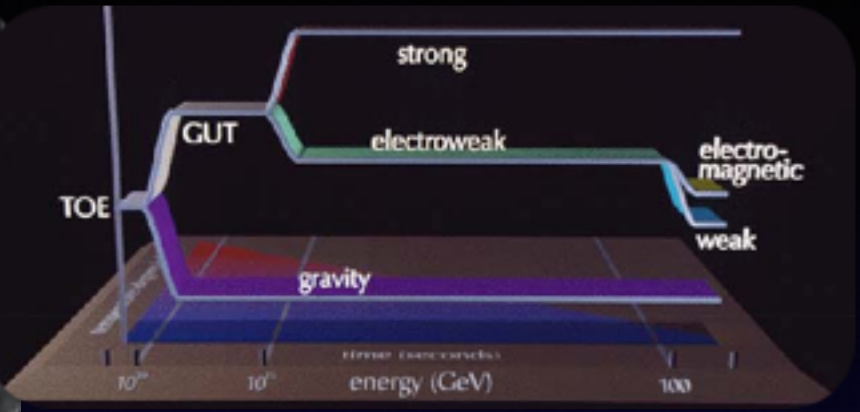
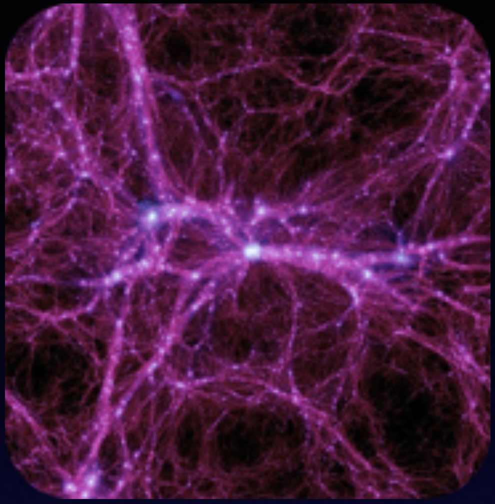
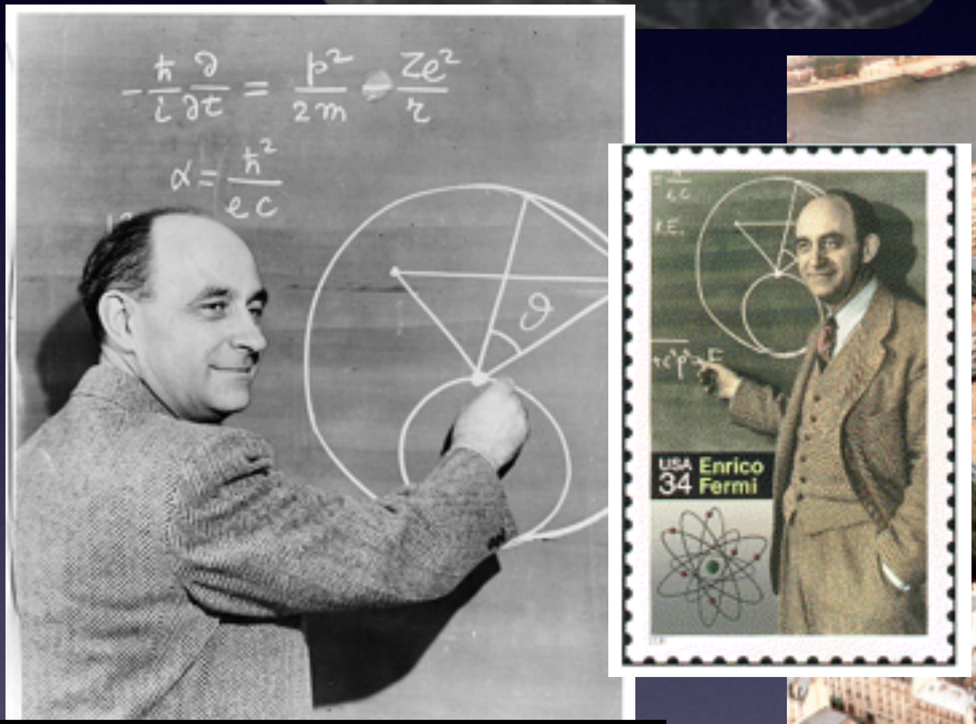
Dark Matter: searches, and models







« *Never underestimate the joy people derive from hearing something they already know.*»
E. Fermi

Yann Mambrini,

University of Paris-Saclay

in collaboration with

G. Arcadi, K. Benakli, Y. Chen, Adoni Dudas, M. Dutra,

P. Ghosh, K. Olive, M. Pierre, F. Queiroz

« *So I am just sitting and waiting, listening, and if something exciting comes, I just jump in*»
G. Gamow

ERC Higgs@LHC

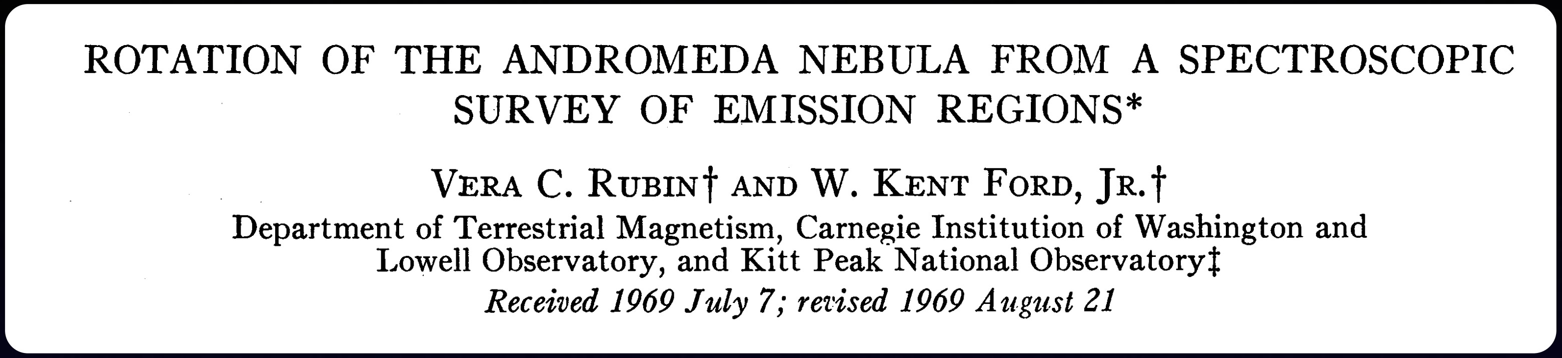
Workshop "Dissecting the LHC results », 20-21 April 2017, LPNHE Jussieu, Paris

A la mémoire de Pierre Binetruy

« 3 messages maximum par talk »

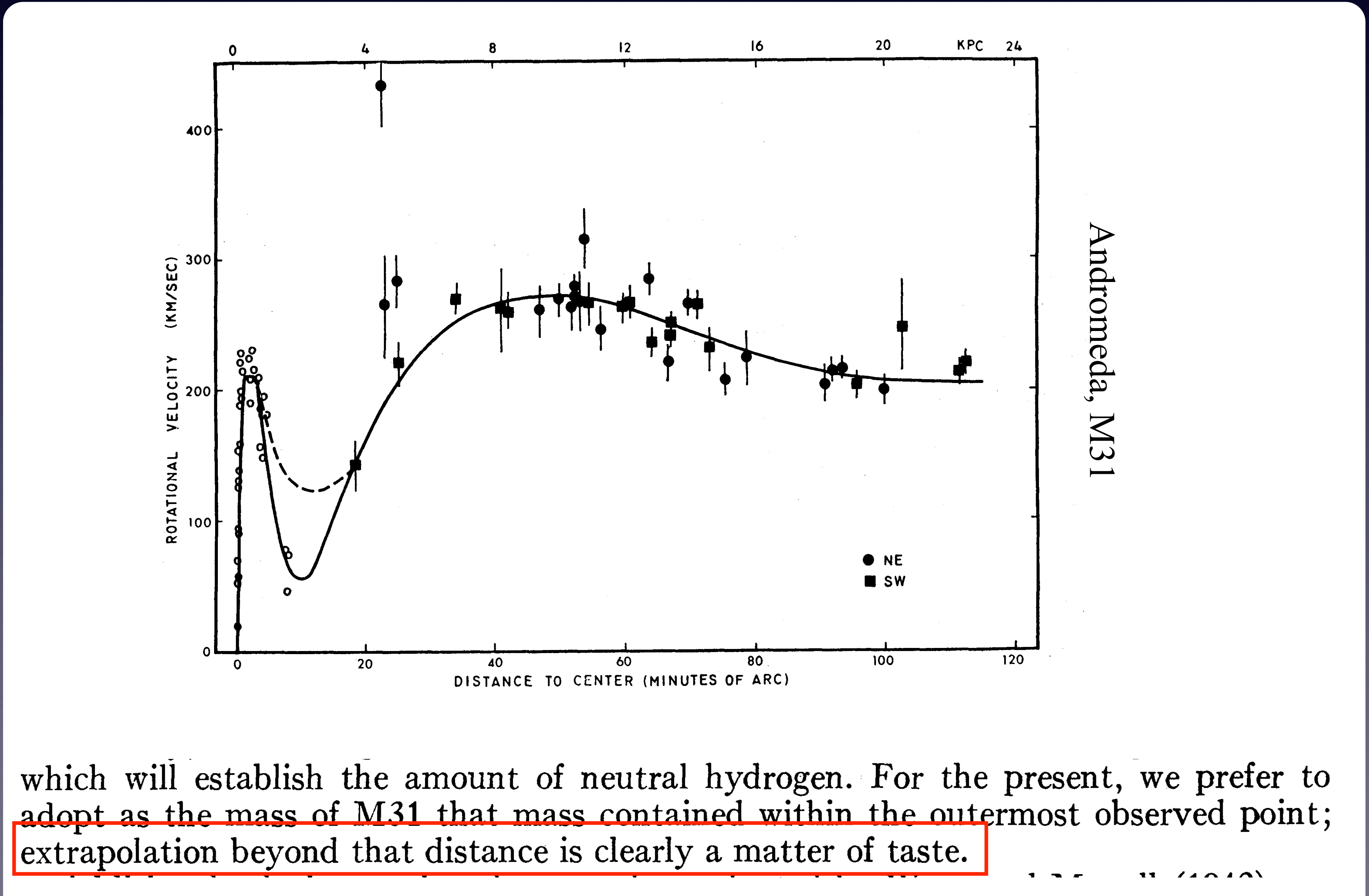
A tribute to Vera Rubin

Vera Rubin
(1928-2016)



ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

Vera C. Rubin† and W. Kent Ford, Jr.†
Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡
Received 1969 July 7; revised 1969 August 21



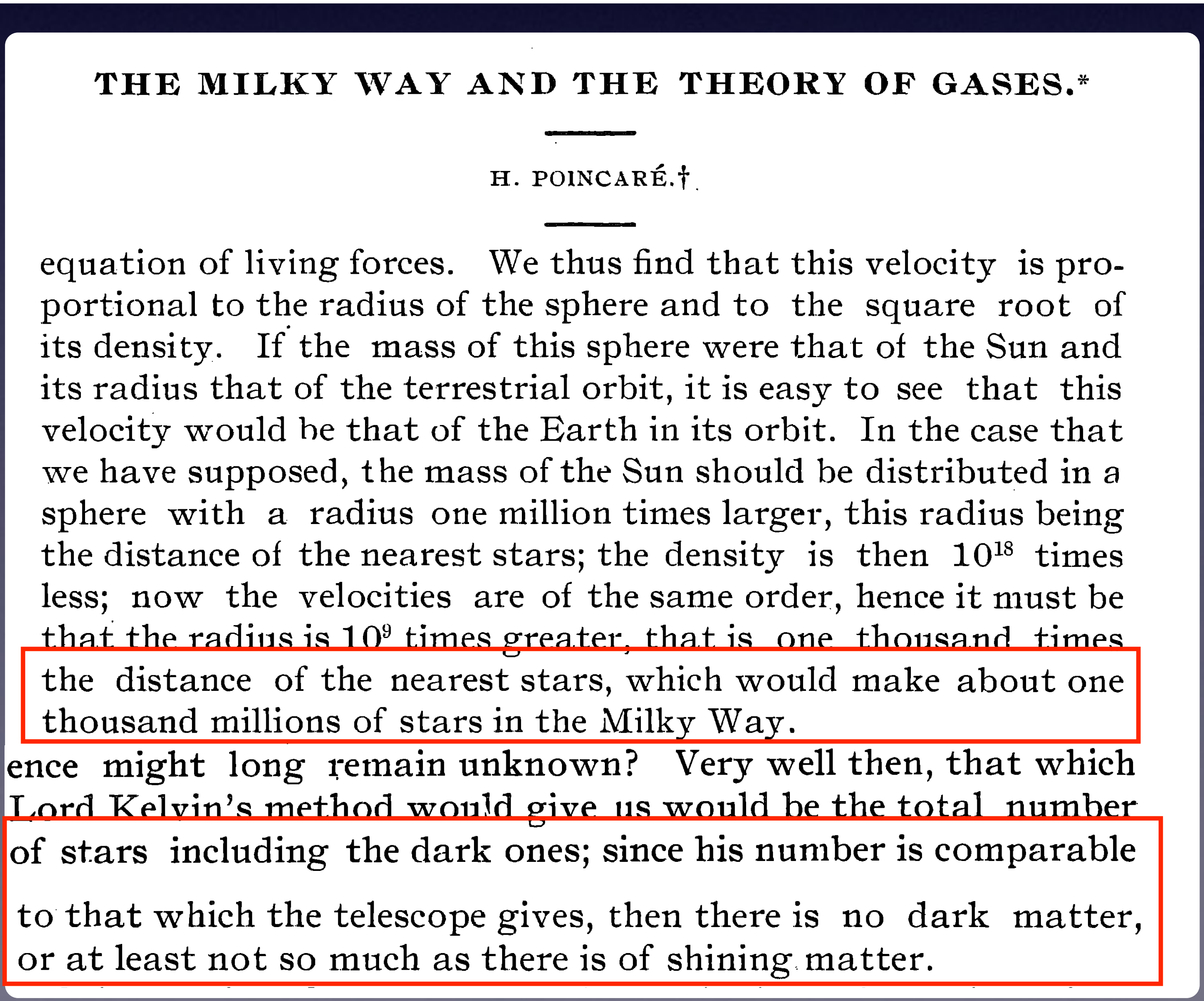
Andromeda, M31

which will establish the amount of neutral hydrogen. For the present, we prefer to adopt as the mass of M31 that mass contained within the outermost observed point; extrapolation beyond that distance is clearly a matter of taste.

The first DM paper

Henri Poincaré

Contrarily to the common belief, the first time the word « dark matter » is proposed in a scientific paper is not Oort in 1932 but Poincaré in 1906. Indeed, Lord Kelvin in 1904 had the genius to apply the kinetic theory of gas recently elaborated, to the galactic structures in his Baltimore lecture (*molecular dynamics and the wave theory of light*). Poincaré was impressed by this idea and computed the amount of stars in the Milky way necessary to explain the velocity of our sun one observes nowadays.



THE MILKY WAY AND THE THEORY OF GASES.*

H. POINCARÉ.†

equation of living forces. We thus find that this velocity is proportional to the radius of the sphere and to the square root of its density. If the mass of this sphere were that of the Sun and its radius that of the terrestrial orbit, it is easy to see that this velocity would be that of the Earth in its orbit. In the case that we have supposed, the mass of the Sun should be distributed in a sphere with a radius one million times larger, this radius being the distance of the nearest stars; the density is then 10^{18} times less; now the velocities are of the same order, hence it must be that the radius is 10^9 times greater, that is one thousand times the distance of the nearest stars, which would make about one thousand millions of stars in the Milky Way.

ence might long remain unknown? Very well then, that which Lord Kelvin's method would give us would be the total number of stars including the dark ones; since his number is comparable to that which the telescope gives, then there is no dark matter, or at least not so much as there is of shining matter.

Using the viral theorem, Poincaré computed first the density of stars around the sun, then supposing it constant, the radius of the sun to the galactic center, and then the number of stars in the Milky Way (~10^9) corresponding to the observations, thus discrediting the existence of dark matter, or dark stars.

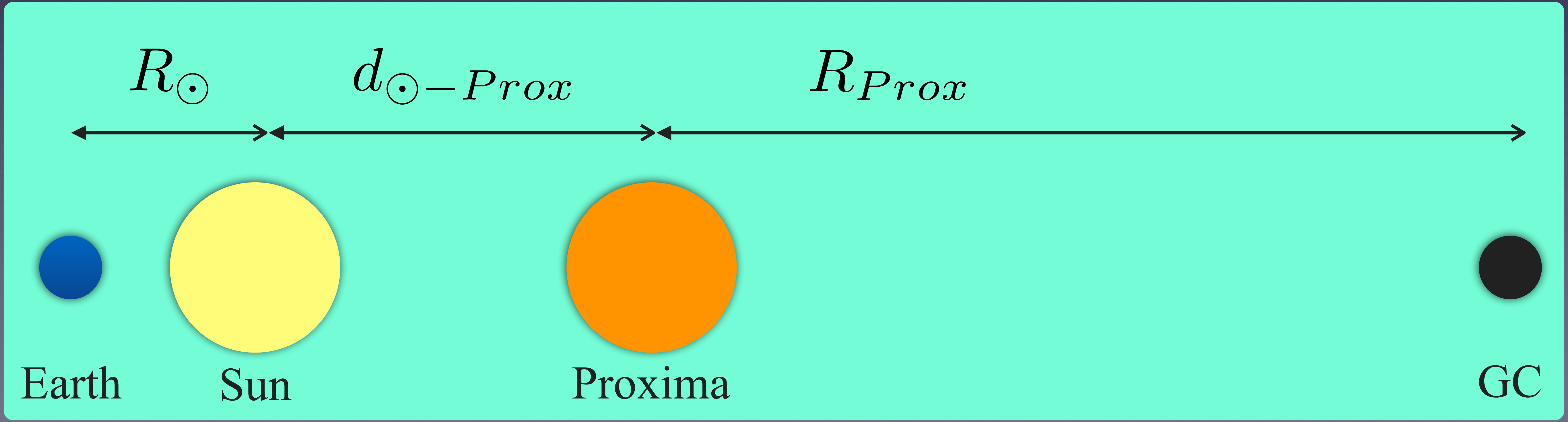
$$v(R) \propto R\sqrt{\rho}$$

$$\frac{v_{earth}(R_\odot)}{v_{sun}(R_{Prox})} = \frac{R_\odot}{R_{Prox}} \frac{\sqrt{\rho_\odot}}{\sqrt{\rho_{Prox}}}$$

$$d_{Prox-\odot} = 10^6 R_\odot \quad \Rightarrow \quad \rho_{Prox} = 10^{-18} \rho_\odot$$

$$v_{earth} \simeq v_{sun} \quad \Rightarrow R_{Prox} = 10^9 R_\odot$$

$$\Rightarrow N_{stars} = \rho_{Prox} \times R^3_{Prox} \simeq 10^9$$



« The waning of the WIMP? Review of Models, Searches and Constraints »

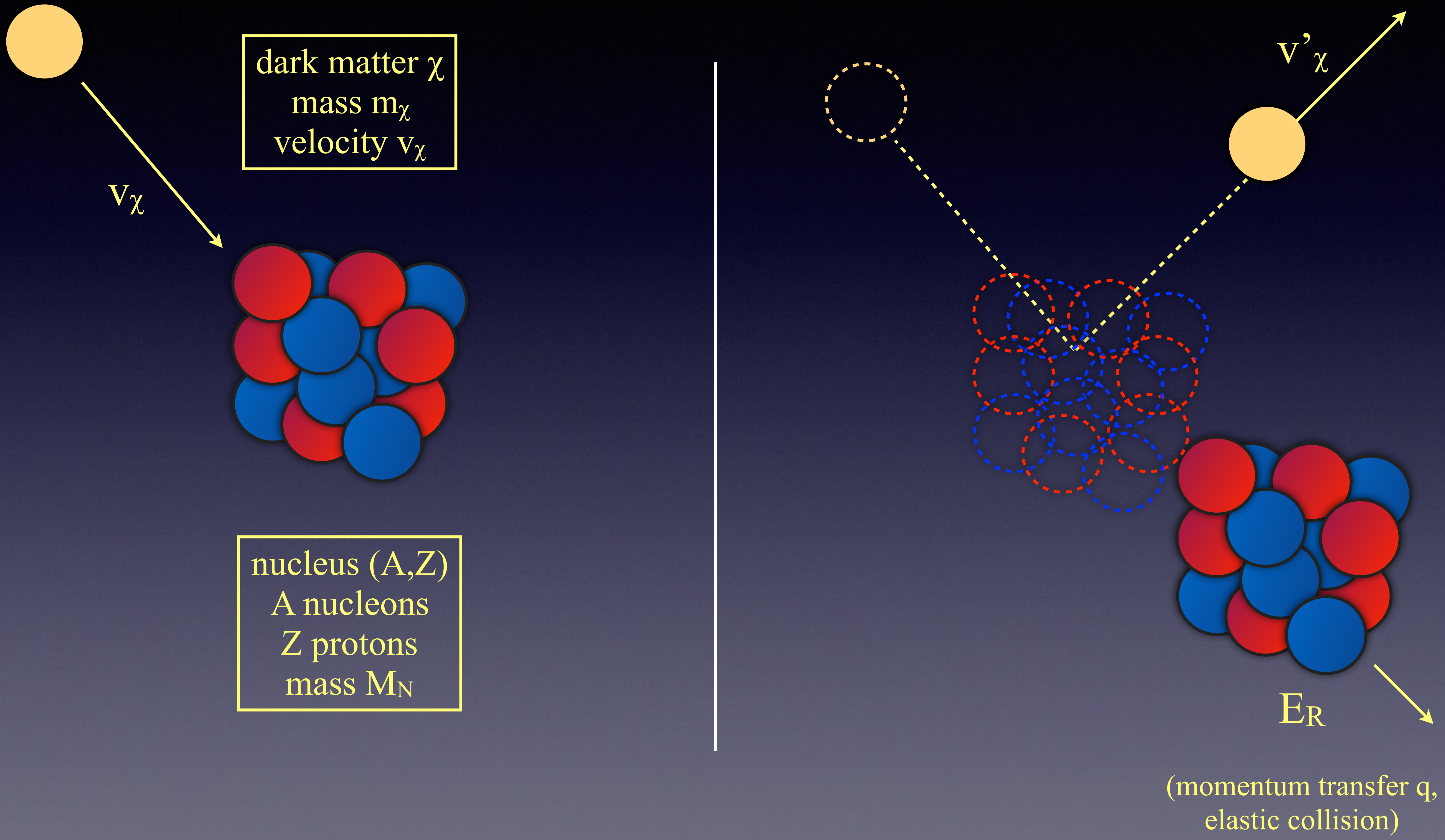
G. Arcadi, M. Dutra, .P. Ghosh, M. Lidner, Y.M.,
M. Pierre, S. Profumo and F. Queiroz;
arXiv:1703.07364

Where are we now?

1

The direct detection race

Direct detection of dark matter (basic principle)

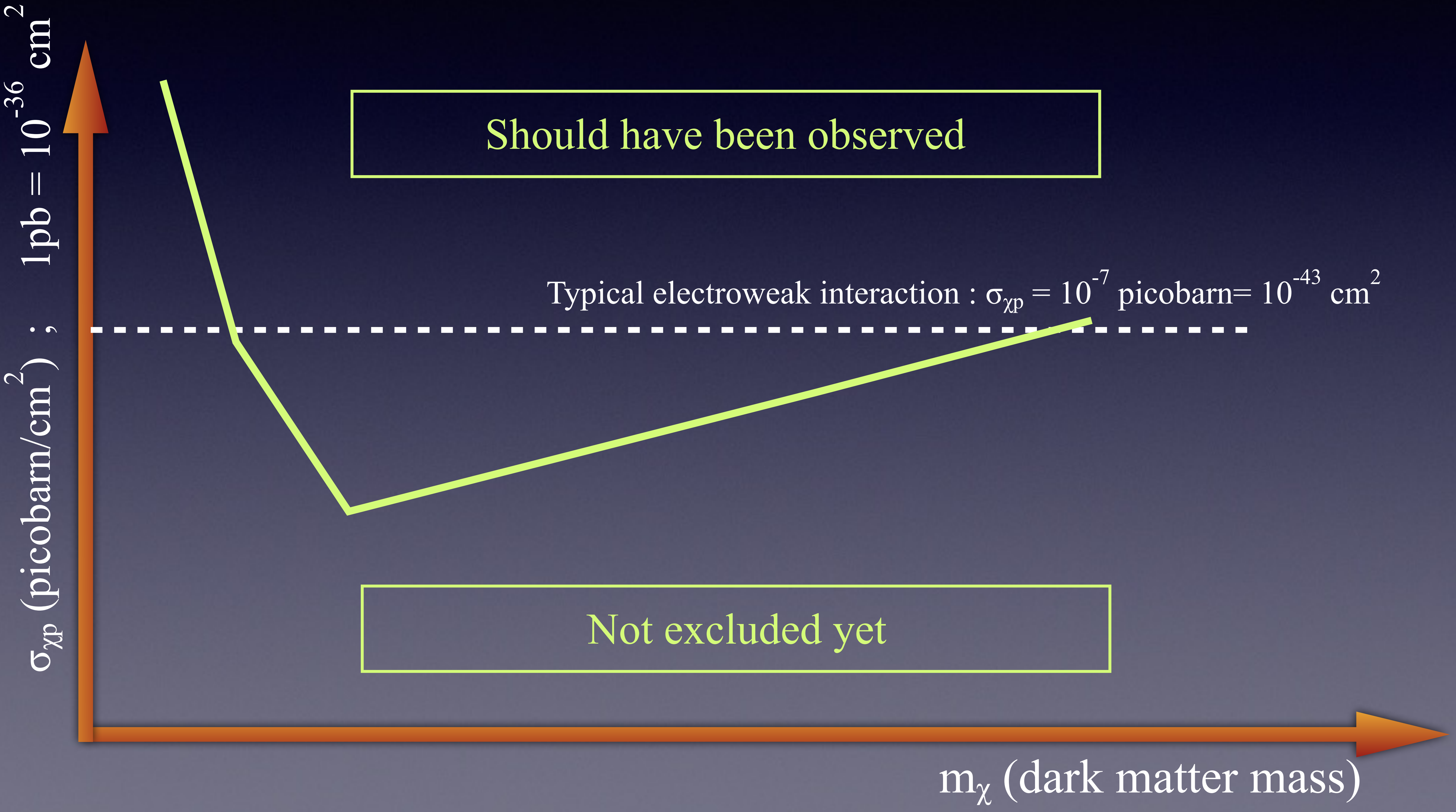


dark matter χ
mass m_χ
velocity v_χ

nucleus (A,Z)
A nucleons
Z protons
mass M_N

(momentum transfer q, elastic collision)

Direct detection of dark matter



$\sigma_{\chi p}$ (picobarn/cm^2) ; 1pb = 10^{-36} cm^2

Should have been observed

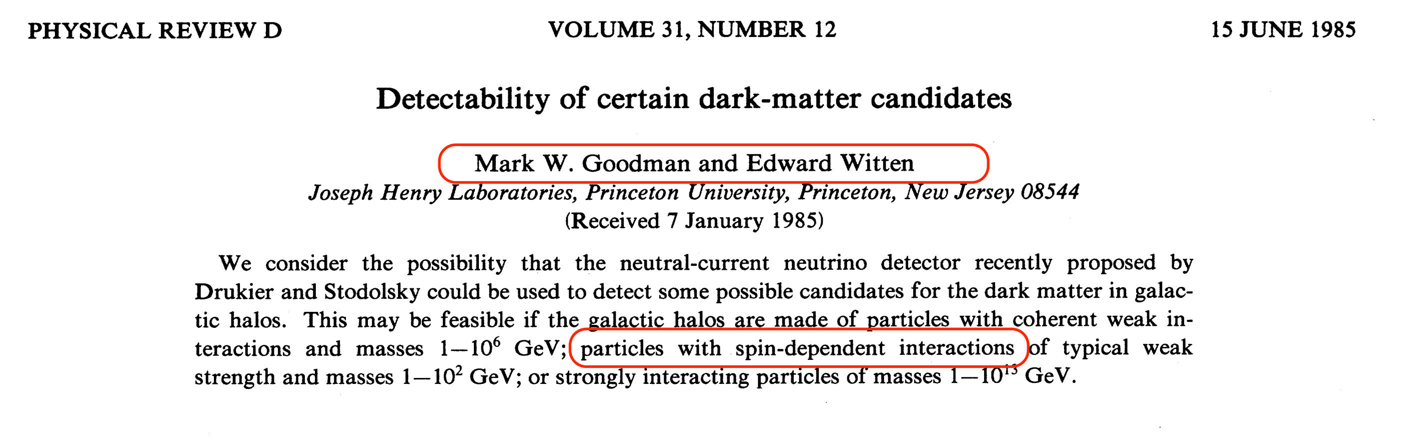
Typical electroweak interaction : $\sigma_{\chi p}$ = 10^{-7} picobarn= 10^{-43} cm^2

Not excluded yet

m_χ (dark matter mass)

The theoretical principle

A paper of Goodman and Witten of 1985 (same year than the second « string revolution »)



PHYSICAL REVIEW D   VOLUME 31, NUMBER 12   15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544

(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses 1—10^6 GeV; particles with spin-dependent interactions of typical weak strength and masses 1—10^2 GeV; or strongly interacting particles of masses 1—10^{13} GeV.

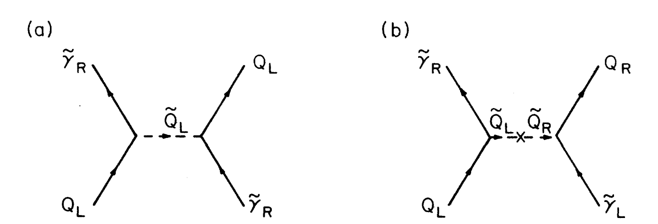
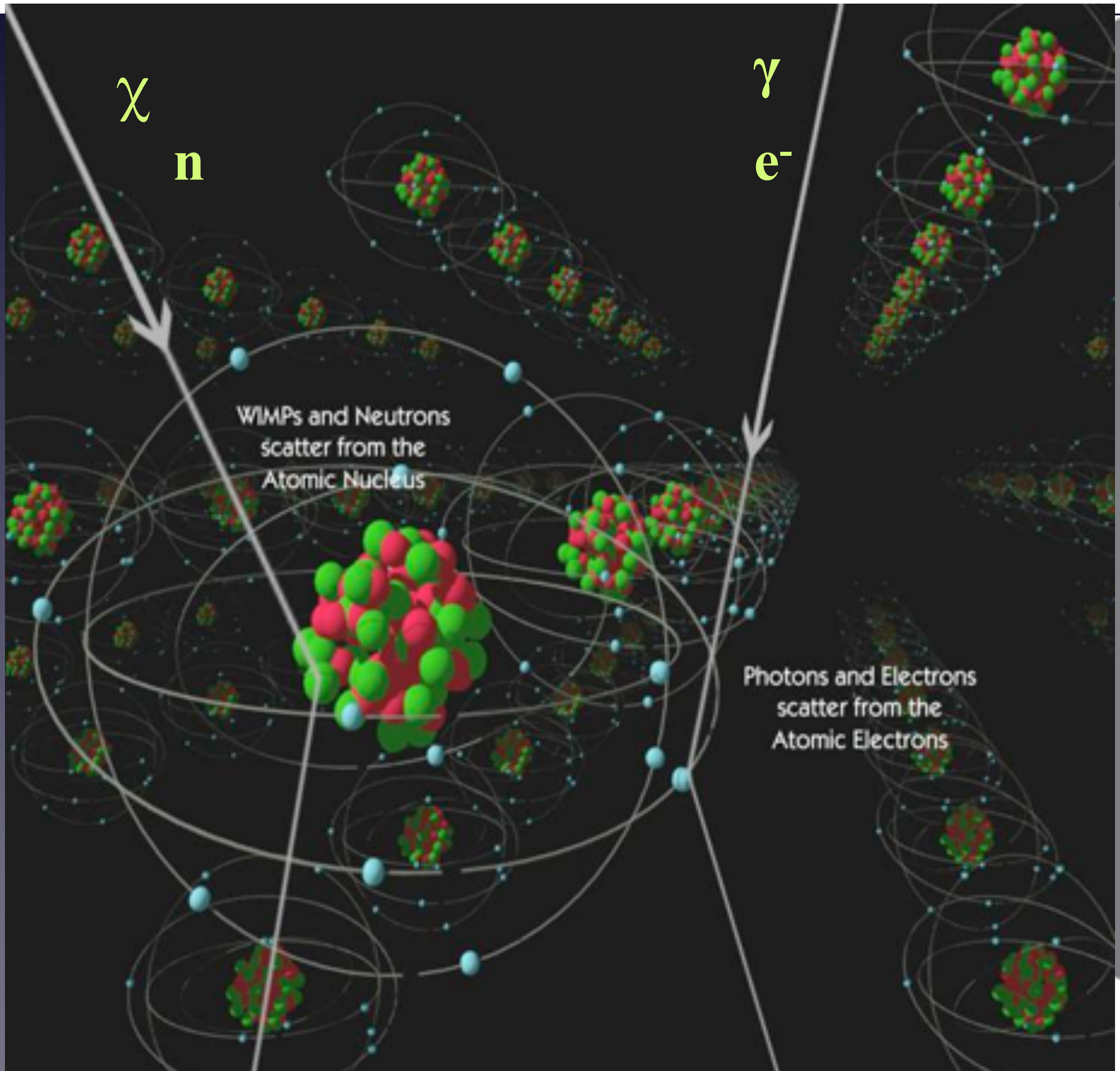
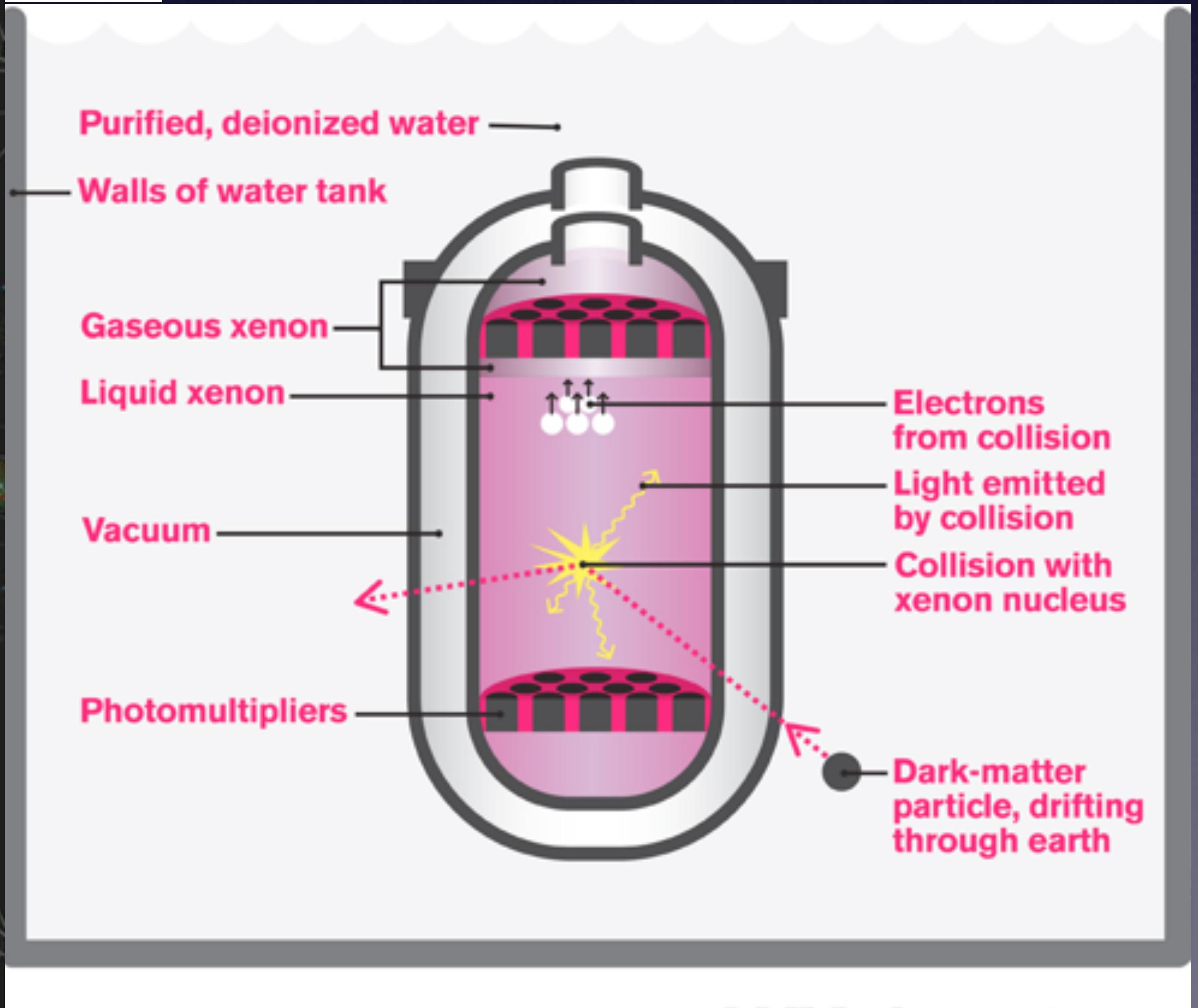


FIG. 1. Exchange of a scalar quark mediates a quark-photino interaction. Part (a), which is always present, gives a spin dependent force; (b), which is present only if there is strong mixing of left- and right-handed scalar quarks, gives a coherent interaction.





