ENERGETIC ALPS FROM DECAYING DARK MATTER

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based on
arXiv: 1806.08569
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KEYWORDS

Dark Matter

Decay

Axion

Supersymmetry

Small-Scale Problems

Axion-Photon Conversion

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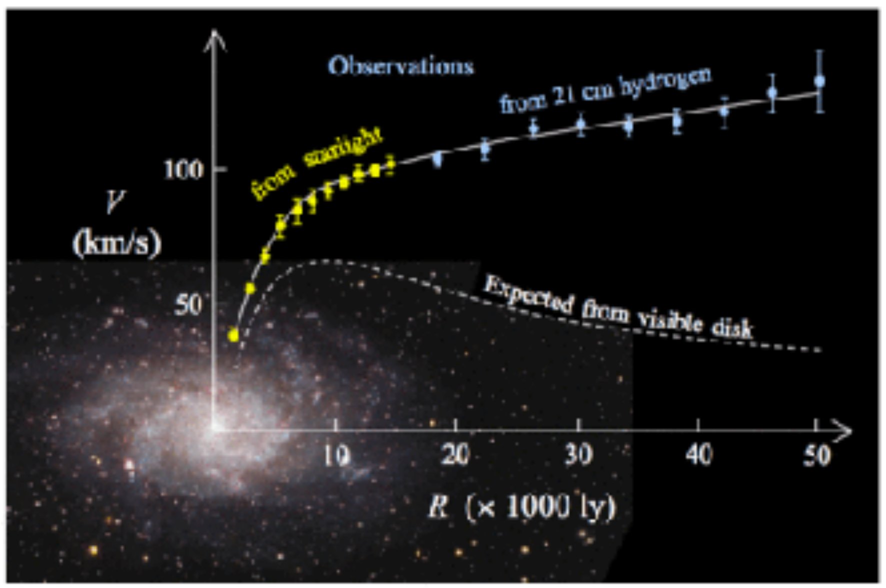
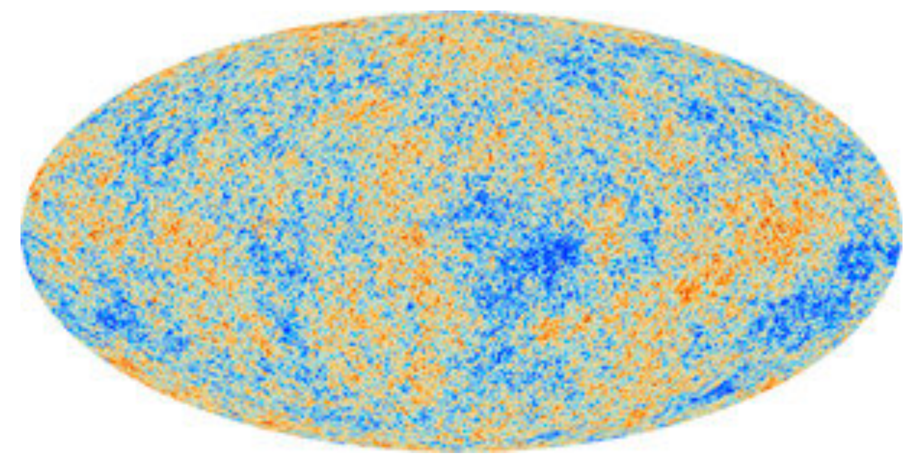
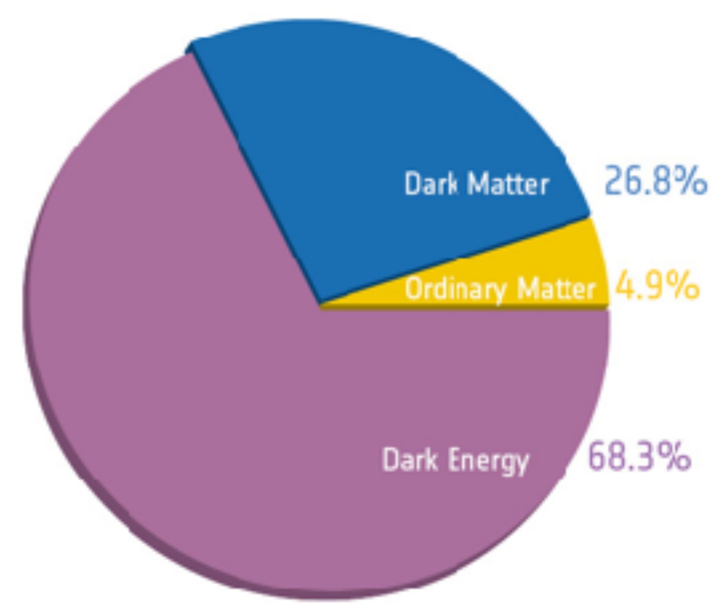
DARK MATTER

- Universe is filled with something unknown, which is called "Dark Matter."
- Observational evidences are



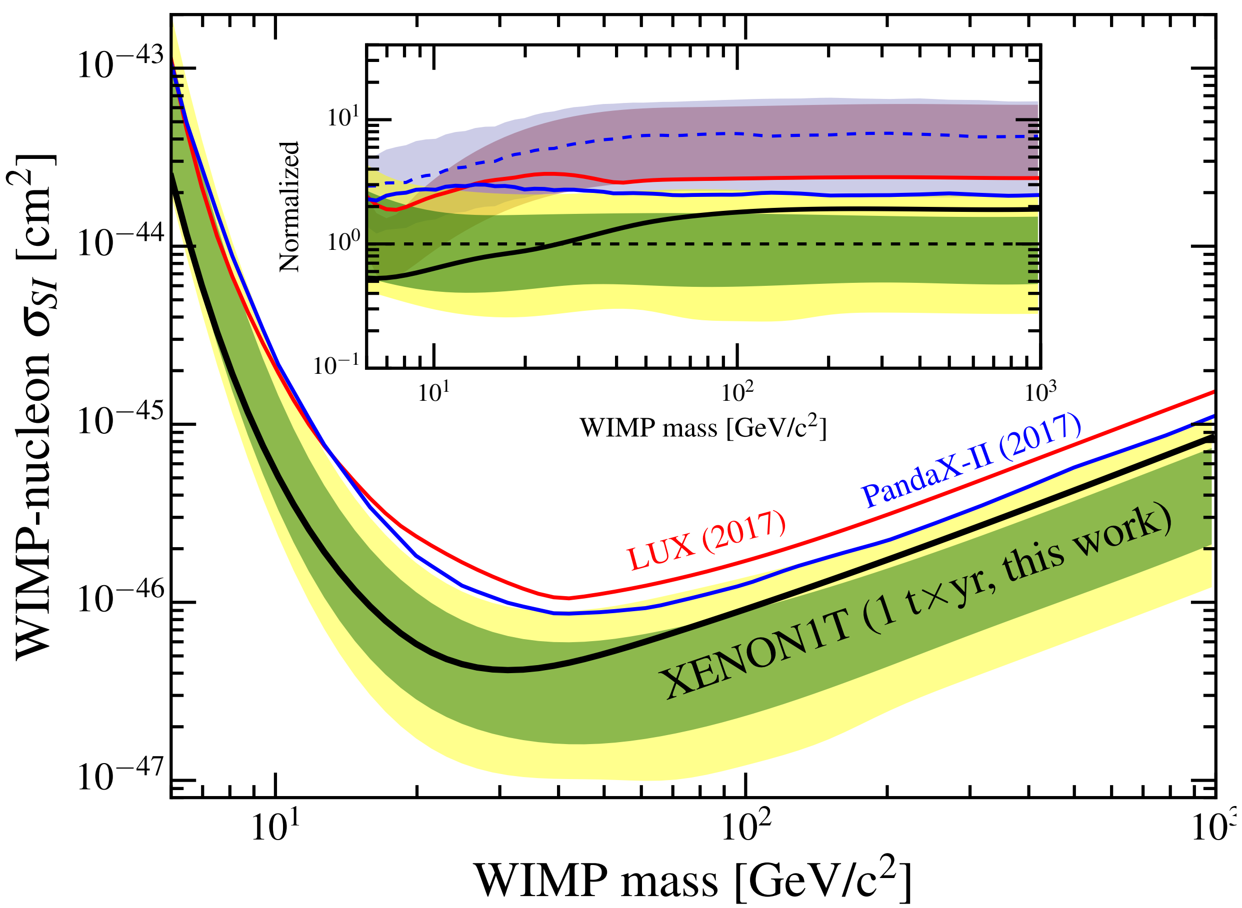


- DM density is ~1/4 of the energy of the Universe.
- All the evidences are gravitational. We do not know any non-gravitational interactions.
- What are DM particles? Stable? Decaying?



