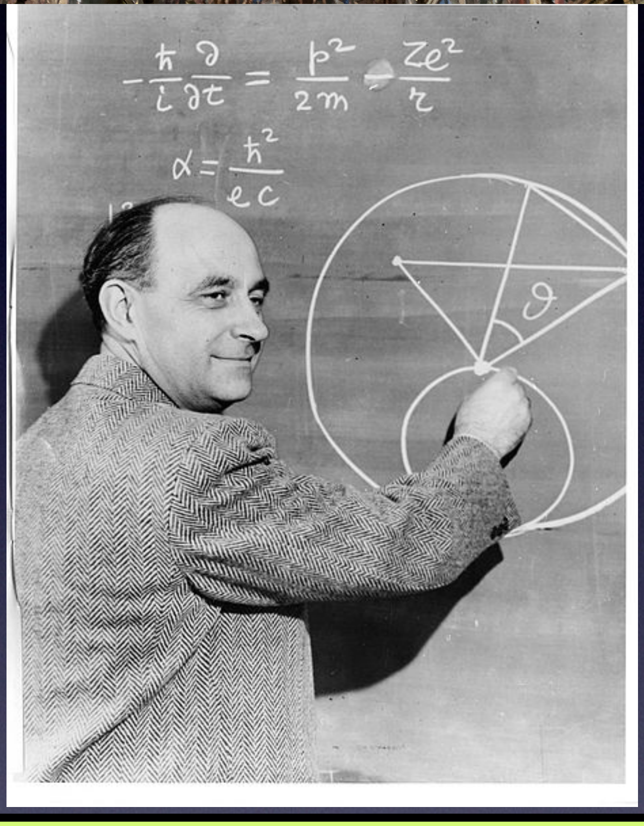
Dark Matter

From the WIMP paradigm to alternative scenarios



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

« It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong.»
R. Feynman

Yann Mambrini, LPT, University of Paris-Saclay

Based on [arXiv:1709.01549 ; 1803.01866 ; 1806.00016 ; 1811.01947 ; 1901.04449; 1902.04584 ; 1905.11407]

Seminar at university Roma 3, Roma, November 12th 2019

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.

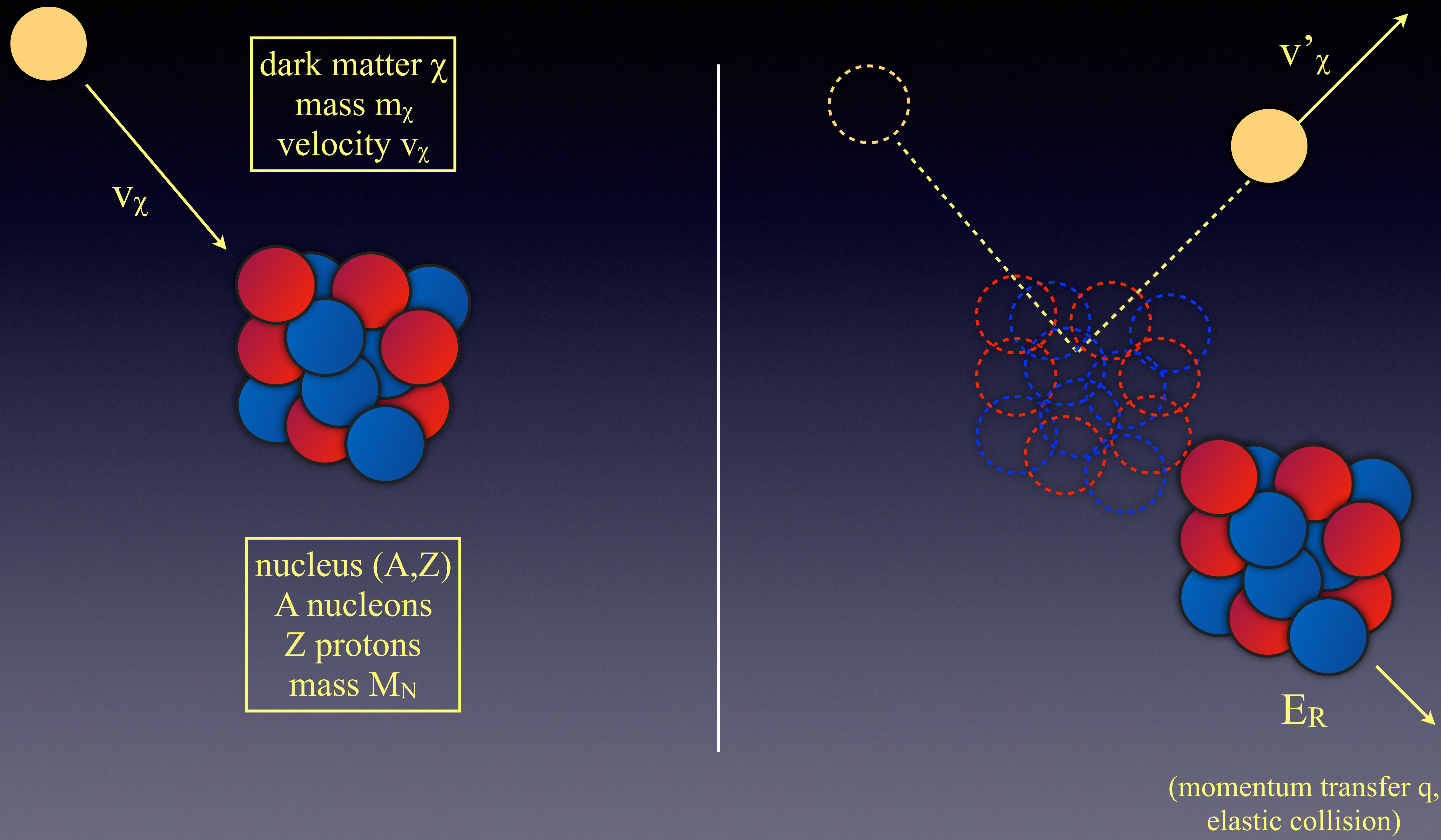
The WIMP paradigm

« 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;

Eur. Phys. J. C **78** (2018) no.3, 203
arXiv:1703.07364

Direct detection of dark matter (basic principle)



Direct detection of dark matter (theory)

Interaction rate (per kg per seconds)

Avogadro

local density of dark matter

momentum transfered to the nucleus

$$dR = \frac{N_0}{A}\frac{\rho_0}{m_\chi}\left(v_\chi \frac{d\sigma}{d|\mathbf{q}|^2}\right)\, d|\mathbf{q}|^2\ f(\mathbf{v}_\chi) d^3\mathbf{v}_\chi$$

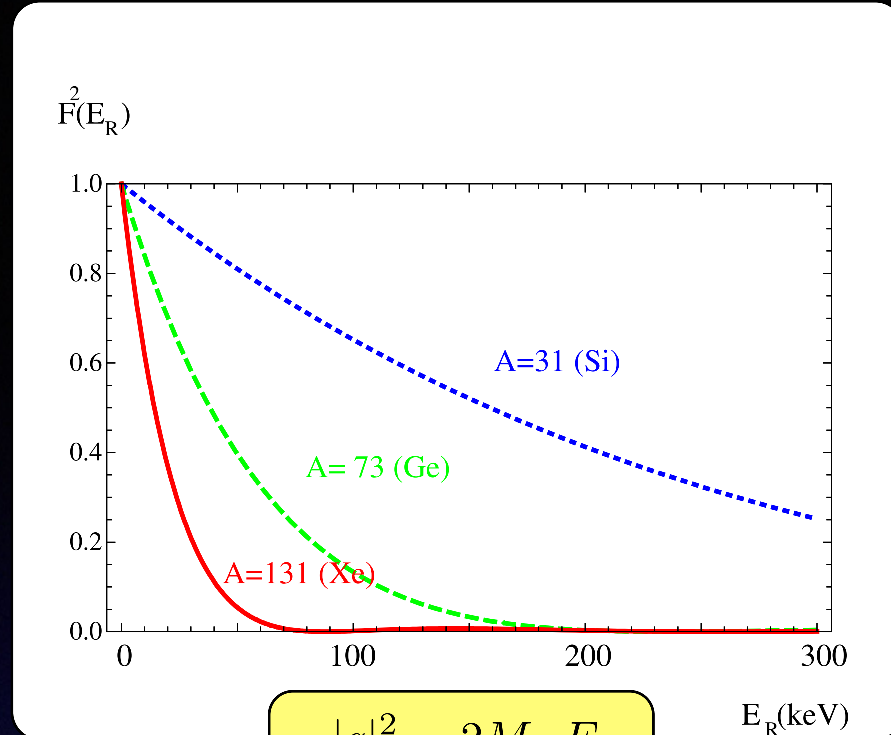
mass number

differential cross section

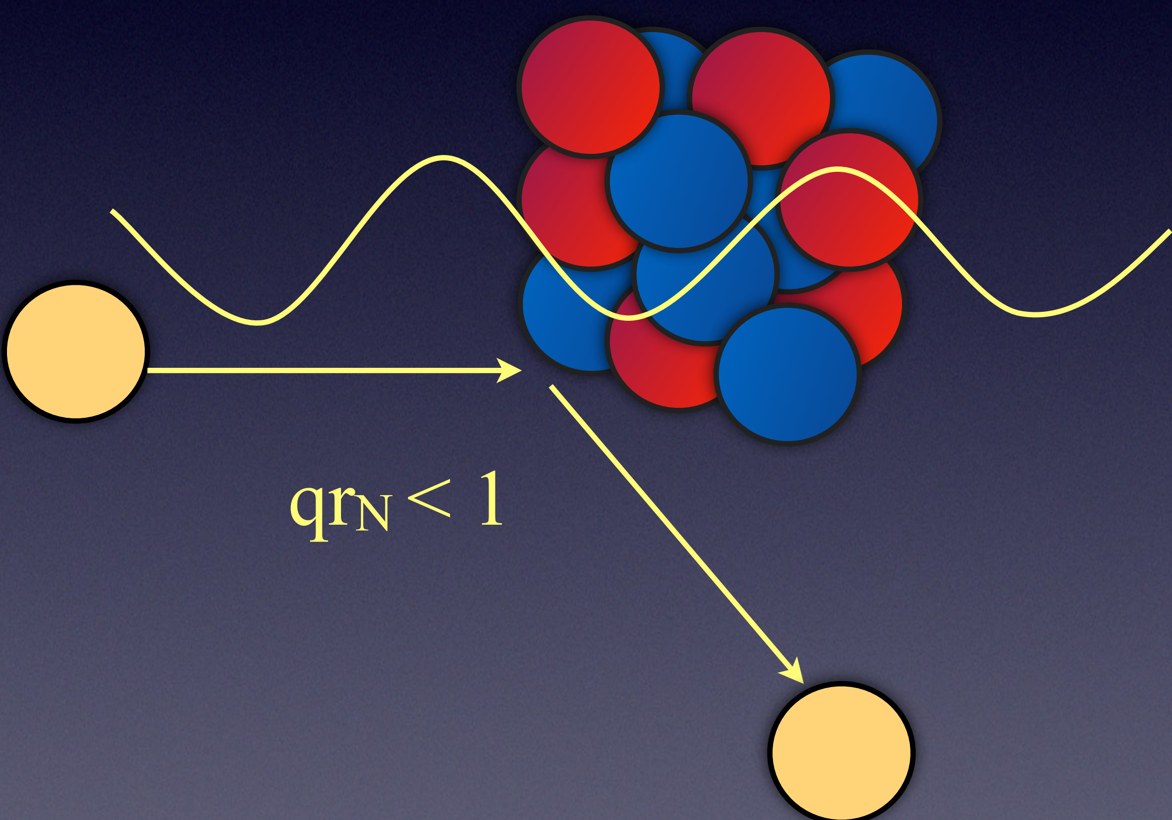
velocity distribution

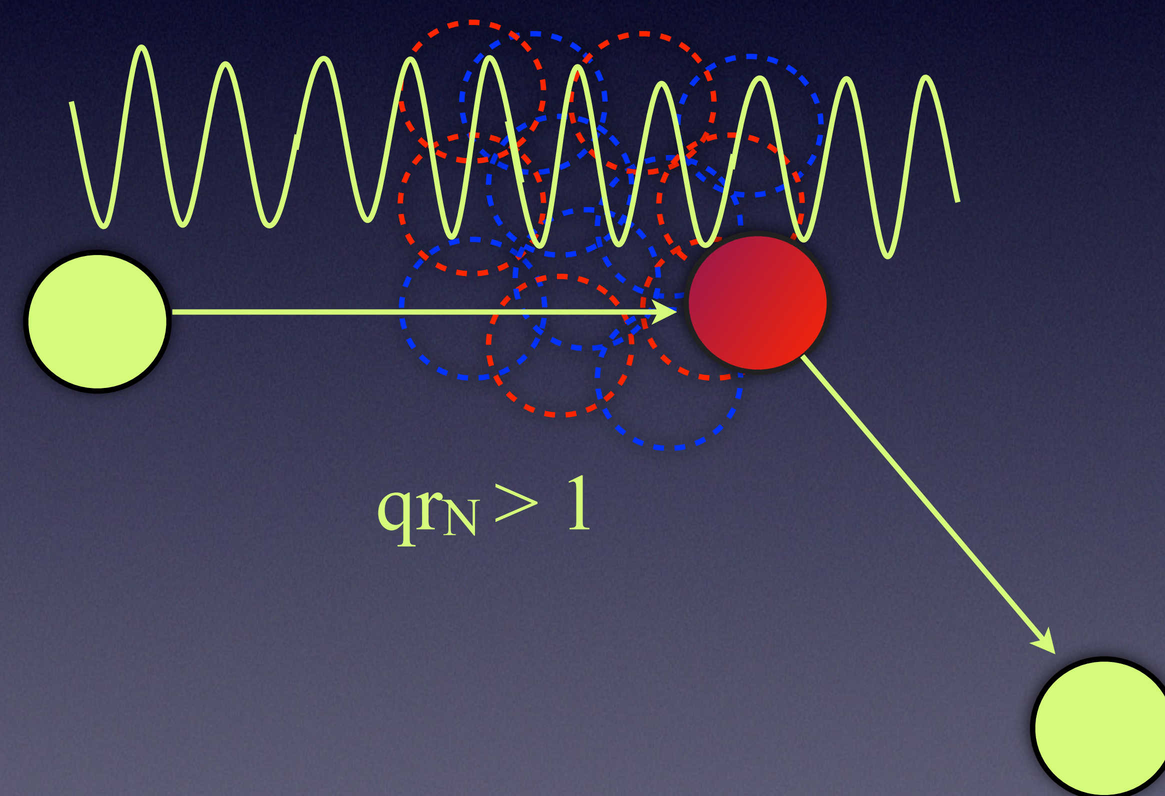
A. Djouadi, A. Falkowski

$$F(q) = \frac{3 j_1(q r_N)}{q r_N} e^{-(qs)^2/2},$$



$$|q|^2 = 2 M_N E_R$$

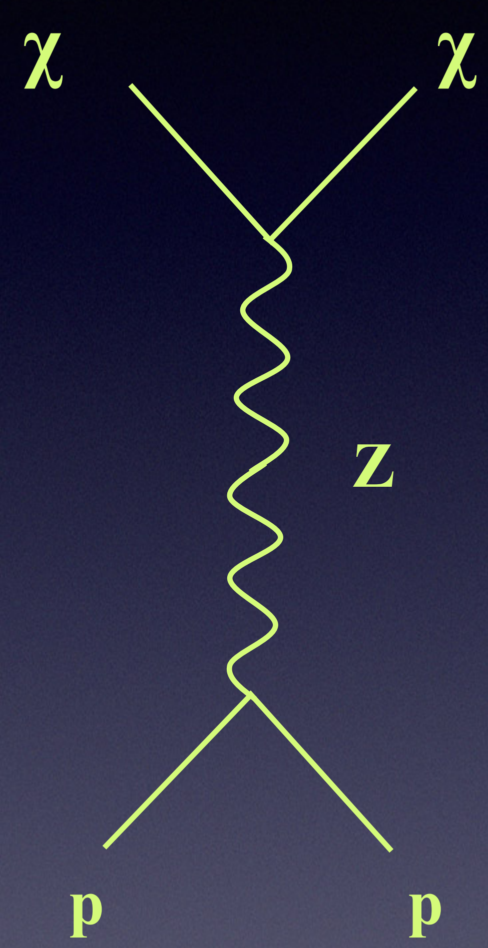




At low momentum transfer (long wavelength), the dark matter « sees » all the nucleus and its A nucleons. the cross section is then proportional to A^2

At large momentum transfer (short wavelength), the dark matter « sees » only the nucleons.