Purified, deionized water

Walls of water tank

Gaseous xenon

Liquid xenon

Vacuum

Photomultipliers

Electrons from collision

Light emitted by collision

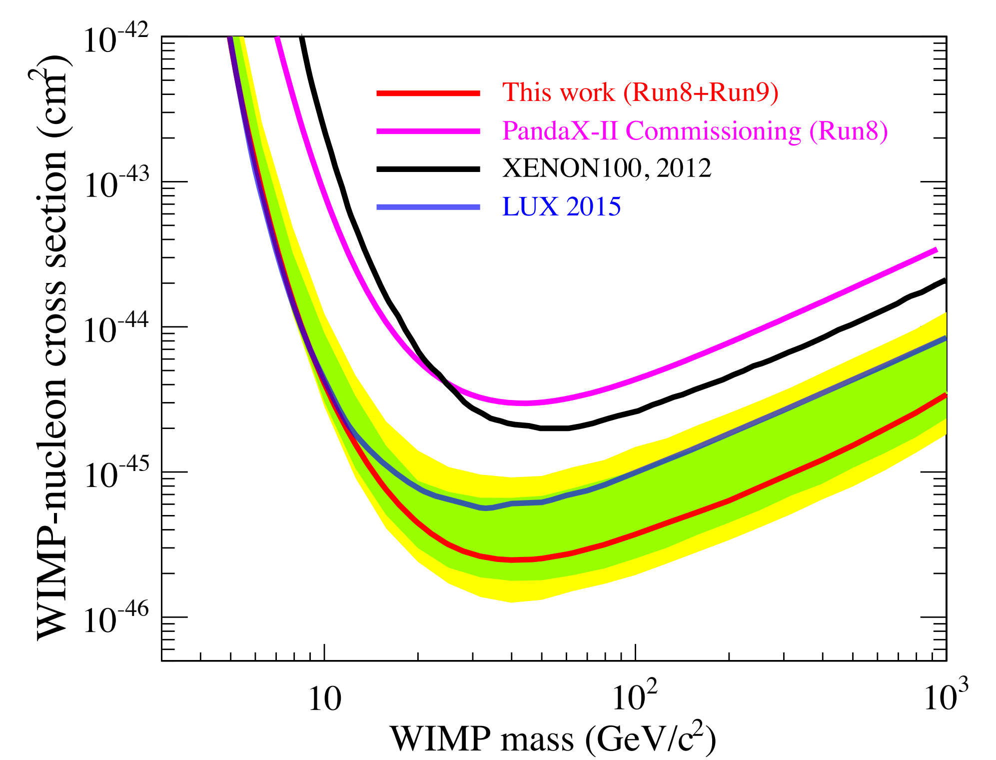
Collision with xenon nucleus

Dark-matter particle, drifting through earth

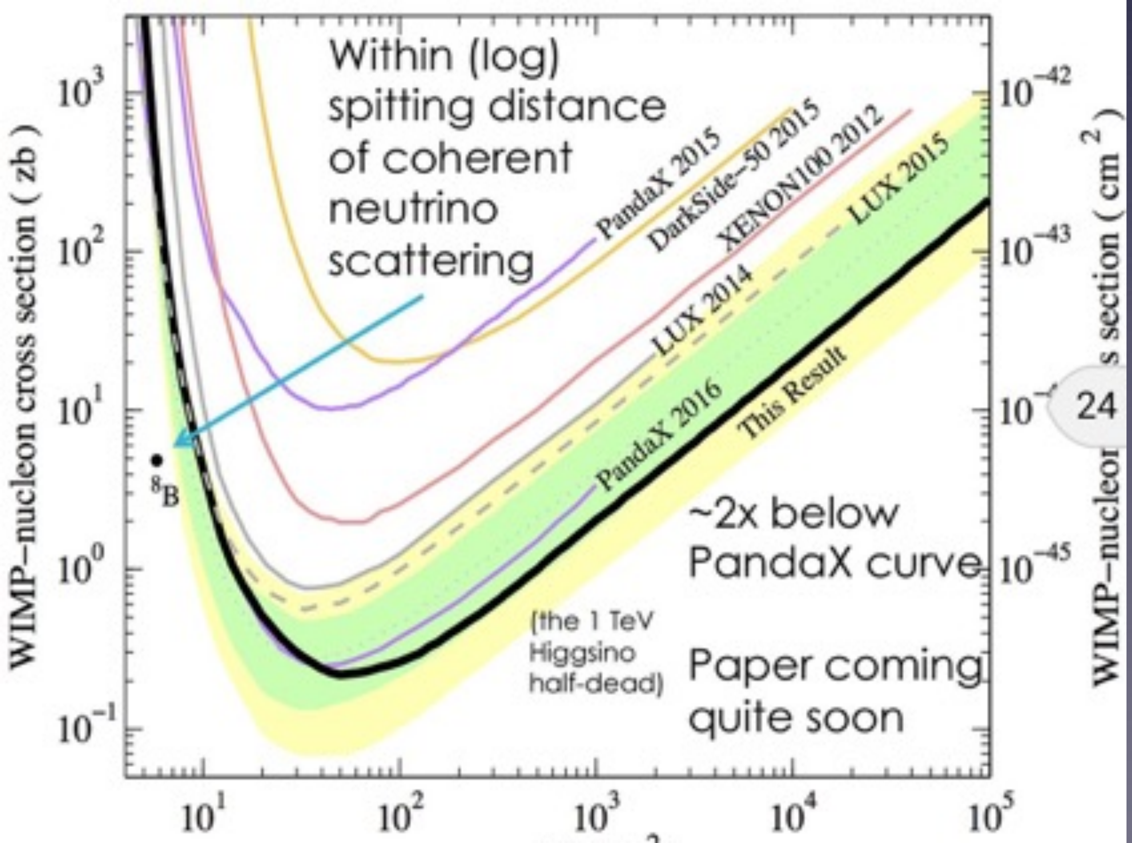
LUX detector

December 2015, the **LUX** collaboration released the best limit on direct detection cross section : **6×10^{-46} cm^2** for a WIMP mass of 40 GeV

July 2016, **PANDAX-II**, after having eliminated the Krypton background early 2016 (by distillation) reached **2.5×10^{-46} cm^2** for a WIMP mass of 40 GeV (March to June 2016 campaign, run 9). One order (!!) of magnitude better than in 2015.



August 2016, **LUX** released a new analysis, giving slightly better limit than **PANDAX-II**:



Within (log) spitting distance of coherent neutrino scattering

~2x below PandaX curve

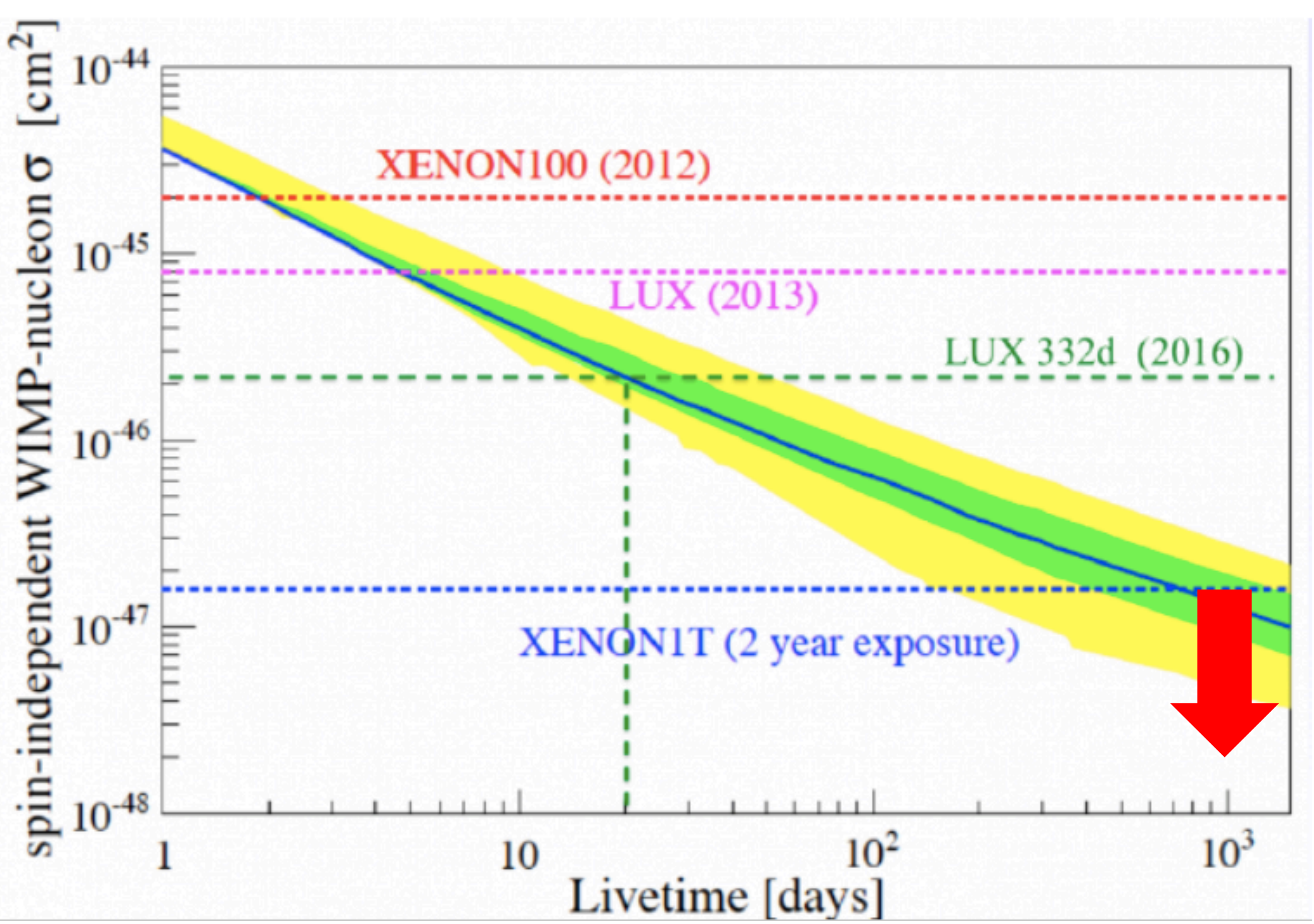
(the 1 TeV Higgsino half-dead)

Paper coming quite soon

• • •

August 2016, the **XENON** collaboration claimed that the latest 332 days LUX limit will be reached by XENON 1T by the end of the year, in less than 20 days!!

XENON1T Sensitivity Projection

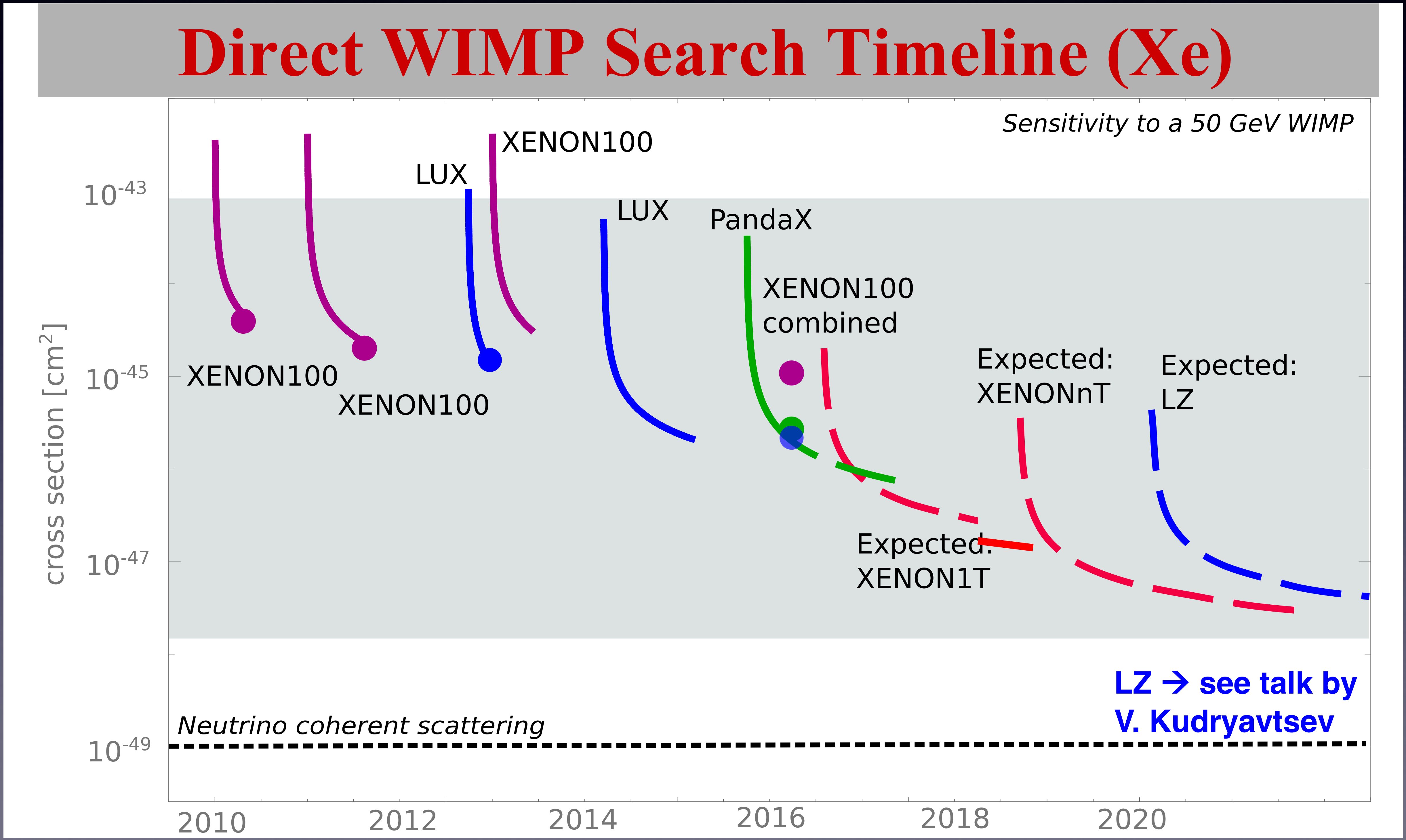


and then XENONnT
→ 20ty
→ x10

is built while XENON1T is running; reuses most parts → faster

• • •

September 2016, **LZ** (**LUX** + **ZEPLIN**) collaboration confirmed that they obtained the DoE approval, beginning the hunt in 2020. LZ consist of 10 tons detector. The entire supply of XENON is already under contract and will be supply under the help of the South Dakota sate.



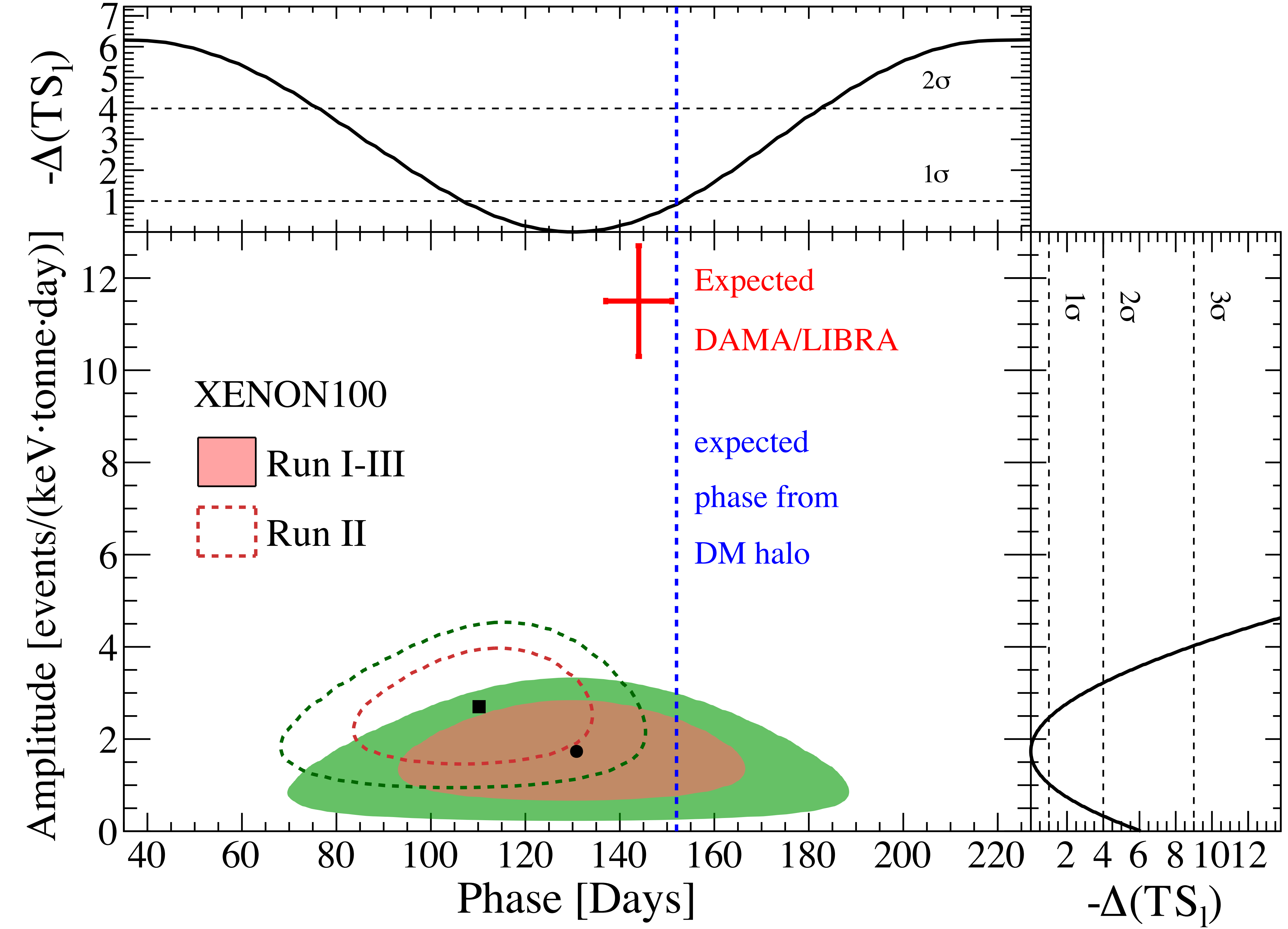
Direct WIMP Search Timeline (Xe)

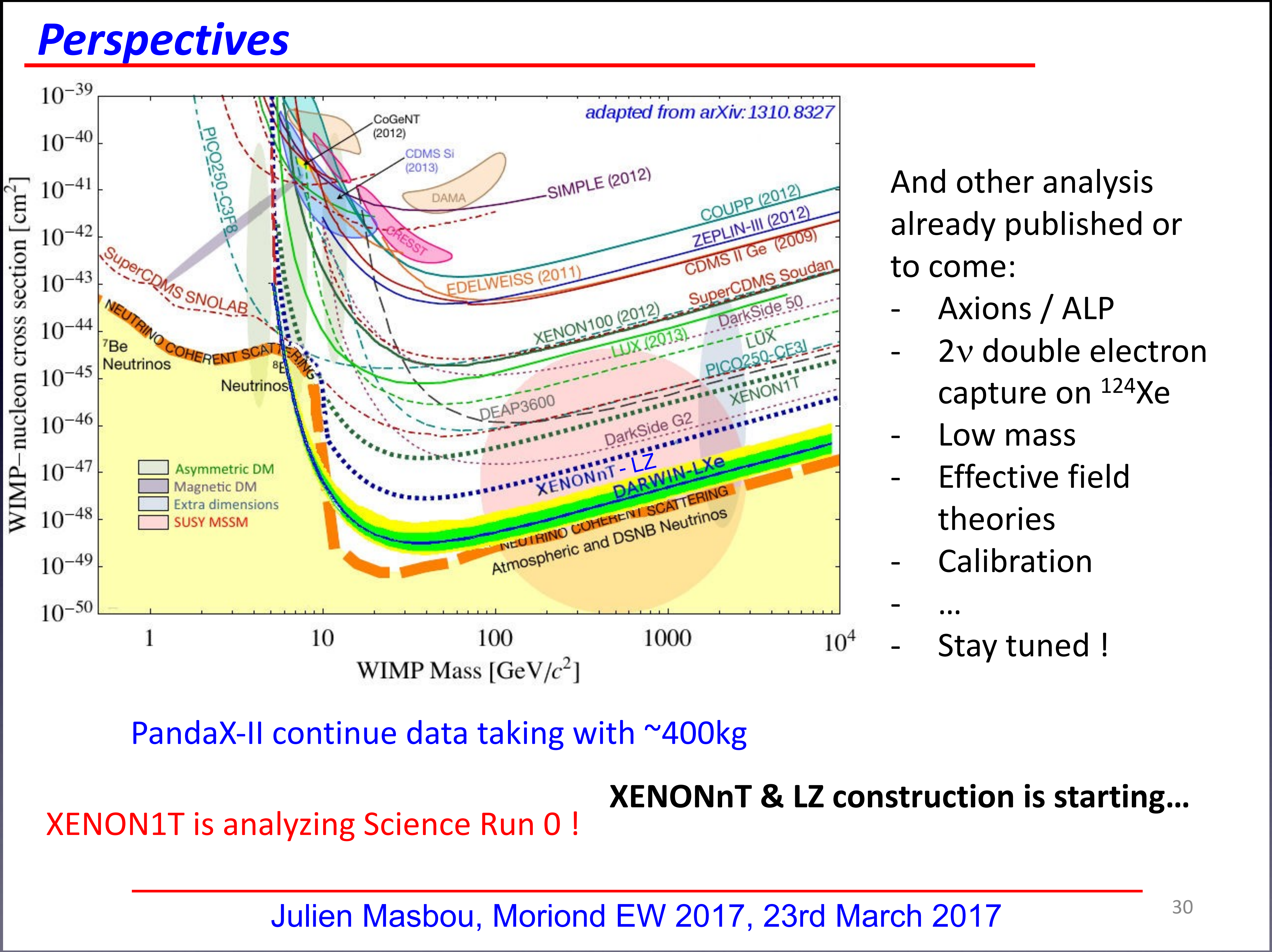
LZ → see talk by V. Kudryavtsev

No oscillation observed at XENON100

arXiv:1701.00769

Which excludes DAMA signal at 5.7σ





Perspectives

And other analysis already published or to come:

- Axions / ALP
- 2ν double electron capture on ^{124}Xe
- Low mass
- Effective field theories
- Calibration
- …
- Stay tuned !

PandaX-II continue data taking with ~400kg

XENONnT & LZ construction is starting…

XENON1T is analyzing Science Run 0 !

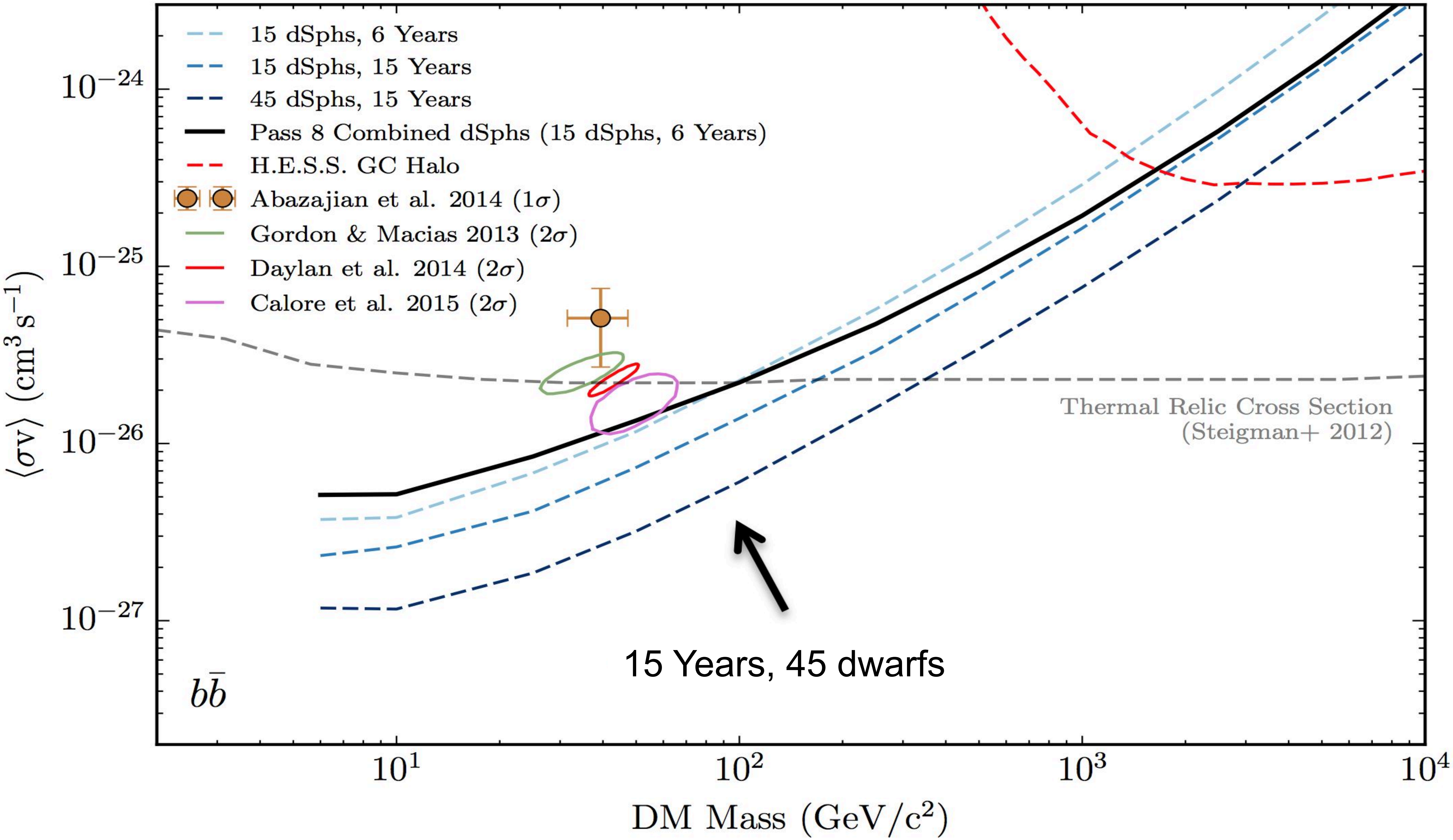
Julien Masbou, Moriond EW 2017, 23rd March 2017

Darwin : maybe, but I won't see it

2

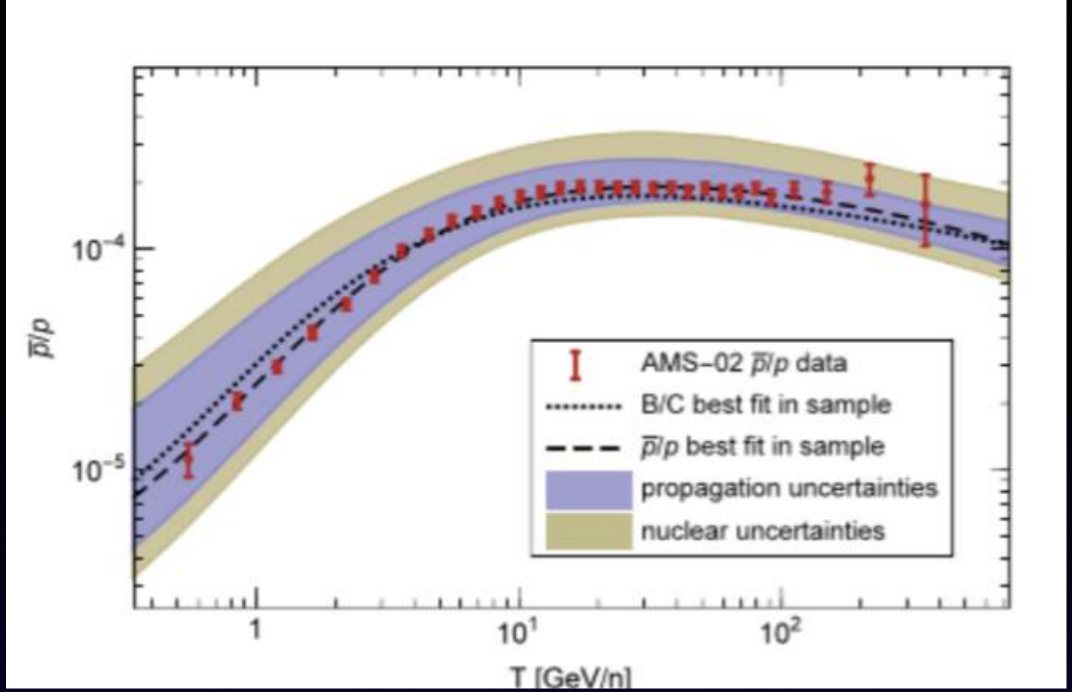
The indirect detection status

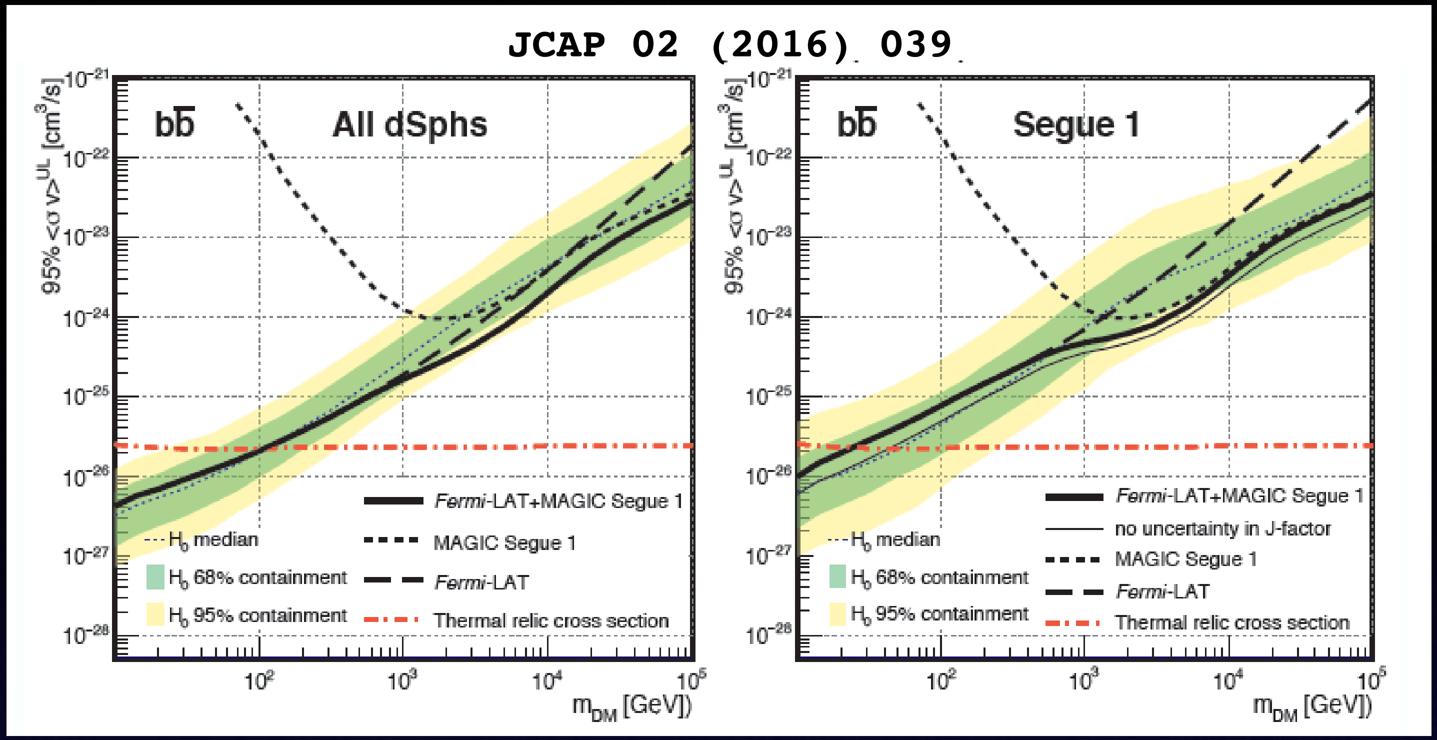
DM limit improvement estimate in 15 years with the composite likelihood approach (2008- 2023)



E. Charles et.al, Phy Rep. 636 2016, arXiv:1605.02016

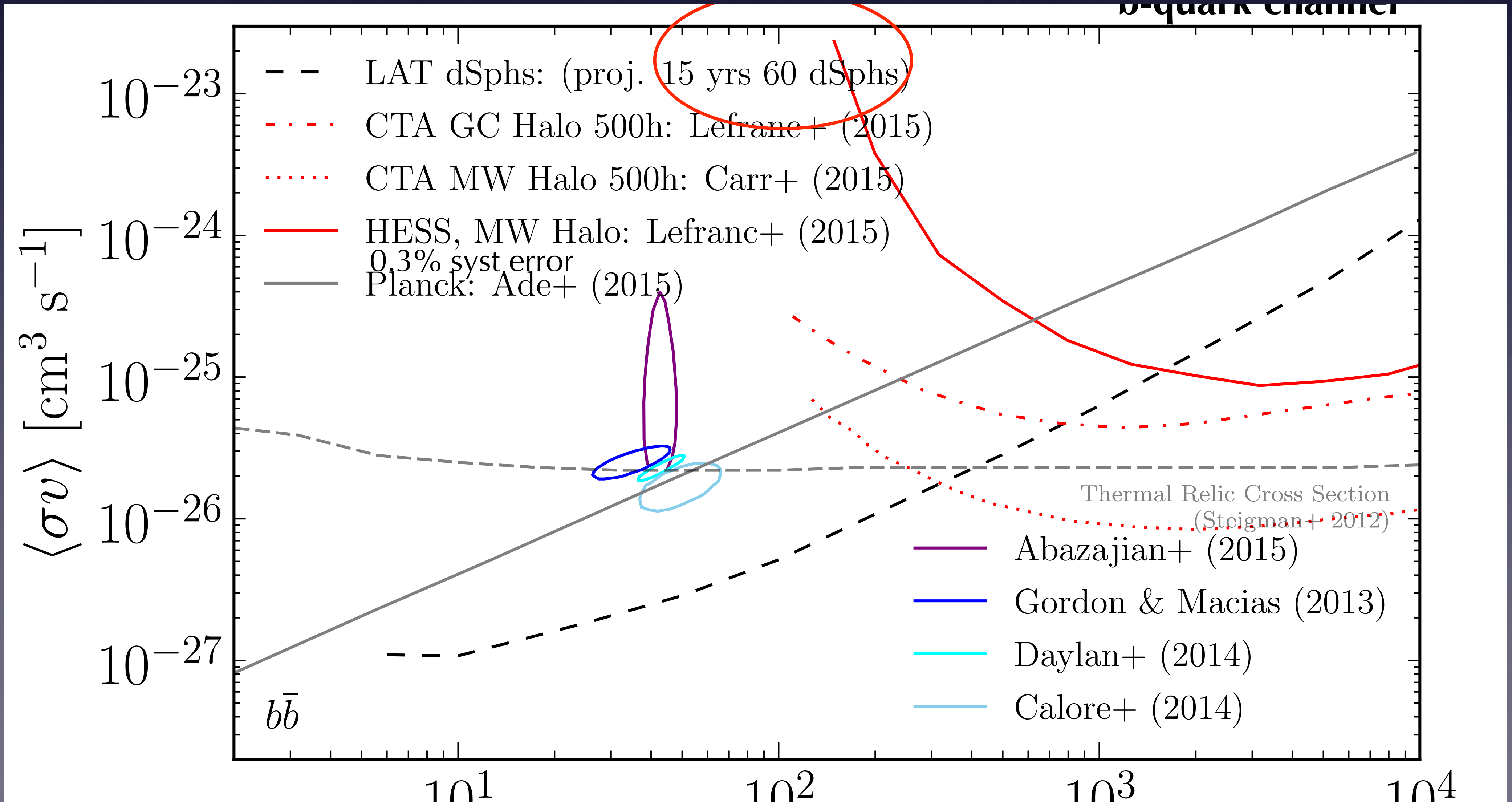
Latest result by FERMI in May: nothing




JCAP 02 (2016) 039

AMS : nothing

MAGIC : nothing



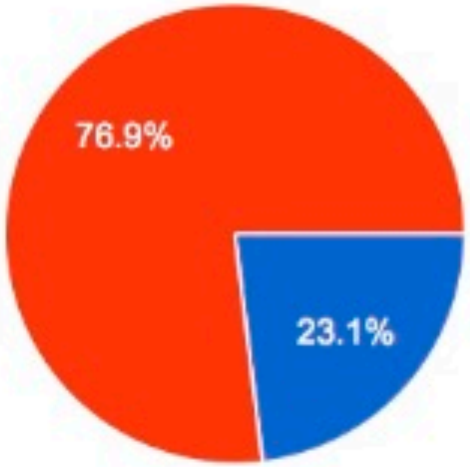
HESS : nothing

CTA : ??

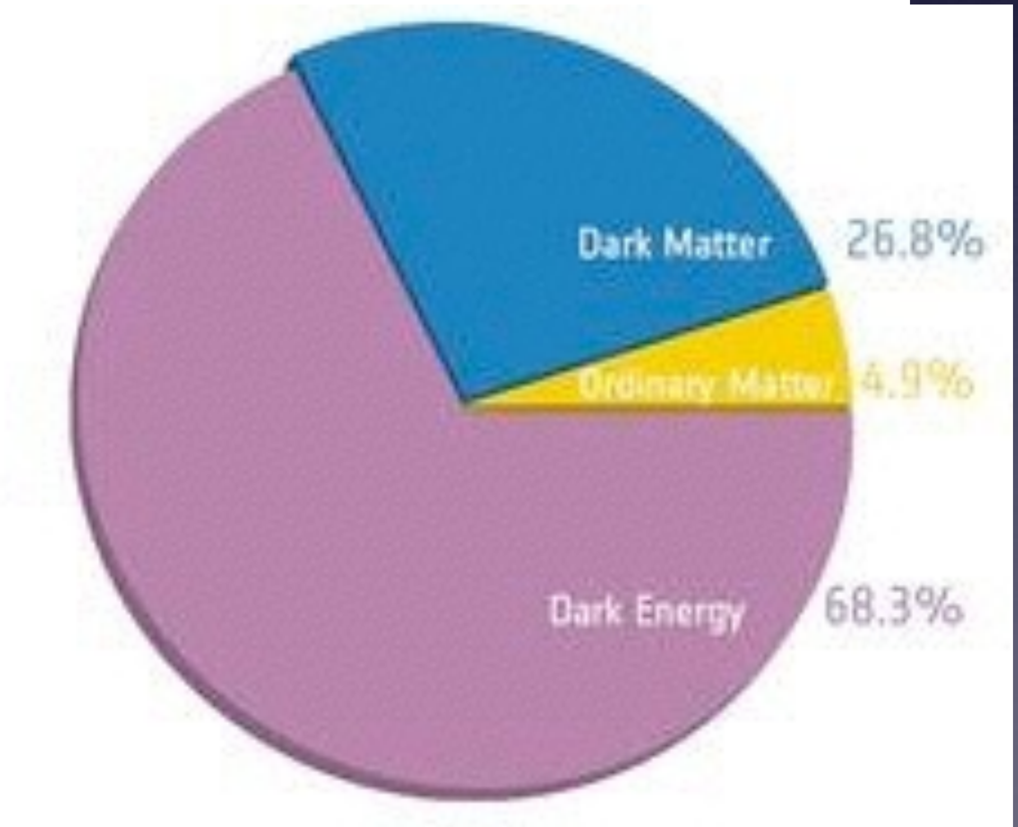
Pool at IFT workshop, September 2016

Will dark matter (either WIMP, axions or other) be detected in the next fifteen years?

No	**12**	23.1%
Yes	**40**	76.9%



At least optimism…



Models

Developing a microscopical approach

On which principle should we extend the microscopic interaction?

Ockham, in Cambridge
13th century

Ockham's razor (*lex parsimoniae*) principle :

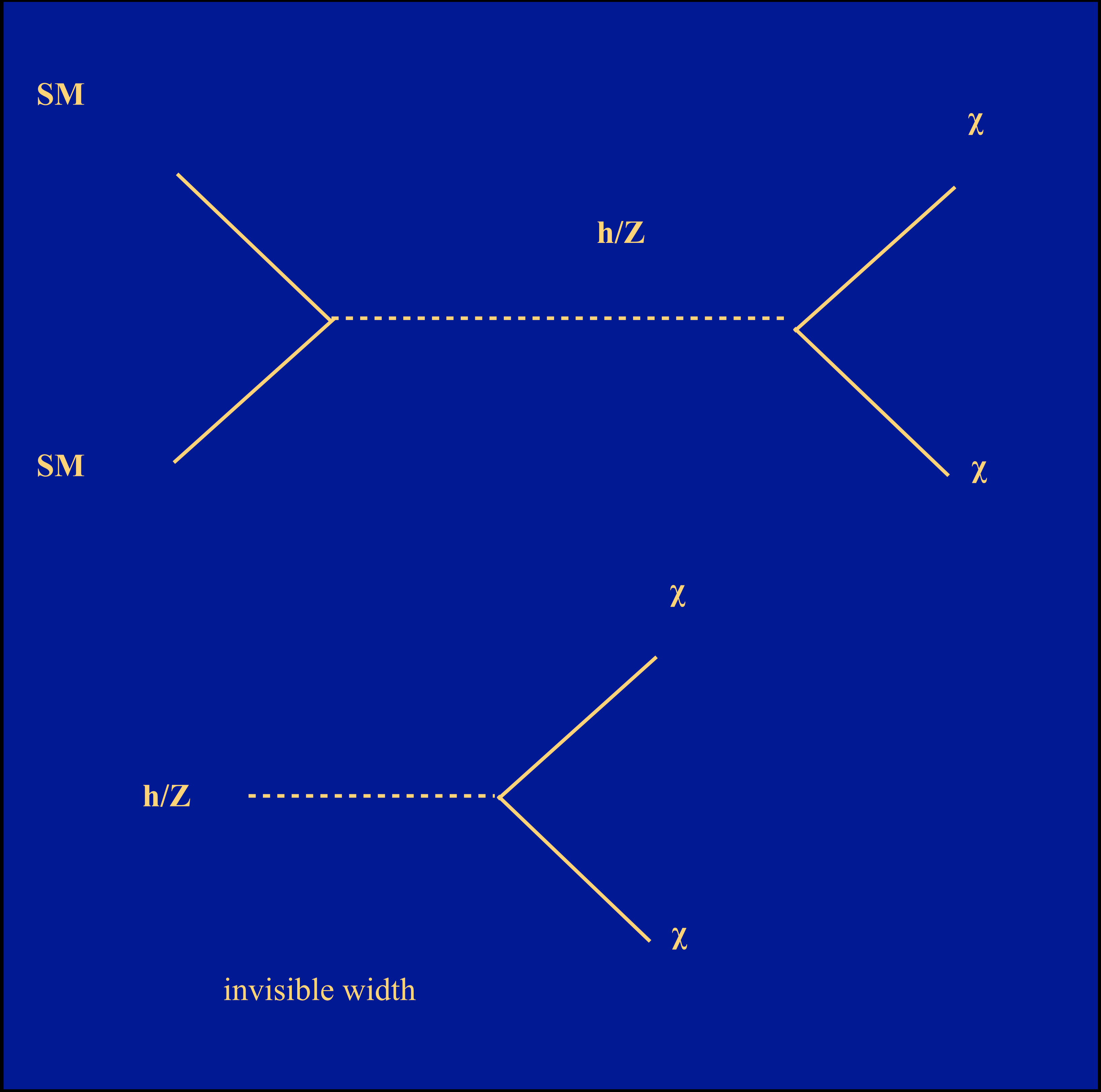
« Pluralitas non est ponenda sine necessitate »

Among competing hypotheses, the one with the fewest assumptions should be selected

(everything should be made as simple as possible..)

