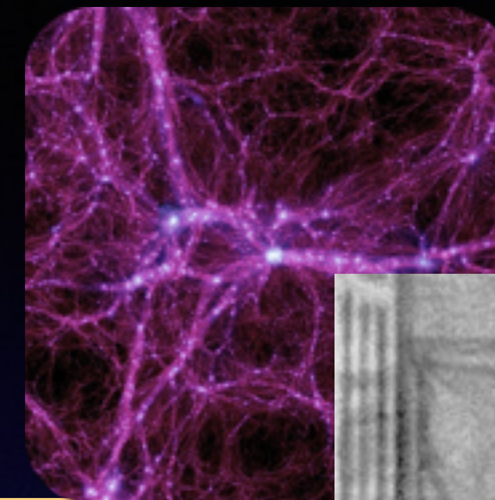
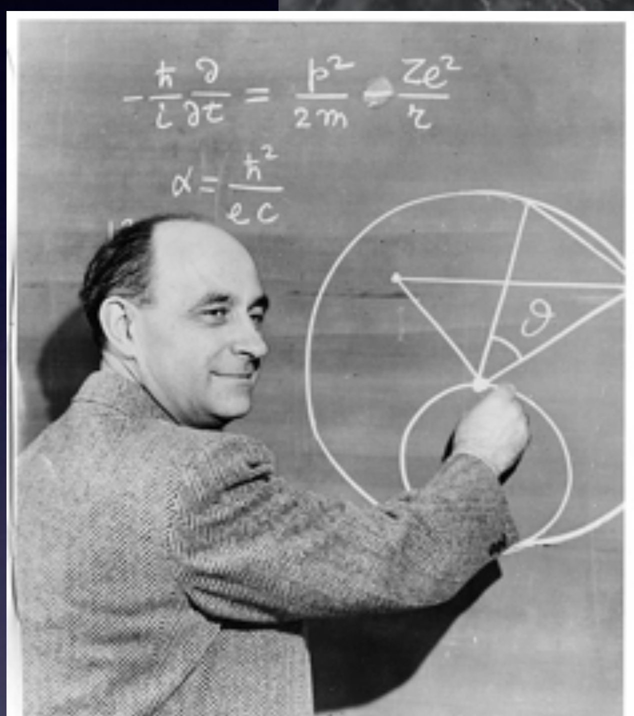
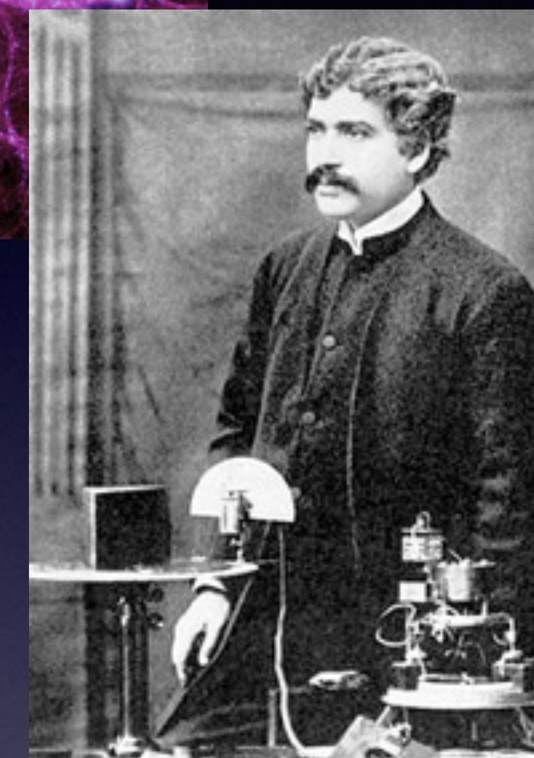
Alternative to WIMP paradigm





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



« The true laboratory is the mind, where behind illusions we uncover the laws of truth.»
J.C. Bose
pioneer in radio signals

Yann Mambrini,

University of Paris-Saclay

in collaboration with K. Benakli, Y. Chen and E. Dudas

http://www.ymambrini.com/My_World/Physics.html

Saha conference on theoretical Physics, early cosmology, 18th of January 2017

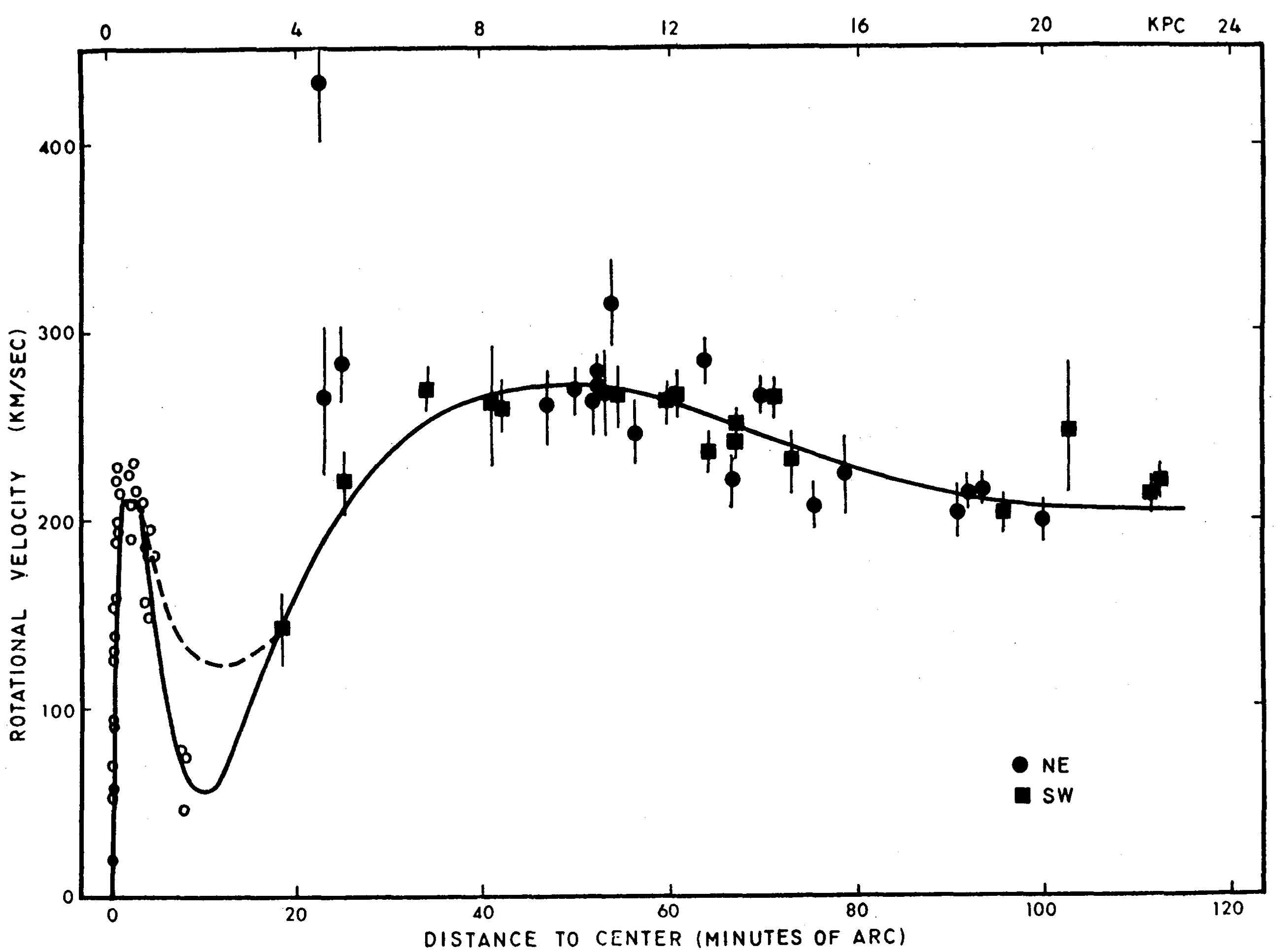
India became (officially) since yesterday associate member of CERN

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.

Henri Poincaré

The first DM paper

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.*

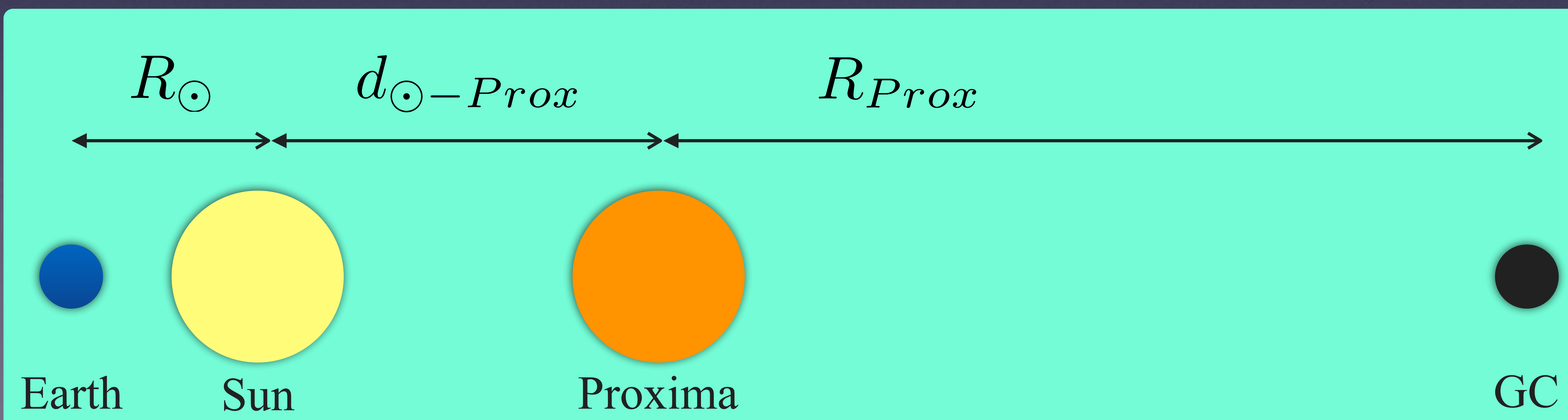
H. POINCARÉ.†

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.

$$
\begin{aligned}
v(R) &\propto R\sqrt{\rho} \\
\frac{v_{earth}(R_\odot)}{v_{sun}(R_{Prox})} &= \frac{R_\odot}{R_{Prox}}\frac{\sqrt{\rho_\odot}}{\sqrt{\rho_{Prox}}} \\
d_{Prox-\odot} = 10^6 R_\odot \quad \Rightarrow \quad \rho_{Prox} &= 10^{-18}\rho_\odot \\
v_{earth} \simeq v_{sun} \quad \Rightarrow R_{Prox} &= 10^9 R_\odot \\
\Rightarrow N_{stars} = \rho_{Prox} \times R_{Prox}^3 &\simeq 10^9
\end{aligned}
$$



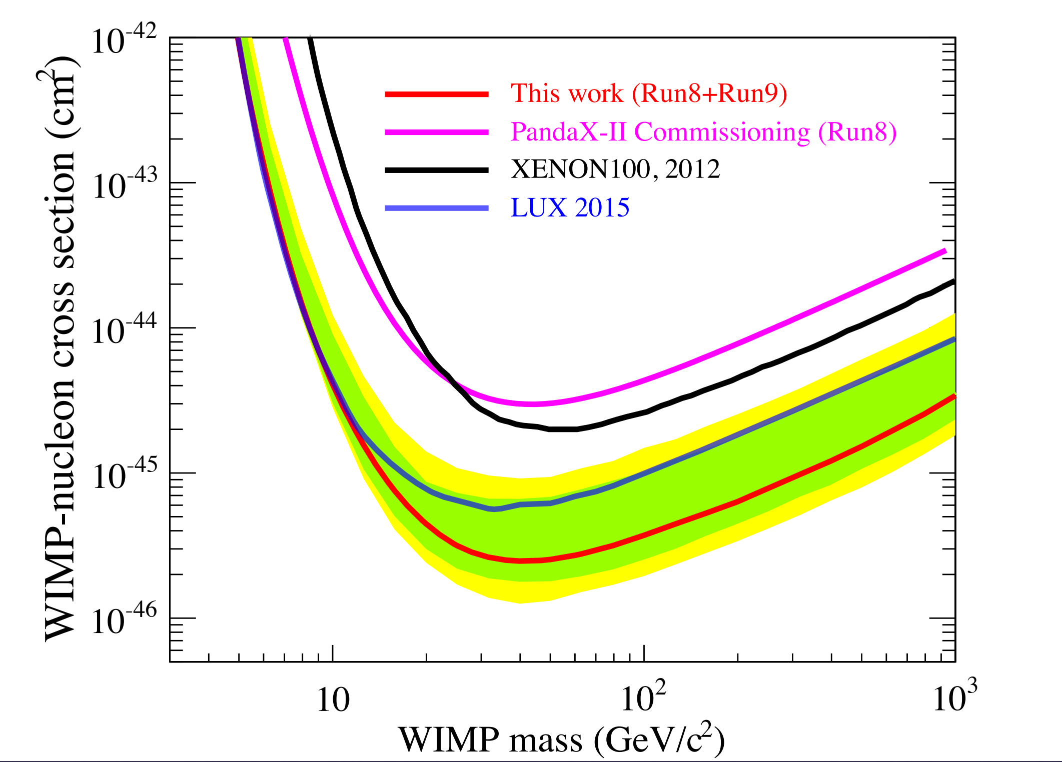
Where are we now?

1

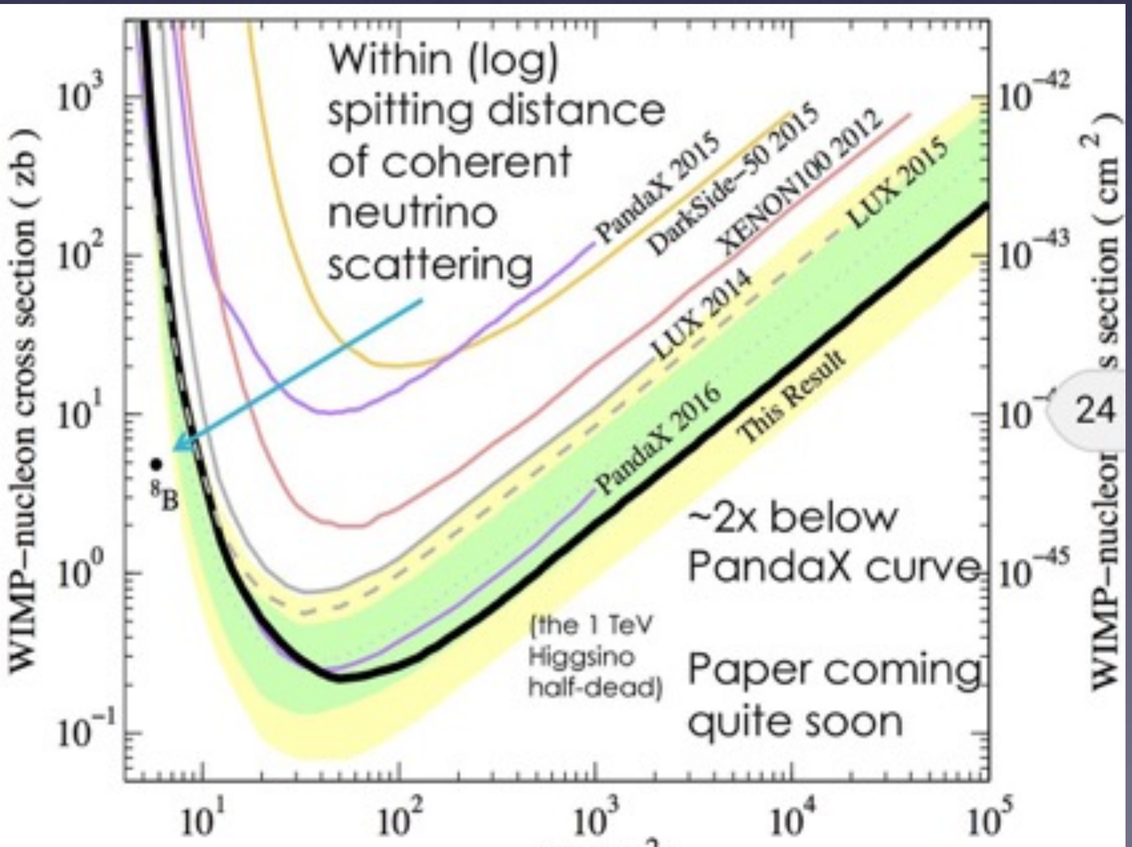
The direct detection race

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.



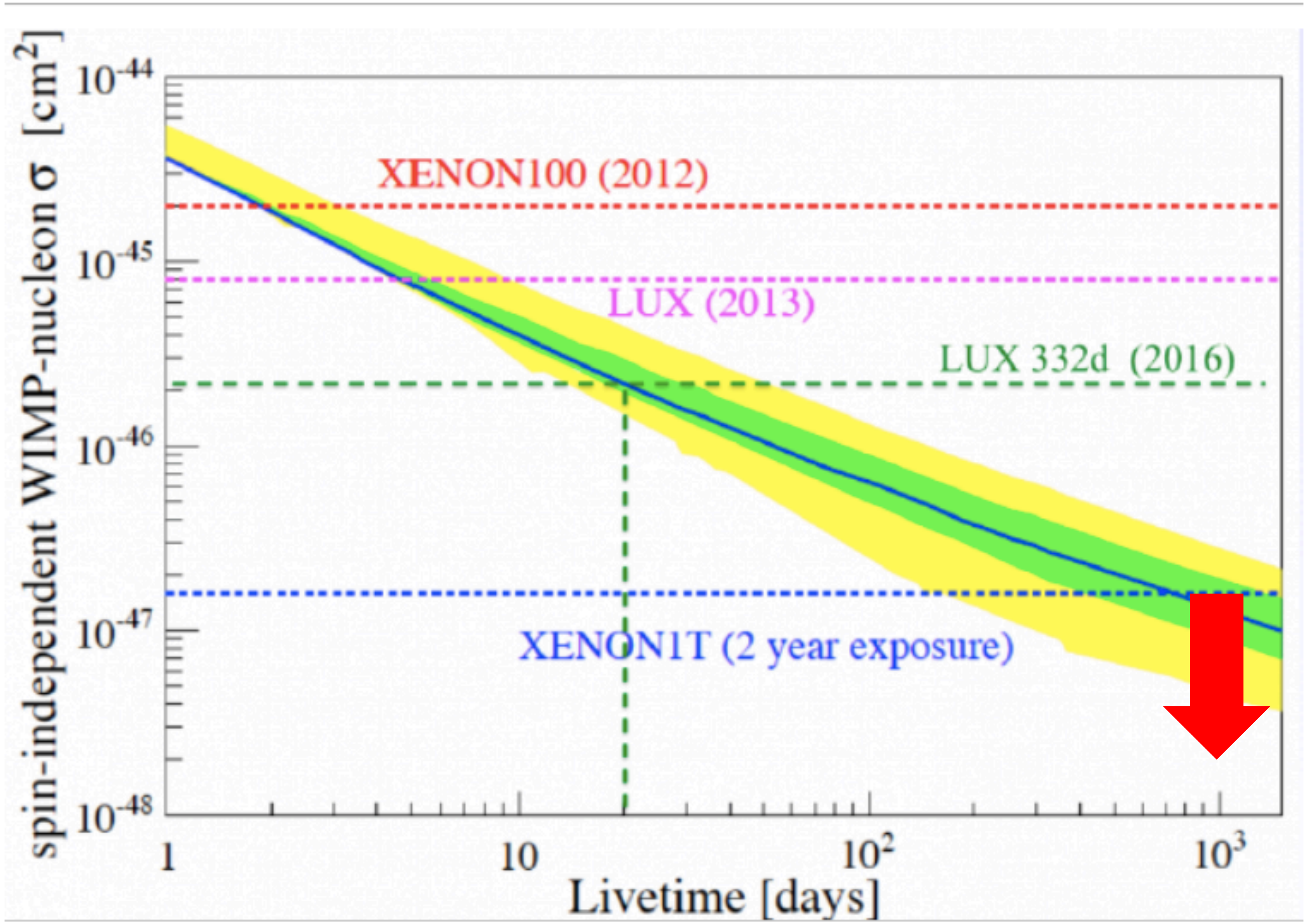
August 2016, **LUX** released a new analysis, giving slightly better limit than **PANDAX-II**:



. . .

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

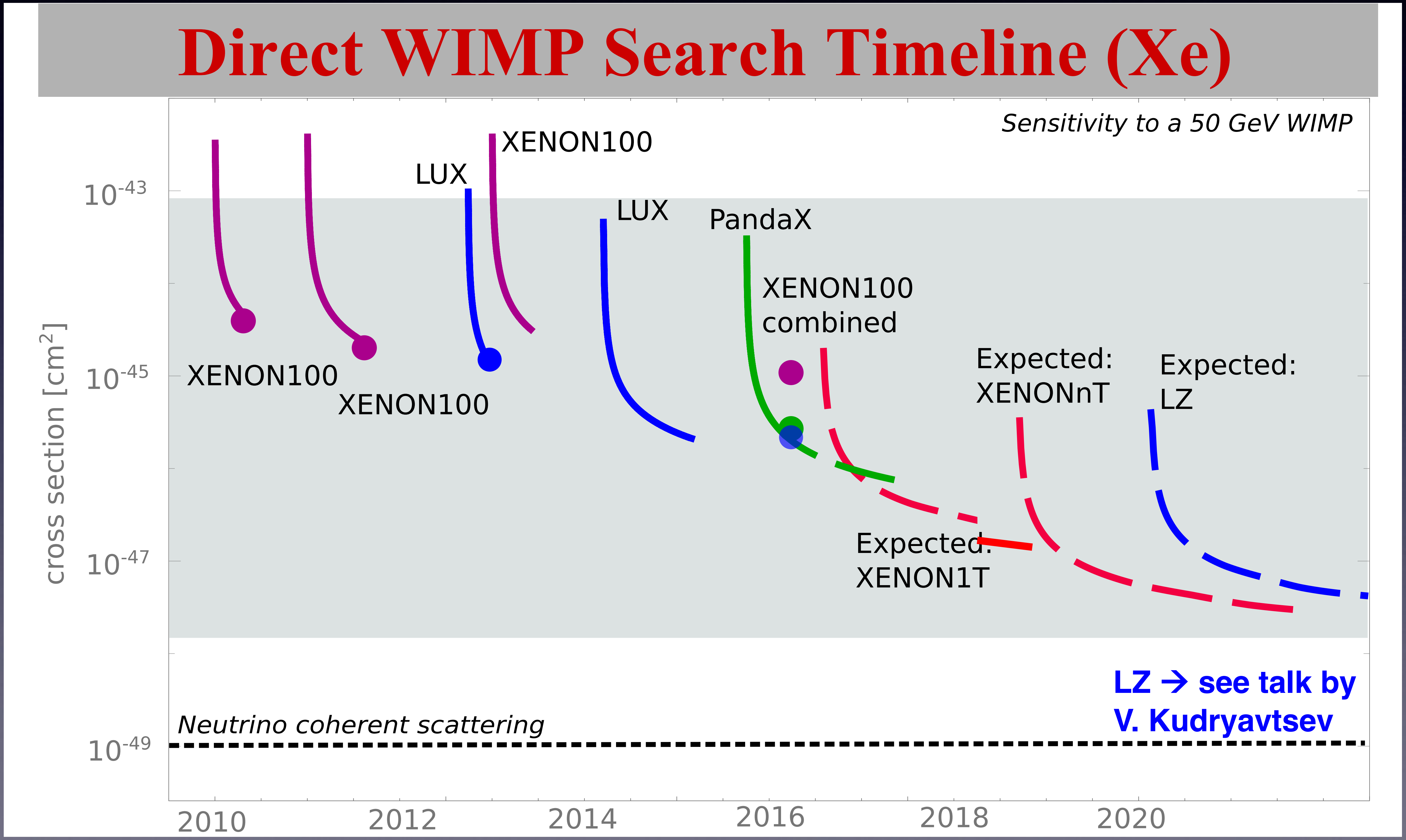


and then XENONnT → 20ty → x10

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

• • •

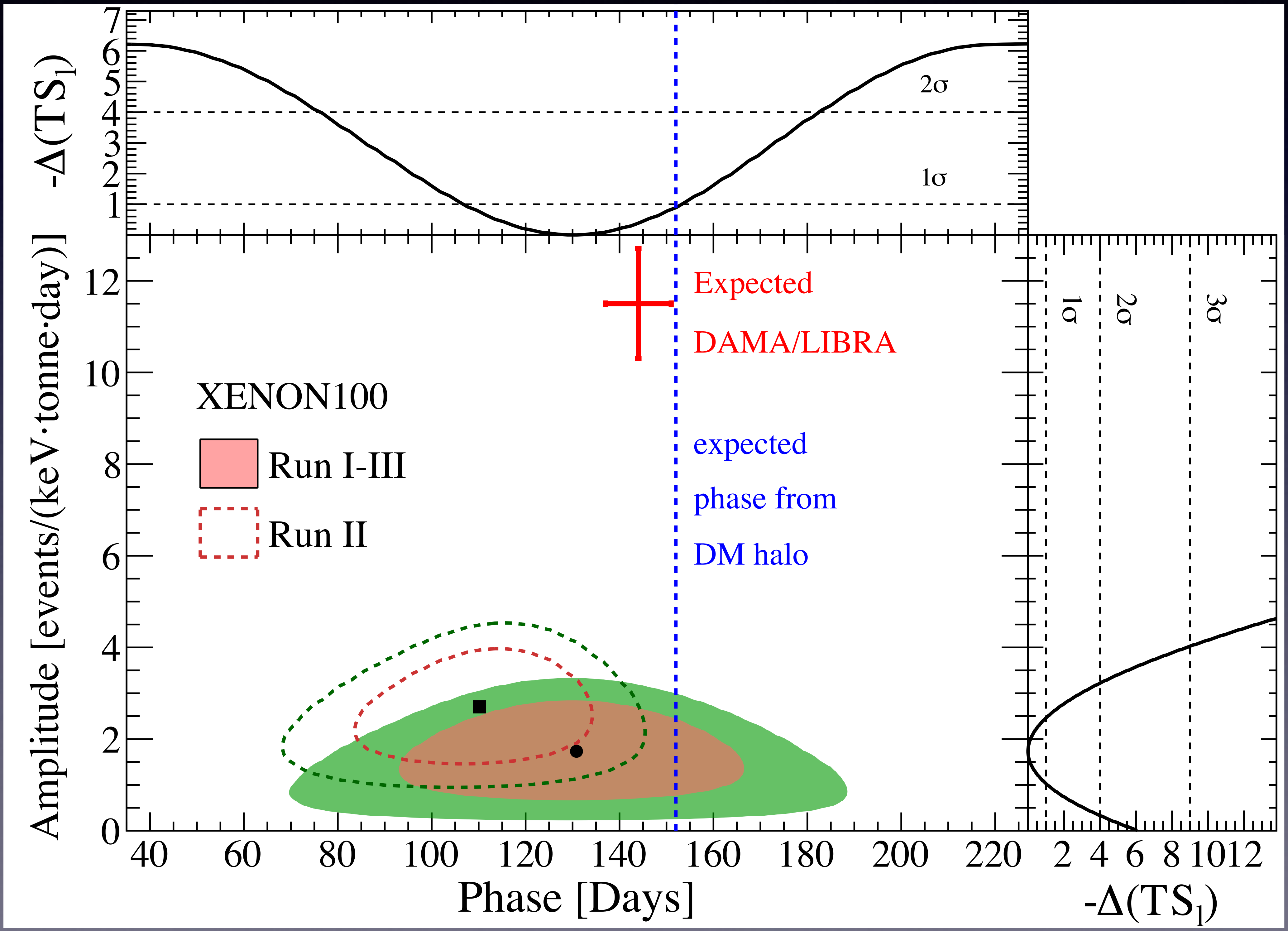
September 2016, **LZ (LUX + ZEPLIN)** collaboration confirmed that they obtained the DoE approval, beginning the hunt in 2020. LZ consist of 10 tons detector. The entire supply of XENON is already under contract and will be supply under the help of the South Dakota sate.