What do we expect for a WIMP :



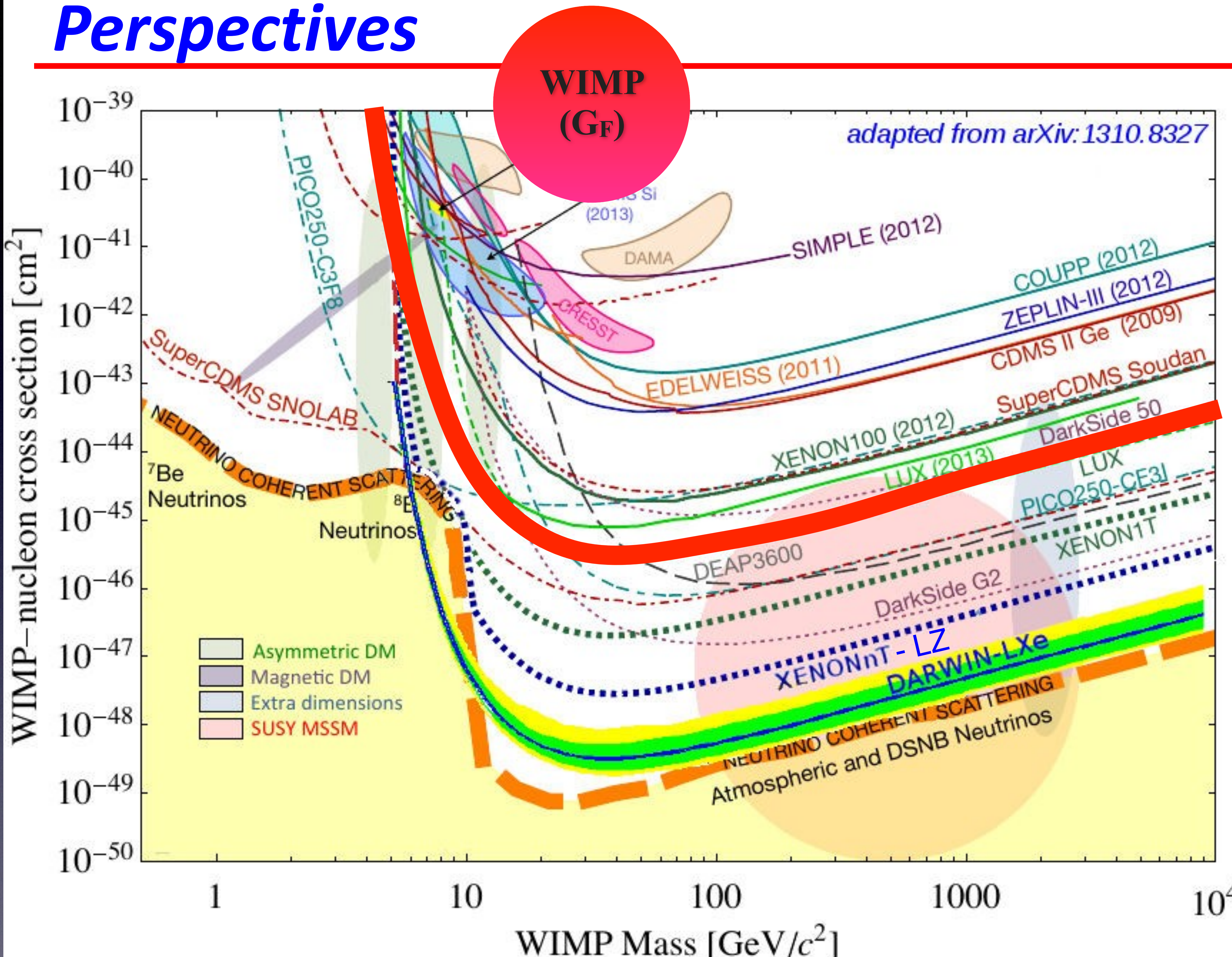
$$\sigma_{EW}(\chi\, p \to \chi\, p) \simeq G_F^2 m_\chi^2$$

$$\simeq \frac{g_2}{M_Z^4} m_\chi^2 \simeq 10^{-9} \left(\frac{m_\chi}{1\ \mathrm{GeV}}\right)^2\ \mathrm{GeV}^{-2}$$

$$= 4 \times 10^{-37} \left(\frac{m_\chi}{1\ \mathrm{GeV}}\right)^2\ \mathrm{cm}^2$$

($1\ \mathrm{GeV}^2 = 10^{-28}\ \mathrm{cm}^2$)

Perspectives



$$g_1 = 0.46;\ \ g_2 = 0.65;\ \ g_3 = 1.22; \qquad \sigma_{dm} \lesssim 10^{-37} \times 10^{-10}\ \text{cm}^2 \Rightarrow g_{dm} \lesssim 10^{-5}$$

Why are we so attached to WIMP-like particle?

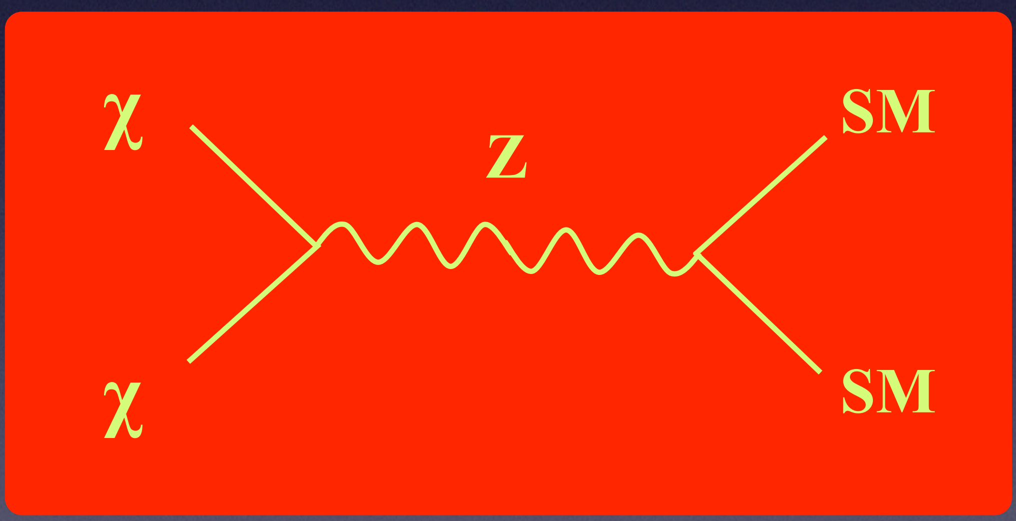
The WIMP miracle !

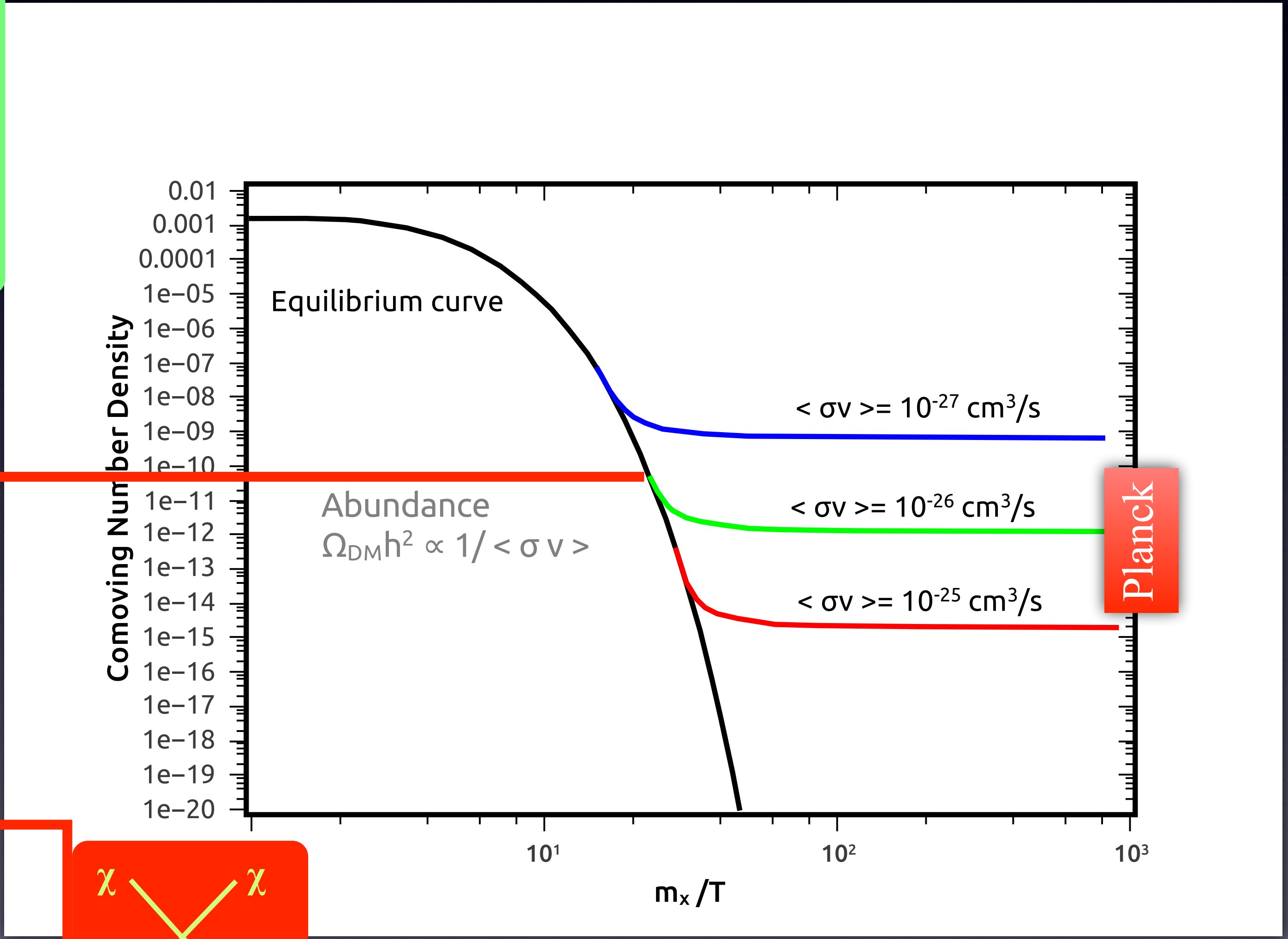
The Boltzmann equation

$$\boxed{\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle \left(n^2 - n_{eq}^2\right)}$$

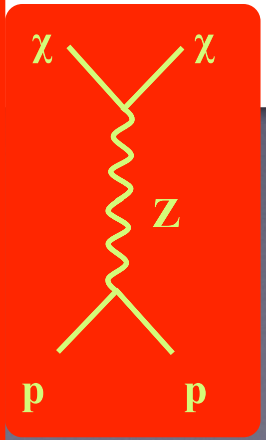
$$\boxed{\Omega_A h^2 \simeq \frac{0.17}{\frac{\langle \sigma v \rangle}{(1.2\times 10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1})}}}$$

$$\langle \sigma v \rangle = 1.2 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$$
$$= 10^{-9} \mathrm{GeV}^{-2} \left(\frac{m_{DM}}{1\ \mathrm{GeV}}\right)^2 \simeq G_F^{-2} \left(\frac{m_{DM}}{1\ \mathrm{GeV}}\right)^2$$





One needs a phase of depletion of dark matter, annihilating to SM to avoid the overabundance. Can we deplete it without even coupling to the SM, and thus avoiding the direct detection conflict?



