

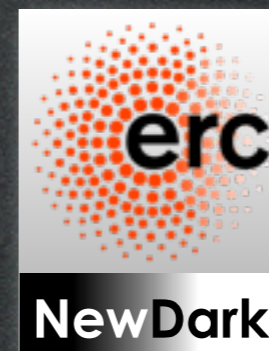
6 December 2016
8th Symposium on Large TPCs, APC Paris

Dark Matter at the crossroads: many constraints and some new ideas

*Or: how we fell in love with WIMPs
and should not dump them (yet)*

Marco Cirelli

(CNRS LPTHE Jussieu Paris)



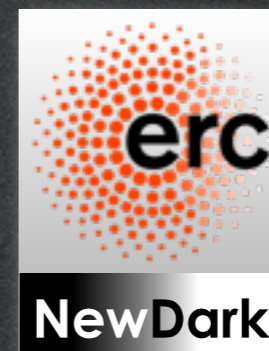
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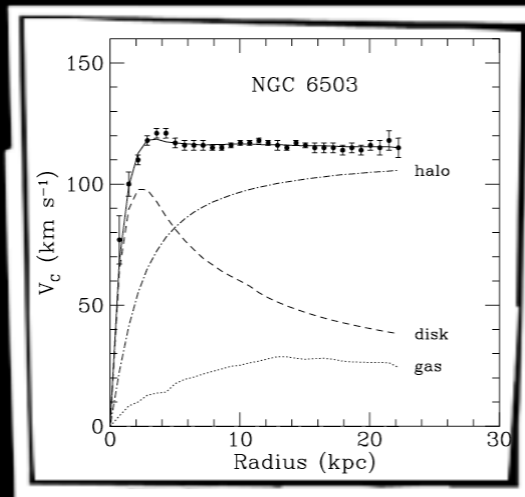
Executive summary

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- DM exists

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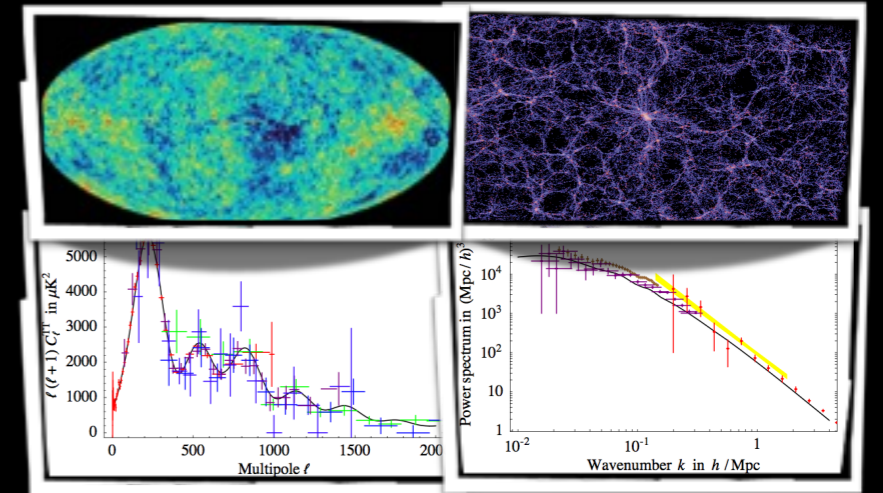
DM exists



galactic rotation curves



weak lensing (e.g. in clusters)



'precision cosmology' (CMB, LSS)

Executive summary

- DM exists
- it's a **new, unknown corpuscule**

*dilutes as $1/a^3$ with
universe expansion*

Executive summary

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82% of total matter

$$\Omega_{\text{DM}} h^2 = 0.1199 \pm 0.0027$$

(notice error!)

[Planck 2015, 1502.01589]

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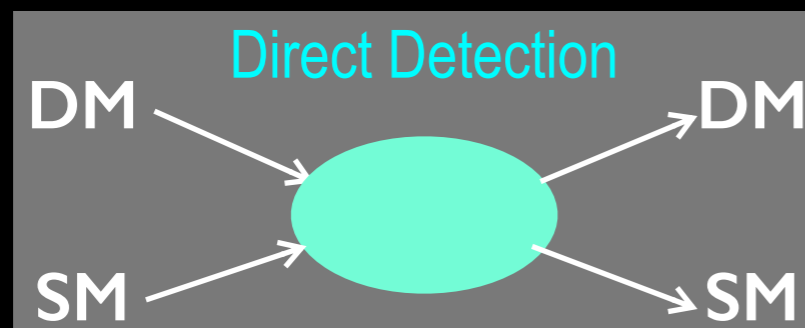
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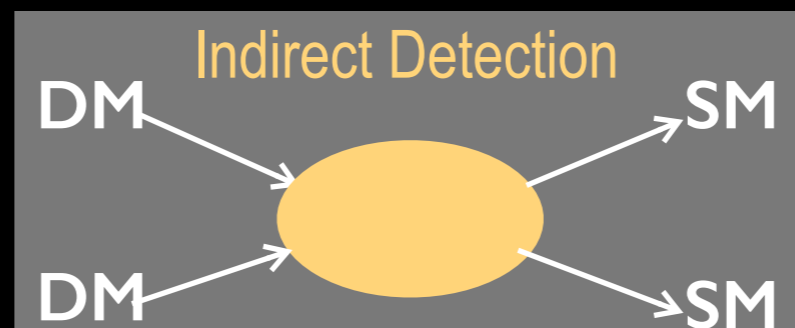
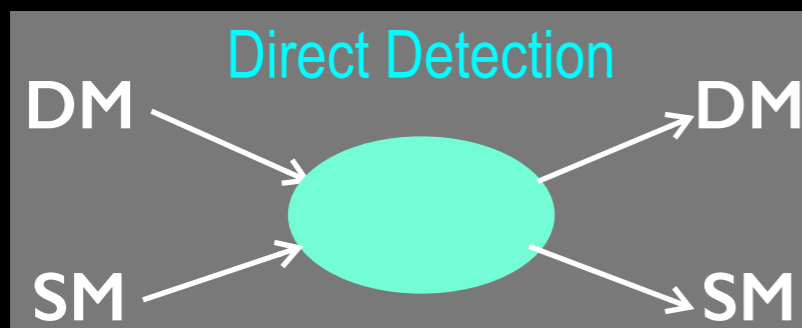
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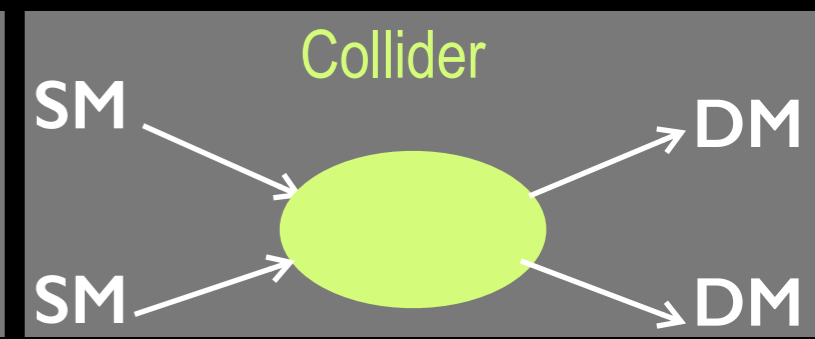
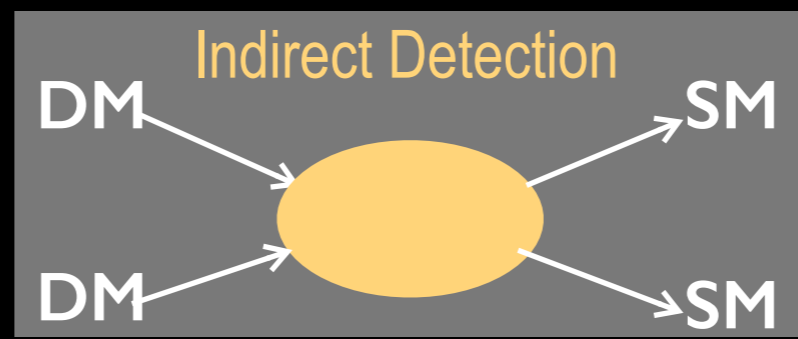
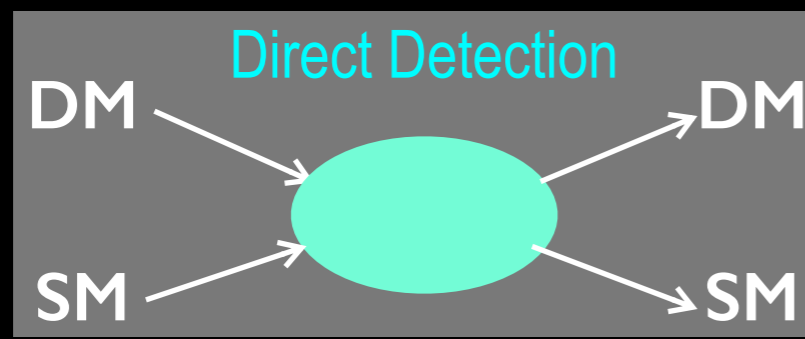
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Mass??

Charge??
Interactions??

Candidates

The Dark Matter
theory space:

Candidates

The Dark Matter
theory space:

**SuSy
DMI**

**Non
SuSy
DMI**

Candidates

The Dark Matter
theory space:

**SuSy
DMI**

**Non
SuSy
DMI**



?

Candidates

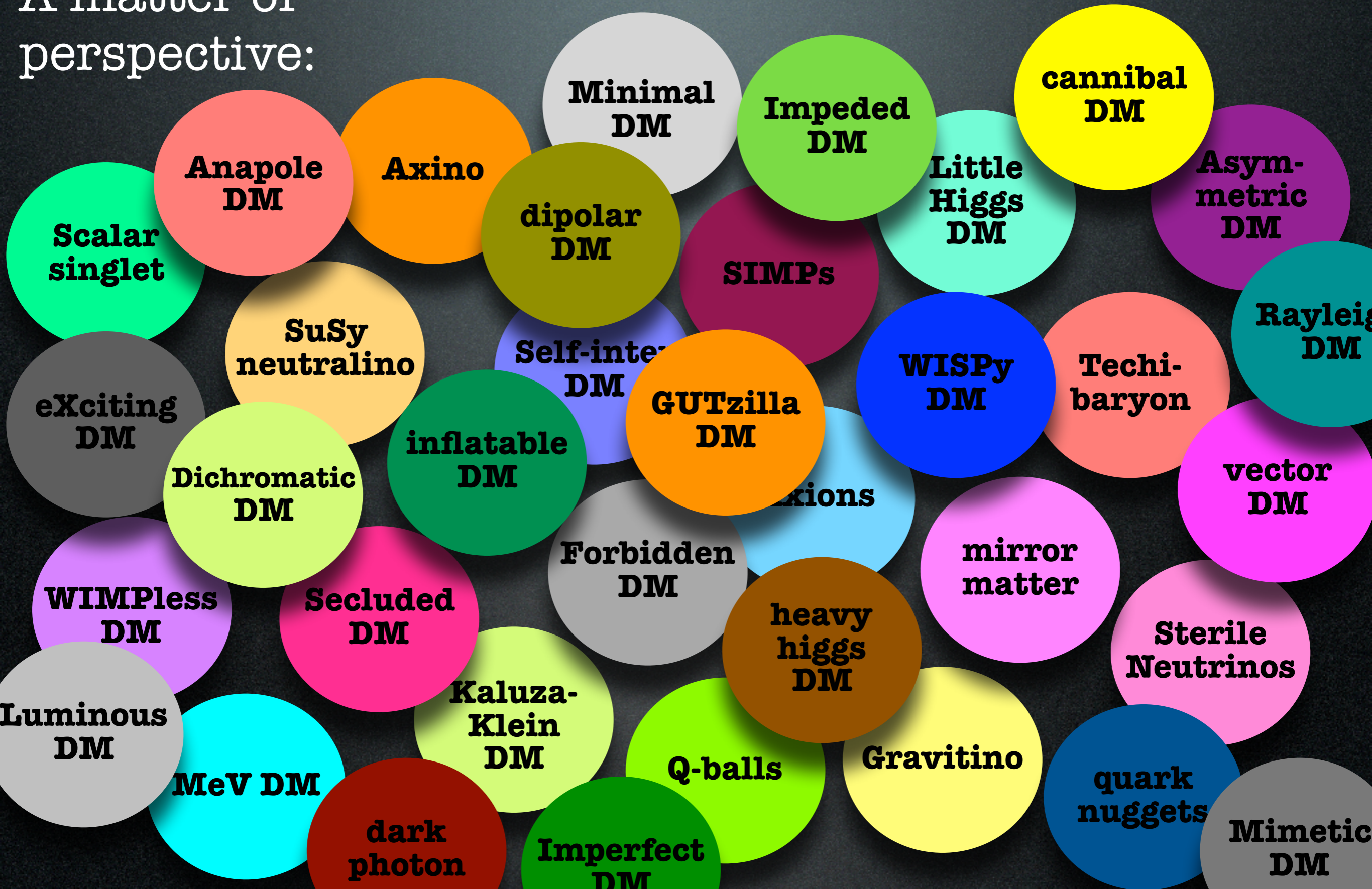
The Dark Matter
theory space:

**SuSy
neutralino**

other
exotic
candi-
dates

Candidates

A matter of perspective:



Candidates

The Dark Matter
theory space:



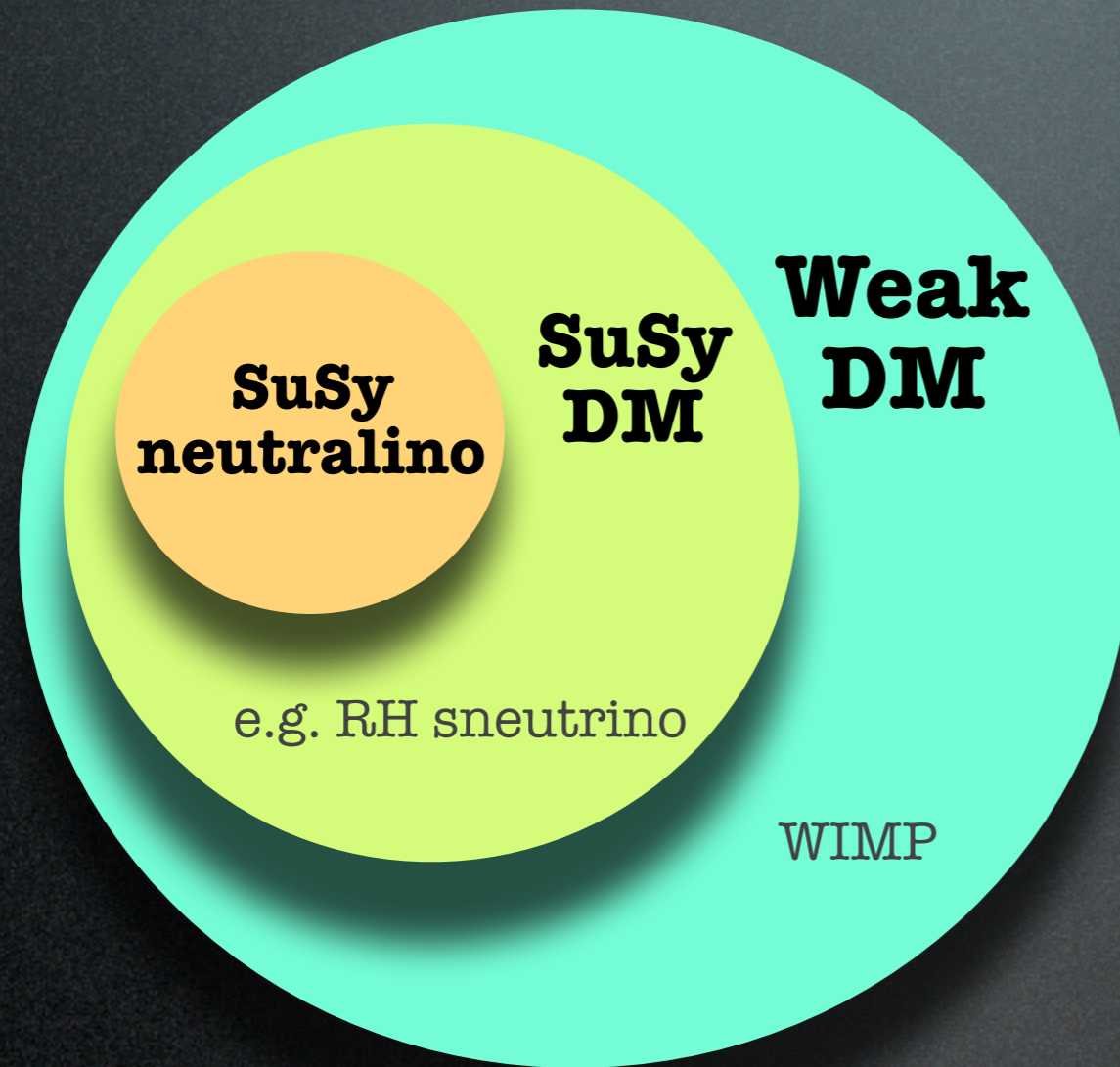
Candidates

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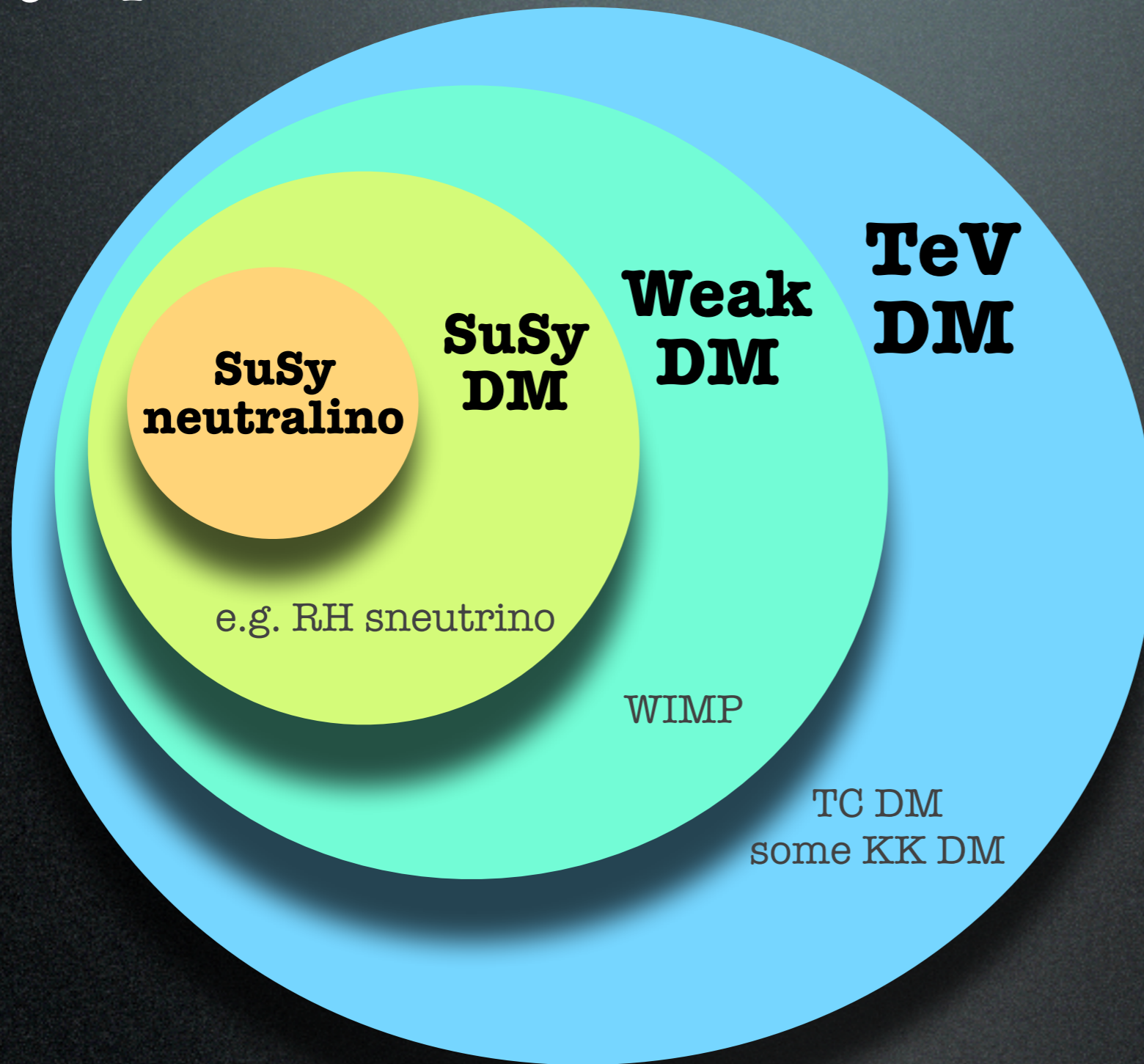
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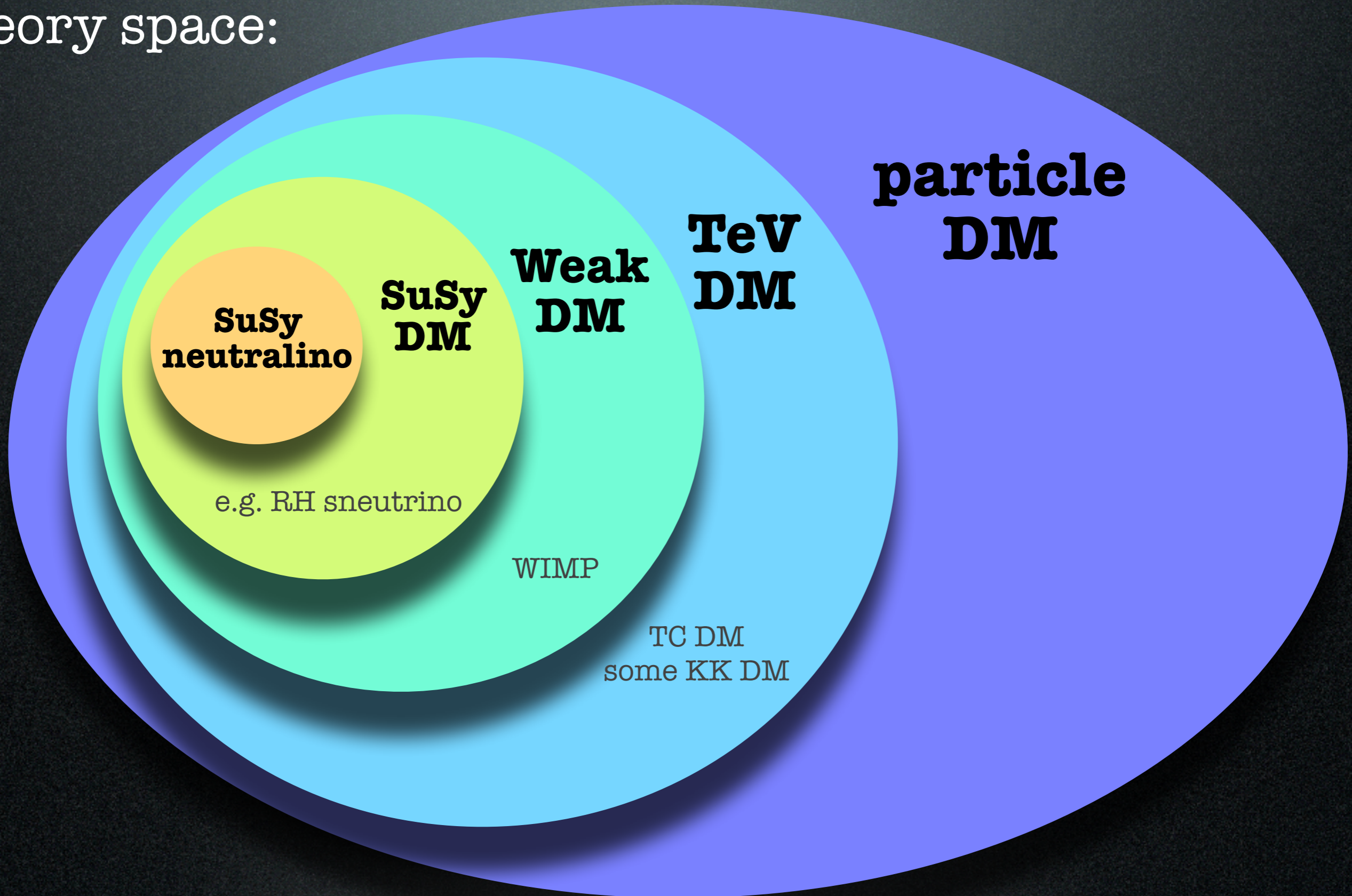
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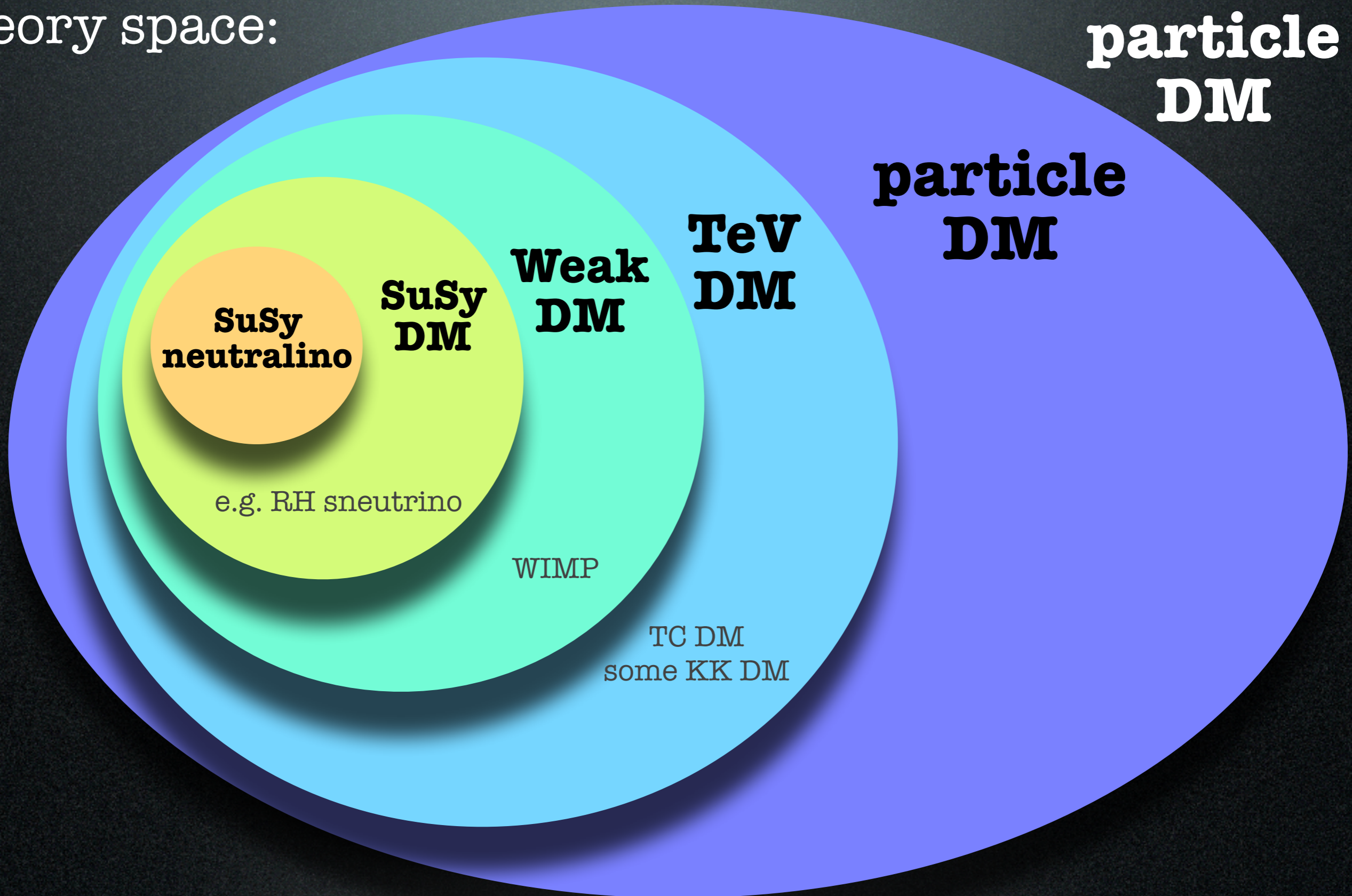
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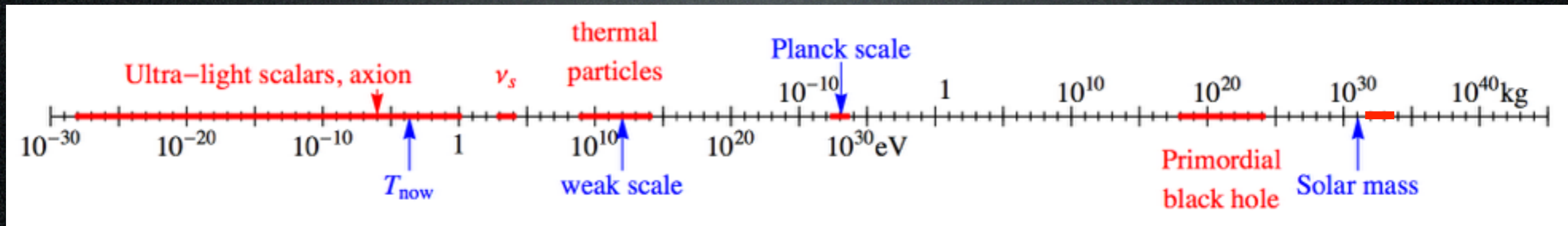
Candidates

