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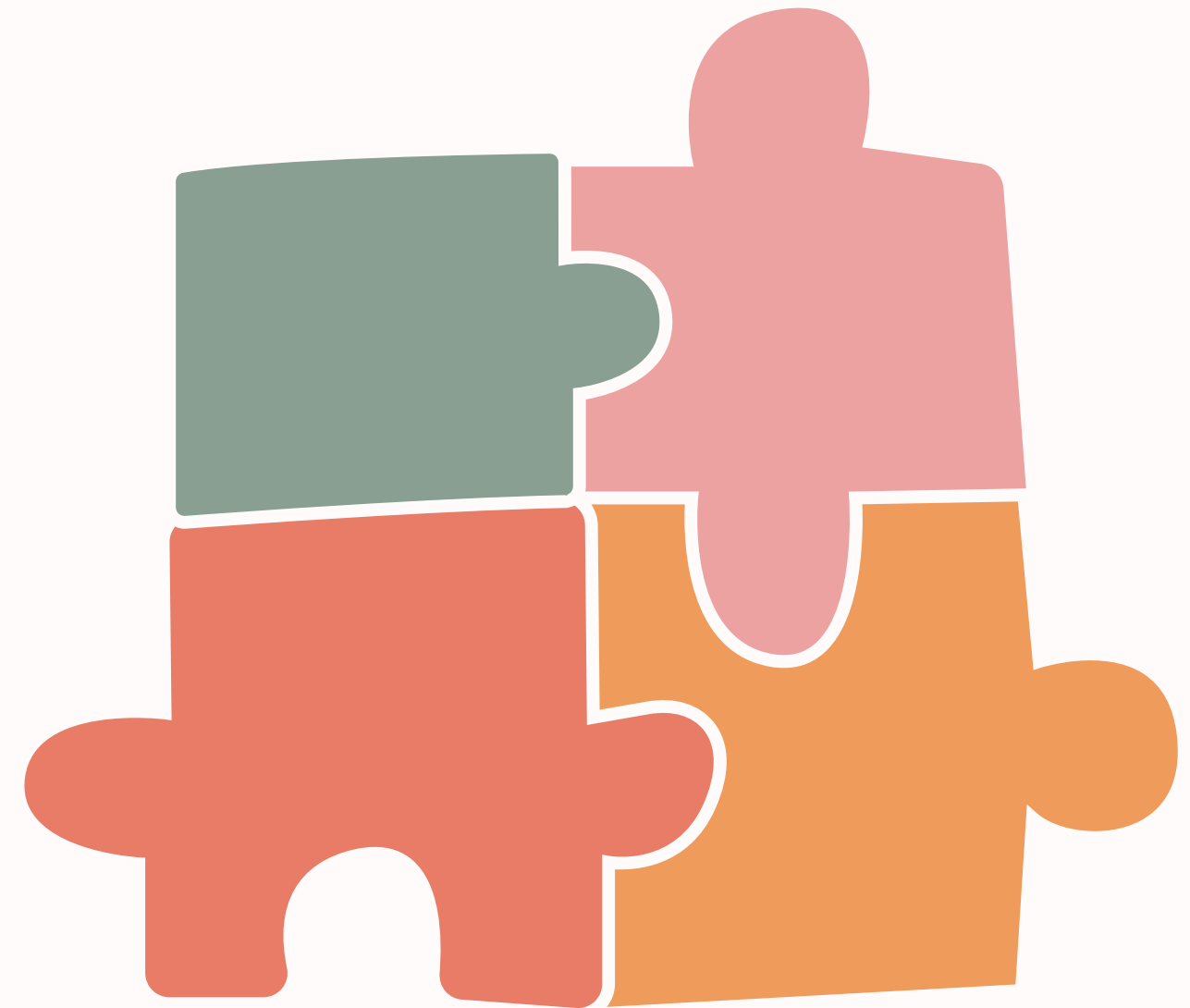


ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA
DEPARTMENT OF PHYSICS AND ASTRONOMY
"AUGUSTO RIGHI"



Sub-GeV scalar DM in a Rich Dark Sector

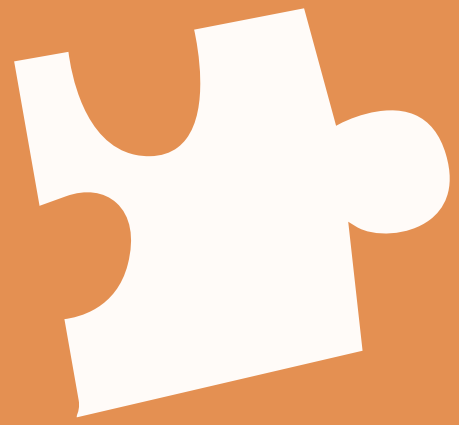
Elina Merkel
University of Bologna



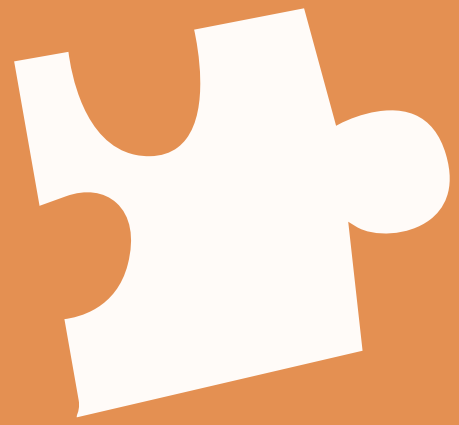
TEVPA, SEPTEMBER 3, 2026

BASED ON WORK IN PROGRESS IN COLLABORATION WITH A. GRANELLI, M. LUCENTE, S. PASCOLI AND S. ROSAURO-ALCARAZ

Plan



Plan

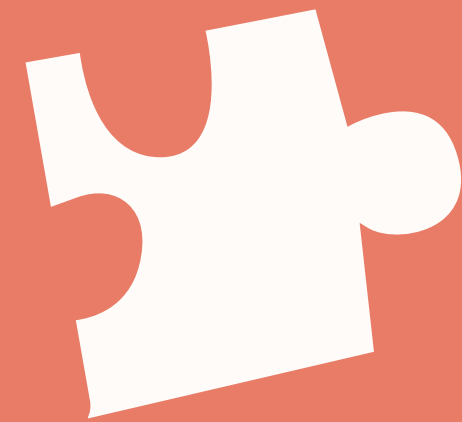


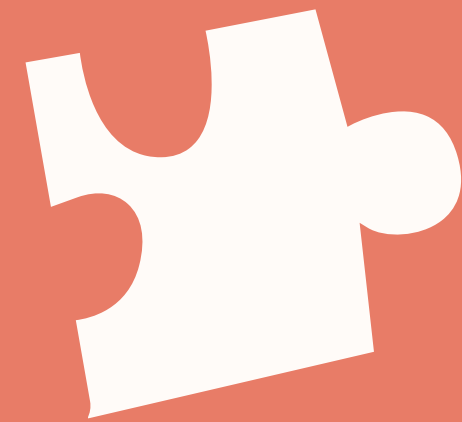
1. Rich Dark Sectors
2. Model & features
3. Thermal history
4. Predictions
5. Summary
6. Bonus 🎉





Rich Dark Sectors





Rich Dark Sectors

- Rich structure
- MeV-GeV
- Interact through portals

Rich Dark Sectors

- Rich structure
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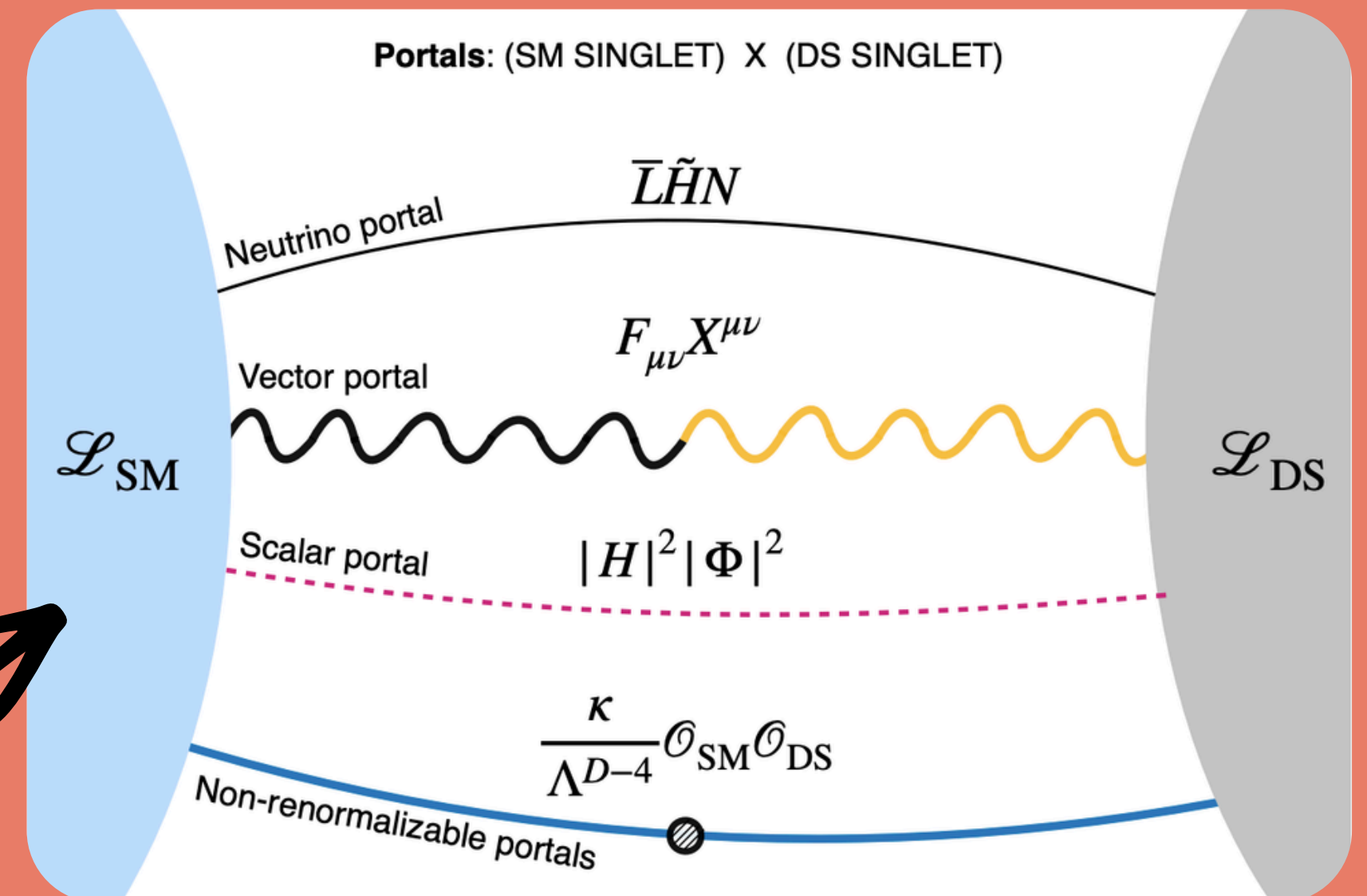
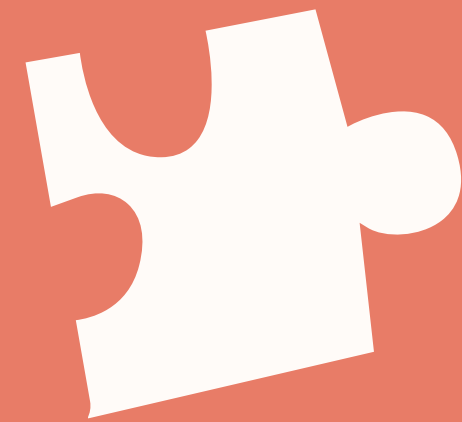


IMAGE FROM ABDULLAHI, COSTA, DE MARCHI, GRANELLI, HOEFKEN-ZINK, HOSTERT, LUCENTE, **EM**, NAVA, PASCOLI, ROSAURO-ALCARAZ, SALA [2505.05663]

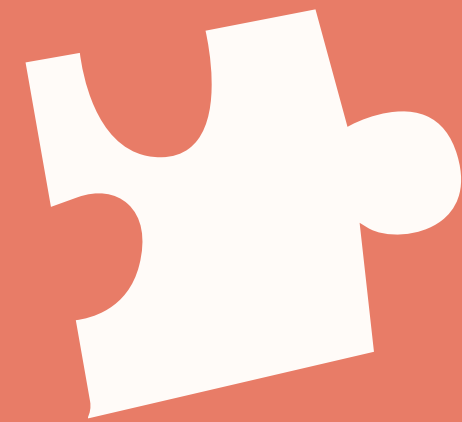


Why Rich Dark Sector?





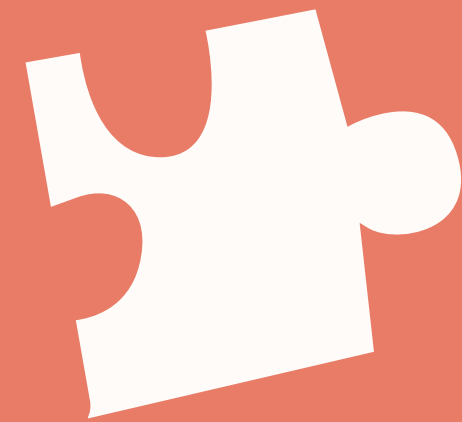
Why Rich Dark Sector?



- Alternative to the “lamp post” of WIMP



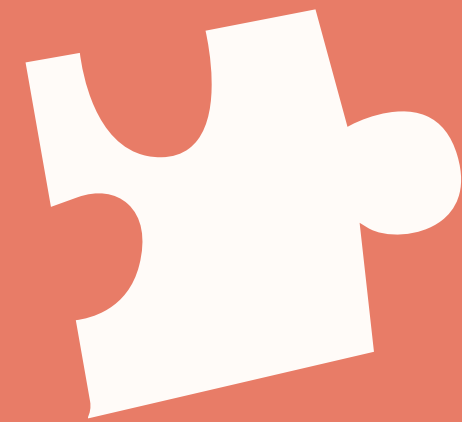
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- SM is non-minimal !



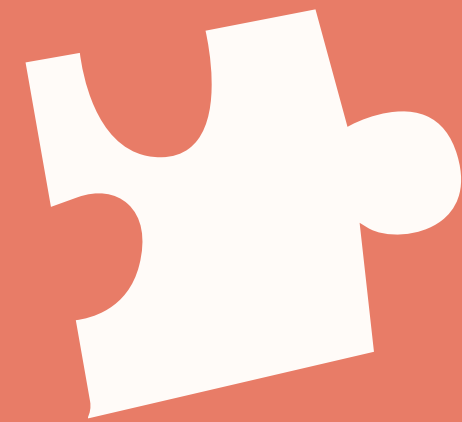
Why Rich Dark Sector?



- Alternative to the “lamp post” of WIMP
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- Address several puzzles in one framework

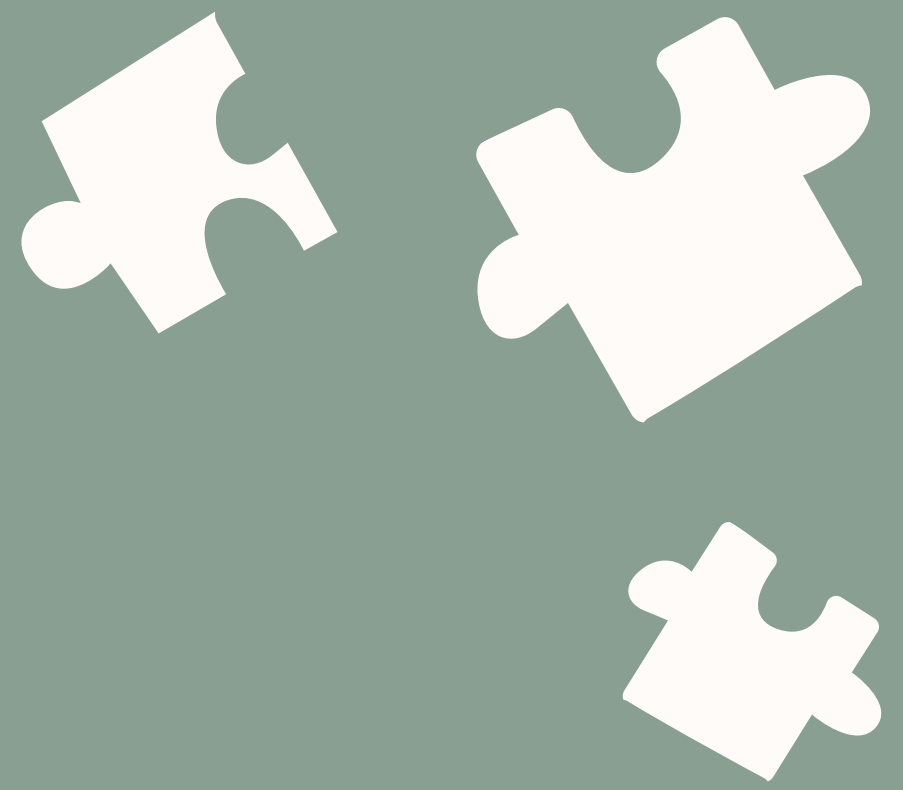


Why Rich Dark Sector?

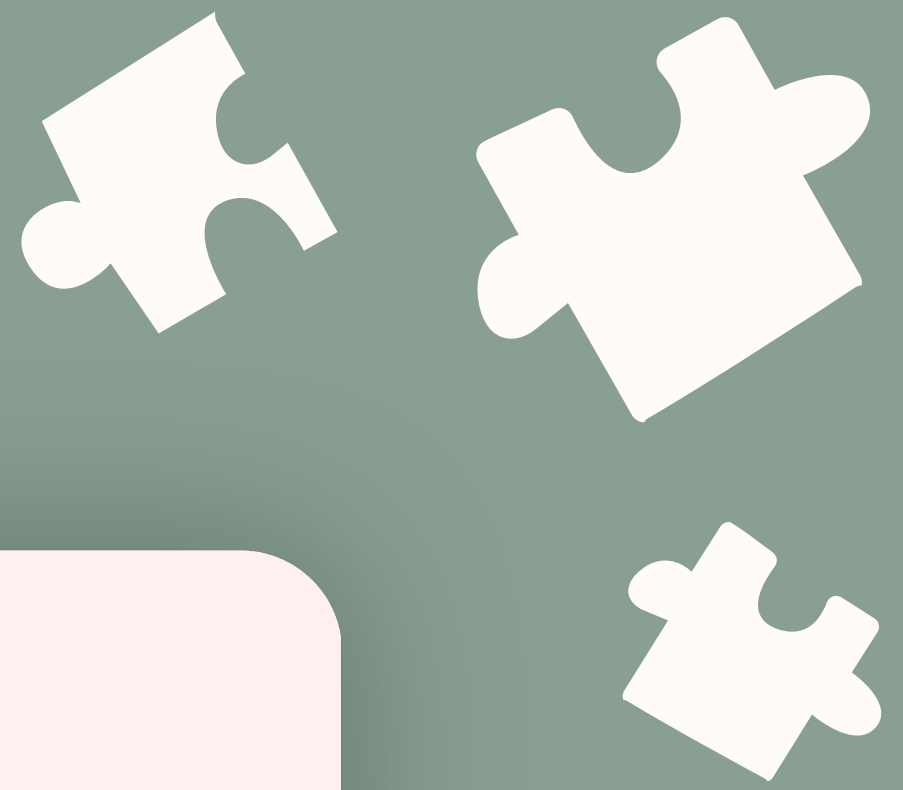


- Alternative to the “lamp post” of WIMP
- SM is non-minimal !
- Address several puzzles in one framework
- Qualitatively new signatures