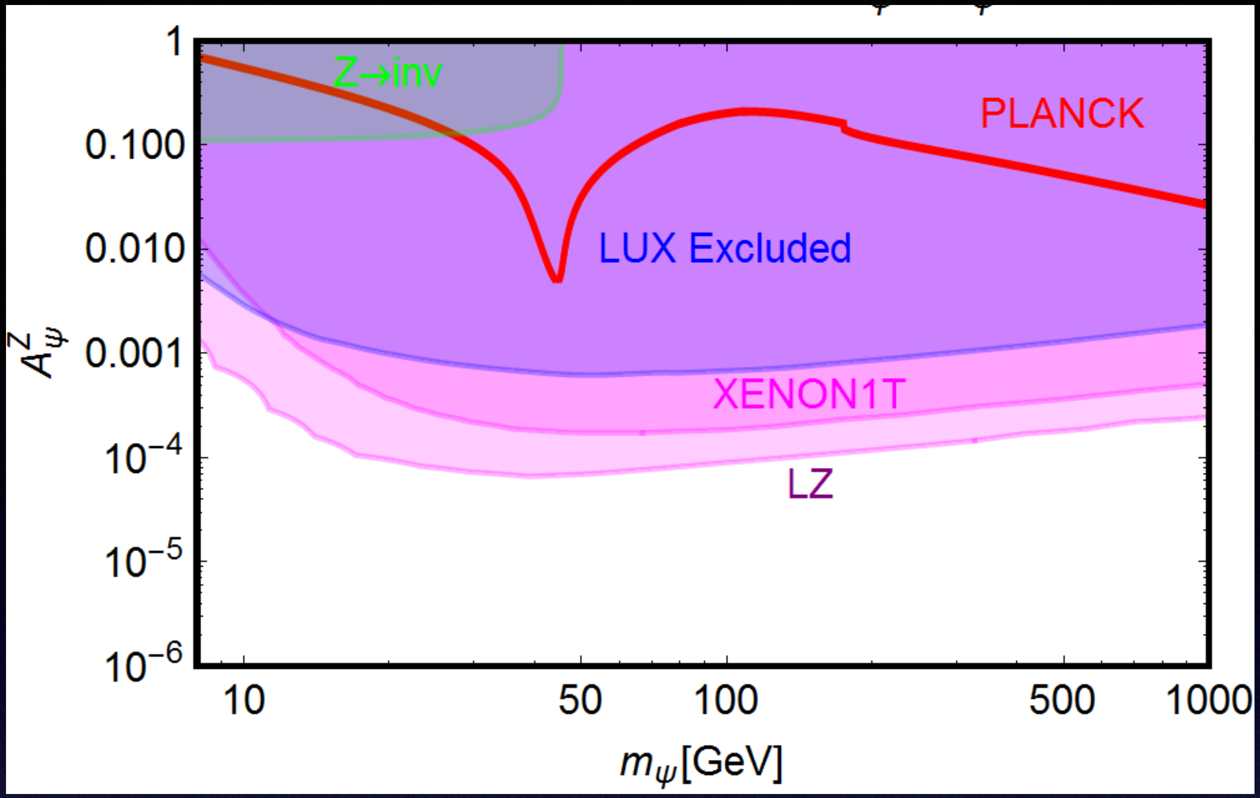
Developing a microscopical approach

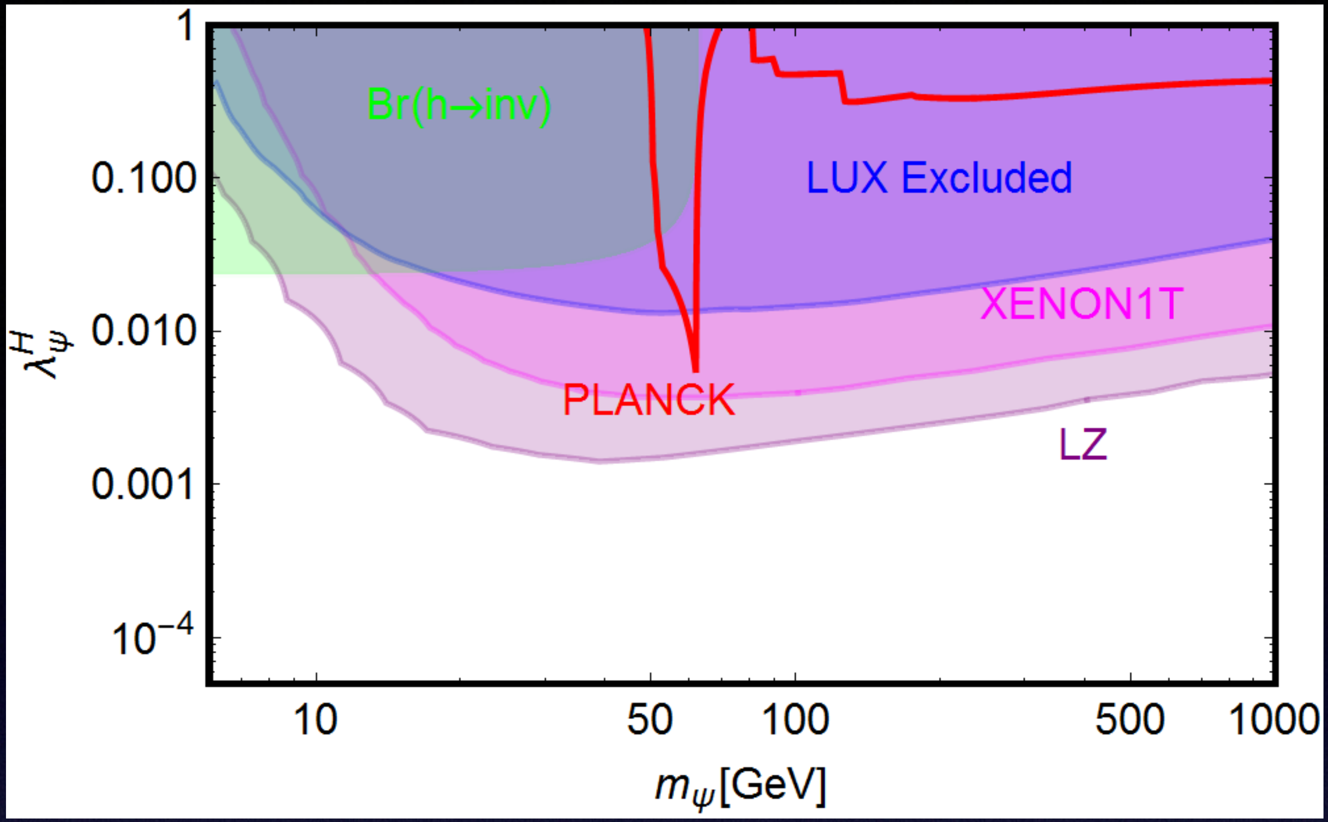
On which principle should we extend the microscopic interaction?

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..)

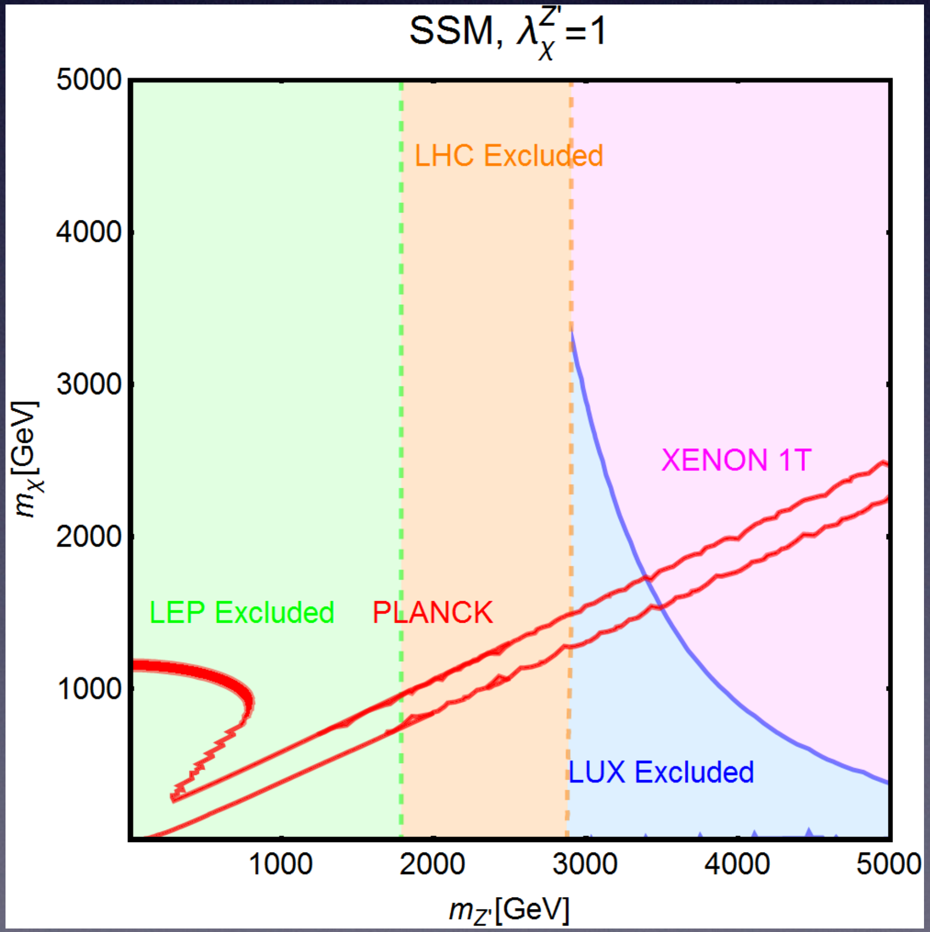
Dark matter couple only with the Standard Model (SM) particles : Higgs-portal, Z-portal, sterile neutrino. Consequences on observables are strong:
Invisible width of the Higgs/Z, LHC/LEP production in the case of portal models, instability and production of monochromatic photons in the case of sterile neutrino.





Z-portal

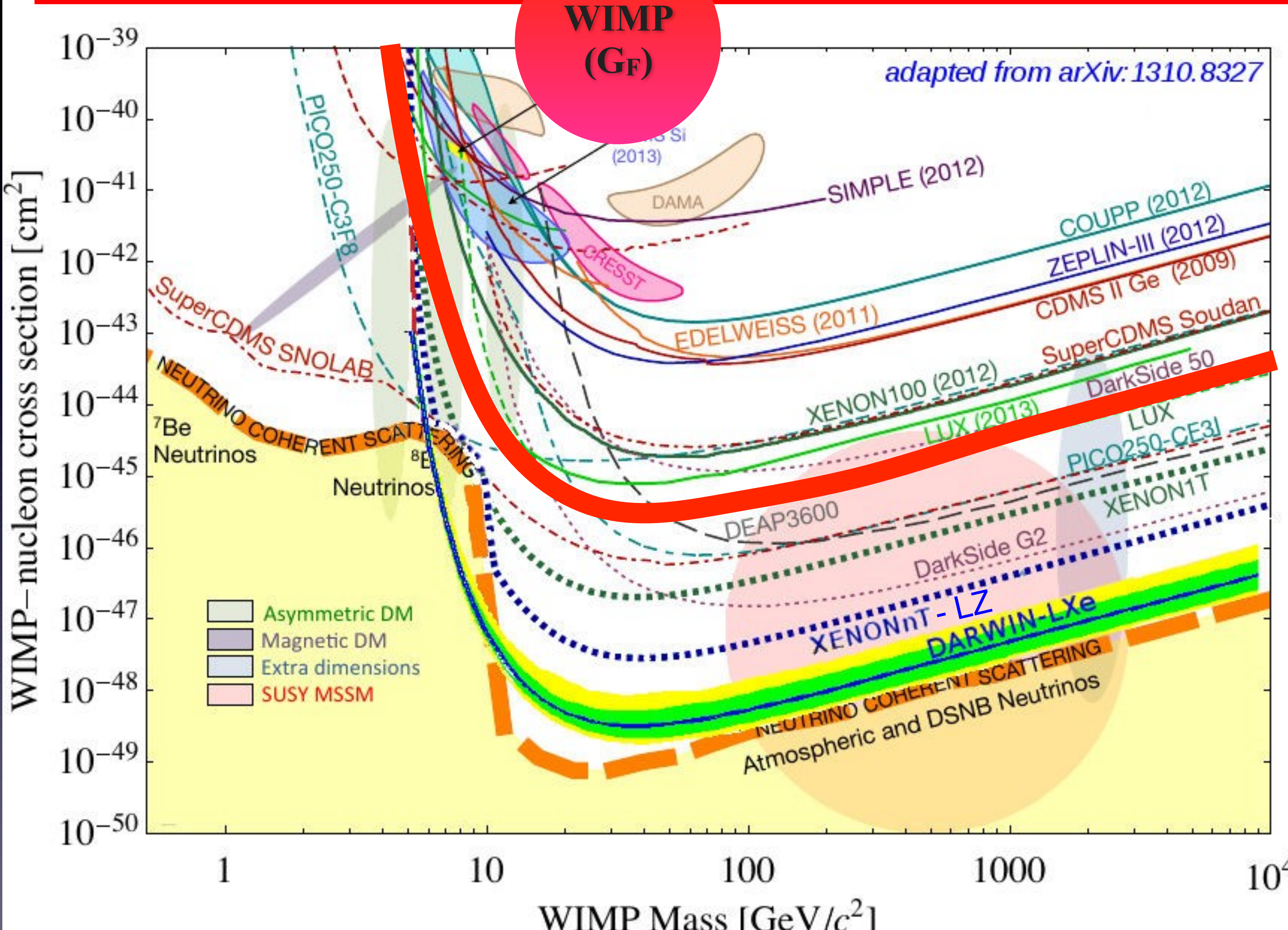
Higgs-portal



Z'-portal

G. Arcadi, M. Dutra, P. Ghosh, M. Lindner, Y.M., M. Pierre, S. Profumo and F. S. Queiroz,
Eur. Phys. J. C **78** (2018) no.3, 203 [arXiv:1703.07364]

Perspectives

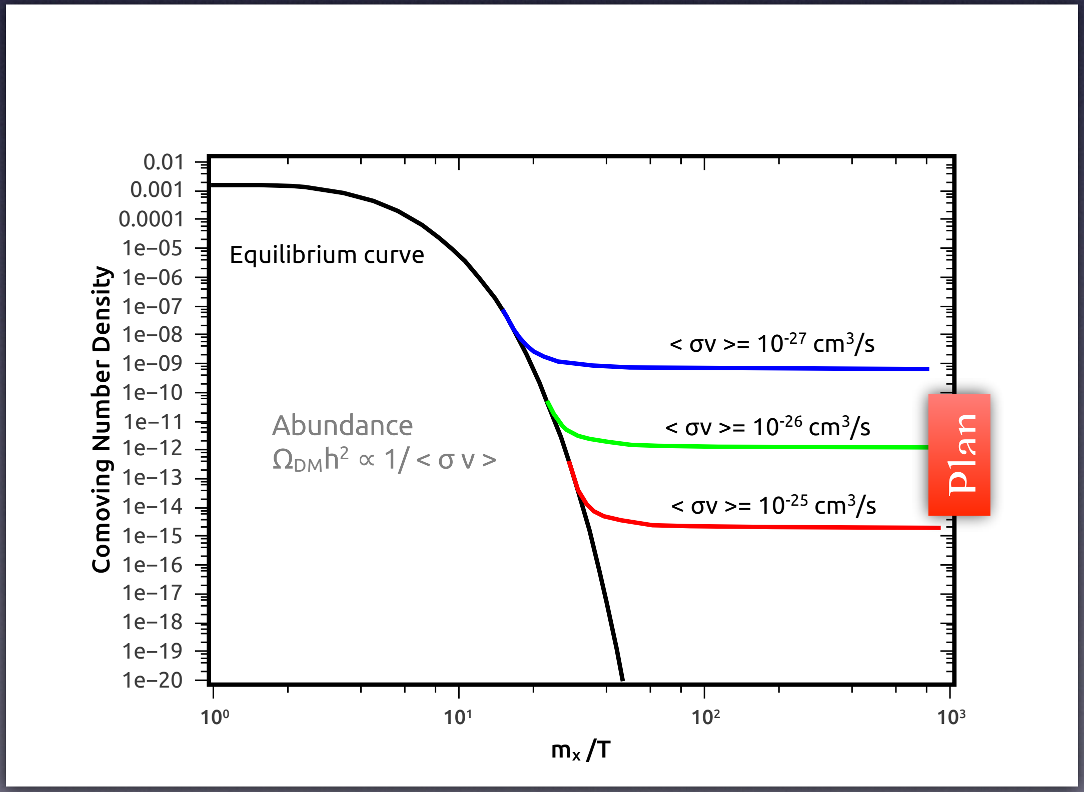


$$g_1 = 0.46;\ \ g_2 = 0.65;\ \ g_3 = 1.22; \qquad \sigma_{dm} \lesssim 10^{-37} \times 10^{-10}\ \text{cm}^2 \Rightarrow g_{dm} \lesssim 10^{-5}$$

$$\text{or } g_{dm} \simeq 1 \text{ and } M_{med} \gtrsim 2\ \text{TeV}$$

Why are we so attached to WIMP-like particle?

