Light Fermionic WIMP Dark Matter with Light Scalar Mediator

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Collaborators:
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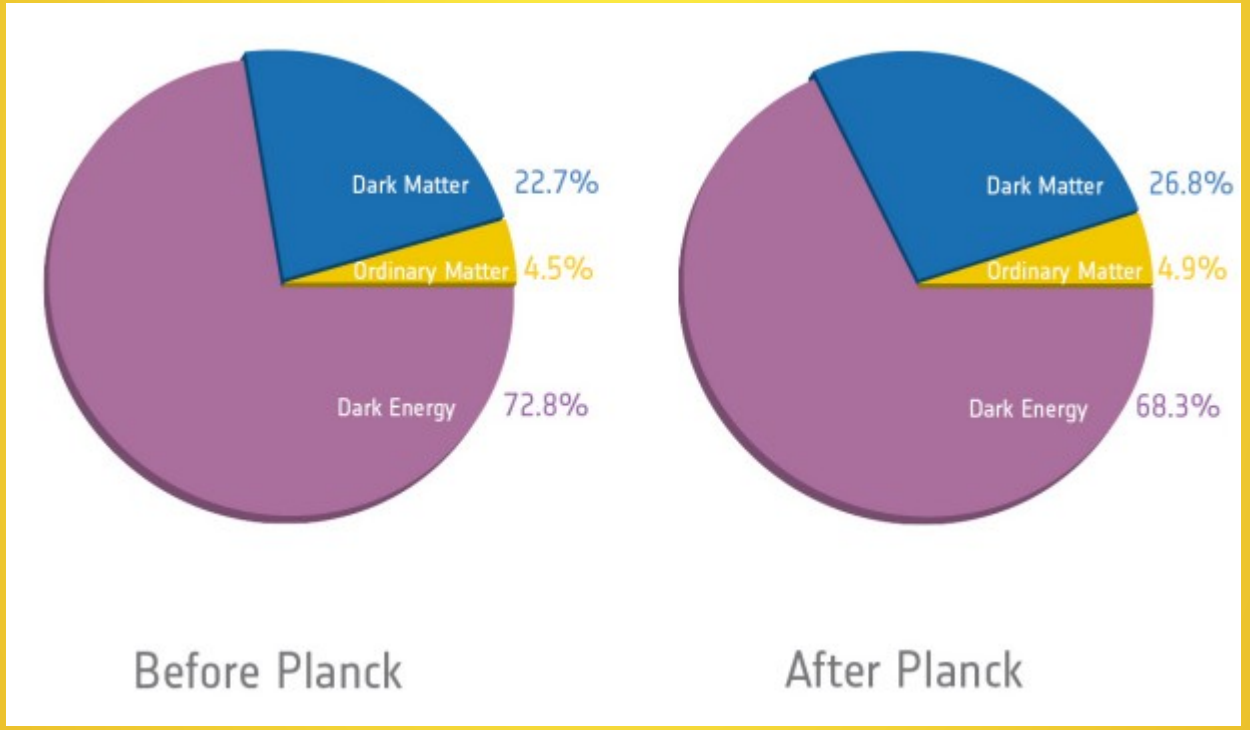
Yue-Lin Sming Tsai (Academia Sinica, Taiwan)

ArXiv: 1811.03292

HPNP2019, The 4th International Workshop on "Higgs as a Probe of New Physics", 18-22 Feb. 2019

Introduction

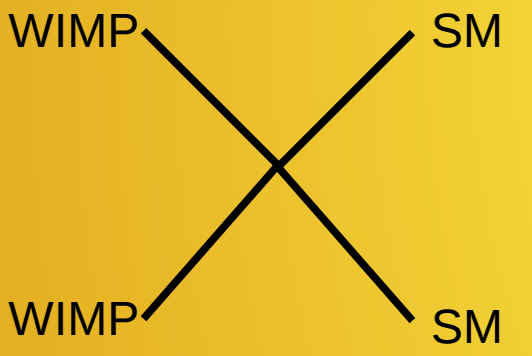
- Dark matter **relic abundance** is about **25%** of our Universe.

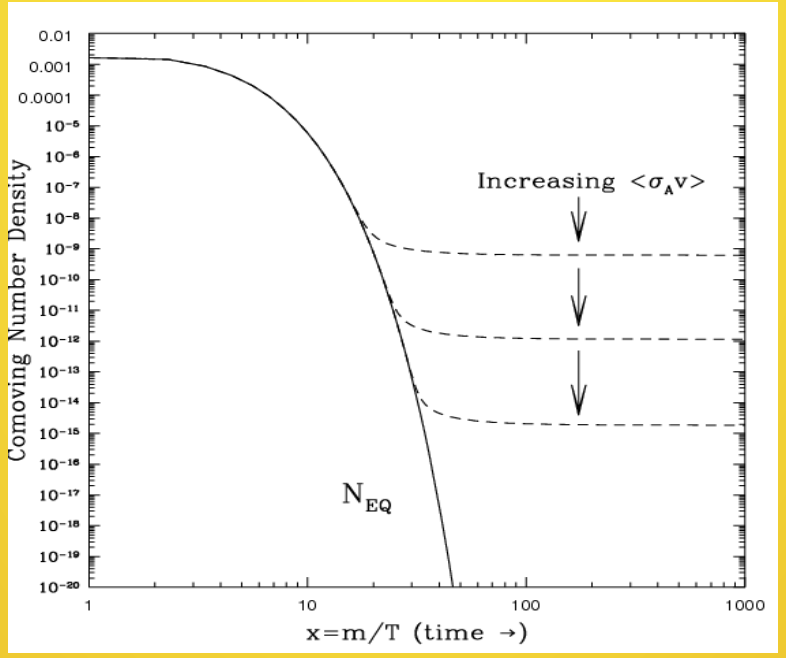


Planck Collaboration

Introduction

- Thermally produced DM: **Freeze-out** mechanism.
- Weakly interacting DM(**WIMP**), gives the correct DM relic abundance.





Dan Hooper: 0901.4090

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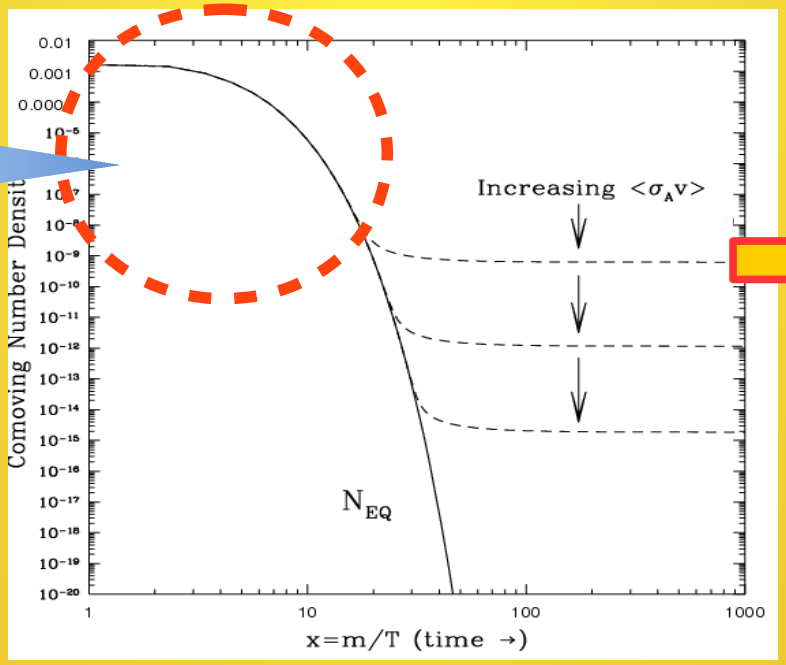
$\langle \sigma v \rangle >$ Hubble Expansion Rate

thermal equilibrium



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DM decouple

Dan Hooper: 0901.4090

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- Weakly interacting massive particle(**WIMP**), gives the correct DM **relic abundance** $\Omega_X = 25\%$.

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

J.L. Feng, J. Kumar: 0803.4196

- $g_{\rm weak} \simeq 0.65$ and $m_{\rm weak} \simeq \mathcal{O}(100)\ {\rm GeV} - 1\ {\rm TeV}$, weak interaction. We called **WIMP DM**.

$$\langle \sigma v \rangle \simeq 3 \times 10^{-26} {\rm cm}^3/{\rm sec}$$

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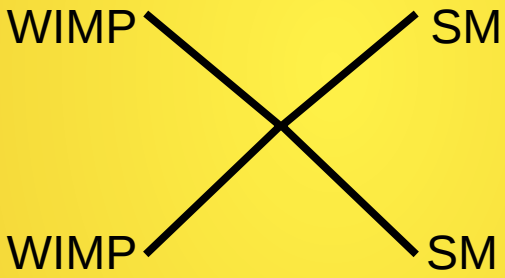
$$\begin{aligned} 10^{-3} \lesssim\ & g_X \ \lesssim 3 \\ 10\ {\rm MeV} \lesssim\ & m_X \ \lesssim 10\ {\rm TeV} \end{aligned}$$

Introduction

- Sub-GeV thermal produced WIMP. Light WIMP.
- Lee-Weinberg limit. Require thermal DM mass larger than GeV.

B. W. Lee, S. Weinberg: PRL. 39(1977), 165.



- Constraint from Cosmic Microwave Background (**CMB**):

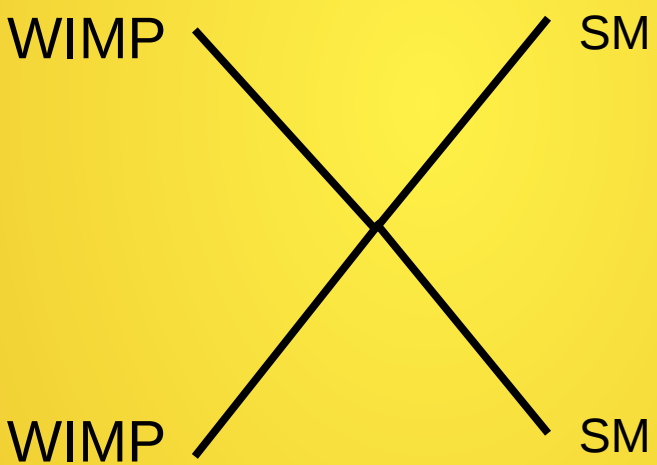
$$\langle \sigma v \rangle_{\rm CMB} / m_\chi \lesssim 3 \times 10^{-28} {\rm cm}^3\,{\rm s}^{-1}\,{\rm GeV}^{-1}$$

- **Cannot** give correct DM relic density, if DM lighter than **10 GeV**.

$$\langle \sigma v \rangle \simeq 3 \times 10^{-26} {\rm cm}^3/{\rm sec}$$

Introduction

- Relic abundance and DM annihilation.
- DM+DM → SM+SM:



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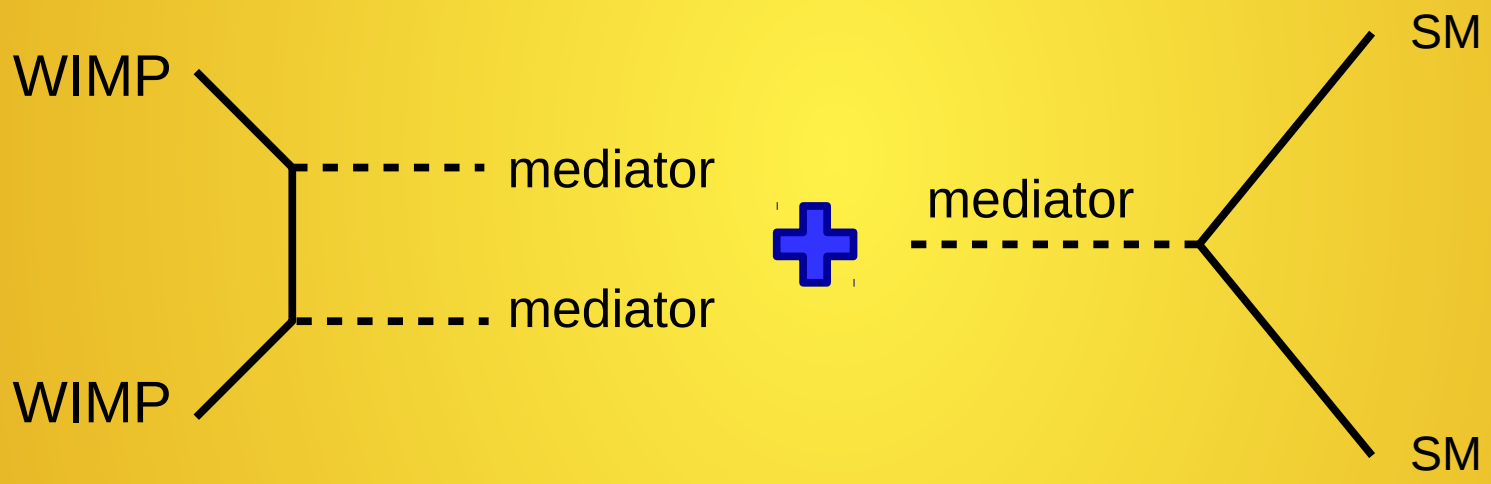
- DM+DM → mediator+mediator & mediator → SM+SM



- The mass of mediator is also Sub-GeV.

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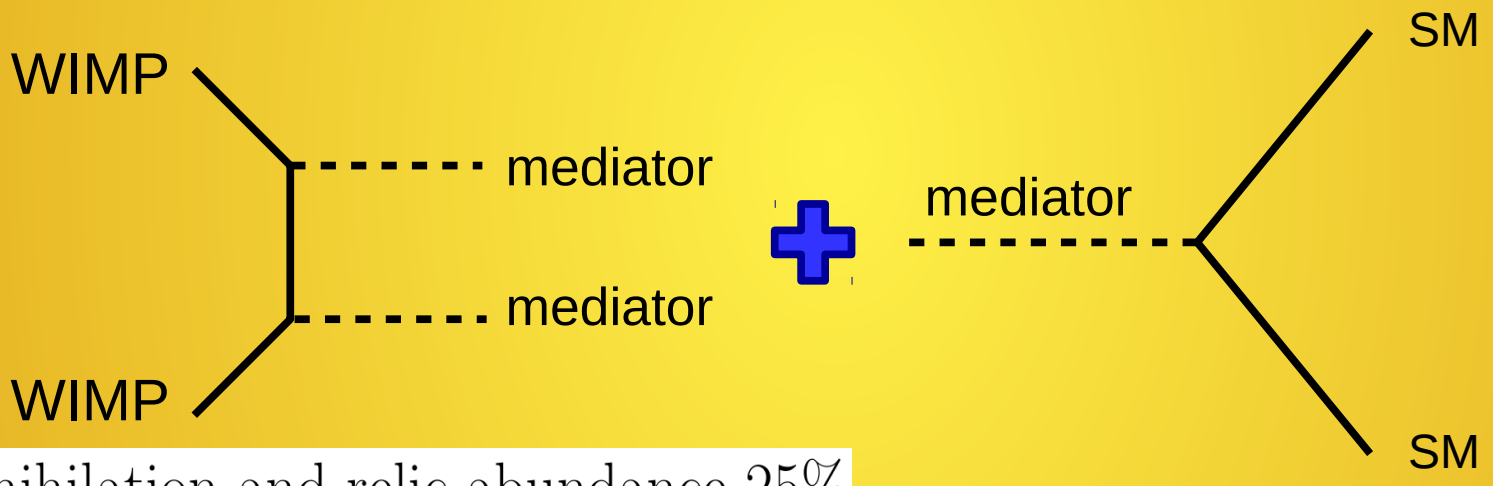

DM annihilation and relic abundance 25%

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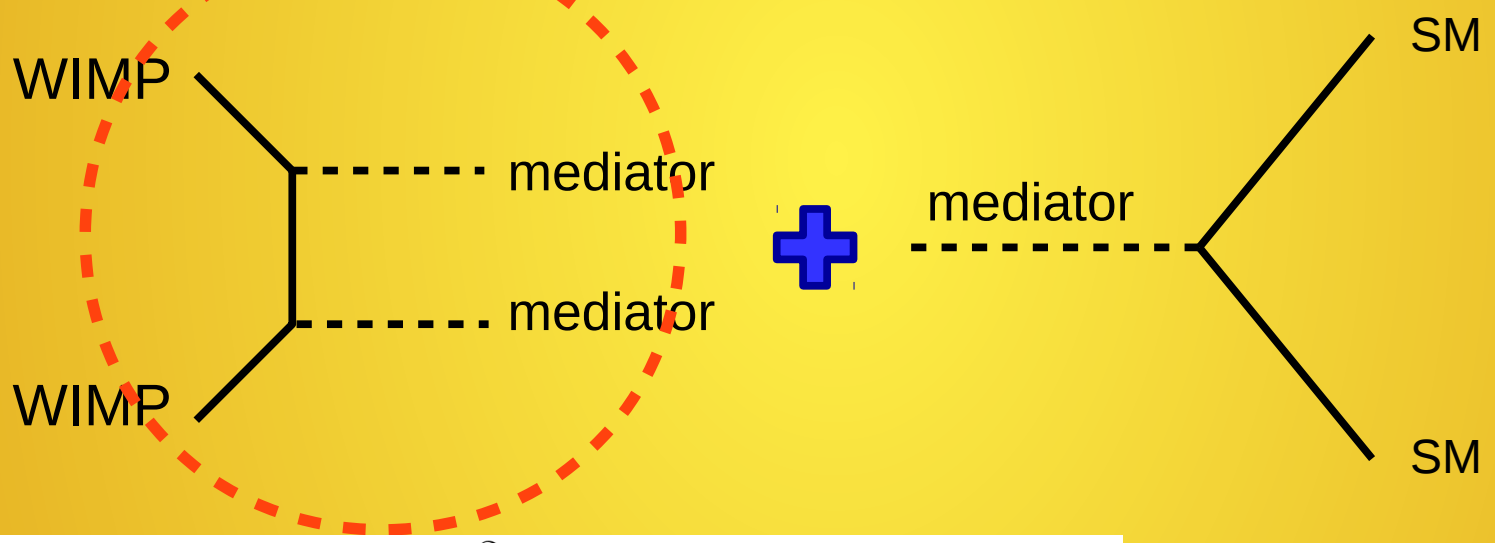

$$p-\text{wave}: \langle \sigma v \rangle \propto v^2, \text{ avoid CMB constraint}$$

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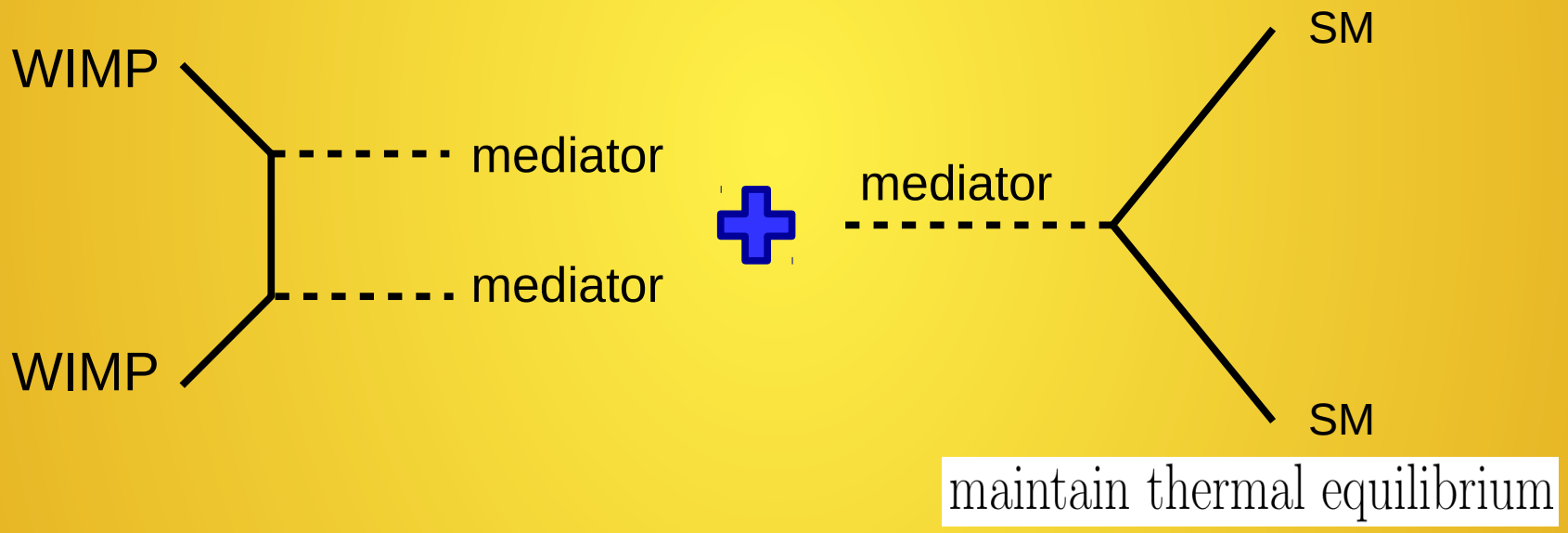

maintain thermal equilibrium

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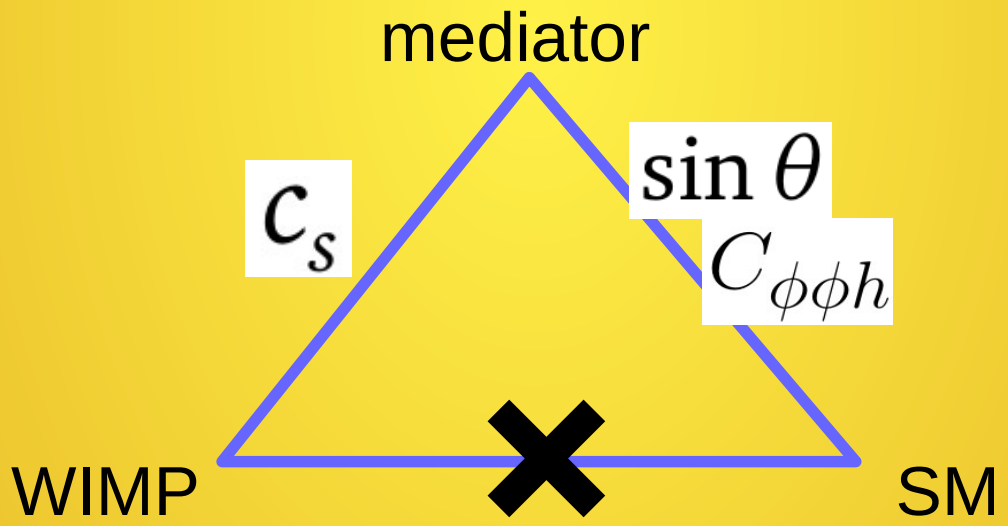
- WIMP ↔ mediator ↔ SM.