Model: RDS with broken $U'(1)$



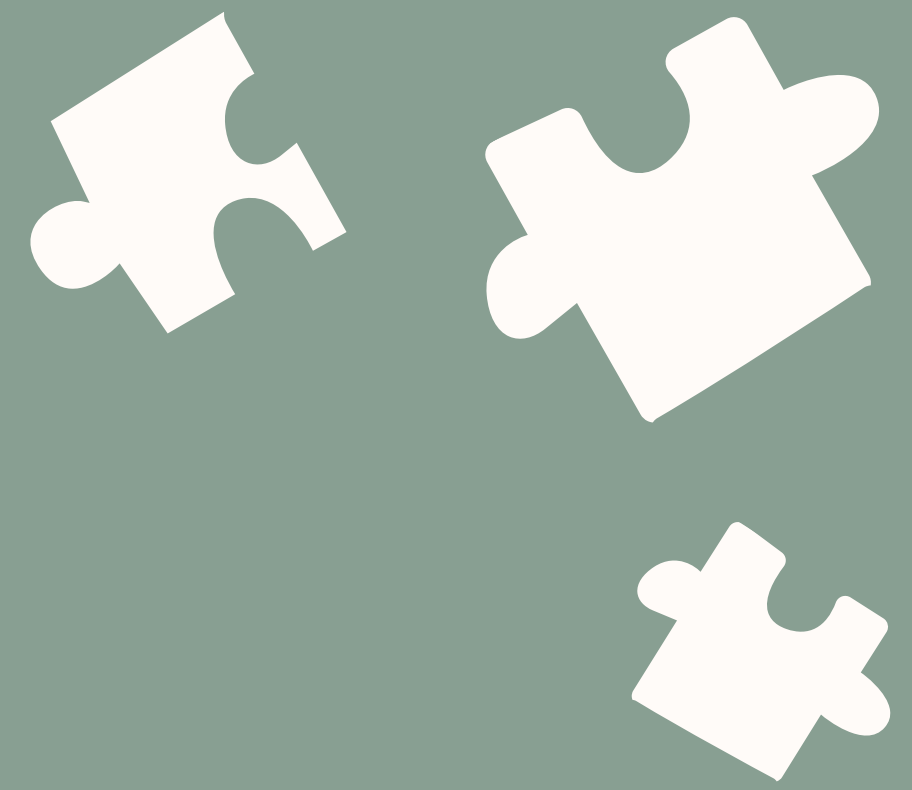
Model: RDS with broken U'(1)



$$\begin{aligned}\mathcal{L} \supset \mathcal{L}_{\text{SM}} &- \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\sin \chi}{2} X_{\mu\nu} B^{\mu\nu} \\ &+ (D_\mu \phi)^\dagger (D^\mu \phi) + (D_\mu \chi)^\dagger (D^\mu \chi) - V_{\text{scalar}}(H, \phi, \chi) \\ &+ \bar{N}_i i \not{D} N_i + \bar{\nu}_D i \not{D} \nu_D \\ &- \left[(\bar{L} \tilde{H}) Y_\nu N^c + \frac{1}{2} \bar{N} M_N N^c + \bar{N} (Y_L \nu_{D_L} \phi + Y_R \nu_{D_R}^c \phi^*) + \bar{\nu}_D M_X \nu_D + \text{h.c.} \right]\end{aligned}$$

$$\begin{aligned}V_{\text{scalar}}(H, \phi, \chi) = & -\mu_H^2 (H^\dagger H) + \lambda_H (H^\dagger H)^2 \\ & -\mu_\phi^2 (\phi^\dagger \phi) + \lambda_\phi (\phi^\dagger \phi)^2 - \lambda_{H\phi} (H^\dagger H) (\phi^\dagger \phi) \\ & + \mu_\chi^2 \chi^\dagger \chi + \lambda_\chi (\chi^\dagger \chi)^2 + \lambda_{H\chi} (H^\dagger H) (\chi^\dagger \chi) + \lambda_{\phi\chi} (\phi^\dagger \phi) (\chi^\dagger \chi)\end{aligned}$$

Key ingredients:



$$\begin{aligned}\mathcal{L} \supset \mathcal{L}_{\text{SM}} &- \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\sin \chi}{2} X_{\mu\nu} B^{\mu\nu} \\ &+ (D_\mu \phi)^\dagger (D^\mu \phi) + (D_\mu \chi)^\dagger (D^\mu \chi) - V_{\text{scalar}}(H, \phi, \chi) \\ &+ \bar{N}_i i \not{D} N_i + \bar{\nu}_D i \not{D} \chi \nu_D \\ &- \left[(\bar{L} \tilde{H}) Y_\nu N^c + \frac{1}{2} \bar{N} M_N N^c + \bar{N} (Y_L \nu_{D_L} \phi + Y_R \nu_{D_R}^c \phi^*) + \bar{\nu}_D M_X \nu_D + \text{h.c.} \right]\end{aligned}$$

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Key ingredients:

1

χ

complex scalar DM

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Key ingredients:

1

χ

complex scalar DM

2

ϕ

- **complex scalar**
- **breaks U'(1) giving mass to the dark photon**
- **couples to DM**

$$\begin{aligned} \mathcal{L} \supset \mathcal{L}_{\text{SM}} &- \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\sin \chi}{2} X_{\mu\nu} B^{\mu\nu} \\ &+ (D_\mu \phi)^\dagger (D^\mu \phi) + (D_\mu \chi)^\dagger (D^\mu \chi) - V_{\text{scalar}}(H, \phi, \chi) \\ &+ \bar{N}_i i \not{D} N_i + \bar{\nu}_D i \not{D} \nu_D \\ &- \left[(\bar{L} \tilde{H}) Y_\nu N^c + \frac{1}{2} \bar{N} M_N N^c + \bar{N} (Y_L \nu_{D_L} \phi + Y_R \nu_{D_R}^c \phi^*) + \bar{\nu}_D M_X \nu_D + \text{h.c.} \right] \end{aligned}$$

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Key ingredients:

1

χ

complex scalar DM

2

ϕ

- **complex scalar**
- **breaks U'(1) giving mass to the dark photon**
- **couples to DM**

3

N_i

- **HNLs**
- **arise from the diagonalization of the mass matrix**
- **mix with active neutrino**

$$\begin{aligned} \mathcal{L} \supset \mathcal{L}_{\text{SM}} &- \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\sin \chi}{2} X_{\mu\nu} B^{\mu\nu} \\ &+ (D_\mu \phi)^\dagger (D^\mu \phi) + (D_\mu \chi)^\dagger (D^\mu \chi) - V_{\text{scalar}}(H, \phi, \chi) \\ &+ \bar{N}_i i \not{D} N_i + \bar{\nu}_D i \not{D} \nu_D \\ &- \left[(\bar{L} \tilde{H}) Y_\nu N^c + \frac{1}{2} \bar{N} M_N N^c + \bar{N} (Y_L \nu_{D_L} \phi + Y_R \nu_{D_R}^c \phi^*) + \bar{\nu}_D M_X \nu_D + \text{h.c.} \right] \end{aligned}$$

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Key ingredients:

mass scale: 10 MeV - 1 GeV

1

χ

complex scalar DM

2

ϕ

- complex scalar
- breaks U'(1) giving mass to the dark photon
- couples to DM

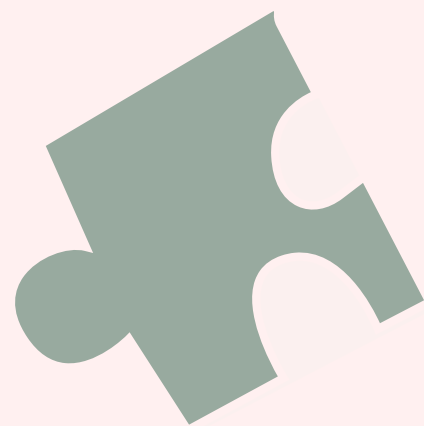
3

N_i

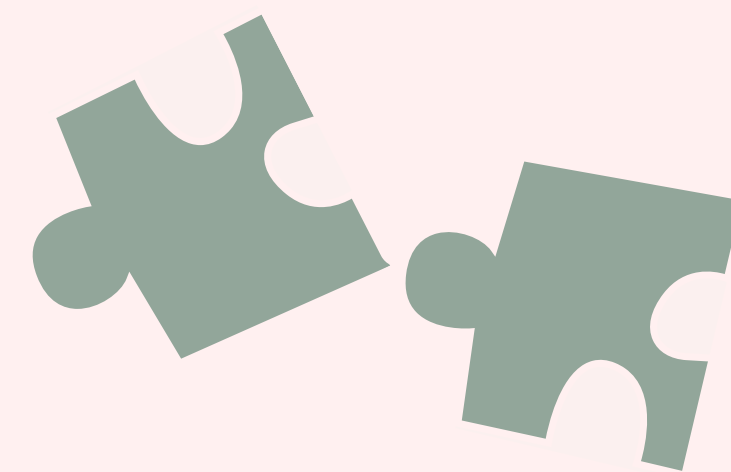
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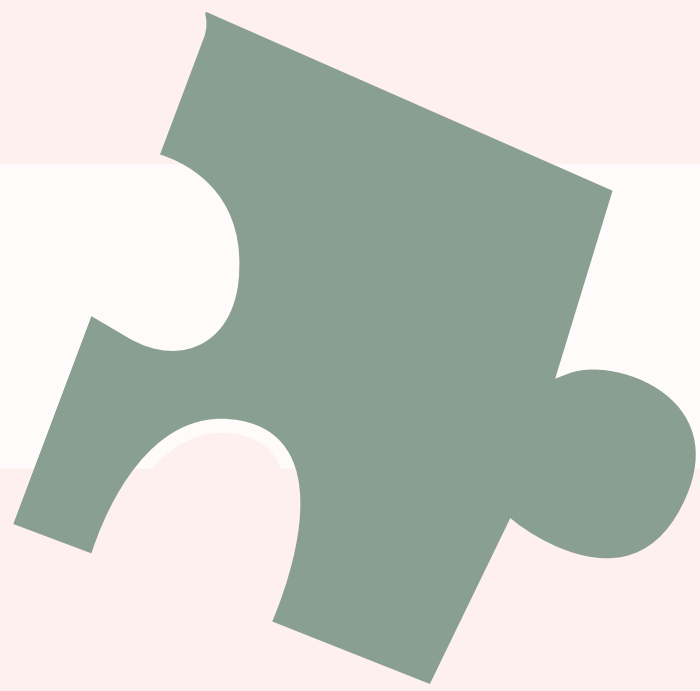
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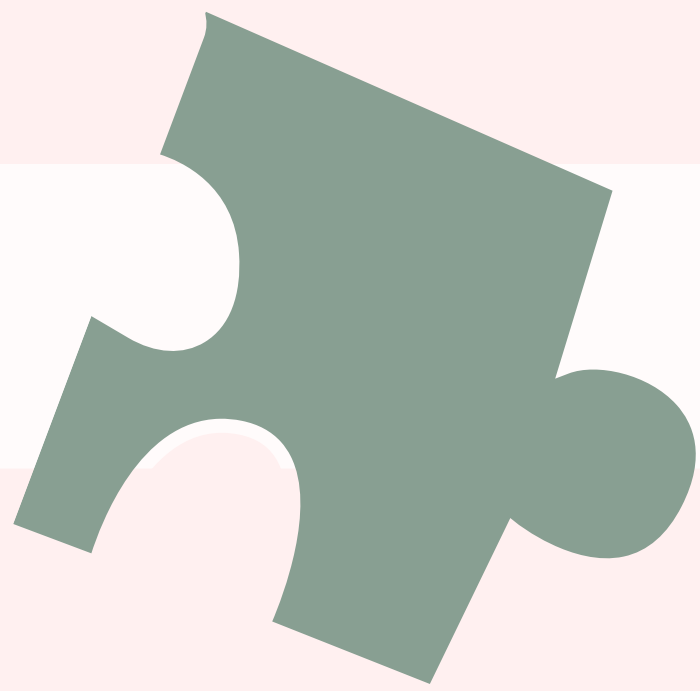
Neutrino masses





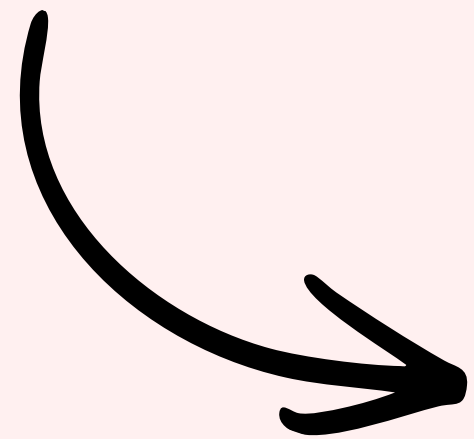
See-saw-like mechanism

$$\mathcal{L}_N \supset (\bar{L}\tilde{H})Y_\nu N^c + \frac{1}{2}\bar{N}M_N N^c + \bar{N} (Y_L \nu_{D_L} \phi + Y_R \nu_{D_R}^c \phi^*) + \bar{\nu}_D M_X \nu_D + \text{h.c.}$$

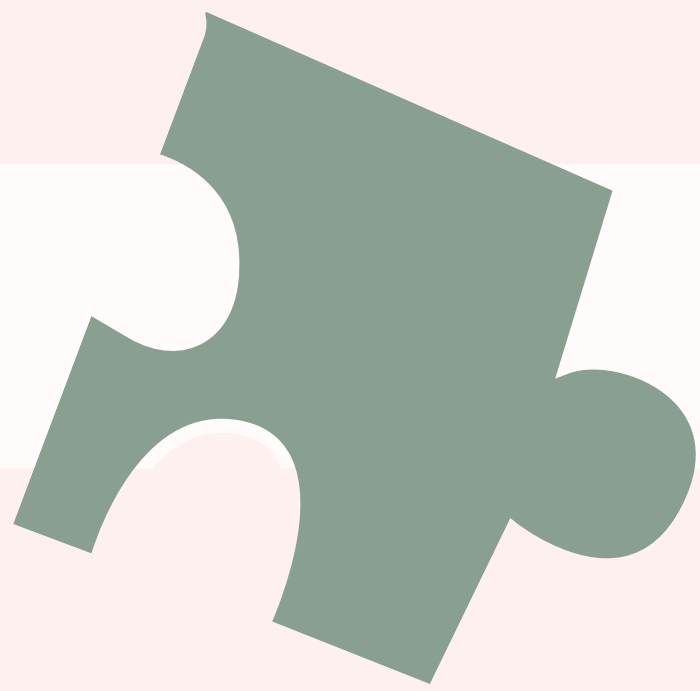


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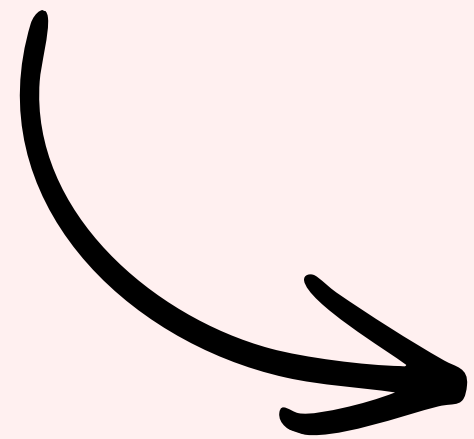


$$\mathcal{M} = \begin{pmatrix} 0 & m_D & 0 & 0 \\ m_D^T & M_N & \Lambda_L & \Lambda_R \\ 0 & \Lambda_L^T & 0 & M_X \\ 0 & \Lambda_R^T & M_X^T & 0 \end{pmatrix}$$



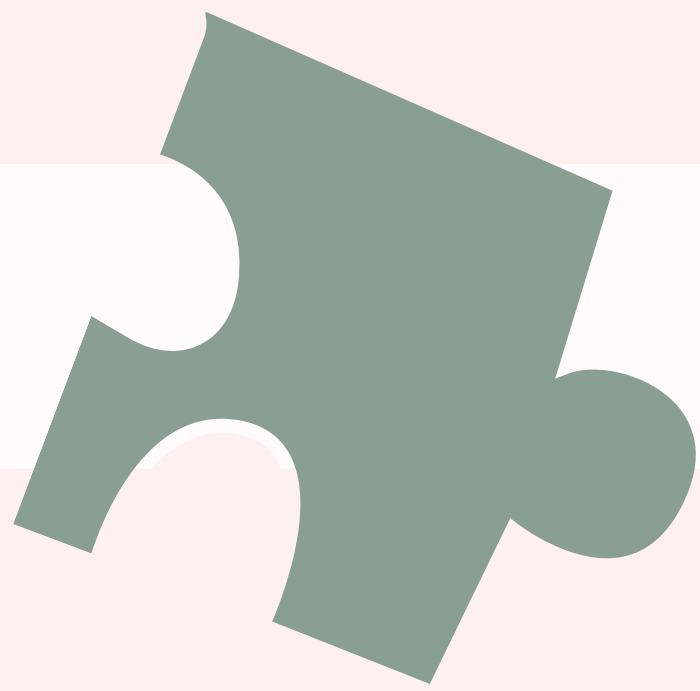
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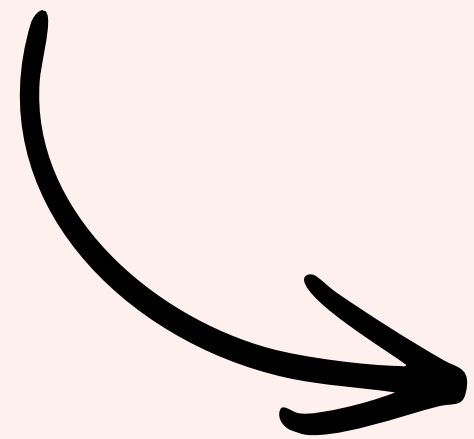
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$$m_D \equiv \frac{v_H Y_\nu}{\sqrt{2}}$$



See-saw-like mechanism

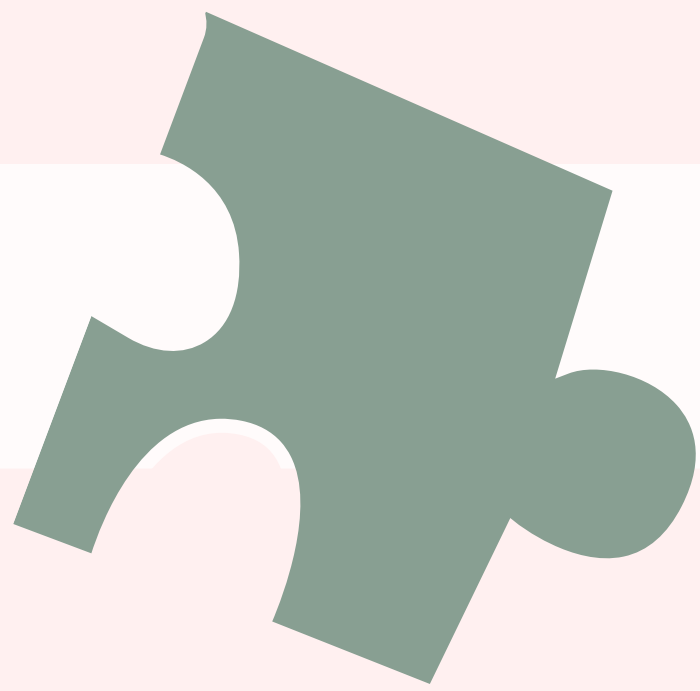
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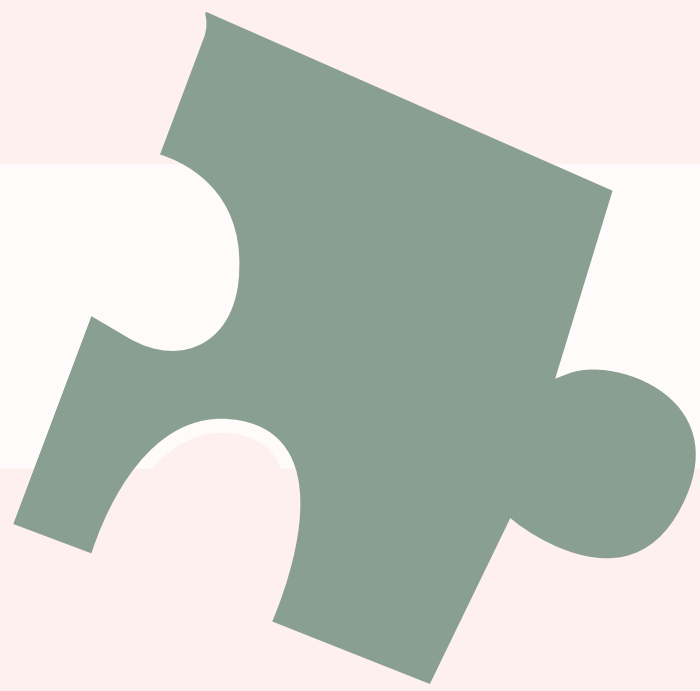
$$m_D \equiv \frac{v_H Y_\nu}{\sqrt{2}}$$

$$\Lambda_{R,L} \equiv \frac{v_\phi Y_{R,L}}{\sqrt{2}}$$



See-saw-like mechanism

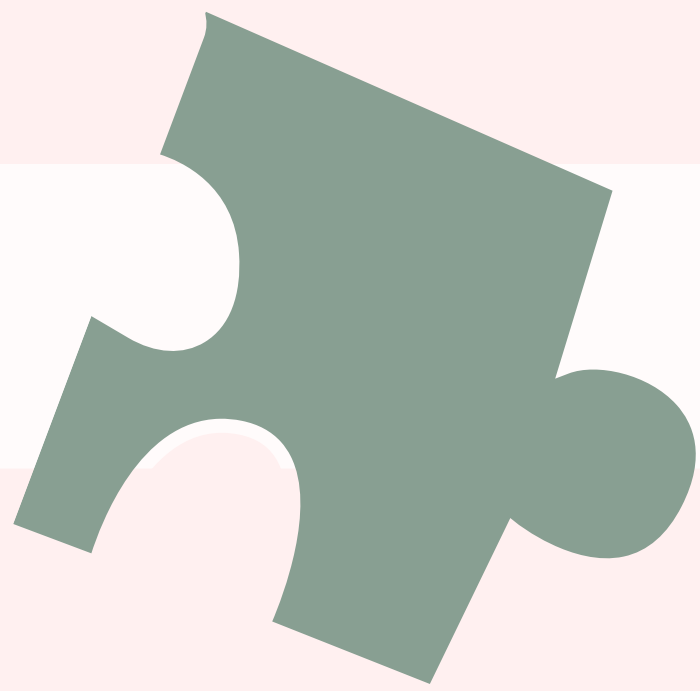
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See-saw-like mechanism

$$\mathcal{M} = \begin{pmatrix} 0 & m_D & 0 & 0 \\ m_D^T & M_N & \Lambda_L & \Lambda_R \\ 0 & \Lambda_L^T & 0 & M_X \\ 0 & \Lambda_R^T & M_X^T & 0 \end{pmatrix}$$