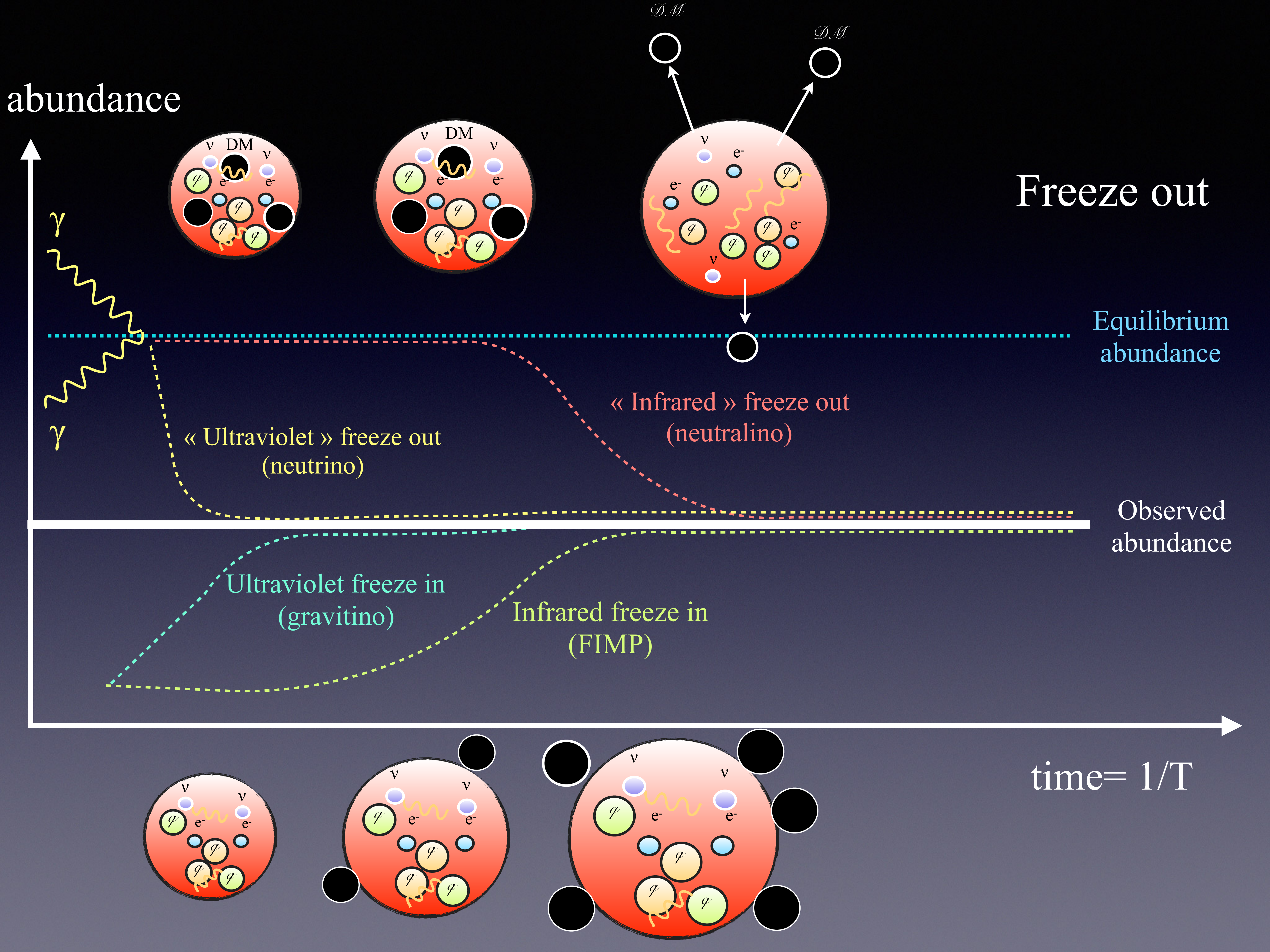
The WIMP miracle ?



Or the fact that the relic abundance do not depend on the initial conditions?

Alternative ways to obtain the right relic abundance

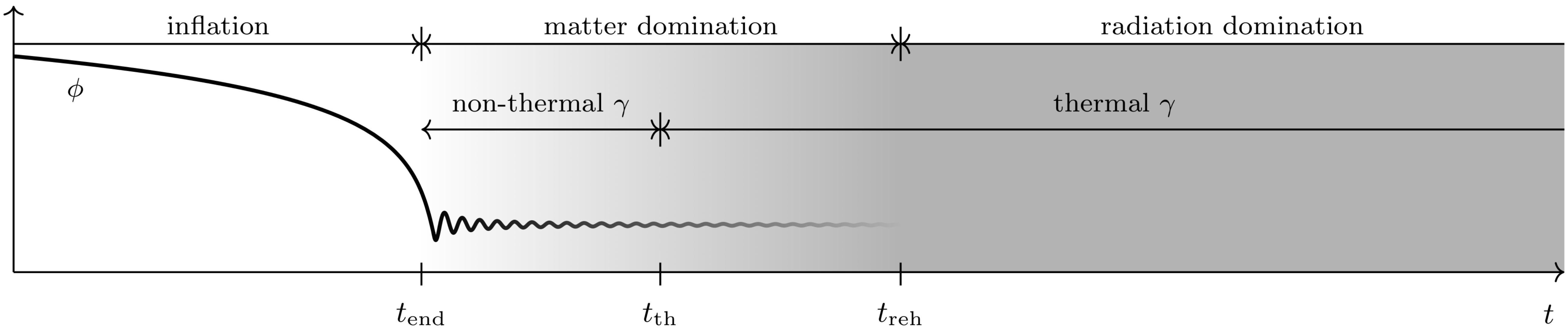
The FIMP:
Freeze-In Massive Particle

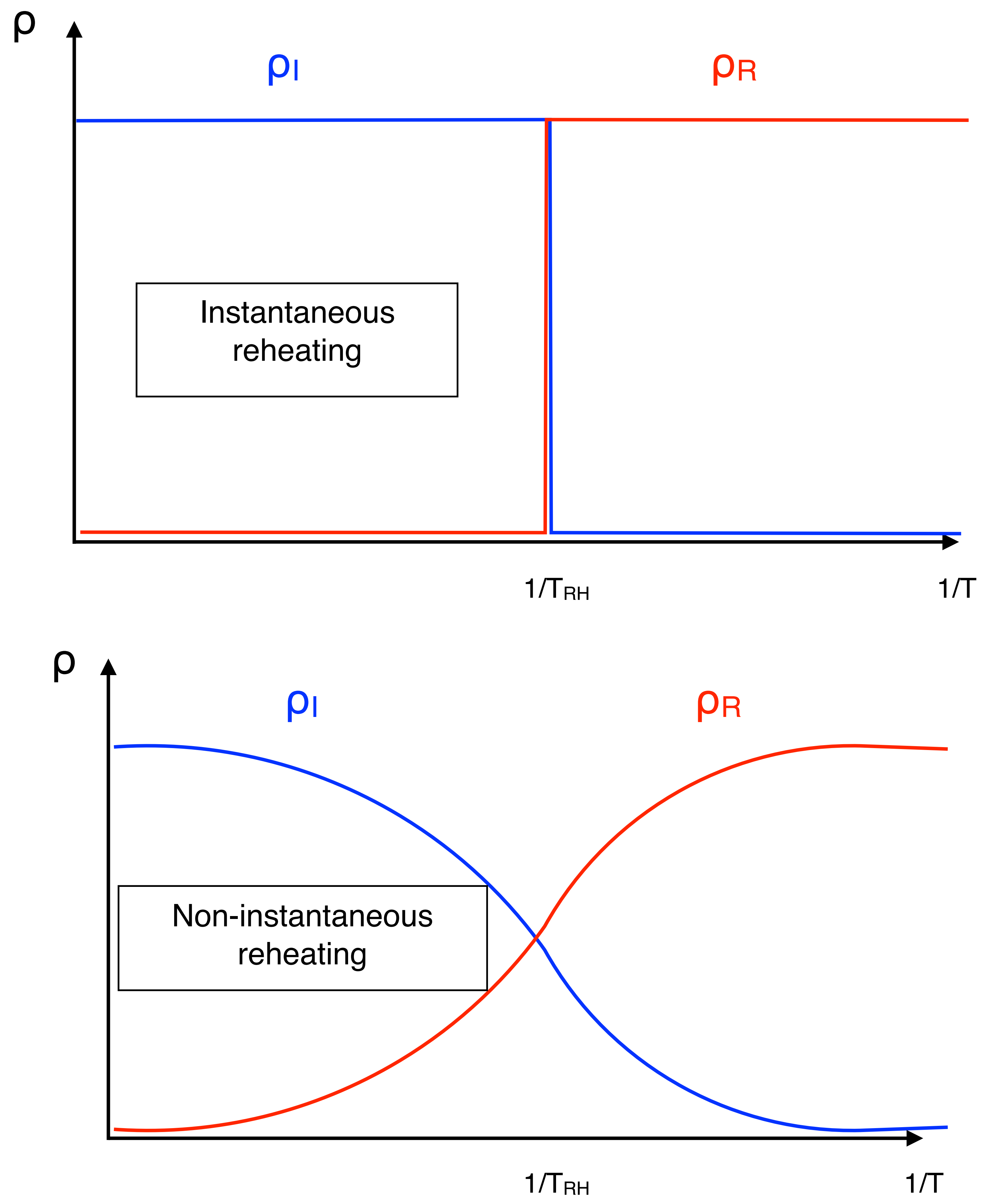


DM
DM
abundance
ν
DM
ν
e-
e-
ν
DM
ν
e-
e-
ν
e-
e-
e-
ν
Freeze out
γ
γ
Equilibrium abundance
« Infrared » freeze out (neutralino)
« Ultraviolet » freeze out (neutrino)
Observed abundance
Ultraviolet freeze in (gravitino)
Infrared freeze in (FIMP)
time= 1/T

UV alternative :
to produce DM before the
thermal equilibrium,
during the reheating

Non-instantaneous reheating: introducing the inflaton


inflation
matter domination
radiation domination
ϕ
non-thermal γ
thermal γ
$t_{\rm end}$
$t_{\rm th}$
$t_{\rm reh}$
t

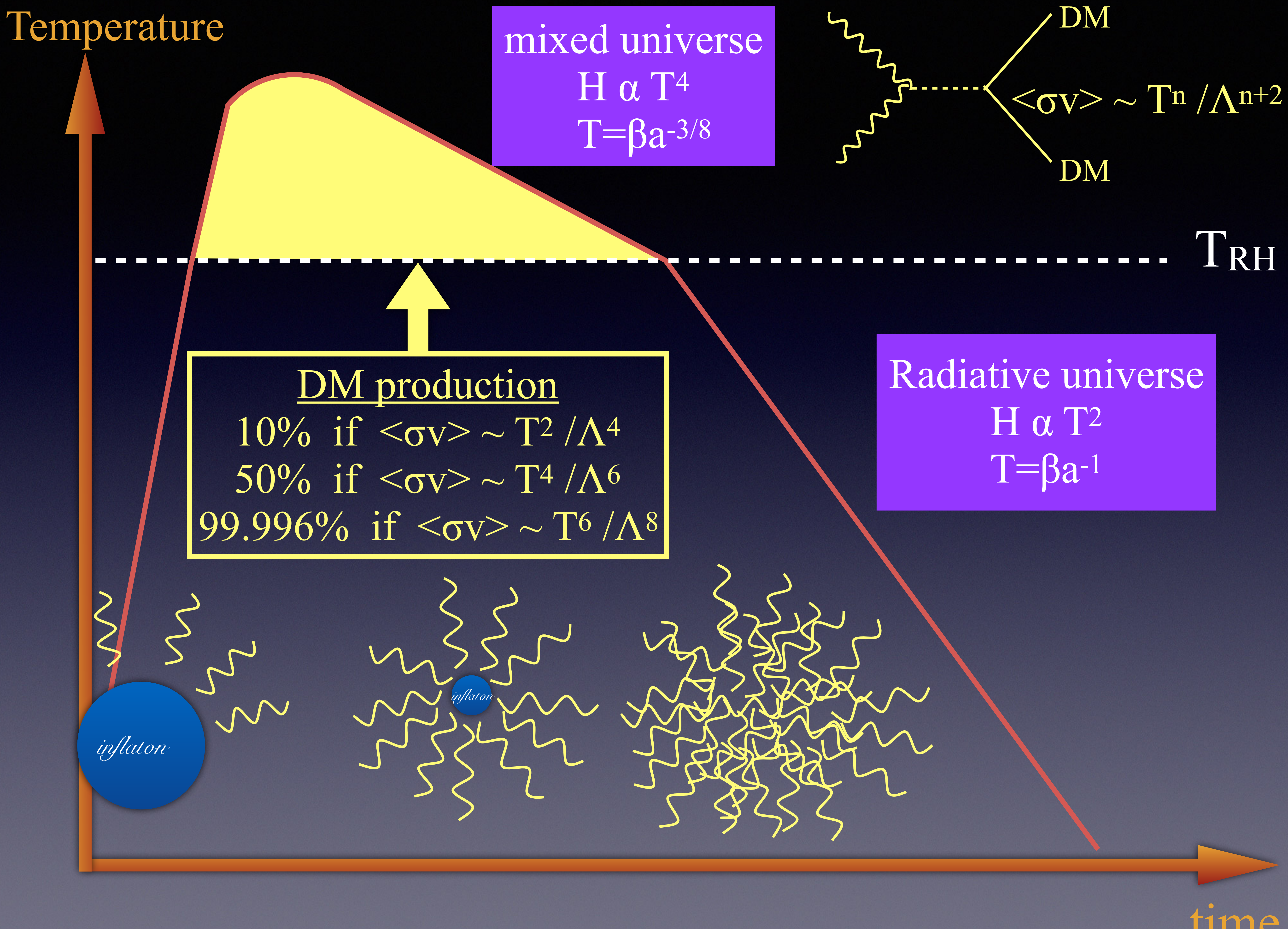


ρ
ρI
ρR
Instantaneous reheating
1/TRH
1/T
ρ
ρI
ρR
Non-instantaneous reheating
1/TRH
1/T

