ALPINO TO ALP: SOLUTION TO SMALL-SCALE PROBLEMS

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based on
arXiv: 1806.08569
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LONG-LIVED PARTICLE

10^{-13} s — 10^{17} s — 10^{26} s — lifetime

Long-Lived Particles

$c\tau \gtrsim 0.01$ mm

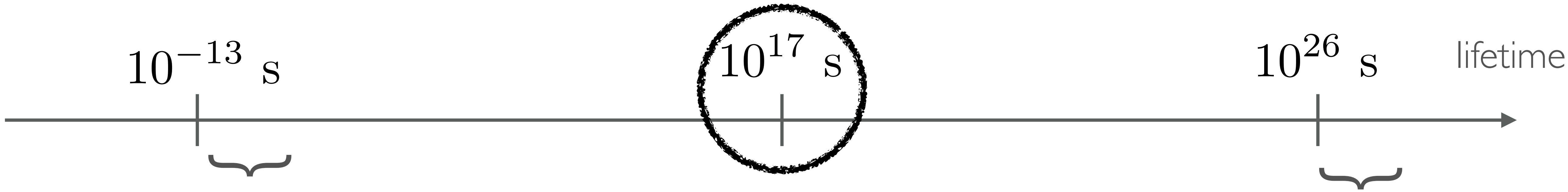
signals in the lab

(meta)-Stable Particles

$\tau \gtrsim 10^{26}$ s

DM; (in)direct detection, ADMX, etc.

LONG-LIVED PARTICLE



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Super-Long-Lived Particles: Decaying Dark Matter

$\tau \sim \tau_U \sim 10^{17}$ s

- Impact on small-scale structure O(10) kpc
- signal on the sky: e.g. gamma-ray

OUTLINE

1. Introduction
2. Late Decaying Dark Matter
3. ALPino to ALP
4. Conclusion

SMALL SCALE PROBLEMS?

- CDM works well at scale >100 kpc.
- Issues arise at scale O(10) kpc or smaller
  - missing satellite problem
  - too-big-to-fail problem
  - core-cusp problem
  - ... and more
- Baryon may solve the problem see Justin's talk
- Debate is not conclusive:

in this talk, these are motivation to consider an alternative non-CDM model.

POPULAR MODELS

- Warm Dark Matter: $m_{\rm WDM} \sim {\rm keV}$

  freestreaming of DM suppresses small scales.

- Fuzzy Dark Matter: $m_{\rm FDM} \sim 10^{-22}~{\rm eV}$

  Long de-Broglie wavelength of DM suppresses small scales.

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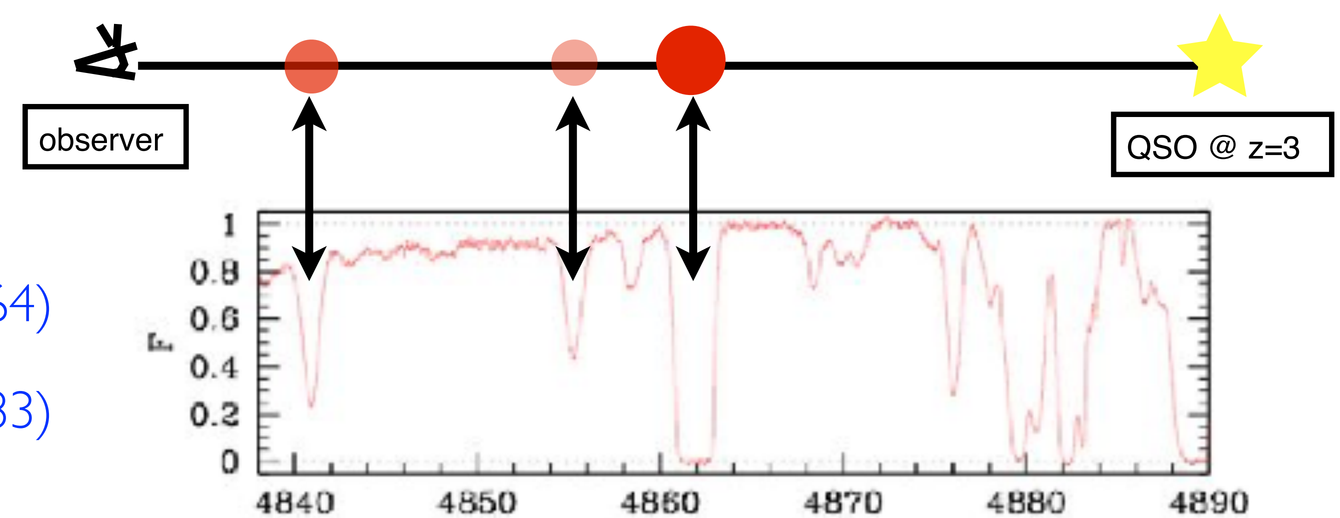
- Ly-alpha forest data constraints:



$m_{\rm WDM} > 5.3~{\rm keV}$ Iršič et al. (1702.01764)

$m_{\rm FDM} > 10^{-21}~{\rm eV}$ Iršič et al. (1703.04683)