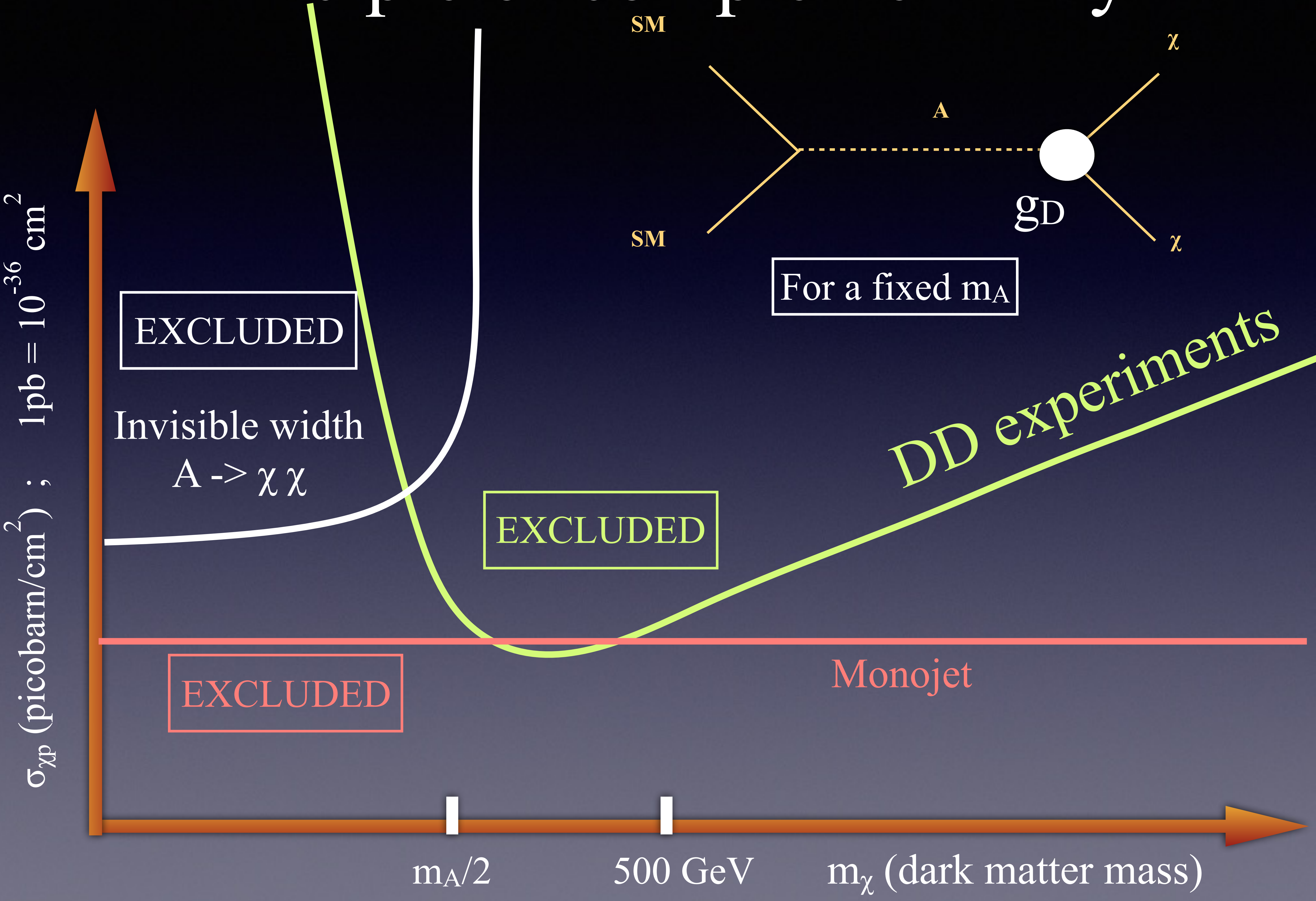
Dark matter couple only with the Standard Model (SM) particles : Higgs-portal, Z-portal, sterile neutrino. Consequences on observables are strong:

Invisible width of the Higgs/Z, LHC/LEP production in the case of portal models, instability and production of monochromatic photons in the case of sterile neutrino.



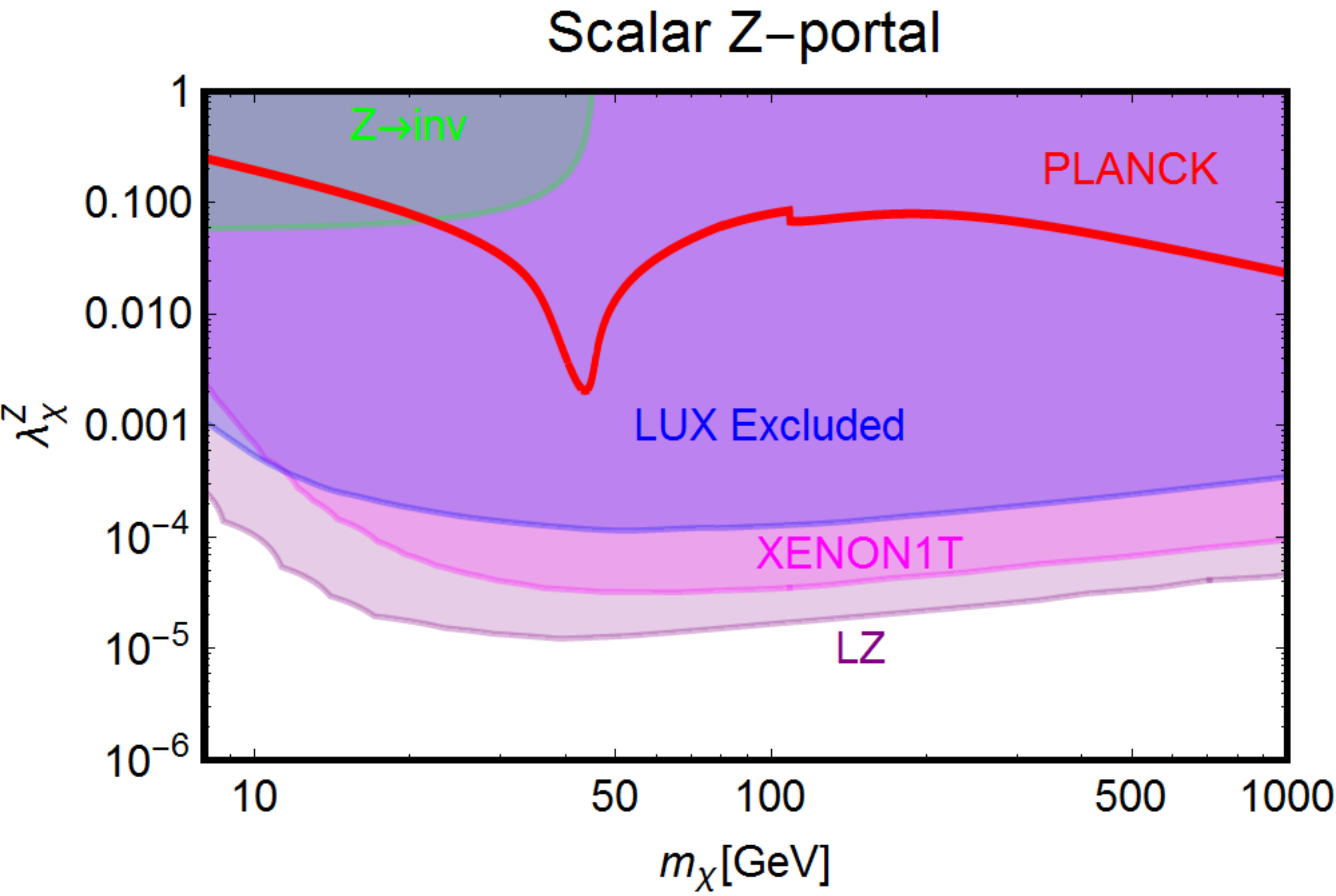
The accelerators constraints are on the measurement of the invisible width of H and Z

Principle of complementarity



Z-portal : scalar DM

$$\mathcal{L} = \lambda_\chi \frac{H^\dagger \overleftrightarrow{D^\mu} H}{\Lambda^2} \chi^* \overleftrightarrow{\partial_\mu} \chi,$$

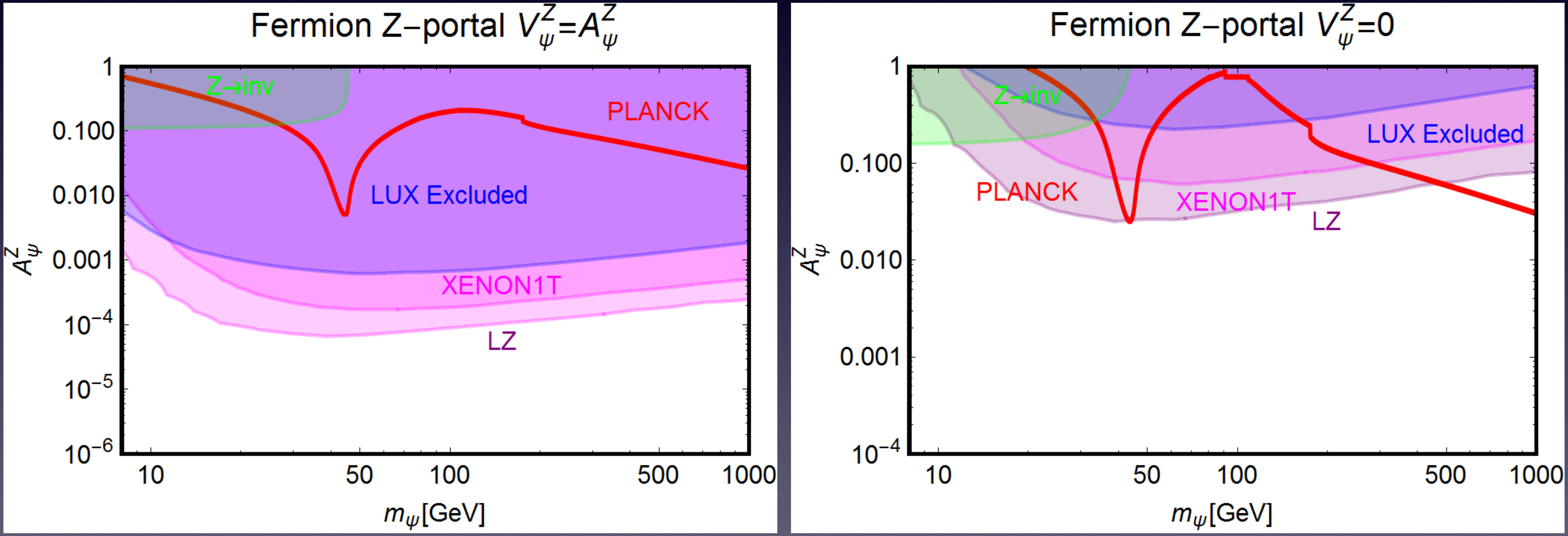


G. Arcadi, Y. M. and F. Richard, JCAP **1503** (2015) 018

G. Arcadi, M. Dutra, .P. Ghosh, M. Lidner, Y.M., M. Pierre, S. Profumo and F. Queiroz; arXiv:1703.07364

Z-portal : fermionic DM

$$\mathcal{L} = \frac{g}{4\cos\theta_W}\overline{\psi}\gamma^{\mu}\left(V_{\psi}^{Z} - A_{\psi}^{Z}\gamma^{5}\right)\psi Z_{\mu}$$

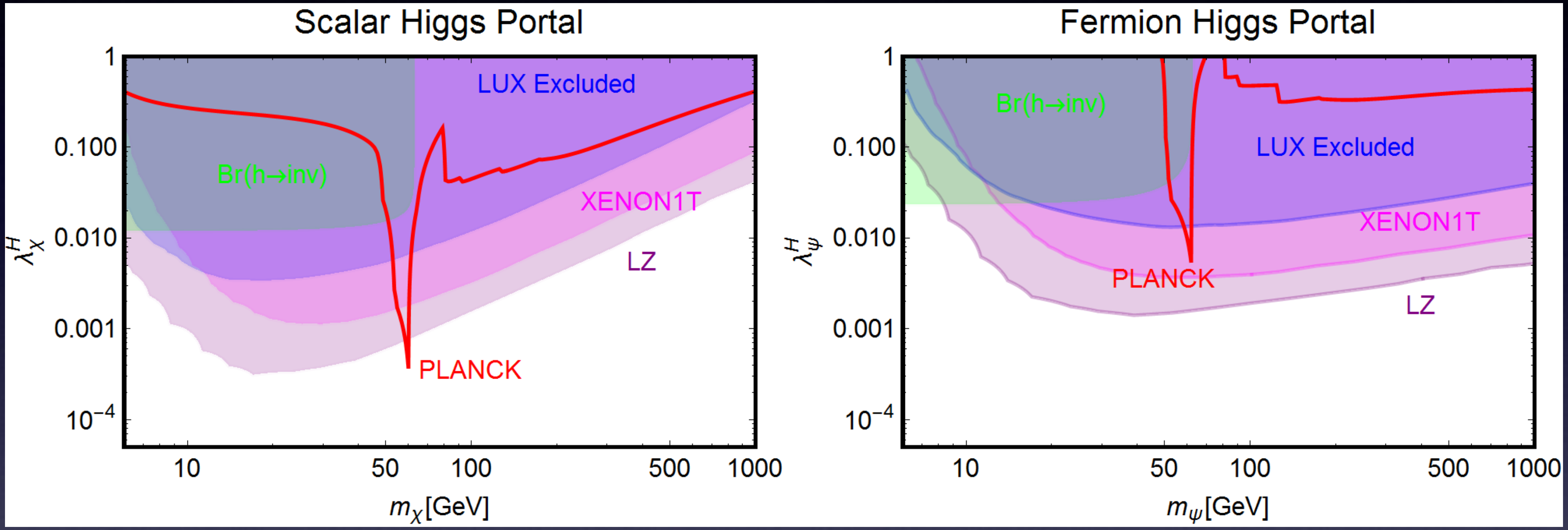


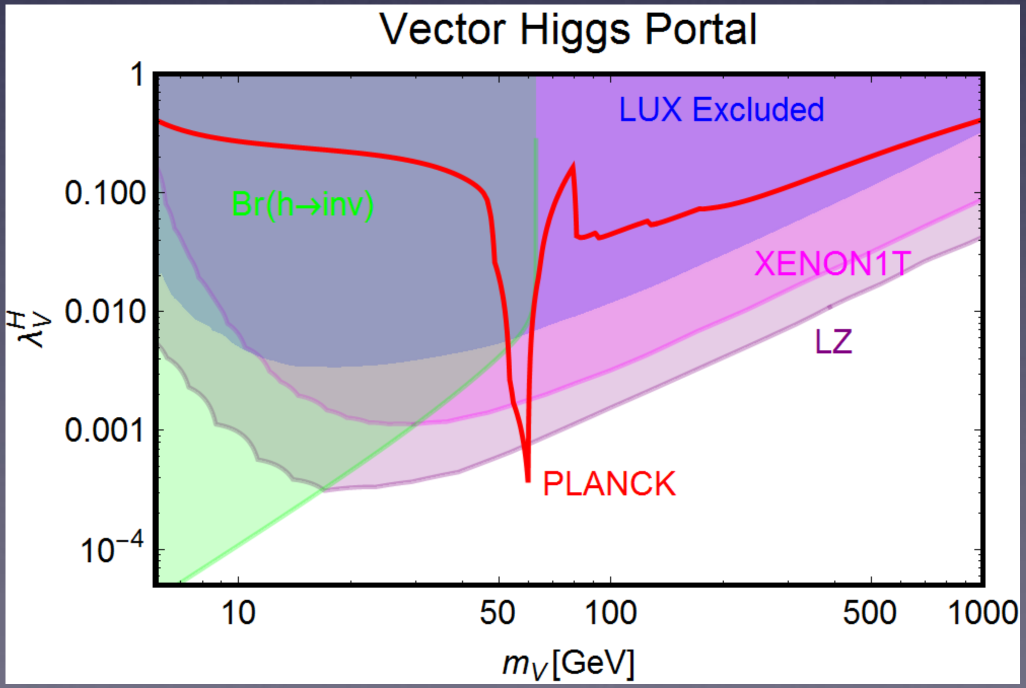
G. Arcadi, Y. M. and F. Richard, JCAP **1503** (2015) 018

G. Arcadi, M. Dutra, .P. Ghosh, M. Lidner, Y.M., M. Pierre, S. Profumo and F. Queiroz; arXiv:1703.07364

Higgs-portal

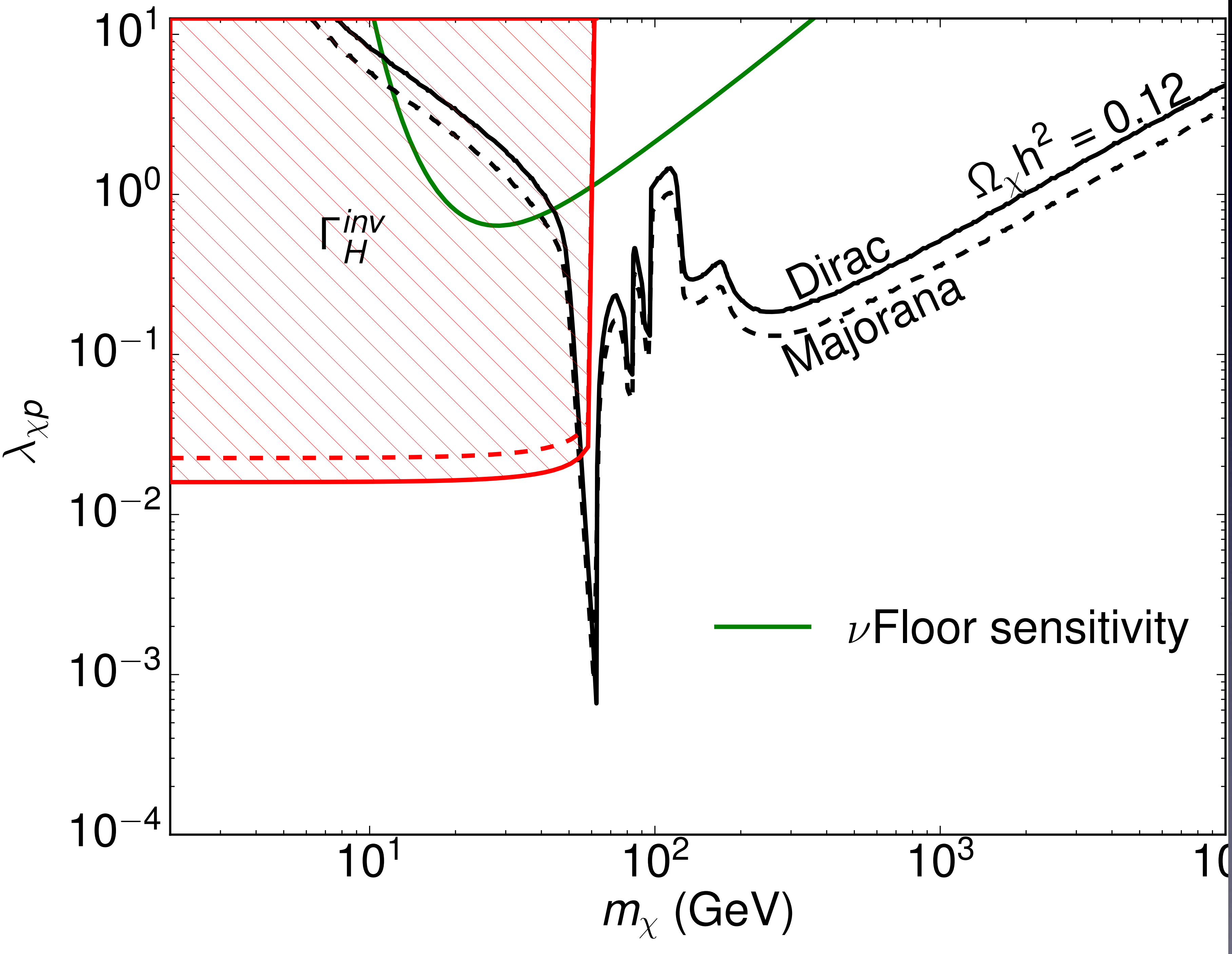
$$\xi\lambda_\chi^H \chi^*\chi H^\dagger H, \qquad \xi\frac{\lambda_\psi^H}{\Lambda}\overline{\psi}\psi H^\dagger H \quad \text{and} \quad \xi\lambda_V^H V^\mu V_\mu H^\dagger H,$$





G. Arcadi, M. Dutra, .P. Ghosh, M. Lidner, Y.M., M. Pierre, S. Profumo and F. Queiroz; arXiv:1703.07364

Higgs-portal : fermionic DM with pseudo scalar coupling



Escudero et al. 1609.09079

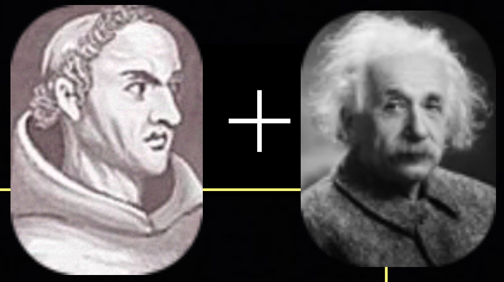
Conclusion

Only Majorana DM > 100 GeV with Z-portal,

or DM with the pseudo scalar coupling to the Higgs with mass> $m_h/2$ survive.

Not a lot of changes in the next generation of DD experiments

G. Arcadi, M. Dutra, .P. Ghosh, M. Lidner, Y.M., M. Pierre, S. Profumo and F. Queiroz; arXiv:1703.07364

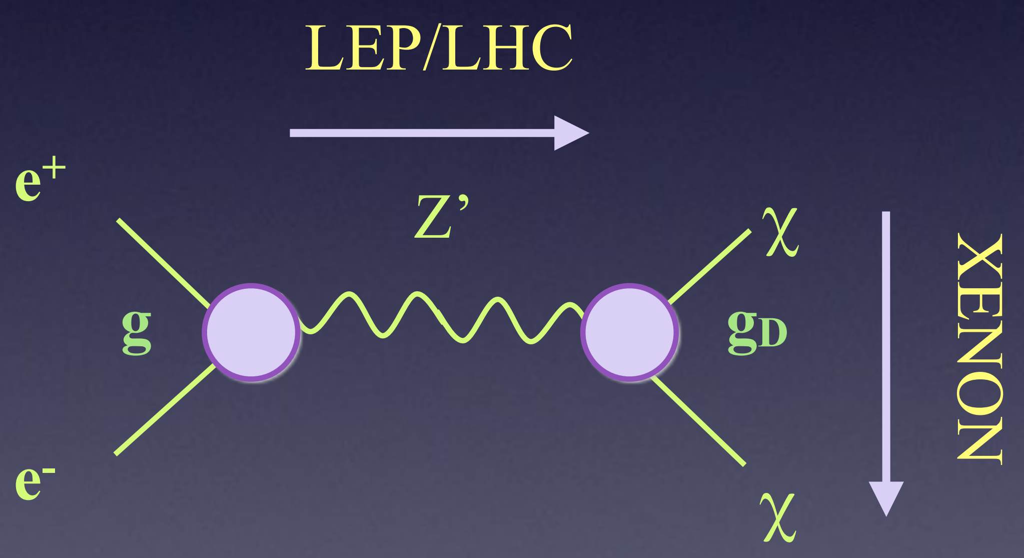


Ockham's razor (*lex parsimoniae*) extended principle :

« Everything should be made as simple as possible.. But not simpler »

Einstein's razor principle (Oxford 1933)

Dark matter couples not only with the Standard Model particles but there exist a dark sector (can be gauged or dynamical) which plays the rôle of the mediator: Z'-portal, supersymmetry or KK modes. Consequences on observables are less strong: no constraints on invisible branching ratio, **light dark matter window is re-opened.**

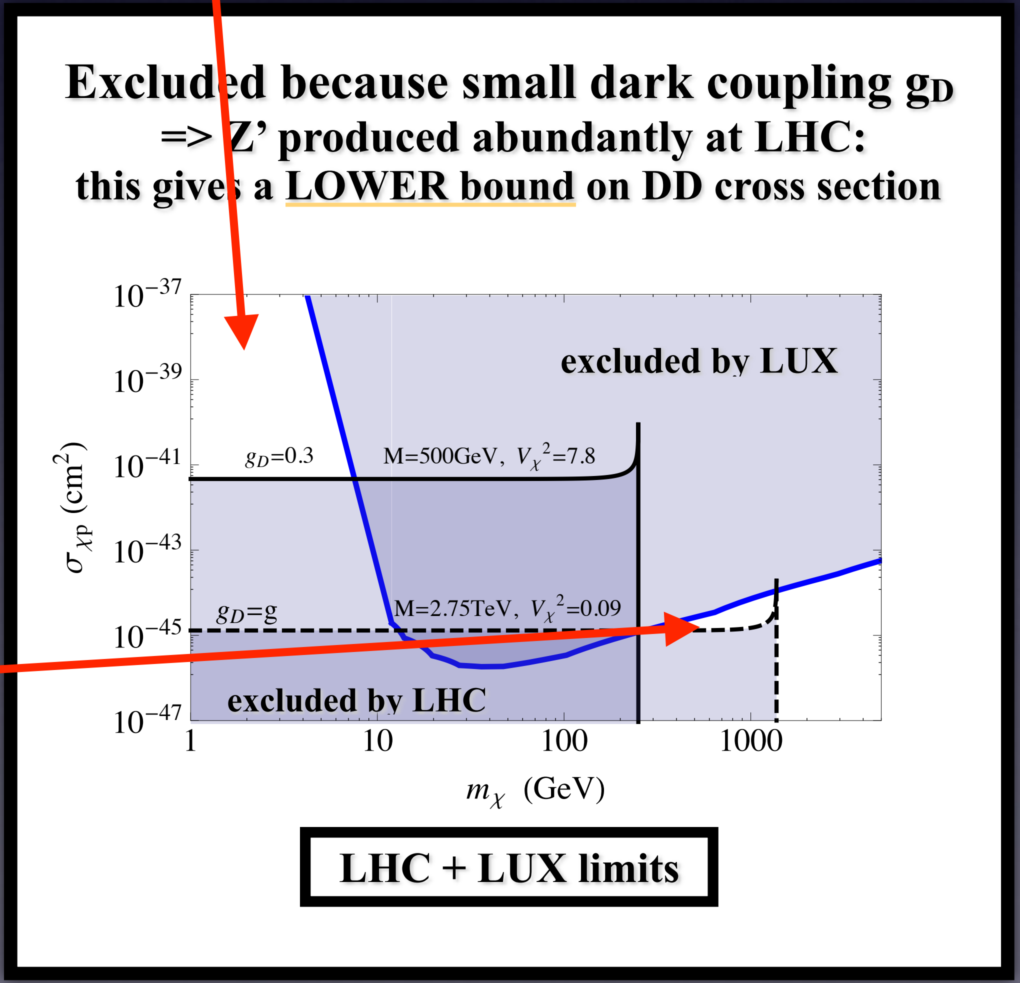


BUT constraints on non-production of Z'

excludes low values for g_D!

(small g_D means Z' should have been observed).

These kind of models already exclude WIMP dark matter (dark matter should be heavier than ~ 300 GeV)



Excluded because small dark coupling g_D => Z' produced abundantly at LHC: this gives a LOWER bound on DD cross section

LHC + LUX limits

G. Arcadi, Y. M., M. Tytgat and B. Zaldivar, JHEP **1403** (2014) 134 ; arXiv:1401.0221

In SO(10) framework

Z' models are motivated by plethora of SM extensions. In unified models, the SM gauge group [rank 4] is embedded into larger representations **SO(10)** [rank 5] or **E6** [rank 6].
Which means, **SO(10)** [**E6**] contain 1 [2] extra U(1)[s] which can be broken at a TeV scale, observable at the LHC

Examples of breaking patterns :

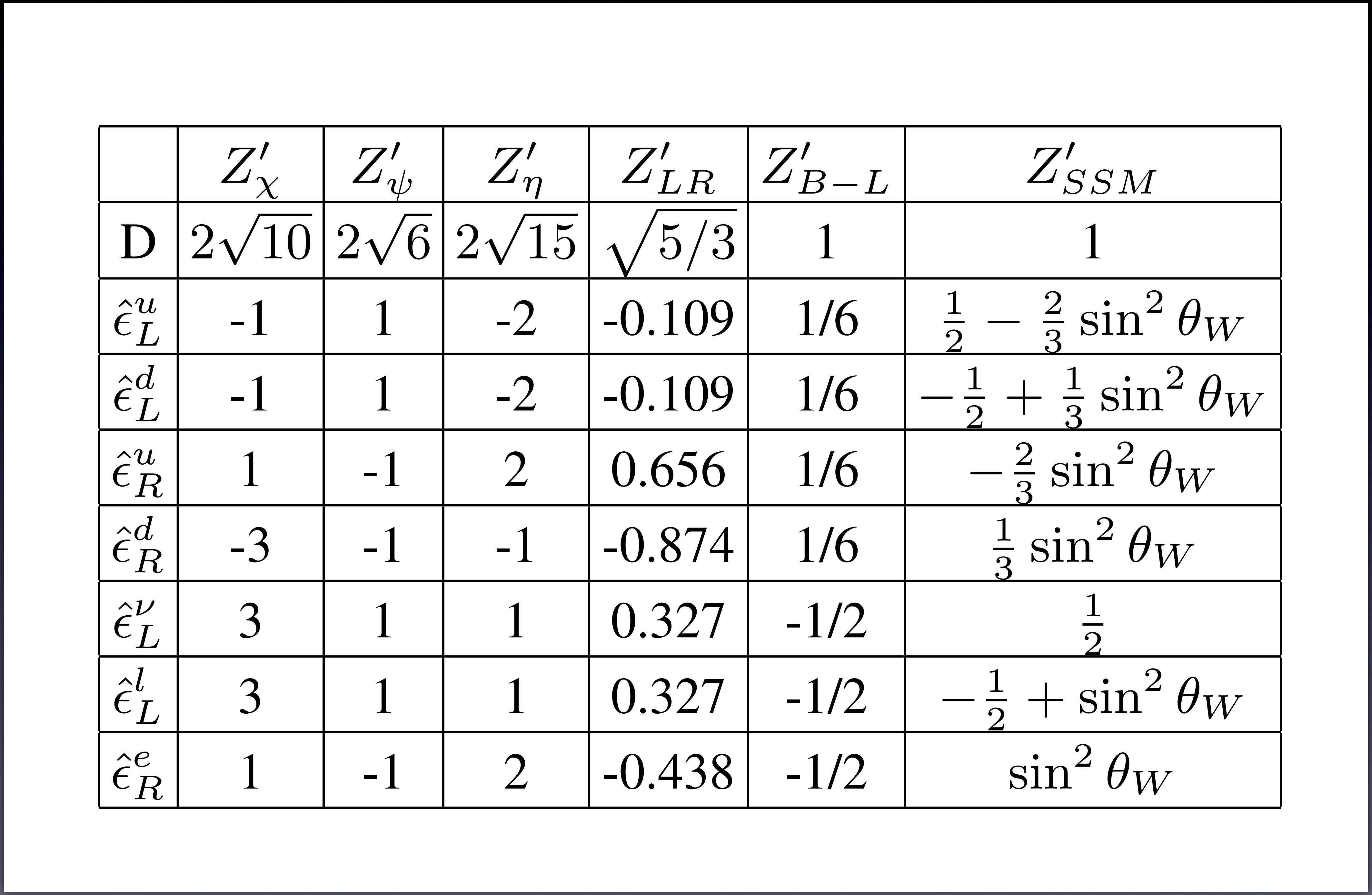
SO(10) -> $SU(3)_C$. $SU(2)_L$. $U(1)_R$. $U(1)_{B-L}$ [Z'_{B-L}]

E_6 -> SO(10) . $U(1)_\psi$ -> SU(5) . $U(1)_\chi$. $U(1)_\psi$ [Z'_χ , Z'_ψ]

E_6 -> SO(10) . $U(1)_\psi$ -> SU(4) . $SU(2)_L$. $SU(2)_R$. $U(1)_\psi$ [Z'_{B-L} , Z'_ψ]

Y. M., K.A. Olive, J. Quevillon and B. Zaldivar; Phys. Rev. Lett. **110**, 241306 (2013), arXiv 1302.4438

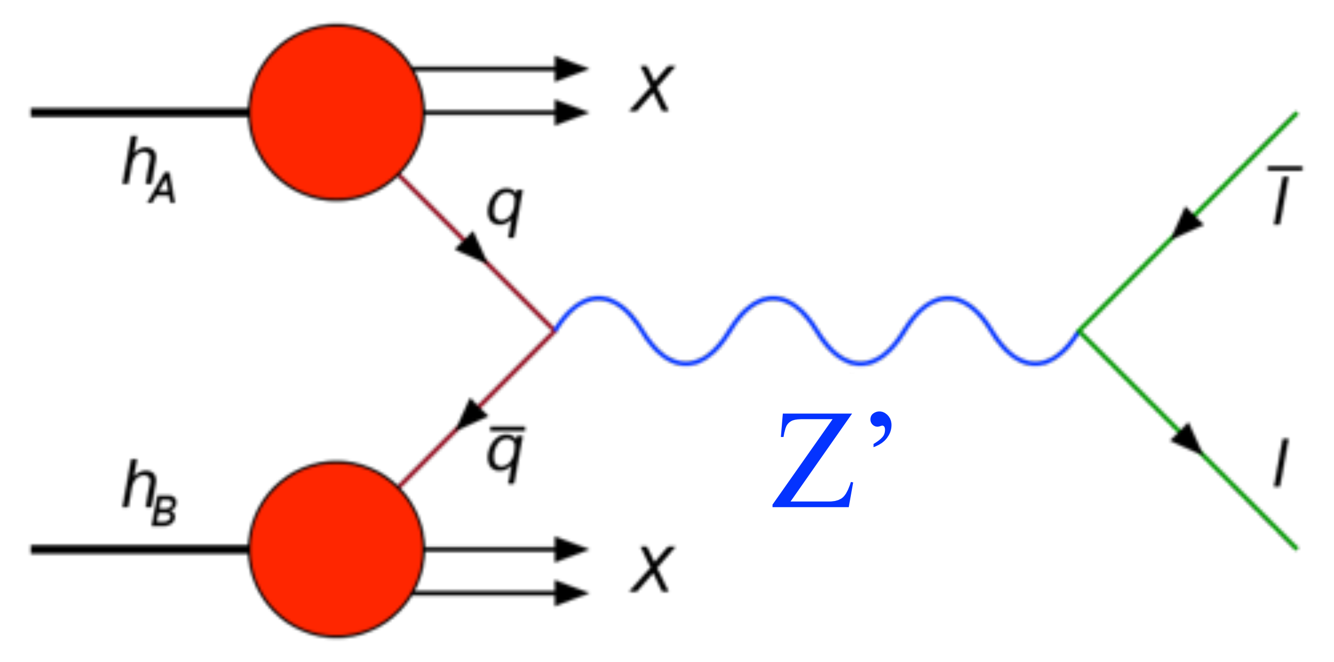
The charges

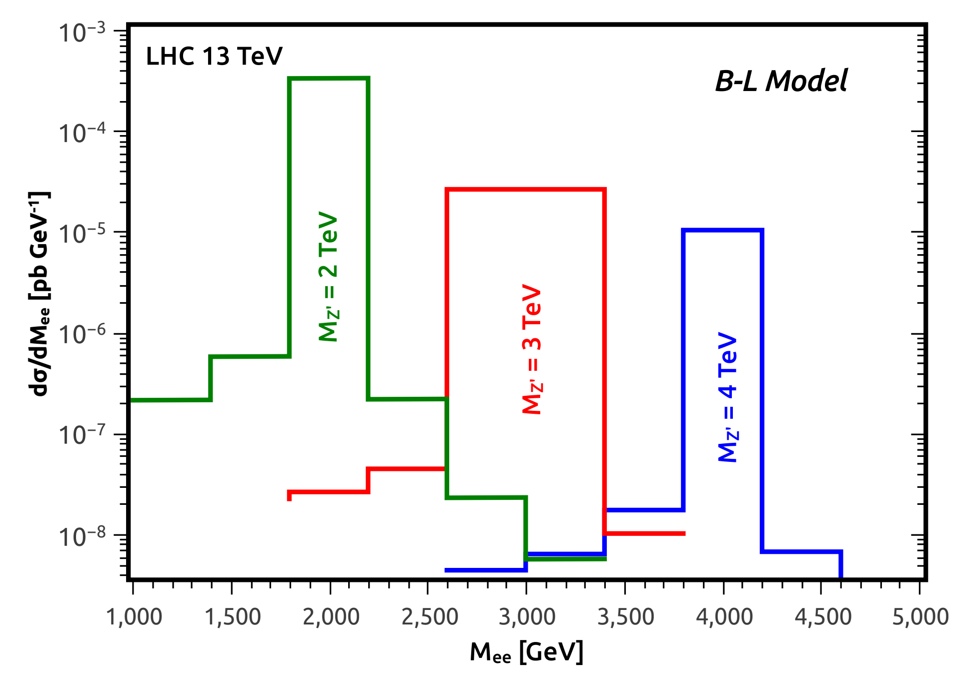


	Z'_χ	Z'_ψ	Z'_η	Z'_{LR}	Z'_{B-L}	Z'_{SSM}
D	$2\sqrt{10}$	$2\sqrt{6}$	$2\sqrt{15}$	$\sqrt{5/3}$	1	1
$\hat{\epsilon}^u_L$	-1	1	-2	-0.109	1/6	$\frac{1}{2} - \frac{2}{3}\sin^2\theta_W$
$\hat{\epsilon}^d_L$	-1	1	-2	-0.109	1/6	$-\frac{1}{2} + \frac{1}{3}\sin^2\theta_W$
$\hat{\epsilon}^u_R$	1	-1	2	0.656	1/6	$-\frac{2}{3}\sin^2\theta_W$
$\hat{\epsilon}^d_R$	-3	-1	-1	-0.874	1/6	$\frac{1}{3}\sin^2\theta_W$
$\hat{\epsilon}^\nu_L$	3	1	1	0.327	-1/2	$\frac{1}{2}$
$\hat{\epsilon}^l_L$	3	1	1	0.327	-1/2	$-\frac{1}{2} + \sin^2\theta_W$
$\hat{\epsilon}^e_R$	1	-1	2	-0.438	-1/2	$\sin^2\theta_W$

The dilepton searches

[Drell-Yan process]