S.Matsumoto, Y.L Sming Tsai, P.Y. Tseng

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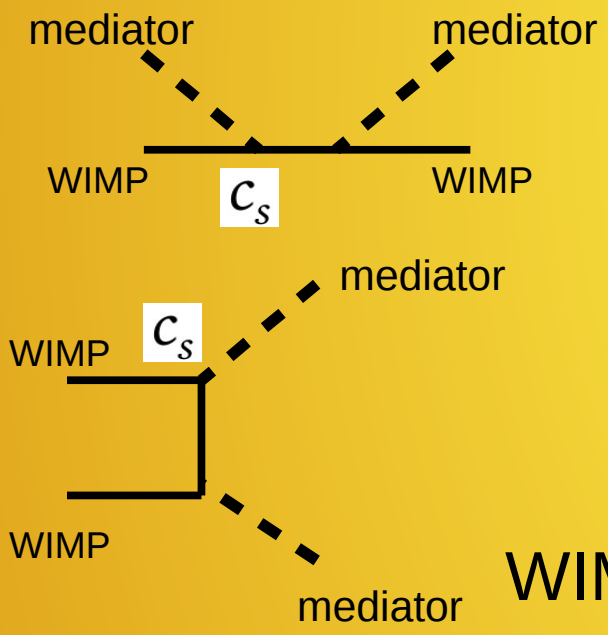

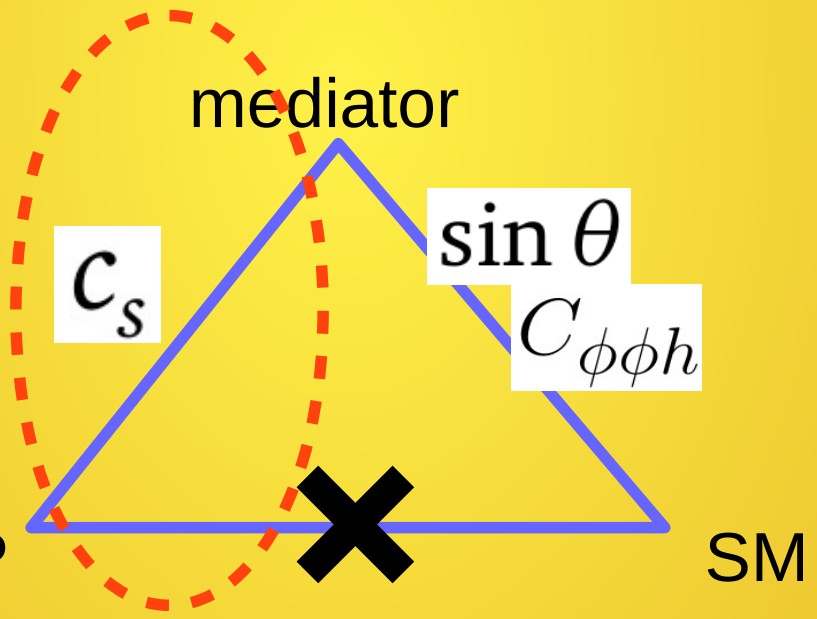

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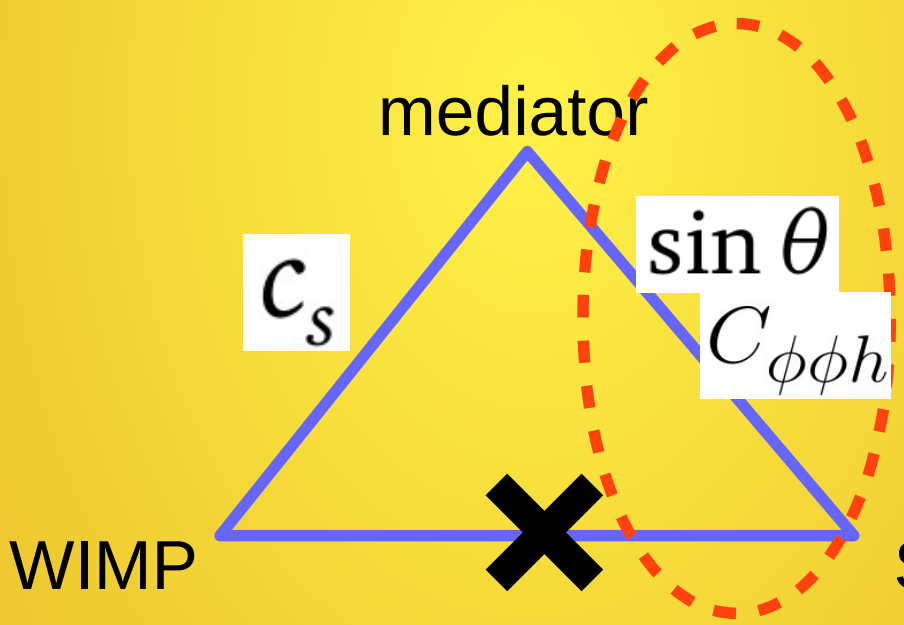

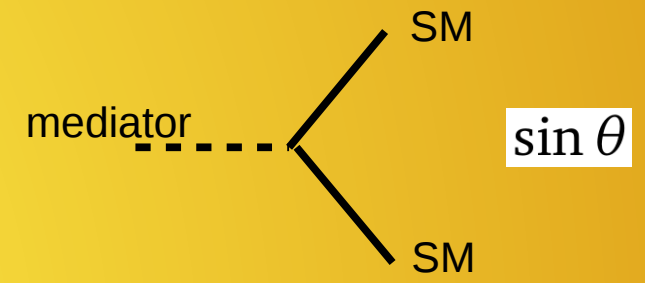

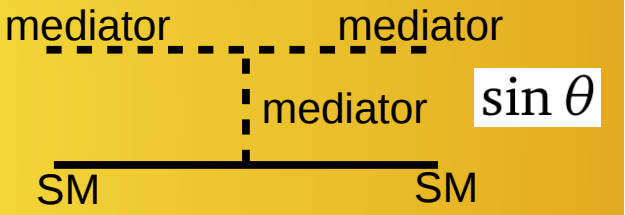

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Light WIMP with scalar mediator

- Minimal Model. Gauge invariant and renormalizability.
- Majorana DM and a scalar mediator:

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{2}\bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \frac{1}{2}(\partial\Phi)^2 - \frac{c_s}{2}\Phi\bar{\chi}\chi - \frac{c_p}{2}\Phi\bar{\chi}i\gamma_5\chi - V(\Phi, H),$$

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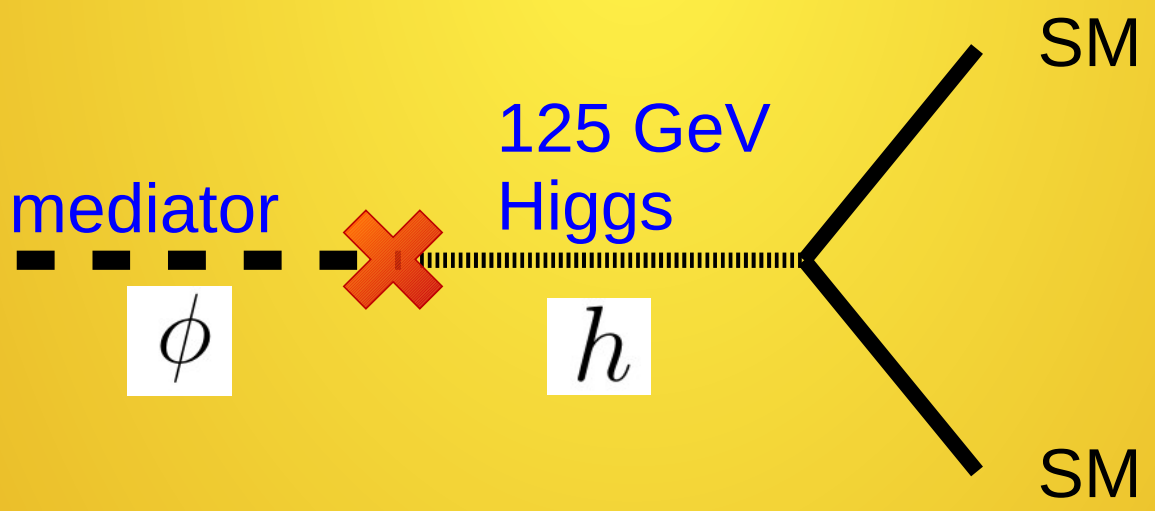
Light WIMP with scalar mediator

- The $A_{\Phi H}\Phi H^{\dagger}H$ allowed the mixing between Higgs doublet and scalar singlet

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



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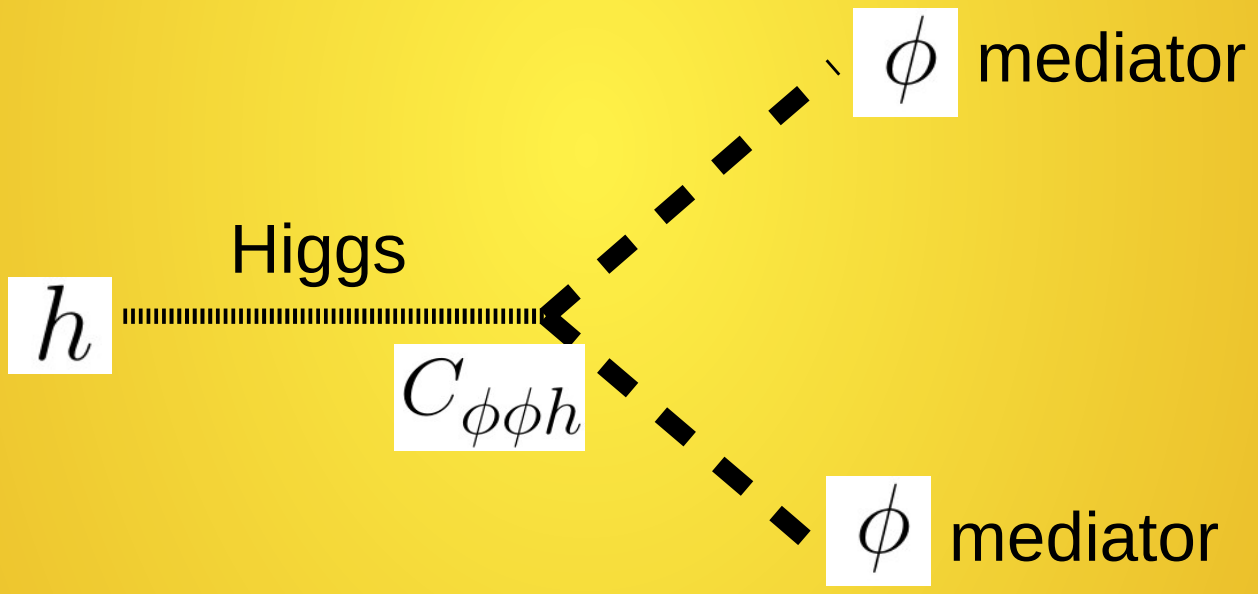
Light WIMP with scalar mediator

- The $\frac{\lambda_{\Phi H}}{2}\Phi^2 H^\dagger H$ give mediator-mediator-Higgs trilinear coupling.

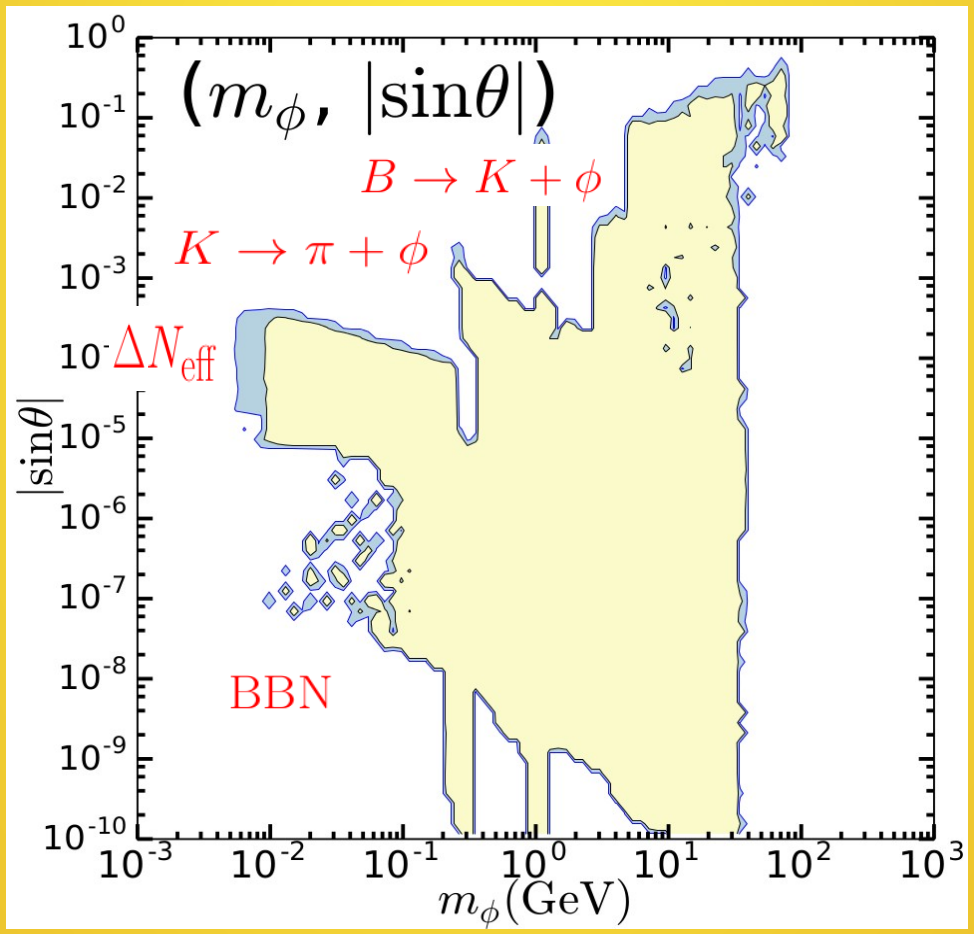


Constraints

- Apriori constraints: **vacuum stability**.
- DM **relic density** & **Kinematic equilibrium** condition.
- Cosmology constraints: **BBN, Neff, CMB**.
- **Direct dark matter detection**.
- Collider constraints: **Kaon, B-meson, Higgs decay**.

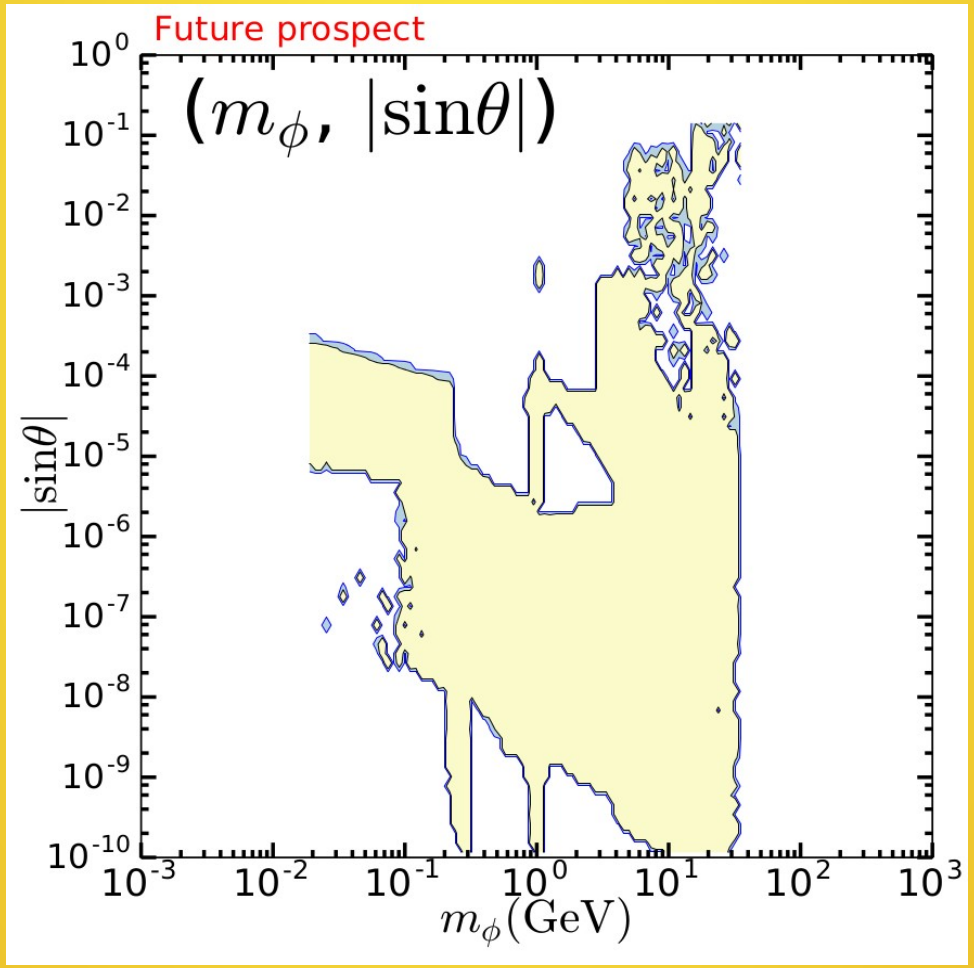
Results

- Under present constraints:



Results

- Under **future** constraints:



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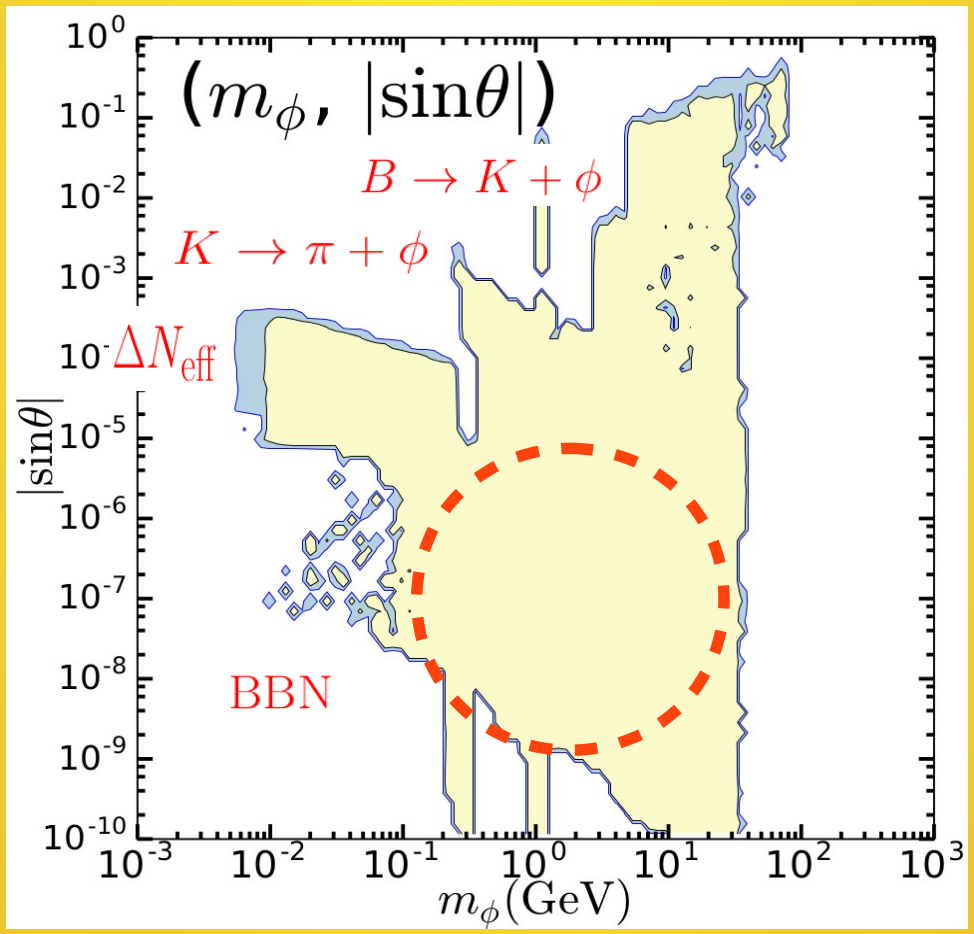

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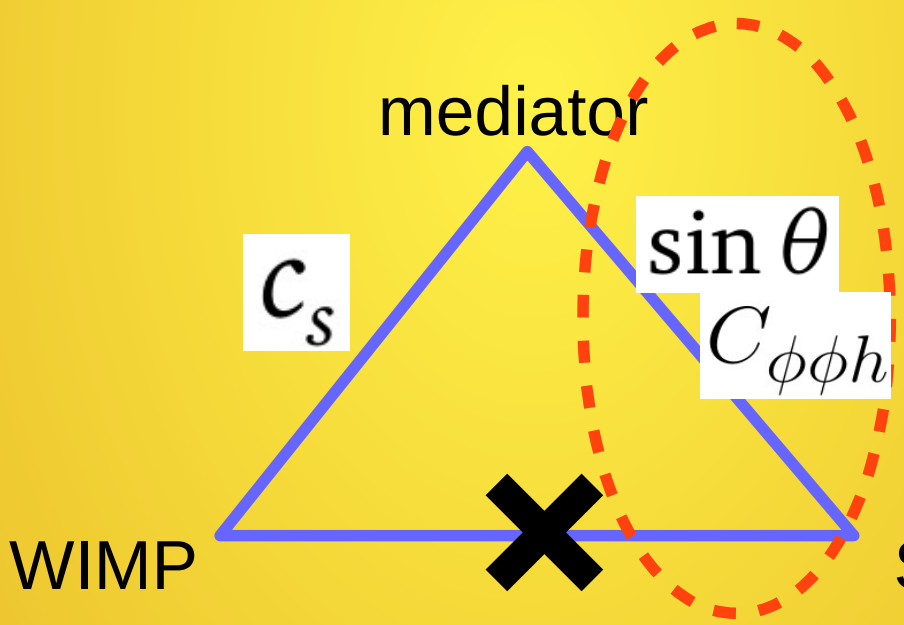

