Exploring super-heavy ALP in cosmology via multi-messenger observations

Yuma Narita
Tohoku Univ, TMU

Axion in Stockholm 2025 (week 3)

NORDITA, Stockholm

10th, July, 2025

TOKYO METROPOLITAN UNIVERSITY

TOHOKU UNIVERSITY

GPPU
GRADUATE PROGRAM ON PHYSICS FOR THE UNIVERSE

Based on arXiv: 2504.15272 in collaboration with Kohta Murase and Wen Yin.

What is multi-messenger astronomy?

Multi-messenger astronomy combines signals from nuclei, neutrinos, and photons.

- Each messenger probes different aspects.
- This process is analogous to a particle physics reaction.
- The source generates extremely high center-of-mass energies.

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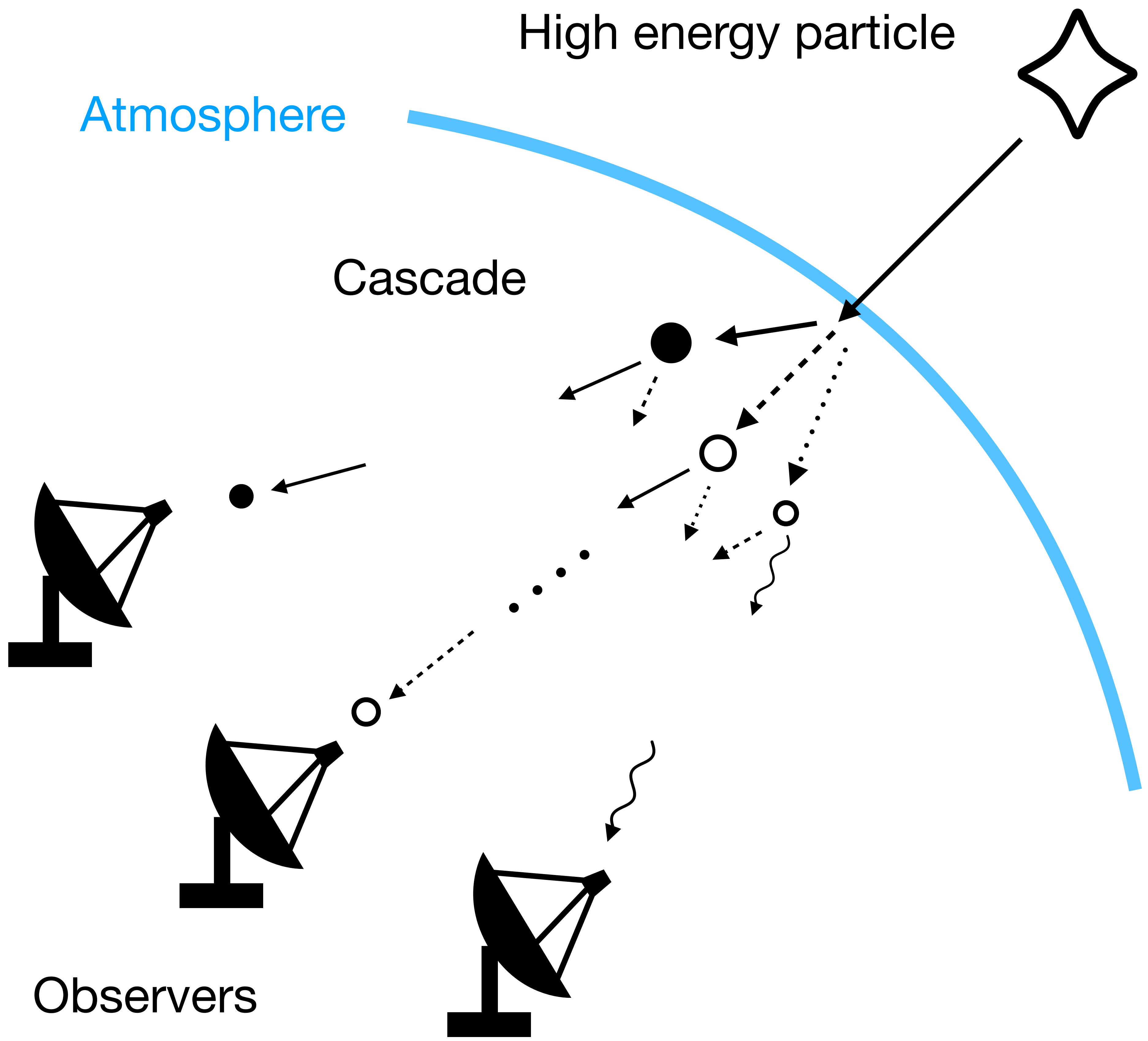
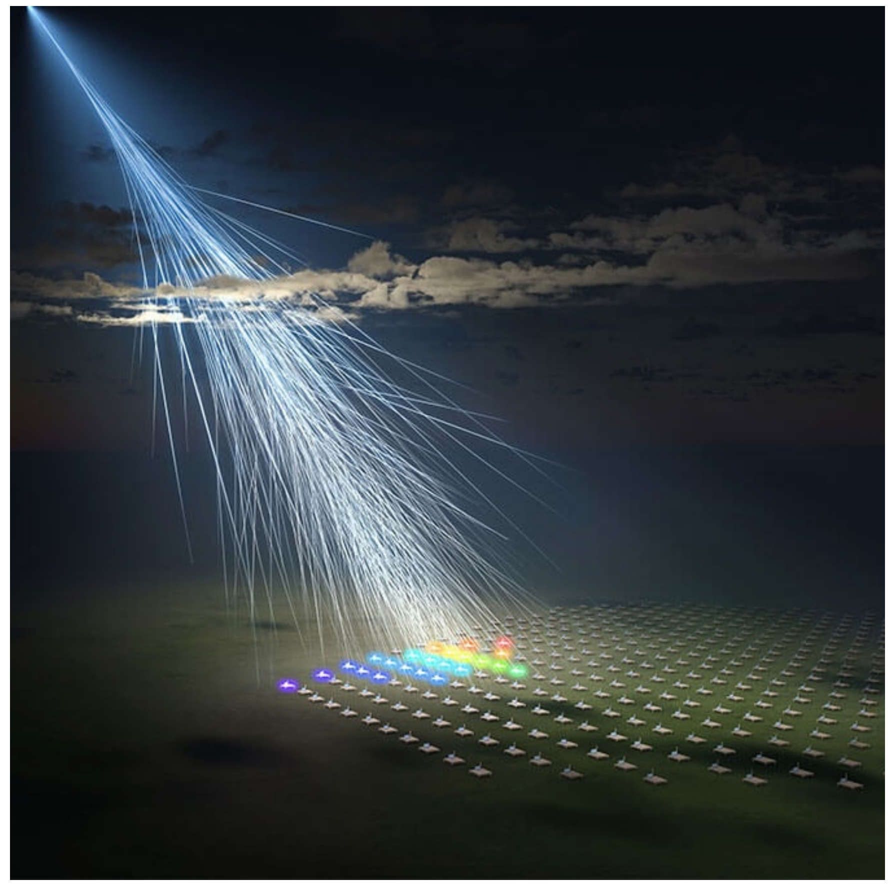
Multi-messenger observations may reveal new physics.



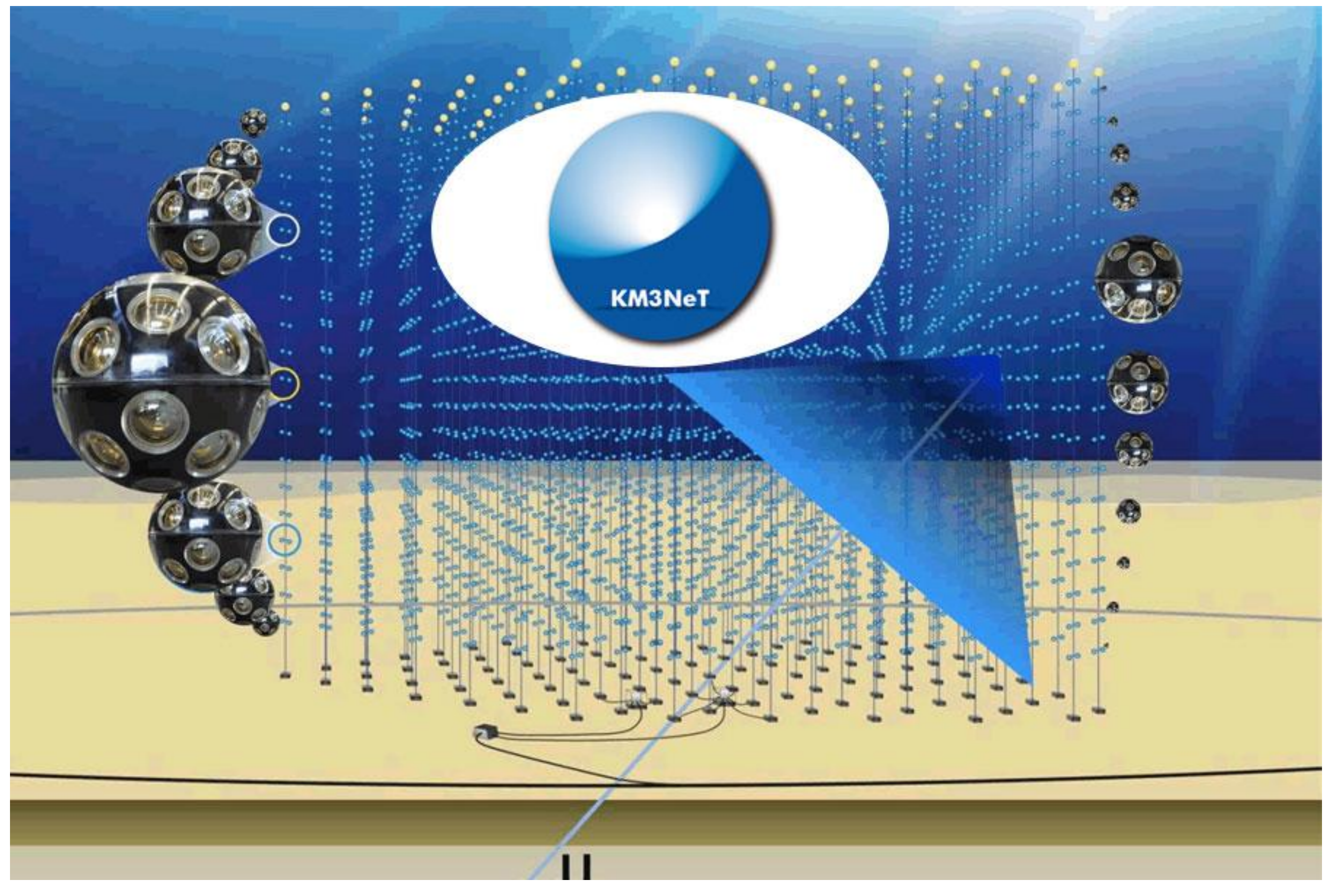
Observations and high-energy events

Various detectors are designed to observe specific cosmic messengers.

- γ-rays → KASCADE, Pierre Auger, etc.
- Neutrinos → IceCube, KM3NeT, etc.
- nuclei → Pierre Auger, Telescope Array (TA), etc.



There exist ultra-high-energy events that challenge standard astrophysical explanations.



- **The AMATERASU particle** : $10^{20}\,\mathrm{eV}$ ultrahigh-energy cosmic ray (UHECR) reported by TA.

Telescope Array Collaboration

- **KM3-230213A** : a $220\,\mathrm{PeV}$ neutrino event observed by KM3NeT.

The KM3NeT Collaboration

https://www.km3net.org/

Super-heavy dark matter

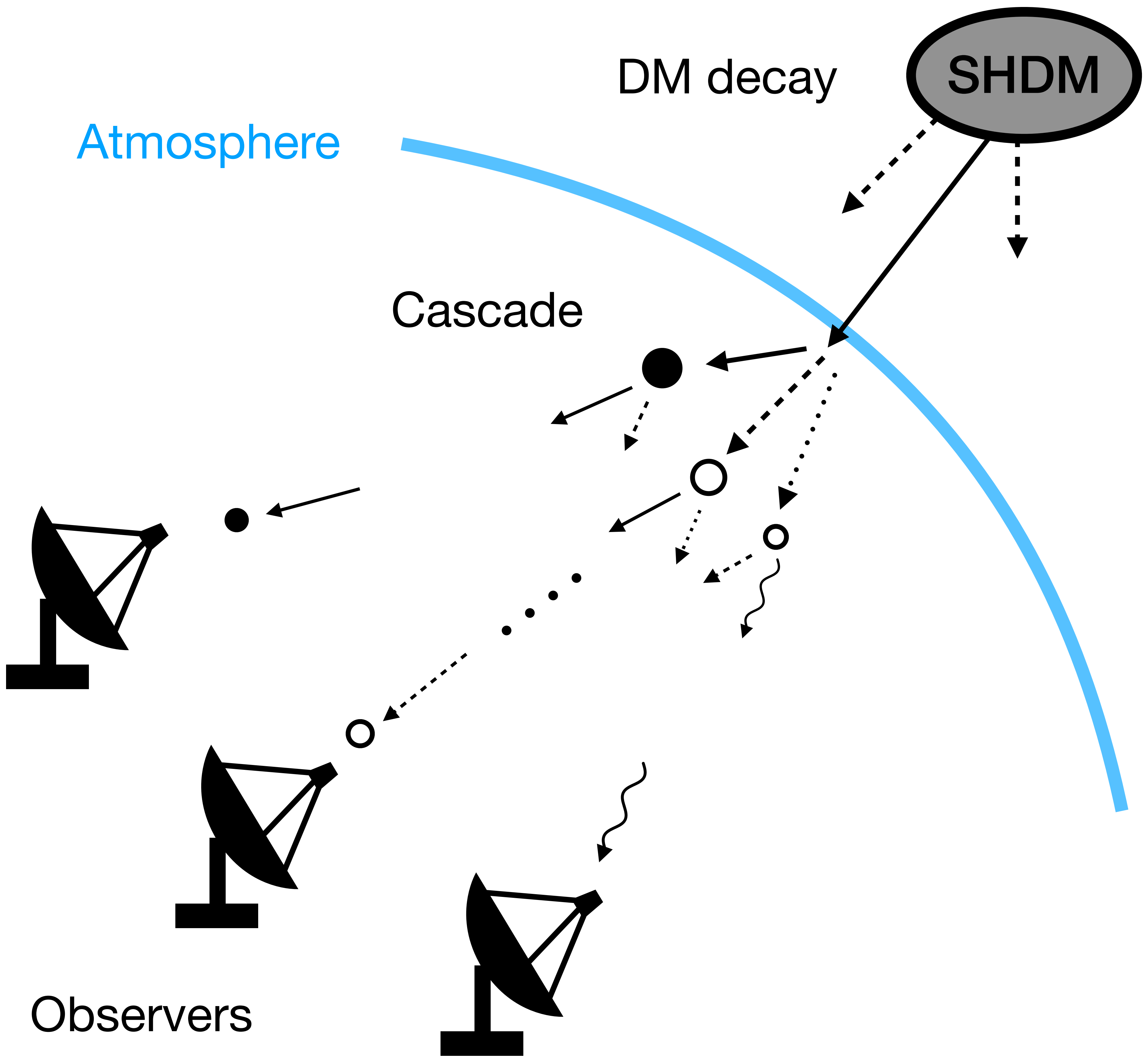
Greene, Prokopec, et al. 1997; Chung, Kolb, et al. 1998, 2000; Chung, Crotty, et al. 2001; Chung, 2003; Kolb, Starobinsky, et al. 2007

These high energy events give new motivations for exploring super-heavy dark matter (SHDM) decay.

This is because Astrophysical scenarios fail to account for these events.

To source UHECRs, DM has to be super-heavy massive $\sim \underbrace{10^{9\text{-}13}\,\mathrm{GeV}}$.

It is comparable to the typical inflaton mass.



What we did

Murase, YN, Wen 2025

- We propose a scenario where ALP DM plays the role of the inflaton in natural inflation.
- There exists a parameter region consistent with both CMB data and the DM relic abundance.
- We compute DM decays into 3-body channels, producing cosmic rays.
- Such decays can partially account for extreme-energy events, including AMATERASU particles and KM3-230213A.