Cartoon by A. Kamada

LATE DECAYING DM

Peter, 1001.3870

Ly-alpha forest data: at $z\sim3$

LATE DECAYING DM

Peter, 1001.3870

Ly-alpha forest data: at z~3

Simple-minded solution:

- → DM is CDM-like until z~3,
- → z<3, DM decay makes daughter DM get kick velocity ~ O(10) km/s: DM is WDM-like

LATE DECAYING DM

Peter, 1001.3870

Ly-alpha forest data: at z~3

Simple-minded solution:

- ➜ DM is CDM-like until z~3,
- ➜ z<3, DM decay makes daughter DM get kick velocity ~ O(10) km/s: DM is WDM-like

N-body Simulation (without baryons) says:

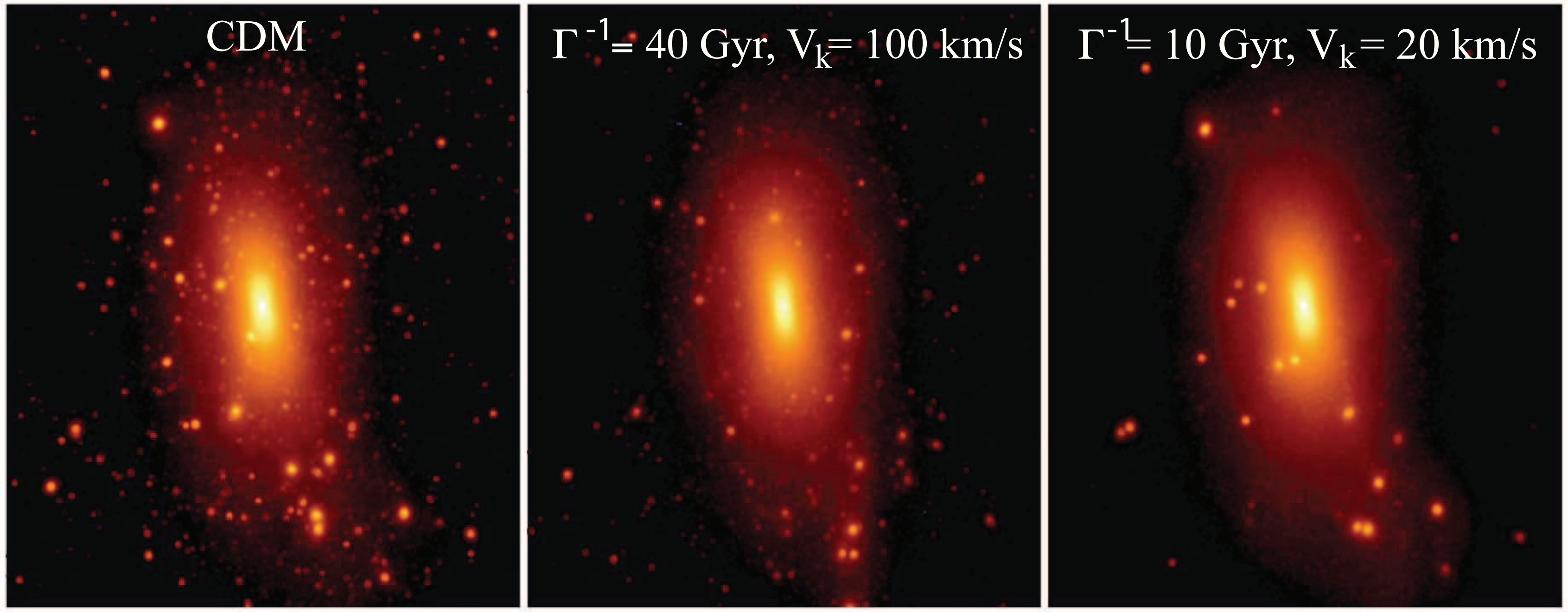
$$\tau_{\rm DDM} \sim 10 \text{ Gyr}$$
$$v_{\rm kick} = 20 - 40 \text{ km/s}$$

Wang et al., 1406.0527

solves the problems.