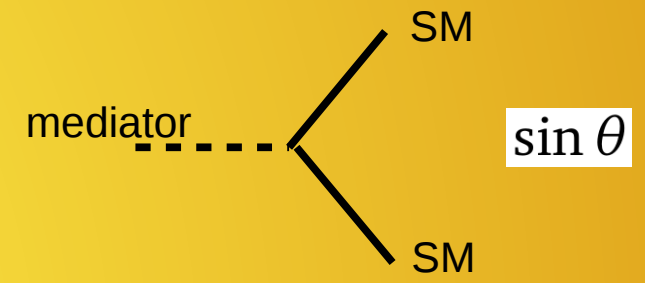

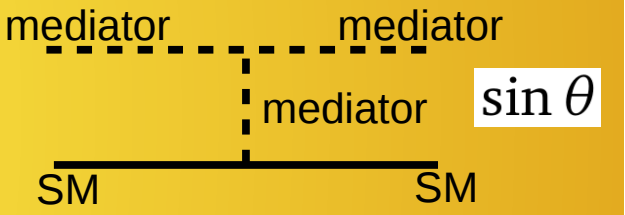

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Results

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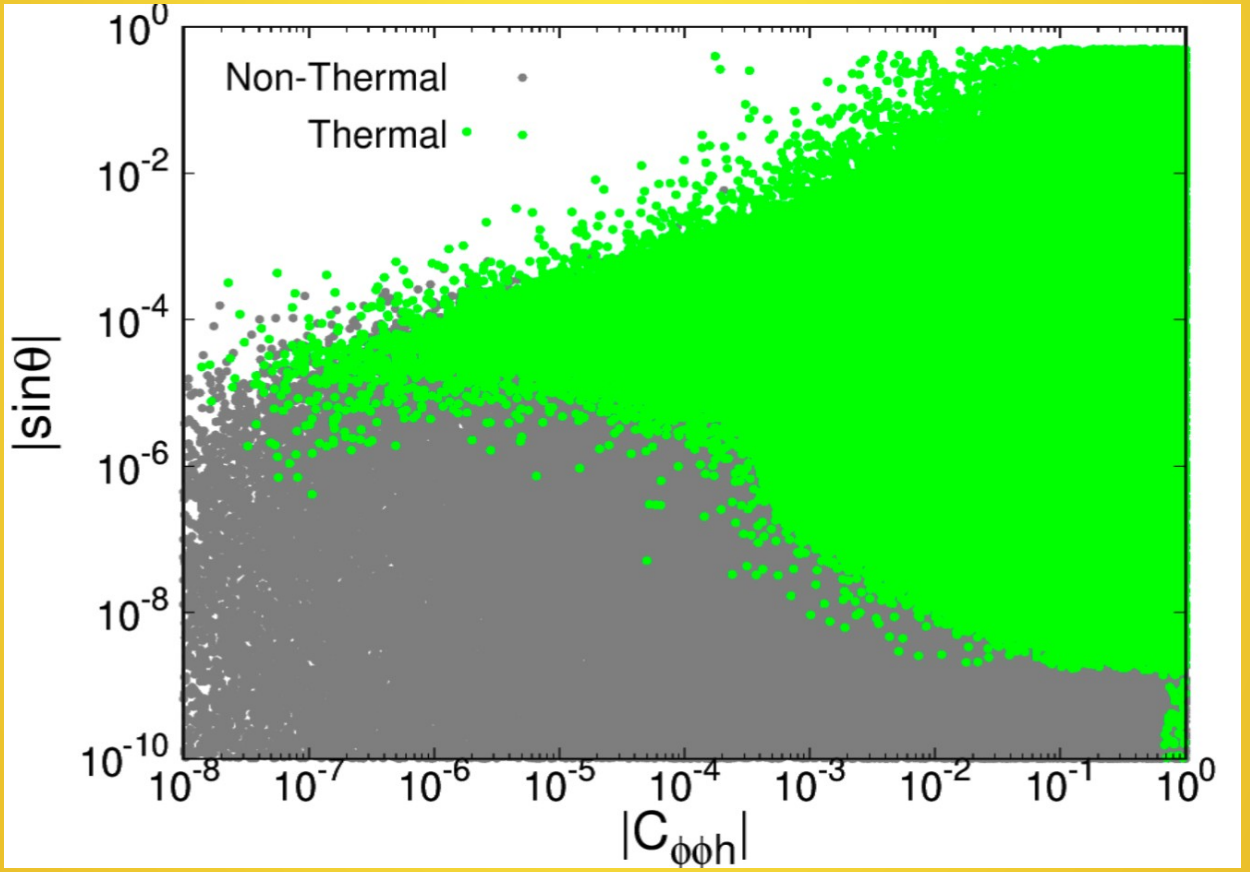
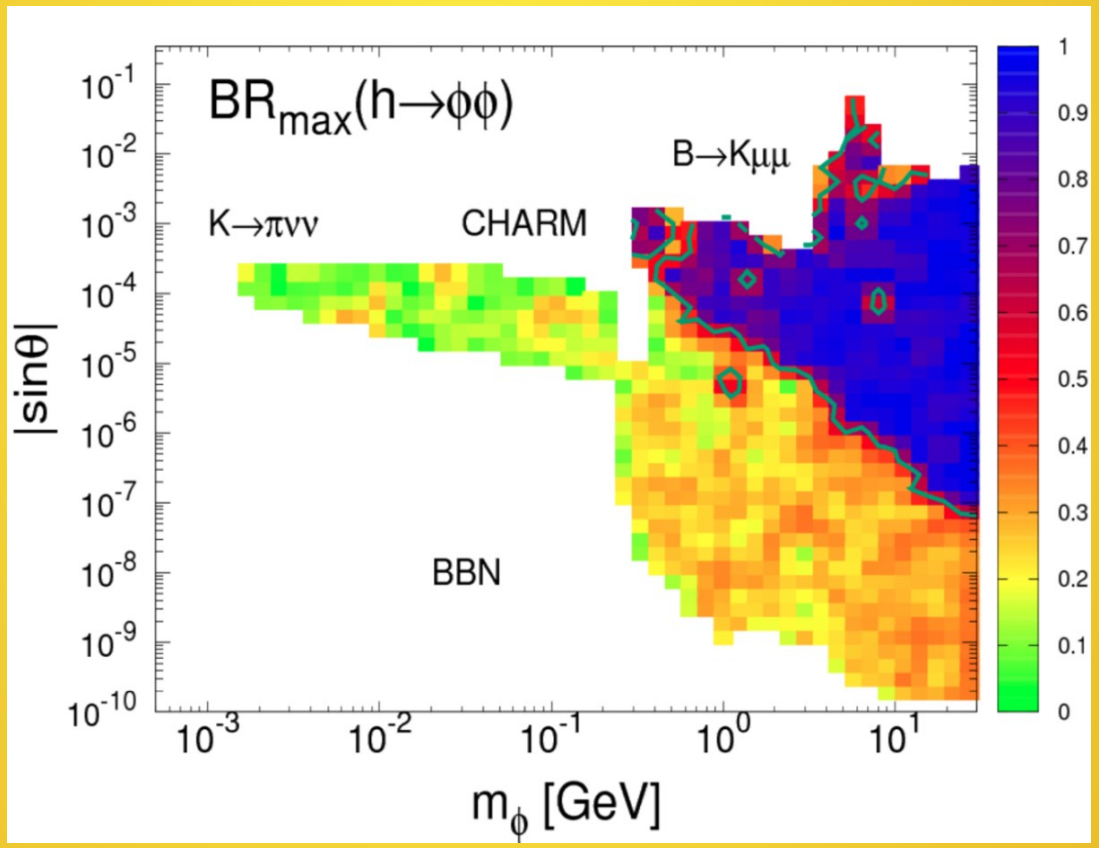


Results

- From the allowed parameter space:



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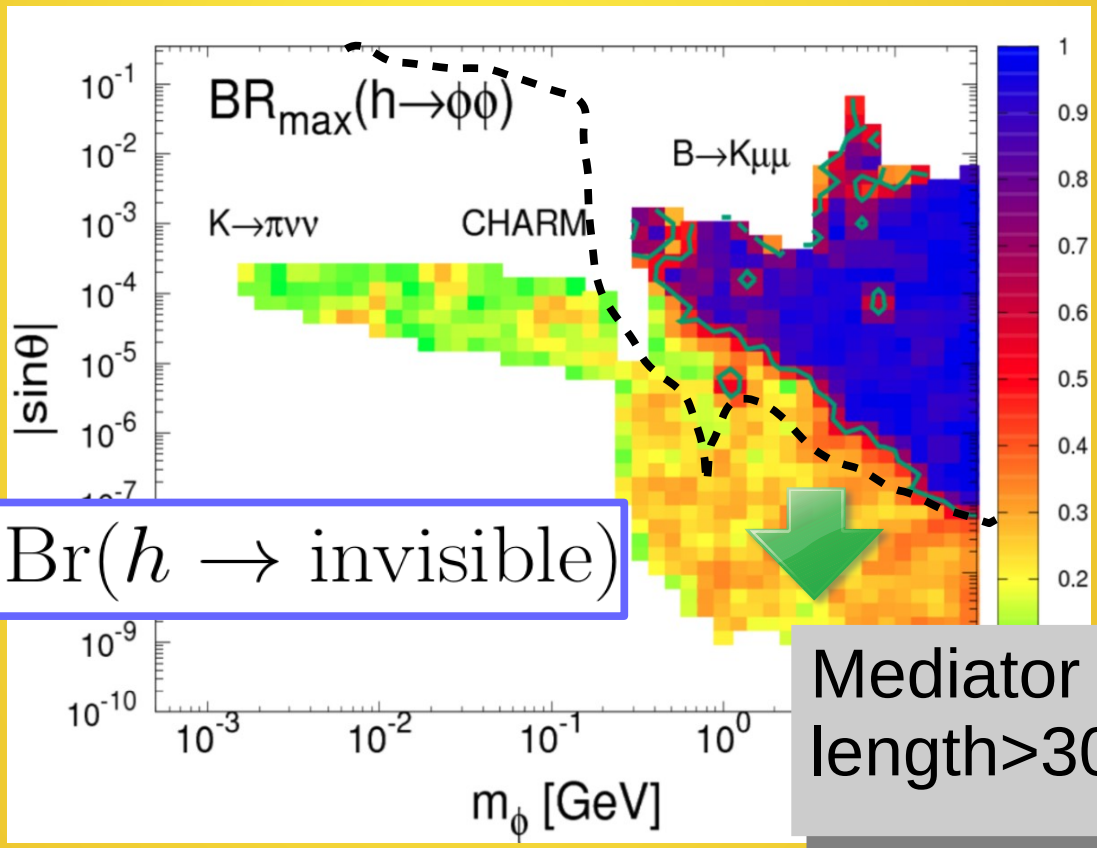


$$\mathrm{Br}(h \to \phi\phi) \Rightarrow \mathrm{Br}(h \to \text{invisible})$$

Mediator decay length>30m

Results

- Interesting signal from 125 GeV Higgs invisible decay at **LHC**.
- Because of the coupling $C_{\phi\phi h}$ the branching ratio of $h \to \phi\phi$ can be large.
- Current LHC limit is: $\mathrm{Br}(h \to \text{invisible}) \lesssim 20\%$
- High luminosity LHC limit will be: $\mathrm{Br}(h \to \text{invisible}) \lesssim 5\%$

Summary

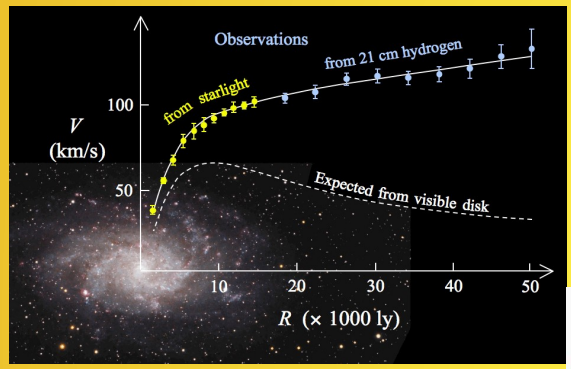
- We demonstrated the light WIMP DM can be **Sub-GeV** with the help of light scalar mediator to maintain **thermal equilibrium** and give correct **relic density**.
- We wrote down a minimal model, which is gauge invariant and renormalizable.
- Many constraints are included.
- The 125 GeV Higgs decays into pair of long-live mediators as invisible decay. Can be searched at LHC.

Thank You !

Back Up

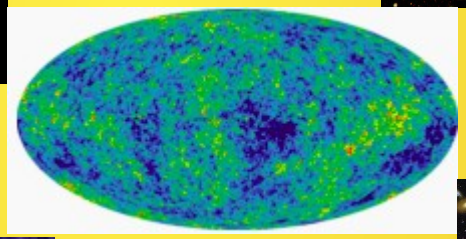
Introduction

- Dark matter



wikipedia.org Extended rotation curve of M33

NASA



astro-ph/0504097

Hubble Space Telescope

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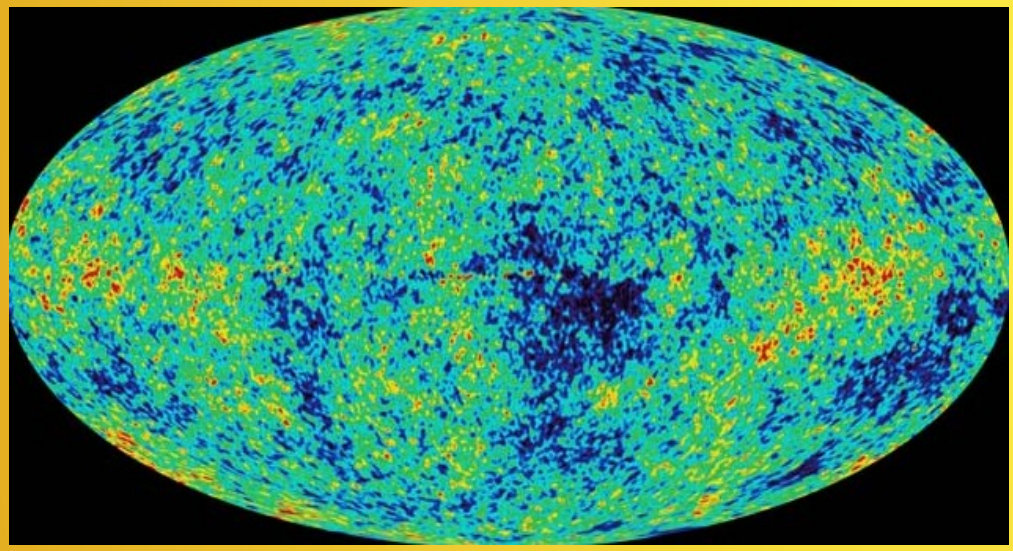
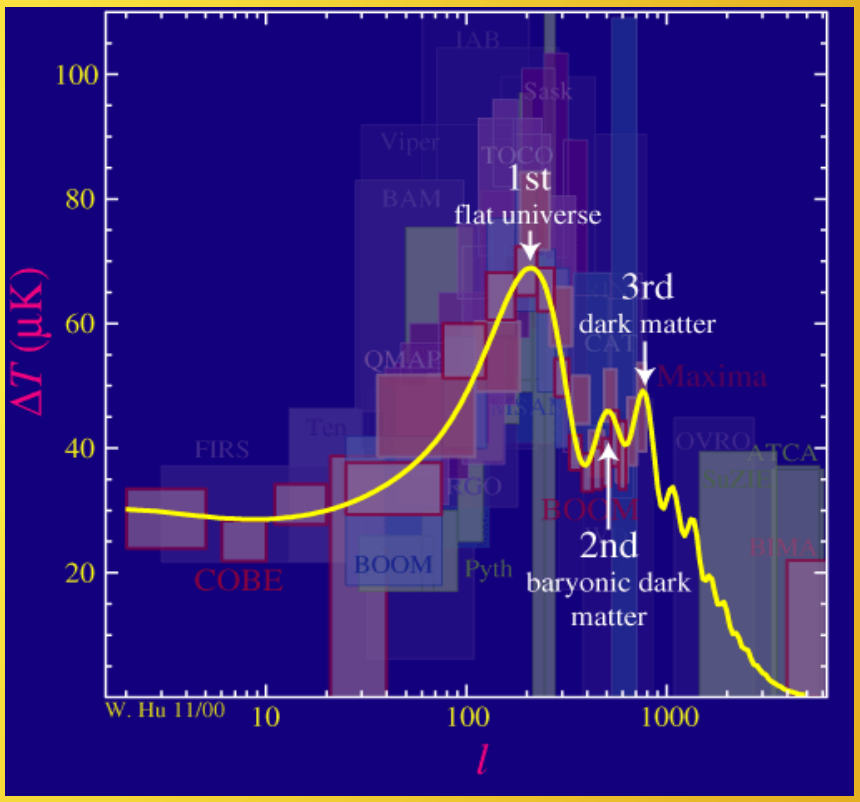


Planck Collaboration



Wayne Hu: Department of Astronomy and Astrophysics U. of Chicago

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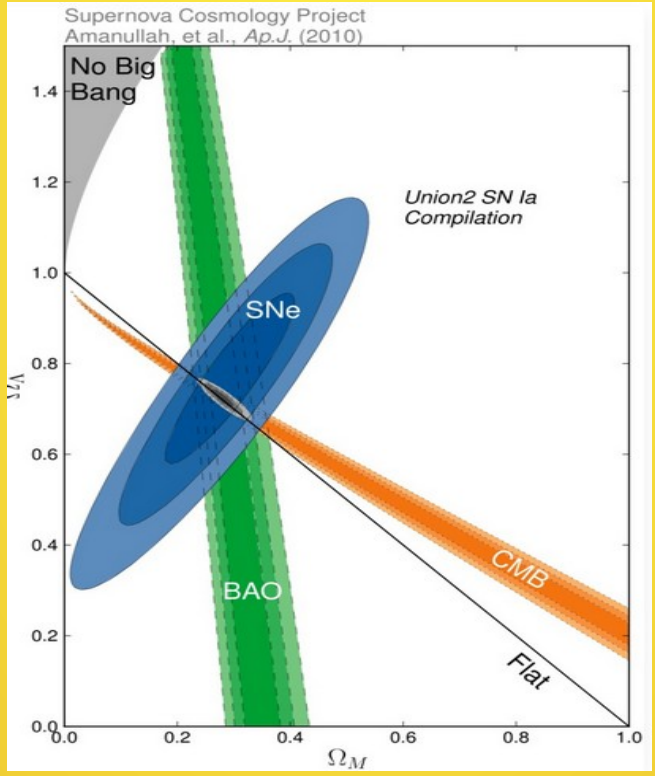

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- Properties of dark matter:
- I). Charge neutral.
- II). Stable or long-live.
- III). Gravity force.
- IV). Non-relativistic.
- V). 25% of our universe.

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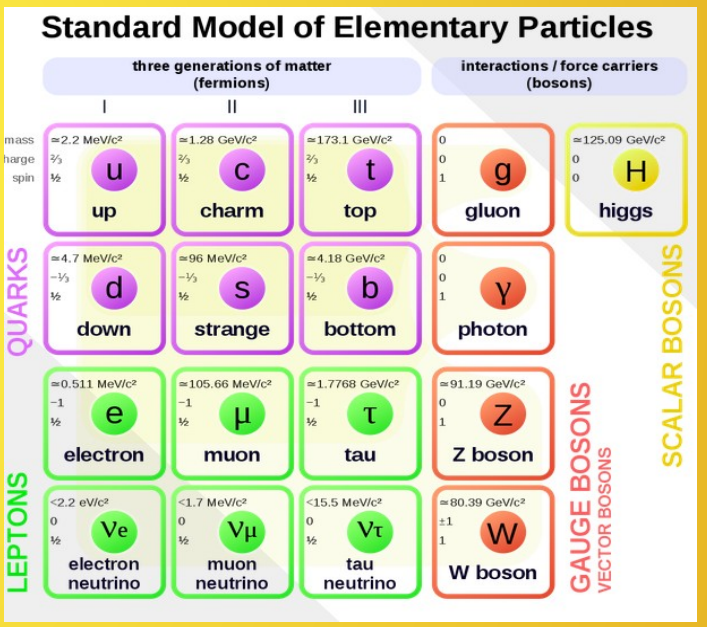

Wikipedia

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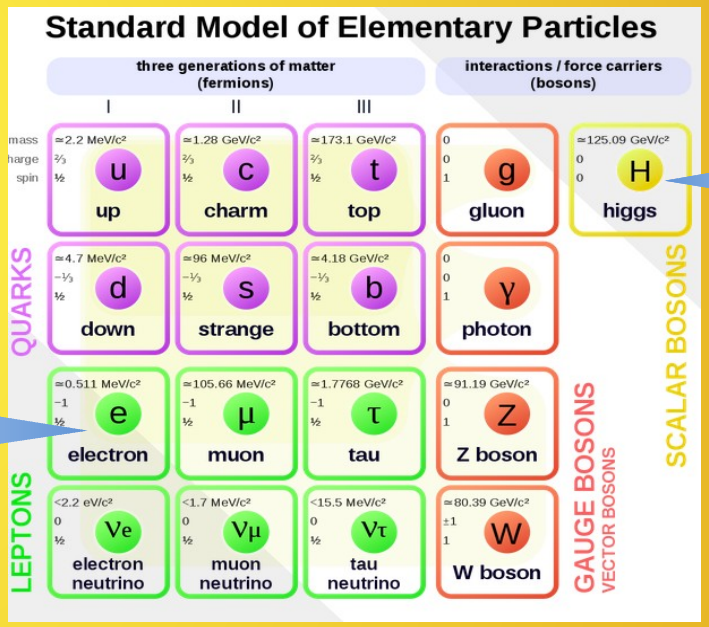

1897 by JJ Thomson

2012 at LHC

Wikipedia

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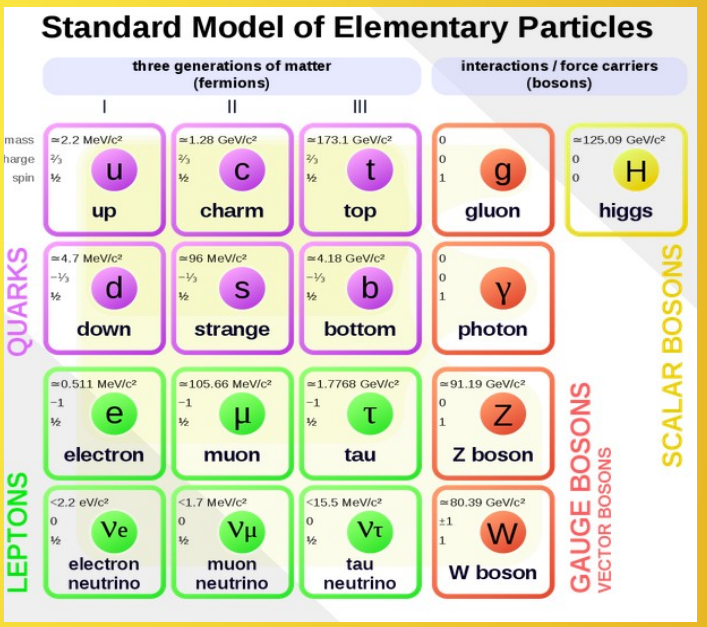

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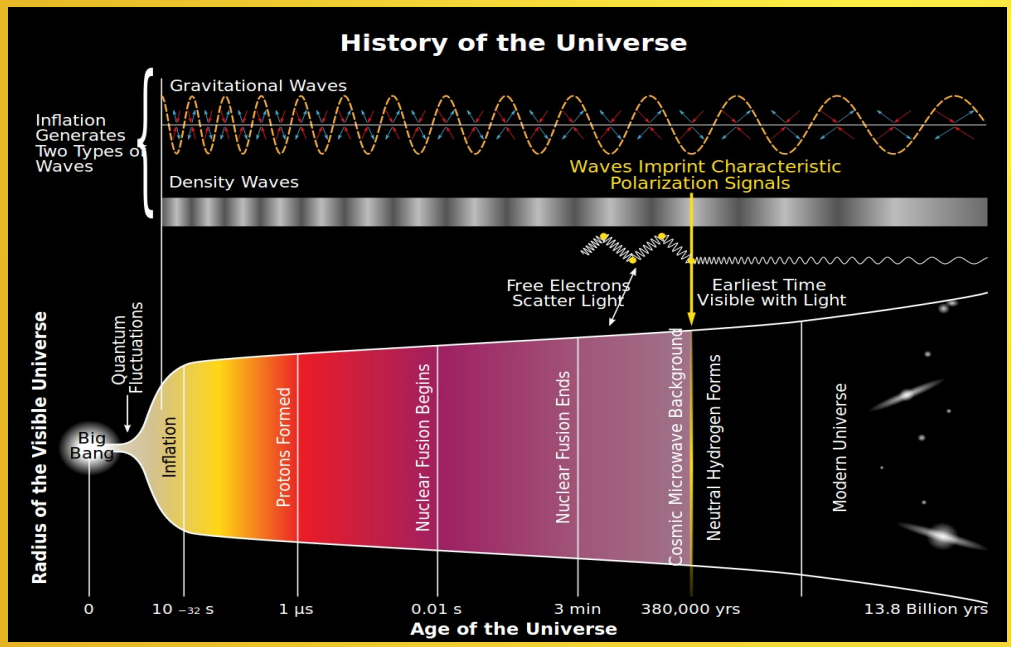

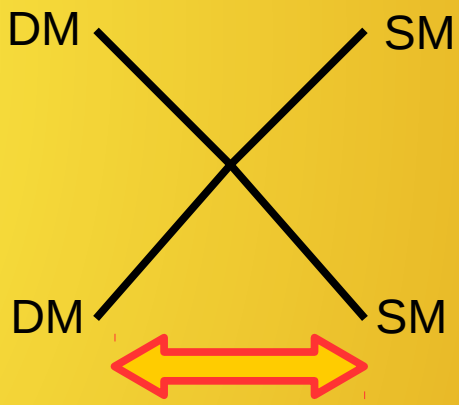

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Thermal equilibrium

Wikipedia

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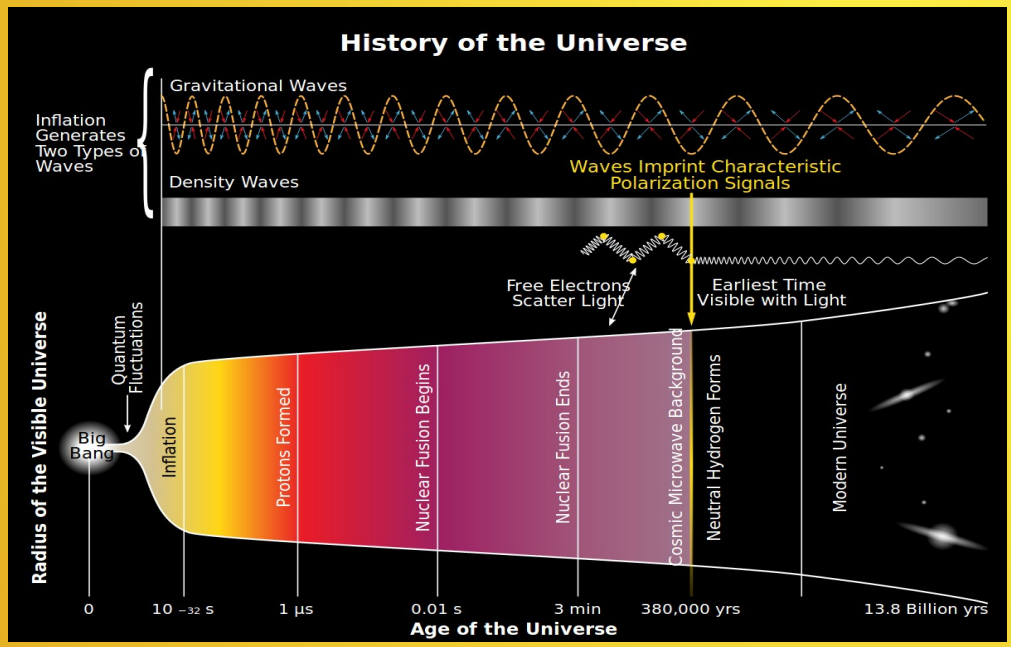
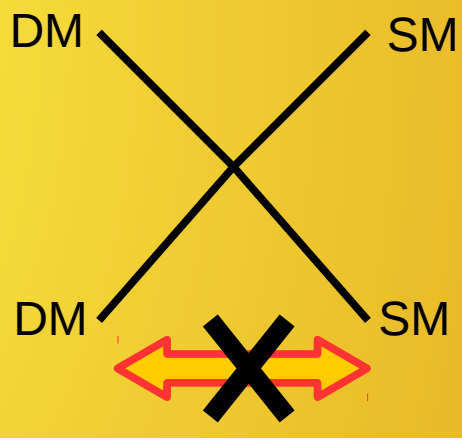


Wikipedia



$\langle \sigma v \rangle <$ Hubble Expansion Rate

DM decouple

Introduction

- The mass of WIMP from O(1) MeV to O(100) TeV.
- O(100) TeV upper limit from the perturbation
- O(1) MeV lower limit from non-relativistic DM. Lighter DM freeze-out in relativistic.