Model	13 TeV,13.3 fb^{-1}	13 TeV,37 fb^{-1}	14 TeV,100 fb^{-1}	14 TeV,300 fb^{-1}	33 TeV,100 fb^{-1}	33 TeV,300 fb^{-1}	100 TeV,5 ab^{-1}
Z'_ψ	3.13 TeV	3.68 TeV	4.46 TeV	5.13 TeV	7.98 TeV	9.47 TeV	30.54 TeV
Z'_η	3.47 TeV	4.04 TeV	4.85 TeV	5.51 TeV	8.85 TeV	10.38 TeV	33.25 TeV
Z'_{B-L}	3.55 TeV	4.11 TeV	5.55 TeV	5.59 TeV	9.03 TeV	10.56 TeV	33.8 TeV
Z'_χ	3.63 TeV	4.19 TeV	5.55 TeV	5.68 TeV	9.23 TeV	10.76 TeV	34.41 TeV
Z'_{SSM}	4.02 TeV	4.59 TeV	6.05 TeV	6.09 TeV	10.21 TeV	11.75 TeV	37.36 TeV
Z'_{LR}	4.23 TeV	4.8 TeV	6.27 TeV	6.31 TeV	10.73 TeV	12.28 TeV	38.92 TeV

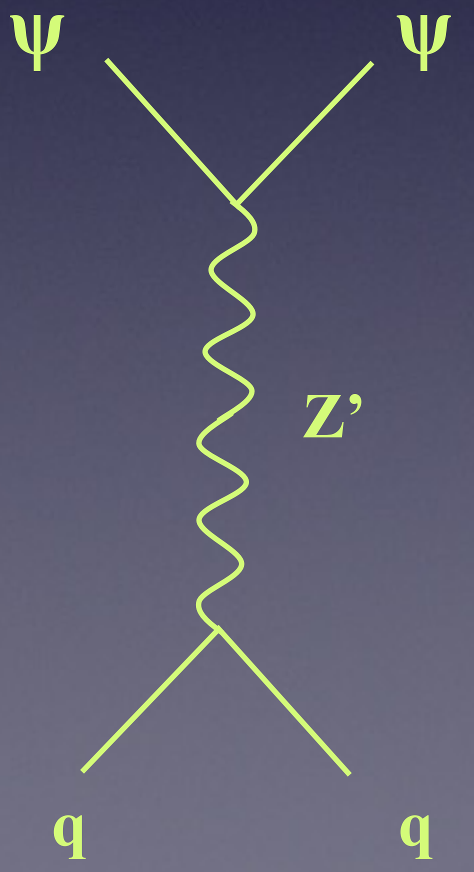
Z'_{SSM} = Z' with SM couplings

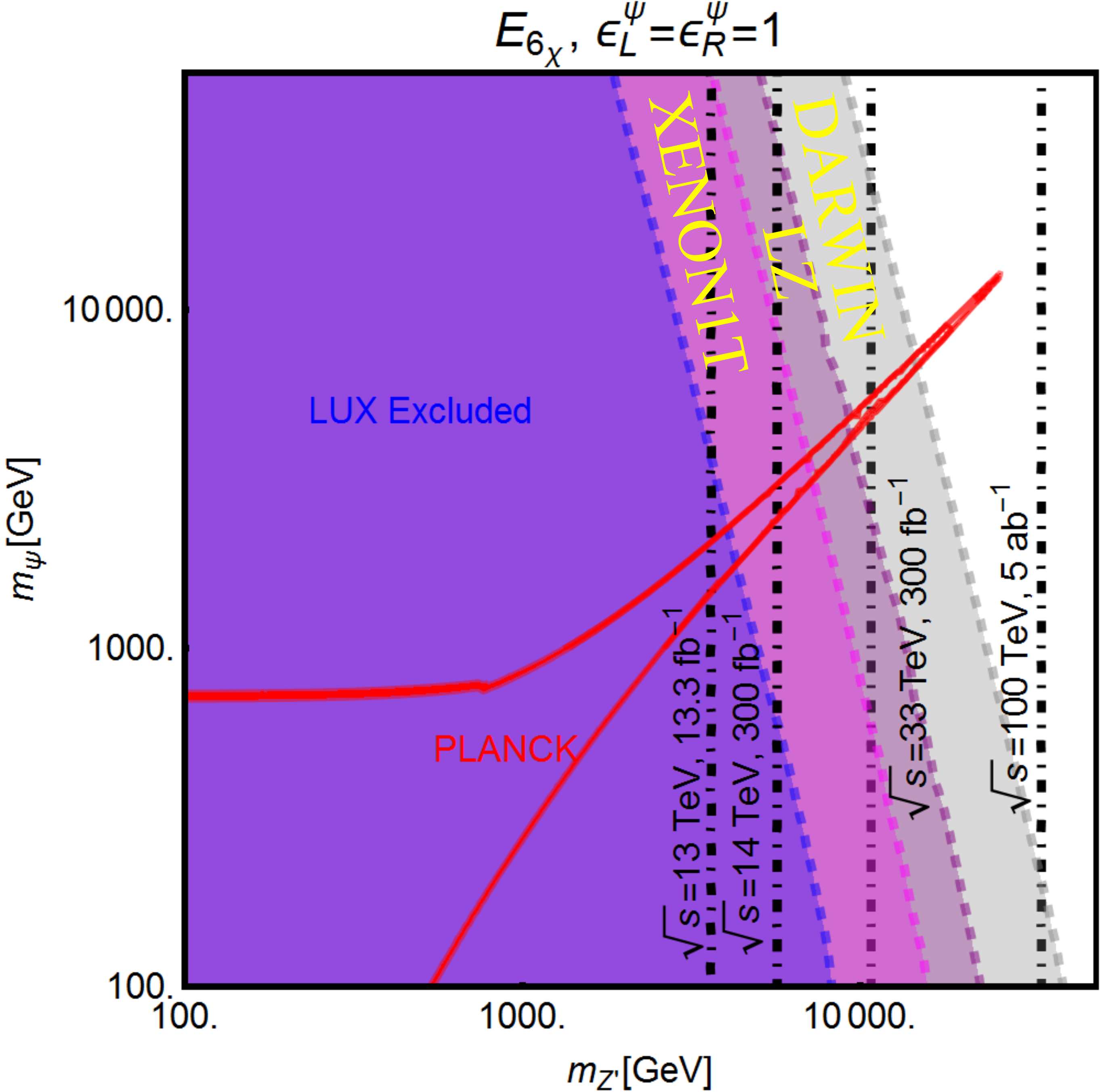
G. Arcadi, M. Lindner, Y.M., M. Pierre, F. Queiroz; arXiv:1704.02328

Adding dark matter constraints

$$\mathcal{L} = g_f \bar{\psi} \gamma^\mu \left(\epsilon_L^\psi P_L + \epsilon_R^\psi P_R \right) \psi Z'_\mu$$

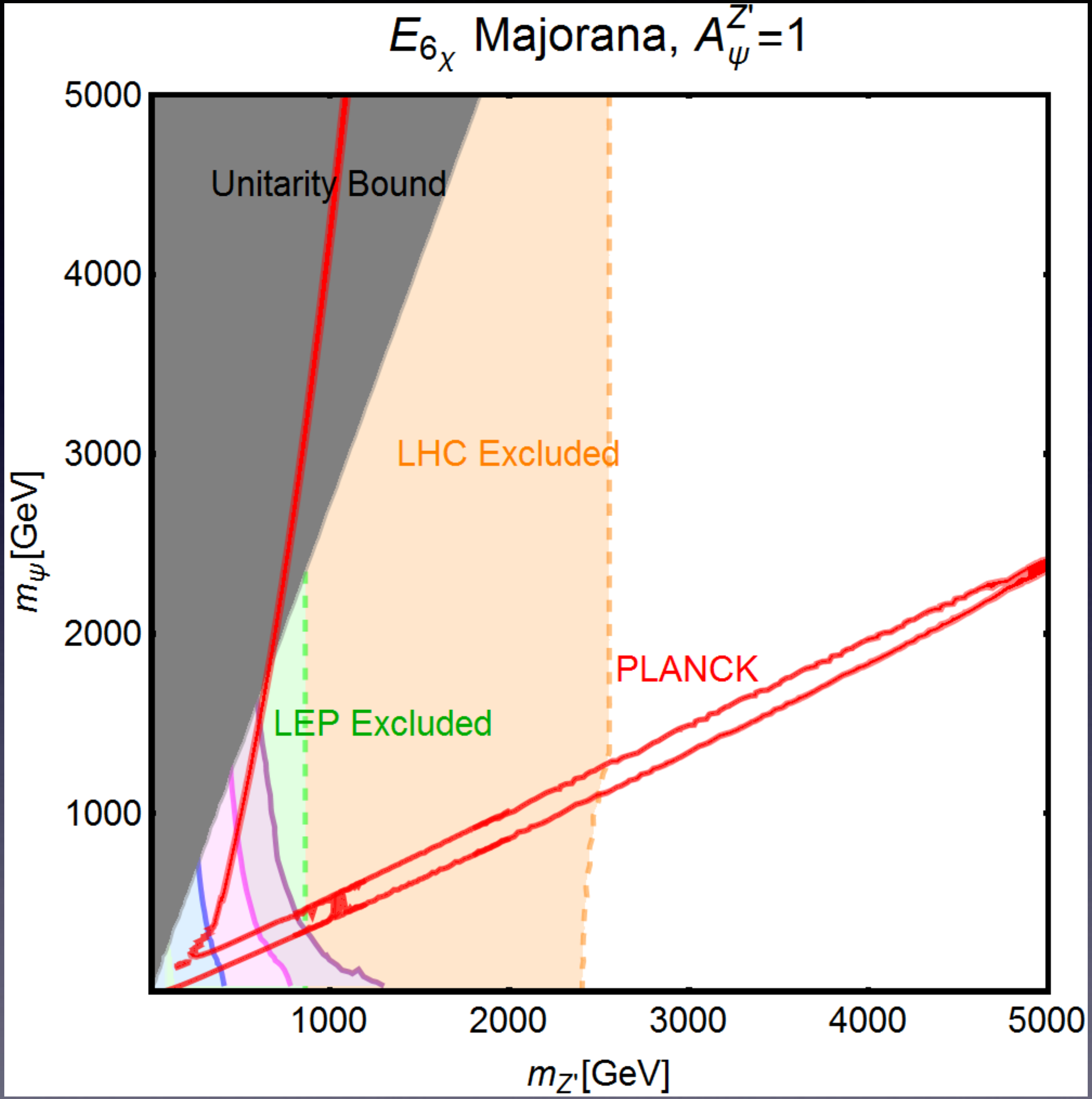
$$\sigma^{\rm SI}_{\psi,p} = \frac{g_f^4 \mu_{\psi p}^2}{\pi m_{Z'}^4} V_\psi^2 \left[f_p \frac{Z}{A} + f_n \left(1 - \frac{Z}{A} \right) \right]^2$$





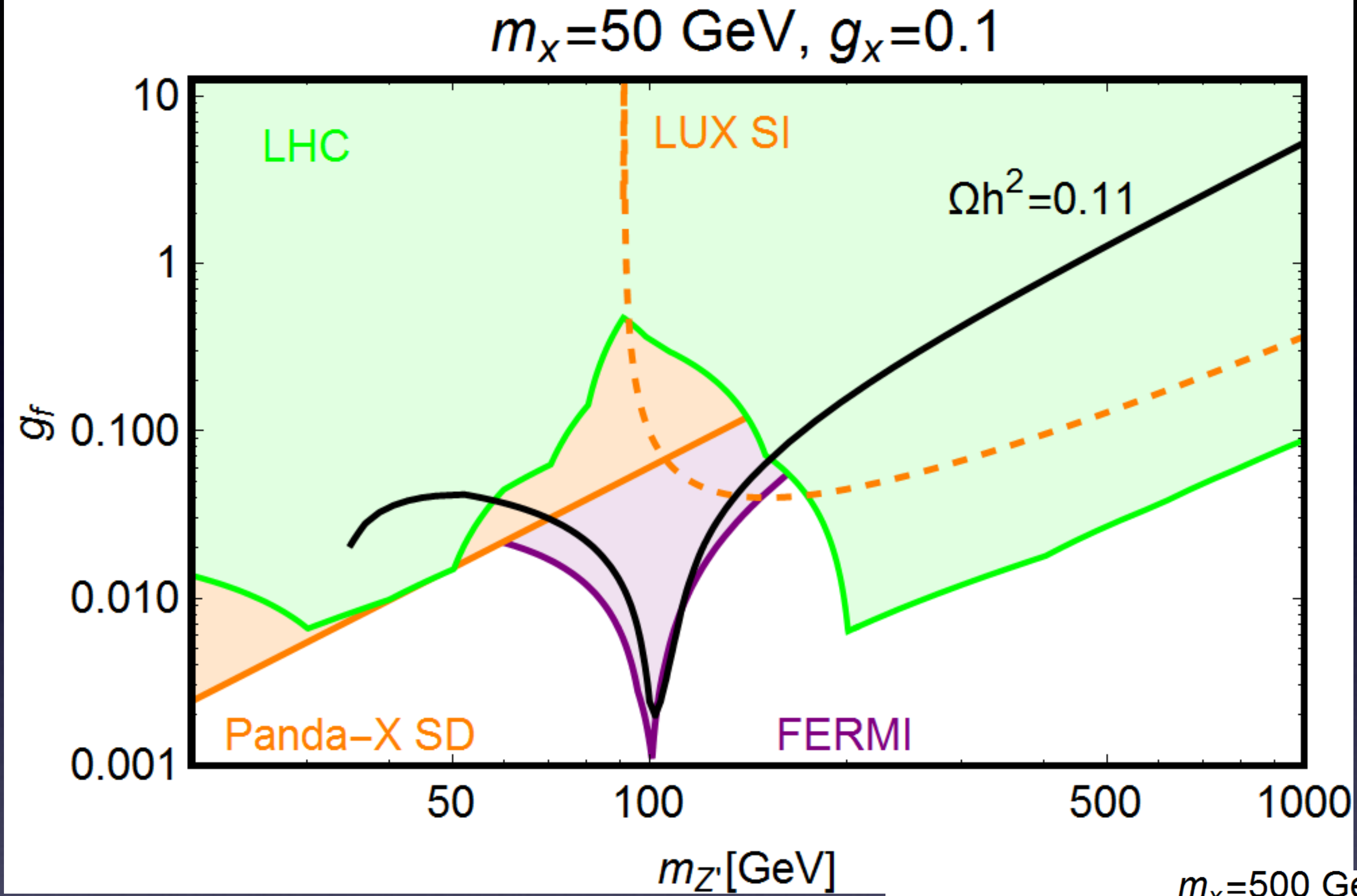
G. Arcadi, M. Lindner, Y.M., M. Pierre, F. Queiroz; arXiv:1704.02328

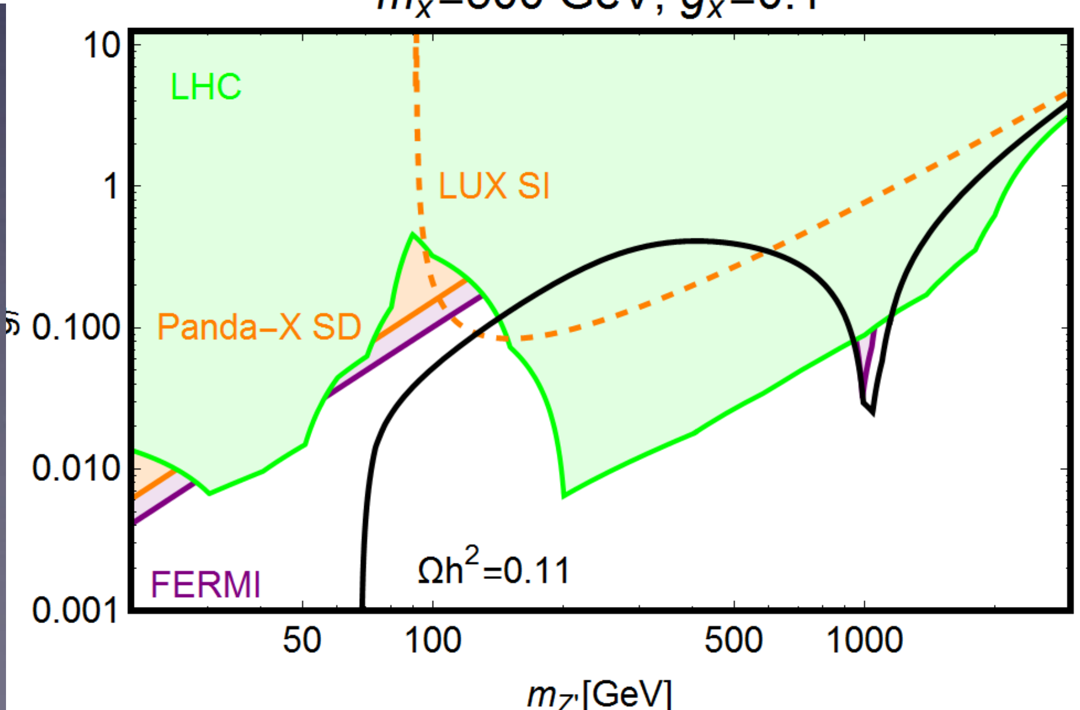
Changing the nature of the coupling..



G. Arcadi, M. Dutra, .P. Ghosh, M. Lidner, Y.M., M. Pierre, S. Profumo and F. Queiroz; arXiv:1703.07364

Adding Indirect detection

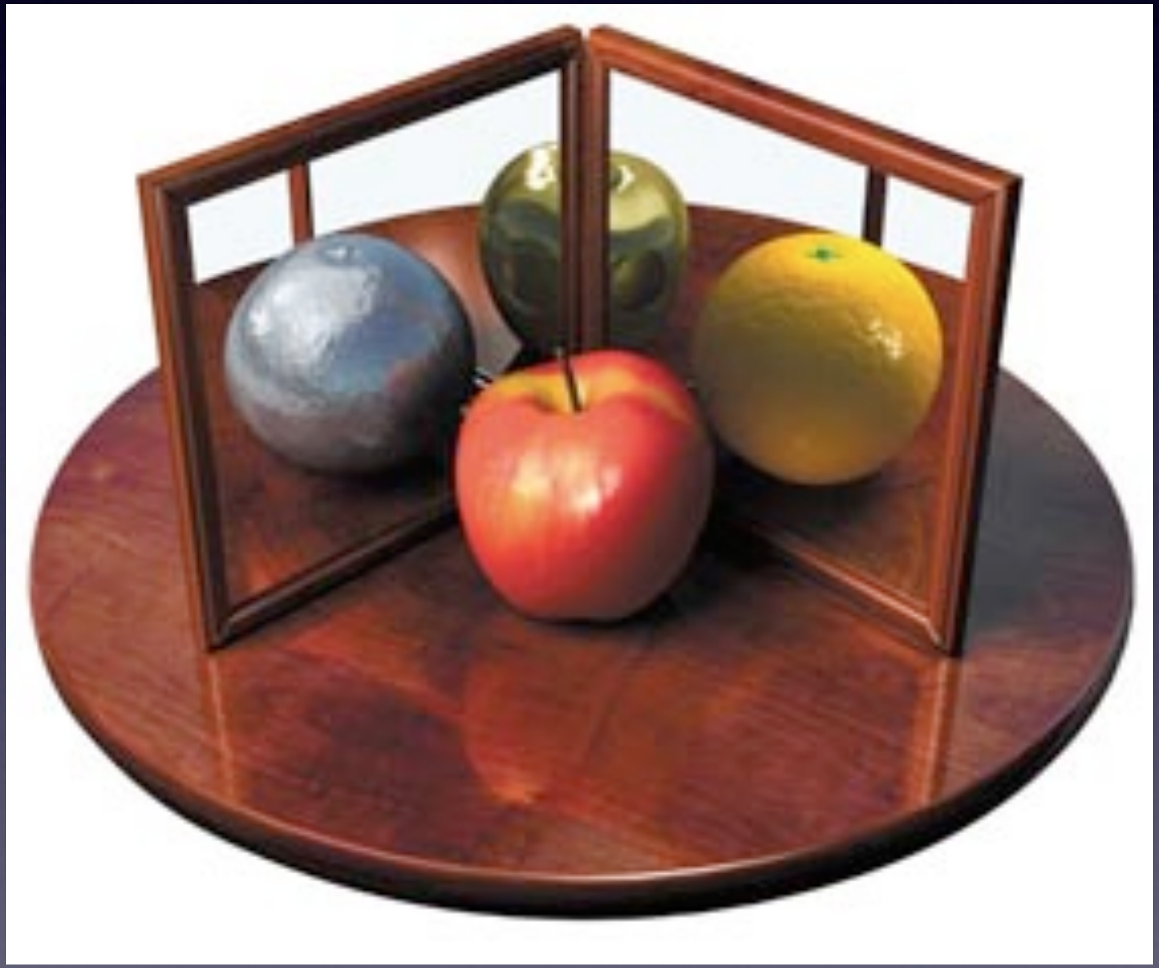




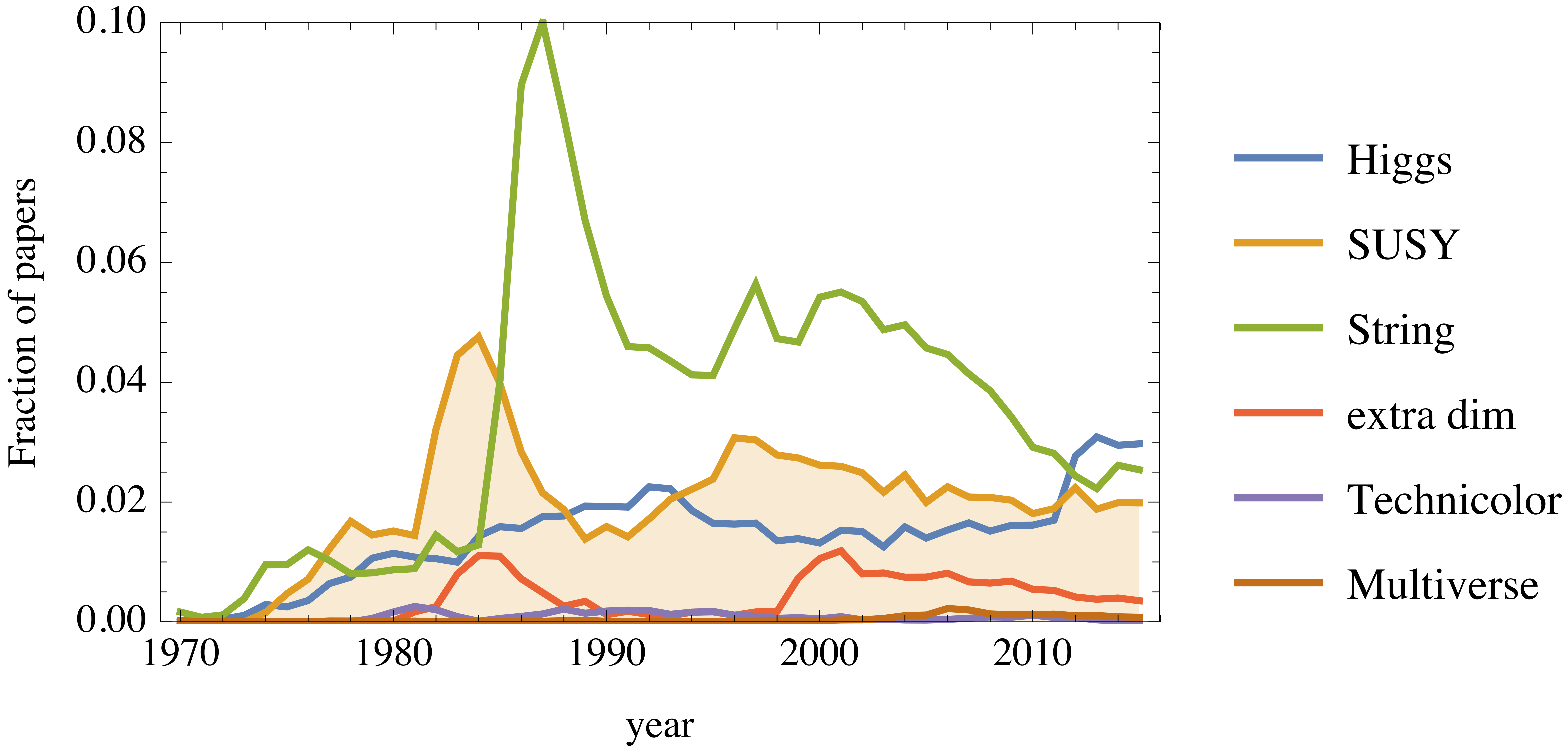
$$\mathcal{L} \supset \left[\bar{\chi}\gamma^\mu(g_{\chi v} + g_{\chi a}\gamma^5)\chi + g_f \bar{f}\gamma^\mu\gamma^5 f\right] Z'_\mu,$$

A. Alves, G. Arcadi, Y. M., F. S. Queiroz, 1612.07282

And SUSY?



Is SUSY alive (and well)?
Not so well, but at least still popular..



Strumia talk, Madrid, September 2016

SUSY and dark matter

SUSY has 2 « natural » dark matter candidates:

- The neutralino, $\tilde{\chi}_1^0$ (50% of the SUSY DM papers on spires)
- The gravitino, $\tilde{g}$ (45% of the SUSY DM papers)

The neutralino is a mixed between Bino, Wino, and Higgsinos:

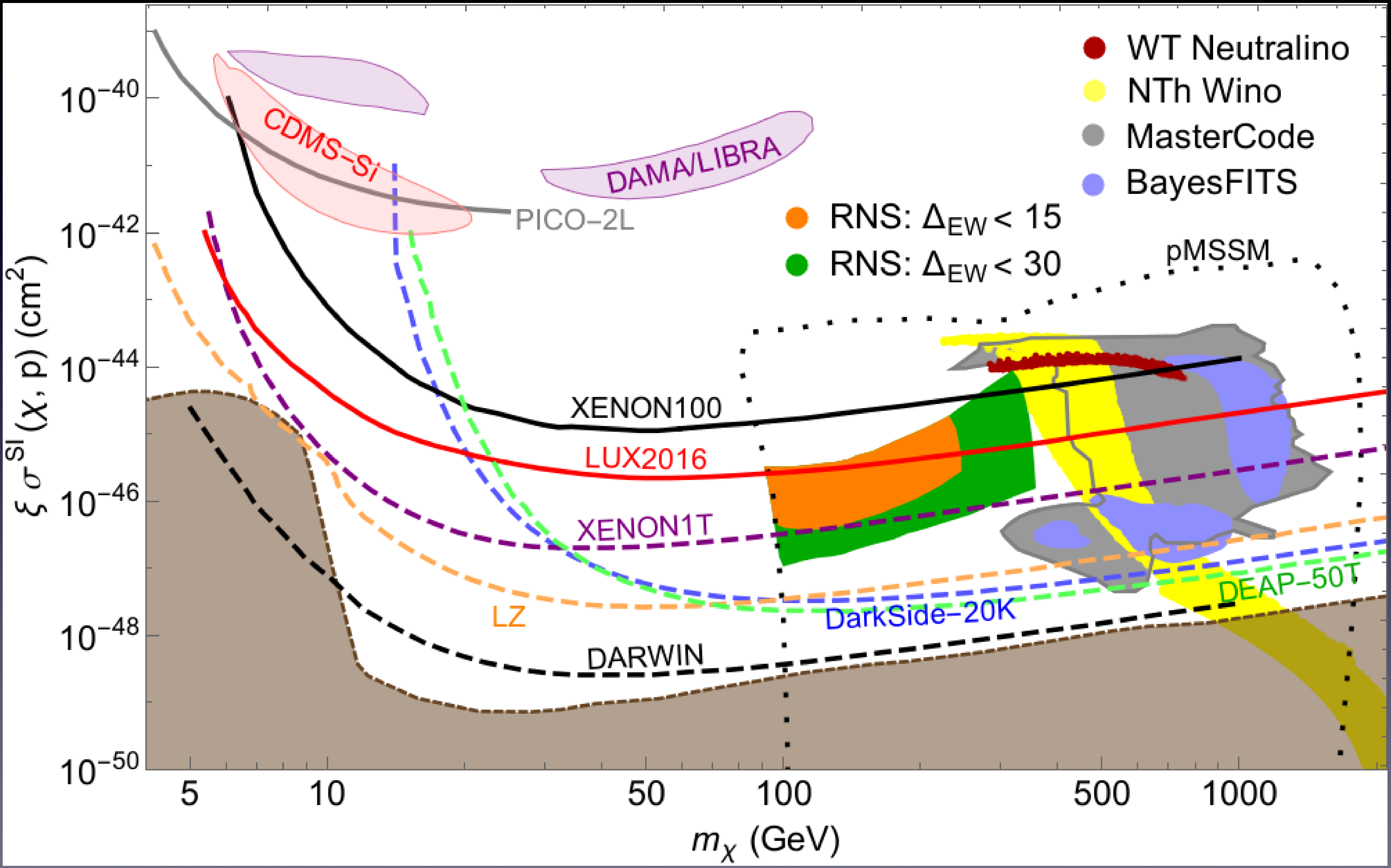
$$\chi_1^0 = c_B\tilde{B} + c_1\tilde{H}_1 + c_2\tilde{H}_2 + c_W\tilde{W}$$

🟥 well tempered

🟨 non thermal wino

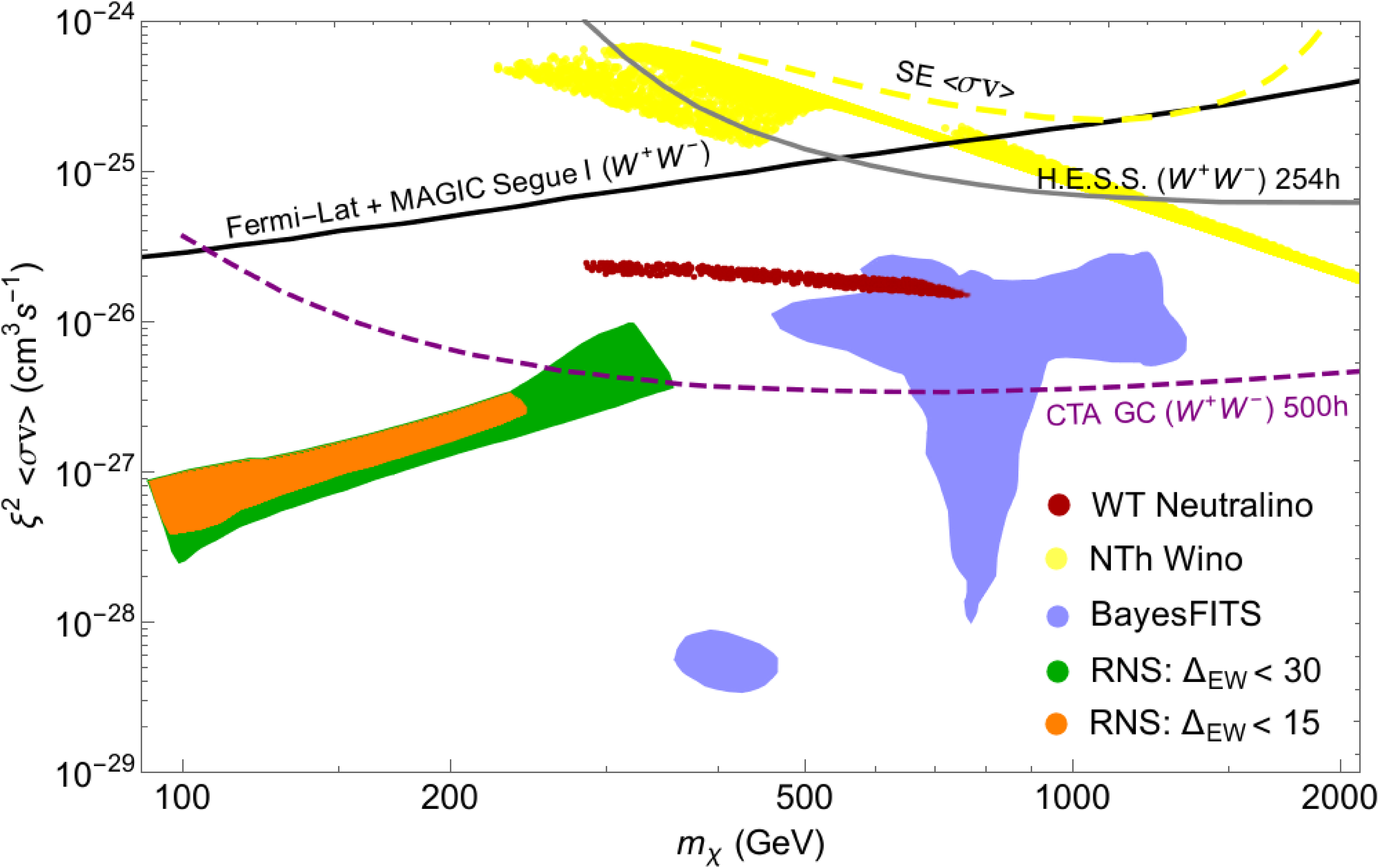
In this sense, he has all the characteristic of a WIMP, and as a consequence suffers from the same constraints listed before

Spin Independant Direct Detection



Baer et al. 1609.06735

Indirect Detection



Baer et al. 1609.06735

SUSY Conclusion (1)

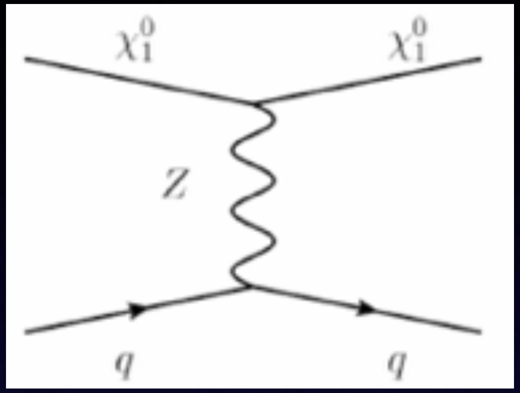
The well tempered neutralino
(mix between Higgsino and Bino)
is excluded by Direct Detection

The Wino neutralino is (almost) excluded by direct detection experiment

If gauginos are not found at LHC, then neutralino can be « pure Higgsino »

The Higgsino dark matter

A pure $SU(2)_L$ dirac doublet (Higgsino) is largely excluded by direct detection experiment, because of its vectorial coupling to the Z (see the Z-portal DM case discussed previously).

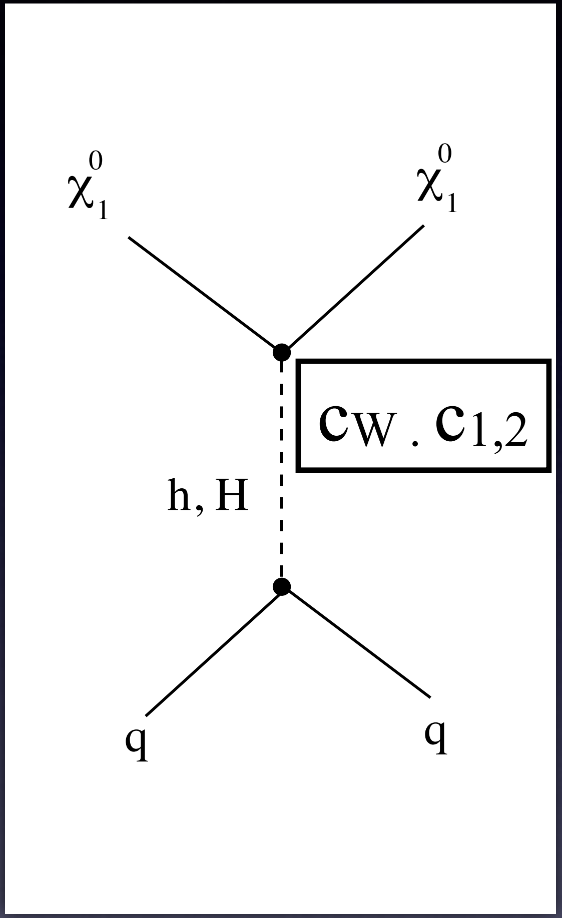


However, once the Dirac components are split to divide it into two Majorana Fermions, they do not have anymore vectorial interactions (only axial ones).
To ensure this, we need : **$\underline{\Delta m_0 > 100 \text{ keV}}$** ($\Lambda_{BSM} < 10^9$ GeV)
This is equivalent to add gaugino component to the Higgsino DM, large M_1, M_2
One loop EW contribution generates $\Delta m_{rad} = 355$ MeV

This scenario is called « Higgsino dark matter ». As was shown by Cirelli et al.*, the thermal relic abundance of pure Higgsino agrees with $\Omega h^2 = 0.12$ if $M_{DM} \sim 1$ TeV

*M. Cirelli, A. Strumia and M. Tamburini, Nucl. Phys. B787, 152 (2007), arXiv:0706.4071

Direct detection of a Higgsino

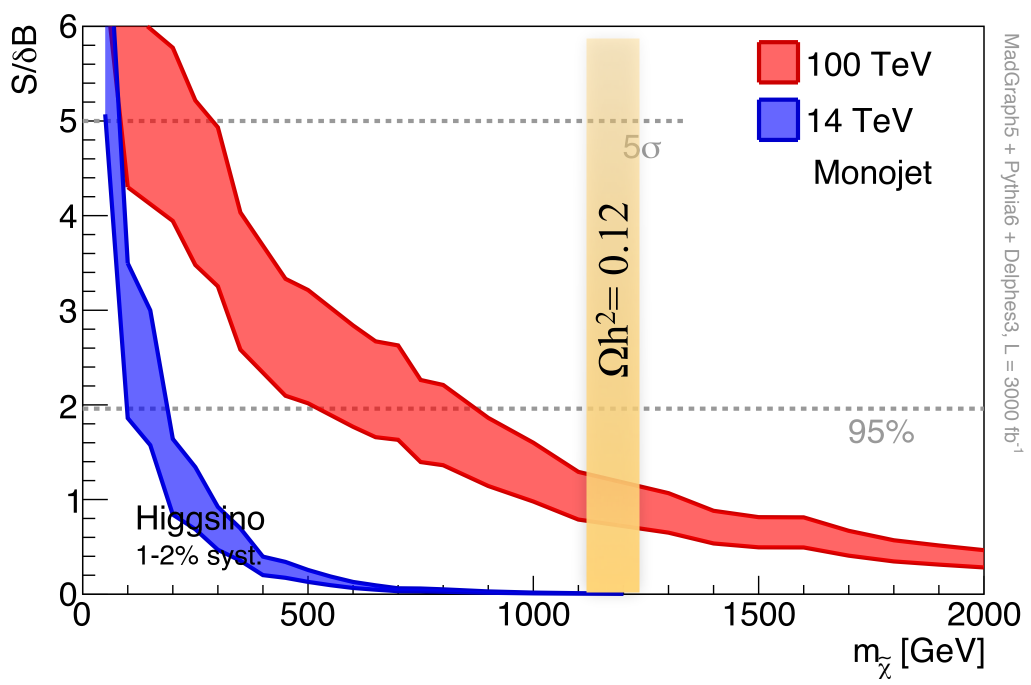


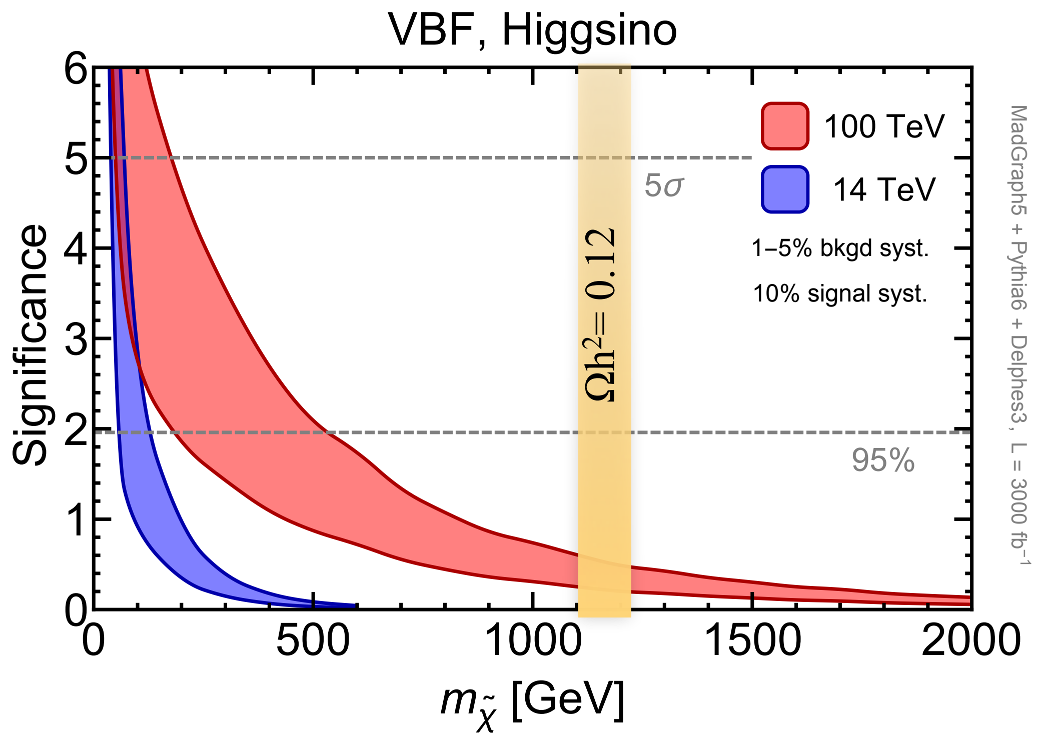
Some mixing (c_W) is necessary to generate a direct detection signal.

