# MeV Majorana DM
# and
# its detection

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# Outline

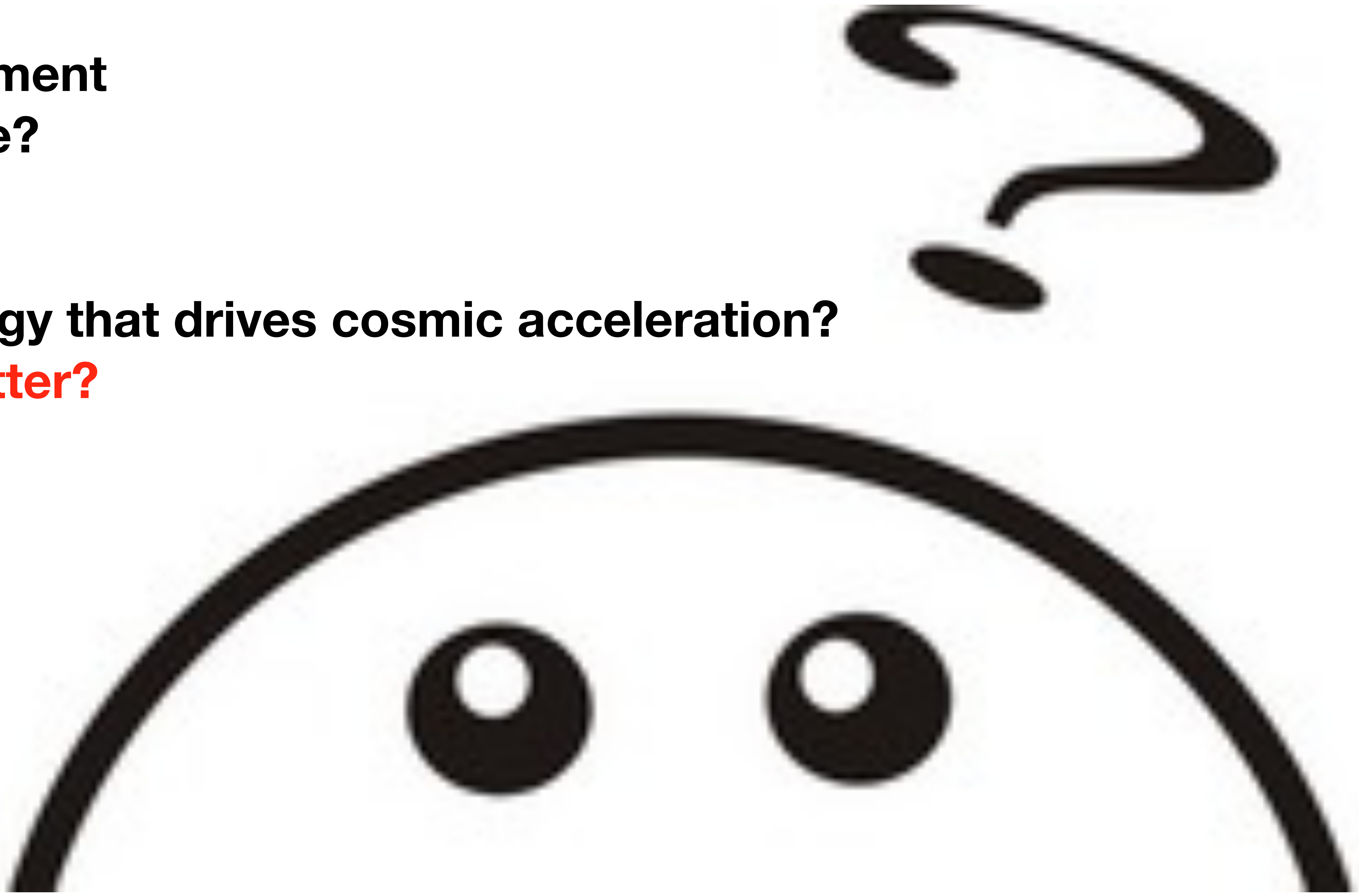
① Motivation: toward a MeV thermal DM.

② Framework: a possible DM and mediator.

③ Searches: from theoretical constraints to experimental limits.

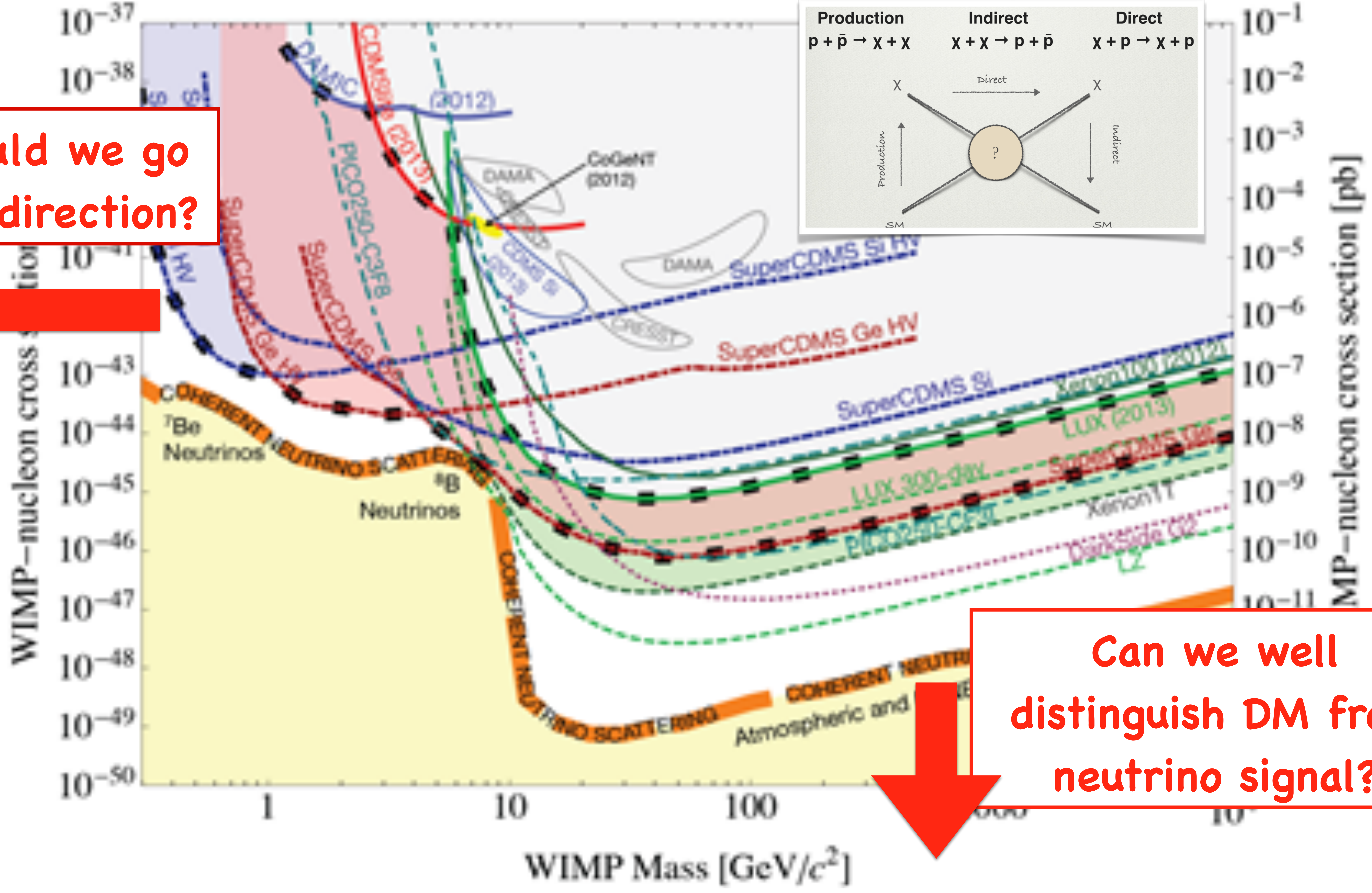
④ Future prospects: potential signals, strategy and method improvement.

Top 10 scientific mysteries for the 21st century
(www.sciencenews.org)
1. The meaning of quantum entanglement
2. Does intelligent life exist elsewhere?
3. Quantum gravity.
...
8. What is the nature of the dark energy that drives cosmic acceleration?
9. What is the identity of the dark matter?
10. How did life originate?



# Motivation: toward a MeV thermal DM.

Questions for the New Century
(Physics of the Universe report,
https://www.nsf.gov)
Q1: What is Dark Matter?
Q2: What is the Nature of Dark Energy?
Q3: How Did the Universe Begin?



Should we go this direction?

Can we well distinguish DM from neutrino signal?

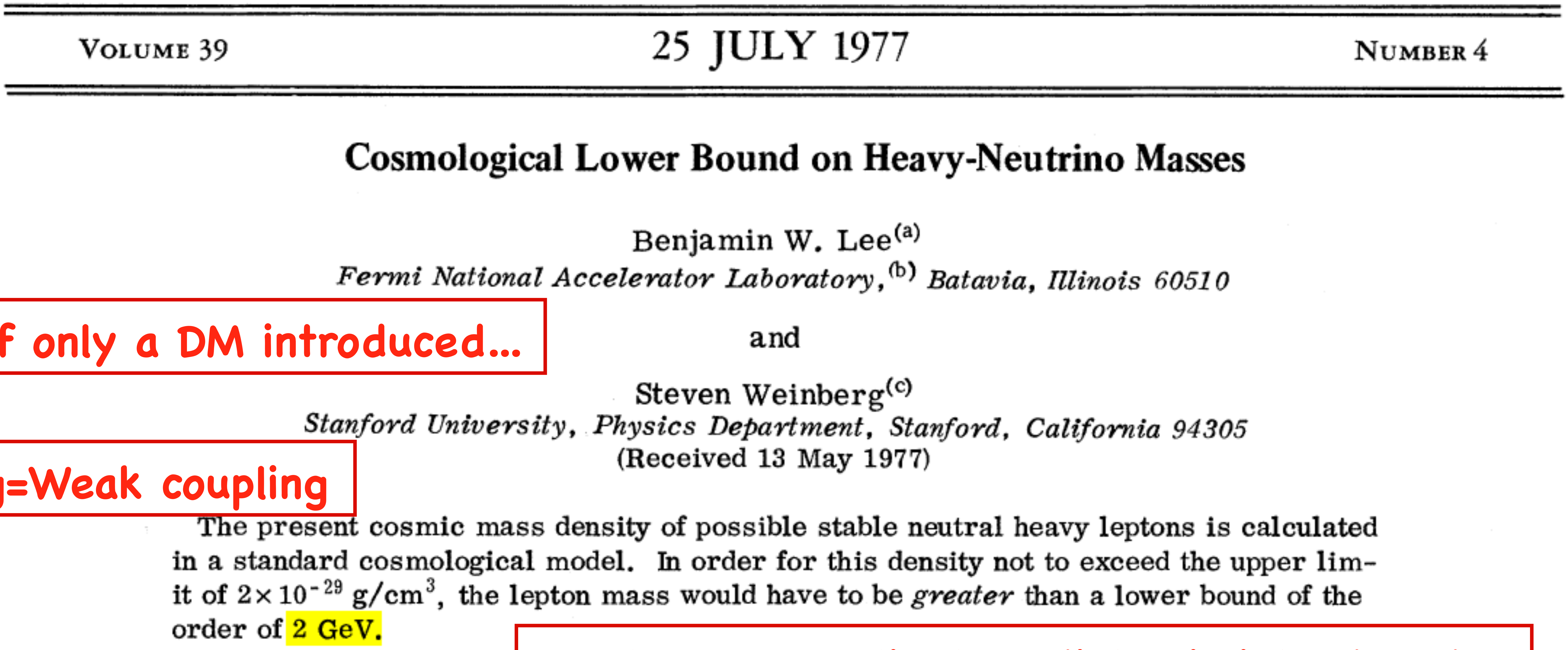
Energy

Luminosity

Experimental choice: higher luminosity OR lower energy?

# The Light DM mass region

Can we go to the region below GeV?



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## Cosmological Lower Bound on Heavy-Neutrino Masses

Benjamin W. Lee[a]
*Fermi National Accelerator Laboratory,*[b] *Batavia, Illinois 60510*

and

Steven Weinberg[c]
*Stanford University, Physics Department, Stanford, California 94305*

(Received 13 May 1977)

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of $2\times10^{-29}$ g/cm$^3$, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.

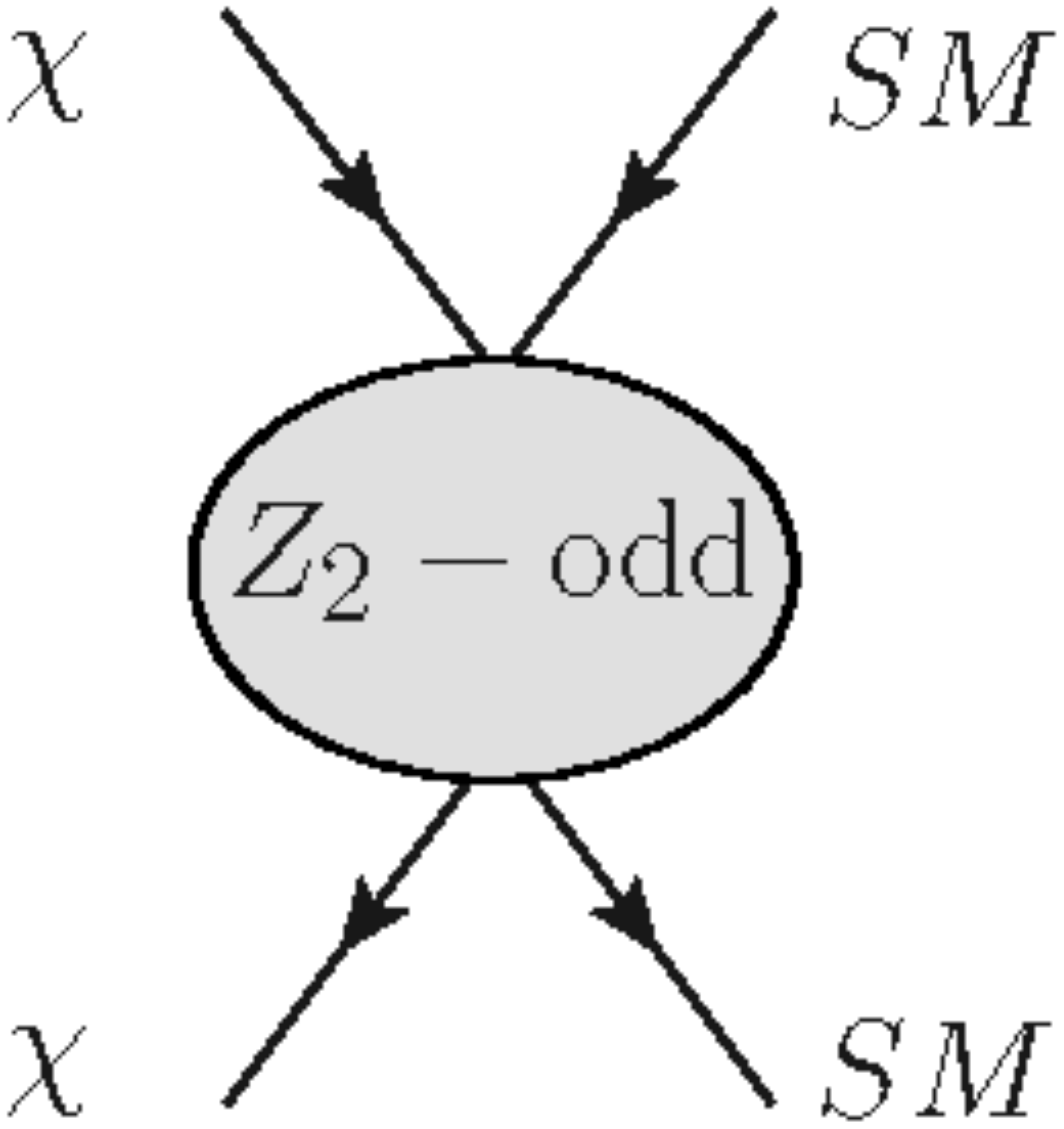
If only a DM introduced…

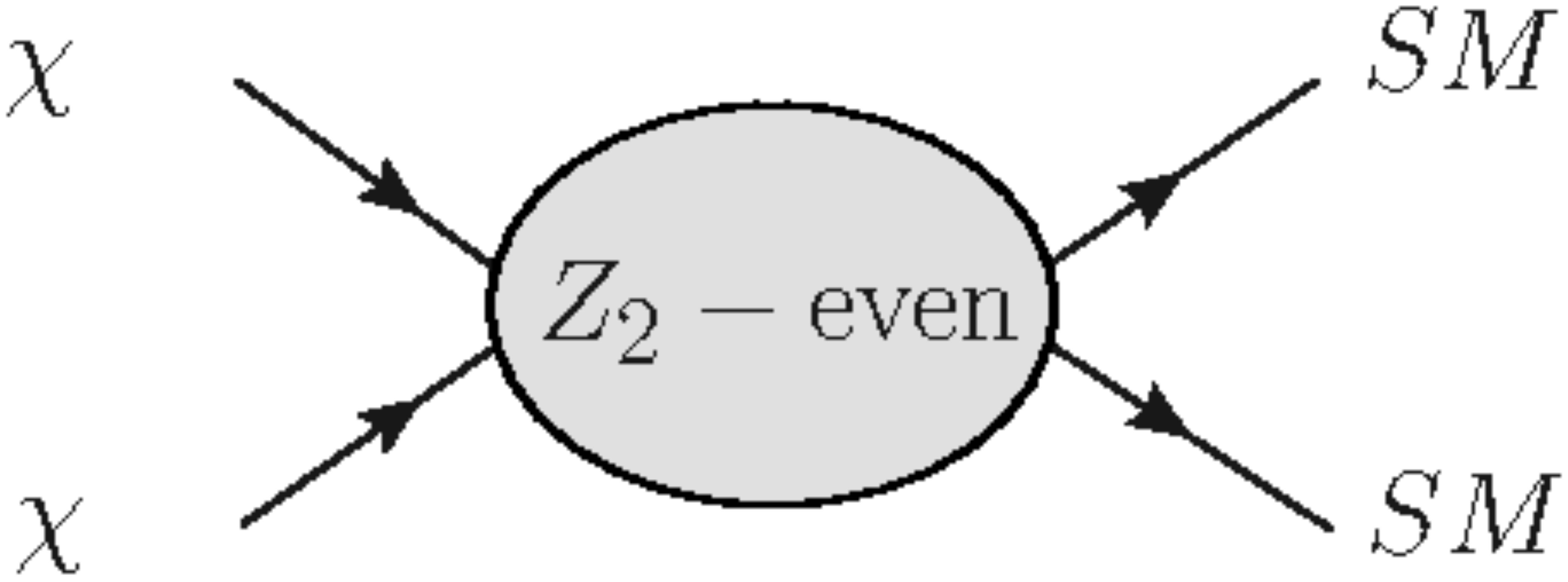
g=Weak coupling

Unless, a new light mediator is introduced!

# Simplicity and Light mediator

Let us see all the possibilities...

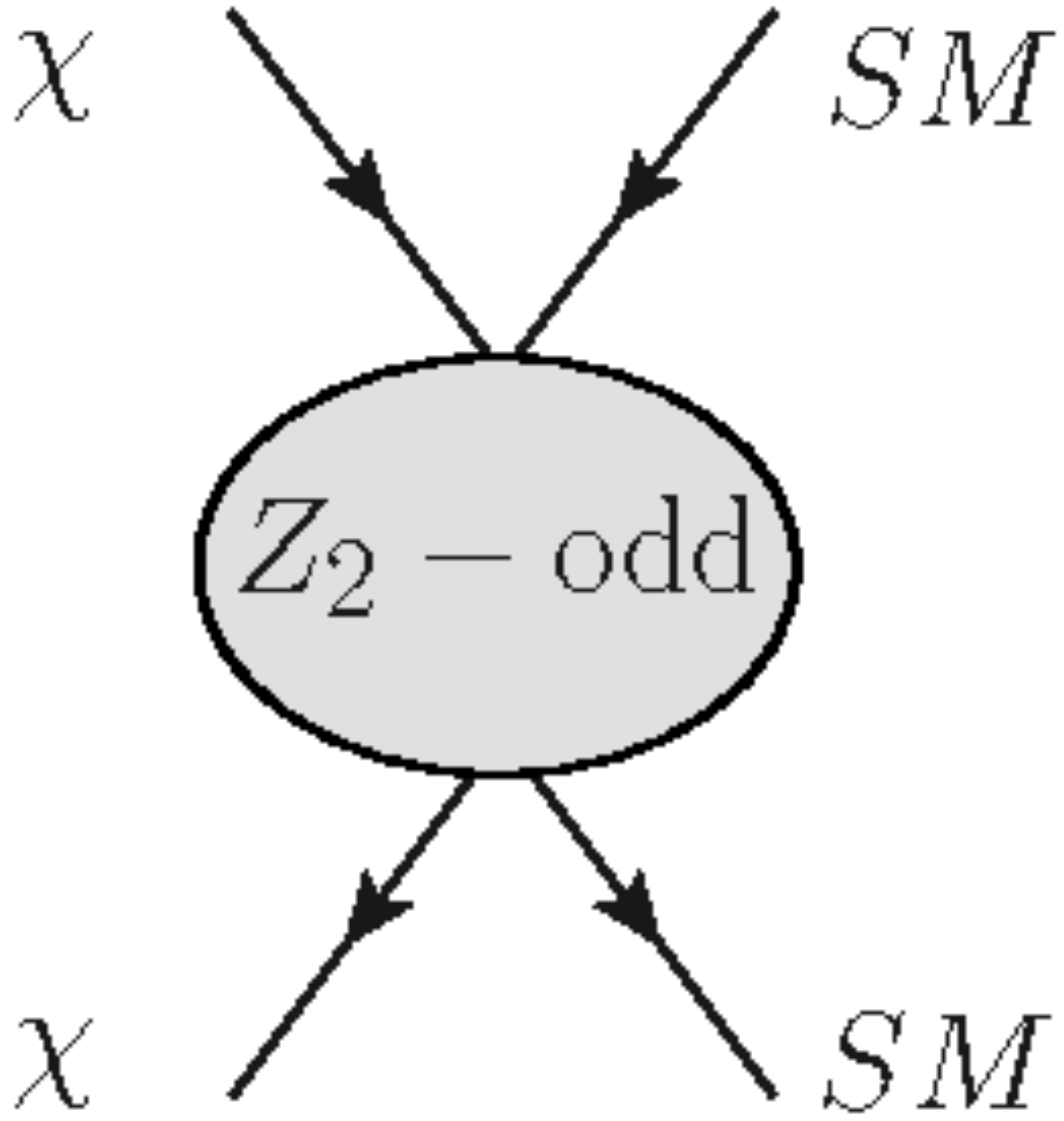




t-channel annihilation

s-channel annihilation

# Simplicity and Light mediator



① Z_2 odd scalar mediator (like squark) + SM fermion. LEP mass limit for charged mediator is heavier than 100 GeV.