J.L. Feng, J. Kumar: 0803.4196

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$

$$10^{-3} \lesssim g_X \lesssim 3$$
$$10\ \mathrm{MeV} \lesssim m_X \lesssim 10\ \mathrm{TeV}$$

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- Supersymmetry theory predict the mass of WIMP around O(100) GeV to 1 TeV.
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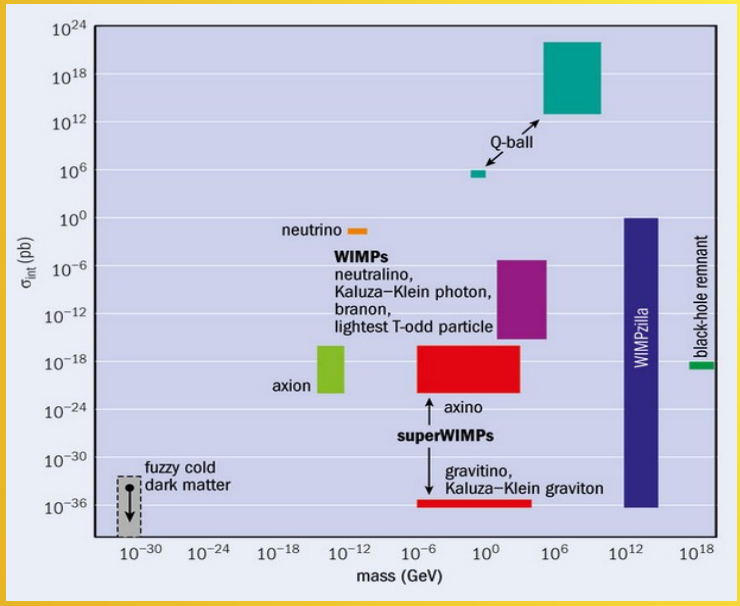
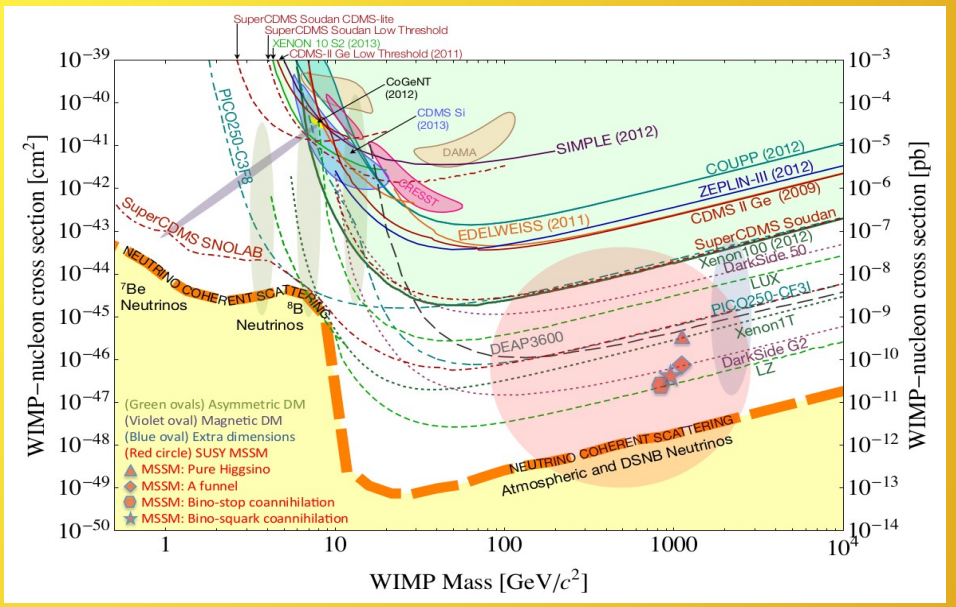


Towards Dark Matter Discovery 2018



P. Cushman et. al.:1310.8327v2

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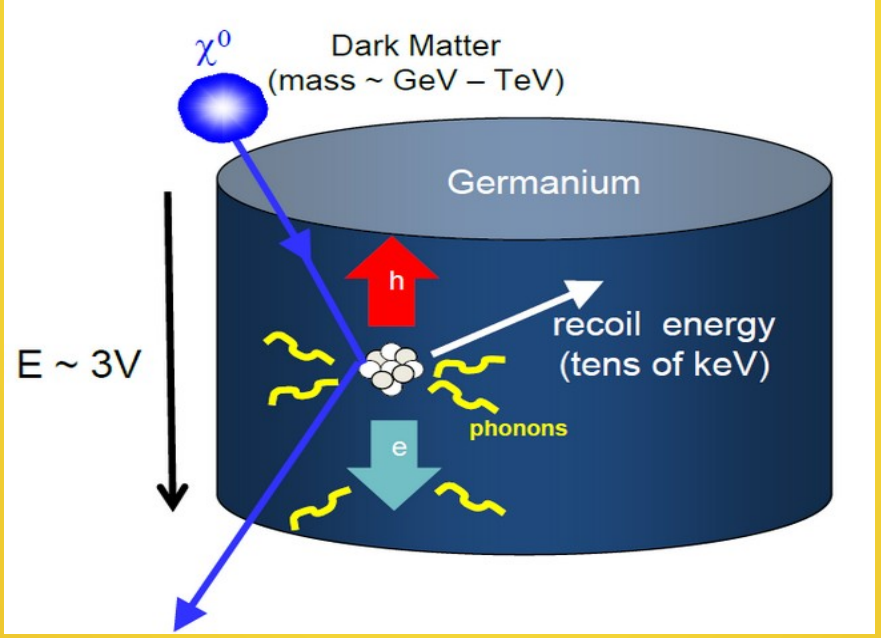
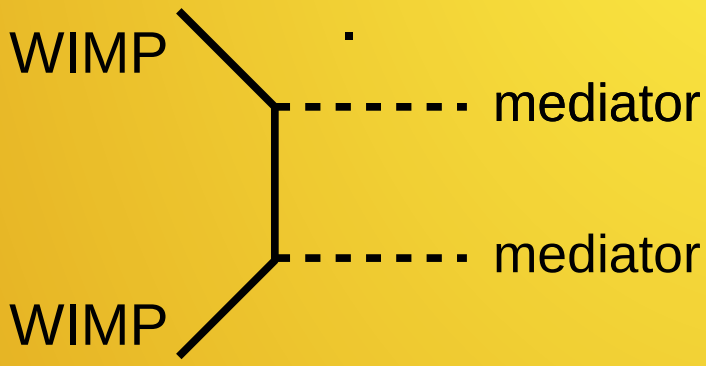
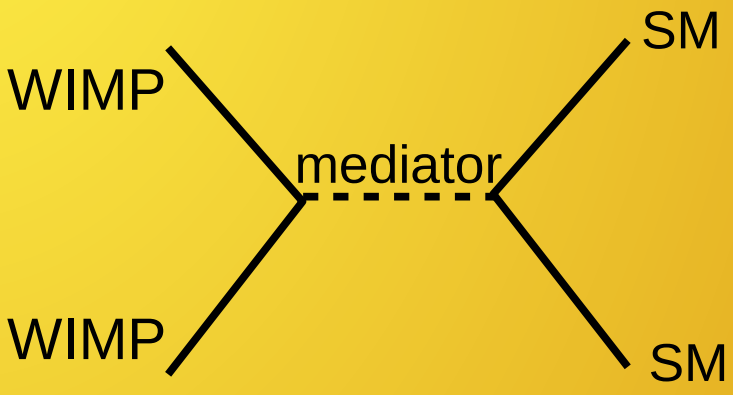


KIPAC, Stanford U.

Constraints

- Relic abundance and thermal equilibrium.
- When $m_\chi \geq m_\phi$, t-channel WIMP annihilate into a pair of mediators.
- When $m_\chi \leq m_\phi$, s-channel WIMP annihilate into $m_\chi \sim m_\phi/2$. The resonance enhancement

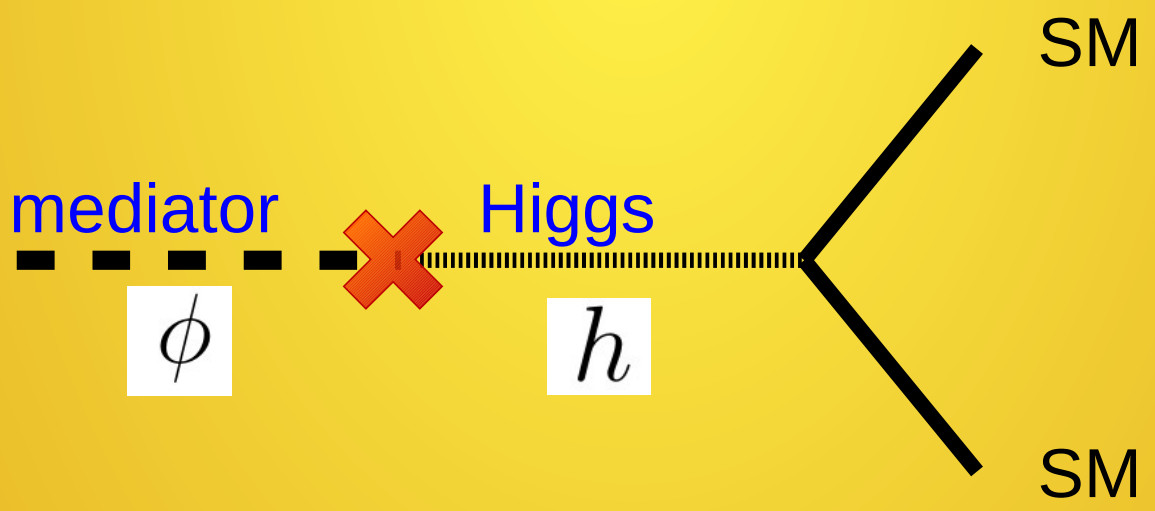




Light WIMP with scalar mediator

- The $A_{\Phi H}\Phi H^{\dagger}H$ allowed the mixing between Higgs doublet and scalar singlet

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



Light WIMP with scalar mediator

- 7 parameters: $m_\chi, m_\phi, c_s, \sin\theta, \mu_\phi^2, \mu_3, \lambda_\Phi$

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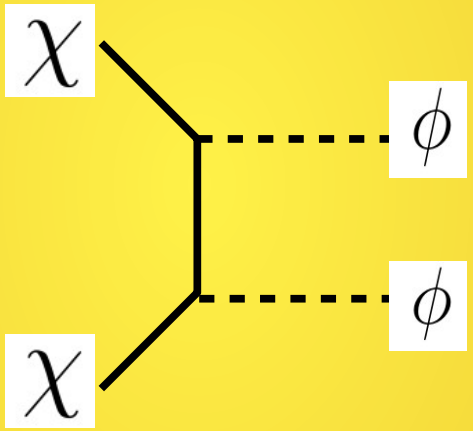

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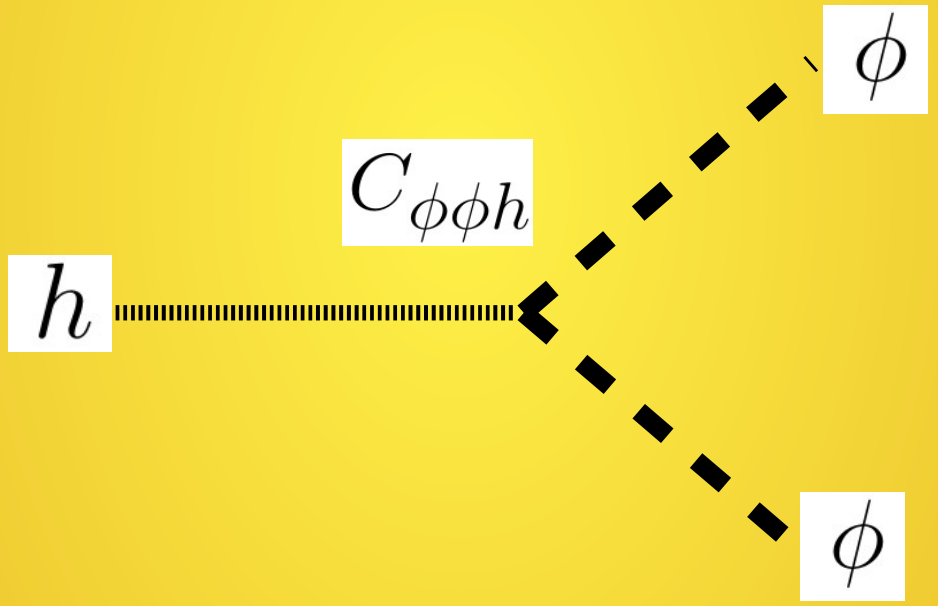
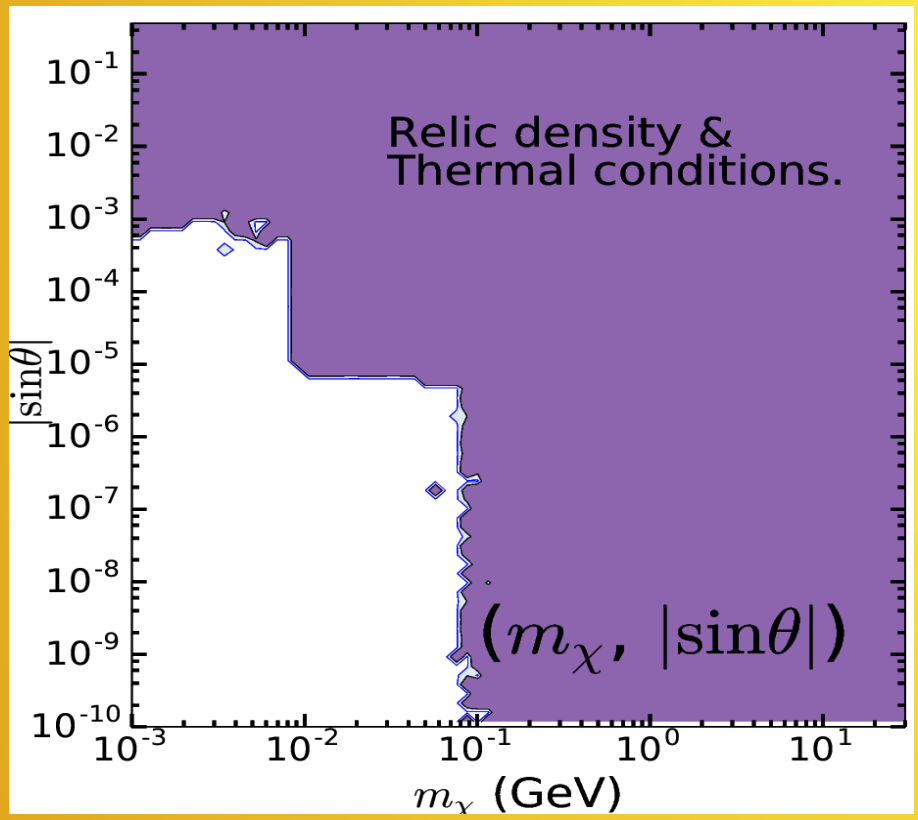
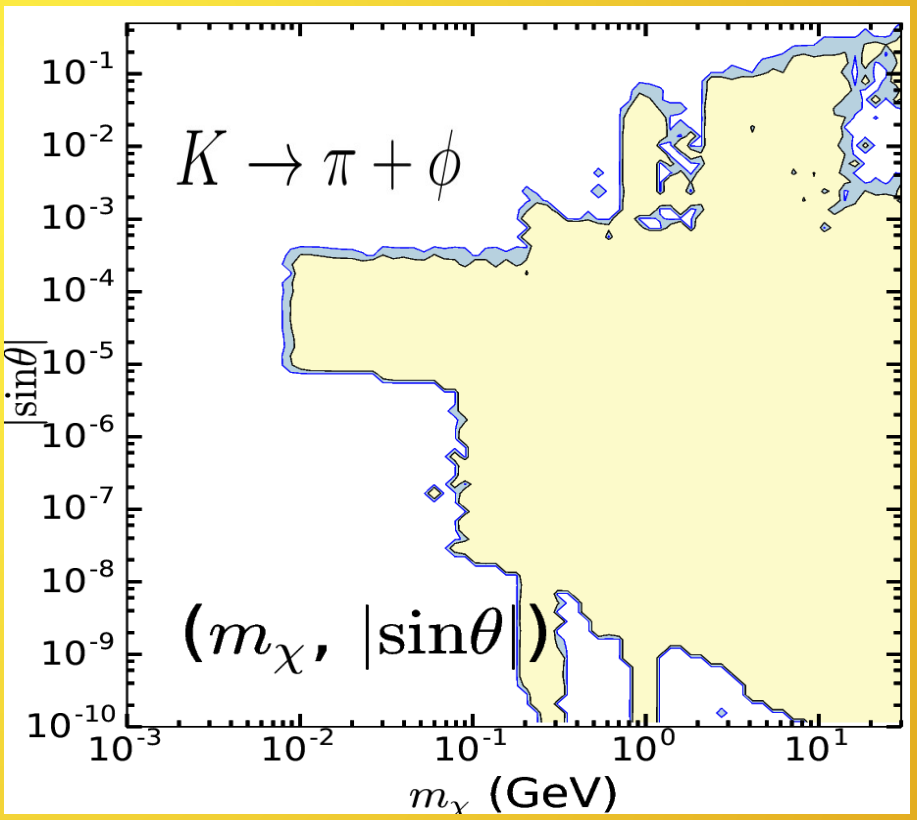


Constraints

- **Kinematic equilibrium** condition+**Kaon** decay:

$$m_\chi \geq 10 \text{ MeV}$$





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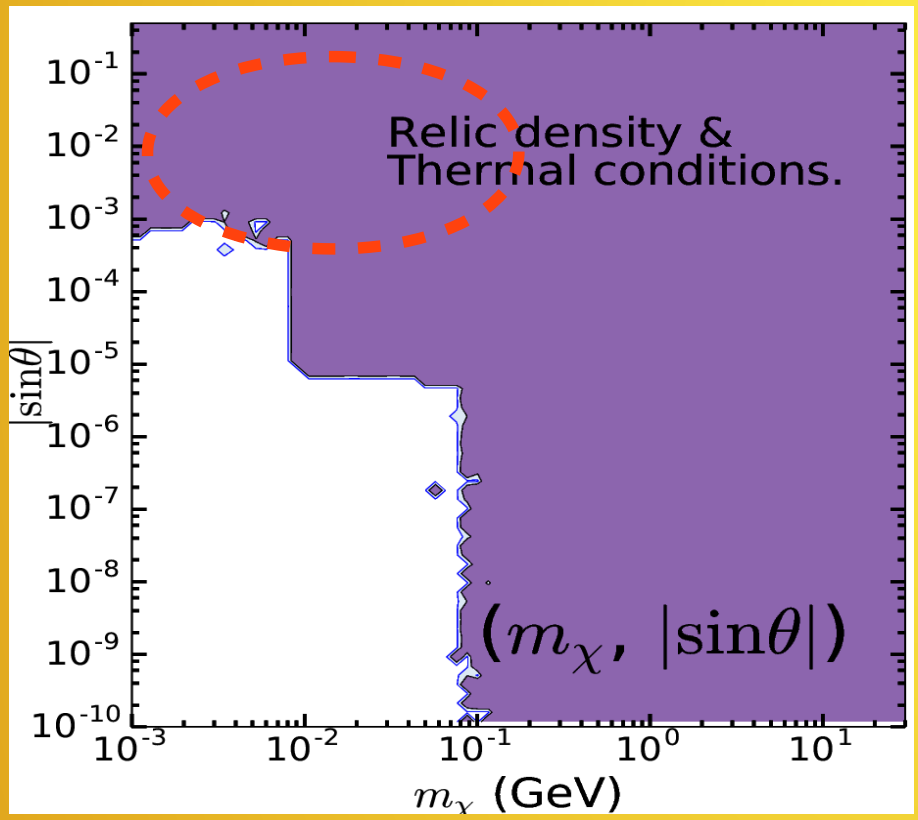
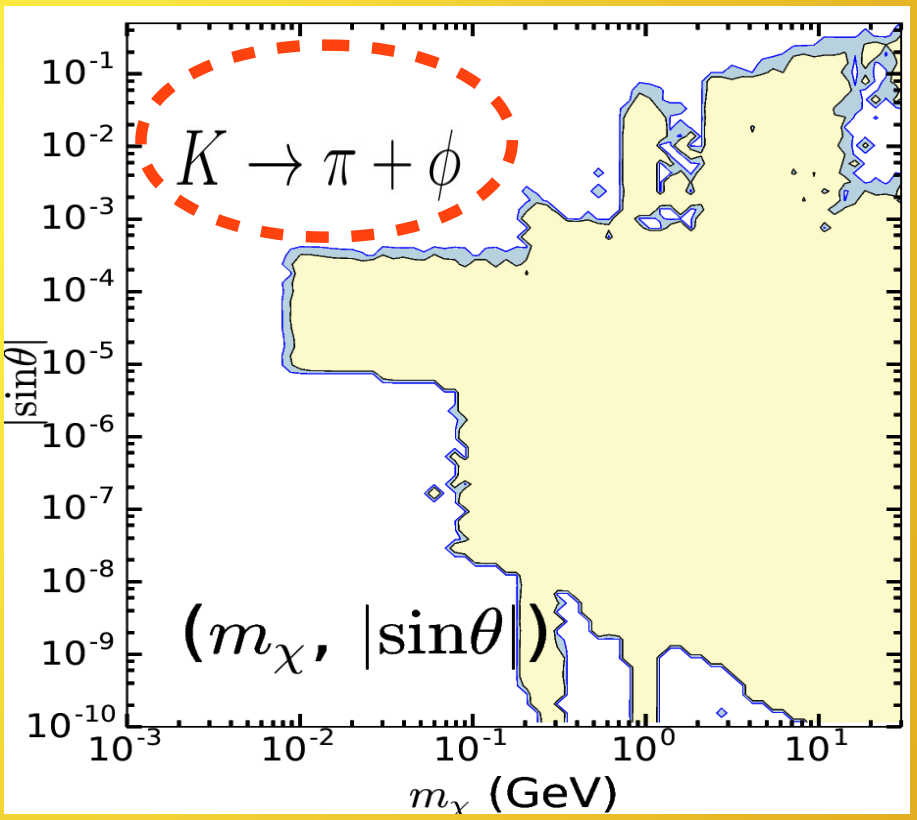
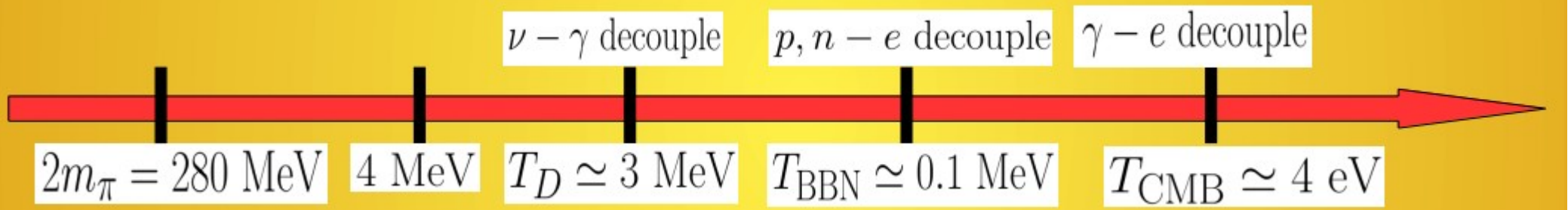