The Dark Matter theory space:



Candidates

A matter of perspective: plausible mass ranges

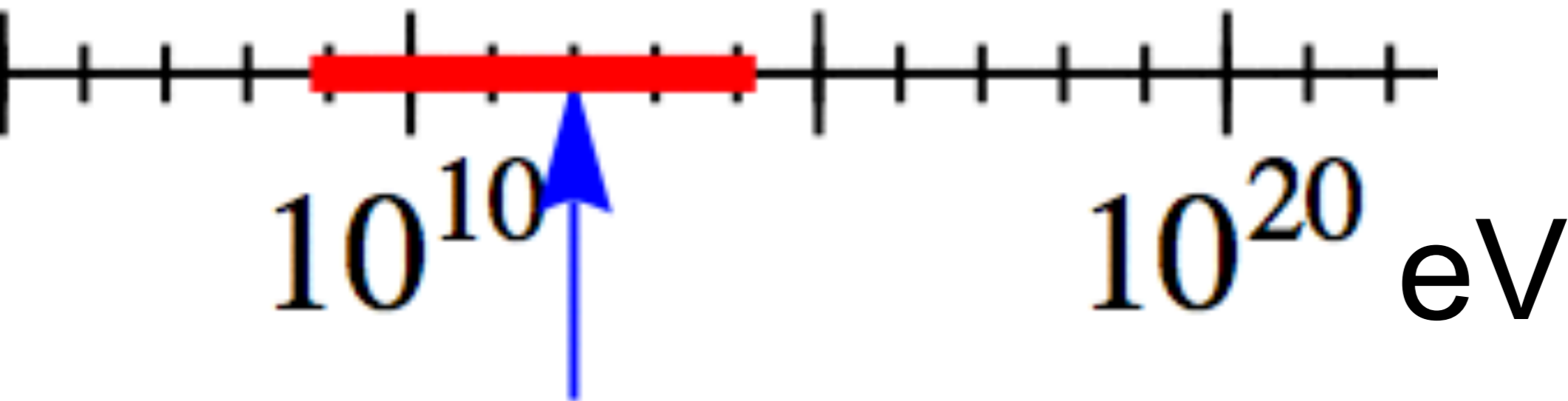


'only' 90 orders of magnitude!

Candidates

A matter of perspective: plausible mass ranges

thermal
particles



weak scale (1 TeV)

Candidates

WIMPs

Candidates

new physics at
the TeV scale



thermal
freeze-out



WIMPs

Candidates

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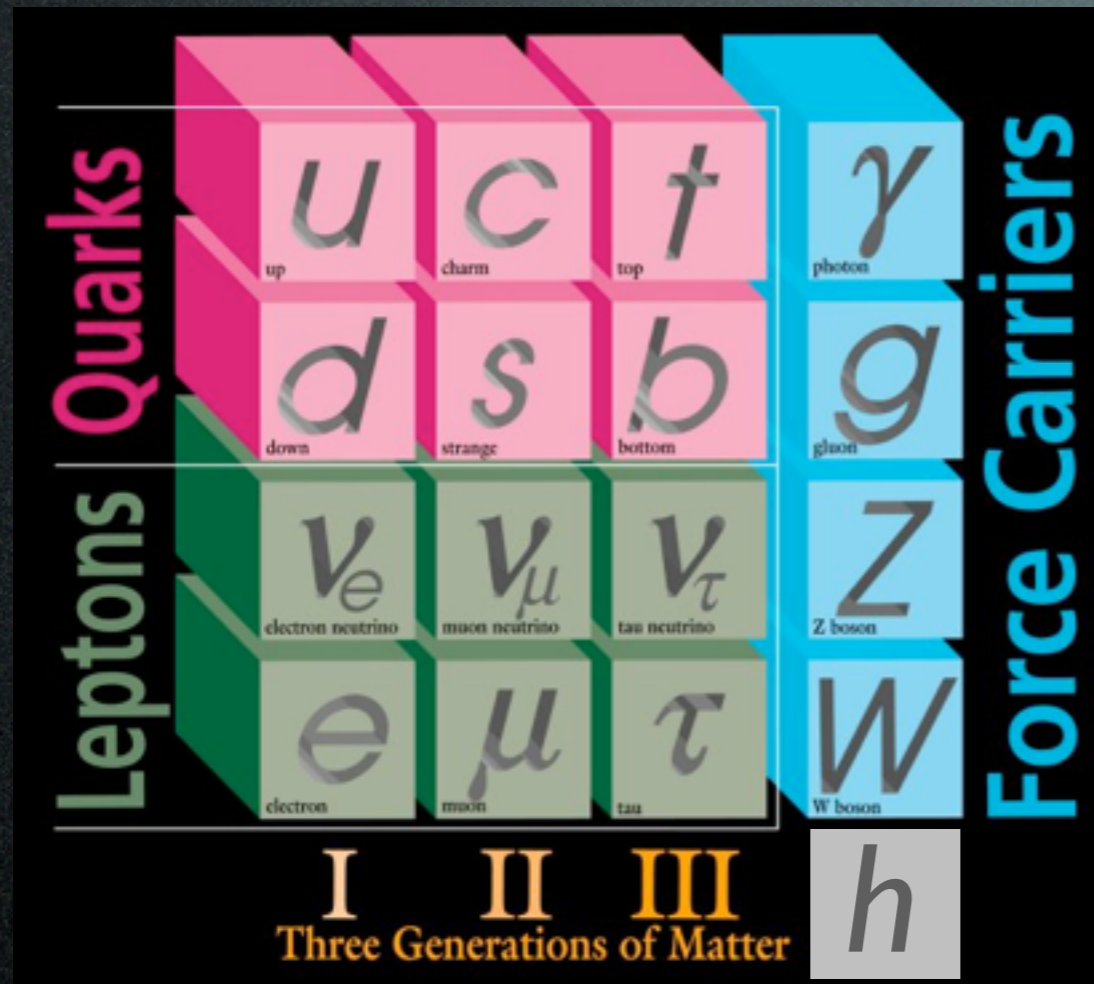
WIMPs

LHC

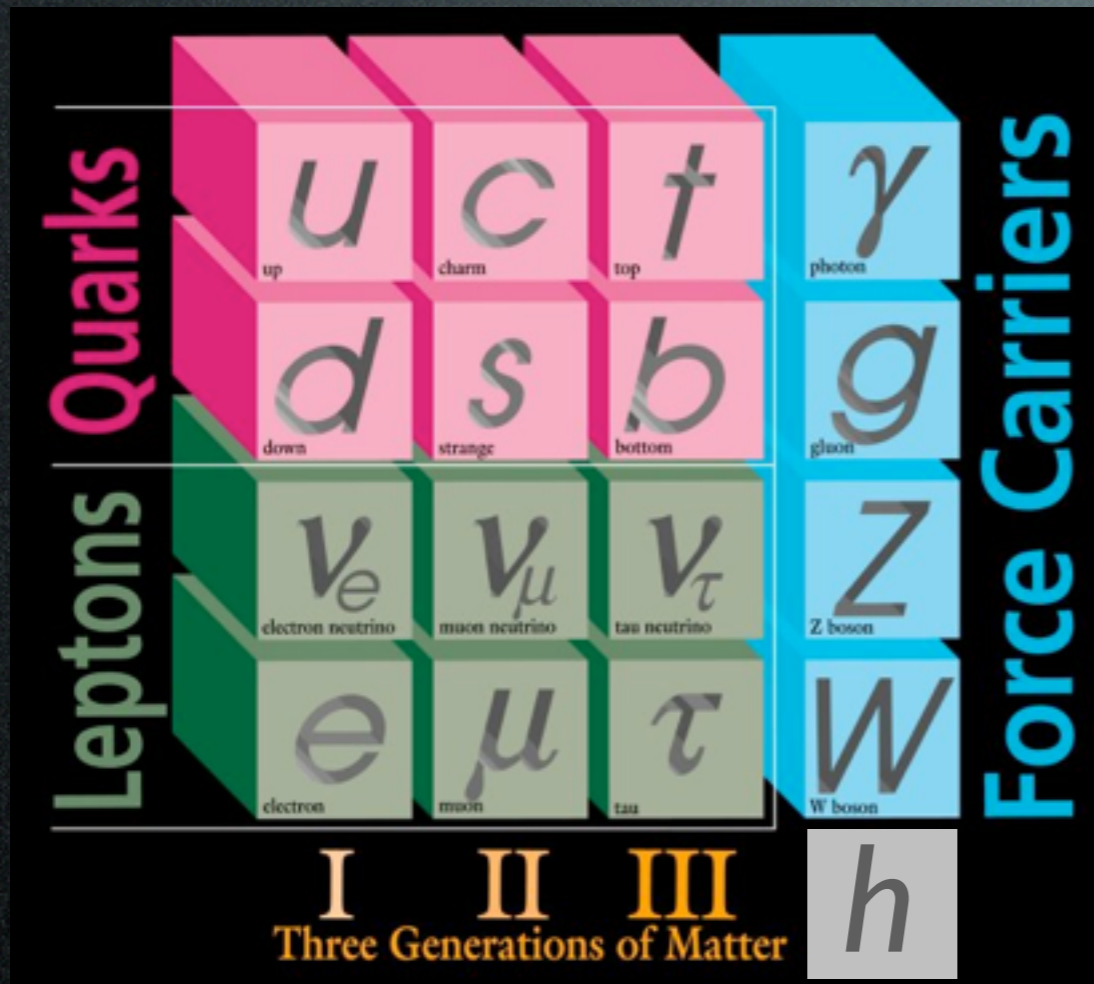
AMS, Fermi, CTA
Antares, Icecube

Direct
Detection

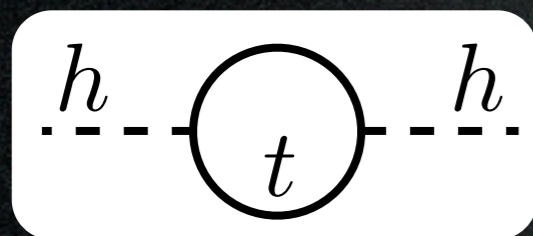
SuSy DM in 2 minutes



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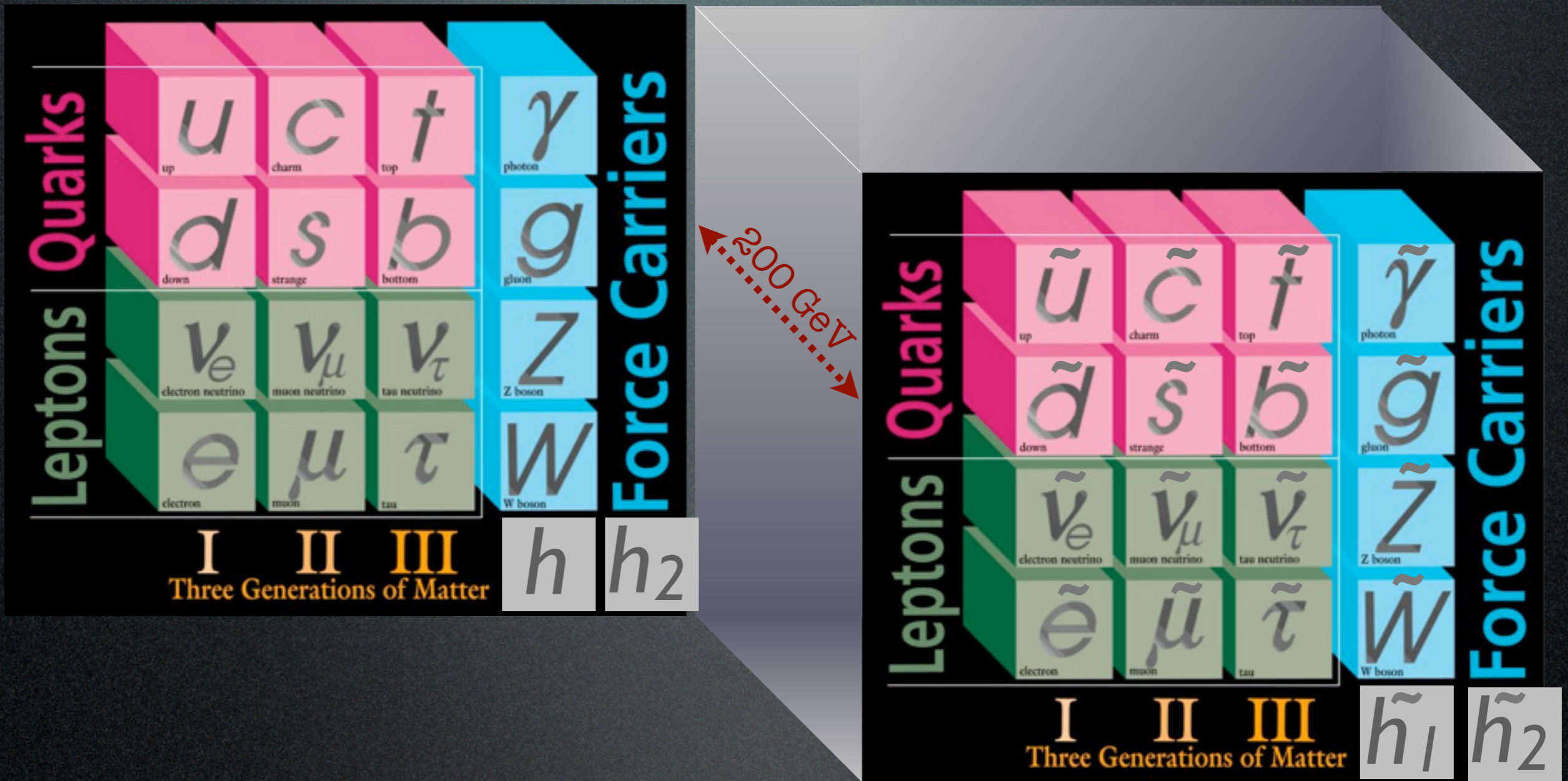


$$m_h \simeq 125 \text{ GeV}$$

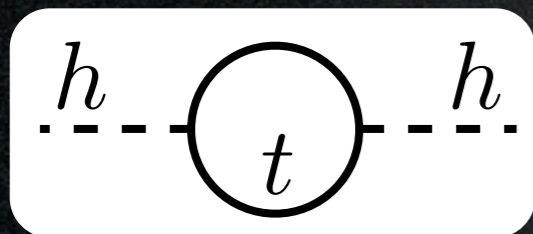


$$\Delta m_h \propto 10^{19} \text{ GeV}$$

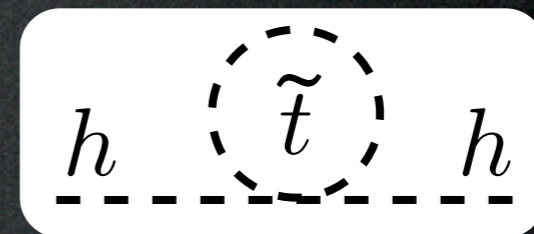
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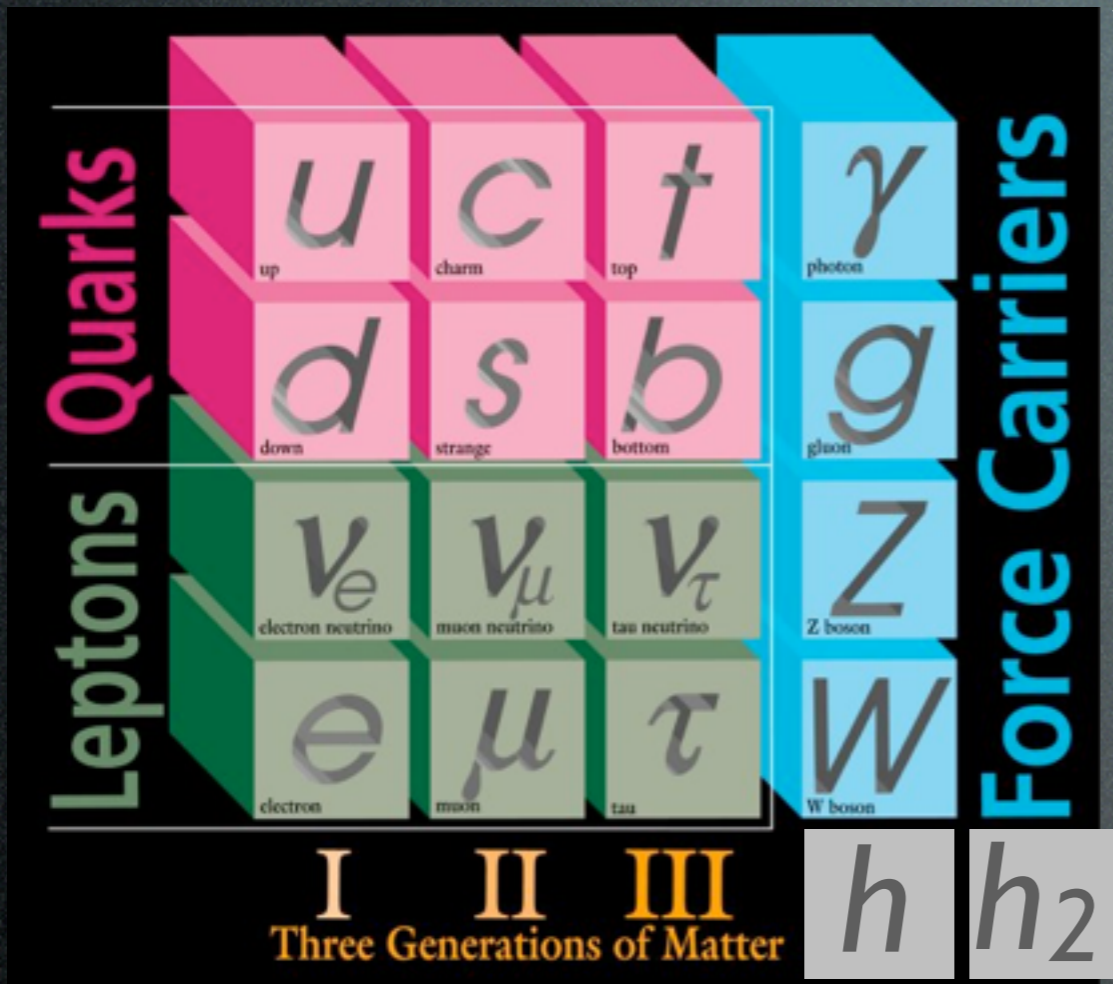


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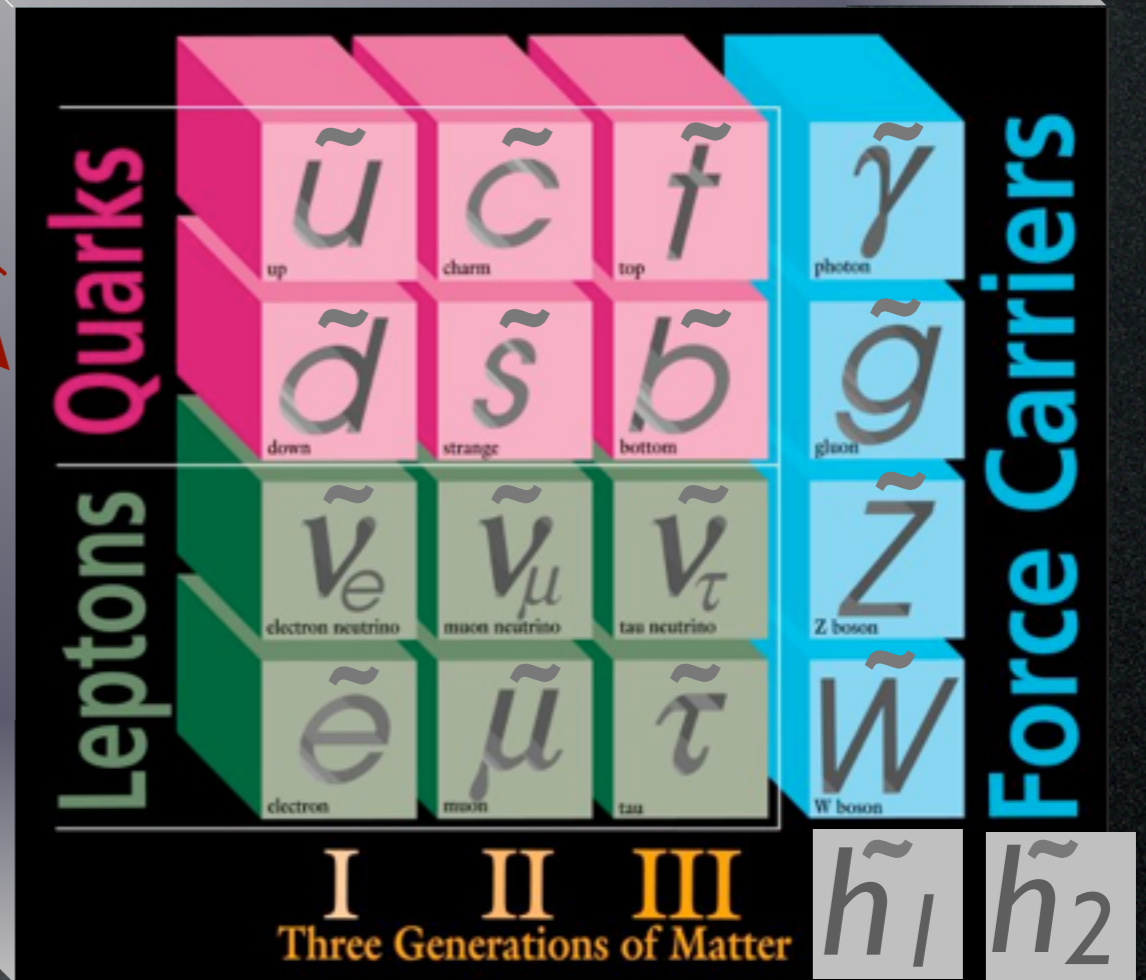


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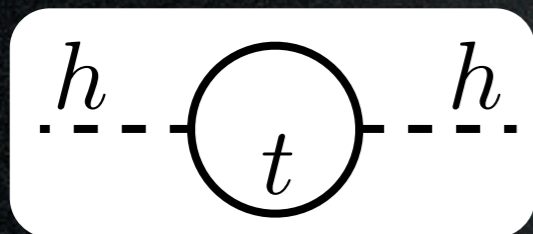