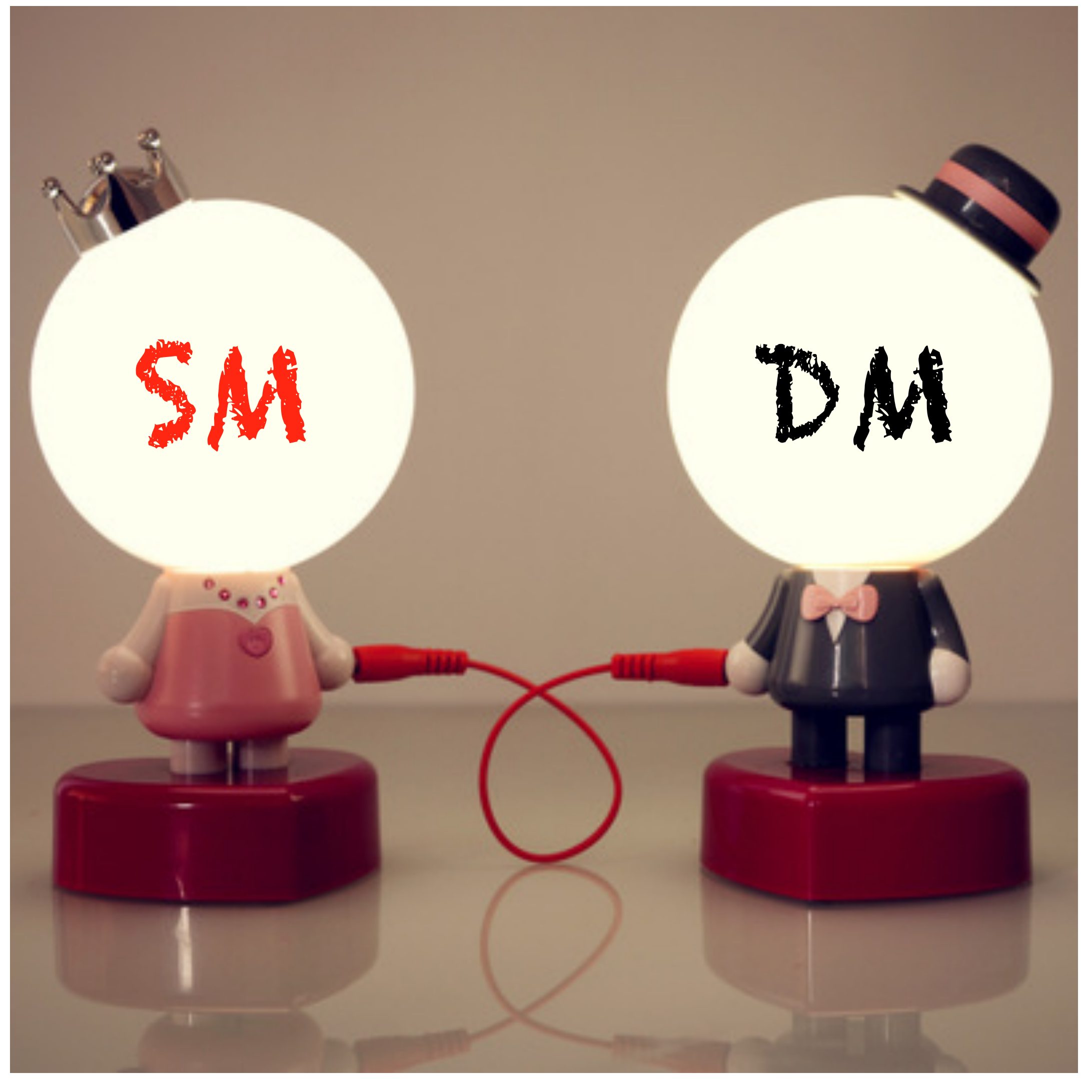
② Z_2 odd fermion mediator (like Chargino) + SM gauge boson. Invisible decay gives a severe limit.

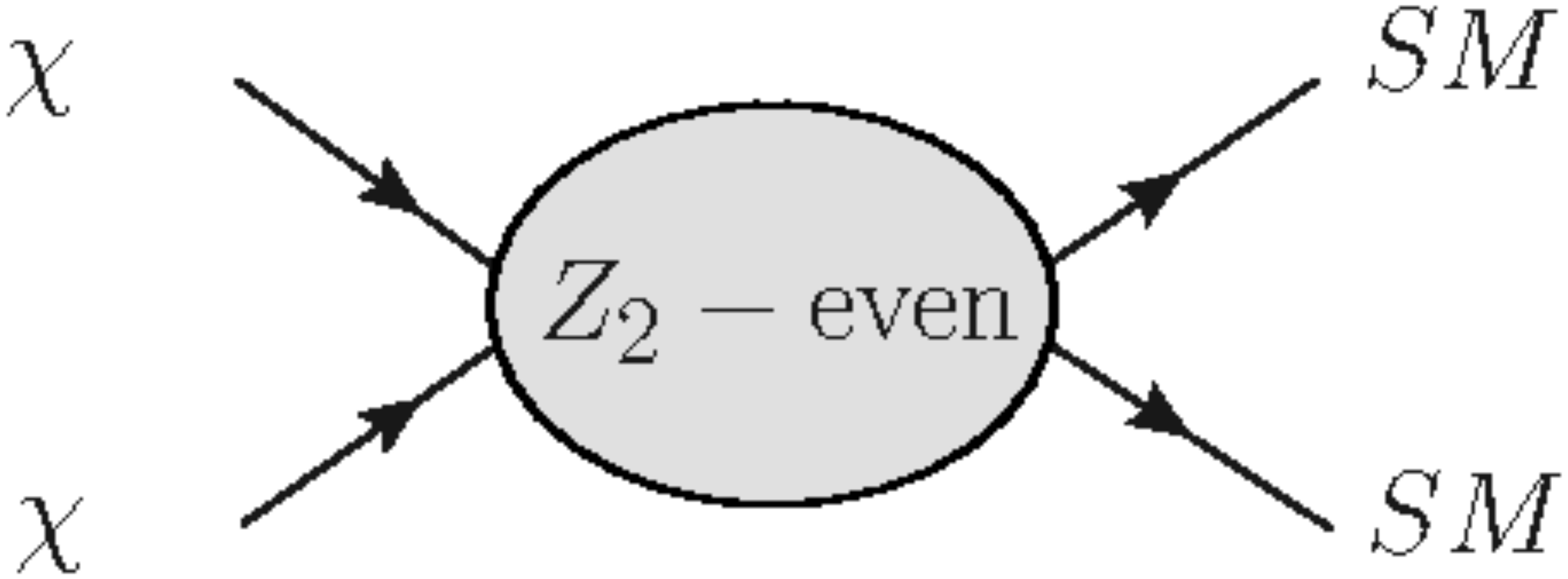
③ **Therefore, a light mediator of the the DM annihilation to SM pair via t-channel cannot be Z_2-odd.**

# Simplicity and Light mediator

ONLY TWO possible mediators:

① dark Higgs
② dark photon





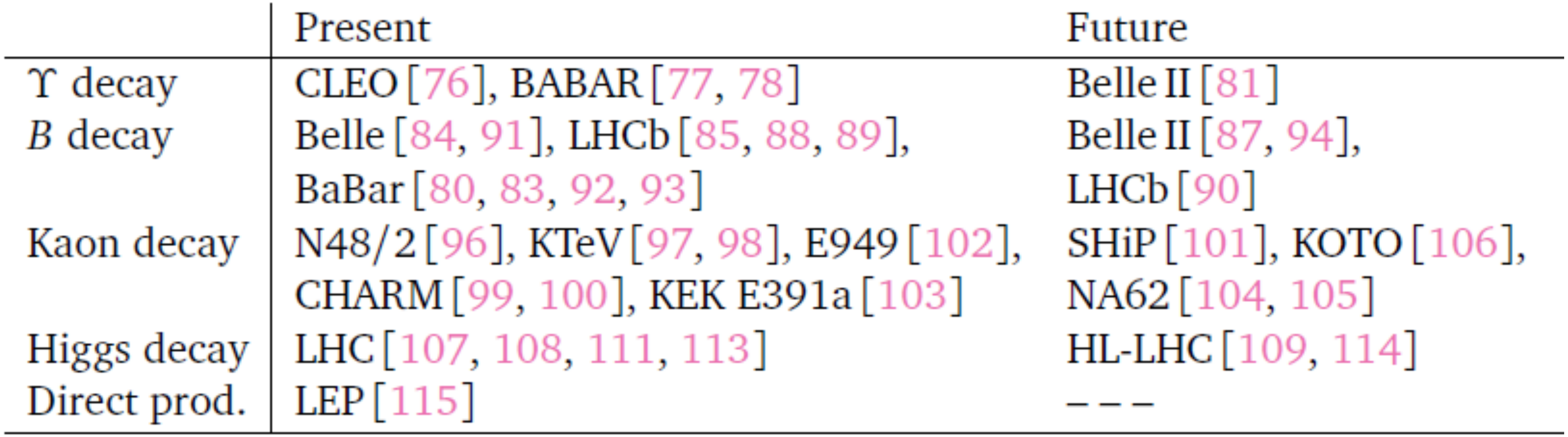
# The Light DM mass region

Why the light mass region is more interesting than small cross section?

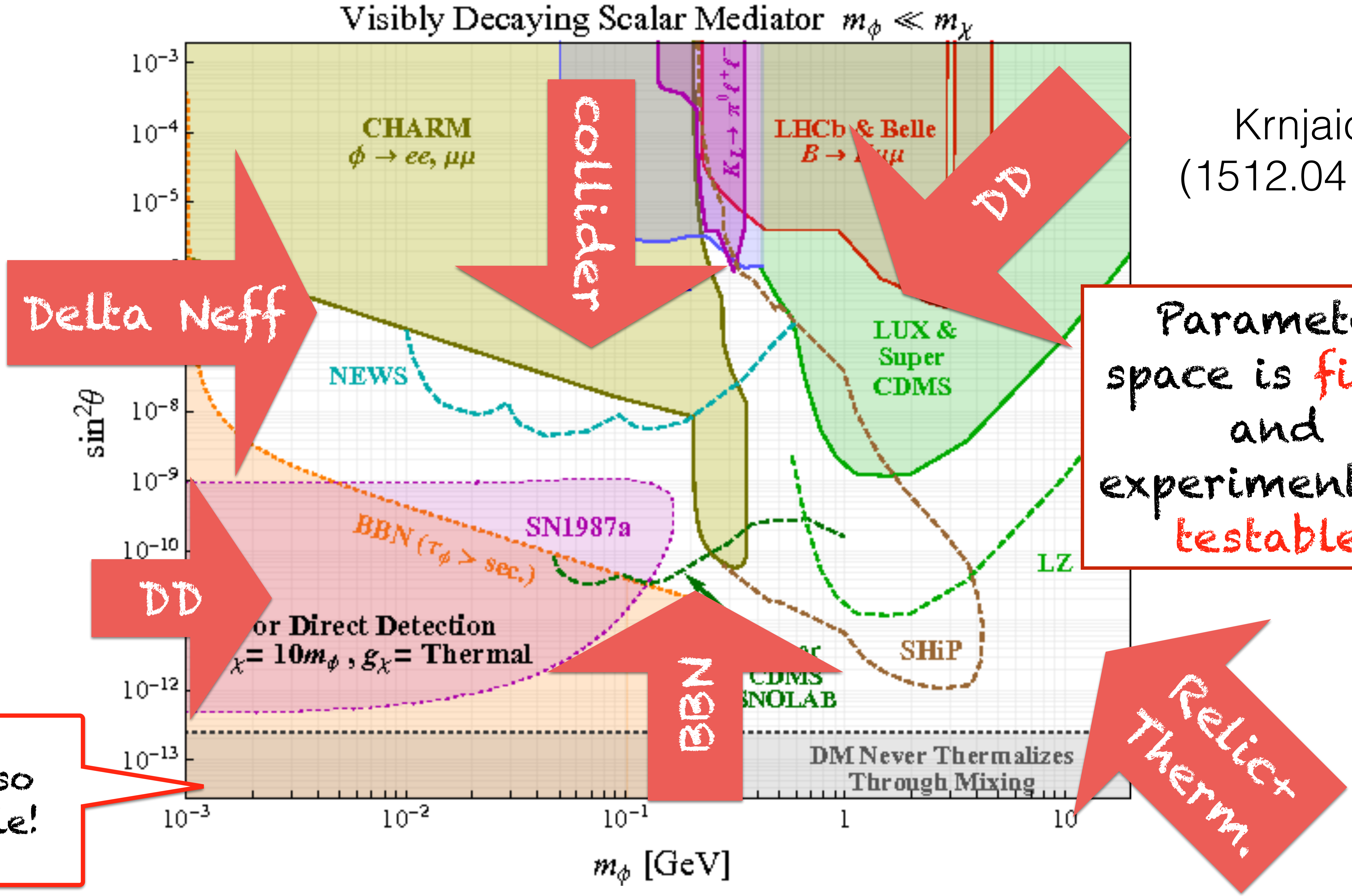
① It is currently very challenge to overcome systematic uncertainties from neutrino background.

② It is expected to see the signal from meson decays, CMB, and BBN data.

③ There are many available detectors: many beam dump experiments.



| | Present | Future |
|---|---|---|
| $\Upsilon$ decay | CLEO [76], BABAR [77, 78] | Belle II [81] |
| *B* decay | Belle [84, 91], LHCb [85, 88, 89],<br>BaBar [80, 83, 92, 93] | Belle II [87, 94],<br>LHCb [90] |
| Kaon decay | N48/2 [96], KTeV [97, 98], E949 [102],<br>CHARM [99, 100], KEK E391a [103] | SHiP [101], KOTO [106],<br>NA62 [104, 105] |
| Higgs decay | LHC [107, 108, 111, 113] | HL-LHC [109, 114] |
| Direct prod. | LEP [115] | – – – |



Krnjaic, (1512.04119)

Parameter space is finite and experimentally testable!

Not so simple!

# Framework: a possible DM and mediator.

# Basic and minimum Lagrangian

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{2}\bar{\chi}(i\not{\partial} - m_\chi)\chi + \frac{1}{2}(\partial\Phi)^2 - \frac{c_s}{2}\Phi\bar{\chi}\chi - \frac{c_p}{2}\Phi\bar{\chi}i\gamma_5\chi - V(\Phi,H),$$

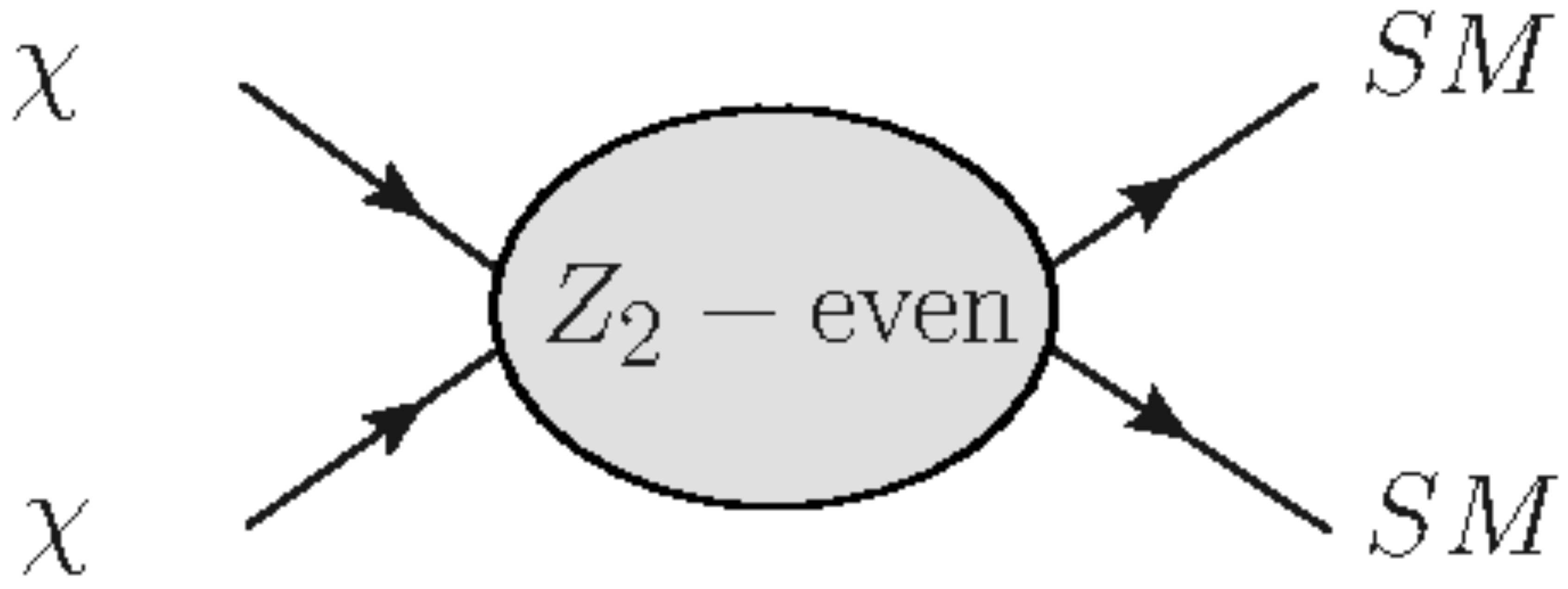
Majorana DM

SM singlet scalar

Scalar interaction

pseudo-scalar interaction

Mixing between New mediator and SM Higgs.



**A minimum setup:**

**one SM singlet Majorana DM +**
**one SM singlet scalar mediator.**

# Higgs potential and Model parameters

$$
\begin{aligned}
V_H(H) &= \mu_H^2 H^\dagger H + \frac{\lambda_H}{2}(H^\dagger H)^2, \\
V_\Phi(\Phi) &= \mu_1^3 \Phi + \frac{\mu_\Phi^2}{2}\Phi^2 + \frac{\mu_3}{3!}\Phi^3 + \frac{\lambda_\Phi}{4!}\Phi^4, \\
V_{\Phi H}(\Phi, H) &= A_{\Phi H}\Phi H^\dagger H + \frac{\lambda_{\Phi H}}{2}\Phi^2 H^\dagger H.
\end{aligned}
$$

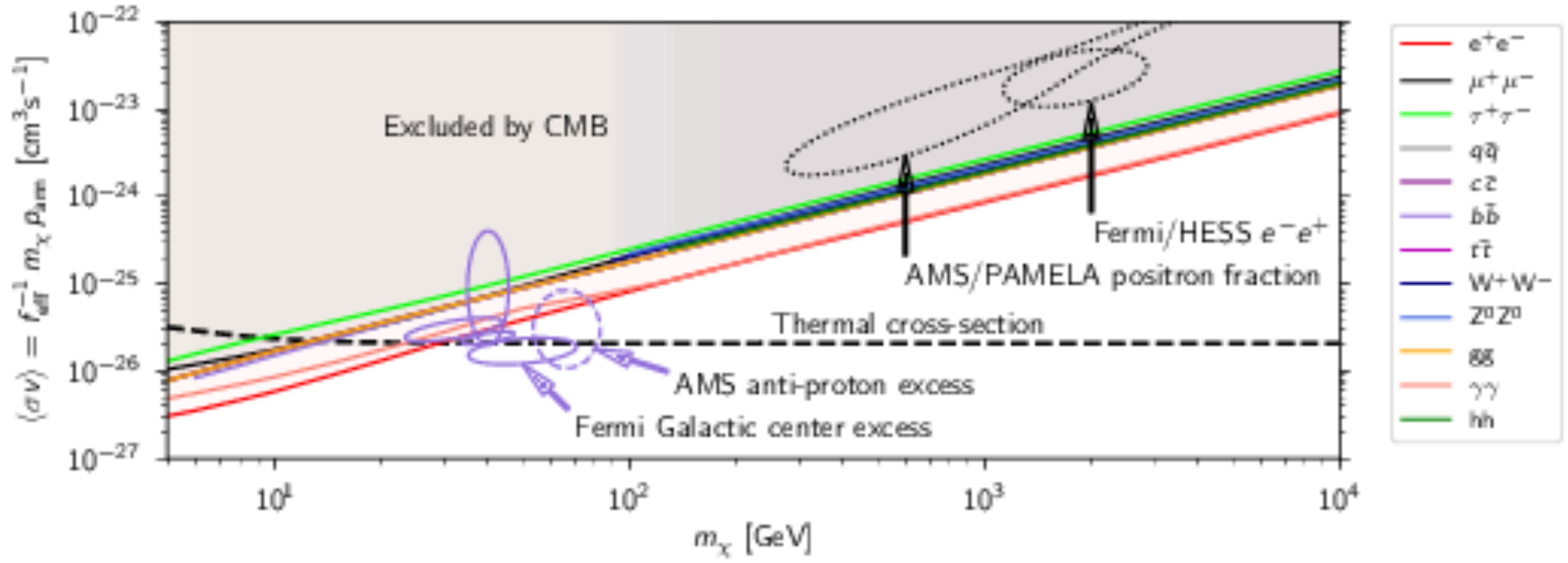
$$
\begin{pmatrix} h \\ \phi \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h' \\ \phi' \end{pmatrix}.
$$

- All the possible terms are included.
- Singlet light Higgs can be mixed with SM Higgs.
- (A_PhiH, la_PhiH)
  -> mixing matrix
  -> (mphi, smix)
- mu1 and muH -> minimum condition
- This model is a "Higgs portal" DM.