Constraints

- Cosmology constraints: **BBN, Neff, CMB**. *Assume mediator is thermal equilibrium with SM*.

$$m_\phi \geq 6 \text{ MeV}$$



m_ϕ BBN : hadronic decay $\tau_\phi < 1$ second

Constraints

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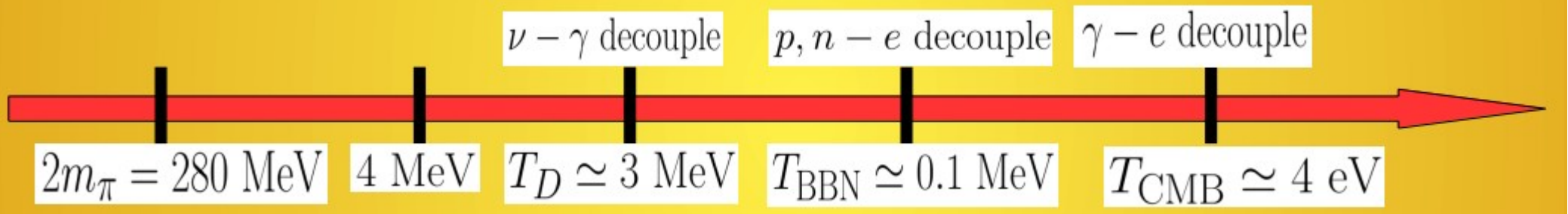

m_ϕ

$$\text{BBN : photo} - \text{disintegrate nuclear}$$

$$\tau_\phi < 10^5 \text{ second}$$

Constraints

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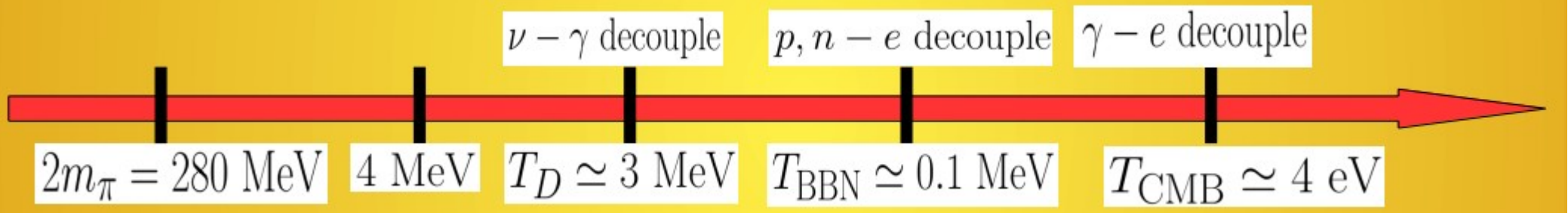

m_ϕ No constraint

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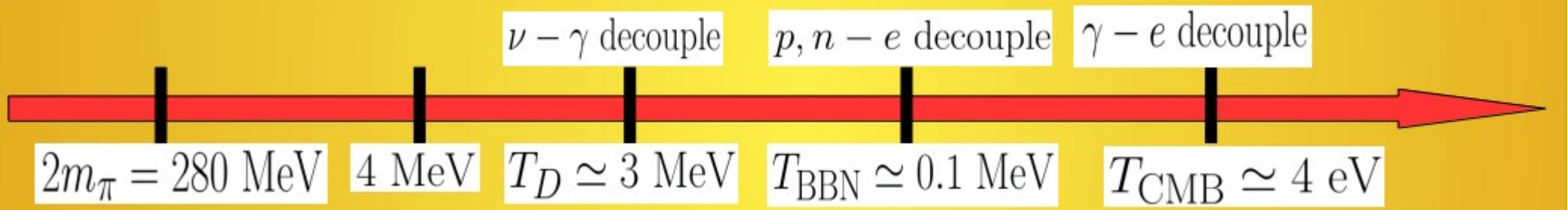


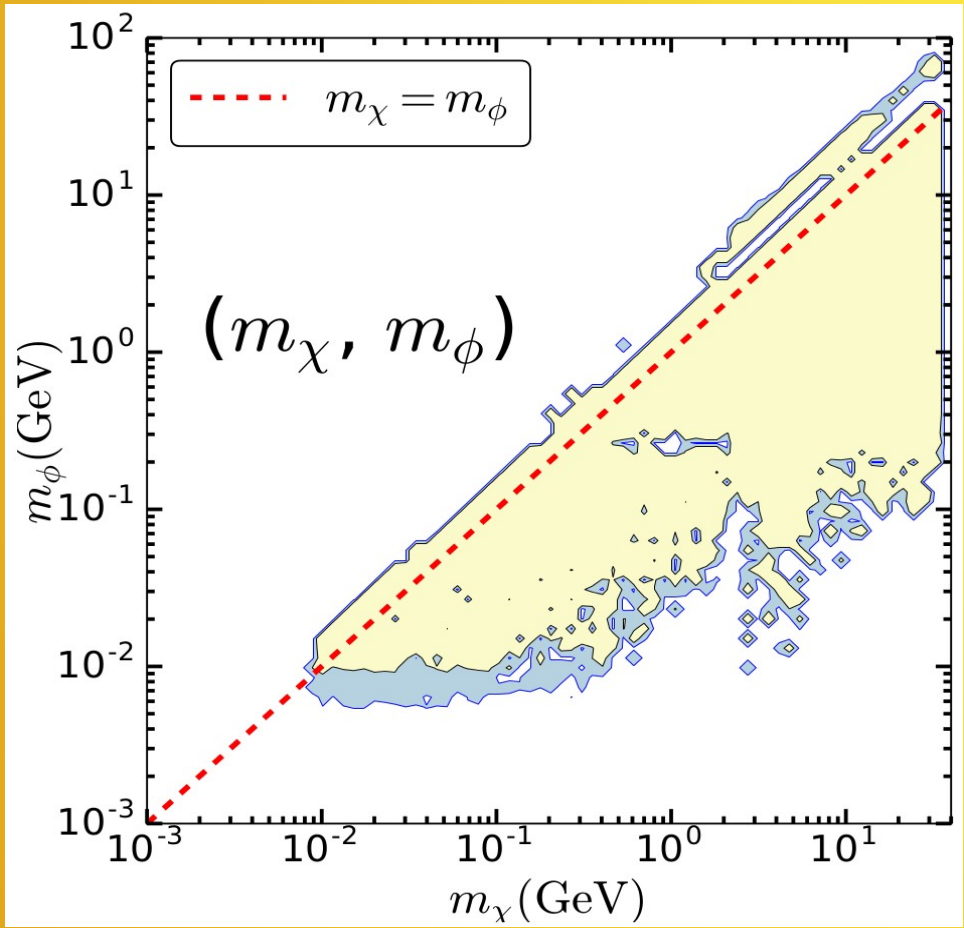
ϕ from relativistic to non-relativistic, inject entropy to $\gamma \Rightarrow$ change the $\left(T_{\rm D}^{(\nu)}/T_{\rm D}^{(\gamma)}\right)$ and $\left(T_{\rm CMB}^{(\nu)}/T_{\rm CMB}^{(\gamma)}\right)$

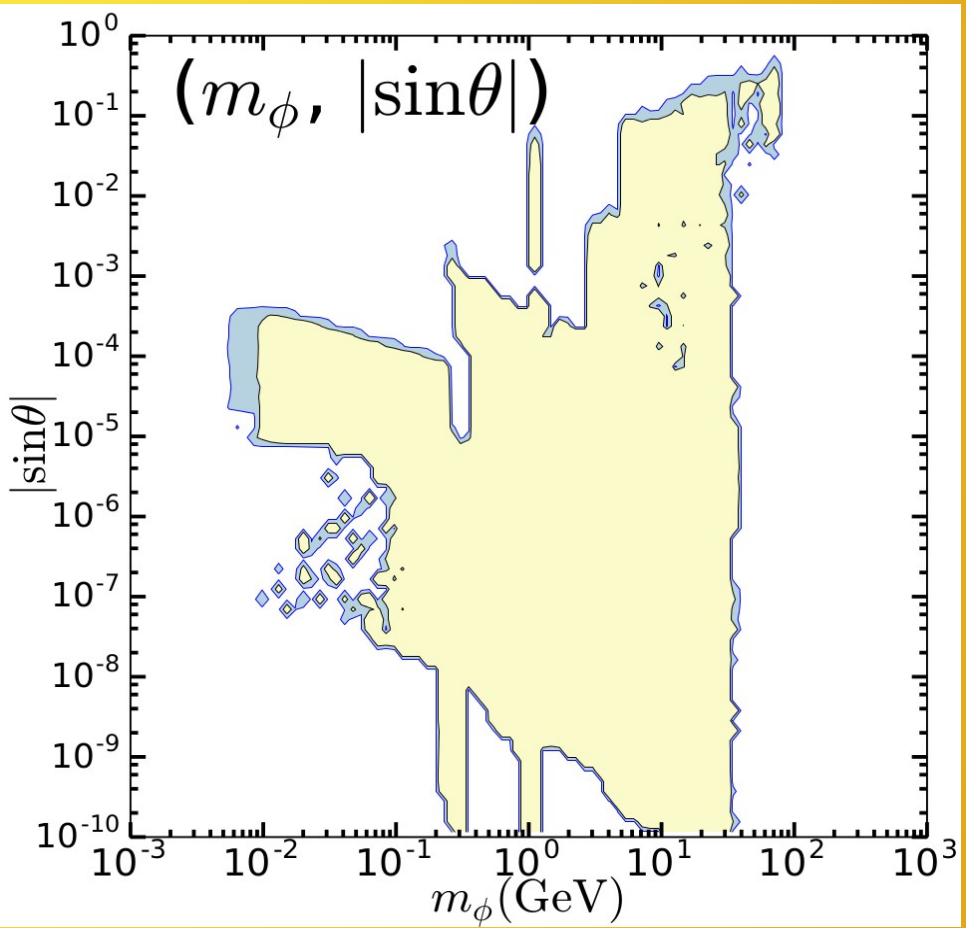
m_ϕ

$\Delta N_{\rm eff}: \; m_\phi \geq 6$ MeV

Results

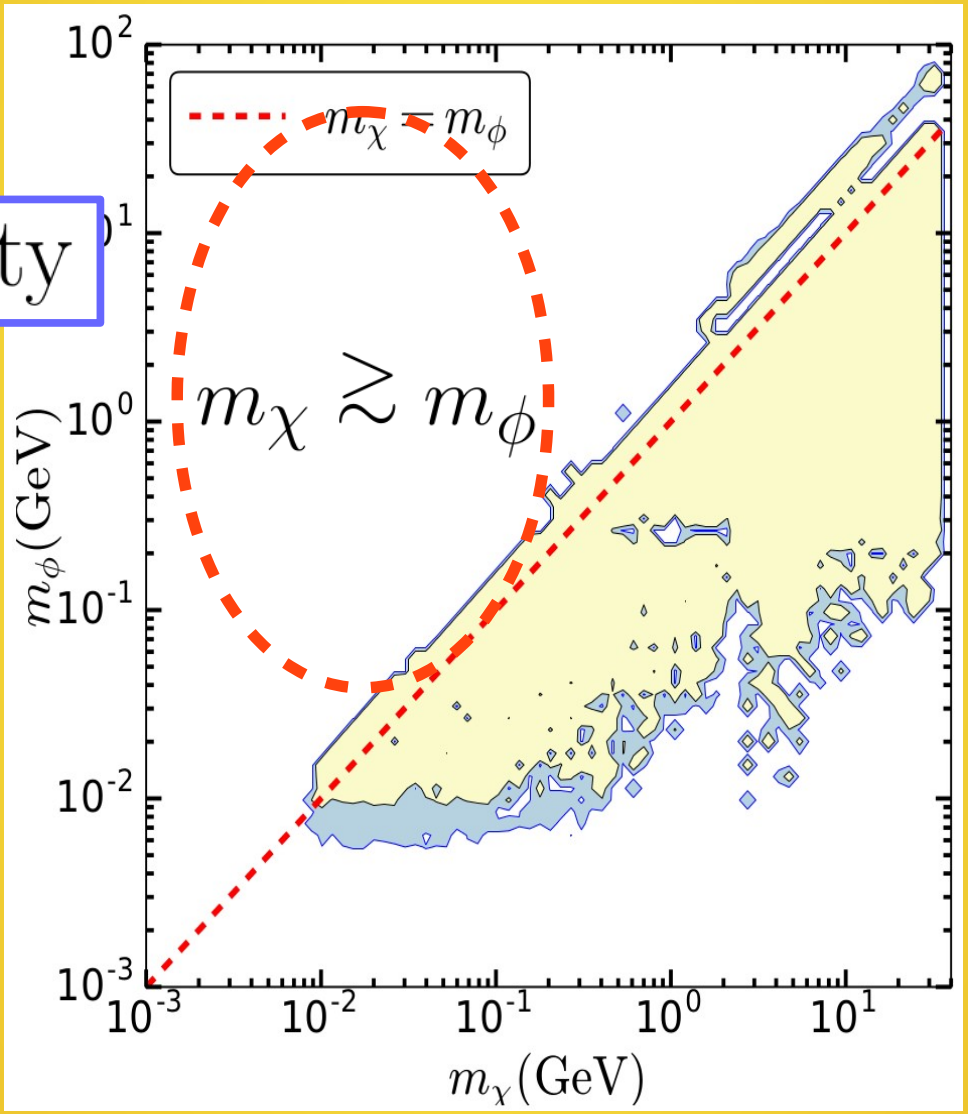
- Under **present** constraints:





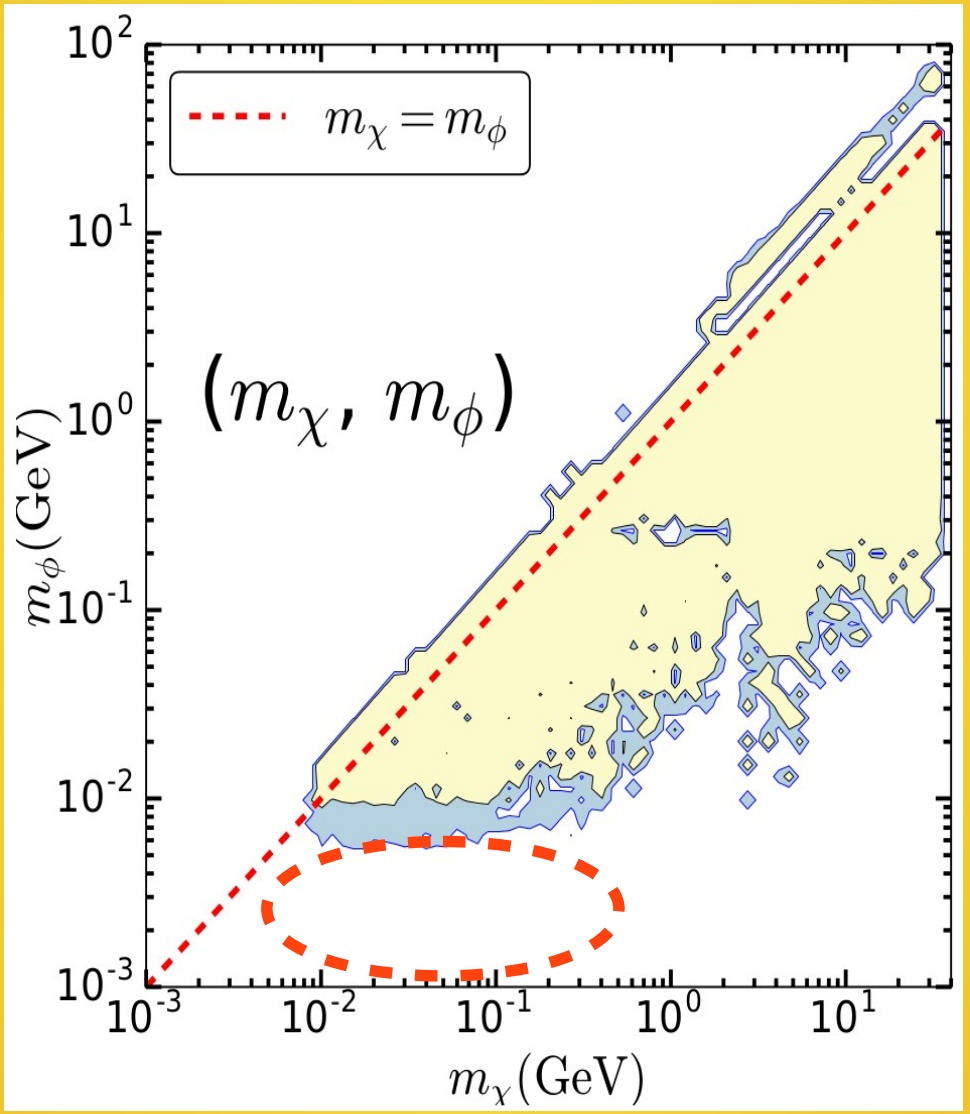
Results

Relic density

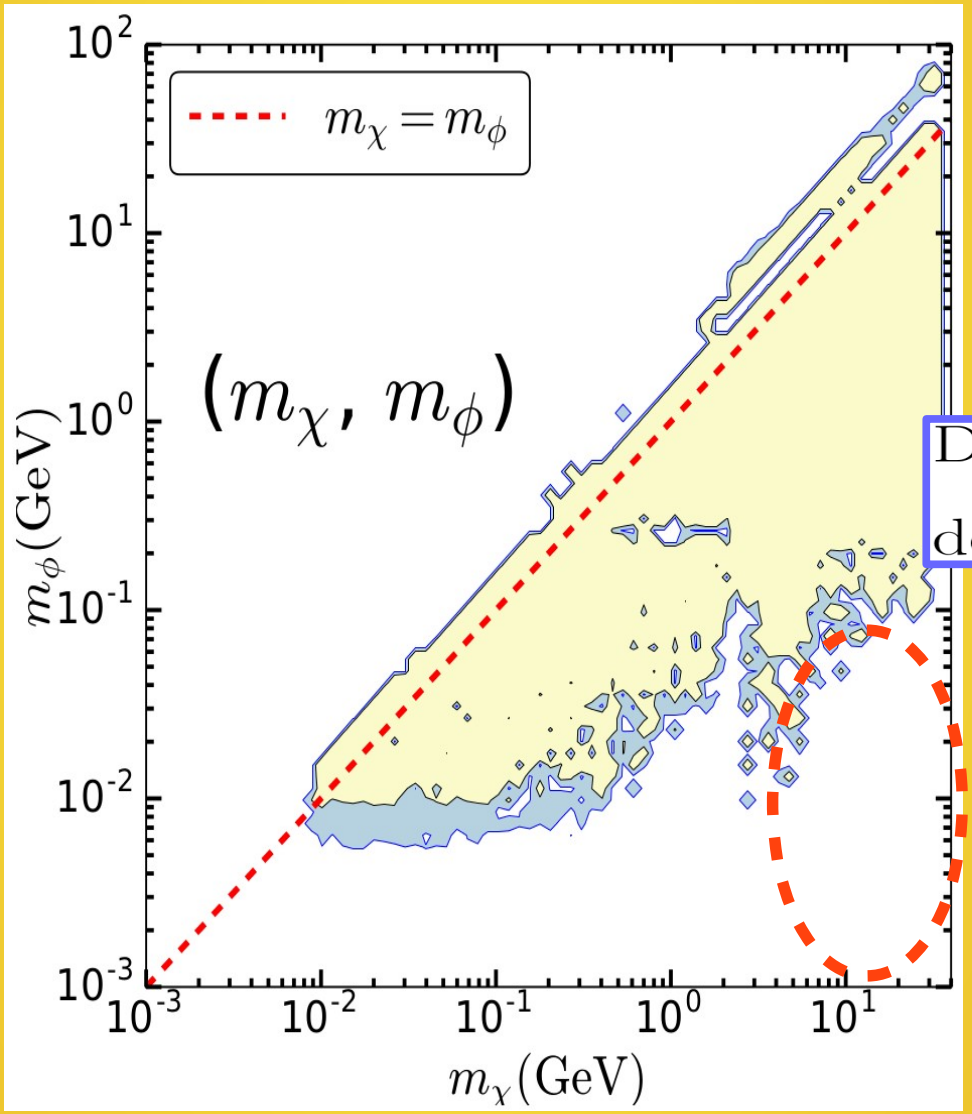


Results

$\Delta N_{\rm eff}$

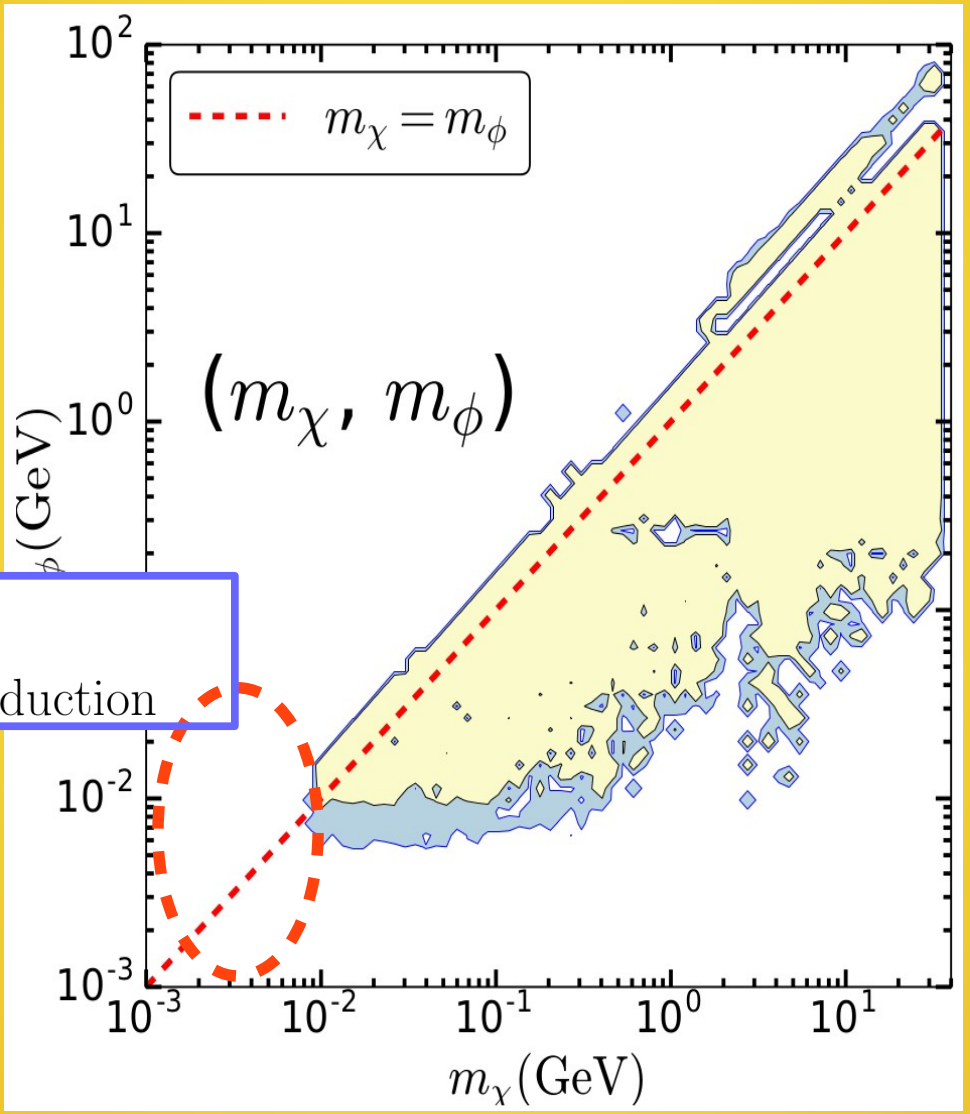


Results



Direct dark matter detection

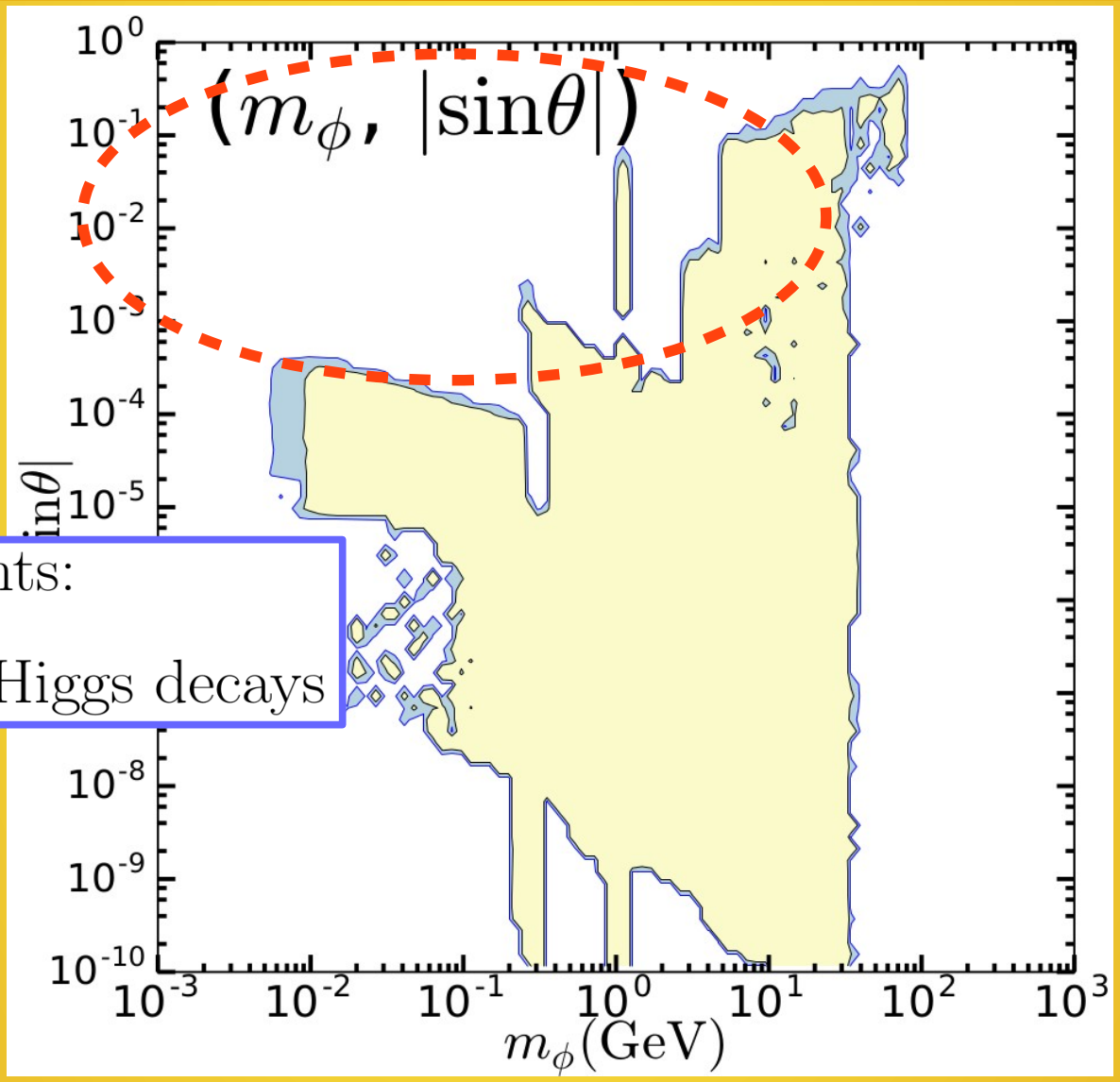
Results



Kaon decay +

Kinematic equilibrium conduction

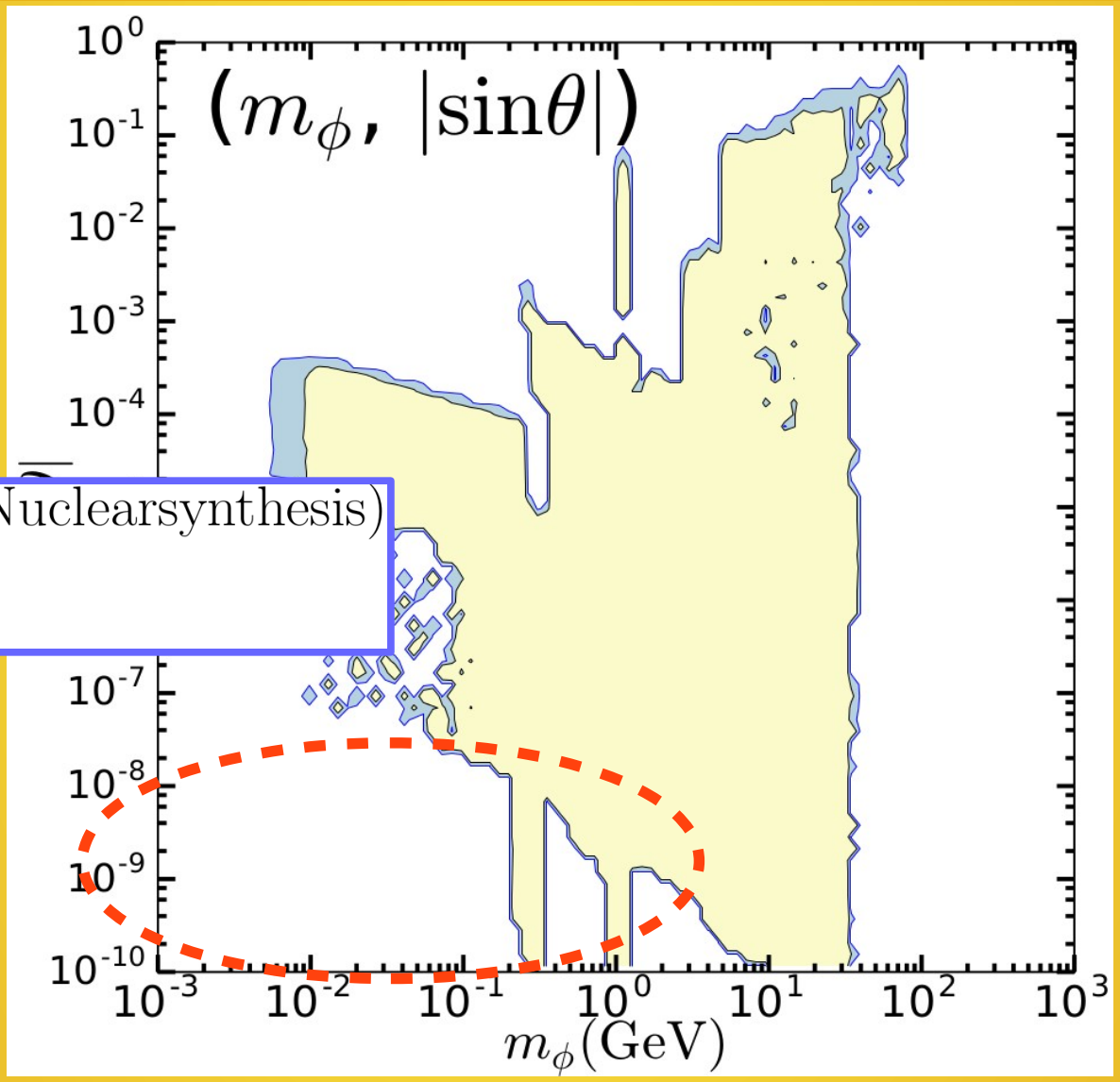
Results



Collider constraints:

Kaon, B-meson, Higgs decays

Results

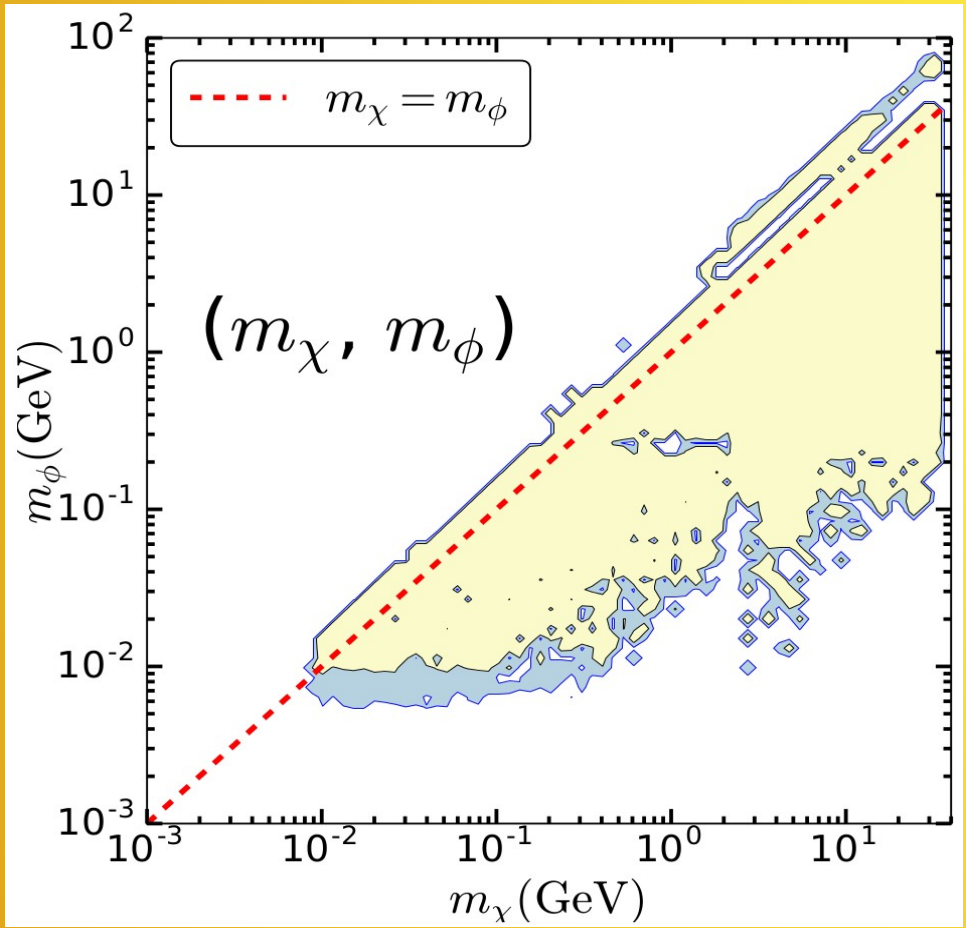


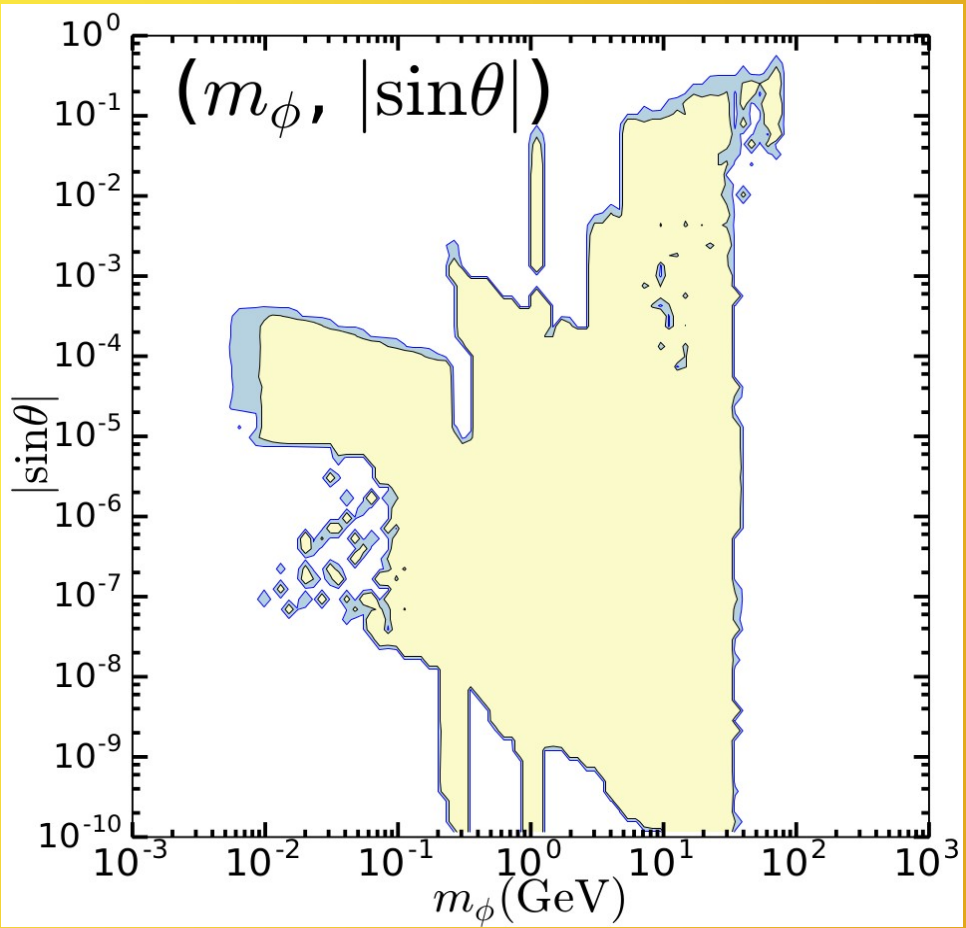
BBN (Big Band Nuclearsynthesis)

$\tau_\phi < 1$ sec.

Results

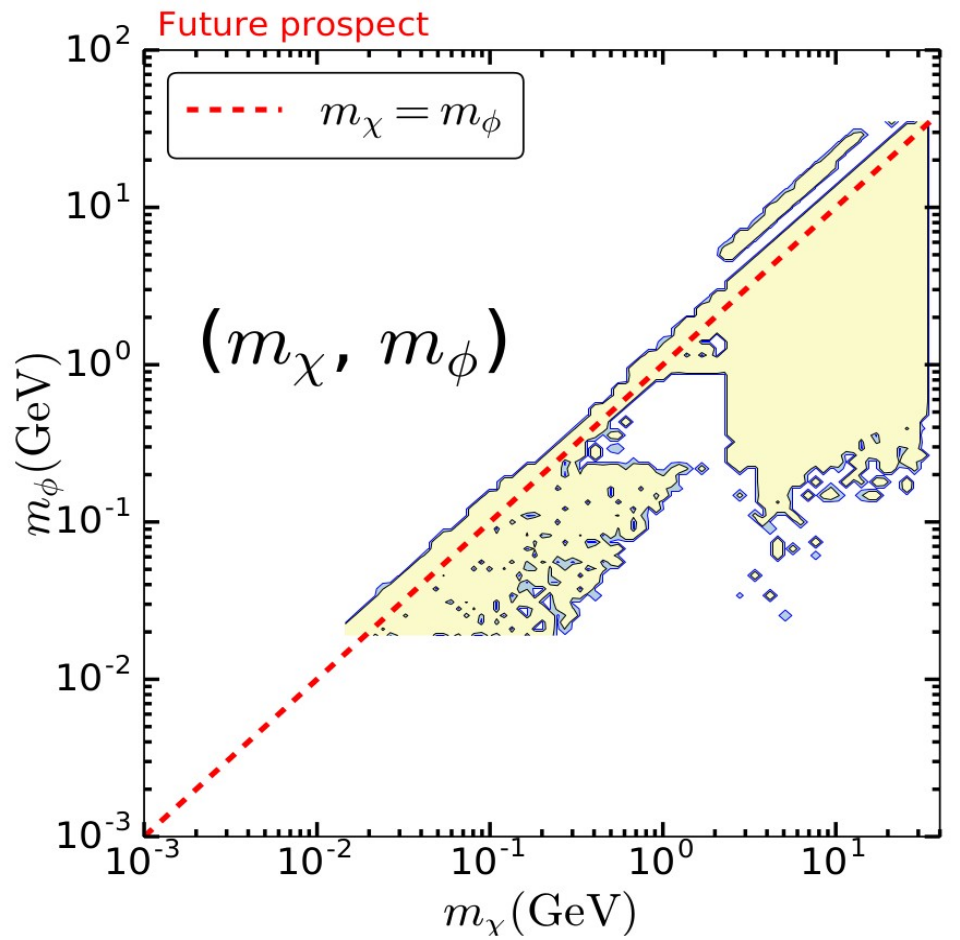
- Under present constraints:

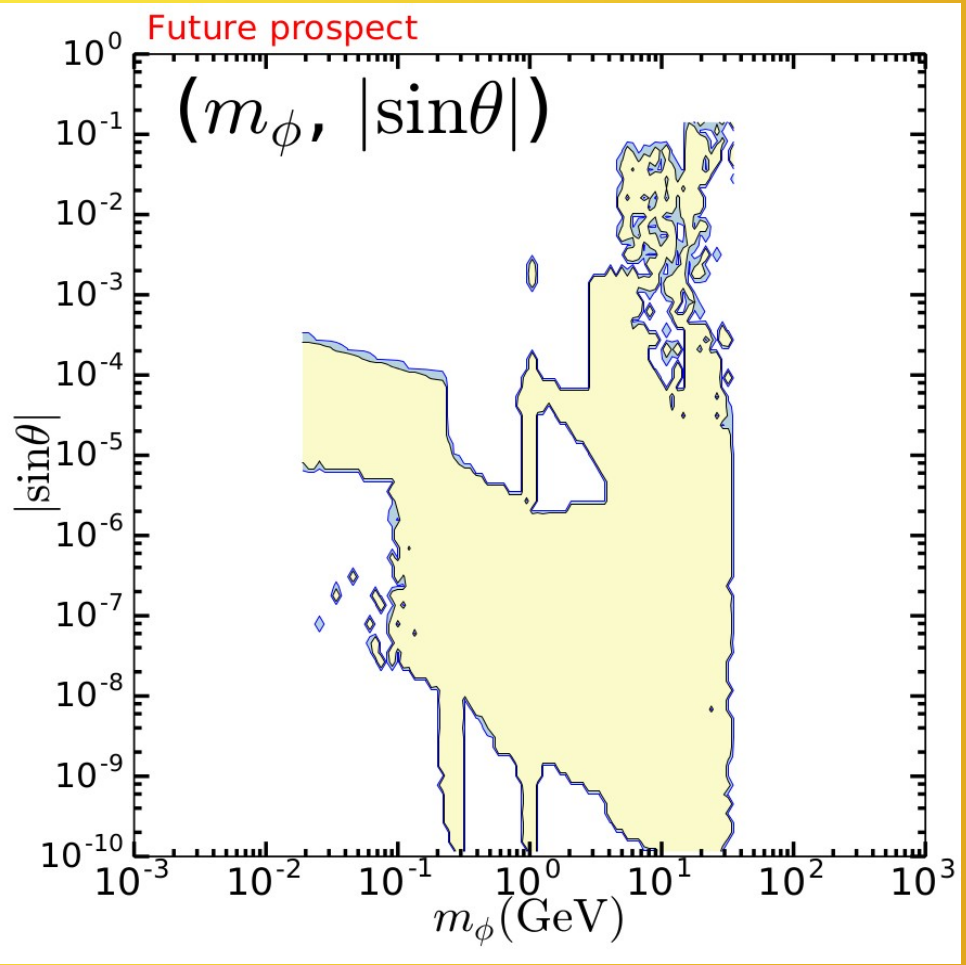




Results

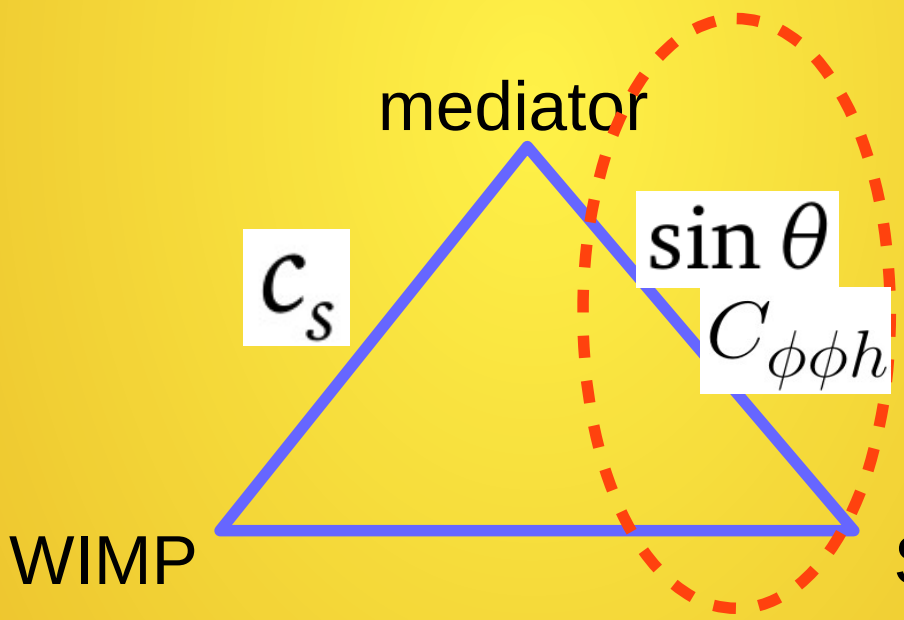
- Under **future** constraints:

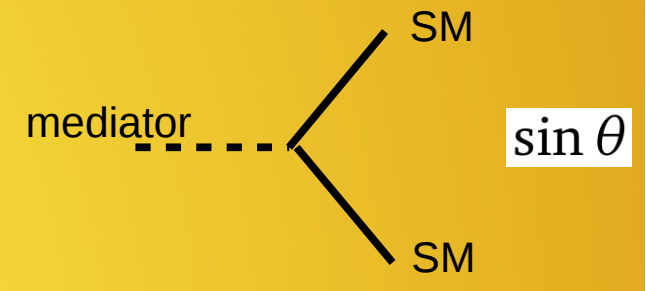


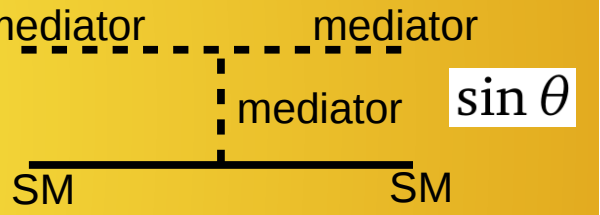


Introduction

- Thermal equilibrium.
- WIMP ↔ mediator ↔ SM.