$$m_\nu = \frac{m_D^2 M_X}{2\Lambda_L \Lambda_R - M_N M_X}$$

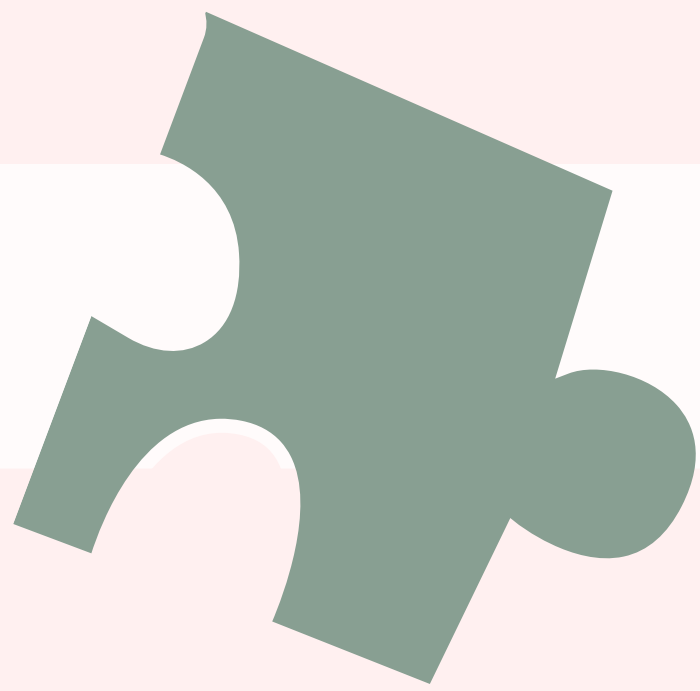


See-saw-like mechanism

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$$m_\nu = \frac{m_D^2 M_X}{2\Lambda_L \Lambda_R - M_N M_X}$$

$$U_{\nu N_i}^2 \propto \frac{m_\nu}{M_{N_i}}$$



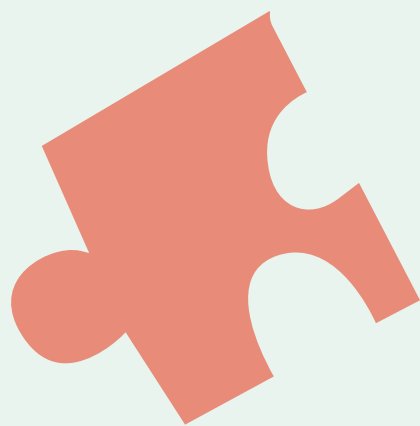
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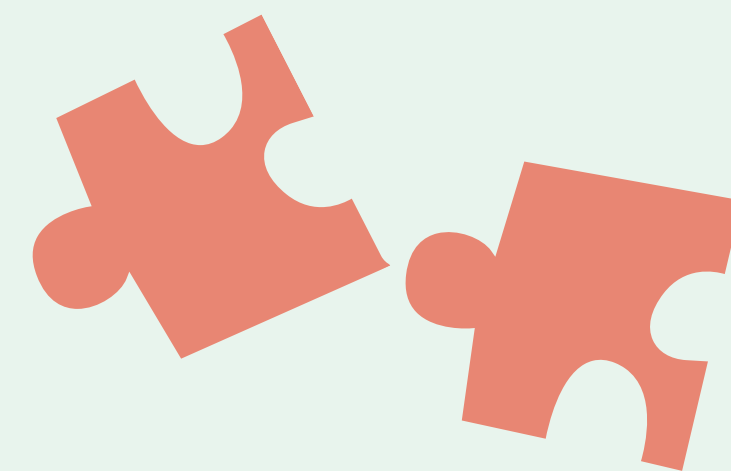
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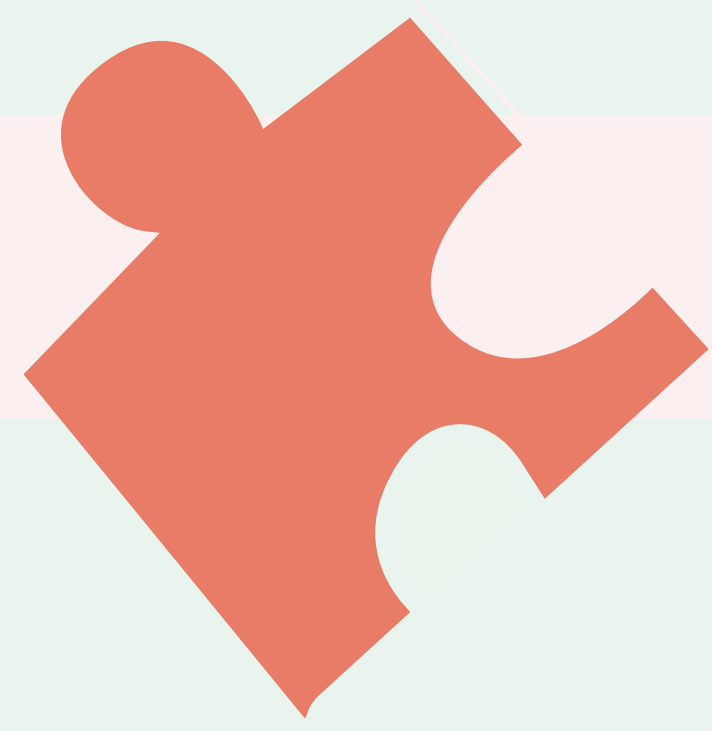
$$U_{\nu N_i}^2 \propto \frac{m_\nu}{M_{N_i}}$$

**diagonalization of the mass matrix leads to
light neutrino mass and active-sterile mixing**



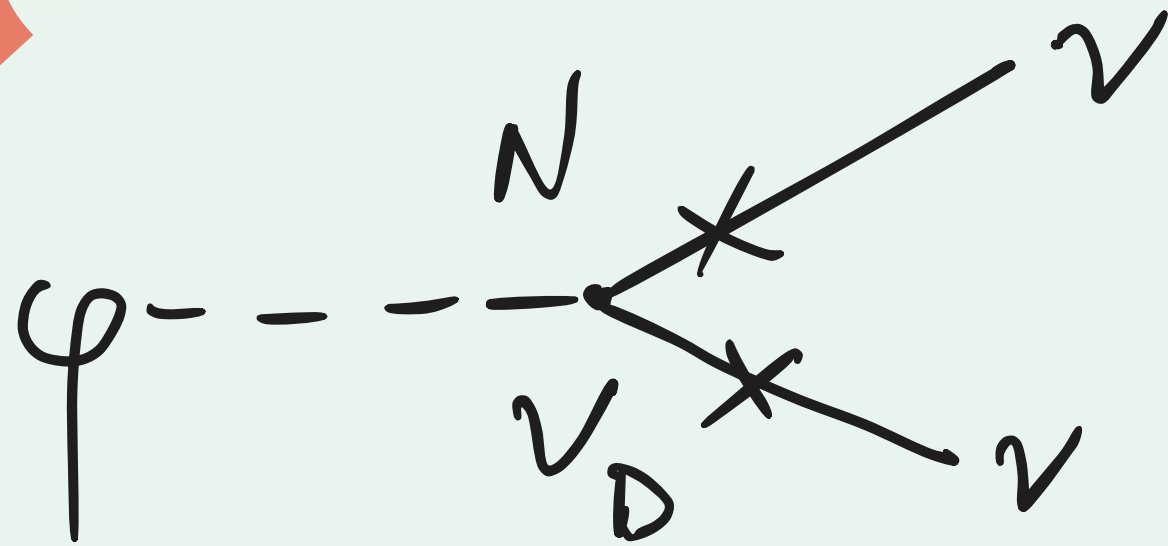
Let's not spoil BBN !



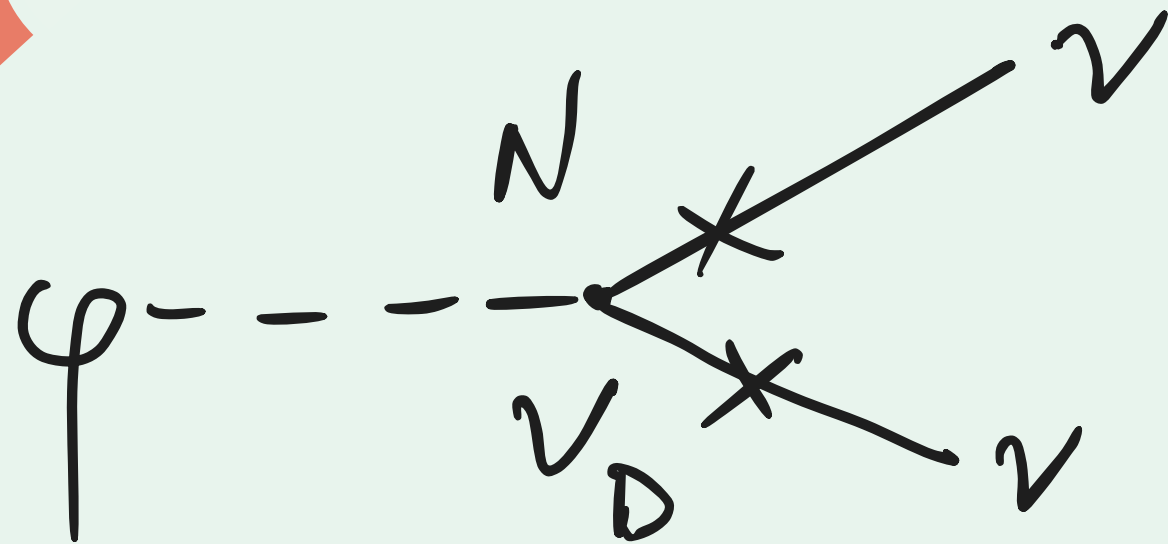


Scalar-neutrino coupling

Scalar-neutrino coupling

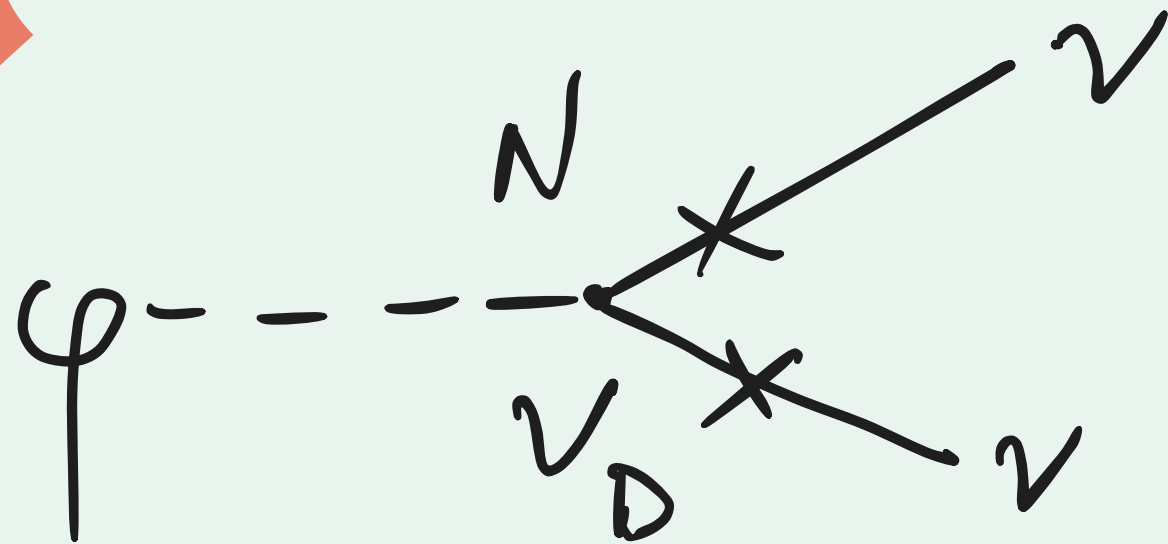


Scalar-neutrino coupling



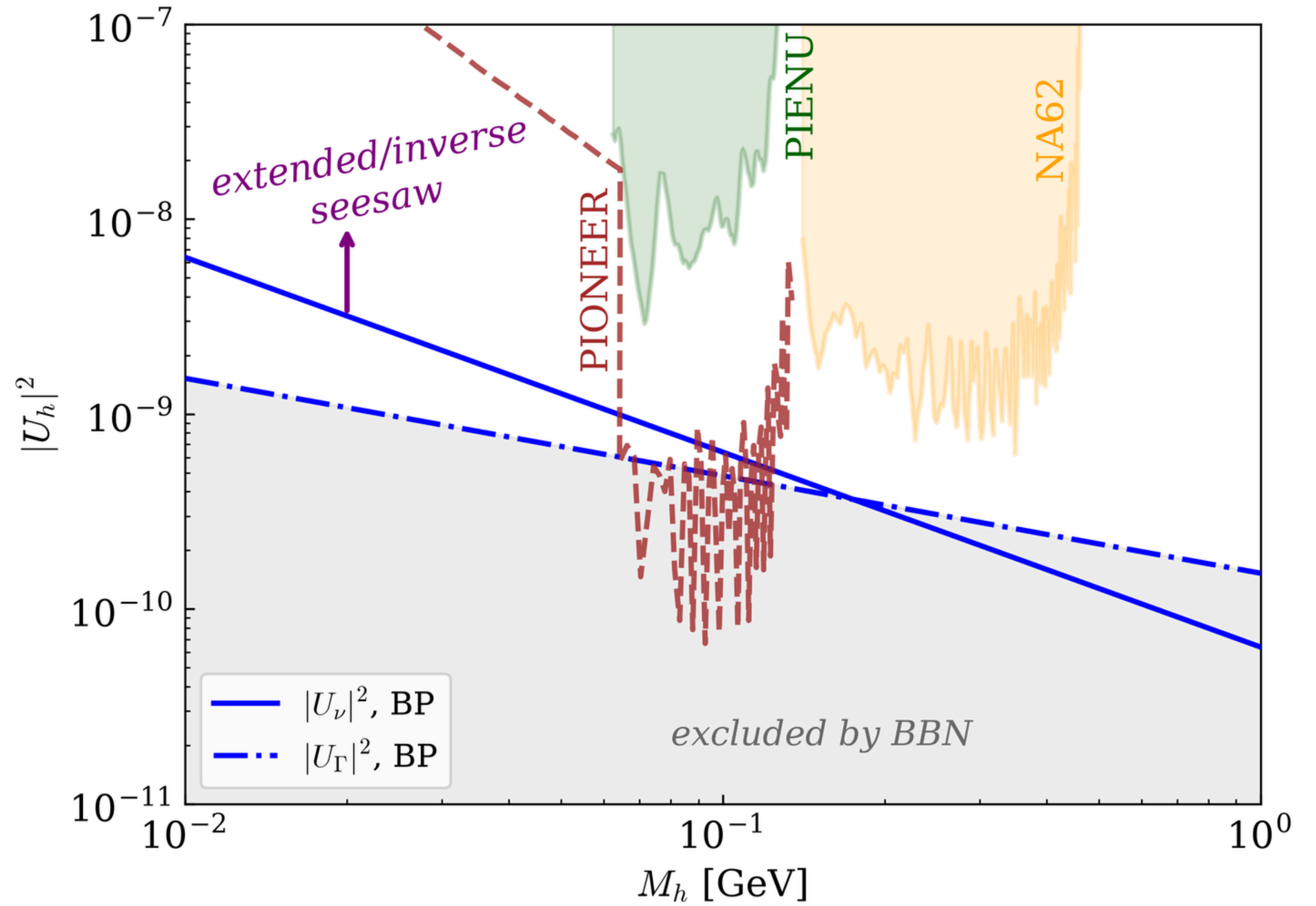
$$\Gamma_{\varphi \rightarrow \nu\nu} = \frac{m_\varphi Y_D^2 U_{\nu N}^2 U_{\nu\nu D}^2}{16\pi}$$

Scalar-neutrino coupling



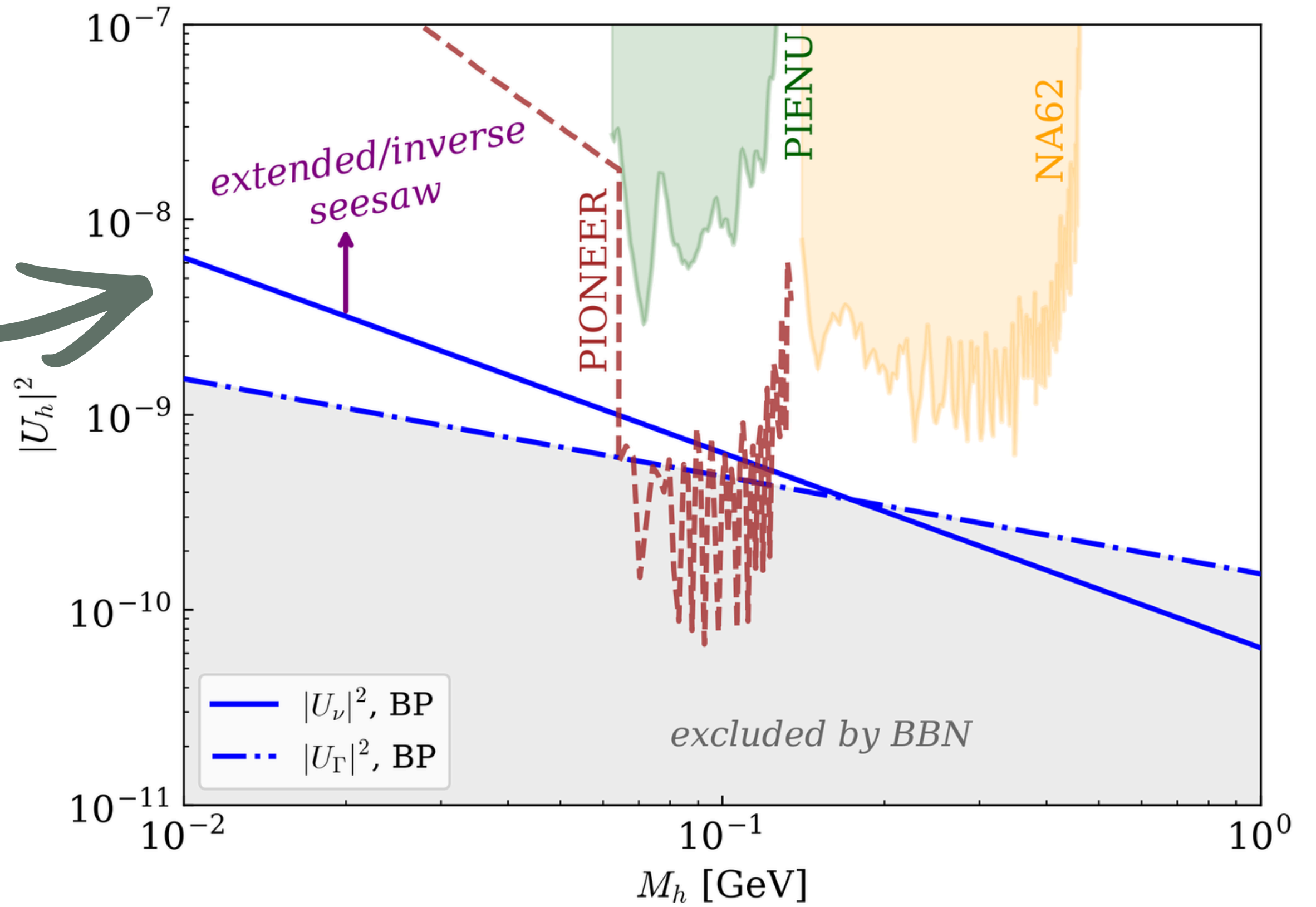
$$\Gamma_{\phi \rightarrow \nu\nu} = \frac{m_\phi Y_D^2 U_{\nu N}^2 U_{\nu\nu D}^2}{16\pi}$$