Before the end of the reheating process, while the Universe was still dominated by the matter (inflaton), but temperature was higher than T_{RH}

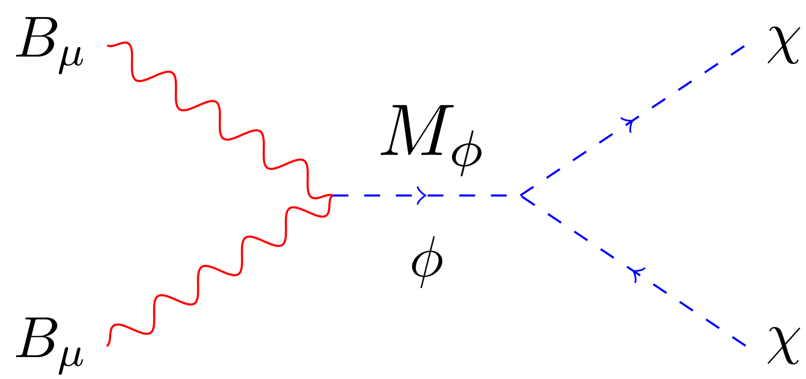
In other words, one should compare the total DM production releasing the hypothesis of instantaneous reheating

M.A.G. Garcia, Y. M., K.A. Olive and M.Peloso; arXiv:1709.01549

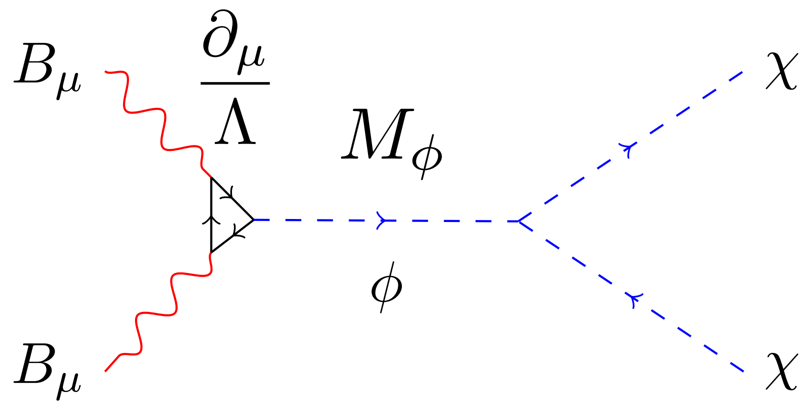


M.A.G. Garcia, Y. M., K.A. Olive and M.Peloso, Phys. Rev. D **96** (2017) no.10, 103510 [arXiv:1709.01549]

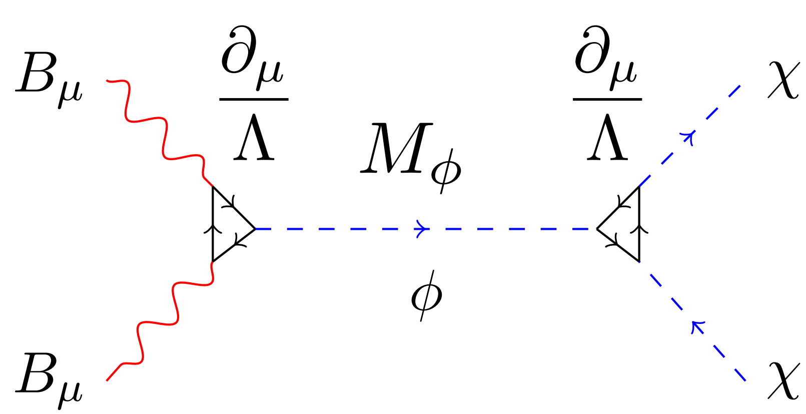
Example of rates



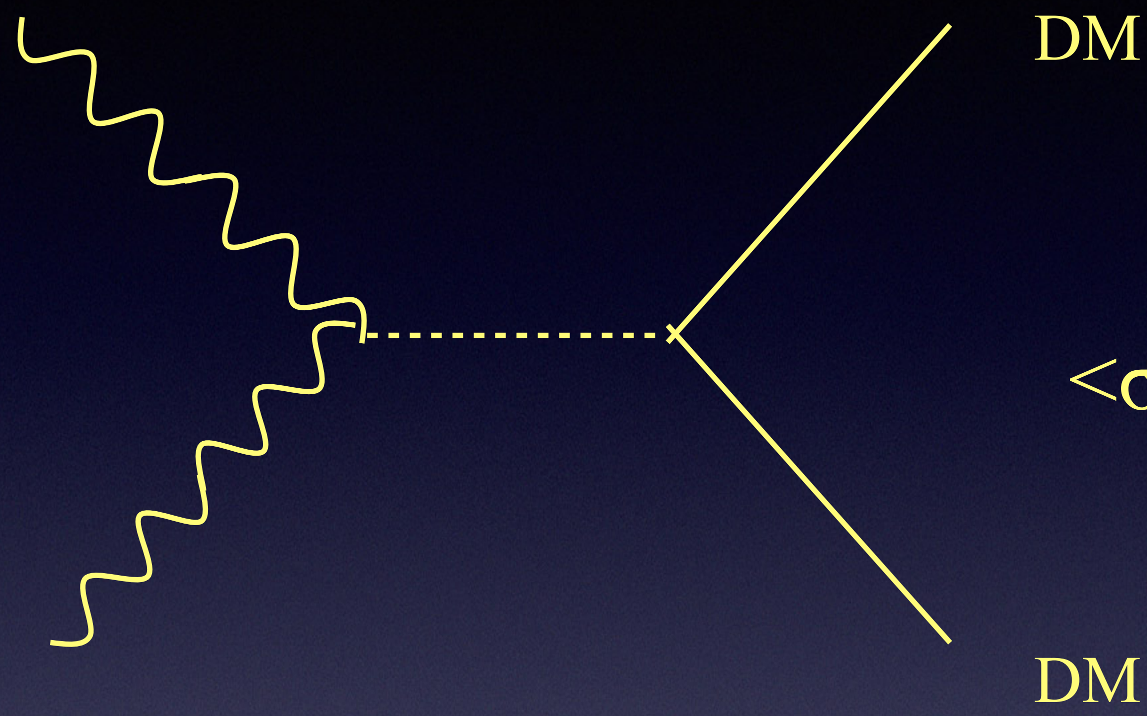
$$R(T) = \frac{T^8}{M_\phi^4}$$



$$R(T) = \frac{T^{10}}{M_\phi^4 \Lambda^2}$$



$$R(T) = \frac{T^{12}}{M_\phi^4 \Lambda^4}$$

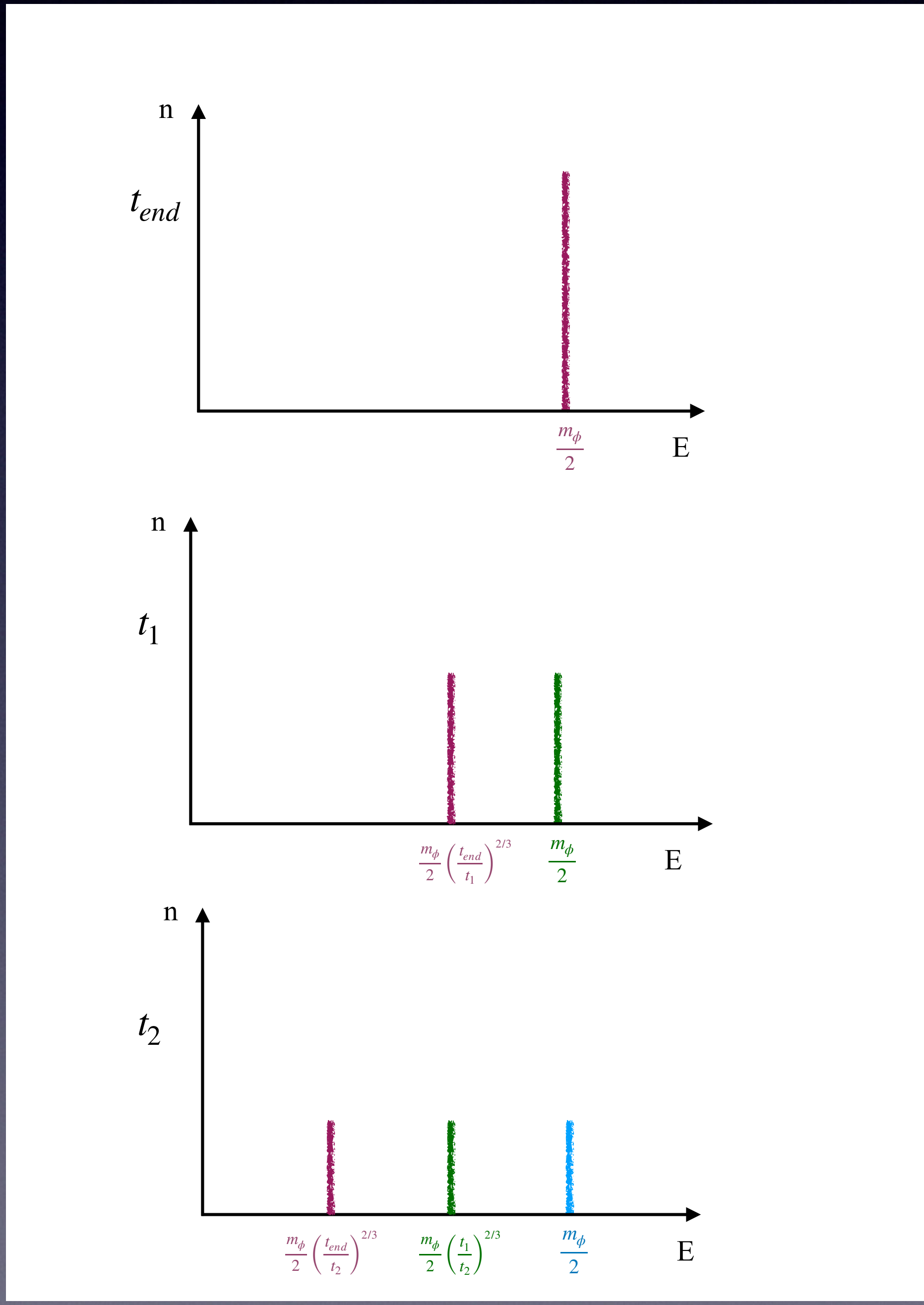


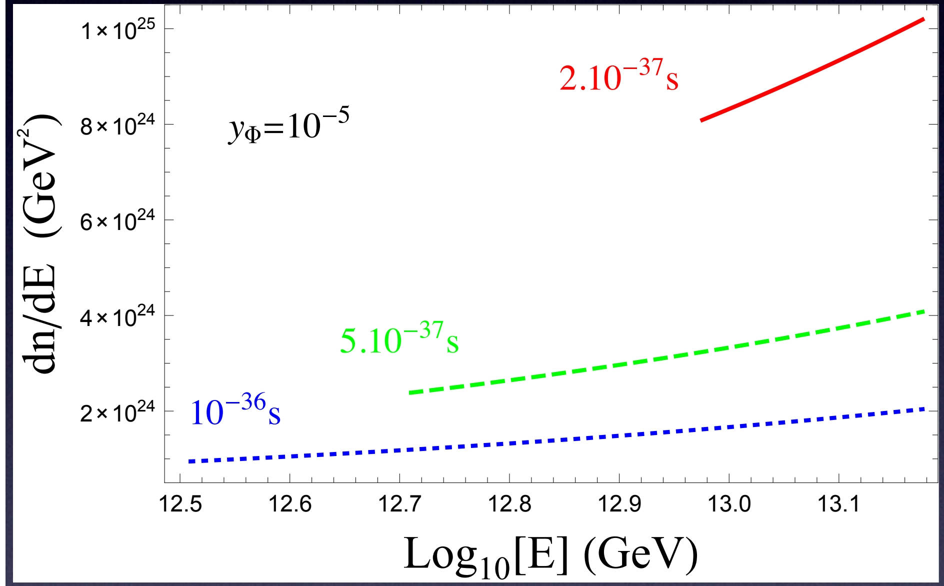
$\langle \sigma v \rangle \sim T^n / \Lambda^{n+2}$

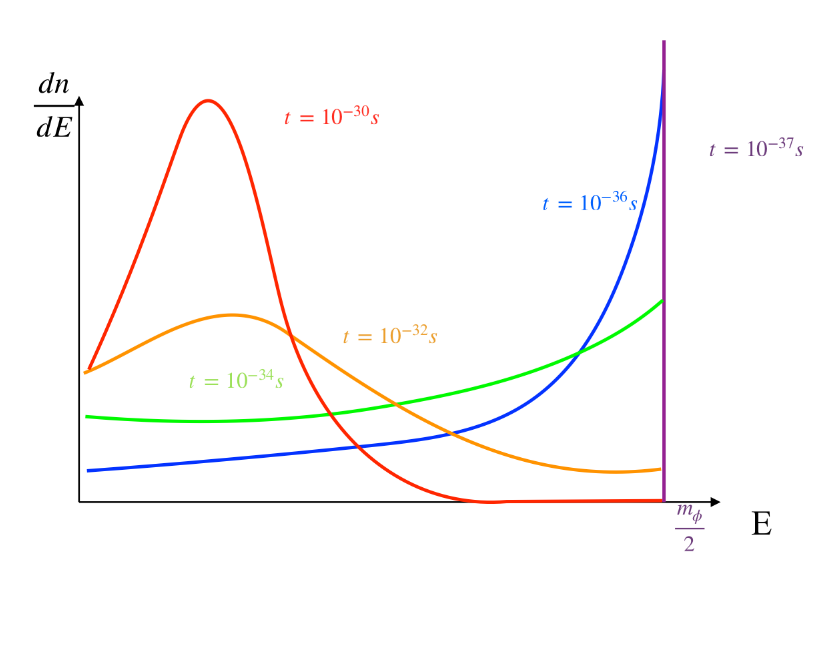
$$\Omega h^2 \propto 0.1 \frac{T_{RH}^{n+1} M_P}{\Lambda^{n+2}} \left(\frac{M_{DM}}{0.1 \text{ EeV}} \right)$$