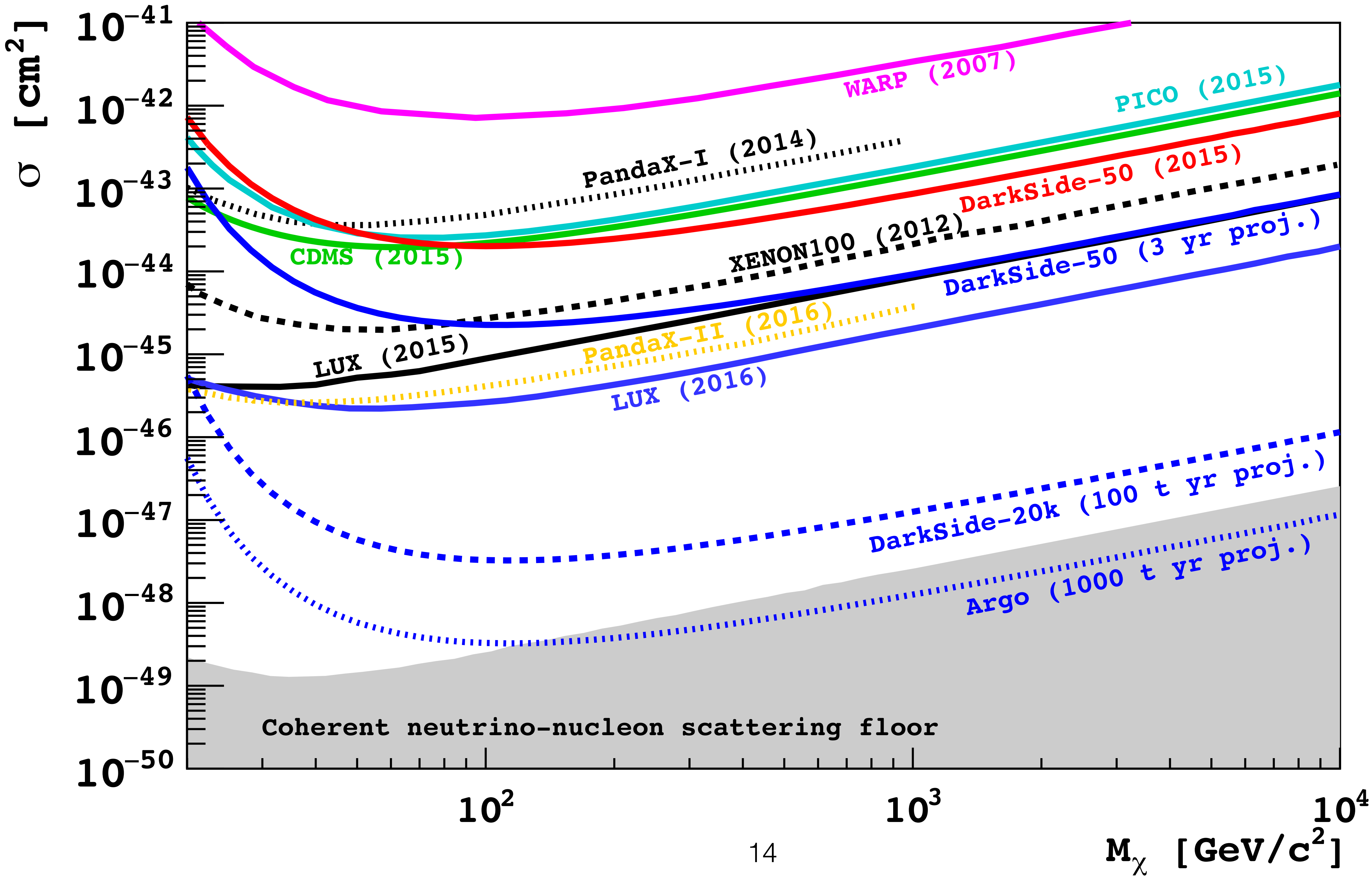
No oscillation observed at XENON100

arXiv:1701.00769

Which exclude DAMA signal at 5.7σ



What next? Sensitivity

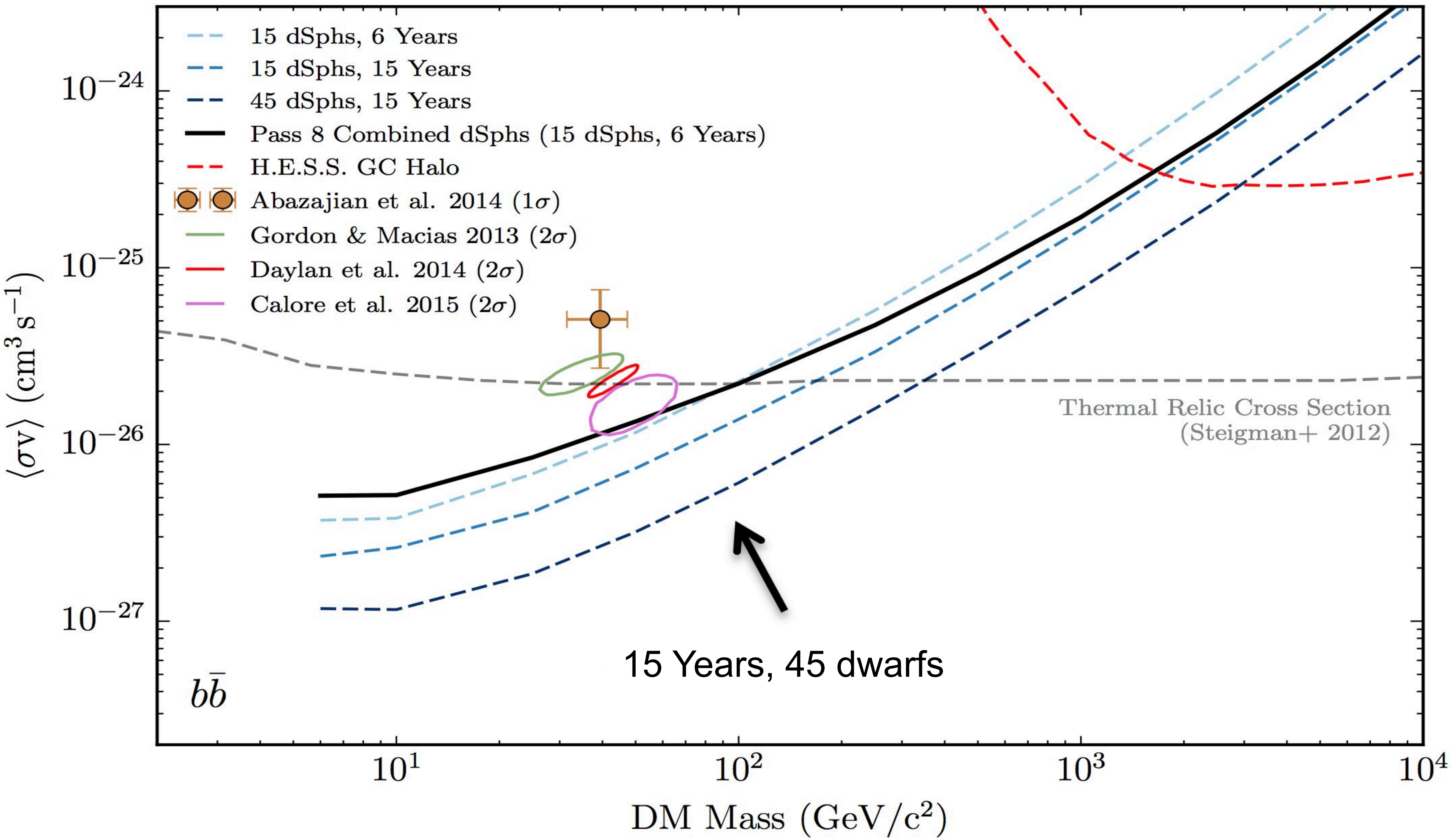


Darkside : maybe, but I won’t see it

2

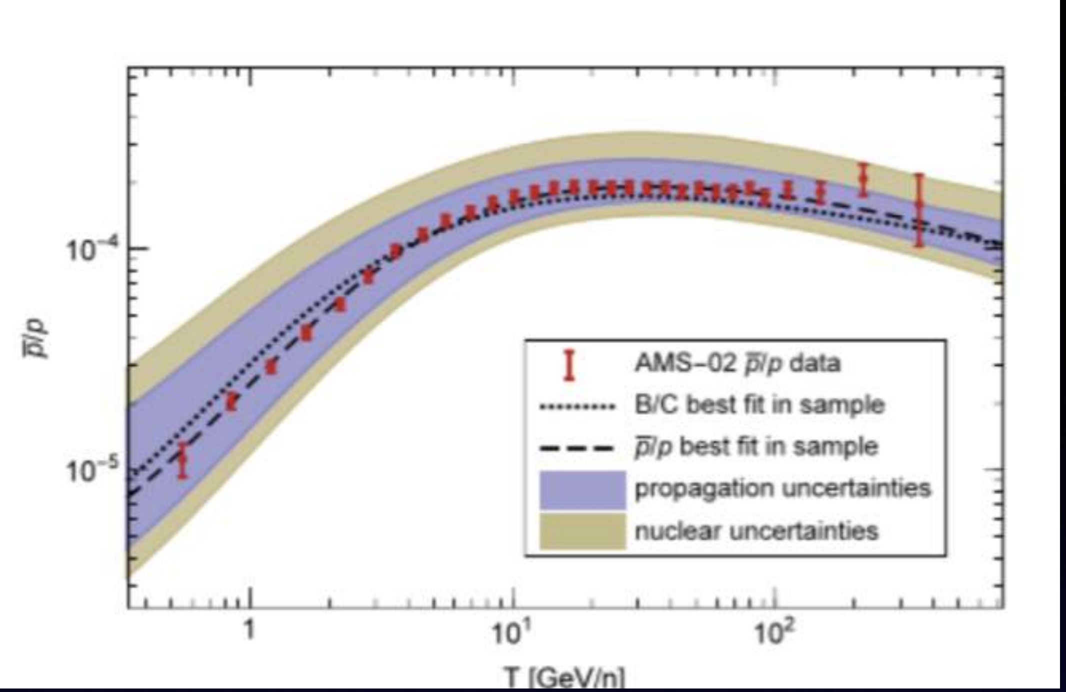
The indirect detection status

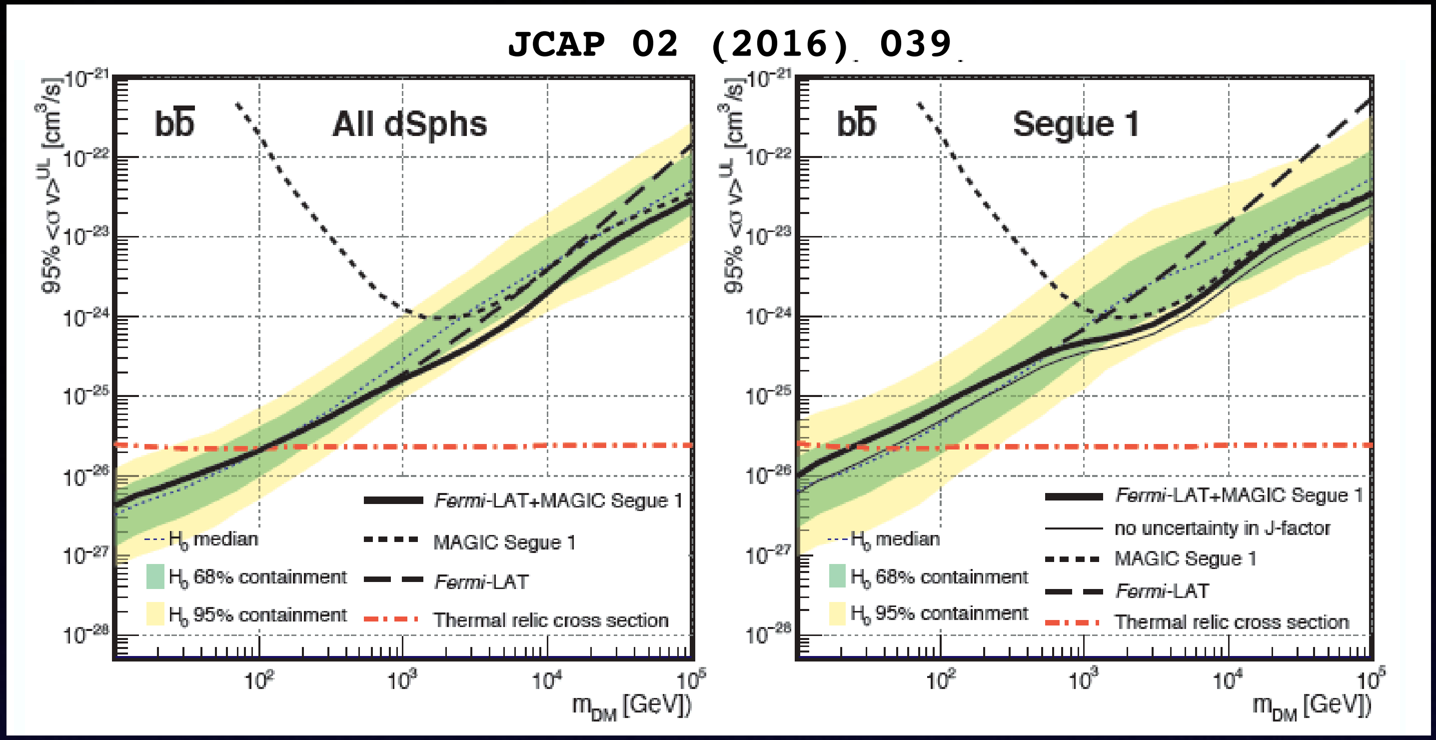
DM limit improvement estimate in 15 years with the composite likelihood approach (2008- 2023)



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

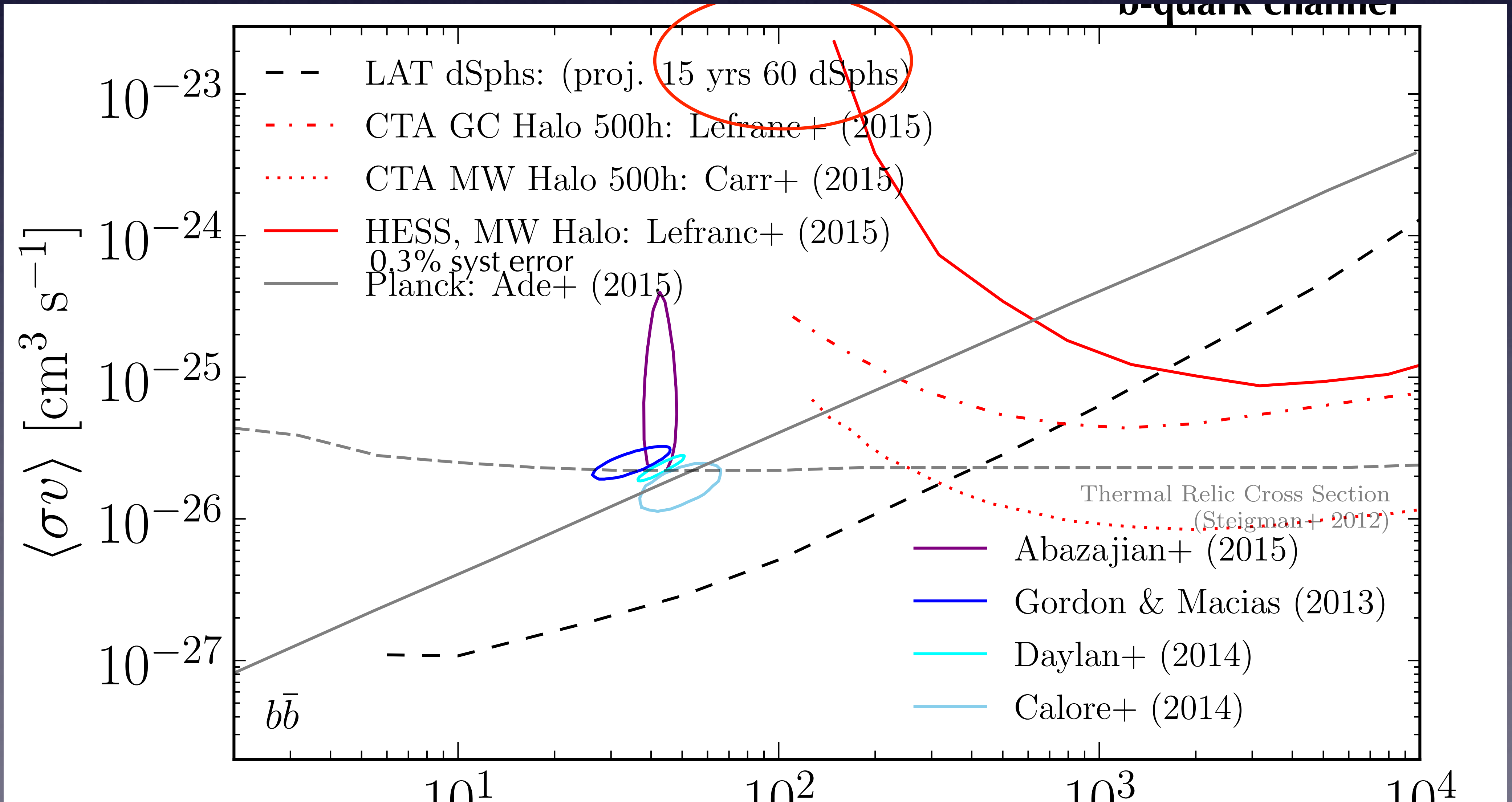
Latest result by FERMI in May: nothing





AMS : nothing

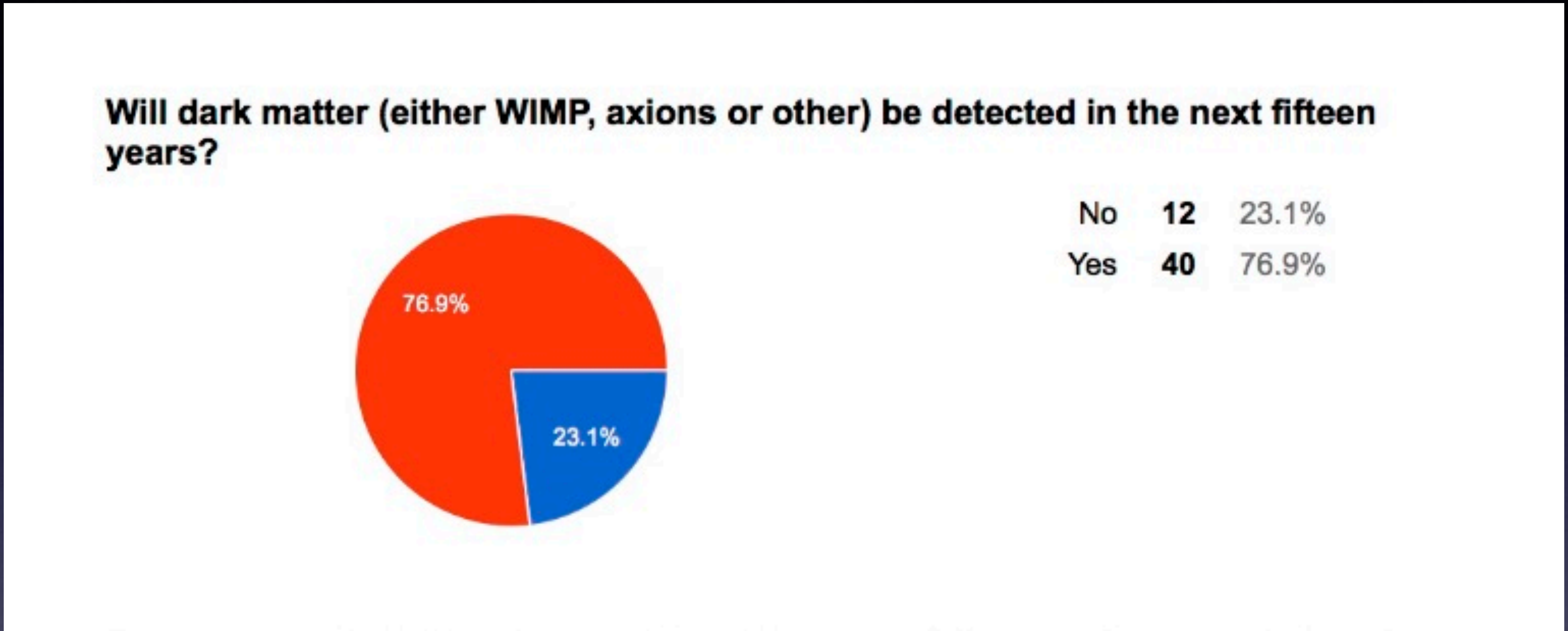
MAGIC : nothing



HESS : nothing

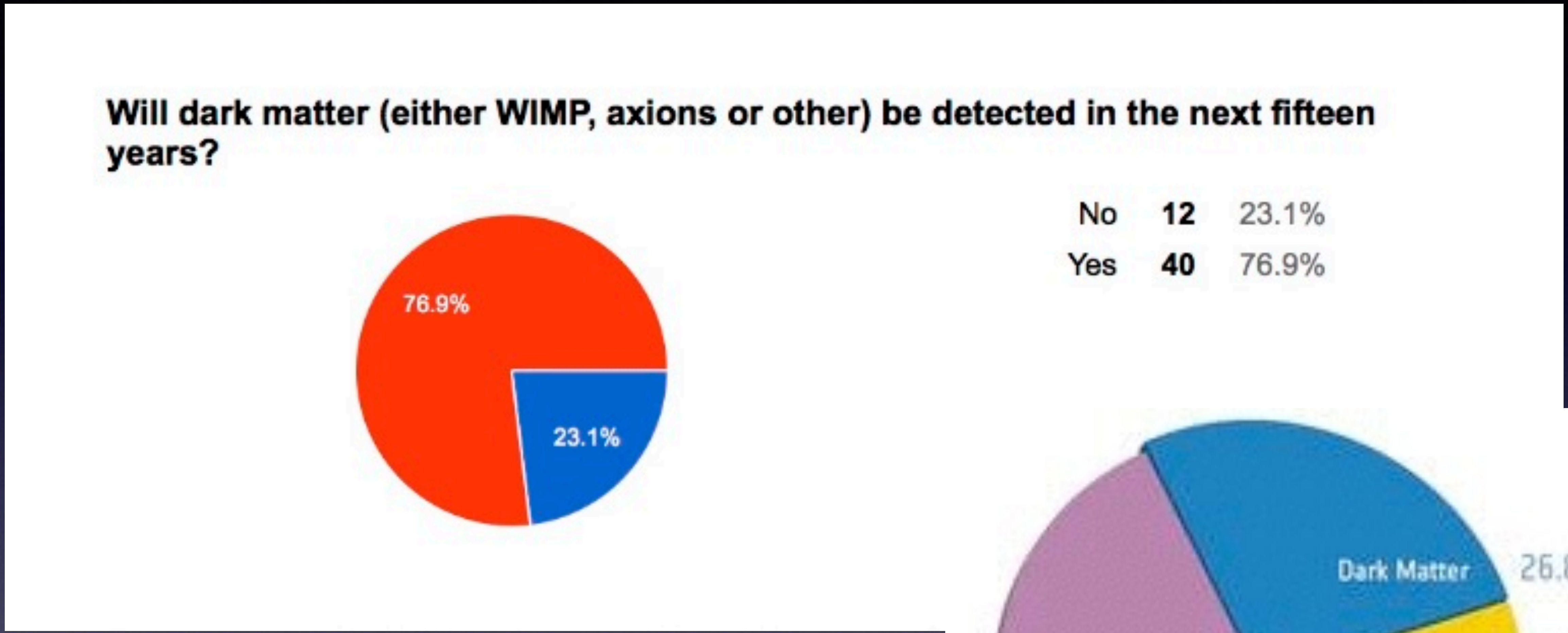
CTA : ??

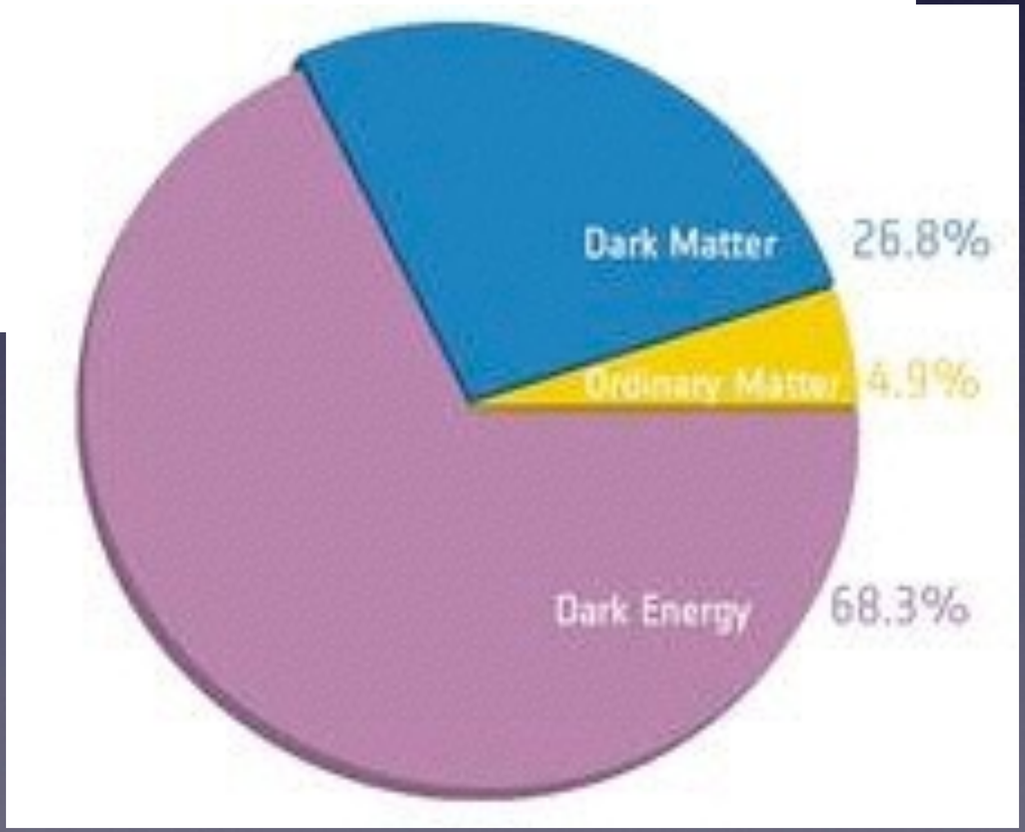
Pool at IFT workshop, September 2016



At least optimism…

Pool at IFT workshop, September 2016





At least optimism…

Consequences on Model Building

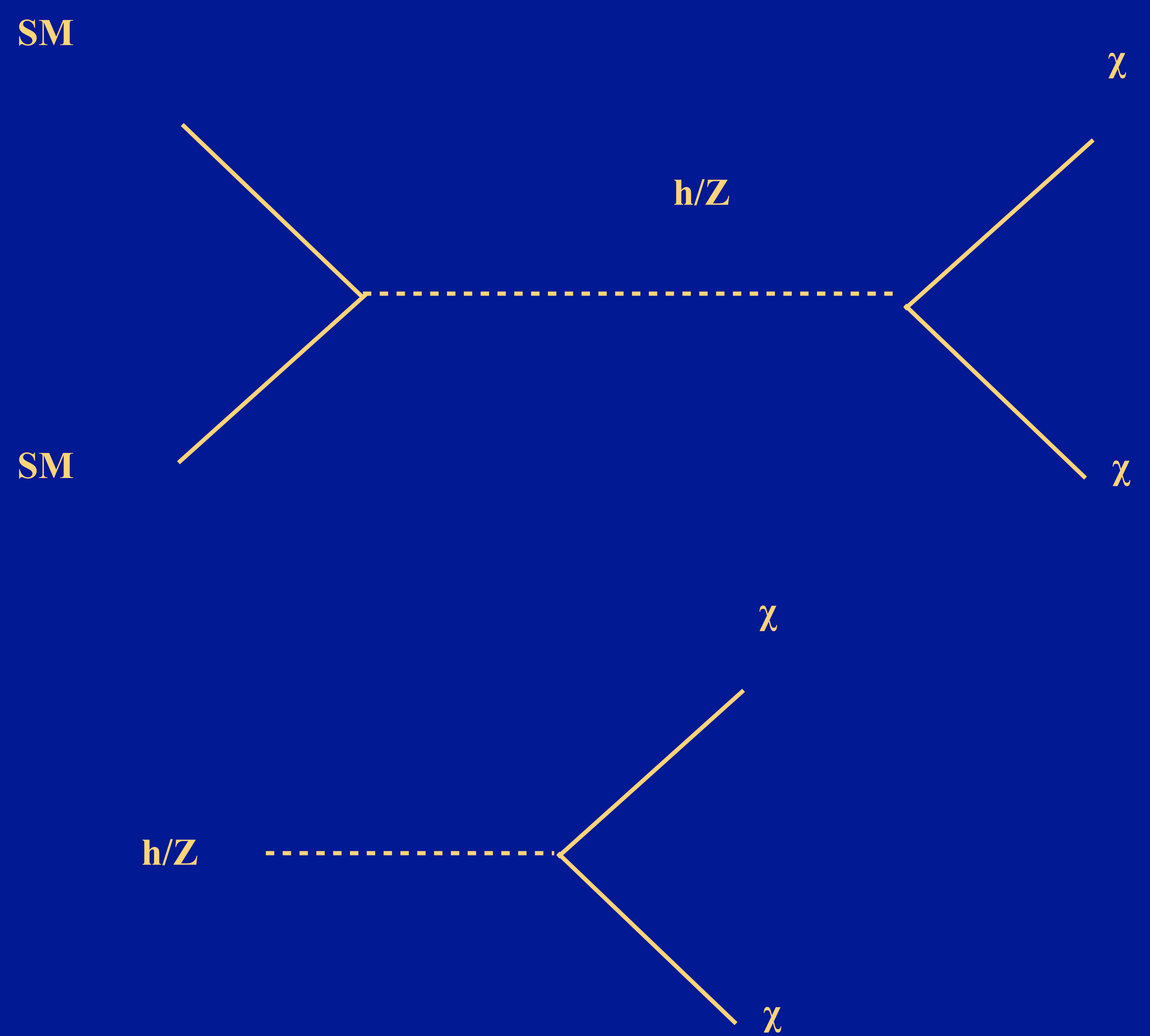
Developing a microscopical approach

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.