# Higgs potential and Model parameters

- The parameters (mu_Phi and lambda_Phi) are not relevant to DM phenomenology but Higgs potential.
- From Higgs invisible decay (LHC), one can have a prior range of theta.
- Based on thermal DM scheme, we choose a rather larger m_phi but it shall be decided later by relic density.

$$
\begin{aligned}
0 \leq & \; m_\chi \; \leq 30\,\mathrm{GeV}, \\
-1 \leq & \; c_s \; \leq 1, \\
0 \leq & \; m_\phi \; \leq 1\,\mathrm{TeV}, \\
-\pi/6 \leq & \; \theta \; \leq \pi/6, \\
-1\,\mathrm{TeV}^2 \leq & \; \mu_\Phi^2 \; \leq 1\,\mathrm{TeV}^2, \\
-1\,\mathrm{TeV} \leq & \; \mu_3 \; \leq 1\,\mathrm{TeV}, \\
-1 \leq & \; \lambda_\Phi \; \leq 1.
\end{aligned}
$$

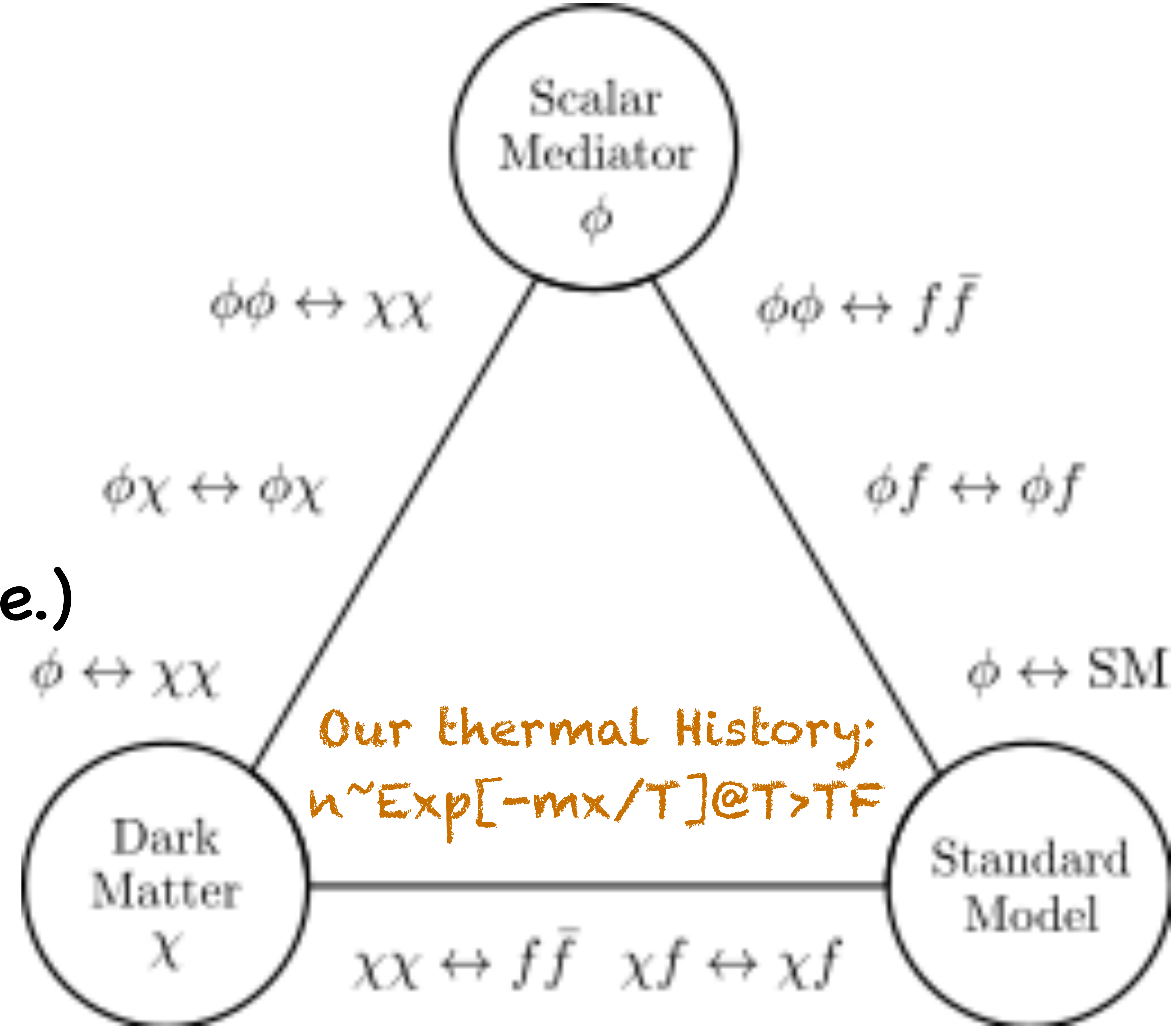


We only consider
cp=0
in this study.

# "Our choice" of thermal scenario

- When DM mainly annihilates to SM particles, then we do not care mediator sector even if the mediator sector is secluded.
  (However, for xx-> ff via resonance, one has to check DM-mediator scattering rate.)

- If DM annihilates to two mediators, then the heat transferred between SM and mediator sector shall be maintained.

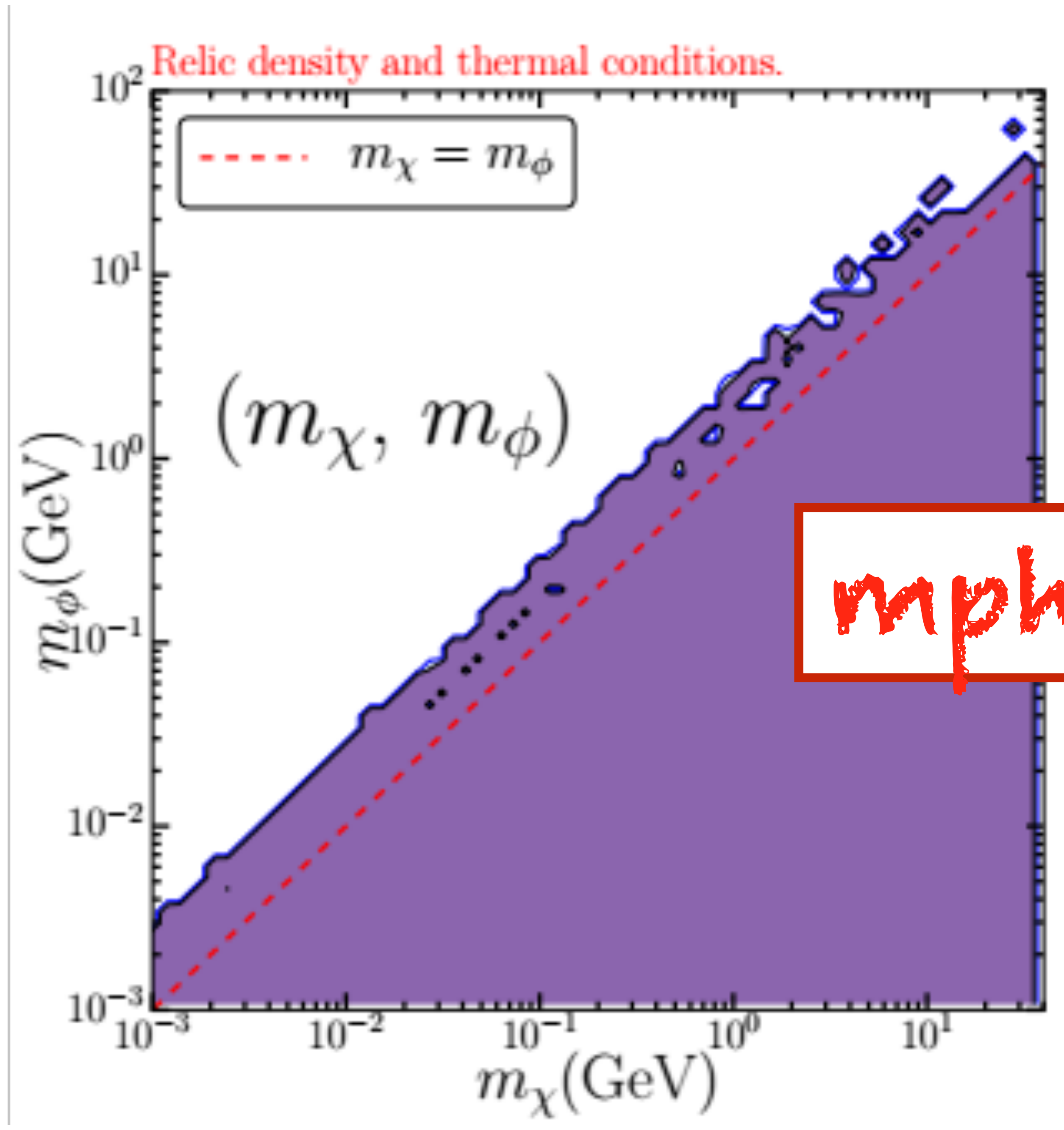


Our thermal History:
n~Exp[-mx/T]@T>TF

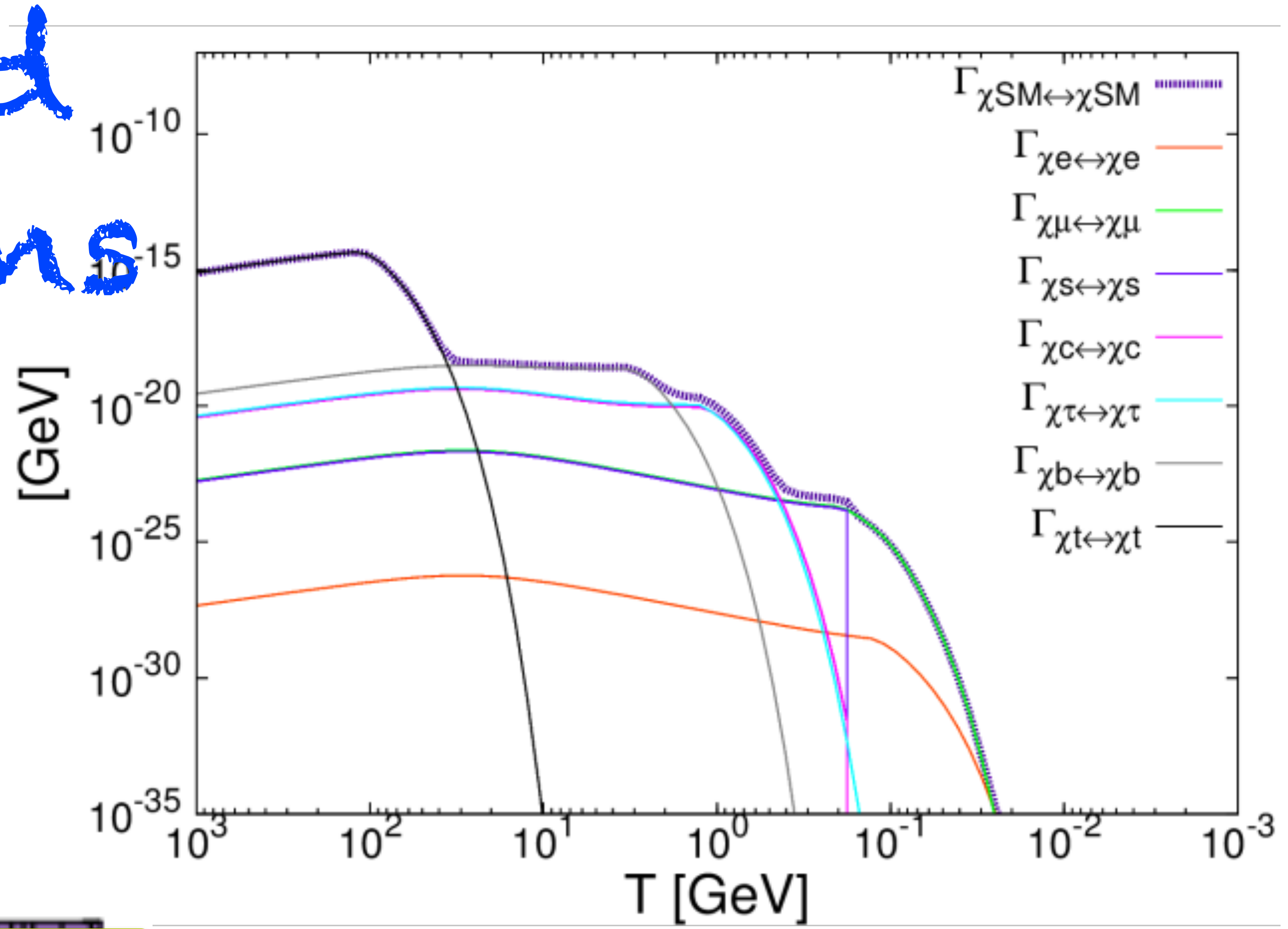
# Searches: from theoretical constraints to experimental limits.

# Relic density and Thermal conditions

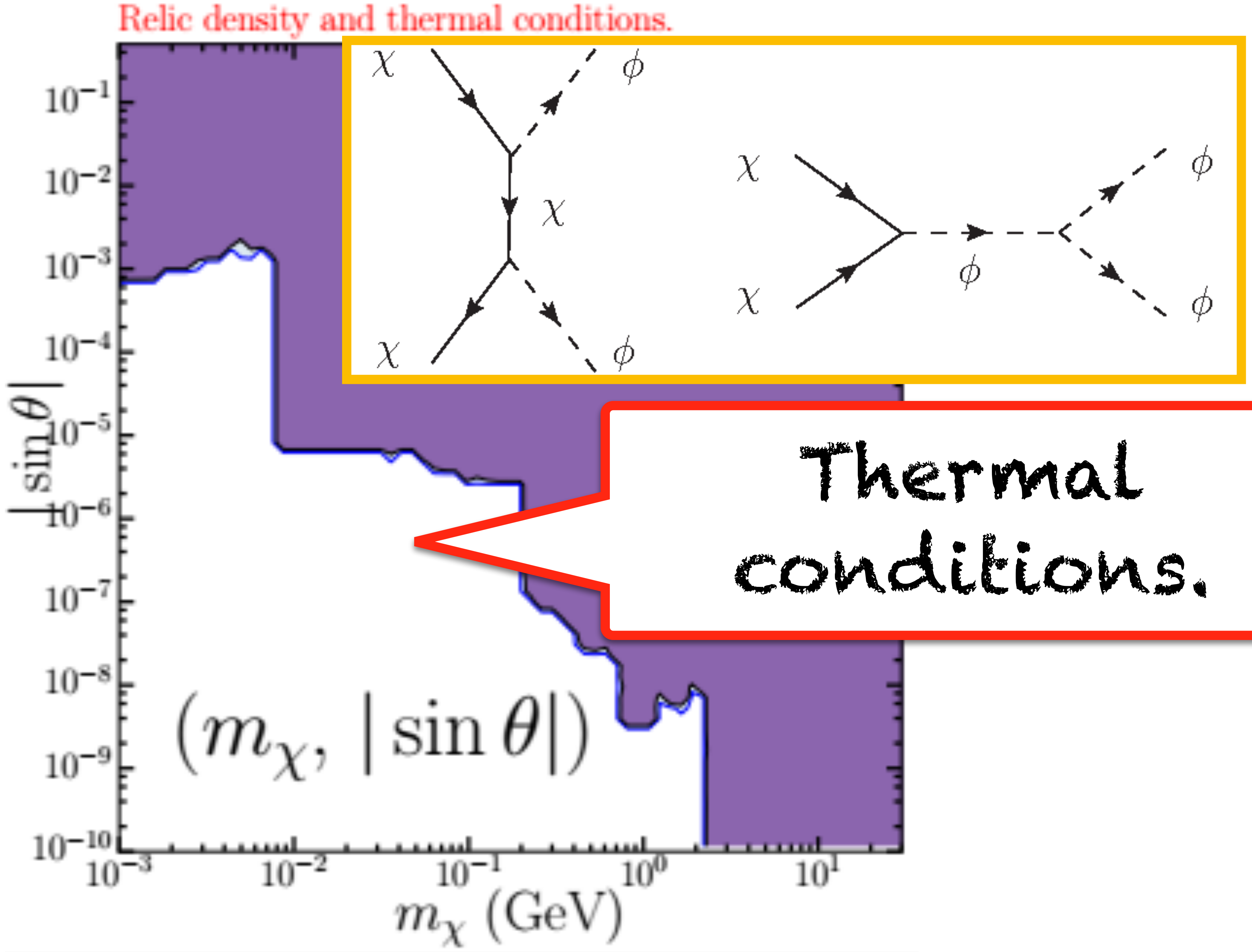
Relic density and thermal conditions.



mphi<4*mx

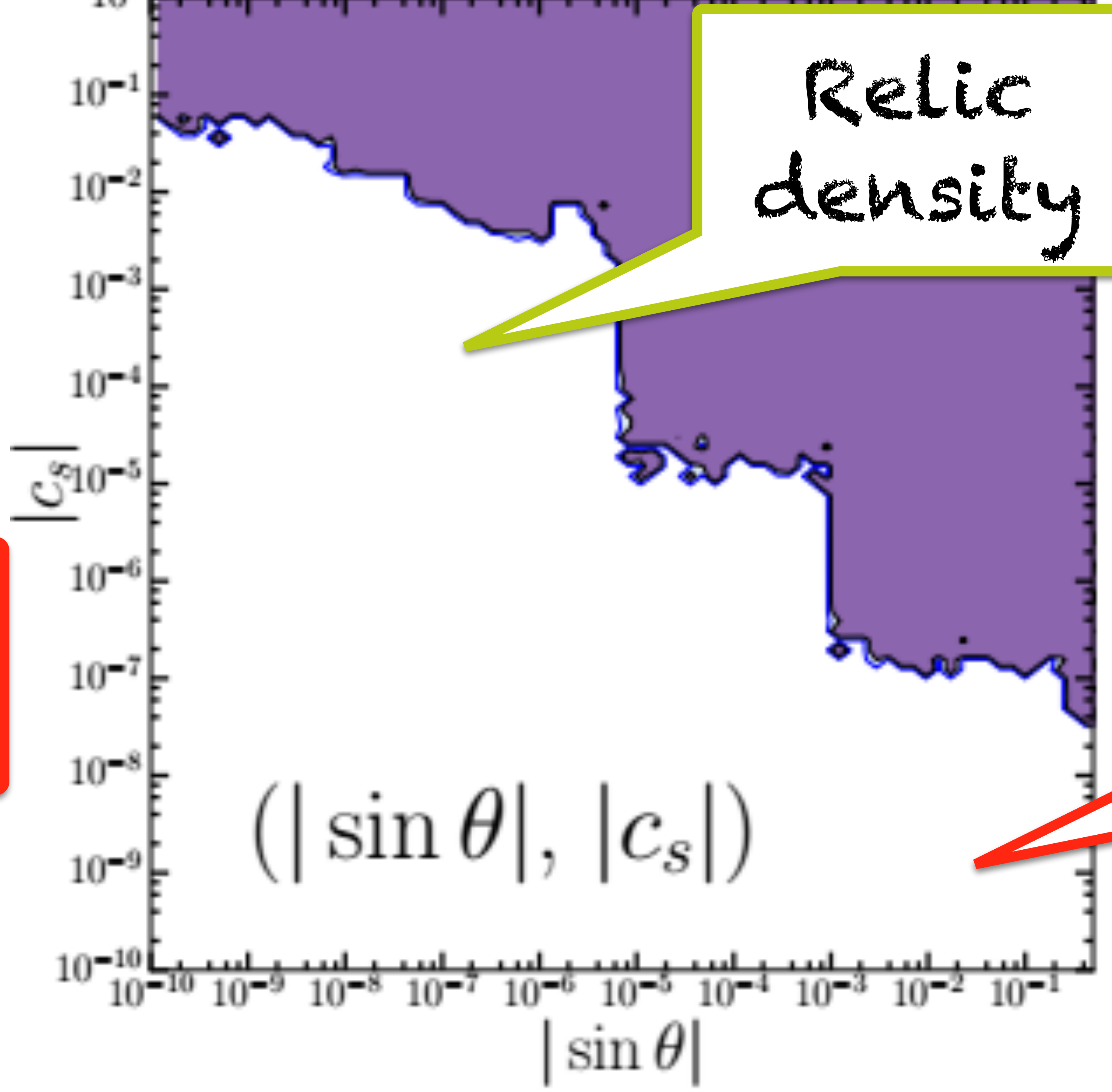


Relic density and thermal conditions.



Thermal conditions.

Relic density and thermal conditions.



Relic density

Thermal conditions.

Thermal condition is a hard cut.

## Constraints from Big Bang Nucleosynthesis

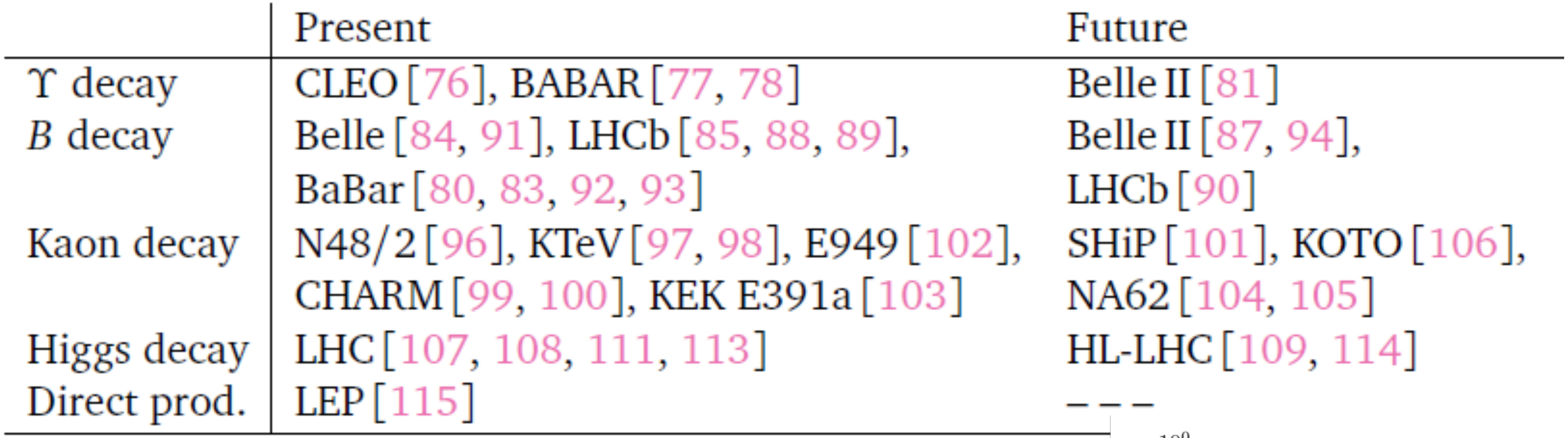
- If phi decay time happens later than BBN era, the successful standard scenario can be spoiled.
- BBN era is between 1 sec to few mins.
- Once hadronic decay happens, we require tau(phi)< 1 sec.
- If phi mainly decays leptonically, [1605.07195] shows tau(phi)<1e5 sec.

Lower coupling limit

## Constraints from Neff at T_CMB

- PLANCK: Neff=2.99 ± 0.17.
- Entropy conservation tells us that phi can modify the ratio of photon to neutrino temperature.
- These two information implies phi has be greater than 5 MeV in 2 sigma level.