K. Kaneta, Y. Mambrini and K. A. Olive,Phys. Rev. D **99** (2019) no.6, 063508 [arXiv:1901.04449]

Refinement: taking into account the non-thermal phase





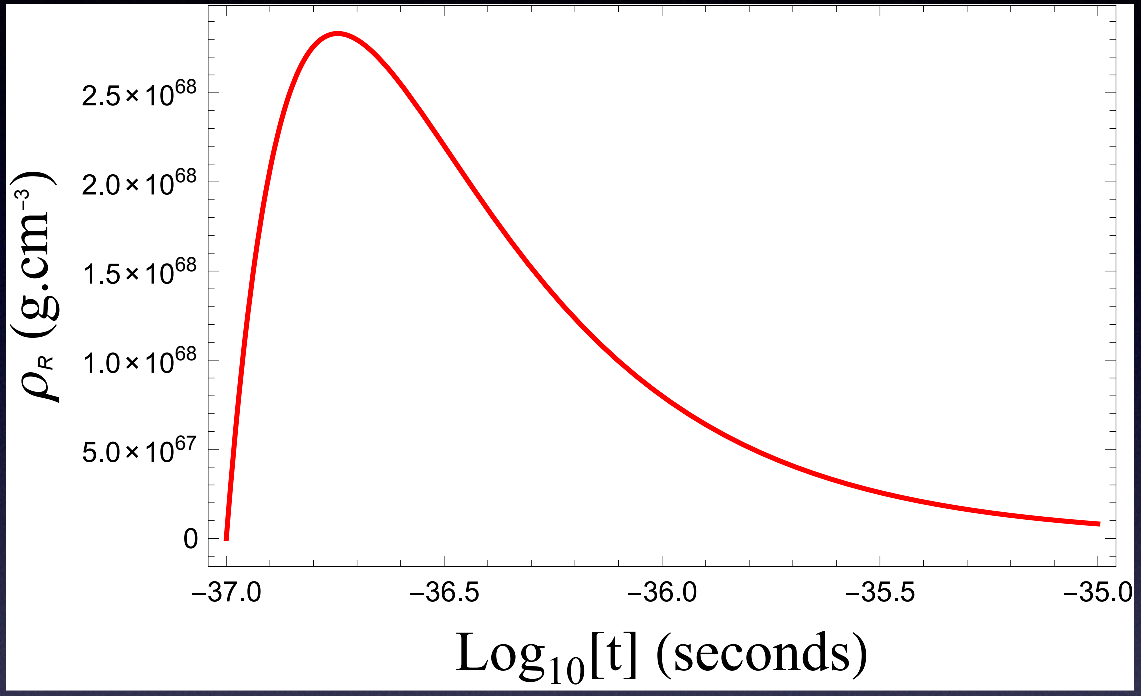


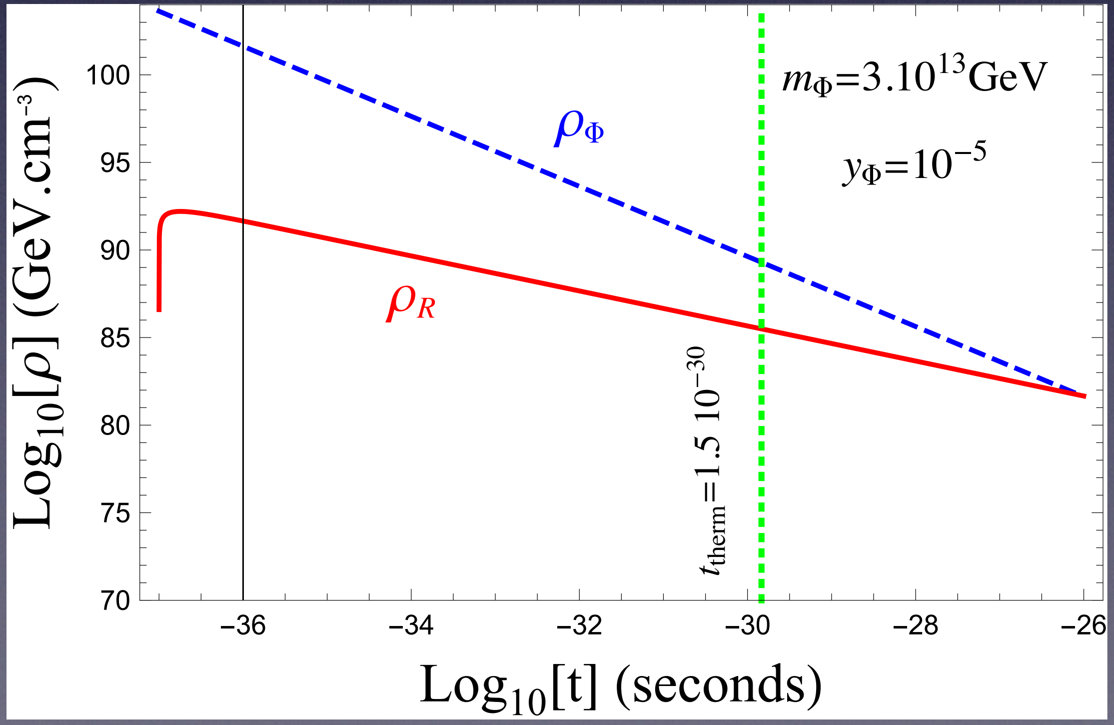
$$f(p) = \frac{8\sqrt{2}\pi^2\Gamma_\phi M_P^2}{p^{3/2}m_\phi^{5/2}t}$$

$$f(p) = \frac{1}{e^{\frac{p}{kT}} \pm 1}$$

M.A.G. Garcia, K. Kaneta, Y. M., K.A. Olive ; arXiv:1911.xxxxx

Refinement: taking into account the non-thermal phase





$$\rho_\phi(t) \simeq \frac{4}{3}\frac{M_P^2}{t^2} e^{-(t-t_{end})\Gamma_\phi} \simeq \frac{4}{3}\frac{M_P^2}{t^2}$$

$$\rho_R(t) \simeq \frac{4}{5}\frac{\Gamma_\phi M_P^2}{t}\left[1-\left(\frac{t_{end}}{t}\right)^{5/3}\right]$$

M.A.G. Garcia, K. Kaneta, Y. M., K.A. Olive ; arXiv:1911.xxxxx

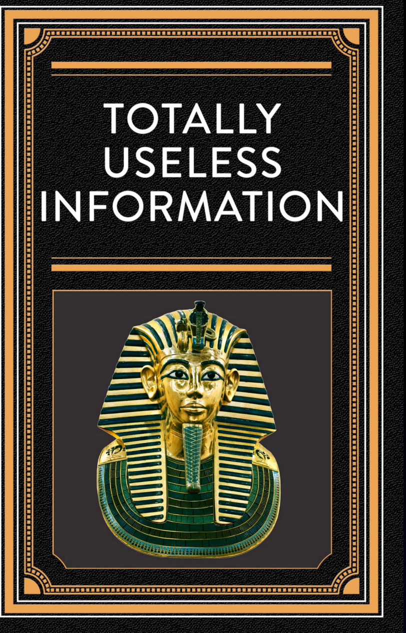
Other recent works on the subject

A. Di Marco, G. De Gasperis, G. Pradisi and P. Cabella, ``Energy Density, Temperature and Entropy Dynamics in Perturbative Reheating," ; arXiv:1907.06084

N. Bernal, F. Elahi, C. Maldonado and J. Unwin, ``Ultraviolet Freeze-in and Non-Standard Cosmologies," ; arXiv:1909.07992.

Parenthesis concerning the EeV scale

$$\Omega h^2 \propto 0.1 \frac{T_{RH}^{n+1} M_P}{\Lambda^{n+2}} \left(\frac{M_{DM}}{0.1 \text{ EeV}} \right)$$



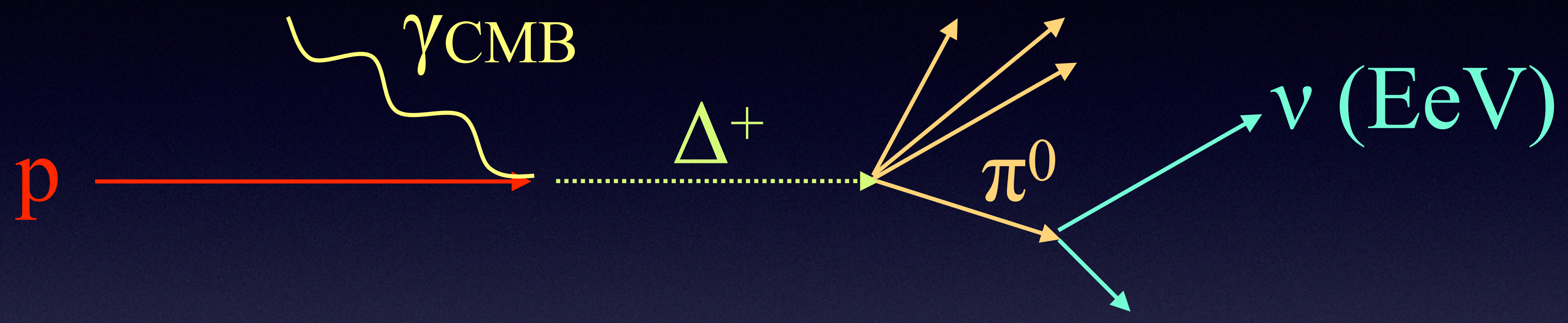
Some Exa-scales (10^{18})

[CSI convention since 1975]

- USA energy consumption per year : 15 Exajoule [= energy needed in Appolo 11 mission to the moon]
- Age of Universe : 0.43 Exasecond
- 1 Exameter = 110 light-years
- Gmail : 1 Exabyte
- 57 Exahashes per second : calculation rate of bitcoin network
- Proton mass = 10^{-9} Exaelectronvolt (!)

Other motivations range from..

Cosmic ray production of EeV neutrino (GZK cut= 50 EeV)



Intermediate sectors in SO(10) unified models

Reheating temperature :

$$T_{RH} = \sqrt{\Gamma_{inflaton} \times M_{Planck}} \simeq EeV$$

EeV Majorana mass M_R => natural see-saw (y_ν=1)

Higgs (meta)stability

FAQs

- How an EeV DM does not overpopulate the Universe?
- But an EeV DM should violate the unitary constraint of ~ 480 TeV no?
- Do you have credible models to justify it?
- Which kind of signature do you expect?

Quick answers

- How an EeV DM does not overpopulate the Universe?

Easily if its production rate is suppressed (Planck scale for gravitino, unification scale for SO(10), RHN mass in see-saw type models...)

- But an EeV DM should violate the unitarity constraint of ~100 TeV no?

Not at all if not produced thermally (gravitino, FIMP..). Unitarity constraint applies only supposing a thermal production cross section.

- Do you have credible models to justify it?

Yes, a lot, and you will see it. But roughly speaking, every model with a BSM scale above the inflaton mass (strings, SUGRA, SO(10), Xtra dim..).

- Which kind of signature do you expect?

Be patient..

The relic abundance computation in the early universe : the general case

$$\frac{d\rho_\Phi}{dt} + 3H\rho_\Phi = -\Gamma_\Phi \rho_\Phi$$ [inflaton Φ]

$$\frac{d\rho_R}{dt} + 4H\rho_R = +\Gamma_\Phi \rho_\Phi$$ [radiation R]

$$\frac{dn_\chi}{dt} + 3Hn_\chi = \boxed{R(T)}$$ [dark matter χ]

$$H^2 = \frac{\rho_\Phi}{3M_P^2} + \frac{\rho_R}{3M_P^2}$$ [scale a]

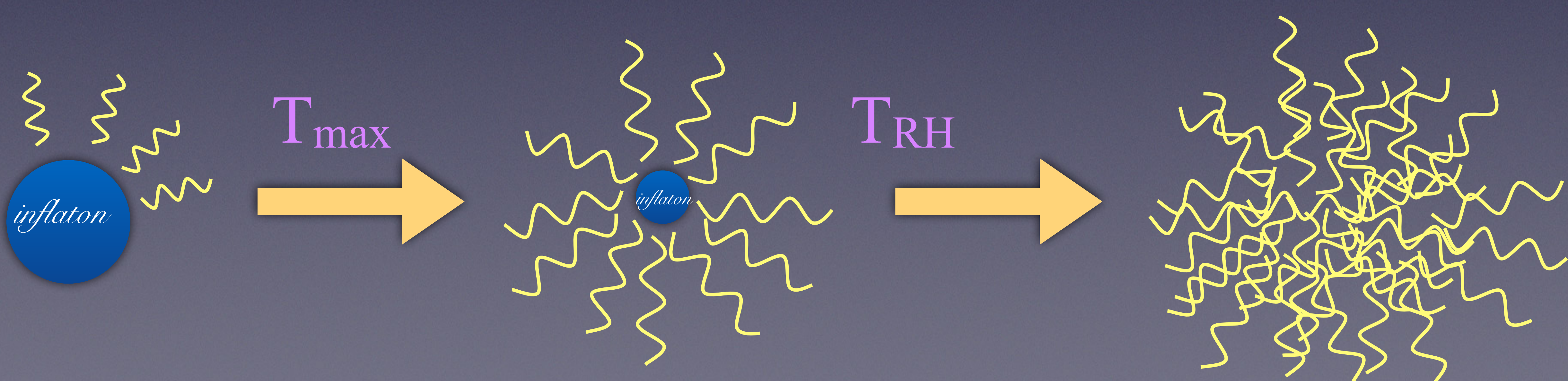
$$\Rightarrow \quad T = \beta a^{-3/8} \quad (H = \frac{\dot{a}}{a})$$

[$T = \beta a^{-1}$ in radiation dominated universe]

$$\Rightarrow \quad H(T) = \frac{5}{6}\frac{\alpha}{\Gamma_I M_P^2} T^4$$

[$H(T) = \frac{\alpha}{3M_P} T^2$ in radiation dominated universe]

$$\boxed{\frac{dY_\chi}{dT} = -\frac{8}{3}\frac{\boxed{R(T)}}{H\ T^9} \quad \text{with } Y_\chi = \frac{n_\chi}{T^8}}$$



$$\boxed{\frac{dY_\chi}{dT} = -\frac{8}{3}\frac{R(T)}{H\ T^9} \quad \text{with } Y_\chi = \frac{n_\chi}{T^8}}$$

$$\boxed{R(T) = \frac{T^{6+n}}{\Lambda^{n+2}}}$$

$$B_F^n = \frac{\Omega_{non\ instantaneous}}{\Omega_{instantaneous}} = \frac{\int_{T_{max}}^{T_{RH}} dn}{\int_{T_{RH}}^{0} dn}$$

$$B_F^{n<6} = \frac{8}{5}\left(\frac{n+1}{6-n}\right)$$

$$B_F^{6} = \frac{56}{5}\ln\left(\frac{T_{max}}{T_{RH}}\right)$$

$$B_F^{n>6} = \frac{8}{5}\left(\frac{n+1}{n-6}\right)\left(\frac{T_{max}}{T_{RH}}\right)^{n-6}$$