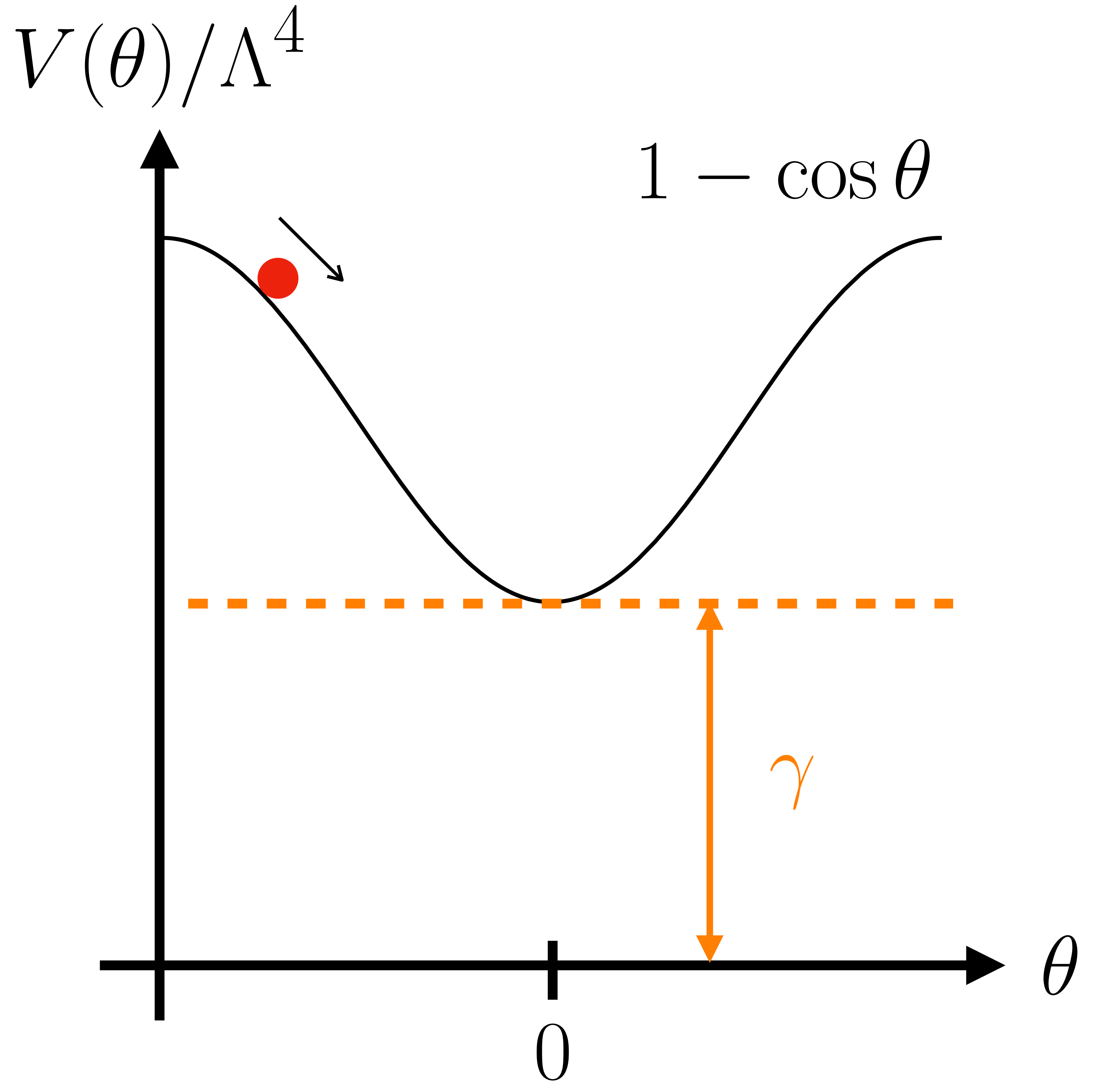
Outline

1. Introduction
2. Inflationary dynamics and DM abundance
3. Phenomenology of decaying ALP DM
4. Summary

Inflaton potential

To save the natural inflation, let us introduce a constant term during inflation,

$$V(\theta) = \Lambda^4 (\gamma + 1 - \cos\theta) \quad \left(\theta \equiv \frac{\phi}{f_\phi}\right).$$



An additional scalar field Ψ that generates vacuum energy during inflation and removes it afterward.

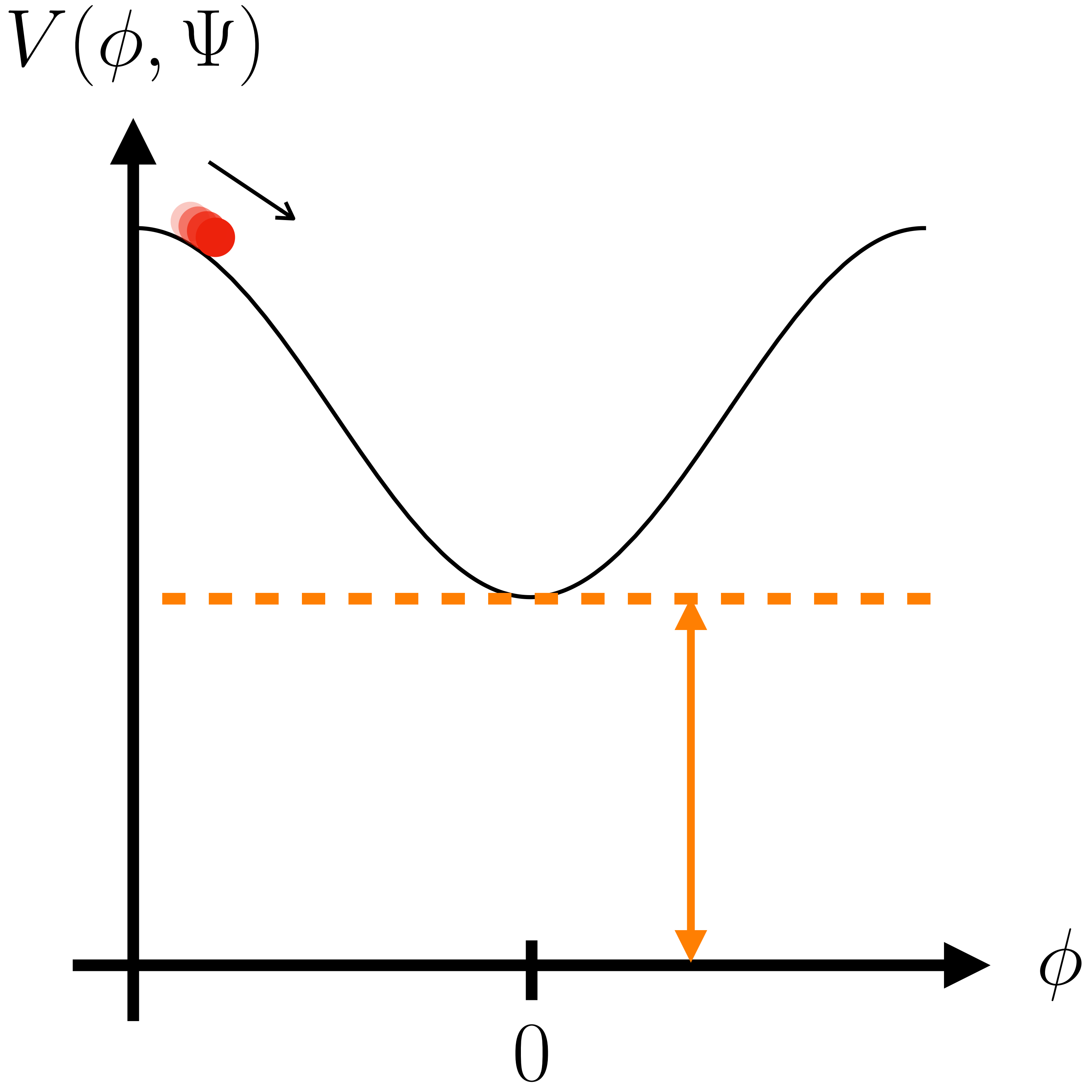
Such a setup is realized in scenarios like

- Double inflation scenario, Bedroya, Vafa 2020; Berera, Calderon 2019; Sasaki, Suyama et al. 2018;
- Hybrid inflation scenario. → I will mainly discuss in this talk.

Dynamics during inflation

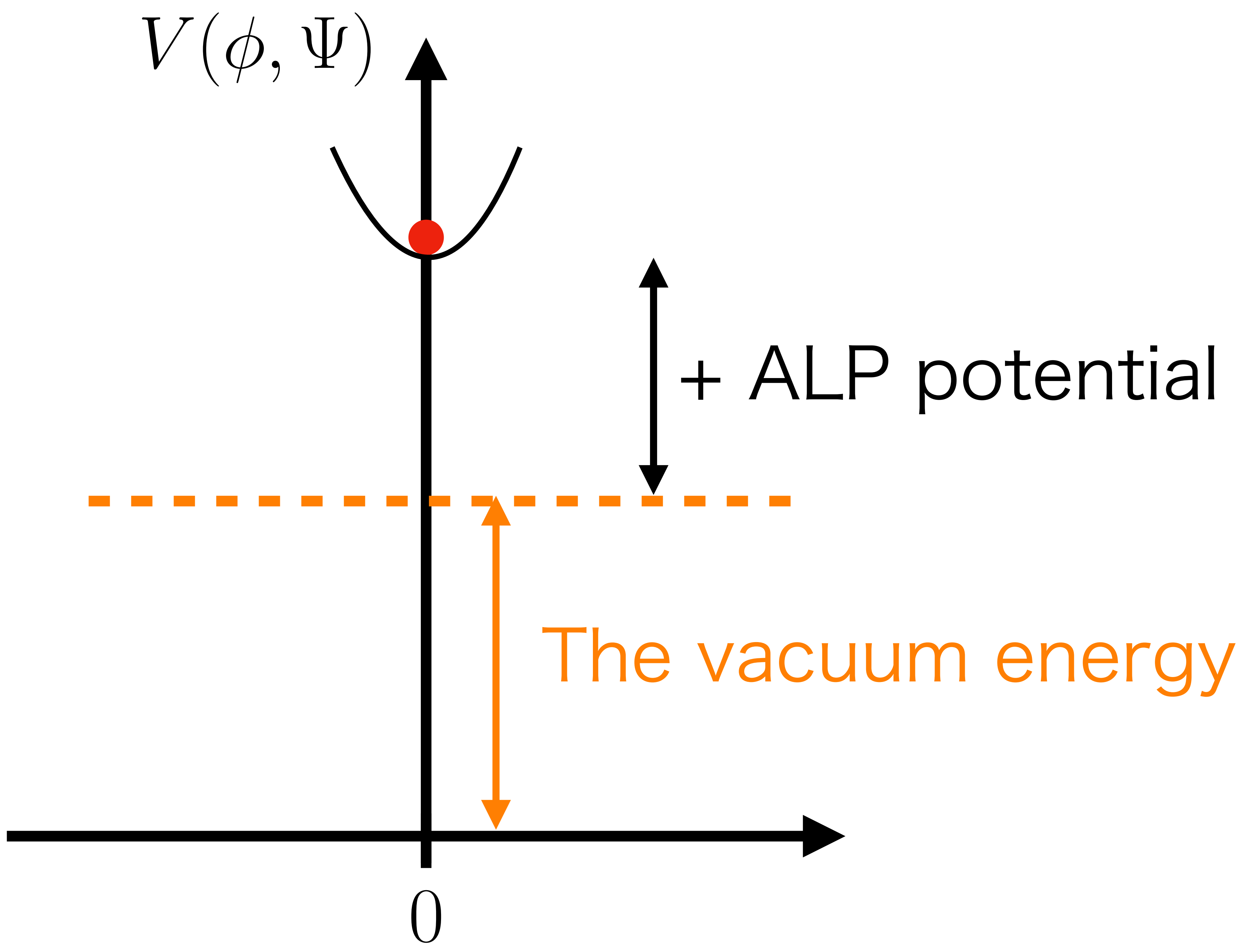
The ALP field ϕ

- slowly rolls.
- generates primordial density fluctuations.



An additional scalar field Ψ

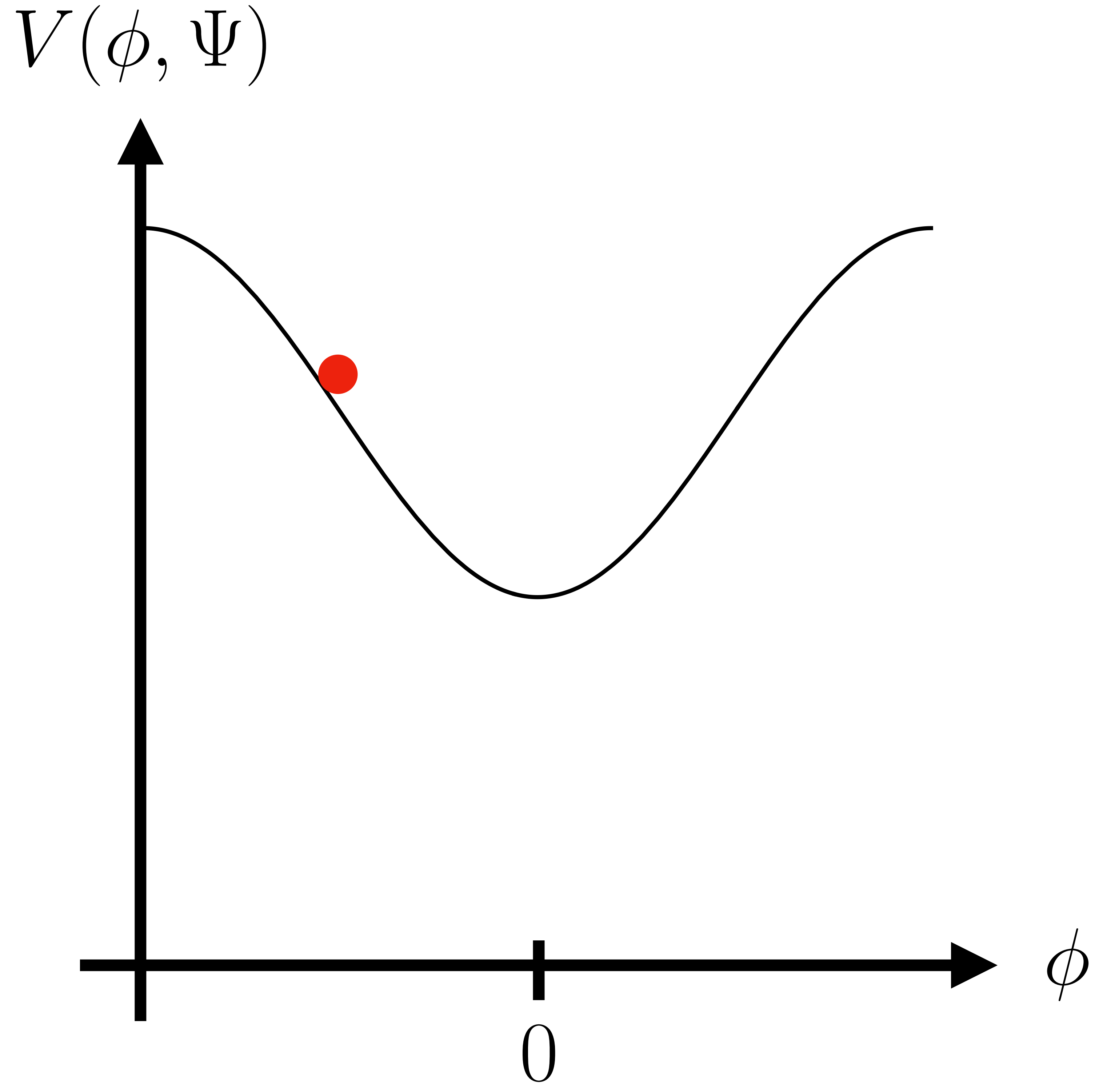
- is integrated out.
- plays a roll of a temporally "dark energy".



Dynamics during inflation

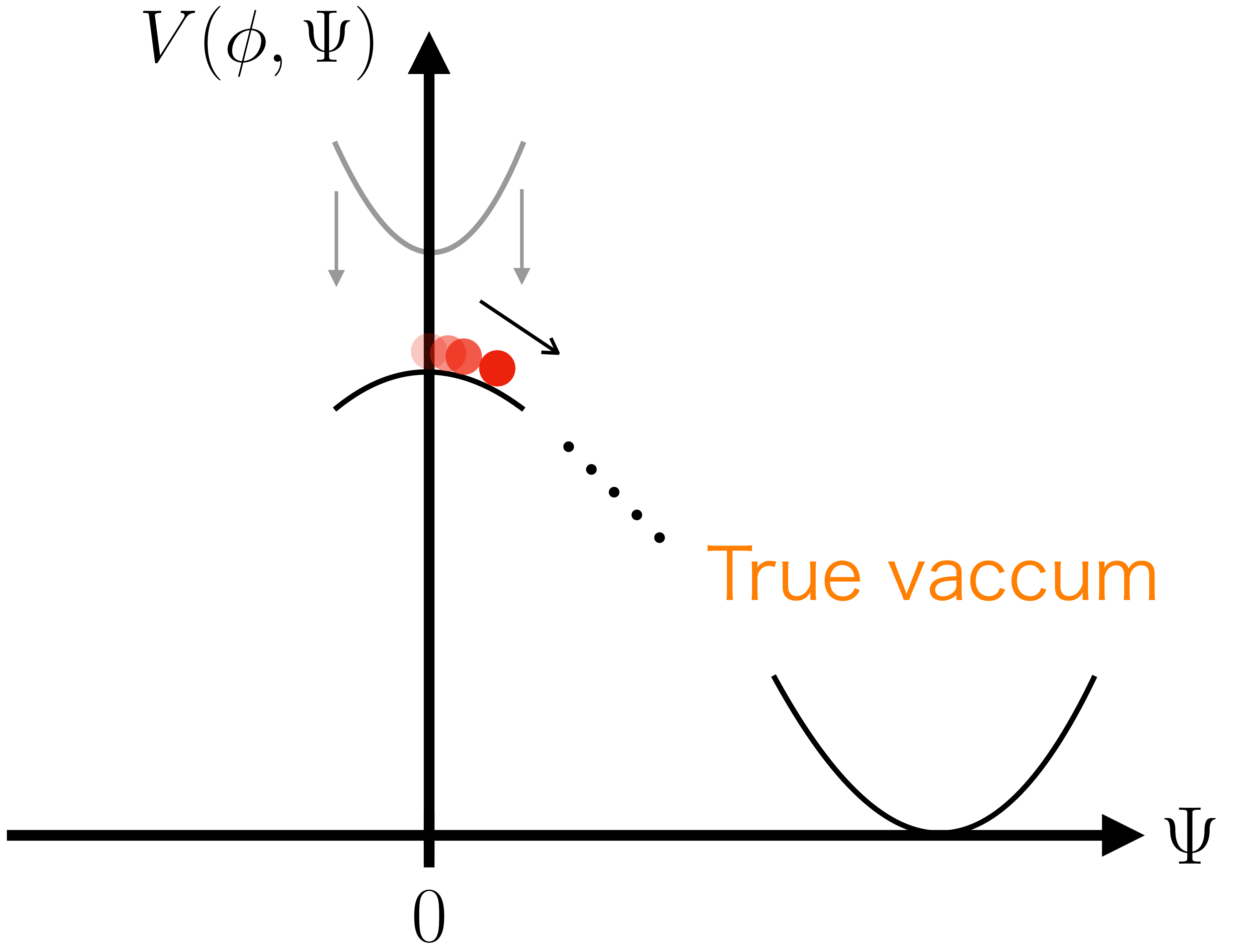
The ALP field ϕ

- slowly rolls, but its slope becomes negligible.