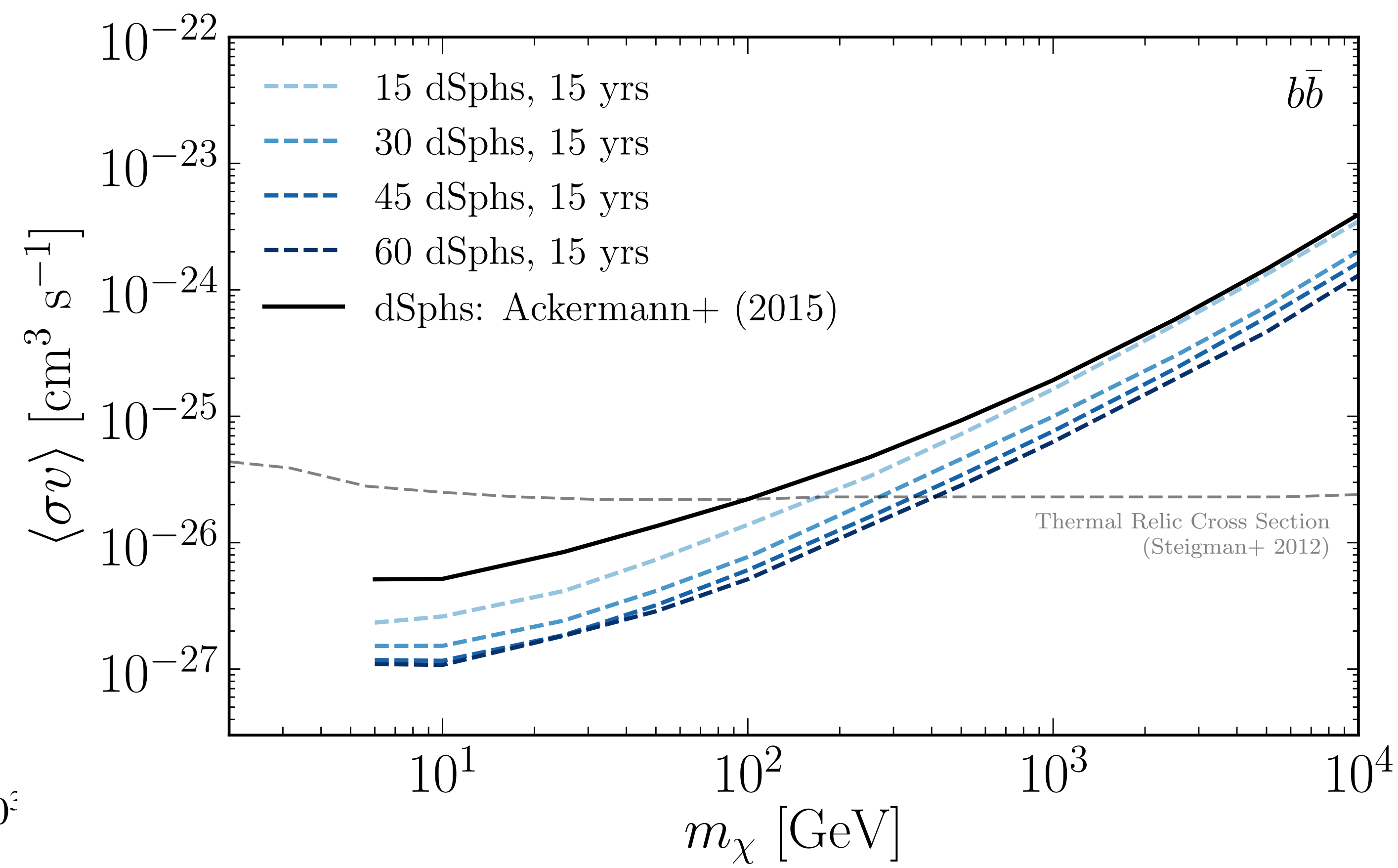
STABLE DM

- Candidates: neutralino (WIMPs), axion, sterile neutrino, ...
- Direct detection:



1805.12562

- Indirect detection:



1605.02016

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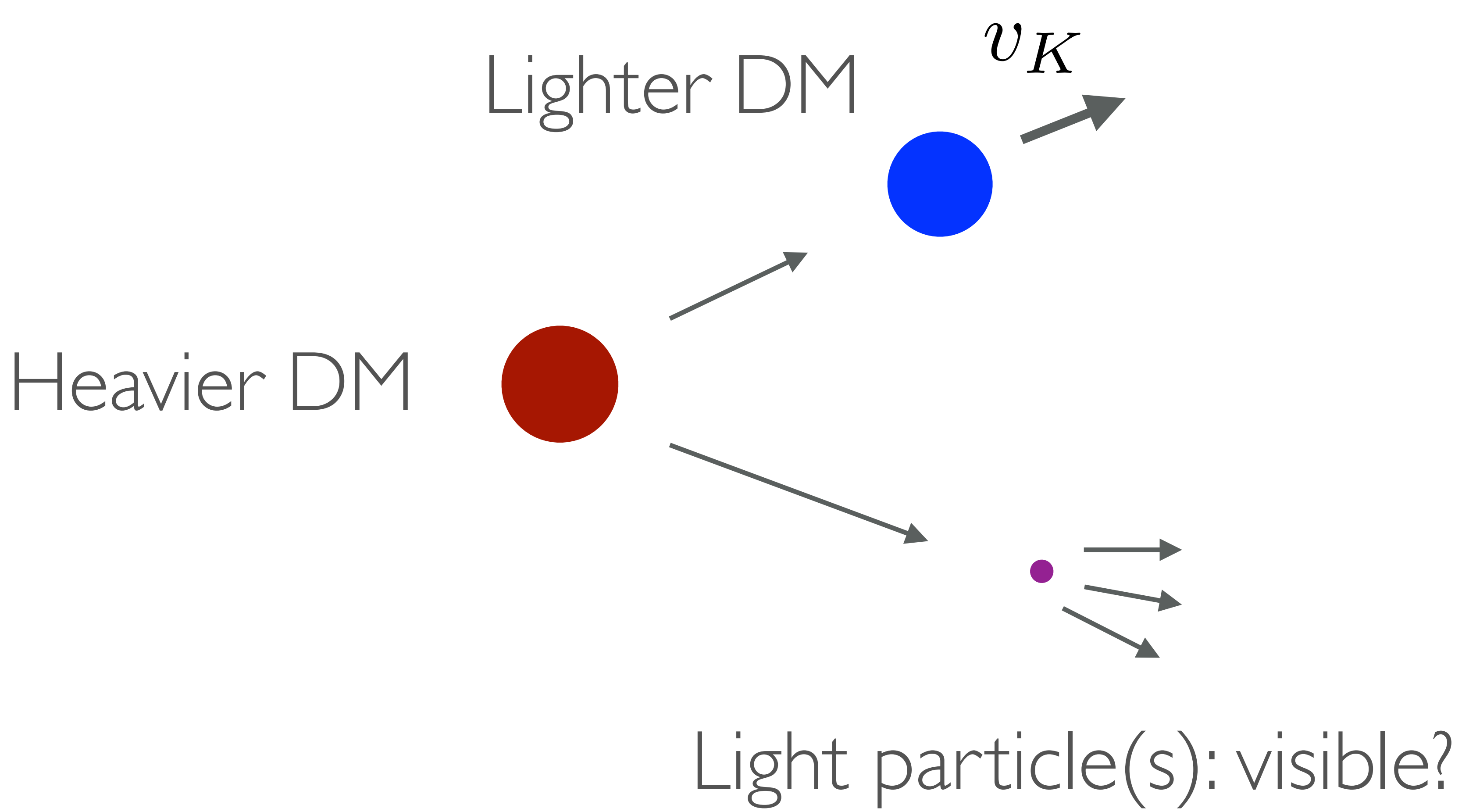
DECAY?

- Decay into SM particles: usual indirect detection, lower bound for life-time ...

DECAY?

- Decay into SM particles: usual indirect detection, lower bound for life-time ...
- DM decay into lighter DM component:



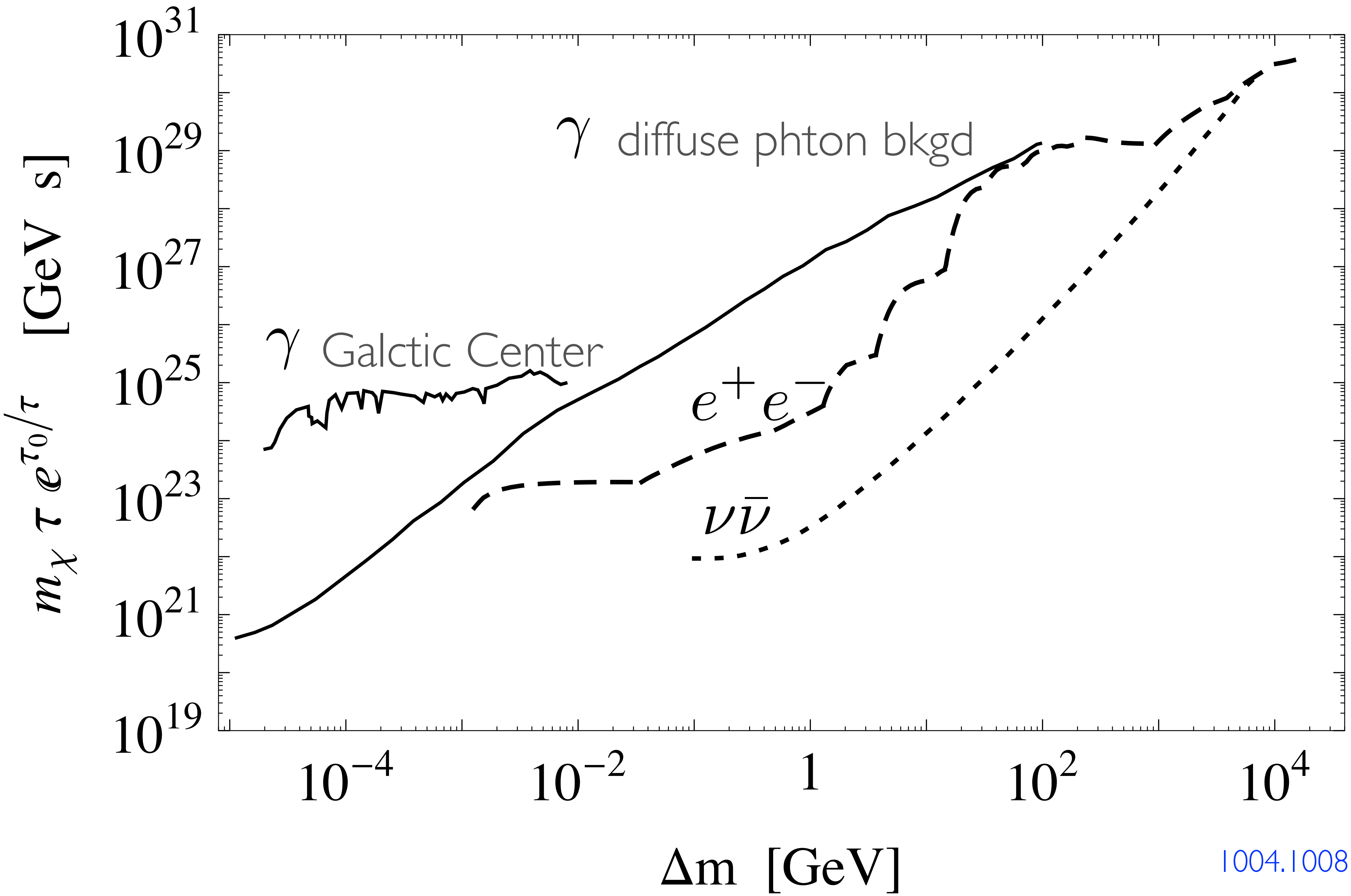
$$\Delta m/m \ll 1$$

- DM density remains the same
- small kick velocity
- visible signal?

DECAY?