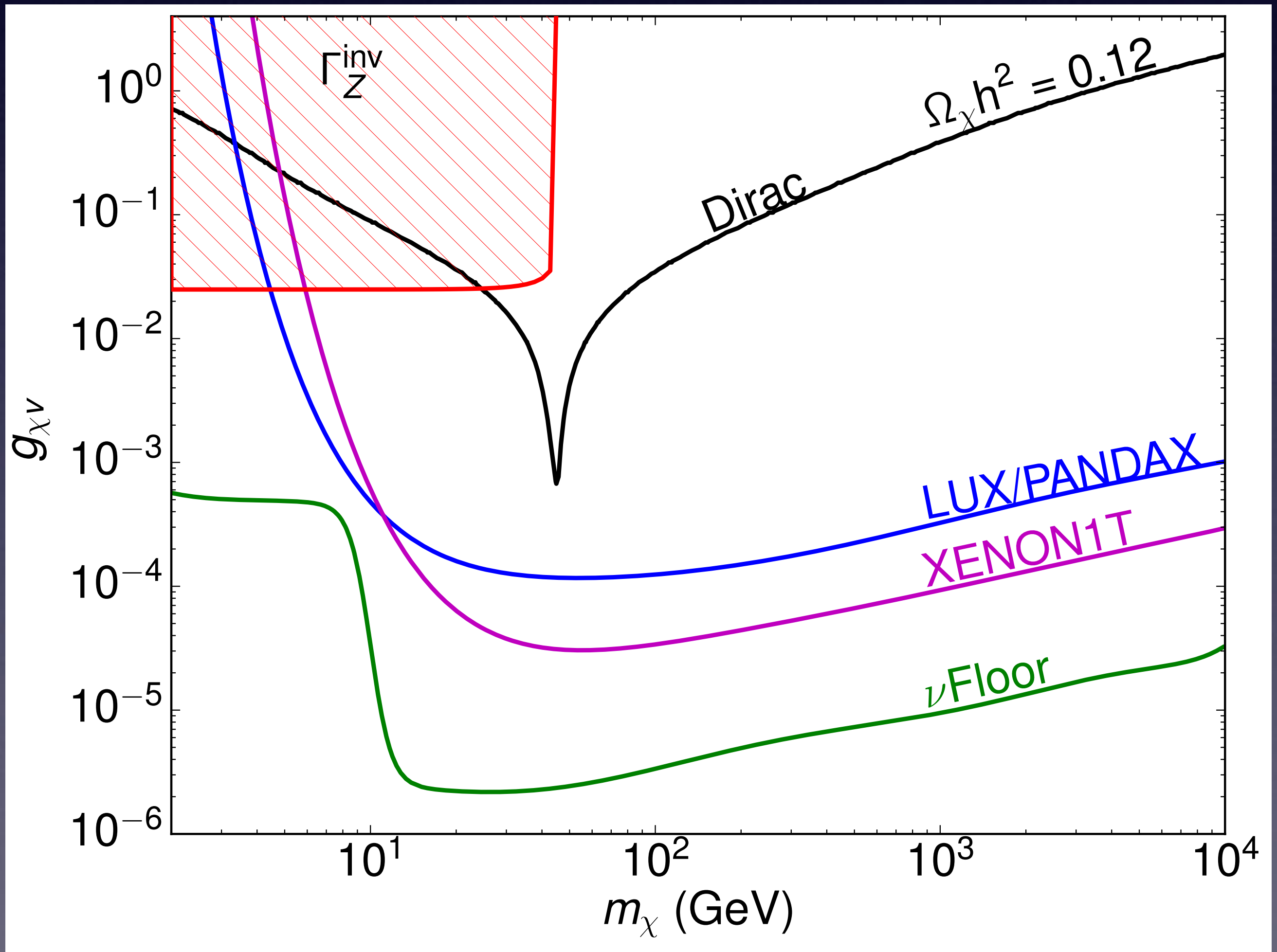


invisible width

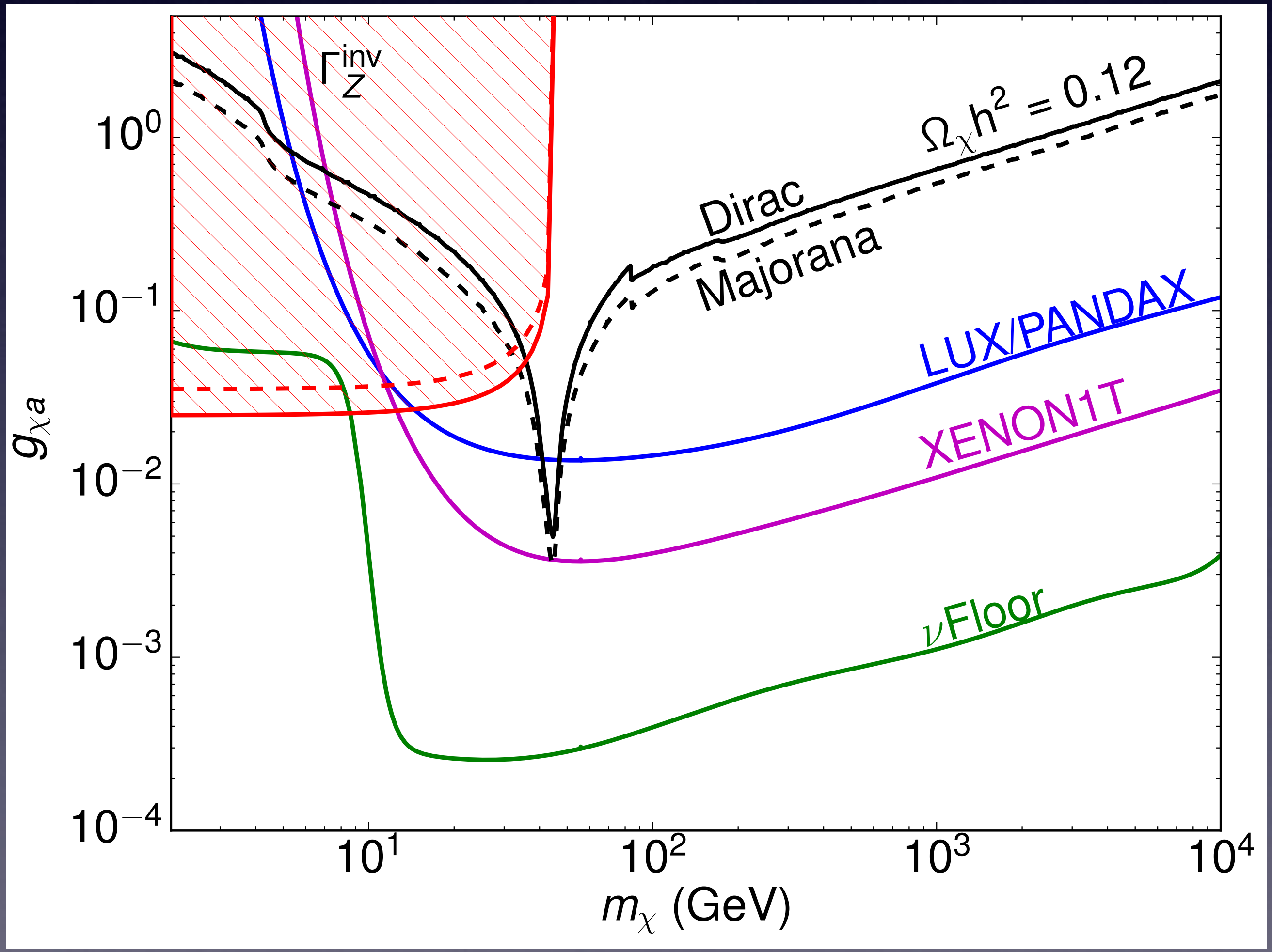
Z-portal : fermionic DM

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

Vectorial coupling



Axial coupling

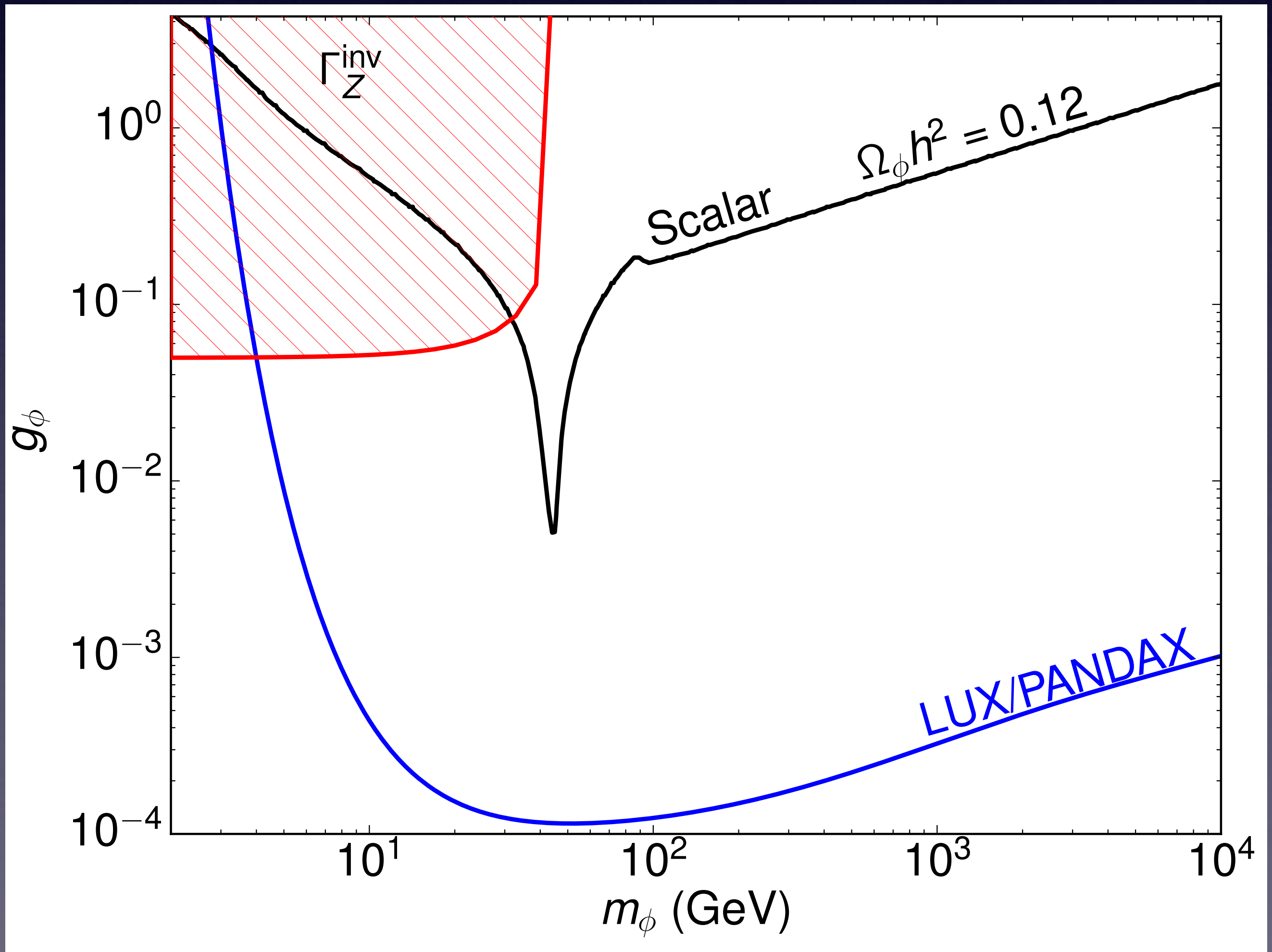


G. Arcadi, Y. M. and F. Richard, JCAP **1503** (2015) 018
Esudero et al. 1609.09079

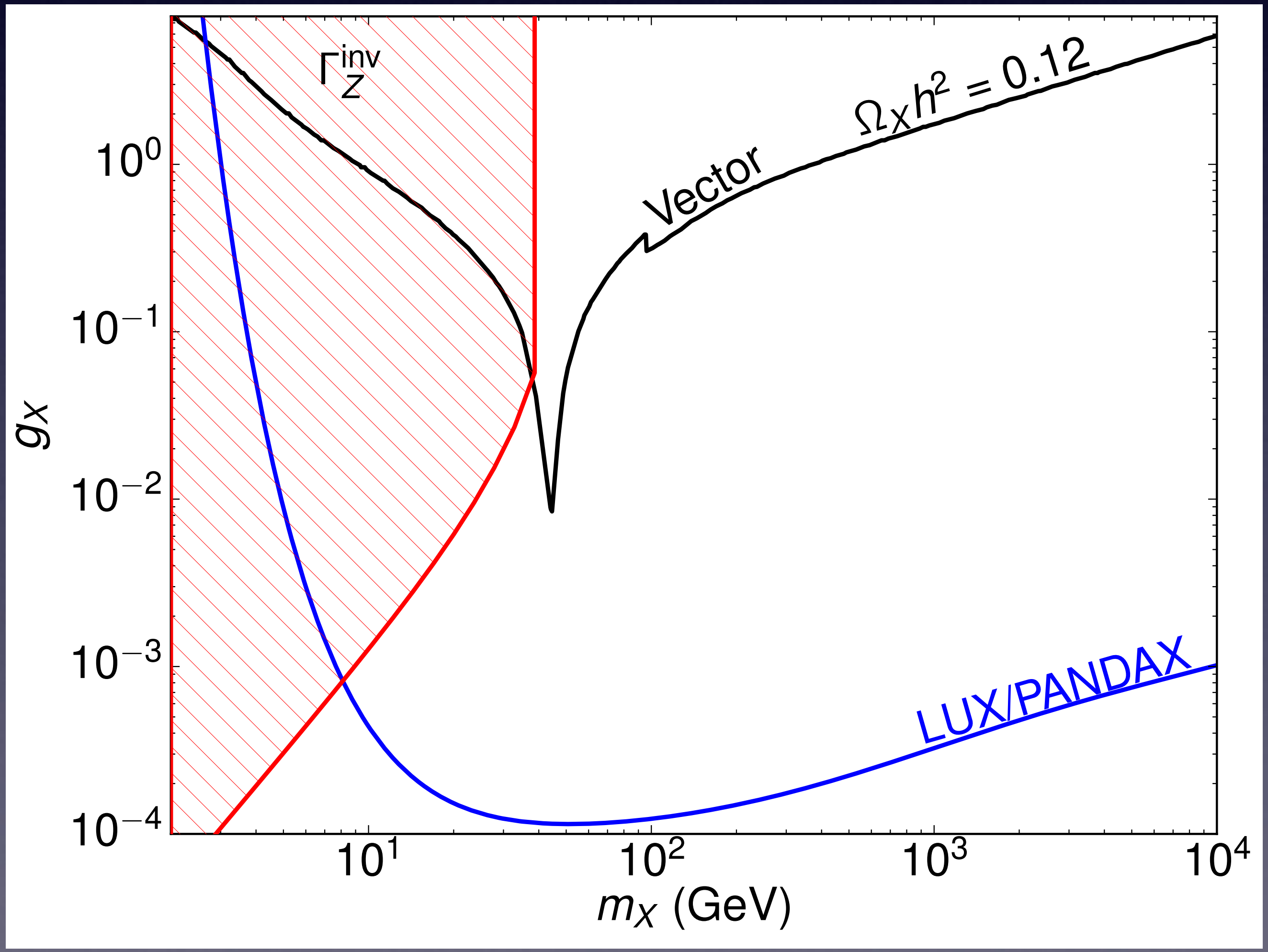
Z-portal : scalar/vectorial DM

$$\mathcal{L} \supset i\, g_\phi \phi^\dagger \overleftrightarrow{\partial_\mu} \phi Z^\mu + g_\phi^2 \phi^2 Z^\mu Z_\mu .$$

Scalar DM



Vectorial DM

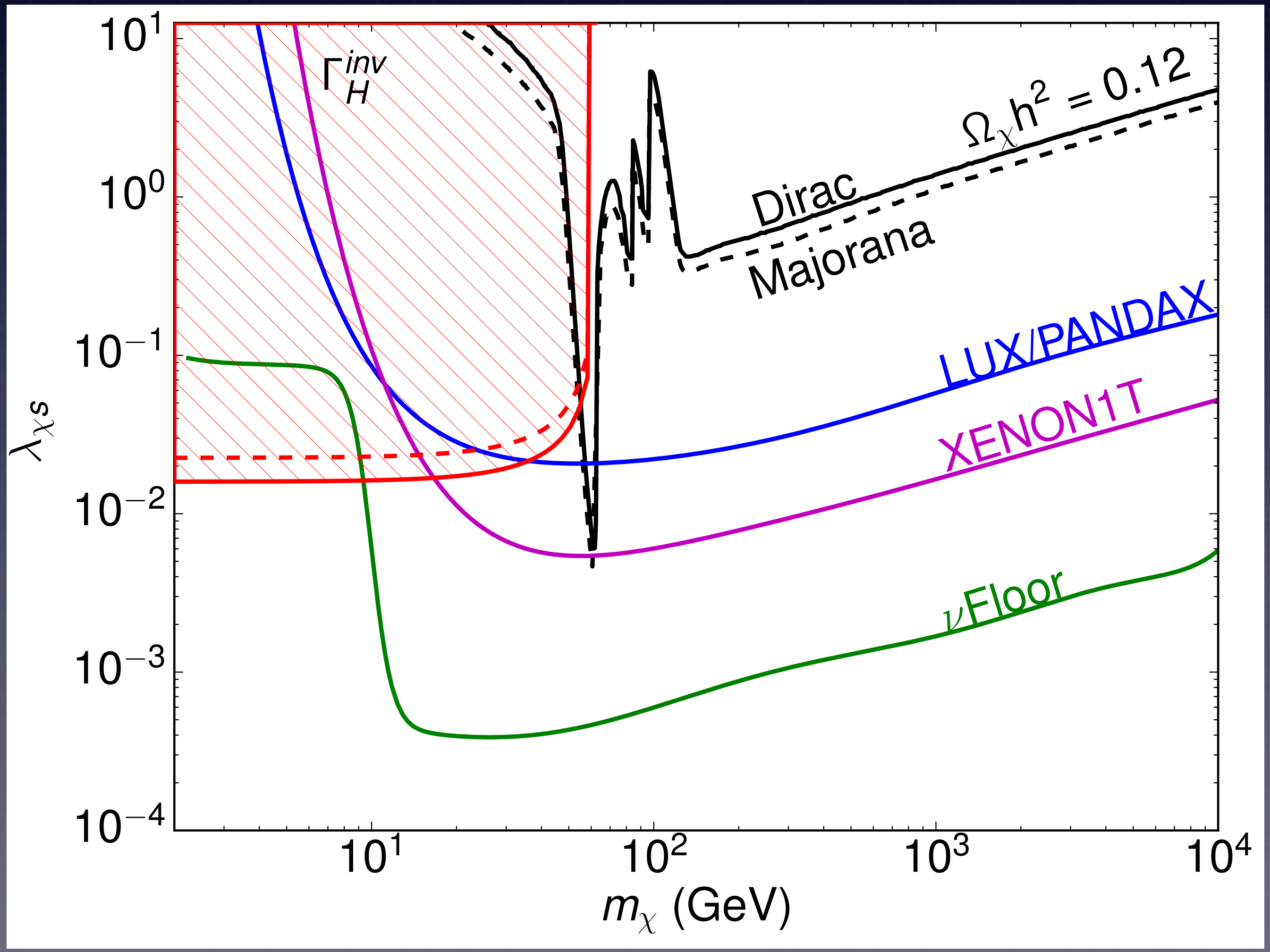


Esudero et al. 1609.09079

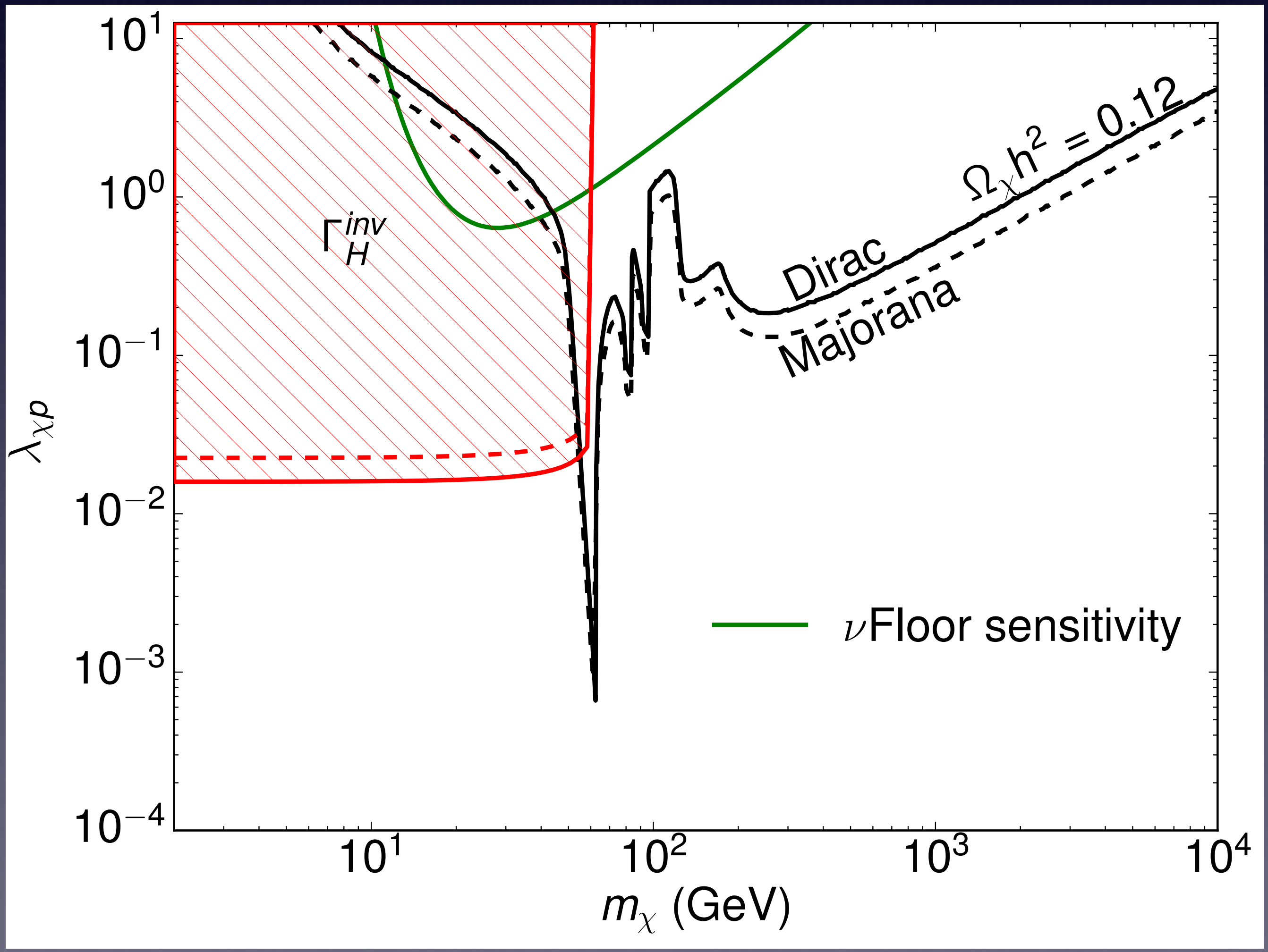
Higgs-portal : fermionic DM

$$\mathcal{L} \supset \left[a\bar{\chi}(\lambda_{\chi s} + \lambda_{\chi p} i\gamma^5)\chi\right] H,$$

Scalar coupling



pseudoscalar coupling



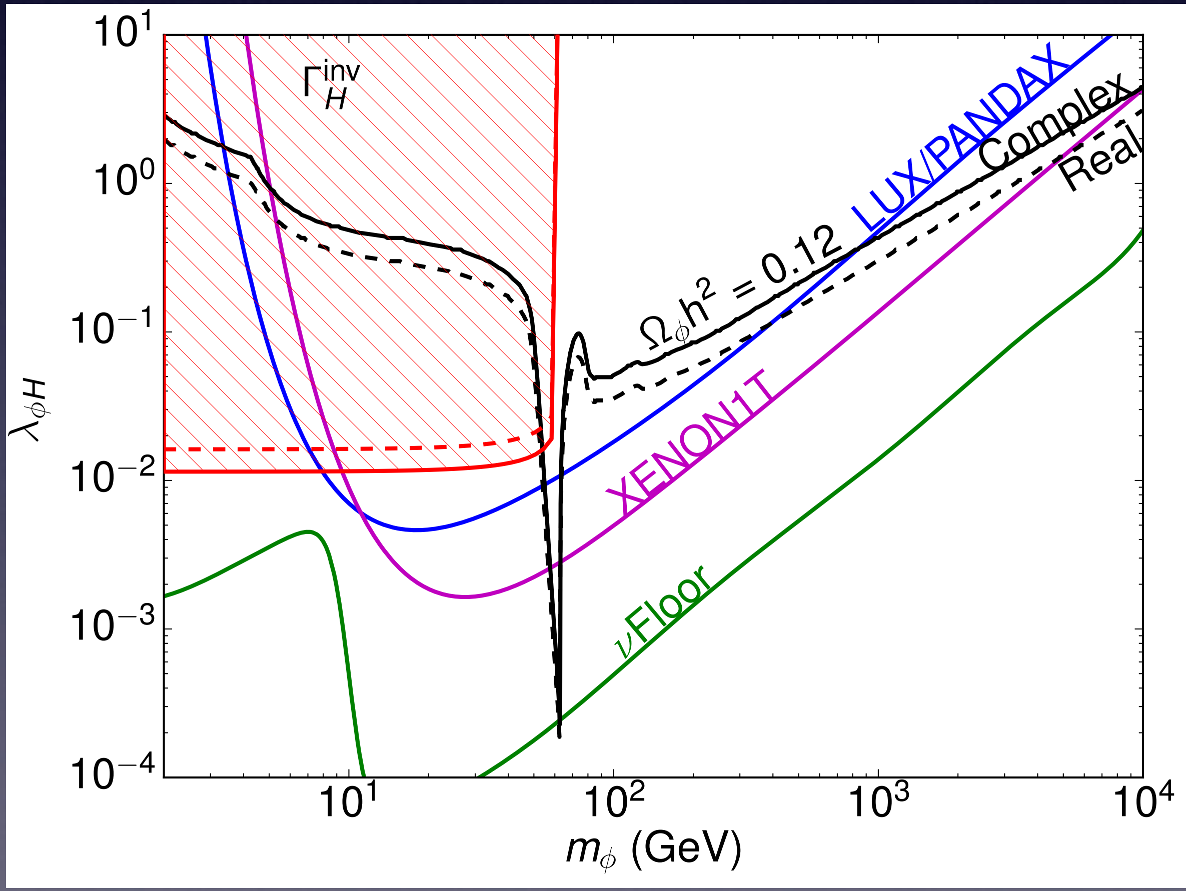
Esudero et al. 1609.09079

Higgs-portal : scalar/vectorial DM

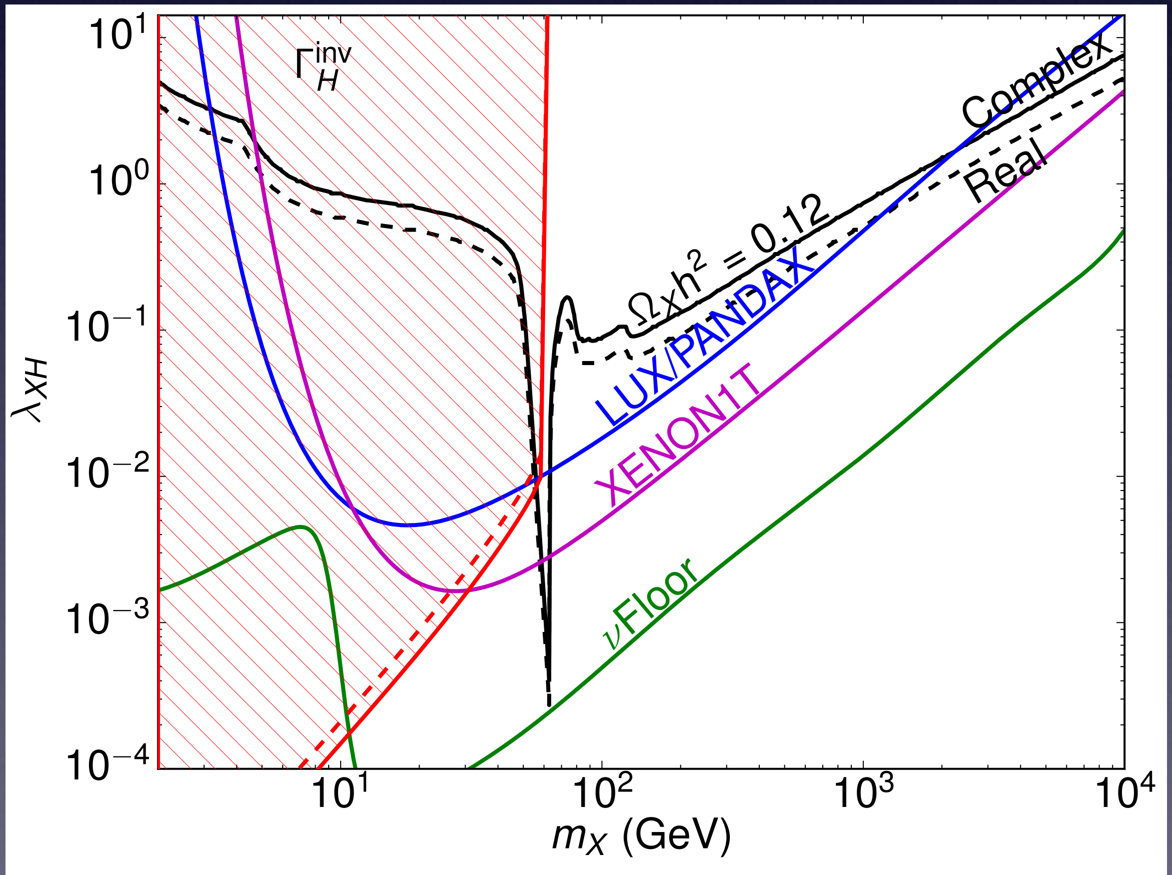
$$\mathcal{L} \supset a\,\lambda_{\phi H}\left[vH\phi^2 + \frac{1}{2}H^2\phi^2\right],$$

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

Scalar DM



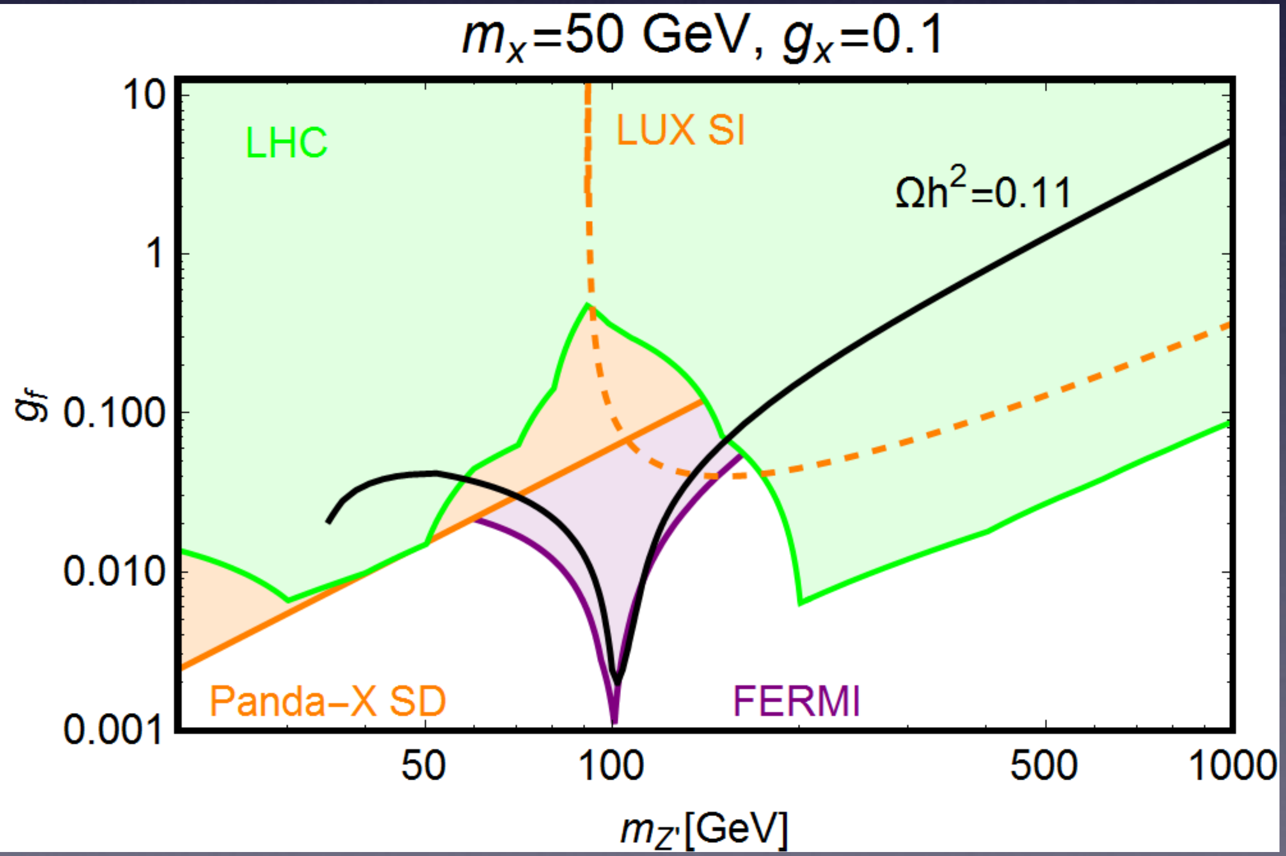
Vectorial DM

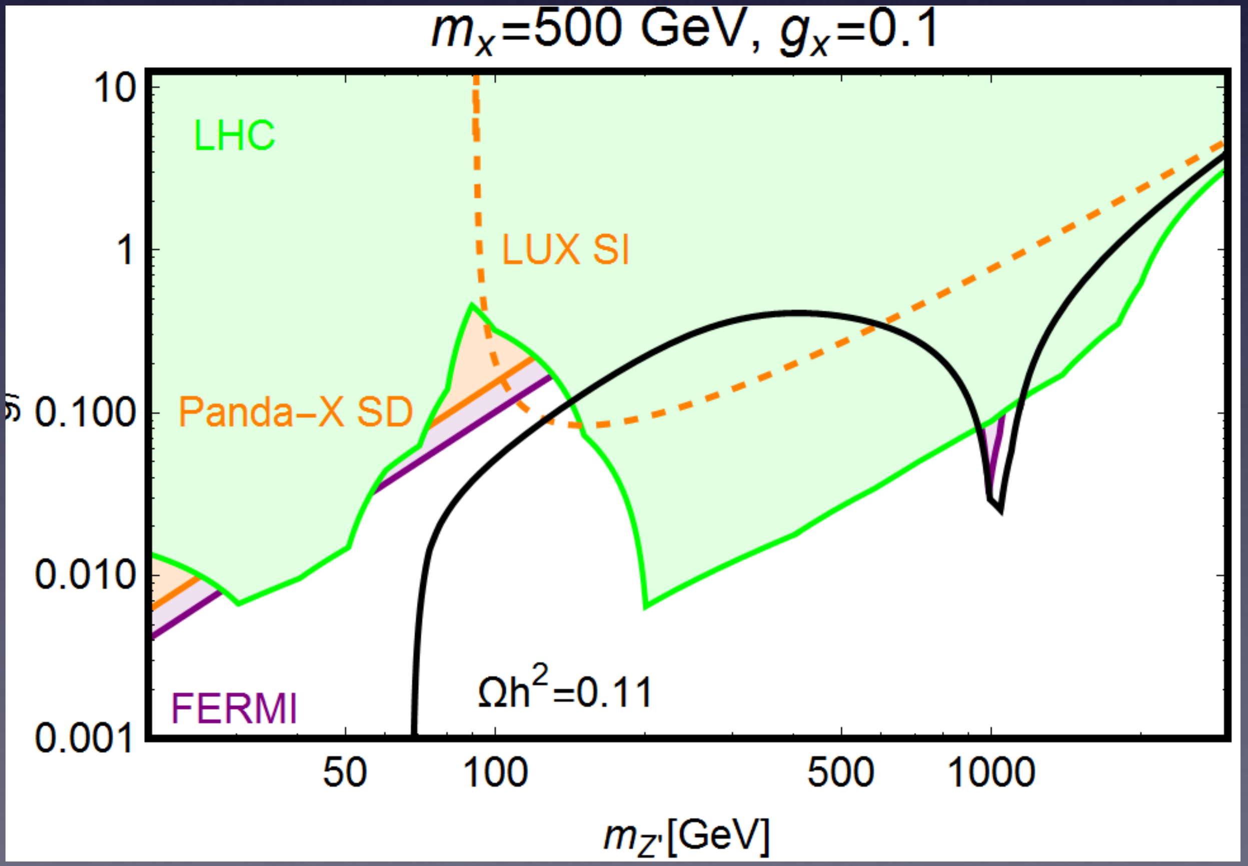


Esudero et al. 1609.09079

Quid about a Z' portal?

