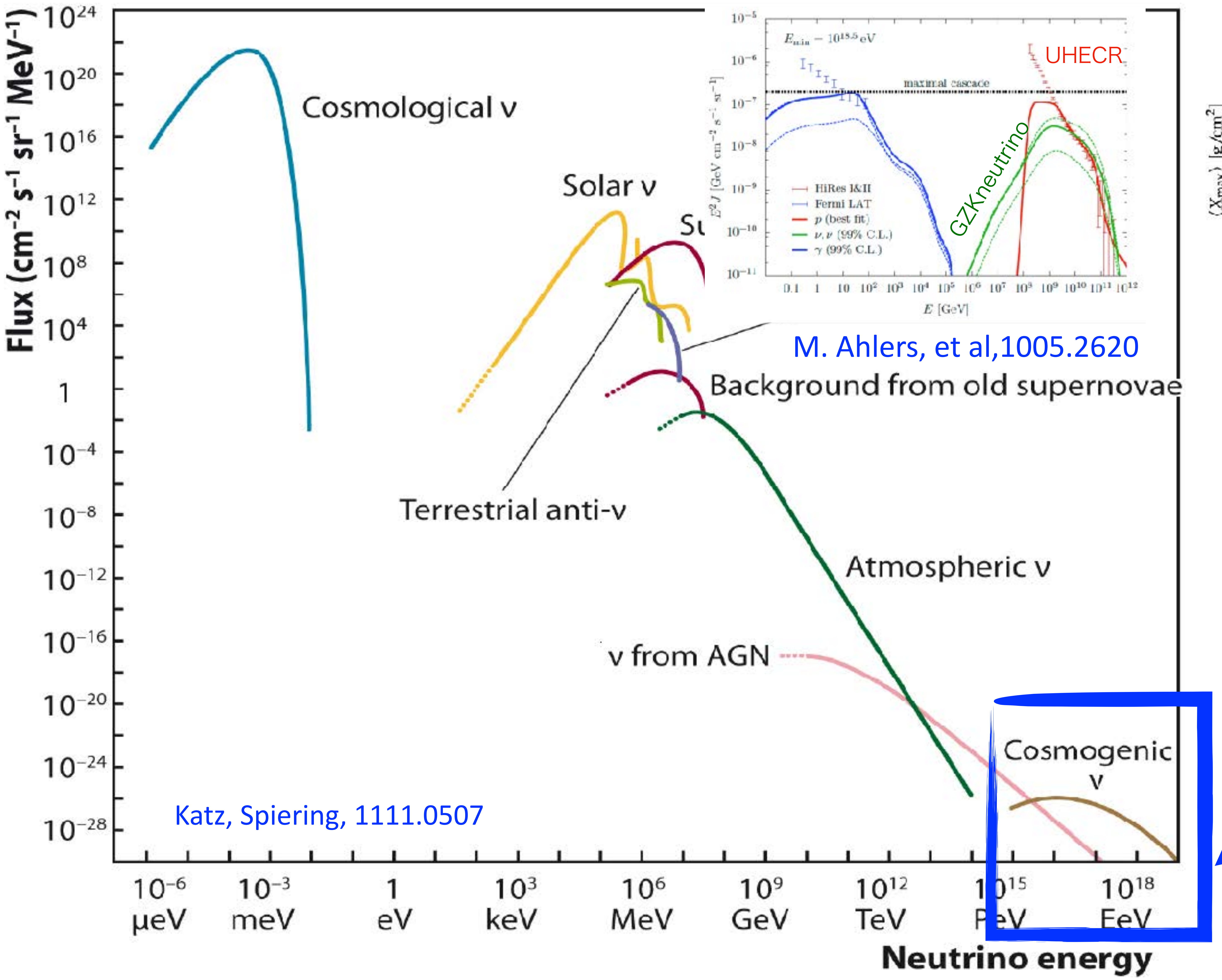
$$DM + N \to DM + \nu/l + N$$



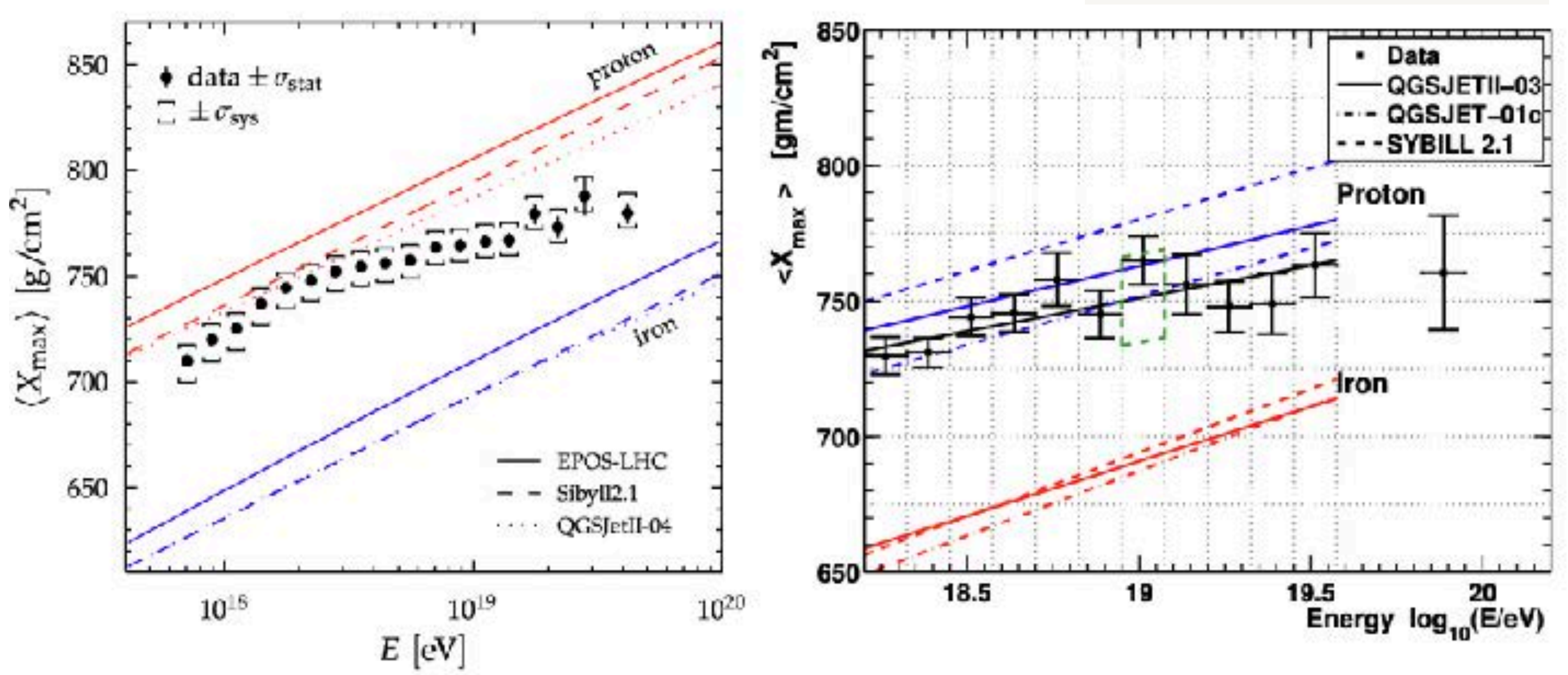
$$E_{CR\nu} \gtrsim m_{\rm DM}^2/m_\nu \sim \frac{(100MeV)^2}{10^{-2}\rm eV} \sim 10^8\,\rm GeV$$

$$c.f.\, m_{\rm DM} \gtrsim 10MeV, (BBN)$$

Do we have such a cosmic-ray to boost the DM?



Unger et al PoS(ICRC2015)307



$$p + \gamma^{\mathrm{CMB,CIB}} \to \Delta^+ \to n e^+ \nu_\mu \bar{\nu}_\mu \nu_e$$

GZK neutrino!

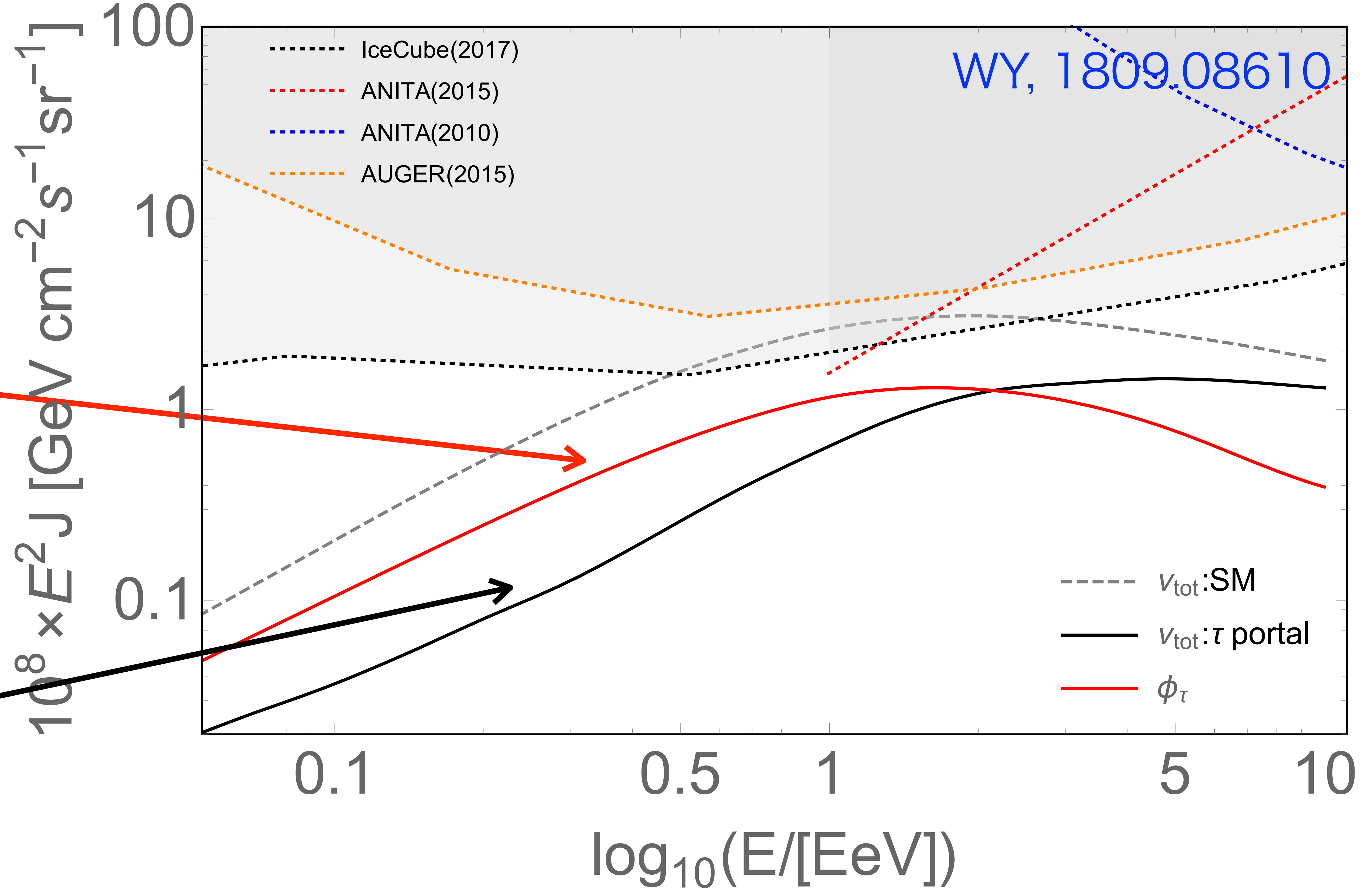
“Guaranteed source”

But not discovered yet.

$\nu_{GZK} + \bar{\nu}_{C\nu B} \to DMDM$ explains the absence of GZK neutrino and predicts highly boosted DM.

Highly boosted DM reaching Earth.