- Strong constraints for $e^+e^-/\gamma/\nu\bar{\nu}$

Yuksel, Kistler 0711.2906
Bell, Galea, Petraki 1004.1008



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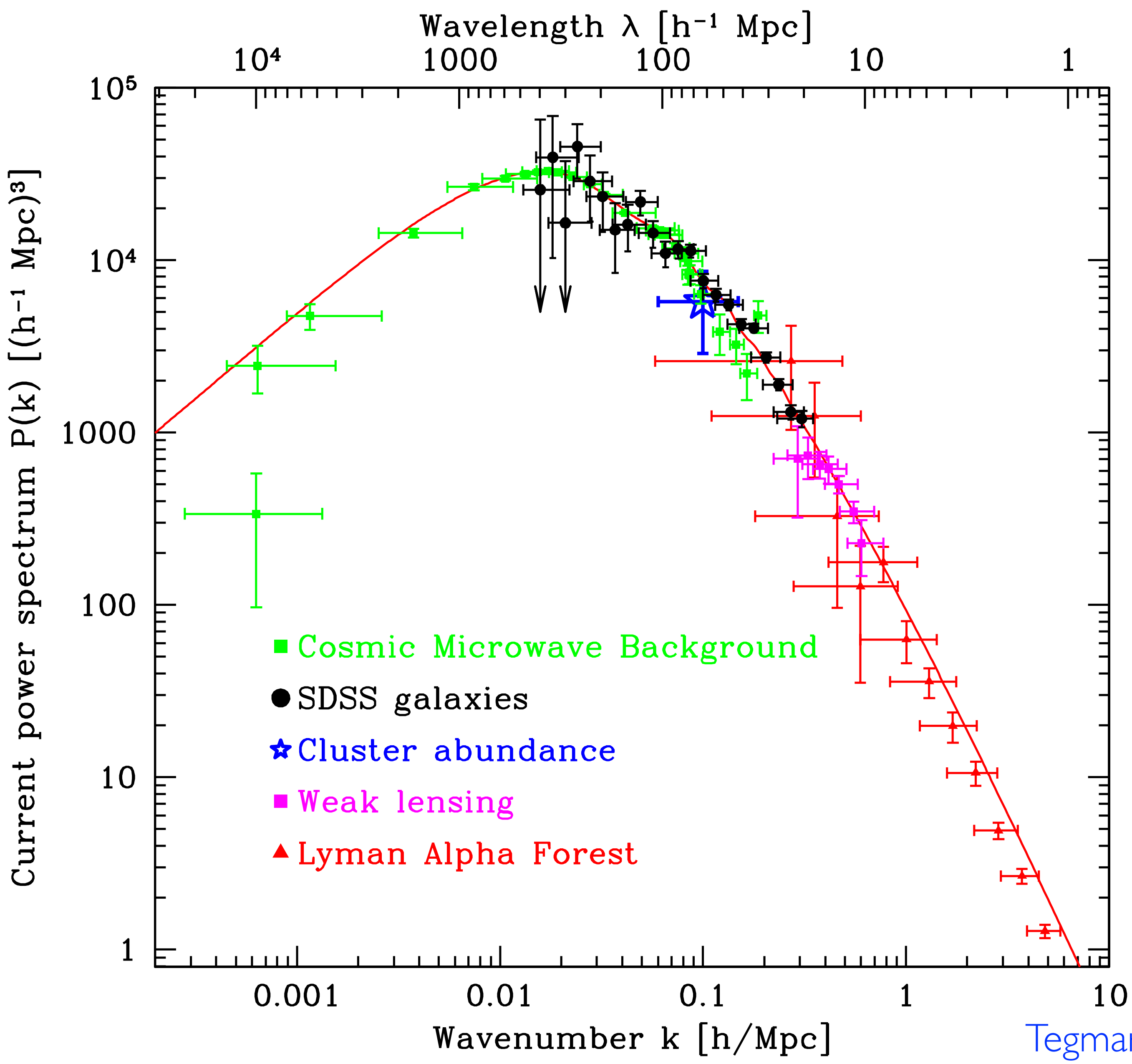
COLD DARK MATTER

- Very good for scale > O(100) kpc



Tegmark et al., astro-ph/0310725

- But discrepancies between N-body simulation and observation arise at small scale, e.g., Milky-way-size halo and subhaloes <O(100) kpc.

SMALL SCALE PROBLEMS

For a recent review, Tulin & Yu, 1705.02358

- **Missing satellite problem**

  In CDM model, structures form "***from the bottom up***."

  producing many subhaloes, **N~O(100)**, with V_{max}=10-30 km/s

  But we observe much less, **O(10)**

- **Too-big-to-fail problem**

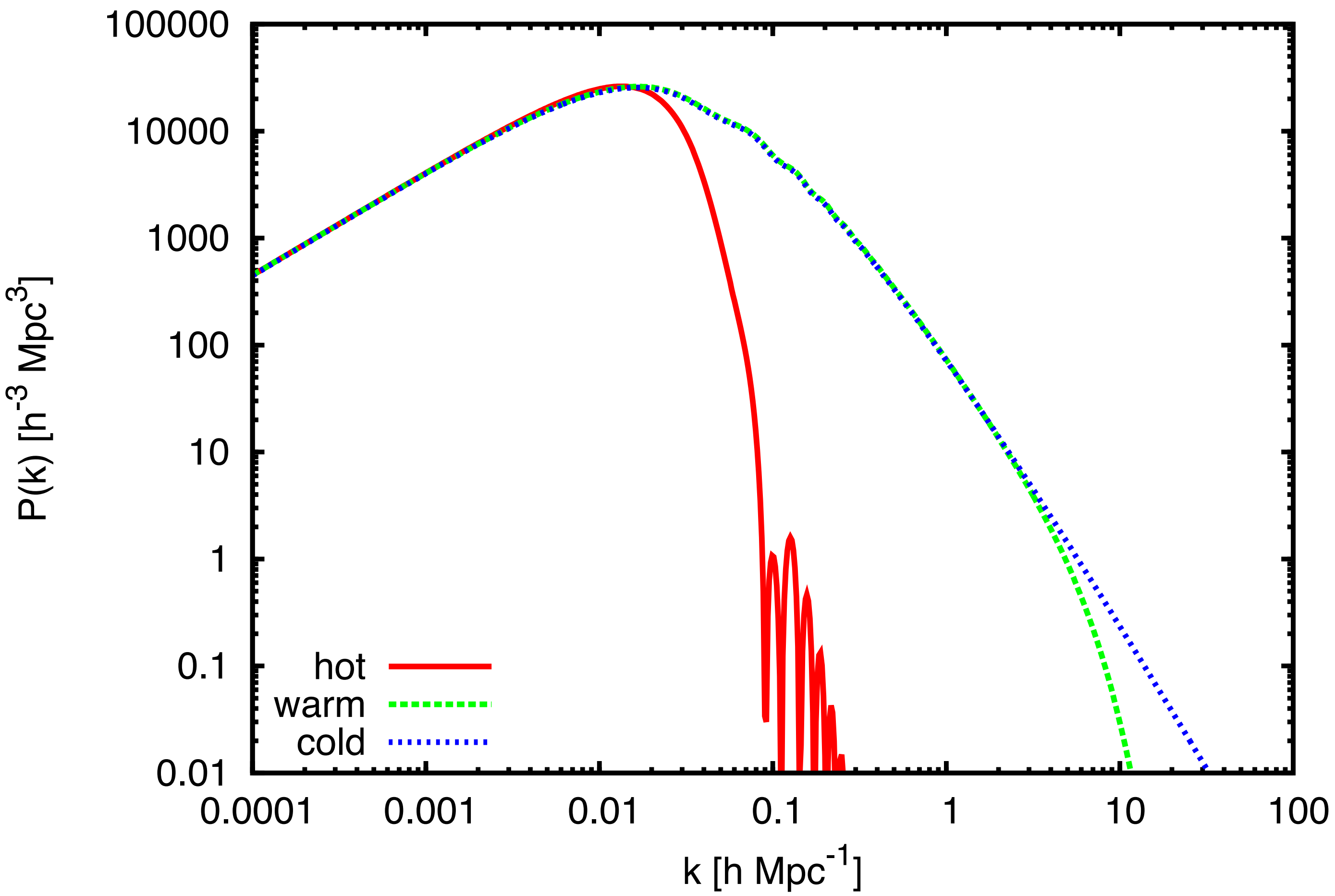
  CDM predicts ~10 subhaloes with V_{max}>30 km/s which should have galaxies: "***too big to fail to form stars***."

- **Core-Cusp problem**

  CDM predicts cusp profile but observed density shows cores in dwarf galax survey

WARM DARK MATTER

- Less cold or non-cold (but not hot) dark matter may solve these problems since freestreaming suppresses small scales
- thermally produced, following thermal (e.g. Fermi-Dirac) distribution, provides the whole DM density