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



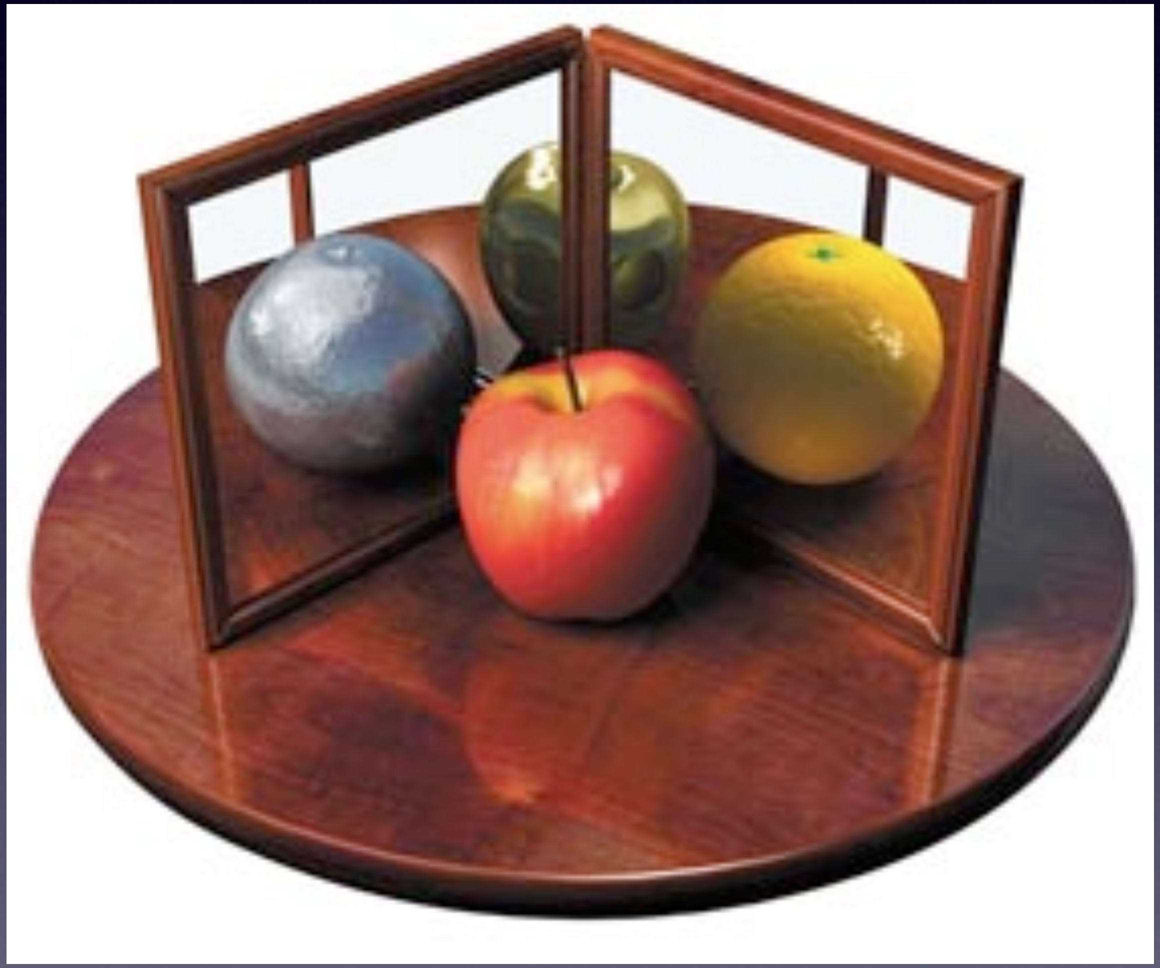


A. Alves, G. Arcadi, Y. Mambrini, F. S. Queiroz, 1612.07282

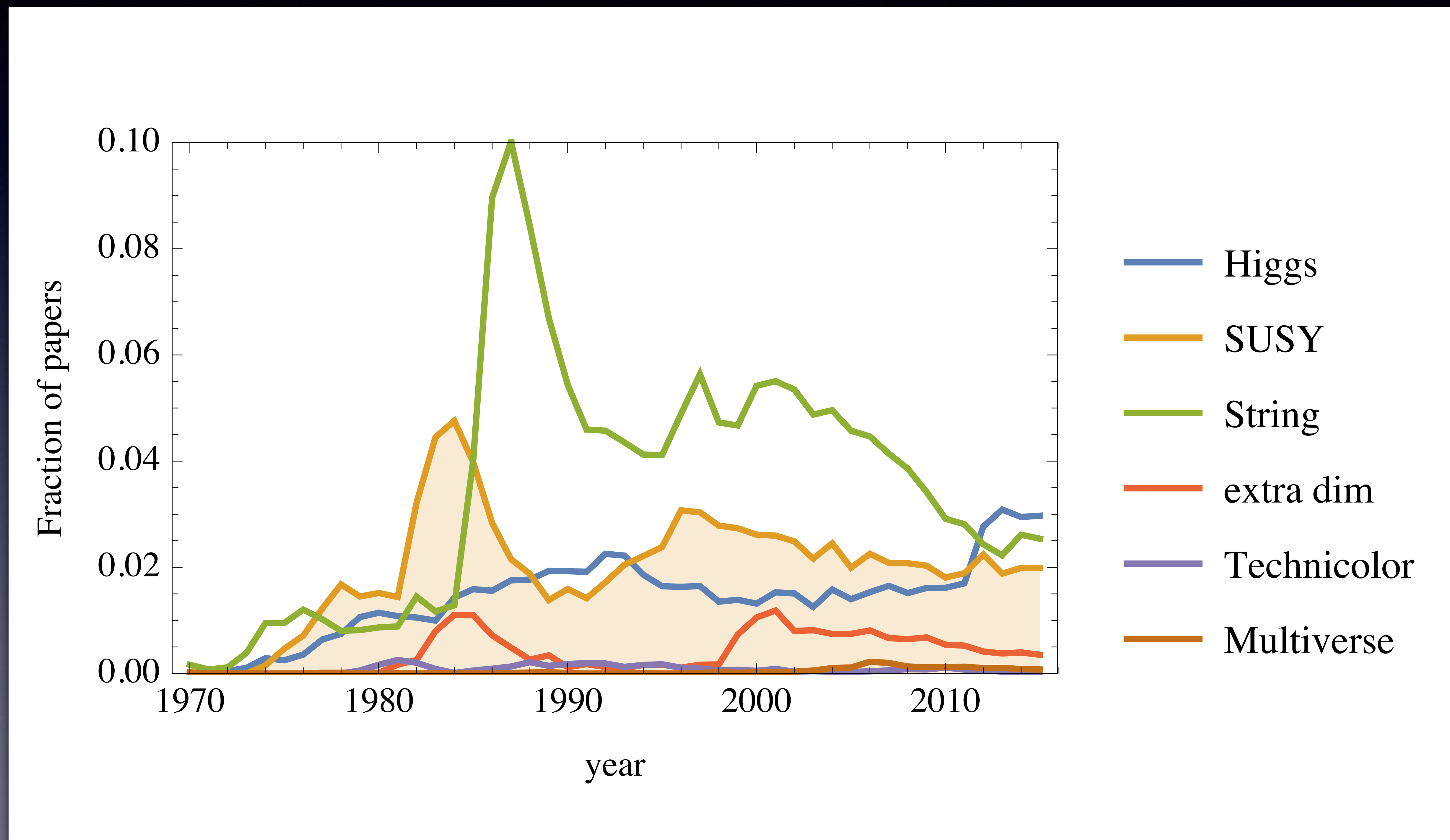
Summary

The only scenarios that are **not excluded** are those in which the dark matter is a **scalar (vector) heavier than 400 GeV (1160 GeV)** with a **Higgs portal** coupling, or a **fermion** with a **pseudoscalar** (CP violating) **coupling** to the Standard Model Higgs boson. **With the exception of dark matter with a purely pseudoscalar coupling** to the Higgs, it is anticipated that planned direct detection experiments **will probe the entire range of models**

And SUSY?



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



SUSY and dark matter

SUSY has 2 « natural » dark matter candidates:

- The neutralino, $\tilde{\chi}_1^0$ (60% of the SUSY DM papers on spires)
- The gravitino, $\tilde{g}$ (49% of the SUSY DM papers)

SUSY and dark matter

SUSY has 2 « natural » dark matter candidates:

- The neutralino, $\tilde{\chi}_1^0$ (60% of the SUSY DM papers on spires)
- The gravitino, $\tilde{g}$ (49% of the SUSY DM papers)

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

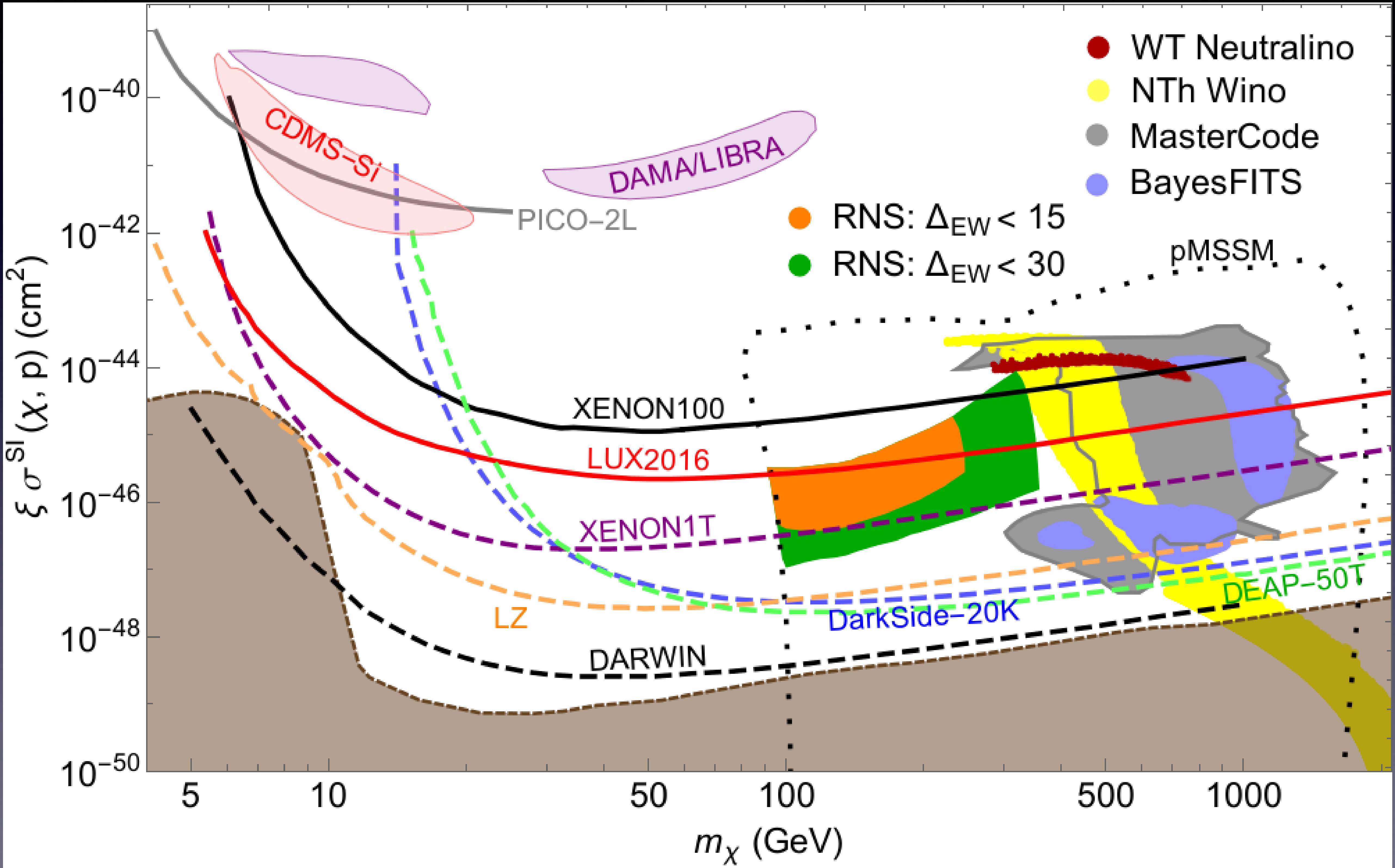
$$\chi_1^0 = c_B \tilde{B} + c_1 \tilde{H}_1 + c_2 \tilde{H}_2 + c_W \tilde{W}$$

well tempered

non thermal wino

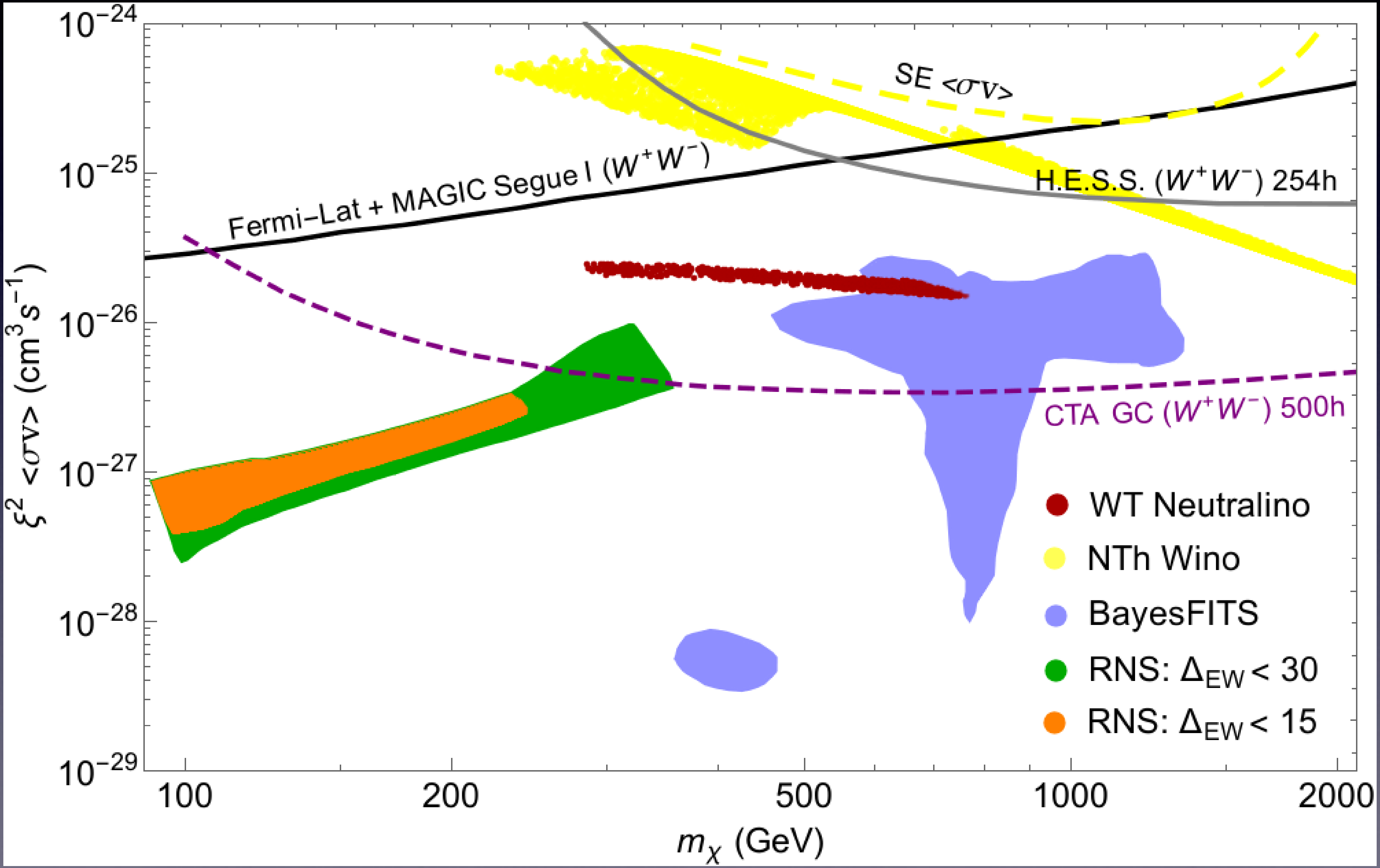
In this sense, he has all the characteristic of a WIMP, and as a consequence suffers from the same constraints listed before

Spin Independant Direct Detection



Baer et al. 1609.06735

Indirect Detection



Baer et al. 1609.06735

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)

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):

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

which is excluded by Tremaine Gunn/structure formation bounds

However..

..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)

However..

..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

$\boxed{\text{The coupling is fixed by the symmetry (breaking)}}$

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

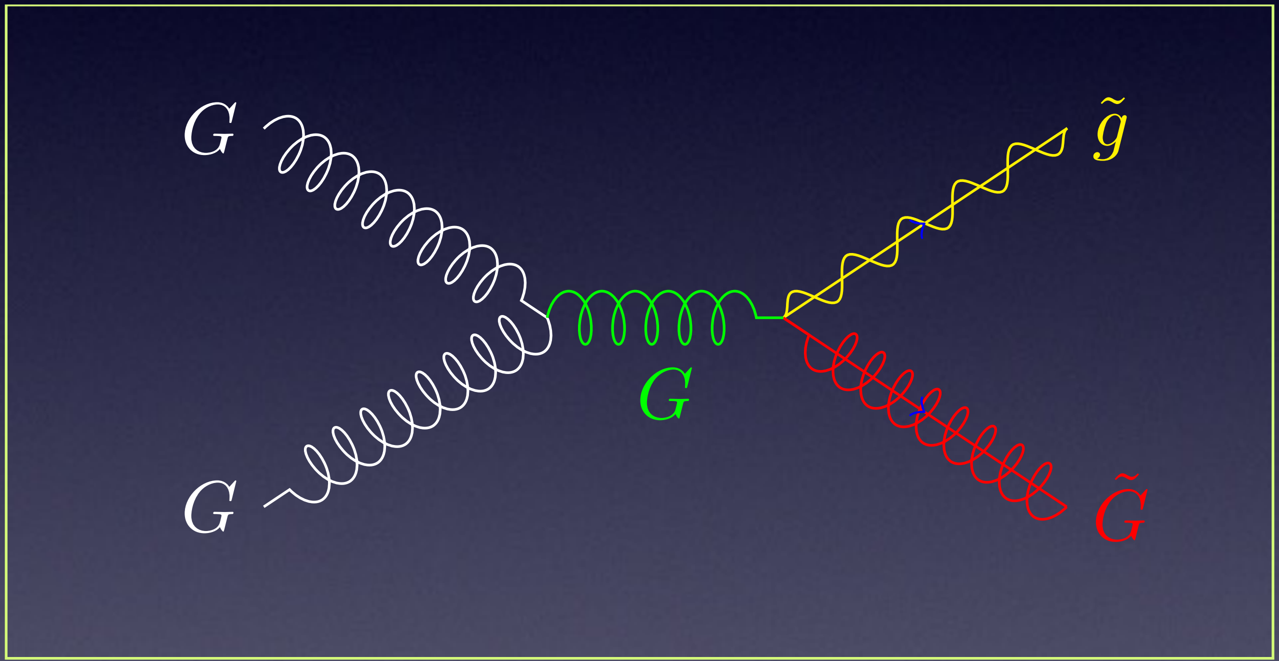
gluon

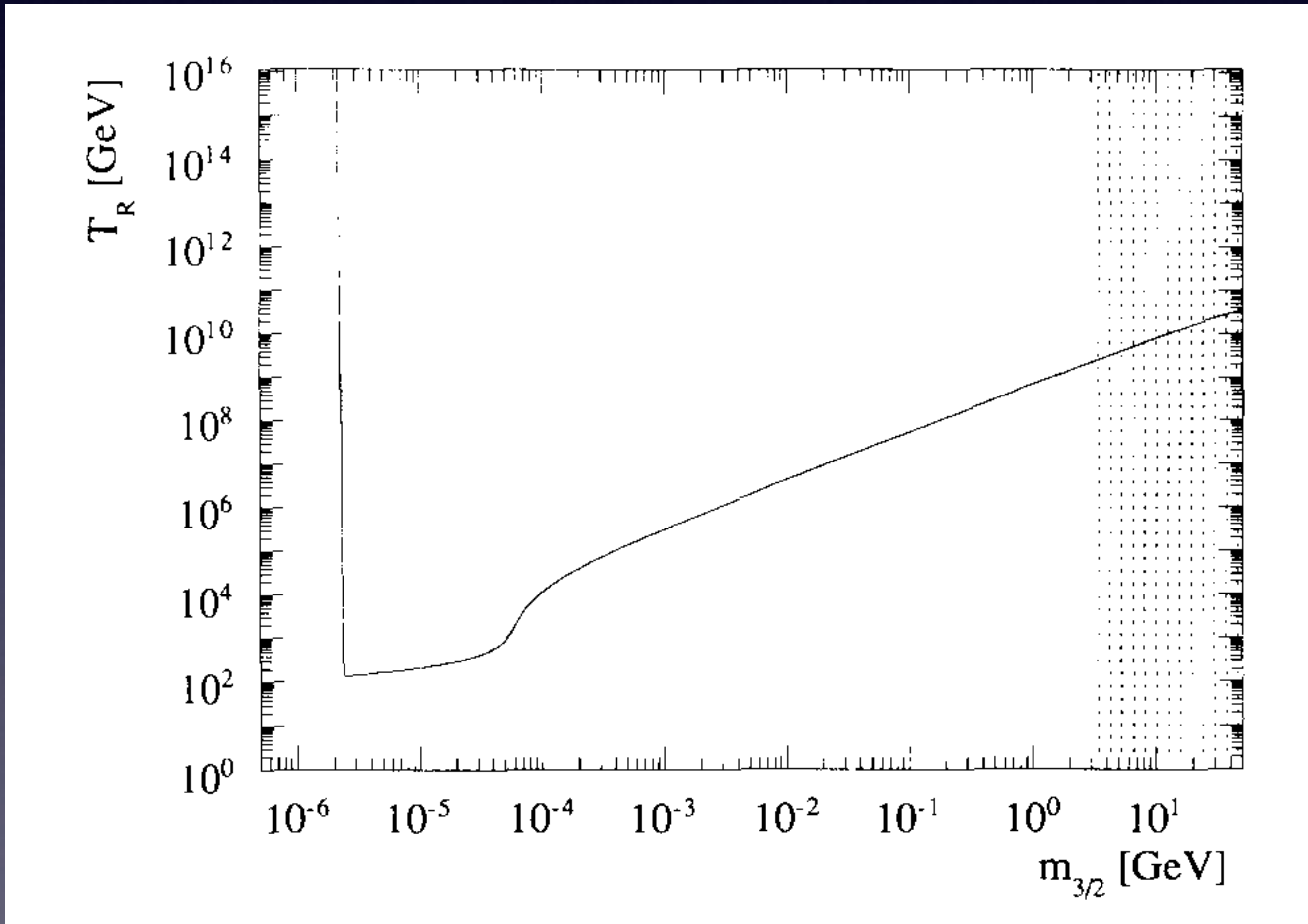
T. Moroi, H. Murayama, M. Yamagushi, Phys. Lett. **B303**, 284-294 (1993)

… 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





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

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

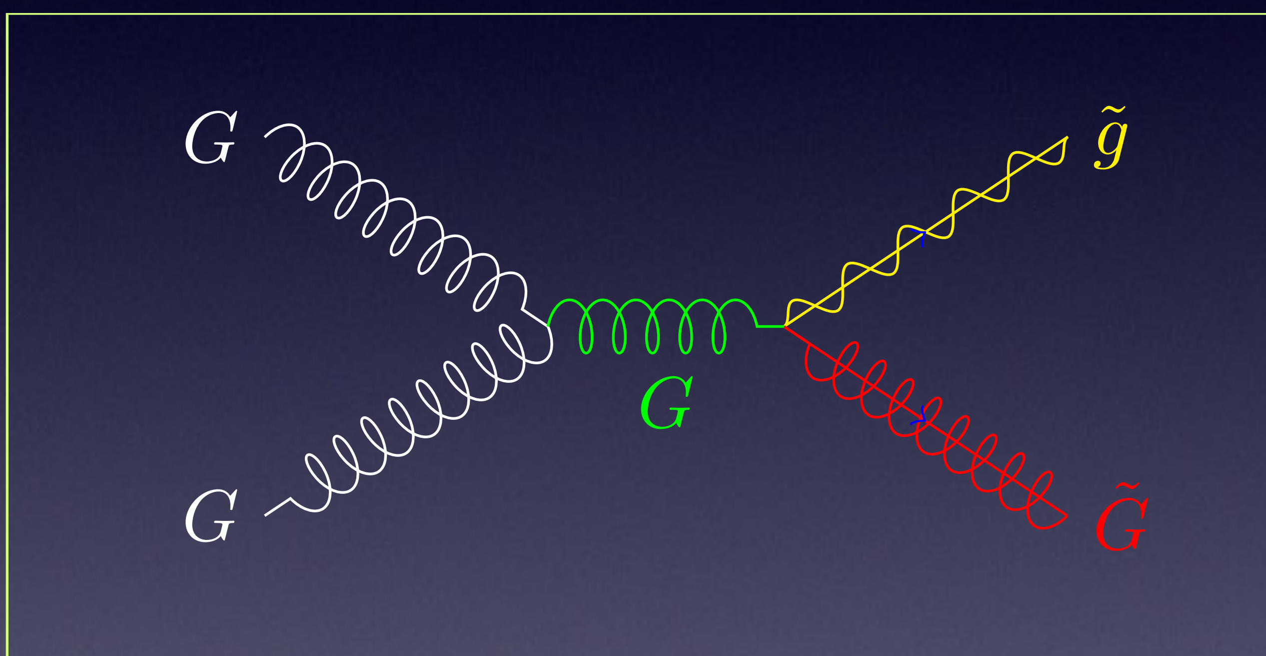
… one can then compute the relic abundance of the gravitino, repopulated by the scattering of SM particles in the thermal bath:

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

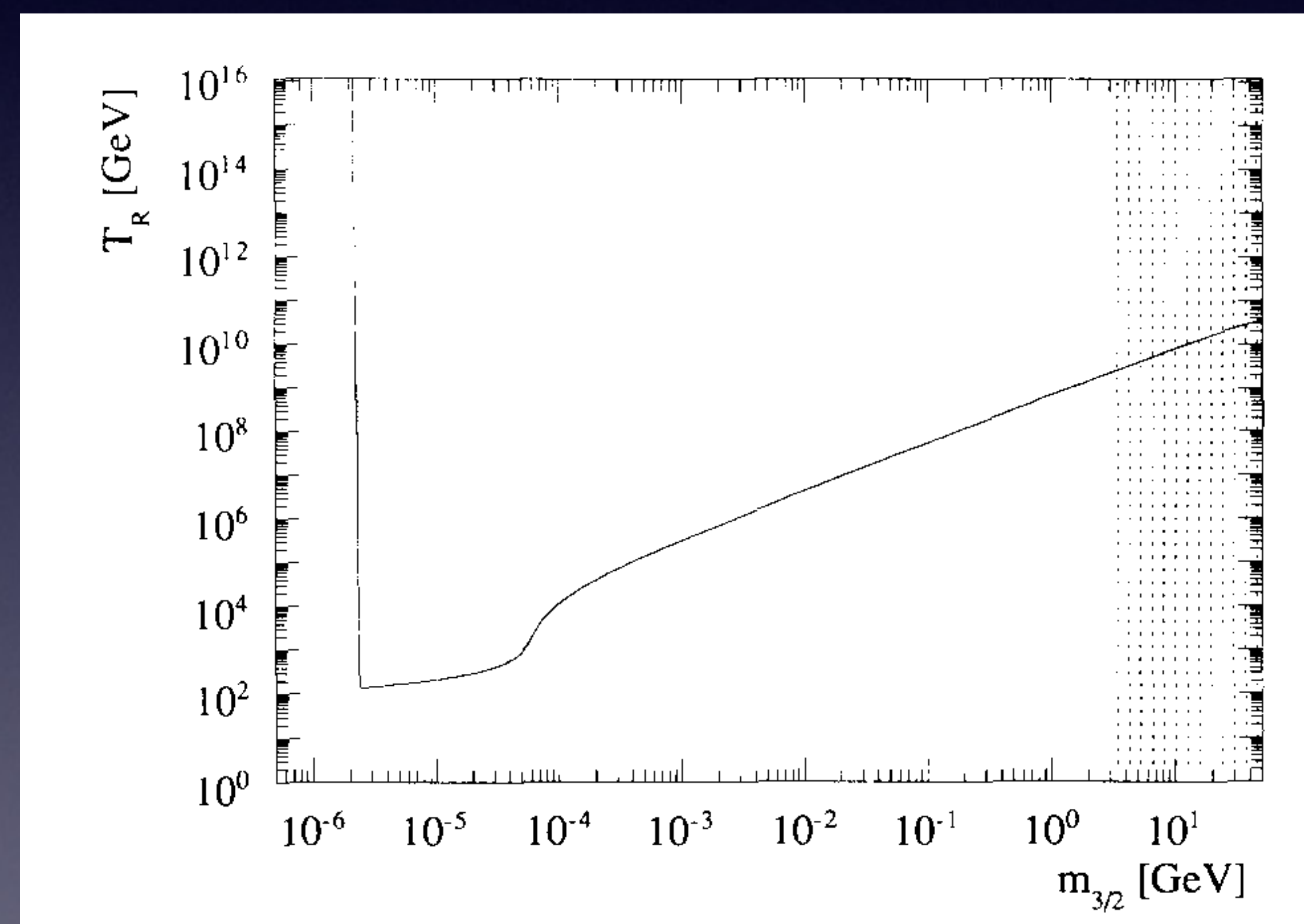
gravitino

gluino

gluon



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



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

.. 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…

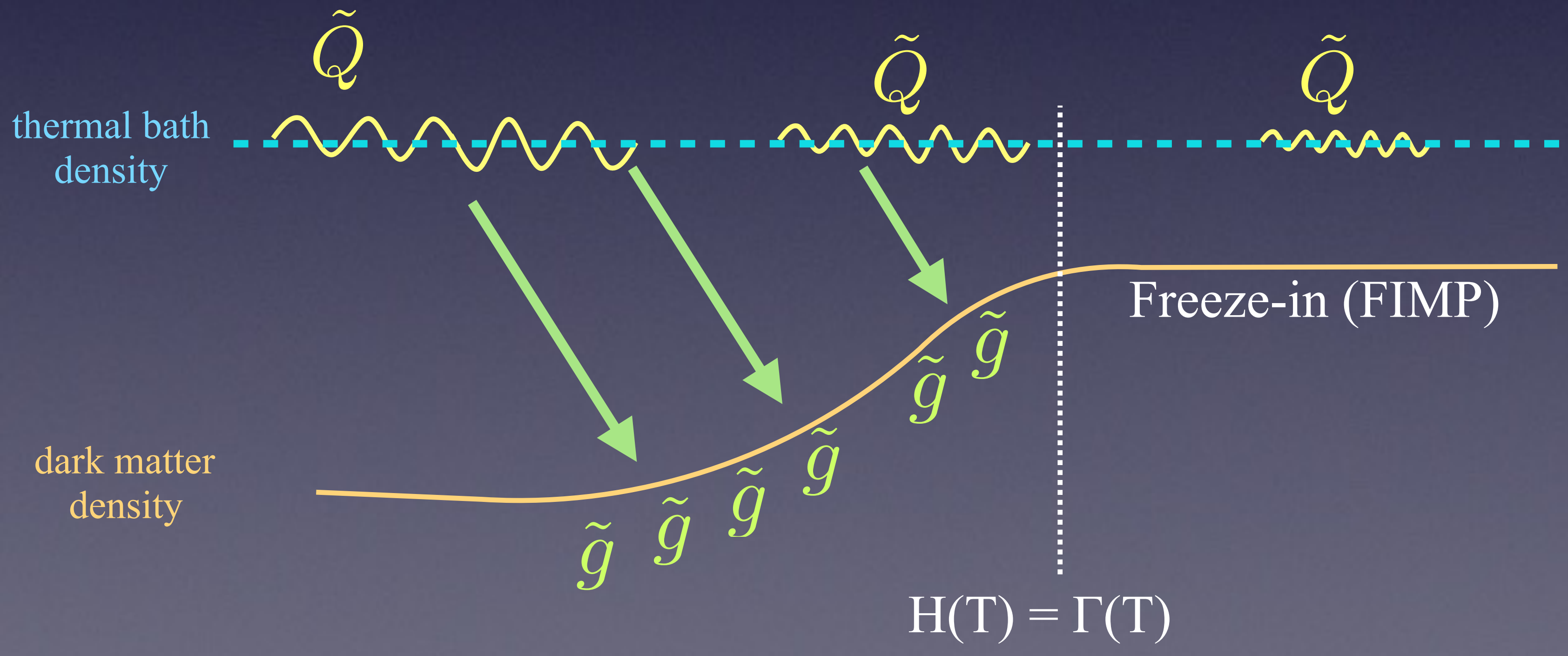
Cheung et al.* showed in 2011 that the freeze in process of gravitino production through the decay of sparticles still in thermal equilibrium should render the Universe overdense if

$T_{RH} > M_{susy}$.

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

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 $T_{RH} > M_{susy}$.

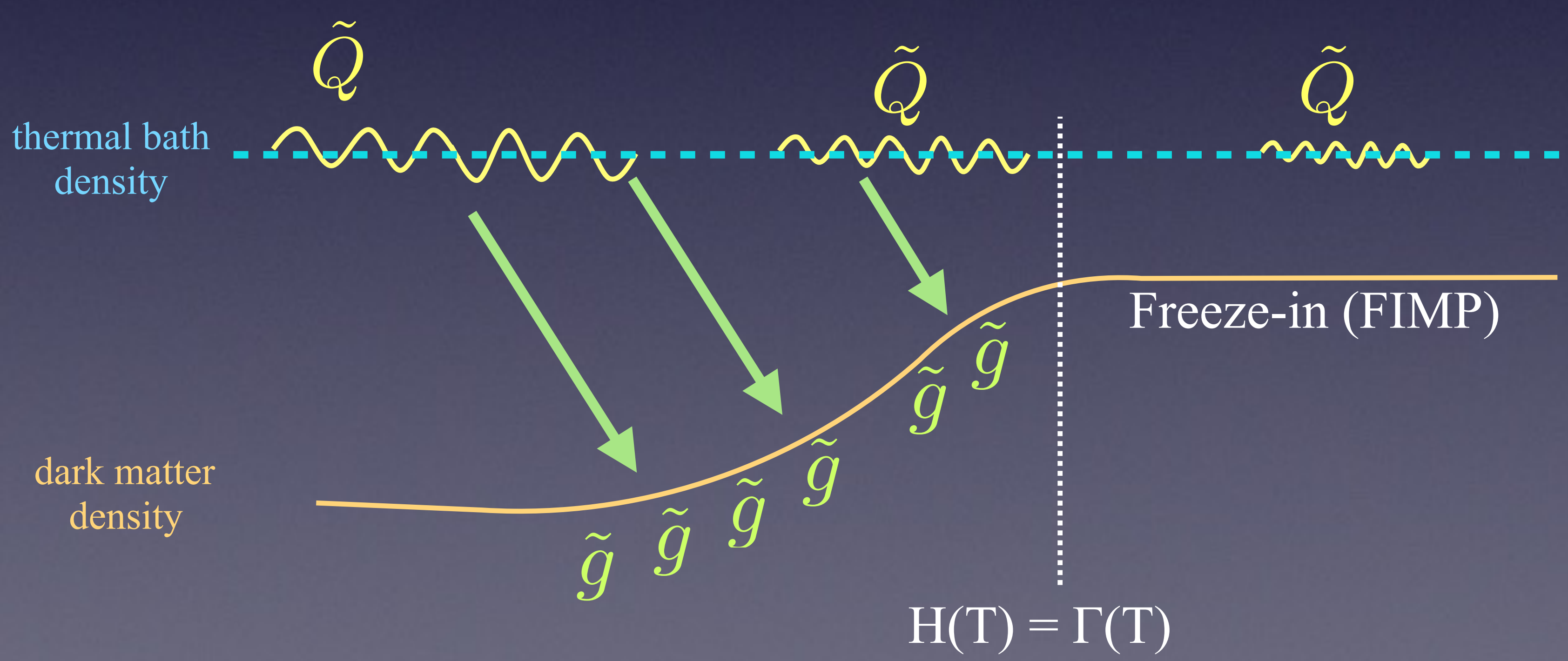
The dark matter is produced from the thermal bath but at a very slow rate, until the expansion rate dominates the annihilation ($H > \Gamma$)



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

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 $T_{RH} > M_{susy}$.