Conclusion:

3 sources of production:

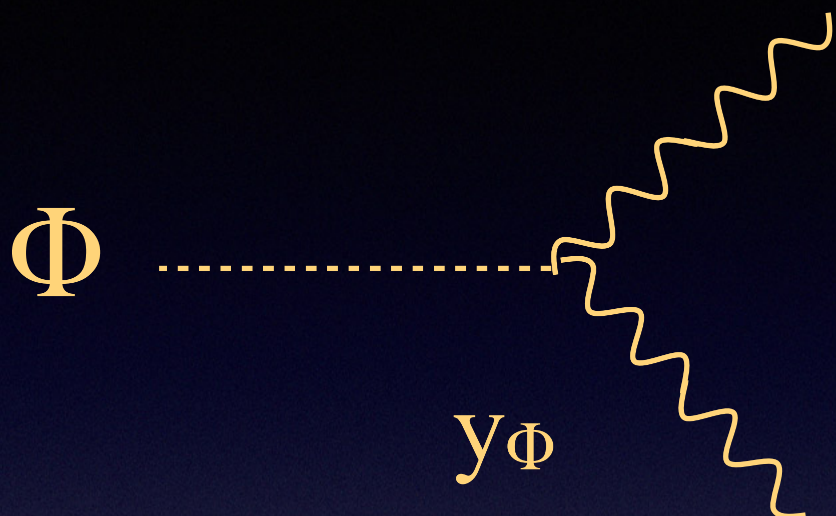
1) From thermal equilibrium (freeze out)
[Higgs-portal, Z/Z'-portal]

2) Out of equilibrium (freeze in)
[gravitino, FIMP]

3) During reheating due to large temperature
[Planck/String interactions]

4) and…

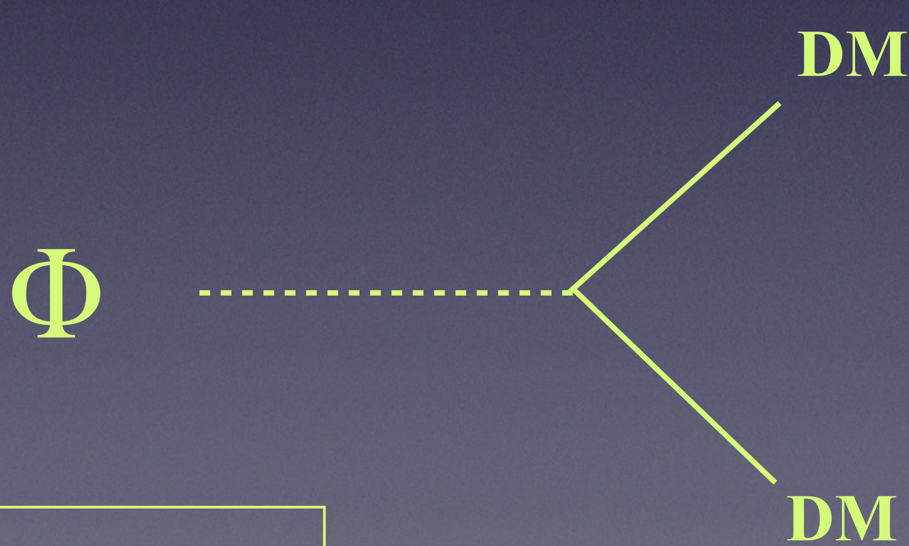
Another DM source: The inflaton decay



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

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

T_{RH}



$$\Omega h^2 = \left(\frac{B_R}{2.0\times 10^{-9}}\right)\left(\frac{T_{RH}}{M_\Phi}\right)\left(\frac{M_{DM}}{10^{10}\text{GeV}}\right)$$

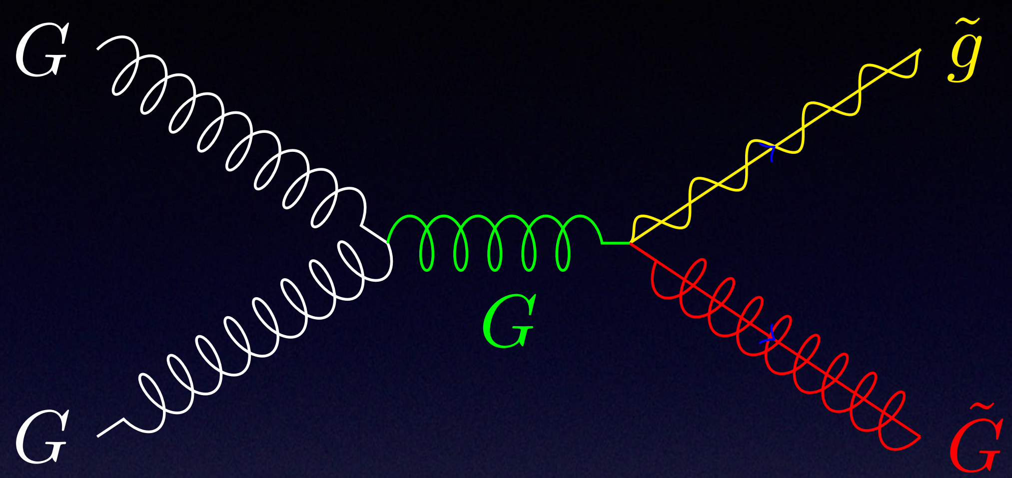
$$B_R = \frac{\Gamma_{\Phi\to DM\ DM}}{\Gamma_\Phi}$$

Ωh^2

K. Kaneta, Y. Mambrini and K. A. Olive,Phys. Rev. D **99** (2019) no.6, 063508 [arXiv:1901.04449]

A concrete example:
Supergravity

Ellis, Kim and Nanopoulos (84) then considered for the first time the dominant process (in fact, they listed 10 processes)



COSMOLOGICAL GRAVITINO REGENERATION AND DECAY

John Ellis, Jihn E. Kim*) and D.V. Nanopoulos

CERN - Geneva

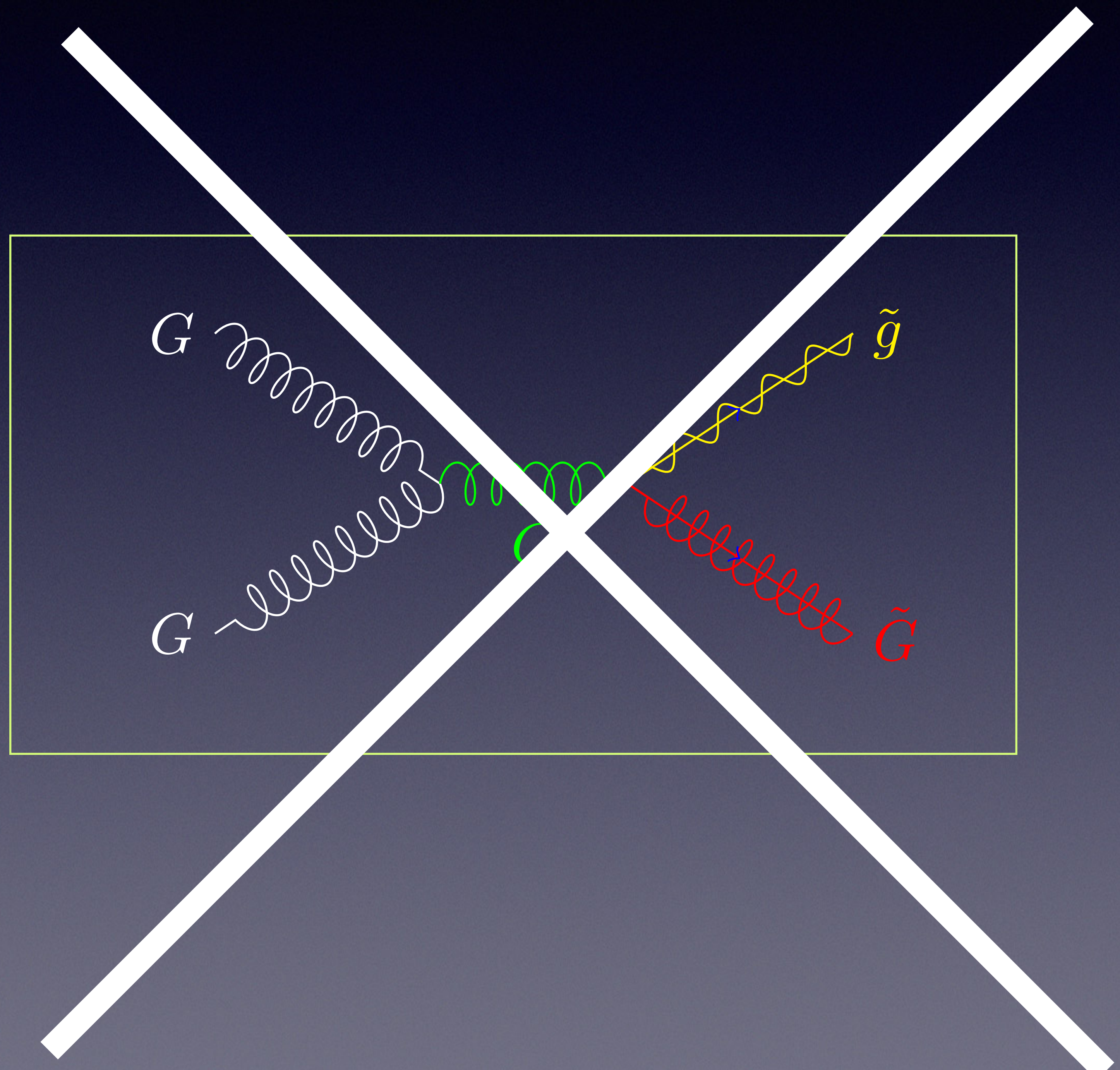
careful analyses of their decay products' disruptive effects on light nuclei and on the microwave background radiation suggest $T_{max} < 10^9 \sim 10^{10}$ GeV.

$$\mathcal{L} = \frac{1}{4M_{\rm Pl}} \bar{\psi}^{\alpha} \gamma_{\alpha} [\gamma^{\mu}, \gamma^{\nu}] \, \tilde{G} \, G_{\mu\nu}$$

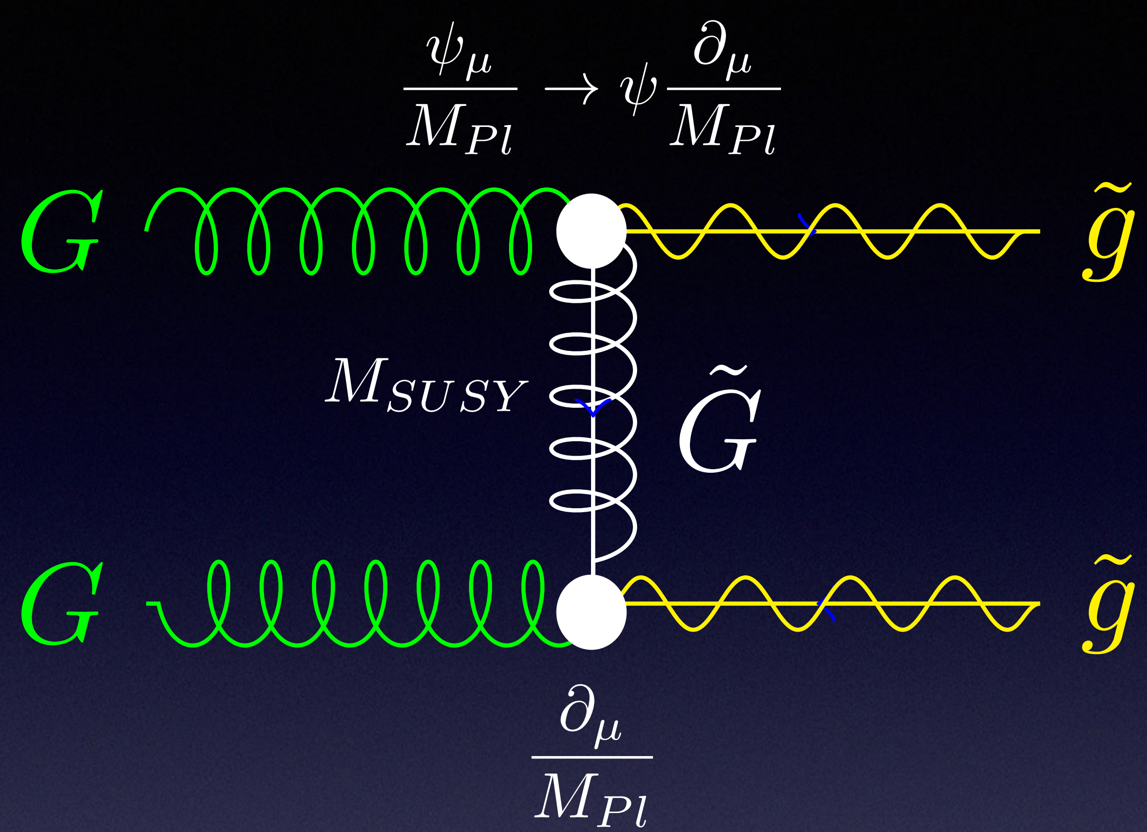
gravitino gluino gluon

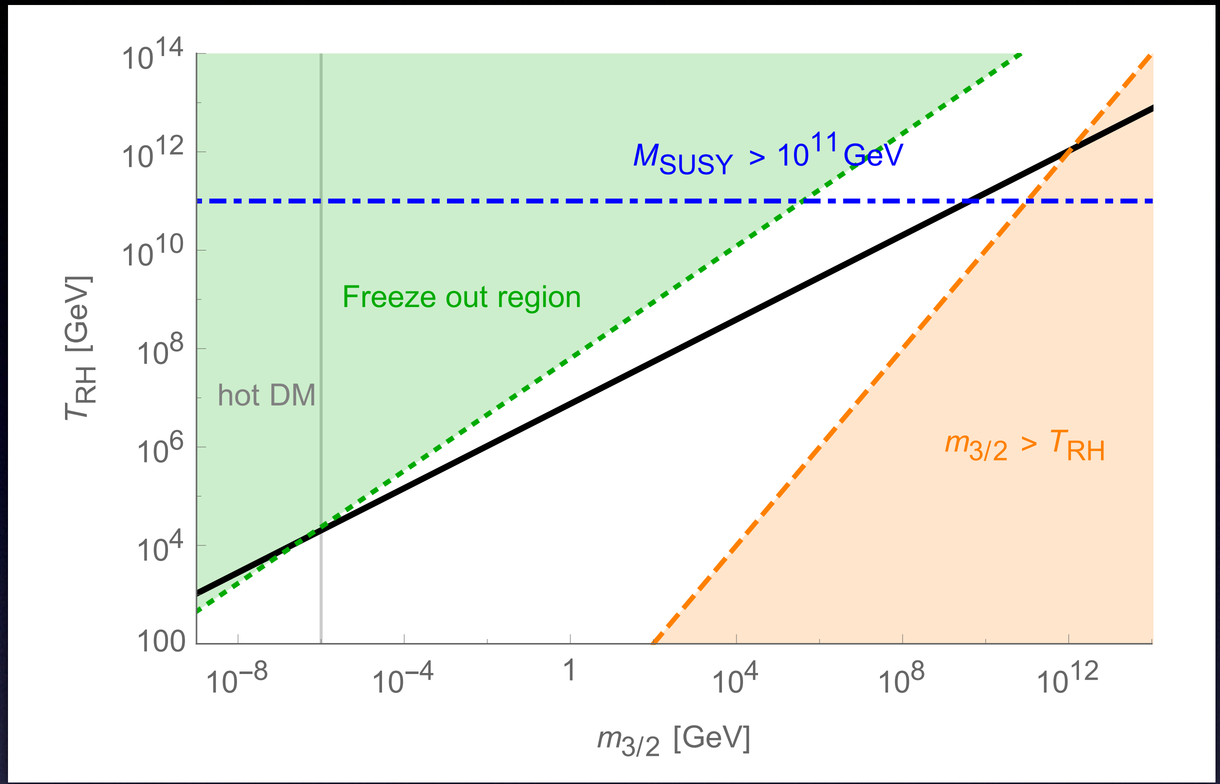
$$\Omega_{3/2} h^2 \sim 0.3 \left(\frac{1 \text{ GeV}}{m_{3/2}} \right) \left(\frac{T_{\rm RH}}{10^{10} \text{ GeV}} \right) \sum \left(\frac{m_{\tilde{G}}}{100 \text{ GeV}} \right)^2$$