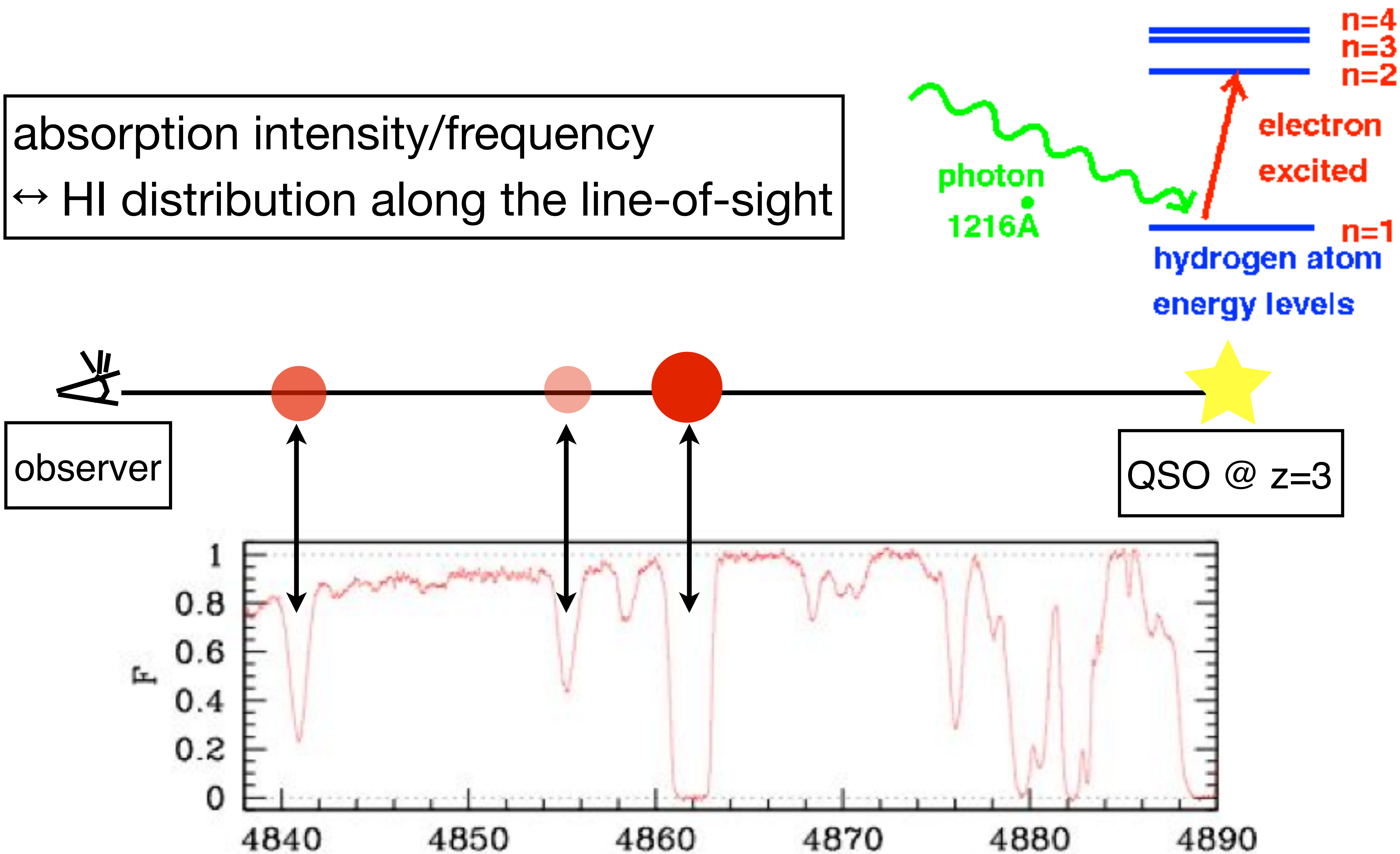


plot by A. Kamada

- Dark Matter with m~ keV e.g. sterile neutrino

LYMAN-ALPHA FOREST

absorption intensity/frequency
↔ HI distribution along the line-of-sight



slide by A. Kamada

LYMAN-ALPHA FOREST

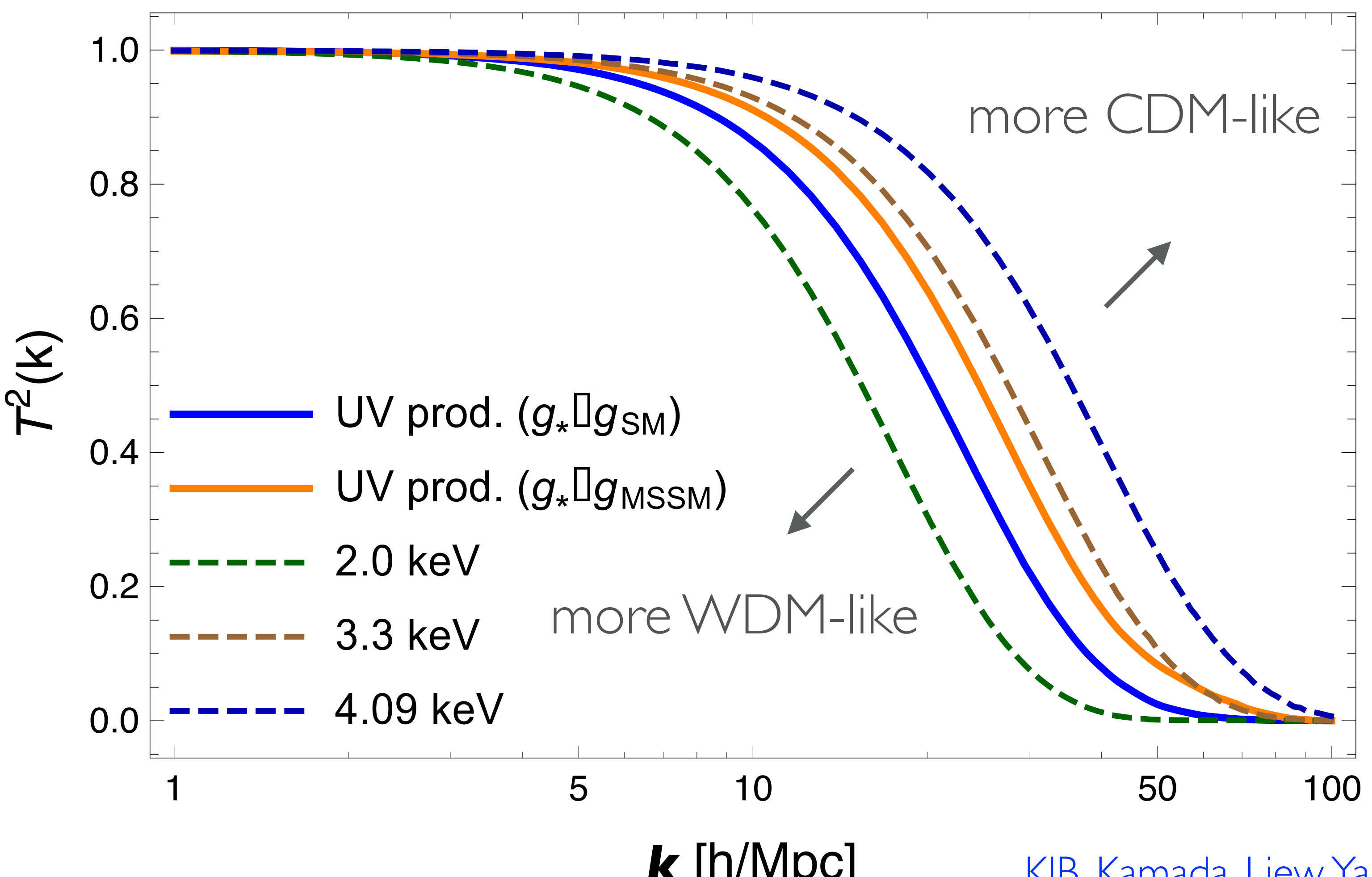
- Improving constraints on "warm dark matter mass"

$m_{\rm WDM} \gtrsim 2.0 \ {\rm keV}$ Viel, Lesgourgues, Haehnelt, Matarrese, Riotto (2005)

$m_{\rm WDM} \gtrsim 3.3 \ {\rm keV}$ Viel, Becker, Bolton, Haehnelt (2013)

$m_{\rm WDM} \gtrsim 4.09 \ {\rm keV}$ Baur, Palanque-Delabrouille, Yèche, Magneville, Viel (2016)

$m_{\rm WDM} \gtrsim 5.3 \ {\rm keV}$ Iršič et al. (2017)



WDM (m~keV) solution is ***not viable***!

KJB, Kamada, Liew, Yanagi, 1707.06418

DECAYING DARK MATTER

Peter, 1001.3870

- Key idea: CDM-like in the early stage WDM-like in the late stage

For Ly-alpha forest ($z\sim3$) For Milky way observation ($z\sim0$)

→ Decaying Dark Matter with lifetime ~ age of the universe

V_{kick} ~ 20-40 km/s

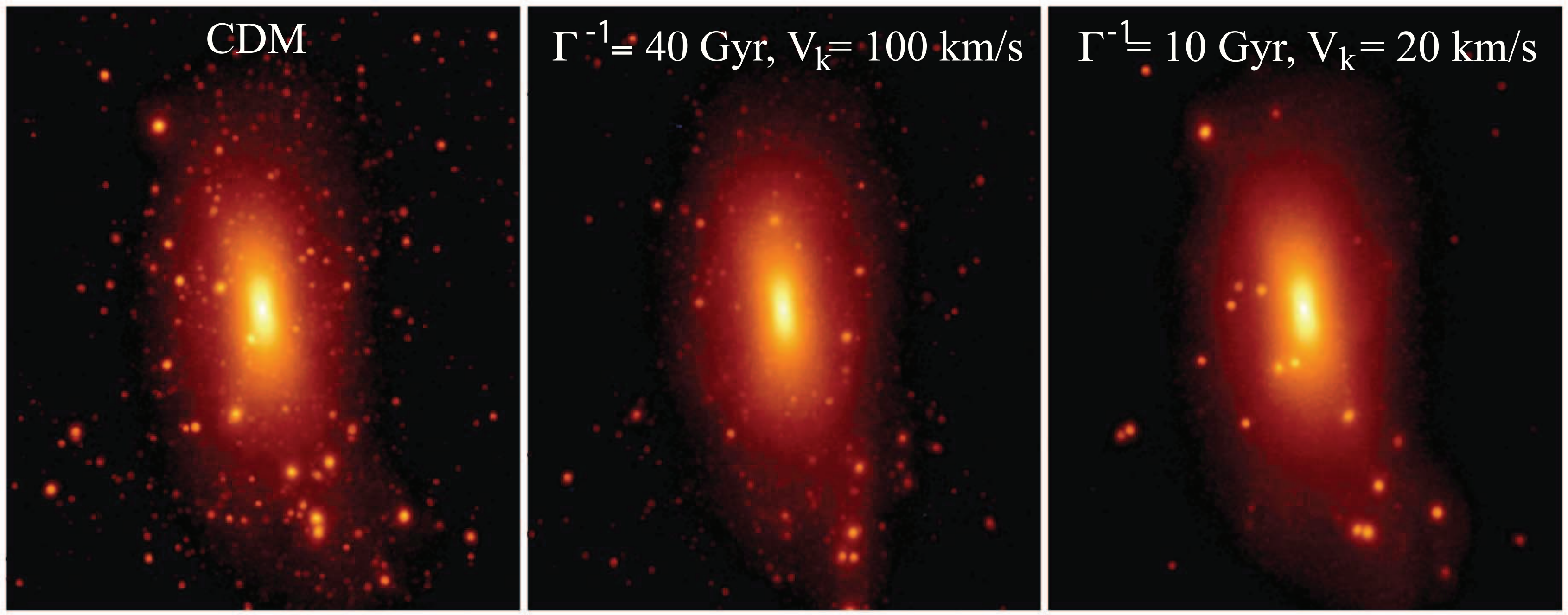
→ DDM → Stable DM + Non-interacting light particle