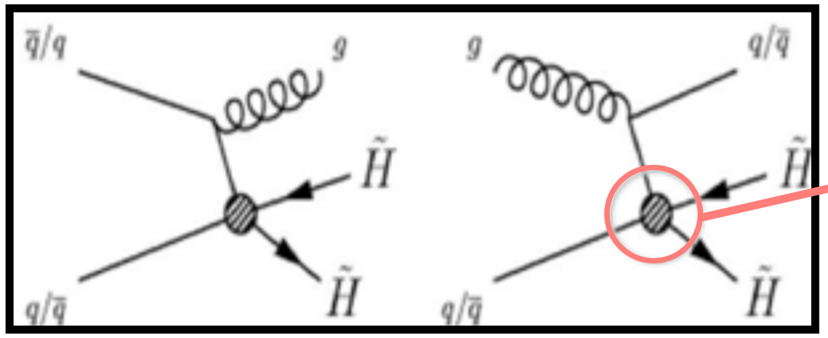
Large $M_{1,2}$ implies (almost) invisible Higgsino.

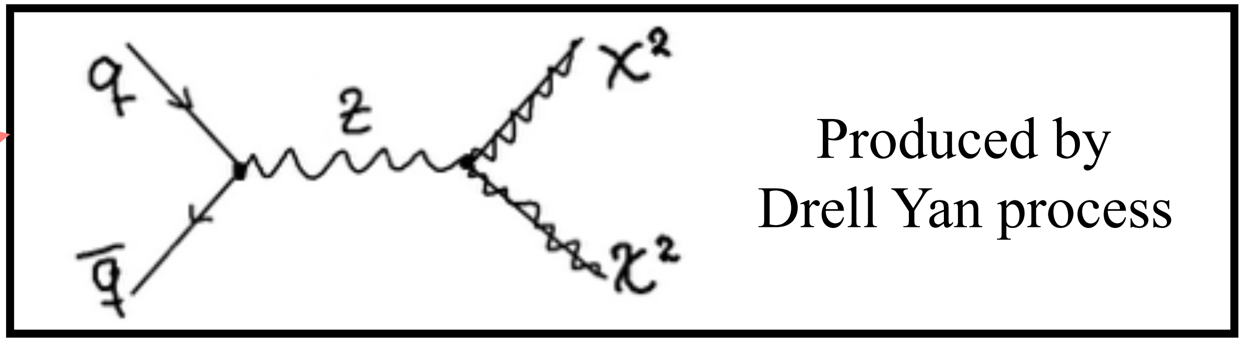
Is it possible to probe it at LHC?

With monojet? No..









Produced by
Drell Yan process

Conclusion: Higgsino dark matter, very hard to detect in direct detection (Majorana) or accelerators with mooniest searches.

T. Golling et al., ``Physics at a 100 TeV pp collider: beyond the Standard Model phenomena,''; arXiv:1606.00947

Using (soft) chargino decay

The mass splitting between chargino χ^+ and neutralino χ^0 can be written

$\Delta m_+ = \Delta m_{\mathrm{tree}}(M_1, M_2) + \Delta m_{\mathrm{rad}}$ (355 MeV)

$$\Delta m_{\mathrm{tree}} \simeq \frac{170\ \mathrm{MeV}}{F(X,Y)} \left(\frac{m_p}{m_{\mathrm{red}}}\right) \left(\frac{\sigma_{\mathrm{SI}}^{(p)}}{10^{-48}\ \mathrm{cm}^2}\right)^{\frac{1}{2}} .$$

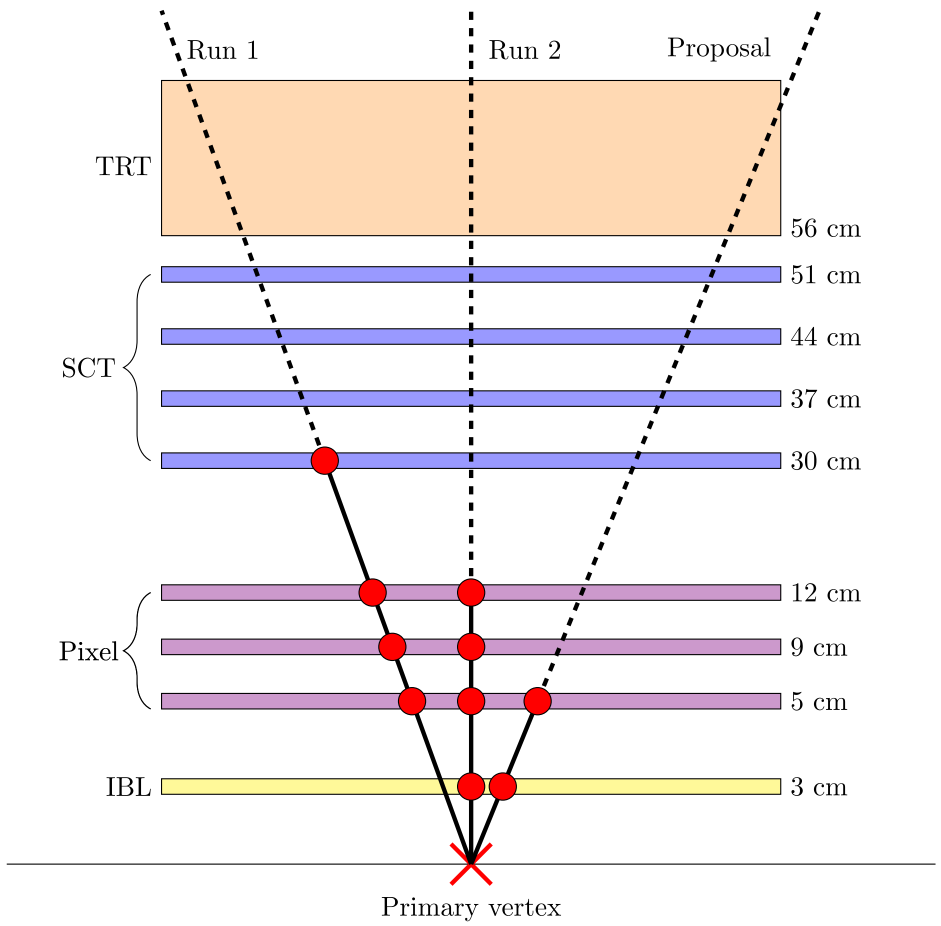
Pure Higgsino : $F(X,Y) \to \infty$

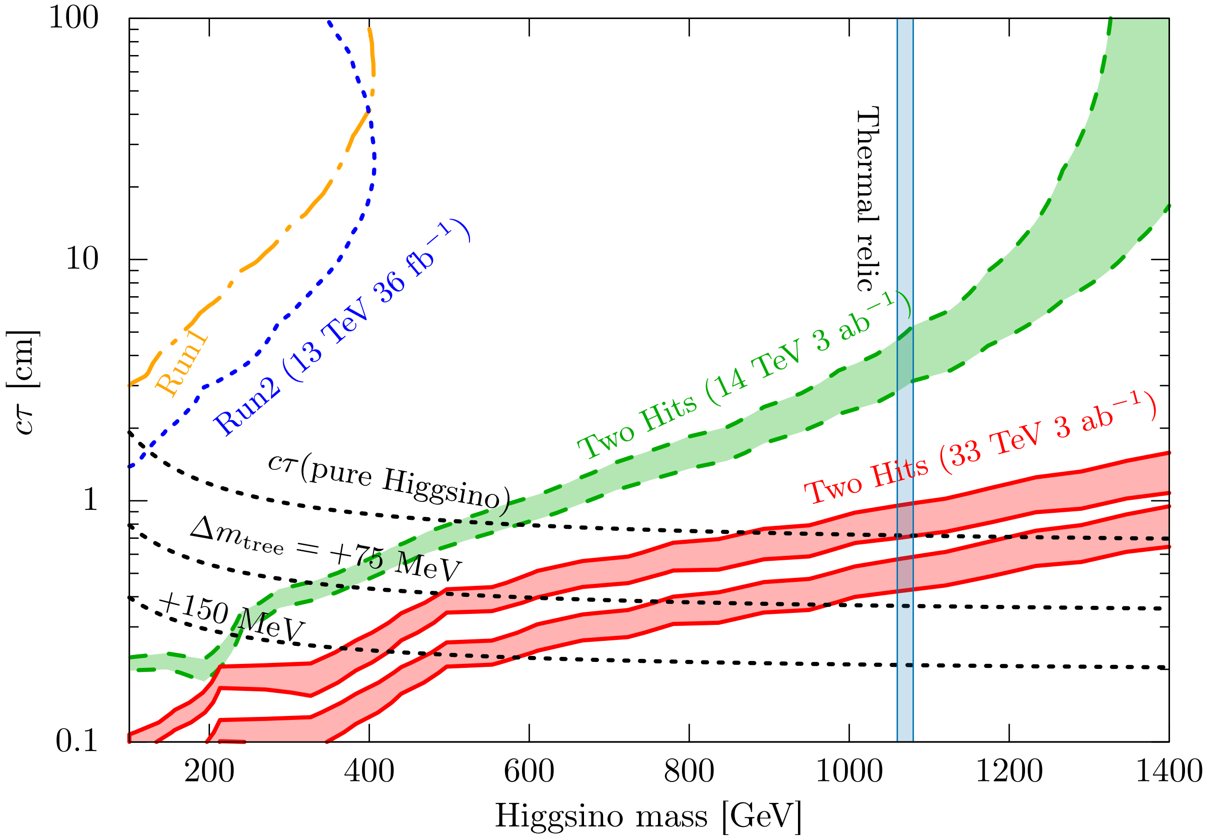
giving a decay length

$$c\tau \simeq 0.7\ \mathrm{cm} \times \left[\left(\frac{\Delta m_+}{340\,\mathrm{MeV}}\right)^3 \sqrt{1 - \frac{m_\pi^2}{\Delta m_+^2}}\right]^{-1}$$

H. Fukuda, N. Nagata, H. Otono and S. Shirai; arXiv:1703.09675

$$c\tau \simeq 0.7\ \text{cm} \times \left[\left(\frac{\Delta m_{+}}{340\,\text{MeV}} \right)^{3} \sqrt{1 - \frac{m_{\pi}^{2}}{\Delta m_{+}^{2}}} \right]^{-1}$$





2 hits in pixel detector

H. Fukuda, N. Nagata, H. Otono and S. Shirai; arXiv:1703.09675

Remark: This strategy can be applied to *any* extra $SU(2)_L$ doublet with one neutral component being the Dark Matter candidate.

The graviton scenario

The gravitino was in fact the first candidate to be proposed as a dark matter, before the neutralino by Pagels and Primack in 1982*

All the computation of relic abundance of graviton until now has been based on the hypothesis of the graviton and/or SUSY partners have been in thermal equilibrium with the primordial plasma.

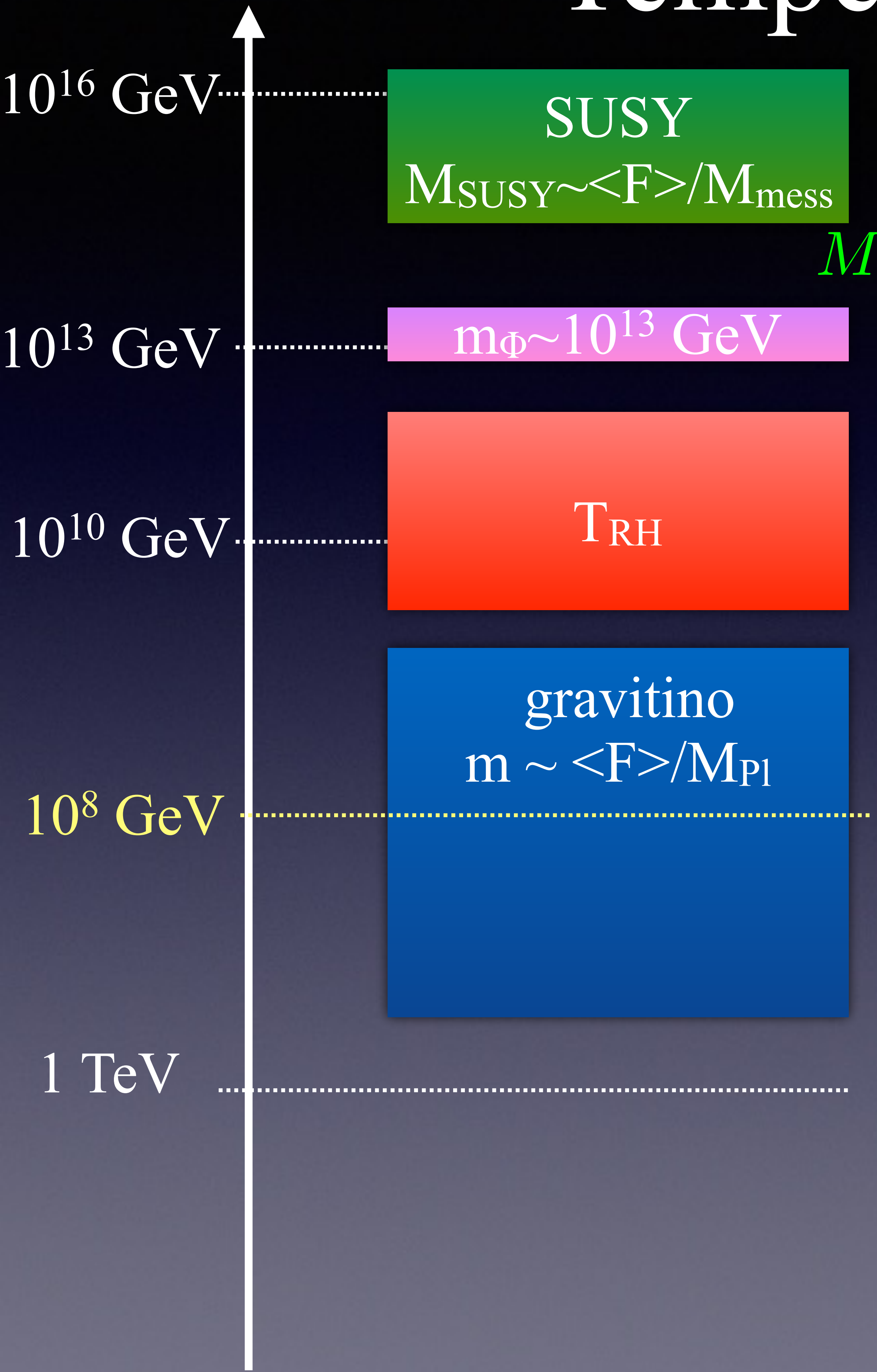
What is happening if we settle just a minimal simple hypothesis:

$M_{SUSY} > M_{inflaton} = M_{\Phi}$

Based on
K. Benakli, Y. Chen, E. Dudas and Y.M. arXiv:1701.06574
and
E. Dudas, Y.M. and K.A. Olive, arXiv:1701.06574

*and notes by P. Fayet, in the Proceeding 16th Rencontres de Moriond, march 1981

Temperature scale



10^{16} GeV

SUSY
$M_{SUSY} \sim \langle F \rangle / M_{mess}$

10^{13} GeV

$m_\Phi \sim 10^{13}$ GeV

10^{10} GeV

T_{RH}

gravitino
$m \sim \langle F \rangle / M_{Pl}$

10^{8} GeV

1 TeV

$$M_{SUSY} = \frac{F}{M_{mess}} > m_\phi \ , M_{mess} > M_{SUSY}$$

$$\Rightarrow F > m_\phi^2 \ , \ \text{with } m_\phi \sim 3 \times 10^{13} \ \text{GeV}$$

$$\Rightarrow m_{3/2} = \frac{F}{M_{Pl}} \gtrsim 0.2 \ \text{EeV}$$

The simple hypothesis $M_{SUSY} > m_\Phi$
gives already a lower bound on
gravitino mass of ~ 10^8 GeV

How to produce gravitino?

Directly from the thermal bath

Generating the interactions

One can deduce the vierbein of the theory, just from the hypothesis that the longitudinal part of the gravitino is the goldstino of the SUSY transformation*

$$e_m^a = \delta_m^a - \frac{i}{2F^2}\partial_m G\sigma^a\bar{G} + \frac{i}{2F^2}G\sigma^a\partial_m\bar{G} \ ,$$

$$L_{2G} = \frac{i}{2F^2}(G\sigma^\mu\partial^\nu\bar{G} - \partial^\nu G\sigma^\mu\bar{G})T_{\mu\nu},$$

I. Antoniadis, E. Dudas, D. M. Ghilencea and P. Tziveloglou, Nucl. Phys. B **841** (2010) 157

Which gives the Lagrangian between the SM and the goldstino

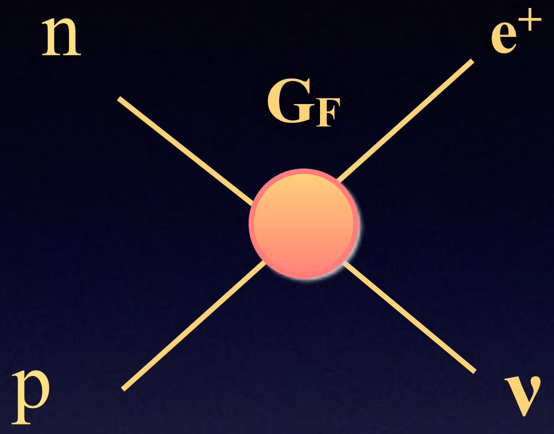
$$\begin{aligned}
&\frac{i}{2F^2}(G\sigma^\mu\partial^\nu\bar{G} - \partial^\nu G\sigma^\mu\bar{G})(\partial_\mu H\partial_\nu H^\dagger + \partial_\mu H\partial_\nu H^\dagger),\\
&\frac{1}{8F^2}(G\sigma^\mu\partial^\nu\bar{G} - \partial^\nu G\sigma^\mu\bar{G}) \times\\
&(\bar{\psi}\bar{\sigma}_\nu\partial_\mu\psi + \bar{\psi}\bar{\sigma}_\mu\partial_\nu\psi - \partial_\mu\psi\bar{\sigma}_\nu\psi - \partial_\nu\psi\bar{\sigma}_\mu\psi),\\
&\sum_a \frac{i}{2F^2}(G\sigma^\xi\partial_\mu\bar{G} - \partial_\mu G\sigma^\xi\bar{G})F^{\mu\nu a}F^a_{\nu\xi}, \qquad (10)
\end{aligned}$$

Notice how the Lagrangian has suppressed coupling (1/F^2) and strong energy/temperature dependance

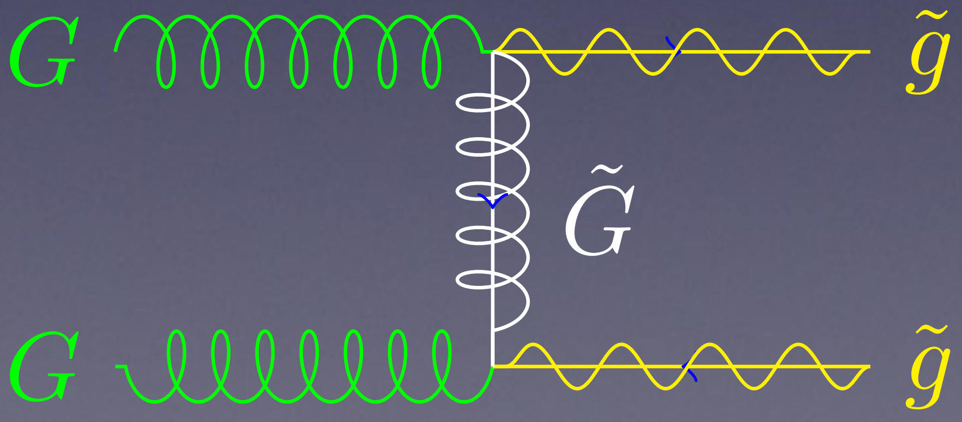
* see the incredibly modern article « Is the Neutrino a Goldstone particle » by D.V. Volkov and V.P. Akulov,Phys. Lett. **B 46** (1973) 109

Another (« a la Fermi ») point of view

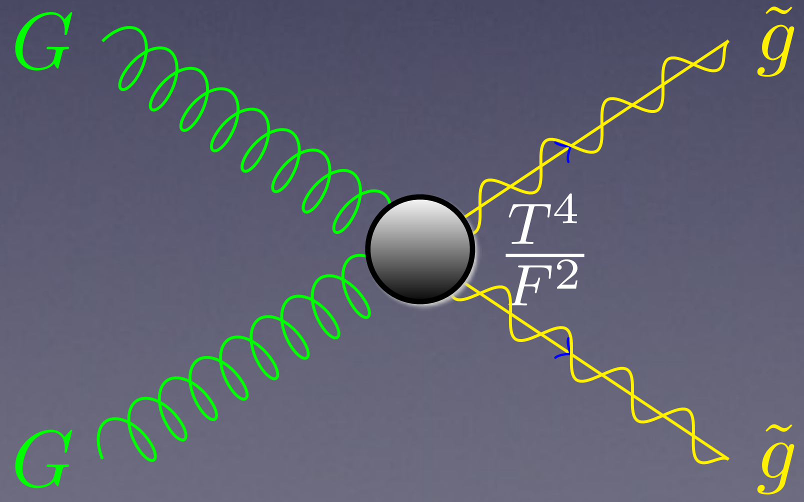
$M_W >> E$



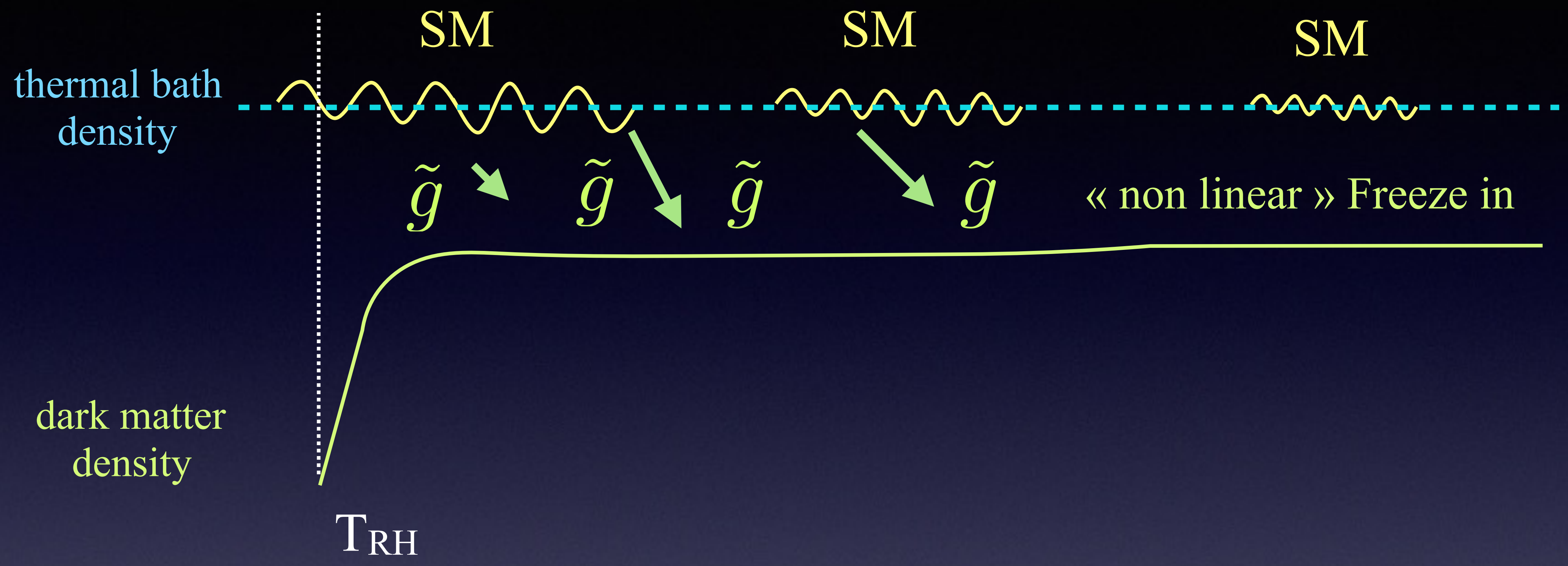
$G_F = 10^{-5}\ \mathrm{GeV}^{-2}$

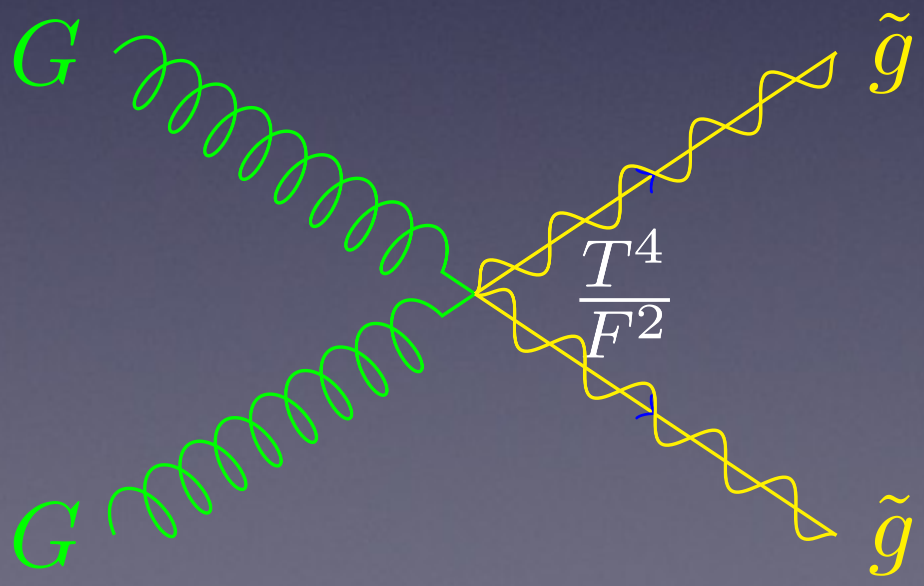


$M_{\tilde{G}} >> E$



The freeze-in mechanism



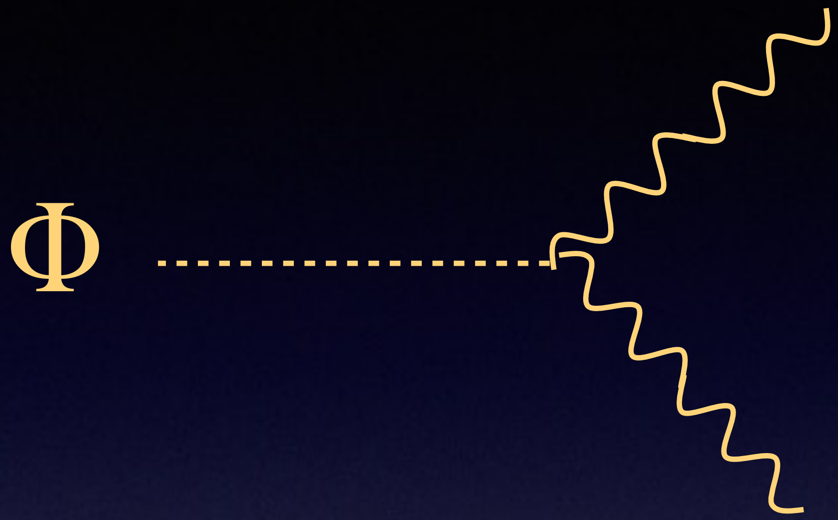


$$\Omega_{3/2}h^2 \simeq 0.11 \left(\frac{0.1\ \text{EeV}}{m_{3/2}}\right)^3 \left(\frac{T_{RH}}{2.0 \times 10^{10}\ \text{GeV}}\right)^7$$

K. Benakli, Y. Chen, E. Dudas and Y.M. arXiv:1701.06574

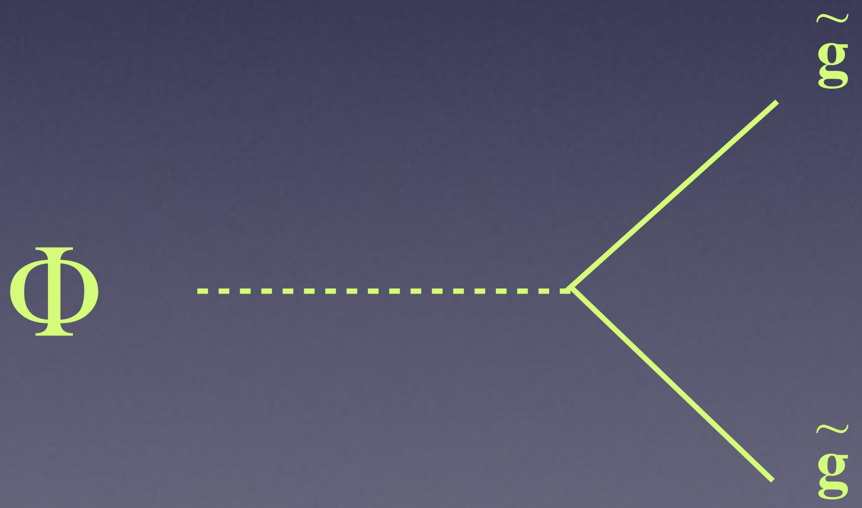
$$\Omega_{3/2}h^2 \simeq 0.11 \left(\frac{100\ \mathrm{GeV}}{m_{3/2}}\right)^3 \left(\frac{T_{\mathrm{RH}}}{5.4\times 10^7\ \mathrm{GeV}}\right)^7$$

Including inflaton decay



$$T_{RH} = \left(\frac{10}{g_s}\right)^{1/4} \left(\frac{2\Gamma_\phi\ M_P}{\pi\ c}\right)^{1/2} = 0.55\frac{y_\phi}{2\pi}\left(\frac{m_\phi\ M_P}{c}\right)^{1/2}$$

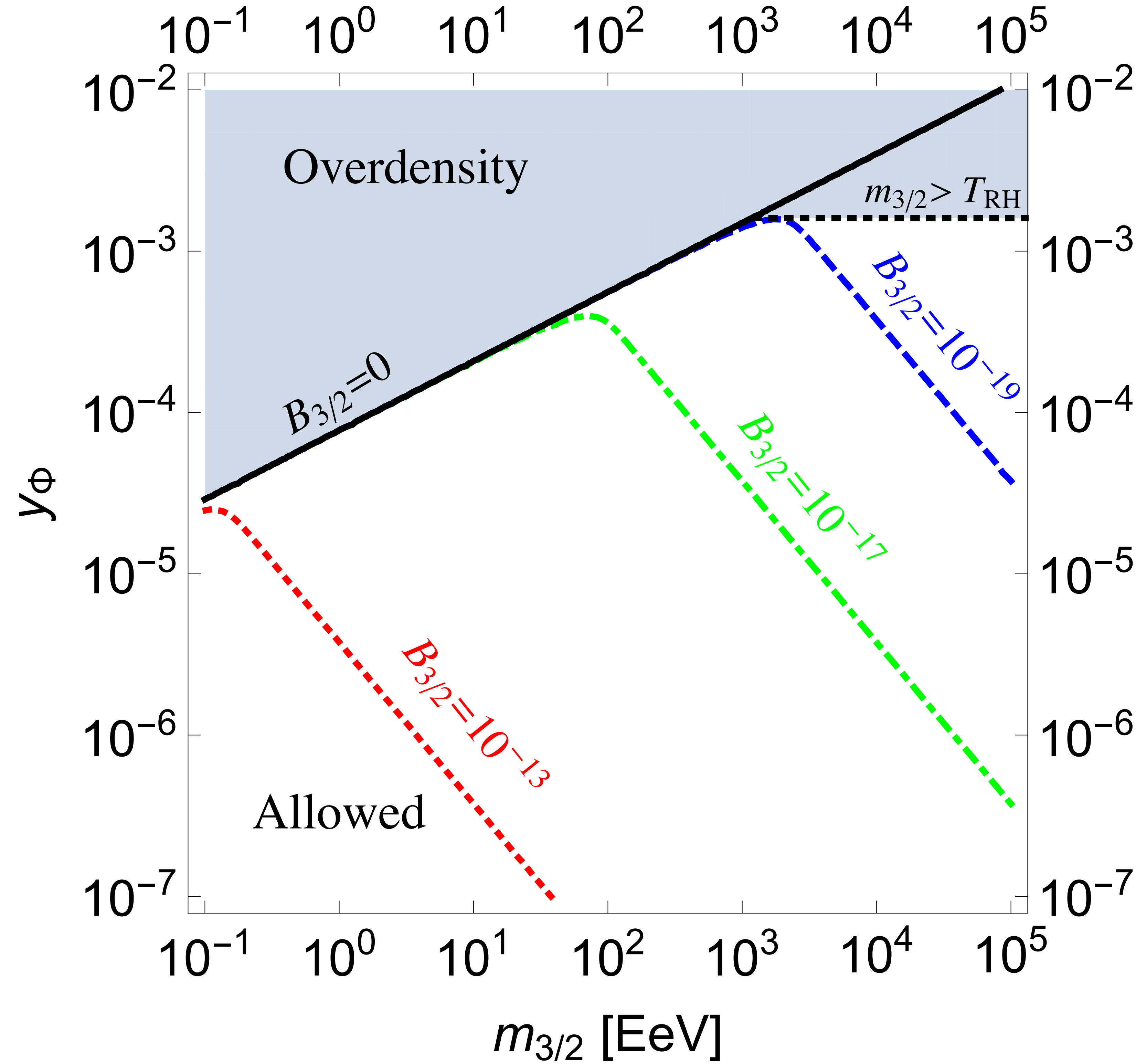
$$\Omega_{3/2}h^2 \simeq 0.11 \left(\frac{0.1\ \mathrm{EeV}}{m_{3/2}}\right)^3 \left(\frac{m_\phi}{3\times 10^{13}\mathrm{GeV}}\right)^{7/2} \left(\frac{y_\phi}{2.9\times 10^{-5}}\right)^7$$



$$\Omega_{3/2}^{decay}h^2 = 0.11\left(\frac{B_{3/2}}{1.3\times 10^{-13}}\right)\left(\frac{y_\phi}{2.9\times 10^{-5}}\right) \times \left(\frac{m_{3/2}}{0.1\ \mathrm{EeV}}\right)\left(\frac{3\times 10^{13}\ \mathrm{GeV}}{m_\phi}\right)^{1/2}$$

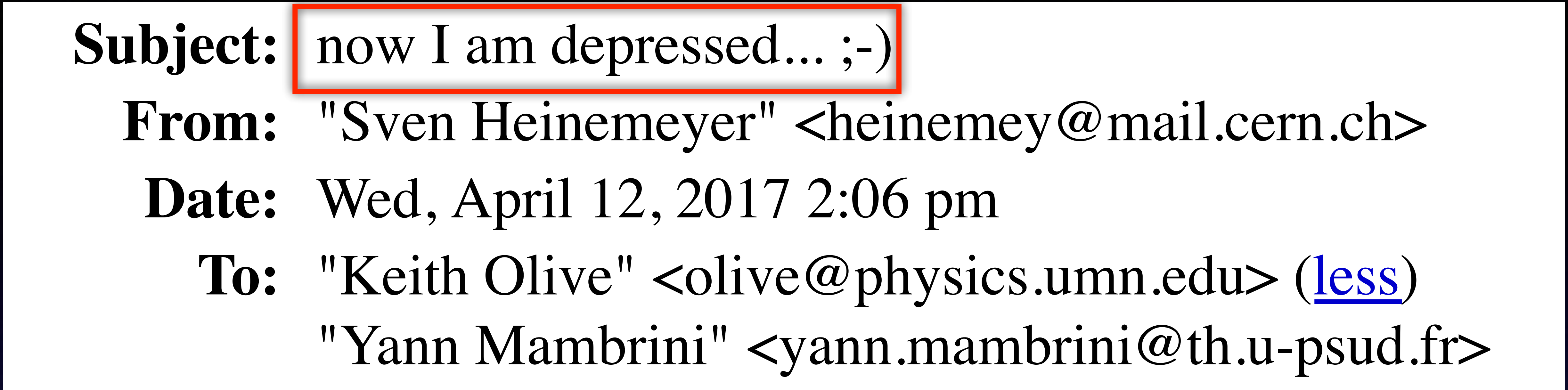
$B_{3/2} = \Gamma_{3/2}/\Gamma_\phi$

E. Dudas, Y.M. and K.A. Olive, arXiv:1701.06574



Conclusion: EeV gravitino is compatible with inflationary scenario and DM constraints.