Suppressed GZK flux



Assumption:

$\nu_{R\tau} \gtrsim O(100)\mathrm{MeV}$

$M_\psi \simeq m_{\phi_\tau} = 15\,\mathrm{MeV}$

$g_{\mathrm{eff}} = 0.5$

Photo-Pion production simulated from CRPropa 3

Reactions such as $\mathrm{DM} + N \to \mathrm{DM} + \tau/\nu_\tau + N \qquad (\sigma \sim \frac{g_{\mathrm{eff}}^2}{16\pi^2}\sigma_{\nu N})$

may be tested in large volume detector experiments even though the DM is light.

- 3. DM longevity by neutrinos.

The 3rd possibility: DM is not WIMP.

- What was the ugly point for WIMP?

Ad-hoc assumptions for longevity.

- Is there any other possibile explanation for DM's longevity?

DM is light and weakly-coupled, like neutirno.

Candiates: Axions etc.

Is there any other possibile explanation for DM's longevity?

New option:

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New option:

DM on Dirac Sea

Batell, WY, 2406.17028

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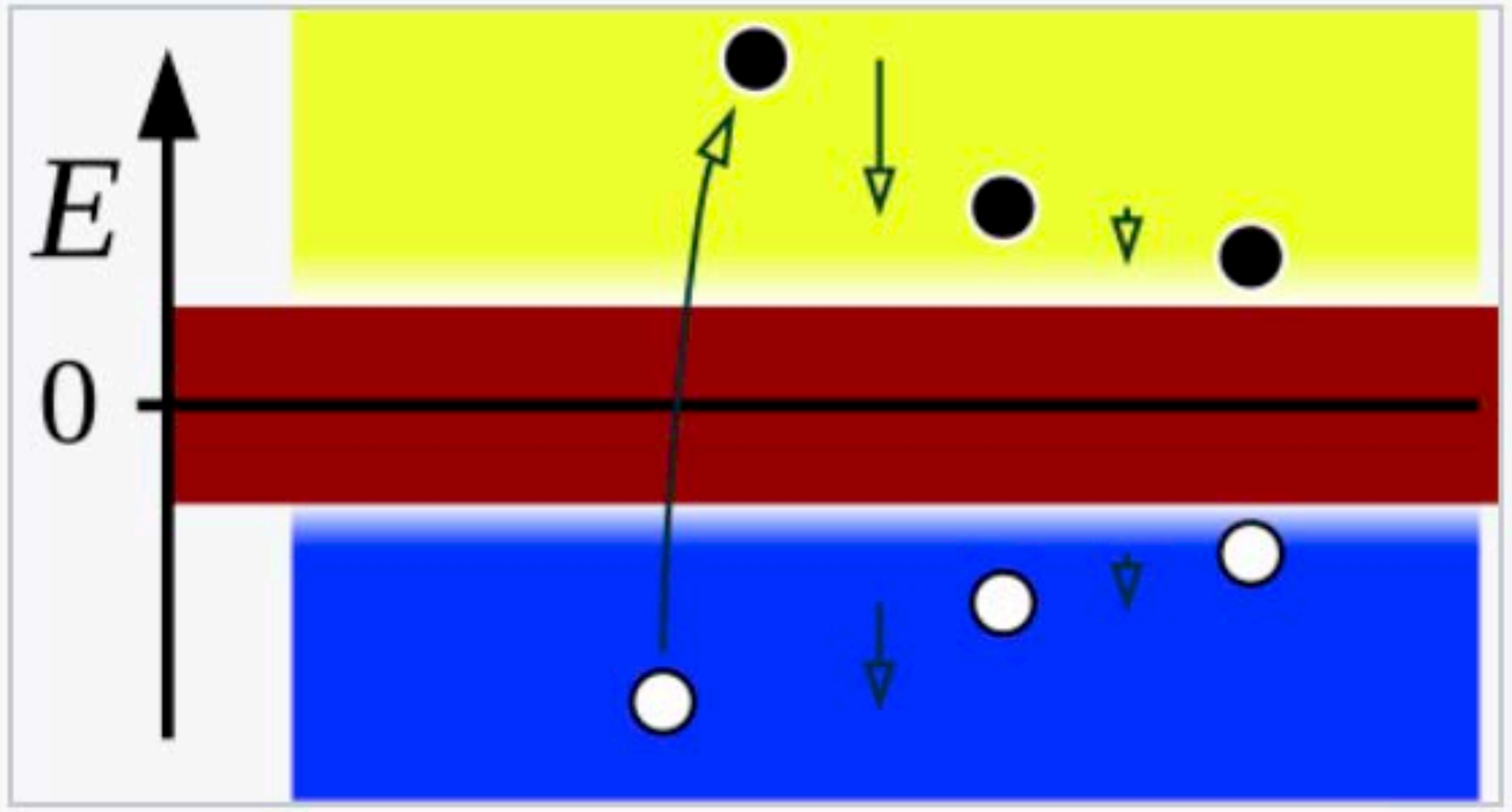
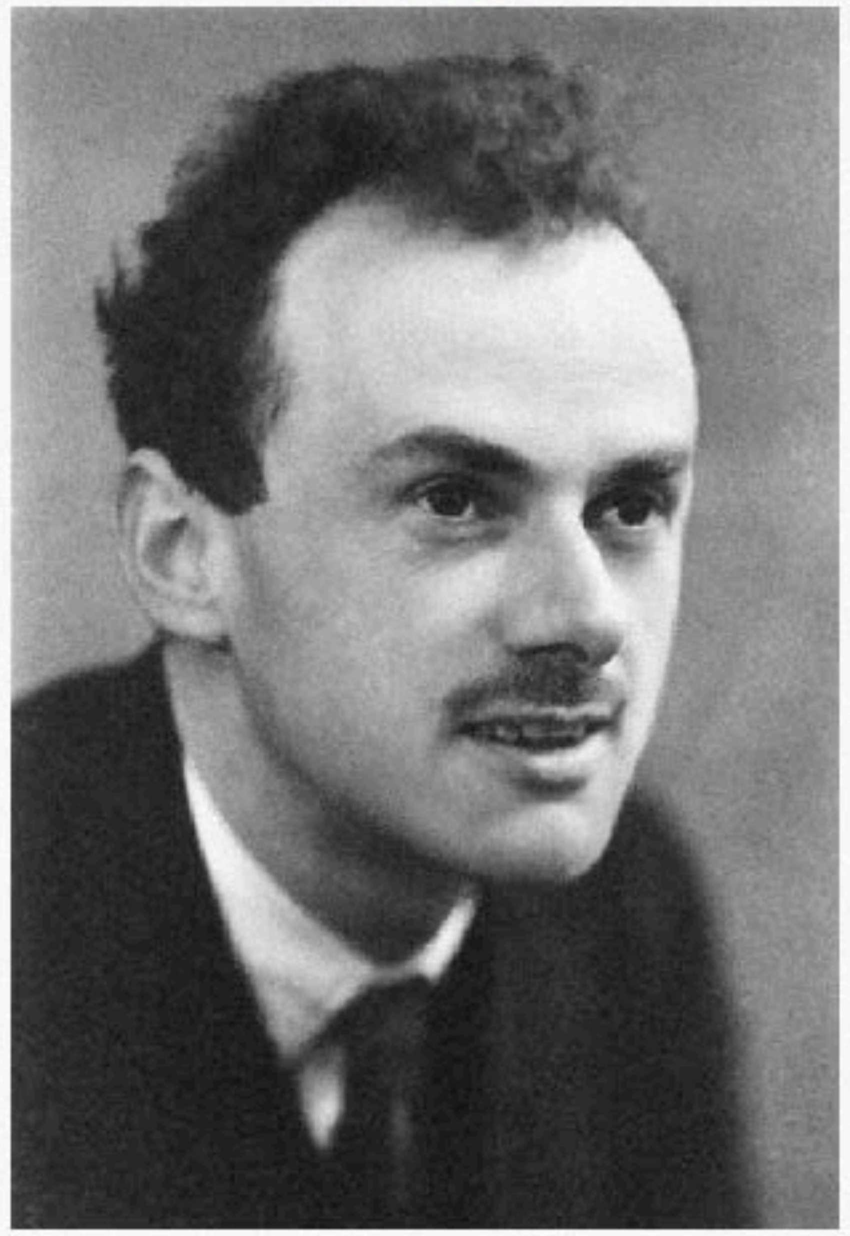