→ feeble interaction & nearly degenerate in mass

$(\Delta m/m \sim 10^{-4})$

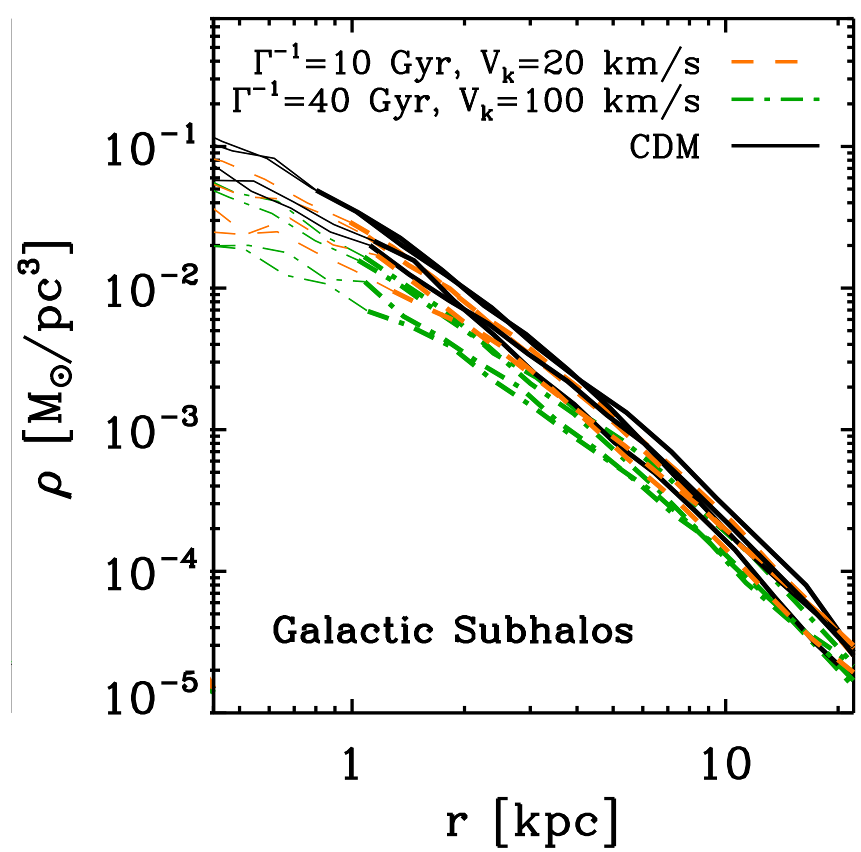
DECAYING DARK MATTER

- Solving missing satellite problem: reducing number of subhaloes

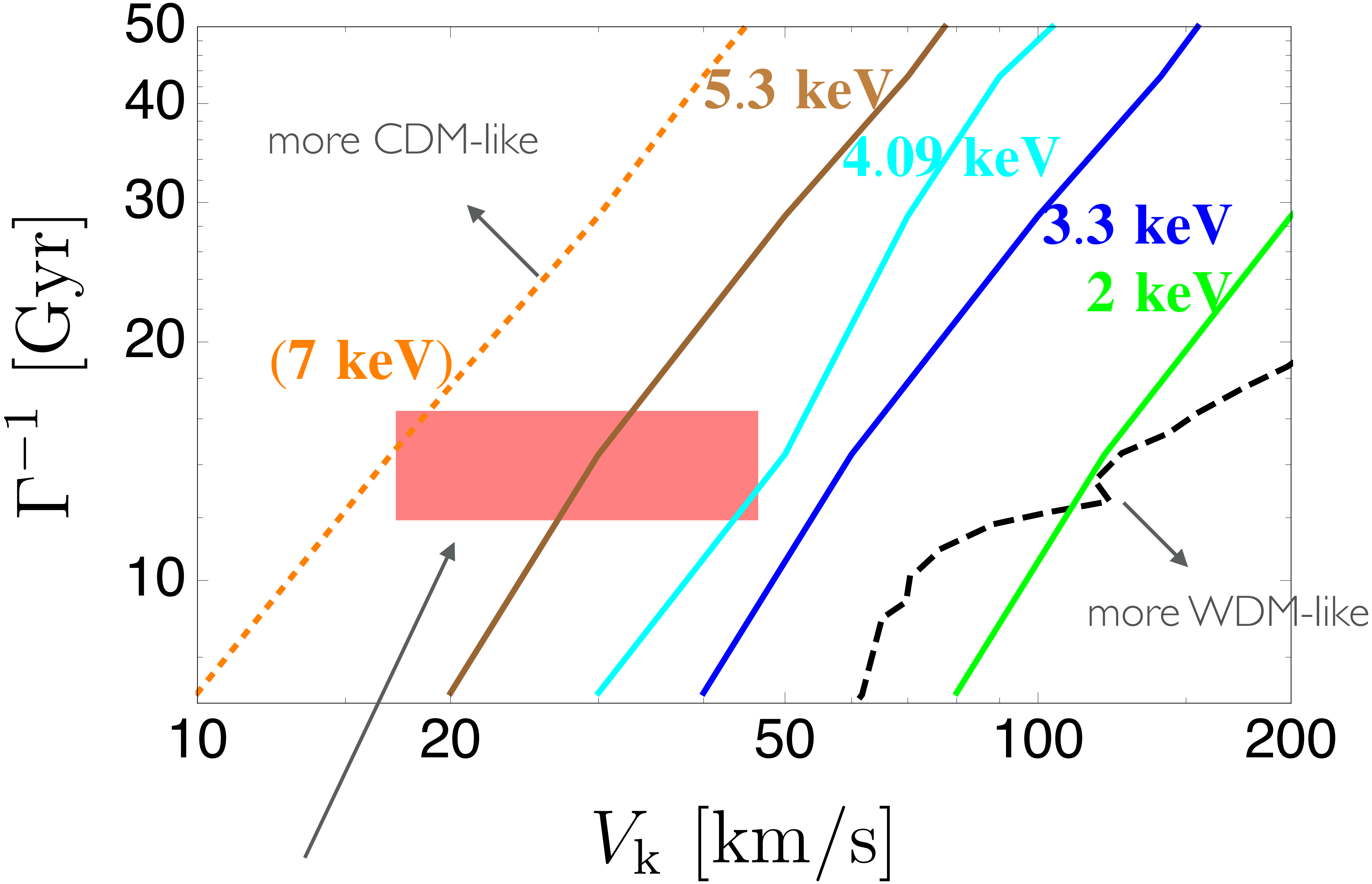


Wang et al., 1406.0527

- Solving too-big-to-fail problem: reducing central densities of subhaloes
- Also alleviating Core-Cusp problem:



DDM: LY-ALPHA FOREST



preferred region to solve
small scale problems

DDM SOLUTION?

- Strong constraints for $e^+e^-/\gamma/\nu\bar{\nu}$

Yuksel, Kistler 0711.2906
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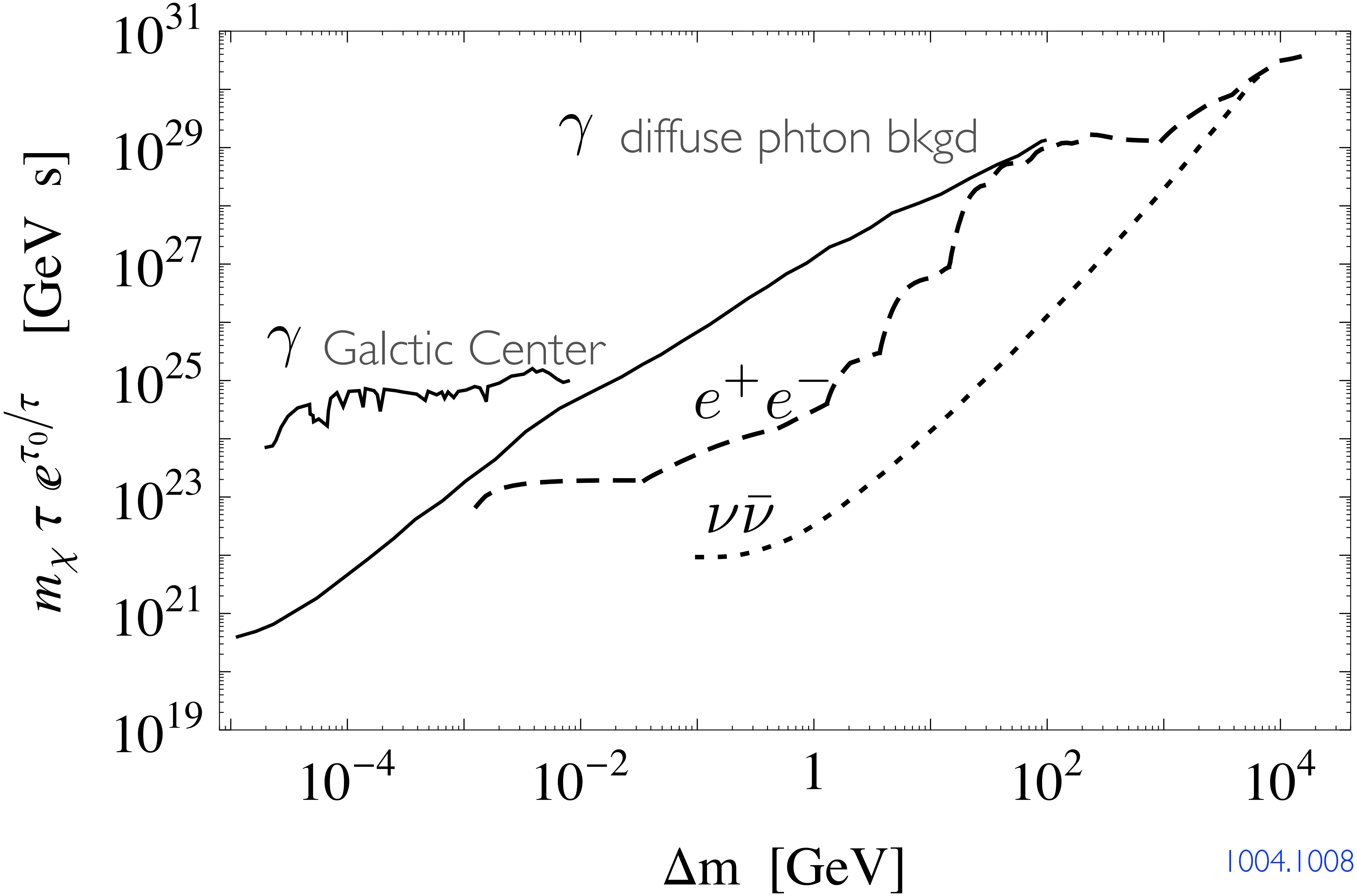

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DDM SOLUTION?