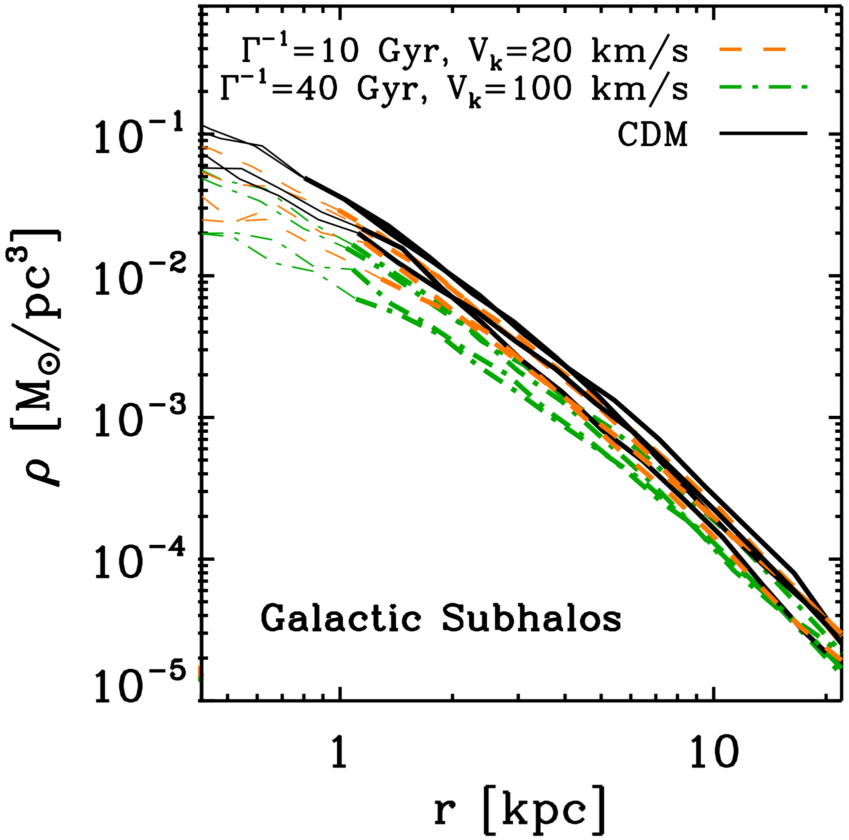
LATE DECAYING DM

- Solving missing satellite problem: reducing number of subhalos

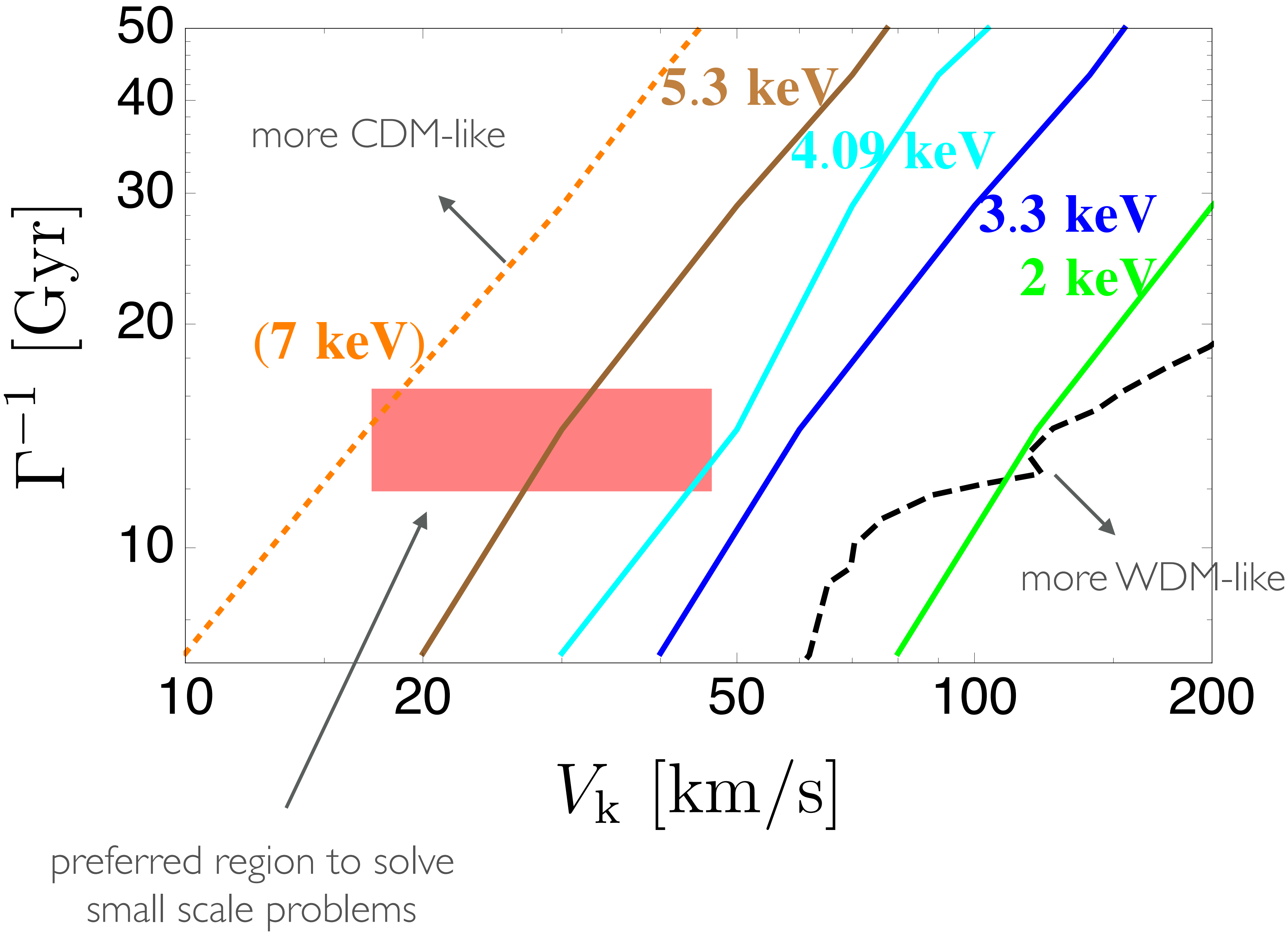


Wang et al., 1406.0527

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



DDM: LY-ALPHA FOREST



HOW TO PROBE?