Lower mass limit



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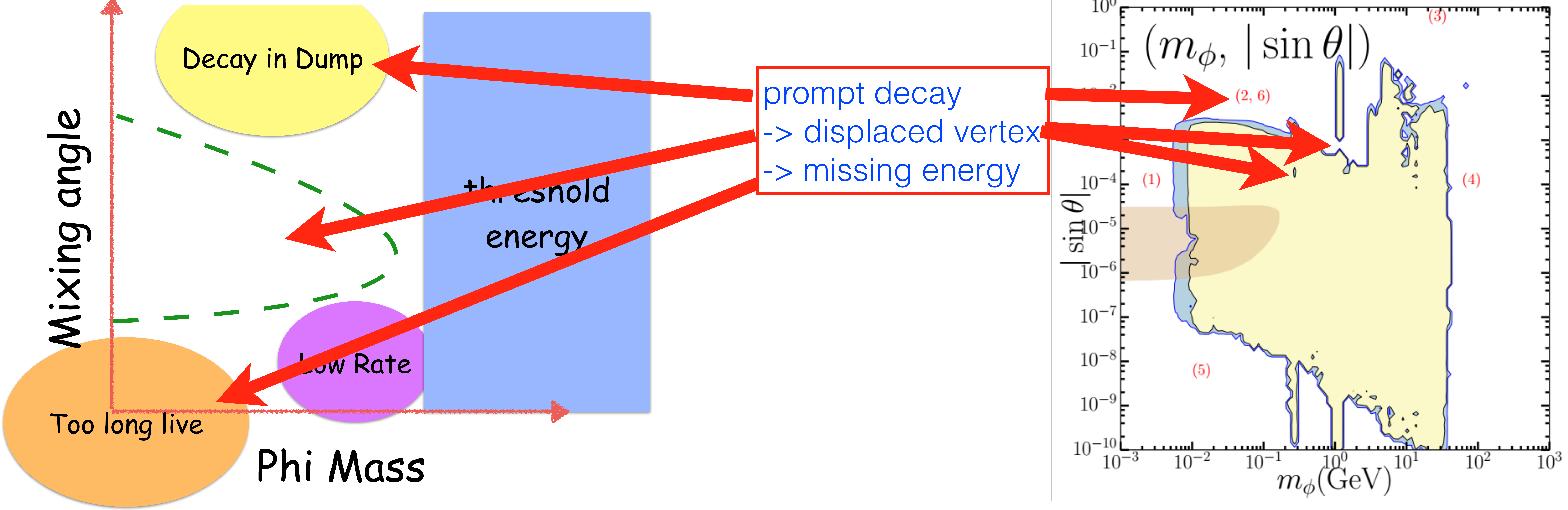
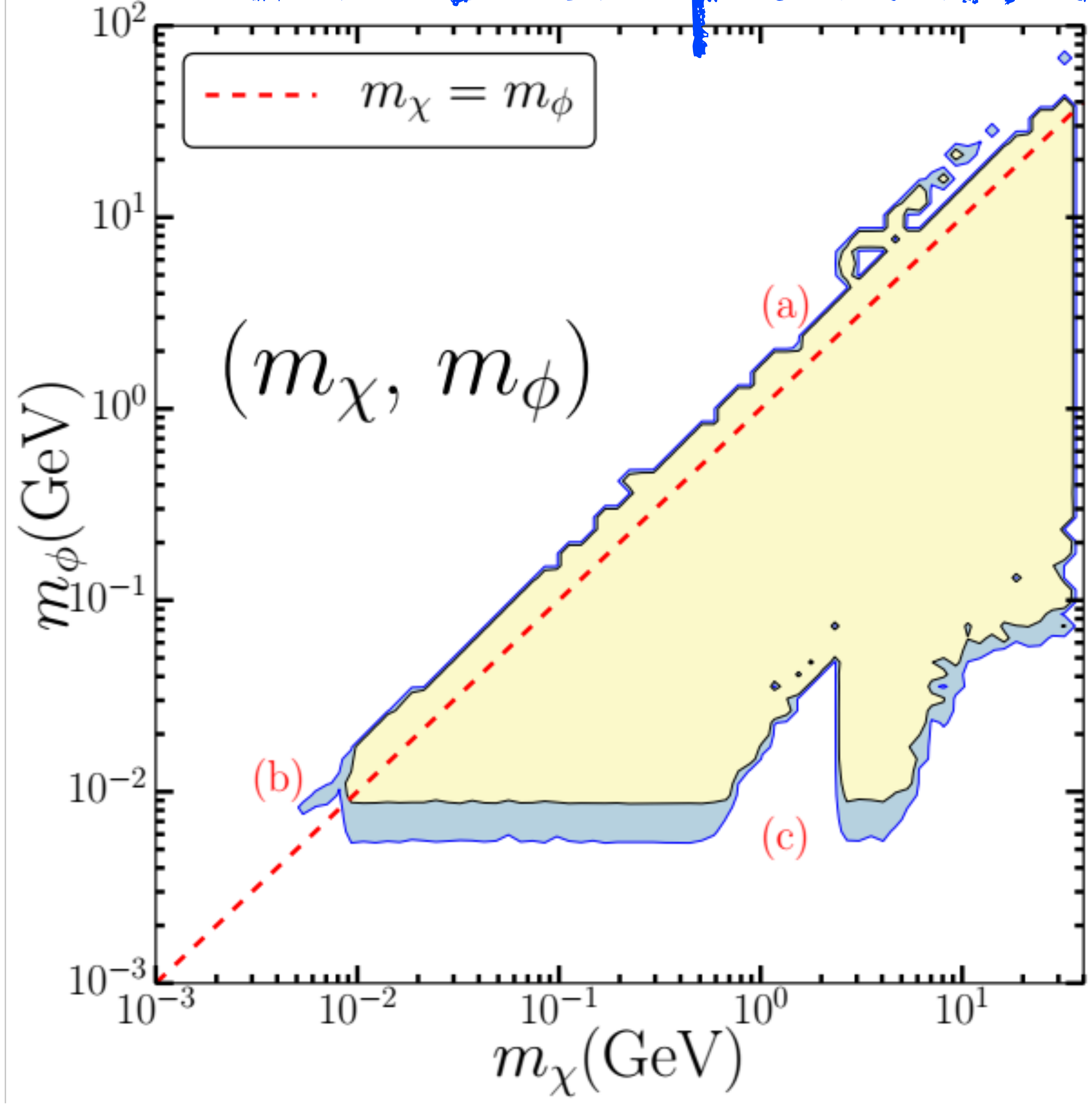
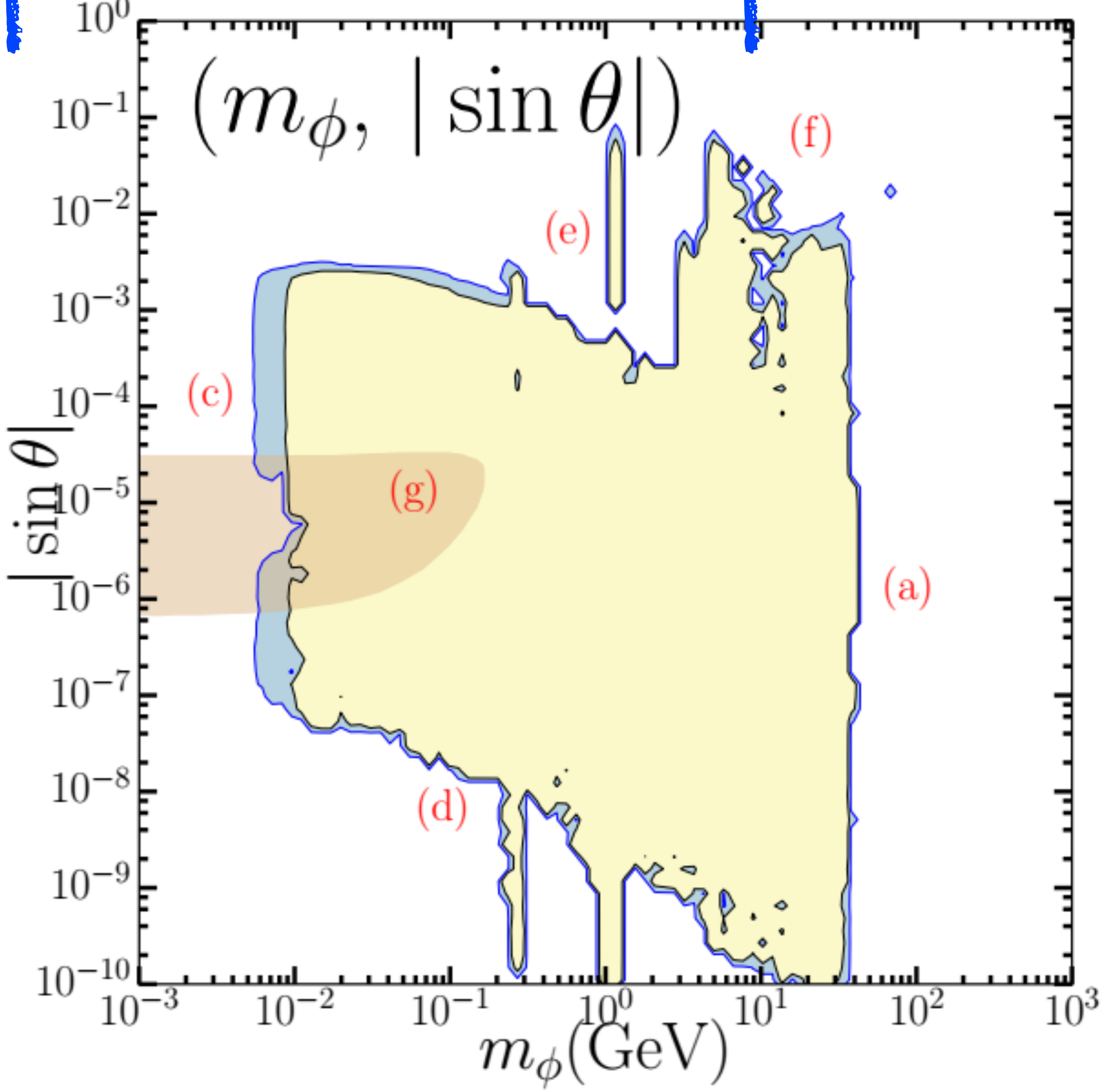


prompt decay
-> displaced vertex
-> missing energy

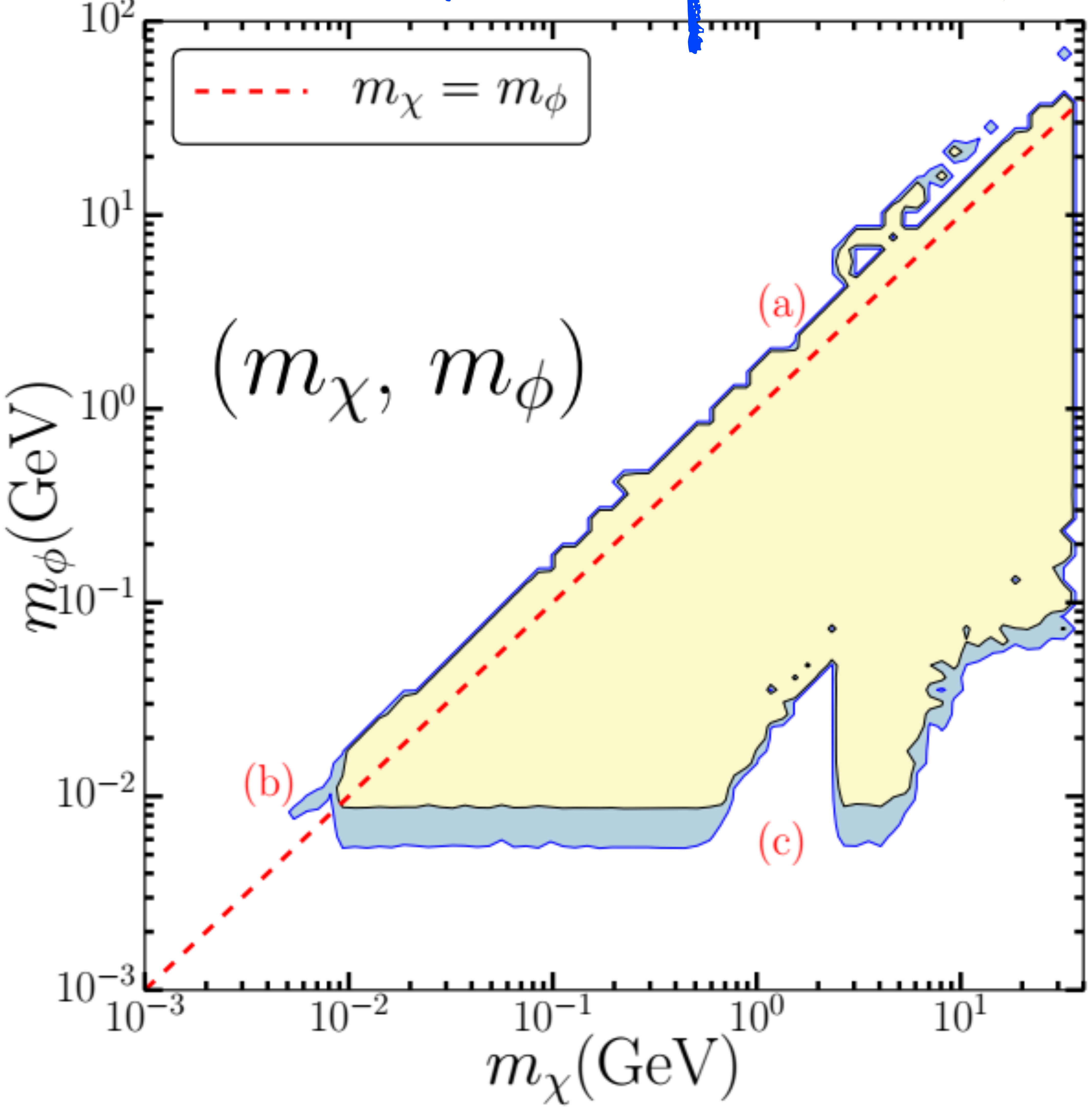
# Global picture of parameter space





Parameter space is finite. Let us go through (a)-(g)

# Global picture of parameter space



Parameter space is finite.

(a) mphi~2*mx, resonance region.

(b) Lower limit of DM and mediator mass due to relic density (mx~mphi) +CMB deltaNeff (mphi<5 MeV).

(c) DM direct detection and relic density constraints.

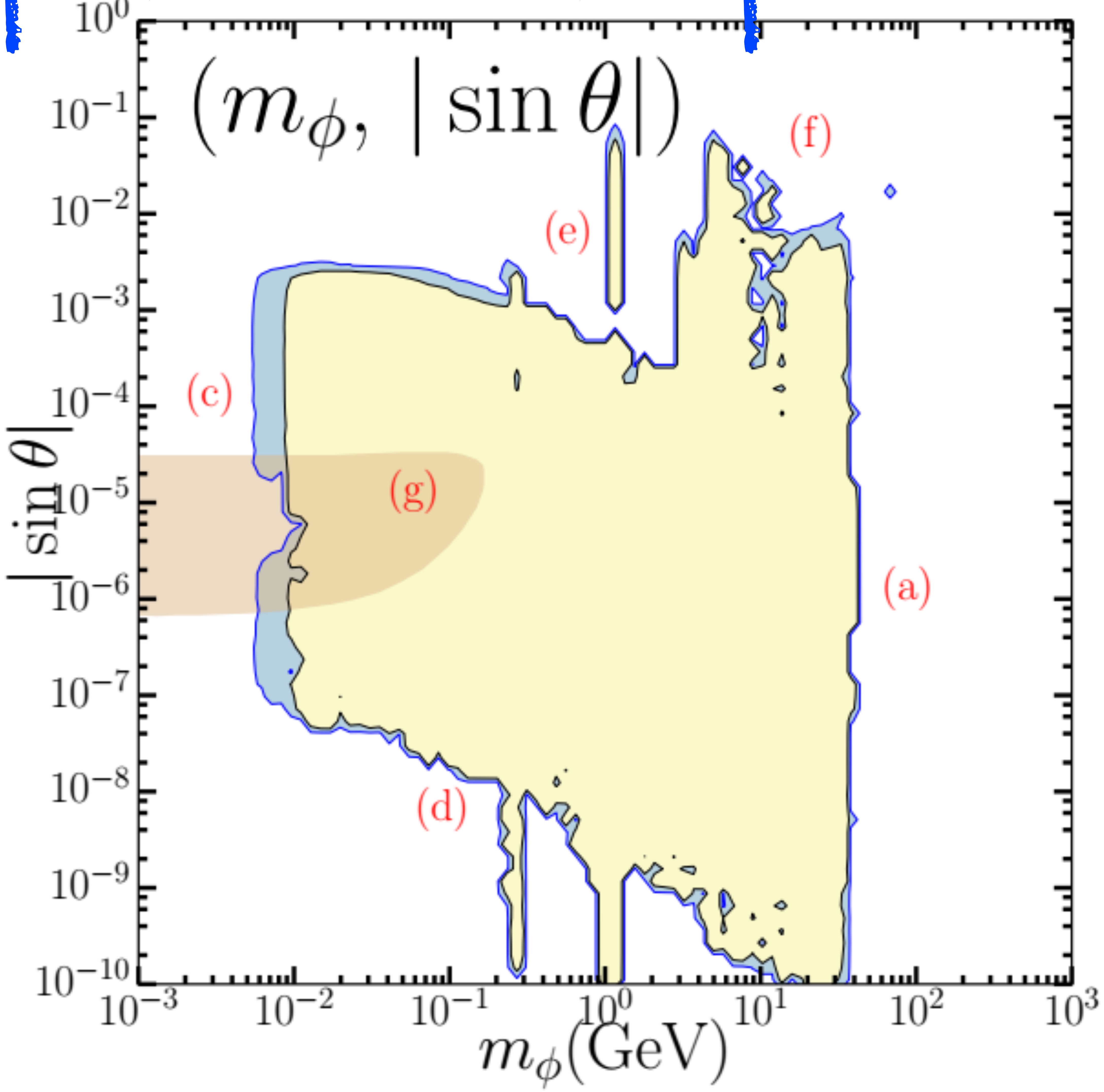
# Global picture of parameter space

(d) BBN (1s for mphi>2*mpi, but 1e5s for mphi<2*mpi), phi decay to 2 muon opens.

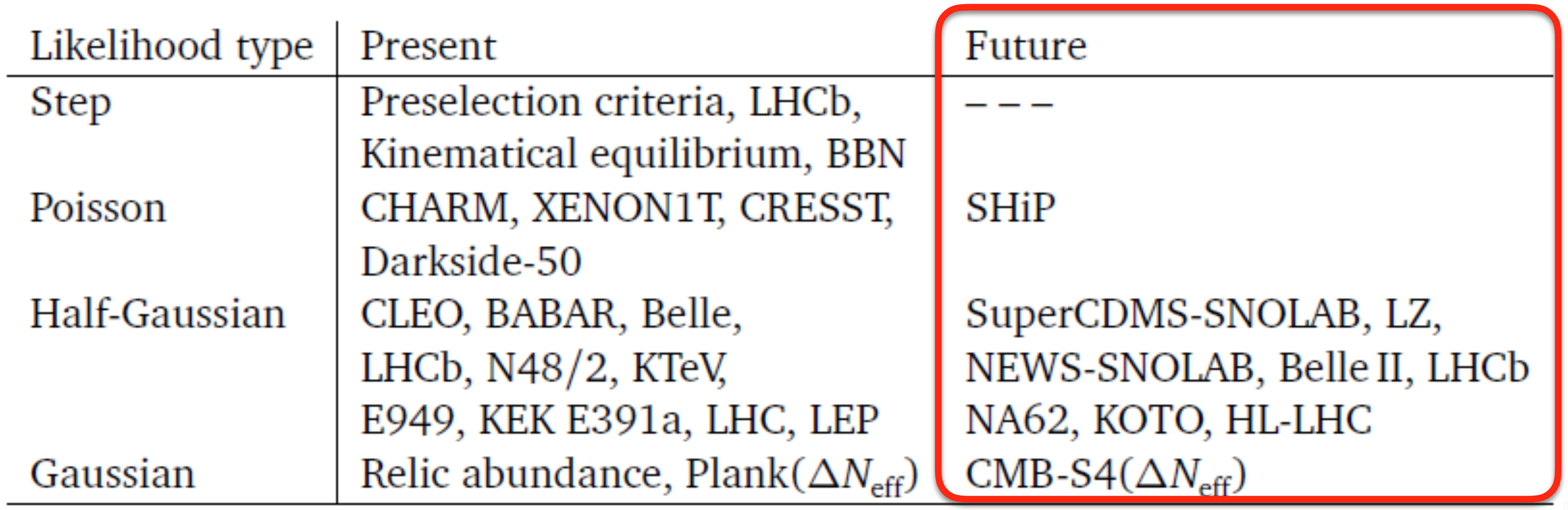
(e) Kaon (mphi<500 MeV), B-meson (500 MeV<mphi<5GeV).

(f) DM direct detection.

(g) SN1987a constraints.



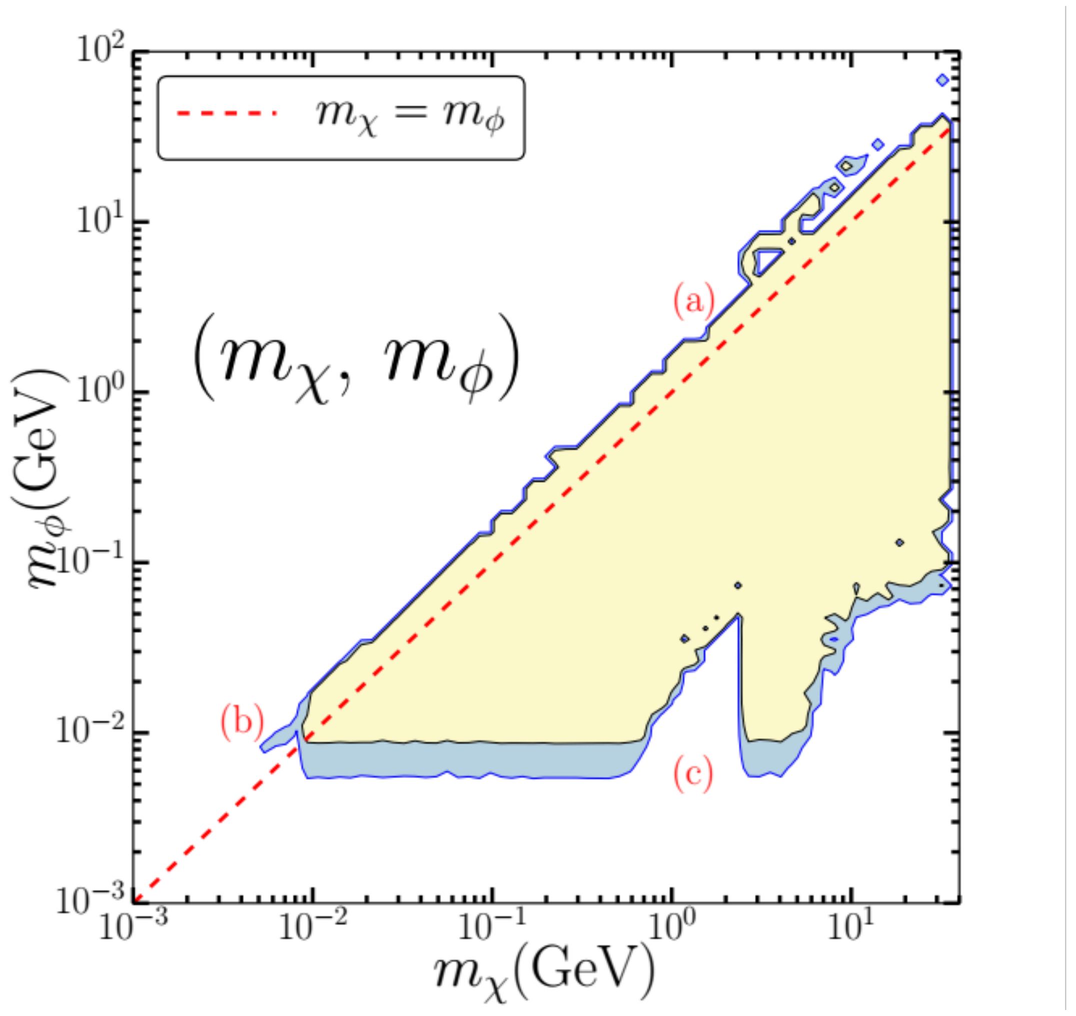
Parameter space is finite.