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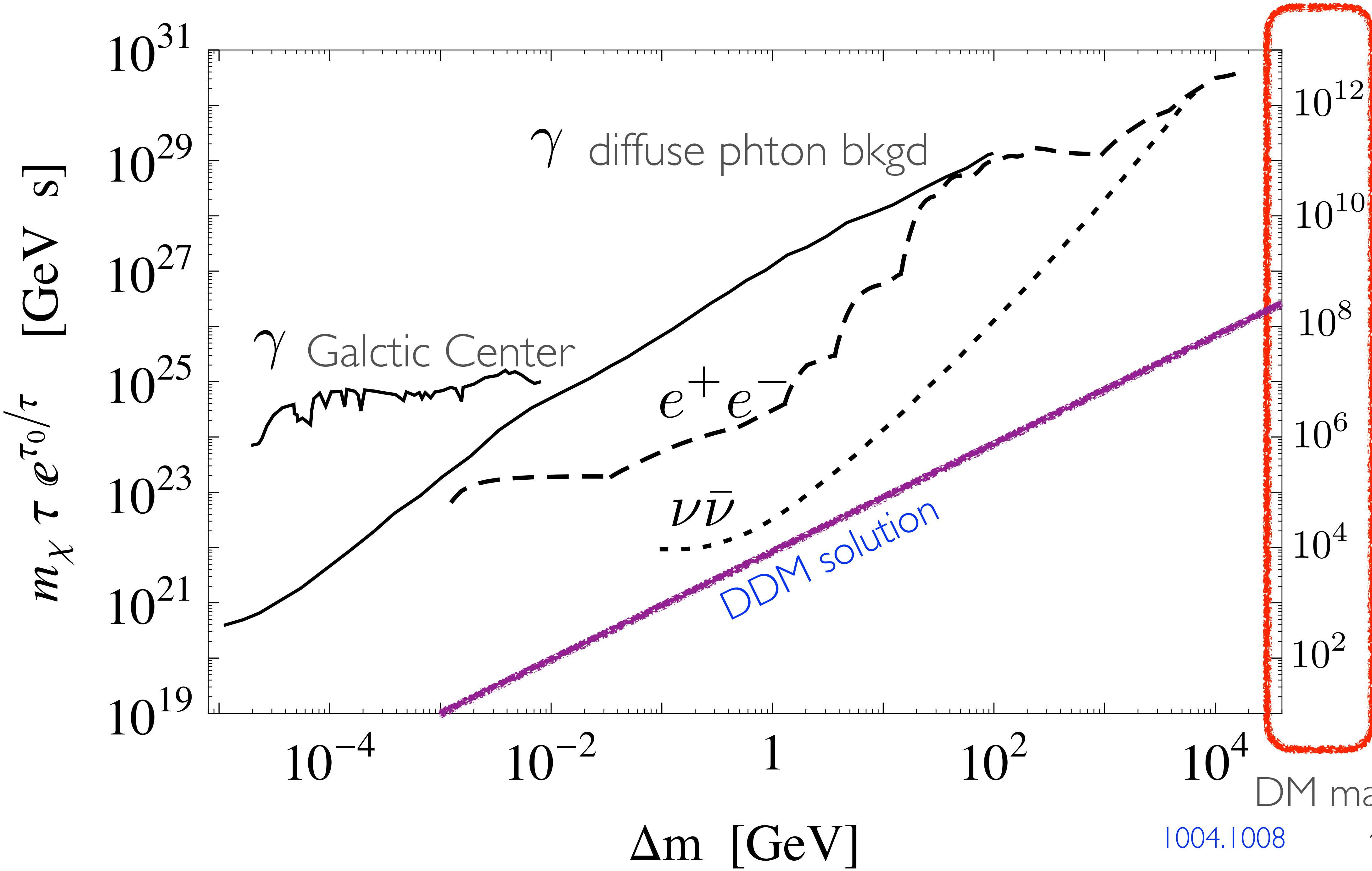

DM mass in GeV for $\tau = \tau_0$

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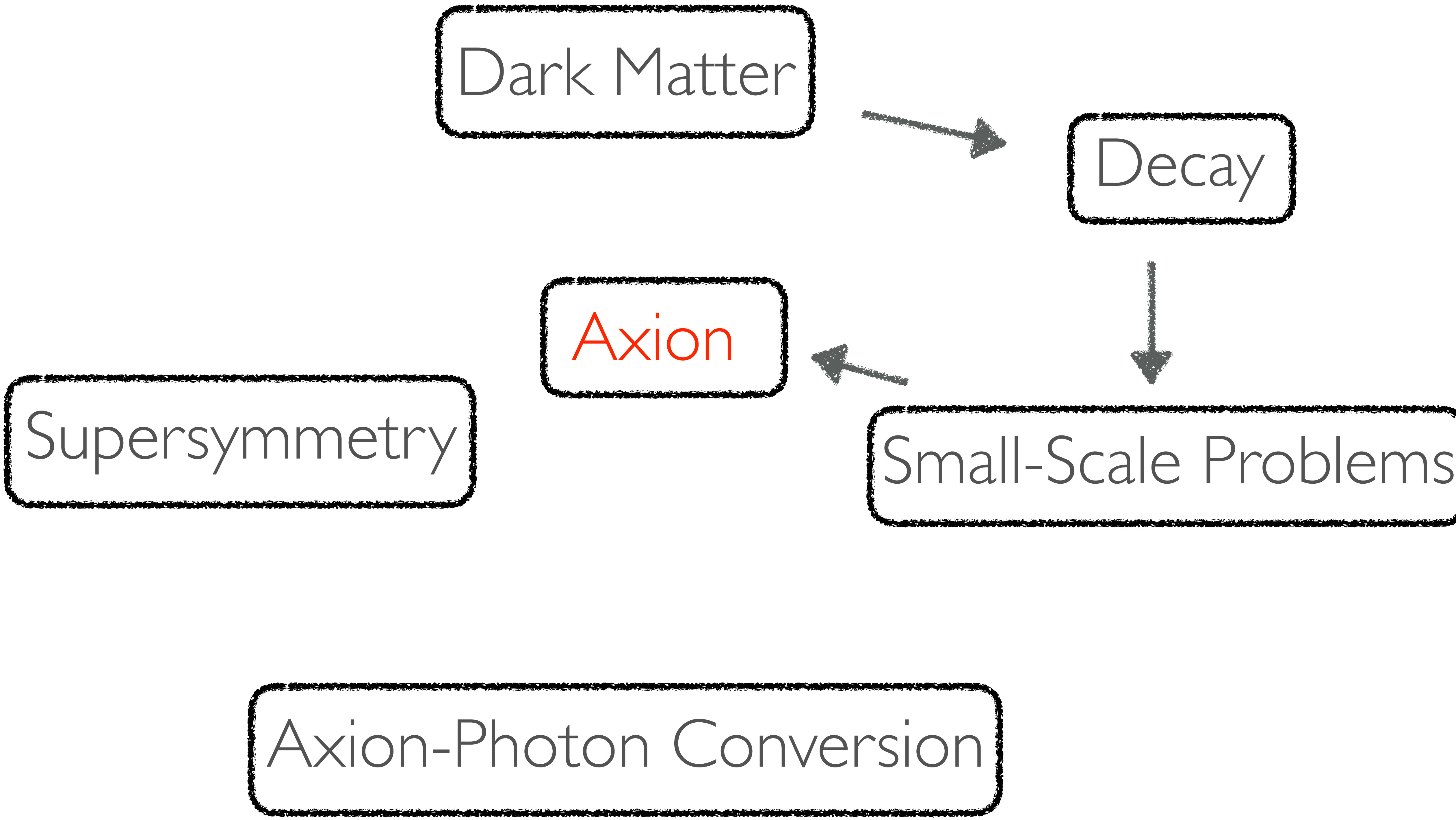
Q1: What particle physics provides DDM scenario?

Q2: What signal can we have?

KEYWORDS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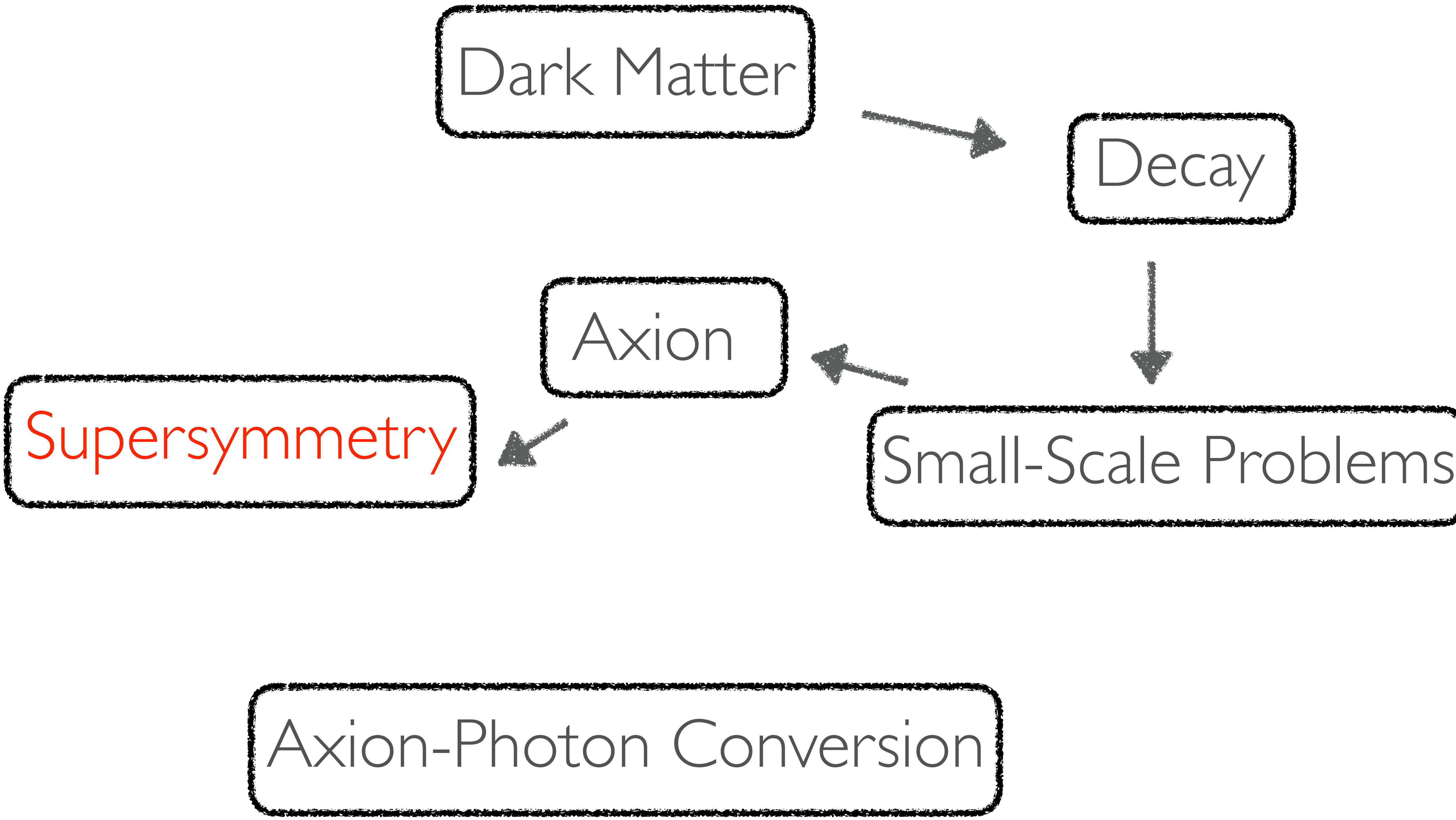
AXION(-LIKE) PARTICLE