An additional scalar field Ψ

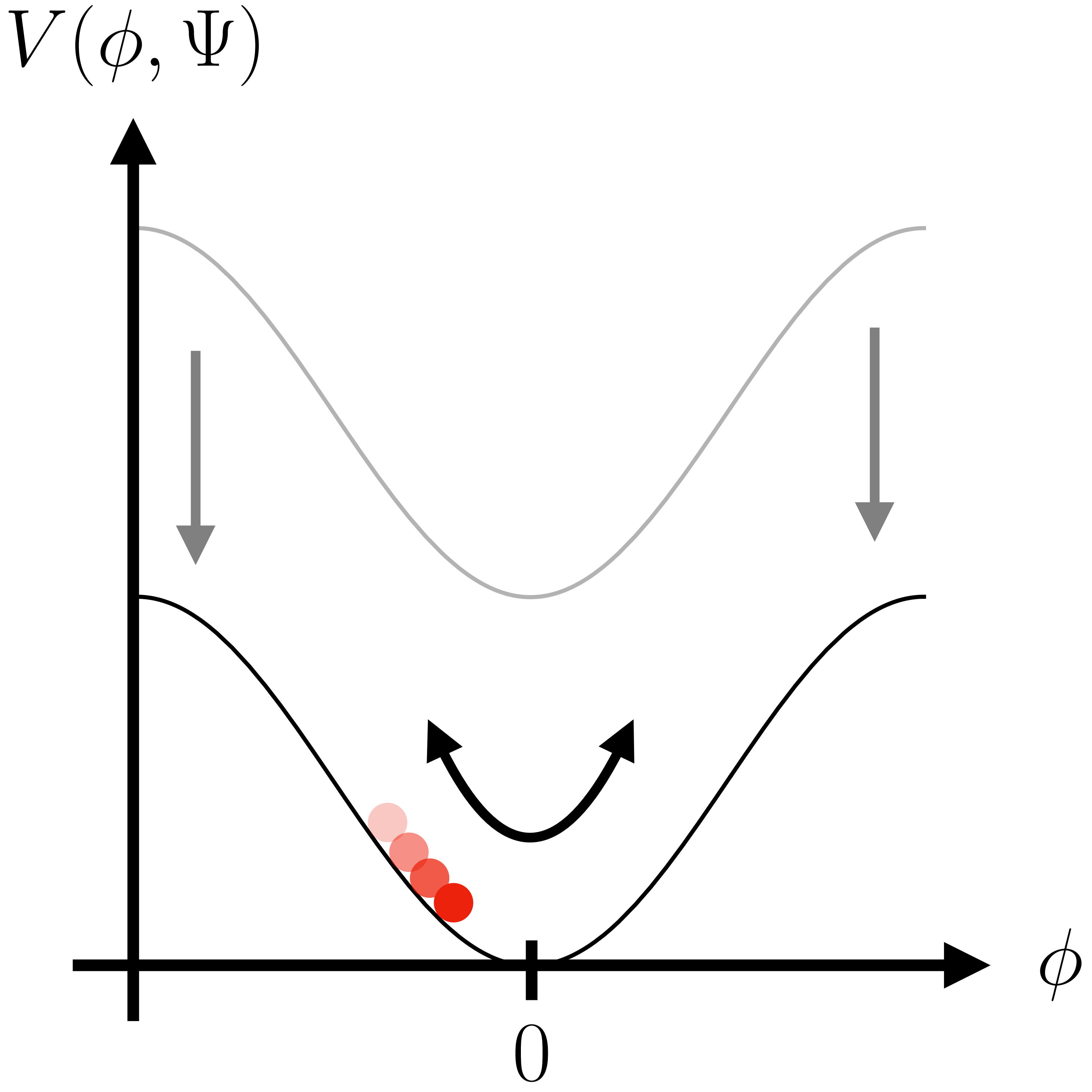
- starts to roll through the mixing.
- drives the inflation instead of ϕ.



Dynamics after inflation

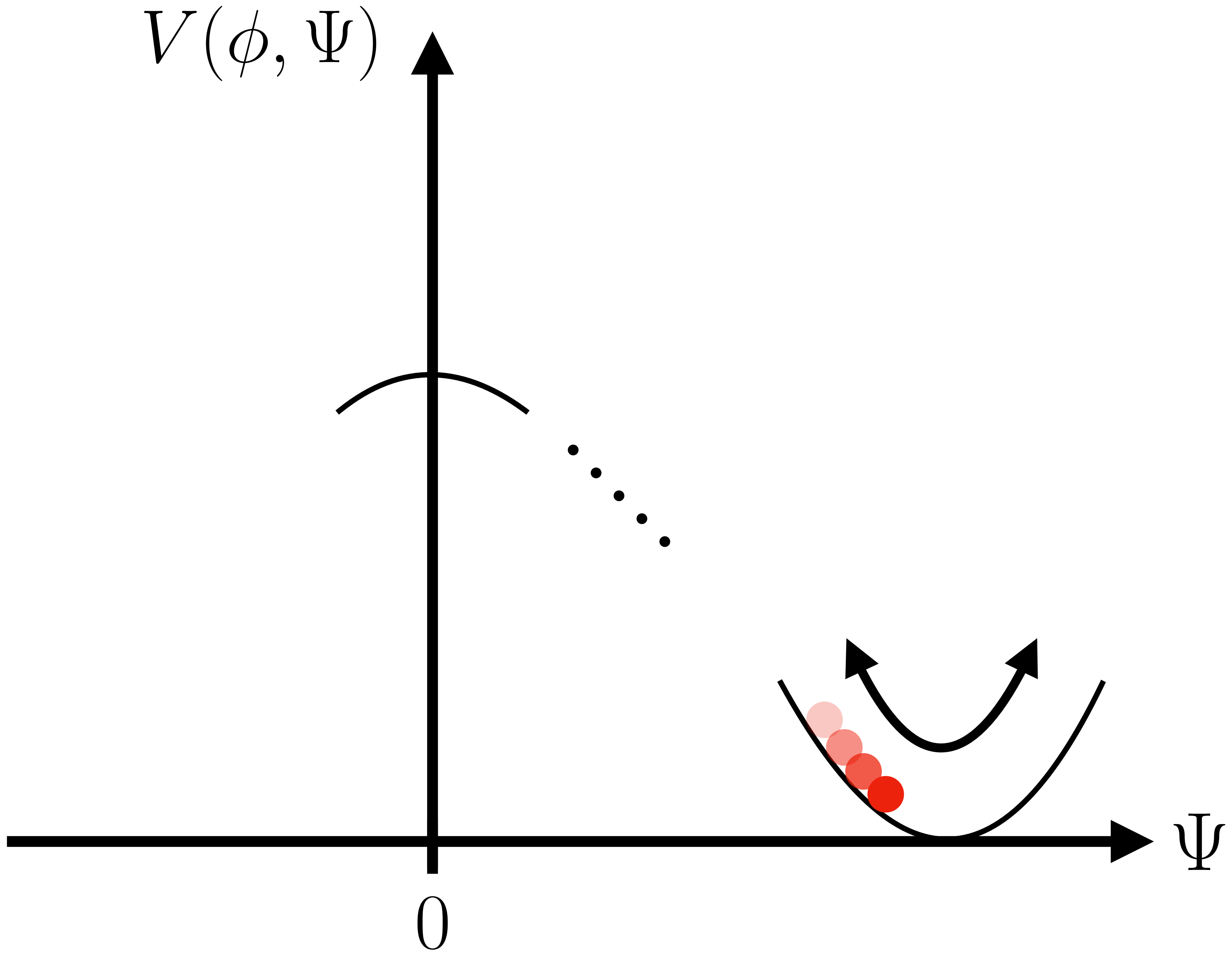
The ALP field ϕ

- behaves as matter.
- remains as SHDM.



An additional scalar field Ψ

- rolls down toward the true vacuum.
- induces reheating.



Determining θ_* from the spectral index

We consider the field value at the end of inflation to be a free parameter.

<u>Observed spectral index</u>

$$n_{s,\mathrm{obs}} = 0.9647 \pm 0.0043$$

Planck 2018 collaboration

Single field slow-roll inflation predicts

$$n_{s,\mathrm{obs}} = 1 + 2\eta(\theta_*) - 6\epsilon(\theta_*). \quad \rightarrow \quad \cos\theta_* \simeq \underbrace{\frac{1}{2}\gamma\frac{f_\phi^2}{M_{\mathrm{pl}}^2}}_{c}(n_{s,\mathrm{obs}} - 1).$$

We can get the field value at the CMB horizon exit.

If

$$① \boxed{c \gtrsim \frac{2}{1 - n_{s,\mathrm{obs}}} \sim 57},$$

the potential fails to match the CMB observations.

<u>The potential during inflation</u>

$$V(\theta) = \Lambda^4(\gamma + 1 - \cos\theta)$$

Other constraints

We predict the value of r where the CMB scale exits the horizon as

$$r \simeq \frac{8}{c\gamma}\left[1 - \frac{c^2}{4}\left(1 - n_{s,\mathrm{obs}}\right)^2\right].$$

Upper limit of tensor-to-scalar ratio

$$r < 0.036 \text{ at } 95\% \text{ confidence}$$

Excluded → ② $c \lesssim 15\frac{f_\phi}{M_{\mathrm{pl}}}$

CMB-S4; LiteBIRD

The future reach is $r = 0.001$.

It is roughly given by $c \sim 89 f_\phi / M_{\mathrm{pl}}$.

We also get the running spectral index at $\theta = \theta_*$,

$$\alpha_s \simeq \frac{2}{c^2} - \frac{(1 - n_{s,\mathrm{obs}})^2}{2}.$$

Observed running of spectral index

$$\alpha_s = -0.0045 \pm 0.0067$$

We do not allow the running beyond the 2σ uncertainty.

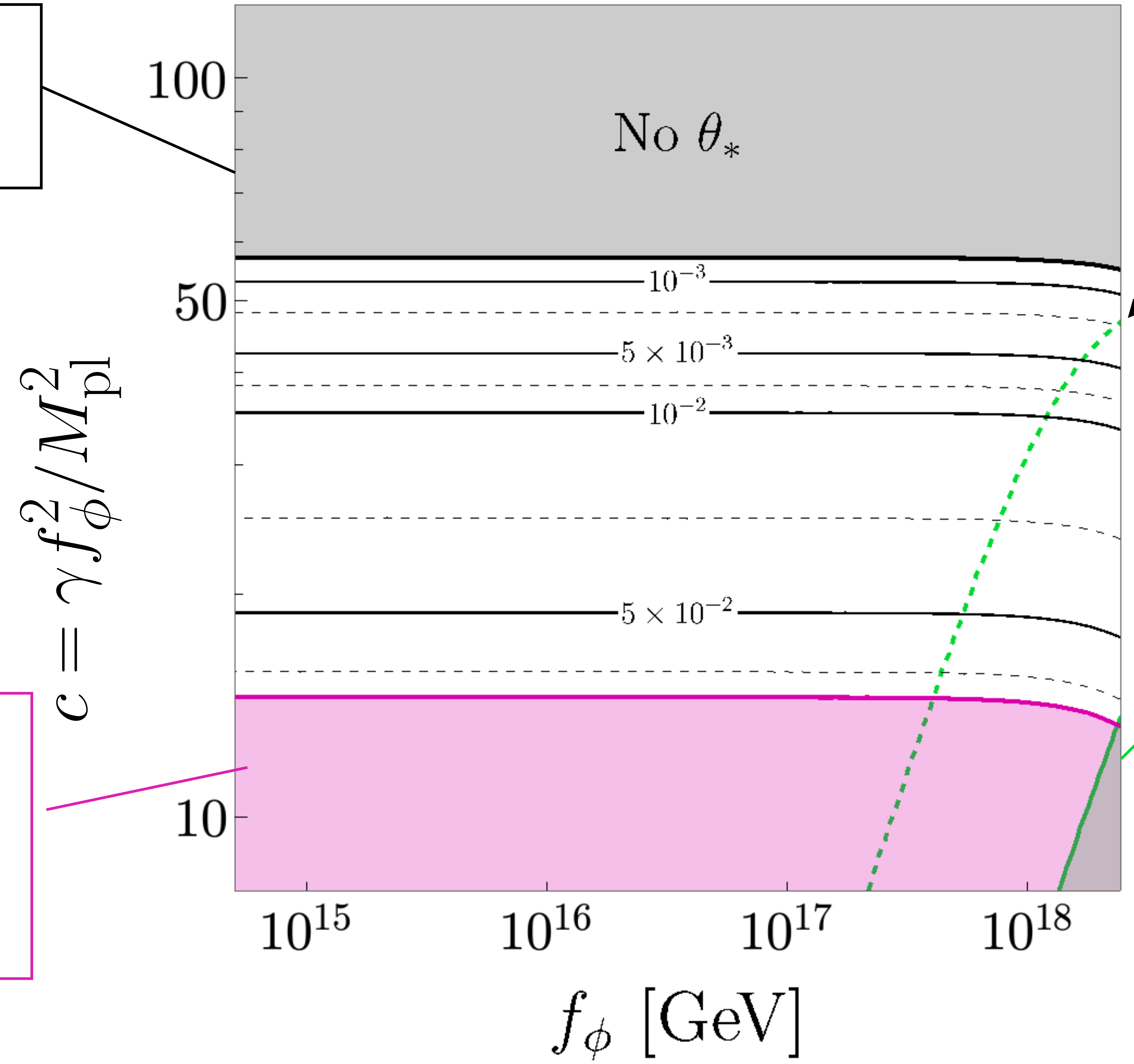
It provides the strong restriction,

③ $c \lesssim 14.$

Viable region for the inflation model

① Constraint from spectral index

$c \gtrsim 57$



future reach line for $r = 0.001$

$(c \sim 89 f_\phi / M_{\rm pl})$

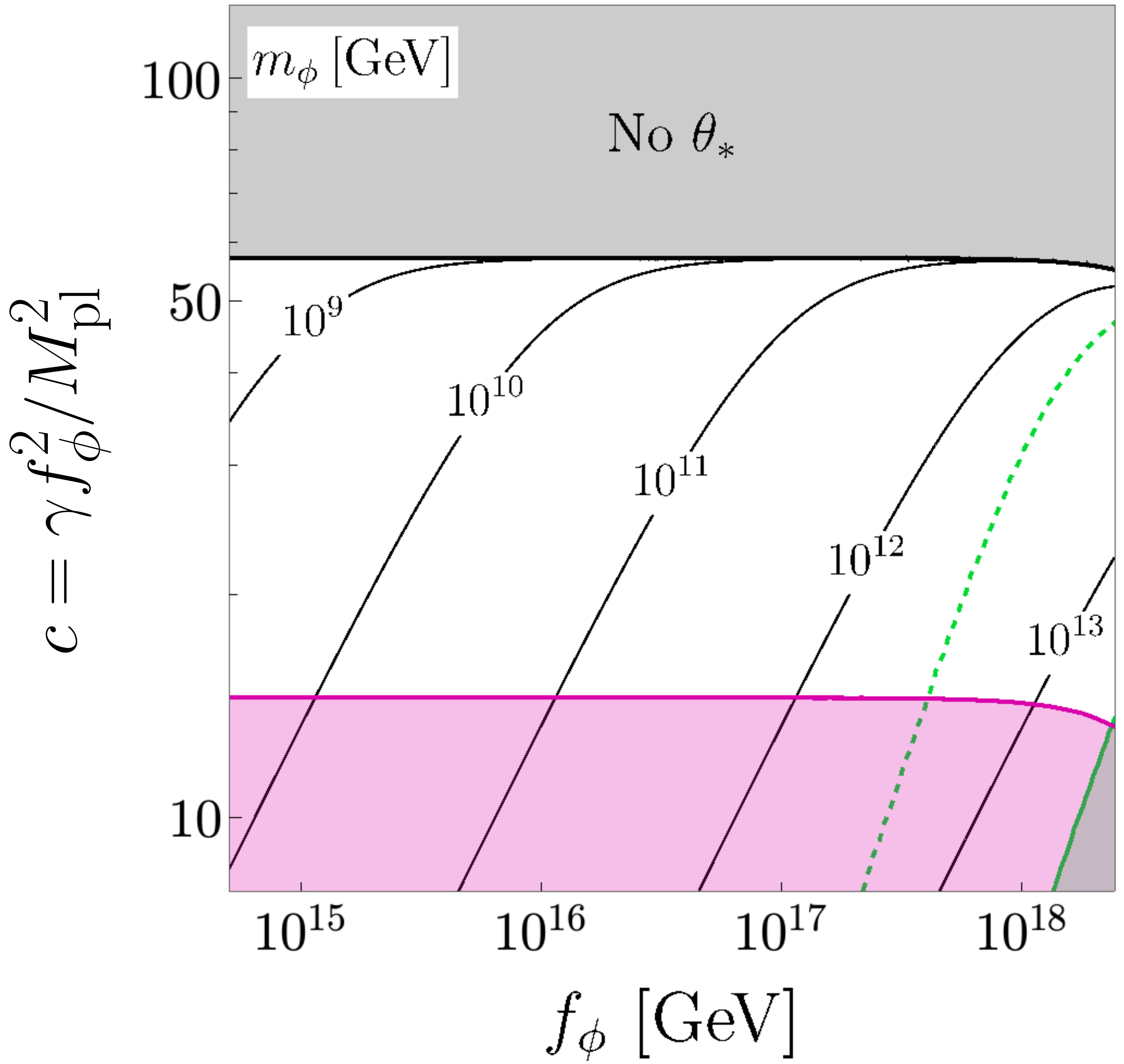
② Constraint from tensor-to-scalar ratio

$$c \lesssim 15 \frac{f_\phi}{M_{\rm pl}}$$

③ Constraint from running spectral index

$c \lesssim 14$

ALP DM mass



ϕ can be DM to oscillate after inflation.

The mass of ϕ at the vacuum is given by

$$m_\phi = \frac{\Lambda^2}{f_\phi}.$$

It is related to the Hubble parameter during inflation,

$$H_{\rm inf}^2 \approx \frac{\gamma \Lambda^4}{3 M_{\rm pl}} = \frac{c}{3} m_\phi^2.$$

Then, we can determine m_ϕ by CMB normalization, $\Delta^2_{\mathcal{R},{\rm obs}} = 2.1 \times 10^{-9}$.