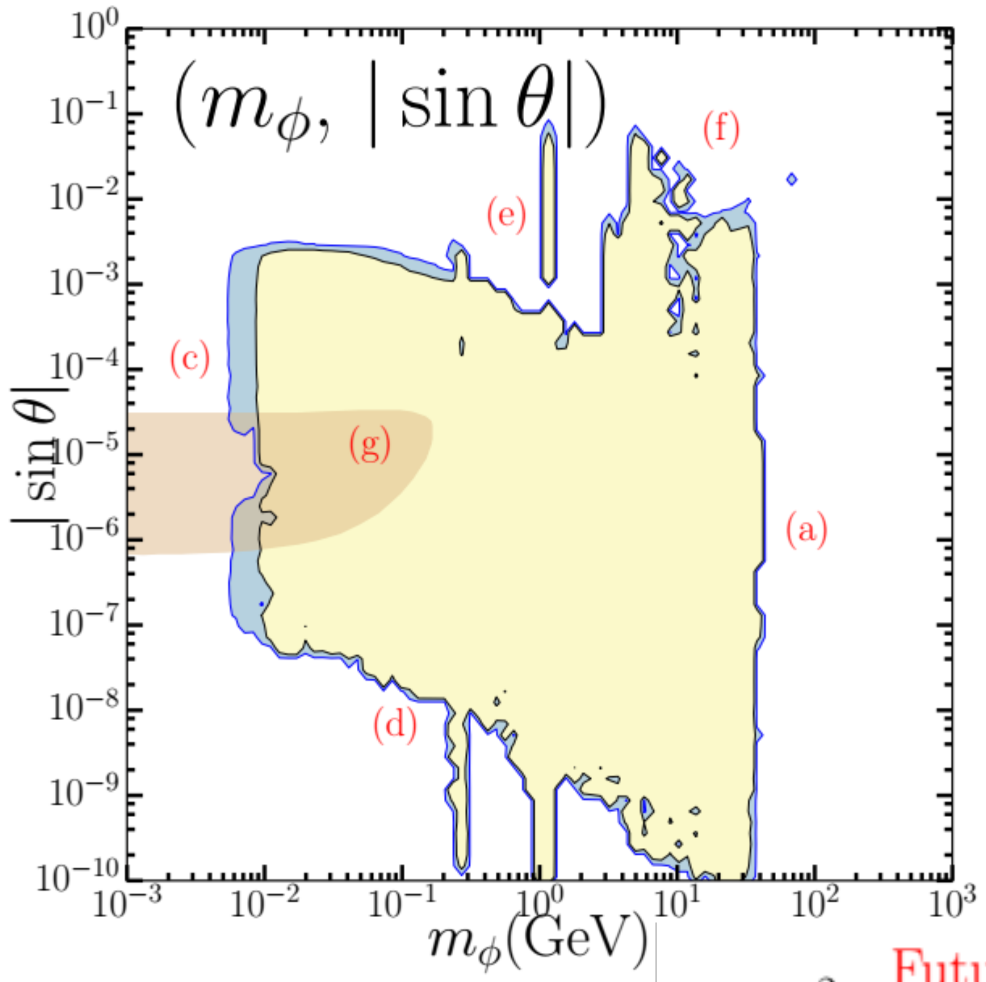


| Likelihood type | Present | Future |
|---|---|---|
| Step | Preselection criteria, LHCb,<br>Kinematical equilibrium, BBN | – – – |
| Poisson | CHARM, XENON1T, CRESST,<br>Darkside-50 | SHiP |
| Half-Gaussian | CLEO, BABAR, Belle,<br>LHCb, N48/2, KTeV,<br>E949, KEK E391a, LHC, LEP | SuperCDMS-SNOLAB, LZ,<br>NEWS-SNOLAB, Belle II, LHCb<br>NA62, KOTO, HL-LHC |
| Gaussian | Relic abundance, Plank($\Delta N_{\rm eff}$) | CMB-S4($\Delta N_{\rm eff}$) |

Future prospects: potential signals, strategy and method improvement.

# Future sensitivity of parameter space





**(h)** Delta Neff will be improved.

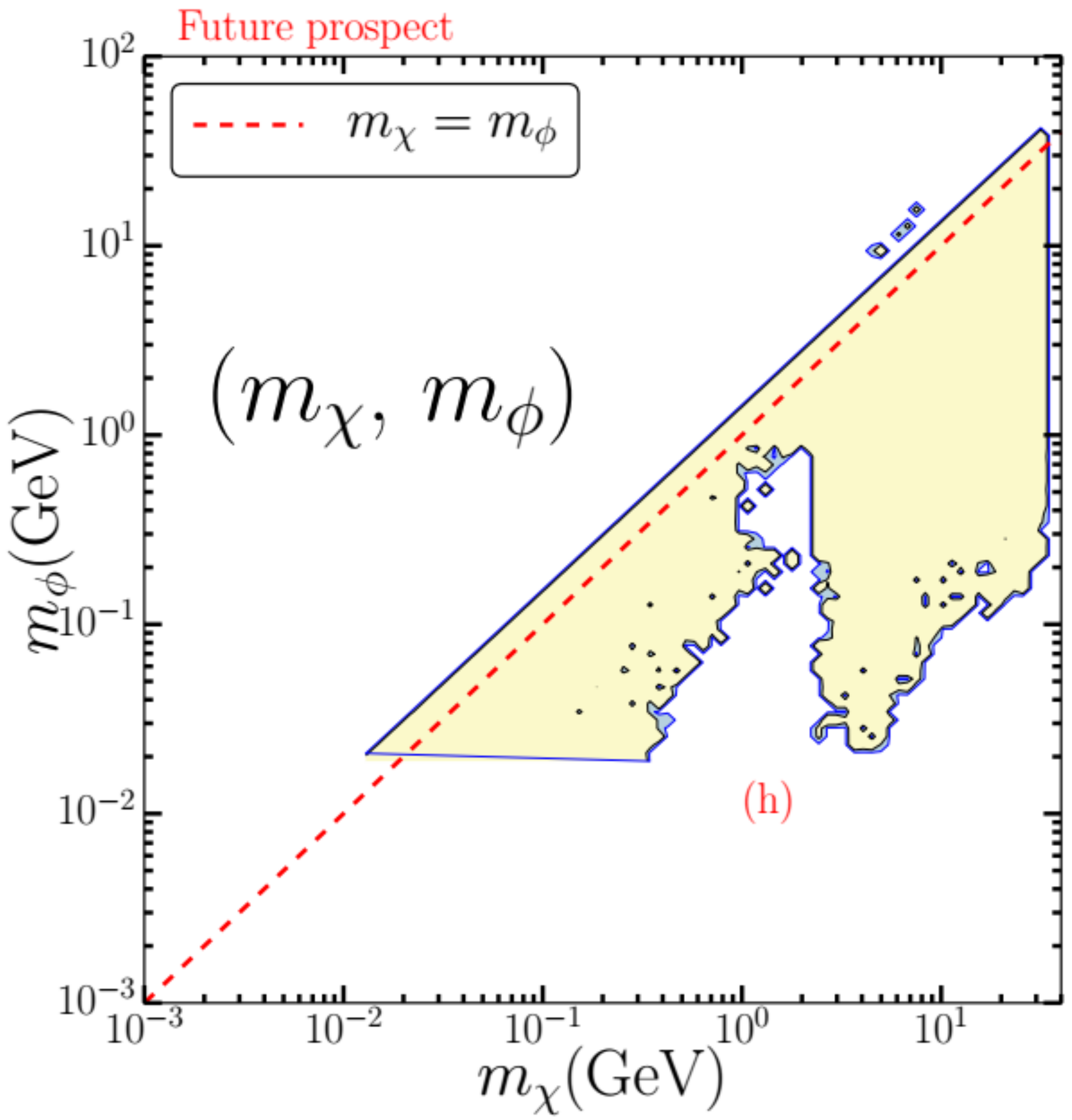
**(i)** Higgs invisible decay.
(ILC and CEPC can do it better.)

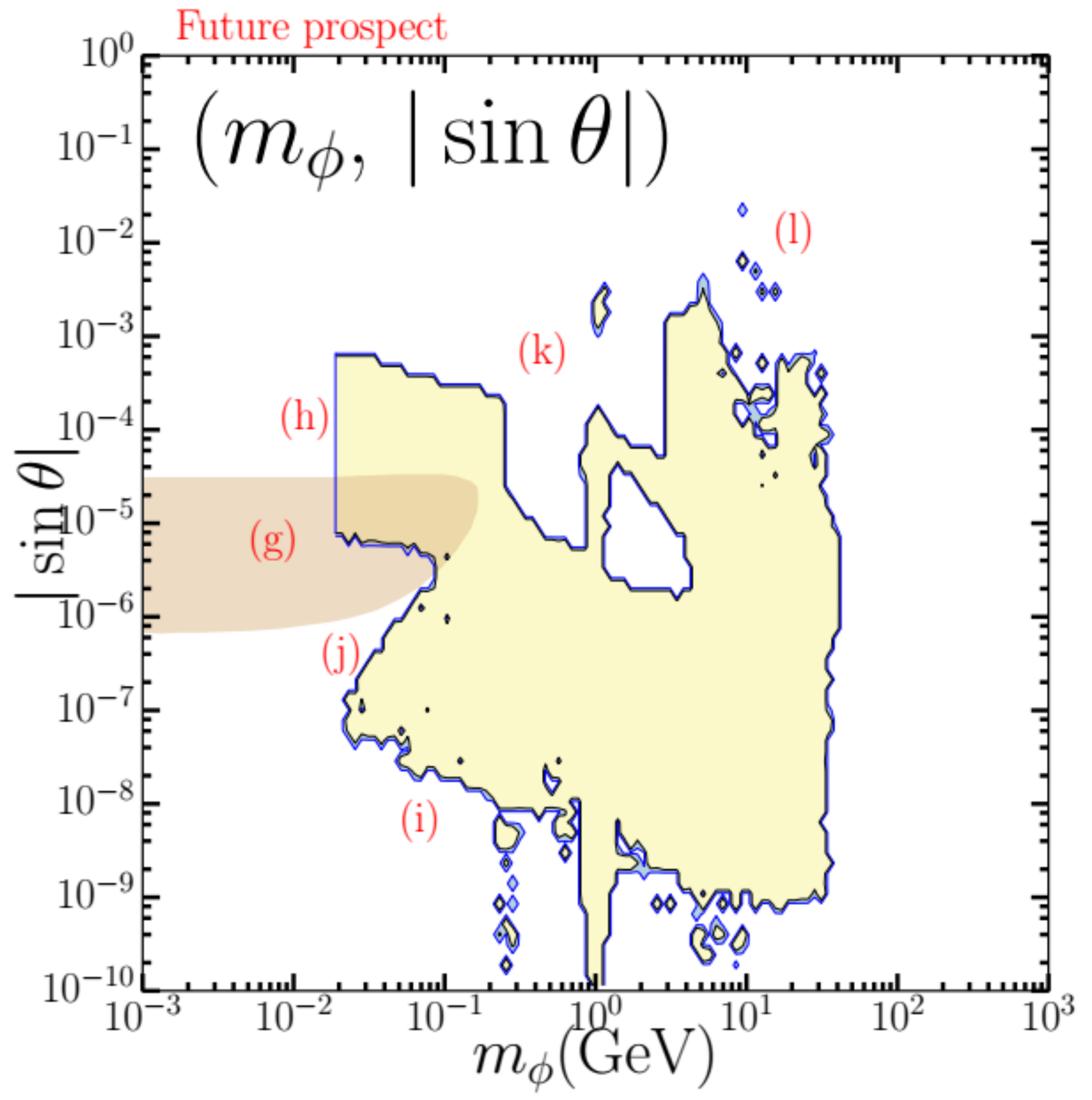
**(j)** DM direct detection.

**(k)** SHiP+LHCb+ Belle II.

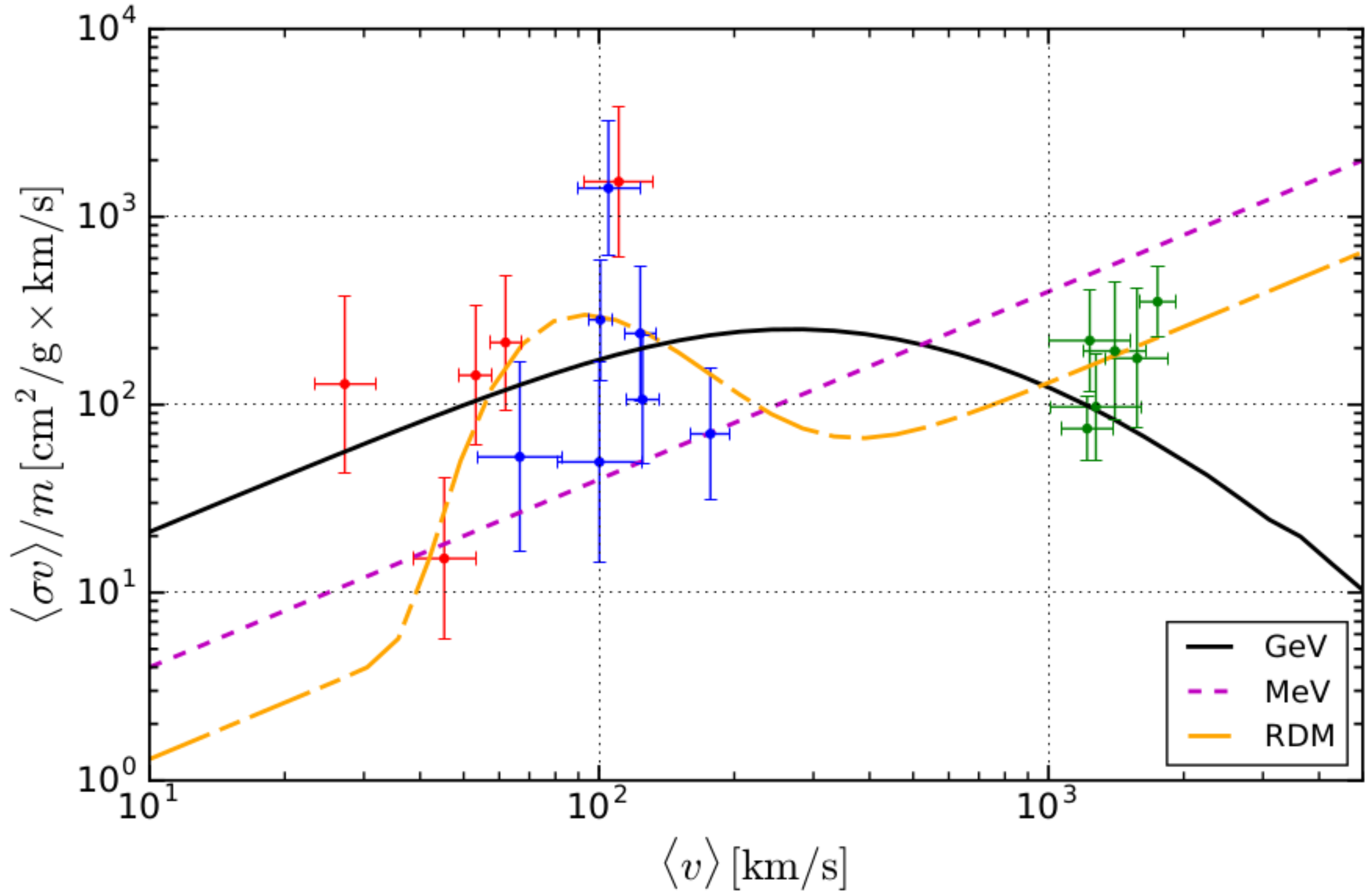
**(l)** DM direct detection (SuperCDMS-SNOLAB, LZ,

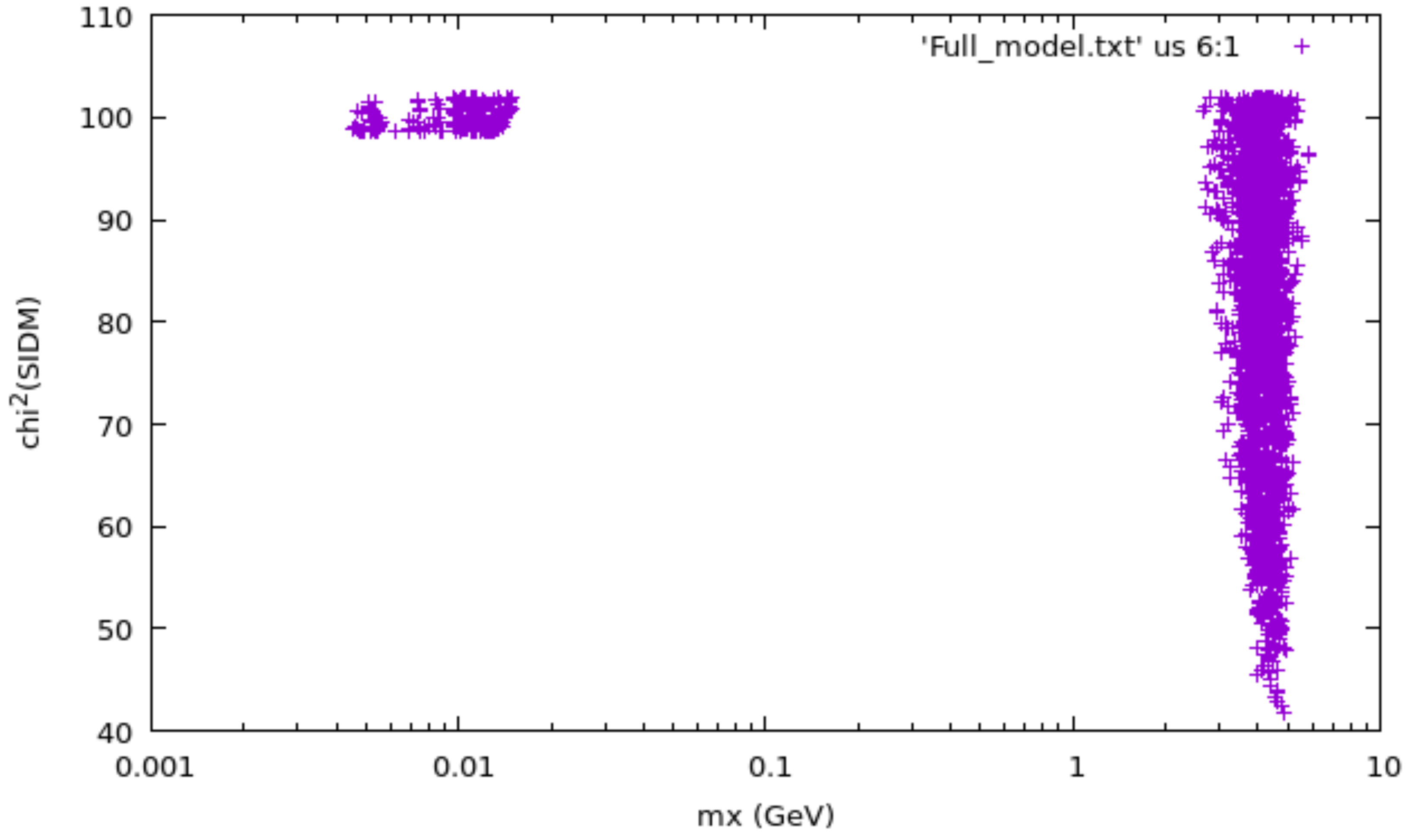
NEWS-SNOLAB)