DDM ⟶ Stable DM + Non-interacting light particle

↖ Should not be EM charged & neutrino

- Axion-like particle: very weakly interacting (~1/f, f>10^9 GeV), well-motivated.
- But induces a visible signal: ALP-photon conversion under magnetic field
- In our galaxy: galactic magnetic field expected, ~few μG
- Photon with E~Δm, signal morphology depends on magnetic field profile

KEYWORDS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AXINO(-LIKE) PARTICLE

DDM → Stable DM + Non-interacting light particle

↑ ALPino ↑ Gravitino ↑ ALP

- Easy to construct in Supersymmetric models
- Good to predict the DDM relic abundance
- Plausible explanation for mass degeneracy of DDM and SDM

Axino mass generated by SUSY breaking, $\sim m_{3/2}$

MASS DEGENERACY

- In SUSY limit, ALP multiplet is massless by shift symmetry.
- SUSY breaking generates ALPino mass: SUGRA says $\sim m_{3/2}$

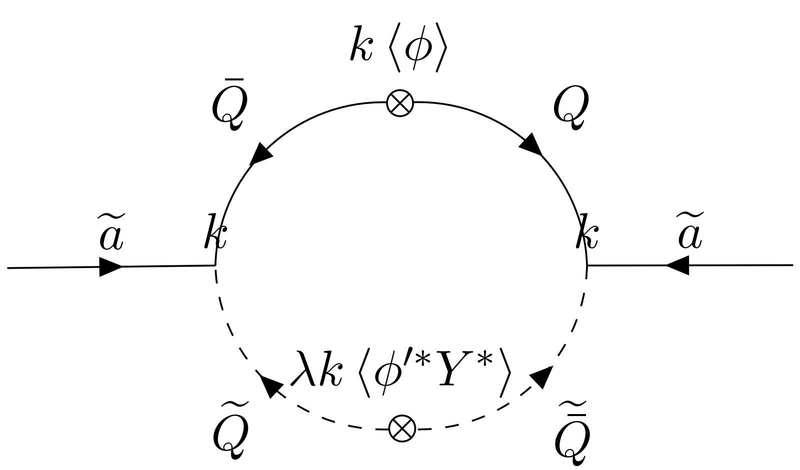
Goto, Yamaguchi; Chun, Kim, Nilles; Chun, Lukas

In a simple example,

$$K = |z|^2 + |\phi|^2 + |\phi'|^2 + |Y|^2$$
$$g\left(\phi,\, \phi',\, Y\right) = \lambda\left(\phi\phi' - f^2\right) Y$$
$$G = K + \ln\left|h\left(z\right) + g\left(\phi,\, \phi',\, Y\right)\right|^2$$

$$\rightarrow \quad M_{AA} = m_{3/2}\left\{1 + \mathcal{O}\left(\frac{|\omega|^2}{\lambda^2 f^2}\right)\right\}.$$

- Loop correction,



$$|m_{\tilde{a},\mathrm{loop}}| \sim \frac{k^2}{(4\pi)^2}\frac{\lambda k\,|\langle\phi'^{*}Y^{*}\rangle|}{k\langle\phi\rangle} \sim \frac{k^2}{(4\pi)^2} m_{3/2}.$$

k~0.1 $\rightarrow$ $(\Delta m/m \sim 10^{-4})$

INTERACTIONS

- Consider an effective Lagrangian,

U(1)$_Y$ SU(N)$_h$

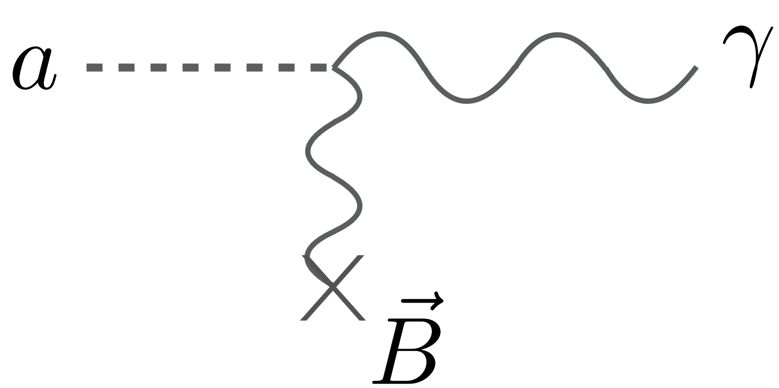
$$W_{\rm eff} \;=\; -\sqrt{2} g_{aB}\, A\, W_B W_B - \sqrt{2} g_{a g_{\rm h}}\, A\, W_{\rm h}^a W_{\rm h}^a\,,$$

for ALPino production, ALP-photon conversion

for ALP mass generation

$\rightarrow$ $\mathcal{L}_{\rm eff} \;\supset\; g_{a\gamma}\, a\, F_{\mu\nu}\widetilde{F}^{\mu\nu}$

$m_a \;\sim\; \Lambda_{\rm h}^2/f$



MASS SCALE

- ALPino-Gravitino interaction,

$$\mathcal{L}_{3/2} = -\frac{1}{2M_{\rm pl}}\partial_\nu a\,\bar{\psi}_\mu\,\gamma^\nu\gamma^\mu i\gamma_5\,\tilde{a}\,,$$

$$\rightarrow \quad \Gamma_{\tilde{a}}^{-1} = \frac{96\pi m_{3/2}^2 M_{\rm pl}^2}{m_{\tilde{a}}^5}\left(1-\frac{m_{3/2}}{m_{\tilde{a}}}\right)^{-2}\left(1-\frac{m_{3/2}^2}{m_{\tilde{a}}^2}\right)^{-3}$$

$$\simeq 10\,{\rm Gyr}\left(\frac{700\,{\rm TeV}}{m}\right)^3\left(\frac{20\,{\rm km/s}}{V_{\rm k}}\right)^5 .$$

- For a successful DDM scenario, Γ^{-1}~10 Gyr, V_k~20-40 km/s, sub-PeV scale is required.

ALPINO RELIC ABUNDANCE

- main production

$$\mathcal{L}_{\rm eff} \supset g_{a\gamma}\, a\, F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

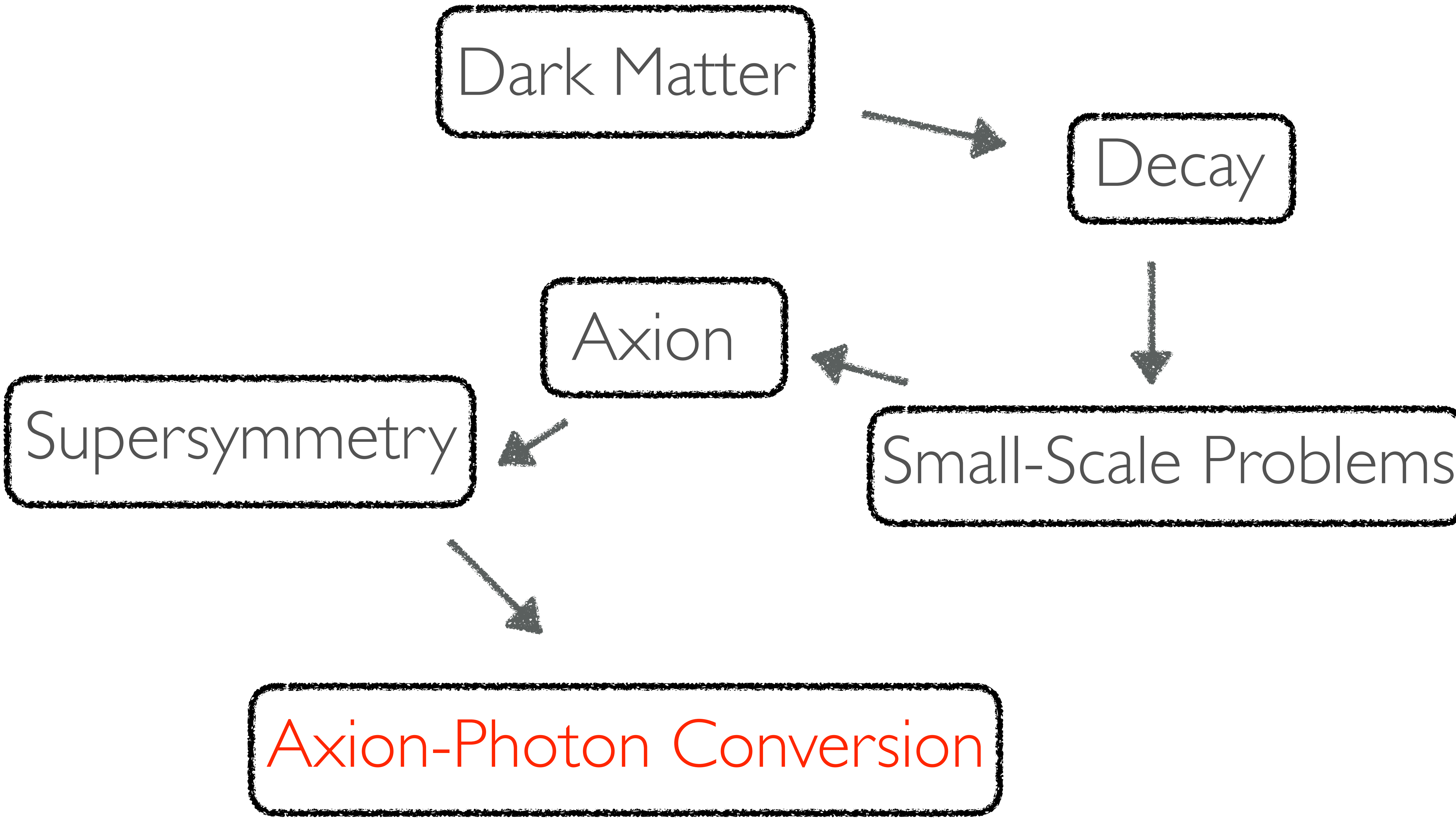
Freeze-out of Lightest MSSM particle, e.g. higgsino → Decay to ALPino

$$Y_{\tilde{a}} \simeq Y_{\rm losp}^{\rm fo} \times \frac{4+p}{1+p}\left[\frac{g_*(T_{\rm R})}{g_*(T_{\rm fo})}\right]^{1/2}\left(\frac{T_{\rm R}}{T_{\rm fo}}\right)^3,$$

$$Y_{\rm losp}^{\rm fo} = 4\times 10^{-13}\,(m_{\rm losp}/1\,{\rm TeV})$$

- Low reheat temperature is required, $T_R \sim 500$ GeV, i.e., ALPino production ***during reheating***