- Lensing can do. see Neelima's talk
- We may need to perform simulation with baryons. see Justin's talk

Instead, we can ask

Q1: What particle physics provides DDM scenario?

Q2: What signal can we have?

DDM ⟶ DM + light particle

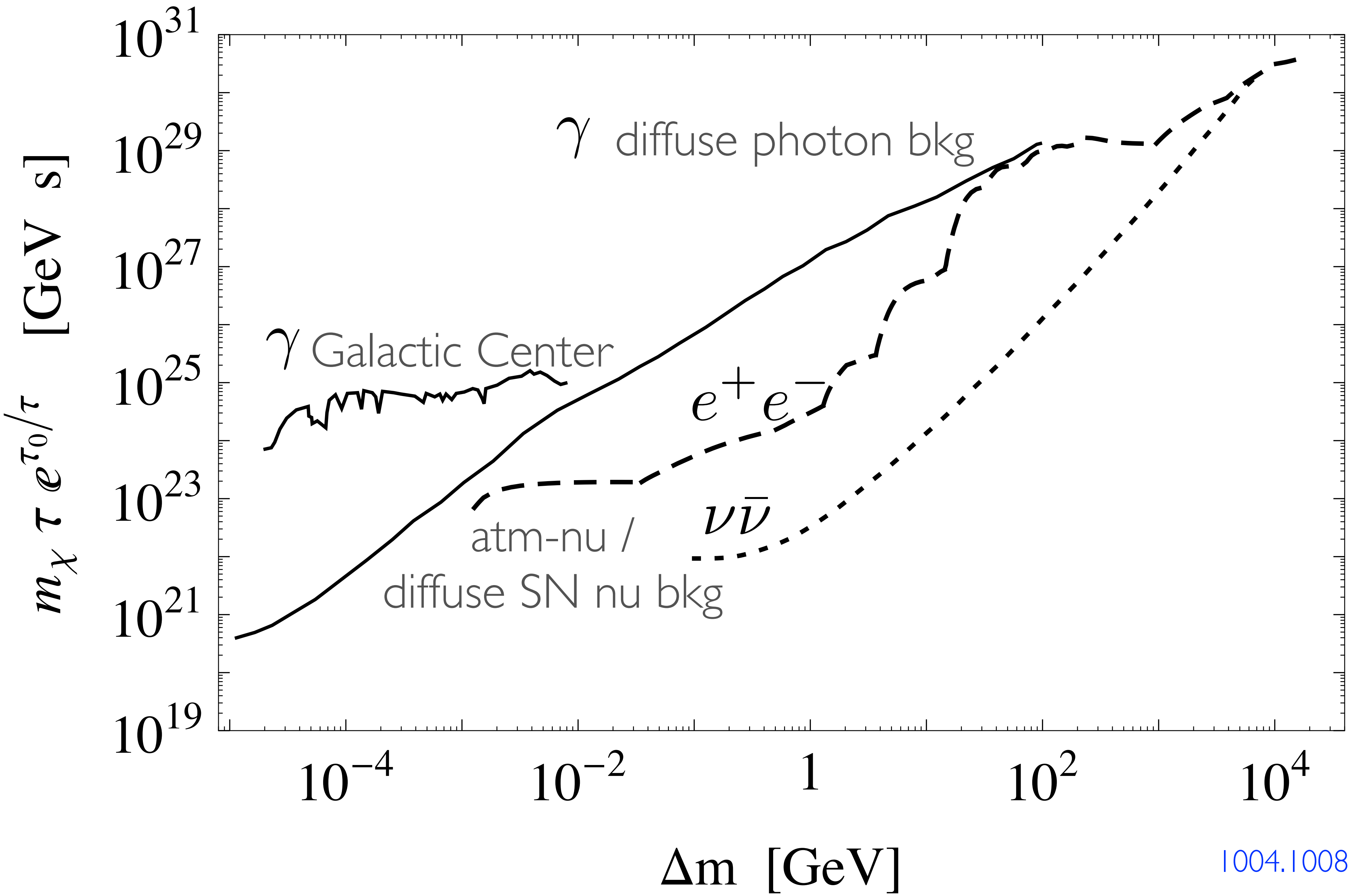
- Good to know

$$\begin{pmatrix} \tau_{\rm DDM} \\ v_{\rm kick} \sim \Delta m/m \end{pmatrix} \rightarrow \begin{pmatrix} \Phi_{\rm signal} \\ E_{\rm signal} \end{pmatrix}$$