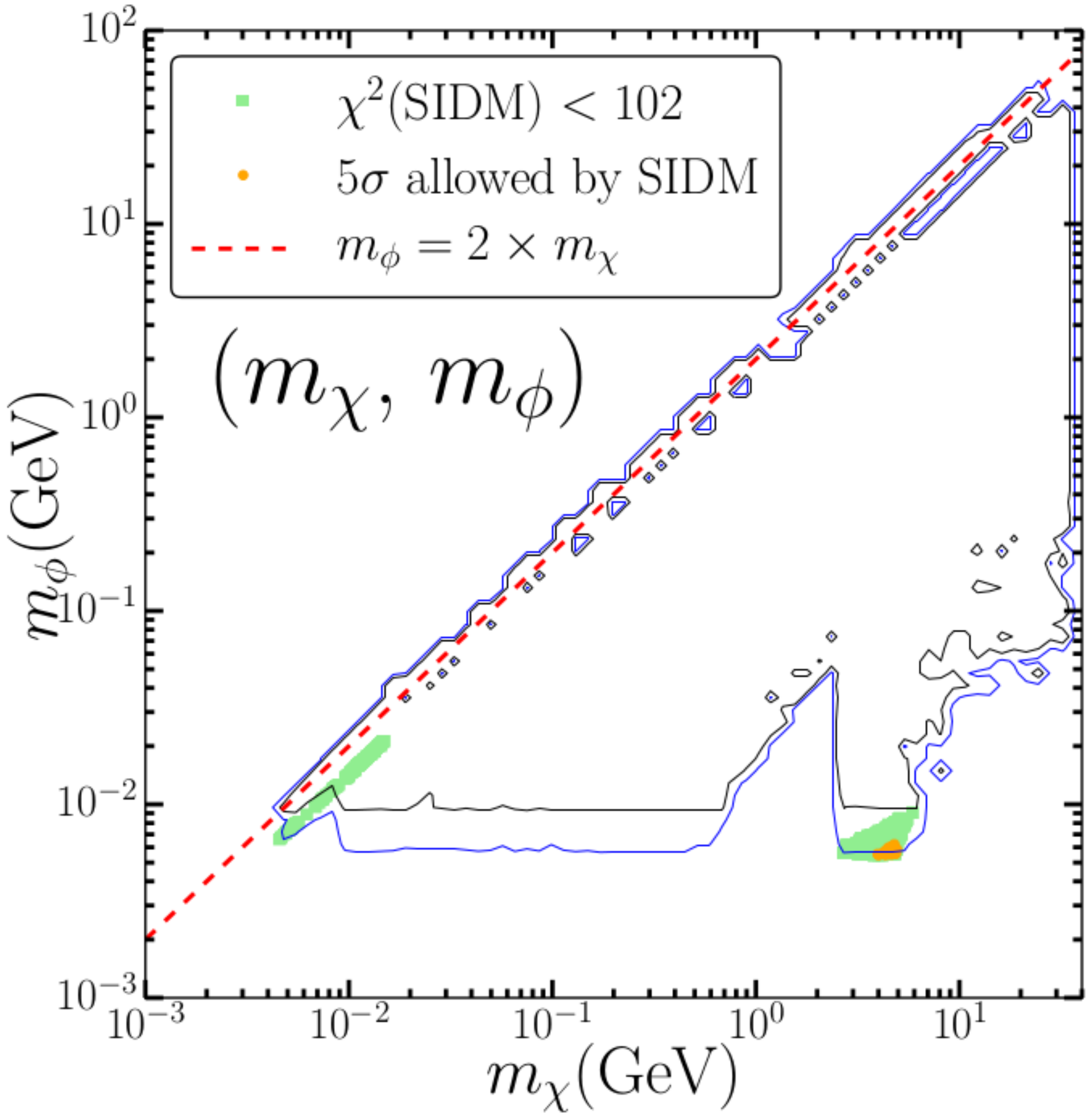


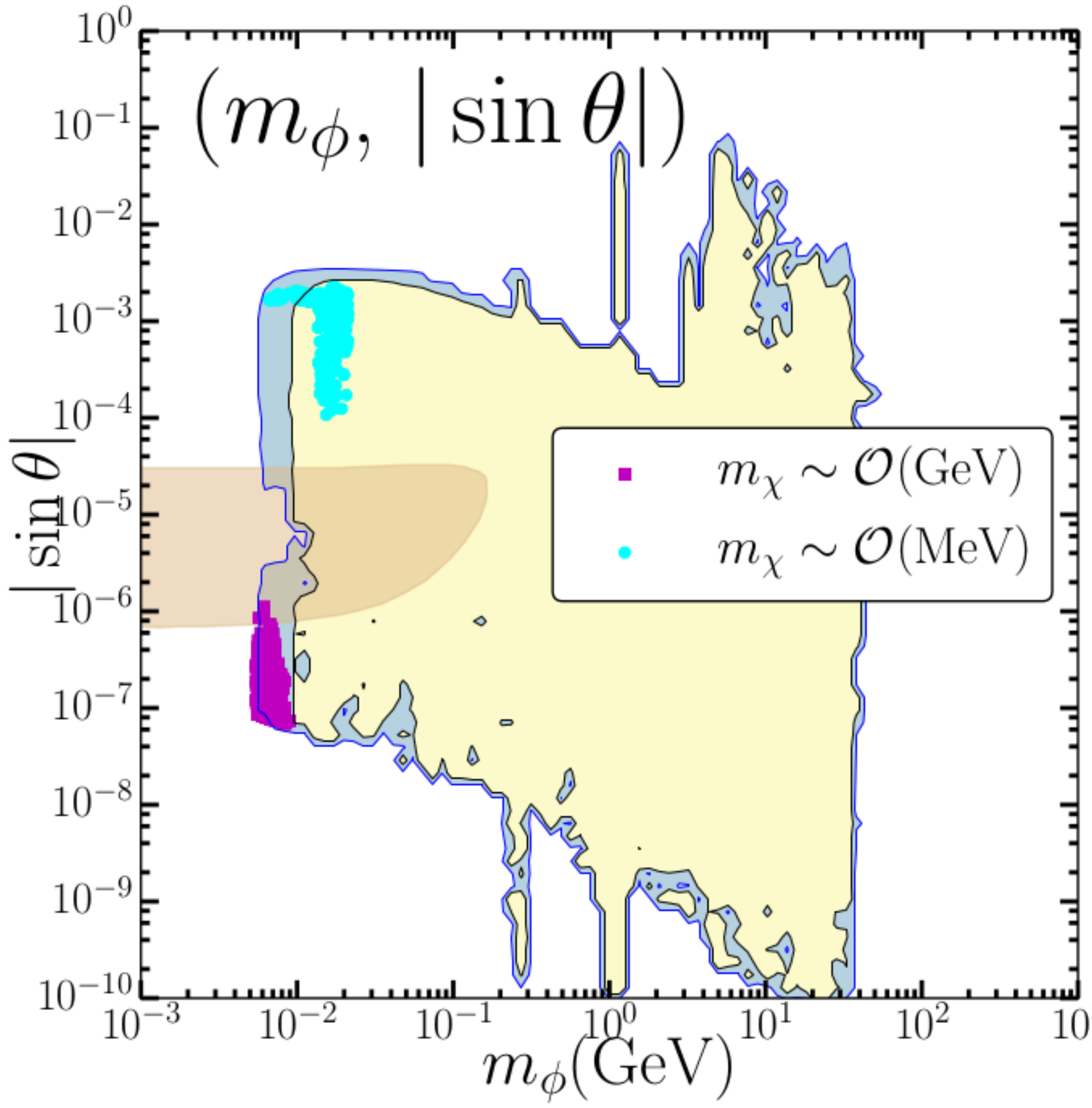


# Self-interacting dark matter



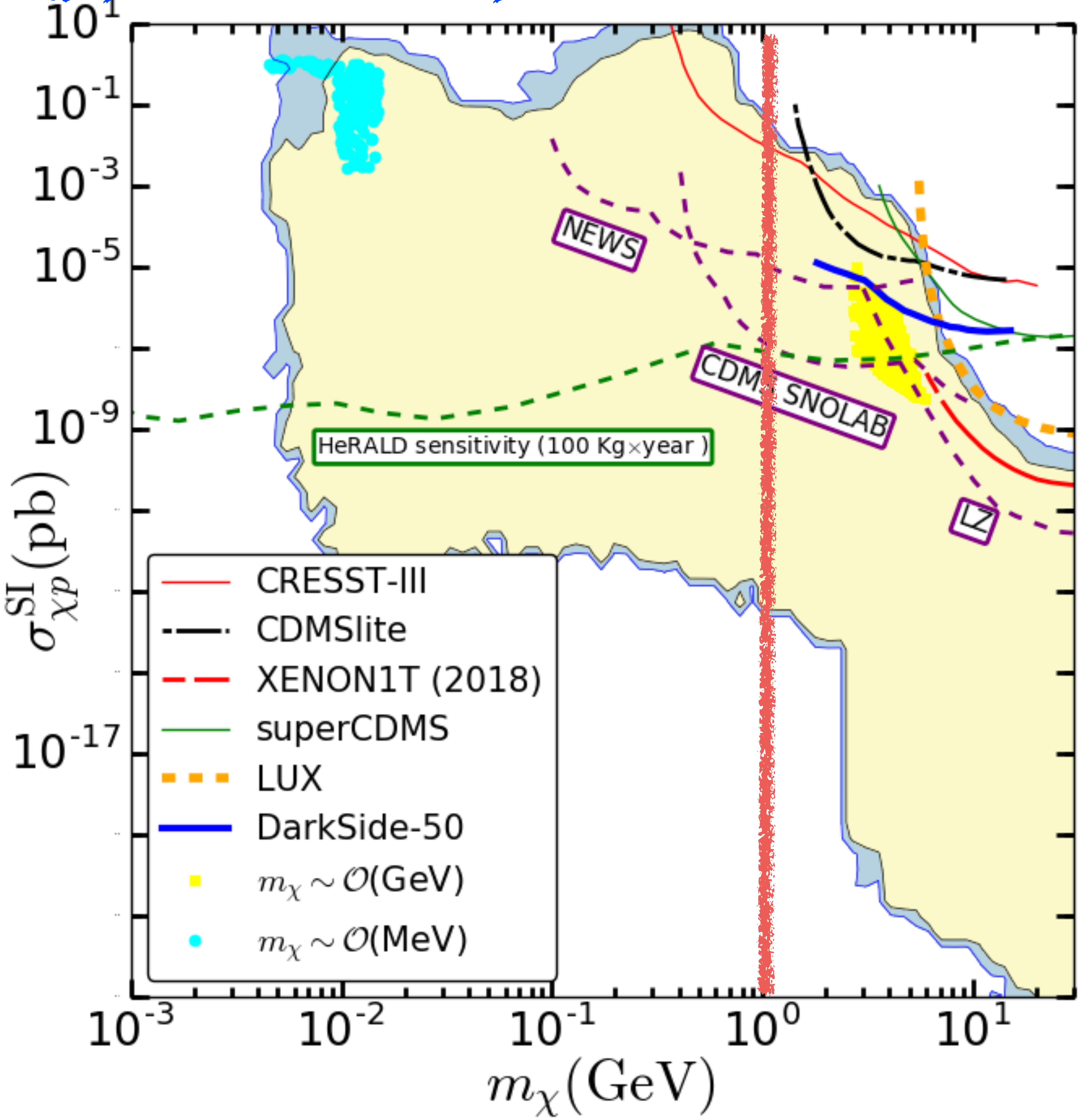






SIDM can be realized in this framework.

# Future direct detection



MeV DM
parameter space
remains but tiny
after HeRALD.

# Conclusion and summary

- **Assumption:** Correct relic density is required to be produced with the thermal condition (initial condition n~exp(-m/T)@T>=TF).

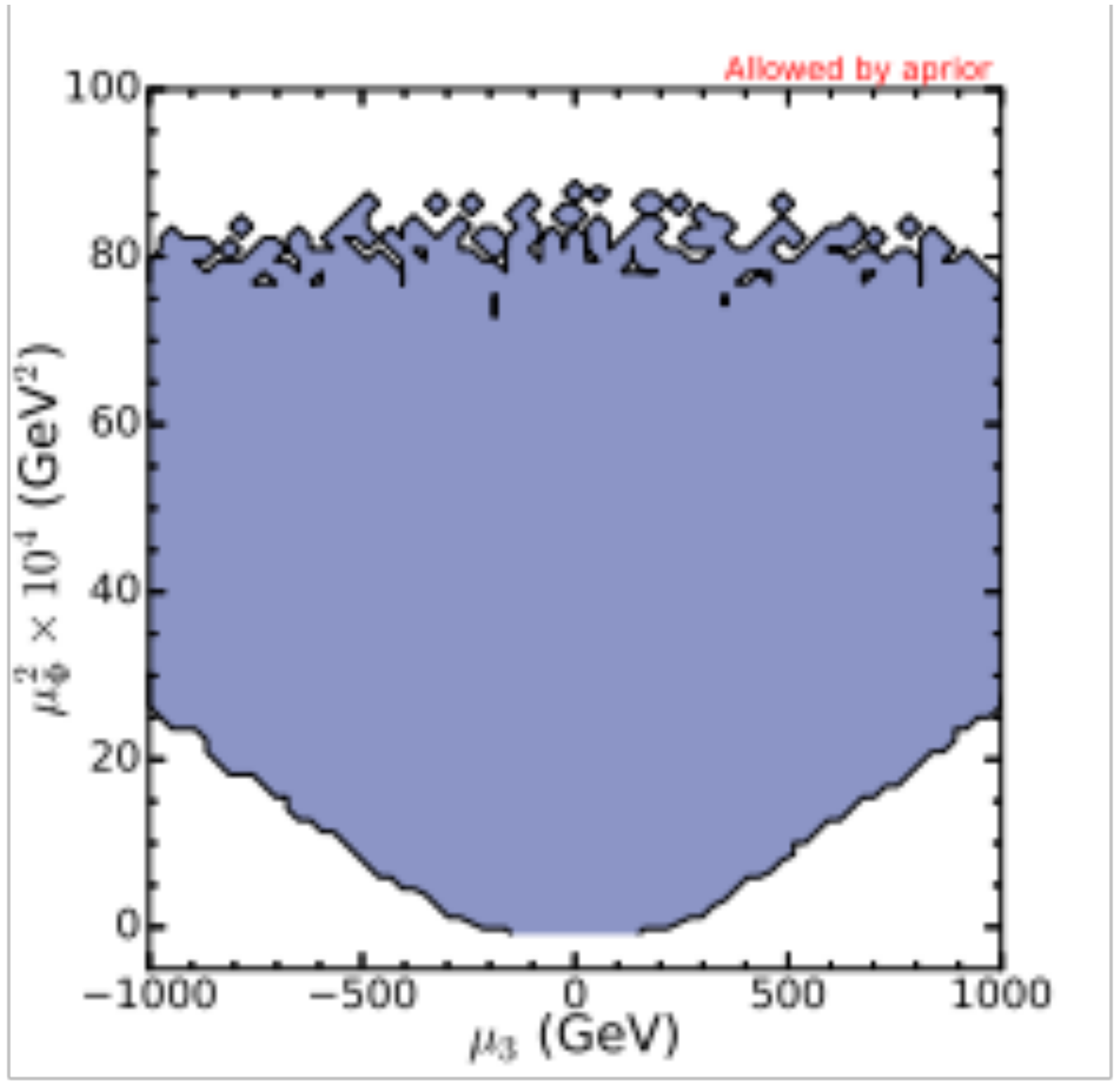
- **Strategy:** A minimal (renormalizable) model with a light fermion WIMP and a light scalar mediator is studied and its width is treated carefully.

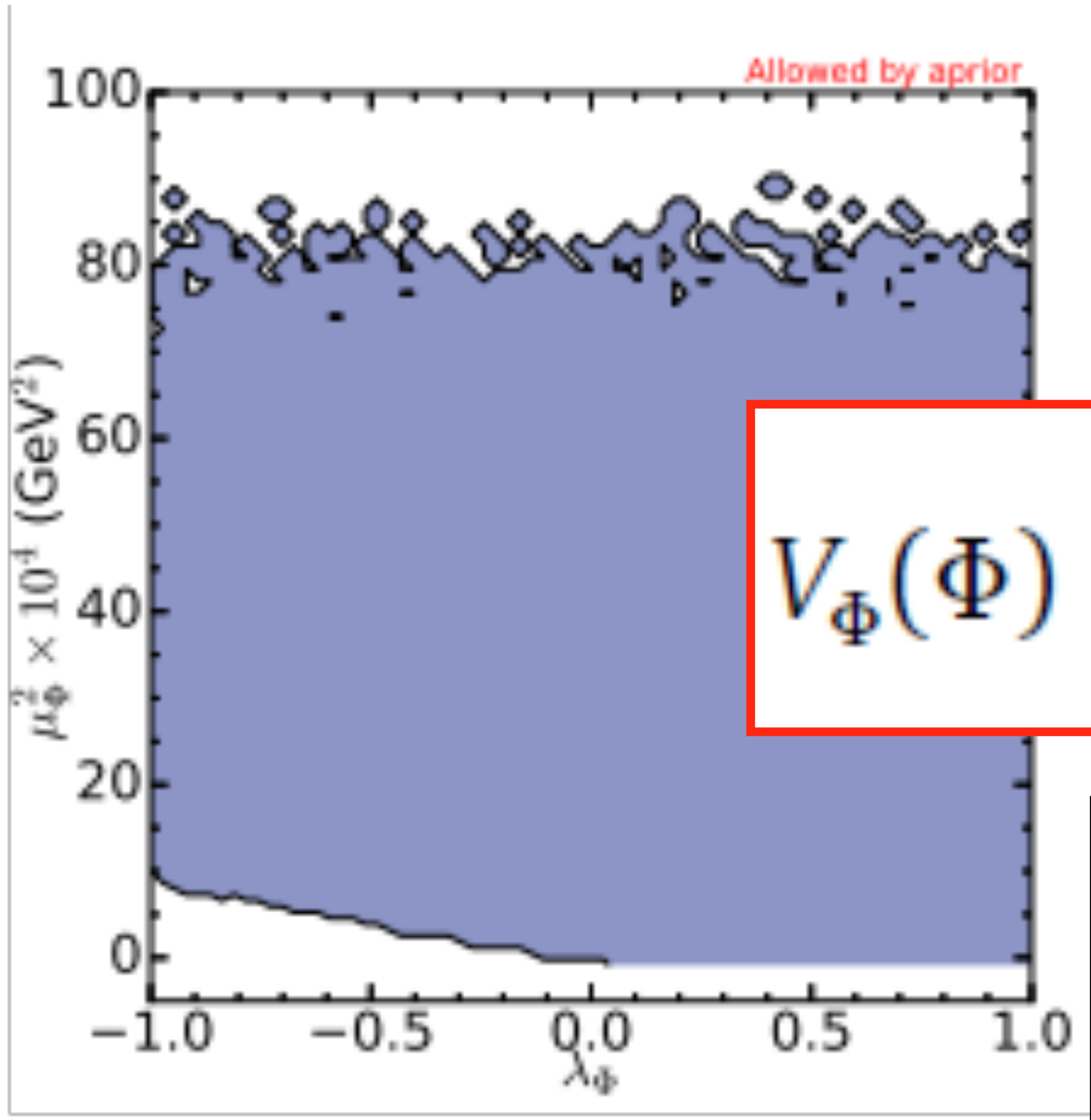
- **Result:** after taking all the constraints into account, the parameter space is finite and lower bound for DM and mediator mass.

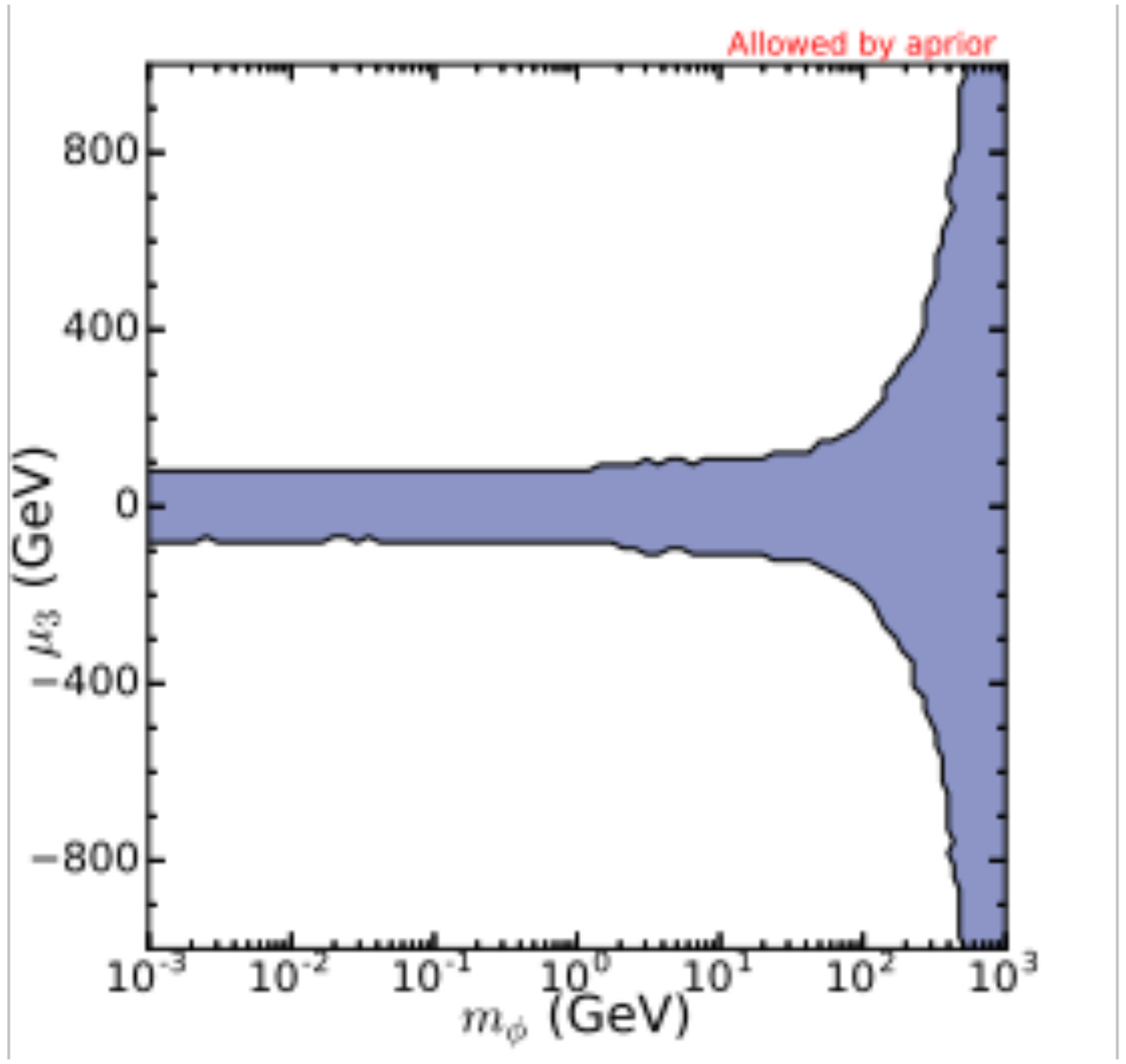
- **Prospect:** future prospect is also performed and it can further bite the parameter space.

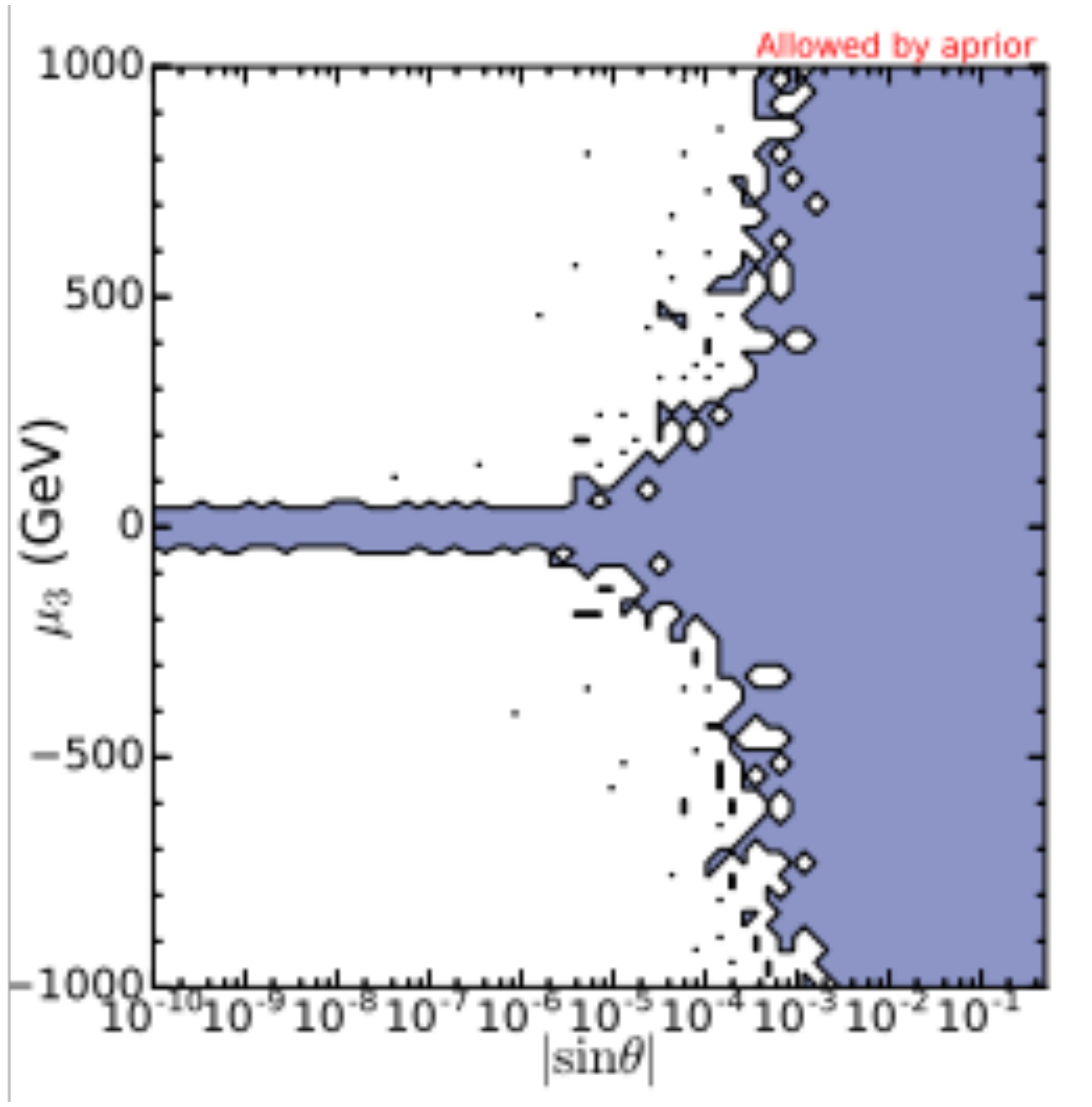
# Backup

# Higgs potential constraints









$$V_\Phi(\Phi) \;=\; \mu_1^3\Phi + \frac{\mu_\Phi^2}{2}\Phi^2 + \frac{\mu_3}{3!}\Phi^3 + \frac{\lambda_\Phi}{4!}\Phi^4$$

- We require vh=240 and vphi=0 must be the minimum within [vh, vphi < 1 TeV] region.
- In the small mass mphi<10 GeV, |mu3| is required to be less than 100 GeV.
- lambda_Phi has to be positive.
- muPhi squared is less than 0.9 TeV^2.