$\approx 200 \text{ GeV}$



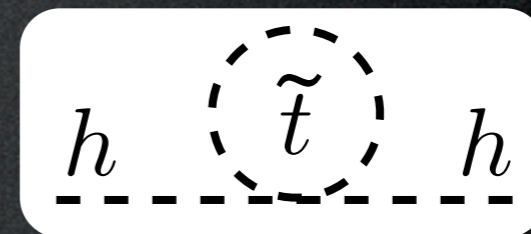
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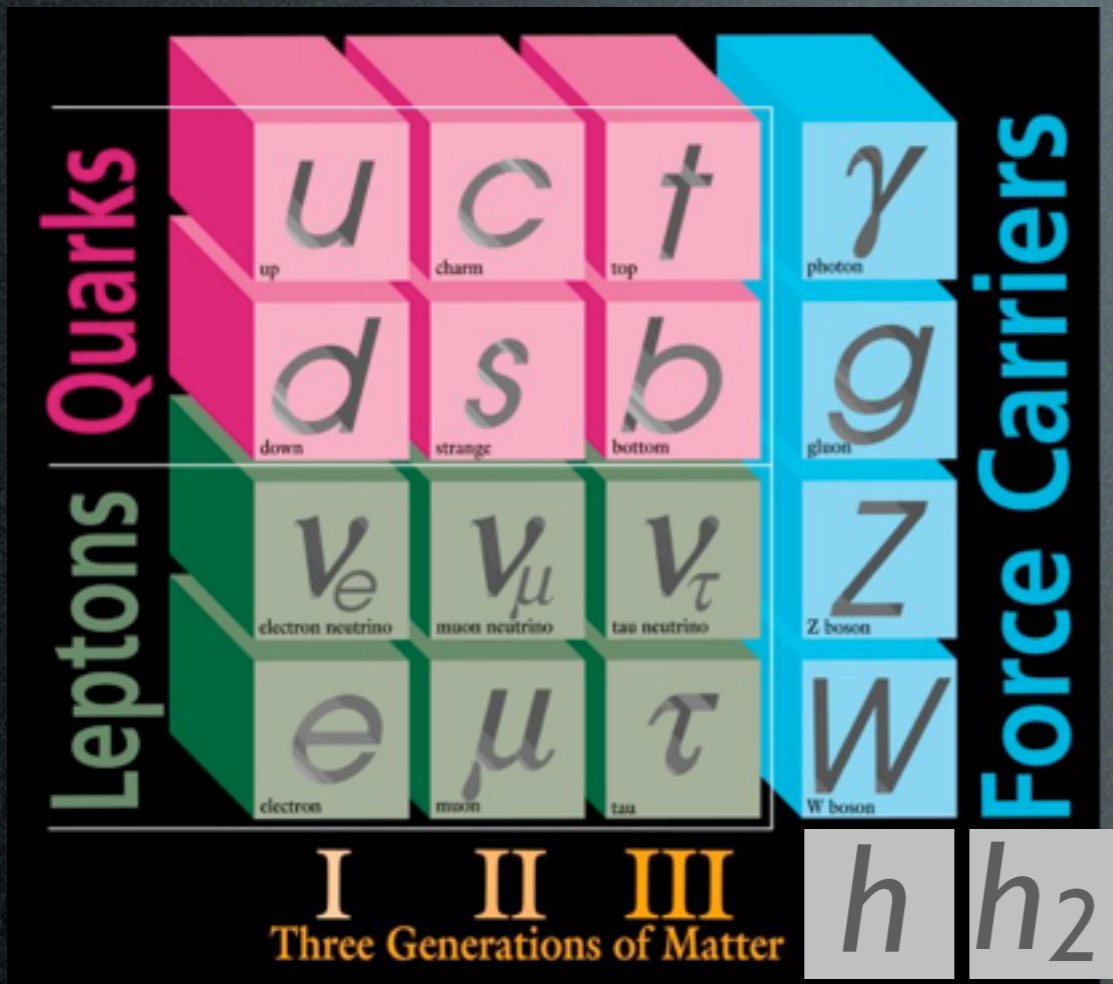
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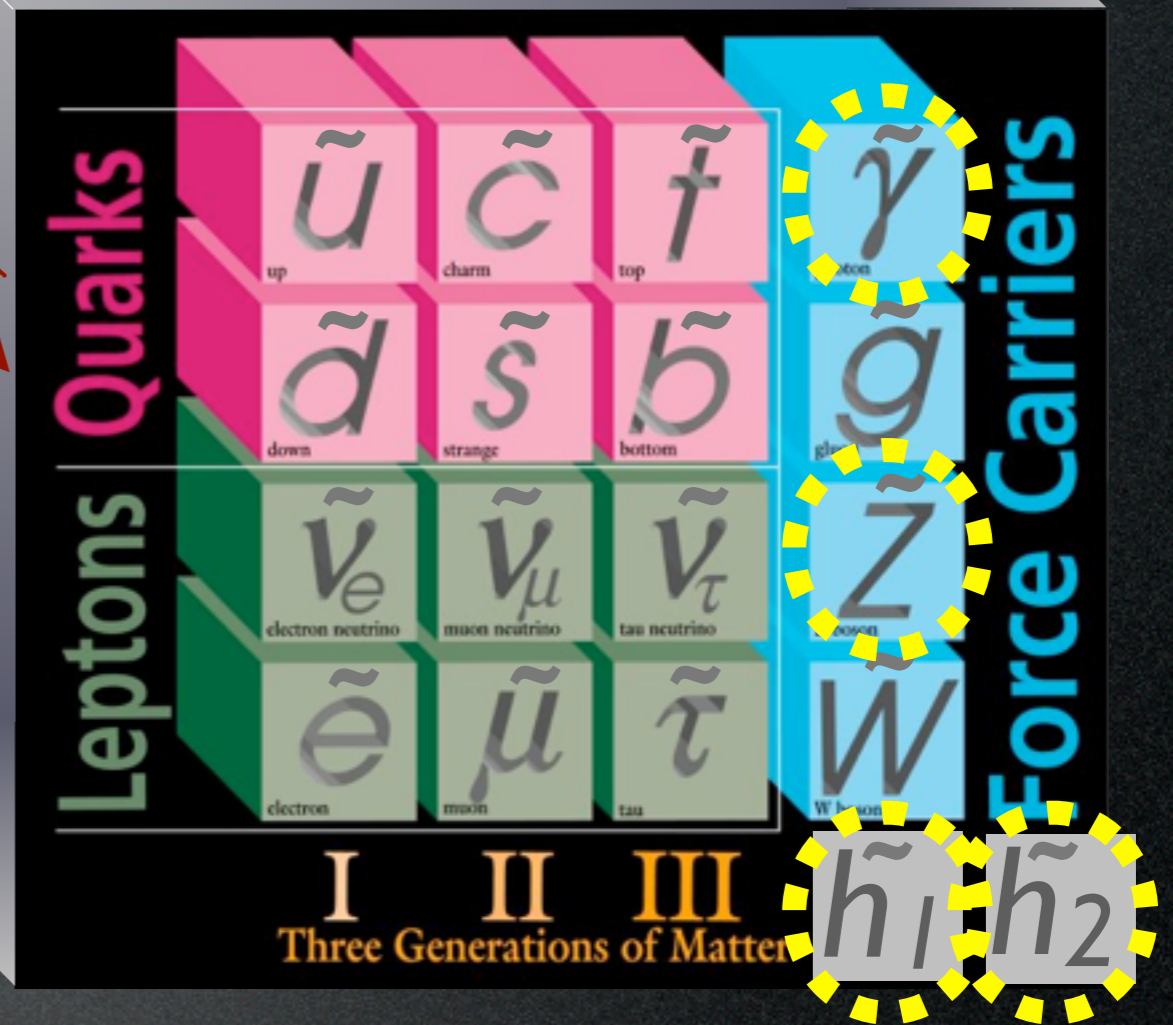


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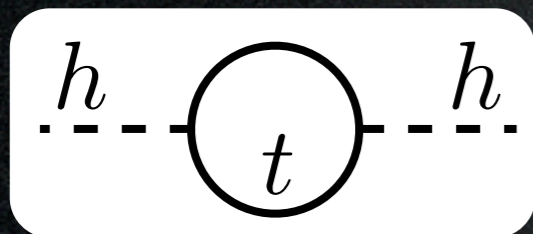


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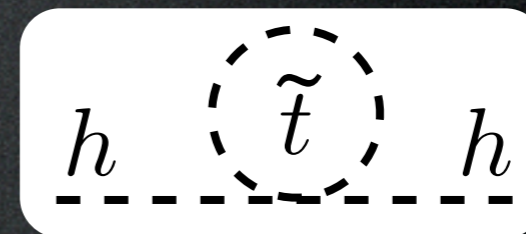
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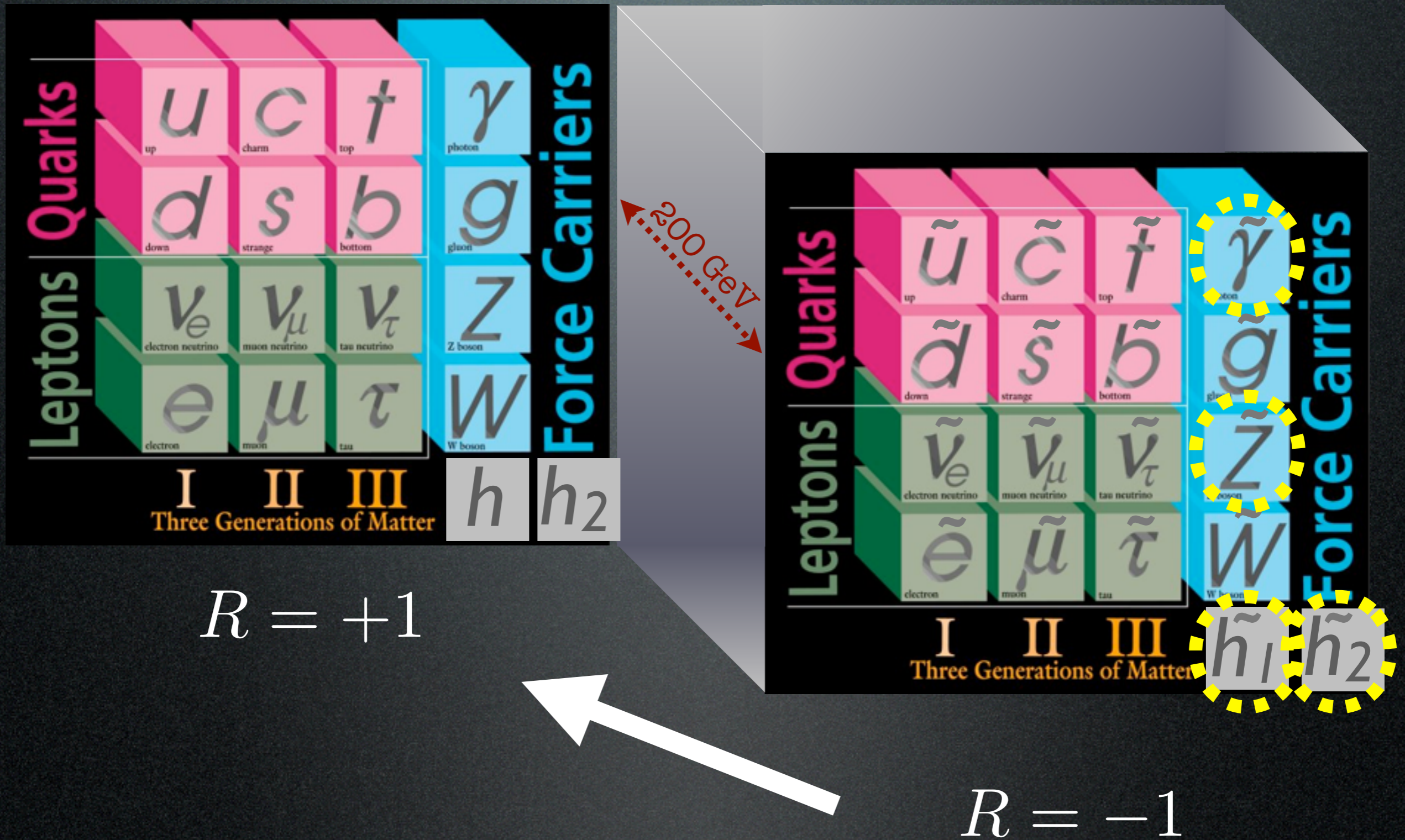
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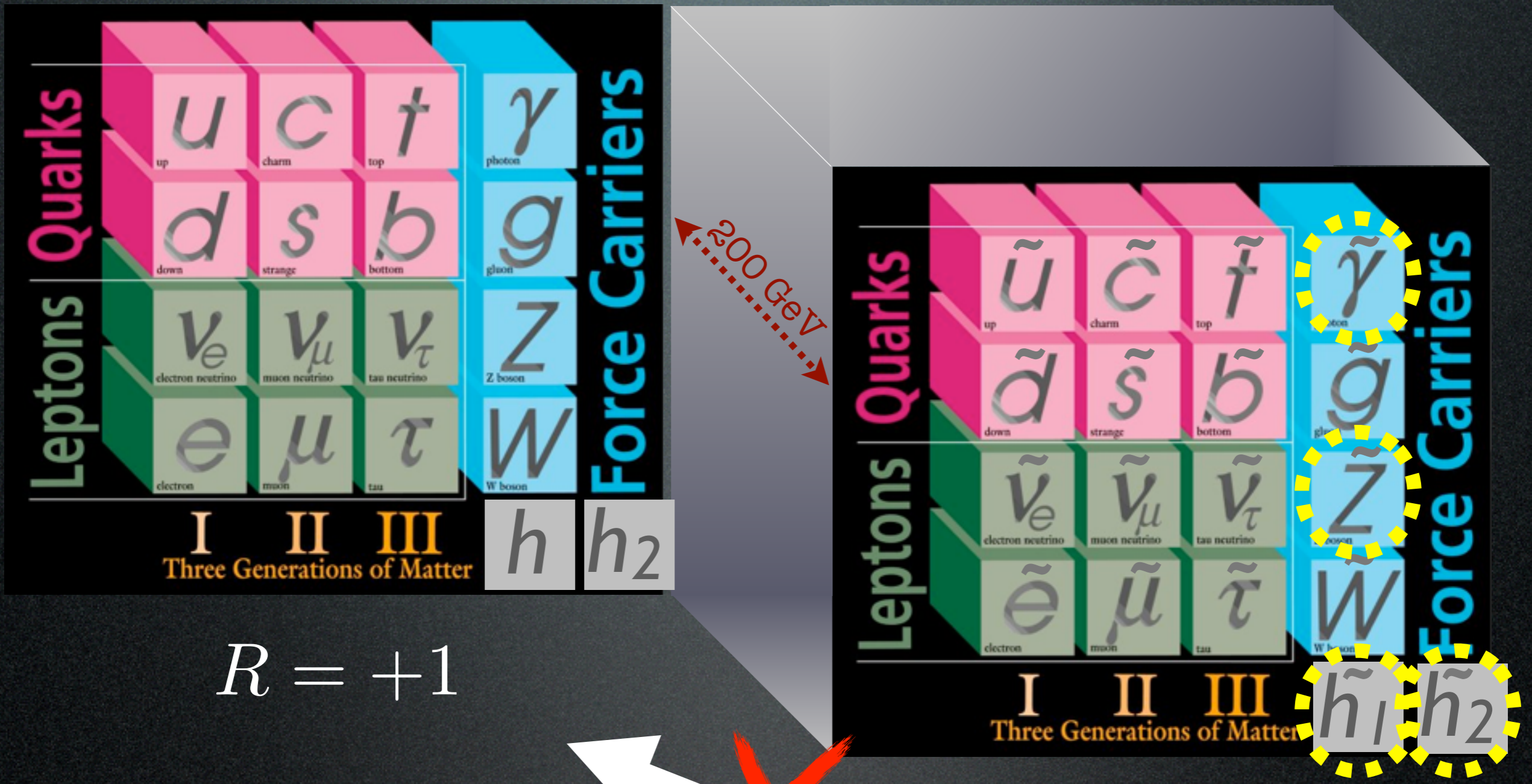


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SuSy DM in 2 minutes



SuSy DM in 2 minutes



$$R = +1$$

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prevent proton decay

Candidates

new physics at
the TeV scale

thermal
freeze-out



WIMPs

LHC

AMS, Fermi, CTA
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Detection

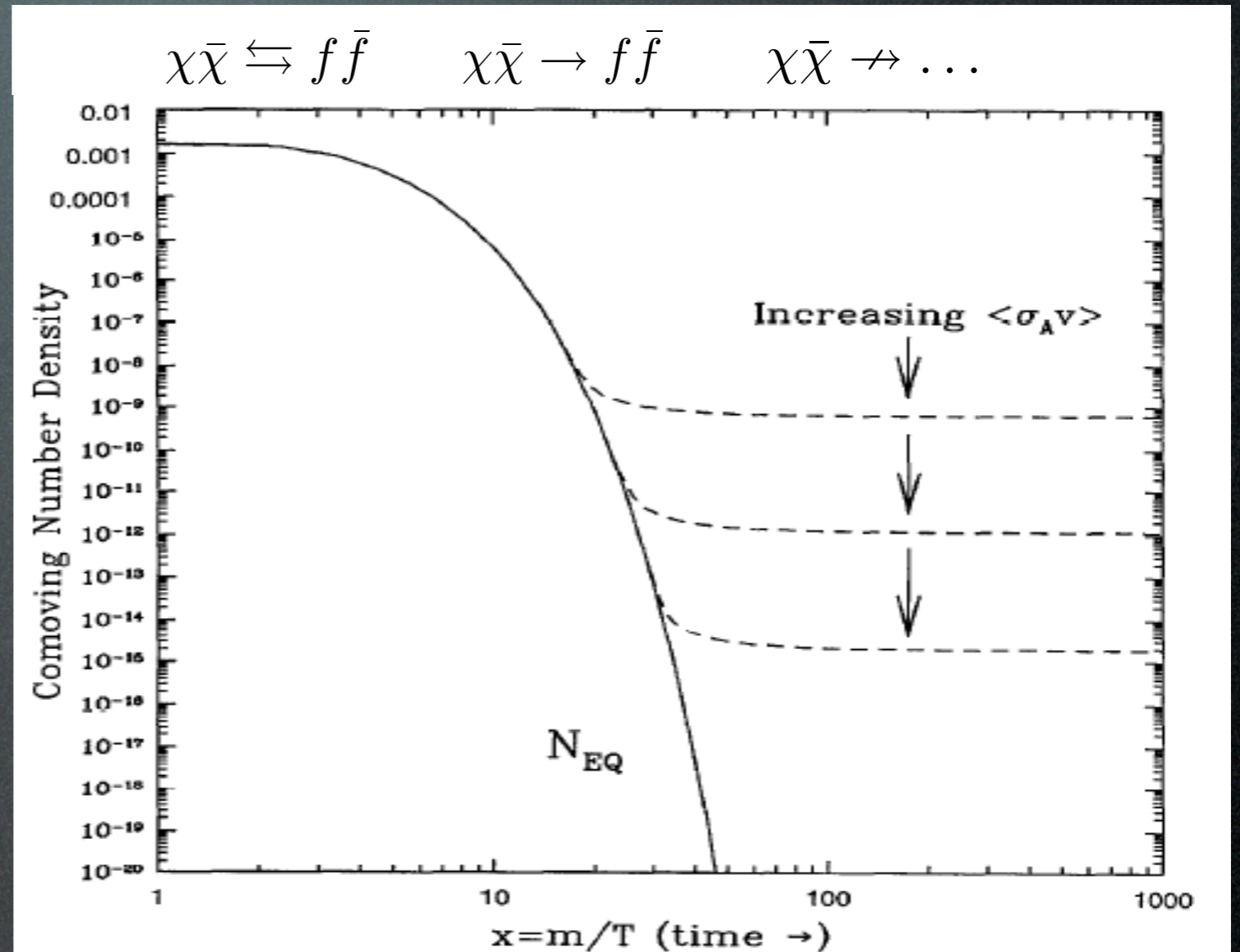
DM as a thermal relic from the Early Universe

Boltzmann equation in the Early Universe:

$$\Omega_X \approx \frac{6 \cdot 10^{-27} \text{ cm}^3 \text{ s}^{-1}}{\langle \sigma_{\text{ann}} v \rangle}$$

Relic $\Omega_{\text{DM}} \simeq 0.23$ for

$$\langle \sigma_{\text{ann}} v \rangle = 3 \cdot 10^{-26} \text{ cm}^3 / \text{sec}$$



Kolb, Turner, The Early Universe, 1995

Weak cross section:

$$\langle \sigma_{\text{ann}} v \rangle \approx \frac{\alpha_w^2}{M^2} \approx \frac{\alpha_w^2}{1 \text{ TeV}^2} \Rightarrow \Omega_X \sim \mathcal{O}(\text{few } 0.1) \quad (\text{WIMP})$$