ϕ promptly decays into light neutrinos
helping to avoid BBN constraints



$$m_\nu = 0.05 \text{ eV}$$

$$U_\nu^2(M_h)$$



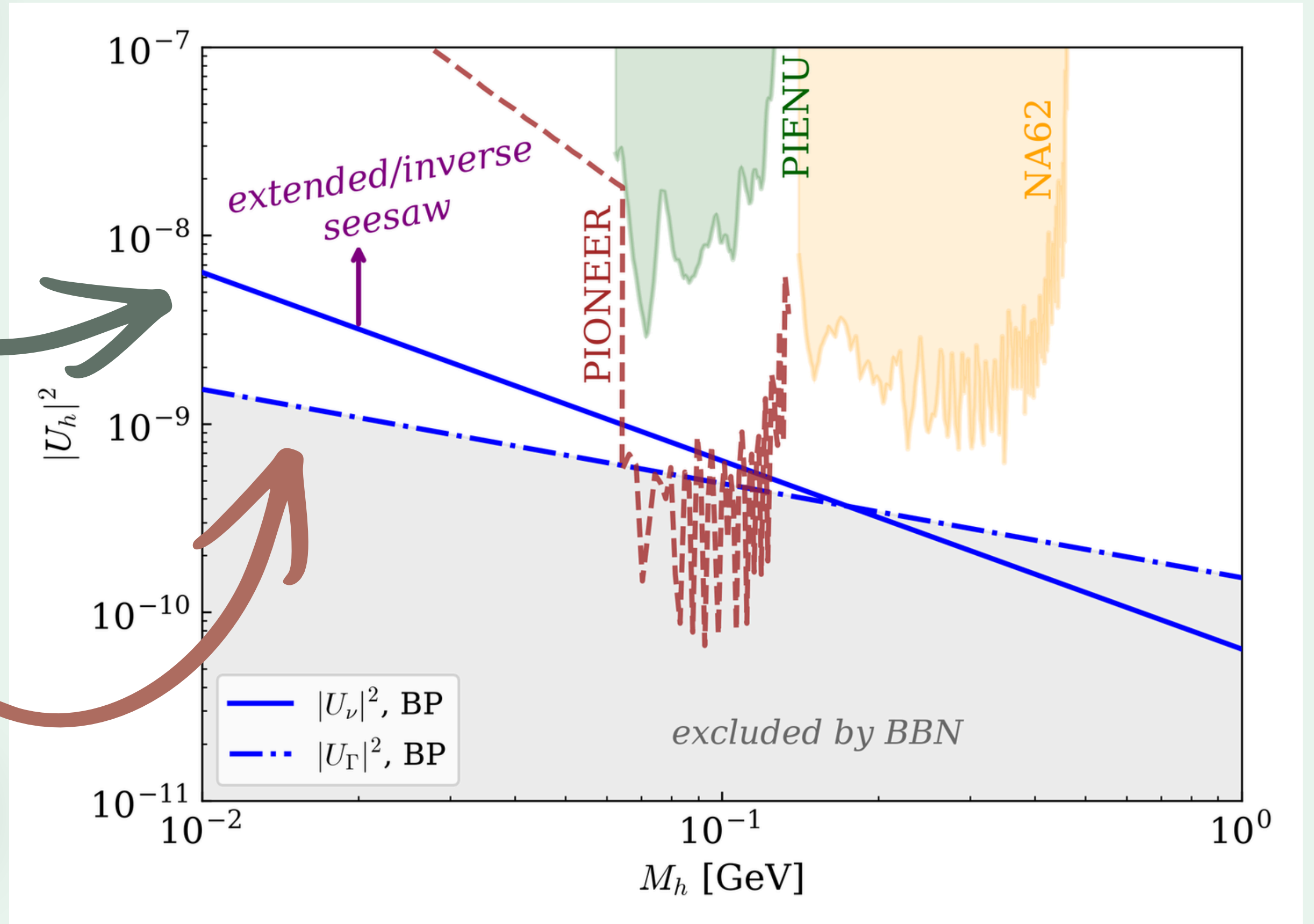
$$m_\nu = 0.05 \text{ eV}$$

$$U_\nu^2(M_h)$$



$$U_{\Gamma_\varphi}^2(M_h)$$

$$\Gamma_{\text{BBN}} \simeq 6.58 \times 10^{-24} \text{ GeV}$$



$$m_\nu = 0.05 \text{ eV}$$

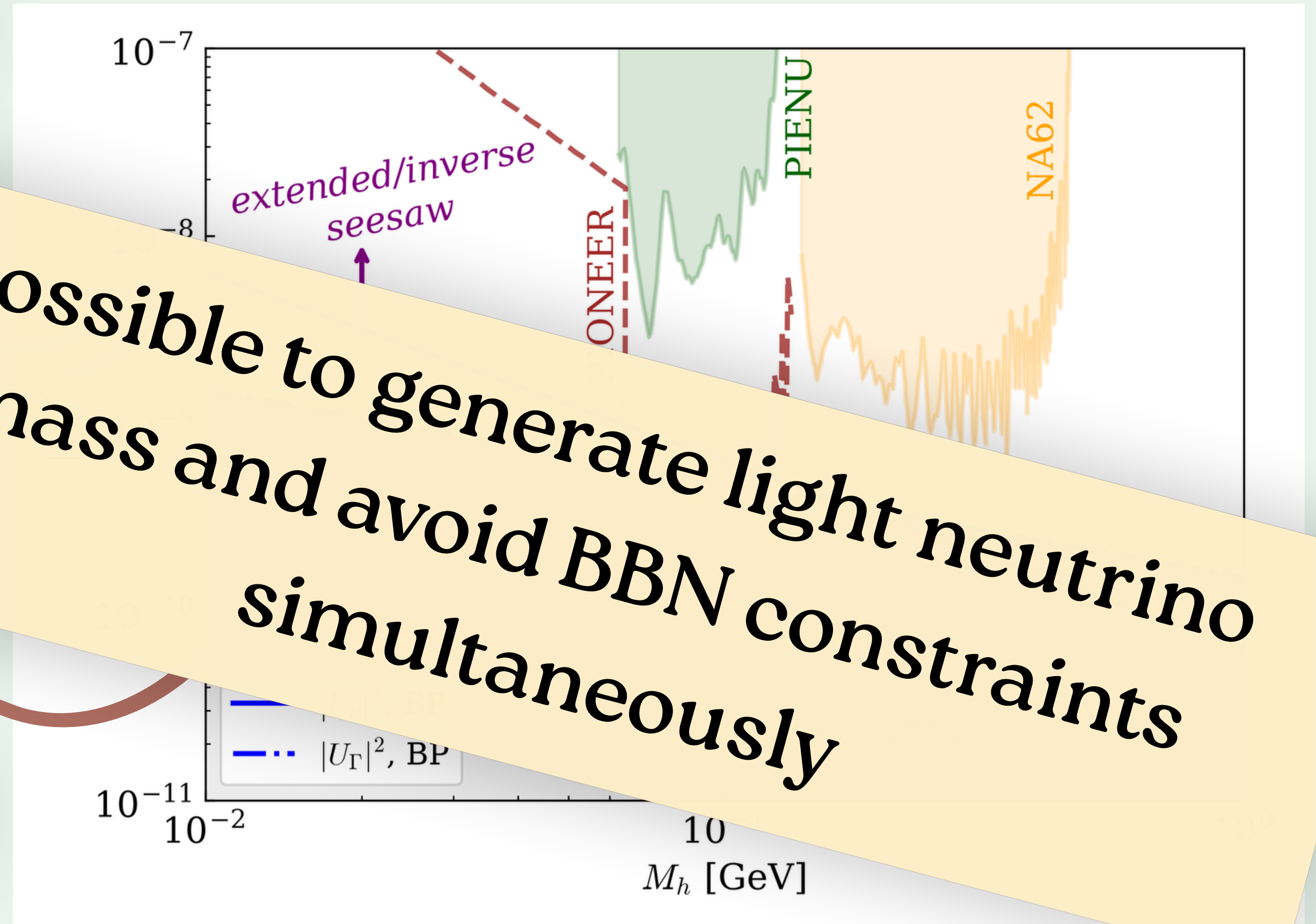
$$2(M_h)$$

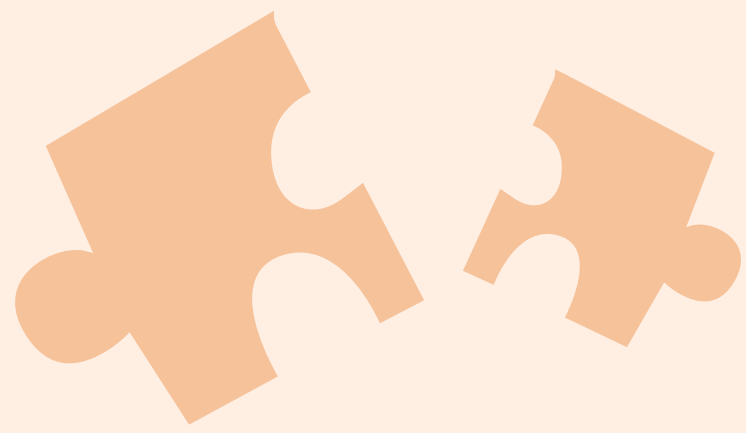


Possible to generate light neutrino mass and avoid BBN constraints simultaneously