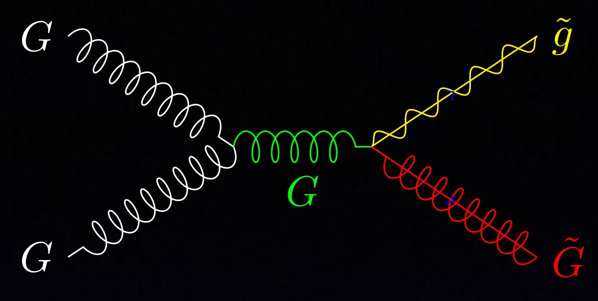
The dark matter is produced from the thermal bath but at a very slow rate, until the expansion rate dominates the annihilation (H > Γ)

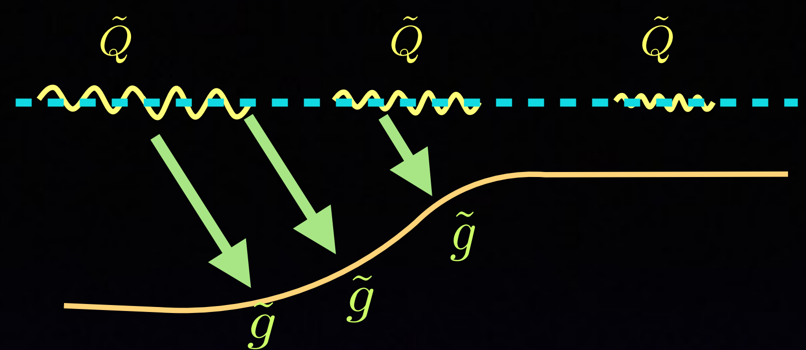


$$\Omega_{3/2}^{decay} h^2 \propto \frac{\sum M_{\tilde{Q}}^3}{m_{3/2} M_{Pl}}$$

but decay will compete with scattering

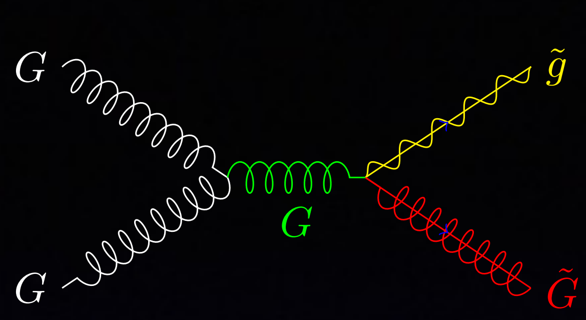
*C. Cheung, G. Elor, and L. Hall, Phys. Rev. D 61 (2011)

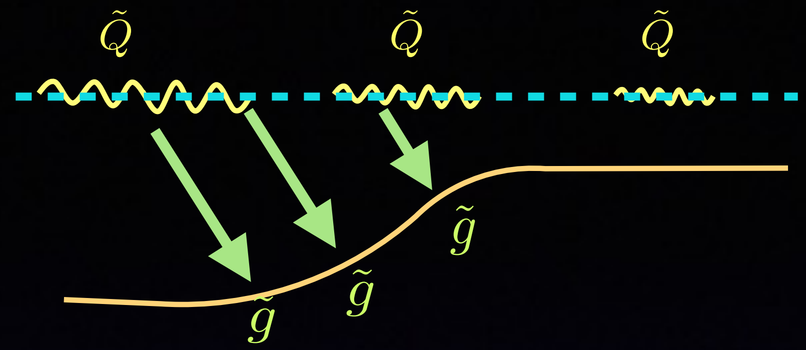




$$\Omega_{3/2}h^2 = \Omega_{3/2}^{scat}h^2 + \Omega_{3/2}^{decay}h^2 \quad \propto \quad \frac{T_{RH}\sum m_{\tilde{G}^2}}{m_{3/2}^2 M_{Pl}} + \frac{\sum M_{\tilde{Q}}^3}{m_{3/2}^2 M_{Pl}}$$

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



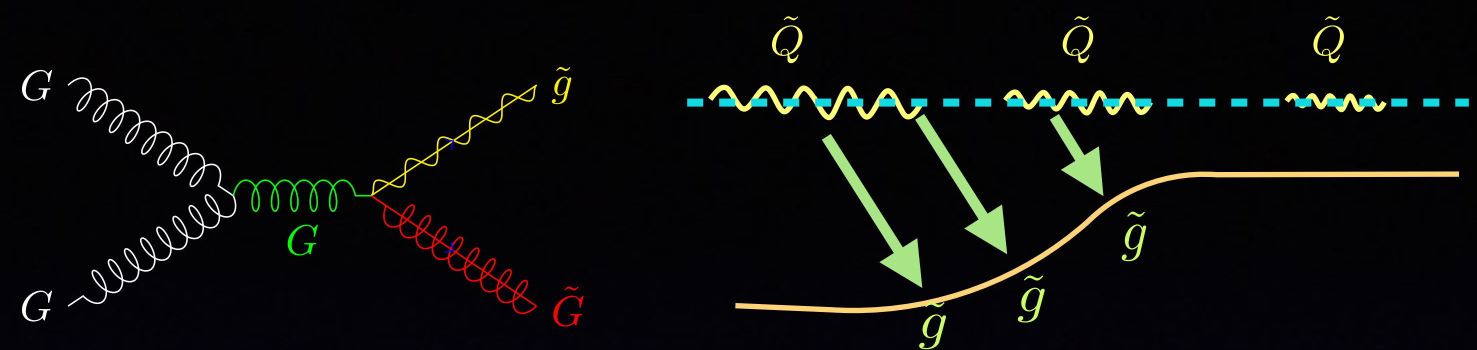


$$\Omega_{3/2}h^2 = \Omega_{3/2}^{scat}h^2 + \Omega_{3/2}^{decay}h^2 \quad \propto \quad \frac{T_{RH}\sum m_{\tilde{G}^2}}{m_{3/2}^2 M_{Pl}} + \frac{\sum M_{\tilde{Q}}^3}{m_{3/2}^2 M_{Pl}}$$

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

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.

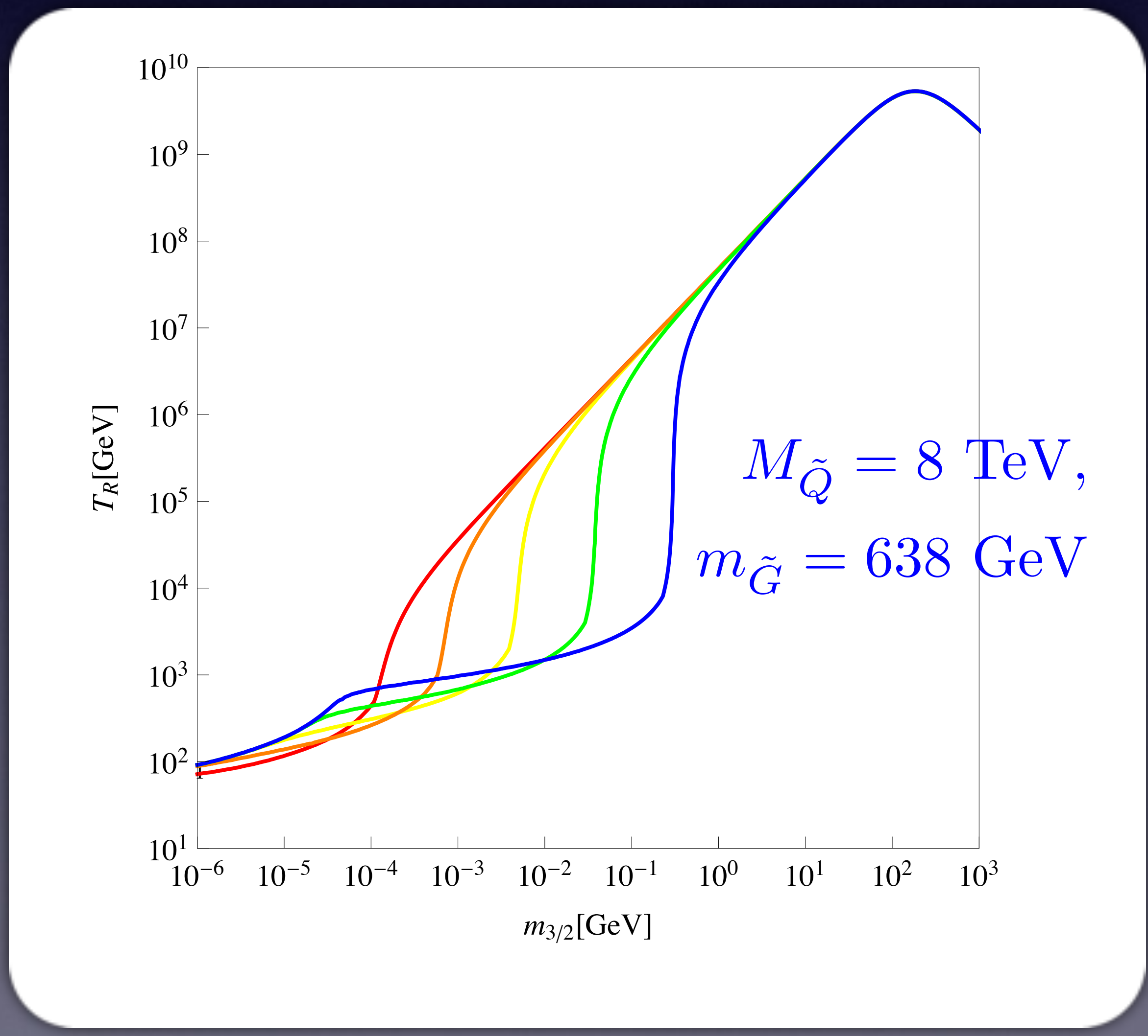
C. Cheung, G. Elor, and L. Hall, Phys. Rev. D 61 (2011)



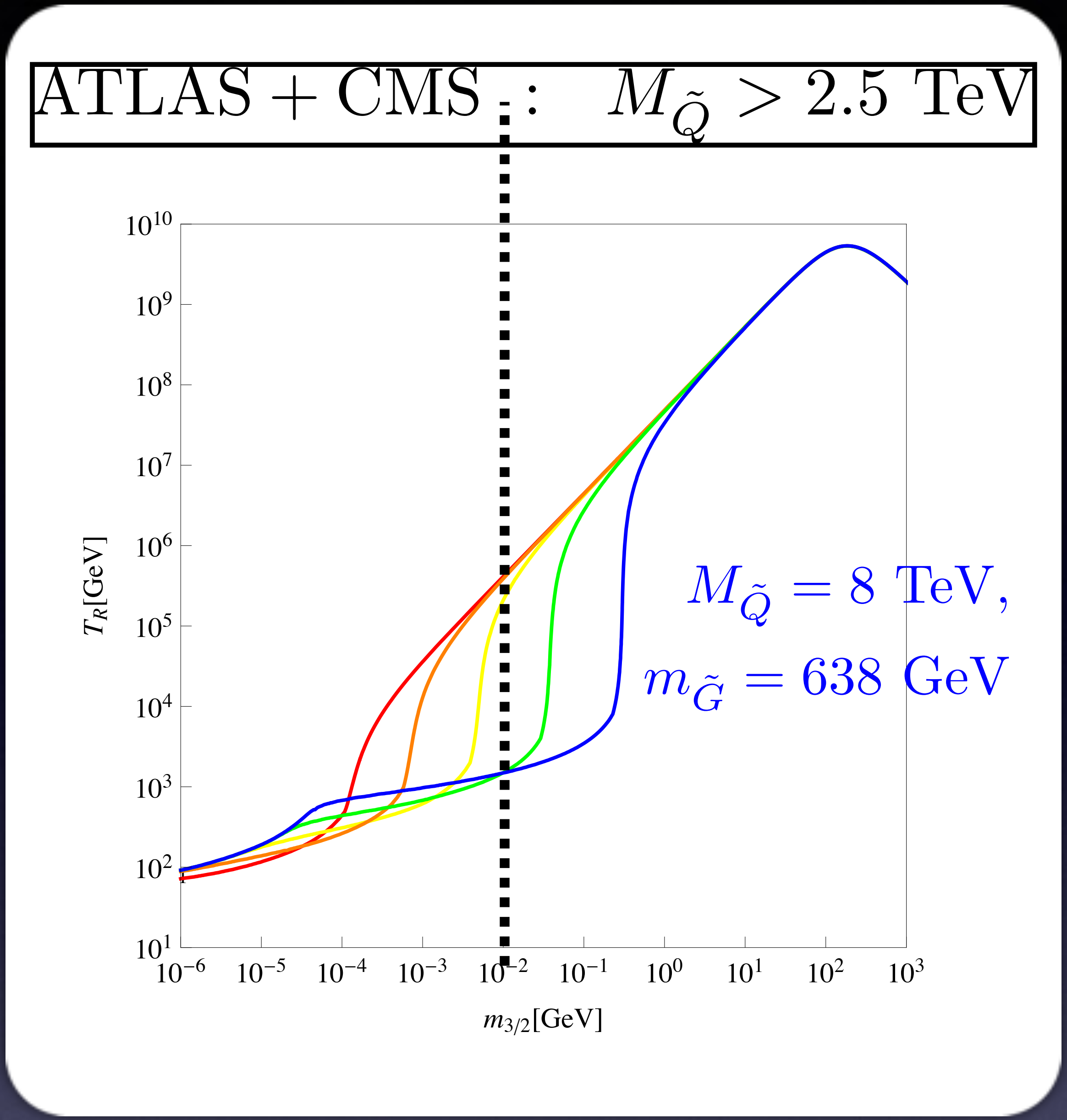
$$\Omega_{3/2}h^2 = \Omega_{3/2}^{scat}h^2 + \Omega_{3/2}^{decay}h^2 \quad \propto \quad \frac{T_{RH}\sum m_{\tilde{G}^2}}{m_{3/2}^2 M_{Pl}} + \frac{\sum M_{\tilde{Q}}^3}{m_{3/2}^2 M_{Pl}}$$

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

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

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.

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* .

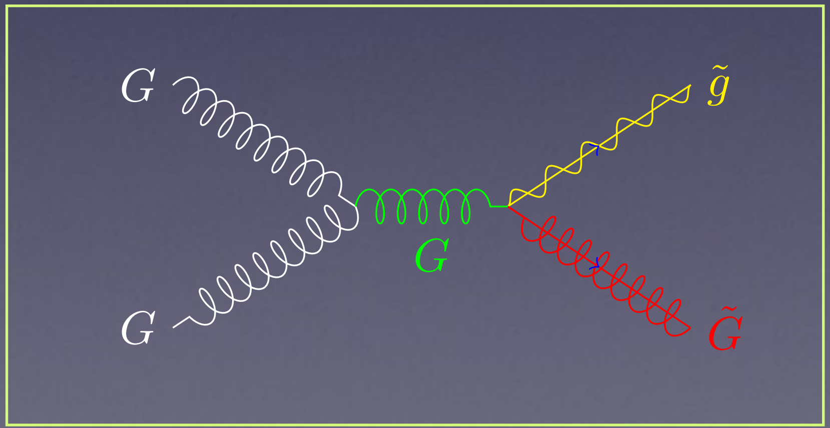
*Except in a narrow region where $M_{susy} \sim T_{RH}$ as we will see

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

* 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

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*

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

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

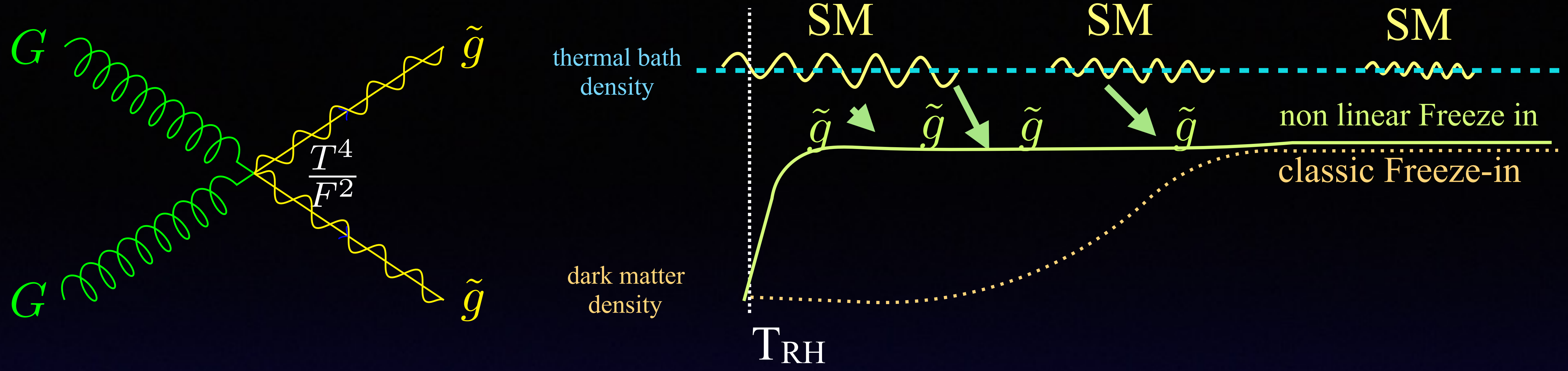
I. Antoniadis, E. Dudas, D. M. Ghilencea and P. Tziveloglou, Nucl. Phys. B **841** (2010) 157

Which gives the Lagrangian between the SM and the goldstino

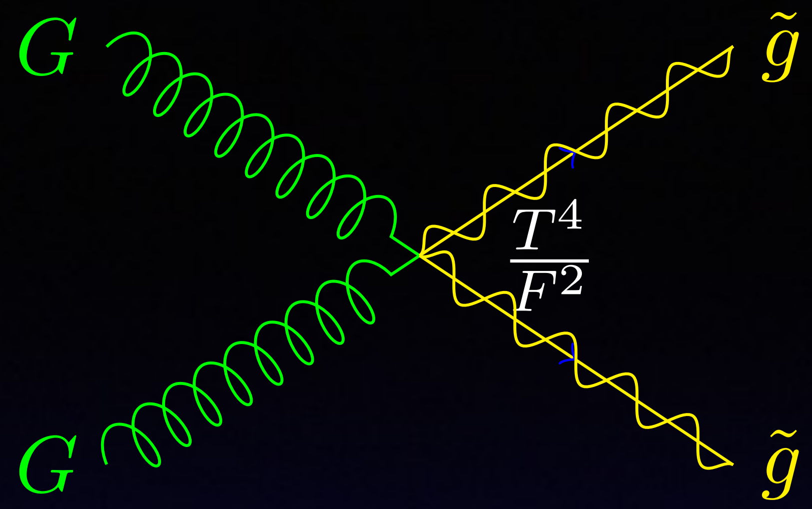
$$\begin{aligned}
&\frac{i}{2F^2}(G\sigma^\mu\partial^\nu\bar{G} - \partial^\nu G\sigma^\mu\bar{G})(\partial_\mu H\partial_\nu H^\dagger + \partial_\mu H\partial_\nu H^\dagger),\\
&\frac{1}{8F^2}(G\sigma^\mu\partial^\nu\bar{G} - \partial^\nu G\sigma^\mu\bar{G}) \times\\
&(\bar{\psi}\bar{\sigma}_\nu\partial_\mu\psi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

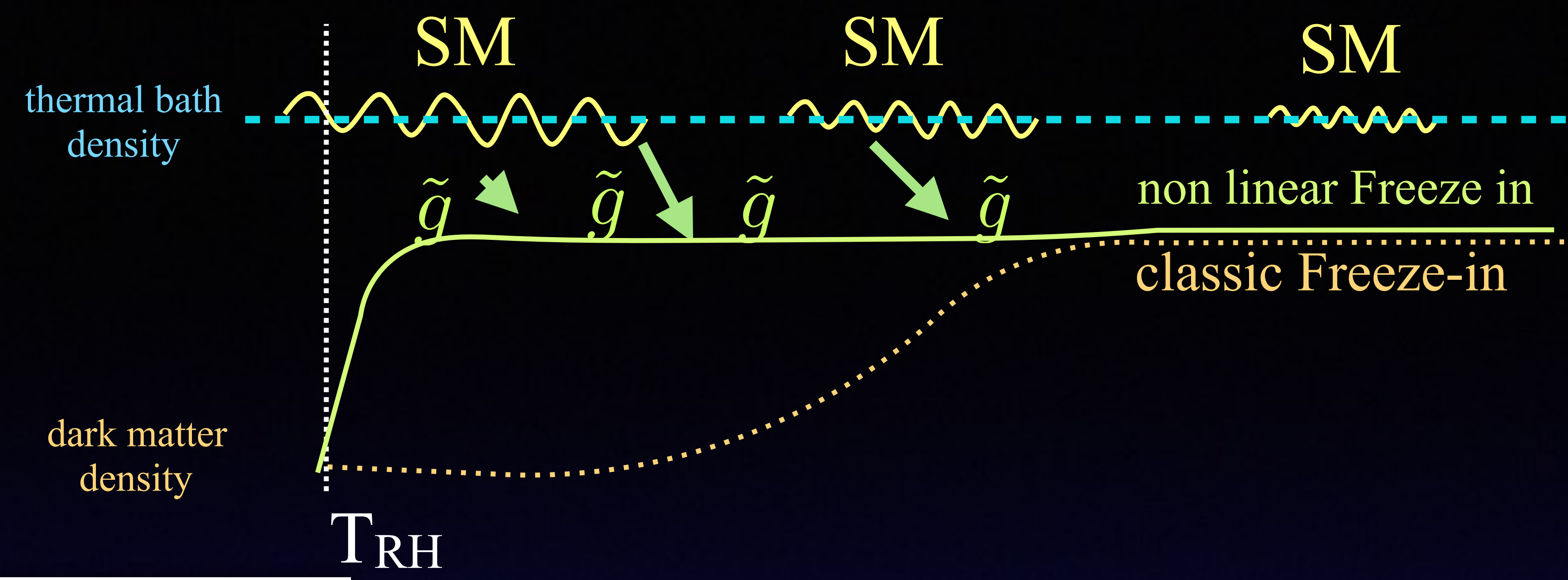
Notice how the Lagrangian has suppressed coupling (1/F^2) and strong energy/ temperature dependance

* 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

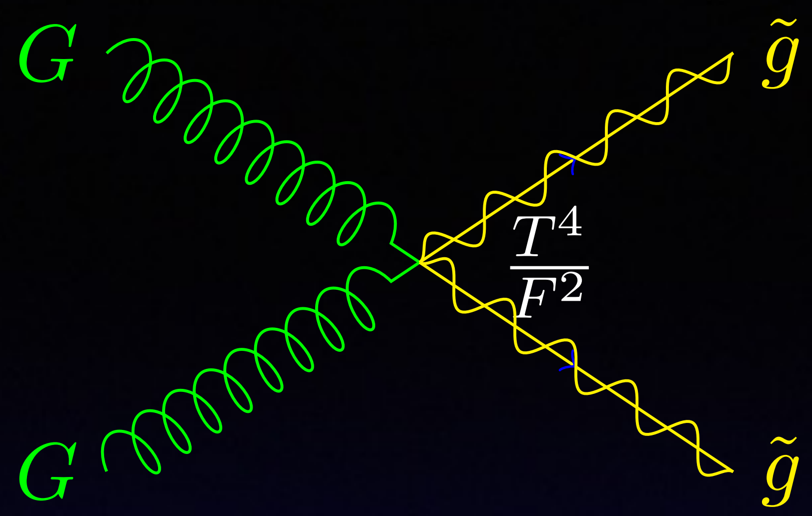


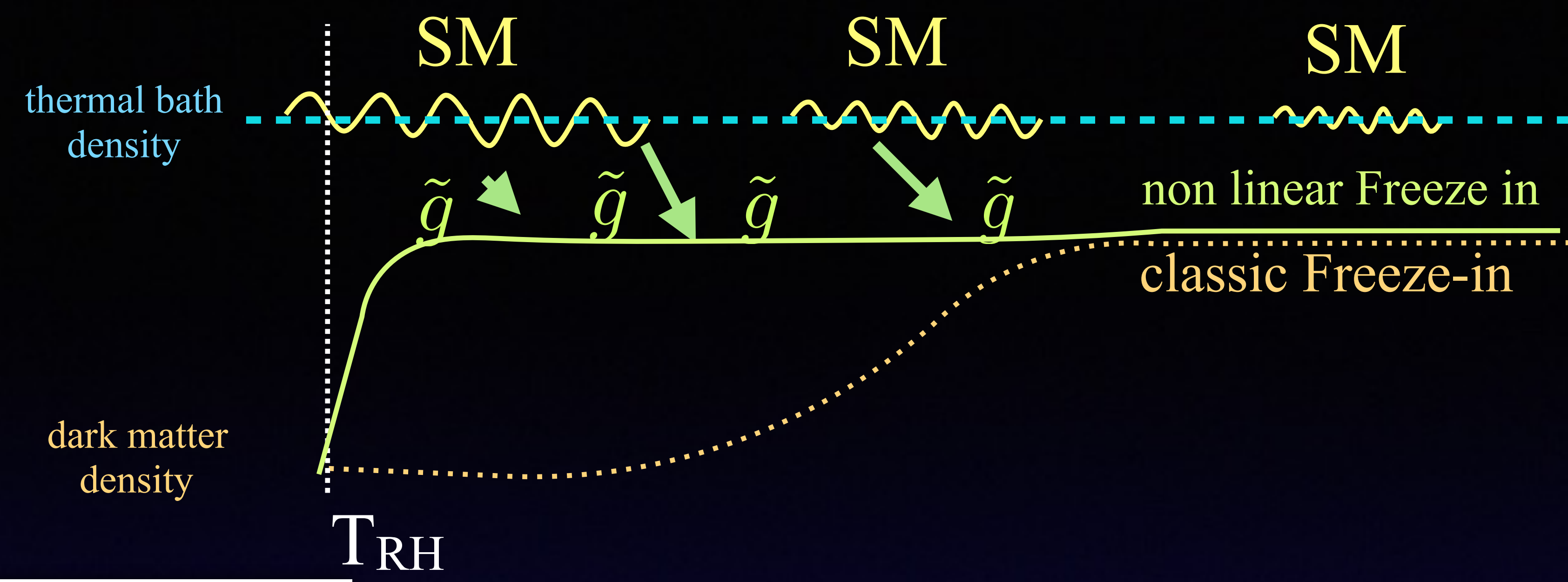
G
G
$\tilde{g}$
$\tilde{g}$
$\frac{T^4}{F^2}$
SM
SM
SM
thermal bath density
$\tilde{g}$
$\tilde{g}$
$\tilde{g}$
$\tilde{g}$
non linear Freeze in
classic Freeze-in
dark matter density
T_{RH}





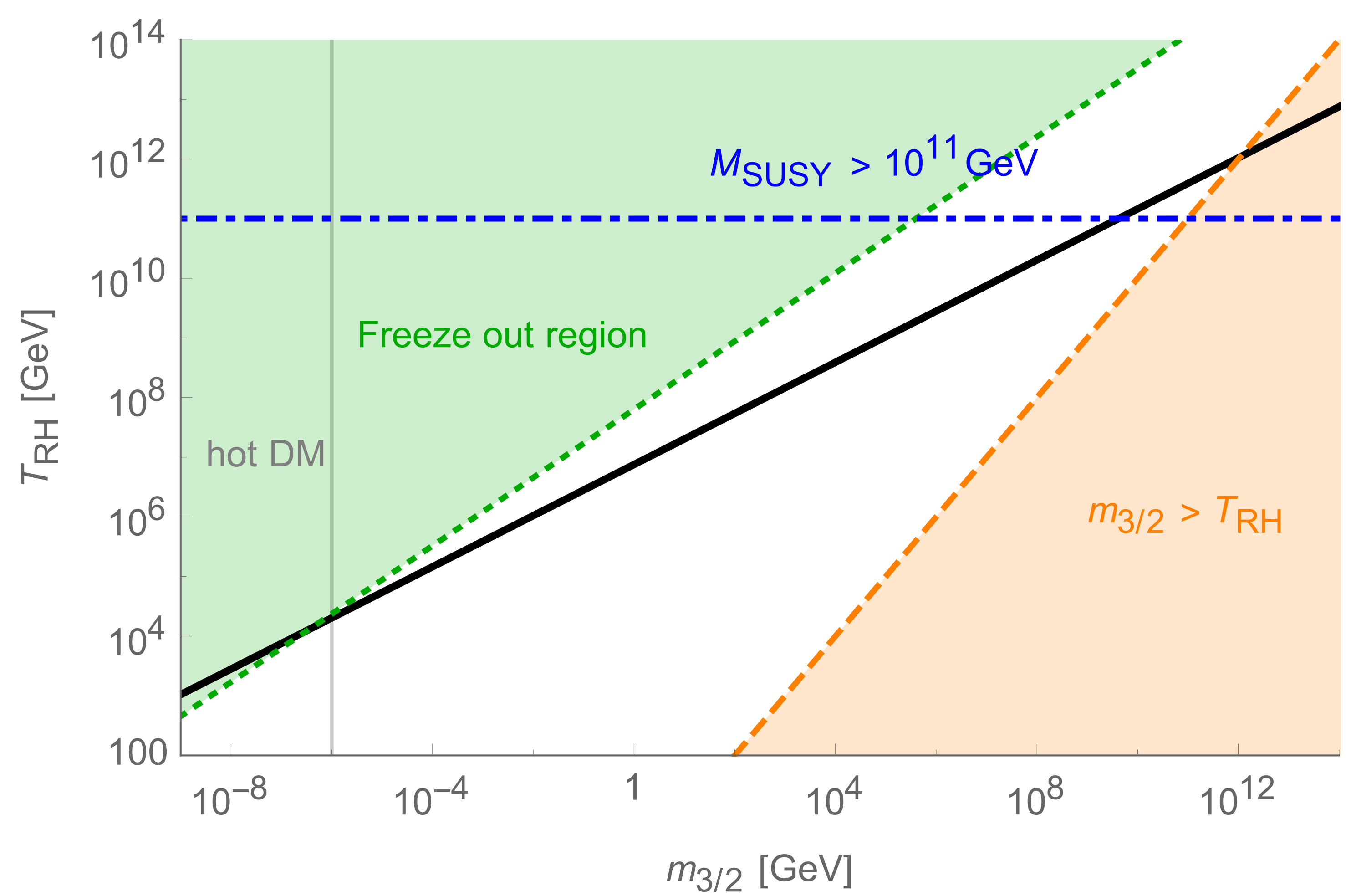
$$\Omega_{3/2}h^2 \simeq 0.11 \left(\frac{100\ \text{GeV}}{m_{3/2}}\right)^3 \left(\frac{T_{\text{RH}}}{5.4 \times 10^7\ \text{GeV}}\right)^7$$