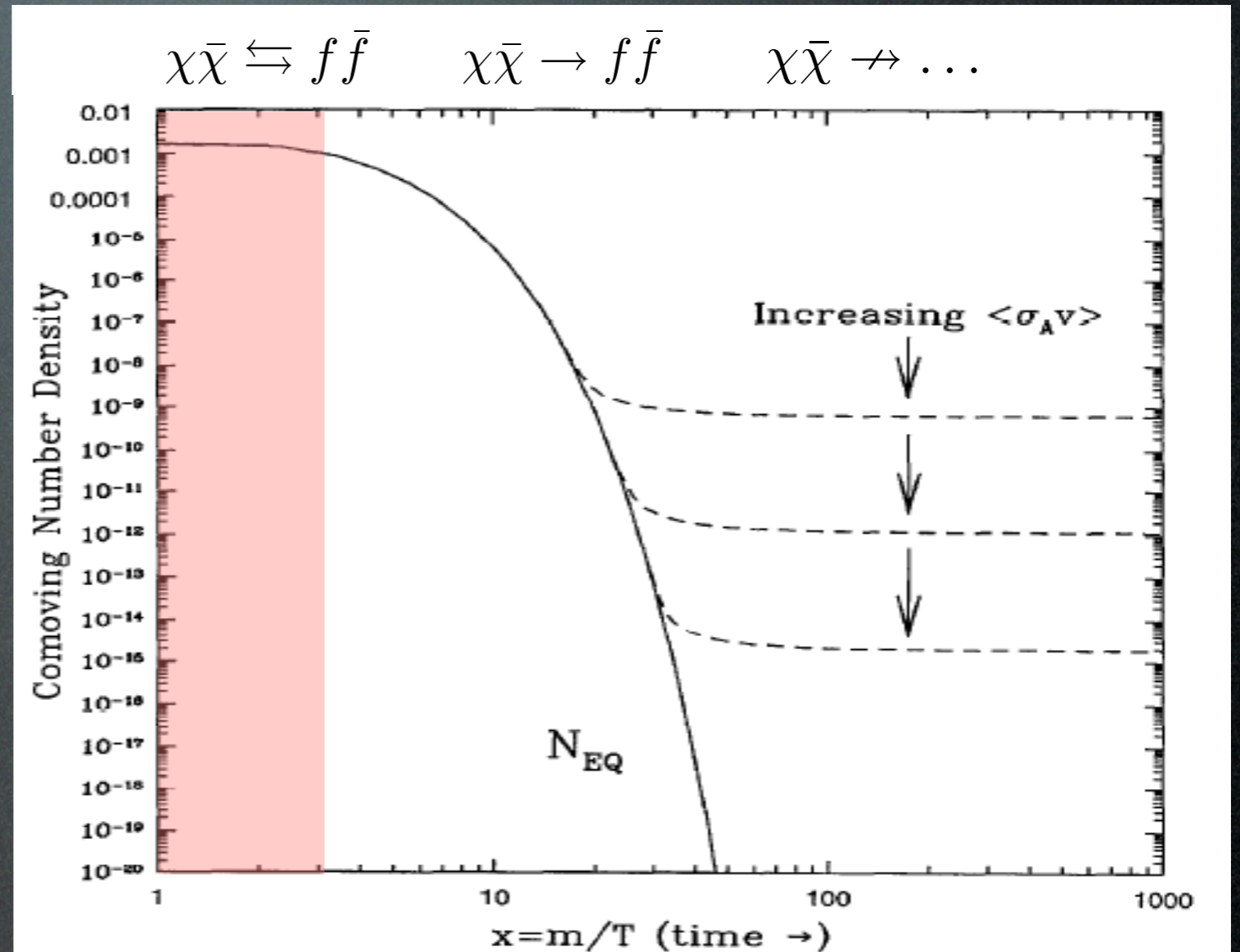
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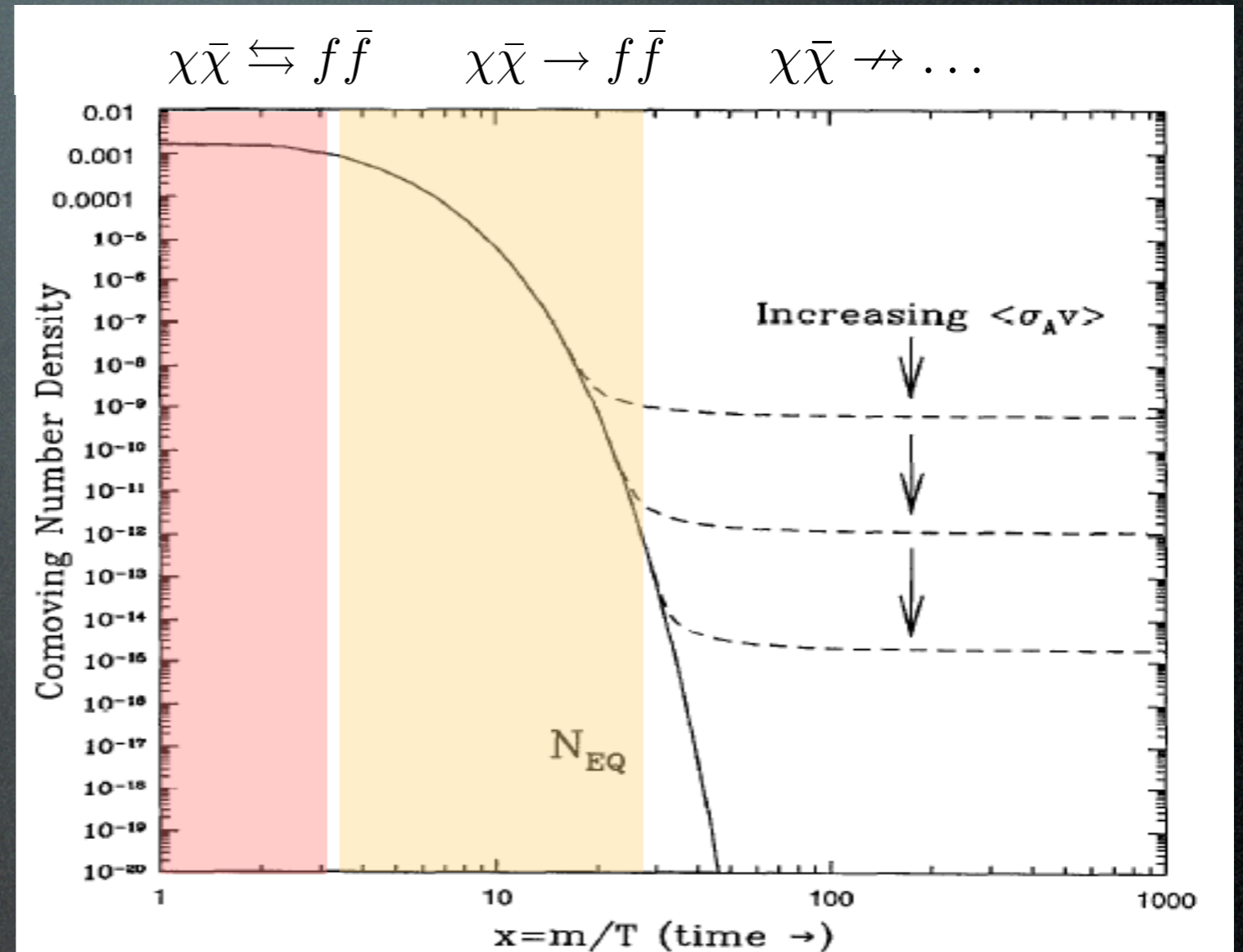
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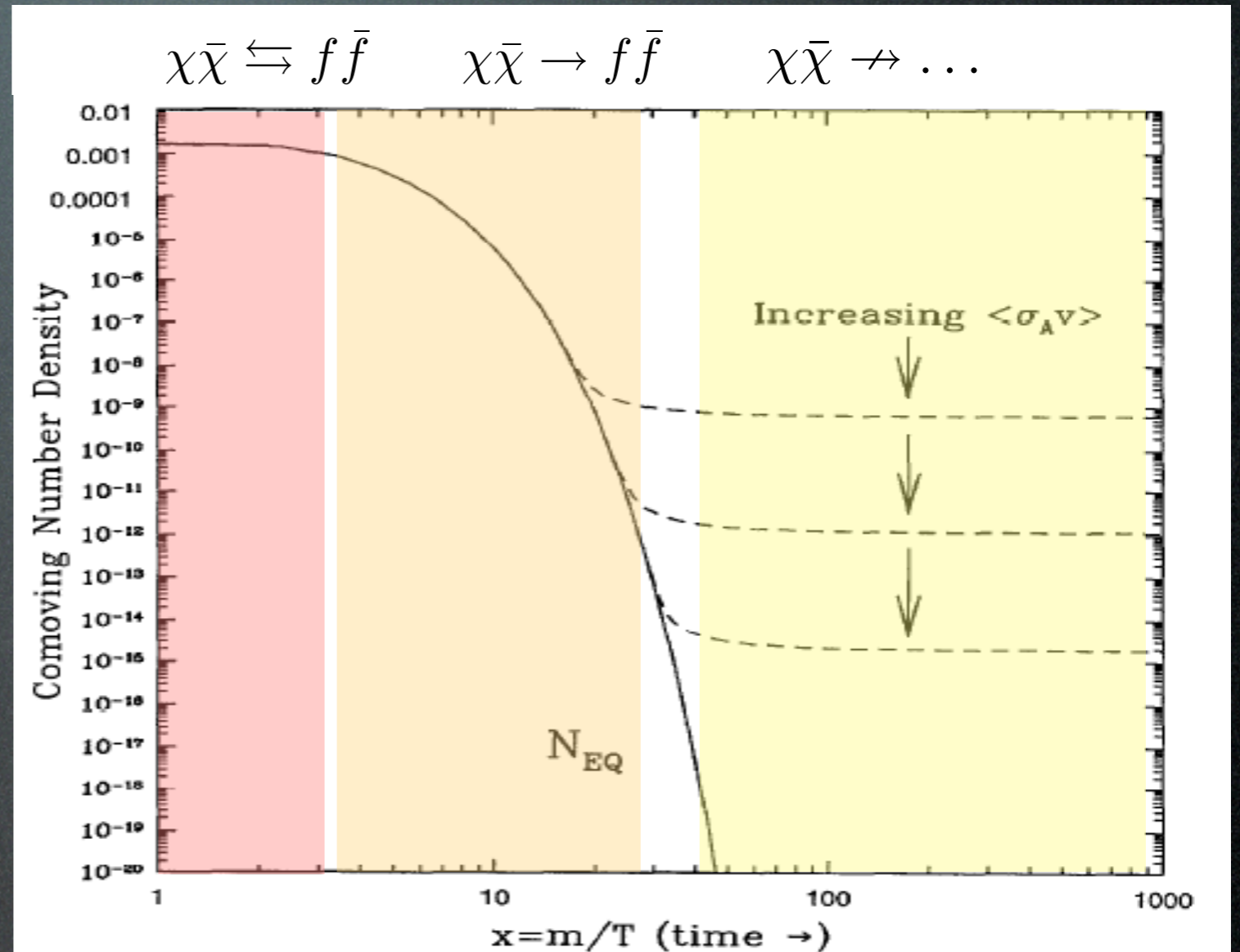
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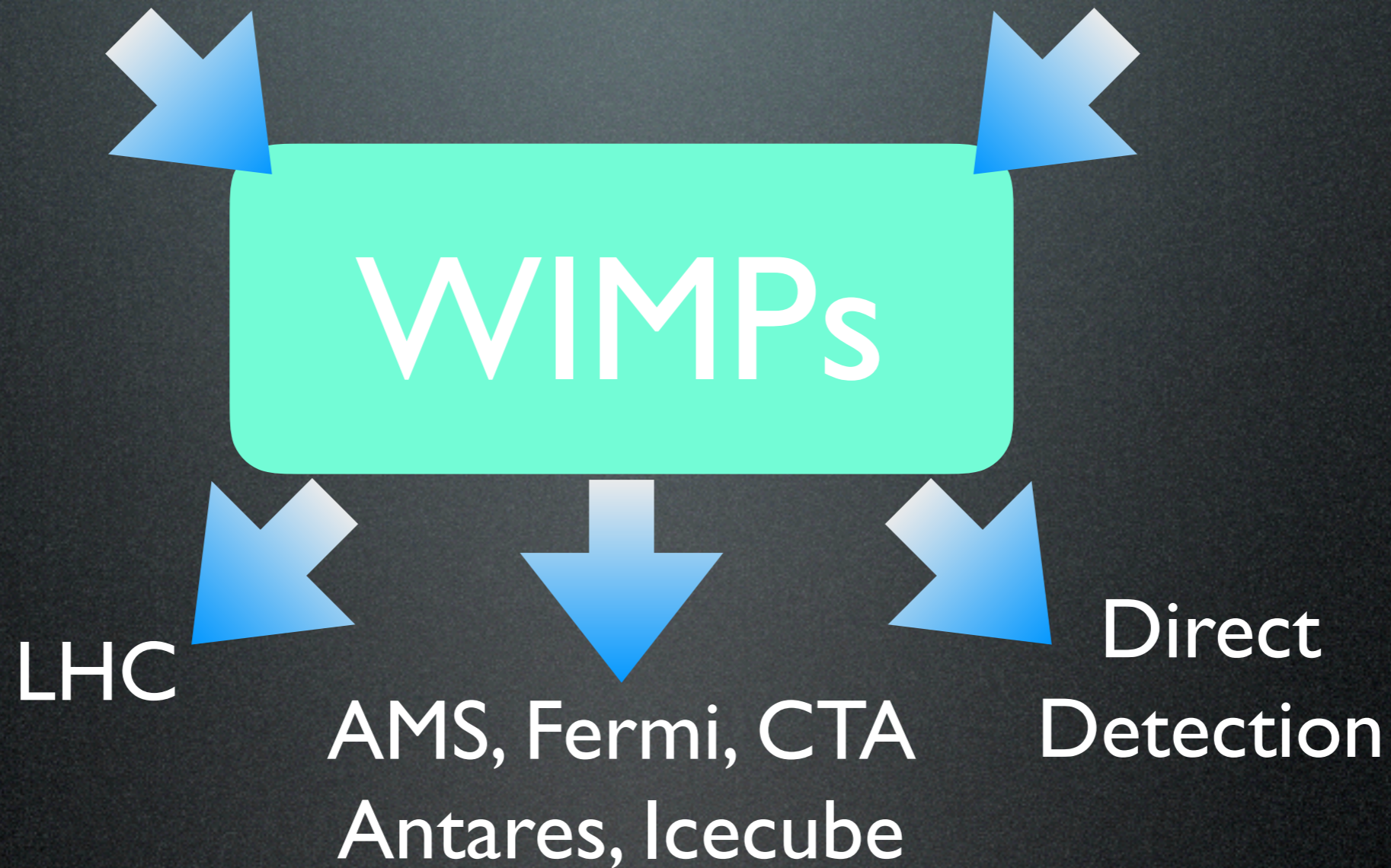
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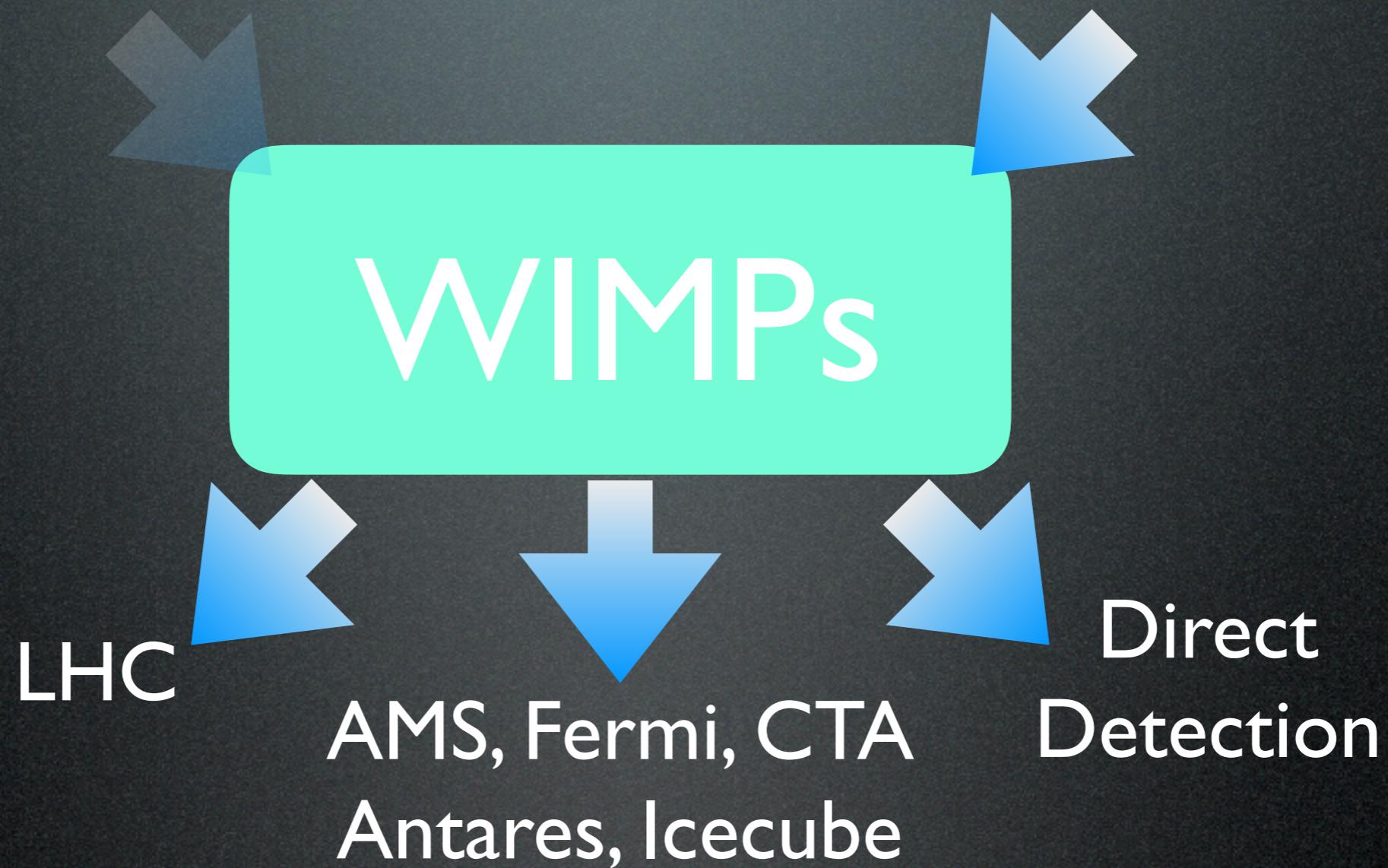


- 1.
- 2.

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freeze-out



1. even without a larger framework, WIMPs are **still appealing**
- 2.

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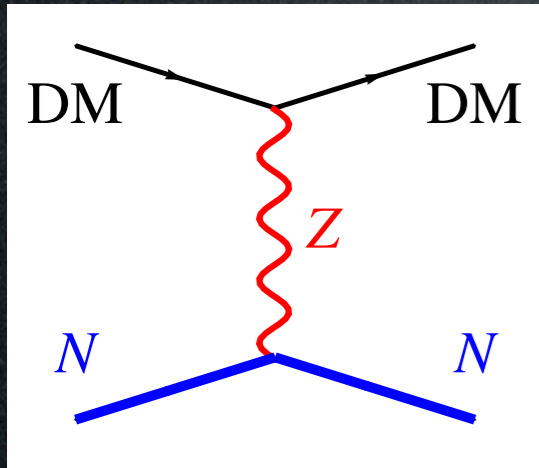
1. even without a larger framework, WIMPs are **still appealing**
2. the three search strategies are **complementary**

WIMP DD: **'theory'**

SM weak scale SI interactions

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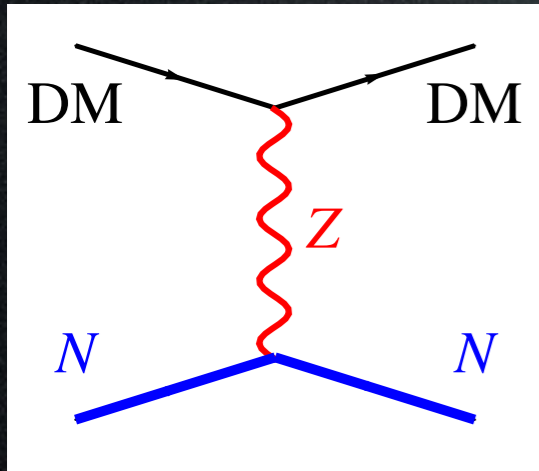


tree level,
vector

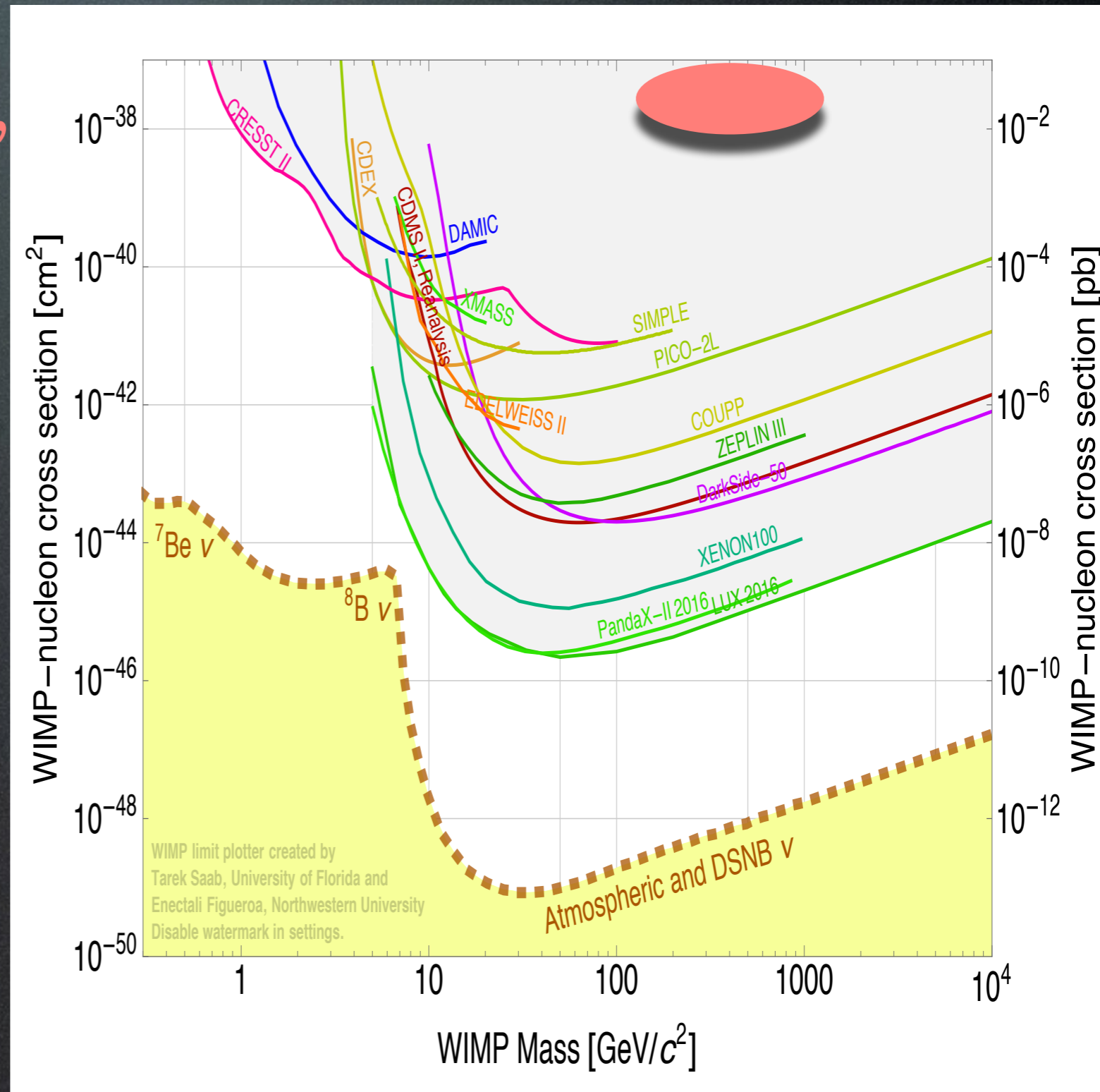
$$\sigma_{\text{SI}} \sim \frac{\alpha^2 m_N^2}{M_Z^4}$$

WIMP DD: 'theory'

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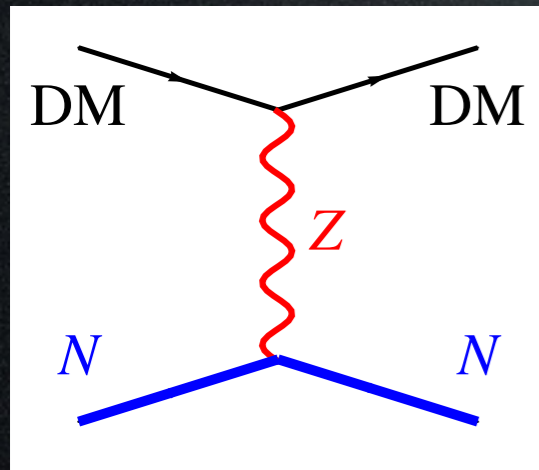


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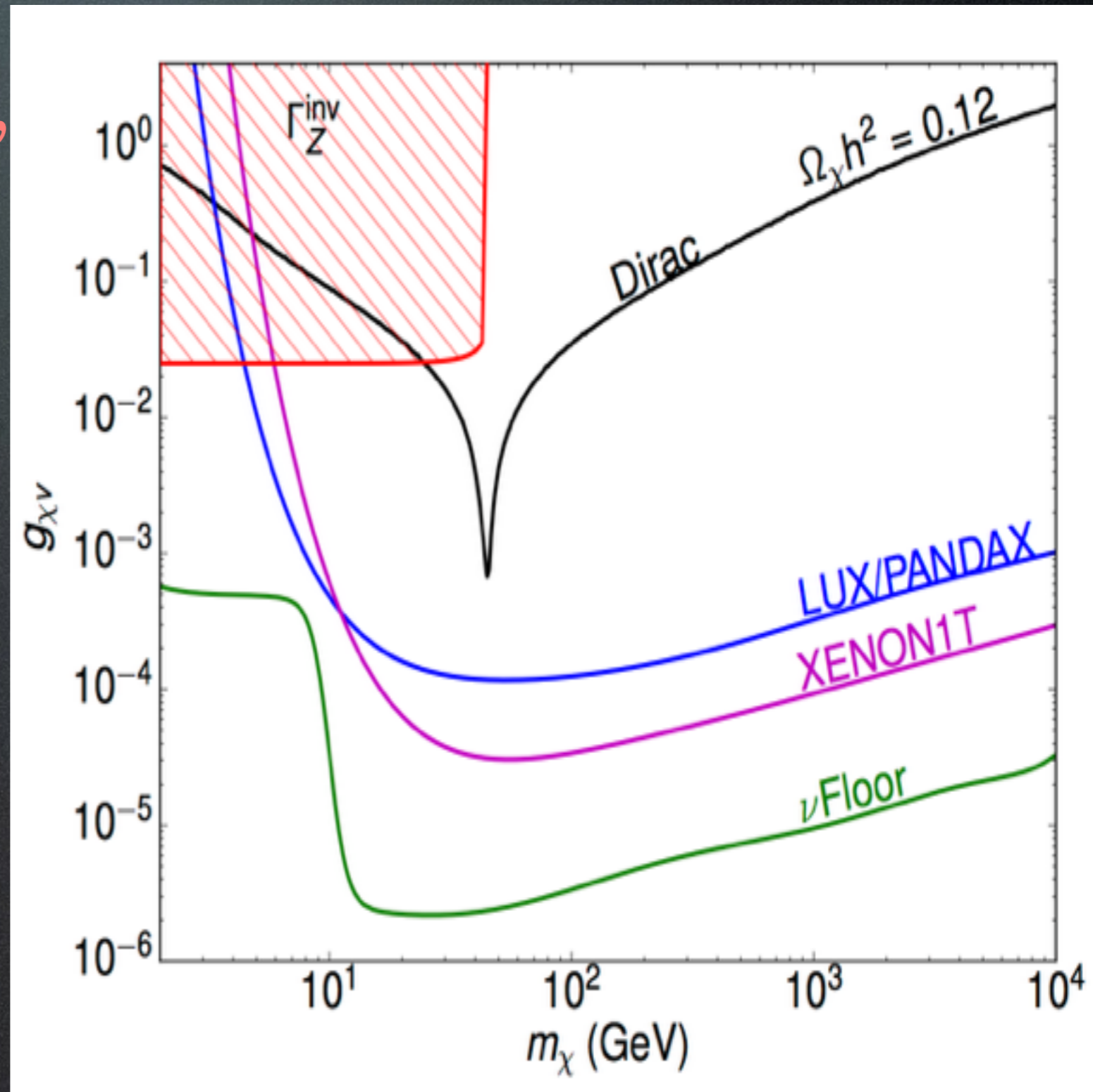


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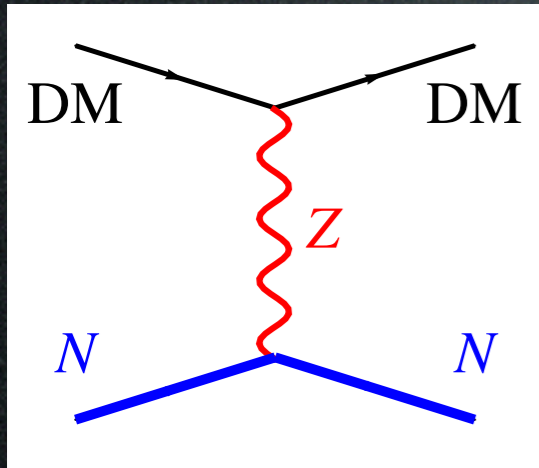