Dirac sea for a massive particle. • particles, • antiparticles

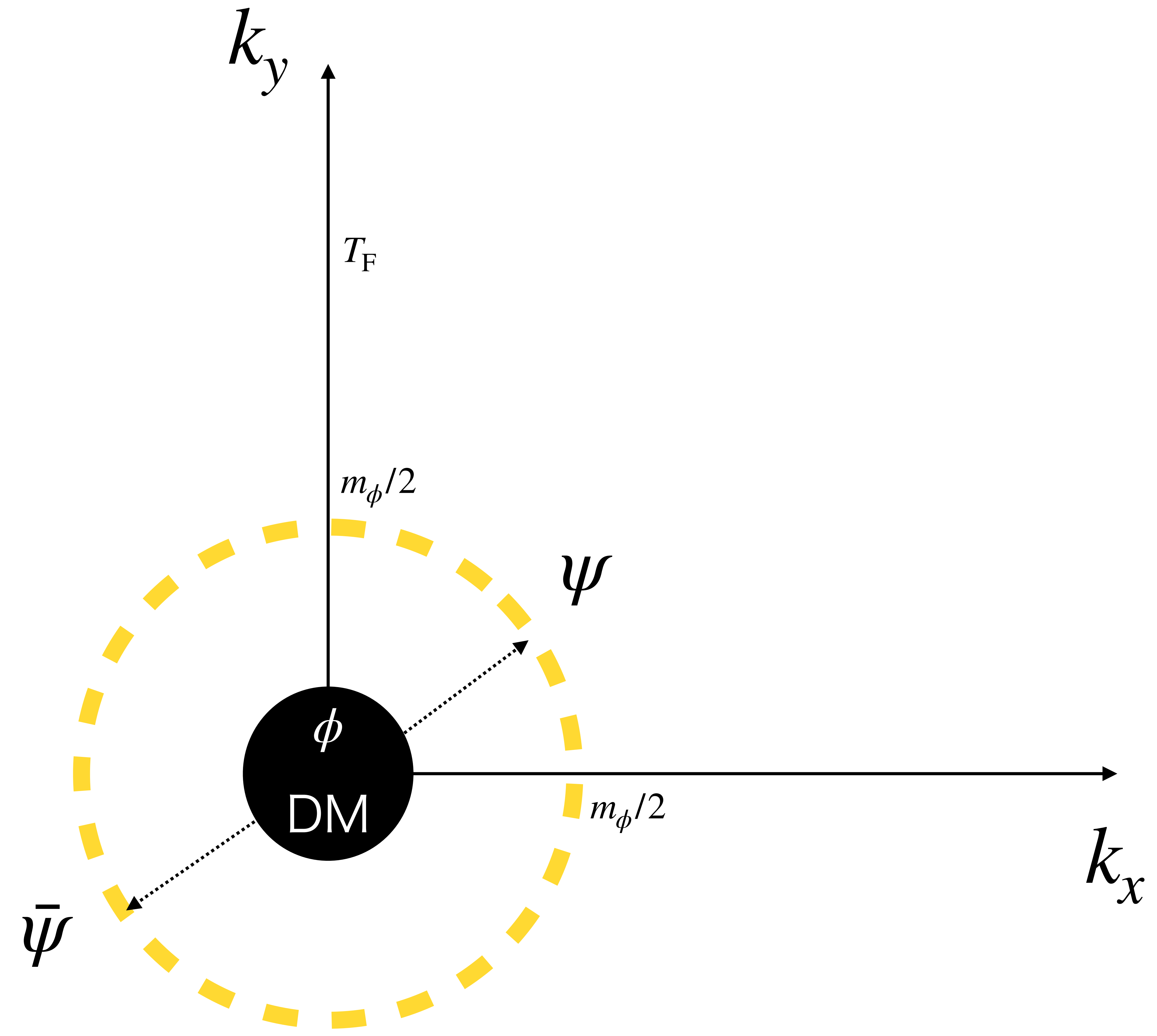
Wikipedia

Paul Dirac
OM FRS



Concepts for DM on Dirac Sea

Batell, WY, 2406.17028



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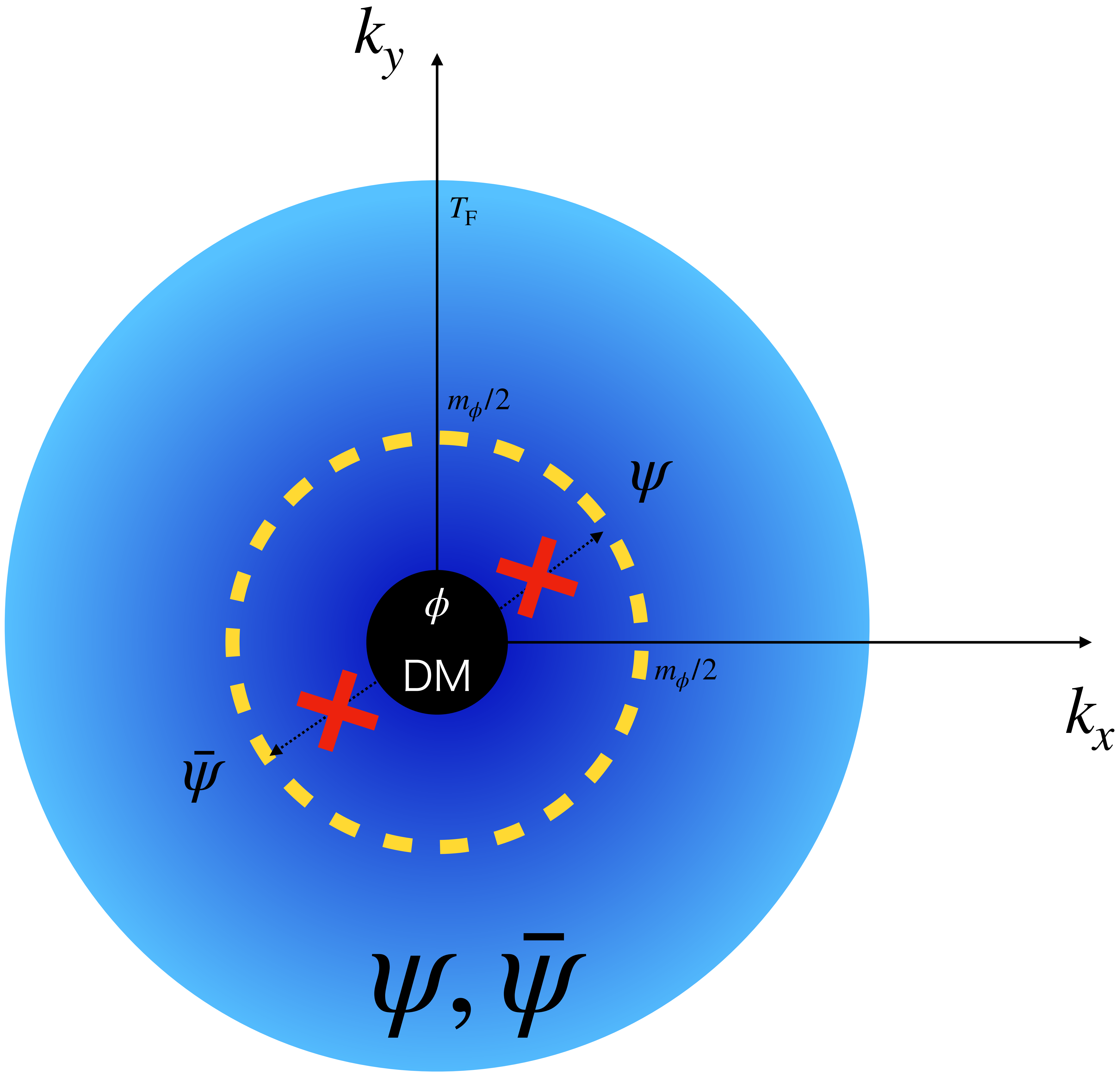

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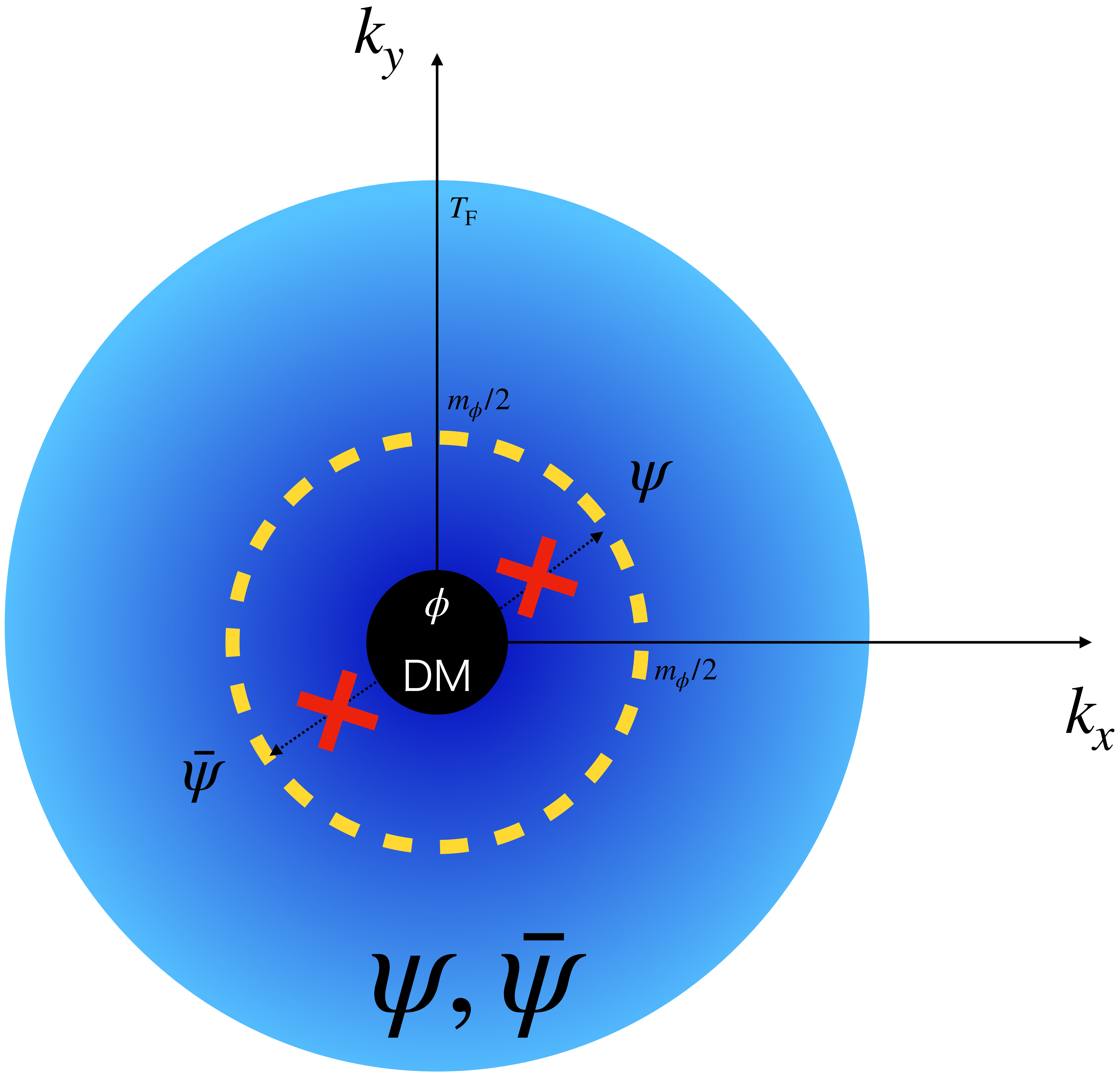

Where do the fermions come?

Concepts for DM on CνB

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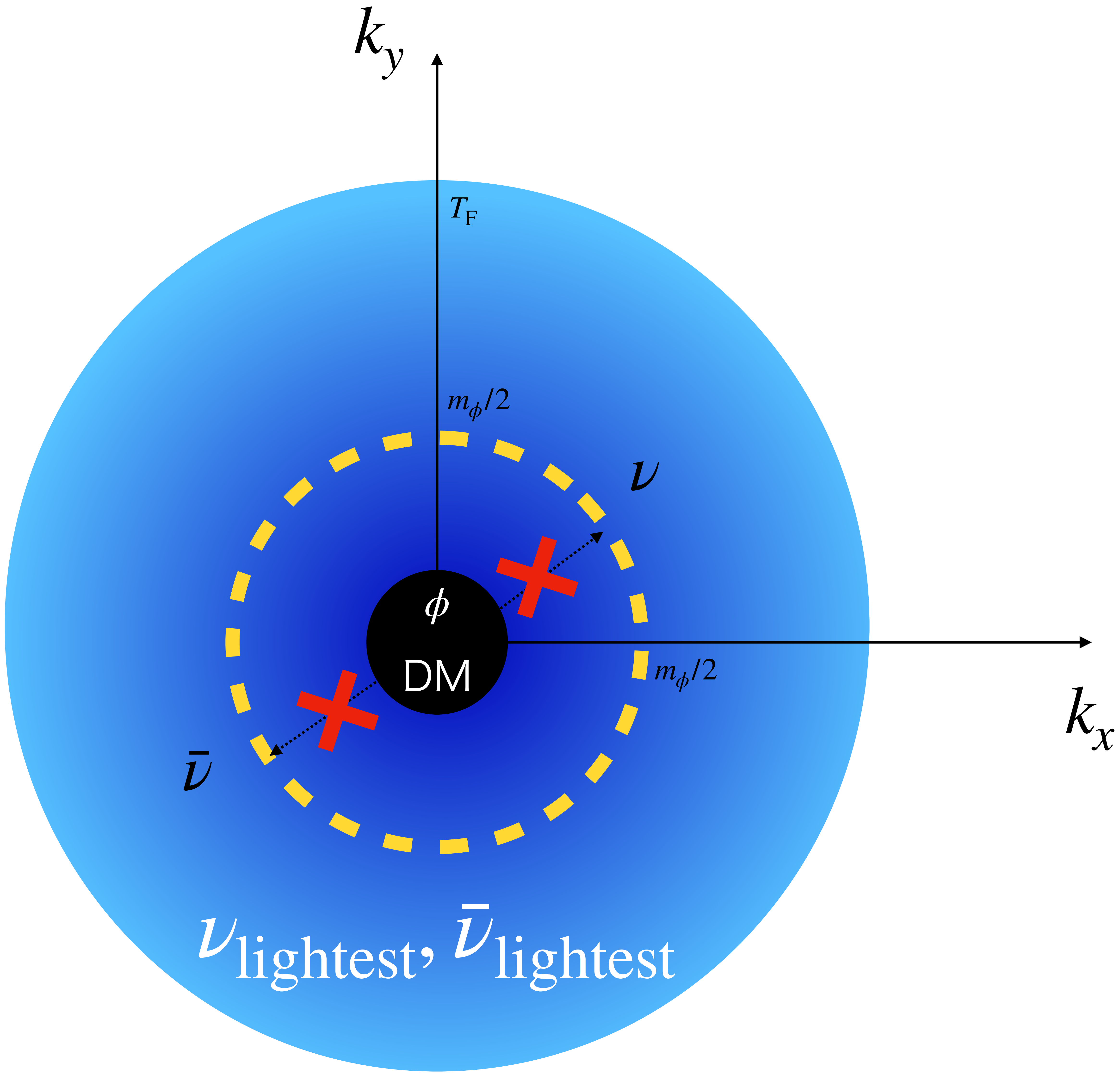
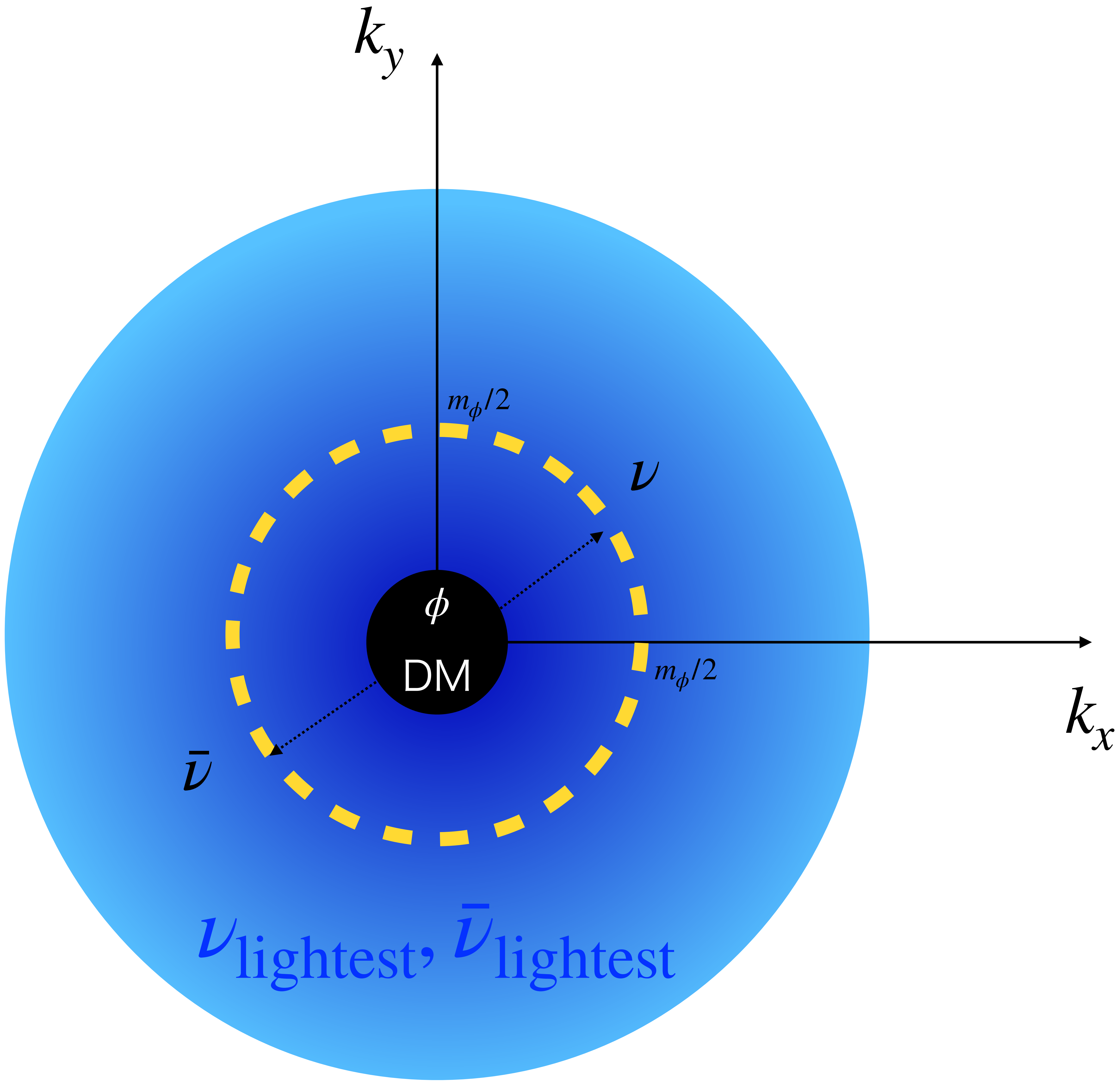