E. Dudas, Y.M. and K.A. Olive, arXiv:1701.06574



Subject: now I am depressed... ;-)

From: "Sven Heinemeyer" <heinemey@mail.cern.ch>

Date: Wed, April 12, 2017 2:06 pm

To: "Keith Olive" <olive@physics.umn.edu> (less)
"Yann Mambrini" <yann.mambrini@th.u-psud.fr>

Conclusion

Axial and/or pseudo scalar couplings
can save the WIMP paradigm

SUSY dark matter very restricted

Interesting non-thermal scenario

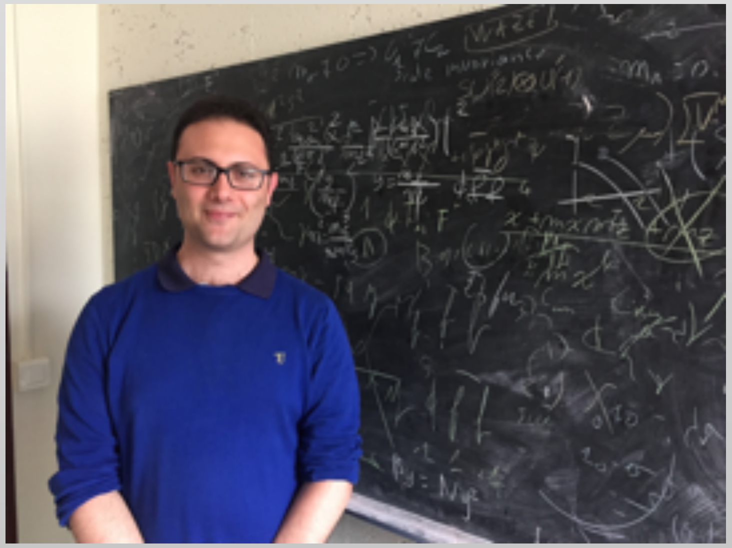
Who really did the job


Maira Dutra


Yifan Chen

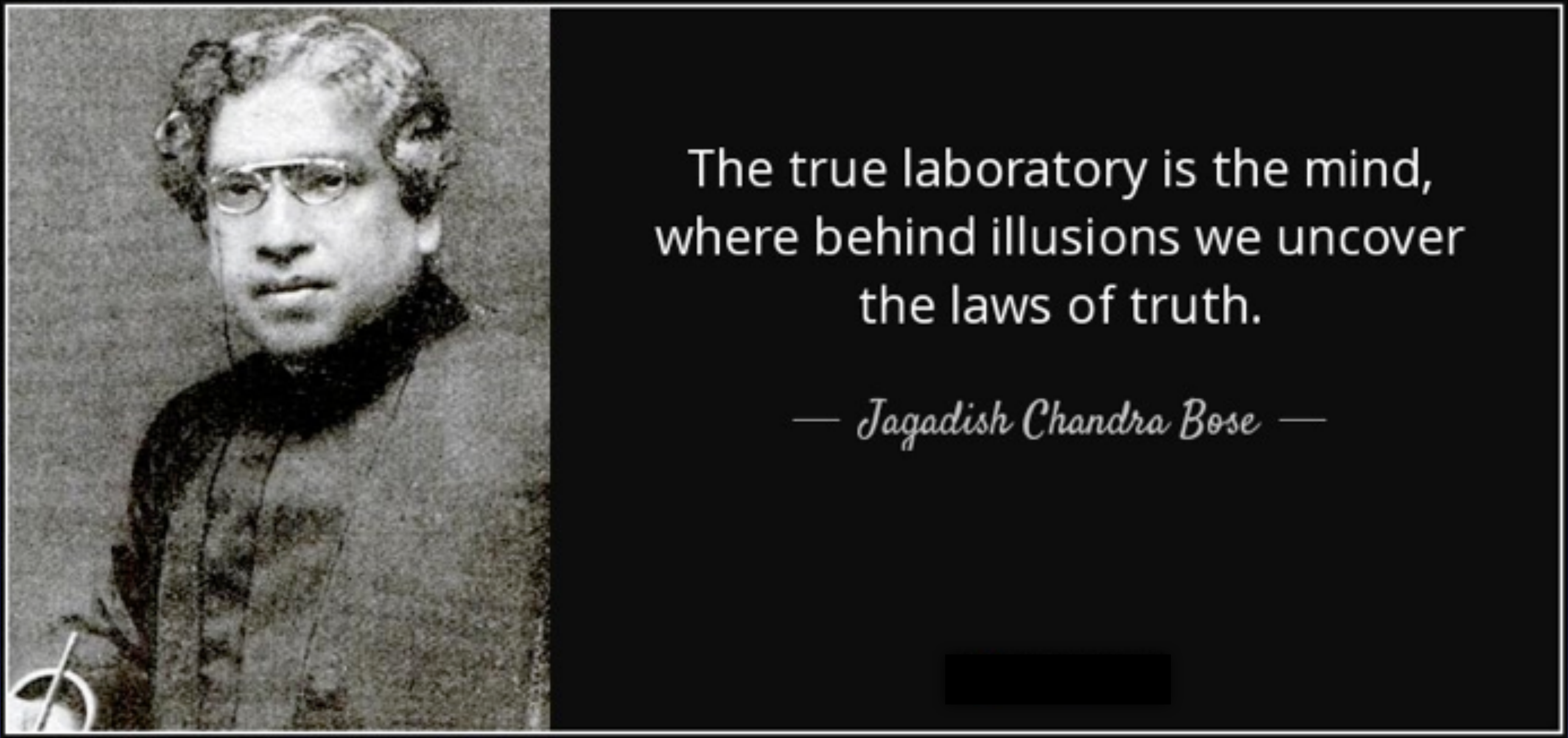

Mathias Pierre


Pradipta Ghosh


Giorgio Arcadi


Farinaldo Queiroz

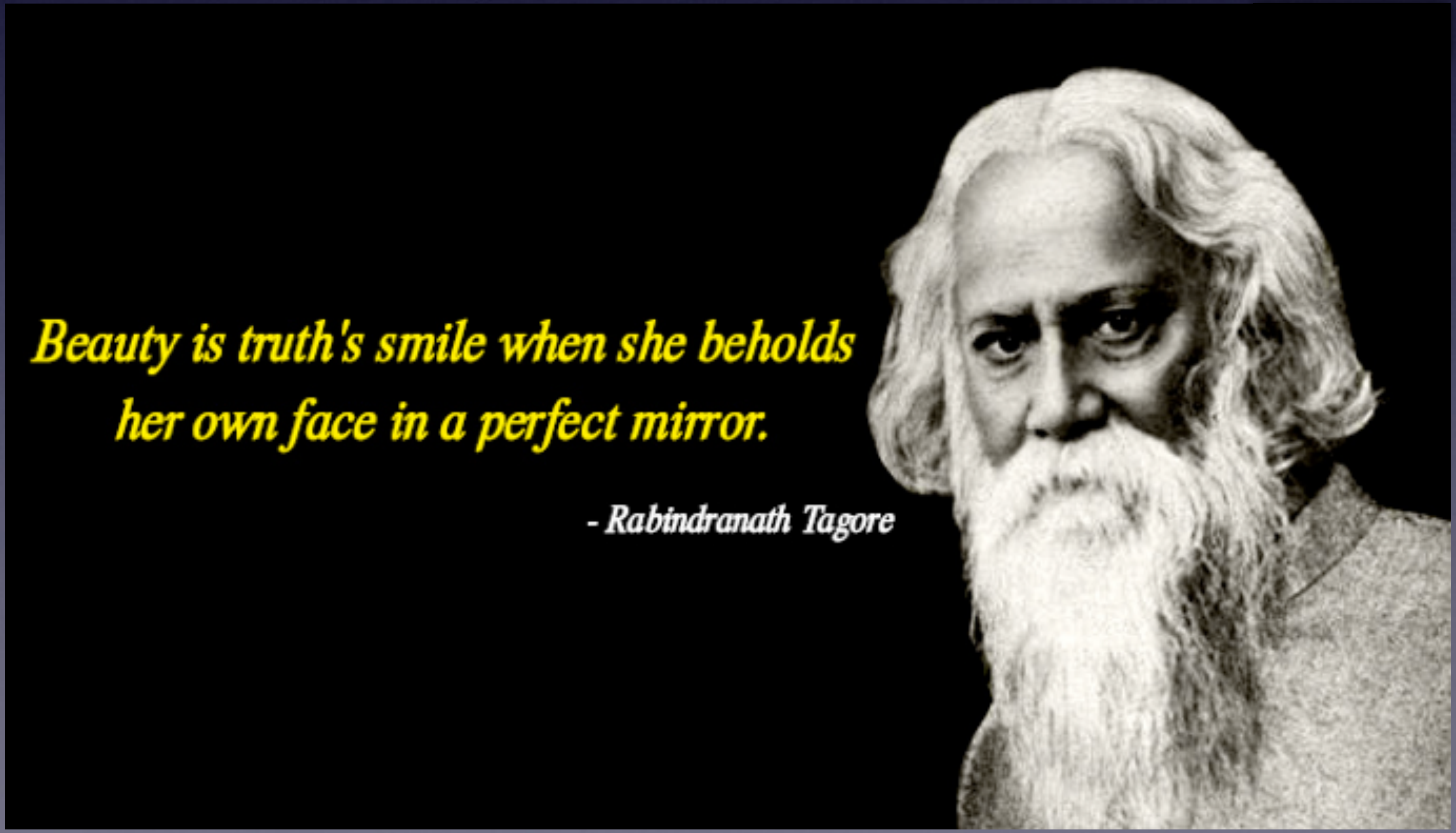
List of references



The true laboratory is the mind, where behind illusions we uncover the laws of truth.

— *Jagadish Chandra Bose* —

[redacted]



Beauty is truth's smile when she beholds her own face in a perfect mirror.

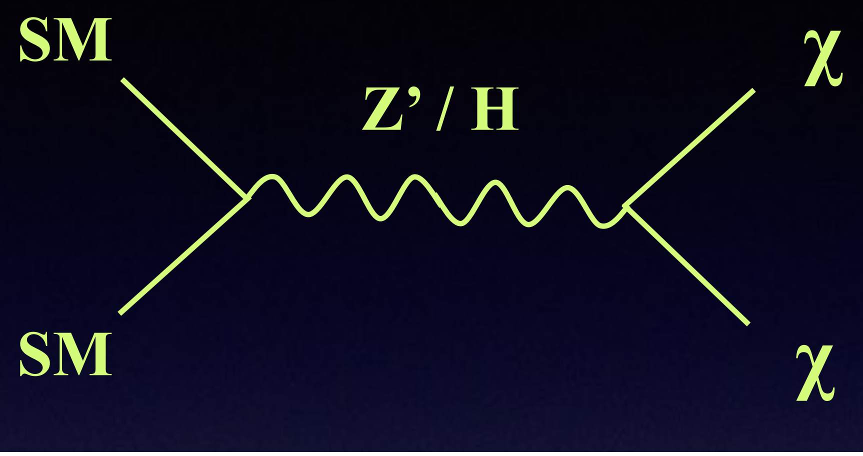
- Rabindranath Tagore

Beslides

The FIMP mechanism

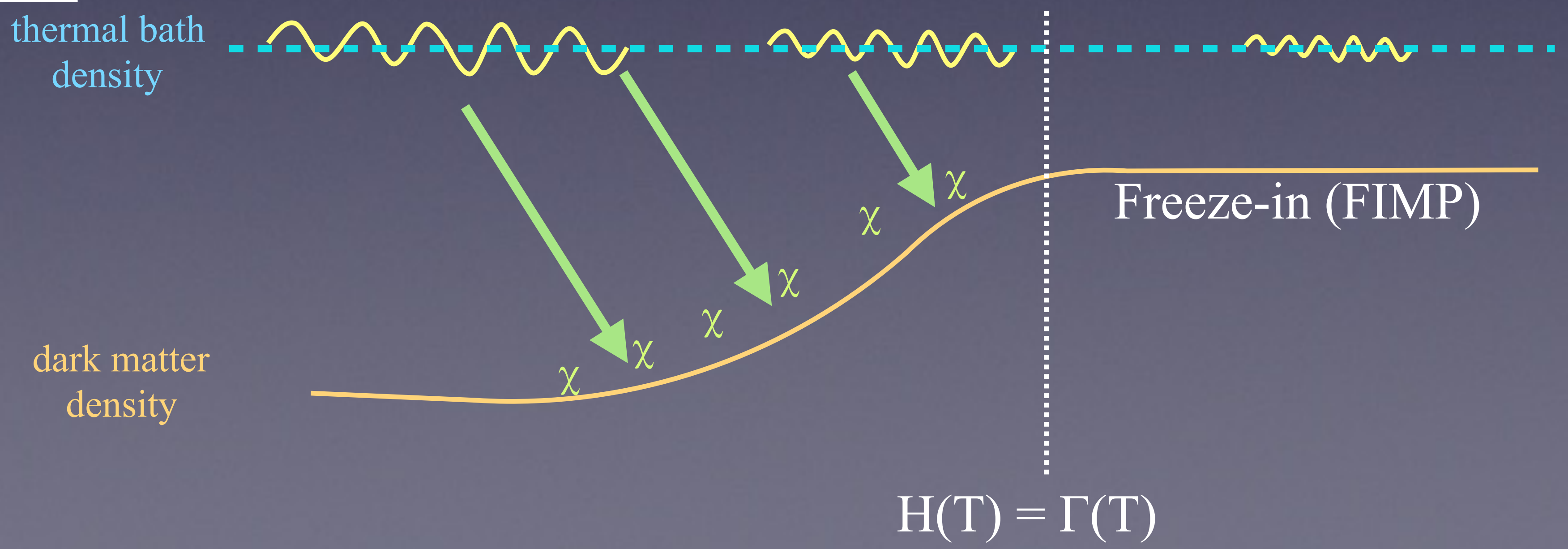
Freezing in the dark matter

Scattering process is too weak to reach kinetic equilibrium with the thermal bath, or because of heavy mediators or reduced couplings



Annihilation is too weak to reach the thermal equilibrium

The dark matter is produced from the thermal bath but at a very slow rate, until the expansion rate dominates the annihilation ($H > \Gamma$)



3 examples

High scale symmetry breaking

Maira Dutra, Yasaman Fazran, Y.M. in preparation

SO(10) particle

Y. M., Natsumi Nagata, Keith Olive

Supergravity scenario

Karim Benakli, Yifan Chen, Emilian Dudas, Y.M., 1701.xxxxx

All these scenarii have in common the fact that their coupling to the Standard Model sector is reduced because the breaking scale is **much heavier than the reheating temperature**:

U(1) breaking scale
Unification scale
SUSY breaking scale

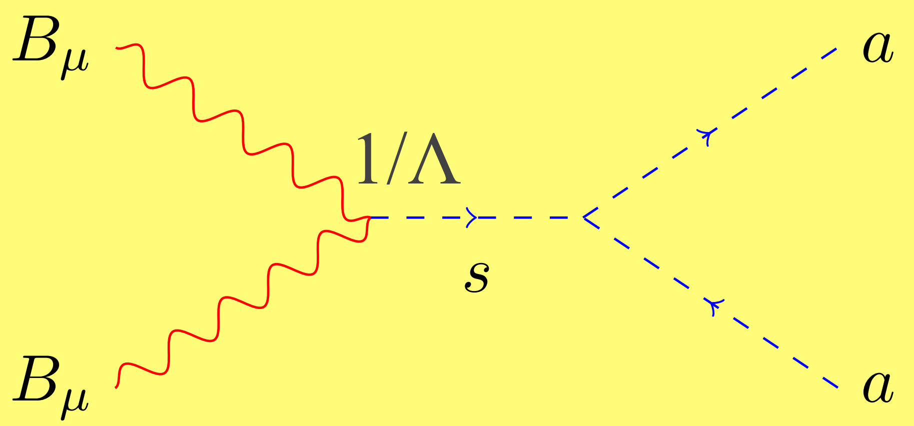
Their early cosmology behavior and phenomenology are however completely different due to their temperature dependance.

U(1) breaking

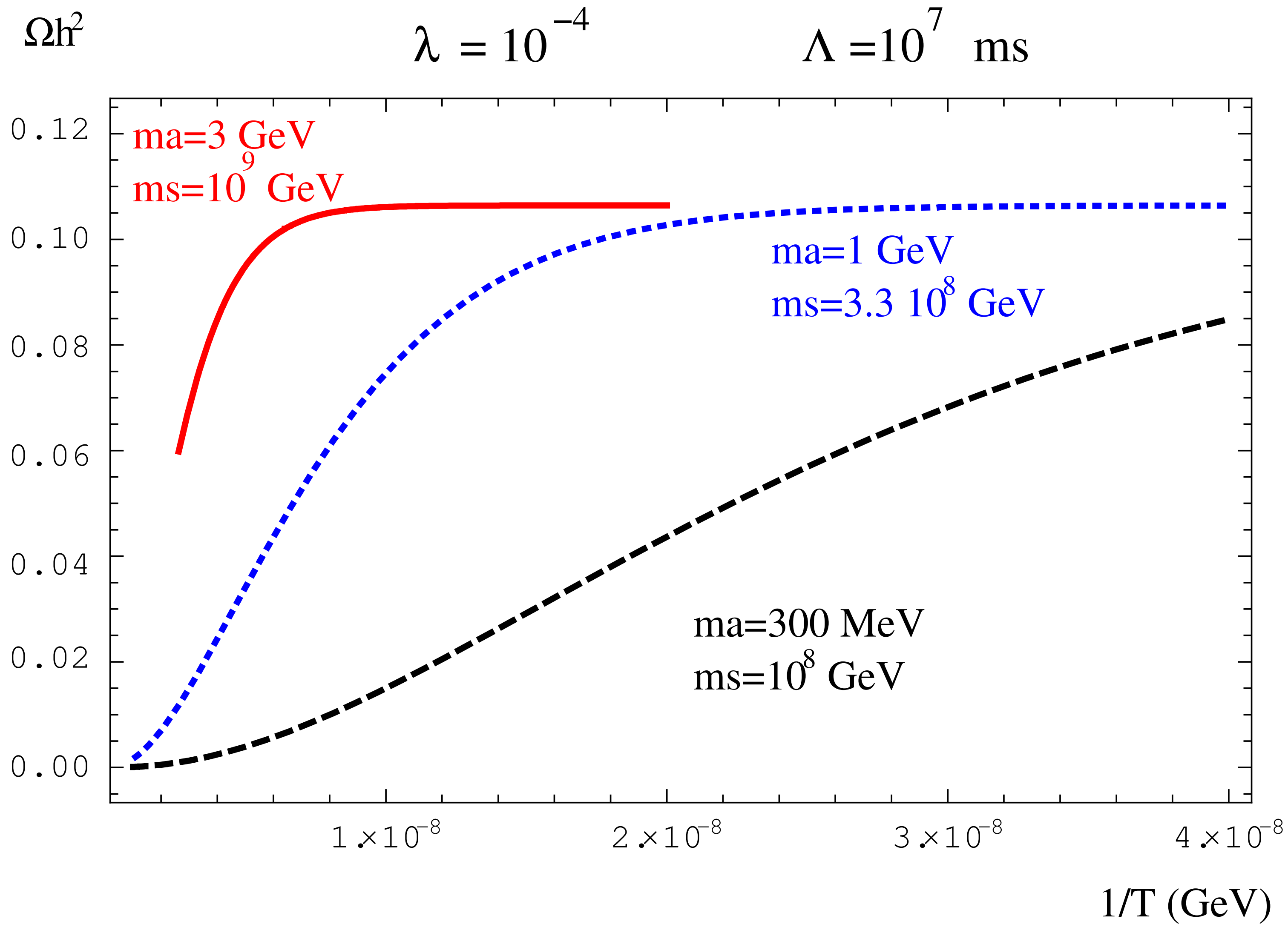
Let suppose the simplest extension of the SM with the addition of a global U(1) symmetry

$$\mathcal{L}_0 = \frac{1}{\Lambda}\Phi B_{\mu\nu}B^{\mu\nu} + \mu_\phi^2|\Phi|^2 - \lambda|\Phi|^4 + \frac{\epsilon_\Phi^2}{2}\Phi^2 + h.c.$$

$$\Phi = \frac{s+ia}{\sqrt{2}},$$

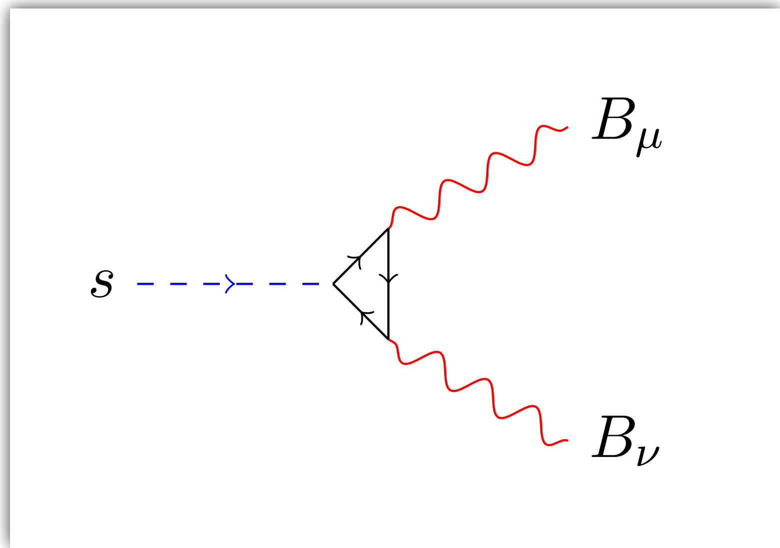


If Λ >> T_{RH}, the production rate of the dark matter a is strongly reduced, and we are in a freeze in context.



A microscopic model

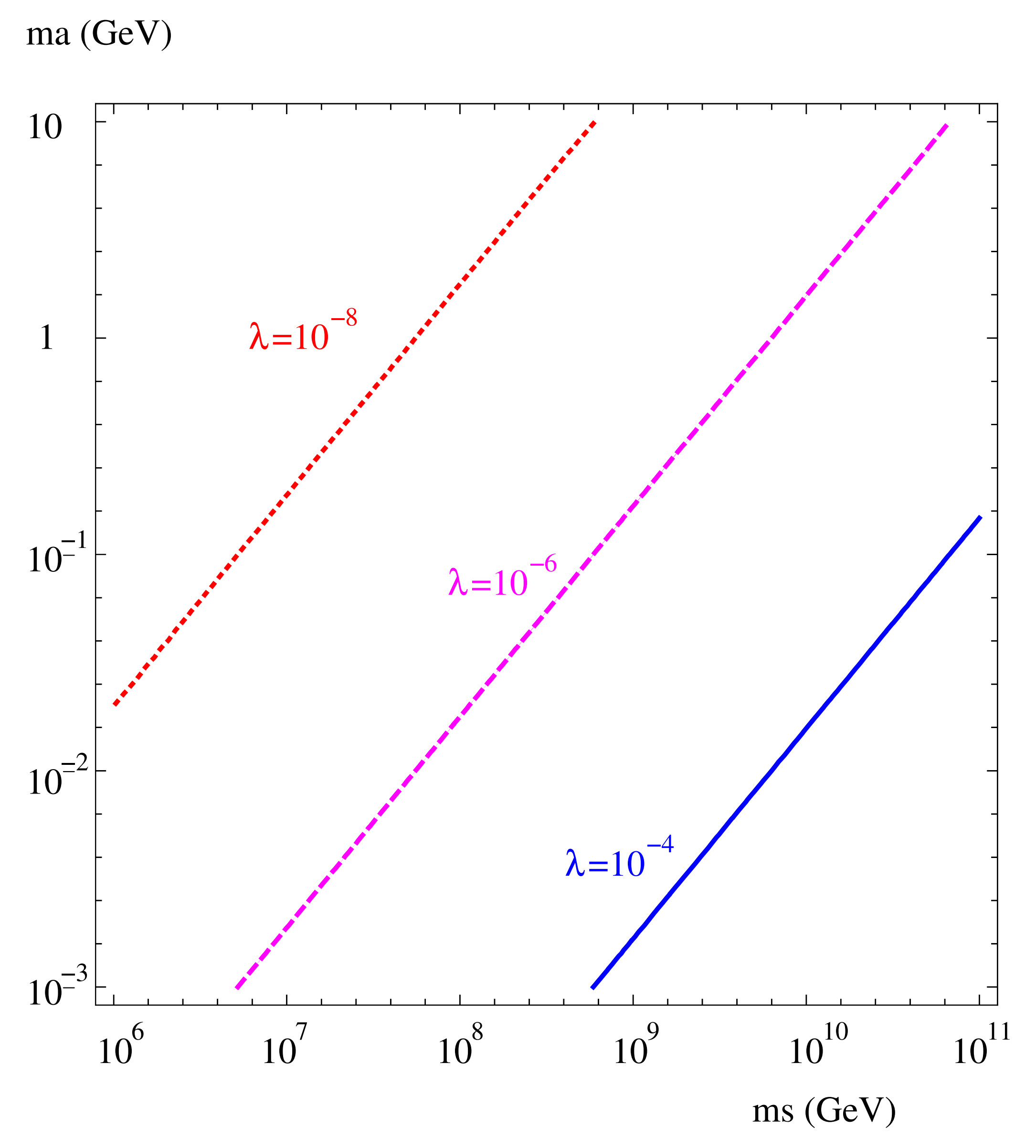
$$\mathcal{L} = \mathcal{L}_0 - \frac{y_F}{\sqrt{2}} s\bar{F}F - M_F \bar{F}F$$



$$\Lambda = \frac{8\pi m_s}{\sqrt{\lambda}\ \alpha_1\ \mathrm{Tr}[Q_f^2]} f_{1/2}(\tau)$$

with $\alpha_1 = g_1^2/4\pi$, $\tau = m_s^2/4M_F^2$ and

$$f_{1/2}(\tau) = 2\frac{\tau + (\tau - 1)\arcsin^2(\sqrt{\tau})}{\tau^2}$$



Conclusion: a breaking scale above the reheating temperature allowed for natural cosmological parameter space

Supergravity scenario

The gravitino dark matter in natural scenario where the SUSY scale is **below** the reheating temperature is given by [Buchmuller] :

$$\Omega_{3/2}h^2 \sim 0.3 \left(\frac{1\ \mathrm{GeV}}{m_{3/2}}\right)\left(\frac{T_{\mathrm{RH}}}{10^{10}\ \mathrm{GeV}}\right)\sum_i c_i \left(\frac{M_i}{100\ \mathrm{GeV}}\right)^2,$$

Let suppose that the supersymmetry breaking scale and the spectrum is much **above** the reheating temperature

$V = F^2 + 1/2\ D^2 \sim F^2$

$$m_{3/2} = \frac{F}{\sqrt{3}M_{Pl}},\quad M_{SUSY} = \frac{F}{\Lambda_{mess}}$$

The hypothesis translates into

$$m_{3/2} \ll T_{RH} \lesssim M_{SUSY} \lesssim \sqrt{F} \lesssim \Lambda_{mess} \ll M_{Pl}$$

Conclusion

We saw that the FIMP paradigm is far to be a … paradigm. And that any scenario where breaking scales are above the reheating temperature, leads to new production mechanism which are as natural as weakly interacting scenario

Needs to find new ways to detect such models

The scales in game

SUGRA reminder

$$V = F^2 + 1/2\, D^2 \sim F^2$$

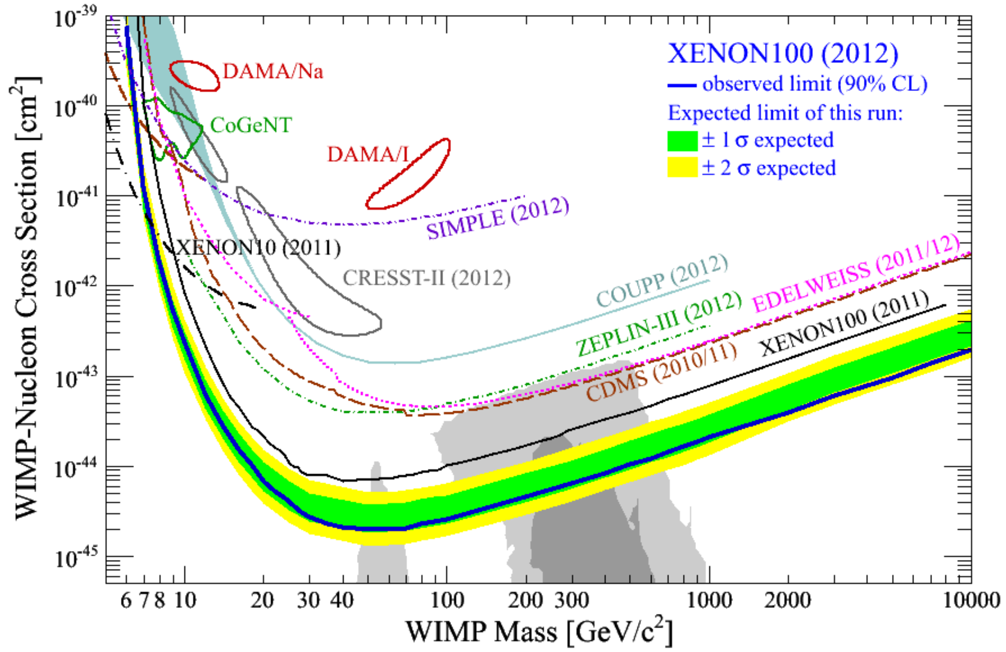
$$m_{3/2} = \frac{F}{\sqrt{3} M_{Pl}}, \quad M_{SUSY} = \frac{F}{\Lambda_{mess}}$$

Once <F> and/or <D> acquire a *vev*, SUSY is broken and generates gravitino mass. The breaking is then mediated to the SUSY sectors by *messengers* to generate the SUSY spectrum

$$m_{3/2} \ll T_{RH} \lesssim M_{SUSY} \lesssim \sqrt{F} \lesssim \Lambda_{mess} \ll M_{Pl}$$

The low energy spectrum is then only the SM plus the gravitino

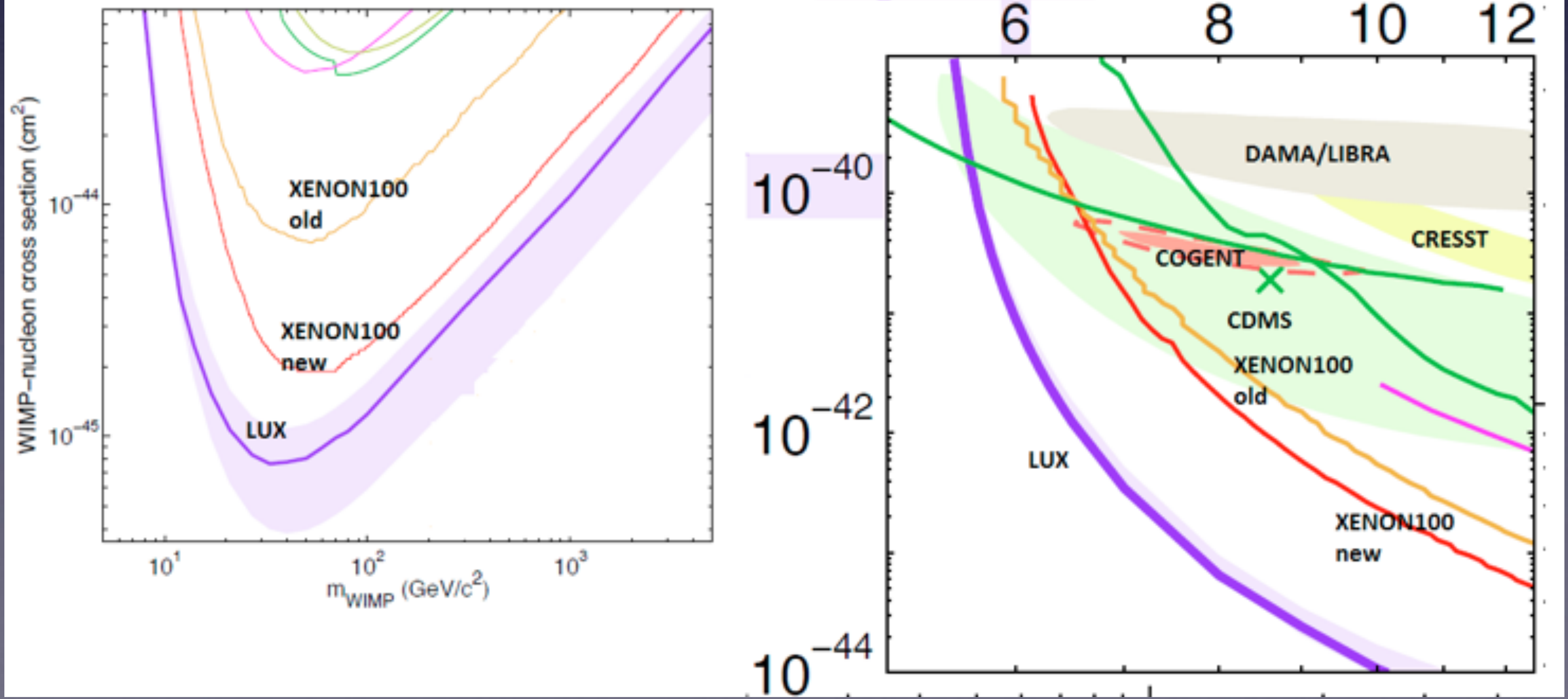
XENON + LUX results

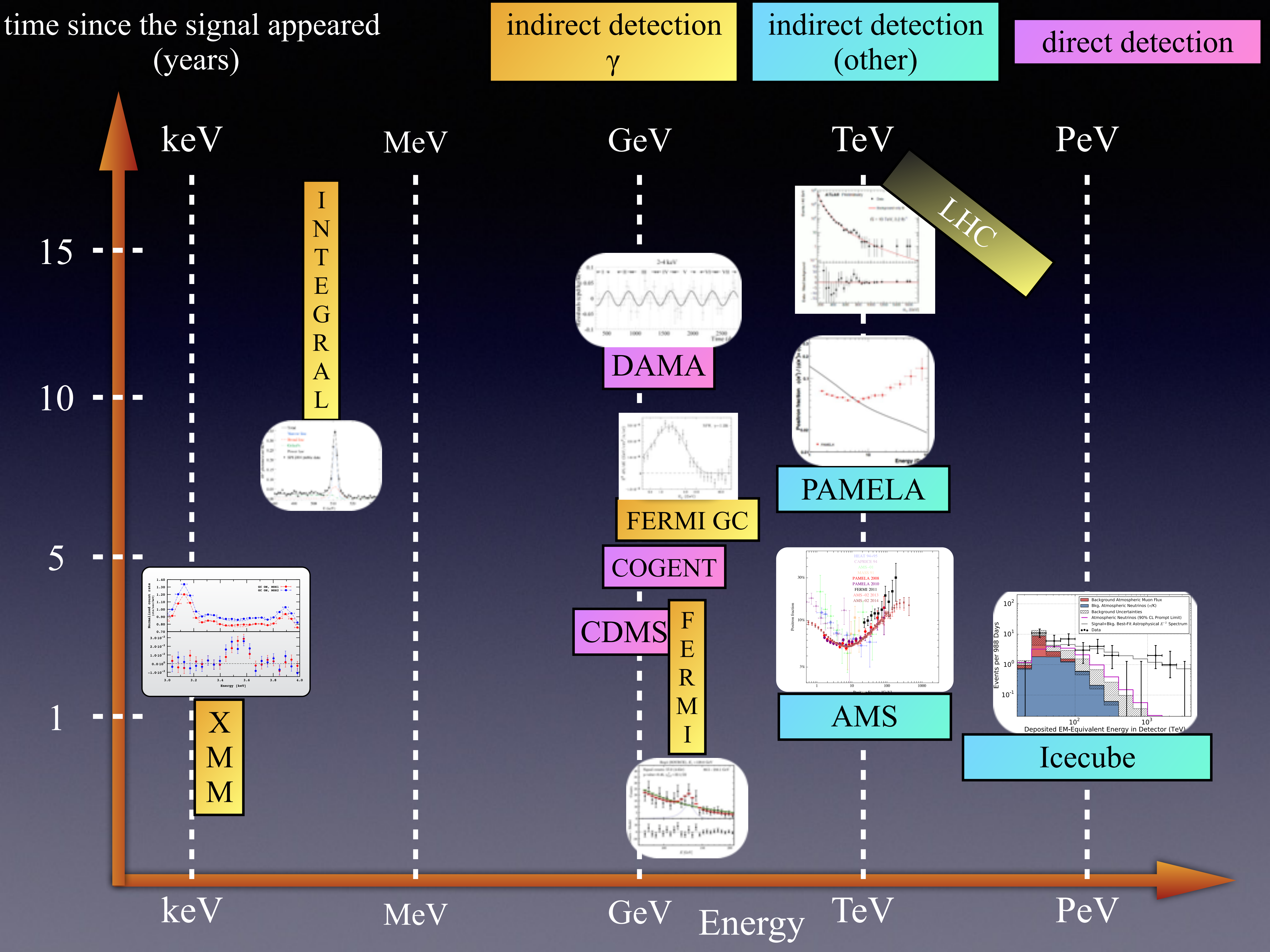


XENON100 (07/12)

XENON100 -> XENON 1 ton
(November 11th 2015)

LUX (1310.8214) -> LUZ (2016)





time since the signal appeared
(years)

indirect detection
γ

indirect detection
(other)

direct detection

keV

MeV

GeV

TeV

PeV

15

10

5

1

INTEGRAL

XMM

DAMA

FERMI GC

COGENT

CDMS

FERMI

LHC

PAMELA

AMS

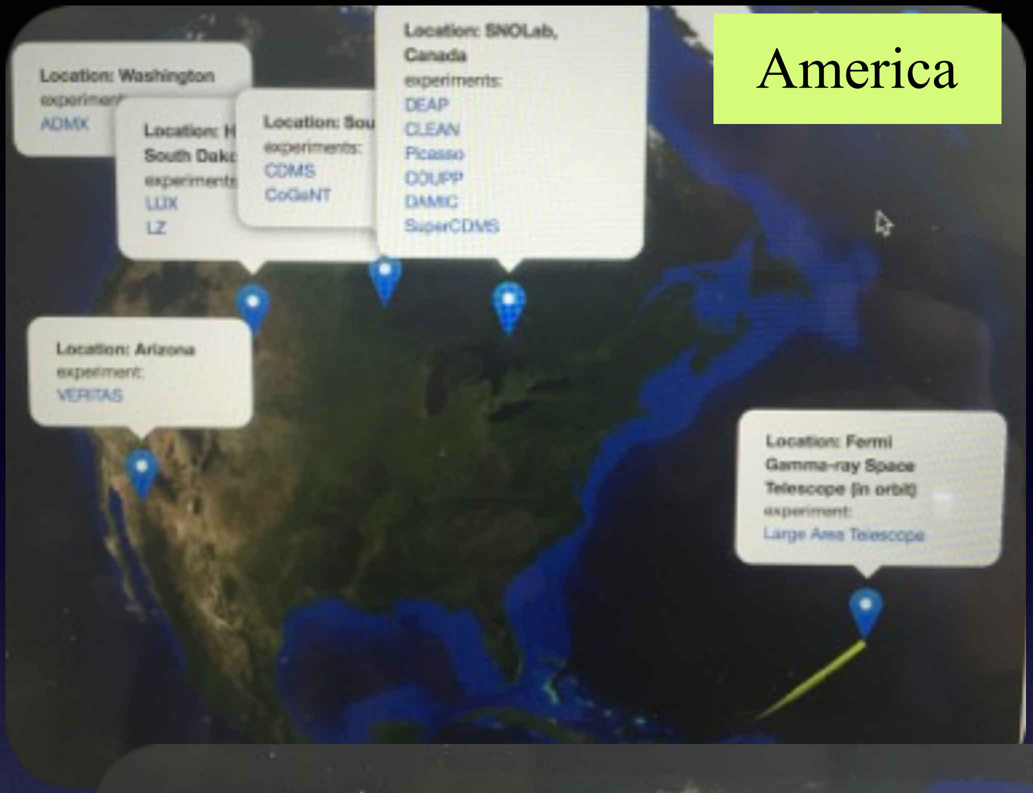
Icecube

Energy

Where on the world map?