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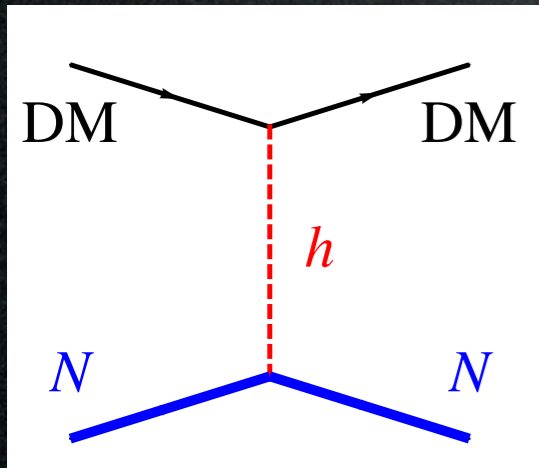
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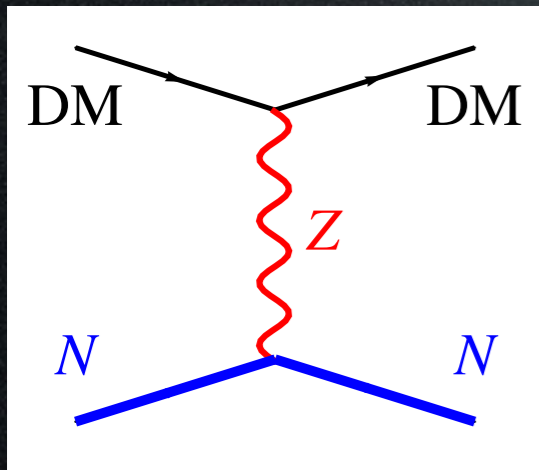


tree level,
scalar

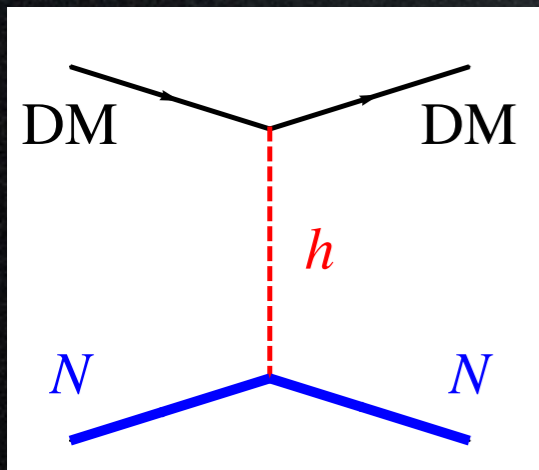
$$\sigma_{\text{SI}} \sim \frac{\alpha^2 m_N^4}{M_h^6}$$

WIMP DD: 'theory'

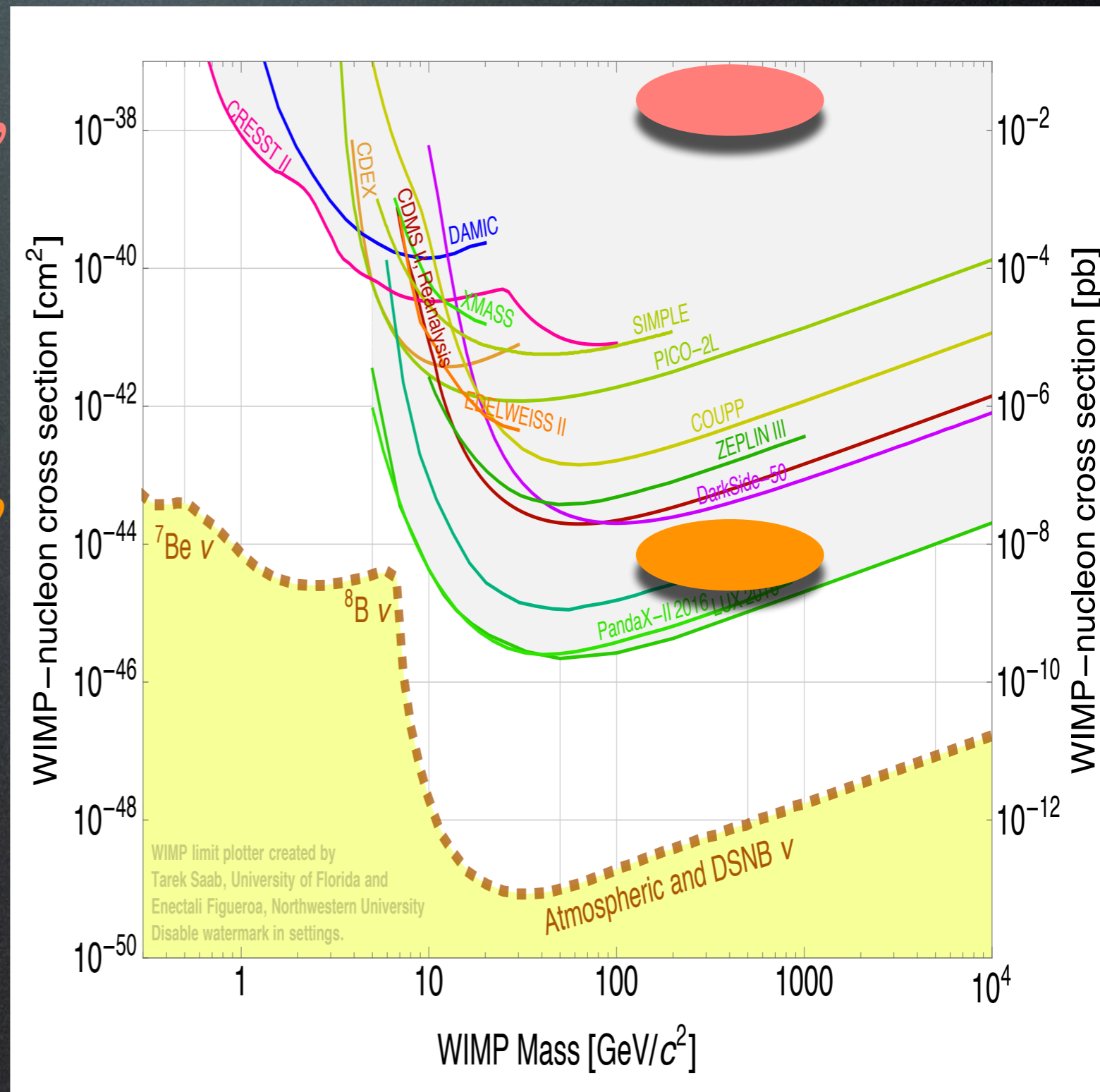
SM weak scale SI interactions



tree level,
vector

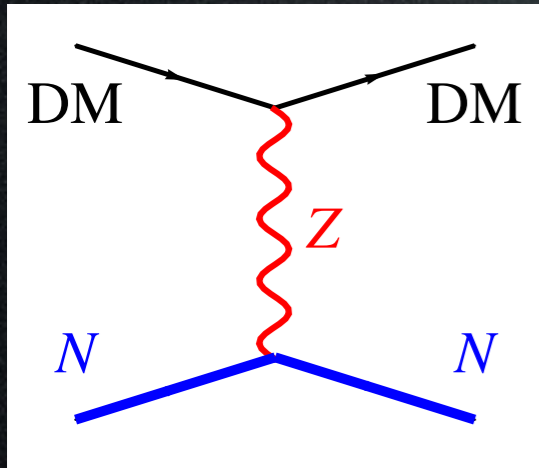


tree level,
scalar

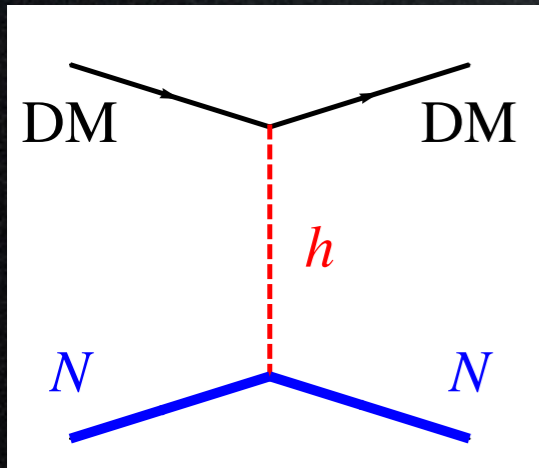


WIMP DD: 'theory'

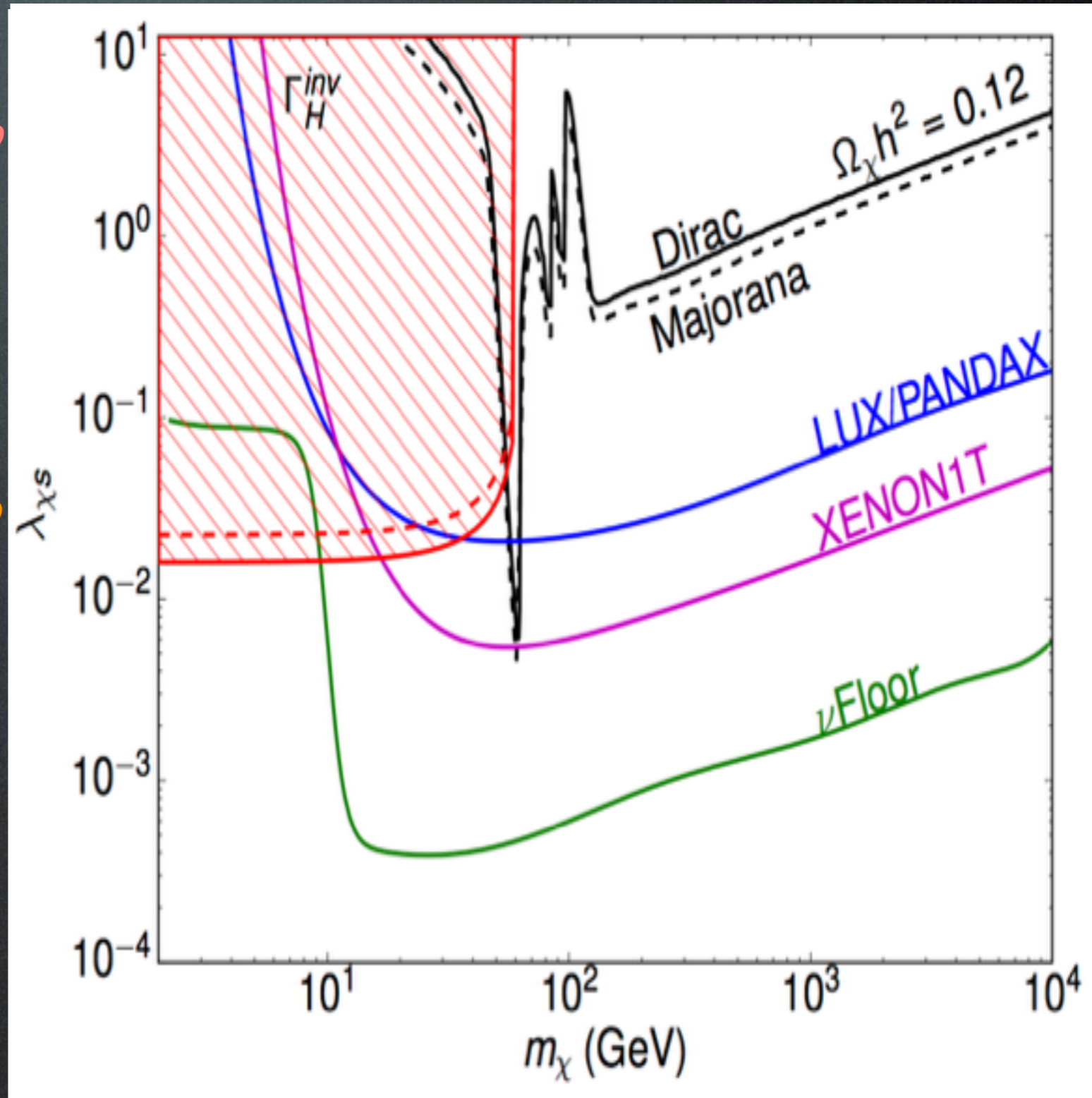
SM weak scale SI interactions



tree level,
vector

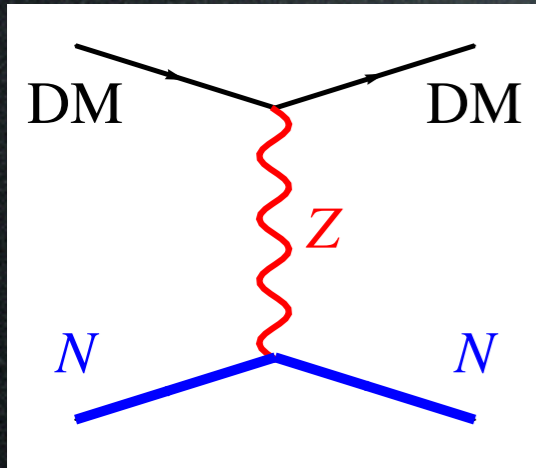


tree level,
scalar



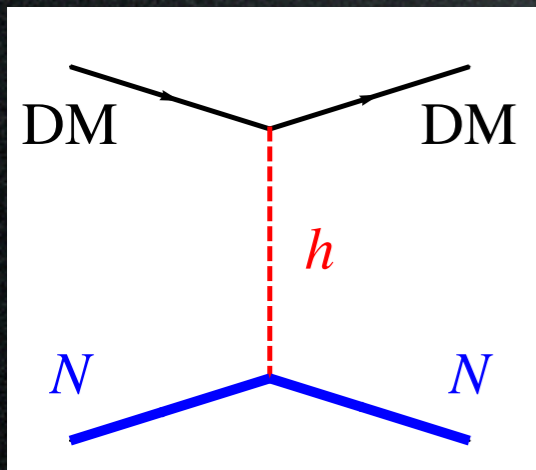
WIMP DD: 'theory'

SM weak scale SI interactions



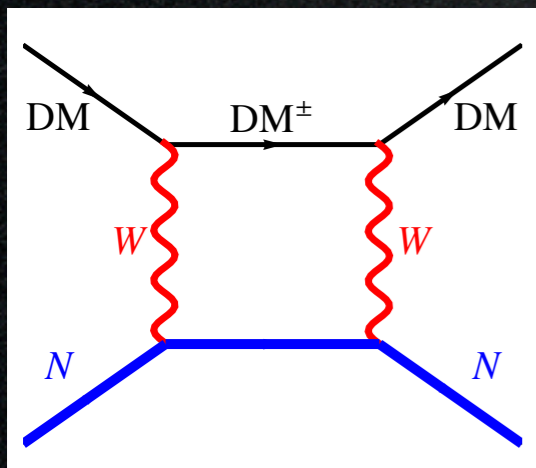
tree level,
vector

$$\sigma_{\text{SI}} \sim \frac{\alpha^2 m_N^2}{M_Z^4}$$



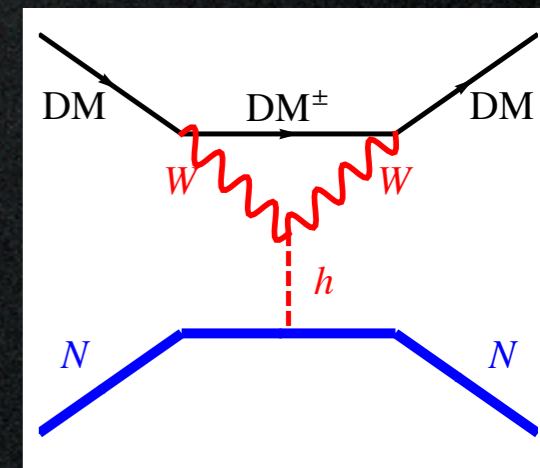
tree level,
scalar

$$\sigma_{\text{SI}} \sim \frac{\alpha^2 m_N^4}{M_h^6}$$



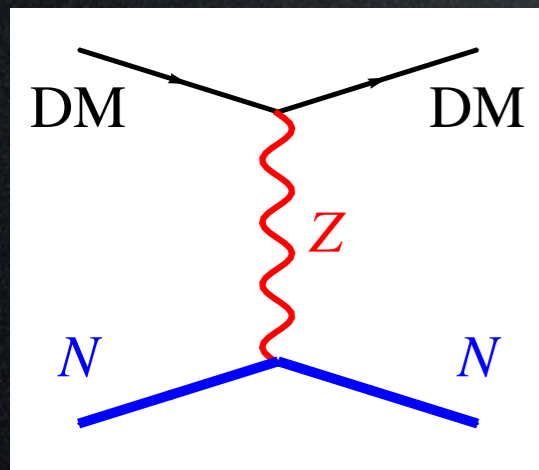
one loop

$$\sigma_{\text{SI}} \sim \frac{\alpha^4 m_N^4}{M_W^6}$$

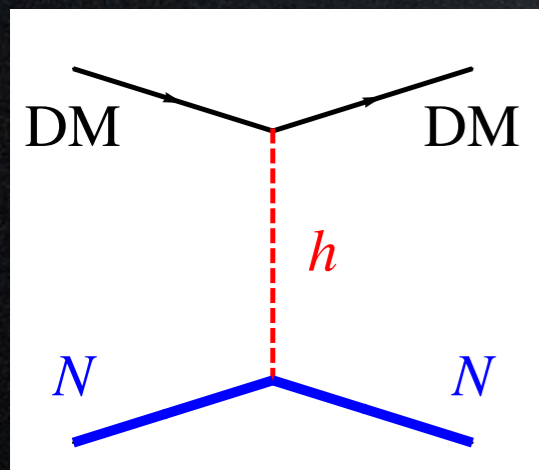


WIMP DD: 'theory'

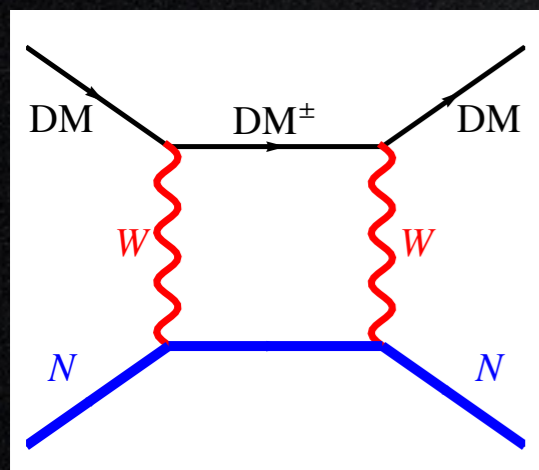
SM weak scale SI interactions



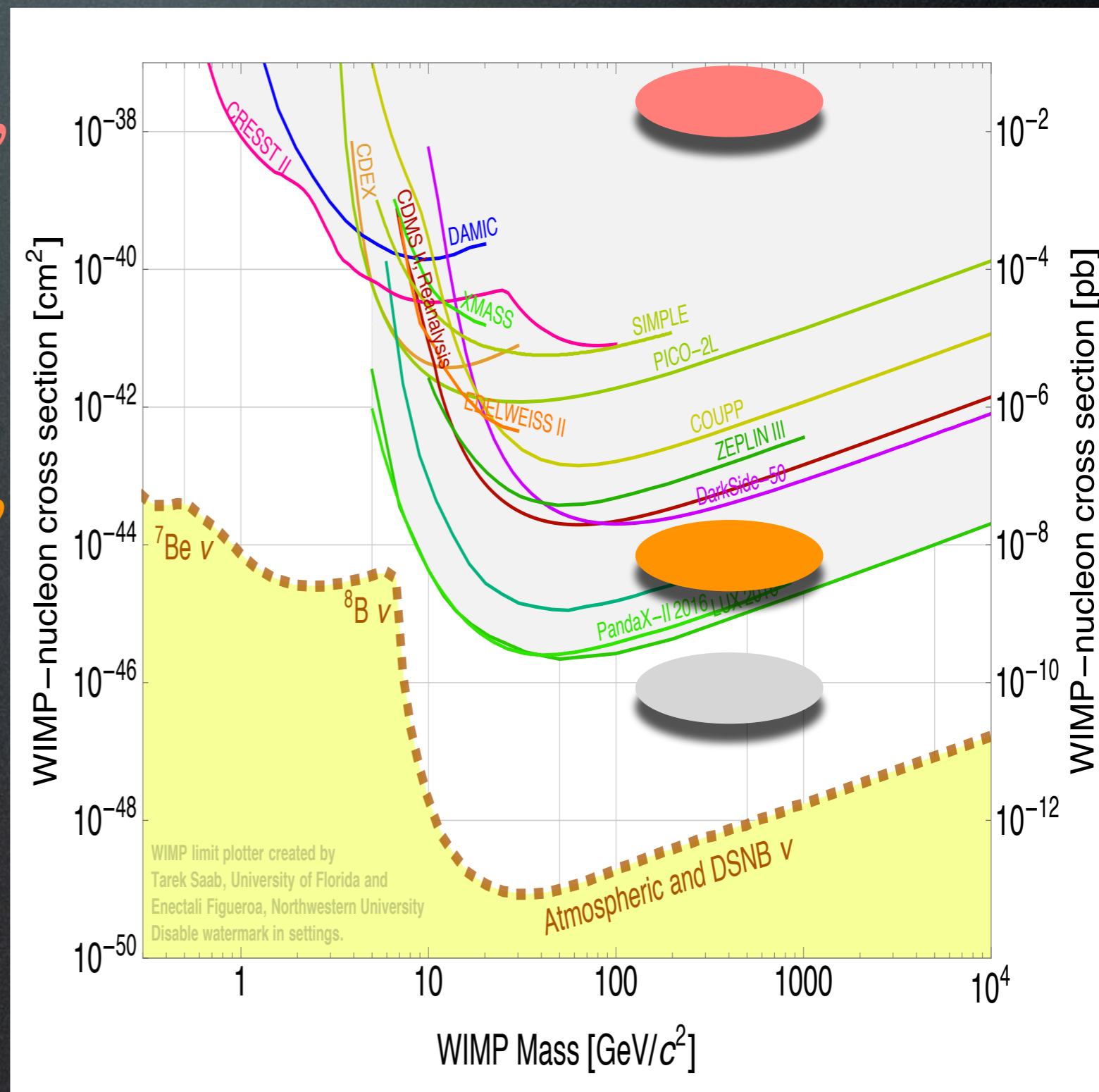
tree level,
vector



tree level,
scalar

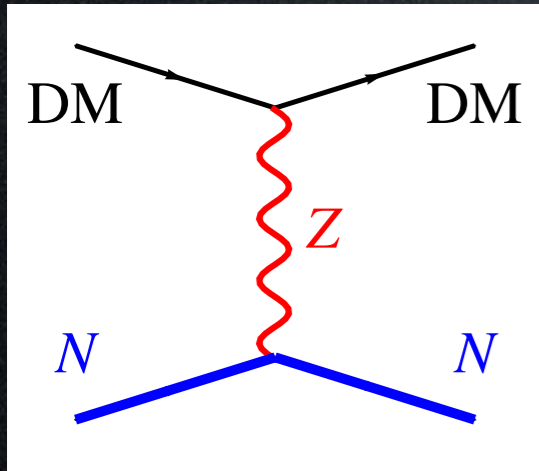


one loop

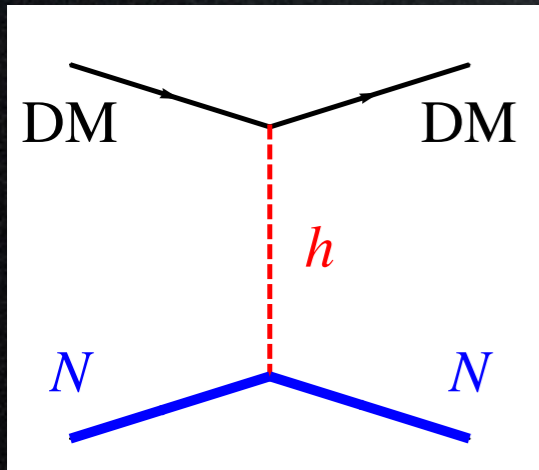


WIMP DD: 'theory'