Where do the fermions come?

CνB!!

The DM on $C\nu B$ stirs $C\nu B$.

Batell, WY, 2406.17028



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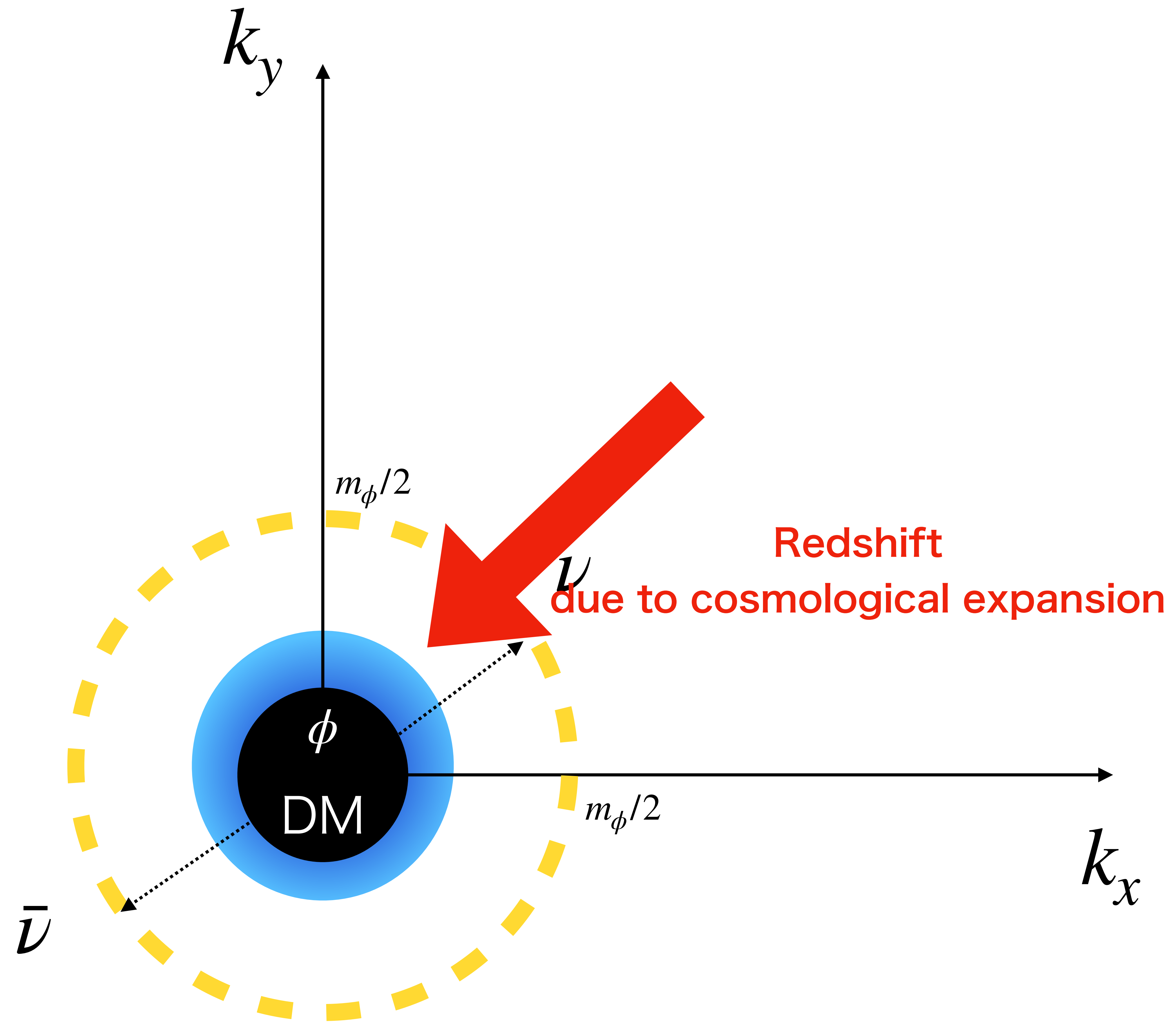
Batell, WY, 2406.17028



$\nu_{\text{lightest}}, \bar{\nu}_{\text{lightest}}$

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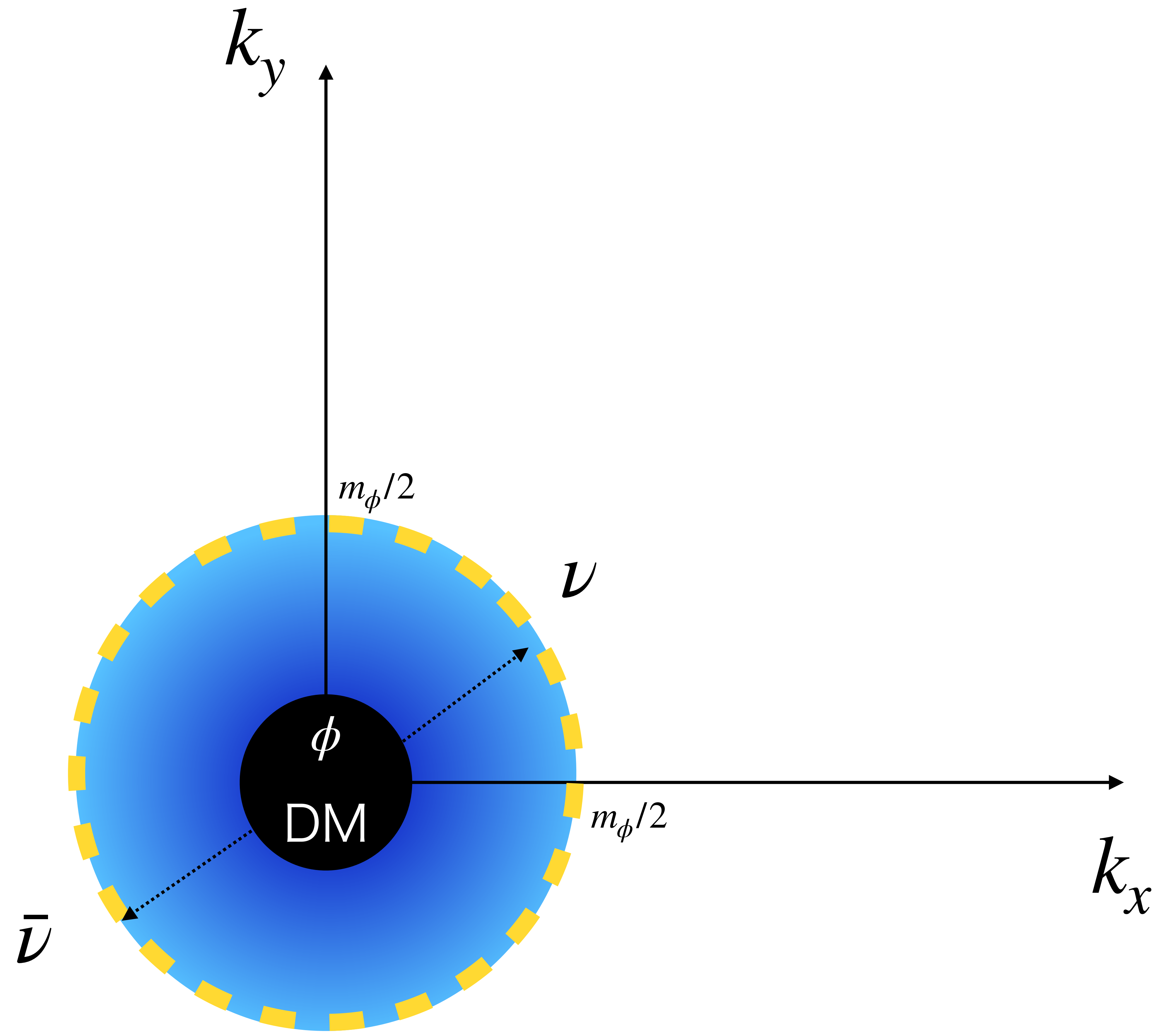