Europe

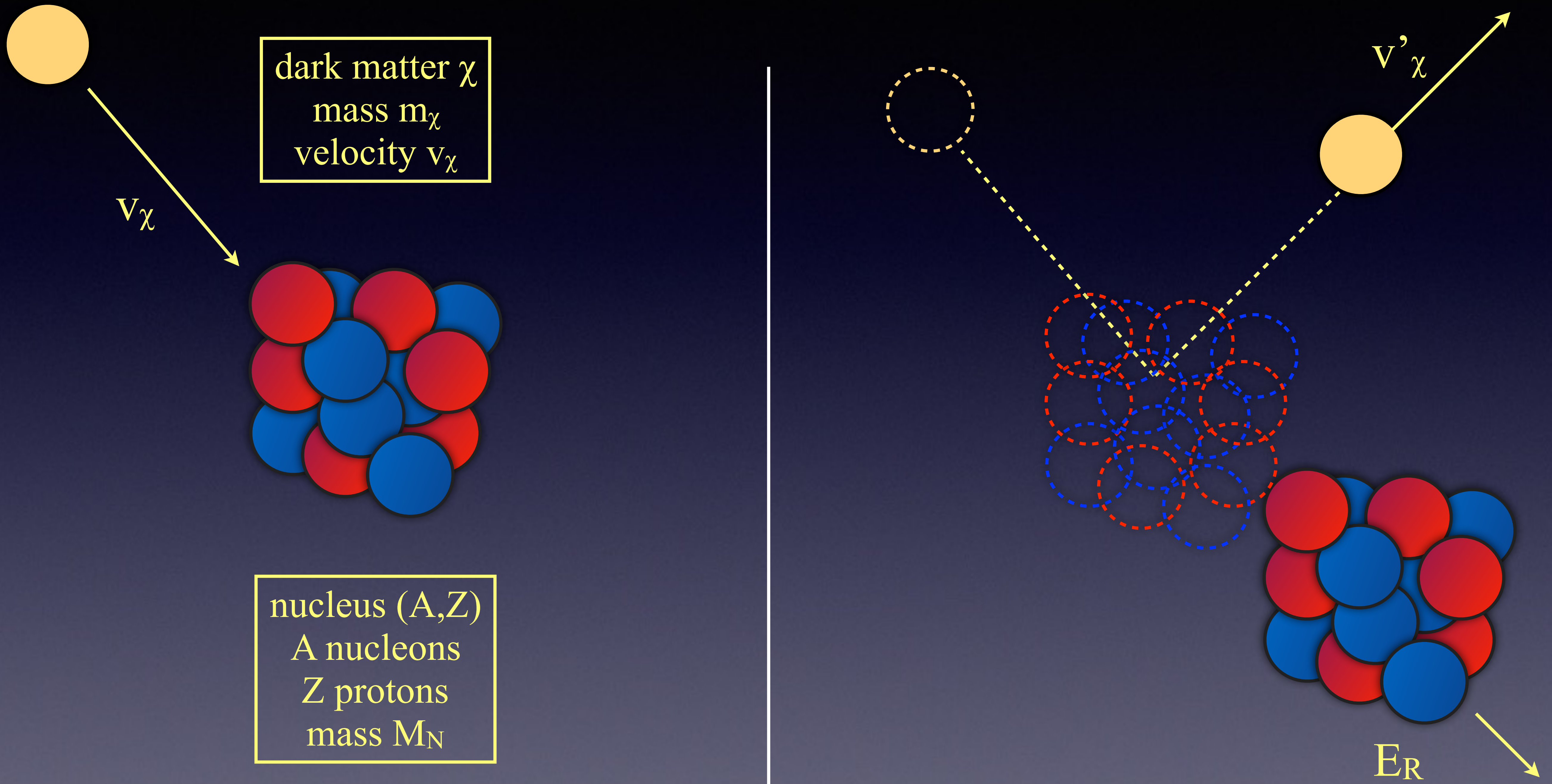
South Pole



America

Asia

Direct detection of dark matter (basic principle)



dark matter χ
mass m_χ
velocity v_χ

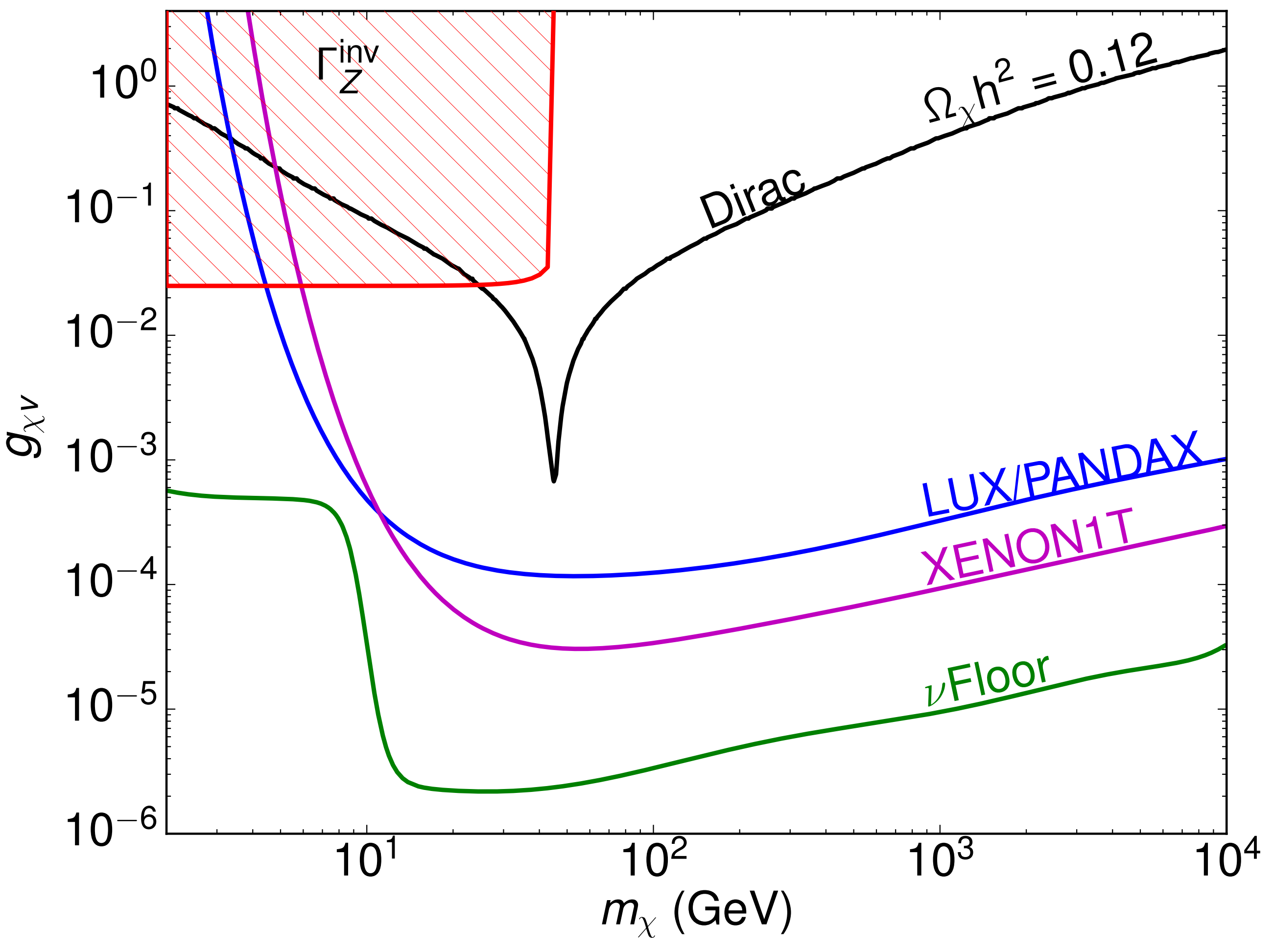
nucleus (A,Z)
A nucleons
Z protons
mass M_N

(momentum transfer q, elastic collision)

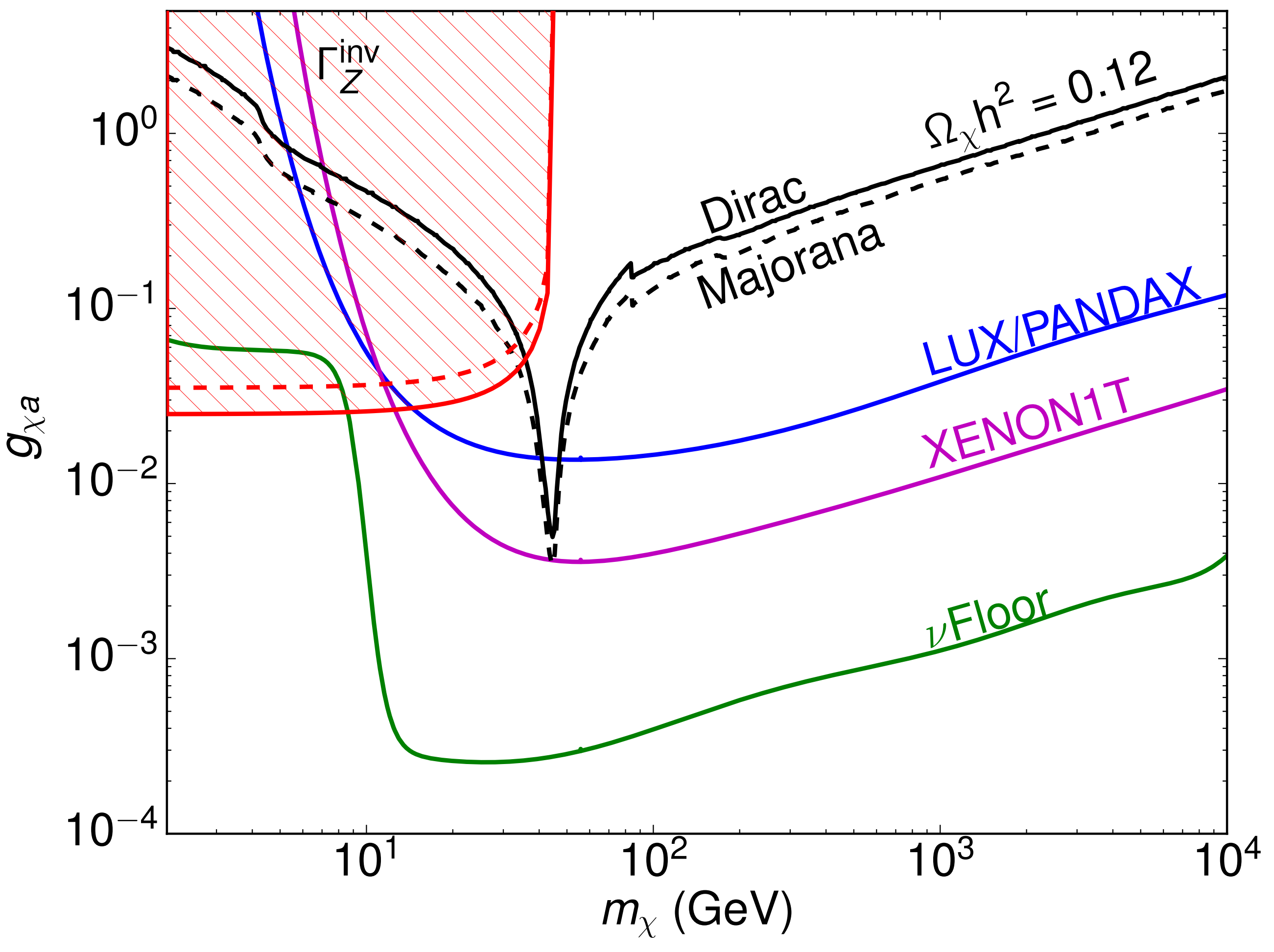
Z-portal : fermionic DM

$$\mathcal{L} \supset \left[a\bar{\chi}\gamma^{\mu}(g_{\chi v} + g_{\chi a}\gamma^{5})\chi\right] Z_{\mu},$$

Vectorial coupling



Axial coupling



G. Arcadi, Y. M. and F. Richard, JCAP **1503** (2015) 018

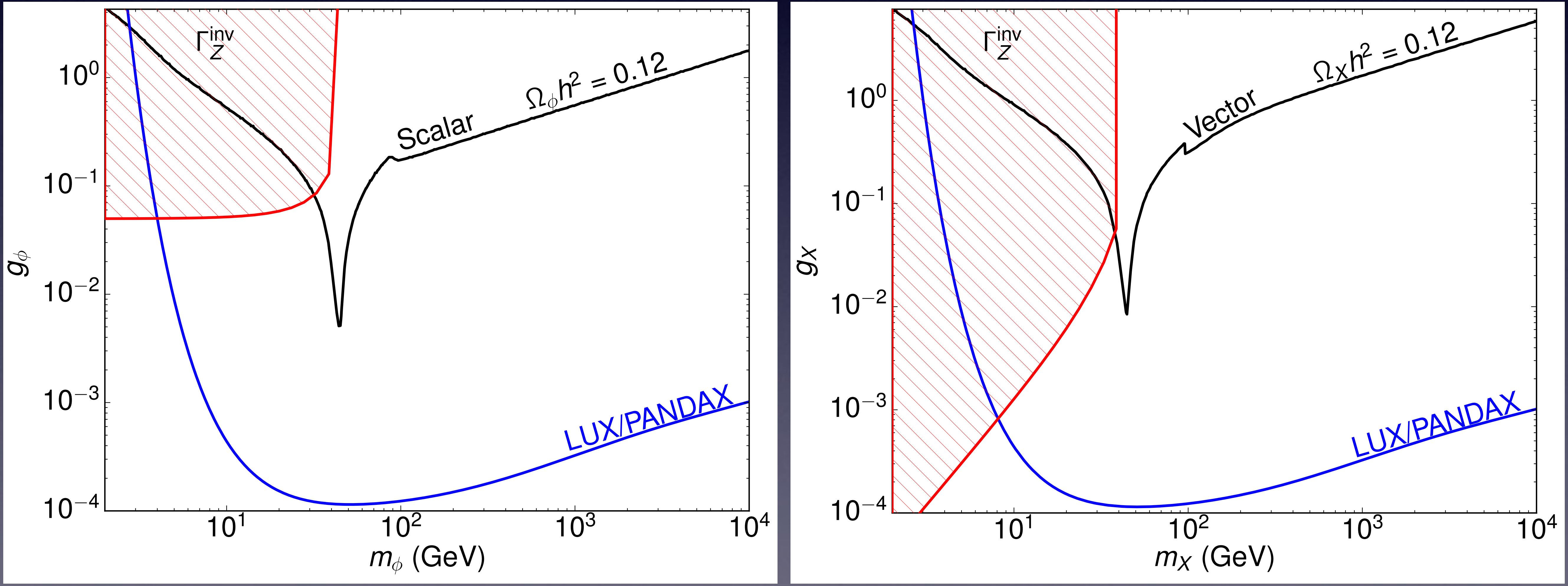
Escudero et al. 1609.09079

Z-portal : scalar/vectorial DM

$$\mathcal{L} \supset i\, g_\phi \phi^\dagger \overset{\leftrightarrow}{\partial}_\mu \phi Z^\mu + g_\phi^2 \phi^2 Z^\mu Z_\mu.$$

Scalar DM

Vectorial DM



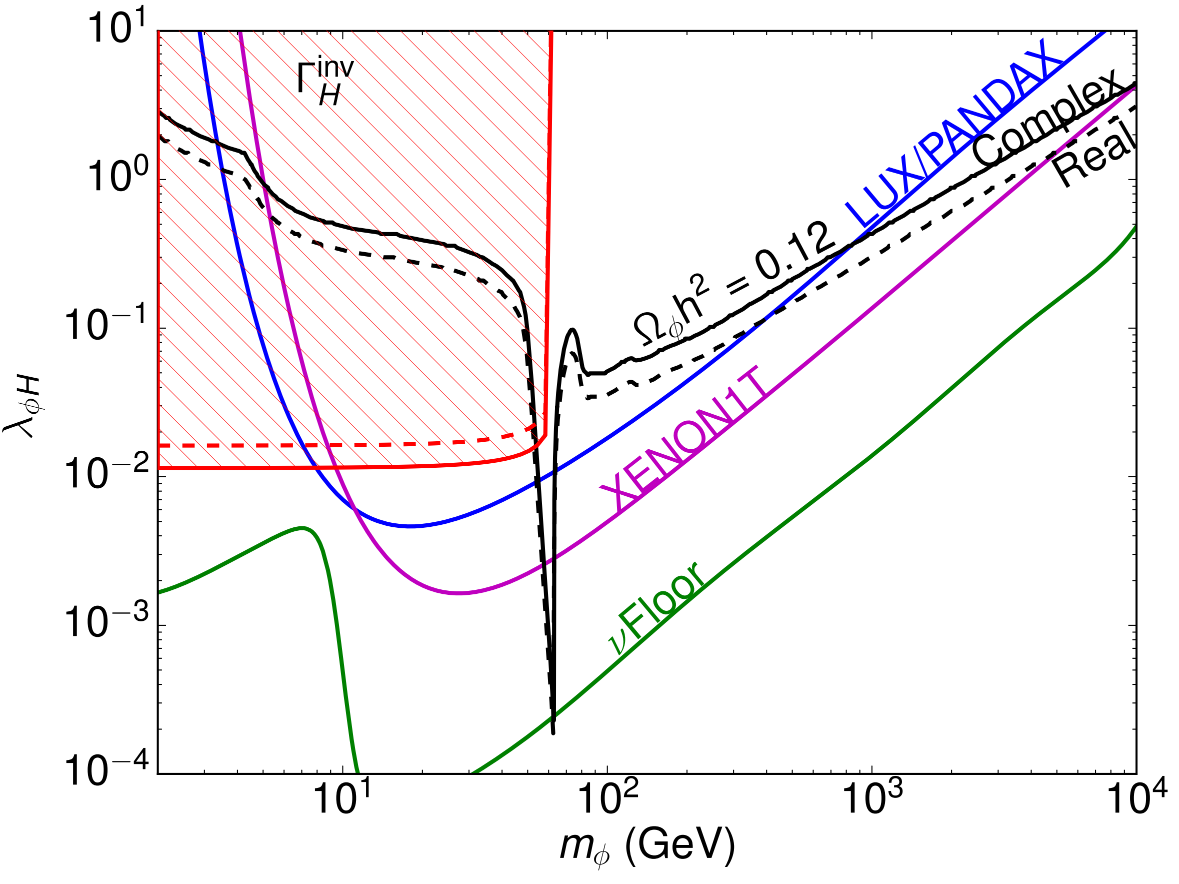
Escudero et al. 1609.09079

Higgs-portal : scalar/vectorial DM

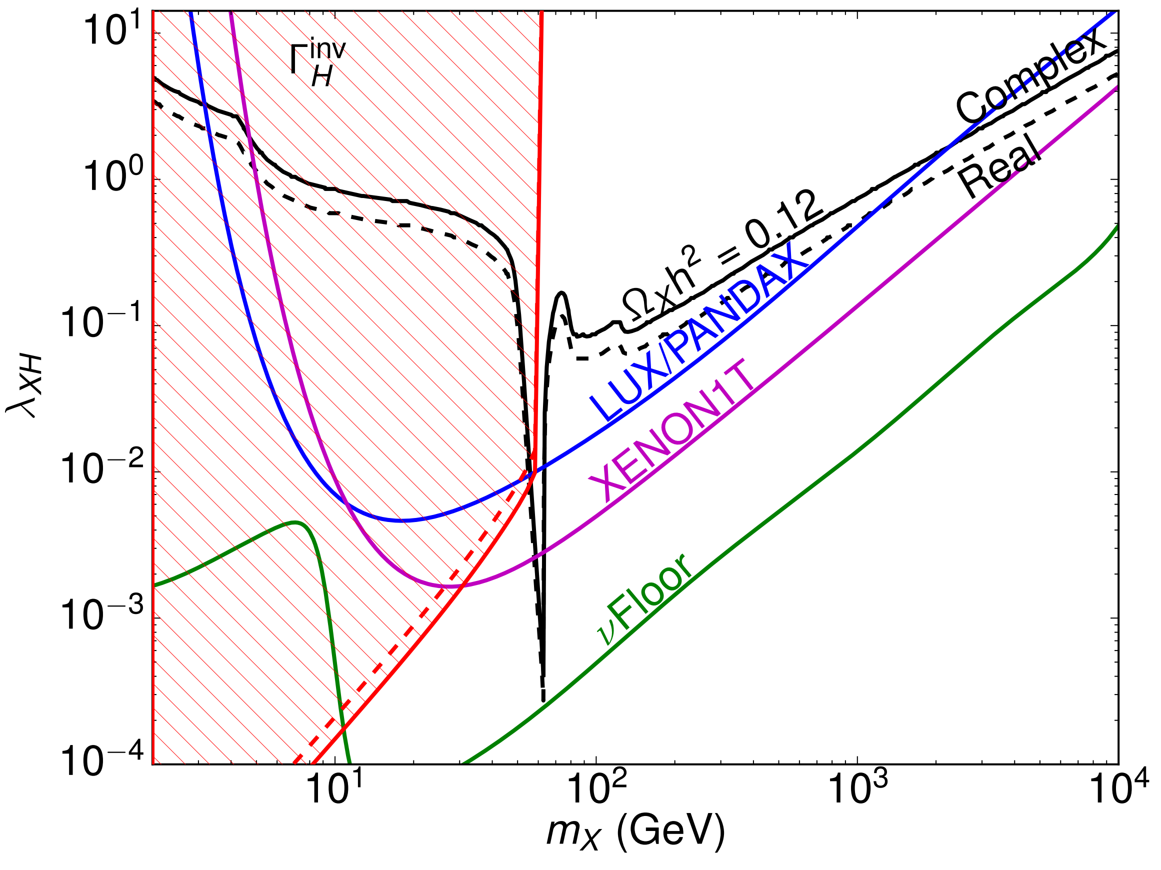
$$\mathcal{L} \supset a\,\lambda_{\phi H}\left[vH\phi^2 + \frac{1}{2}H^2\phi^2\right],$$

$$\mathcal{L} \supset a\lambda_{XH}\left[vHX^\mu X^\dagger_\mu + \frac{1}{2}H^2 X^\mu X^\dagger_\mu\right]$$

Scalar DM



Vectorial DM



Escudero et al. 1609.09079

```
H^2 = \left( \frac{\dot a}{a} \right)^2 = \frac{8 \pi G}{3} \rho_{rad}(T) = \frac{8 \pi G}{3} \frac{\pi^2}{15} T^4
\\
aT = \mathrm{cste} ~~~~ \Rightarrow ~~~~ \frac{da}{a} = - \frac{dT}{T}
\\
\frac{dT}{T^3}= -\sqrt{\frac{8 \pi^3 G}{45}} dt ~~~~\Rightarrow ~~~~ t = \frac{M_{PL}}{T^2}\sqrt{\frac{45}{32
\pi^3}} \simeq 0.2 \frac{M_{PL}}{T^2}
\\
t \simeq 3 \times 10^{27}~\mathrm{GeV^{-1}} \sim 200 ~\mathrm{seconds}
\\
n(t_D) \sigma v ~ t_D \simeq 1 ~~~~\Rightarrow n(t_D) \simeq \frac{1}{\sigma v t_D}
\\
v = \sqrt{\frac{3 T_D}{m_p}}\times c \simeq 5 \times 10^8 ~\mathrm{cm ~s^{-1}}
\\
T^{now} = \left(\frac{\rho_m^{now}}{\rho_m(10^9~\mathrm{K})}\right)^{1/3} 10^9~\mathrm{K} = \left( \frac{10^{-30}}
{1.78 \times 10^{-6}~\mathrm{g/cm^3}} \right)^{1/3}10^9~\mathrm{K} \simeq 8 ~\mathrm{K}


\psi_\mu \sim i \sqrt{\frac{2}{3}}\frac{1}{m_{3/2}}\partial_\mu \psi

H = h e^{i \frac{\theta}{<H>}} ~~\Rightarrow ~~ W_\mu = i \frac{1}{<H>} \partial_\mu \theta

\mathrm{with}~~ m_{3/2} = \frac{<F>}{\sqrt{3}M_{Pl}}

{\cal L} = \frac{i m_{\tilde G}}{8 \sqrt{6}~ m_{3/2} ~ M_{Pl}} {\color{yellow} \bar\psi} ~  [\gamma_\mu, \gamma_\nu]
{\color{red} \tilde G} ~ {\color{green} G_{\mu \nu}}


\Omega_{3/2} h^2 \sim 0.3 \left( \frac{1 ~\mathrm{GeV}}{m_{3/2}} \right) \left( \frac{T_{\mathrm{RH}}}{10^{10}~
\mathrm{GeV}} \right) \sum
\left( \frac{m_{\tilde G}}{100~\mathrm{GeV}} \right)^2


\Omega_{3/2} h^2 = {\color{yellow} \Omega_{3/2}^{scat} h^2 } + {\color{red}\Omega_{3/2}^{decay} h^2} ~~ \propto~~
{\color{yellow} \frac{T_{RH}\sum  m_{\tilde G^2}}{m_{3/2}^2 M_{Pl}}} +{\color{red} \frac{ \sum M^3_{\tilde Q}}
{m^2_{3/2} M_{Pl}} }
```

The equations

```
n_{e^-} + n_{e^+} = n_{\nu} + n_{\bar \nu} = \frac{3}{2} n_{\gamma}


n_{e^-} + n_{e^+} = 0 ~ ; ~~ n_{\nu} + n_{\bar \nu} = \frac{1}{2} n_{\gamma}


\frac{\ddot a}{a} = - \frac{4 \pi G}{3}  \rho ~\Rightarrow ~ q(t) = - \frac{1}{H^2} \frac{\ddot a}{a} = \frac{4 \pi
G}{3 H^2} \rho
\\
= \frac{1}{2} \frac{\rho}{\rho_c}= \frac{1}{2} \Omega,
 ~~~~~~ \mathrm{with} ~ H^2 = \frac{8 \pi G}{3} \rho_c


n(T_f) \langle \sigma v \rangle = H(T_f) ~~ \Rightarrow ~~\left(T_f m \right)^{3/2} e^{-m/T_f} \langle \sigma v
\rangle < \frac{T_f^2}{M_{Pl}} ~~\Rightarrow ~~ T_f=\frac{m}{\ln{M_{Pl}}} = \frac{m}{26}


\frac{dY}{dT} = \frac{T^2}{H(T)} \langle \sigma v \rangle Y^2 ~~\Rightarrow ~~ Y(T_{now}) = \frac{1}{M_{Pl} T_f
\langle \sigma v \rangle } = \frac{26}{M_{Pl} m \langle \sigma v \rangle }



\Omega = \frac{\rho}{\rho_c} = \frac{n \times m}{\rho_c} = \frac{Y \times n_\gamma \times m}{\rho_c} = \frac{26
\times 400~\mathrm{cm^{-3}}}{\rho_c M_{Pl} \langle \sigma v \rangle} < 1
~~~~~~~~
\Rightarrow \langle \sigma v \rangle > 10^{-9} h^{-2} ~\mathrm{GeV^{-2}}


\langle \sigma v \rangle \simeq G_F^2 m^2 > 10^{-9} ~\mathrm{GeV^{-2}} ~~\Rightarrow ~~ m > 2 ~\mathrm{GeV}



\frac{dY_{a}}{dx_s} =\left( \frac{45}{g_* \pi} \right)^{3/2} \frac{1}{4 \pi^2} \frac{M_P}{m_{a}^5}x_s^4 R

{\color{white} \chi^0_1=} {\color{red} c_B \tilde B + c_1 \tilde H_1 + c_2 \tilde H_2} {\color{yellow} + c_W \tilde
W}
```

The equations

Y_{\tilde G} = \frac{n_{\tilde G}}{n_\gamma} \simeq 10^{-8} \left(\frac{m_{3/2}}{1 ~ \mathrm{GeV}} \right)

The graviton case, a nightmare scenario?

The gravitino was in fact the first candidate to be proposed as a dark matter, before the neutralino by Pagels and Primack in 1982*

All the computation of relic abundance of graviton until now has been based on the hypothesis of the graviton and/or SUSY partners have been in thermal equilibrium with the primordial plasma.

What is happening if we settle just a minimal simple hypothesis:

$$M_{SUSY} > M_{inflaton} = M_{\Phi}$$

Based on
K. Benakli, Y. Chen, E. Dudas and Y.M. arXiv:1701.06574
and
E. Dudas, Y.M. and K.A. Olive, arXiv:1701.06574

*and notes by P. Fayet, in the Proceeding 16th Rencontres de Moriond, march 1981

The gravitino dark matter

The gravitino was in fact the first candidate to be proposed as a dark matter, before the neutralino by Pagels and Primack in 1982

H. Pagels and J.R. Primack, Phys. Rev. Lett. 48 (1982) 223

It is indeed a completely natural candidate, with the problematic issue of its non-detectability, especially when R-parity is conserved (no smoking gun decay modes)

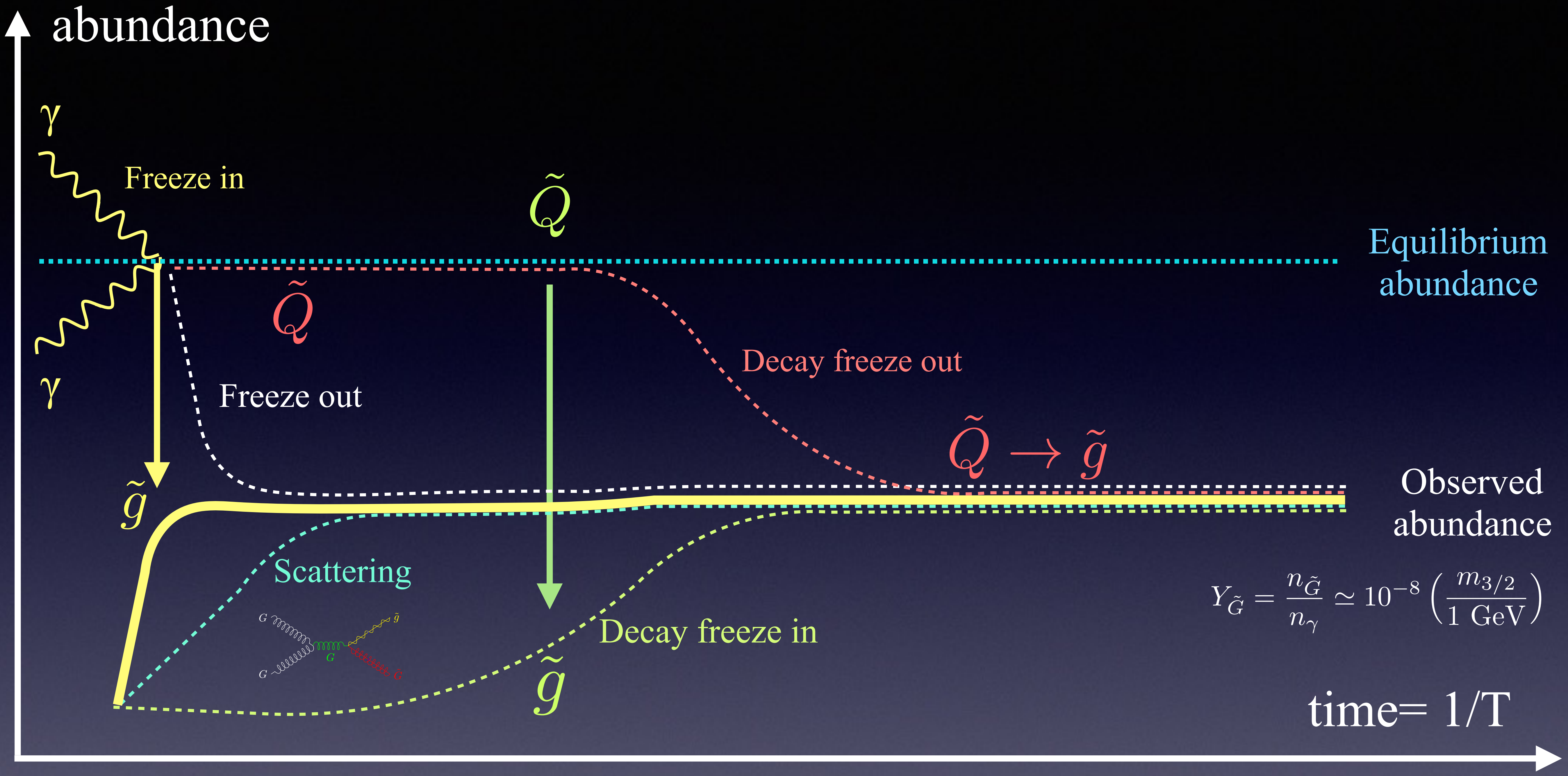
However, at first sight, if one supposed that it thermalized and decoupled quite early in the Universe (due to its reduced coupling to the Standard model), its mass is (naively) restricted to ~ keV (the « Cowsik-Mc Clelland analog of the neutrino):

$$\boxed{\Omega_{3/2} = \frac{n_{3/2} m_{3/2}}{\rho_c^0} \simeq \frac{n_\gamma \times \left(\frac{2}{g_*^{MSSM}}\right) m_{3/2}}{10^{-5} h^2 \ \mathrm{GeV/cm^{-3}}} \simeq \frac{0.1}{h^2} \left(\frac{m_{3/2}}{300 \ \mathrm{eV}}\right)}$$

which is excluded by Tremaine Gunn/structure formation bounds

If the gravitino cannot be produced by the thermalization of the primordial plasma, how can it be present in the Universe?

Several mechanisms can enter in the game: **scattering** of thermal particles, or **decays** of heavier supersymmetric partners or through the **freeze in** mechanism. However, the constraints are still quite severe on the gravitino mass if one wants to avoid its overabundance.



$$Y_{\tilde{G}} = \frac{n_{\tilde{G}}}{n_\gamma} \simeq 10^{-8} \left(\frac{m_{3/2}}{1\ \mathrm{GeV}} \right)$$

The scattering process

..In 1993, Moroi, Murayama and Yamaguchi take the goldstino interaction to compute its production rate through SM scattering

T. Moroi, H. Murayama, M. Yamagushi, Phys. Lett. **B303**, 284-294 (1993)

In gauge symmetry, where the transformation parameter **θ** (phase of the Higgs), which represent the (would be) massless goldstone mode of the theory is eaten to give the longitudinal mode of the gauge boson. By analogy, in supergravity (local supersymmetry), the would be fermionic goldstone (goldstino) **ψ** is eaten by the gauge field to give mass to the gravitino (SuperHiggs mechanism)

$$H = h e^{i\frac{\theta}{f}} \quad \Rightarrow \quad B_\mu \sim i\frac{1}{f}\partial_\mu\theta$$

$$\boxed{\psi_\mu \sim i\sqrt{\frac{2}{3}}\frac{1}{m_{3/2}}\partial_\mu\psi}$$

with $m_{3/2} = \dfrac{< F >}{\sqrt{3}M_{Pl}}$

<F> being the breaking scale of SUSY

The coupling is fixed by the symmetry (breaking)

T. Moroi, H. Murayama, M. Yamagushi, Phys. Lett. **B303**, 284-294 (1993)

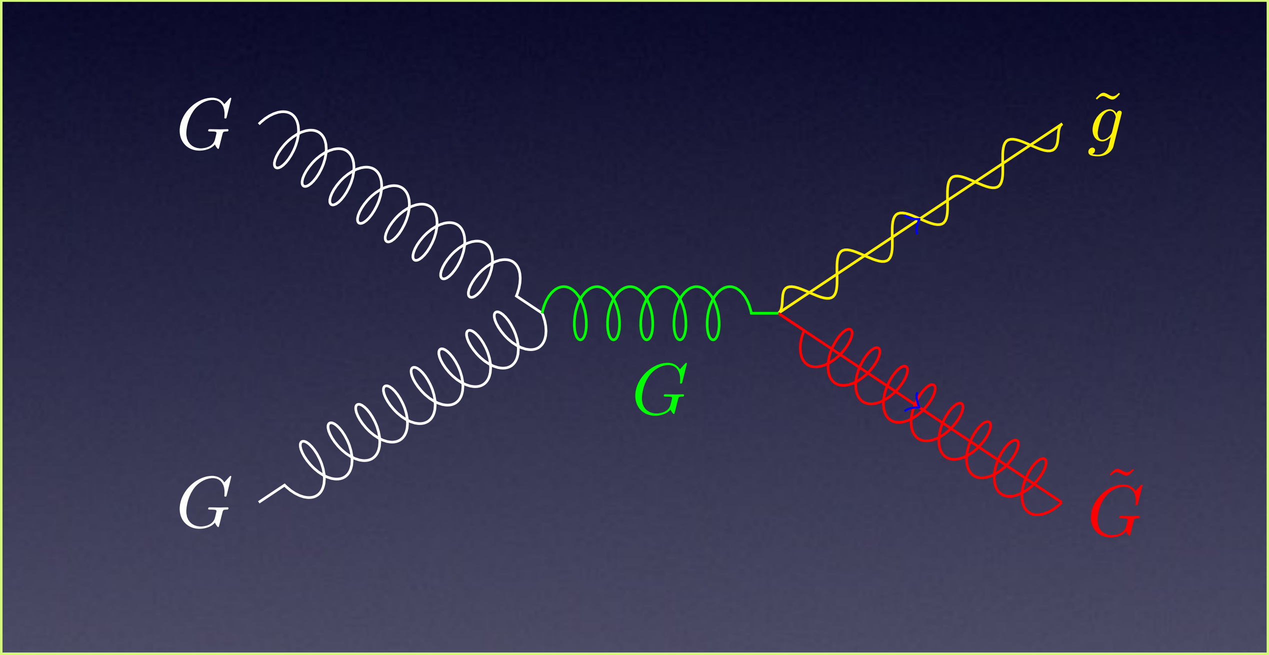
… one can then compute the relic abundance of the gravitino, repopulated by the scattering of SM particles in the thermal bath:

$$\mathcal{L} = \frac{i m_{\tilde G}}{8\sqrt{6}\, m_{3/2}\, M_{Pl}} \bar{\psi}\, [\gamma_\mu, \gamma_\nu] \tilde{G}\; G_{\mu\nu}$$

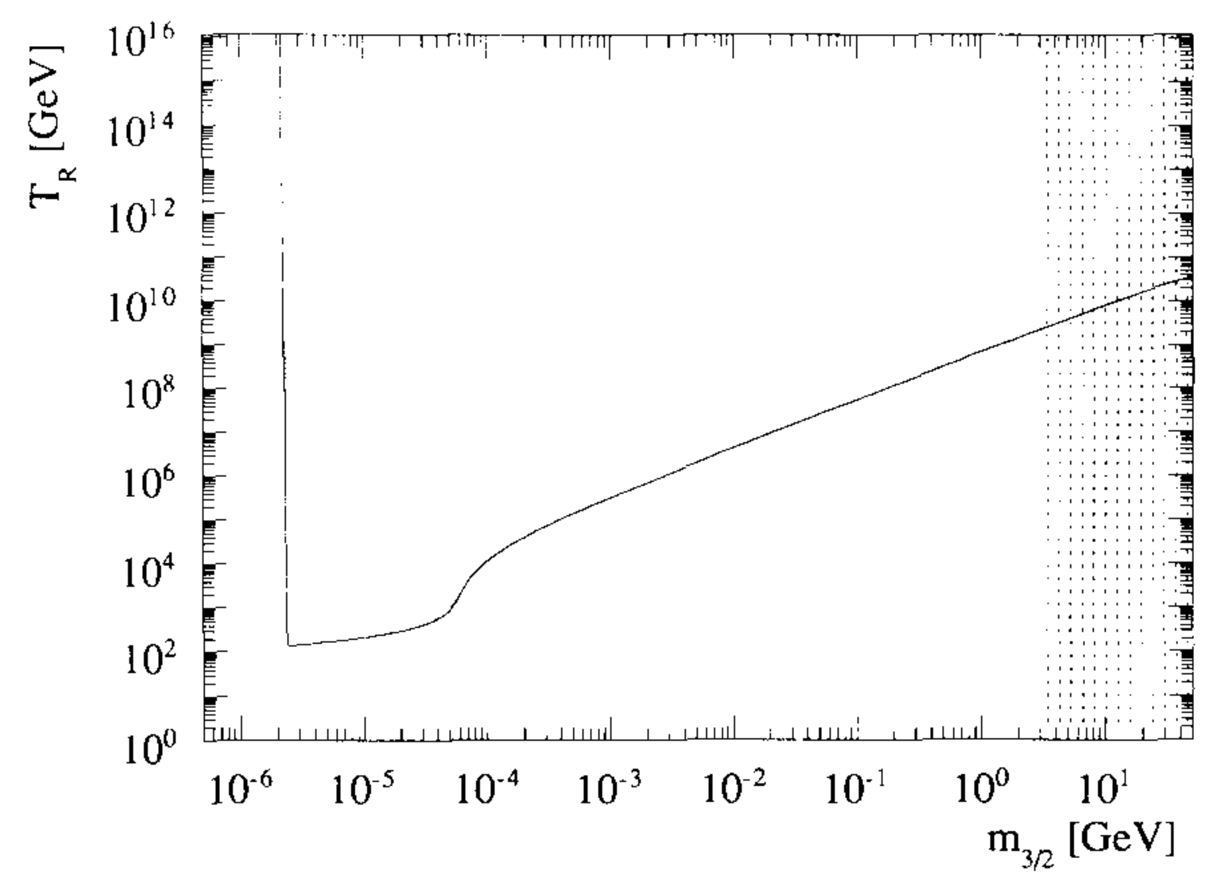
gravitino

gluino

gluon



$$\Omega_{3/2}h^2 \sim 0.3 \left(\frac{1\ \text{GeV}}{m_{3/2}}\right)\left(\frac{T_{\text{RH}}}{10^{10}\ \text{GeV}}\right)\sum\left(\frac{m_{\tilde G}}{100\ \text{GeV}}\right)^2$$



The thermal scattering has reopened a cosmologically viable window ($m_{3/2} > 1$ keV) but..