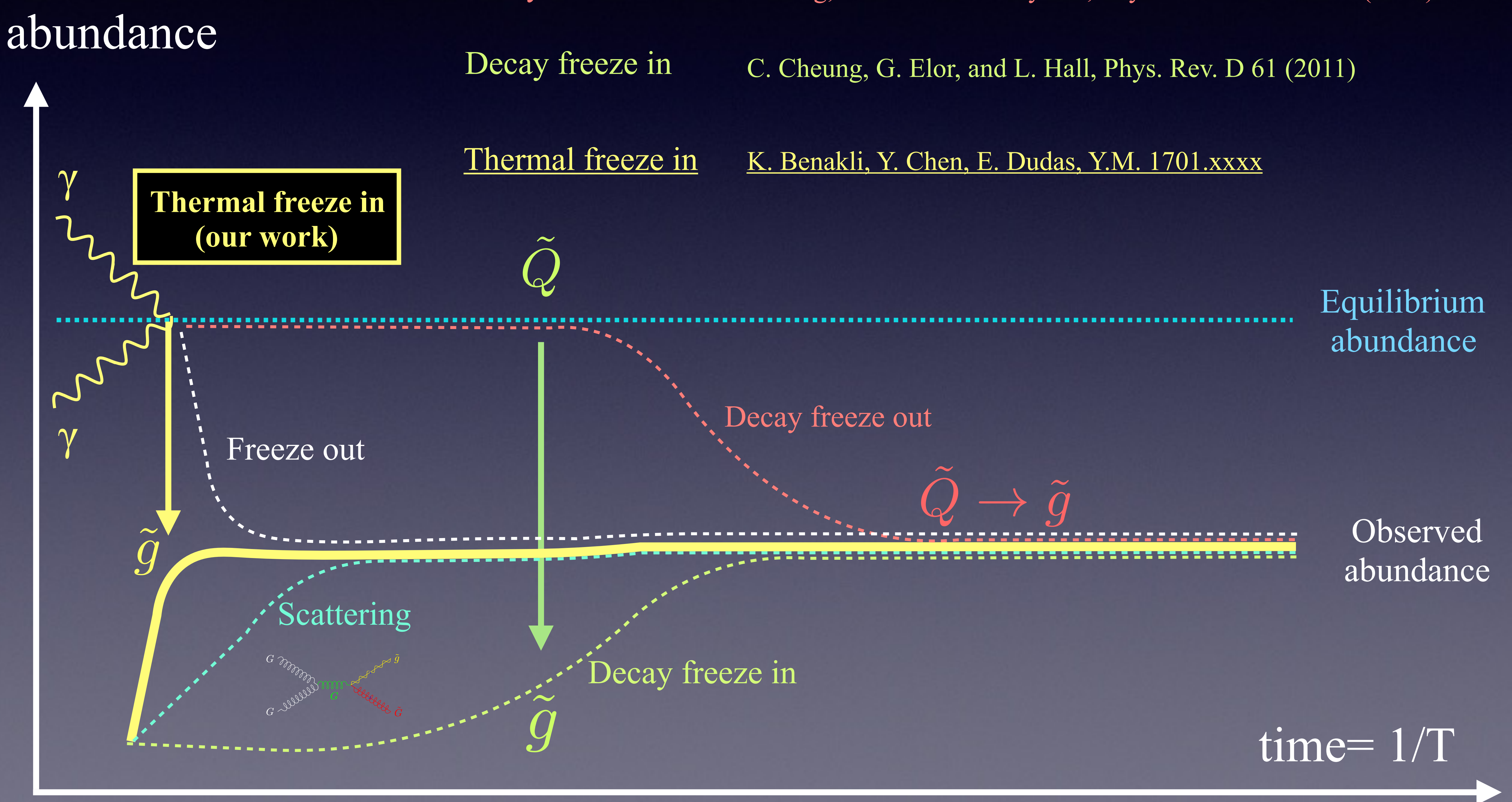
$$\Omega_{3/2}h^2 \simeq 0.11 \left(\frac{100 \text{ GeV}}{m_{3/2}}\right)^3 \left(\frac{T_{\rm RH}}{5.4 \times 10^7 \text{ GeV}}\right)^7$$

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

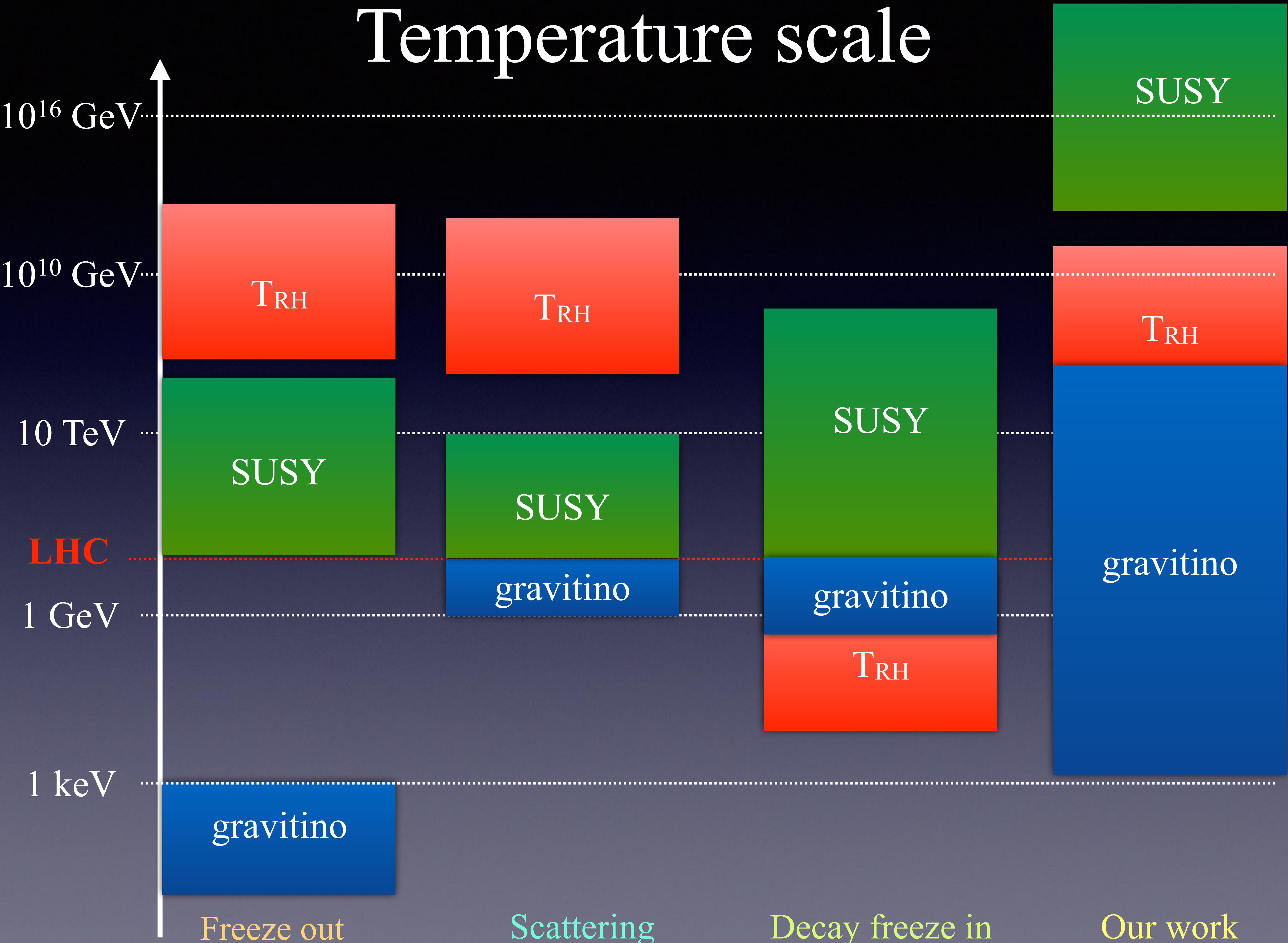


Summary: populating the Universe with gravitino

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



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. »

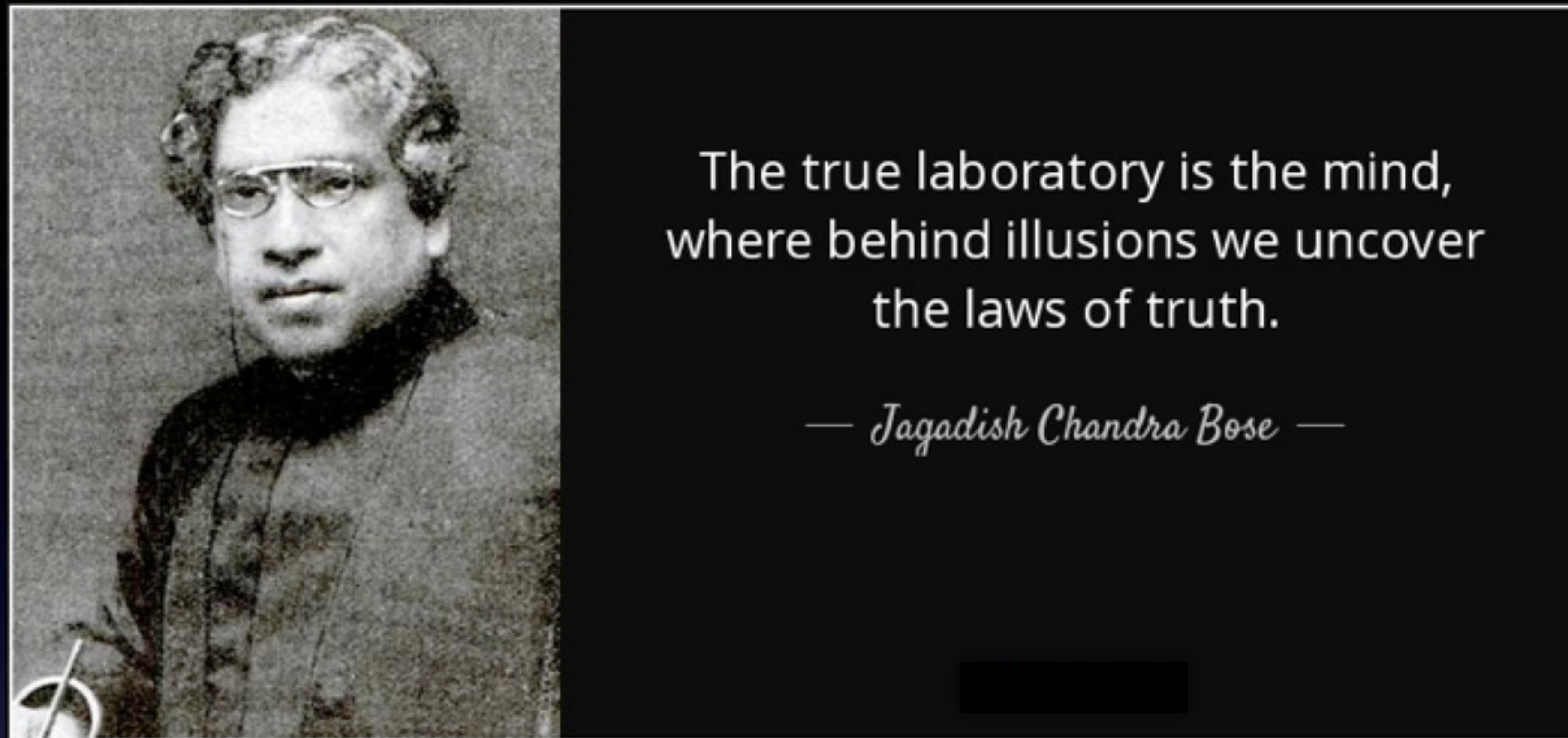
H. Nicolai, CERN courier Jan. 2017

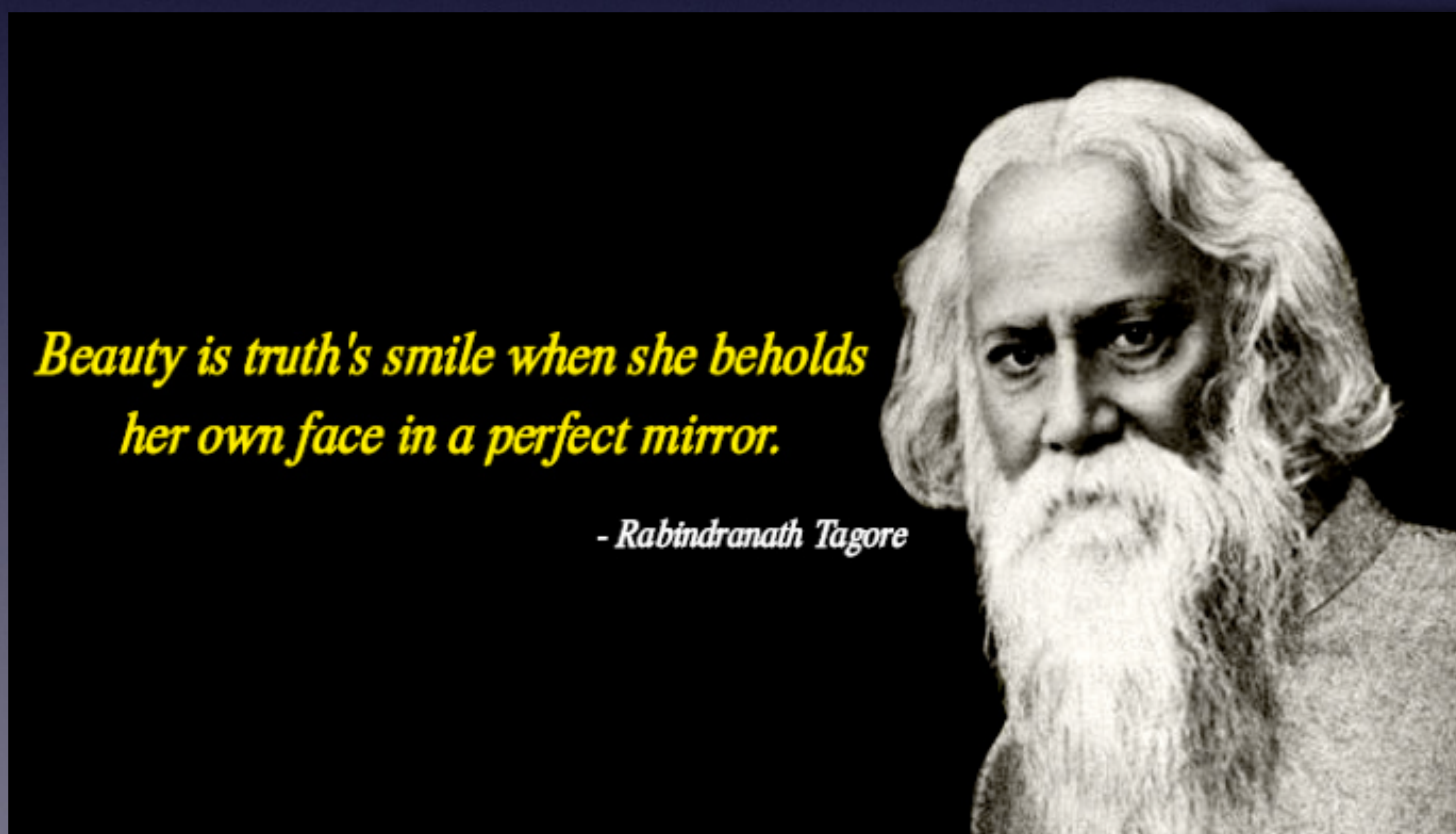
Conclusion

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 <u>thermal</u> freeze in mechanism.

That a minimal model of gravitino dark matter.

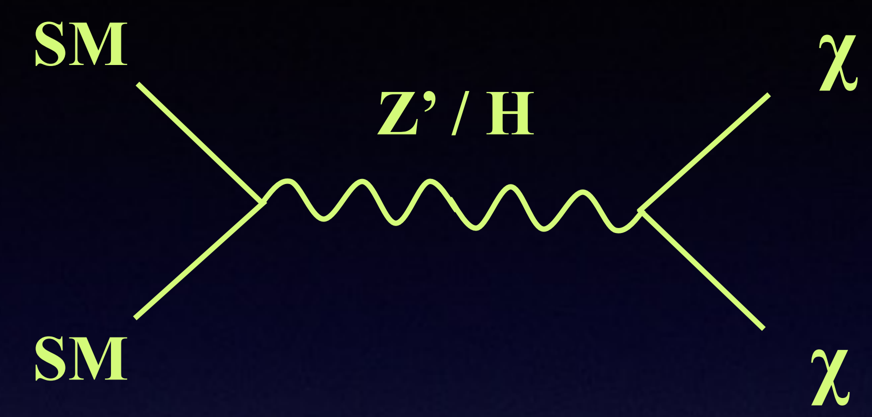

The true laboratory is the mind, where behind illusions we uncover the laws of truth.
— Jagadish Chandra Bose —


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

Beslides

The FIMP mechanism

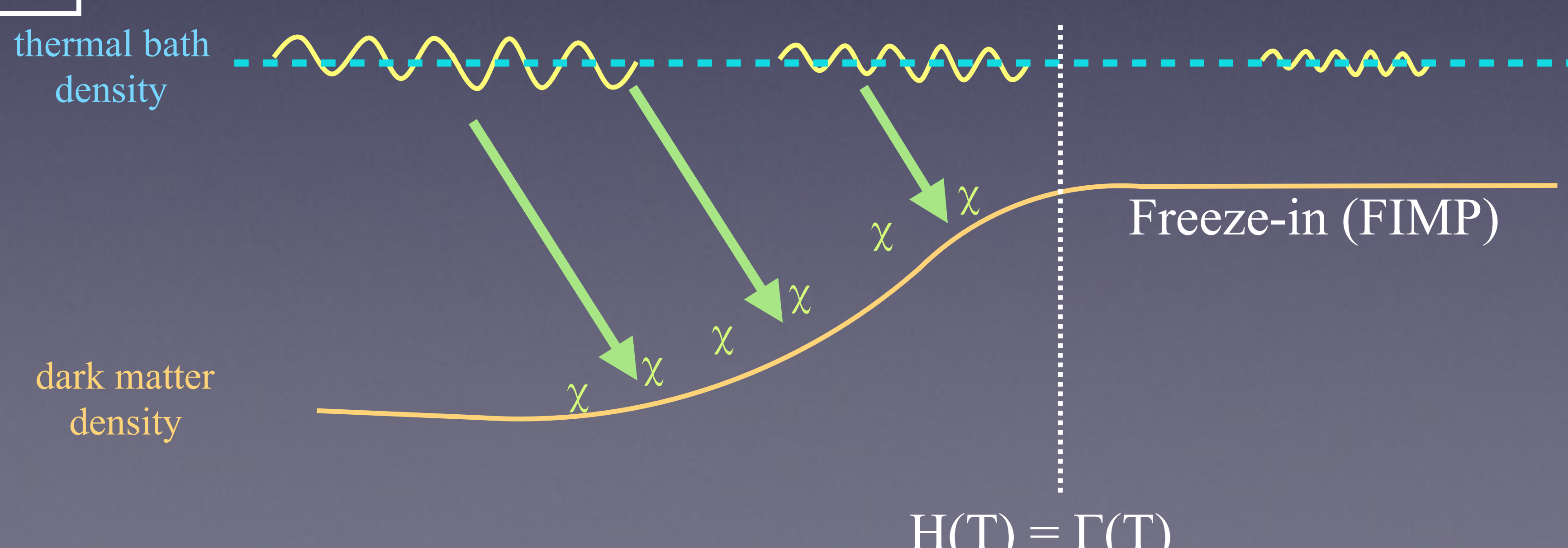
Freezing in the dark matter



Annihilation is too weak to reach the thermal equilibrium

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

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



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

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

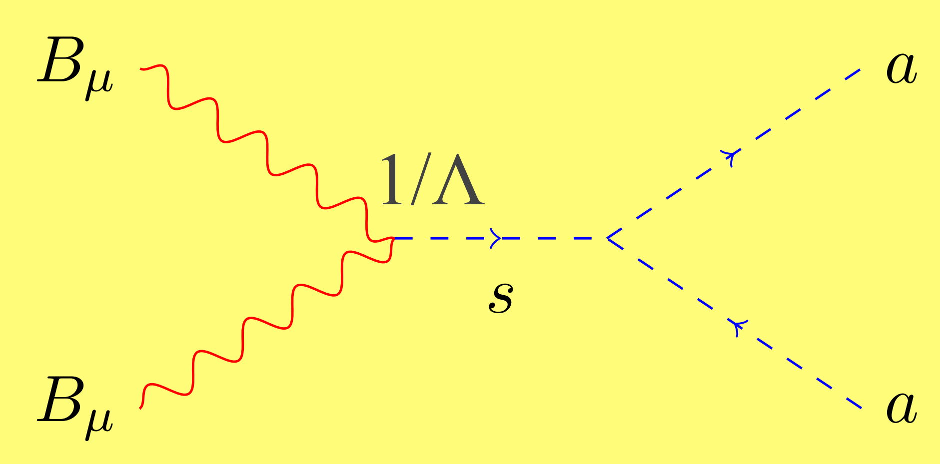
$$\Phi = \frac{s+ia}{\sqrt{2}}$$

U(1) breaking

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

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

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



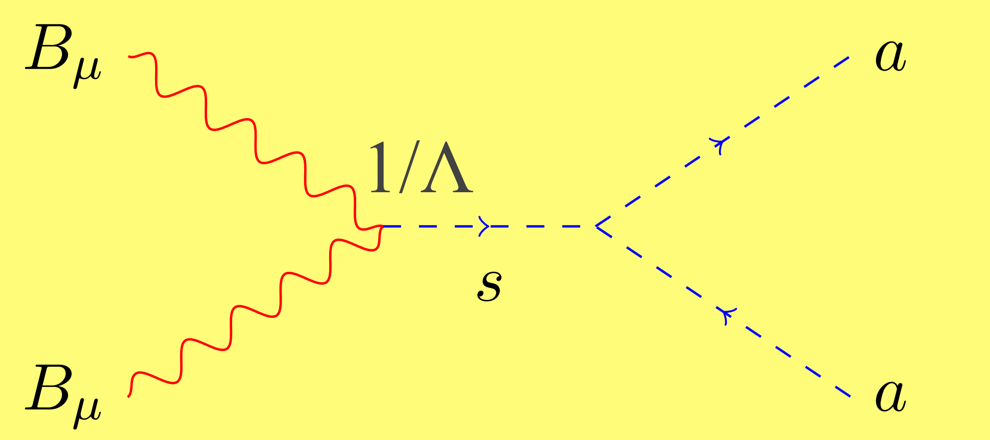
If $\Lambda >> T_{RH}$, the production rate of the dark matter a is strongly reduced, and we are in a freeze in context.

U(1) breaking

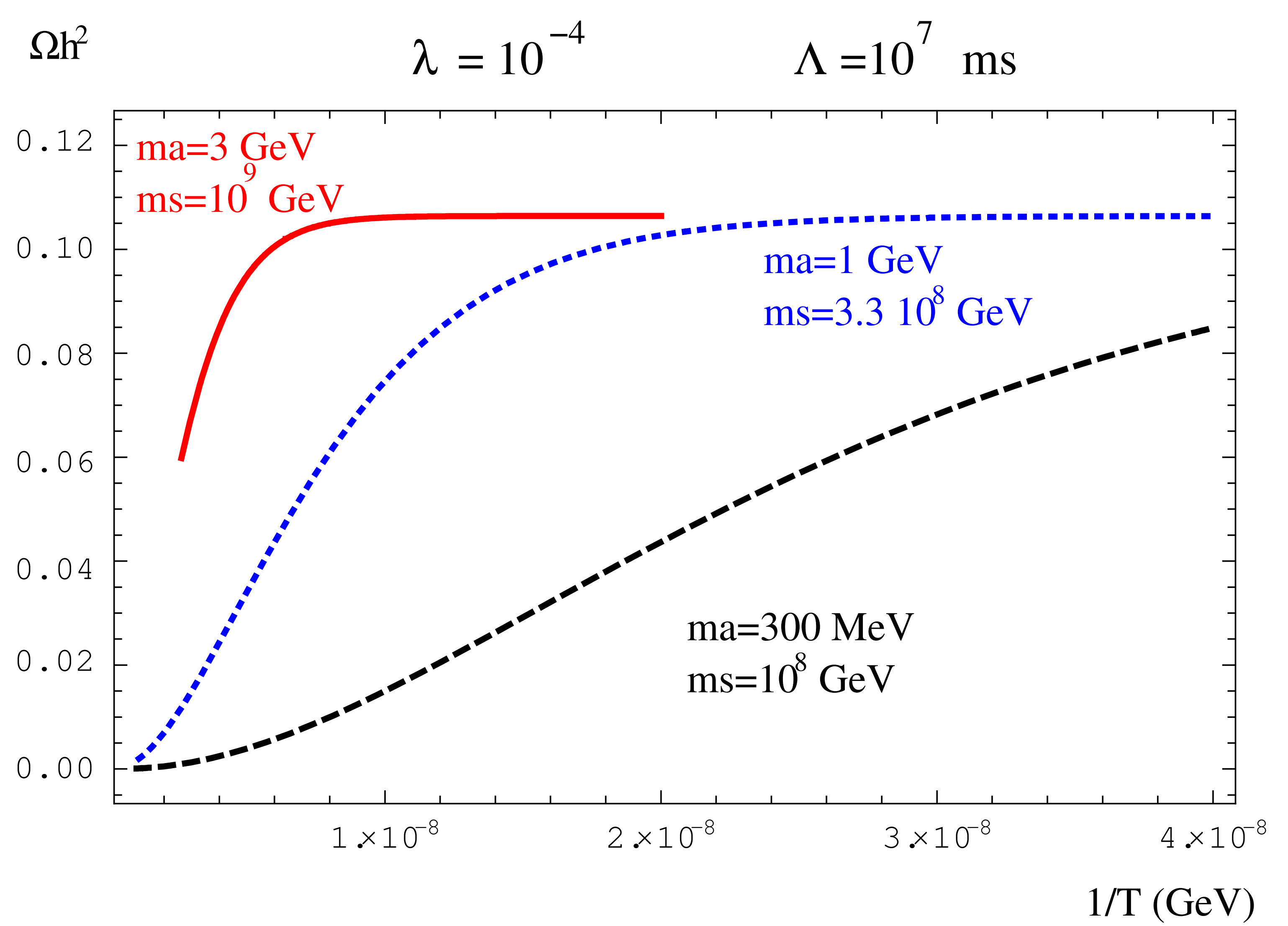
Let suppose the simplest extension of the SM with the addition of a global U(1) symmetry

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

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

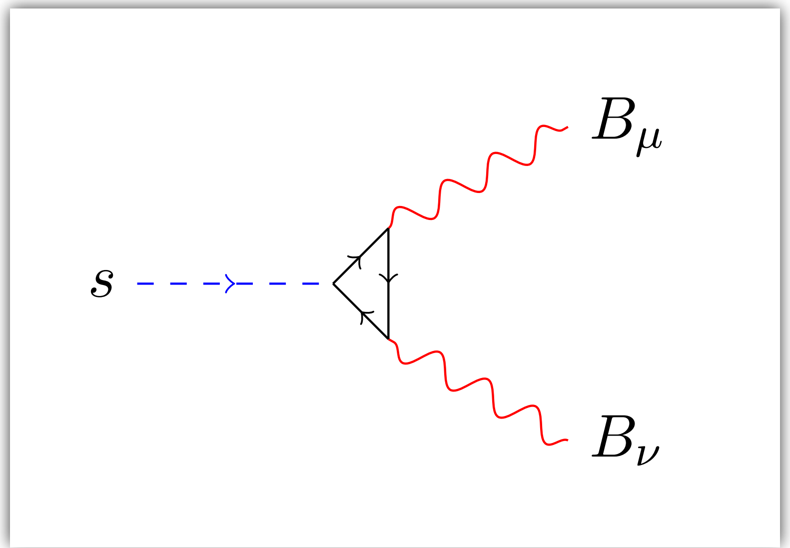


If $\Lambda >> T_{RH}$, the production rate of the dark matter a is strongly reduced, and we are in a freeze in context.



A microscopic model

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



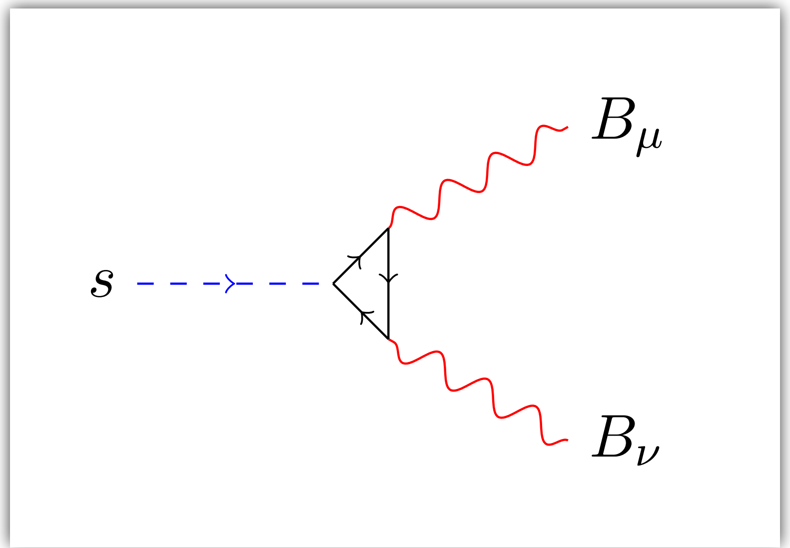
$$\Lambda = \frac{8\pi m_s}{\sqrt{\lambda}\, \alpha_1 \ \mathrm{Tr}[Q_f^2]} f_{1/2}(\tau)$$

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

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

A microscopic model

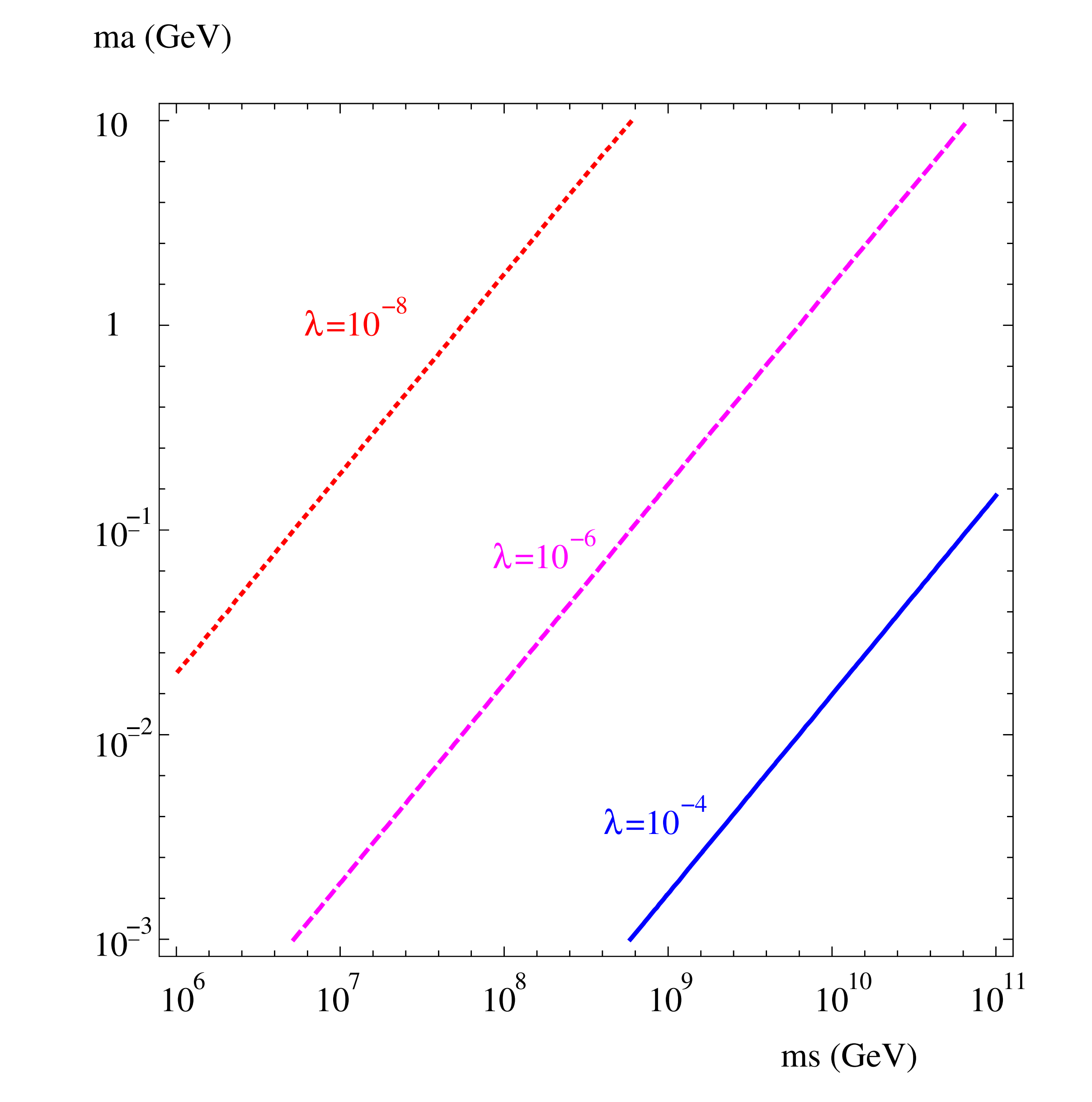
$$\mathcal{L} = \mathcal{L}_0 - \frac{y_F}{\sqrt{2}} s\bar{F}F - M_F \bar{F}F$$