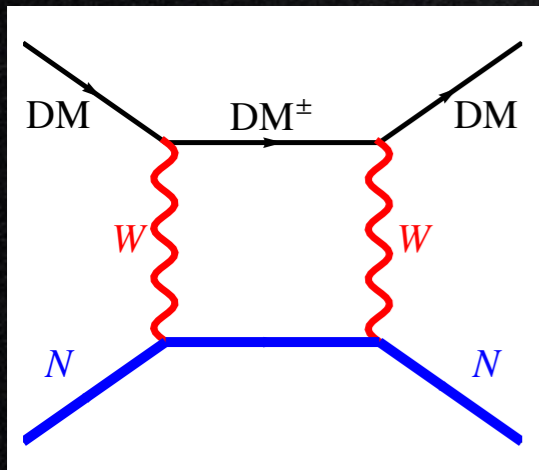
SM weak scale SI interactions



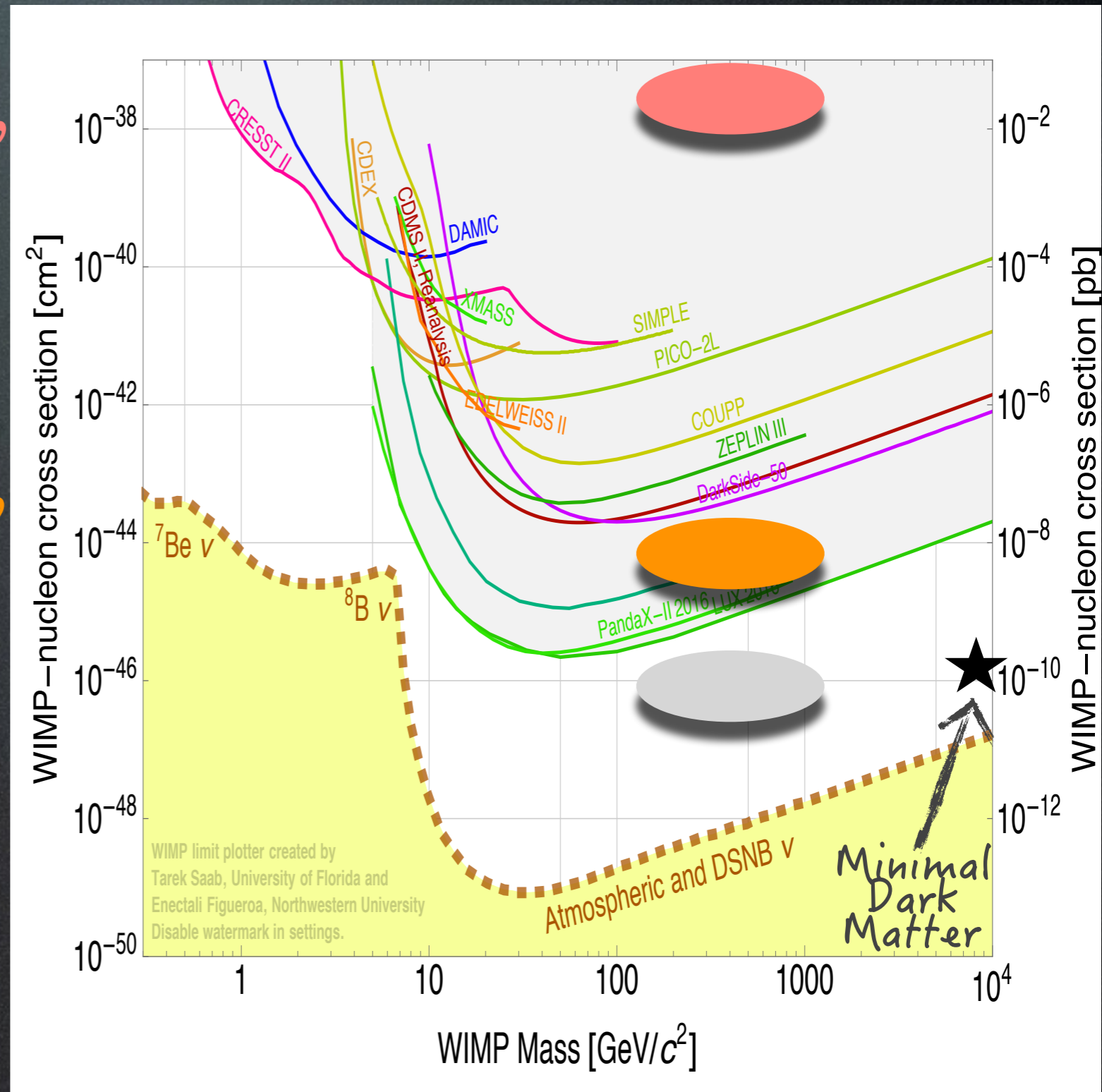
tree level,
vector



tree level,
scalar



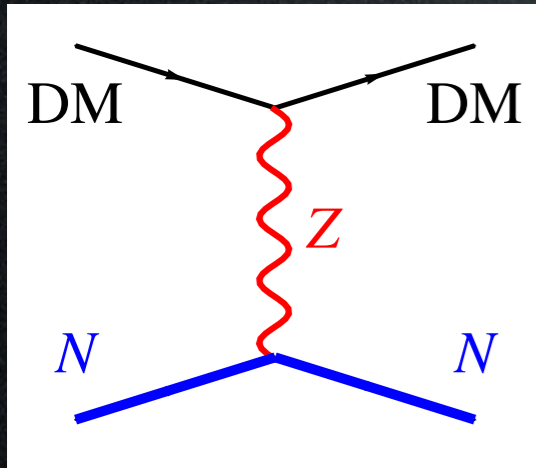
one loop



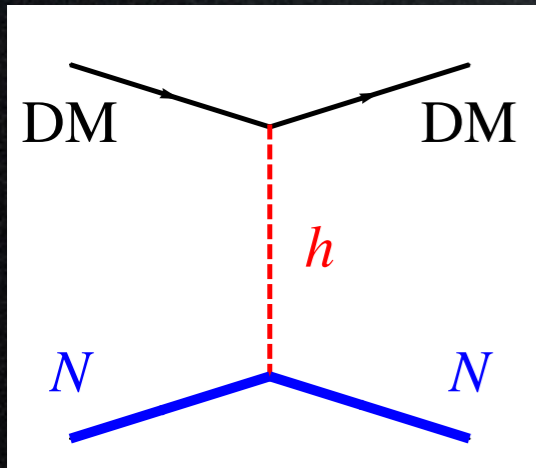
WIMP DD: 'theory'

SM weak scale SI interactions

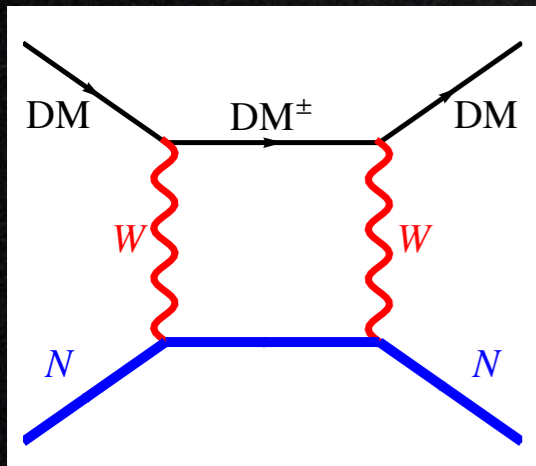
Still viable under
which conditions?



tree level,
vector



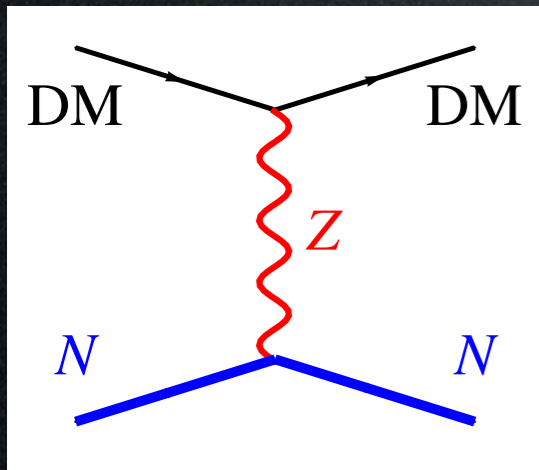
tree level,
scalar



one loop

WIMP DD: 'theory'

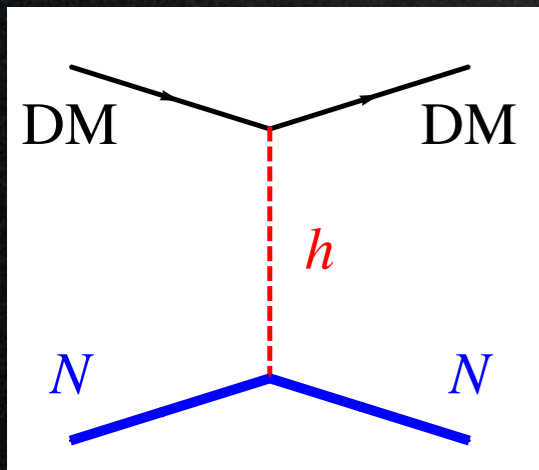
SM weak scale SI interactions



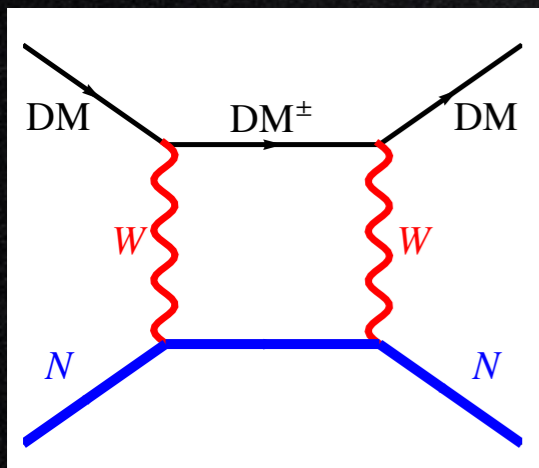
~~tree level,
vector~~

Still viable under
which conditions?

- real particle
(Majorana fermion, real scalar)



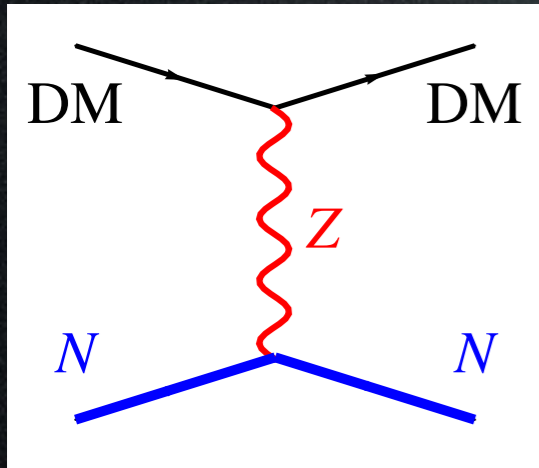
tree level,
scalar



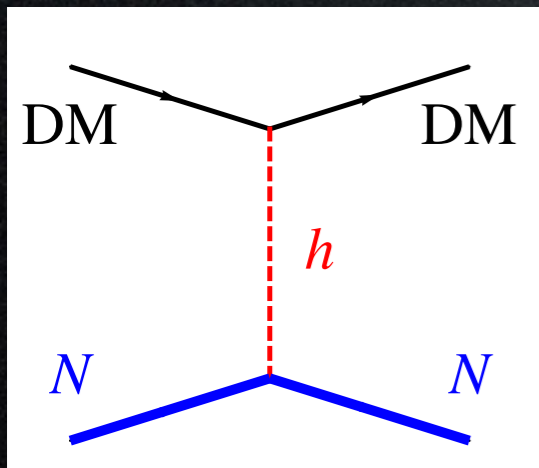
one loop

WIMP DD: 'theory'

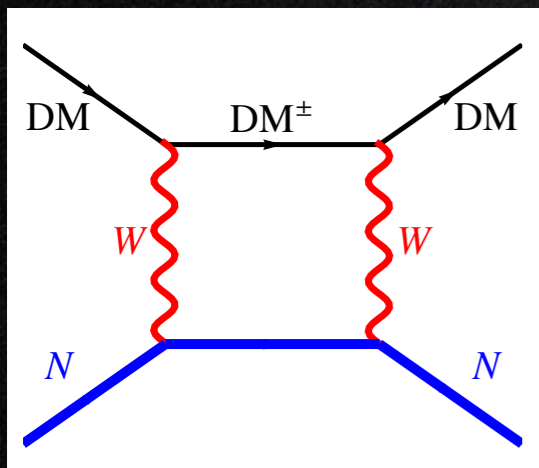
SM weak scale SI interactions



~~tree level,
vector~~



~~tree level,
scalar~~



one loop

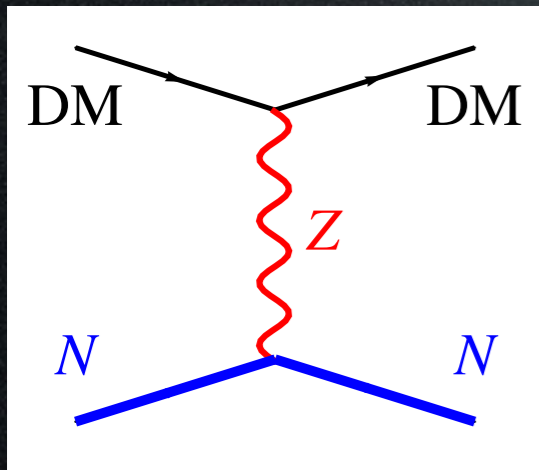
Still viable under
which conditions?

- real particle
(Majorana fermion, real scalar)

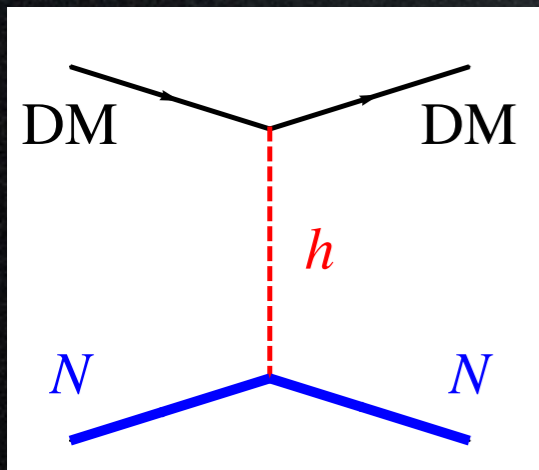
- hypercharge $Y = 0$

WIMP DD: 'theory'

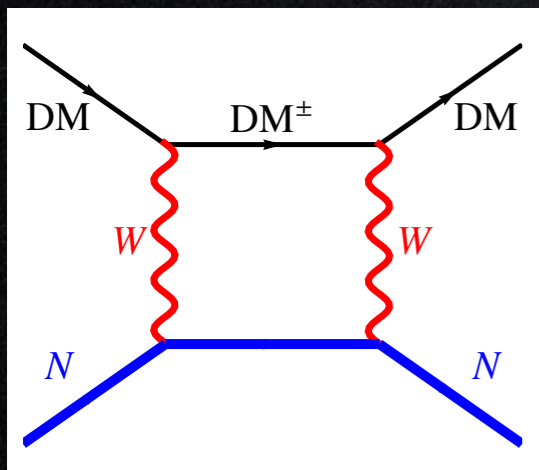
SM weak scale SI interactions



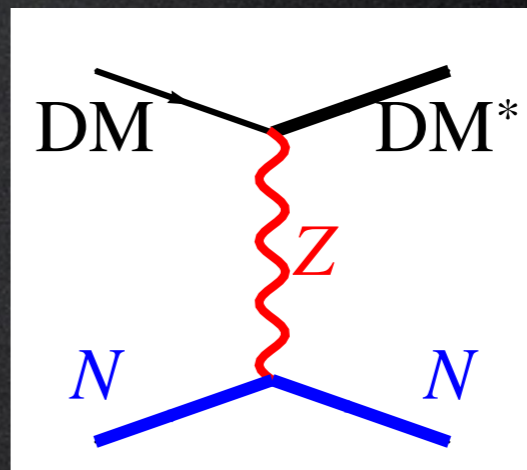
~~tree level,
vector~~



~~tree level,
scalar~~



one loop



Still viable under which conditions?

- real particle
(Majorana fermion, real scalar)
- hypercharge $Y = 0$
- SD interactions only
- inelastic scattering

Candidates

new physics at
the TeV scale

thermal
freeze-out



WIMPs

LHC

AMS, Fermi, CTA
Antares, Icecube

Direct
Detection

1. even without a larger framework, WIMPs are **still appealing**
2. the three search strategies are **complementary**

Candidates

new physics at
the TeV scale

thermal
freeze-out



WIMPs

LHC

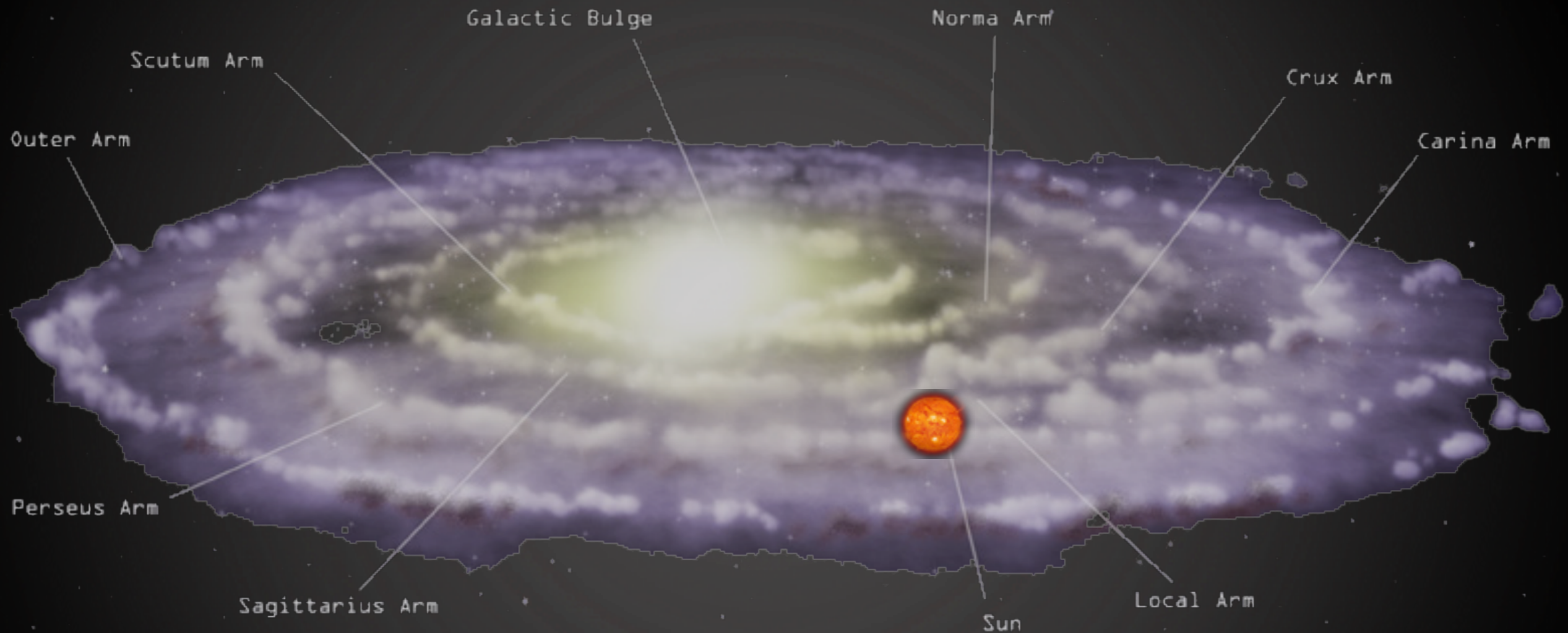
AMS, Fermi, CTA
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Direct
Detection

1. even without a larger framework, WIMPs are **still appealing**
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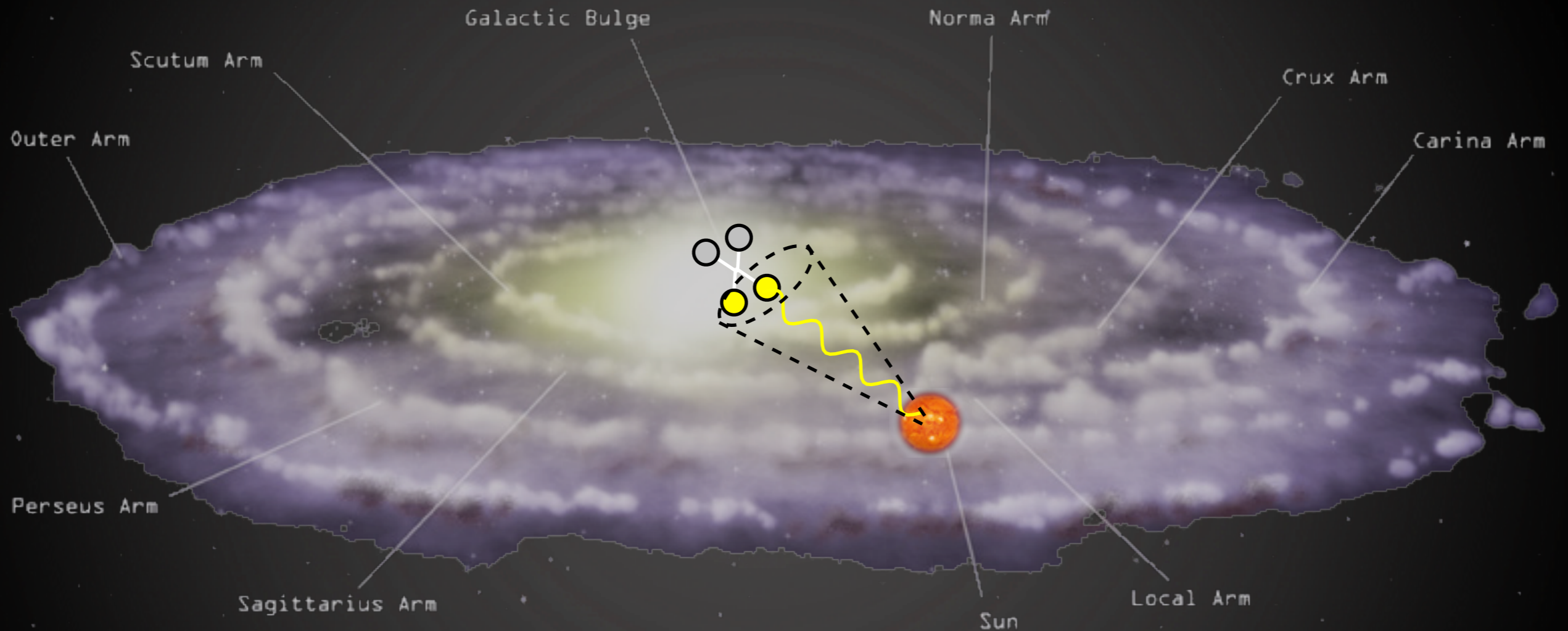
Indirect Detection

γ from MDM annihilations



Indirect Detection

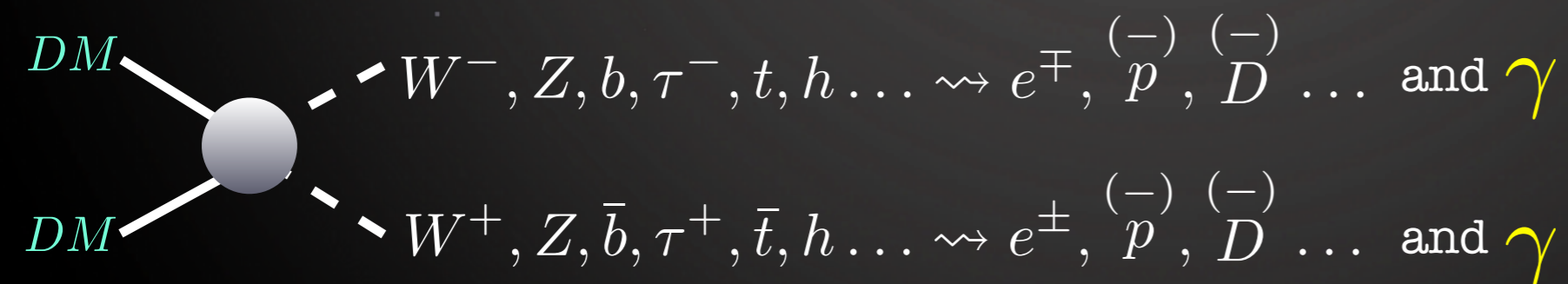
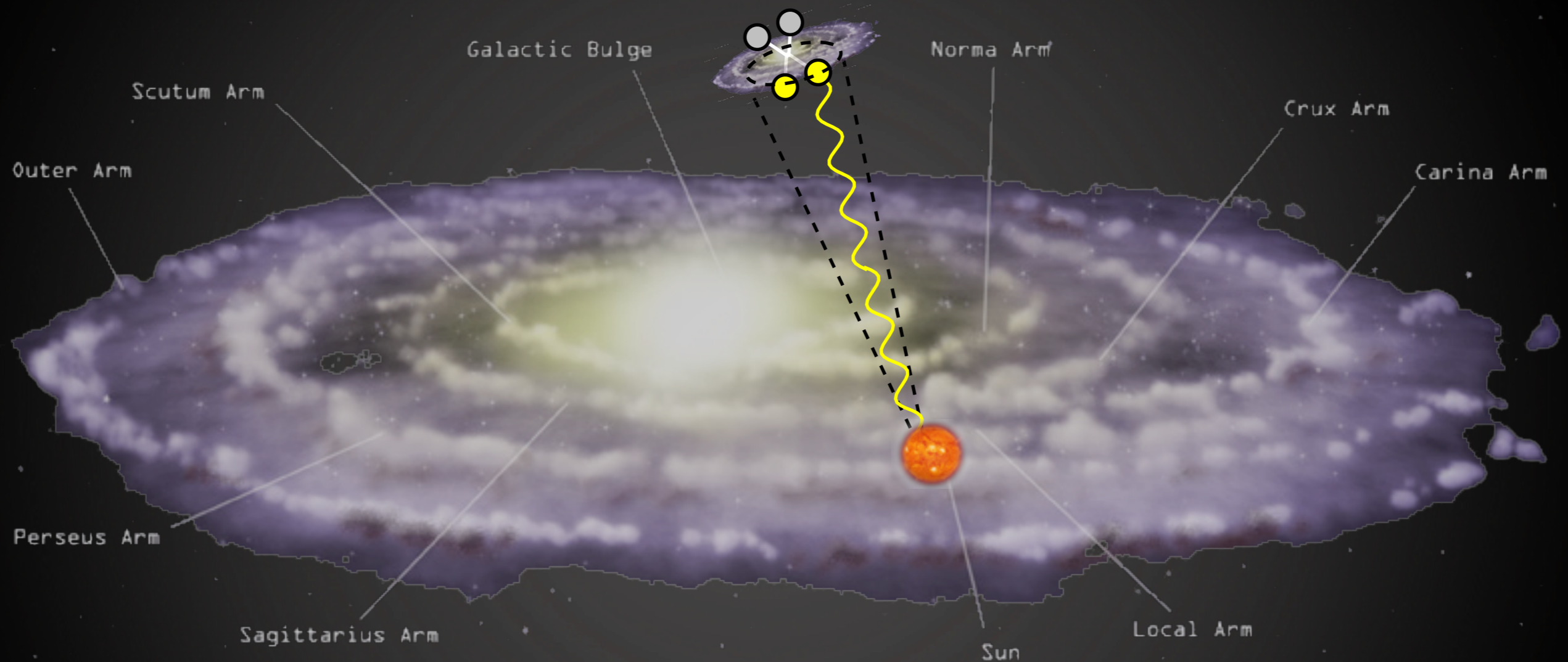
γ from MDM annihilations in galactic center



$$\begin{aligned} DM &\rightarrow W^-, Z, b, \tau^-, t, h \dots \rightsquigarrow e^{\mp}, \overset{(-)}{p}, \overset{(-)}{D} \dots \text{ and } \gamma \\ DM &\rightarrow W^+, Z, \bar{b}, \tau^+, \bar{t}, h \dots \rightsquigarrow e^{\pm}, \overset{(-)}{p}, \overset{(-)}{D} \dots \text{ and } \gamma \end{aligned}$$