The initial phase for DM oscillation

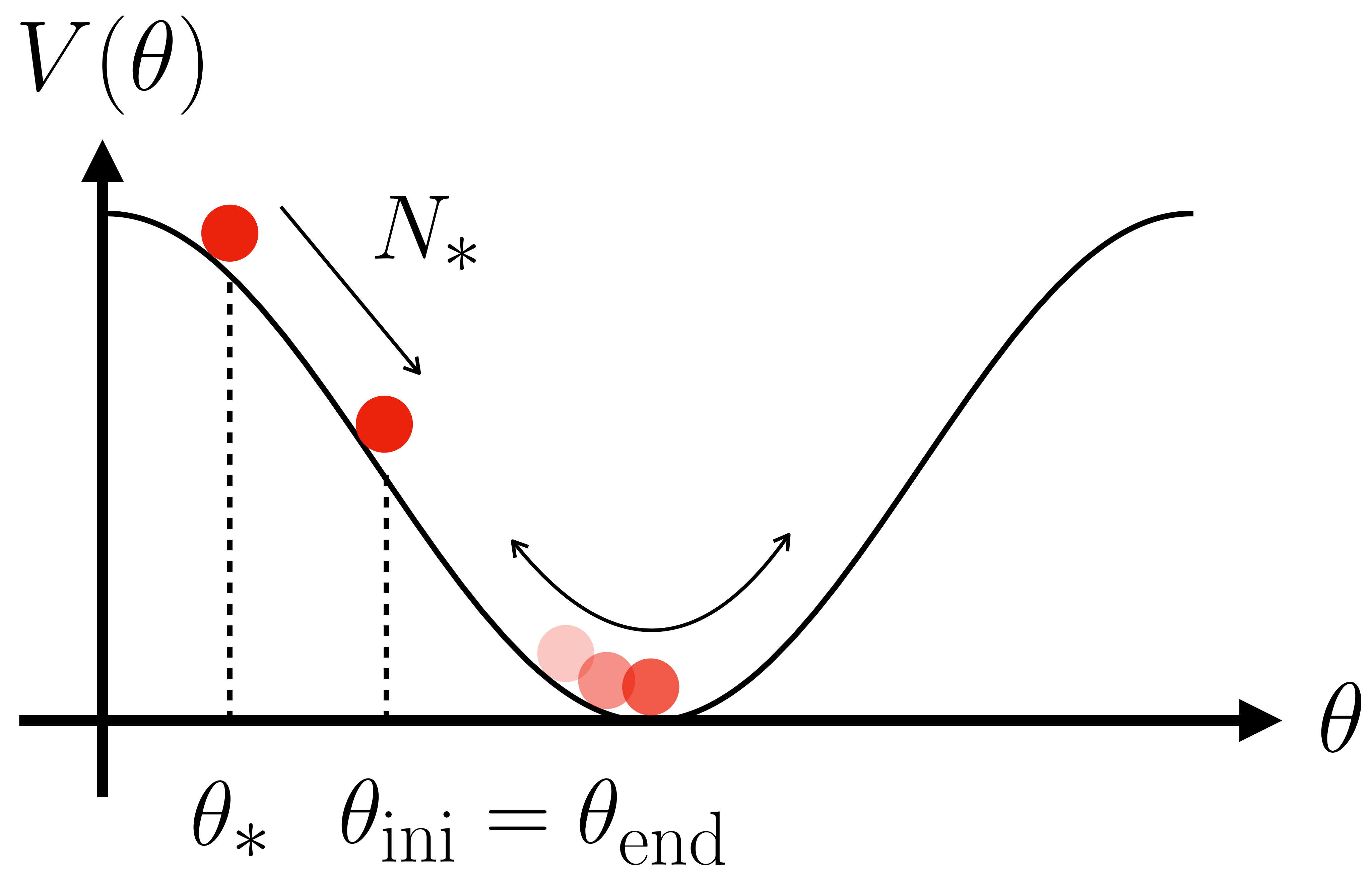
The initial angle $\theta_{\rm ini}$ is important to estimate DM abundance.

If ϕ does not change after inflation, we can consider

$$\theta_{\rm ini} = \theta_{\rm end}.$$

$\theta_{\rm end}$ is determined by the e-folding number, N_*,

$$\theta_{\rm end} \simeq 2\arctan\left(e^{-N_*/c}\sqrt{\frac{2+c(1-n_{s,{\rm obs}})}{2-c(1-n_{s,{\rm obs}})}}\right).$$



The e-folding number

$$N_* \equiv \ln\left(\frac{a_{\rm end}}{a_*}\right) \approx \int_{\phi_{\rm end}}^{\phi_*} \frac{V}{\partial\phi V} {\rm d}\phi$$

Prediction from misalignment mechanism

Through the misalignment mechanism, the DM abundance is given by

$$\Omega_\phi h^2 \simeq 0.12\,\theta_{\rm i}^2 \left(\frac{m_\phi}{4.7\times 10^{-15}\,{\rm eV}}\right)^{1/2}\left(\frac{f_\phi}{10^{15}\,{\rm GeV}}\right)^2 ,$$

Workman et al. 2022

without fine-tuning $\theta_{\rm i}$ ($\theta_{\rm i} = \mathcal{O}(1)$).

The predicted extremely small DM mass has triggered attempts to reduce its relic abundance.

- To apply fine-tuning to $\theta_{\rm i}$
- To set $f_\phi \ll M_{\rm pl}$
- Late-time entropy production → This work

Kawasaki, Takahashi et al. 2005; Kawasaki, Nakayama et al. 2014

Late reheating scenario

① Ψ field takes over the inflation energy,

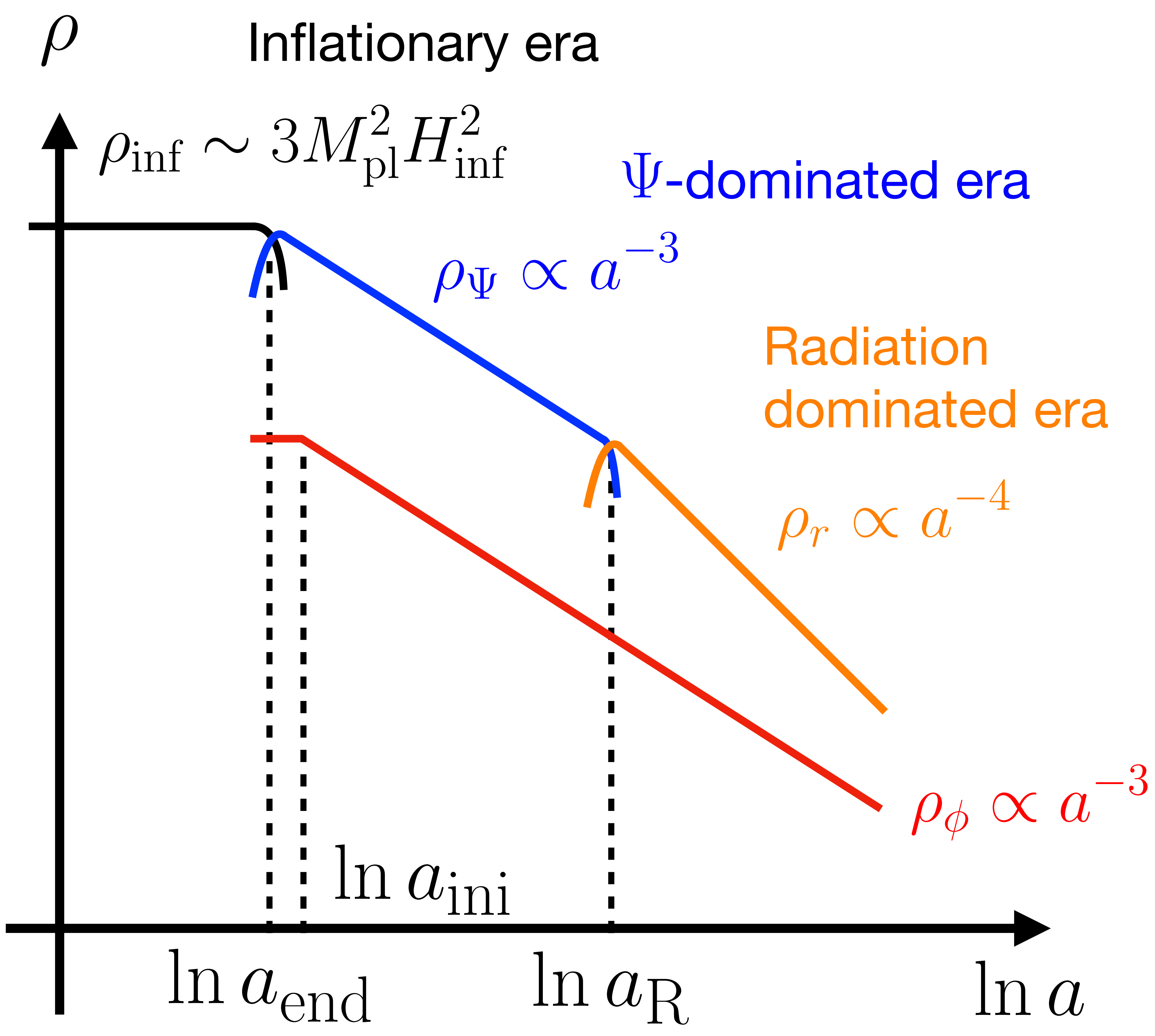
$$\rho_\Psi \sim 3M_{\rm pl}^2 H_{\rm inf}^2.$$

② ϕ field begins to oscillate after inflation,

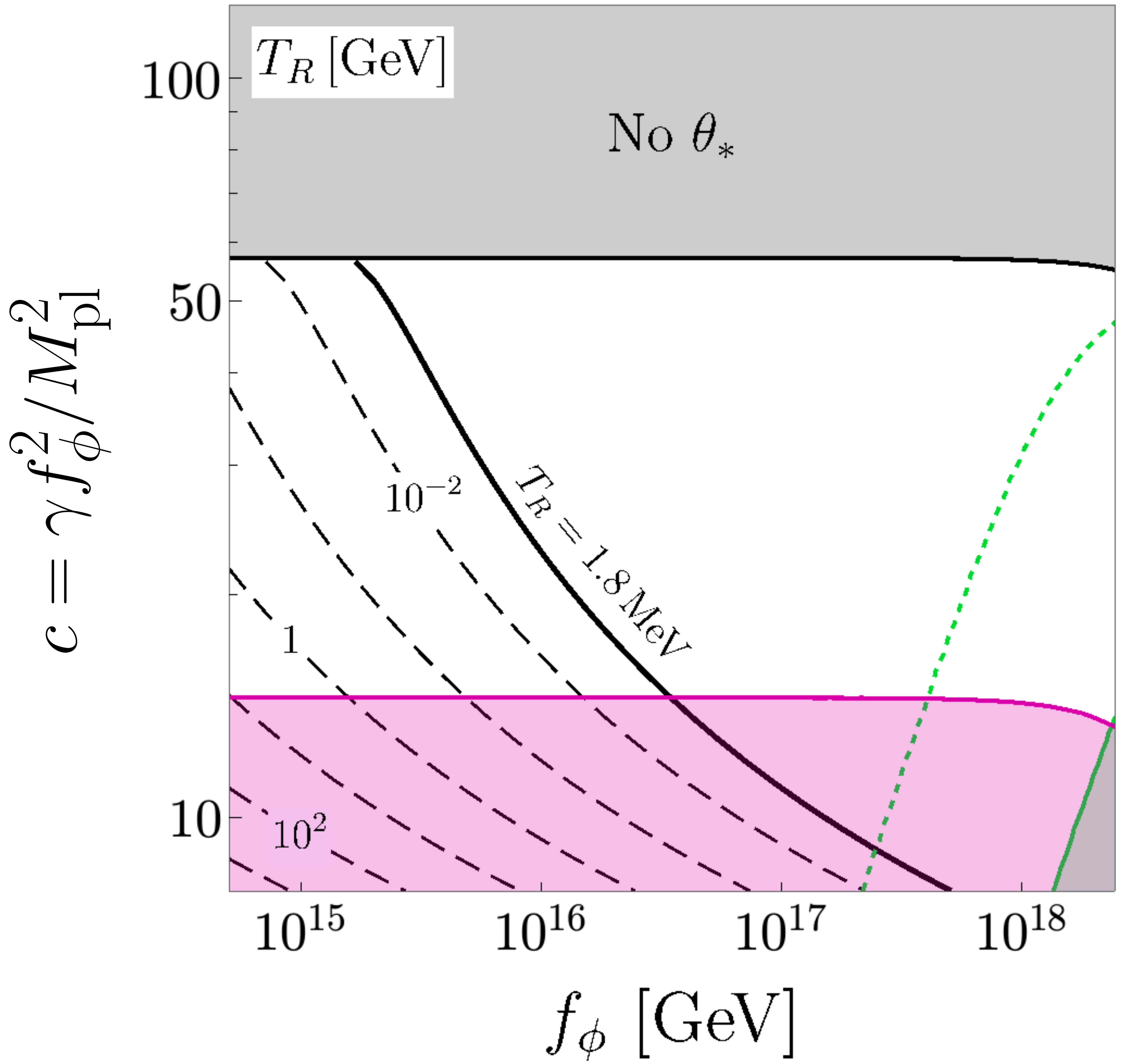
$$m_\phi \sim H \simeq \sqrt{\rho_\Psi/(3M_{\rm pl}^2)}.$$

③ Both ρ_ϕ and ρ_Ψ scale as a^{-3} after the onset of ϕ field oscillation.

④ Around $\rho_\Psi = \rho_r$, the universe is reheated and enters a radiation-dominated era.



DM abundance



The ALP abundance can be estimated as

$$\Omega_\phi \simeq 0.25\,\theta_{\mathrm{end}}^2 \frac{T_R}{10\,\mathrm{MeV}} \left(\frac{f_\phi}{10^{15}\,\mathrm{GeV}} \right)^2 .$$

The DM abundance decreases by a low reheating temperature.

$T_R = 1.8\,\mathrm{MeV}$ is conservative lower bound from BBN. Hasegawa, Hiroshima et al. 2019

This bound does not apply in double inflation scenario.

DM decay and flux prediction

We consider the DM decay from Milky Way.

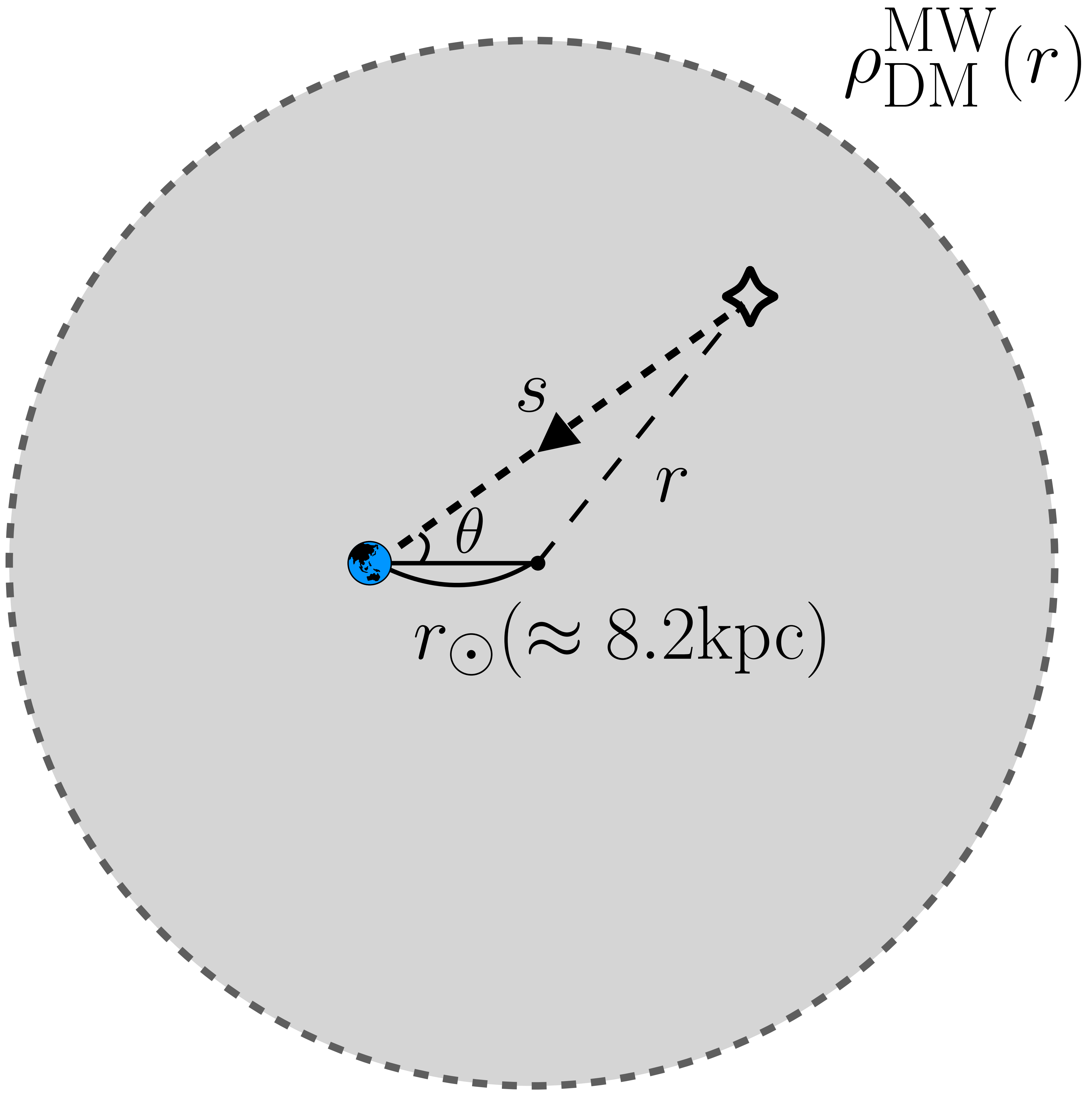
The predicted flux per solid angle is

$$\Phi(E) = \frac{1}{4\pi}\int s^2 \mathrm{d}s\mathrm{d}\Omega \frac{1}{4\pi s^2}\frac{1}{\tau_{\rm DM}}\frac{\mathrm{d}N_{\rm DM}}{\mathrm{d}E}\frac{\rho_{\rm DM}^{\rm MW}(r)}{m_{\rm DM}},$$

where $\rho_{\rm DM}^{\rm MW}(r)$ represents the DM dist. in our galaxy, which we adopt as: Navarro, Frenk et al. 1997

$$\rho_{\rm DM}^{\rm MW}(r) = \frac{\rho_0}{r/r_s(r/r_s+1)^2}.$$

$(\rho_0 \approx 0.46\mathrm{GeV/cm^3},\ r_s \approx 14.4\mathrm{kpc})$ fitted from Gaia DR2



DM decay spectra

To obtain the flux of SM particles in DM decay, we require a particle theory.