KEYWORDS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ALP-PHOTON CONVERSION

- Under magnetic field, ALP is converted to photon.

$$\mathcal{L}_{\rm eff} \supset g_{a\gamma}\, a\, F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

Eq. of motion →

$$\left(E_\gamma + i\partial_z + \begin{pmatrix} \Delta_e & \Delta_{\rm B} \\ \Delta_{\rm B} & \Delta_a \end{pmatrix}\right)\begin{pmatrix} A_{\parallel}(z) \\ a(z) \end{pmatrix} = 0\,,$$

$$\Delta_e \approx -\frac{\omega_{\rm p}^2}{2E_\gamma}\,,\quad \omega_{\rm p}^2 = \frac{4\pi\alpha_{\rm em} n_e}{m_e}\,,$$

$$\Delta_a = -\frac{m_a^2}{2E_\gamma}\,,\quad \Delta_{\rm B} = \frac{g_{a\gamma}B_{\rm T}}{2}\,,$$

Conv. Prob. (for homogeneous magnetic field)

→

$$P_{a\gamma}(s,\Omega) \simeq 2\times 10^{-7}\left|\frac{B_T(s,\Omega)}{\mu{\rm G}}\right|^2\left(\frac{10^{-8}\,{\rm eV}}{m_a}\right)^4 \times\left(\frac{g_{a\gamma}}{10^{-13}\,{\rm GeV}^{-1}}\right)^2\left(\frac{E_\gamma}{47\,{\rm GeV}}\right)^2,$$

$$g_{a\gamma} \simeq 0.4 * 10^{-15}\ {\rm GeV}^{-1} \times \left(\frac{m_a}{10^{-6}\ {\rm eV}}\right)$$

Photon flux

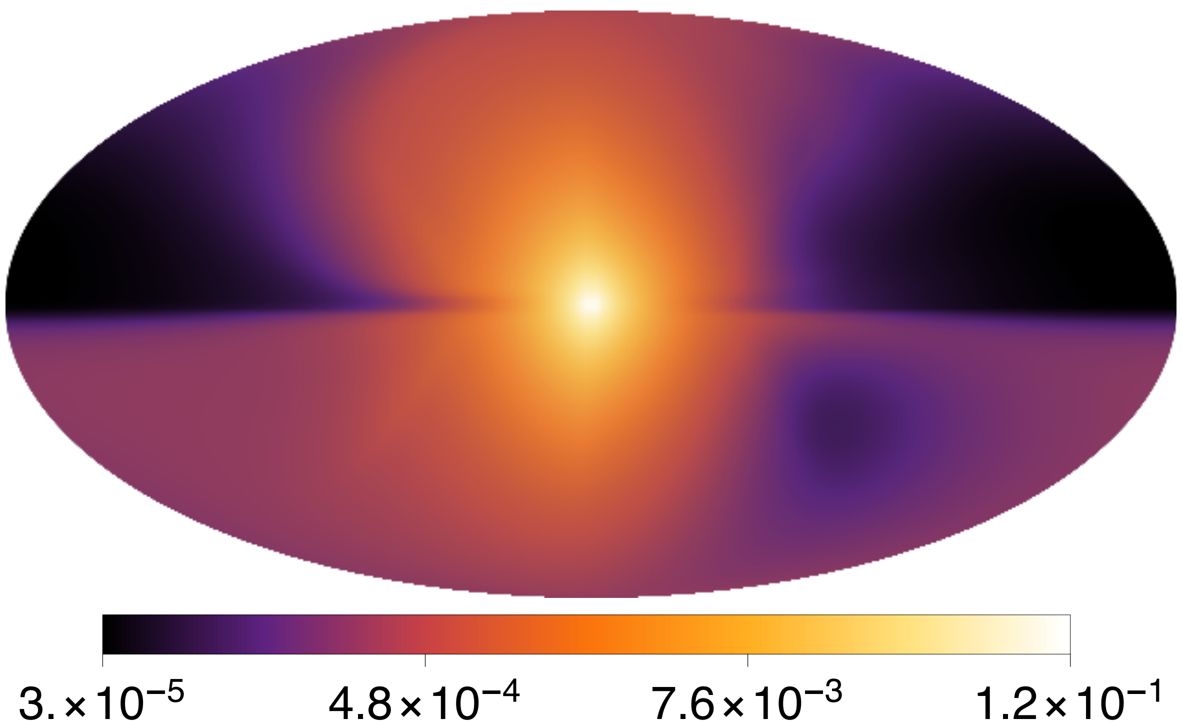
$$E_\gamma^2\frac{d^2\Phi_\gamma^a}{dE_\gamma d\Omega} \simeq 6\times 10^3\, J_{\rm D,ROI}\, e^{-\Gamma_{\tilde a}T_0}\,{\rm MeV/cm^2/s/sr} \times\left(\frac{E_\gamma}{47\,{\rm GeV}}\right)^2\left(\frac{700\,{\rm TeV}}{m_{\tilde a}}\right)\left(\frac{\Gamma_{\tilde a}}{10\,{\rm Gyr}}\right) \times\left(\frac{1\,{\rm GeV}}{\Delta E}\right)\left(\frac{1\,{\rm sr}}{\Delta\Omega_{\rm ROI}}\right),$$

$$J_{\rm D,ROI} \simeq 22\times P_{a\gamma}$$

Fermi-LAT (observed):

$$E_\gamma^2\frac{d^2\Phi_\gamma^{\rm obs}}{dE_\gamma d\Omega} \simeq 6\times 10^{-4}\,{\rm MeV/cm^2/s/sr}\,,$$

SIGNAL MORPHOLOGY

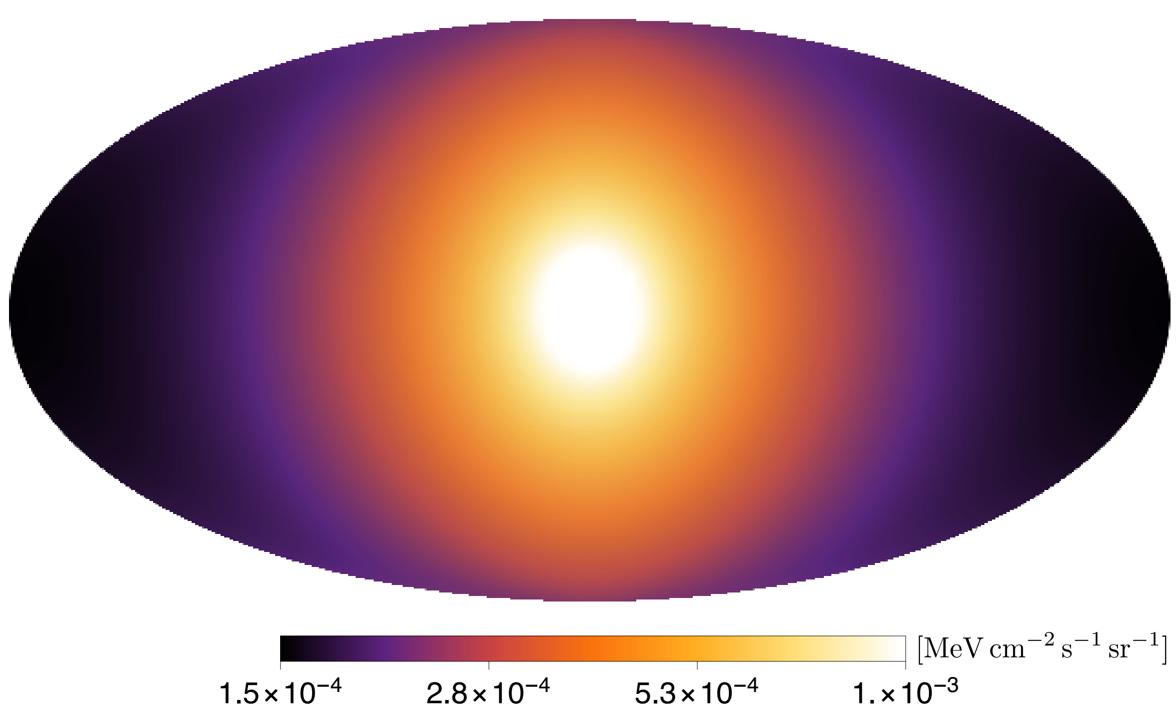


Our scenario

$E_\gamma = 47\,\mathrm{GeV}$ $g_{a\gamma} = 10^{-13}\,\mathrm{GeV}^{-1}$

$\tau_{\tilde{a}} \sim 3 \times 10^{17}\ \mathrm{s}$ $m_a = 10^{-8}\,\mathrm{eV}$

Magnetic field profile from Jansson & Farrar,
Astrophys. J., vol. 757, p. 14, 2012



Simple Decaying DM to diphoton

$E_\gamma = 47\,\mathrm{GeV}$ $m_{\mathrm{DM}} = 94\,\mathrm{GeV}$

$\tau_{\mathrm{DM}} \simeq 10^{28}\,\mathrm{s}.$

SUMMARY

- Cold dark matter (CDM) is successful to explain current universe.
- Shortcomings arise at small scale structure, <O(100) kpc.
- Warm dark matter (WDM) was a good solution, but is disfavored by Ly-alpha forest data.
- ***Decaying dark matter*** (tau~10 Gyr, V_k~30 km/s) is a good alternative.
- Axino-like particle ⟶ Axion-like particle + Gravitino provide a good decaying dark matter scenario.
- ALP-photon conversion produces distinct signal; morphology, energy scale.