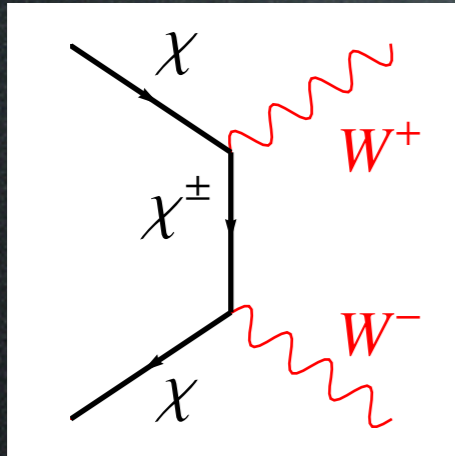
Indirect Detection

γ from MDM annihilations in dwarf galaxies



Indirect Detection

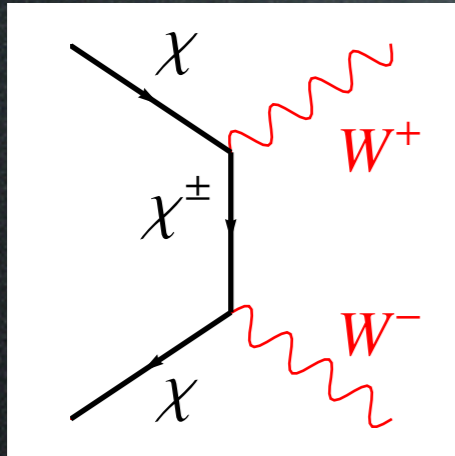
γ from MDM annihilations



$$+ W^\pm, Z \rightarrow \bar{p}, e^+, \gamma \dots$$

Indirect Detection

γ from MDM annihilations

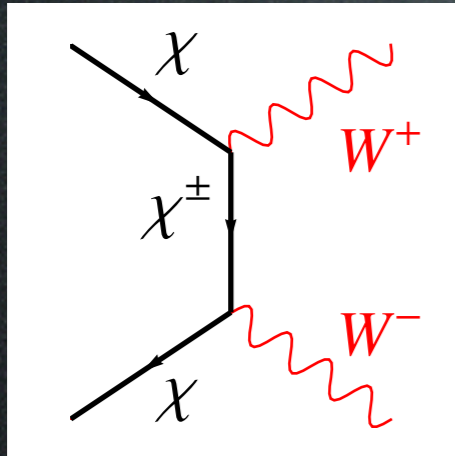


continuum

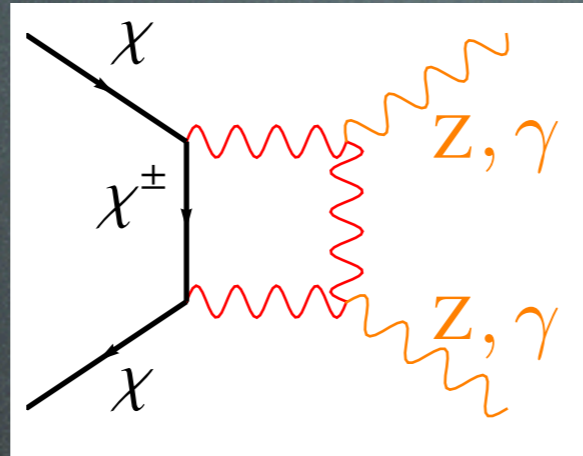
$$+ W^{\pm}, Z \rightarrow \bar{p}, e^{+}, \gamma \dots$$

Indirect Detection

γ from MDM annihilations



continuum



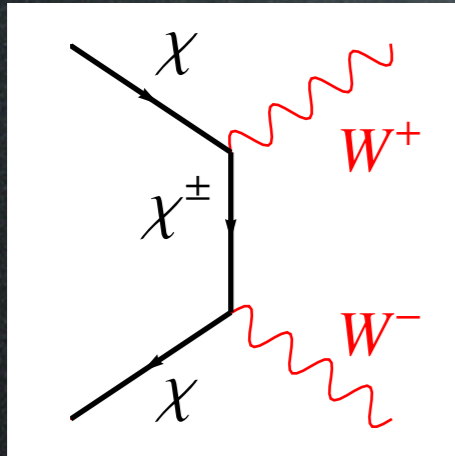
line(s)
(+ continuum)

$$+ W^\pm, Z \rightarrow \bar{p}, e^+, \gamma \dots$$

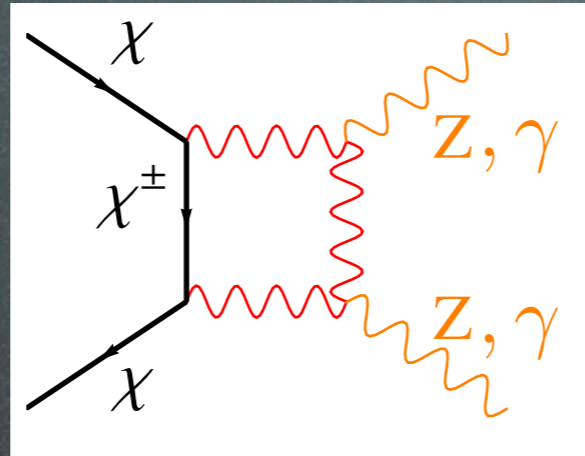
(channels for MDM with $Y=0$)

Indirect Detection

γ from MDM annihilations



continuum



line(s)
(+ continuum)

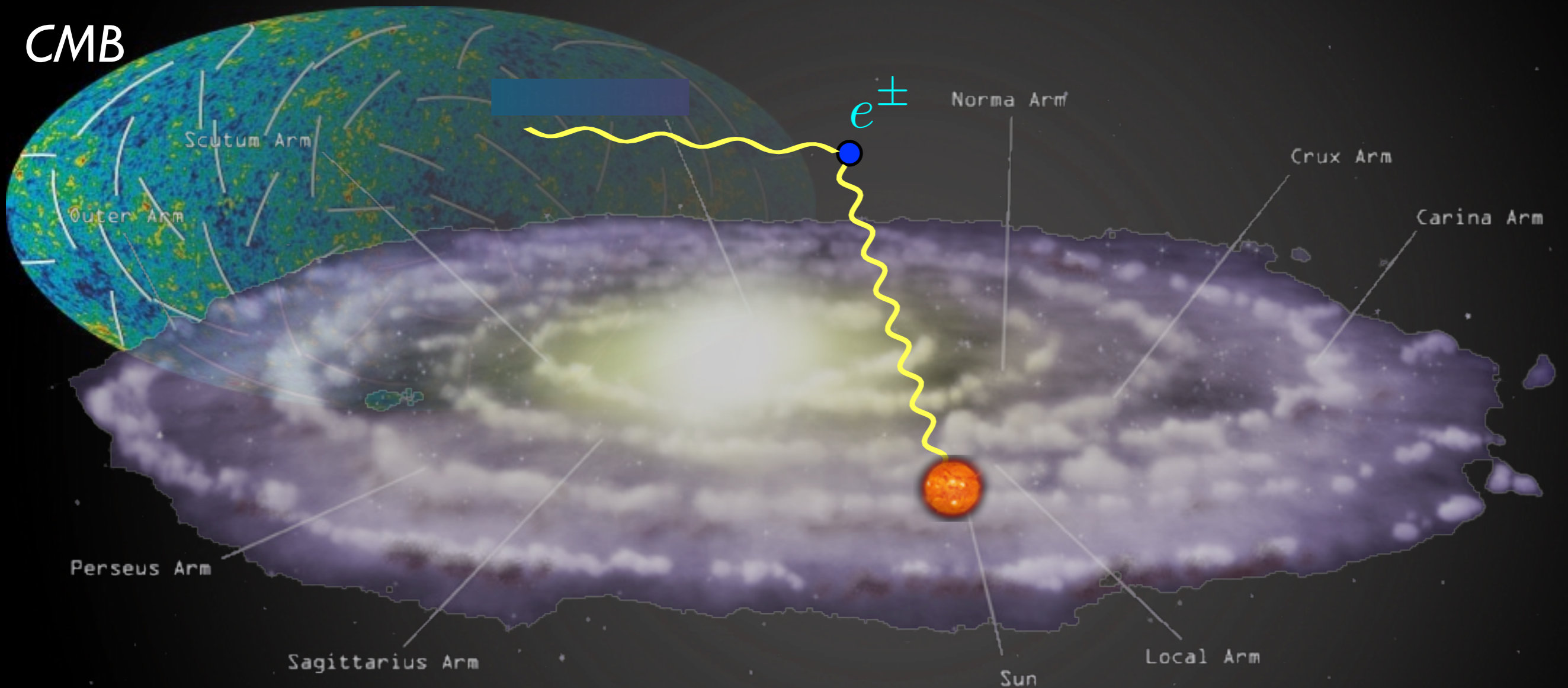
$$+ W^\pm, Z \rightarrow \bar{p}, e^+, \gamma \dots$$

(channels for MDM with $Y=0$)

+ ICS

Secondary emission

γ from Inverse Compton on e^\pm in halo

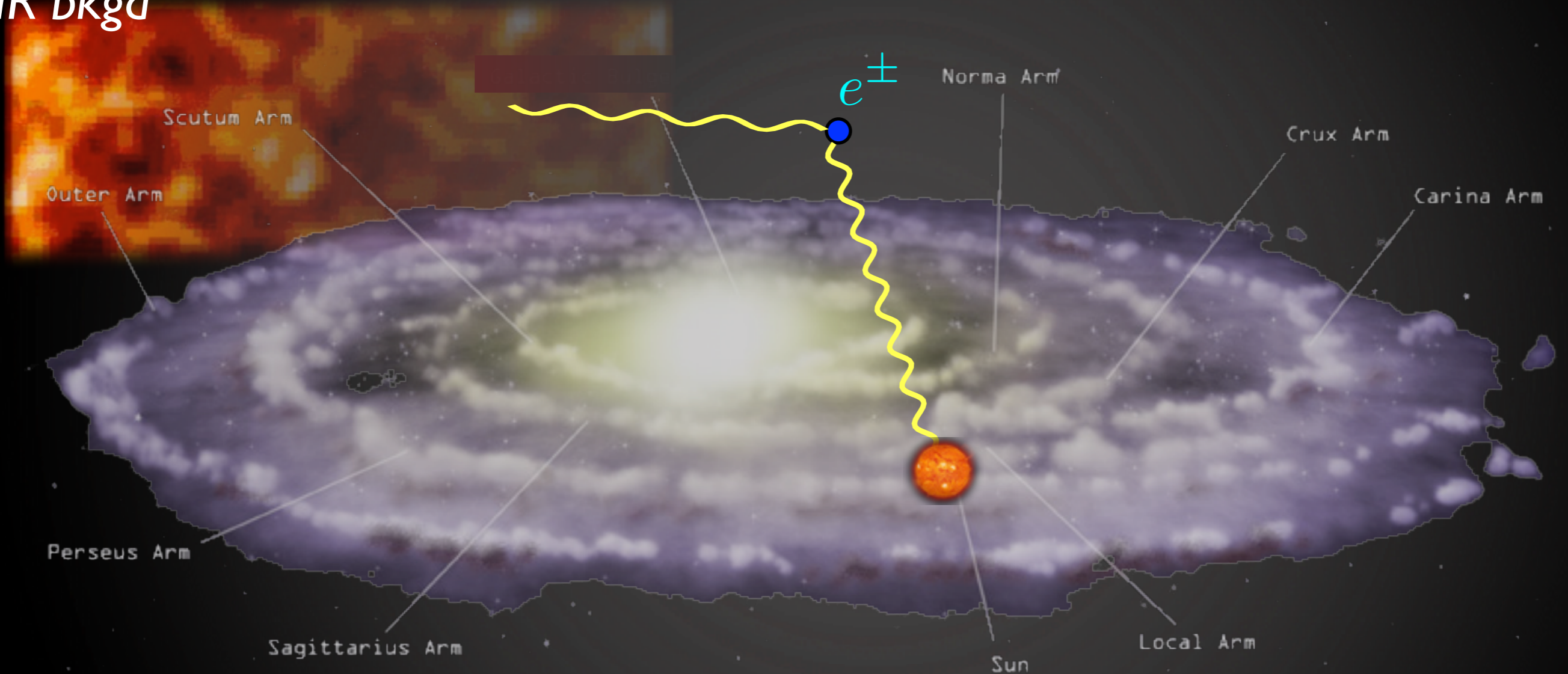


- upscatter of CMB, infrared and starlight photons on energetic e^\pm
- probes regions outside of Galactic Center

Secondary emission

γ from Inverse Compton on e^\pm in halo

IR bkgd

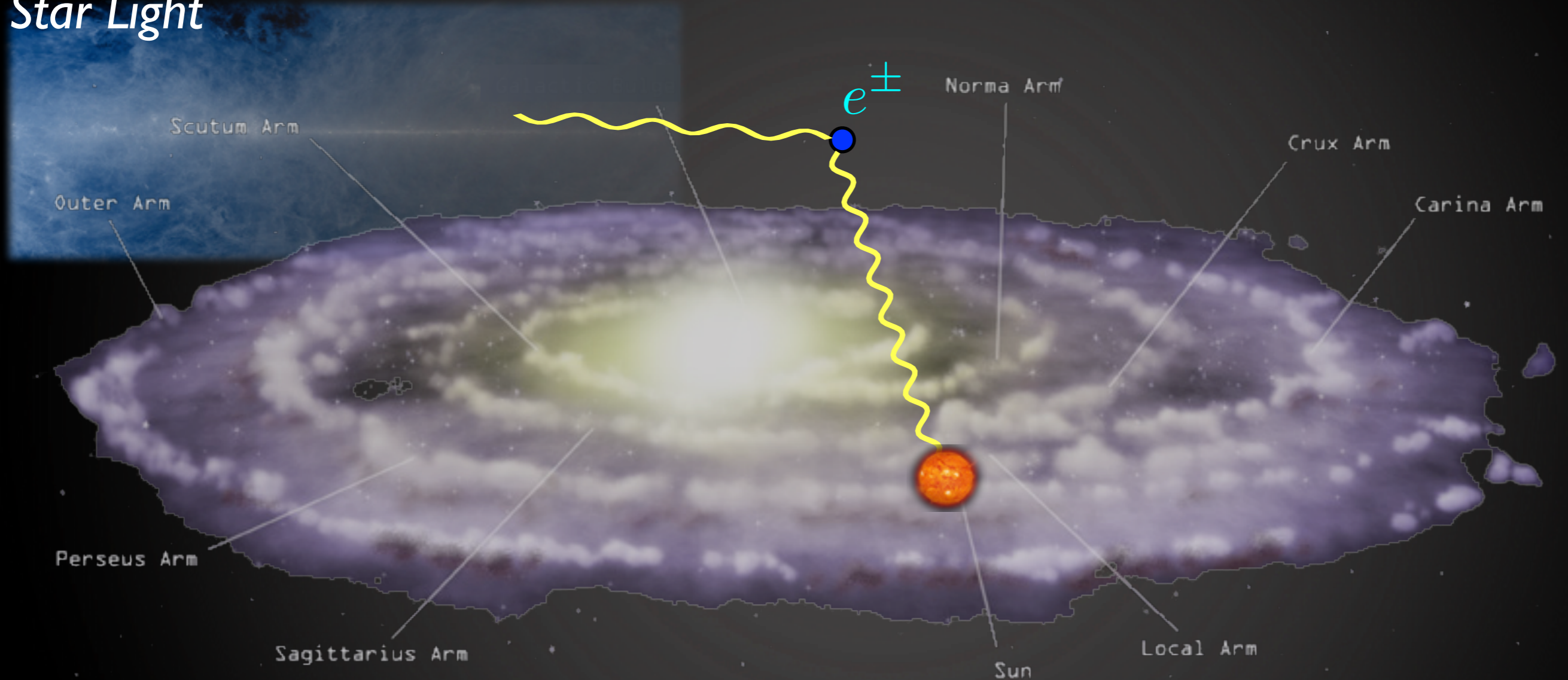


- upscatter of CMB, infrared and starlight photons on energetic e^\pm
- probes regions outside of Galactic Center

Secondary emission

γ from Inverse Compton on e^\pm in halo

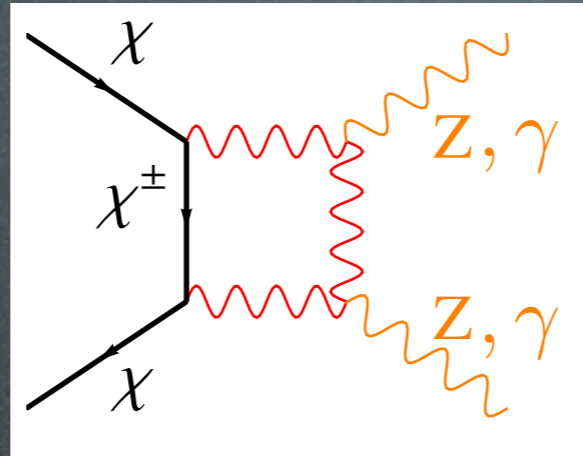
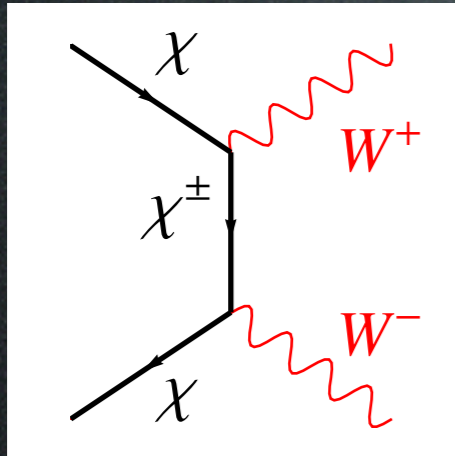
Star Light



- upscatter of CMB, infrared and starlight photons on energetic e^\pm
- probes regions outside of Galactic Center

Indirect Detection

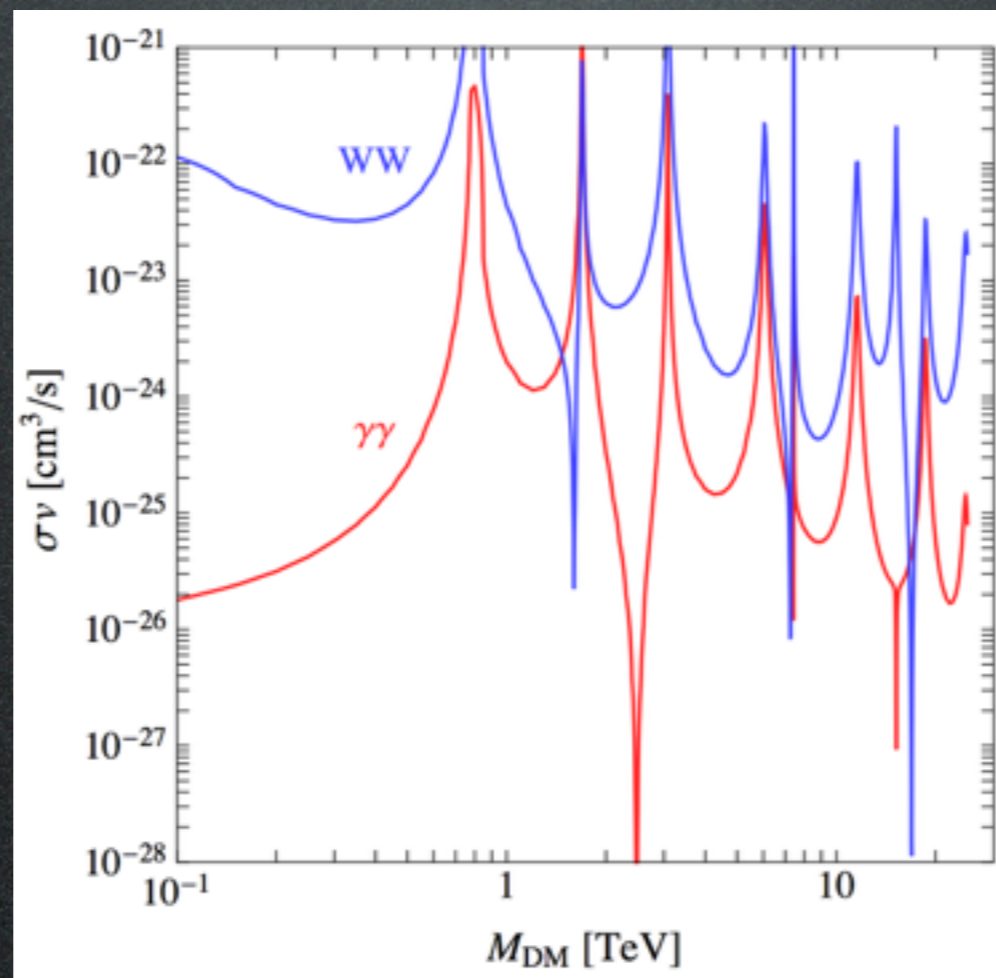
γ from MDM annihilations



$$+ W^{\pm}, Z \rightarrow \bar{p}, e^{+}, \gamma \dots$$

(channels for MDM with $Y=0$)

Enhanced cross section due to ‘Sommerfeld corrections’

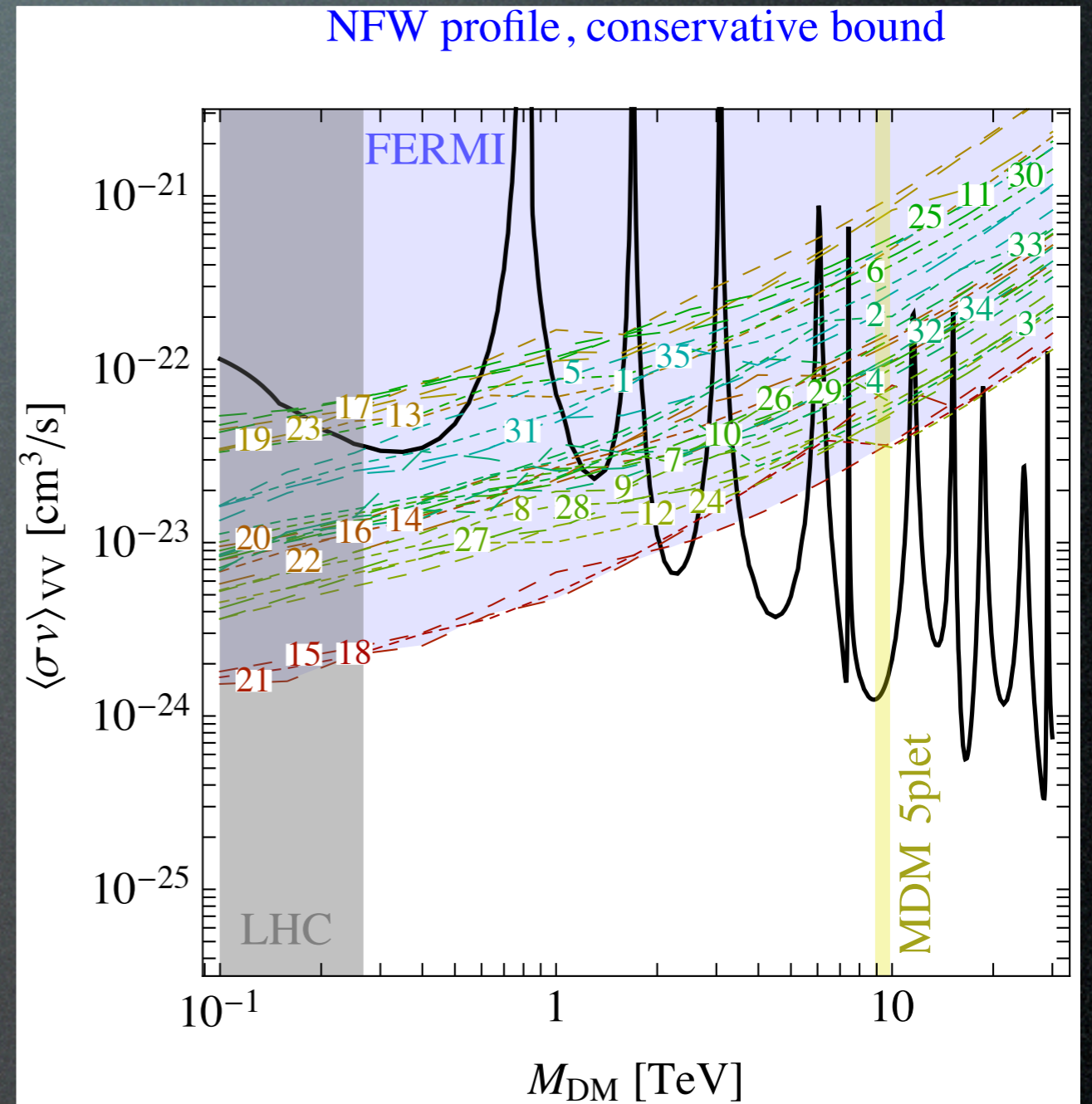
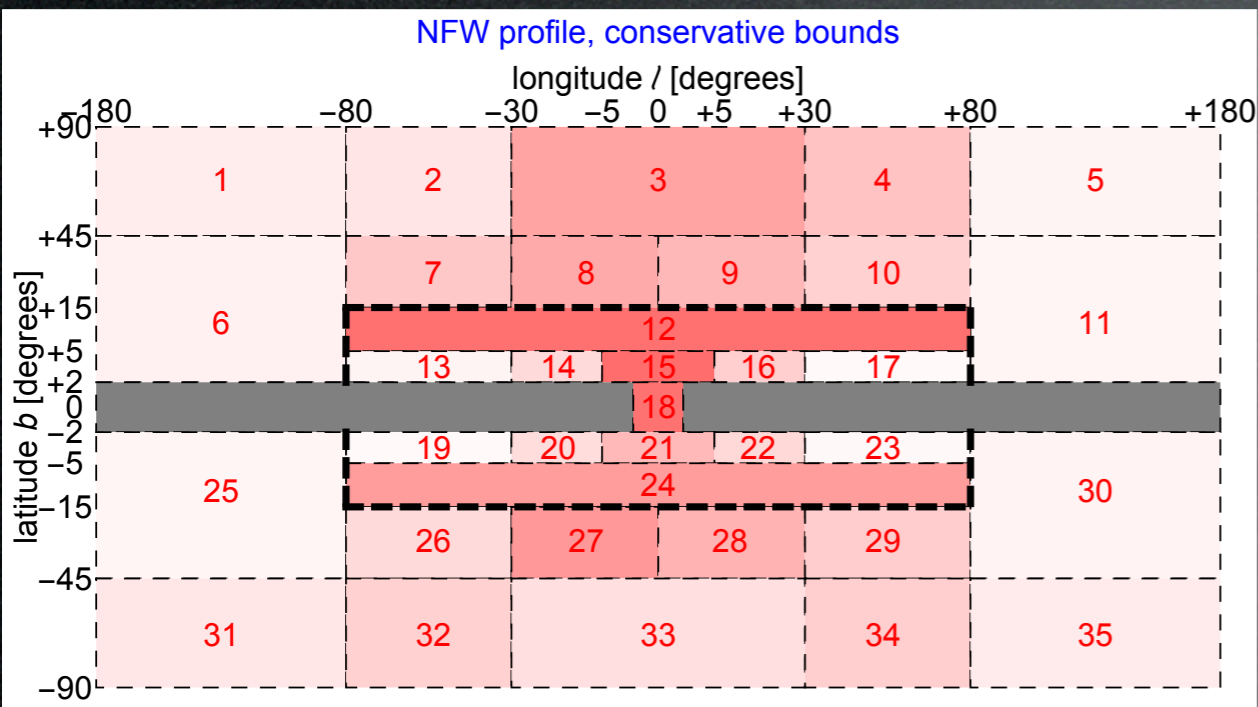
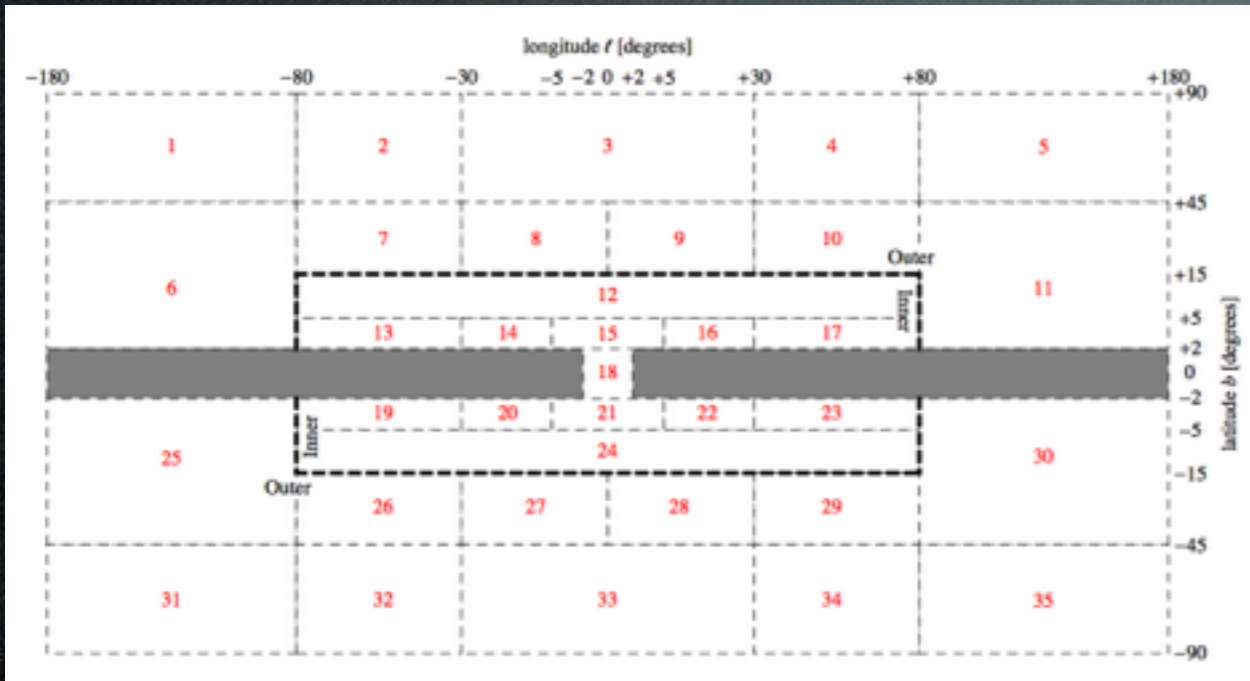