$$U_{\Gamma\varphi}^2(M_h)$$

$$\Gamma_{\text{BBN}} \simeq 6.58 \times 10^{-24} \text{ GeV}$$



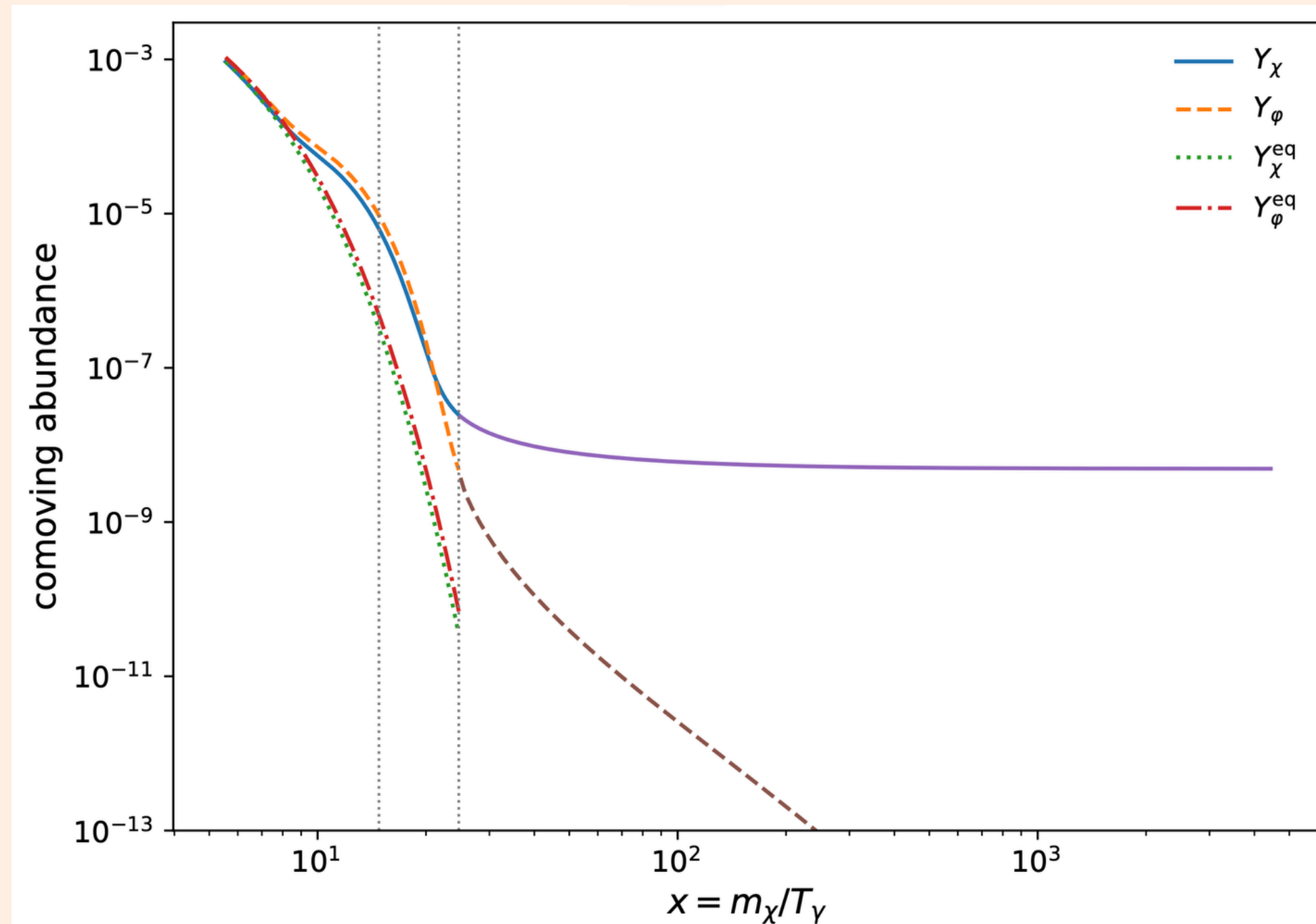


Thermal history

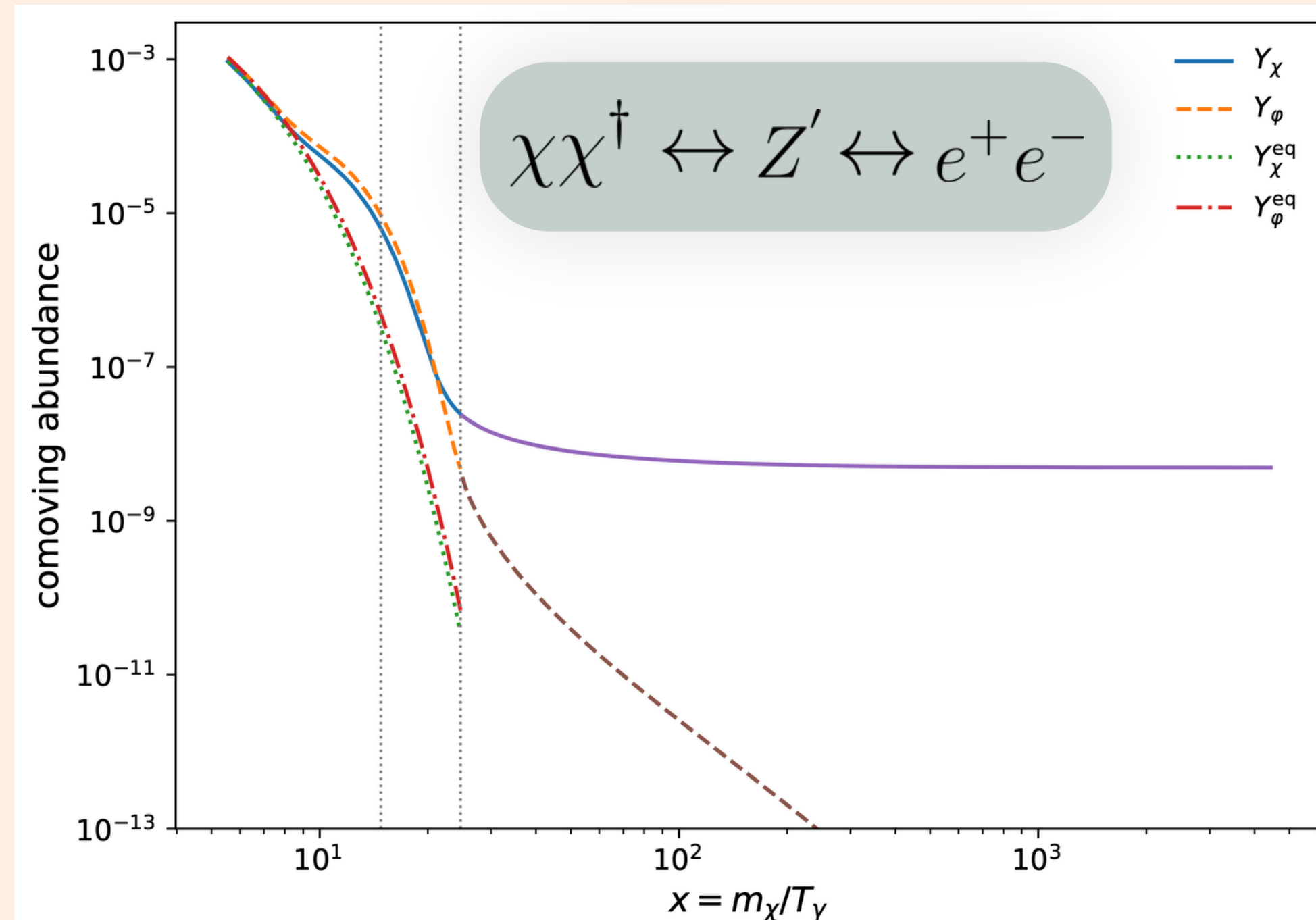
Thermal freeze-out



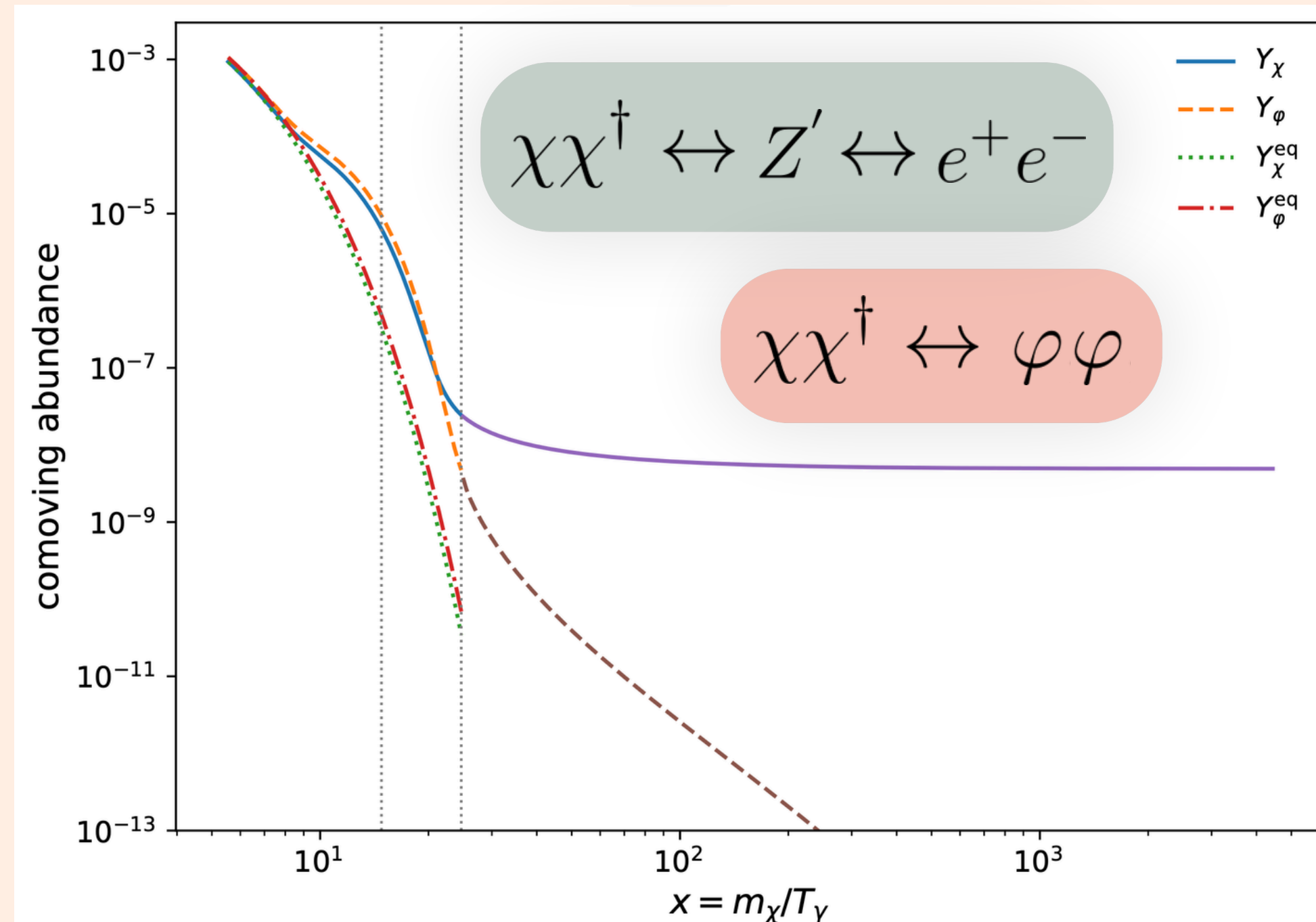
Thermal freeze-out



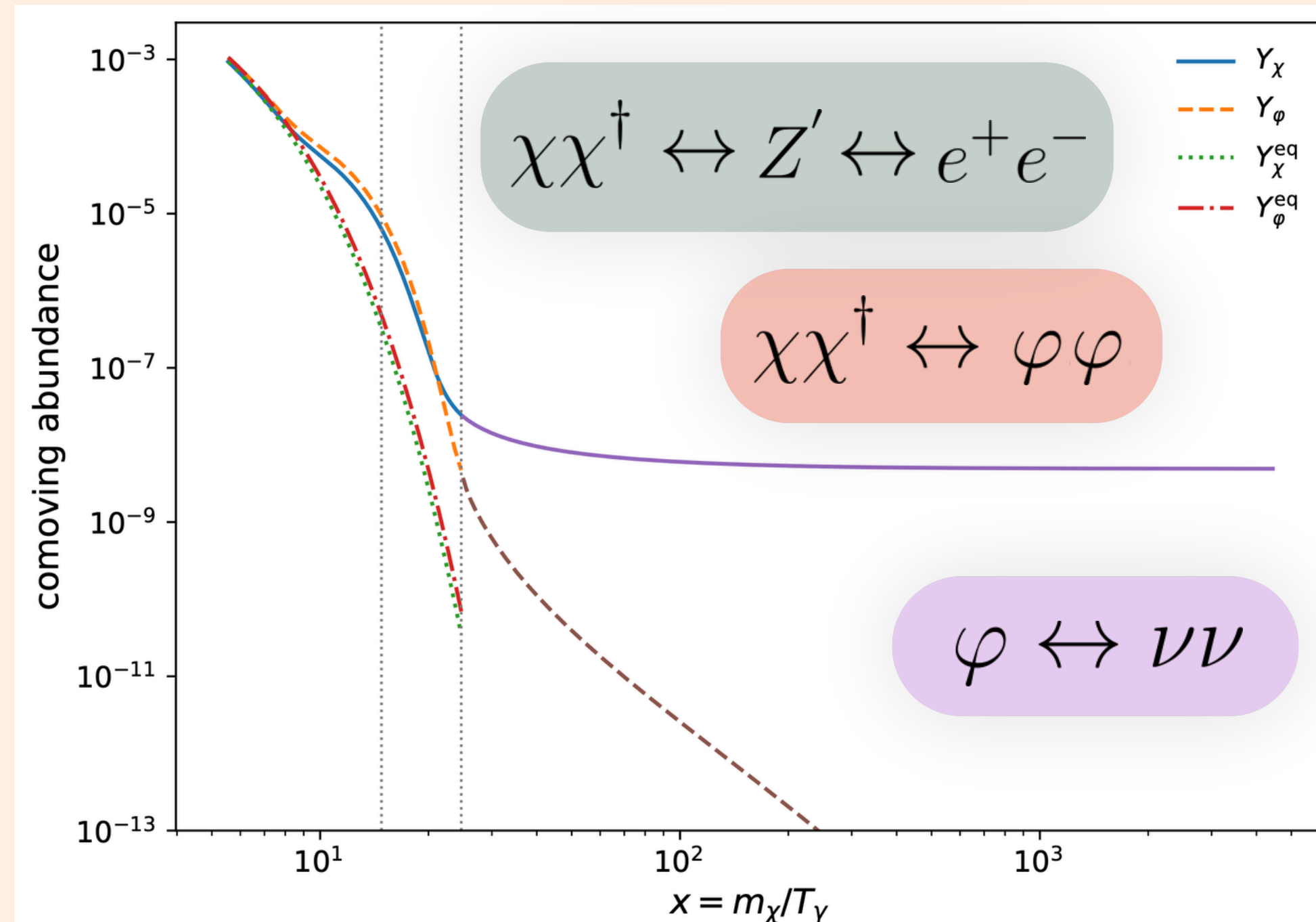
Thermal freeze-out



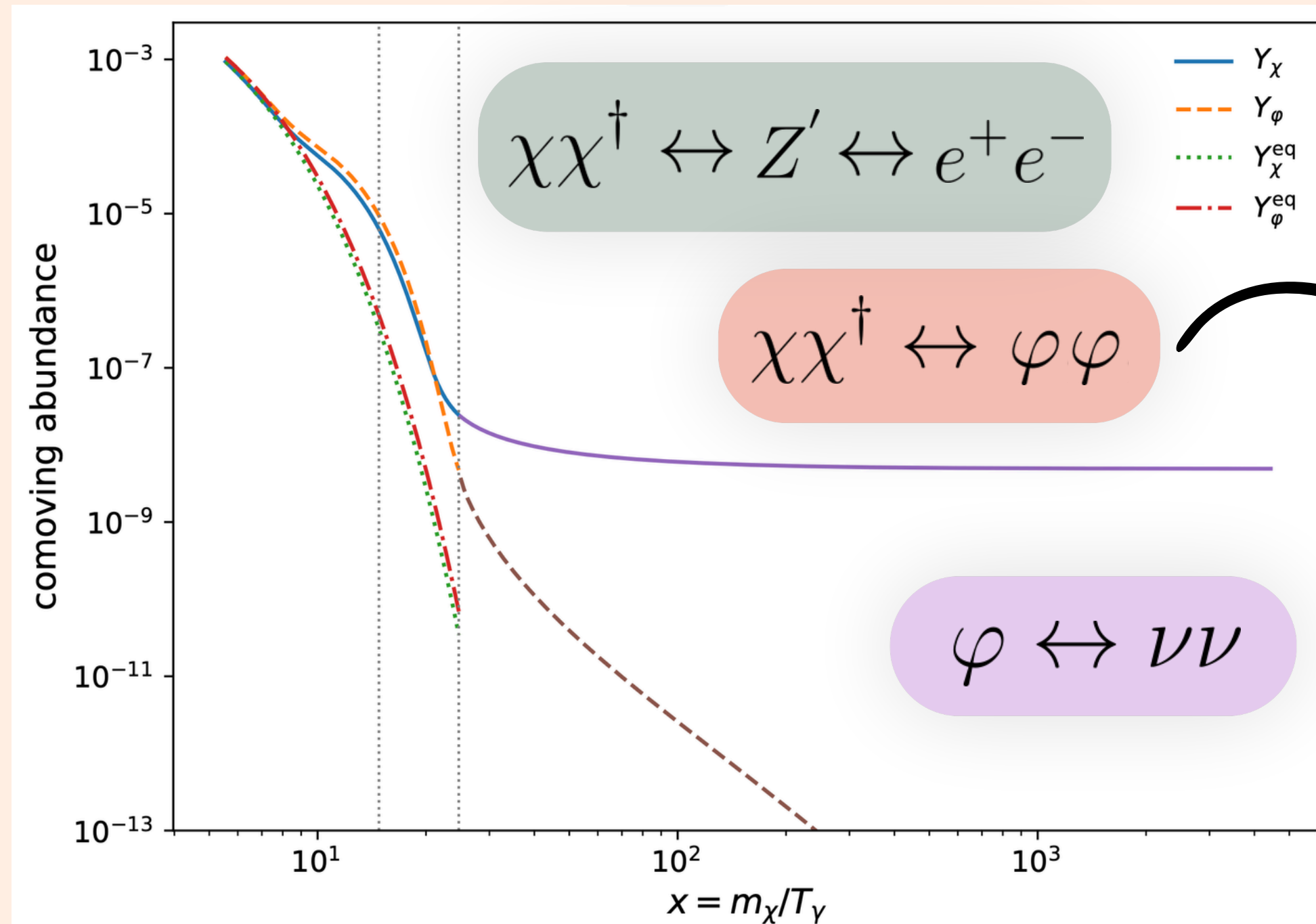
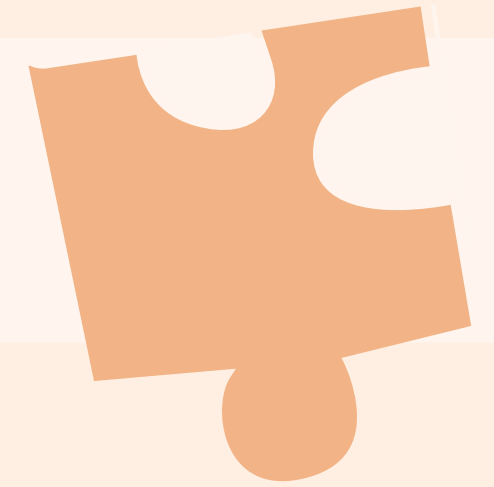
Thermal freeze-out



Thermal freeze-out



Thermal freeze-out



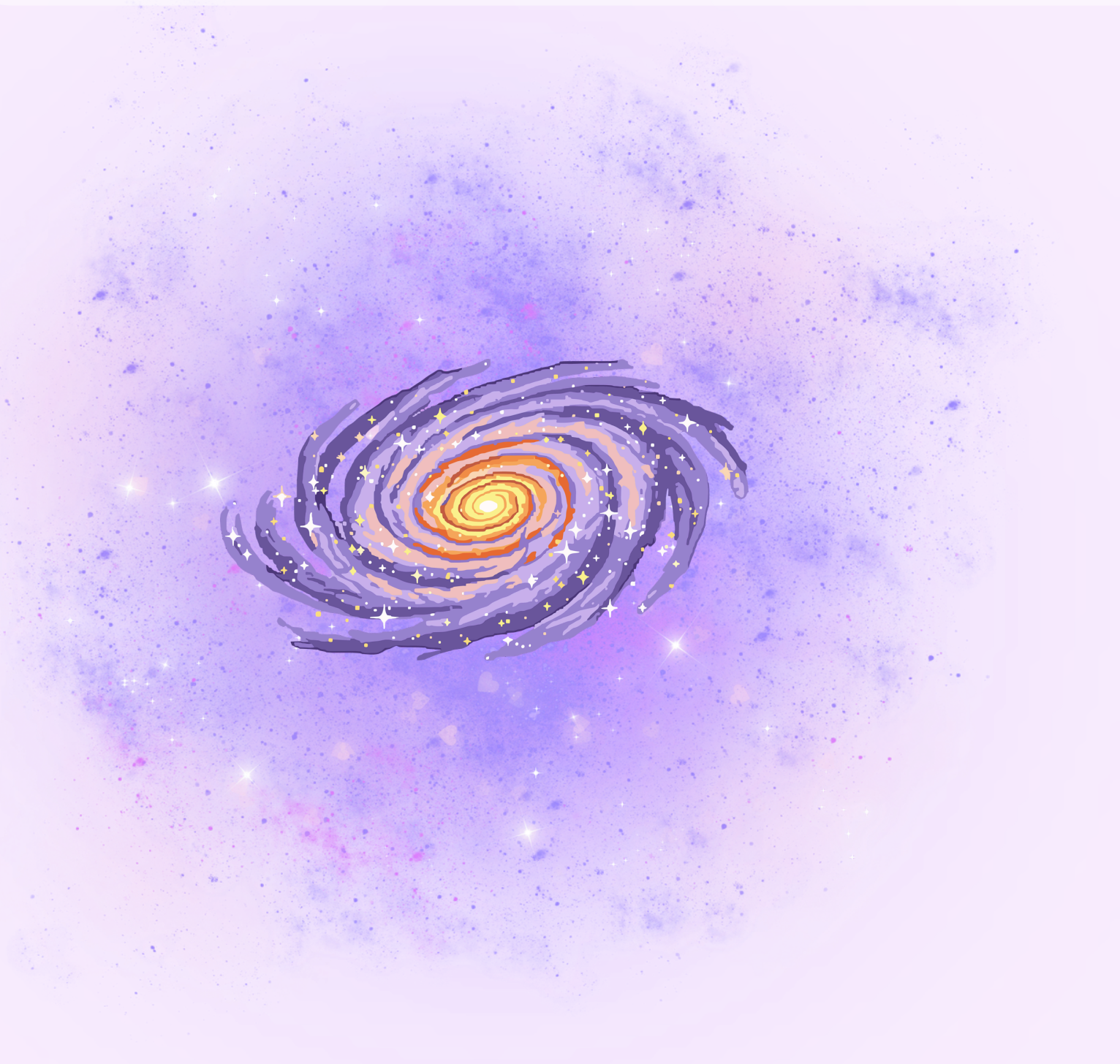
Relic abundance fixes

$$\lambda_{\chi\phi} = 6.20 \times 10^{-5}$$

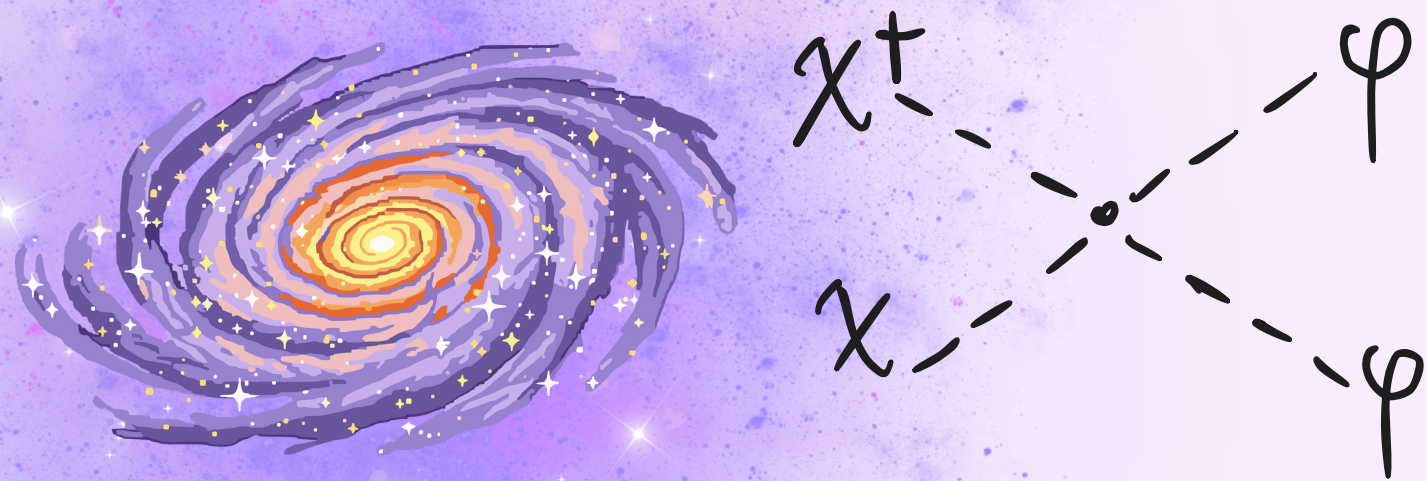
Predictions?

Neutrino signal

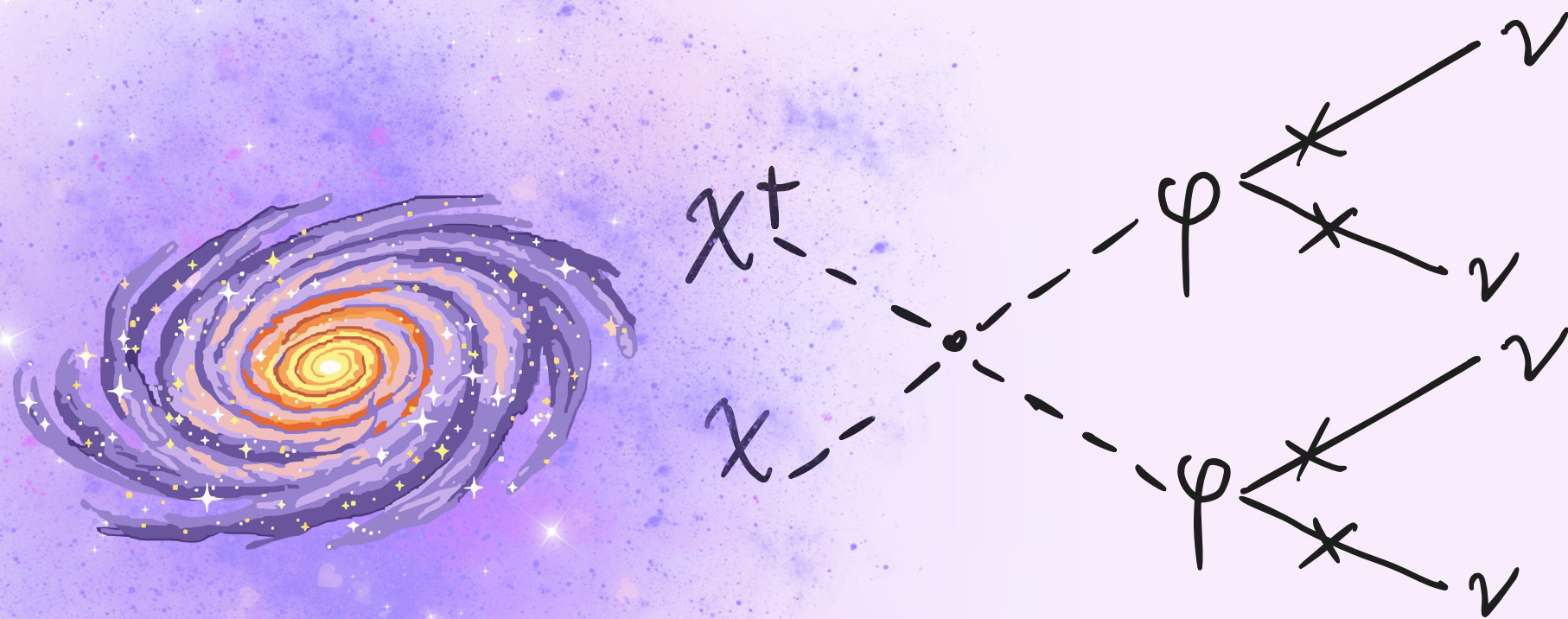
Neutrino signal



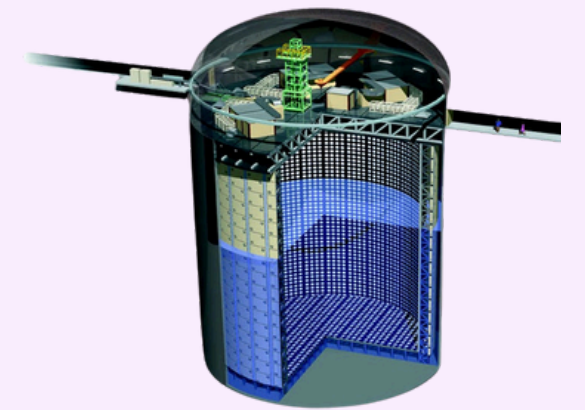
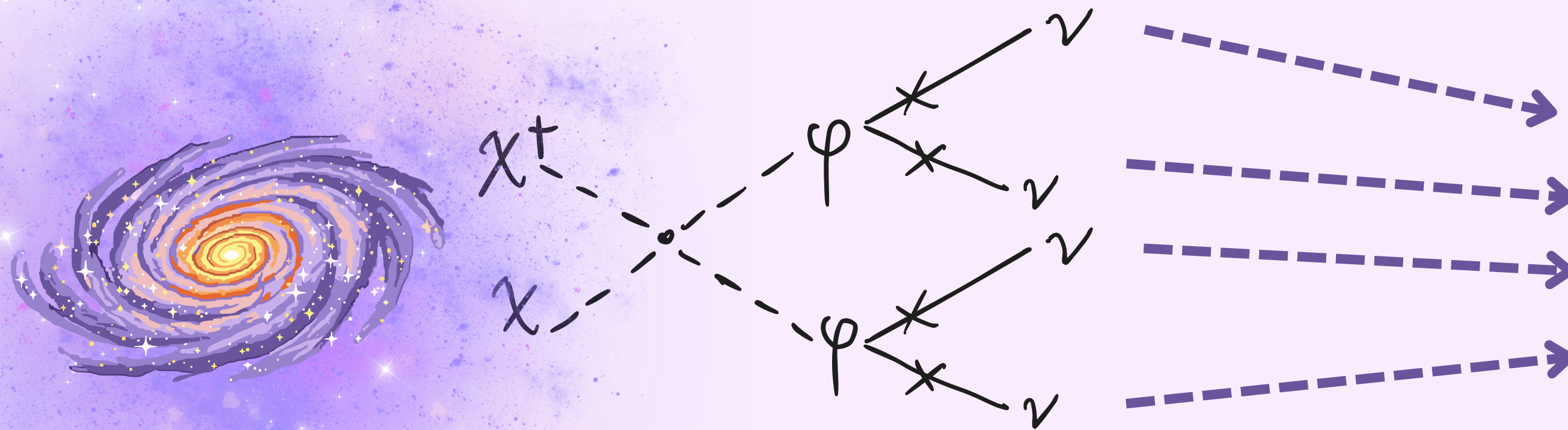
Neutrino signal