LIGHT PARTICLE

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

Yuksel, Kistler 0711.2906
Bell, Galea, Petraki 1004.1008



1004.1008

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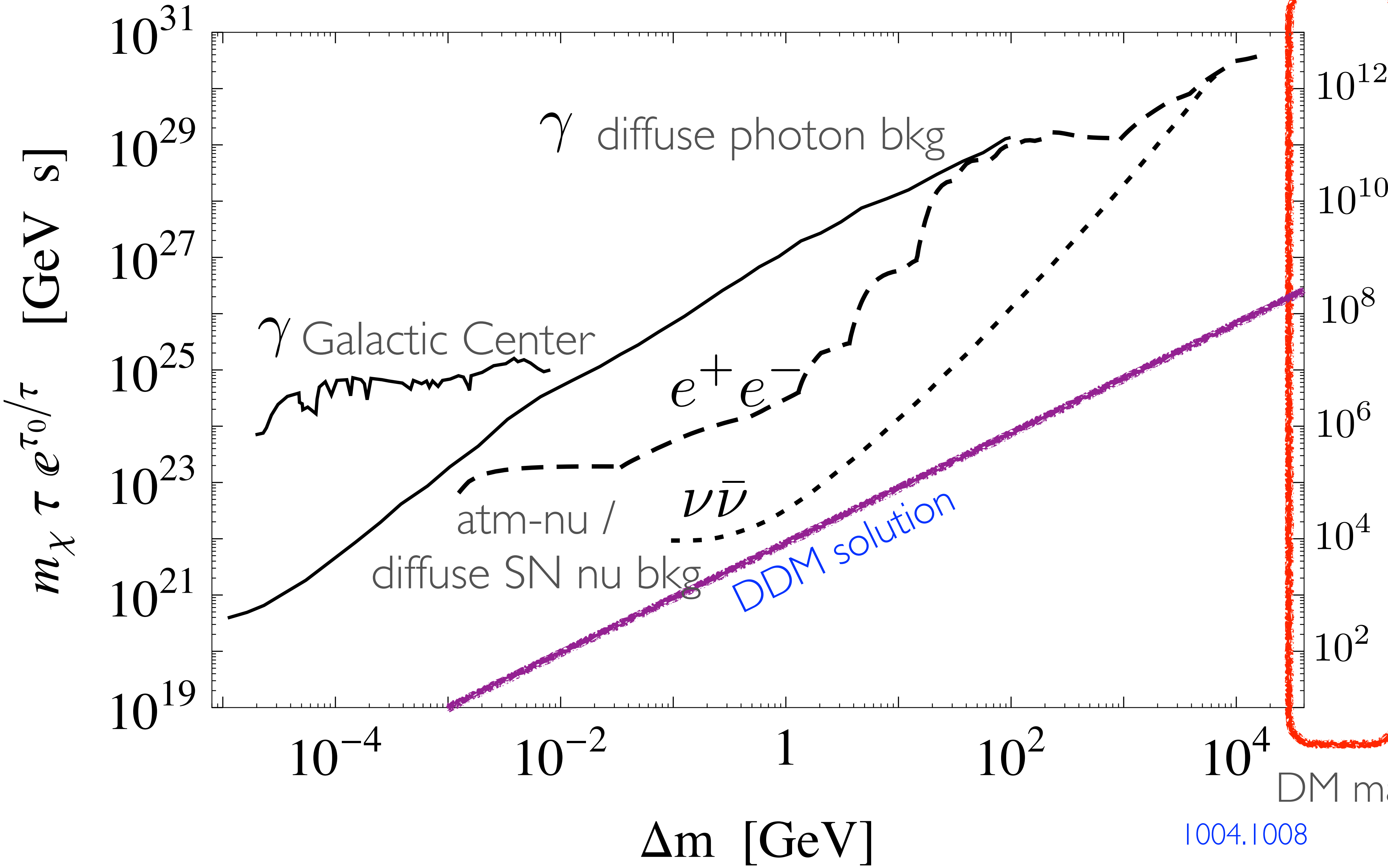


DM mass in GeV for $\tau = \tau_0$

1004.1008

Q: What is viable light particle?

AXION(-LIKE) PARTICLE

DDM ⟶ Stable DM + 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

AXINO(-LIKE) PARTICLE

DDM ⟶ Stable DM + Non-interacting light particle

ALPino (→ DDM), Gravitino (→ Stable DM), ALP (→ Non-interacting light particle)

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

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 ~$m_{3/2}$

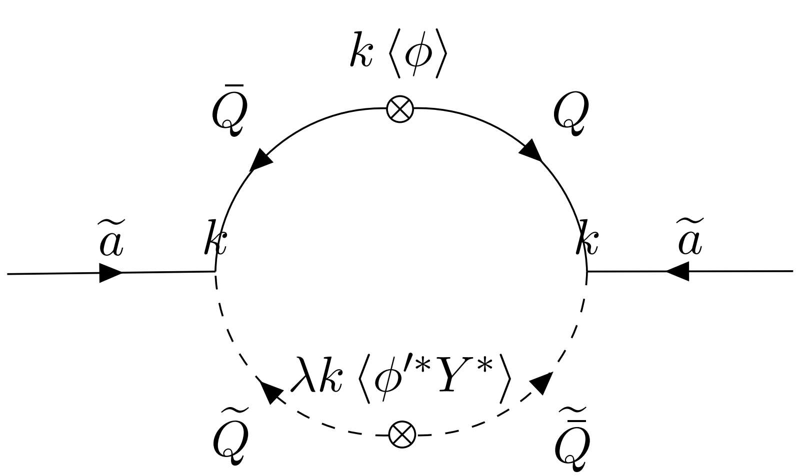
Goto, Yamaguchi; Chun, Kim, Nilles; Chun, Lukas