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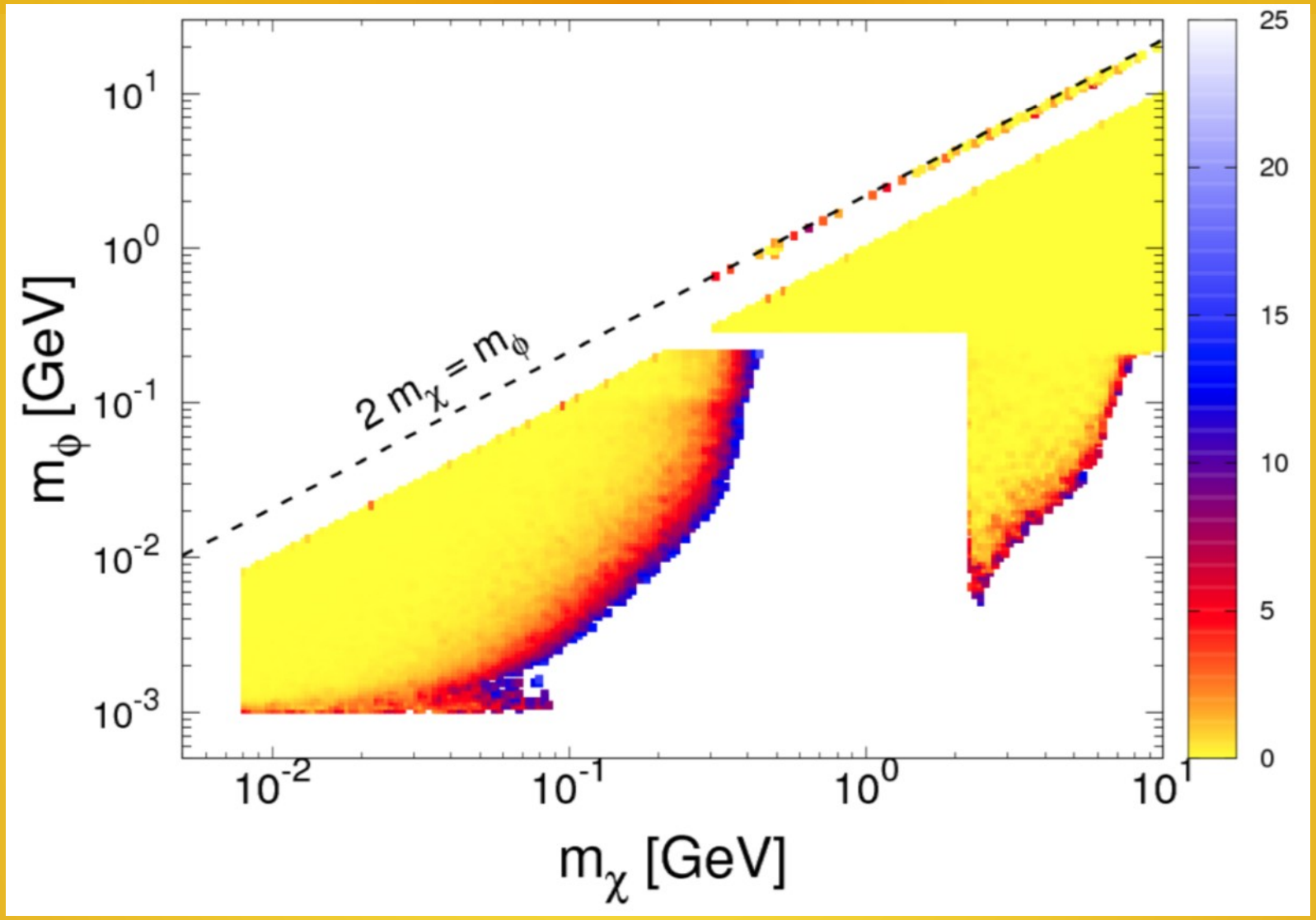
Constraints



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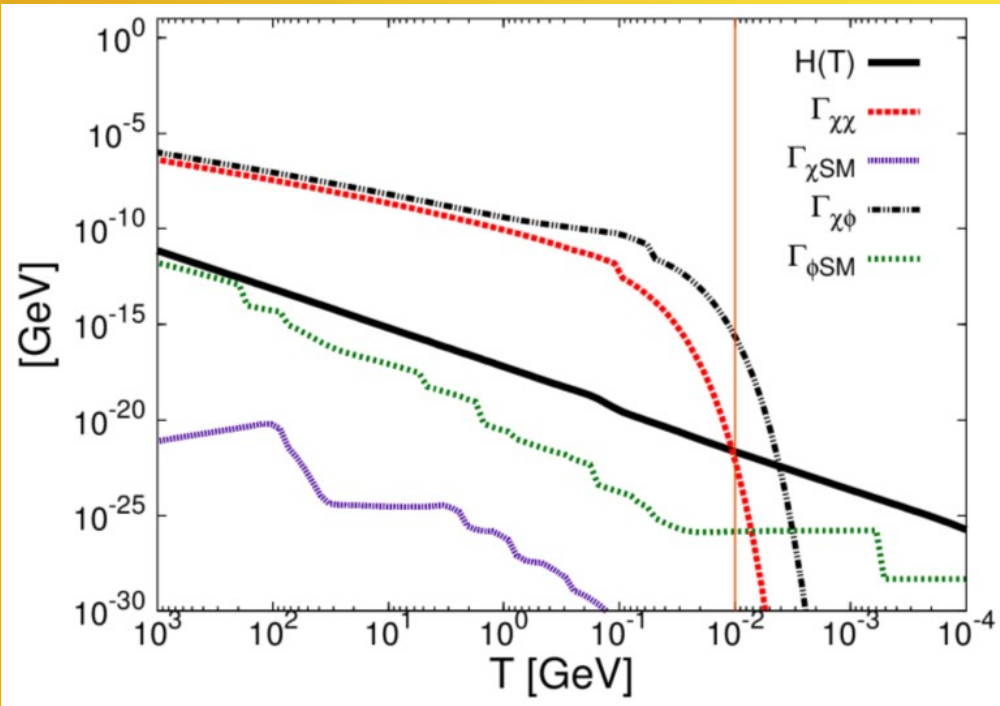
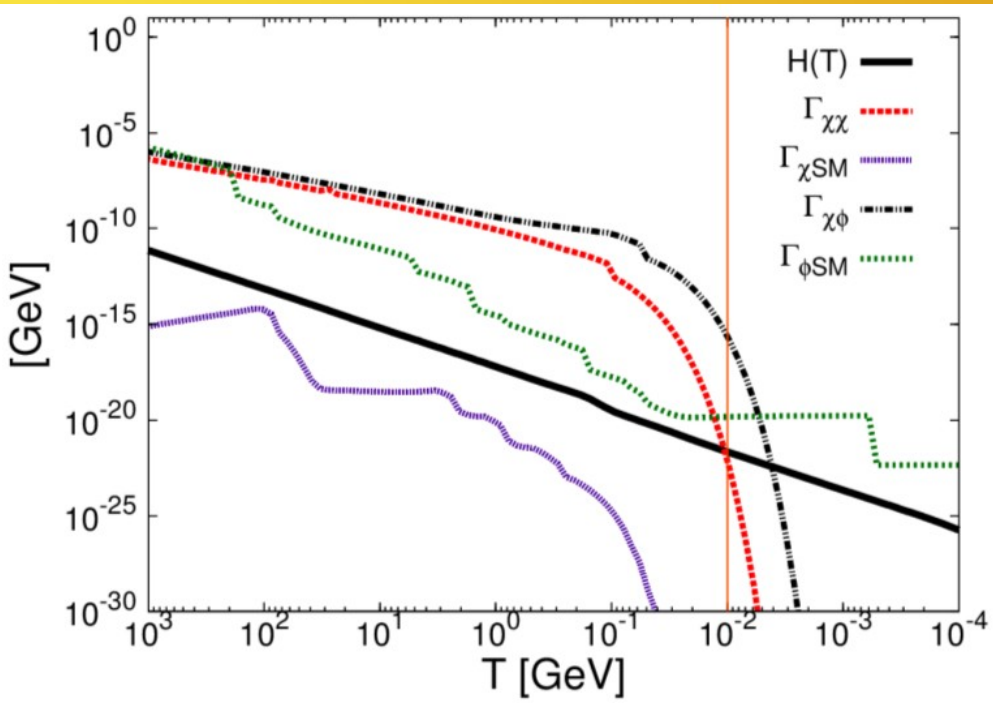




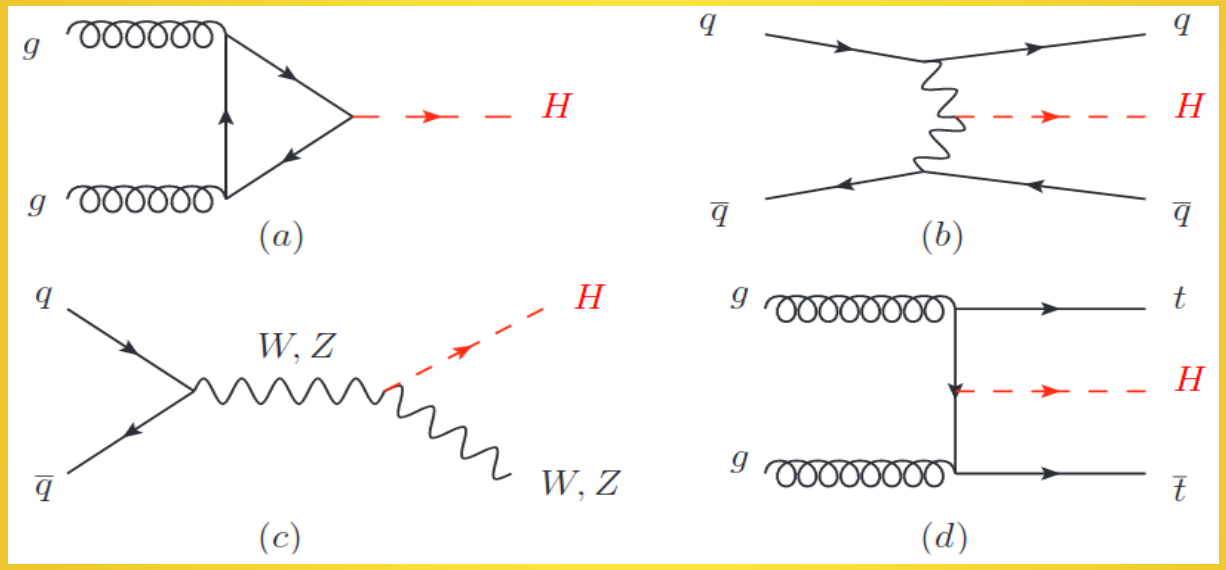
$(m_\chi, c_s, m_\phi, \sin\theta, \mu_3) =$

$(200\text{MeV}, 0.022, 100\text{MeV}, 10^{-6}, 10\text{MeV})$

$(200\text{MeV}, 0.1, 50\text{MeV}, 10^{-3}, 10\text{MeV})$

Higgs Production at LHC

- The production mechanism: ggF, VBF, Vh, tth.



C.Grojean: 1708.00794

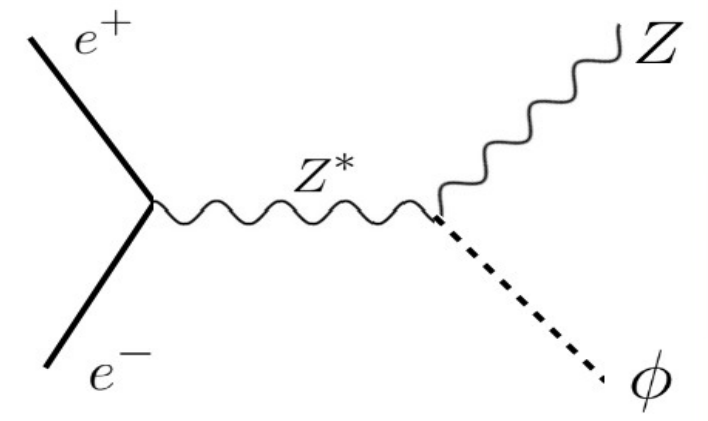
$$\text{ProductionRate}:$$

$$\text{ggF} = 80\%, \text{VBF} = 15\%, \text{Vh} = 4.5\%, \text{t}\bar{\text{t}}\text{h} = 0.5\%$$

K.Cheung, J.S.Lee, P.Y.Tseng: 1302.3794

Constraints

- When the mediator is lighter than 10 GeV. The LEP constraint is stronger than that from ILC, because of lower center mass energy. Y. Wang,J. List,M. Berggren: 1801.08164



ILC

- From the Higgs-mediator-mediator coupling, in small mixing angle limit, s.t. decay length is longer than ~30m. For example, $m_\phi = 20\ \mathrm{GeV}, \sin\theta < 10^{-7}$

$$C_{\phi\phi h} \simeq \frac{2(m_\phi^2 - \mu_\Phi^2)}{v_H}$$

$$\Gamma(h \to \phi\phi) \simeq \frac{C_{\phi\phi h}^2}{32\pi m_h}$$

$$\Delta\mathrm{BR}(h_{125} \to \text{invisible}) \lesssim 0.44\%$$

$$\Rightarrow C_{\phi\phi h} < 0.7\ \mathrm{GeV}, \text{or } |m_\phi^2 - \mu_\Phi^2| < 90\ \mathrm{GeV}^2$$

Light WIMP with scalar mediator

- Higgs precision measurement at LHC:

$$\Delta \mathrm{BR}(h_{125} \to ZZ) \lesssim 10\% \Rightarrow |\sin\theta| \lesssim 0.32$$

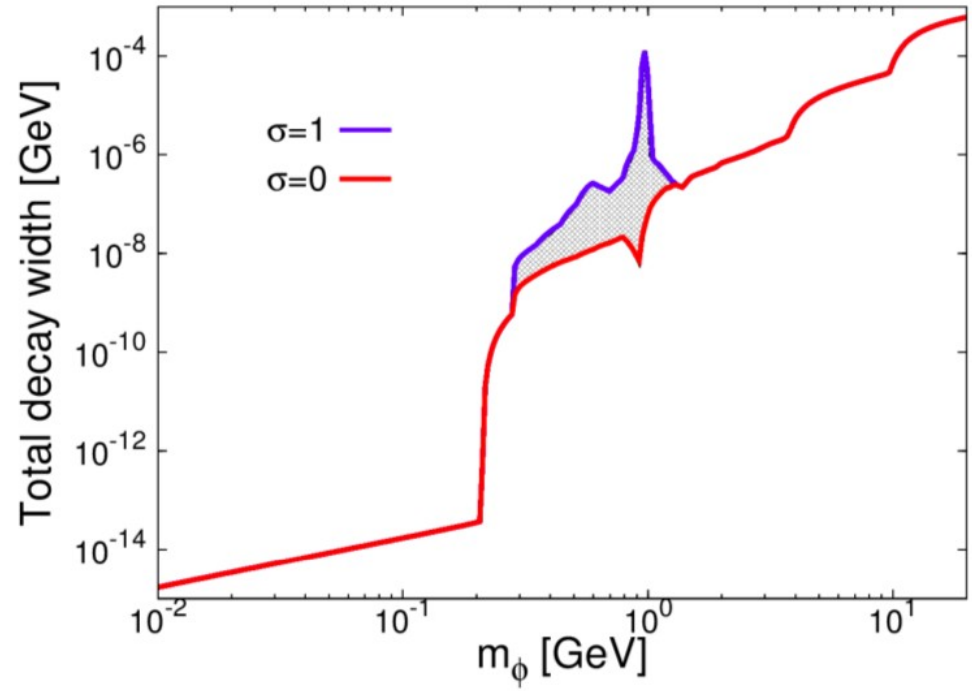
- At ILC (250GeV), improve the Higgs precision measurement:

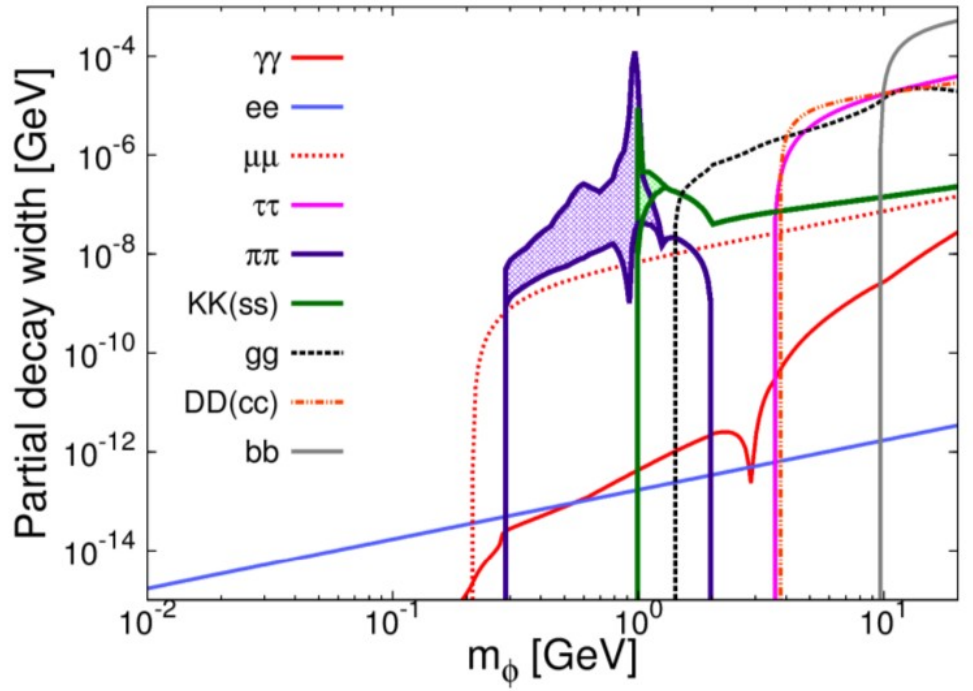
$$\Delta \mathrm{BR}(h_{125} \to ZZ) \lesssim 0.5\% \Rightarrow |\sin\theta| \lesssim 0.07$$

H. Baer et. al., ILC: 1306.6352

Light WIMP with scalar mediator

- Mediator width and branching ratio:





$$\sin\theta = 1,\ \Gamma_\phi \propto \sin^2\theta$$

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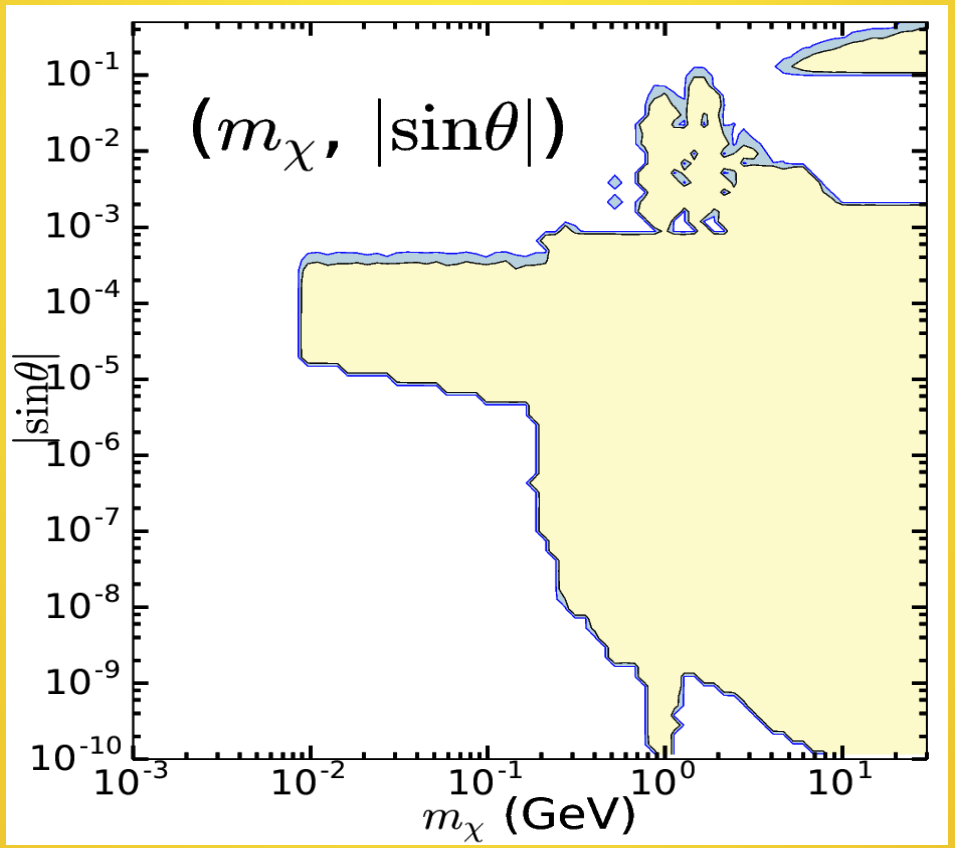
Constraints

- Current experimental constraints for light WIMP. Lower mass limit for WIMP **9MeV**.