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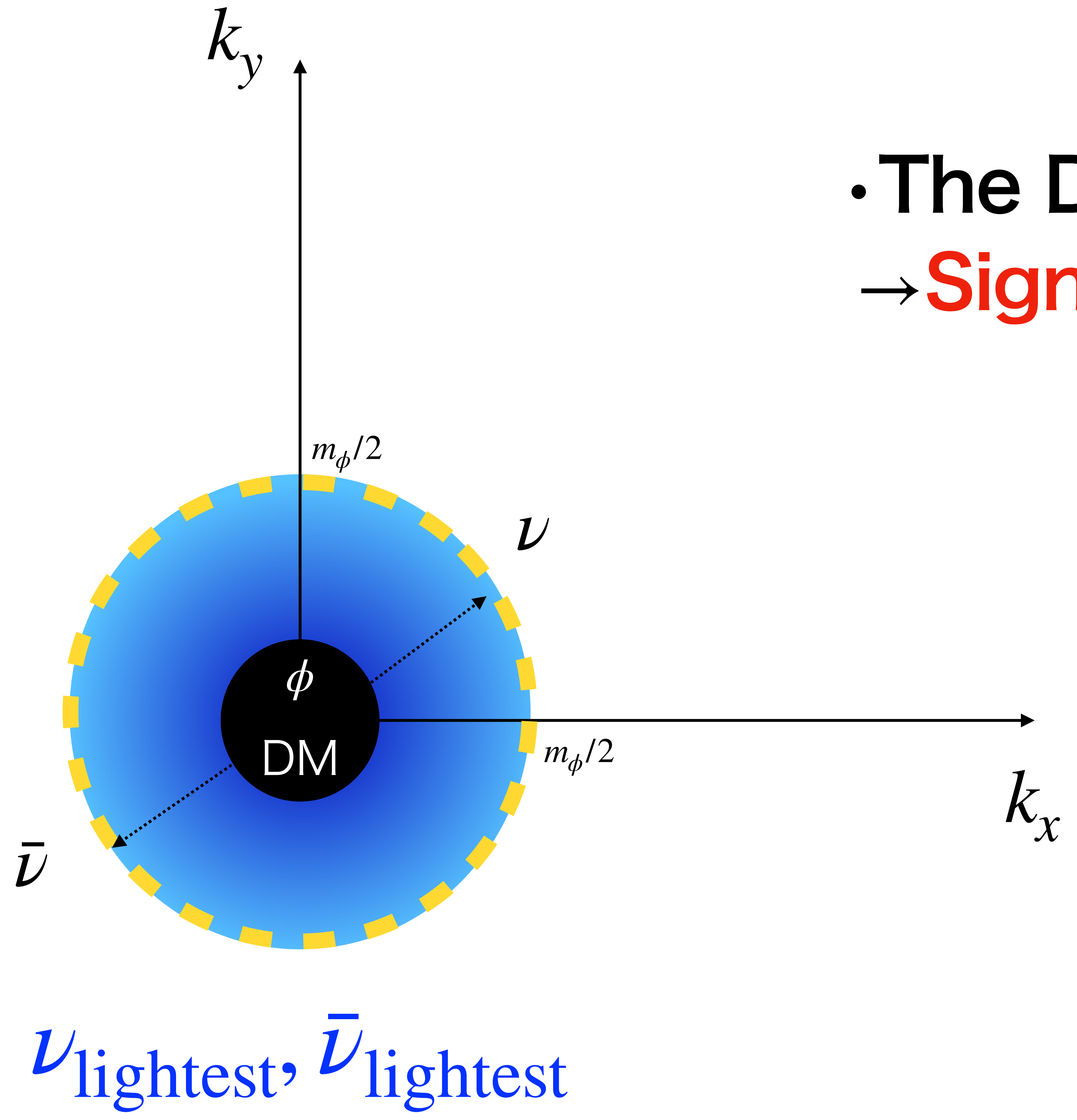

- The DM fullfils the fermi-sphere

→Significant overdensities of latetime $C\nu B$!

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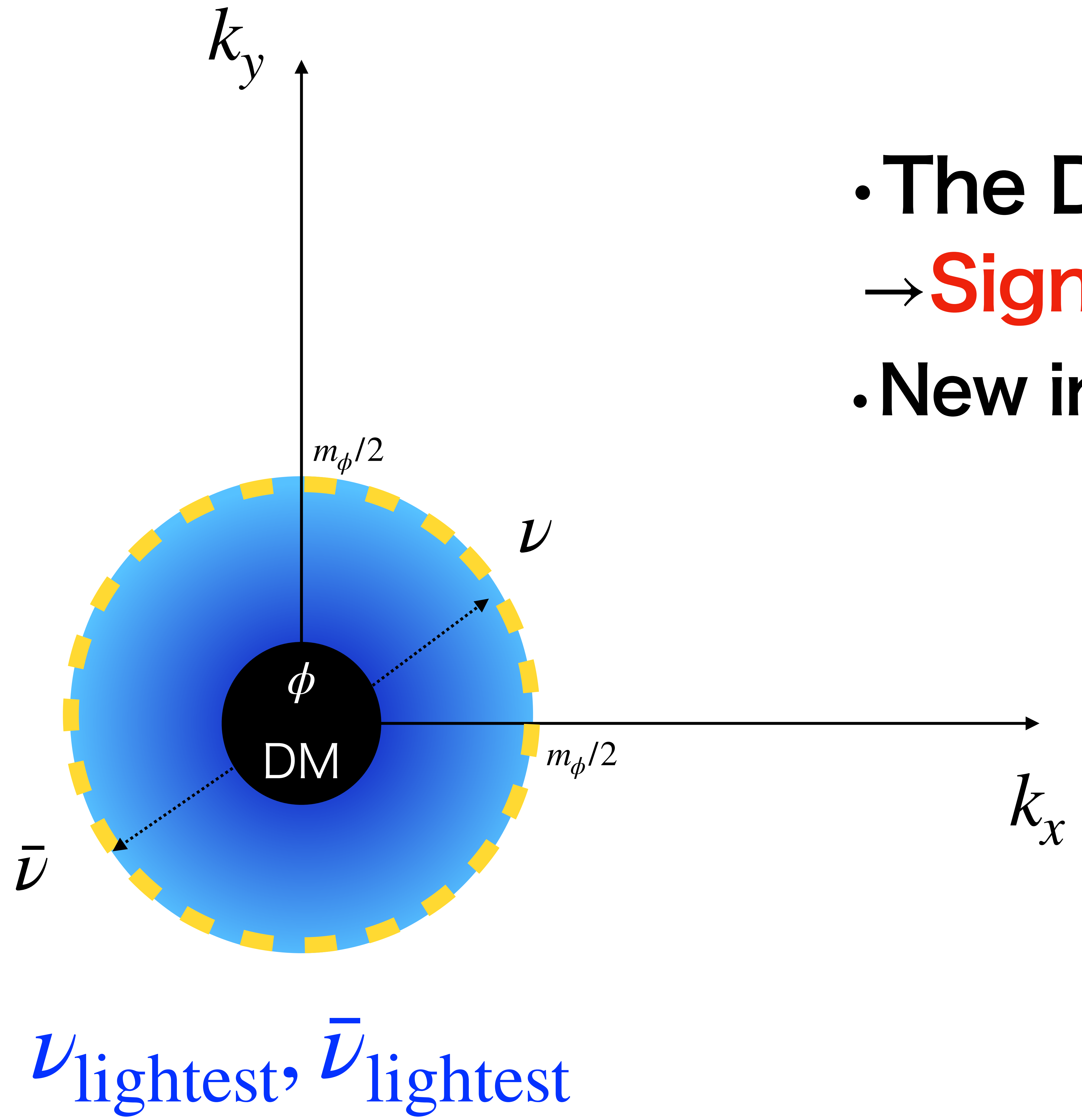
Batell, WY, 2406.17028



- The DM fullfils the fermi-sphere

→ **Significant overdensities** of latetime $C\nu B$!

- New interaction induces $C\nu B$ decays.

$$\nu_3 \to \phi(\text{boosted}) + \nu_{1,2}$$

A cascade!, No Pauli-Block for boost ϕ

$$\nu_2 \to \phi(\text{boosted}) + \nu_1, \quad \phi(\text{boosted}) \to 2\nu_1$$

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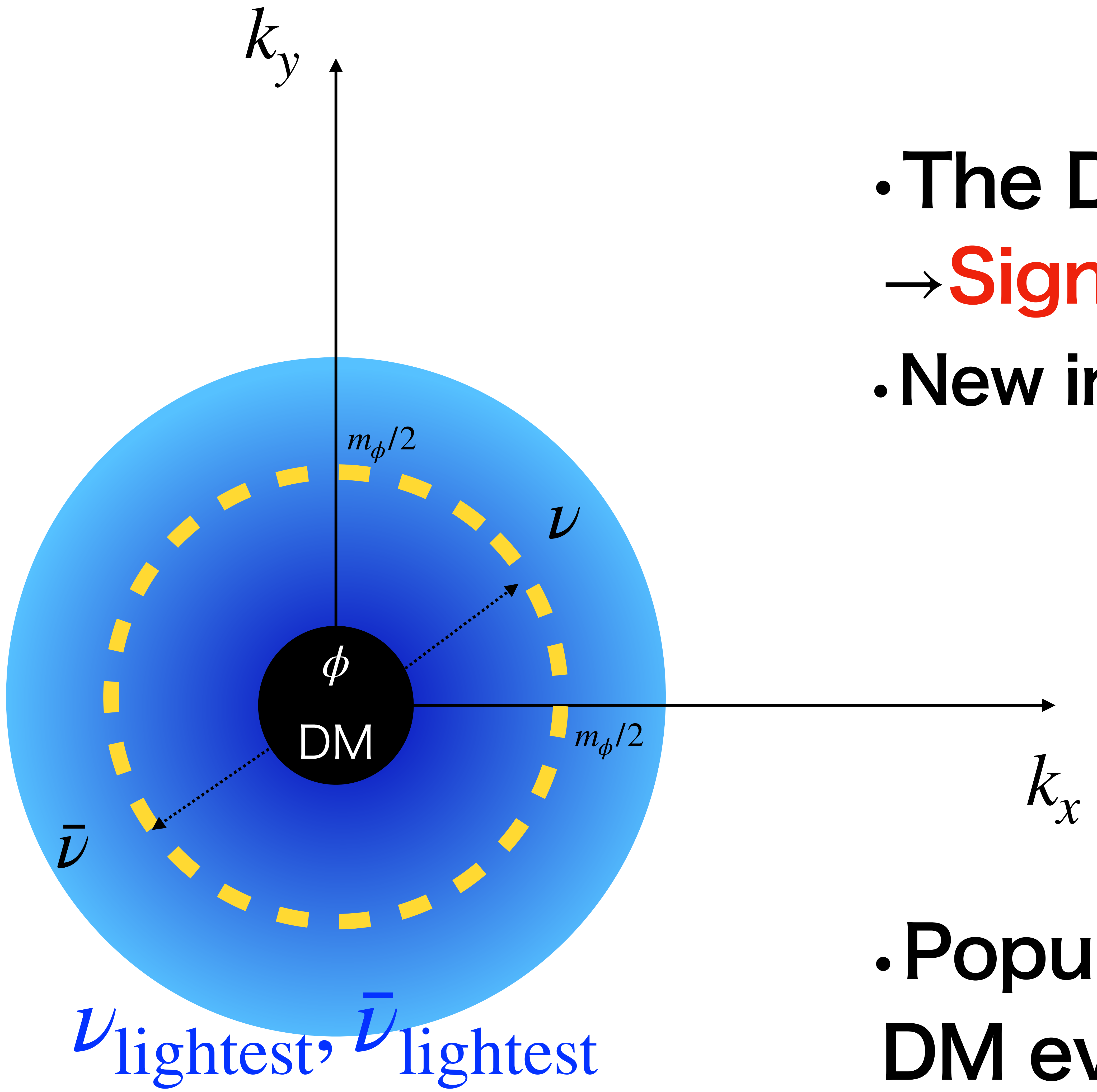
Batell, WY, 2406.17028