Hisano et al., 2004, 2005
Cirelli, Strumia, Tamburini 2007

Cirelli, Hambye, Panci, Sala, Taoso
1507.05519

Indirect Detection

FERMI diffuse galactic:

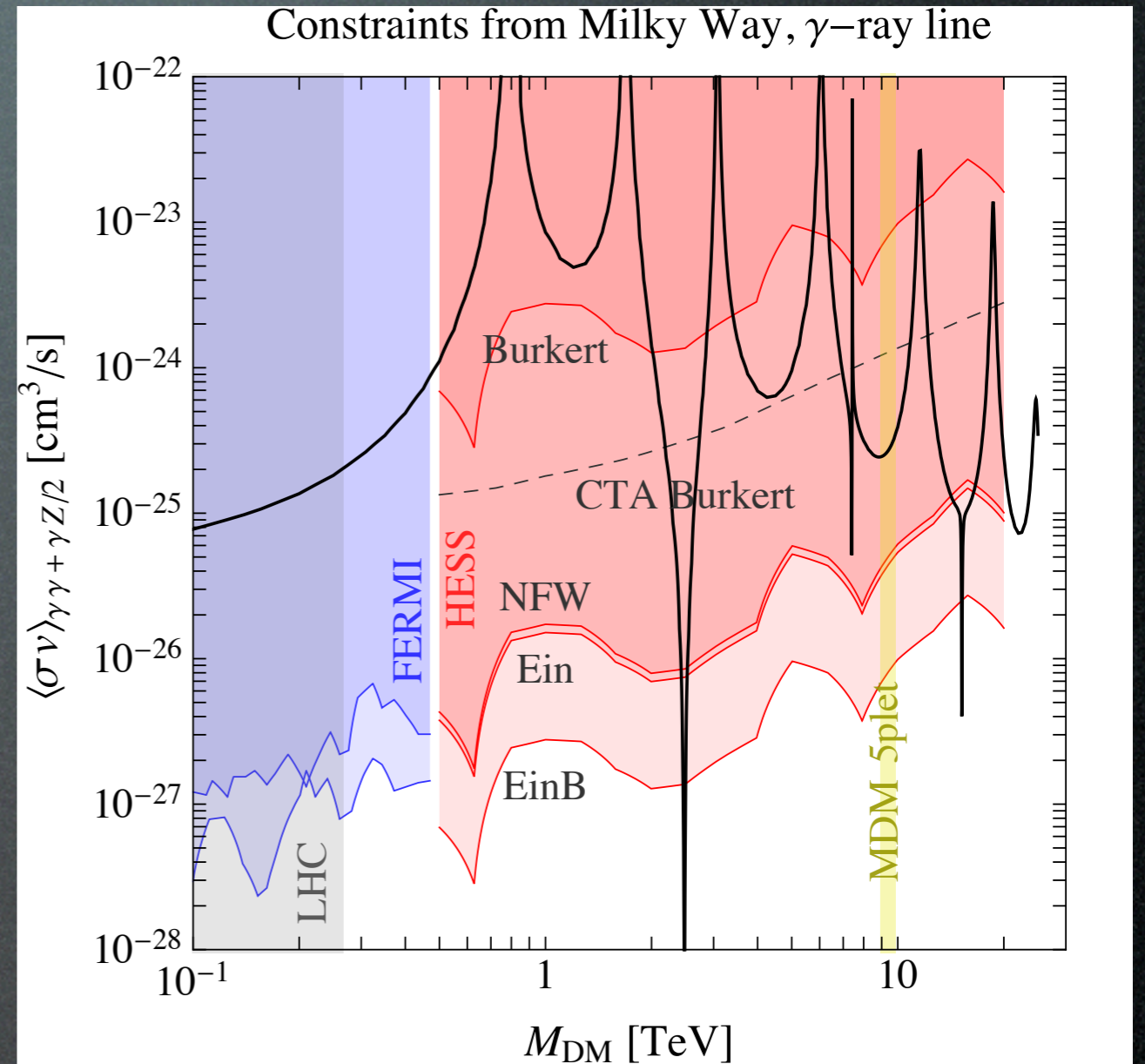


Indirect Detection

MW center area, search for γ -ray lines:

FERMI: 1506.00013

HESS: 1301.1173



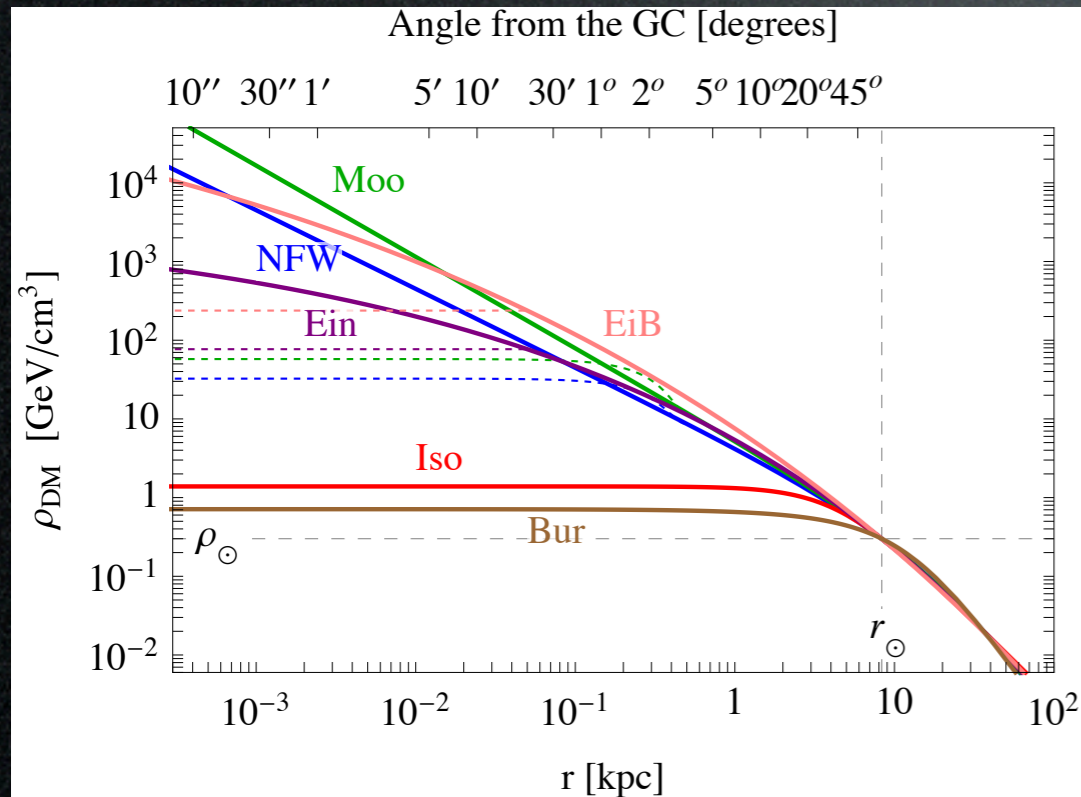
Indirect Detection

MW center area, search for γ -ray lines:

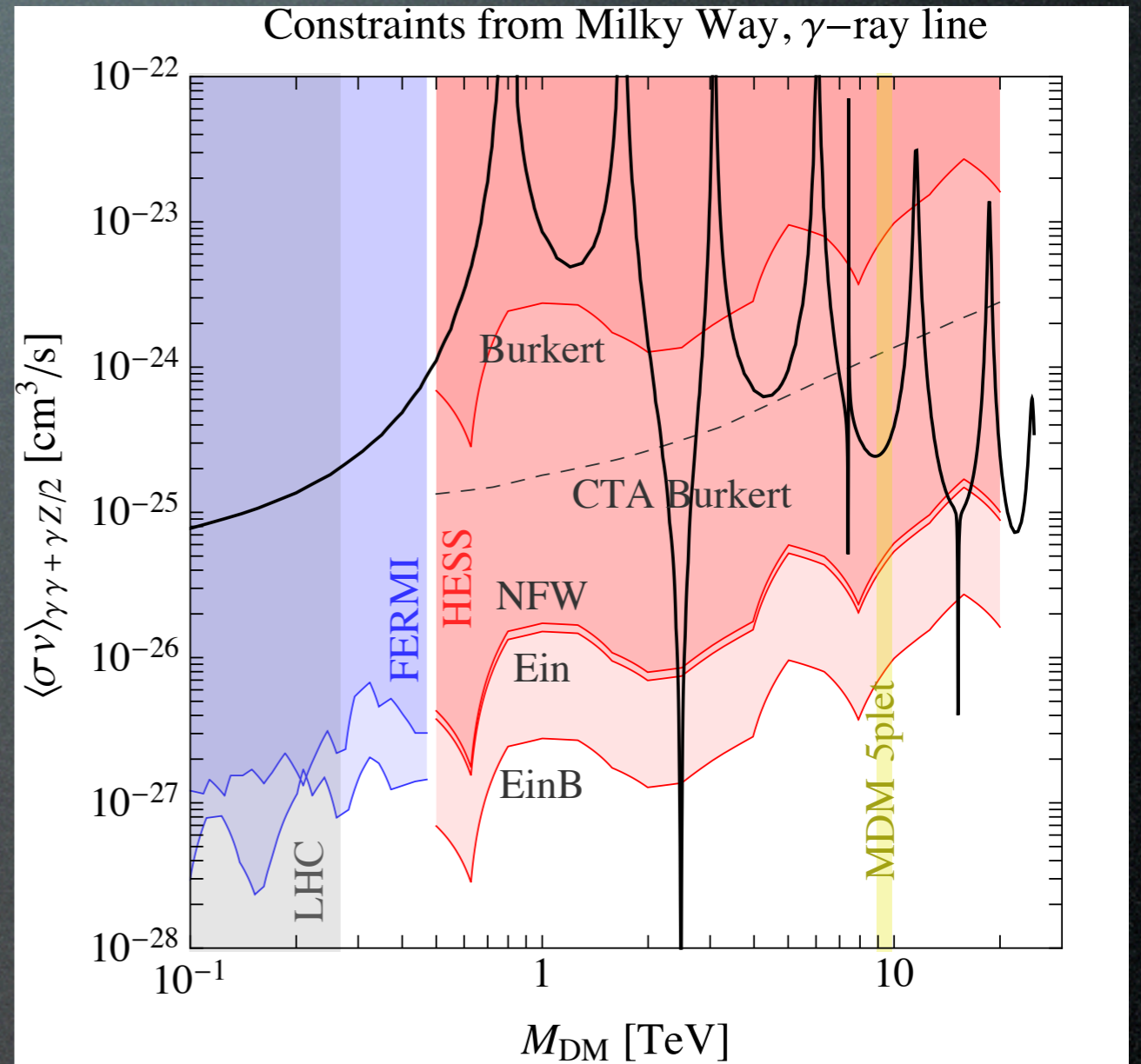
FERMI: 1506.00013

HESS: 1301.1173

Uncertainties in DM profile:



e.g. Cirelli et al., 1012.4515



Cirelli, Hambye, Panci, Sala, Taoso 1507.05519

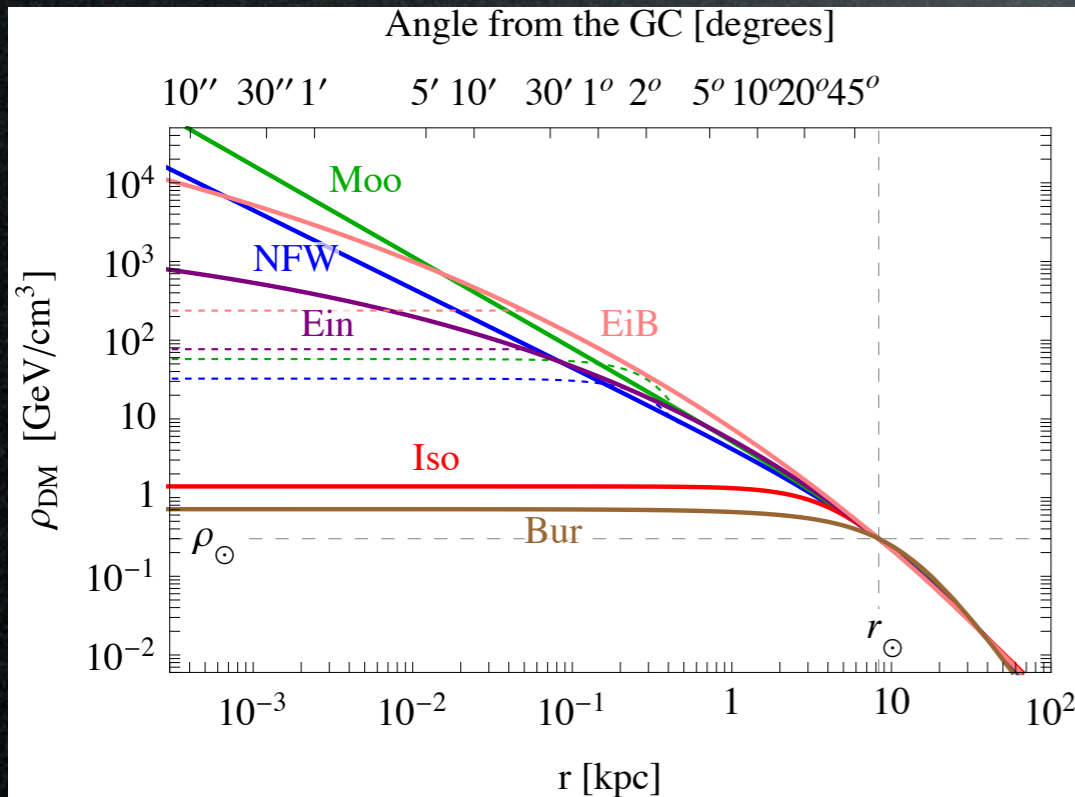
Indirect Detection

MW center area, search for γ -ray lines:

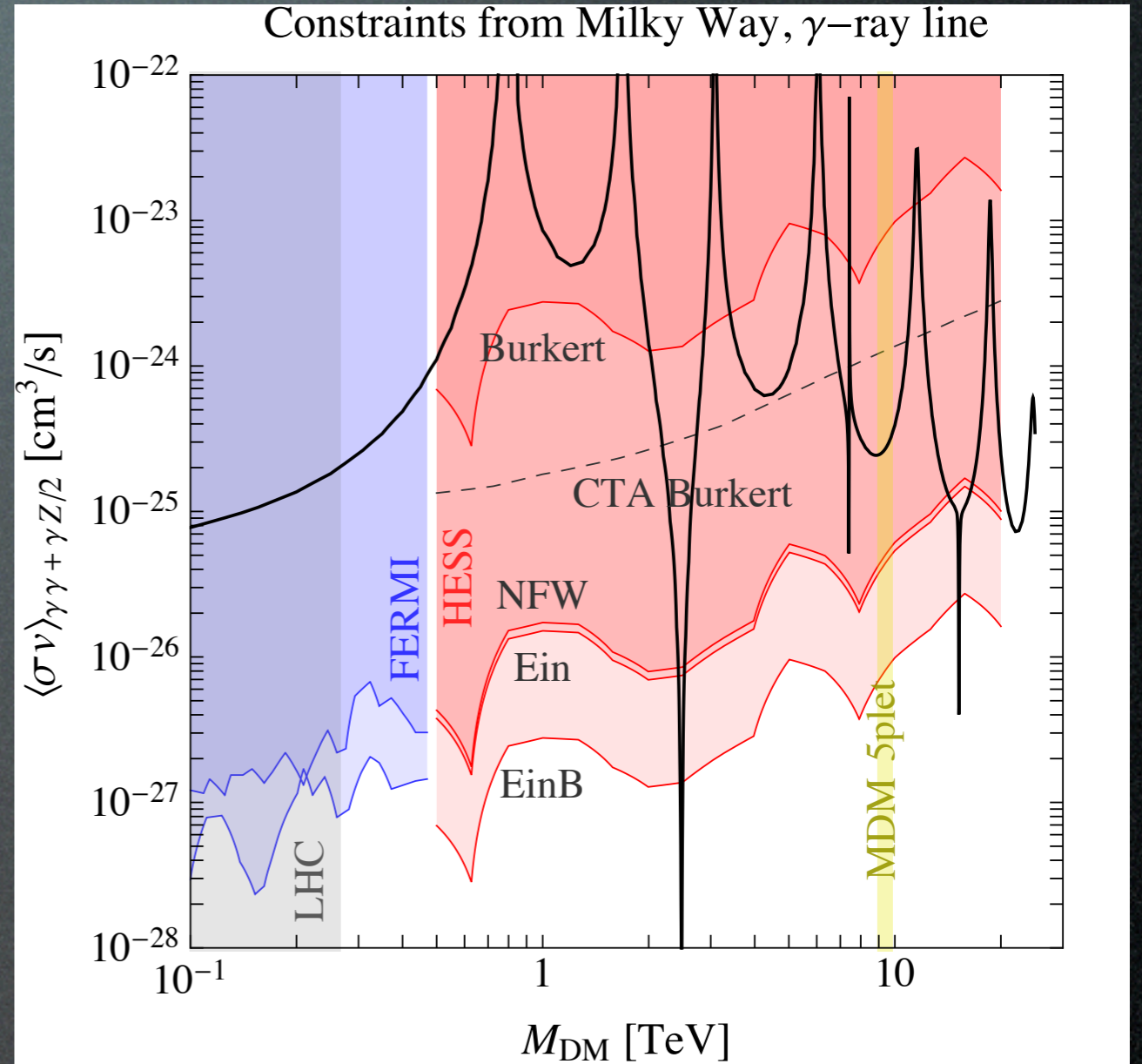
FERMI: 1506.00013

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Cirelli, Hambye, Panci, Sala, Taoso 1507.05519

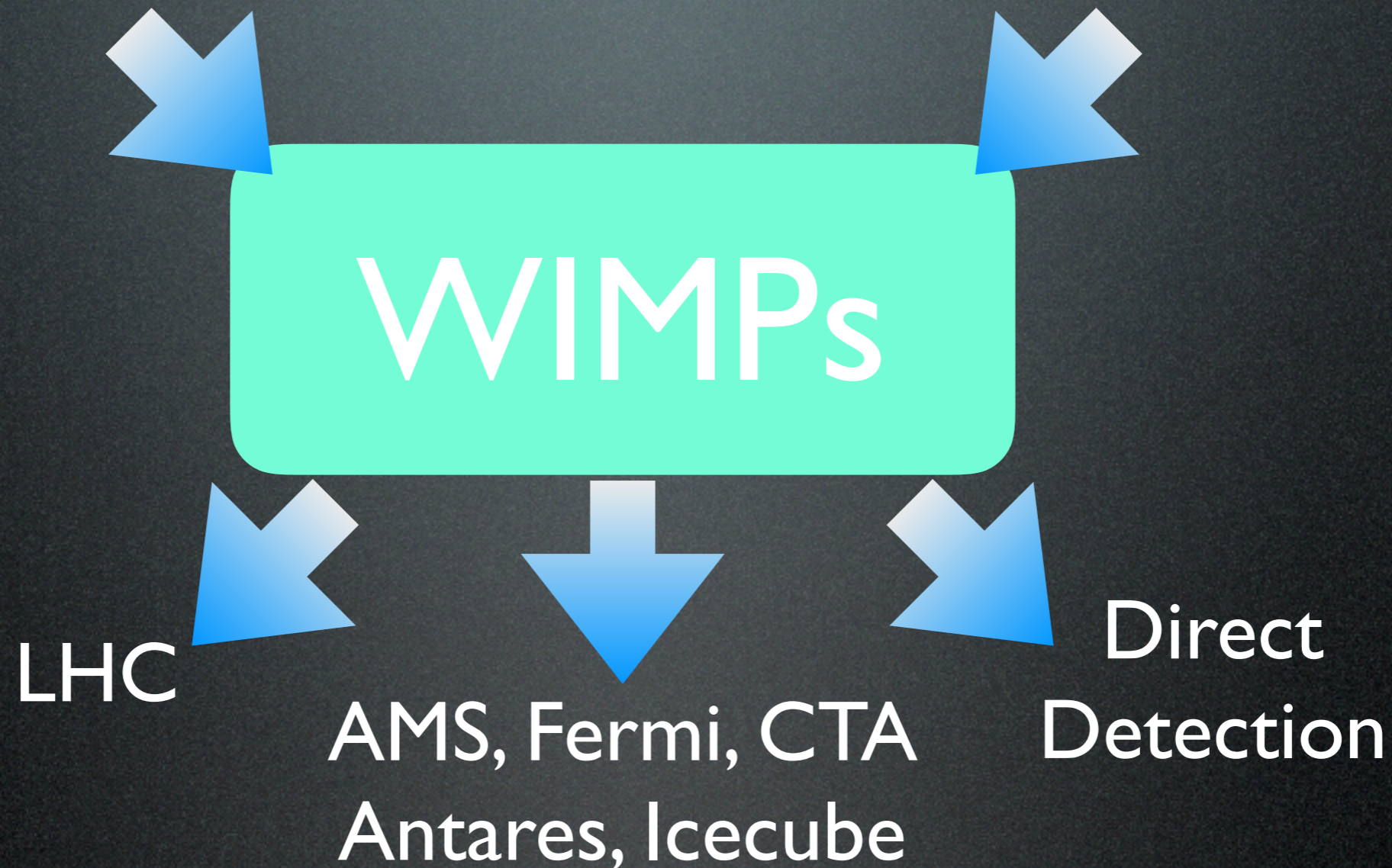
➔ MDM excluded if cuspy
 MDM not probed if cored

Consistent conclusions in: Garcia-Cely et al. 1507.05536

Conclusions

new physics at
the TeV scale

thermal
freeze-out



1. even without a larger framework, WIMPs are **still appealing**
2. the three search strategies are **complementary**