Since the DM is a spin-zero scalar field and is much heavier than the weak scale, the main decay channels are expected to be,

$$\phi \to H\bar{q}q,\ \overline{H}\bar{l}l,\ gg,\ AA,\ BB.$$

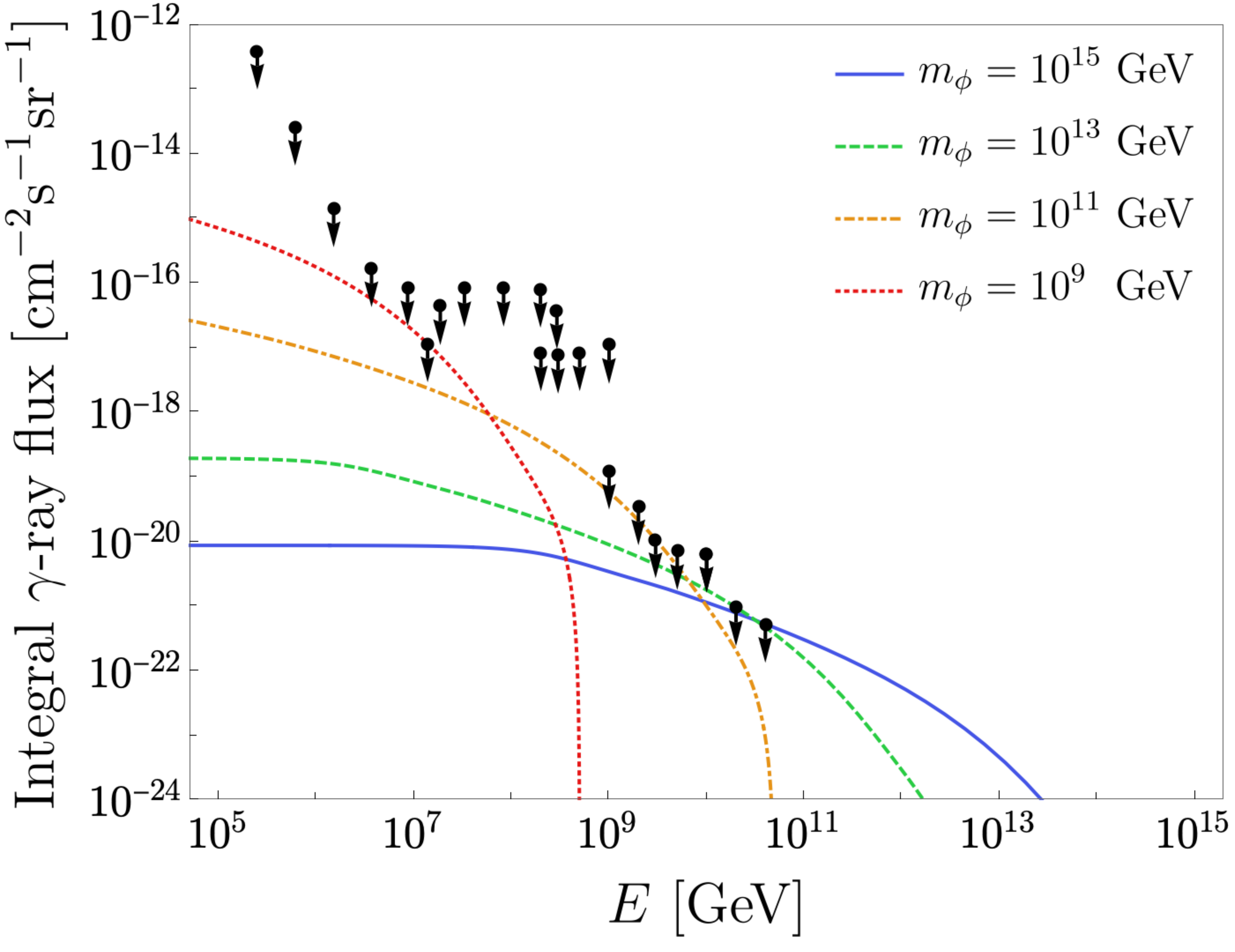
These decay channels have already been considered by using `HDMSpectra`.

Bauer, Rodd et al. 2020 ; Das, Murase et al. 2023

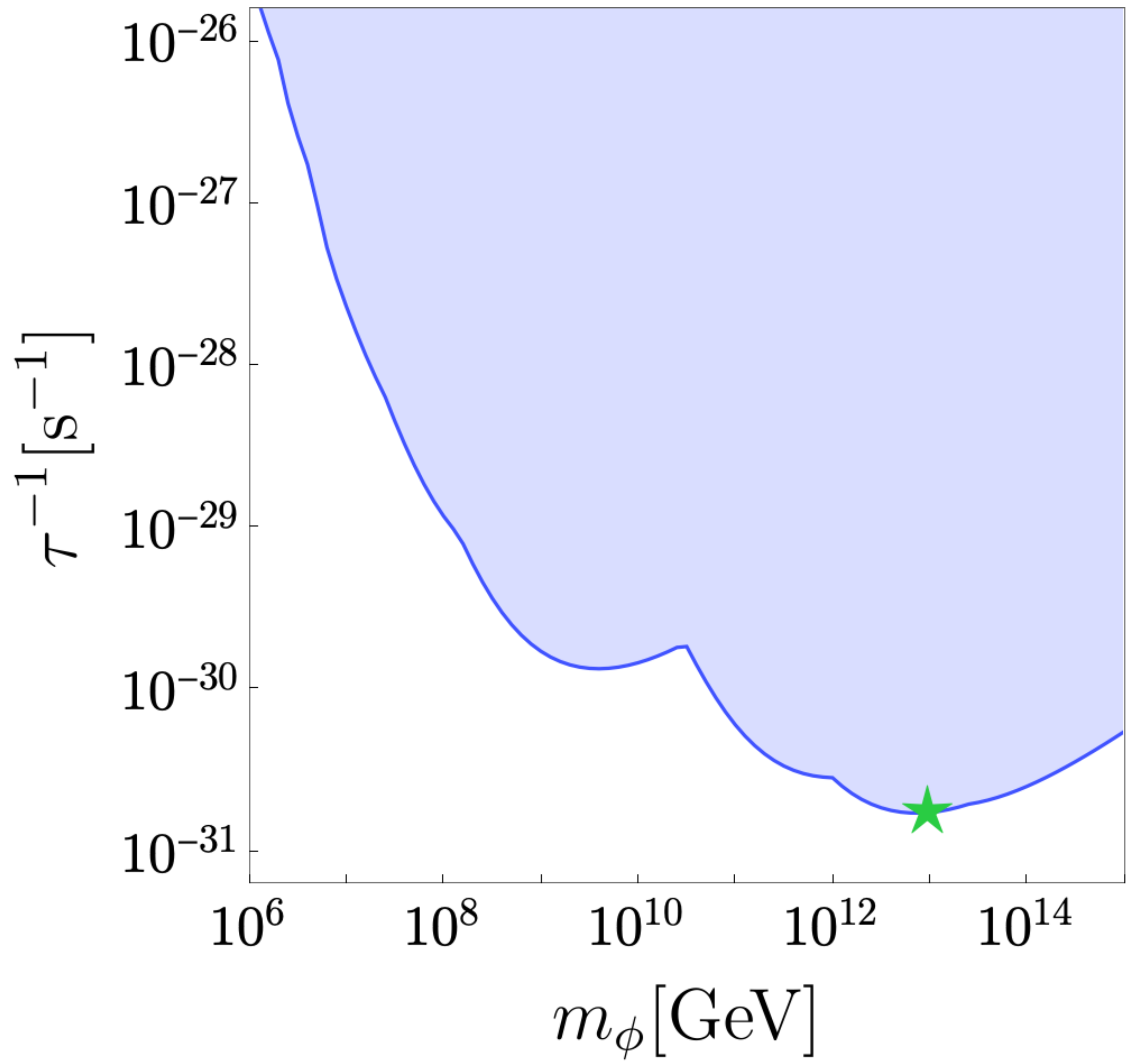
✗ The ALP decay into two fermions is forbidden by chirality arguments.

We will discuss the possibilities of the three-body decays.