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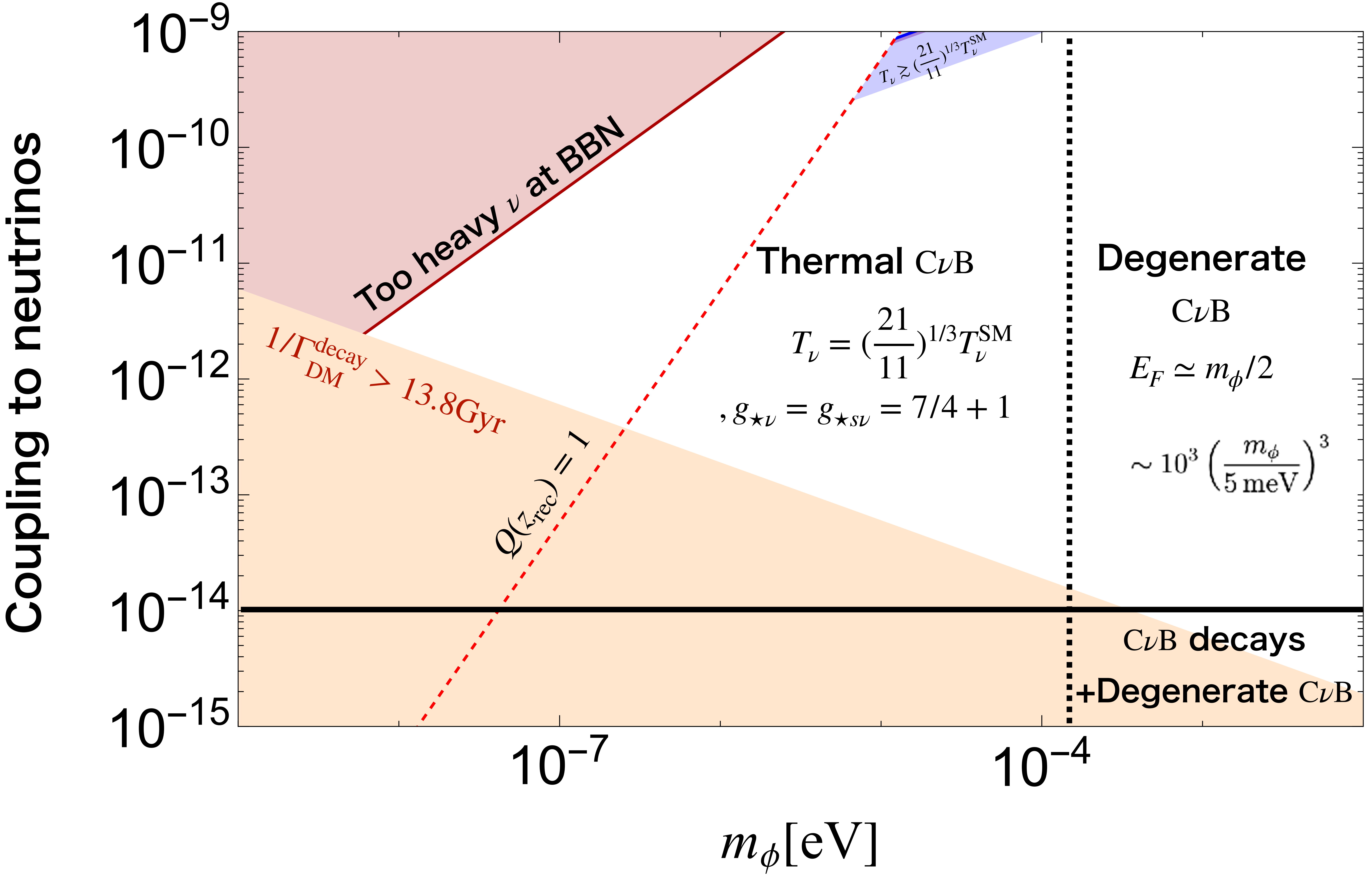
- Populating $C\nu B$ at early time through DM evaporation.

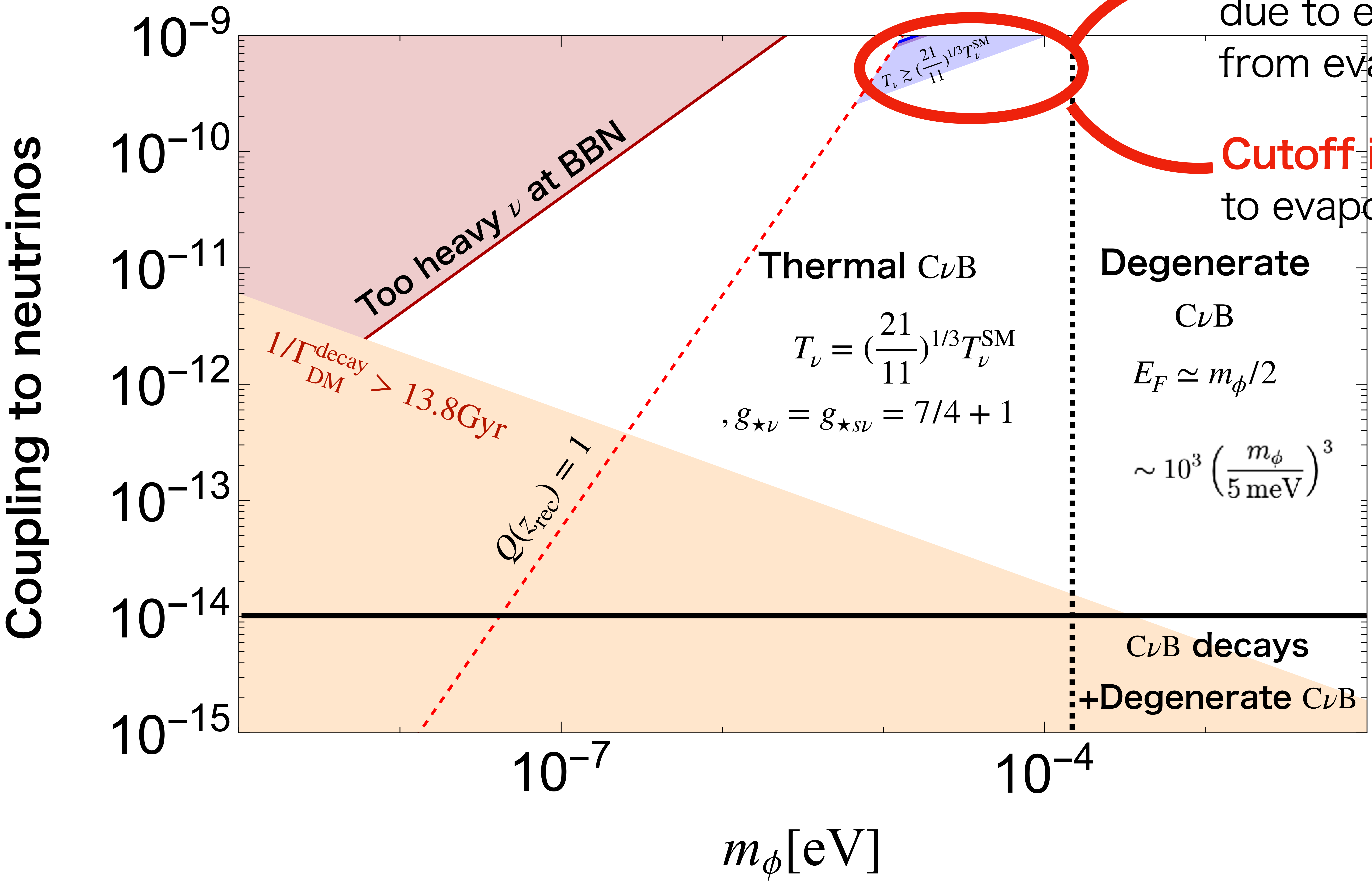
Parameter region, and prediction on $C\nu B$.

Batell, WY, 2406.17028



Parameter region, and prediction on $C\nu B$.

Batell, WY, 2406.17028

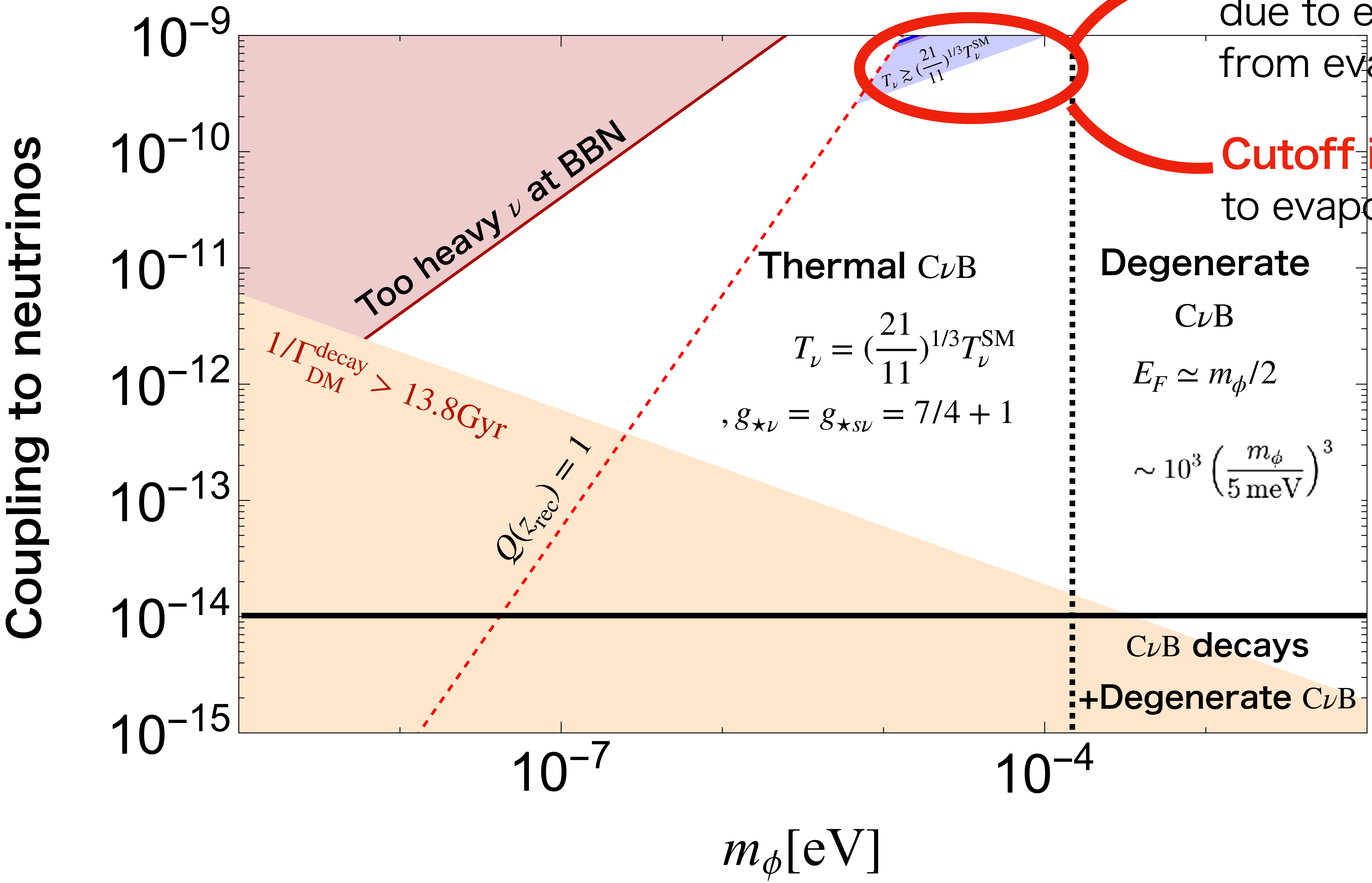


Hubble tension alleviated due to extra neutrino from evaporating DM.

Cutoff in DM density due to evapolation **(->cored-profile).**

Parameter region, and prediction on $C\nu B$.

Batell, WY, 2406.17028



Hubble tension alleviated due to extra neutrino from evaporating DM.

Cutoff in DM density due to evapolation **(->cored-profile).**

A precise measuremet of $C\nu B$ may probe this scenario.

Conclusions

Neutrino was considered as dominant dark matter 40 years ago, but it was wrong.

Recently, more mysteries have been appeared.

- What is DM?
- Then what roles the $C\nu B$ plays?
  - Cutoff for GZK neutrino? Check the CR-Boosted DM!
    WY, 1809.08610
  - DM on $C\nu B$? Check the $C\nu B$ and DM profile!
    Batell, WY, 2406.17028
  - Other possibilites exist as well.

Backup

Summary of 2nd possibility, lighter WIMP

It is being probed in different approaches.