# Dark Higgs decay

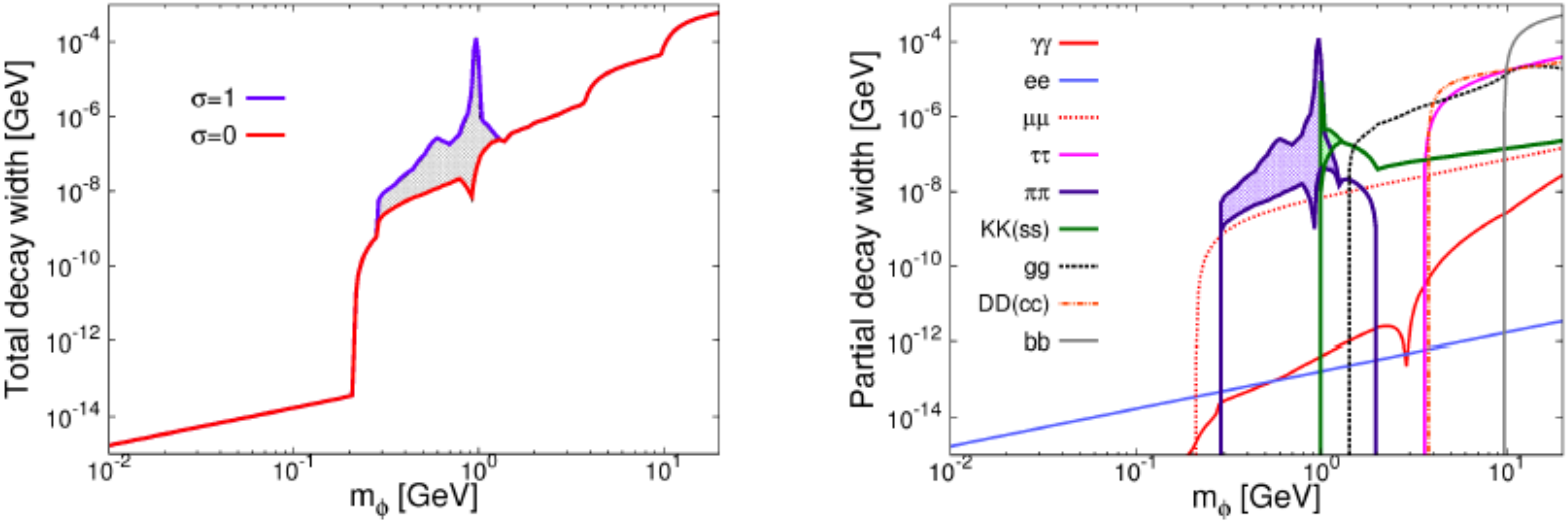
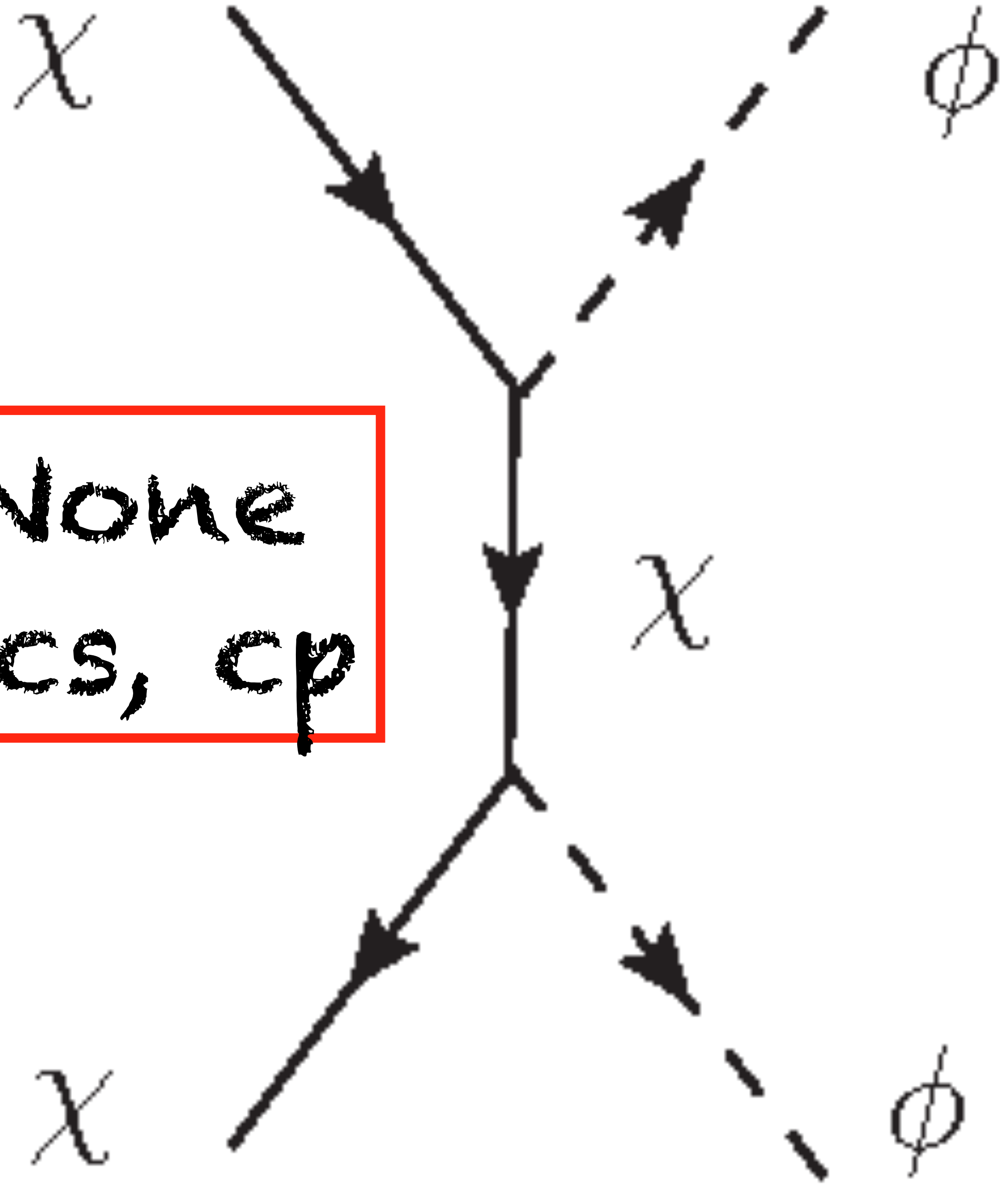


Figure 1: *(Left panel) The total decay width of the mediator $\phi$ assuming that* $\sin\theta = 1$ *and $\phi$ does not decay into a WIMP pair. The gray band indicates the theoretical uncertainty due to non-perturbative QCD effects. (Right panel) Partial decay widths contributing to the total width.*

One nuisance parameter is included to account for QCD effects.

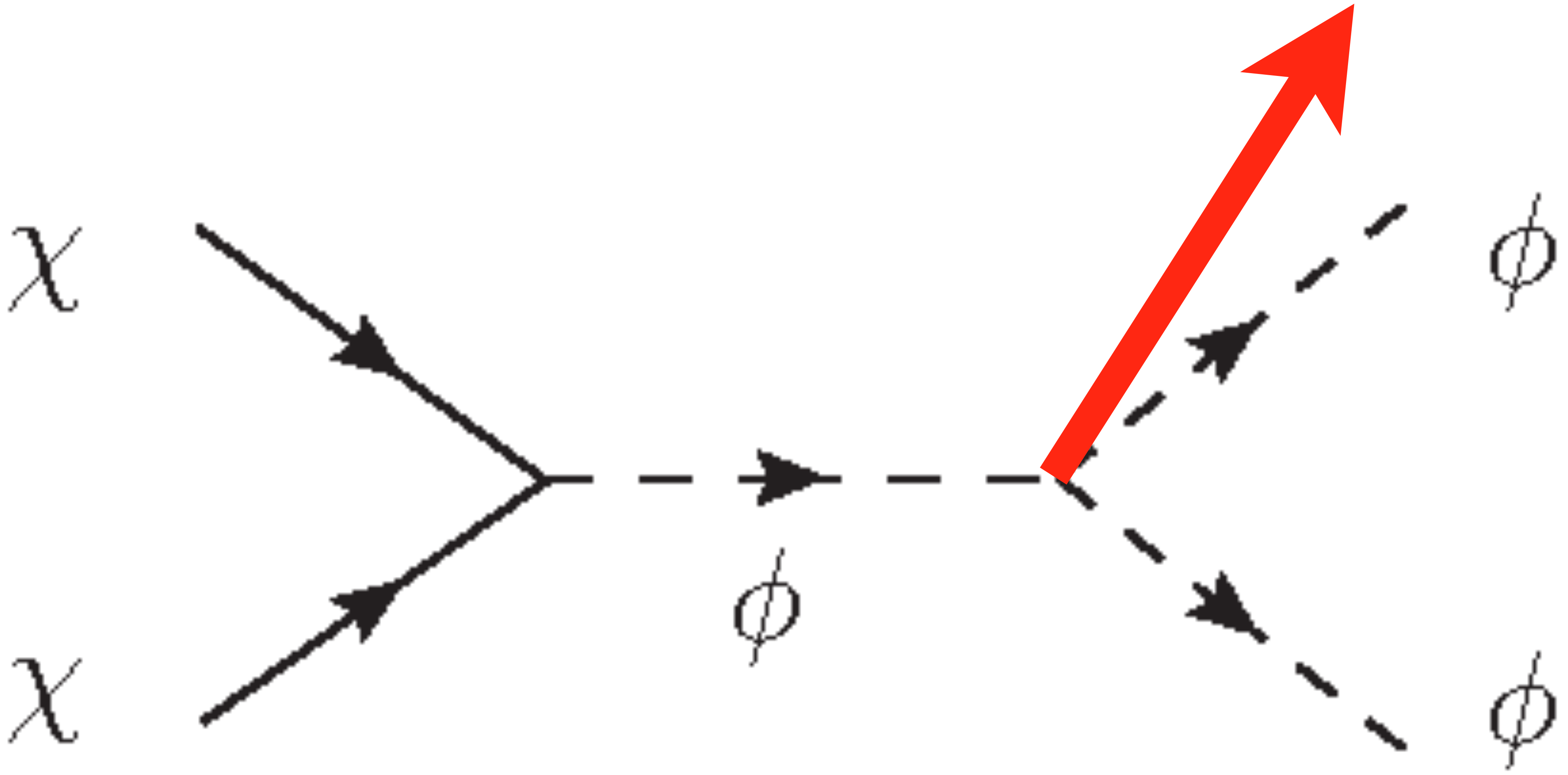
# Annihilation cross section and light mediator

$$-\frac{c_s}{2}\Phi\bar{\chi}\chi - \frac{c_p}{2}\Phi\bar{\chi}i\gamma_5\chi$$



s-wave: None
p-wave: cs, cp

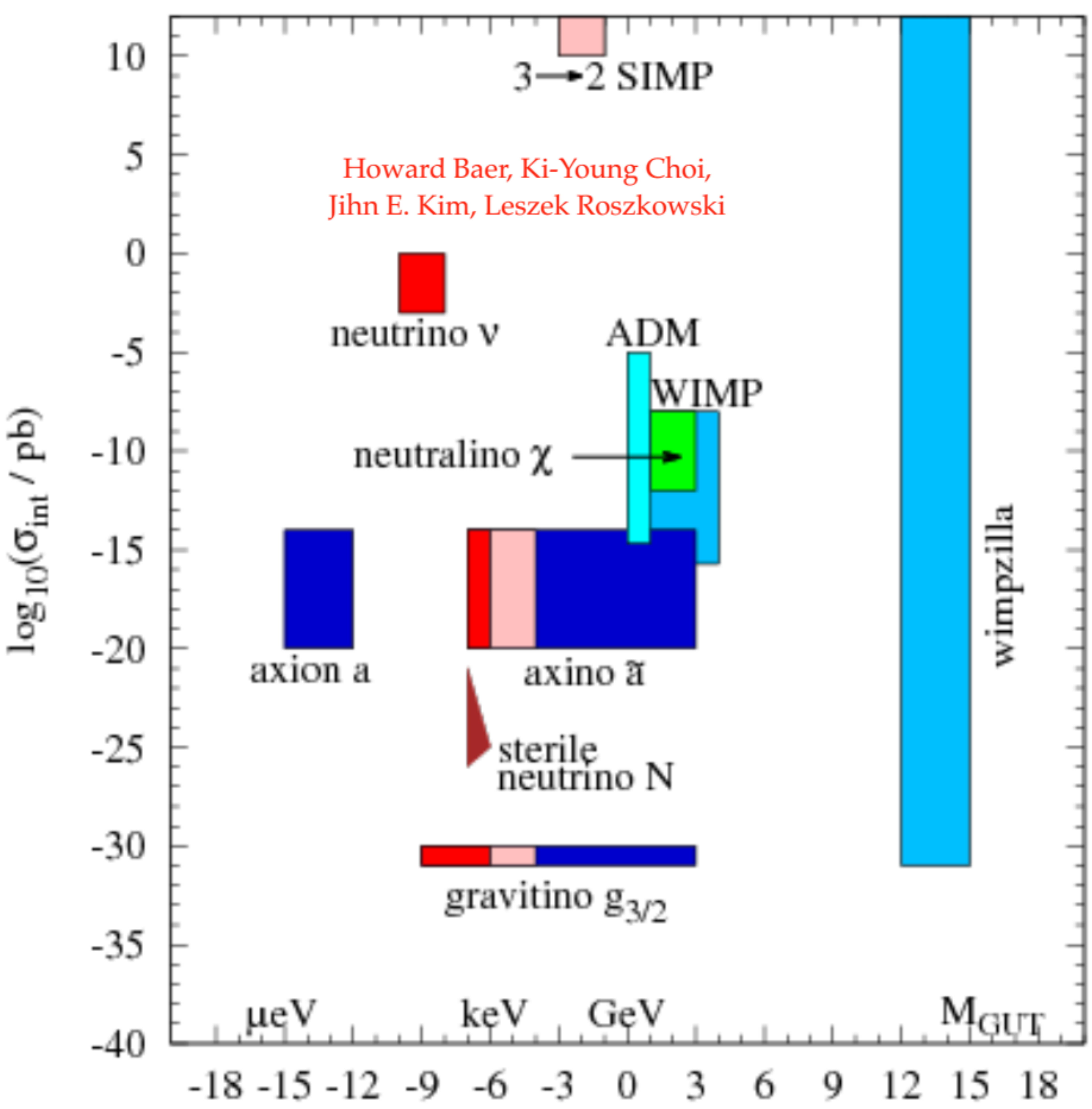
$$c_{\phi\phi\phi} = 3\lambda_H v_H s_\theta^3 + 3A_{\Phi H} c_\theta s_\theta^2 + \mu_3 c_\theta^3 + 3\lambda_{\Phi H} v_H c_\theta^2 s_\theta$$



s-wave: cp
p-wave: cs, cp

Scalar coupling cs only provide p-wave

# There are so many DM models located at different mass scales.



Howard Baer, Ki-Young Choi,
Jihn E. Kim, Leszek Roszkowski

## A few particle dark matter theories:

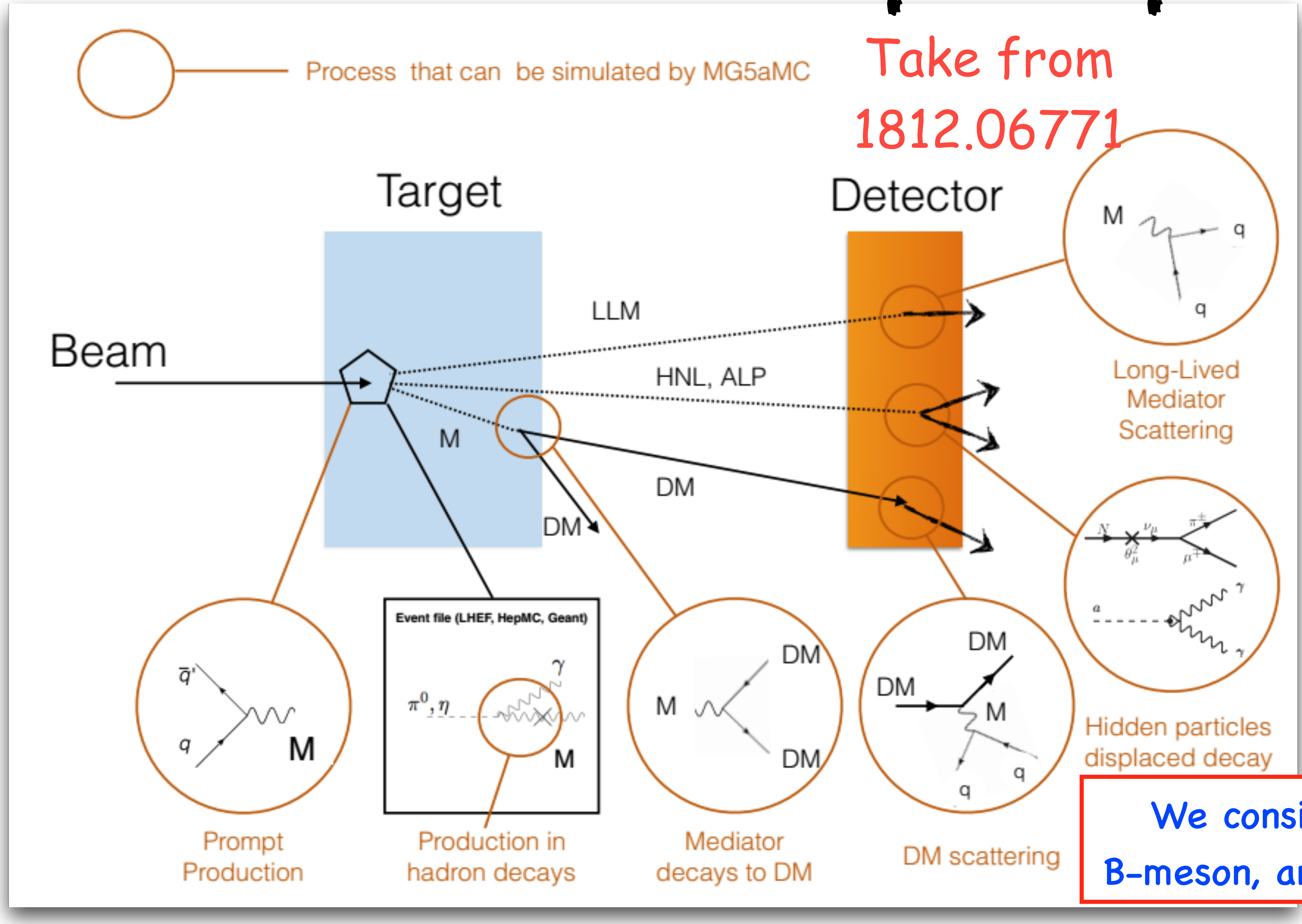
- axion
- sterile neutrino
- SUSY DM
  - neutralino in MSSM
  - Bino/Wino/Higgsino/Photino
  - sneutrino
  - gravitino
  - decaying gravitino
  - gravitino with large messenger mass
  - split SUSY DM
  - bound states for Sommerfeld enhancement
  - bino in $E_6$SSMwith massless inert singlets
  - neutralino from axion decay
  - NMSSM DM
  - mixed axion/neutralino
  - invisible photino
  - etc., etc. etc.
- Kaluza-Klein DM
- leptophilic DM
- leptophilic from non-abelian discrete symmetry
- asymmetric DM
- scalar singlet DM
- superGUT unified
- mirror DM

- non-thermal from decay of moduli
- resonance with momentum dependence
- helicity modification due to QED corrections
- dipole moment interacting DM
- dark instanton
- bosonic gas DM
- anti-baryonic
- ultra-light bosonic DM
- invisible photino
- T13 flavor symmetry decaying DM
- hydrodynamic vacuum DM
- dilatation anomaly DM
- bulk viscous unified DM
- ELKO field DM
- two singlet DM
- cosmic braneworld ultra-light DM
- superheavy quark clusters
- luxino
- non-canonical kinetic term DM
- branes filled with scalar fields
- real gauge singlet
- Higgs portal
- number theory DM
- asymmetric sneutrino
- modified Ricci model DM
- vacuum solitons
- complex singlet scalar
- D4 x Z2 flavor group DM
- non-minimal KK DM
- axion portal cascade
- light (MeV mass) DM

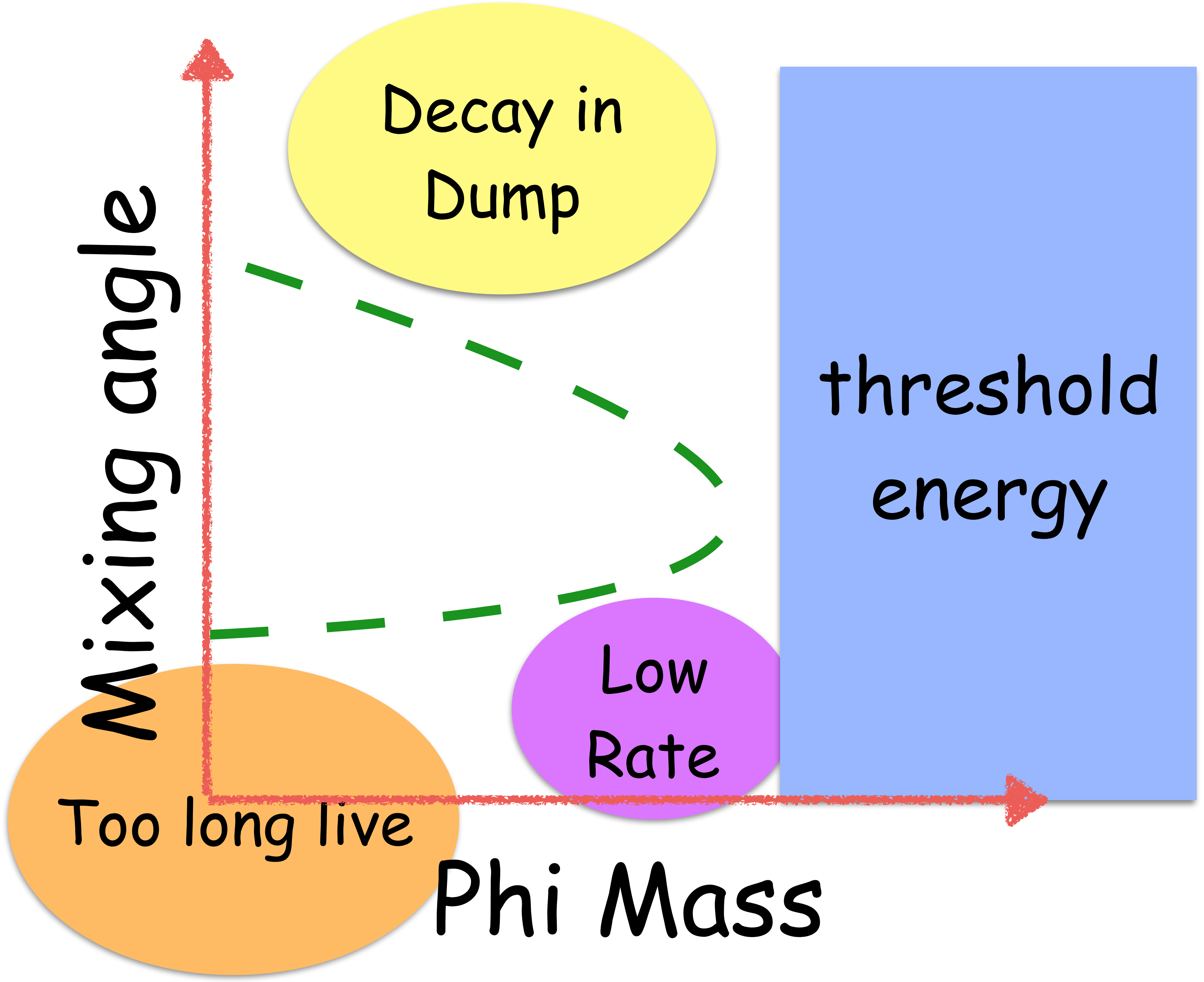
- two singlet DM
- self-interacting DM
- isospin violating DM
- inert Higgs
- skyrmion in littlest Higgs model
- techni-dilaton DM
- type-II seesaw mSUGRA DM
- vector DM
- goldsini
- WIMPless DM
- inert triplet DM
- vacuum solitons
- BEC from U(1) symmetry breaking
- eXciting DM (XDM)
- inelastic DM (iDM)
- flavor SU(3)Q triplet/singlet
- isospin violating
- axion-like repulsive DM
- D6 flavor symmetry
- warped Radion
- G2-MSSM
- gauged right-handed neutrino
- integration constant Horava DM
- tensor-four-scalar
- scalarons in R2 gravity
- secluded DM
- etc., etc., etc., etc., etc.