Neutrino signal



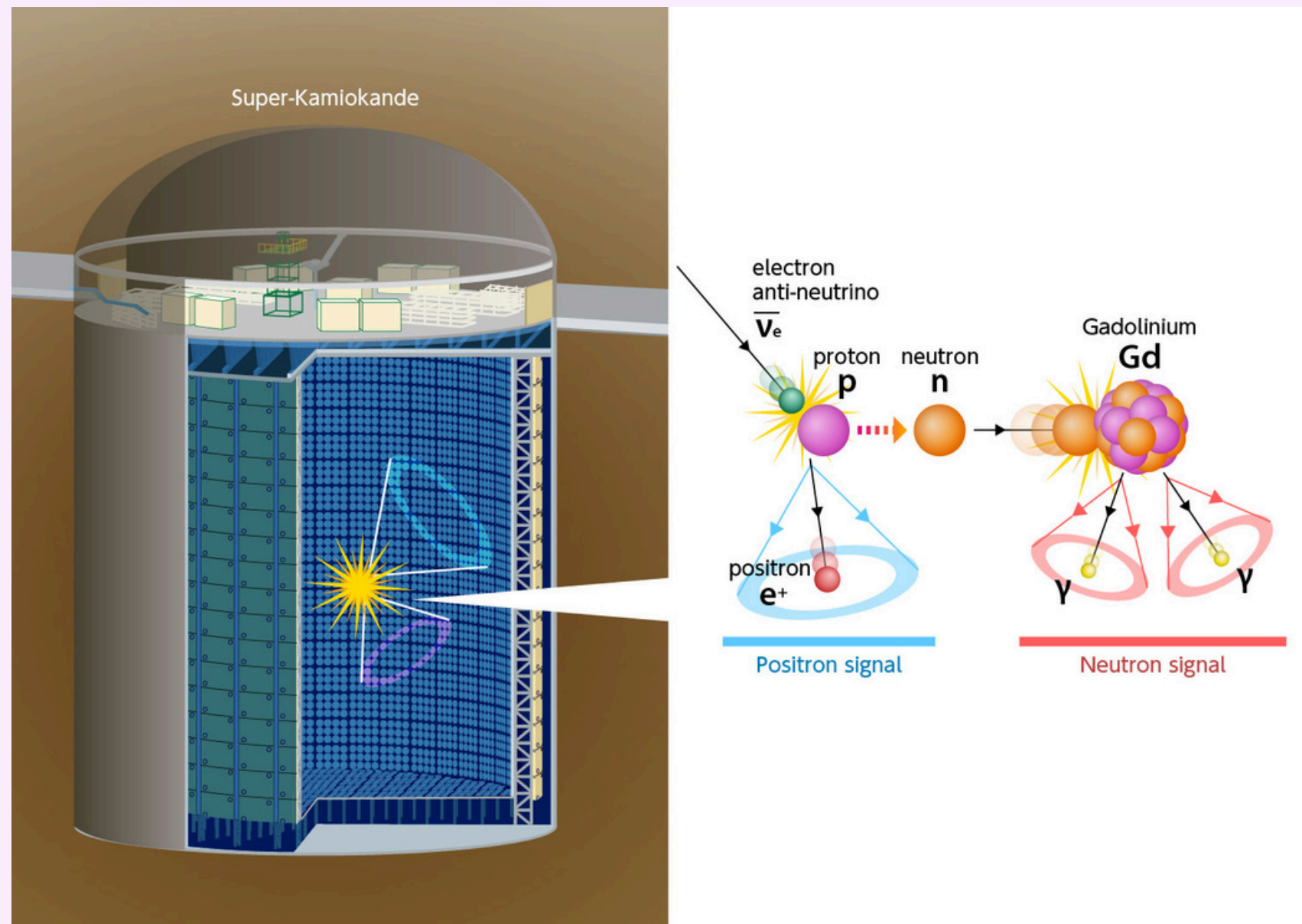
Neutrino signal @SK



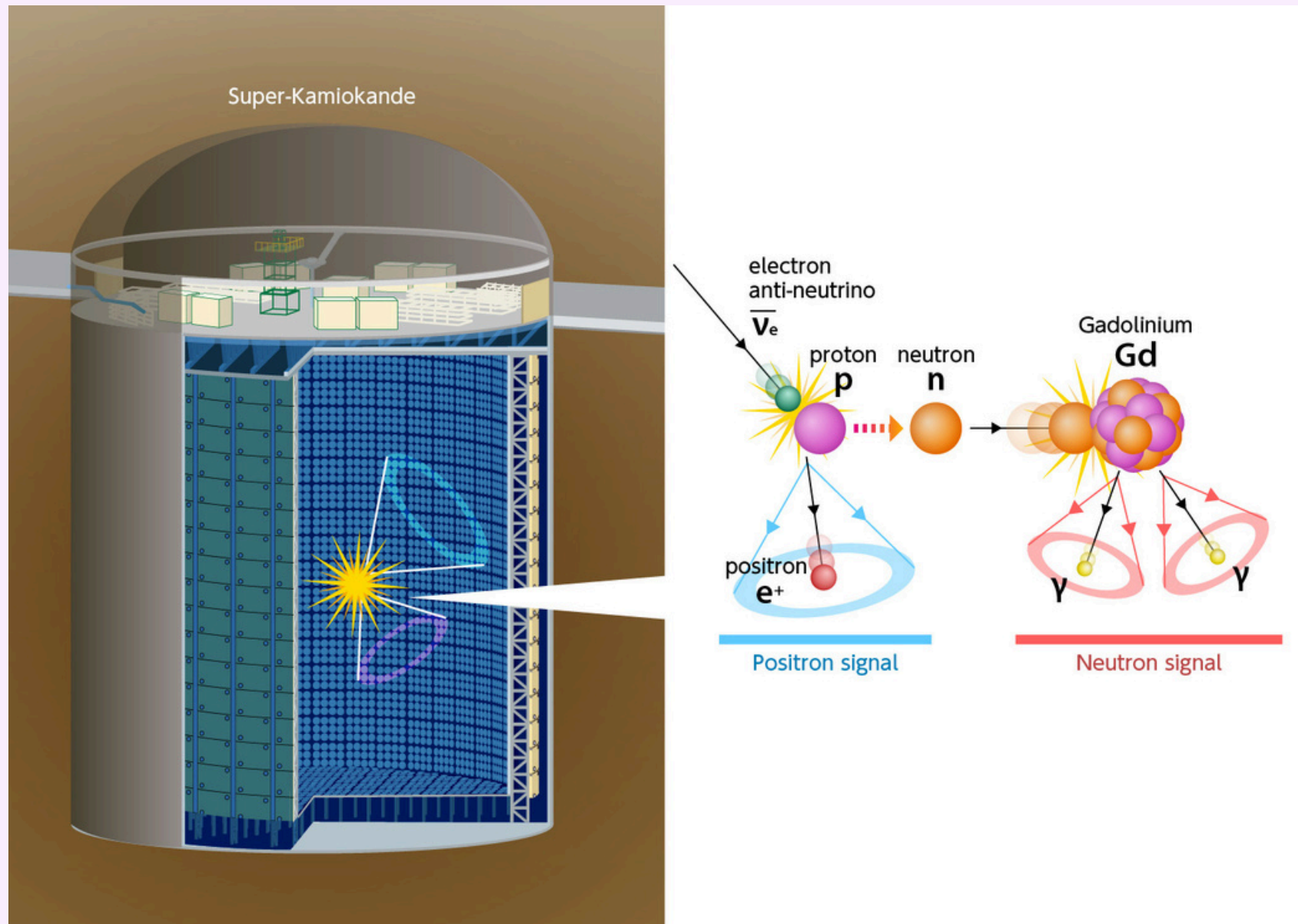
SUPER KAMIOKANDE

Neutrino signal @SK

Neutrino signal @SK

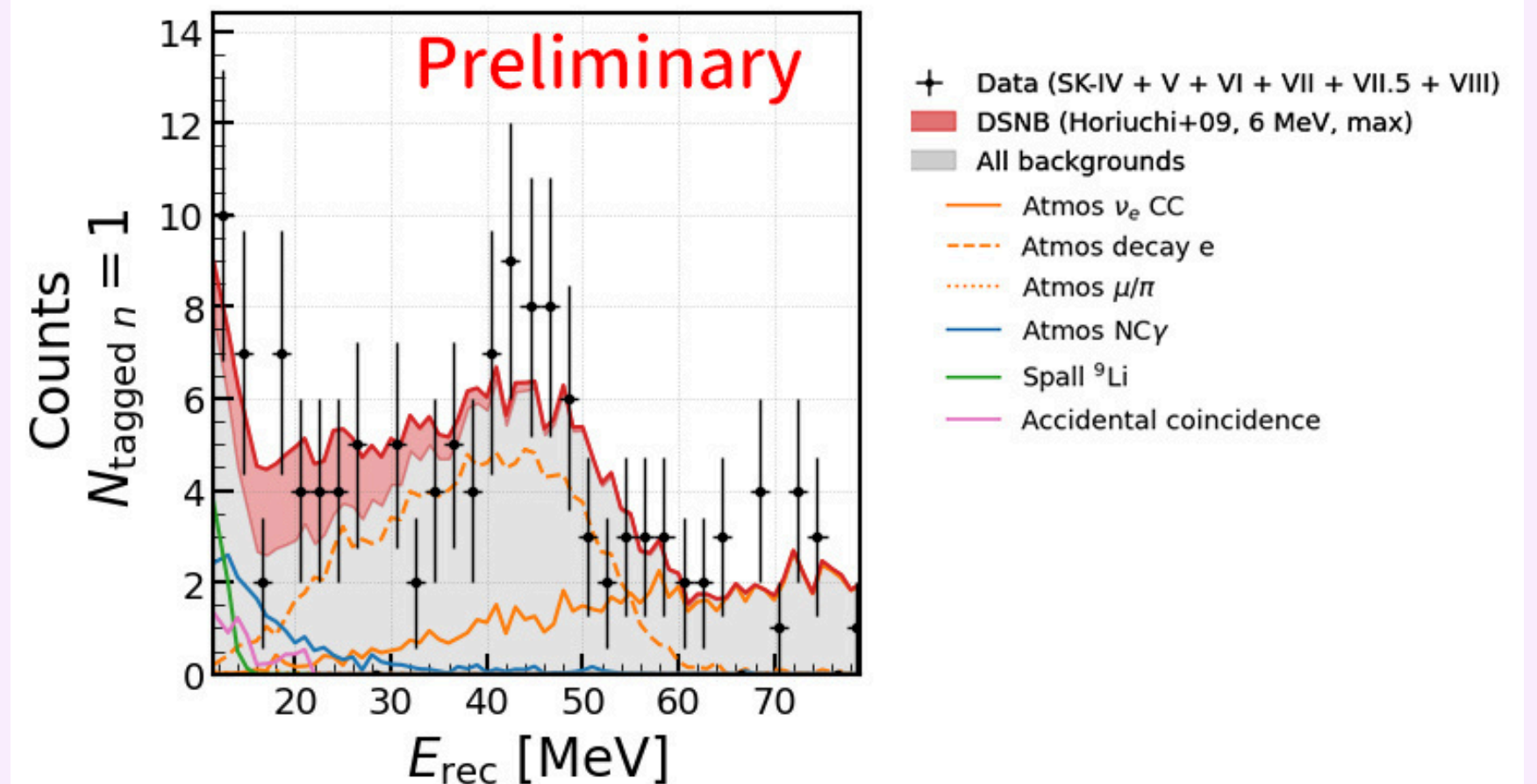


Neutrino signal @SK



Super-Kamiokande Reports the First Indication of the Diffuse Supernova Neutrino Background — A clue to the faint “whispers” imprinted across cosmic history —

2026.6.26 News



Neutrino signal @SK

Testing MeV dark matter with neutrino detectors

Sergio Palomares-Ruiz and Silvia Pascoli

IPPP, Department of Physics, Durham University, Durham DH1 3LE, United Kingdom

MeV particles have been advocated as Dark Matter (DM) candidates in different contexts. This hypothesis can be tested indirectly by searching for the Standard Model (SM) products of DM self-annihilations. As the signal from DM self-annihilations depends on the square of the DM density, we might expect a sizable flux of annihilation products from our galaxy. Neutrinos are the least detectable particles in the SM and a null signal in this channel would allow to set the most conservative bound on the total annihilation cross section. Here, we show that neutrino detectors with good energy resolution and low energy thresholds can not only set bounds on the annihilation cross section but actually test the hypothesis of the possible existence of MeV DM, i.e. test the values of the cross section required to explain the observed DM density. At present, the data in the (positron) energy interval [18–82] MeV of the Super-Kamiokande experiment is already able to put a very stringent bound on the annihilation cross section for masses between ~ 15 –130 MeV. Future large experiments, like megaton water-Čerenkov or large scintillator detectors, will improve the present limits and, if MeV DM exists, would be able to detect it.

PACS numbers: 14.60.St, 95.35.+d, 95.55.Vj

PALOMARES-RUIZ, PASCOLI [0710.5420]

Neutrino signal @SK

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PACS numbers: 14.60.St, 95.35.+d, 95.55.Vj

PALOMARES-RUIZ, PASCOLI [0710.5420]

Dark Matter Interpretation of the Super-Kamiokande Antineutrino Excess and Predictions for JUNO

Alessandro Granelli^{a,†}, Silvia Pascoli^{b,c,‡} and Salvador Rosauero-Alcaraz^{d,§}

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^d*Université Clermont-Auvergne, CNRS, LPCA, 63000 Clermont-Ferrand, France,*

**LPCA pour Laboratoire de Physique de Clermont Auvergne*

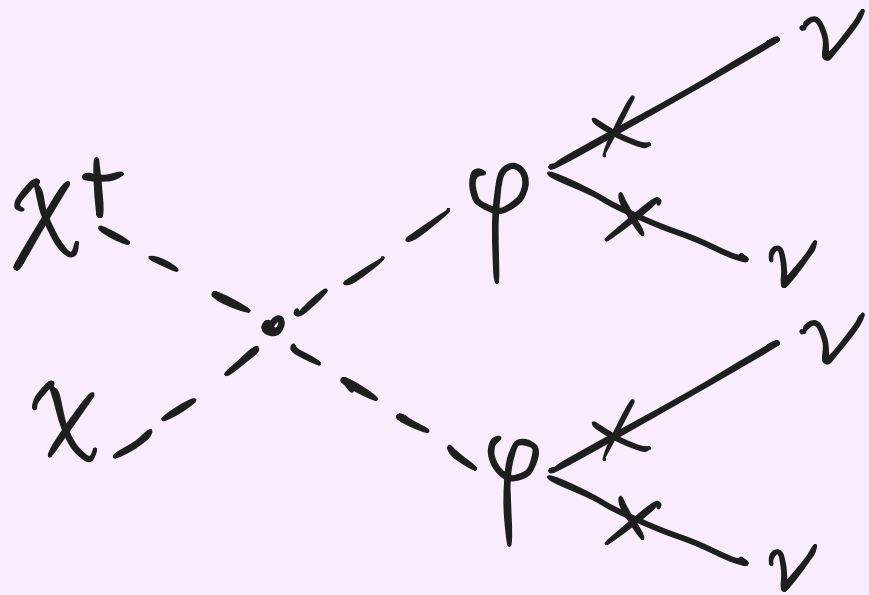
Abstract

Super-Kamiokande has reported a small excess of electron antineutrino events in the 20 MeV energy range, in the search for the diffuse supernova neutrino background. We interpret this signal as a possible indication of dark matter that annihilates dominantly into neutrinos, pointing to a thermal dark matter candidate with *s*-wave annihilation and with mass in the tens of MeV range. This mass scale naturally fits into rich dark sector extensions of the Standard Model. Neutrino experiments, including JUNO, will be able to test this hypothesis in the coming years.

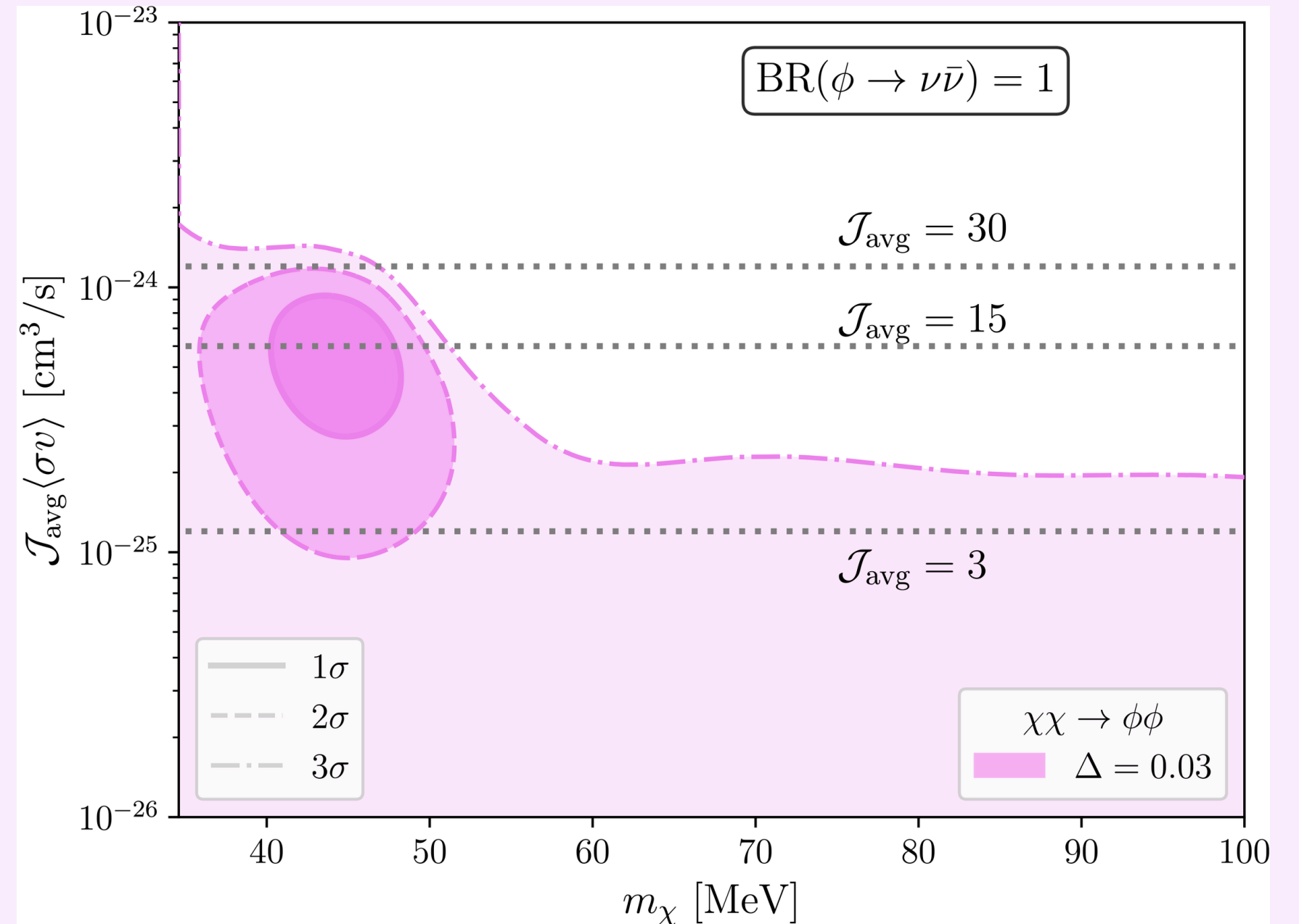
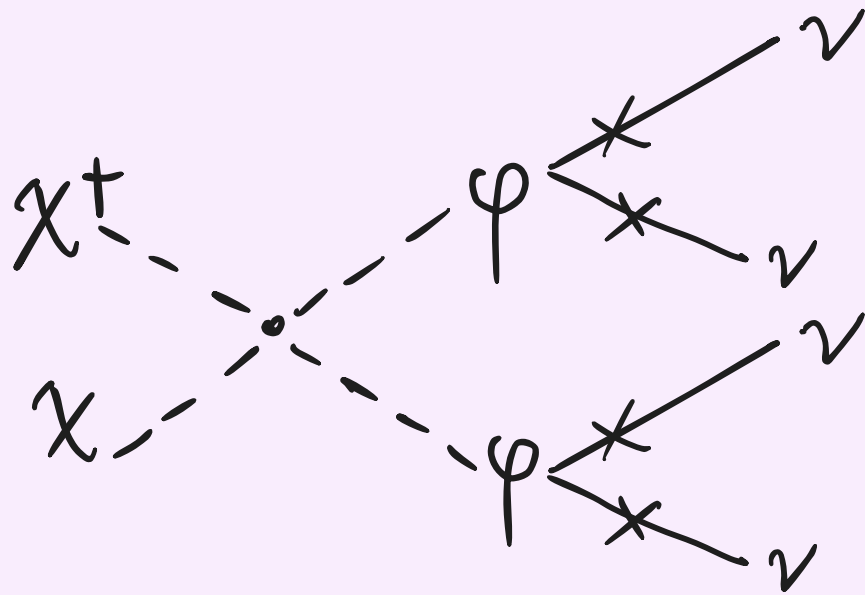
GRANELLI, PASCOLI, ROSAUERO-ALCARAZ [2605.20162]