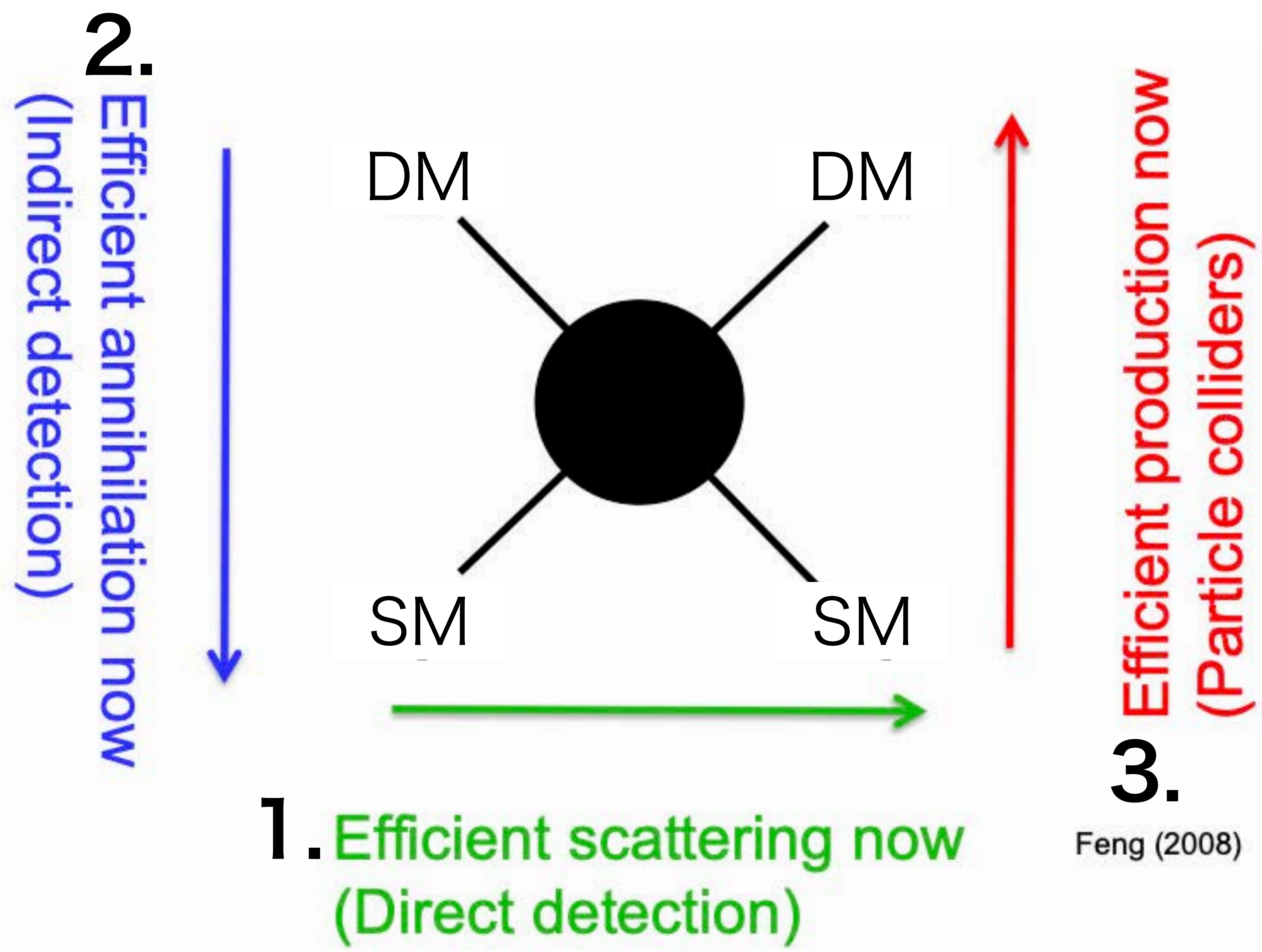
- **Indirect detection: Future neutrino detectors**, e.g. DUNE, Hyper-Kamiokande, **should do a very good job.**
  (A good energy resolution can be powerful for the DM search, because of the line spectrum of neutirnos.)
- **Direct detection of boosted DM by cosmic-ray accelation could be powerful!**

WY, 1809.08610

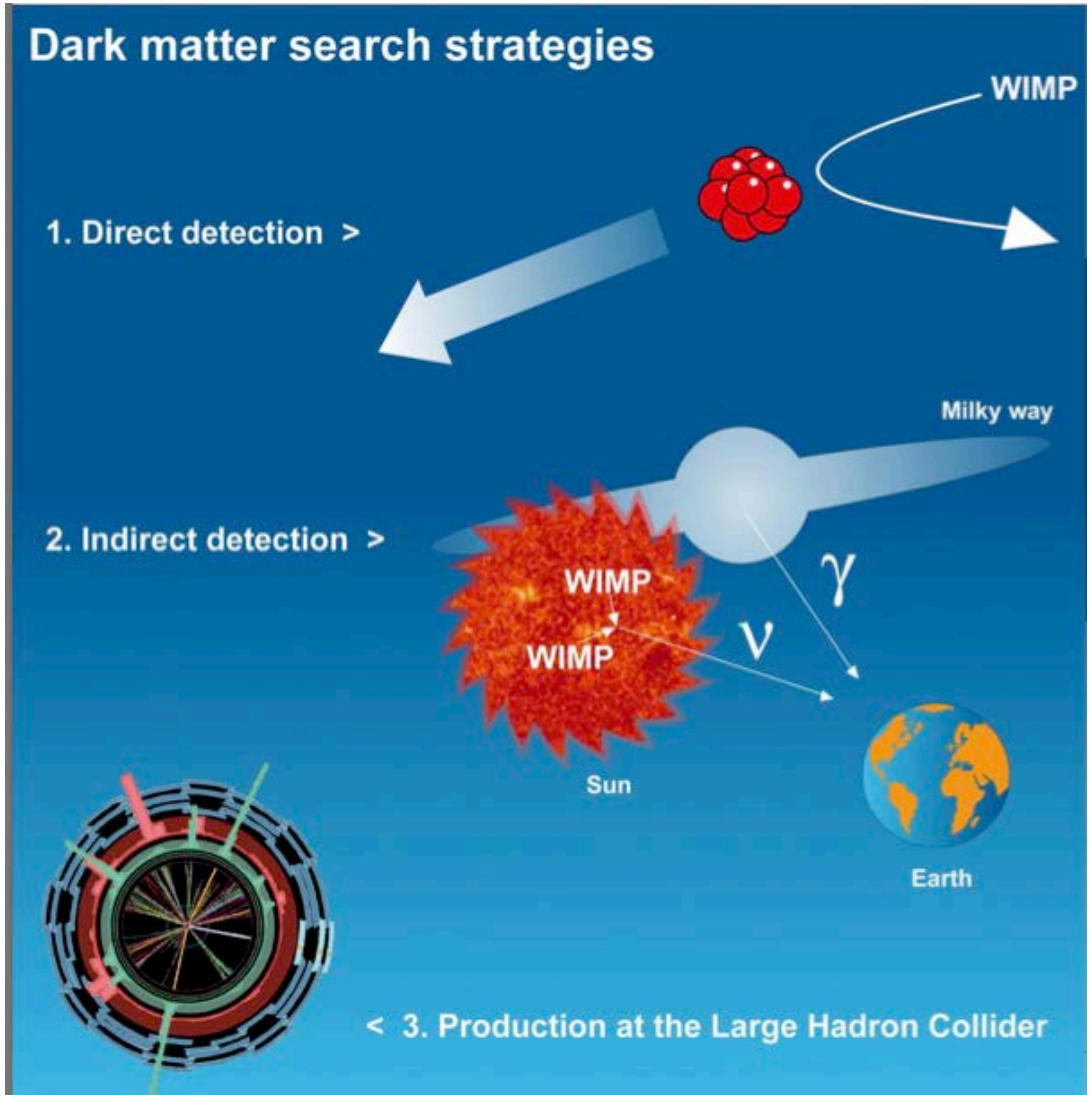
Summary for the 1st possibility

- A discovery from direct detection is just around the corner, so stay tuned.

How to detect WIMP DM?



Feng (2008)



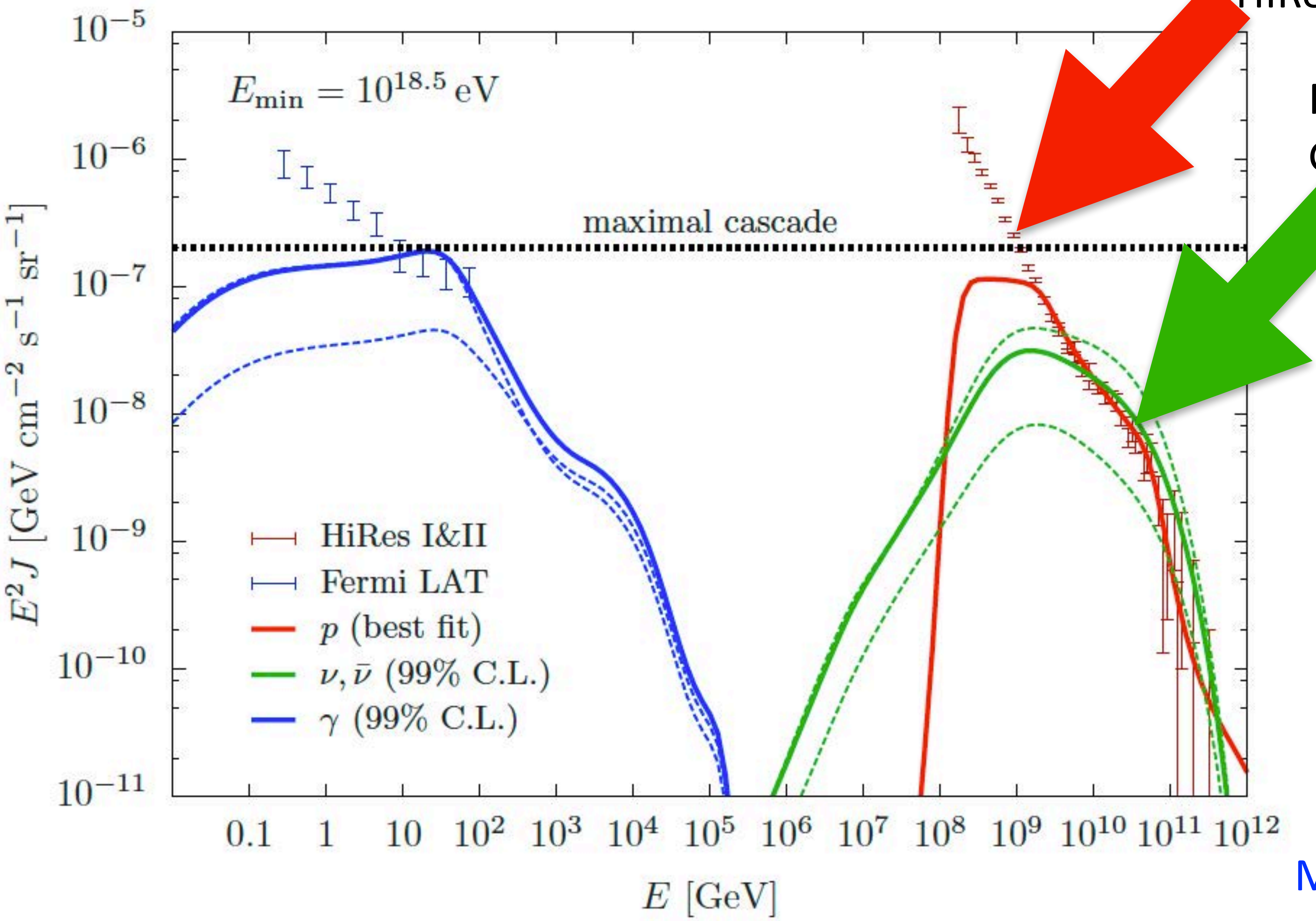
Greisen–Zatsepin–Kuzmin(GZK) neutrino

A “guaranteed source” of high energy neutrino flux.

$$p + \gamma^{\text{CMB,CIB}} \to \Delta^{+} \to n e^{+} \nu_{\mu} \bar{\nu}_{\mu} \nu_{e}$$