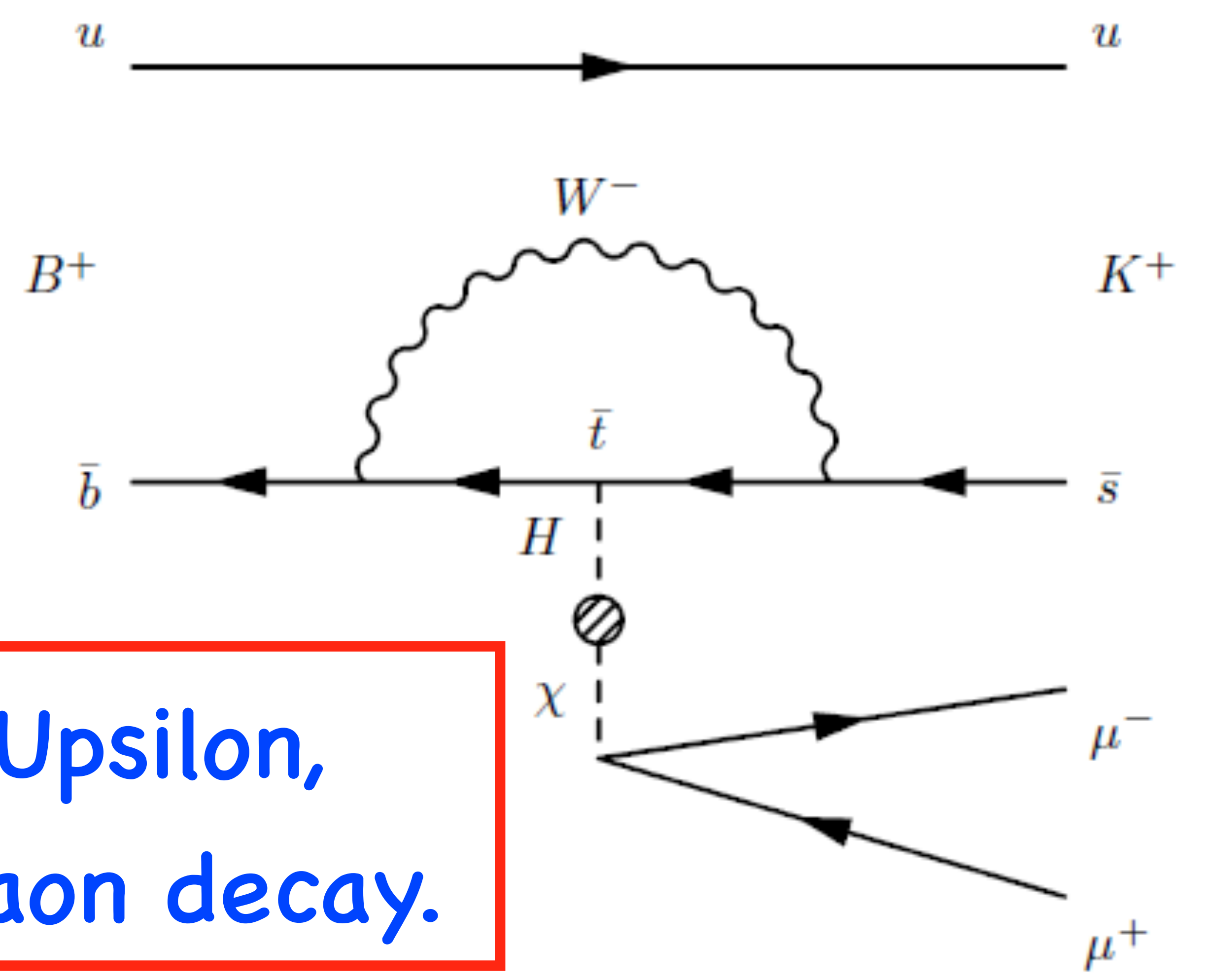
Taken from Griest (2014).

# Beam Dump experiments



Take from 1812.06771





We consider Upsilon, B-meson, and Kaon decay.

# Upsilon decay

- It is b-bbar bound state.
- Detection channel: upsilon(1S,2S,3S) decays to photon and phi and then phi decays to lepton pairs.
- For Phi mass smaller than upsilon mass (9.4 GeV), it allows us to study mu mu or tau tau invariant mass.
- CLEO and Babar can do the job.
- Present constraint is not as strong as Kaon and B-meson.

$$\gamma_\phi \simeq m_\Upsilon/(2m_\phi) \simeq 25.$$

- However, the decay length (gamma*tau*c~O(0.1) mm) which is shorter than the present Barbar sensitivity of displaced vertex searches, O(1) cm.

# B-meson decay

- B-meson mass around 5.3 GeV.
- Detection channel: b-quark decays to phi and s-quark (loop-level).
- BaBar : $\mathrm{Br}(B \to X_s \phi)\,\mathrm{Br}(\phi \to e^- e^+, \mu^- \mu^+, \pi^- \pi^+, K^- K^+)$
- LHCb: $B^\pm \to K^\pm + \phi \to K^\pm + \mu^- \mu^+$ and $B^0 \to K^{*0} + \phi \to K^{*0} + \mu^- \mu^+$
- Present constraint bits parameter space of MeV DM.
- Future constraints: Belle II (50 ab-1), LHCb (300 times).

# Search for long-lived scalar particles in $B^+ \to K^+\chi(\mu^+\mu^-)$ decays

LHCb,
Phys. Rev. D 95, 071101 (2017)
1612.07818

$$B^\pm \to K^\pm + \phi \to K^\pm + \mu^-\mu^+$$

$$B^0 \to K^{*0} + \phi \to K^{*0} + \mu^-\mu^+.$$

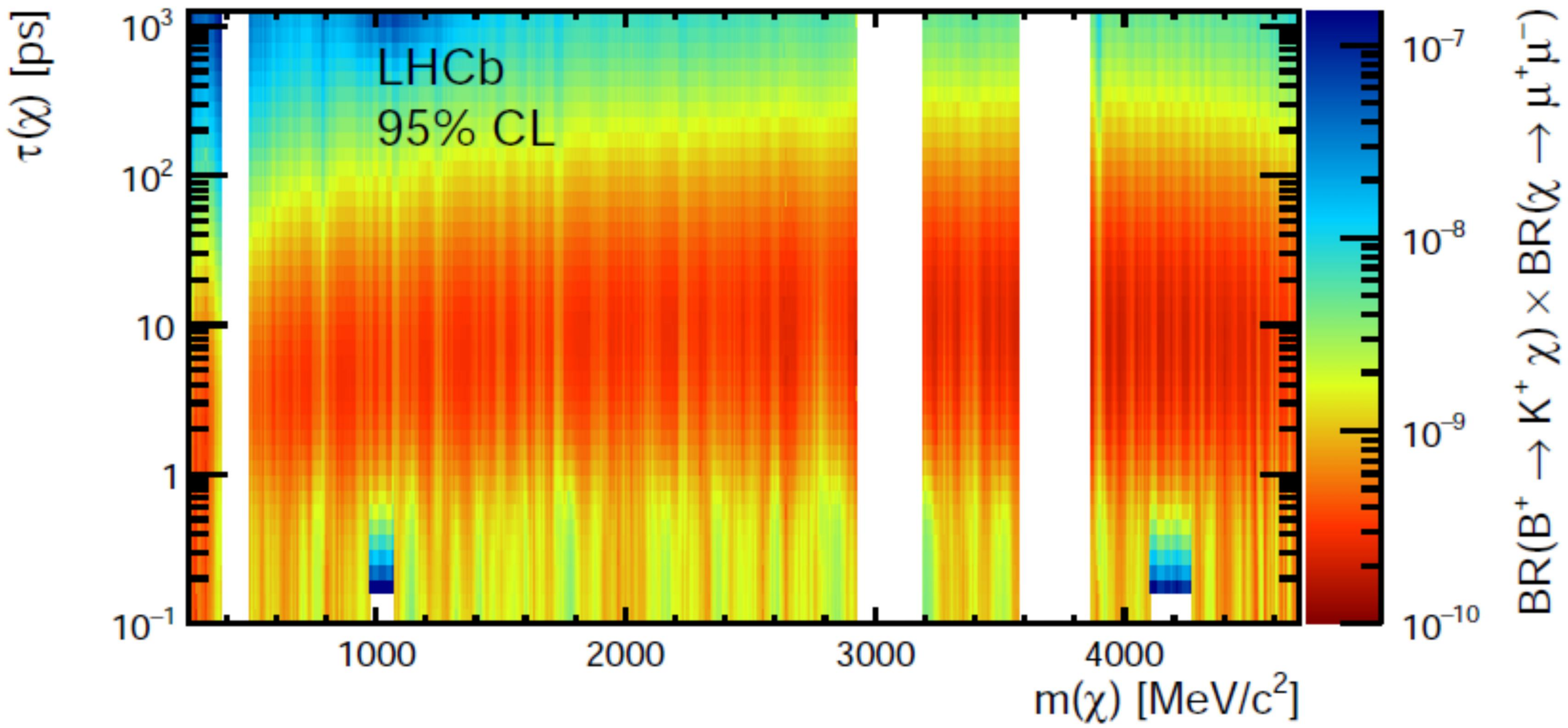
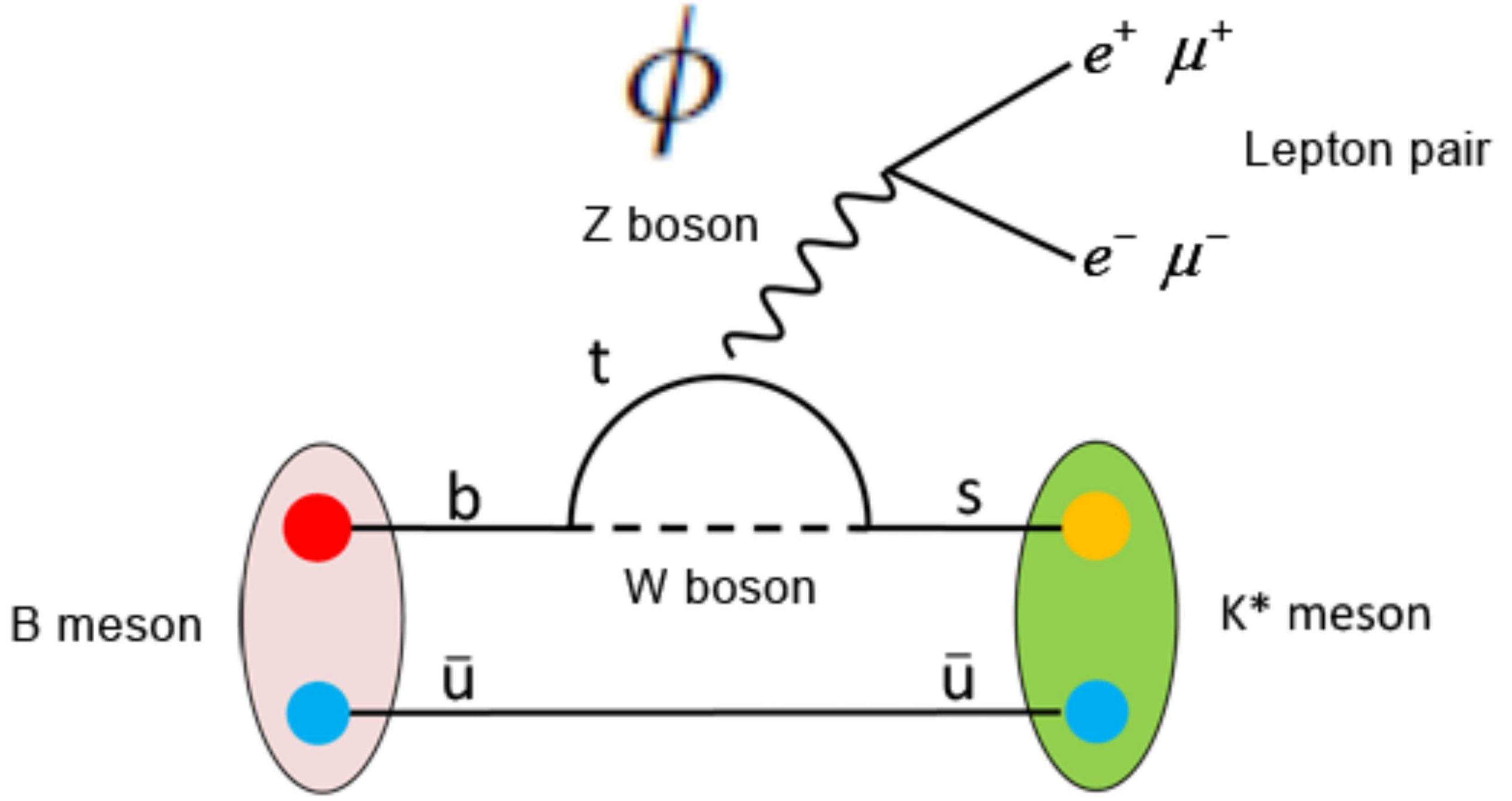


Figure 4: Excluded branching fraction for the $B^+ \to K^+\chi(\mu^+\mu^-)$ decay as a function of $m(\chi)$ and $\tau(\chi)$ at 95% CL. Regions corresponding to the fully-vetoed $K^0_S$, $J/\psi$, $\psi(2S)$ and $\psi(3770)$ and to the partially-vetoed $\phi$ and $\psi(4160)$ are excluded from the figure. All systematic uncertainties are included in the calculation of the upper limit.



it gives a stringent constraint in the region of $m_\phi \geq 1.5$ GeV.

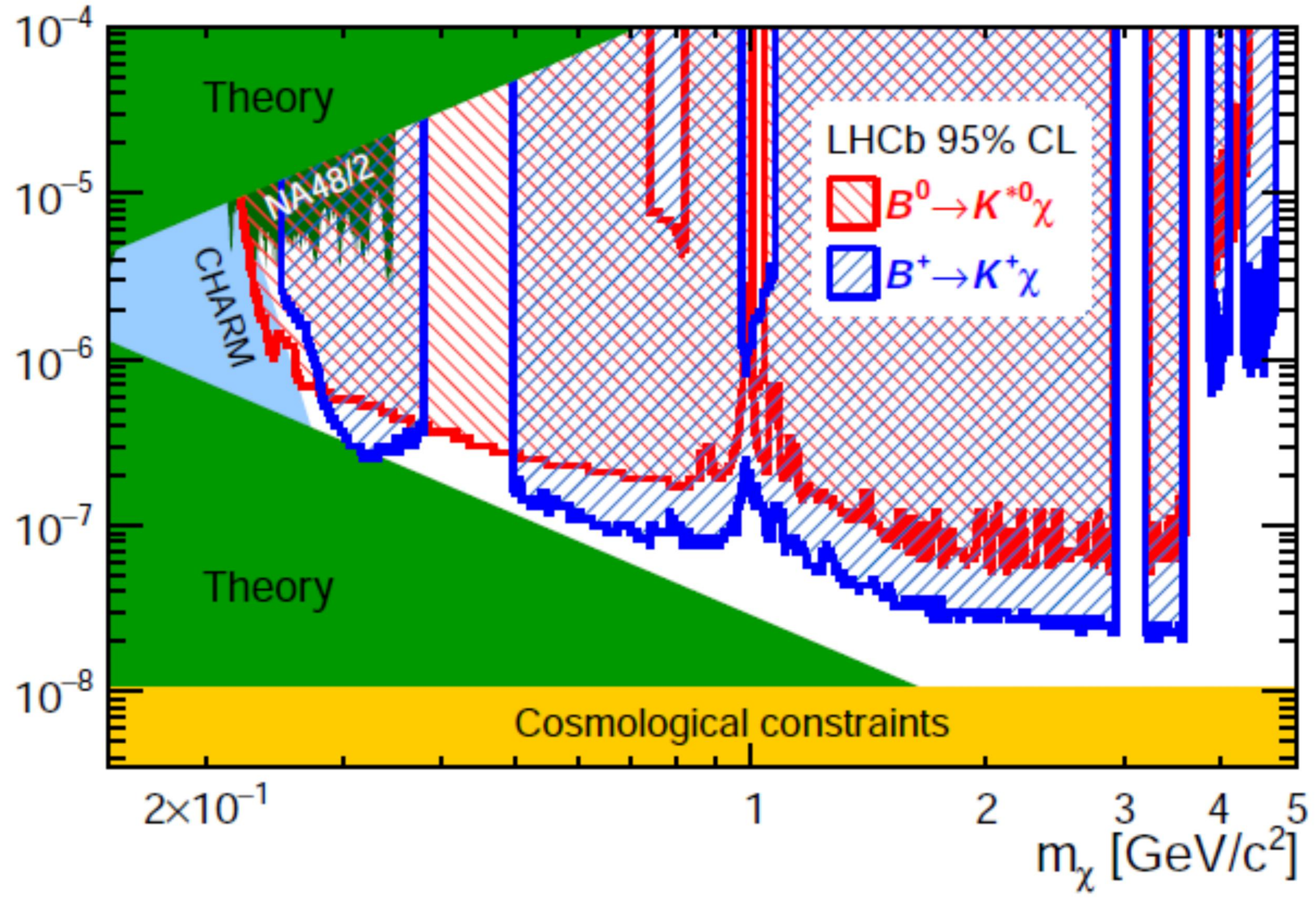


Figure 5: Parameter space of the inflaton model described in Refs. [2–4]. The region excluded at 95% CL by this analysis is shown by the blue hatched area. The region excluded by the search with the $B^0 \to K^{*0}\chi(\mu^+\mu^-)$ decay [8] is indicated by the red hatched area. Direct experimental constraints set by the CHARM experiment [7] and NA48 experiments [7,28] and regions forbidden by theory or cosmological constraints [4] are also shown.

# Kaon decay

$$K^+ : u\bar{s}$$

$$K_L : \frac{d\bar{s} - s\bar{d}}{\sqrt{2}}$$

$$s \rightarrow d + \phi$$

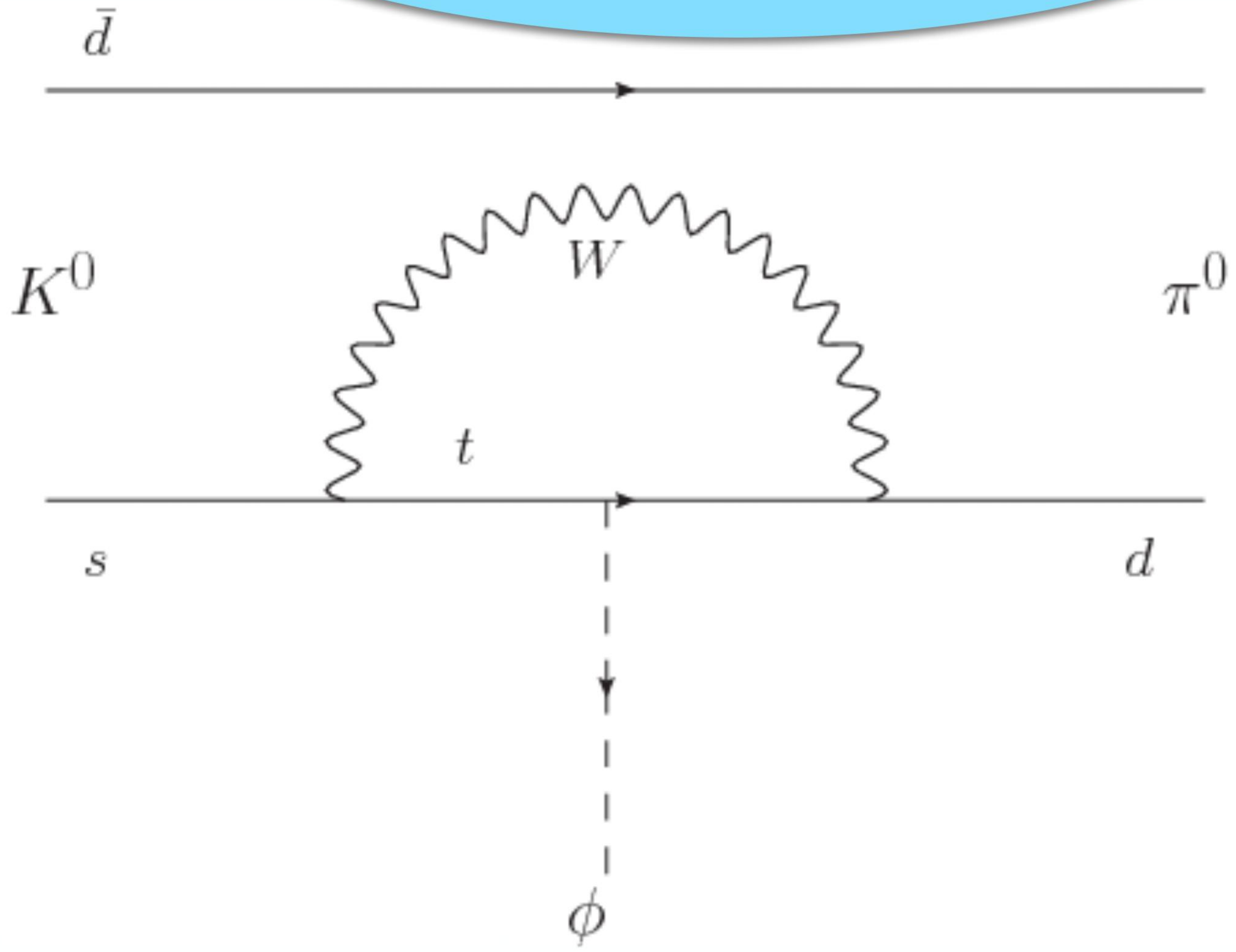
$$N_{\mathrm{TH.}} = 2.9\times 10^{17}\times\frac{\sigma_\phi}{\sigma_\pi}\times\mathcal{P}_{\mathrm{dec}} < 2.3 \text{ @ } 95\%\mathrm{C.L.}$$

$$\frac{\sigma_\phi}{\sigma_{\pi^0}} \simeq 3\left[\frac{\chi_s}{2}\mathrm{Br}(K^\pm \to \pi^\pm\phi) + \frac{\chi_s}{4}\mathrm{Br}(K_L \to \pi^0\phi) + \chi_b\,\mathrm{Br}(B \to \phi + X_s)\right]$$

chi_s:
fraction of strange quarks
produced by pp.

chi_b:
fraction of bottom quarks
produced by pp.

$$P_{\mathrm{dec}} = -\exp\left[-\frac{L_2}{\gamma\beta c\tau_\phi}\right] + \exp\left[-\frac{L_1}{\gamma\beta c\tau_\phi}\right]$$



For CHARM:
L1=L2-35 m=480 m
L2: total distance