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

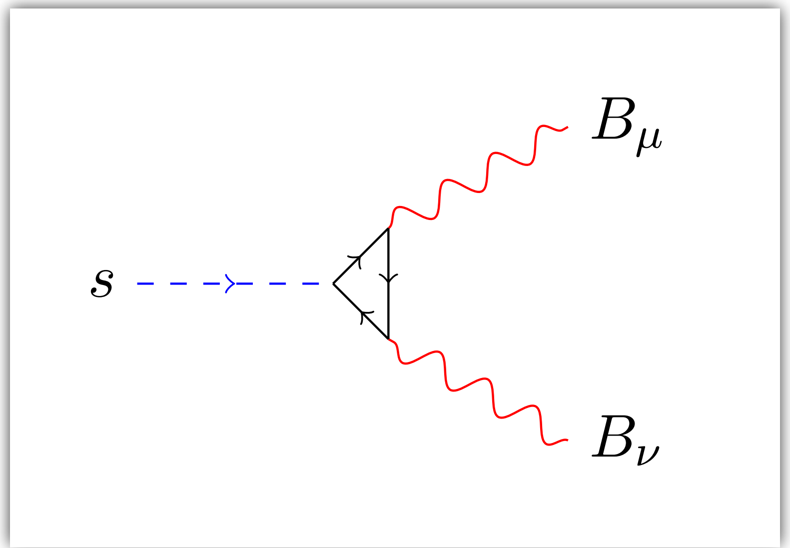
with $\alpha_1 = g_1^2/4\pi$, $\tau = m_s^2/4M_F^2$ and

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



A microscopic model

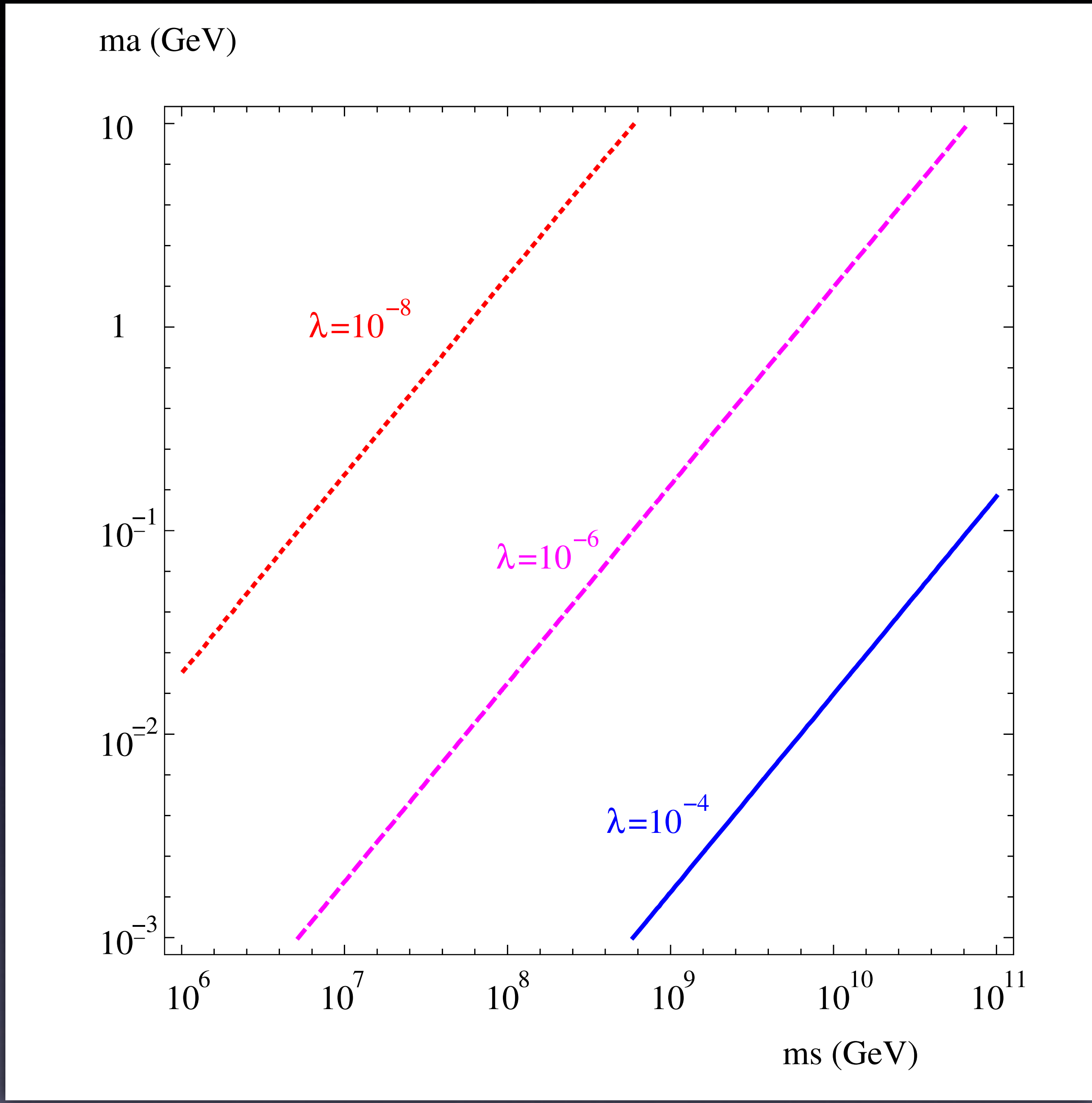
$$\mathcal{L} = \mathcal{L}_0 - \frac{y_F}{\sqrt{2}} s\bar{F}F - M_F \bar{F}F$$



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

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] :

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

Supergravity scenario

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

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

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

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

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

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

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

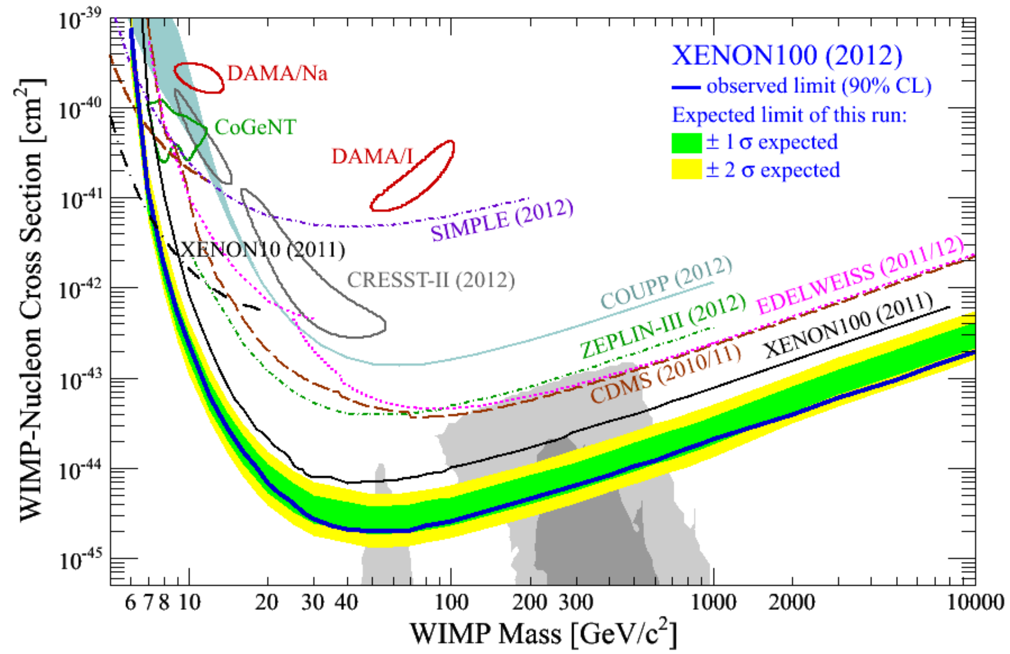
$$m_{3/2} = \frac{F}{\sqrt{3} M_{Pl}}, \quad M_{SUSY} = \frac{F}{\Lambda_{mess}}$$

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

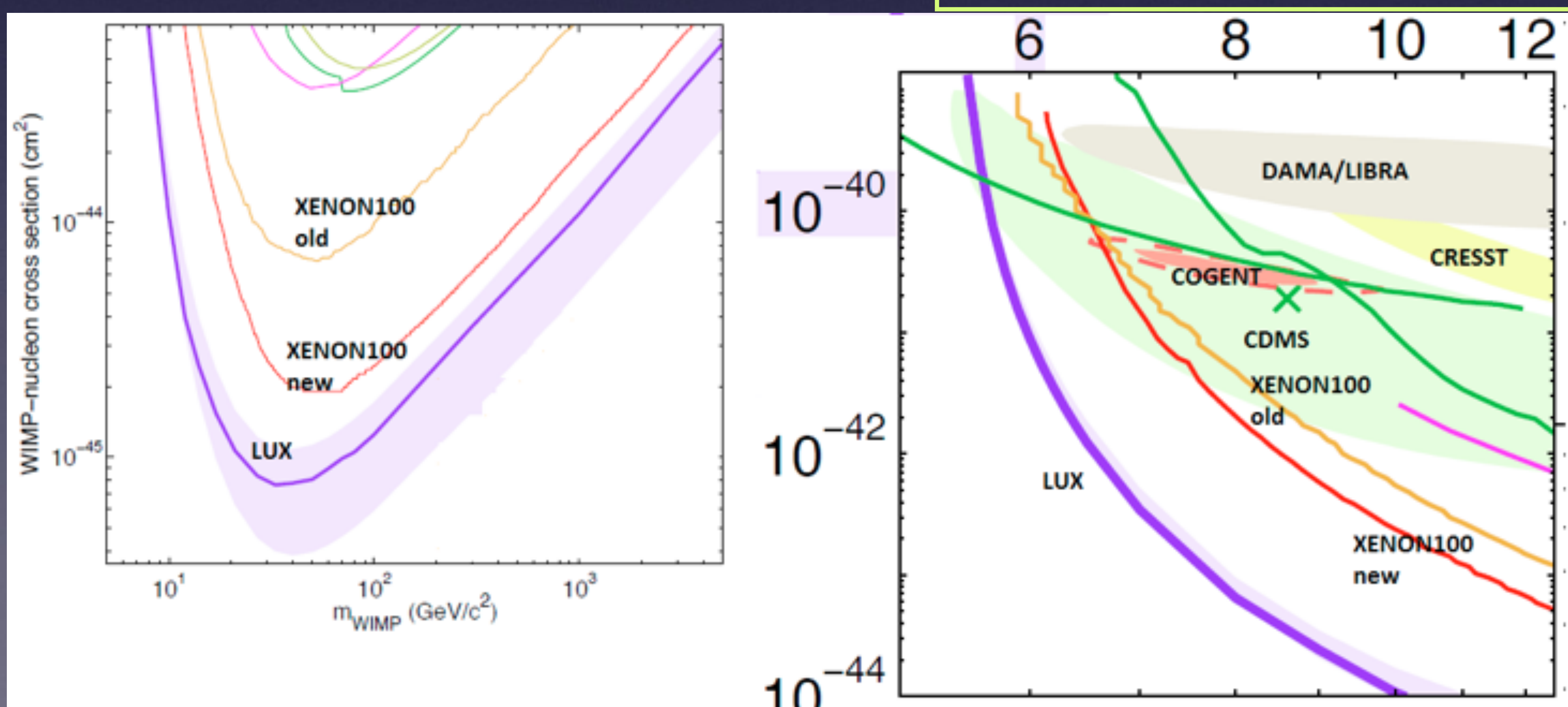
XENON + LUX results

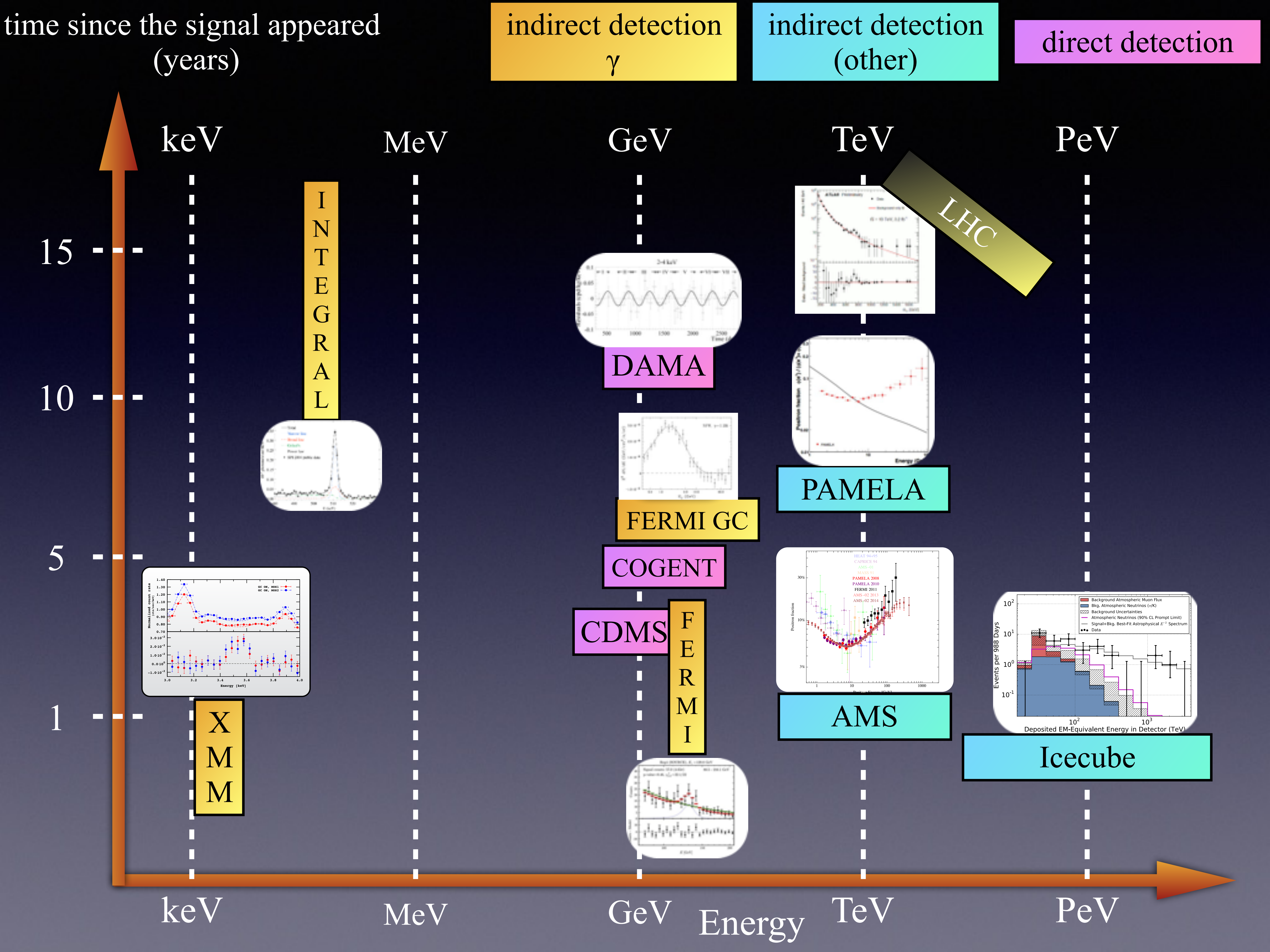


XENON100 (07/12)

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

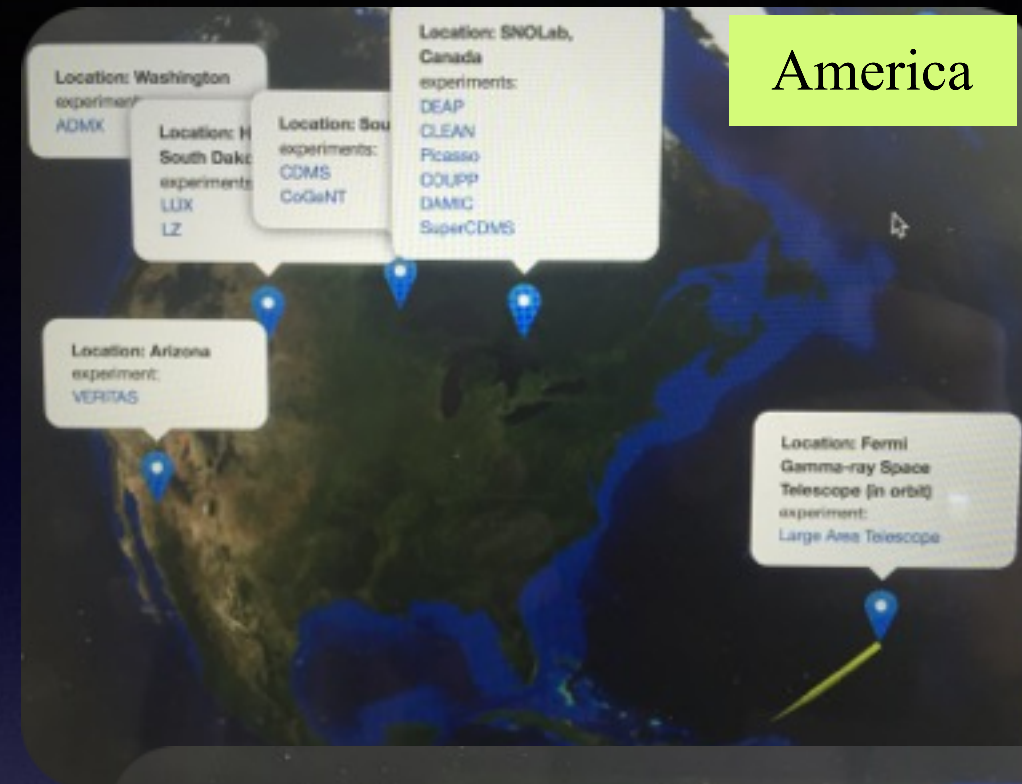
LUX (1310.8214) -> LUZ (2016)

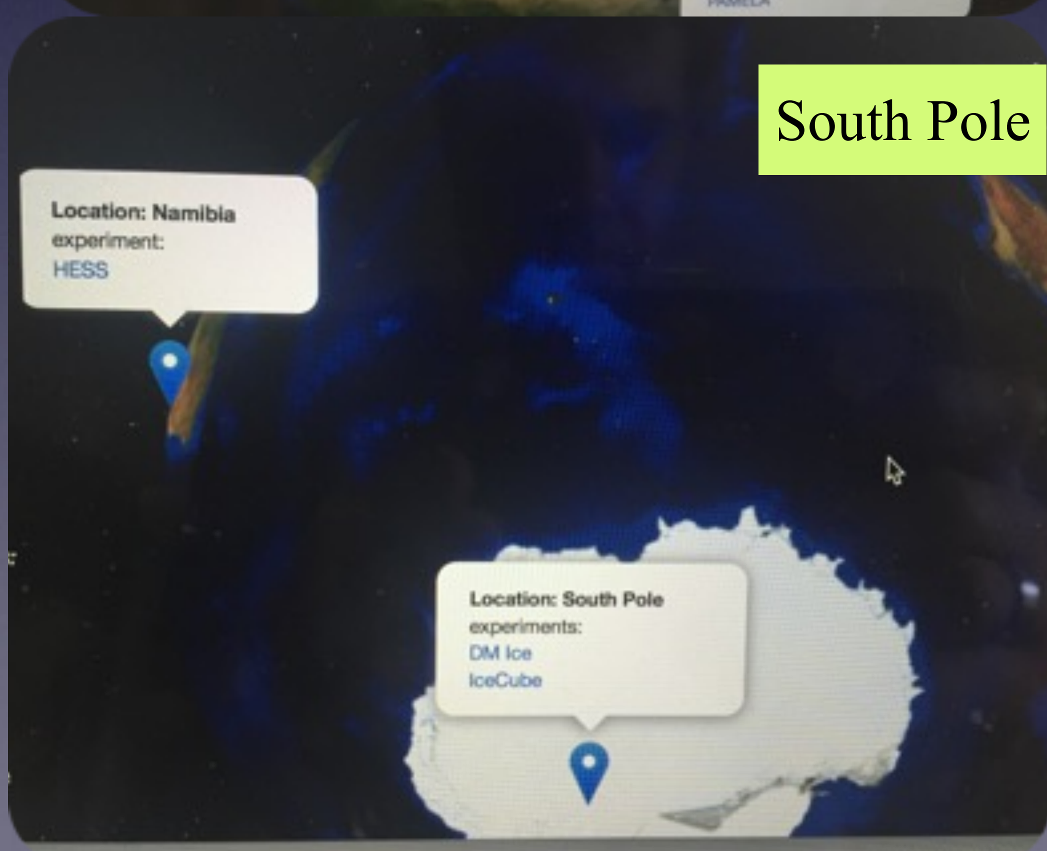


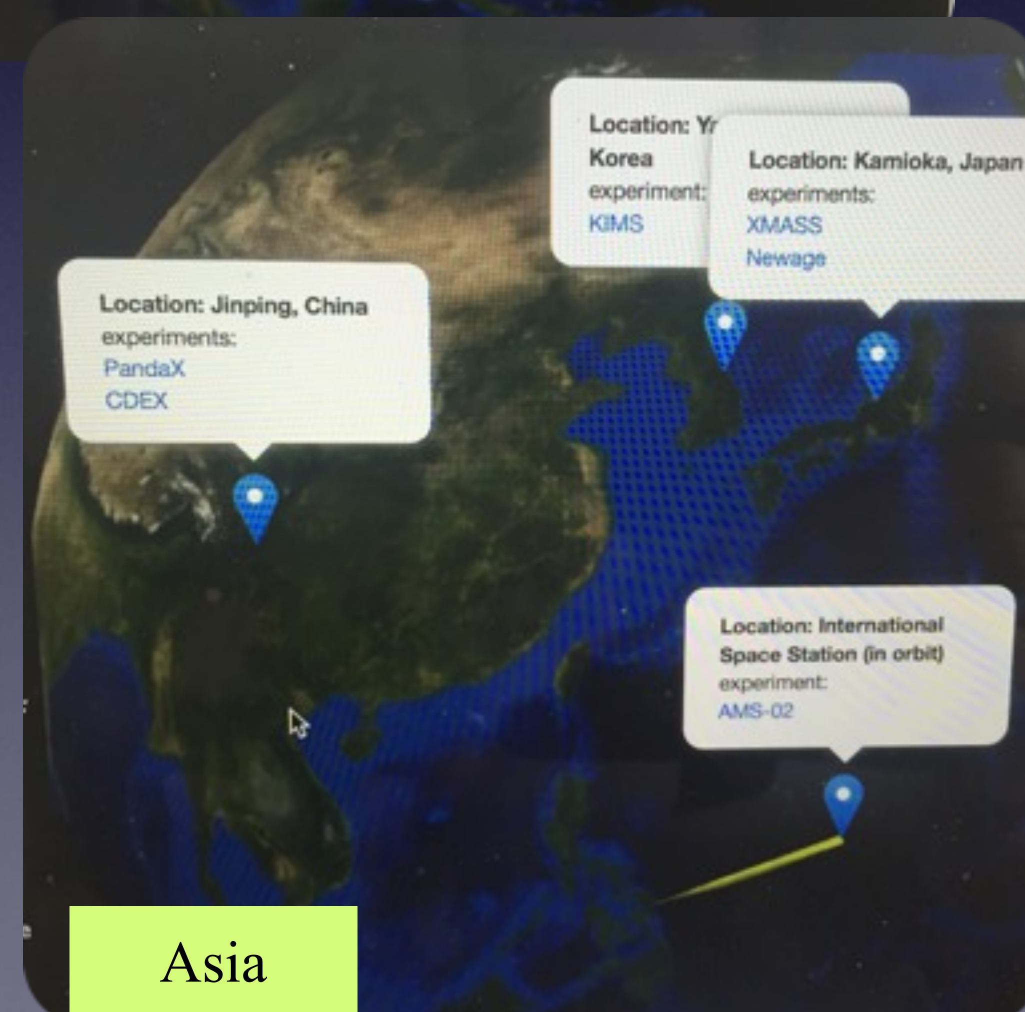


time since the signal appeared (years)
indirect detection γ
indirect detection (other)
direct detection
keV
MeV
GeV
TeV
PeV
15
10
5
1
INTEGRAL
DAMA
LHC
PAMELA
FERMI GC
COGENT
CDMS
FERMI
XMM
AMS
Icecube
Deposited EM-Equivalent Energy in Detector (TeV)
Events per 988 Days
keV
MeV
GeV
Energy
TeV
PeV

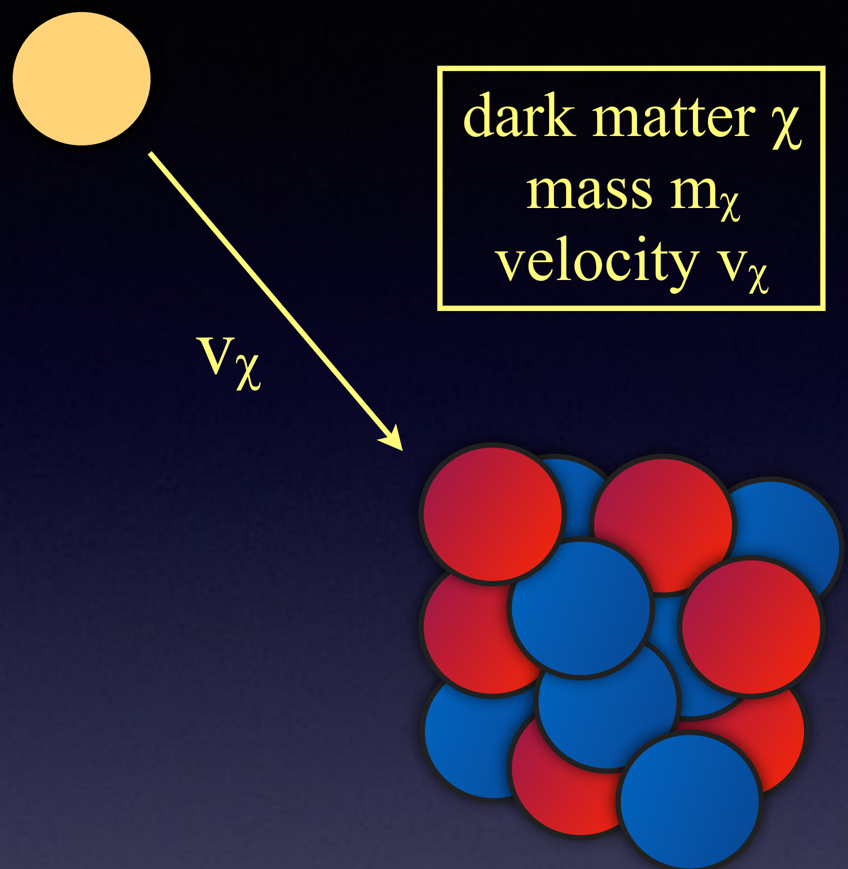
Where on the world map?







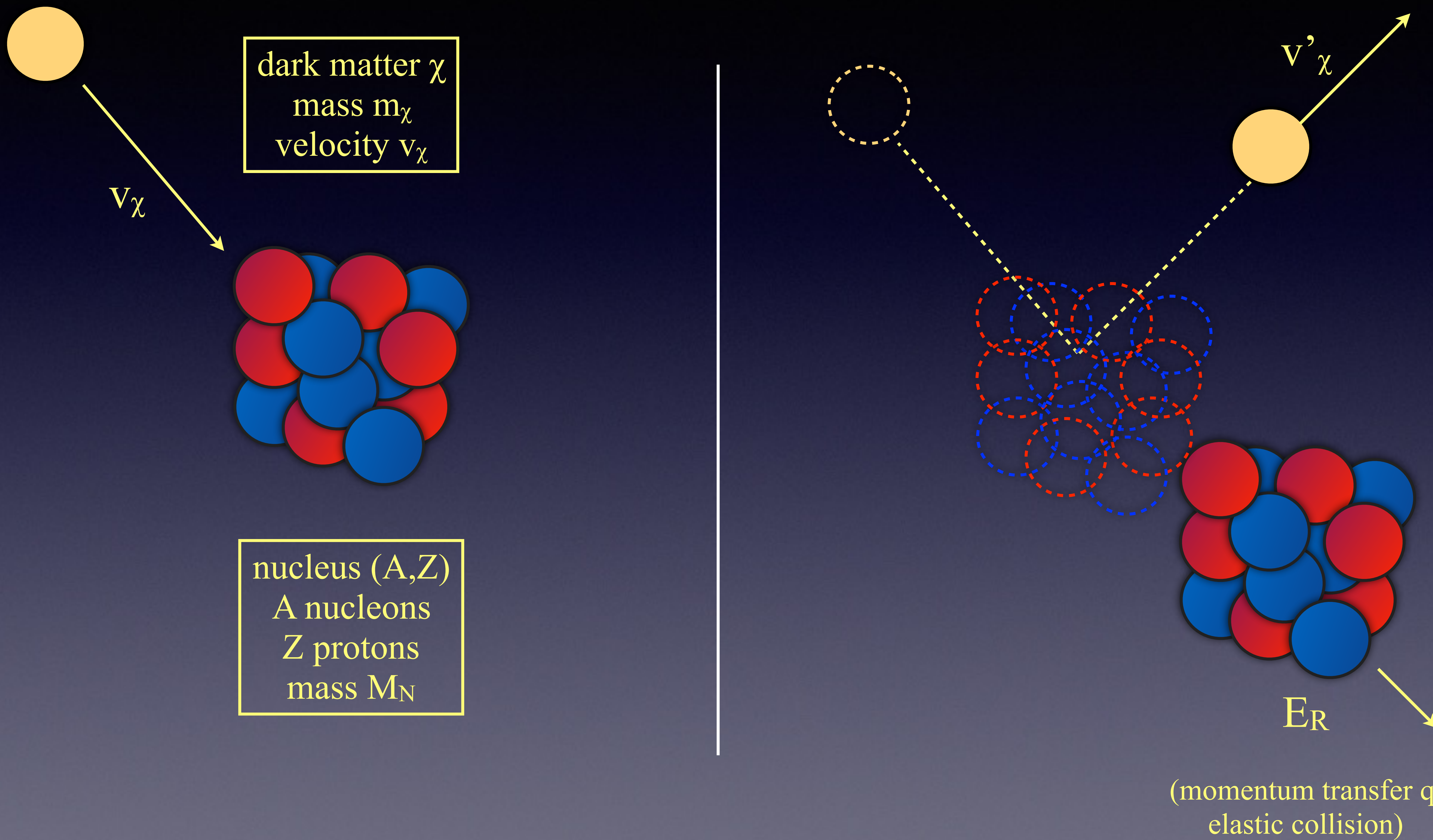
Direct detection of dark matter (basic principle)



dark matter χ
mass m_χ
velocity v_χ

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

Direct detection of dark matter (basic principle)



```
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

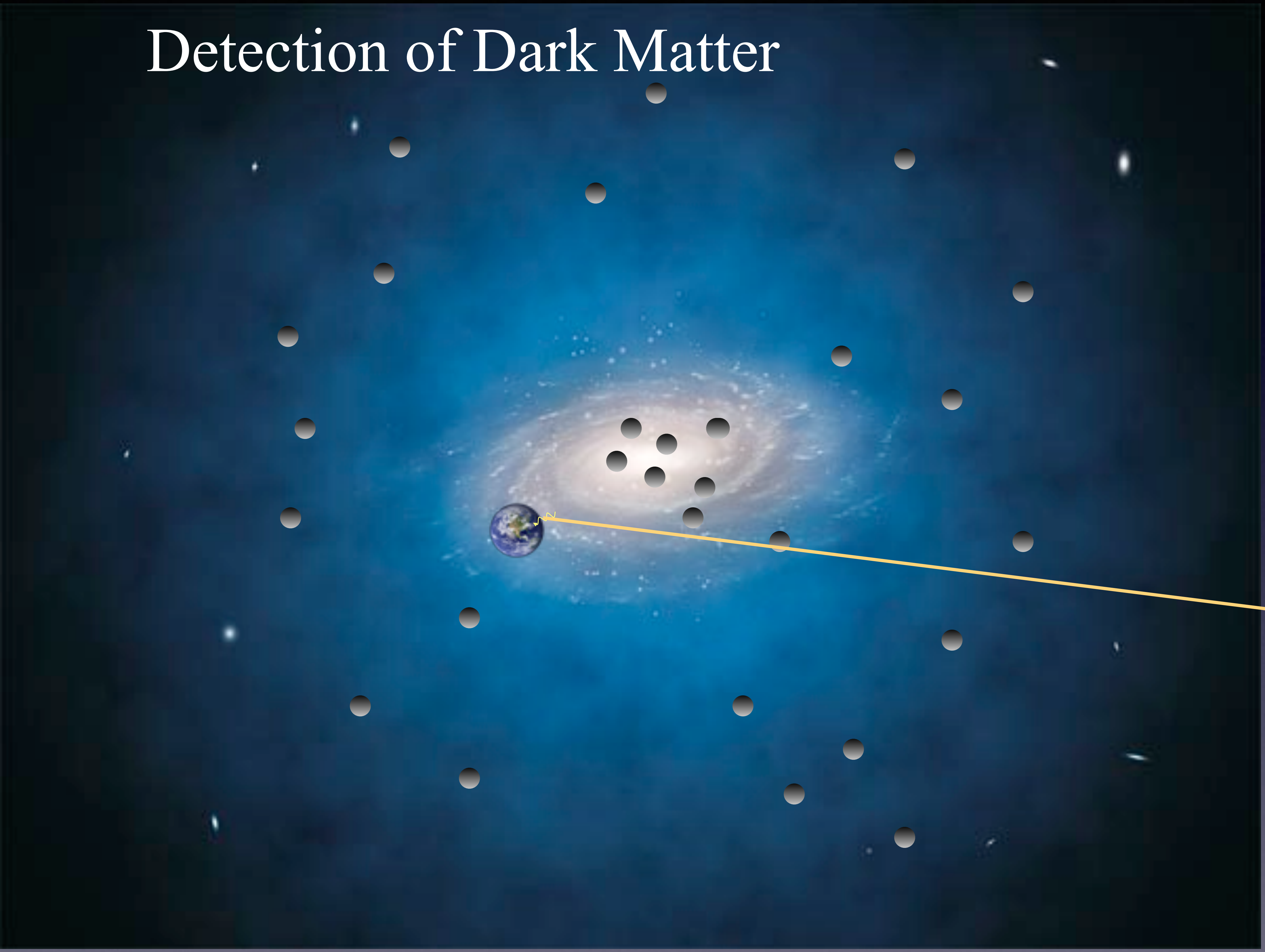
n_{e^-} + n_{e^+} = n_{\nu} + n_{\bar \nu} = \frac{3}{2} n_{\gamma}