19 May 2026

Neutrino signal @SK

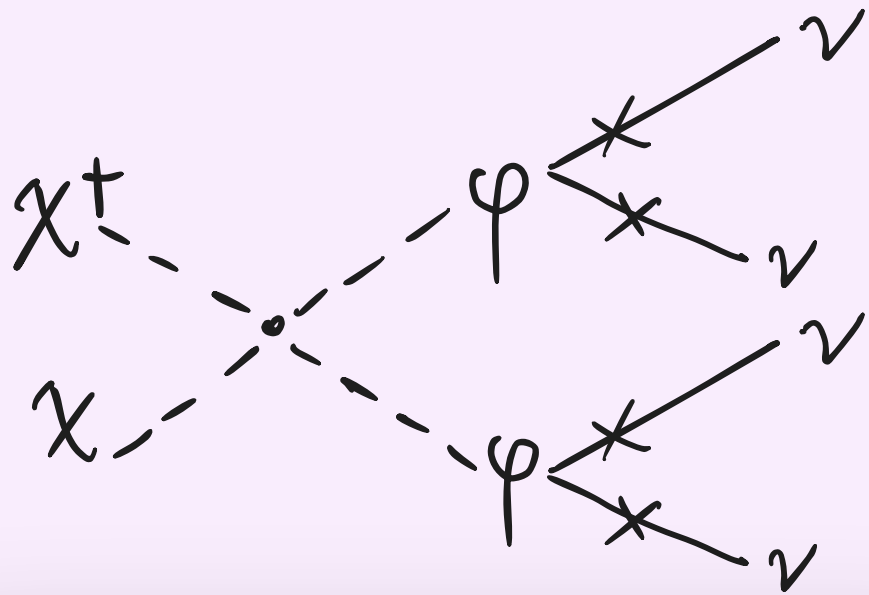


Neutrino signal @SK

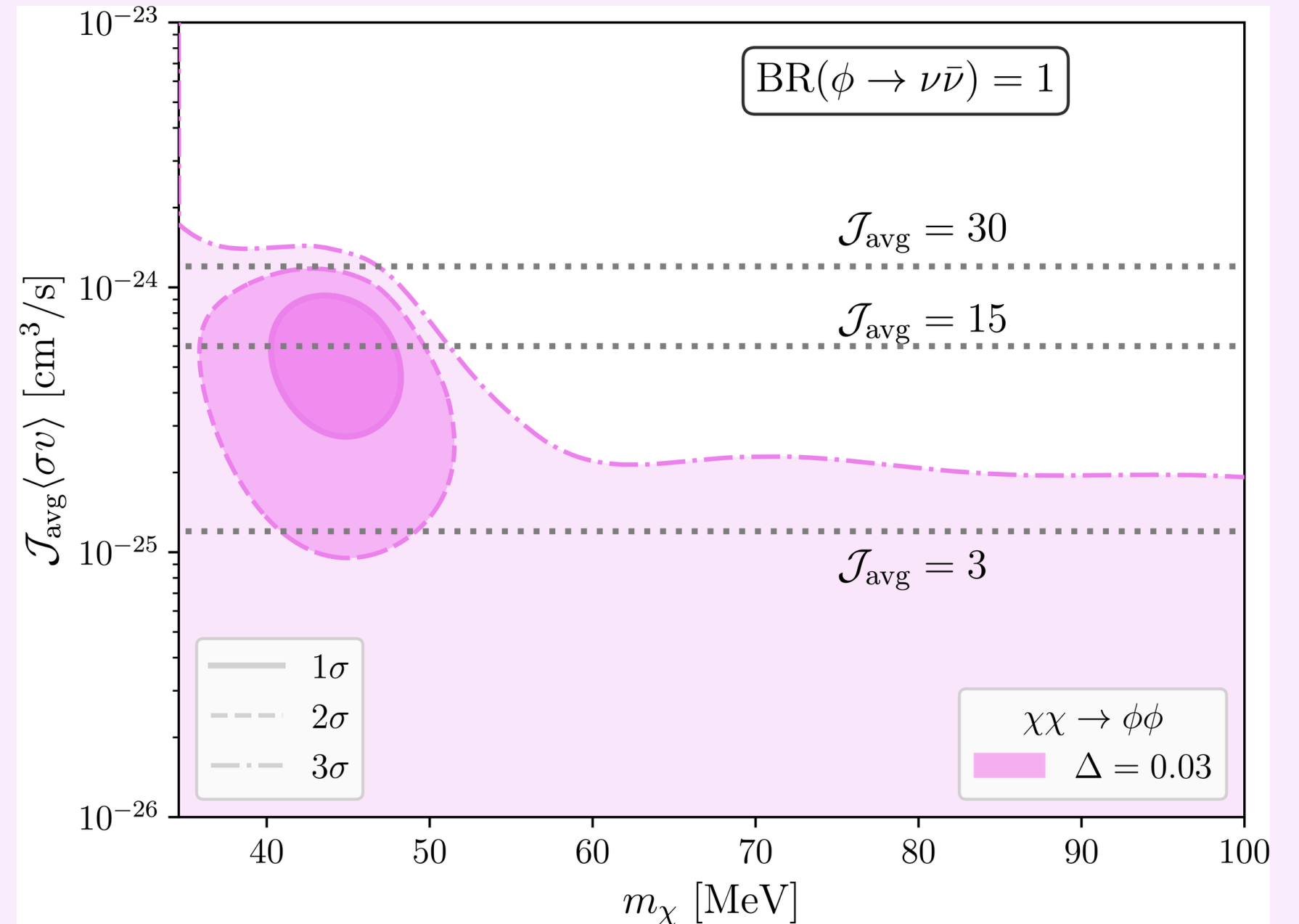


PLOT BY S. ROSAURO-ALCARAZ

Neutrino signal @SK



Relic abundance
cross section for
 $m_\chi \sim 40 \text{ MeV}$



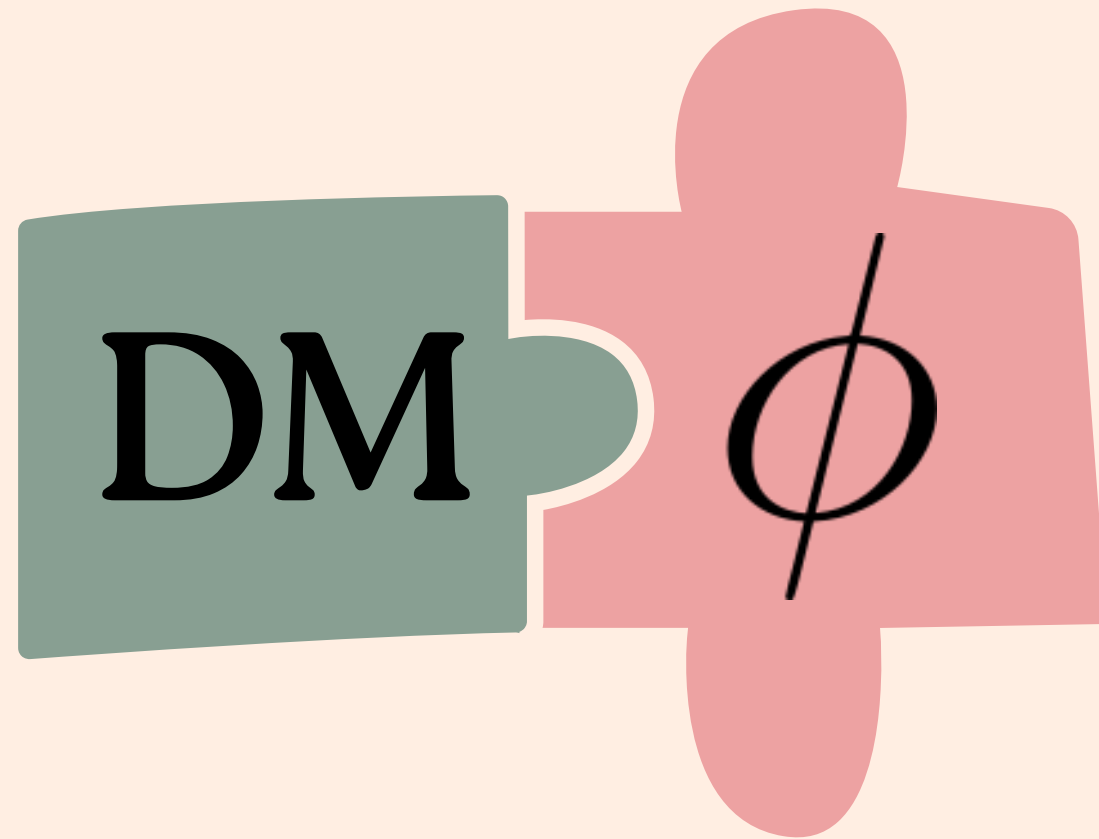
PLOT BY S. ROSAURO-ALCARAZ

Summary

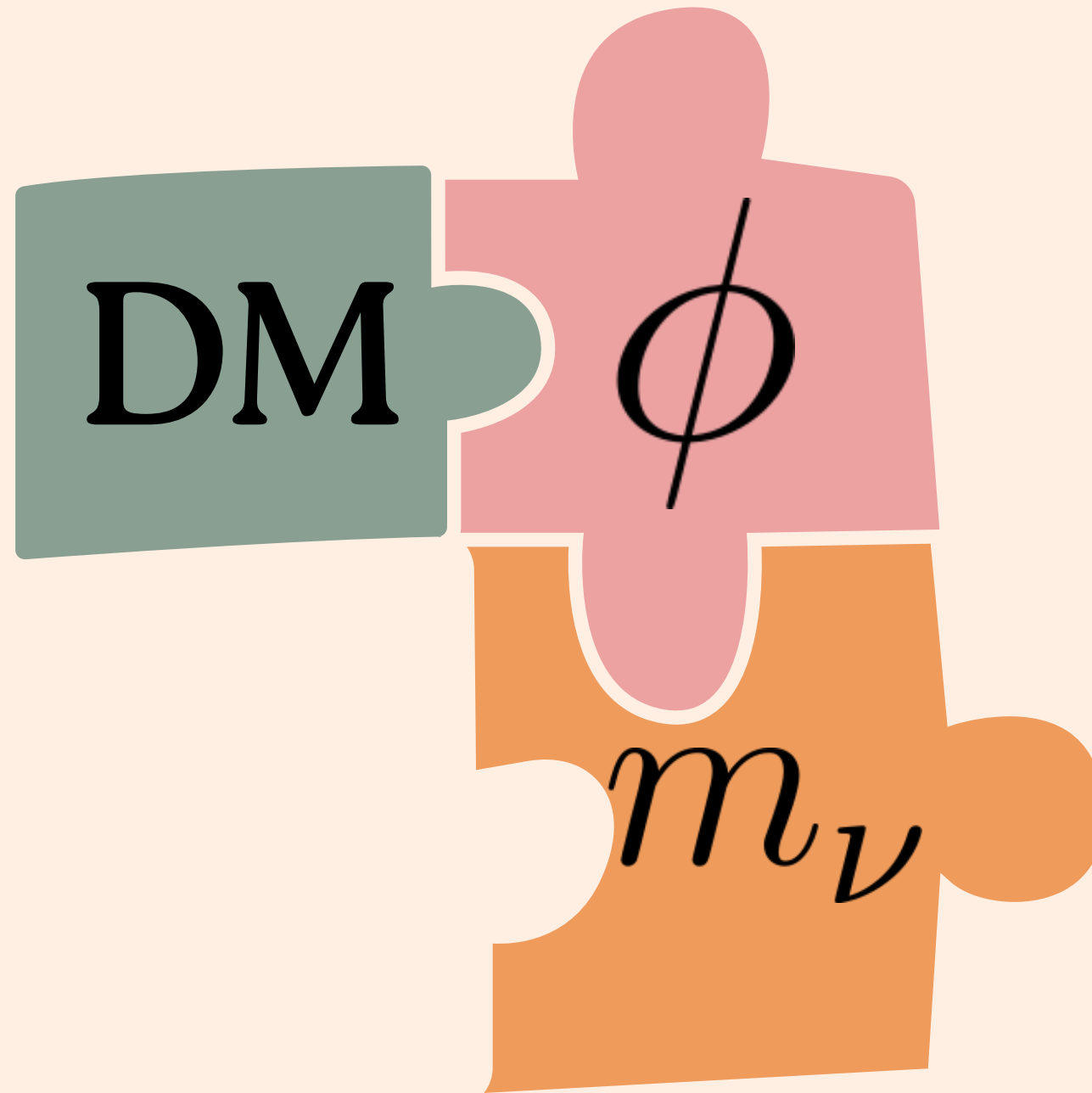
Summary



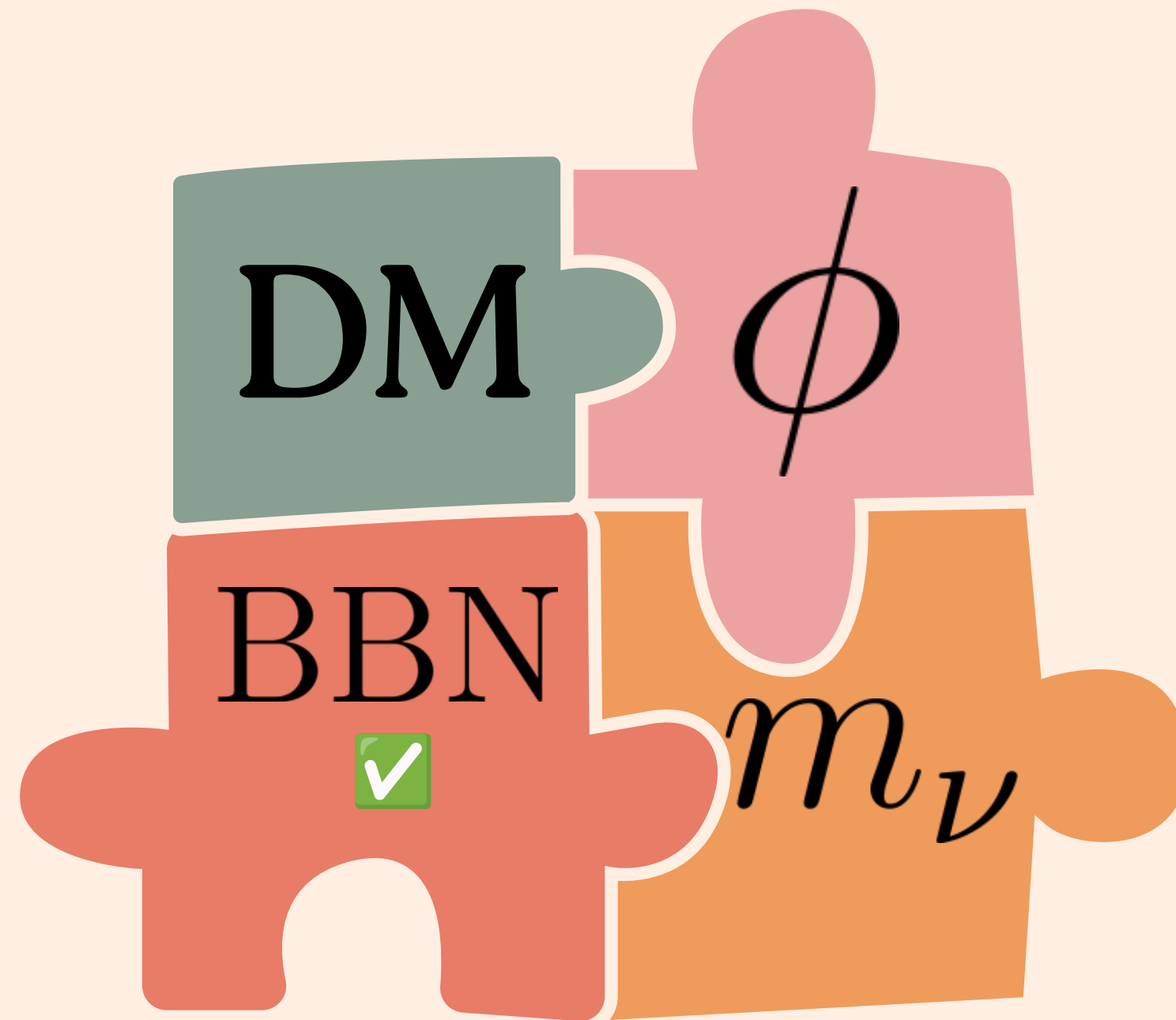
Summary



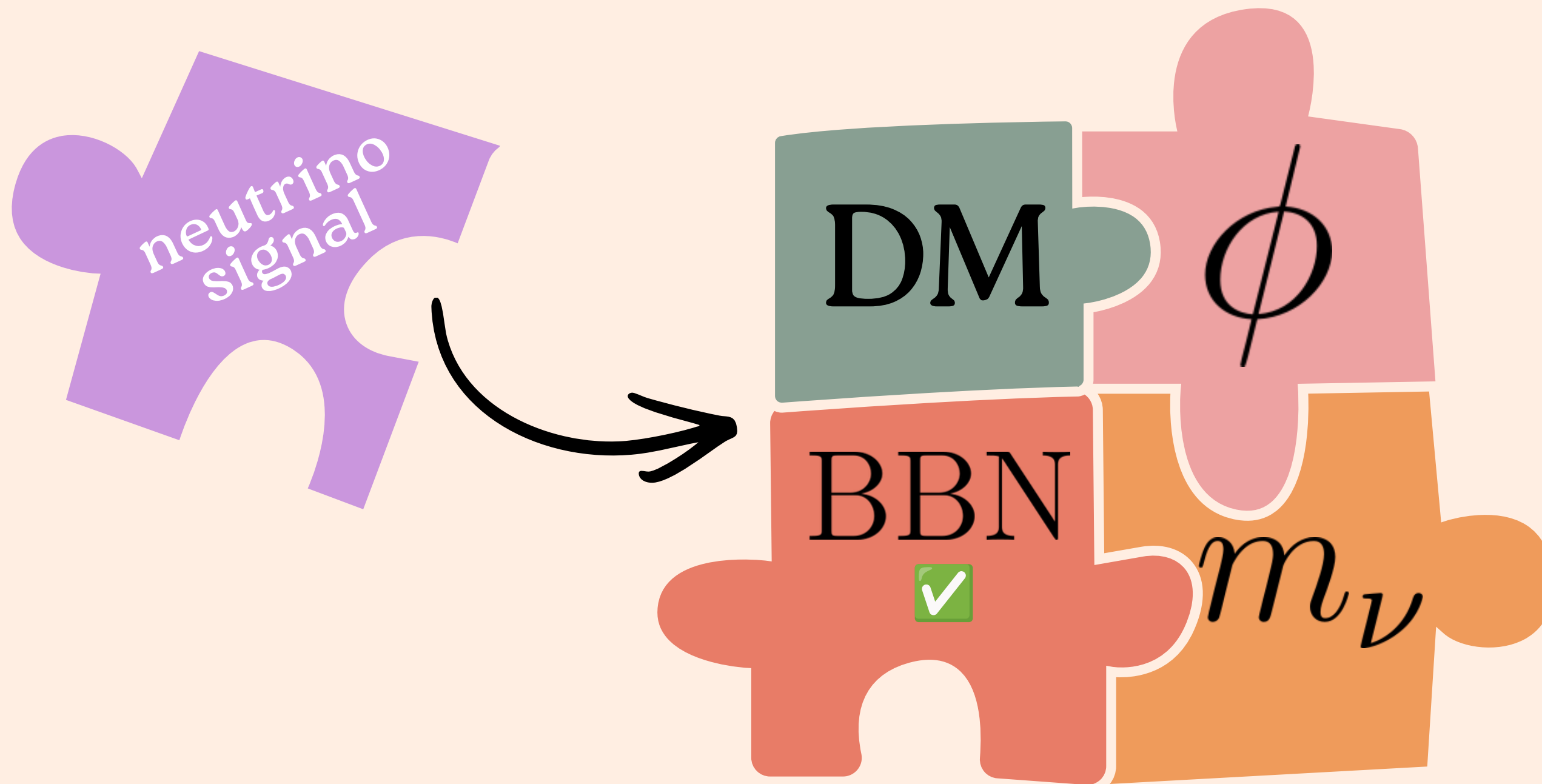
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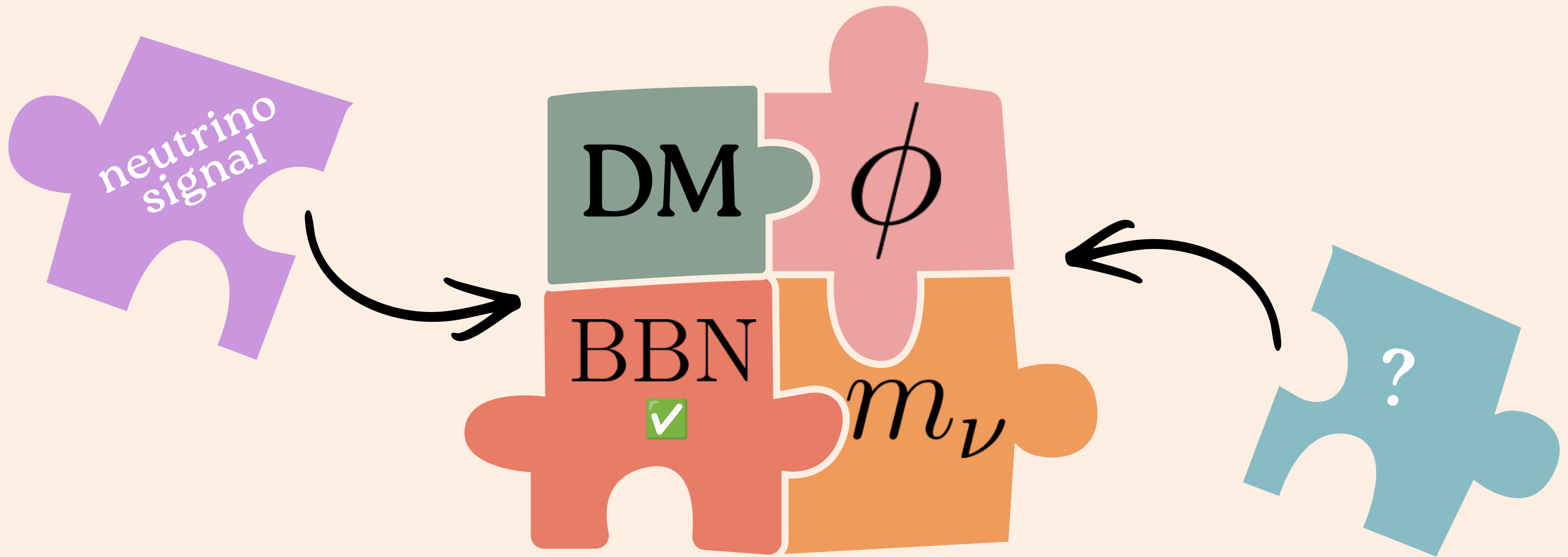
Summary



Summary



Summary



Bonus 🎉

Dark Sectors

Dark Sectors for kids



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Authors: *E. Merkel, D. Jiménez, F. Bellini, S. Pascoli, L. Fabbri, L. Vianello*