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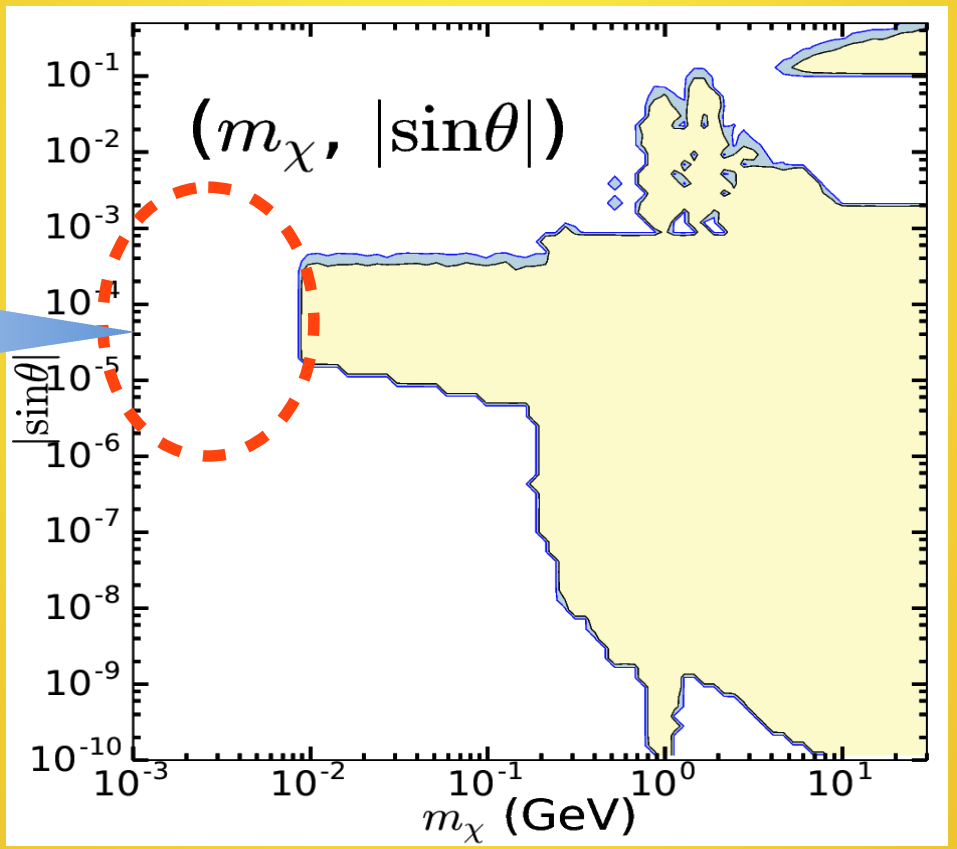
Constraints

- Current experimental constraints for light WIMP. Lower mass limit for WIMP **9MeV**.

thermal equilibrium



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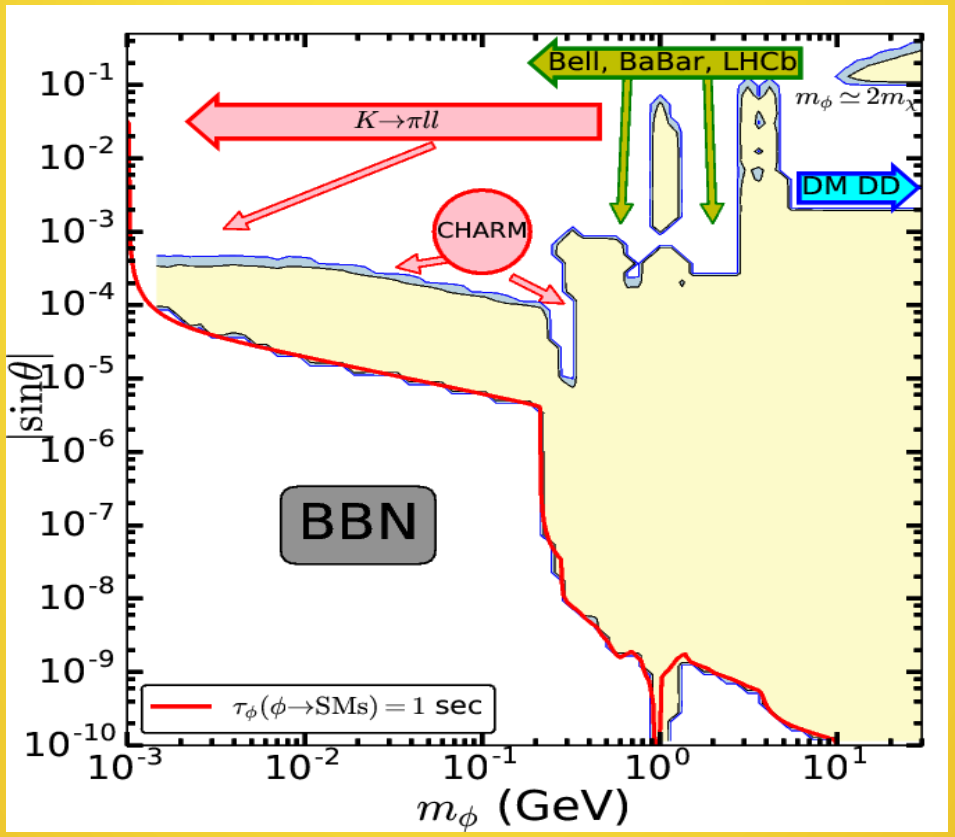
Constraints

- Current experimental constraints for light mediator. Lower limit for mediator mass **1 MeV**.



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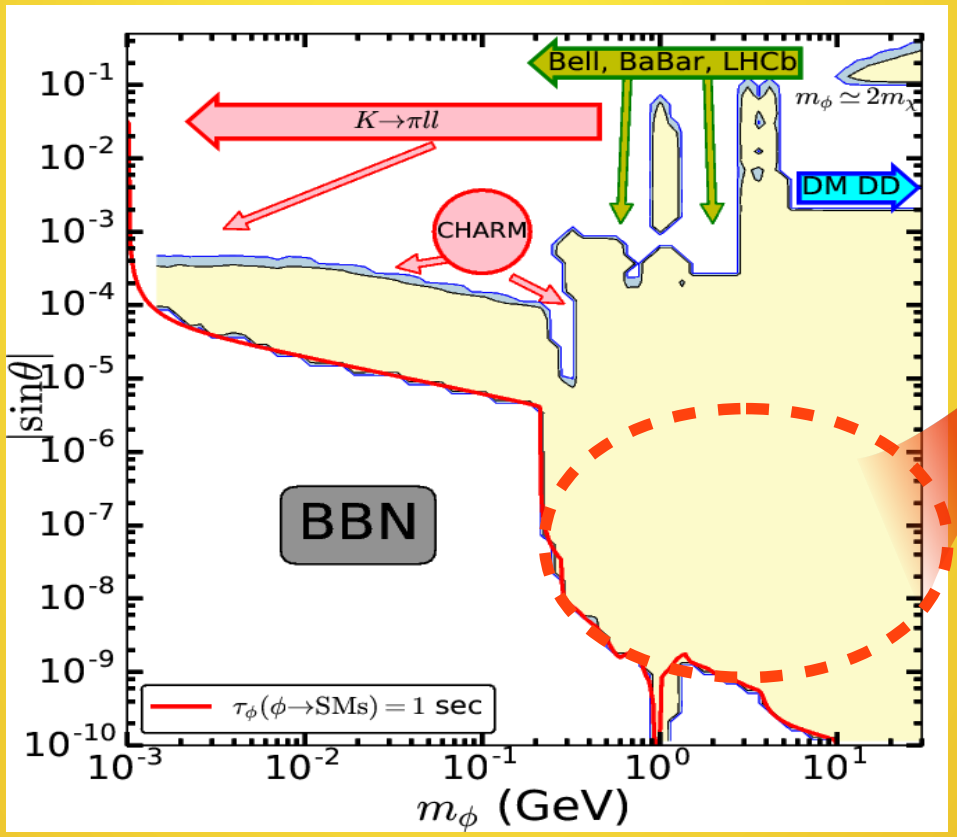
Constraints

- Current experimental constraints for light mediator



The $\sin\theta$ too small,

but $C_{h\phi\phi}$ need to be large

to maintain thermal equilibrium.

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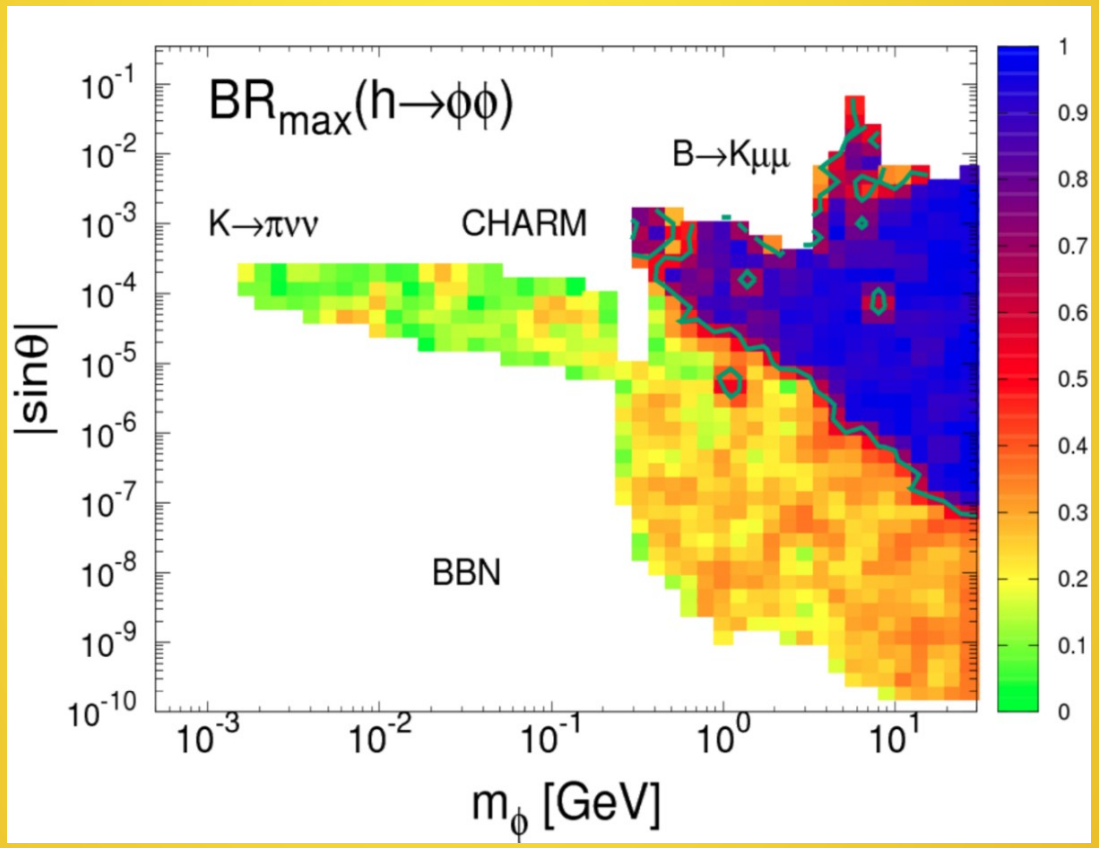
Constraints

- Current experimental constraints for light mediator



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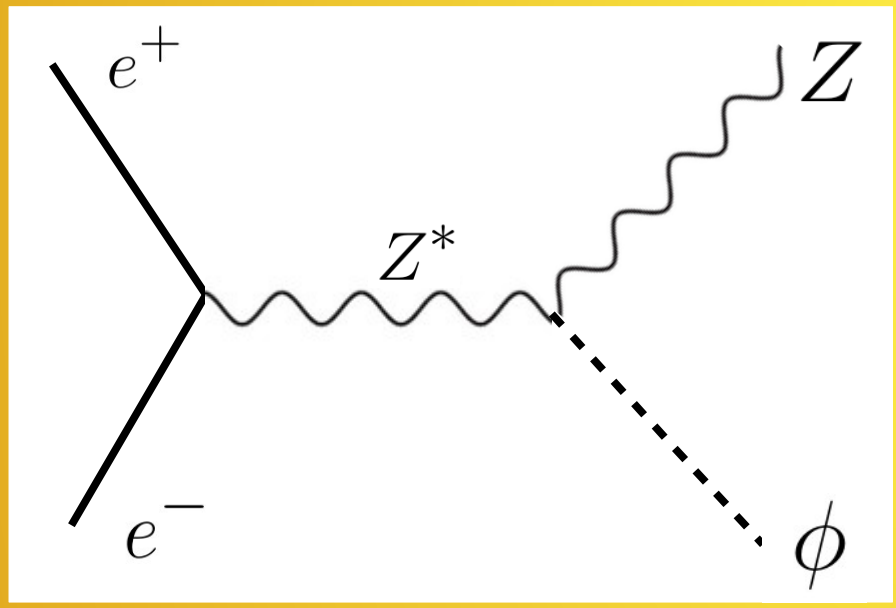
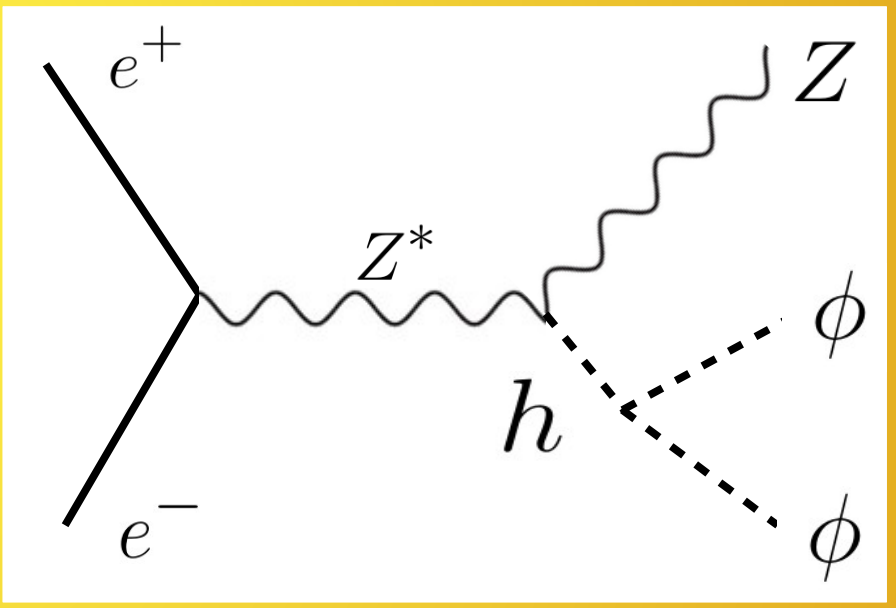
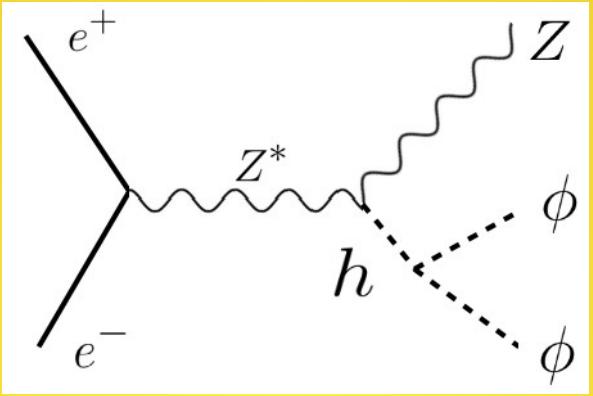
Constraints

- Mediator produced at ILC





Constraints

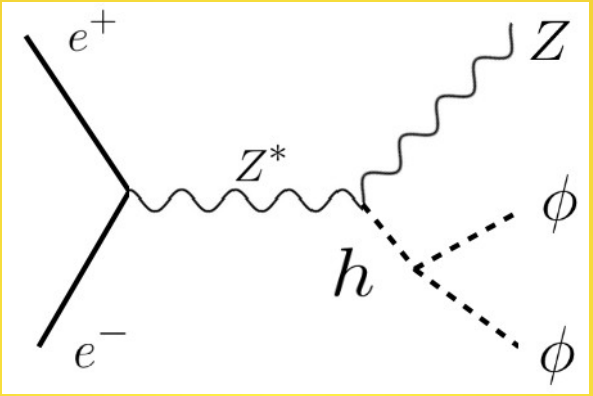


- From the Higgs-mediator-mediator coupling

$$C_{\phi\phi h} \simeq \frac{2(m_\phi^2 - \mu_\Phi^2)}{v_H}$$

$$\Gamma(h \to \phi\phi) \simeq \frac{C_{\phi\phi h}^2}{32\pi m_h}$$

Constraints



- If the mixing angle with Higgs is very small, mediator becomes long-live particle.

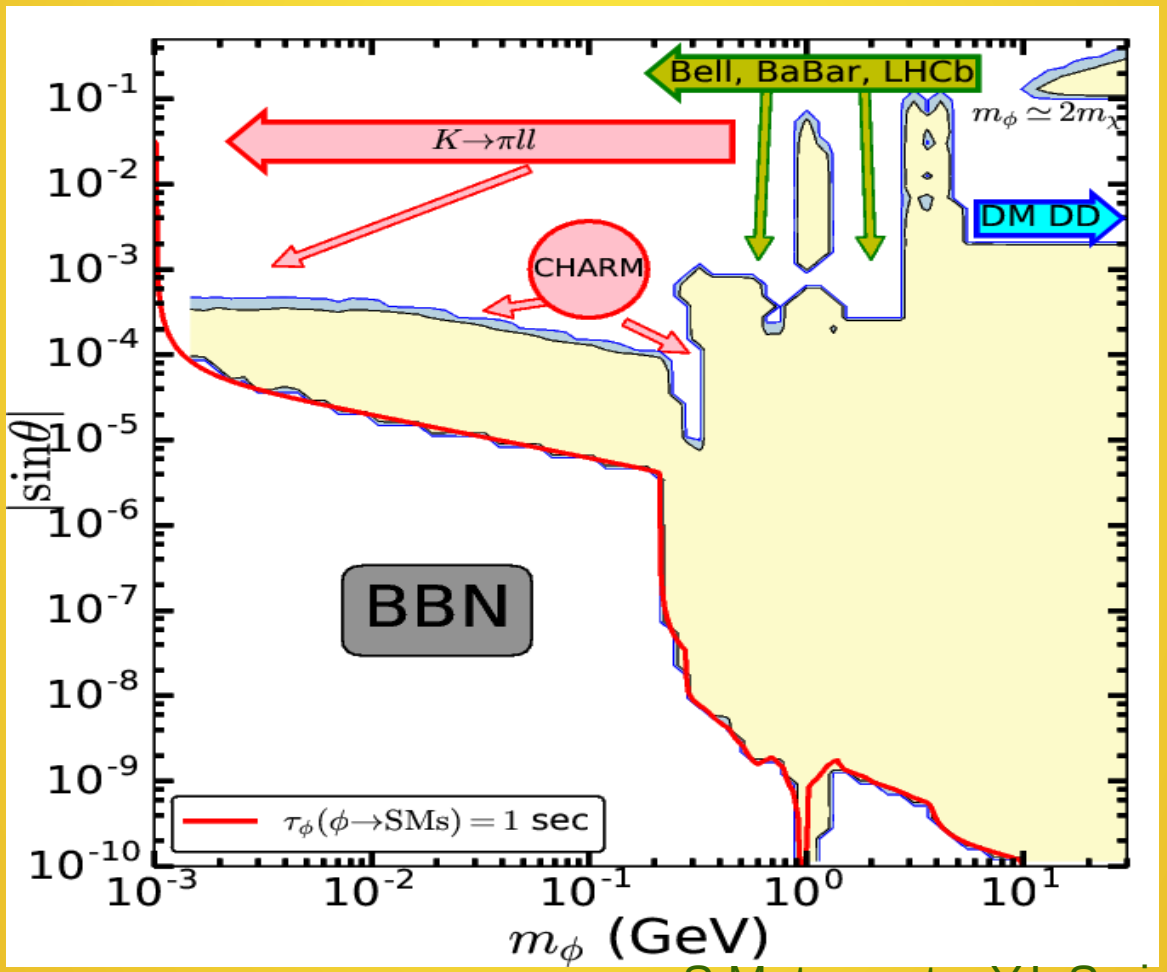
- Invisible Higgs decay at ILC (250GeV):

$$\Delta \mathrm{BR}(h_{125} \to \text{invisible}) \lesssim 0.44\%$$

H. Baer et. al., ILC: 1306.6352

Constraints

Invisible Higgs decay at ILC (250GeV):



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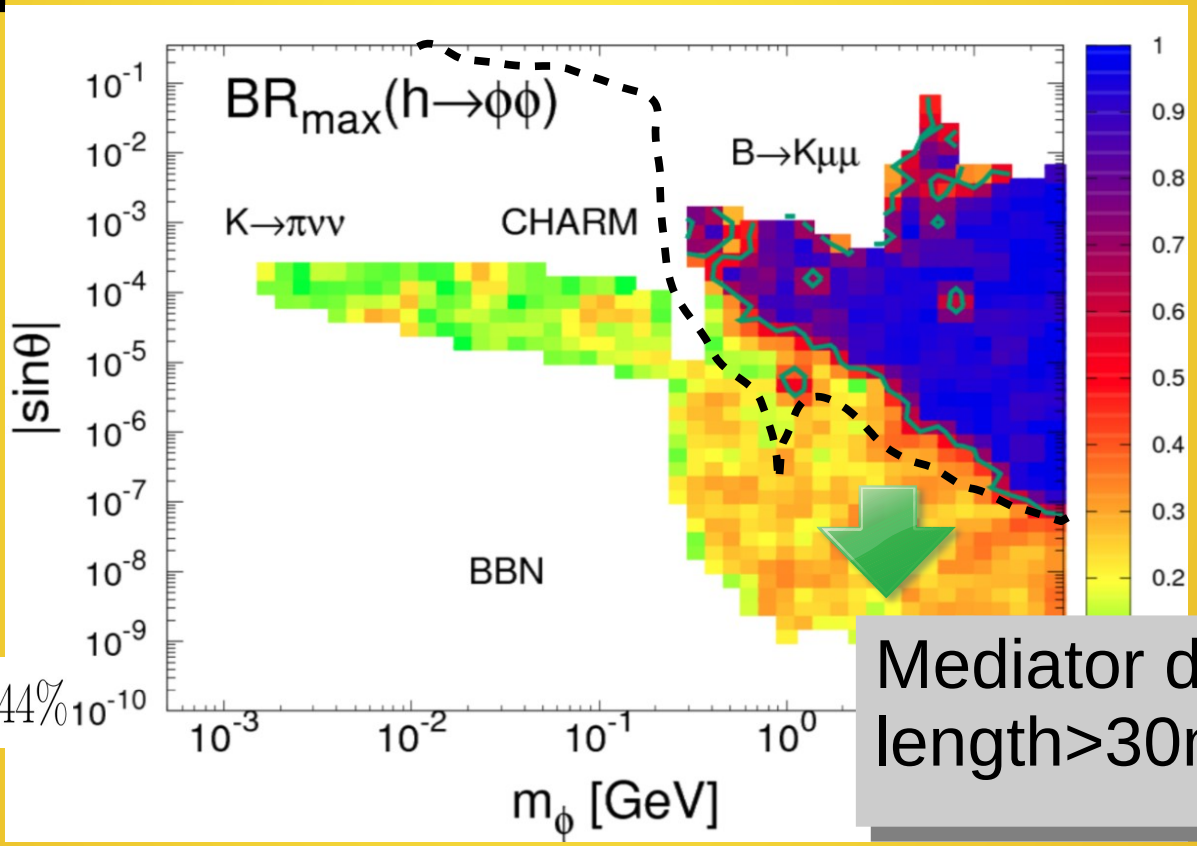
Constraints

- Current experimental constraints for light mediator

$$C_{\phi\phi h} \simeq \frac{2(m_\phi^2 - \mu_\Phi^2)}{v_H}$$

$$\Gamma(h \to \phi\phi) \simeq \frac{C_{\phi\phi h}^2}{32\pi m_h}$$



Mediator decay length>30m

$\Delta BR(h_{125} \to \text{invisible}) \lesssim 0.44\%$

H. Baer et. al., ILC: 1306.6352

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