The freeze out process

The freeze out process is the mechanism describing the population of graviton through the decay of the Next to Lightest Supersymmetric Particle (NLSP) into gravitino, once the NLSP is out of equilibrium. The NLSP can be a sermon or a neutralino. We will take the neutralize case for illustration

See Keith’ paper of 1983

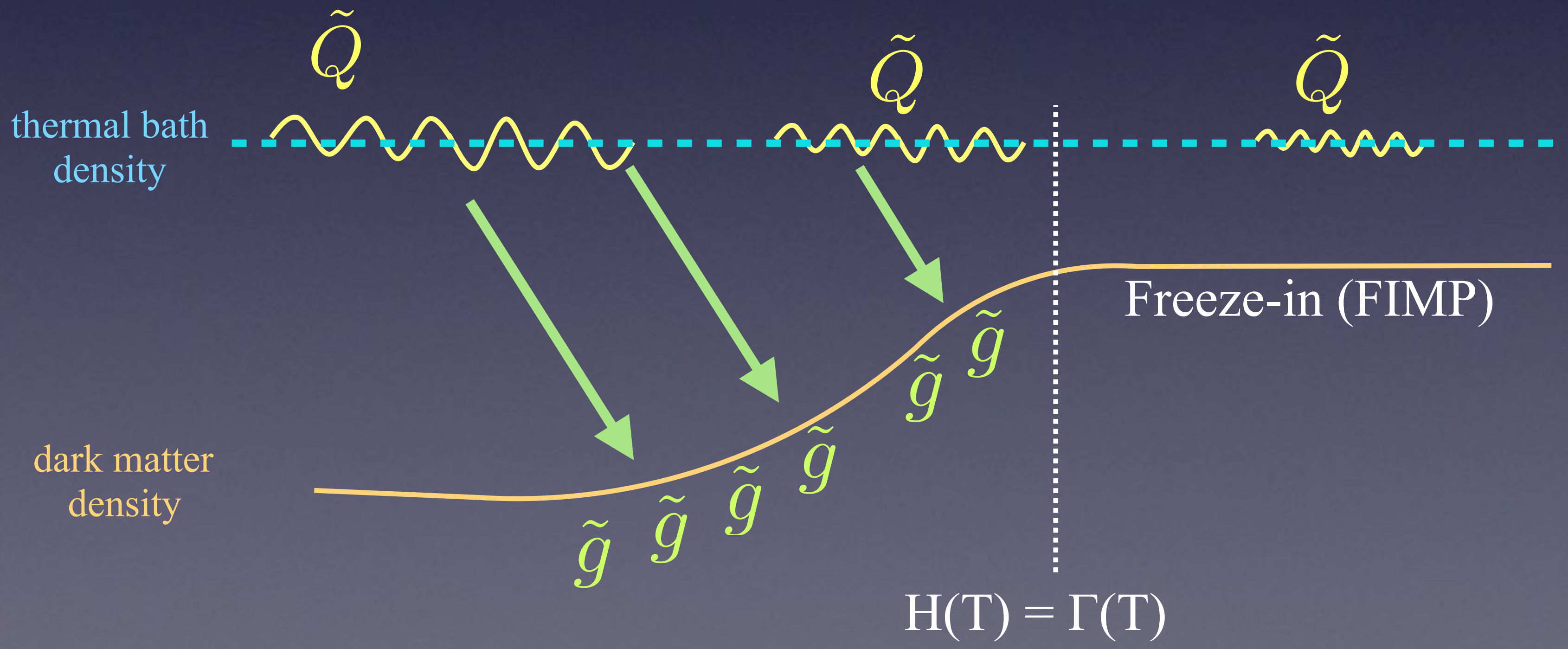
Add a slide about decay NLSP and BBN
(Stefen..)

.. non-discovery of gluino at LHC pushes lower bound on gluino masses, and thus upper bound on T_{RH} of $\sim 10^7$ GeV which can be problematic for some leptogenesis scenario.

But, even in this case…

Cheung et al.* showed in 2011 that the freeze in process of gravitino production through the decay of sparticles still in thermal equilibrium should render the Universe overdense if $T_{RH} > M_{susy}$.

The dark matter is produced from the thermal bath but at a very slow rate, until the expansion rate dominates the annihilation (H > Γ)

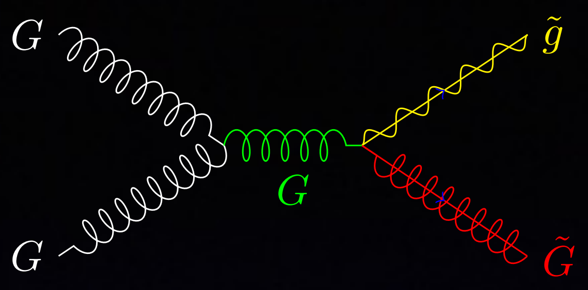


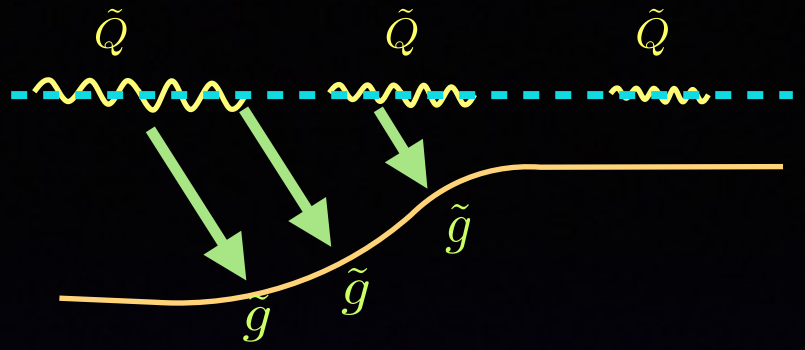
$$\Omega_{3/2}^{decay} h^2 \propto \frac{\sum M_{\tilde{Q}}^3}{m_{3/2} M_{Pl}}$$

but decay will compete with scattering

---

*C. Cheung, G. Elor, and L. Hall, Phys. Rev. D 61 (2011)

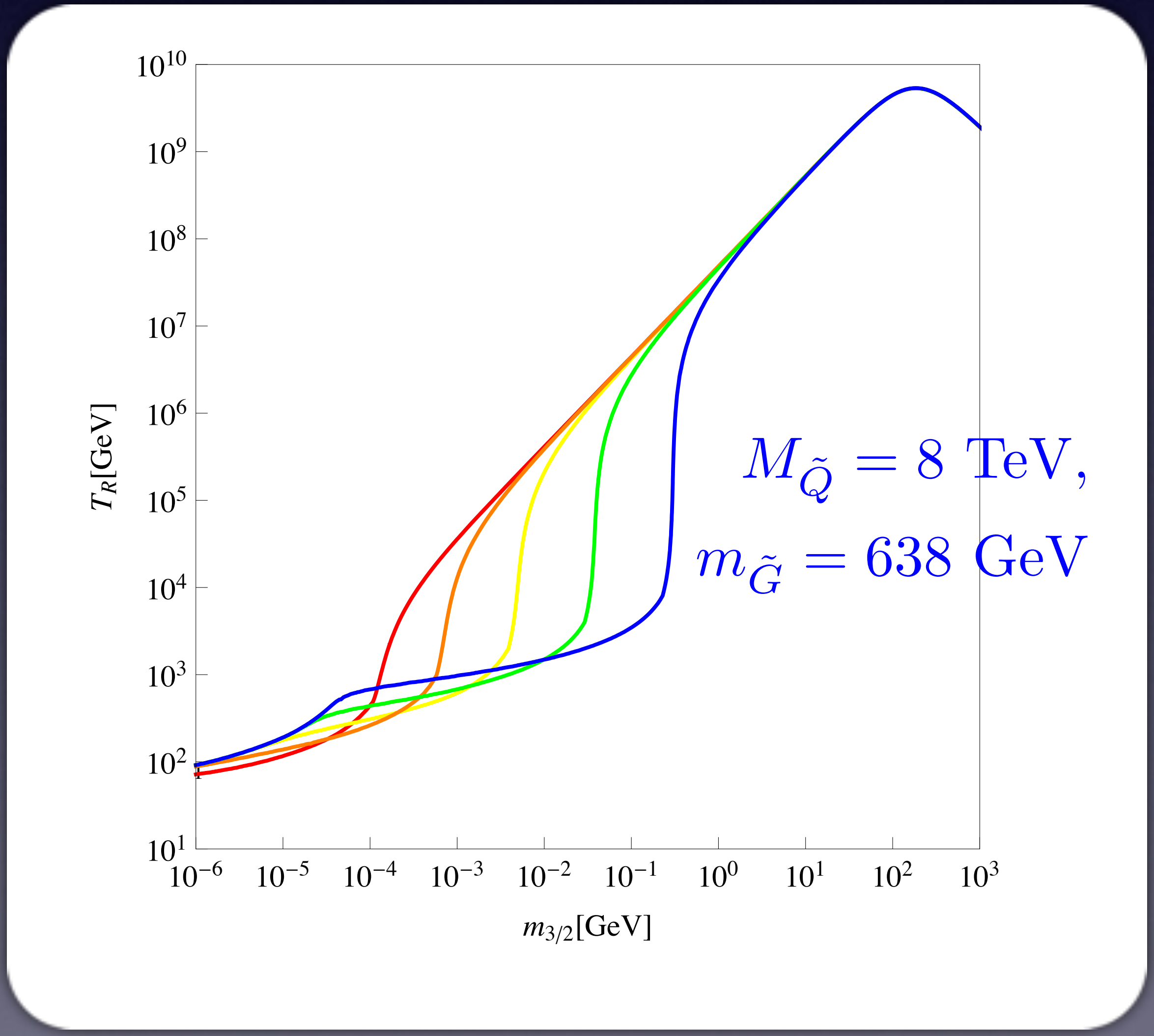




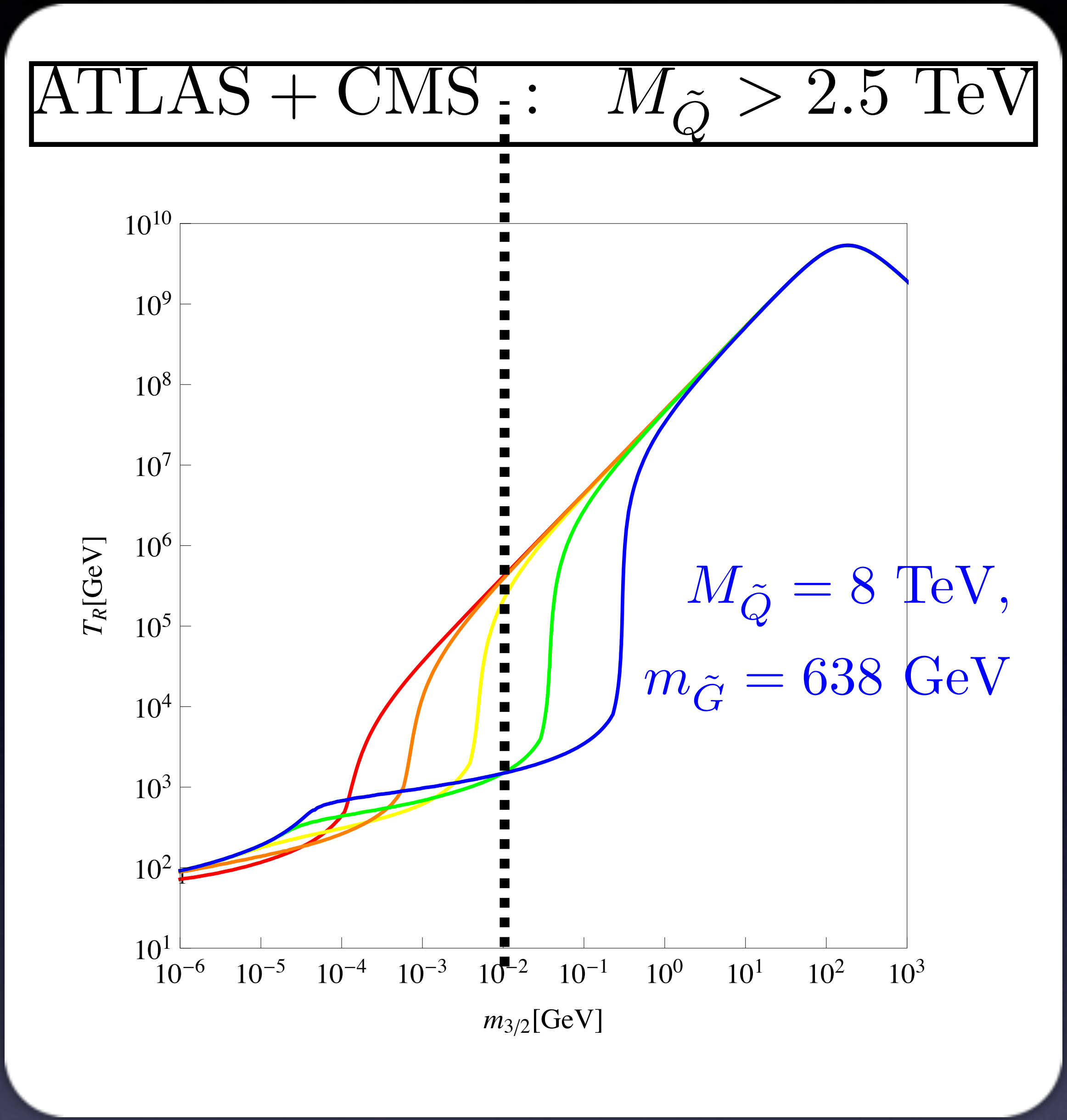
$$\Omega_{3/2}h^2 = \Omega^{scat}_{3/2}h^2 + \Omega^{decay}_{3/2}h^2 \quad \propto \quad \frac{T_{RH}\sum m_{\tilde{G}^2}}{m_{3/2}^2 M_{Pl}} + \frac{\sum M_{\tilde{Q}}^3}{m_{3/2}^2 M_{Pl}}$$

If $T_{RH} M_{\tilde{Q}}^2 < m_{\tilde{G}}^3$

Then, the relic abundance is given by the decay modes and quickly over-densify the Universe, unless $T_{RH} < M_{susy}$, in which case only the exponential queue of the SUSY distribution plays a role.



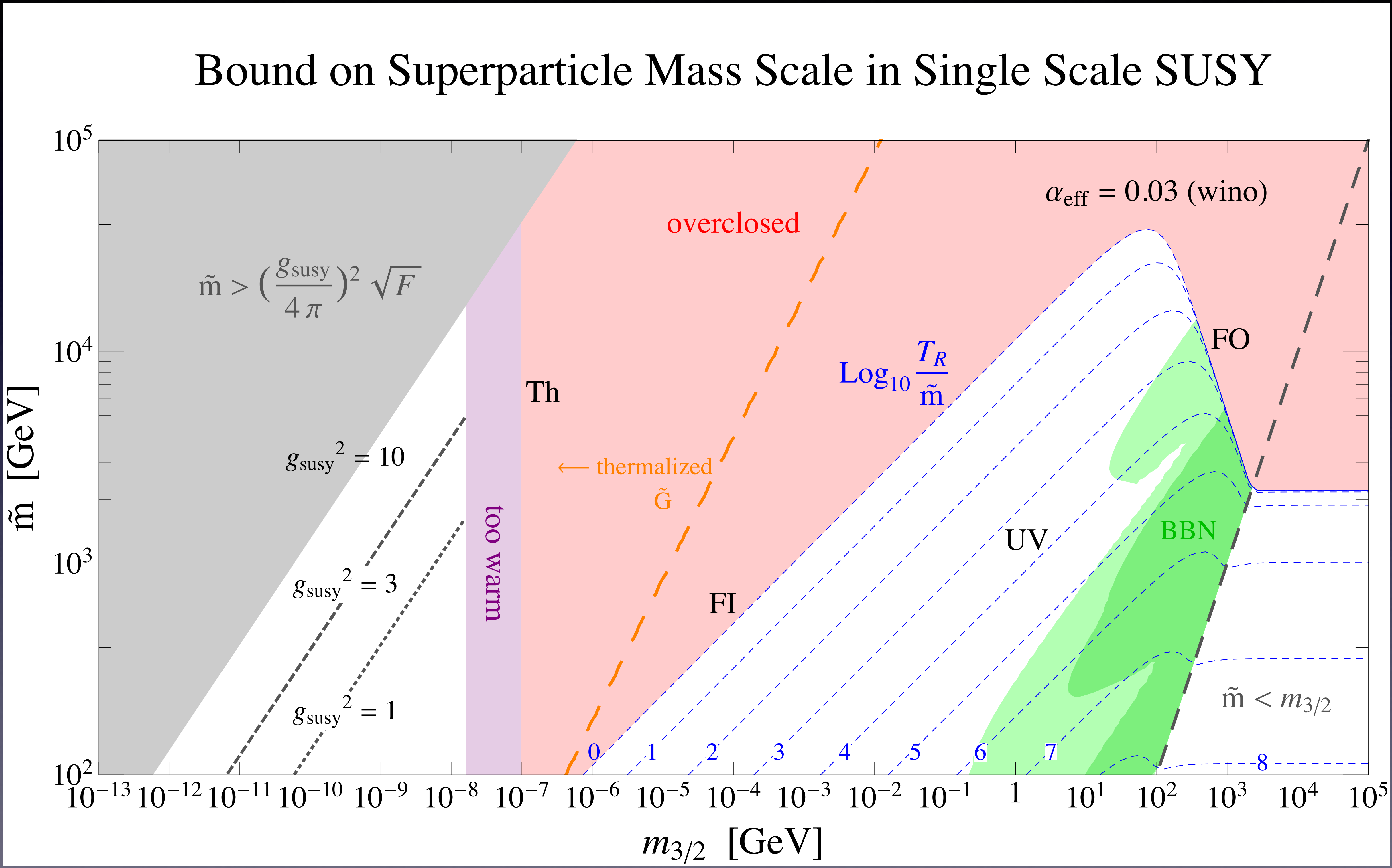
C. Cheung, G. Elor, and L. Hall, Phys. Rev. D 61 (2011)



Conclusion : the combination of freeze in and scattering convoluted with the last LHC limits on squark masses pushes toward very low reheating temperature, below the squark masses

Add a slide about freeze out production
(see references in paper of Volansky or Arcadi 1507.05584)

Add a comment on that plot Tell that BBN constraint restrict a lot (m less than GeV scale) Tell later that this is NOT our case.



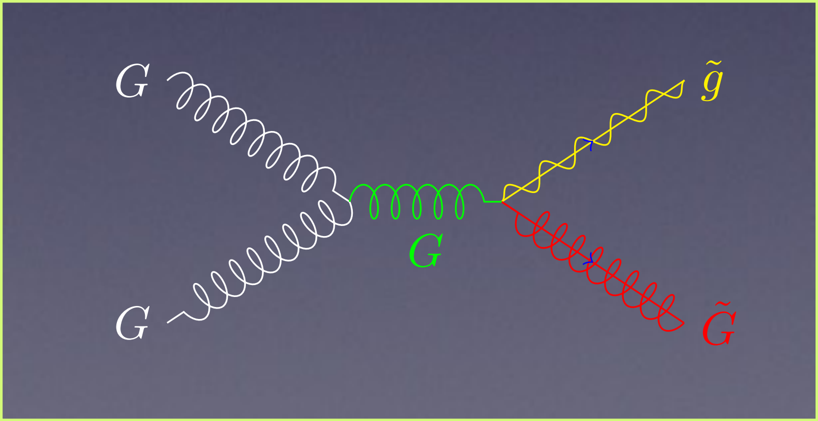
L. J. Hall, J. T. Ruderman and T. Volansky, JHEP **1502** (2015) 094

Now, let’s turn around the paradigm

Let’s suppose that instead of working with such low (and inconvenient) reheating temperature below the SUSY scale, it is the SUSY scale which is pushed much above the reheating temperature.

With such a minimalistic hypothesis, we forbid naturally the gravitino and SUSY partners to thermalize, and exclude the possibility of overproduction from sparticles decay* .

But, in the meantime, we also kinematically forbid the scattering production:



So how to produce the gravitino?

---

*Except in a narrow region where $M_{susy} \sim T_{RH}$ as we will see

By a freeze in mechanism sourced in the Thermal bath

Indeed, while the SUSY sector is not anymore in equilibrium with the thermal bath (and never was), there is still a possibility to produce gravitino through its vierbein (direct) coupling of its goldstino part to the SM.

This model by its simplicity and naturalness can be considered as « a minimal model of gravitino dark matter »

K. Benakli, Y. Chen, E. Dudas, Y.M. 1701.xxxx

The scales in game

SUGRA reminder

$$V = F^2 + 1/2\, D^2 \sim F^2$$

$$m_{3/2} = \frac{F}{\sqrt{3}M_{Pl}}, \quad M_{SUSY} = \frac{F}{\Lambda_{mess}}$$

Once <F> and/or <D> acquire a *vev*, SUSY is broken and generates gravitino mass. The breaking is then mediated to the SUSY sectors by *messengers* to generate the SUSY spectrum

$$m_{3/2} \ll T_{RH} \lesssim M_{SUSY} \lesssim \sqrt{F} \lesssim \Lambda_{mess} \ll M_{Pl}$$

The low energy spectrum is then only the SM + the gravitino

Generating the interactions

One can deduce the vierbein of the theory, just from the hypothesis that the longitudinal part of the gravitino is the goldstino of the SUSY transformation*

$$e_m^a = \delta_m^a - \frac{i}{2F^2}\partial_m G\sigma^a\bar{G} + \frac{i}{2F^2}G\sigma^a\partial_m\bar{G} \ ,$$

$$L_{2G} = \frac{i}{2F^2}(G\sigma^\mu\partial^\nu\bar{G} - \partial^\nu G\sigma^\mu\bar{G})T_{\mu\nu},$$

I. Antoniadis, E. Dudas, D. M. Ghilencea and P. Tziveloglou, Nucl. Phys. B **841** (2010) 157

Which gives the Lagrangian between the SM and the goldstino

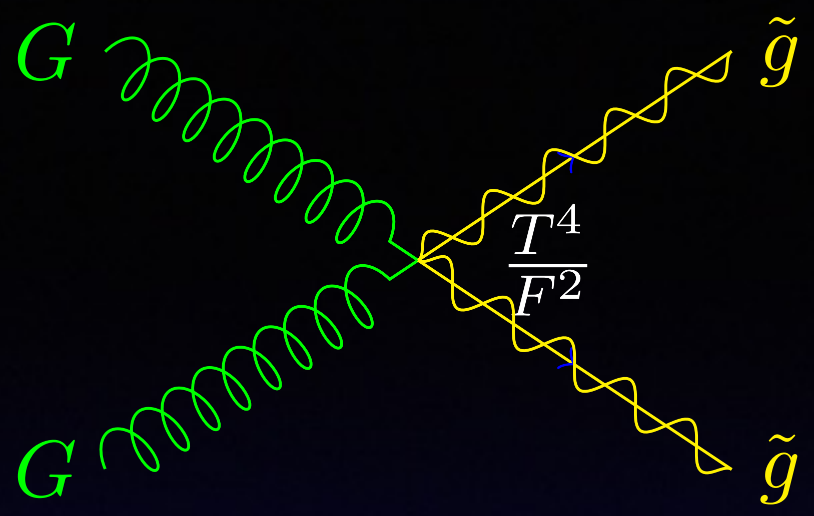
$$\begin{aligned}
&\frac{i}{2F^2}(G\sigma^\mu\partial^\nu\bar{G} - \partial^\nu G\sigma^\mu\bar{G})(\partial_\mu H\partial_\nu H^\dagger + \partial_\mu H\partial_\nu H^\dagger),\\
&\frac{1}{8F^2}(G\sigma^\mu\partial^\nu\bar{G} - \partial^\nu G\sigma^\mu\bar{G}) \times\\
&(\bar{\psi}\bar{\sigma}_\nu\partial_\mu\psi + \bar{\psi}\bar{\sigma}_\mu\partial_\nu\psi - \partial_\mu\psi\bar{\sigma}_\nu\psi - \partial_\nu\psi\bar{\sigma}_\mu\psi),\\
&\sum_a \frac{i}{2F^2}(G\sigma^\xi\partial_\mu\bar{G} - \partial_\mu G\sigma^\xi\bar{G})F^{\mu\nu a}F^a_{\nu\xi},
\end{aligned} \tag{10}$$

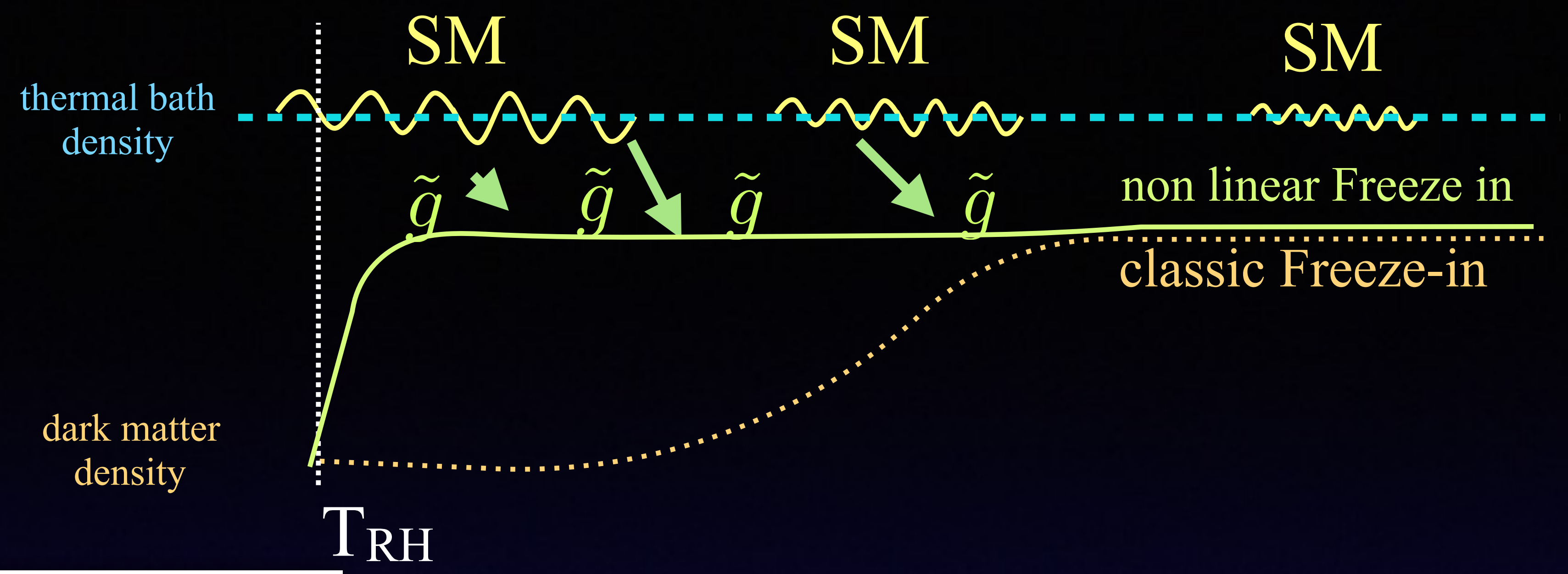
Notice how the Lagrangian has suppressed coupling (1/F^2) and strong energy/temperature dependance

---

* see the incredibly modern article « Is the Neutrino a Goldstone particle » by D.V. Volkov and V.P. Akulov,Phys. Lett. **B 46** (1973) 109

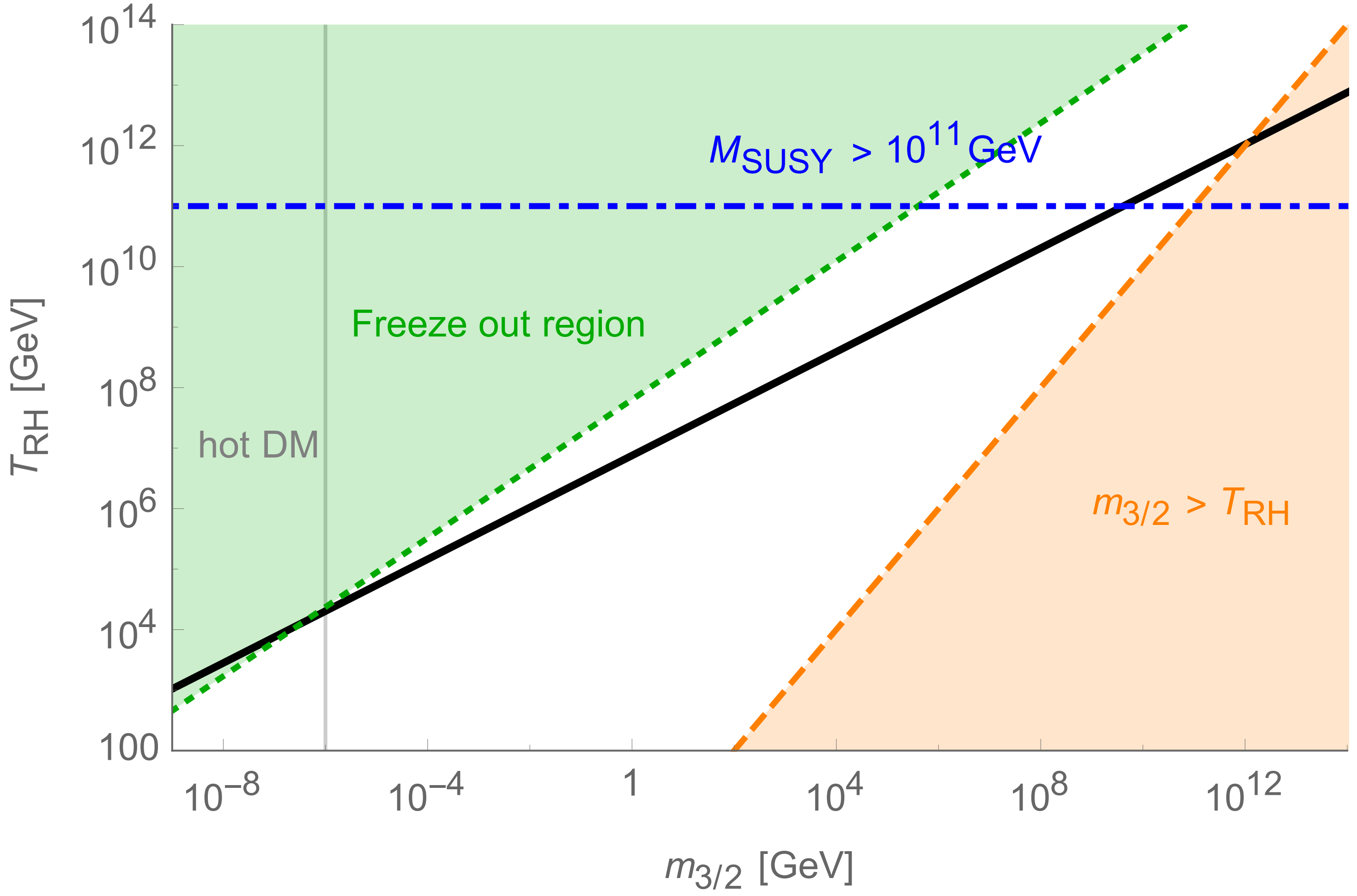
Add a slide about microscopic interpretation
(Keith idea)





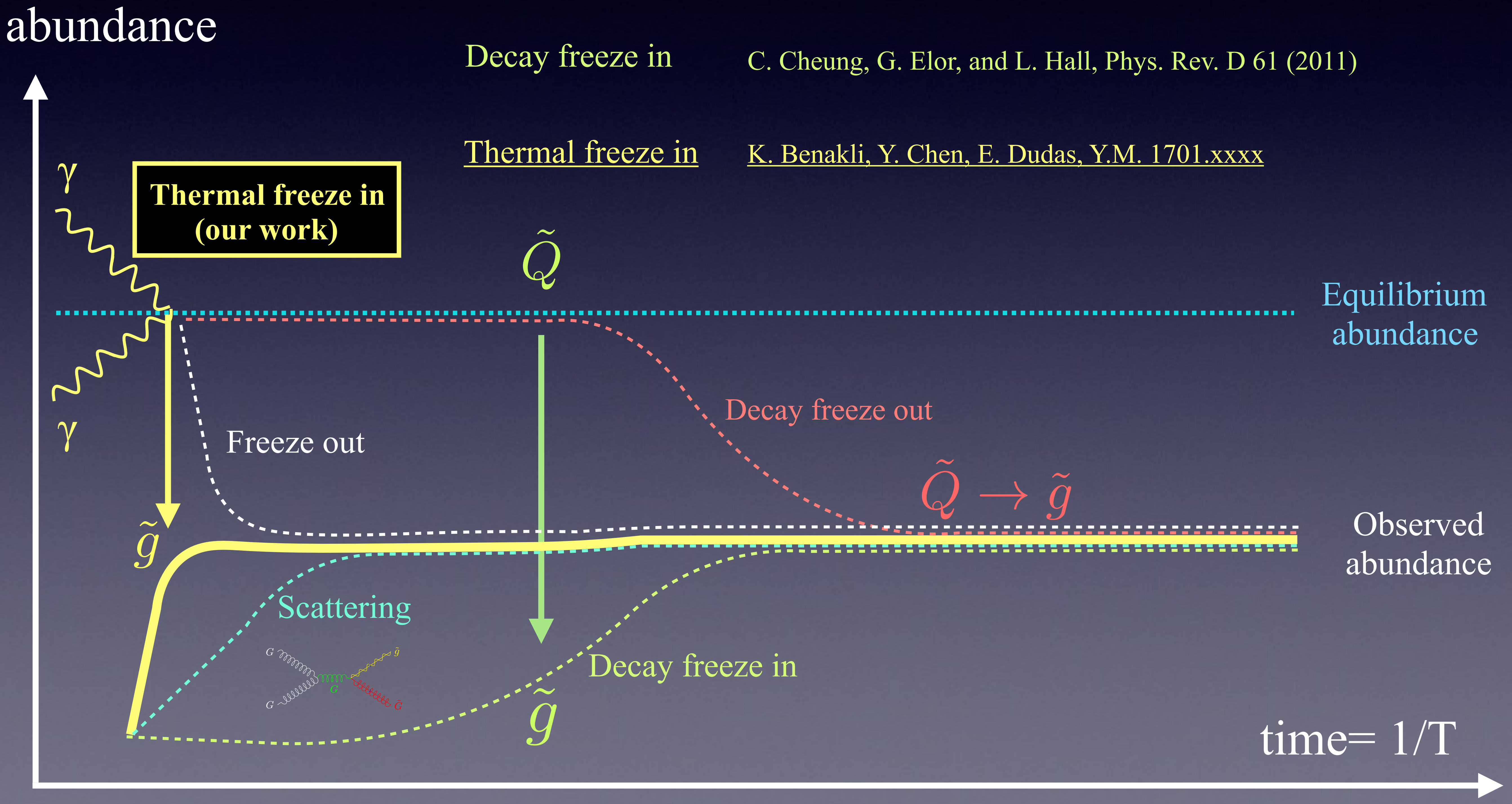
$$\Omega_{3/2}h^2 \simeq 0.11 \left(\frac{100\ \mathrm{GeV}}{m_{3/2}}\right)^3 \left(\frac{T_{\mathrm{RH}}}{5.4\times 10^7\ \mathrm{GeV}}\right)^7$$

Heavy gravitino is compatible with high T_{RH} and no LHC SUSY signals while still giving the right amount of relic abundance.

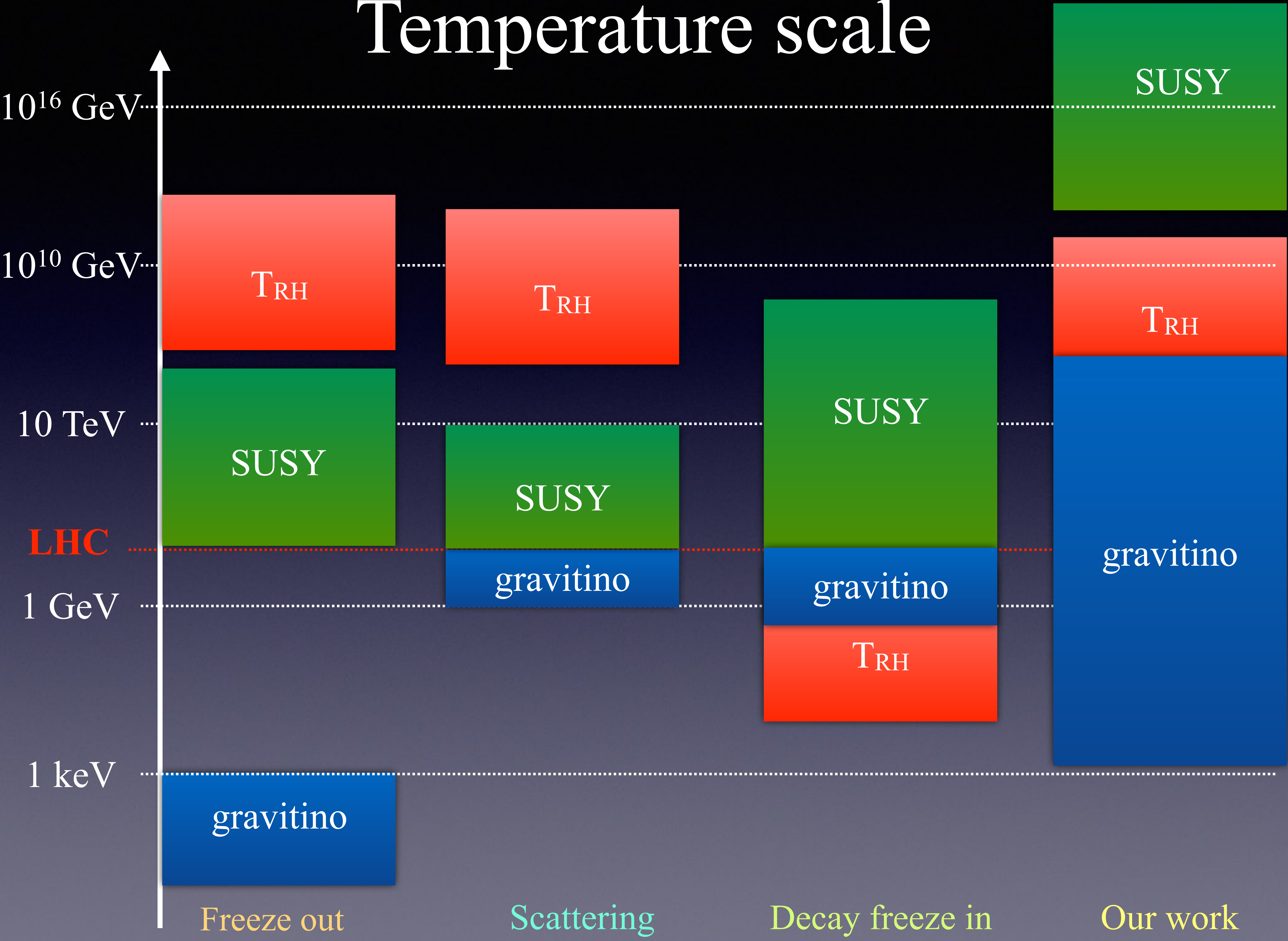


Summary: populating the Universe with gravitino

Freeze out	H. Pagels and J.R. Primack, Phys. Rev. Lett. 48 (1982) 223
Scattering	T. Moroi, H. Murayama, M. Yamagushi, Phys. Lett. **B303**, 284-294 (1993)
Decay freeze out	J.L. Feng, S. Su and F. Takayama, Phys. Rev. **D70** 075019 (2004)
Decay freeze in	C. Cheung, G. Elor, and L. Hall, Phys. Rev. D 61 (2011)
Thermal freeze in	K. Benakli, Y. Chen, E. Dudas, Y.M. 1701.xxxx



Temperature scale



10^{16} GeV

10^{10} GeV

10 TeV

LHC

1 GeV

1 keV

Freeze out

T_{RH}

SUSY

gravitino

Scattering

T_{RH}

SUSY

gravitino

Decay freeze in

SUSY

gravitino

T_{RH}

Our work

SUSY

T_{RH}

gravitino

pré-conclusion

> *« To the great disappointment of many, experimental searches at the LHC so far have found no evidence for the superpartners predicted by N = 1 supersymmetry. However, there is no reason to give up on the idea of supersymmetry as such, since the refutation of low-energy supersymmetry would only mean that the most simple-minded way of implementing this idea does not work. Indeed, the initial excitement about supersymmetry in the 1970s had nothing to do with the hierarchy problem, but rather because it offered a way to circumvent the so-called Coleman–Mandula no-go theorem – a beautiful possibility that is precisely not realised by the models currently being tested at the LHC. »*

H. Nicolai, CERN courier Jan. 2017

Conclusion

We built the simplest low energy SUSY extension, where the only light super partner is the gravitino, whereas SUSY scale is pushed above the reheating temperature.

Through its goldstino component, the gravitino still couples (very weakly) to the standard model, and allows for the right amount of dark matter through a thermal freeze in mechanism.

That a minimal model of gravitino dark matter.