In a simple example,

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

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

- 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,

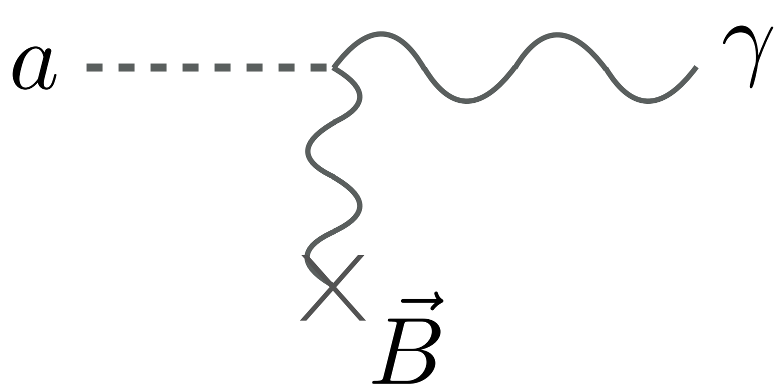
U(1)Y SU(N)h

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

↗ for ALPino production, ALP-photon conversion

↖ for ALP mass generation

$$\rightarrow \quad \mathcal{L}_{\rm eff} \;\supset\; g_{a\gamma}\, a\, F_{\mu\nu} \widetilde{F}^{\mu\nu} \qquad\qquad m_a \;\sim\; \Lambda_{\rm h}^2/f$$



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

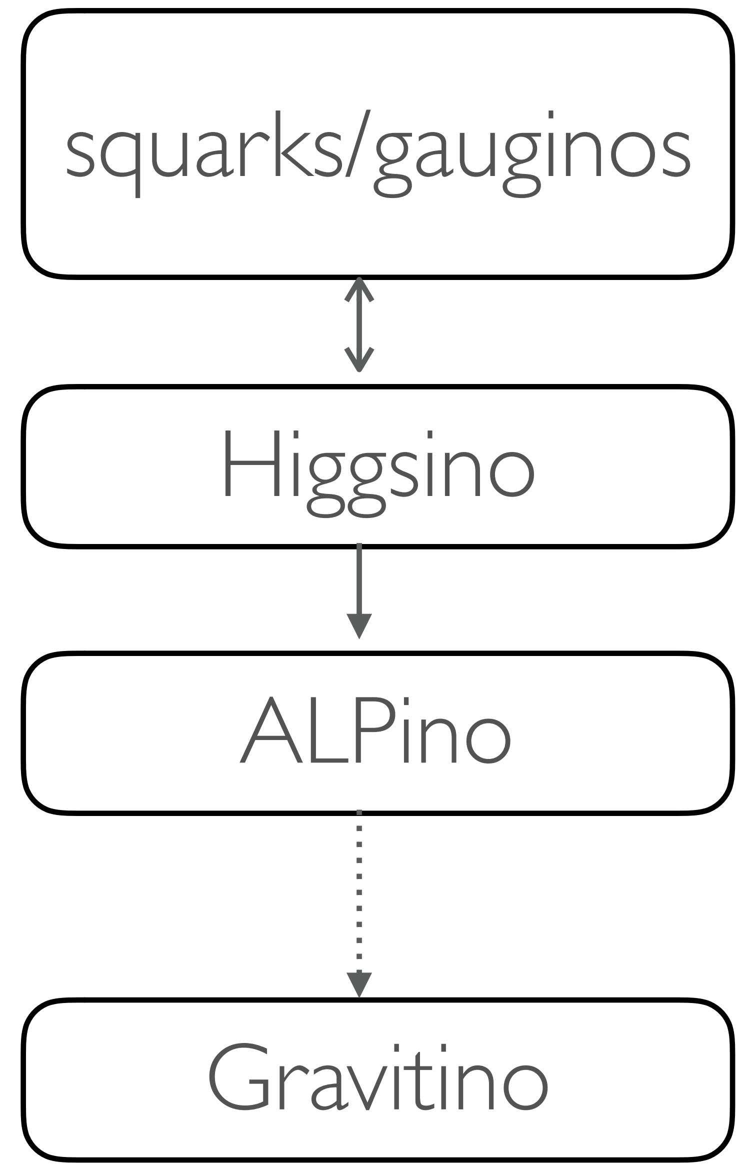
Freeze-out of Lightest
MSSM particle, e.g. higgsino

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

→ Decay to ALPino

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

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



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

Signal of ALPino decay

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 →

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

$$\Delta_e \approx -\frac{\omega_{\rm p}^2}{2E_\gamma}\,,\quad \omega_{\rm p}^2 = \frac{4\pi\alpha_{\rm em} n_e}{m_e}\,,$$
$$\Delta_a = -\frac{m_a^2}{2E_\gamma}\,,\quad \Delta_{\rm B} = \frac{g_{a\gamma}B_{\rm T}}{2}\,,$$