γ-rays constraints for $\phi \to H\bar{q}q$

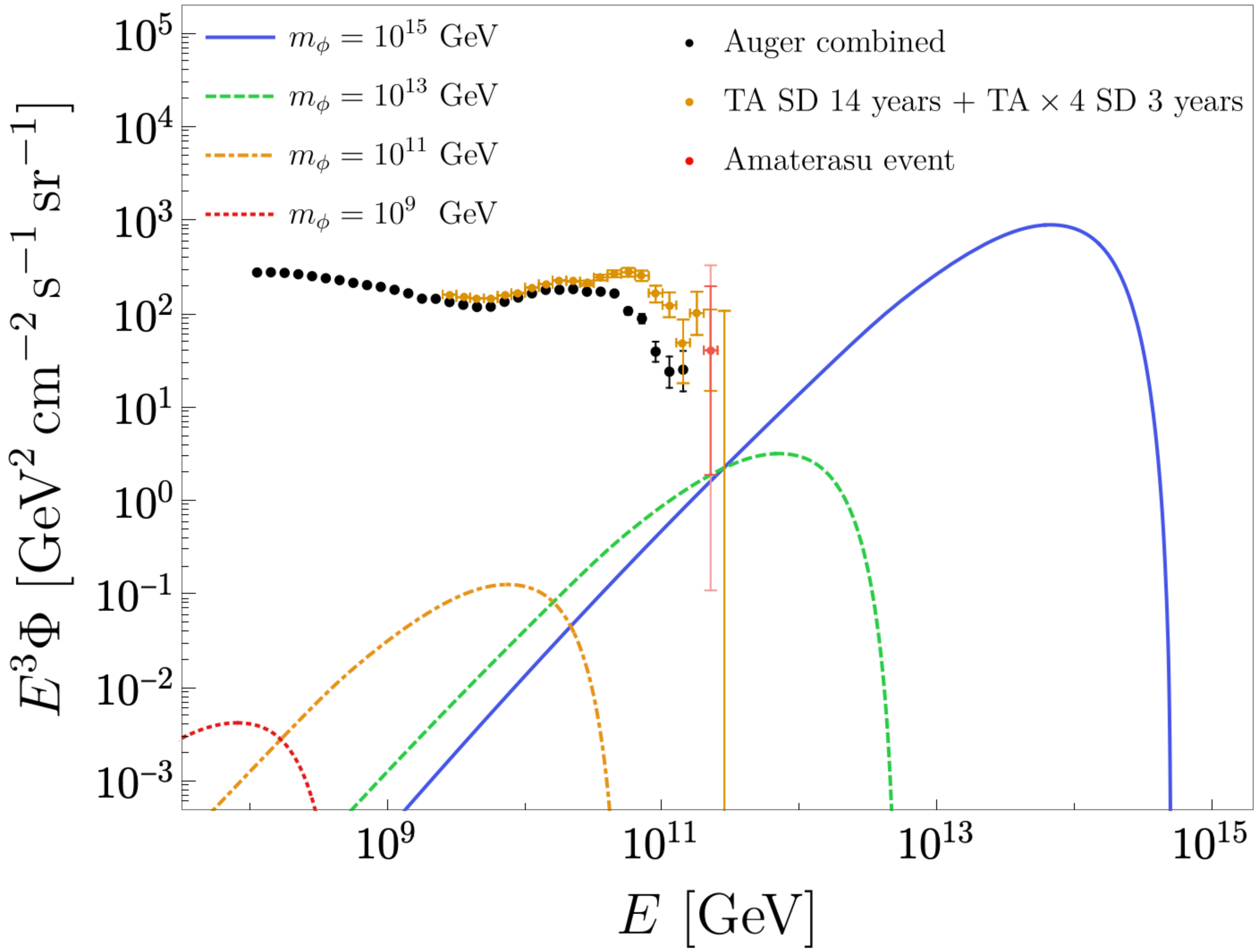


γ-ray flux

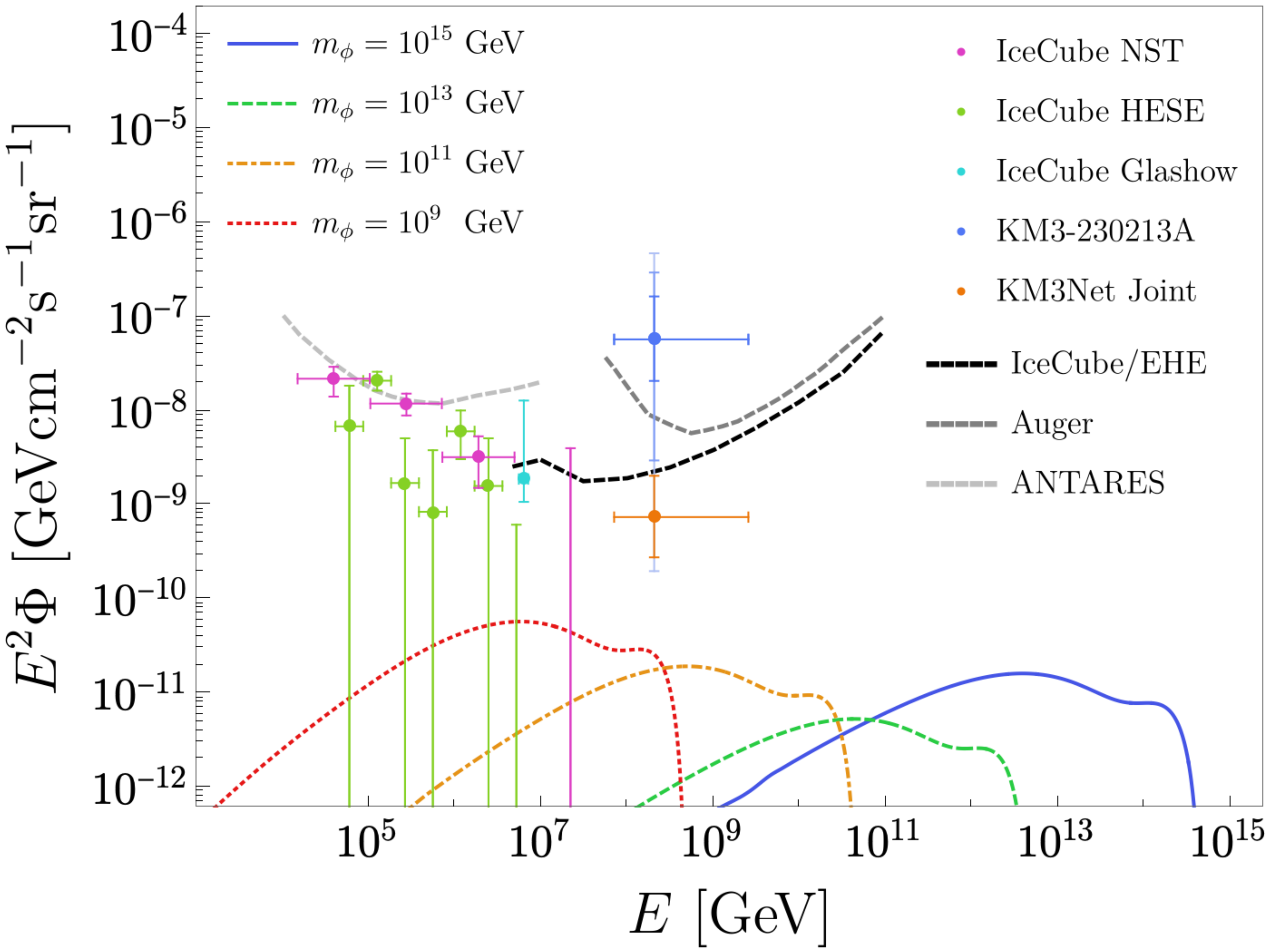


DM lifetime

Flux results from $\phi \to H\bar{q}q$

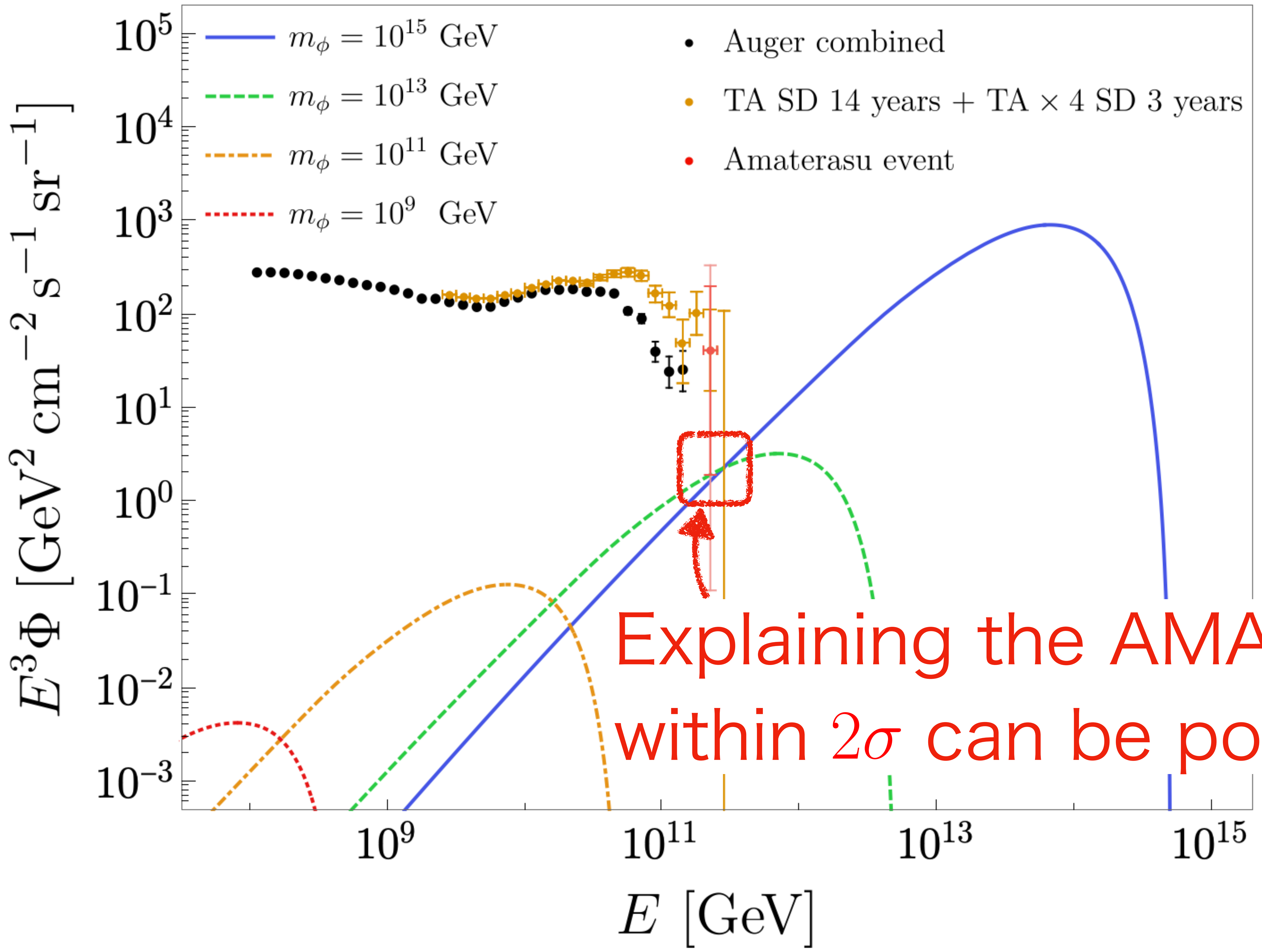


Nucleon flux



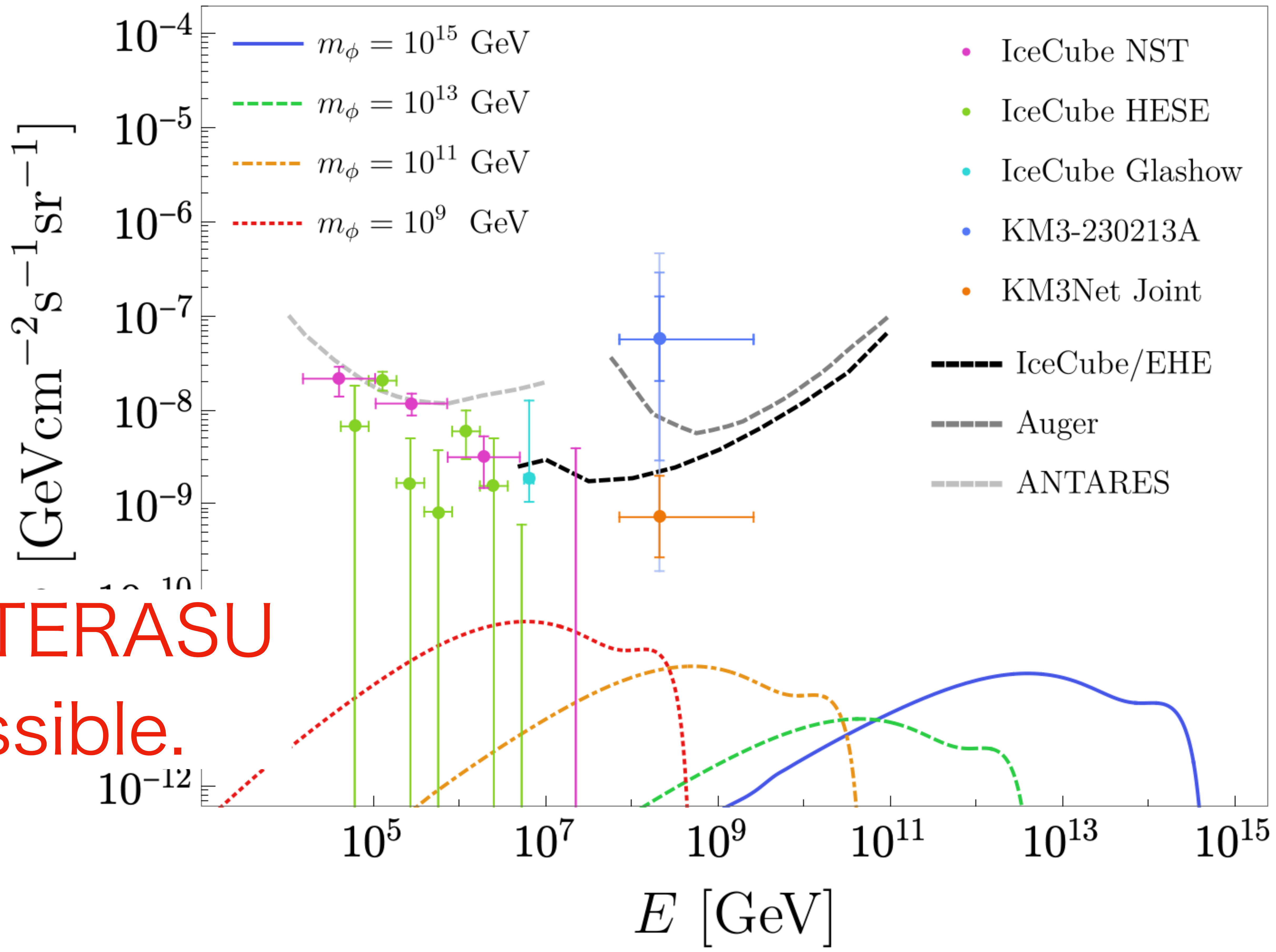
Neutrino flux

Flux results from $\phi \to H\bar{q}q$



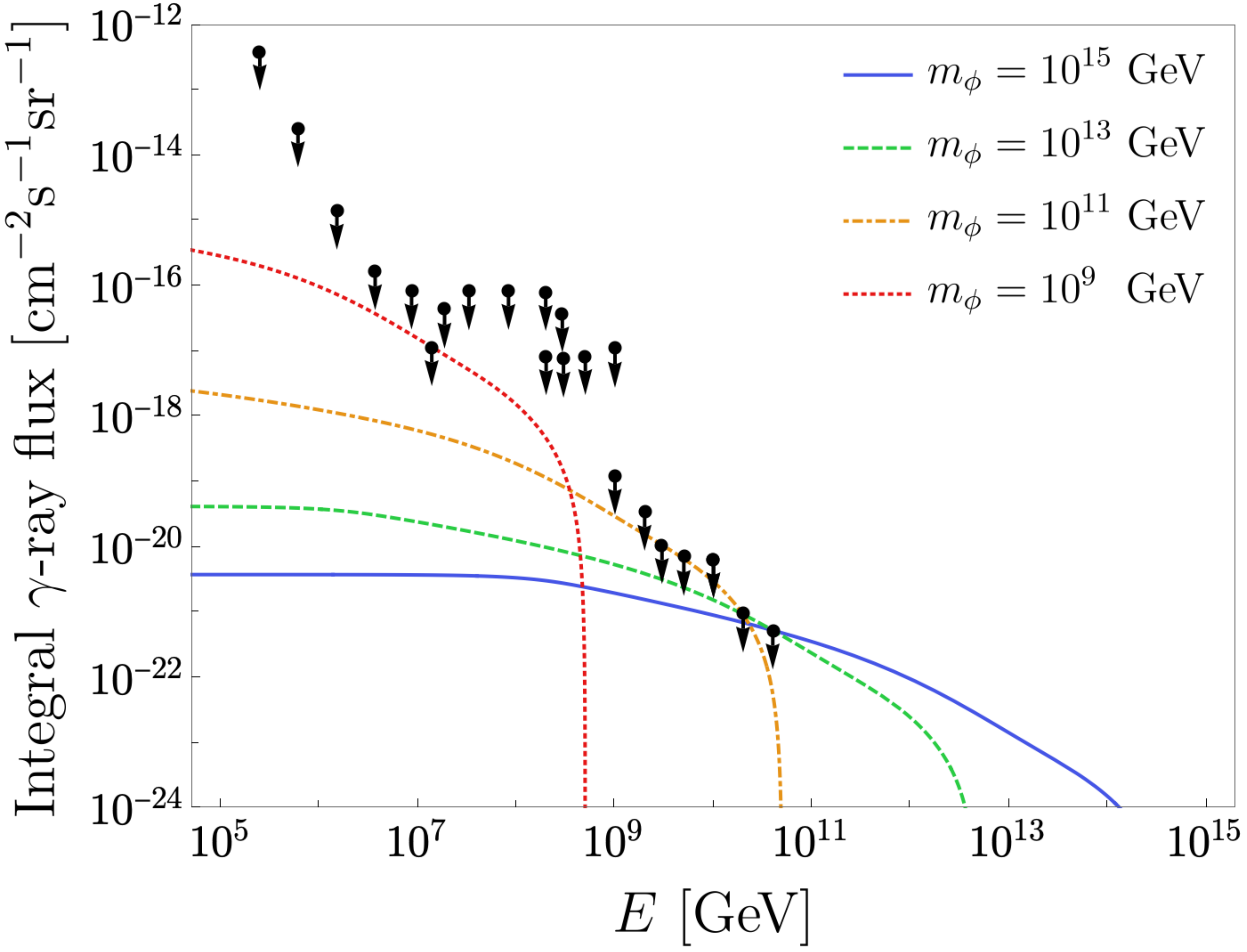
Nucleon flux

Explaining the AMATERASU within 2σ can be possible.