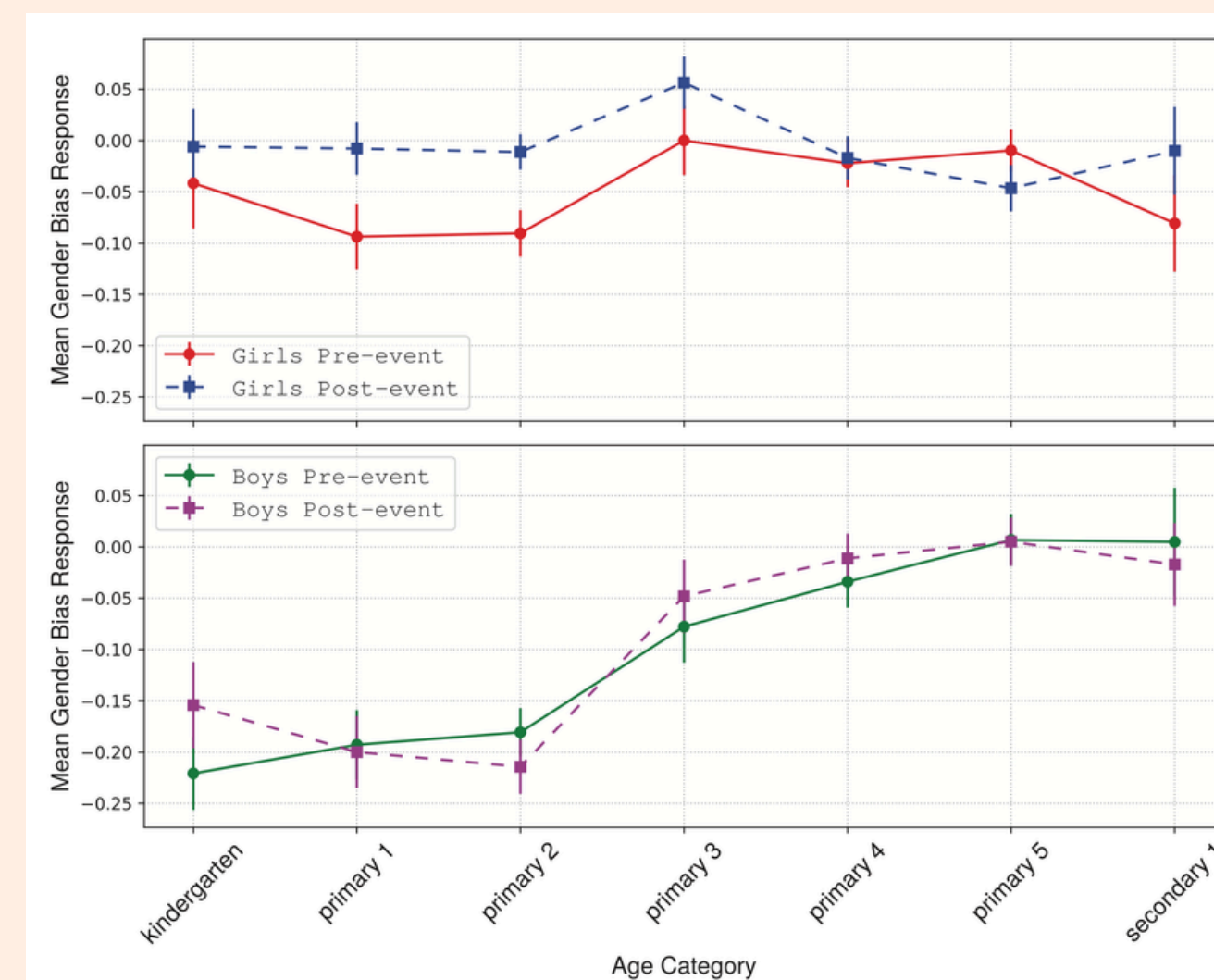
DOI: [10.1393/ncc/i2025-25255-2](https://doi.org/10.1393/ncc/i2025-25255-2)

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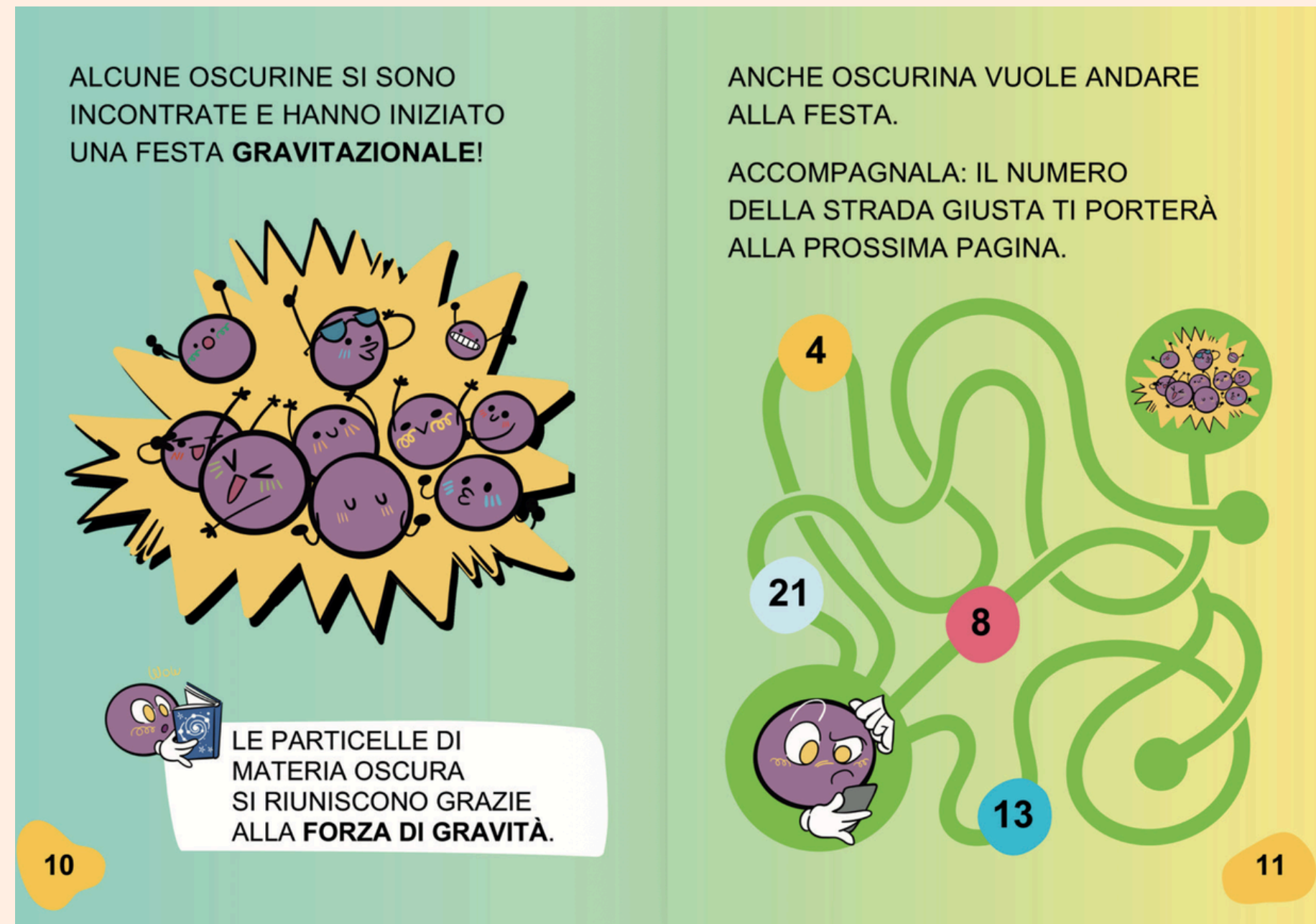
PLOT FROM **EM**, JIMÉNEZ, BELLINI, PASCOLI, FABBRI, IANELLO,
INVISIBILI OUTREACH PROJECT, IL NUOVO CIMENTO C, ISSUE 4, 2025



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Core Concept

Astronomy and Physics

Collection Article

Published: June 12, 2026

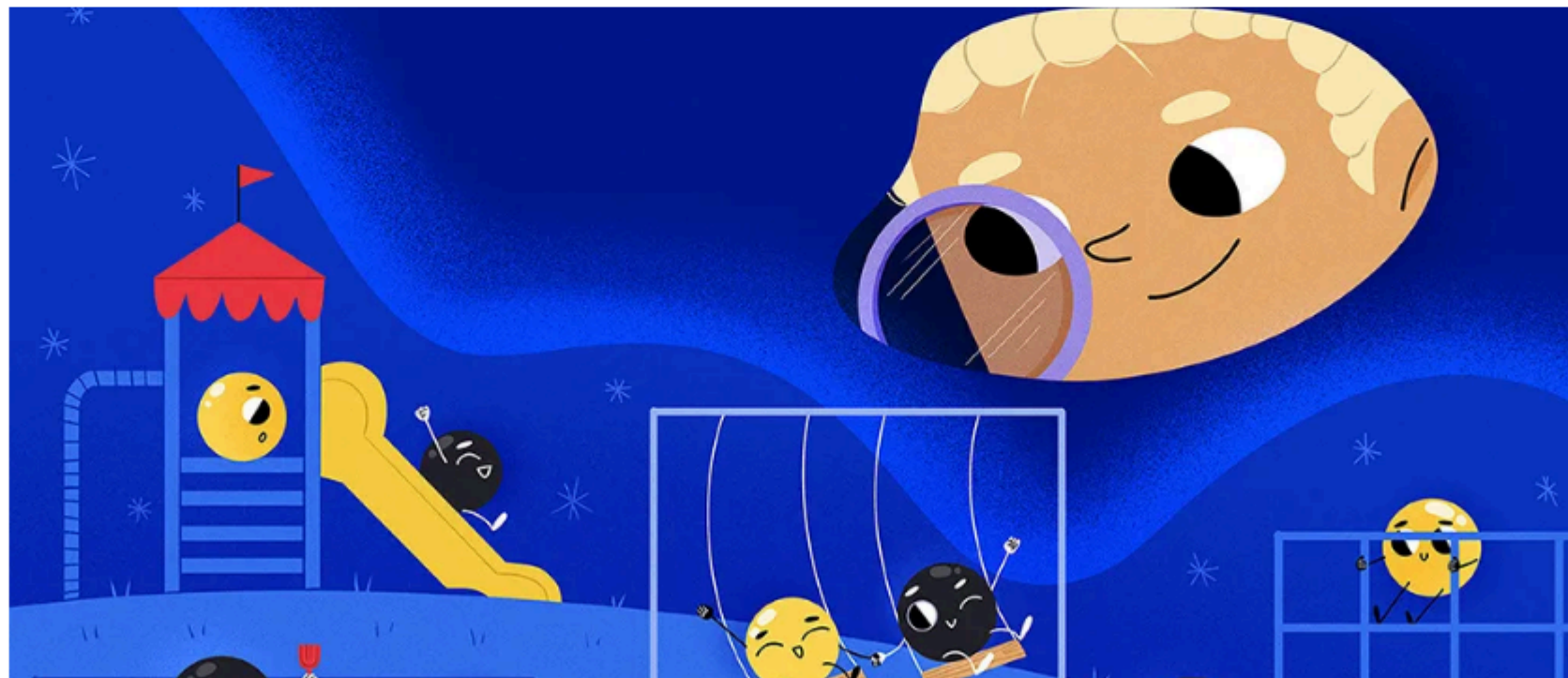
Is a Dark World Hiding in Our Universe—And How Can We Find It?

Authors

 [Michele Lucente](#)  [Silvia Pascoli](#)  [Elina Merkel](#)  [Gaia Fontana](#)  [Francesca Bellini](#)  [Laura Fabbri](#)
 [Alessandra Fanfani](#)

Young Reviewers

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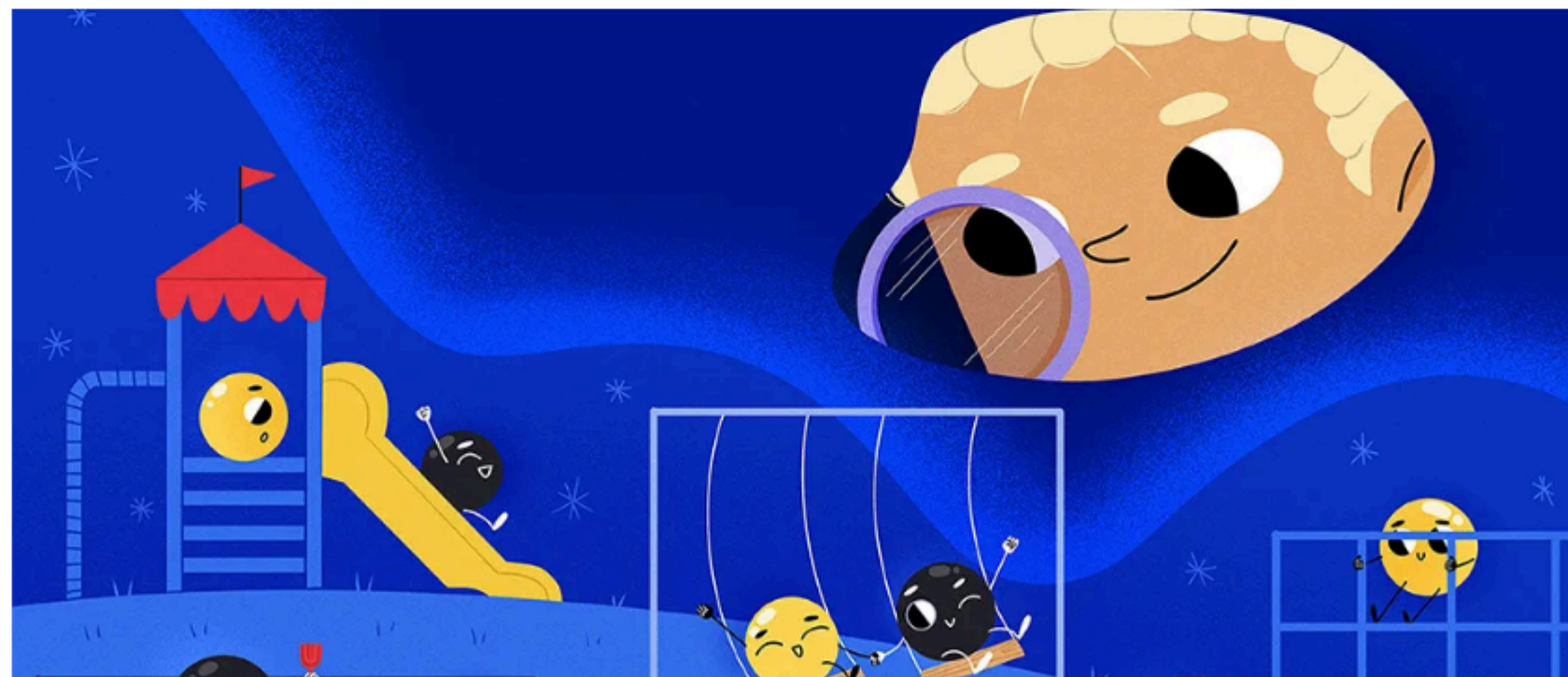
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Frontiers for Young
Minds article



Dark Sectors for kids

ILLUSTRATION BY GAIA FONTANA



Frontiers for Young
Minds article



One last thing...



Join karaoke night !



Karaoke TEVPA
WhatsApp group

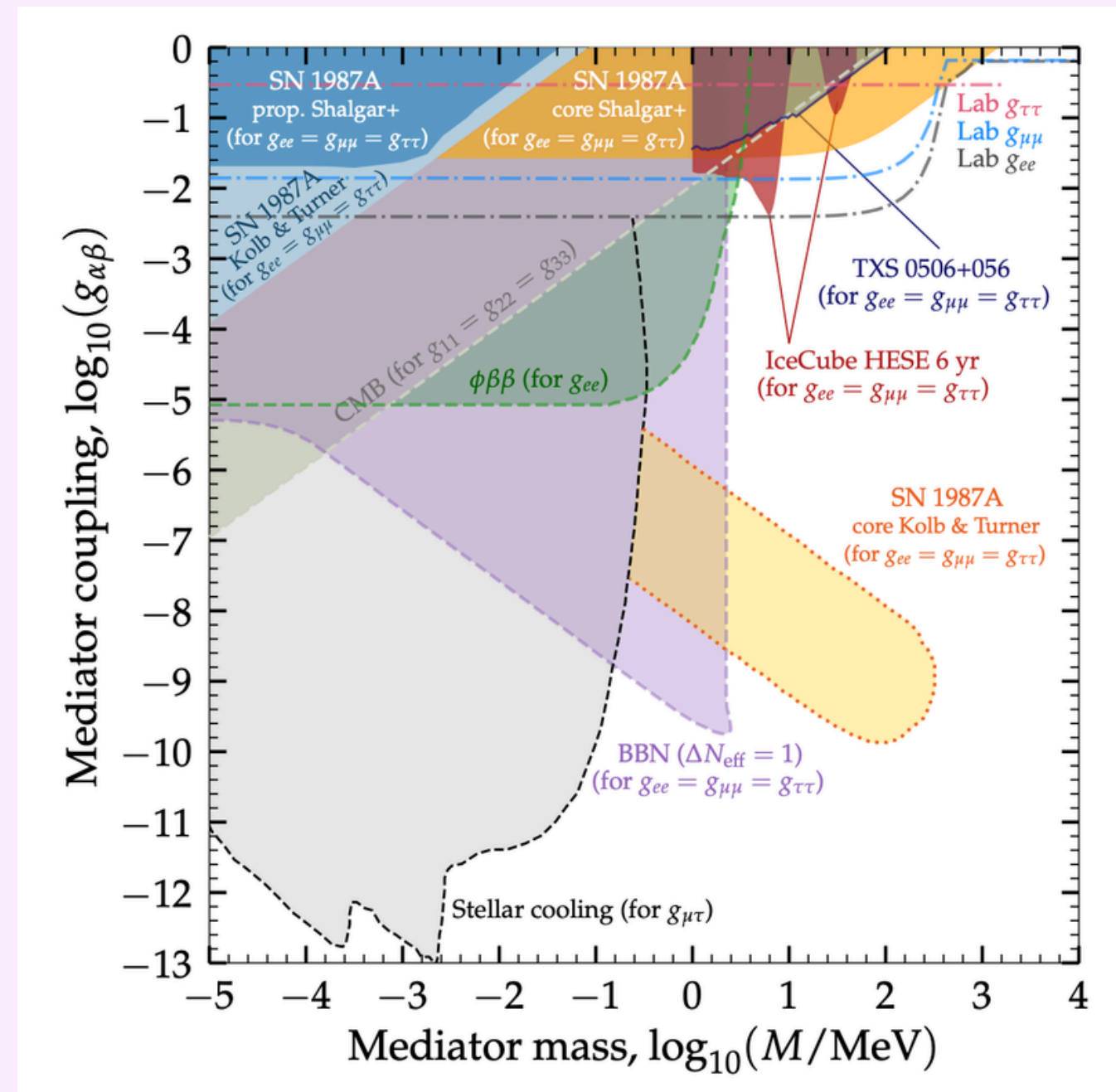


PARTY!

**Thank you for
your
attention!**

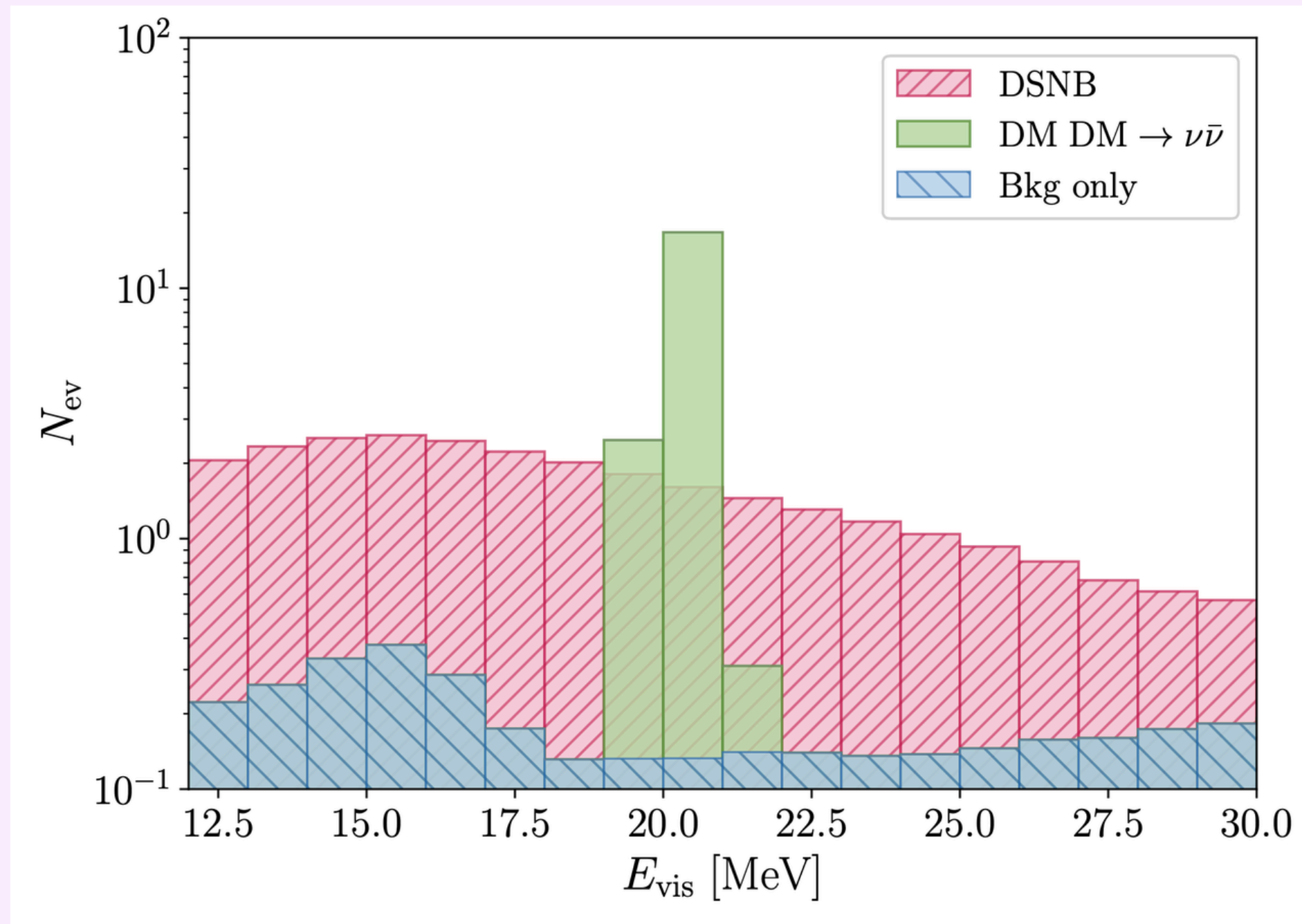
Backup

SN constraints



NEUTRINO SELF-INTERACTIONS: A WHITE PAPER
[2203.01955]

Prediction for JUNO



GRANELLI, PASCOLI, ROSAURO-ALCARAZ [2605.20162]