```
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}
```

General principle of dark matter detection

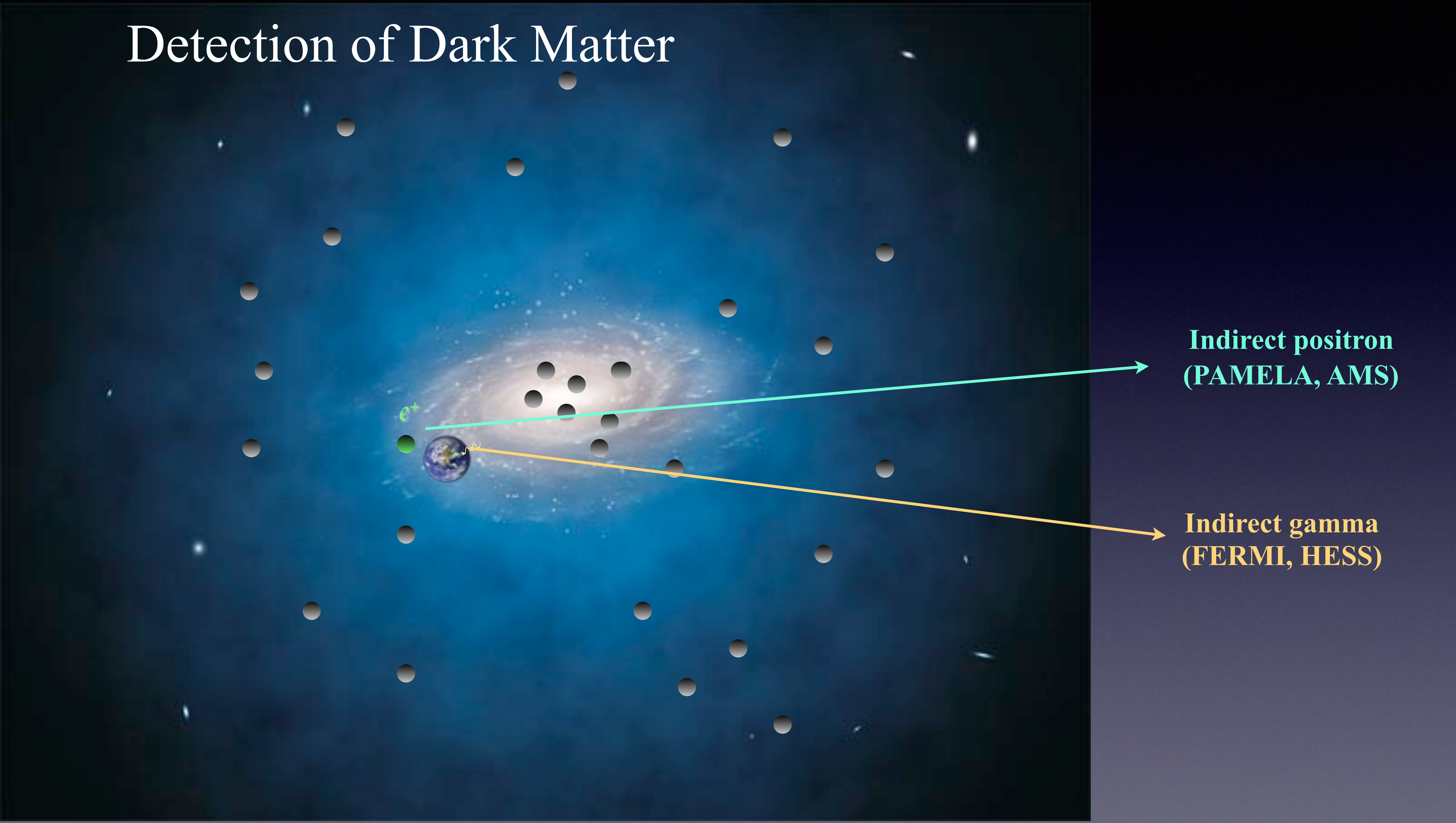
General principle of dark matter detection

General principle of dark matter detection

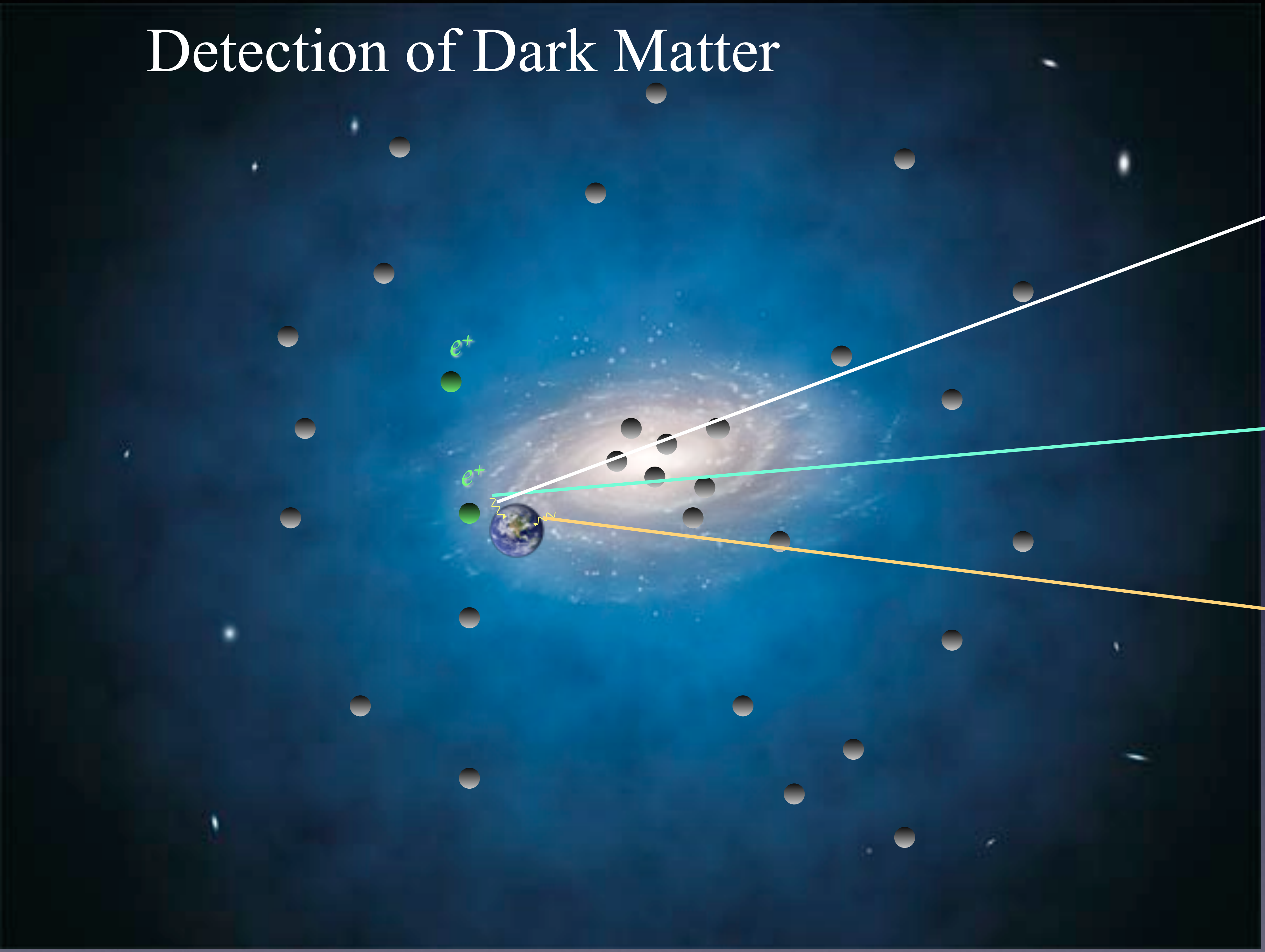


Indirect gamma
(FERMI, HESS)

General principle of dark matter detection



General principle of dark matter detection

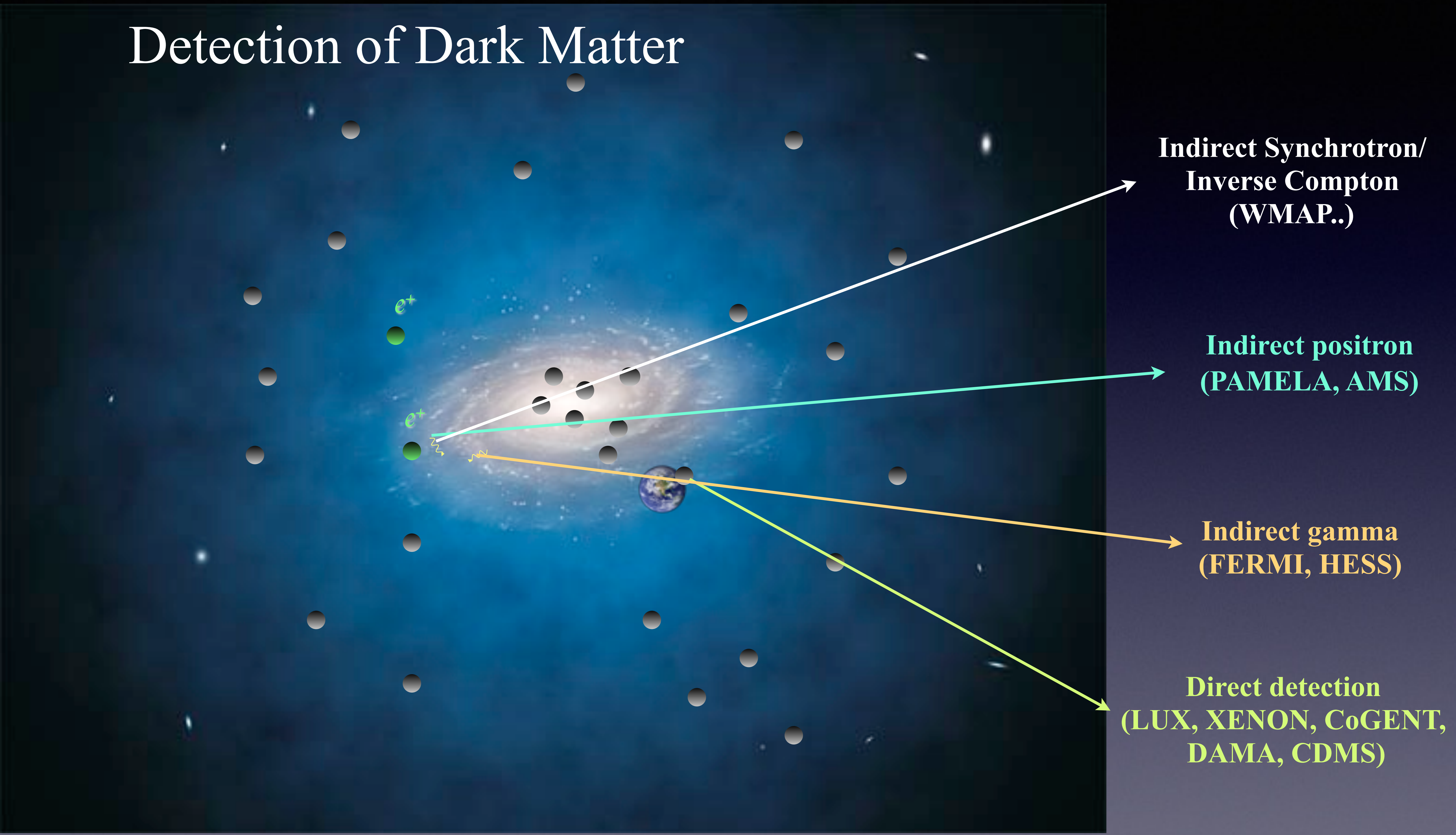


Indirect Synchrotron/ Inverse Compton (WMAP..)

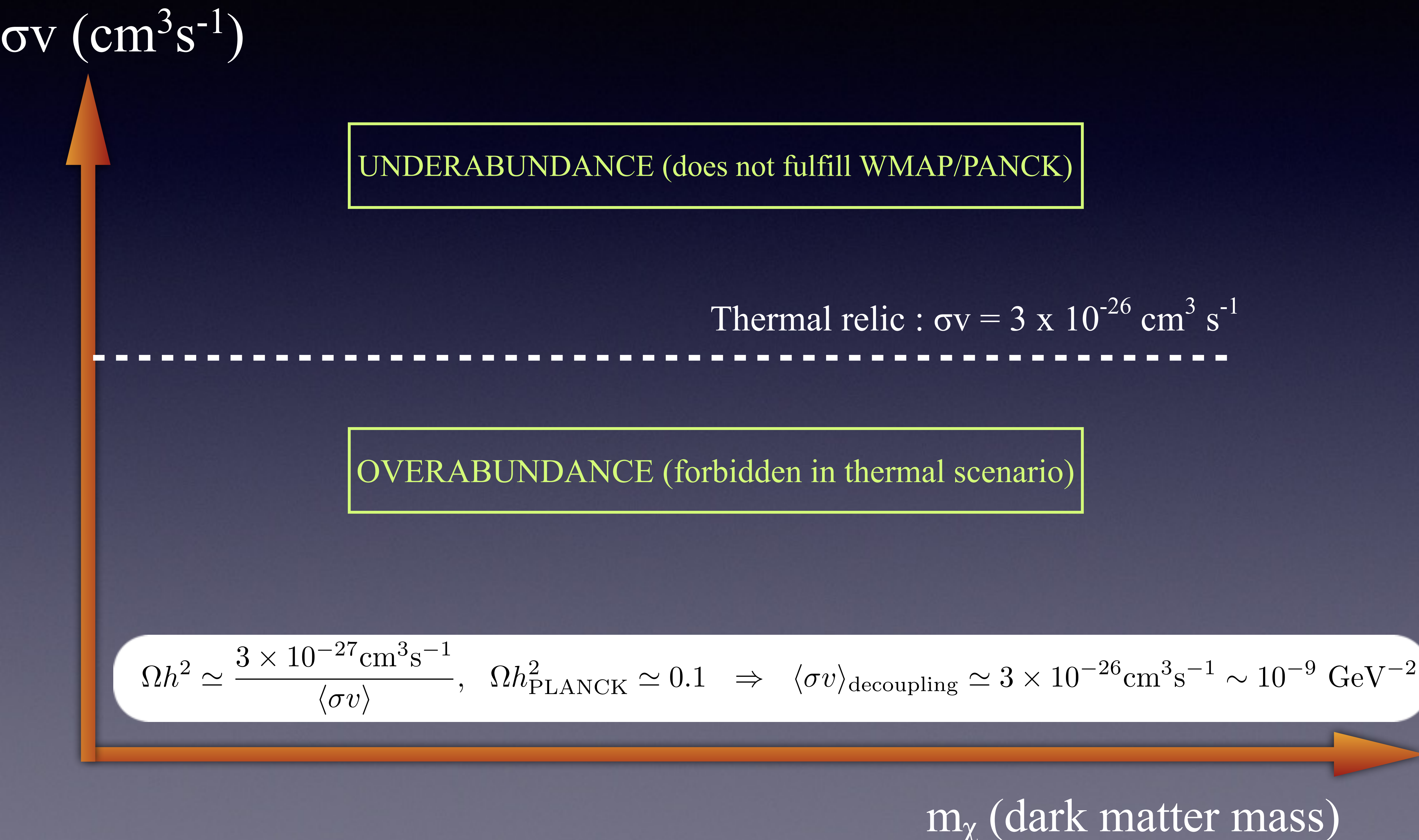
Indirect positron (PAMELA, AMS)

Indirect gamma (FERMI, HESS)

General principle of dark matter detection



Indirect detection of dark matter (experience)



$$\Omega h^2 \simeq \frac{3\times 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma v\rangle}, \quad \Omega h^2_{\mathrm{PLANCK}} \simeq 0.1 \quad \Rightarrow \quad \langle\sigma v\rangle_{\mathrm{decoupling}} \simeq 3\times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1} \sim 10^{-9}\ \mathrm{GeV}^{-2}$$

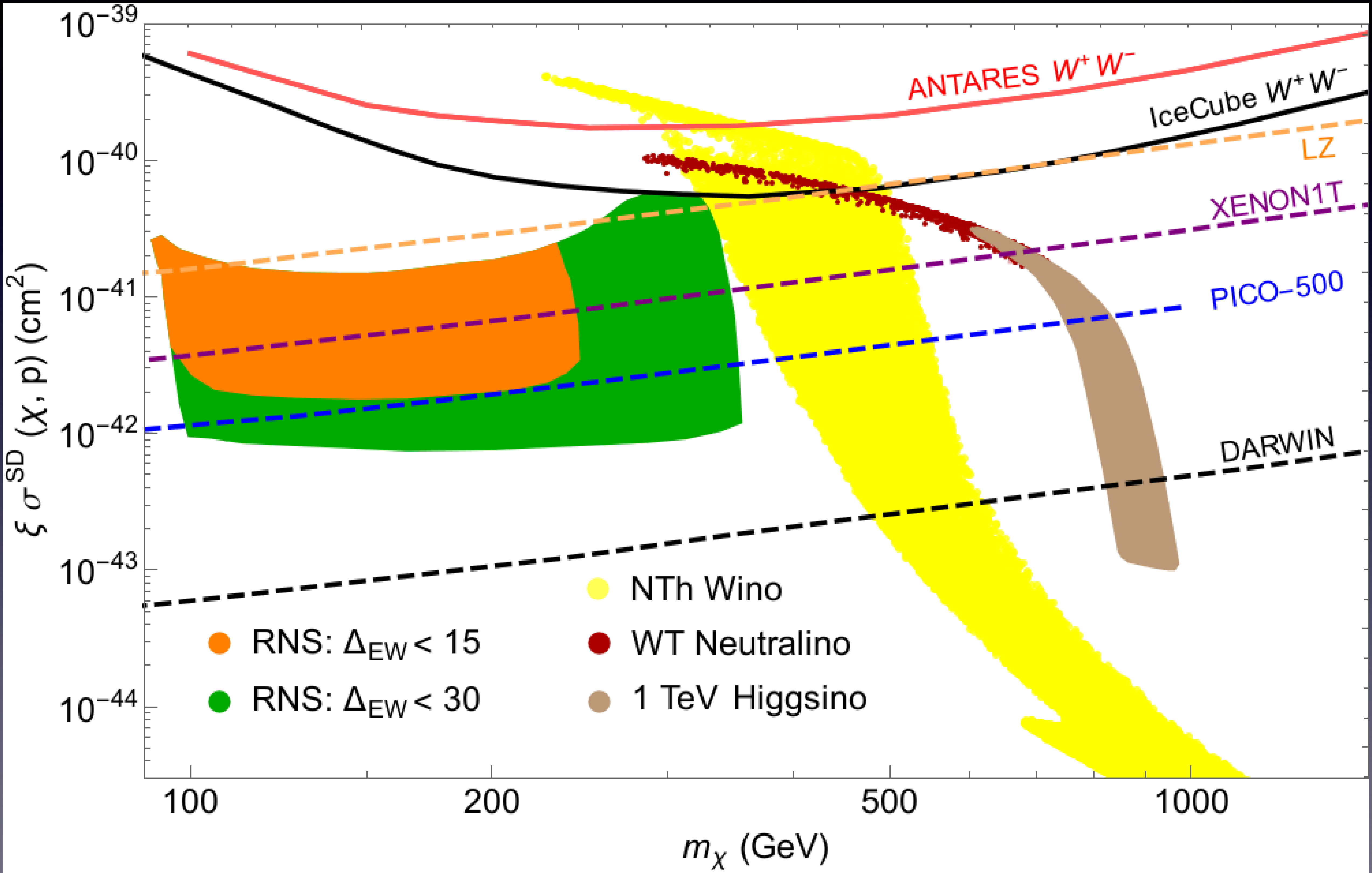
Conclusion

As we just see, the WIMP paradigm in the simplest extensions, or in more complex supersymmetric frameworks is already pushed toward narrow regions, or fine tuned parameter space.

It seems then natural to think out of the « thermal » box, to allows couplings unrelated to the electroweak scale.

In fact, the more general dark matter, if generated in another sector of the theory (unified gauge theory, supergravity, extra dimension, heavy sector..)
<u>should not have coupling related to the electroweak symmetry breaking scale!!</u>

Spin Dependant



Baer et al. 1609.06735

A new discovery..

Seth Shostak

But.. reminding an (almost) unknown article by **Rogstad and Shostak** (Caltech) from 1972 where they computed the dark matter component to be **80% of the total mass** (!!), studying 5 different galaxies.

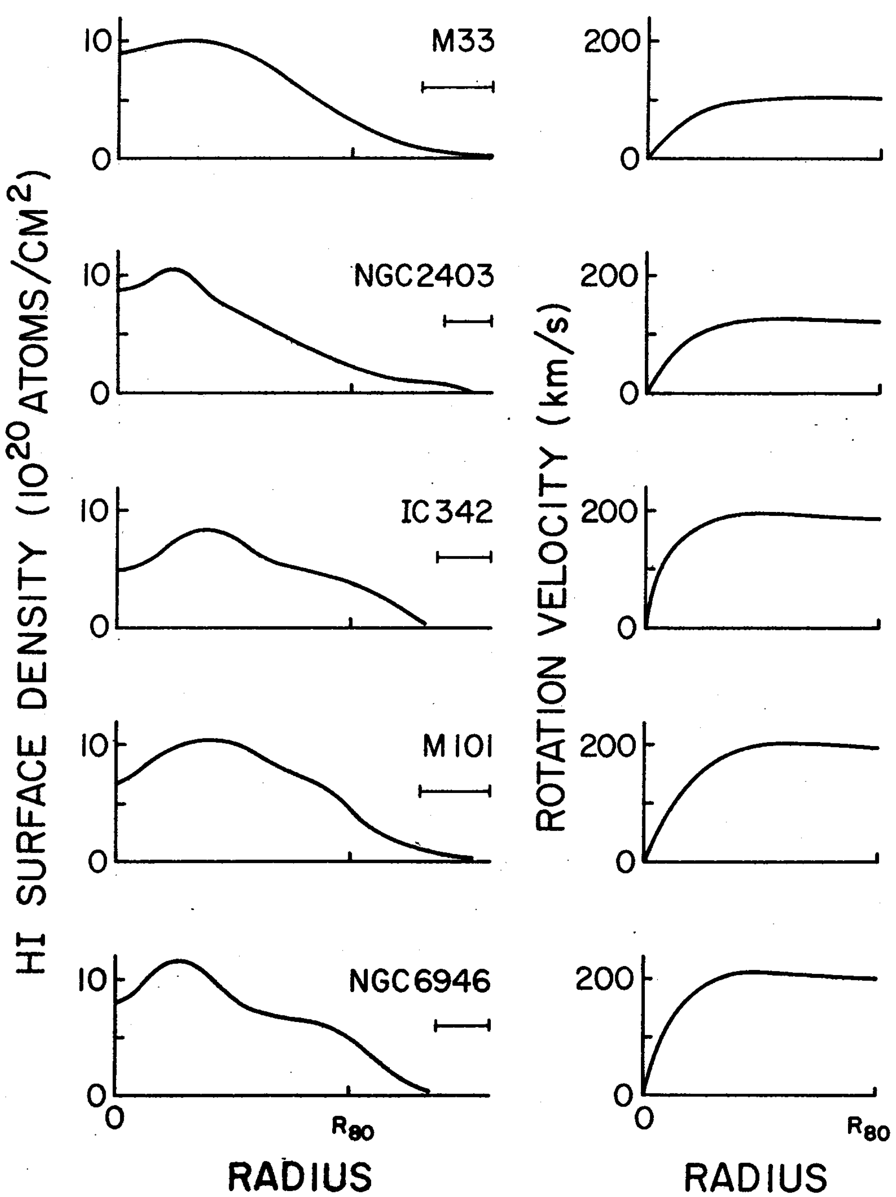
GROSS PROPERTIES OF FIVE Scd GALAXIES AS DETERMINED FROM 21-CENTIMETER OBSERVATIONS

D. H. ROGSTAD AND G. S. SHOSTAK*
Owens Valley Radio Observatory, California Institute of Technology
Received 1972 March 28

A new discovery..


Seth Shostak

But.. reminding an (almost) unknown article by **Rogstad and Shostak** (Caltech) from 1972 where they computed the dark matter component to be **80% of the total mass** (!!), studying 5 different galaxies.



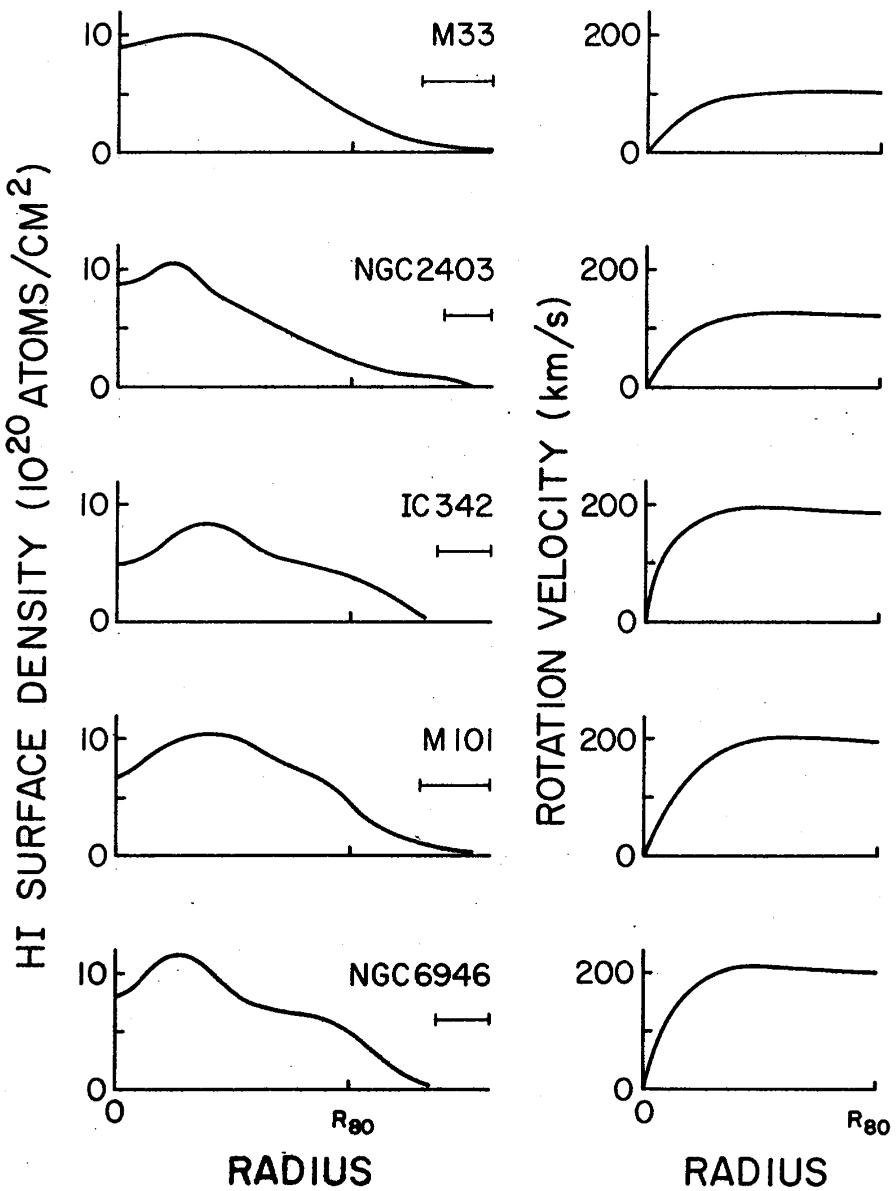
GROSS PROPERTIES OF FIVE Scd GALAXIES AS DETERMINED FROM 21-CENTIMETER OBSERVATIONS

D. H. Rogstad and G. S. Shostak*
Owens Valley Radio Observatory, California Institute of Technology

Received 1972 March 28

A new discovery..

But.. reminding an (almost) unknown article by **Rogstad and Shostak** (Caltech) from 1972 where they computed the dark matter component to be **80% of the total mass** (!!), studying 5 different galaxies.



GROSS PROPERTIES OF FIVE Scd GALAXIES AS DETERMINED FROM 21-CENTIMETER OBSERVATIONS

D. H. Rogstad and G. S. Shostak*

Owens Valley Radio Observatory, California Institute of Technology

Received 1972 March 28

TABLE 1

Integral Properties of Five Scd Galaxies

Parameter	M33	NGC 2403	IC 342	M101	NGC 6946
Type	SA(s)cd	SAB(s)cd	SAB(rs)cd	SAB(rs)cd	SAB(rs)cd
Luminosity class	Sc II–III	Sc III	Sc I	Sc I	Sc I(II)
Distance (Mpc)	0.72	3.25	4.5	6.9	10.1
i (°)	55	60	25	22	30
P.A. (°)	22	126	40	35	62
V_{sys} (km s^{-1})	−180	+128	+ 25	+240	+ 40
V_{max} (km s^{-1})	103	126	192	202	208
R_{opt} (kpc)	8.7	13.7	26.1	28.1	27.9
R_{80} (kpc)	7.9	13.0	25.2	27.1	27.2
R_{80}/R_{opt}	0.91	0.95	0.97	0.96	0.97
L_B ($10^9 L_\odot$)	3.2	6.1	41.4	31.7	97.5
S_{1420} (f.u.)	3.1	0.5	1.6	0.8	1.6
P_{1420} (10^{20} W Hz^{-1})	1.93	6.35	39.0	45.6	194
M_{HI} ($10^9 M_\odot$)	1.64	3.5	14.7	18.5	21.2
M_{80} ($10^{10} M_\odot$)	1.63	3.14	13.9	16.2	17.8
σ_{HI} (10^{20} atoms cm^{-2})	9.1	7.7	7.1	9.5	8.7
M_{HI}/M_{80} (percent)	10.1	11.1	10.6	11.4	11.8
M_{HI}/L_B	0.51	0.57	0.36	0.58	0.22
log (P_{1420}/L_B)	10.78	11.02	10.97	11.16	11.30

In addition, we confirm here the requirement for low-luminosity material in the outer regions of these galaxies ($M/L \sim 20$), assuming exponentially decreasing surface luminosities (Freeman 1970). The global mass-luminosity ratio M_{80}/L_B for the three un-