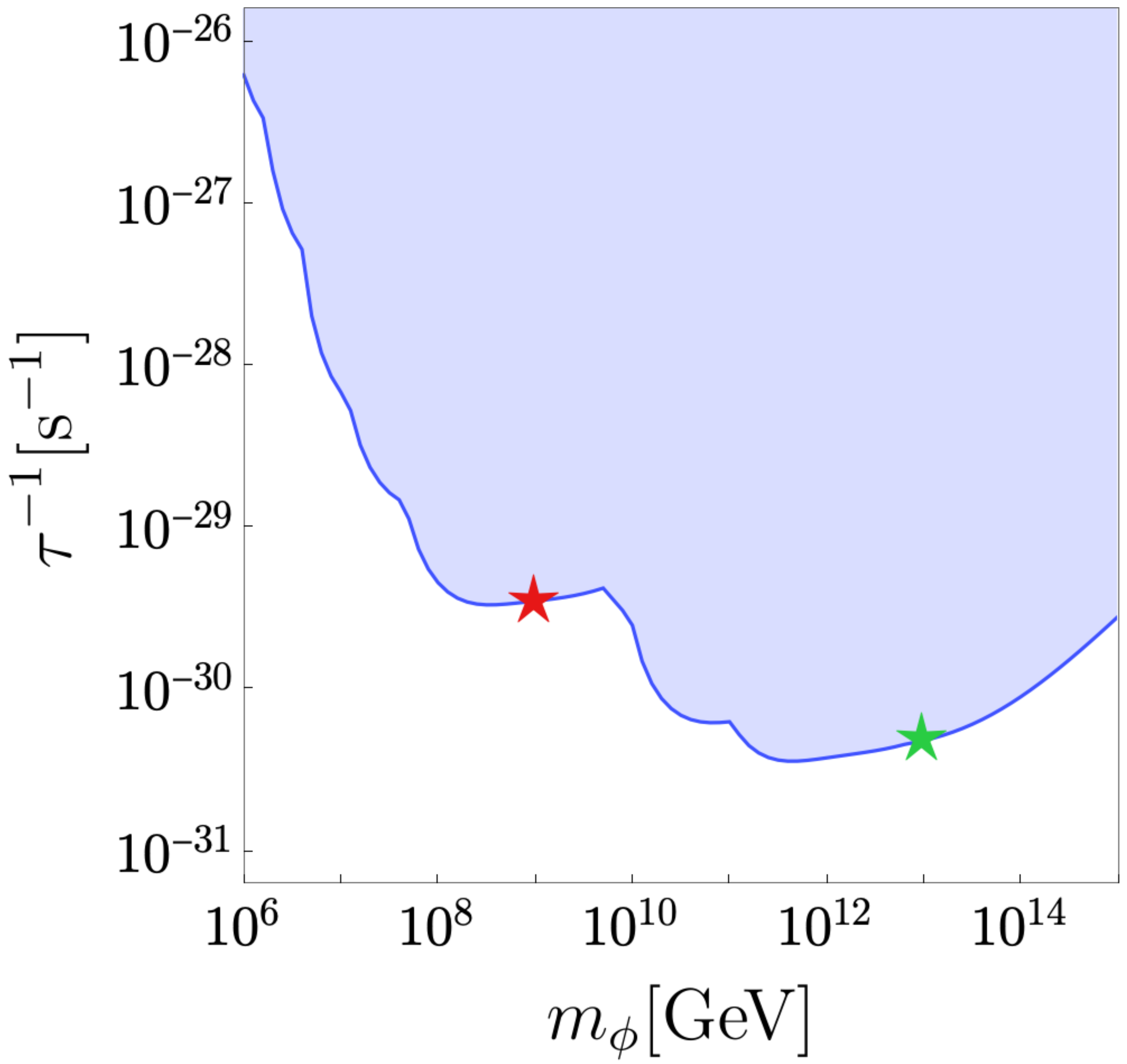


Neutrino flux

γ-rays constraints for $\phi \to \overline{H}\bar{l}l$

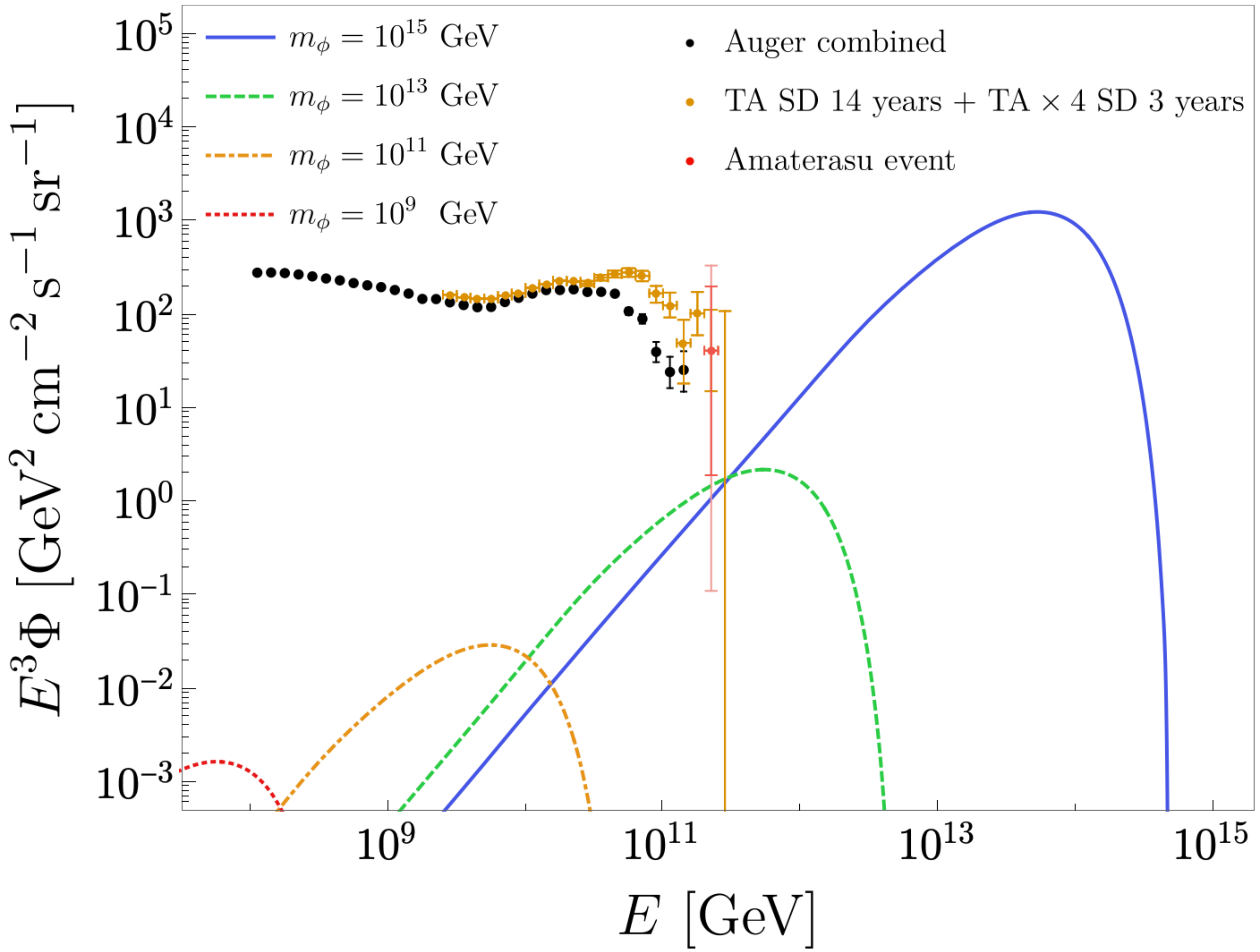


γ-ray flux

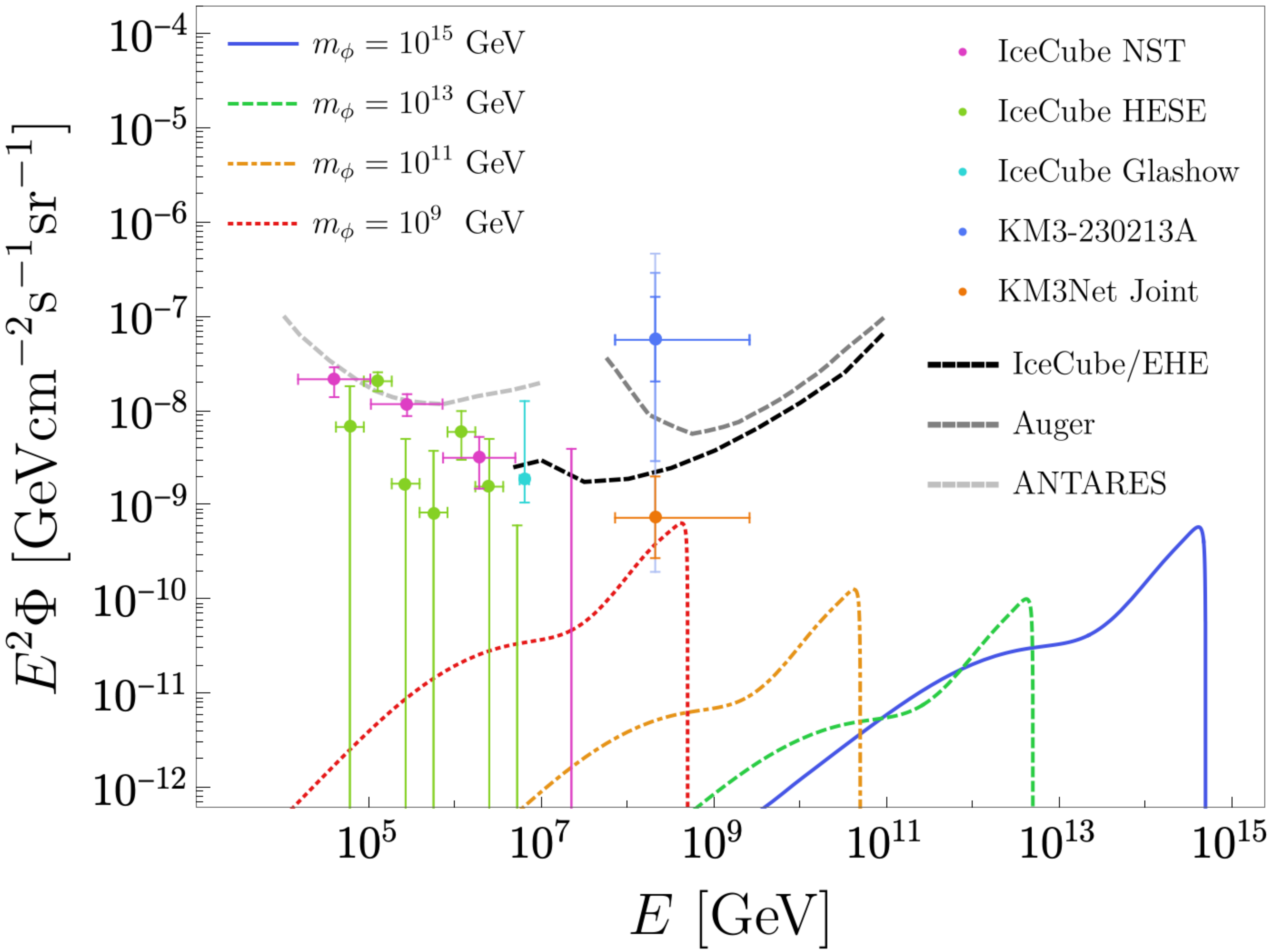


DM lifetime

Flux results from $\phi \to \overline{H}\bar{l}l$

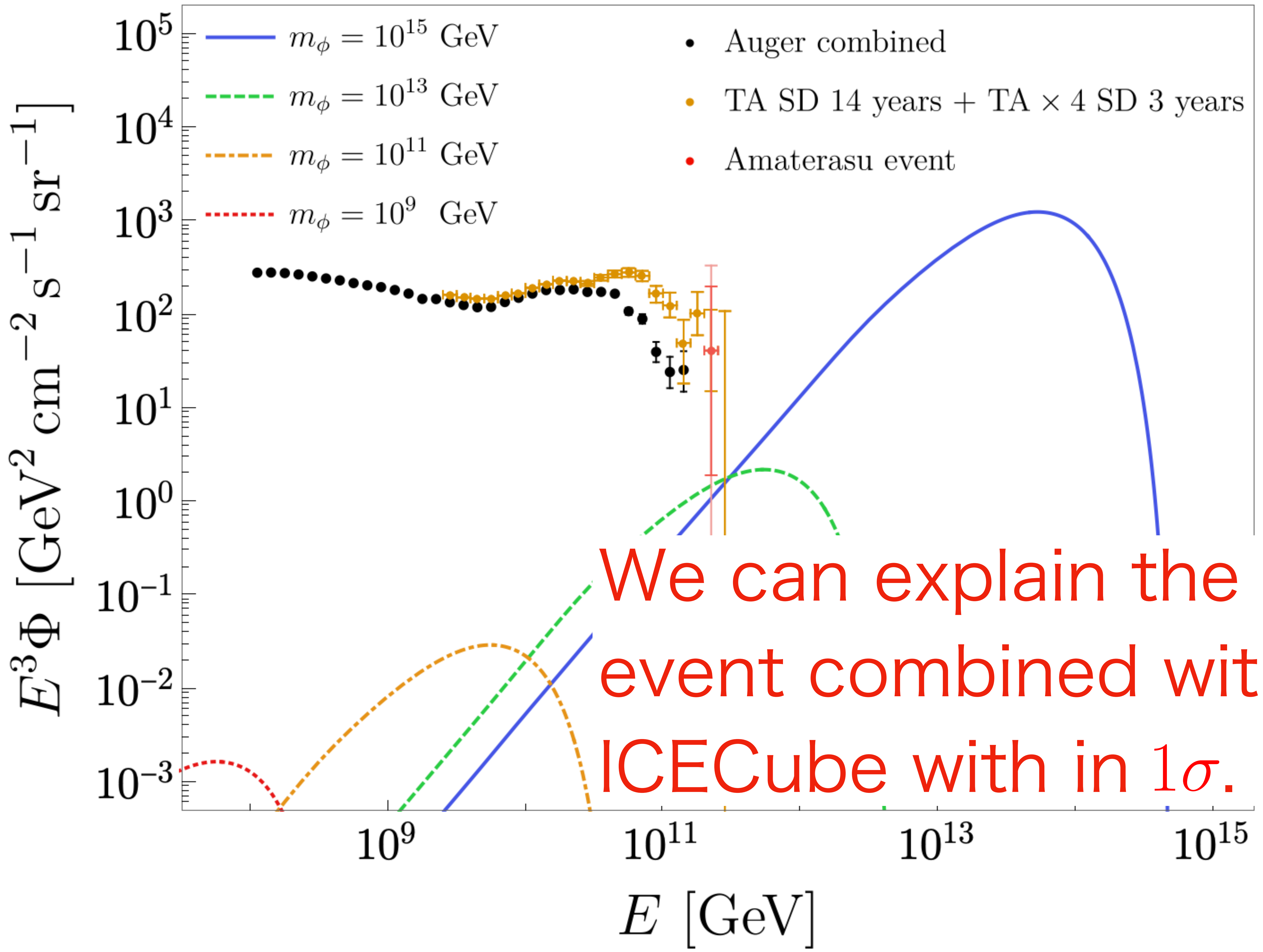


Nucleon flux

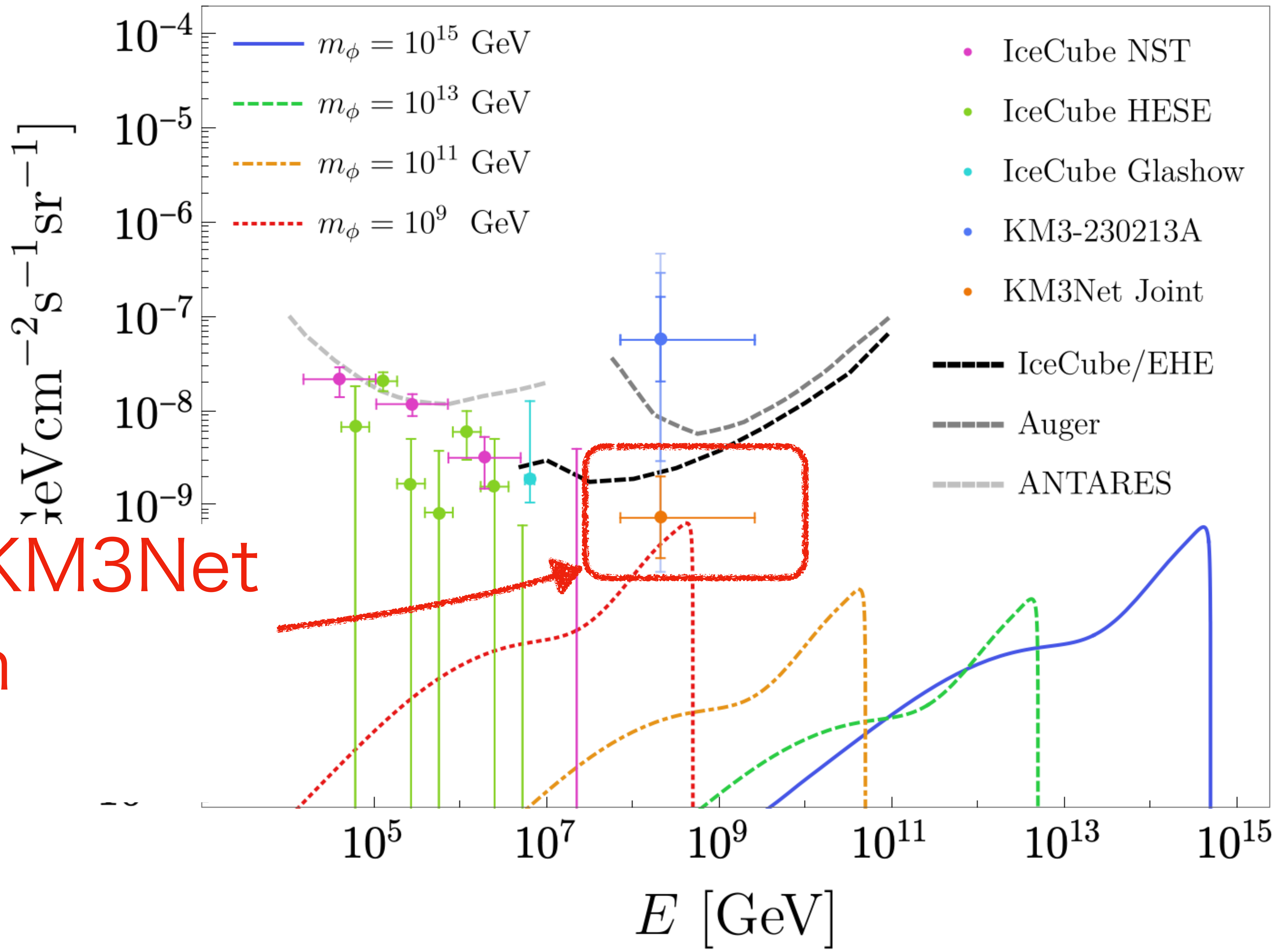


Neutrino flux

Flux results from $\phi \to \overline{H}\bar{l}l$



Nucleon flux



Neutrino flux

We can explain the KM3Net event combined with ICECube with in 1σ.

Summary

- We proposed a model where an ALP field ϕ plays the dual role of inflaton and SHDM.
- A viable region exists that satisfies both CMB constraints (n_s, r, α_s) and the observed DM relic abundance.
- We analyzed the various decay channels of SHDM and computed the resulting fluxes of γ-rays, nucleons, and neutrinos.
- The scenario predicts observational signatures in the future via CMB(Lite-BIRD, CMB-S4), UHECRs (TA×4, AugerPrime), and neutrino observatories (IceCube-Gen2, KM3NeT).

Late reheating scenario

Let us estimate the ALP abundance.

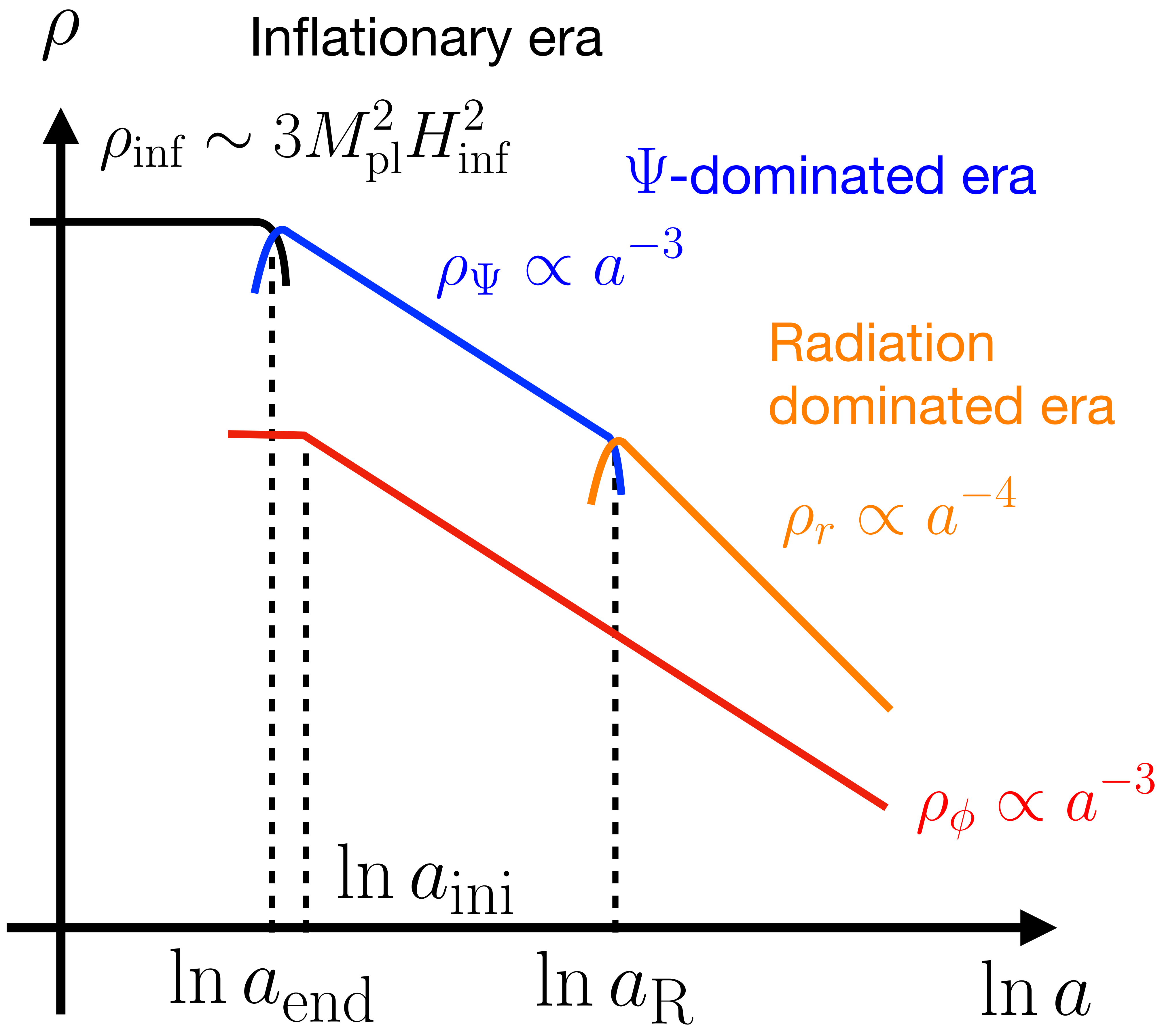
②, ③ → Energy density ratio,

$$R_\rho \equiv \frac{\rho_\phi}{\rho_\Psi} \simeq \frac{\rho_{\phi,\mathrm{ini}}}{3M_{\mathrm{pl}}^2 m_\phi^2}, \qquad \left(\rho_{\mathrm{ini}} = \frac{1}{2} m_\phi^2 f_\phi^2 \theta_{\mathrm{end}}^2\right)$$

is conserved until reheating.