HIRes Data for UHECR

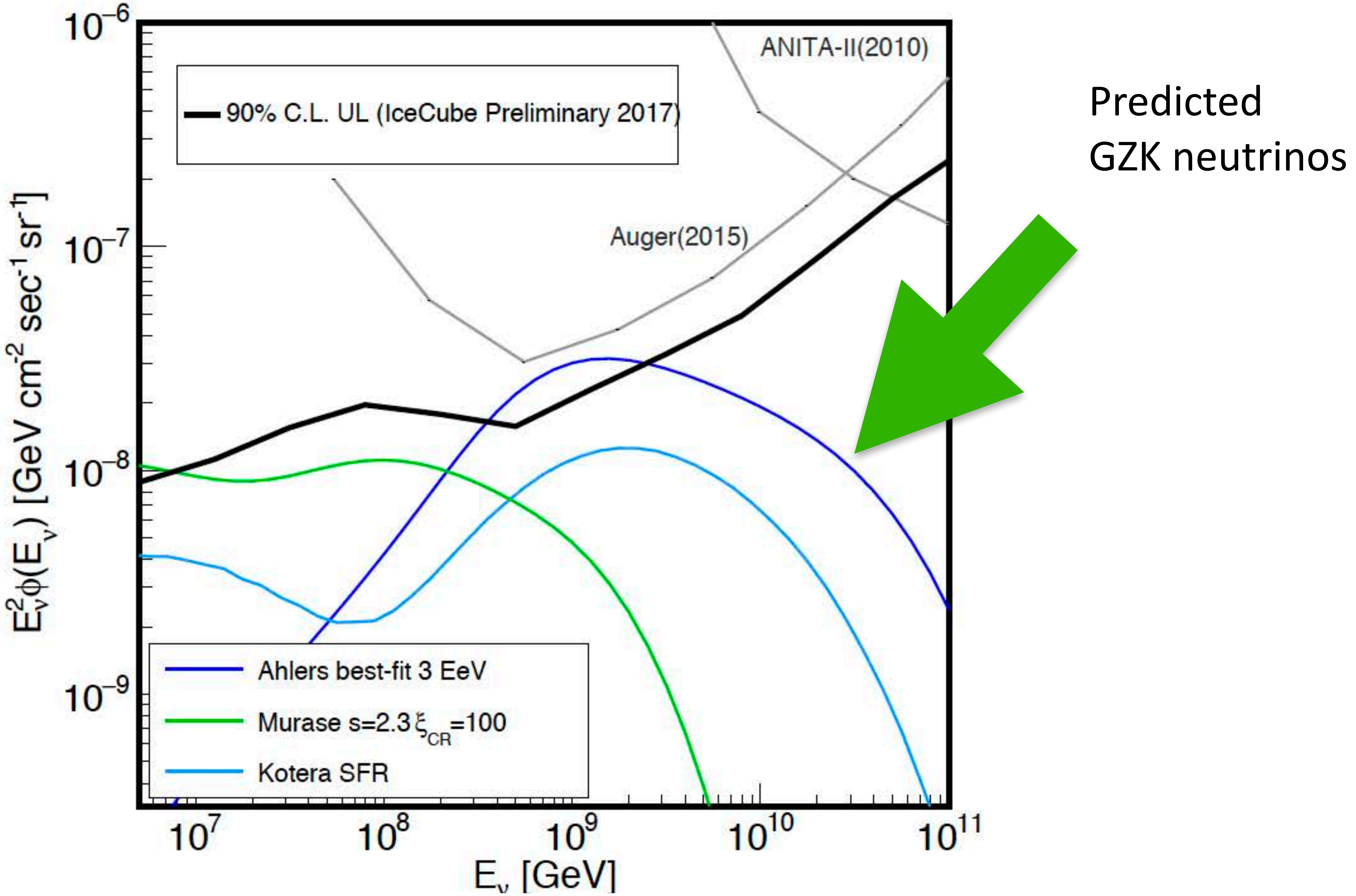
Predicted GZK neutrinos



- The GZK mechanism predicts the UV cutoff of the UHECR spectrum, which is observed.
- The GZK neutrinos should be produced.

M. Ahlers, et al,1005.2620

9 year data of IceCube Observatory



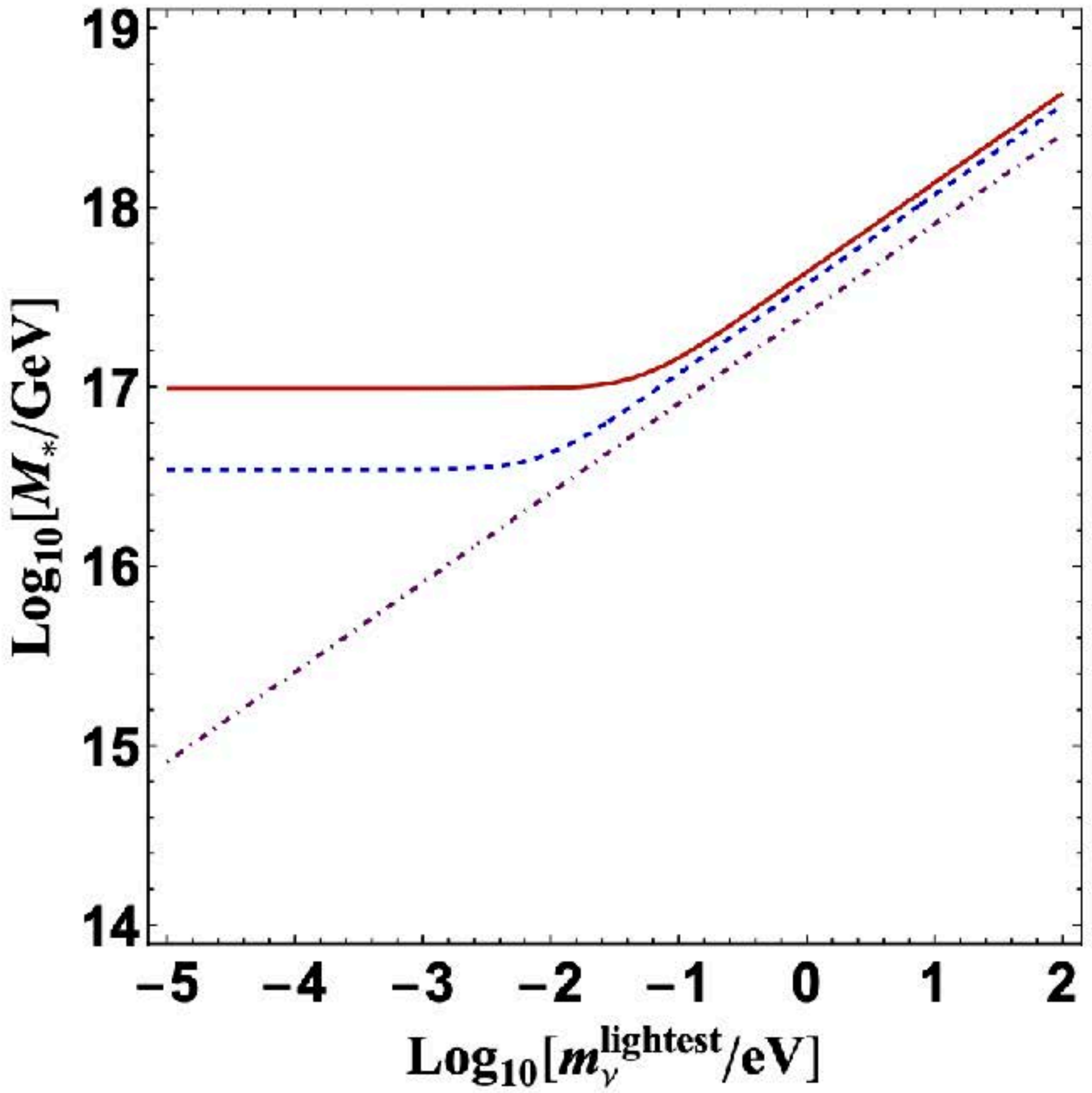
IceCube Collaboration, 1710.01191

GZK neutrinos assuming proton UHECR within SM are in tension with observation.

1. UHECR=Heavy nuclei?
2. New Physics?

CnuB is sensitive to the existence of dark sector

$$\frac{HL\phi\psi}{M_*}$$



From my old note (not published)

Fig. 4: The stability bounds for the CνB neutrinos. The red solid, blue dashed and purple dot-dashed lines correspond to the ν_3, ν_2 and ν_1, respectively, from top to bottom. Below the lowest bound, almost no neutrinos compose the CνB in the current universe. ψ, ϕ are assumed to be massless for simplicity. Normal ordering and majorana neutrino is assumed, with $\delta_{13} = -\pi/2$.

CnuB is sensitive to the existence of dark sector

$$\mathcal{L} \supset g' Z'_\mu \left(\bar{L}_\mu \gamma^\mu L_\mu - \bar{L}_\tau \gamma^\mu L_\tau - \bar{e}_\mu \gamma^\mu e_\mu + \bar{e}_\tau \gamma^\mu e_\tau \right).$$

From my old note (not published)

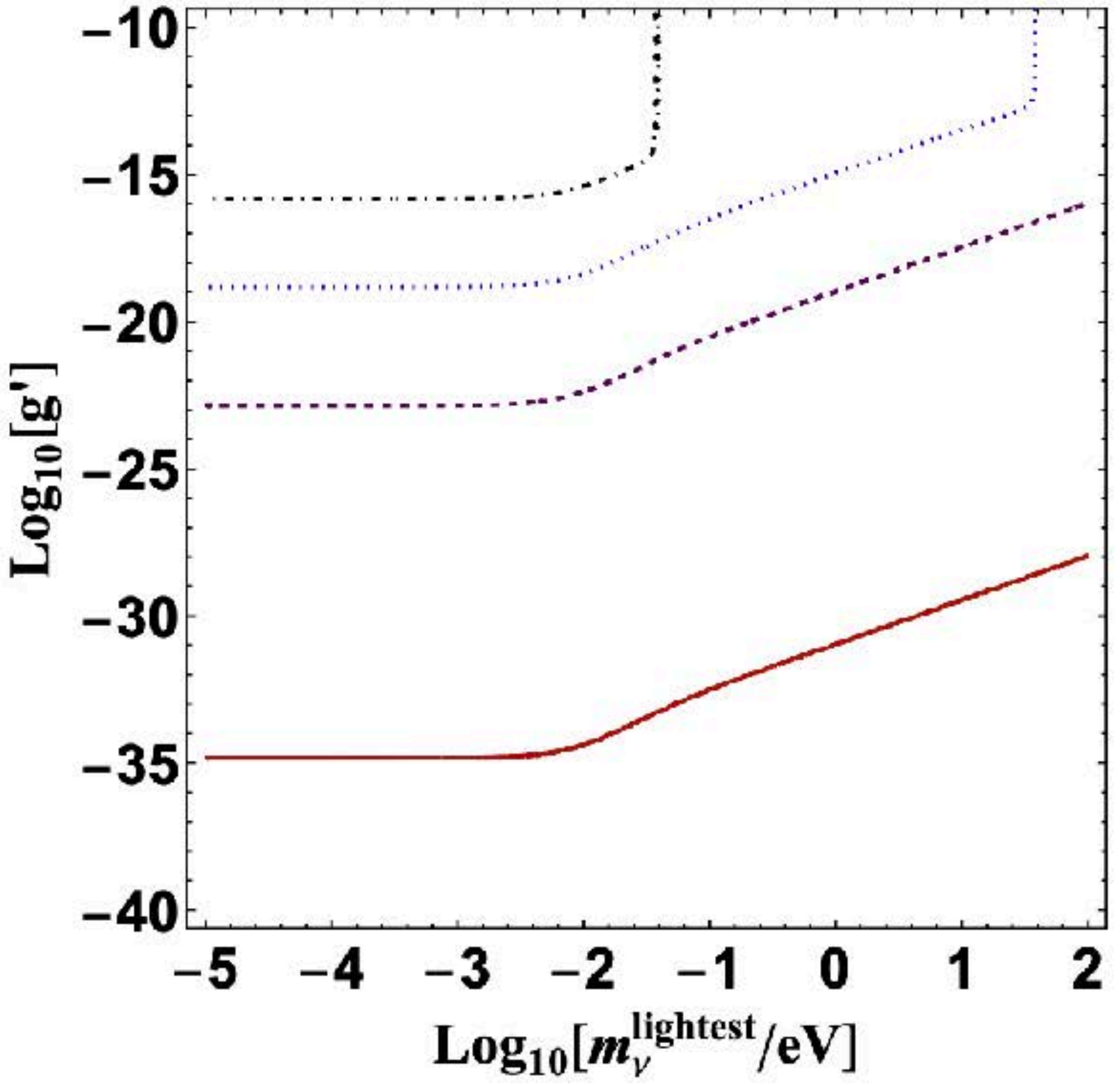


Fig. 3: The bounds for the CνB decays. Below the bounds, the neutrinos in the CνB in the current universe are mostly the lightest one. The lines correspond to the Z' mass $m_{Z'} = 10^{-22}, 10^{-10}, 10^{-6},$ and 10^{-3} eV from bottom to top. Normal ordering and Majorana neutrino are assumed, with $\delta_{13} = -\pi/2$.