Conv. Prob. (for homogeneous magnetic field)

→

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

* QCD axion

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

Photon flux

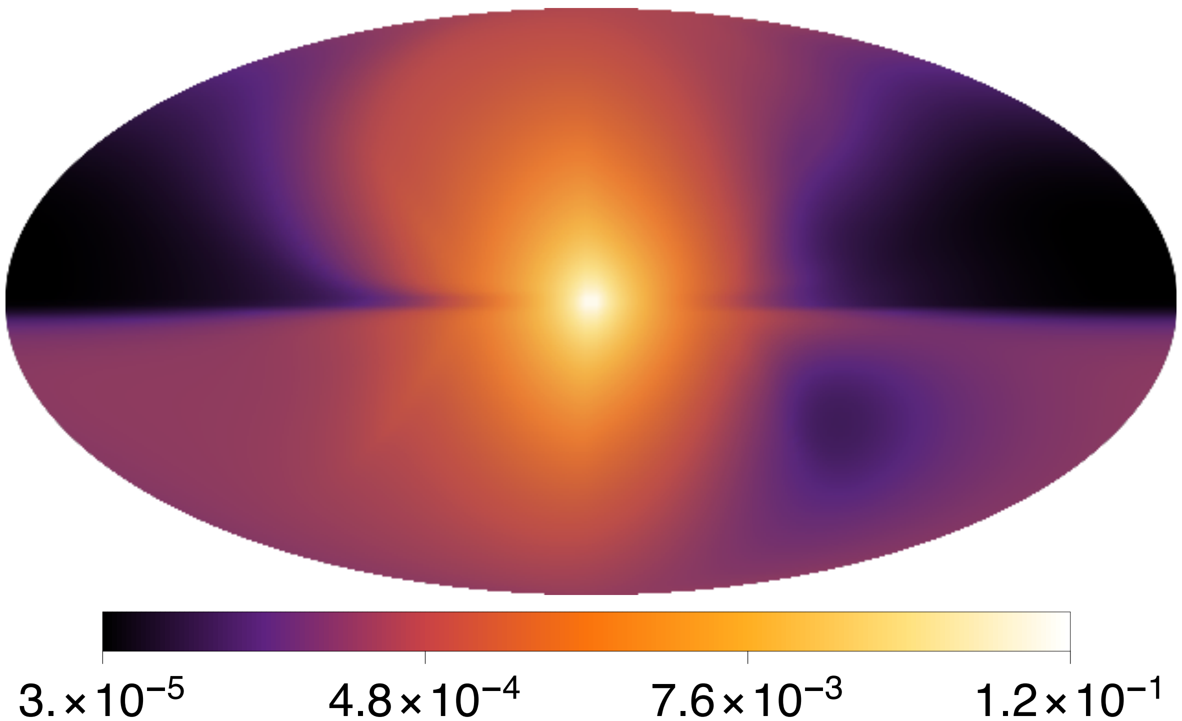
$$E_\gamma^2\frac{d^2\Phi_\gamma^a}{dE_\gamma d\Omega} \simeq 6\times 10^3\, J_{\rm D,ROI}\, e^{-\Gamma_{\tilde a}T_0}\,{\rm MeV/cm^2/s/sr} \times\left(\frac{E_\gamma}{47\,{\rm GeV}}\right)^2\left(\frac{700\,{\rm TeV}}{m_{\tilde a}}\right)\left(\frac{\Gamma_{\tilde a}}{10\,{\rm Gyr}}\right) \times\left(\frac{1\,{\rm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