④ We can drive the relation between the ϕ yield and energy density ratio,

$$\left.\frac{\rho_\phi}{s}\right|_{\mathrm{reheating}} = \frac{\rho_\phi}{\rho_r} \times \frac{3}{4} T_R = R_\rho \times \frac{3}{4} T_R.$$



Spectra from particle cascade

The flux from DM decay

$$\Phi(E) = \frac{1}{4\pi} \int s^2 \mathrm{d}s \mathrm{d}\Omega \frac{1}{4\pi s^2} \frac{1}{\tau_{\mathrm{DM}}} \frac{\mathrm{d}N_{\mathrm{DM}}}{\mathrm{d}E} \frac{\rho_{\mathrm{DM}}^{\mathrm{MW}}(r)}{m_{\mathrm{DM}}}$$

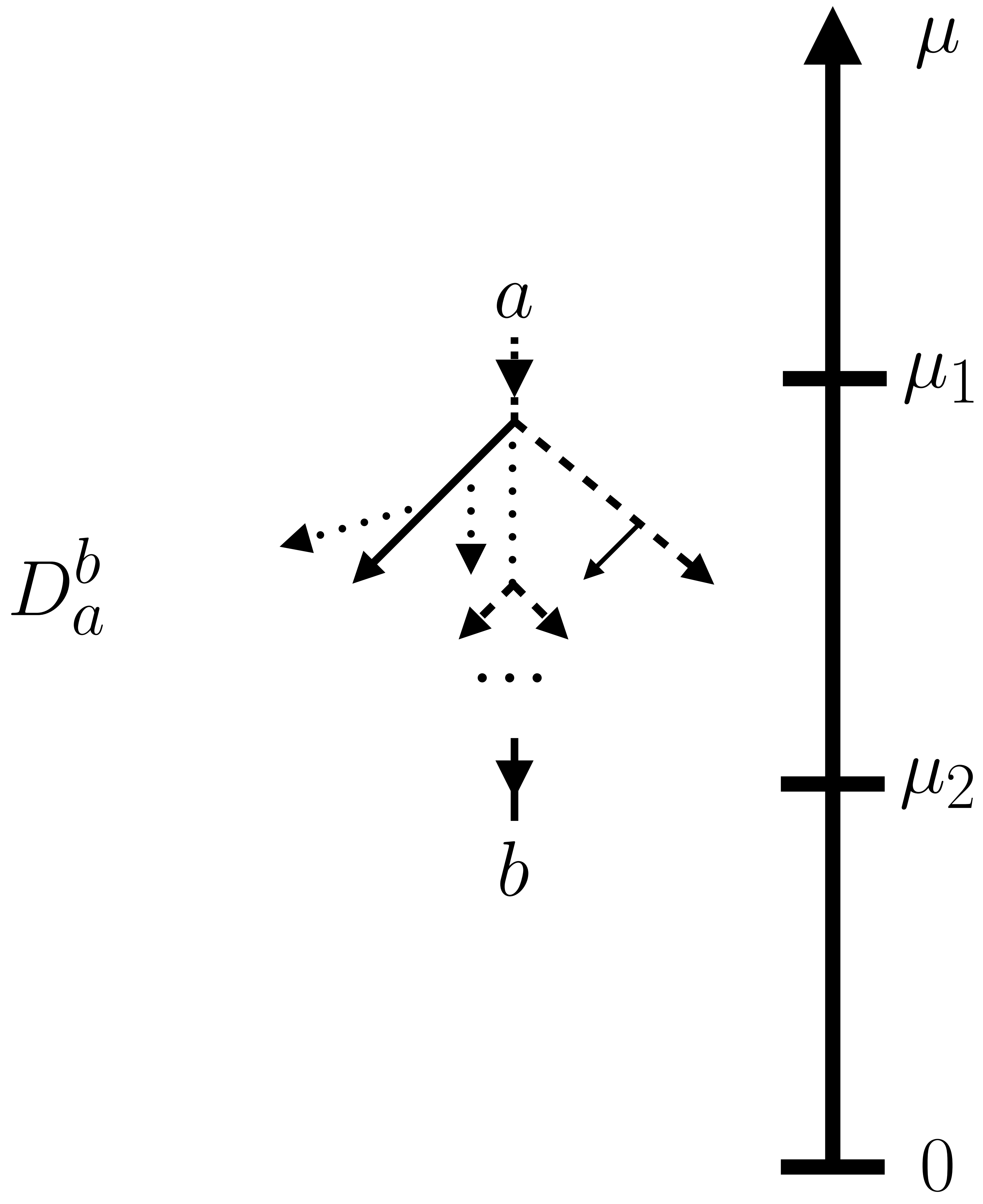
$\mathrm{d}N_{\mathrm{DM}}/\mathrm{d}E$ is model-dependent and is typically obtained through numerical simulations.

➡ We use `HDMSpectra`. Bauer, Rodd et al. 2020;

This code provide a fragmentation function (probability density function),

a momentum fraction

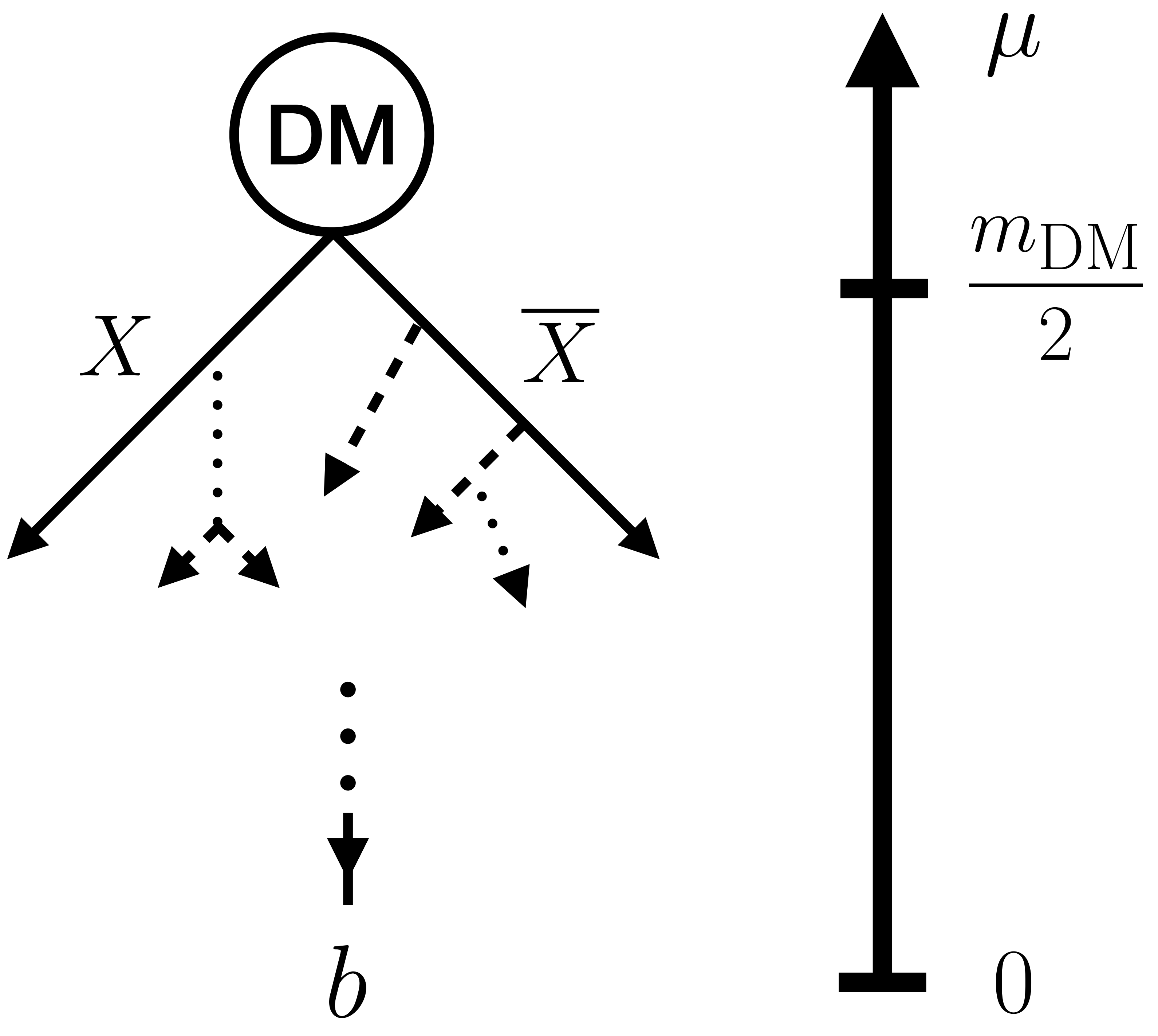
$$D_a^b(x; \mu_1, \mu_0).$$

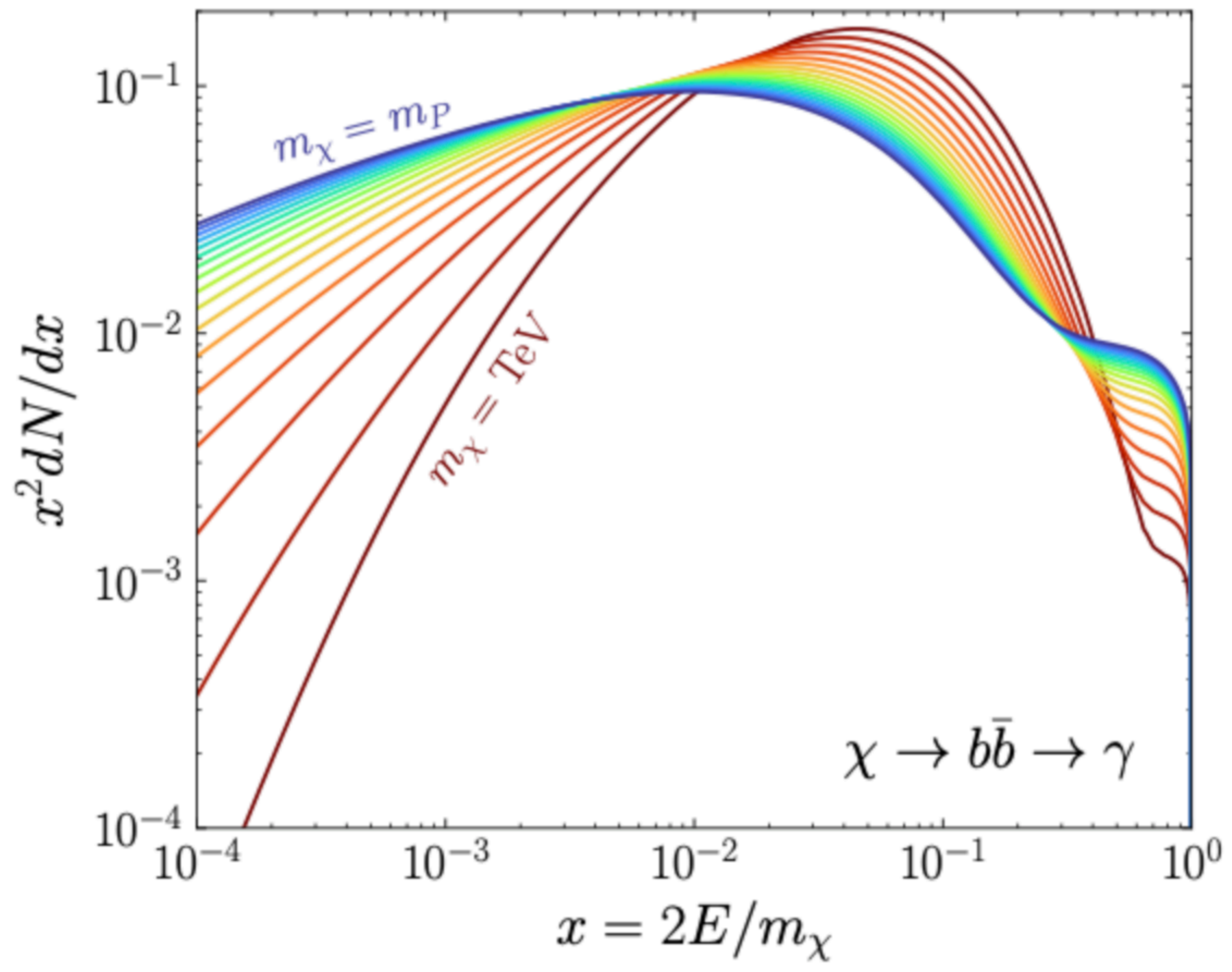


Spectra from particle cascade

If the DM decay is seeded by $\mathrm{DM} \to X\overline{X}$ for an arbitrary SM state X, we can write the spectrum of the observed particle (e.g. γ-rays) as

$$\frac{\mathrm{d}N_{\mathrm{DM}\to X\overline{X}\to\gamma}}{\mathrm{d}x} = D_X^{\gamma}(x; m_{\mathrm{DM}}/2, 0) + D_{\overline{X}}^{\gamma}(x; m_{\mathrm{DM}}/2, 0). \qquad (x = 2E/m_{\mathrm{DM}})$$





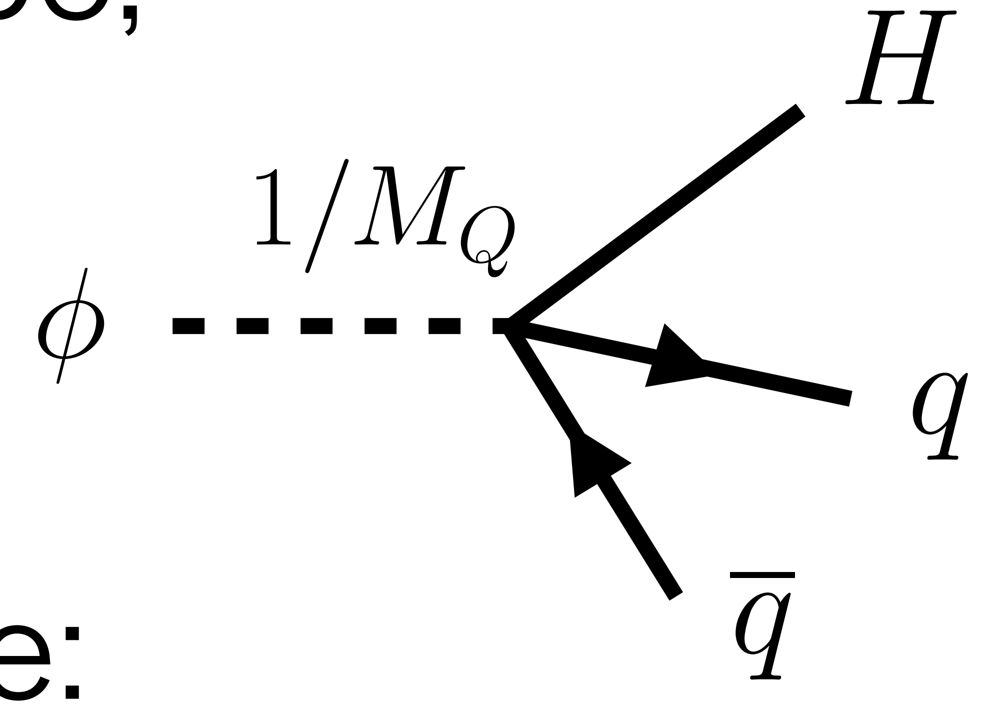
In this case, we can easily obtain the energy spectrum using `HDMSpectra`.

This figure is taken from https://arxiv.org/pdf/2007.15001.

The DM decay channel: $\phi \to H\overline{q}q$

For concreteness, let us consider an interaction of the type,

$$\mathcal{L} \supset -\frac{\phi H \overline{u} \hat{P}_L Q}{M_Q} + \text{h.c.}\,.$$



There are six types of decay channels in the broken phase:

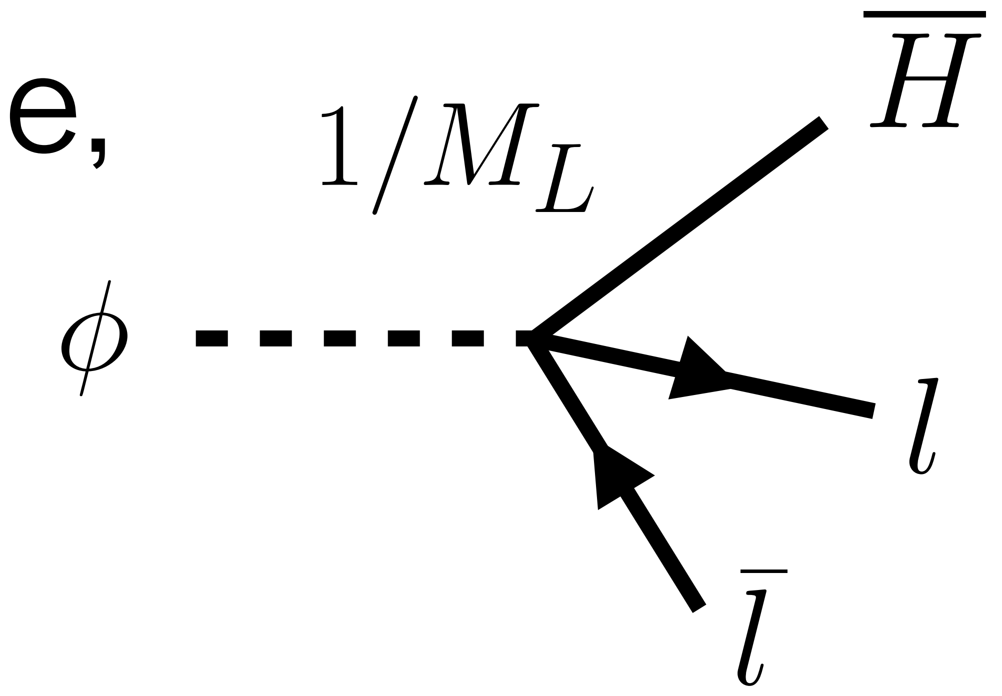
$$\phi \to h\overline{u}_L u_R,\ \phi \to W_- \overline{d}_L u_R,\ \phi \to Z\overline{u}_L u_R,$$
$$\phi \to h u_L \overline{u}_R,\ \phi \to W_+ d_L \overline{u}_R,\ \phi \to Z u_L \overline{u}_R.$$

Then, from the fractional distribution $f_Y(E)$ for $Y = h, u_L, d_L, \ldots \text{etc.}$, we obtain

$$\frac{\mathrm{d}N}{\mathrm{d}E} = \sum_Y \int_E^\infty \mathrm{d}\ln E_Y\, f_Y(E_Y) D_Y^X(E_X/E_Y; m_\phi/3, 0).$$

The DM decay channel: $\phi \to \overline{H}\bar{l}l$

For concreteness, let us consider an interaction of the type,



$$\mathcal{L} \supset -\frac{\phi\overline{H}\overline{e}_R\hat{P}_L L}{M_L} + \mathrm{h.c.}\,.$$

Similar to the case of $\phi \to H\overline{q}q$, there are six types of decay channels:

$$\phi \to h\overline{e}_L e_R,\ \phi \to W_+\overline{\nu}_L e_R,\ \phi \to Z\overline{e}_L e_R,$$
$$\phi \to he_L\overline{e}_R,\ \phi \to W_-\nu_L\overline{e}_R,\ \phi \to Ze_L\overline{e}_R.$$

Then, from the fractional distribution $f_Y(E)$ for, we obtain

$$\frac{\mathrm{d}N}{\mathrm{d}E} = \sum_Y \int_E^\infty \mathrm{d}\ln E_Y\, f_Y(E_Y) D_Y^X(E_X/E_Y; m_\phi/3, 0).$$