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

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

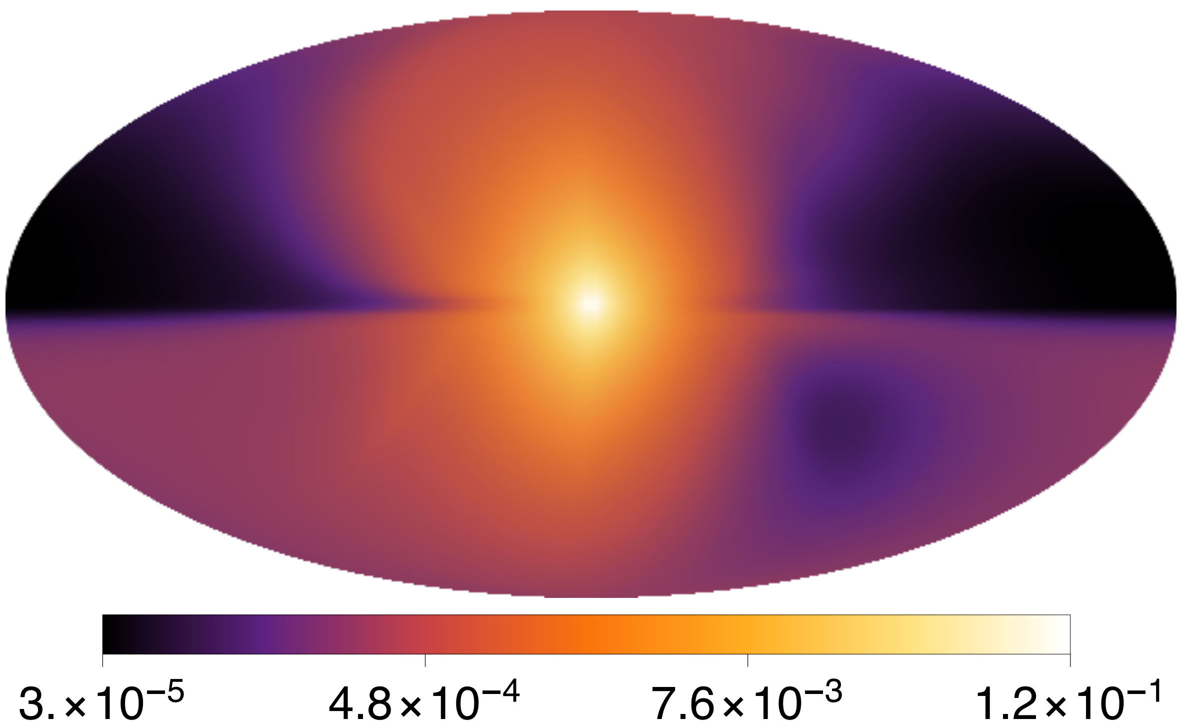
$E_\gamma = 47\,\mathrm{GeV}$ $g_{a\gamma} = 10^{-13}\,\mathrm{GeV}^{-1}$

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

Magnetic field profile from Jansson & Farrar,

Astrophys. J., vol. 757, p. 14, 2012

SIGNAL MORPHOLOGY



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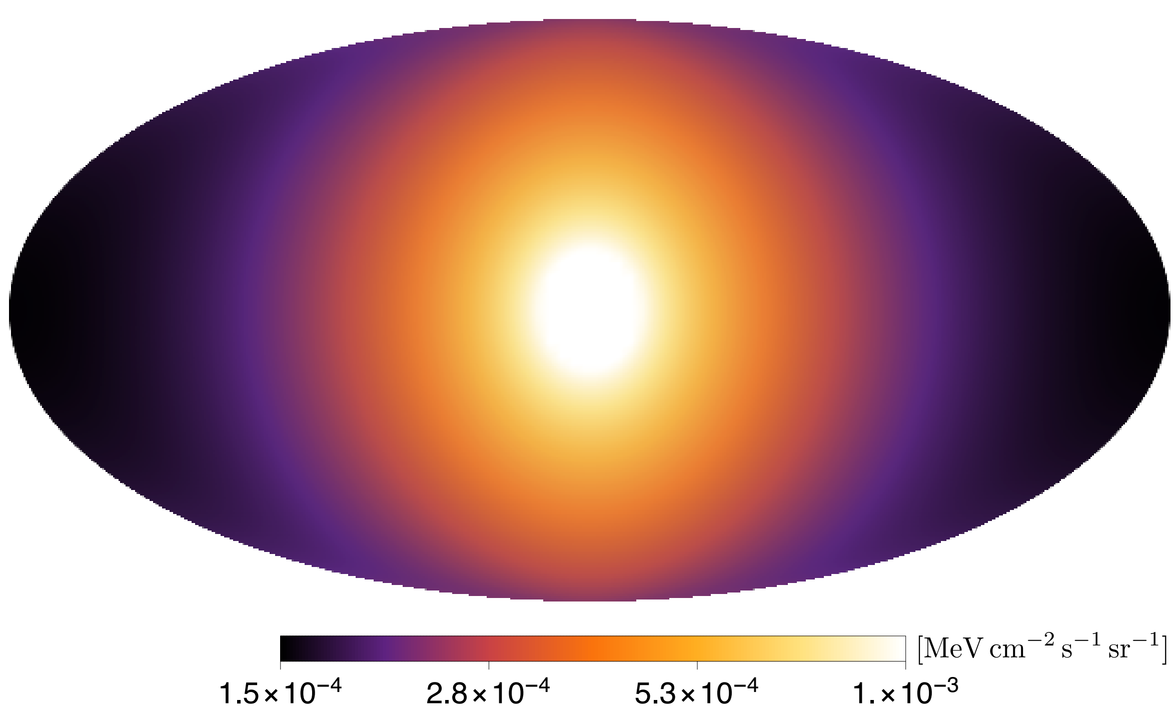

Meta-stable DM decay to diphoton

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

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

CONCLUSION

- Cold dark matter (CDM) is successful to explain current universe.
- Shortcomings arise at small scale structure, <O(100) kpc.
- *Decaying dark matter* (tau~10 Gyr, V_k~30 km/s) is a good & interesting alternative.
- Axino-like particle ⟶ Axion-like particle + Gravitino provide a good decaying dark matter scenario.
- ALP-photon conversion produces distinct signal; morphology, energy scale.
- Gravitational probes are also important in future research.