High-scale supersymmetry: $M_{SUSY} >> T_{max}$



High scale supergravity





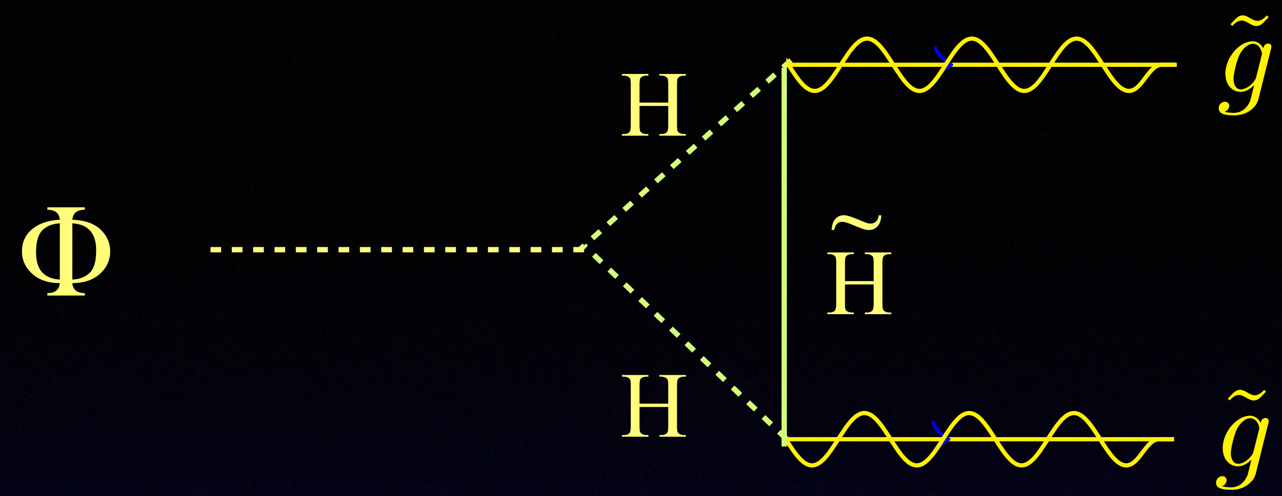
$$R(T) = \frac{T^{12}}{M_{SUSY}^4 M_{Pl}^4}$$

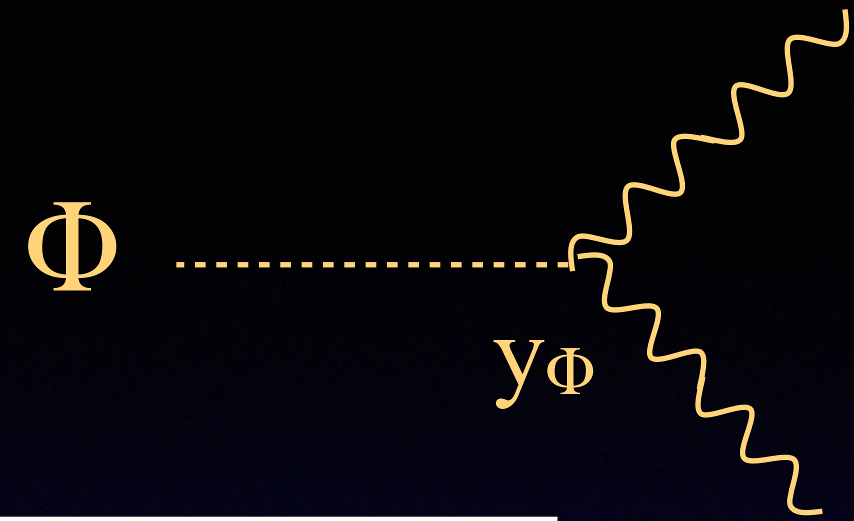
$$\Omega_{3/2}h^2 \simeq 0.11 \left(\frac{0.1\ \mathrm{EeV}}{m_{3/2}}\right)^3 \left(\frac{T_{RH}}{2\times 10^{10}}\right)^7 \times \frac{56}{5} \ln\left(\frac{T_{max}}{T_{RH}}\right)$$

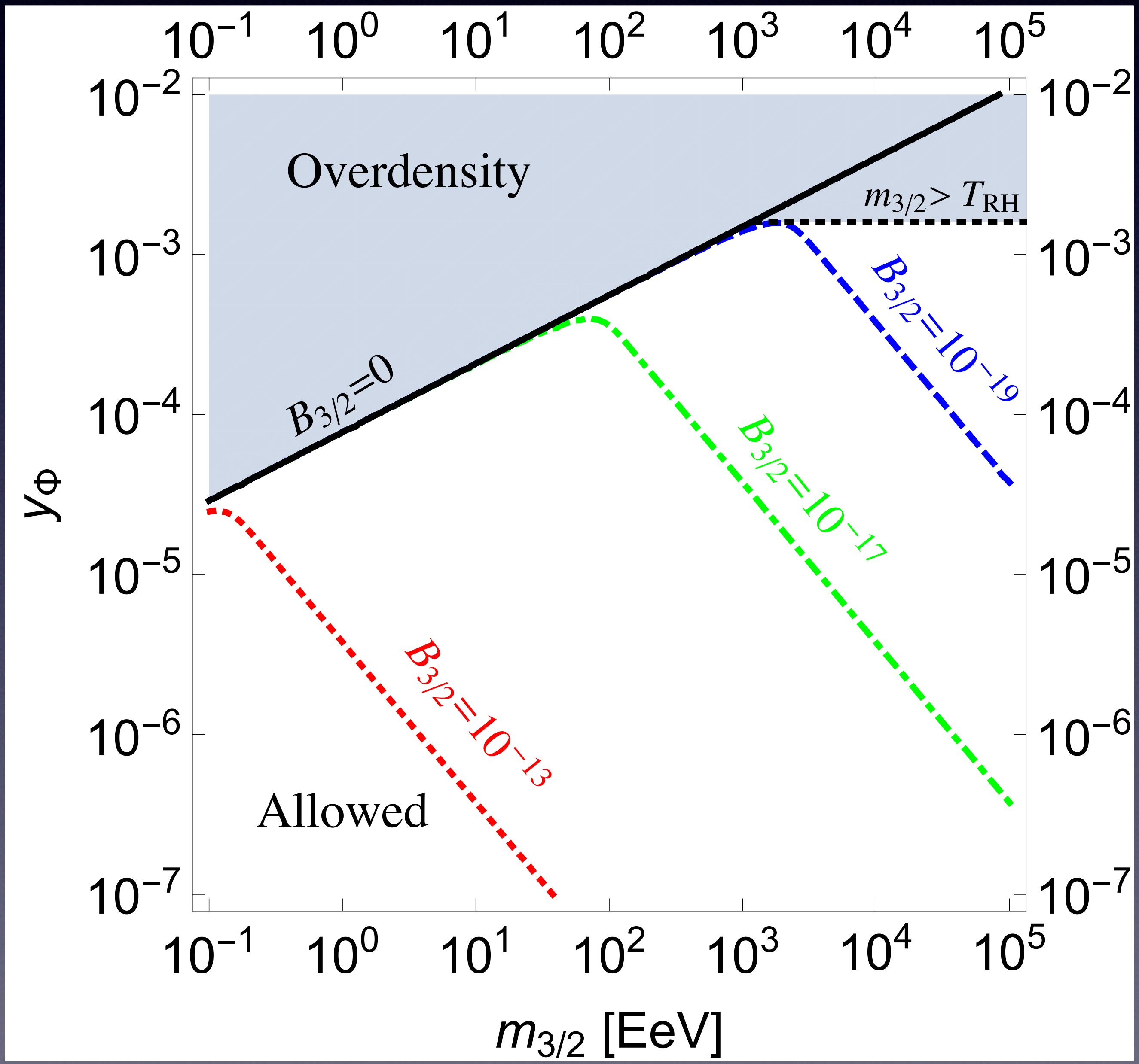
K. Benakli, Y. Chen, E. Dudas and Y. M.; Phys.Rev. D95 (2017) [arXiv:1701.06574]

E. Dudas, Y. M. and K. Olive, Phys. Rev. Lett. **119** (2017) no.5, 051801 [arXiv:1704.03008]

Adding the contribution from radiative decay of the inflaton







E. Dudas, T. Gherghetta, Y. M., K.A. Olive ; Phys.Rev. D96 (2017) no.11, 115032 [arXiv:1710.07341]

K. Kaneta, Y. M. and K. A. Olive, ``Radiative Production of Non-thermal Dark Matter,'' [arXiv:1901.04449]

Other models where care should be taken proceeding with early Universe computation

SO(10)

G. Bhattacharyya, M. Dutra, Y. M. and M. Pierre, ``Freezing-in dark matter through a heavy invisible Z′,''
Phys. Rev. D **98** (2018) no.3, 035038 [arXiv:1806.00016]

Massive spin 2

Nicolás Bernal, Maíra Dutra, Y. M., K. Olive, M. Peloso, M. Pierre ; Phys.Rev. D97 (2018) 115020 [arXiv:1803.01866]

« string inspired » moduli fields

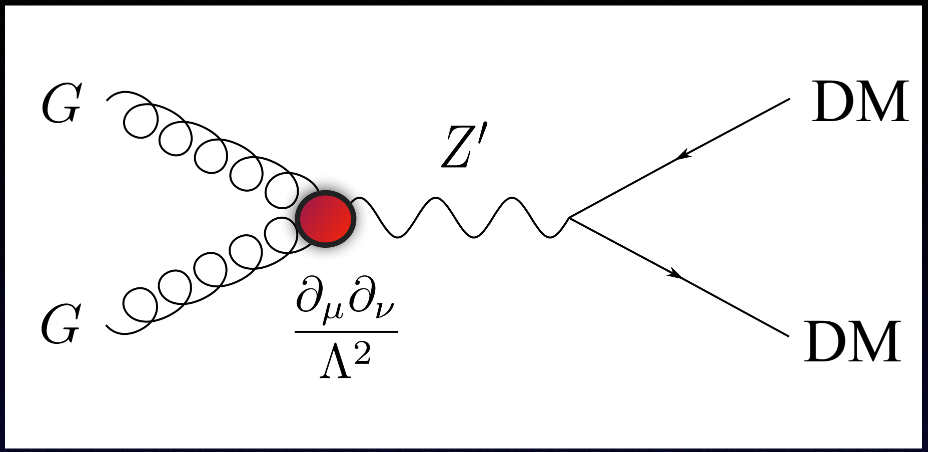
D. Chowdhury, E. Dudas, M. Dutra and Y. M. ; Phys.Rev. D99 (2019) no.9, 095028 [arXiv:1811.01947]

Loop generated kinetic mixing

D. A. Banerjee, G. Bhattacharyya, D. Chowdhury and Y. M. ; [arXiv:1905.11407]

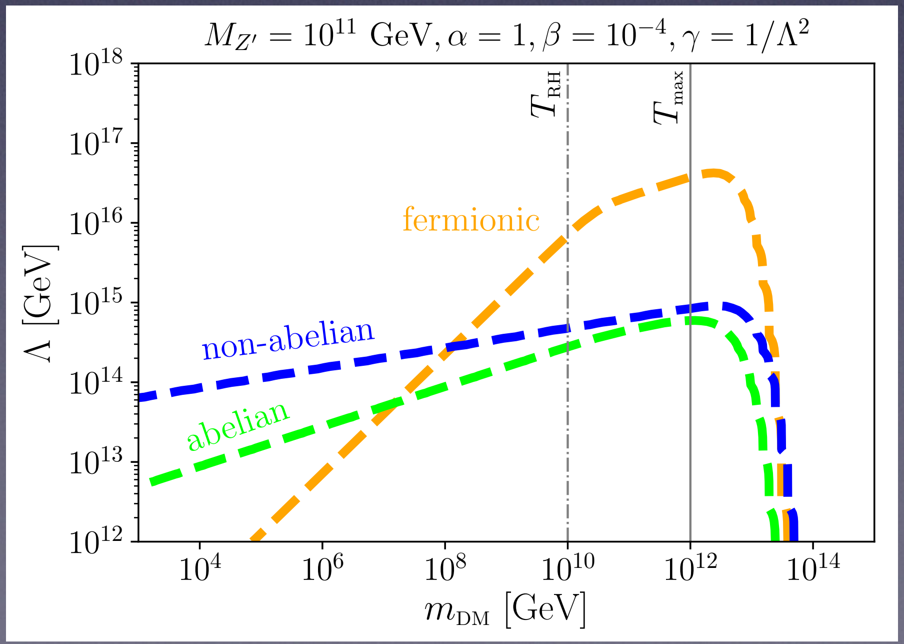
Spin-1 mediator

[arXiv:1806.00016]



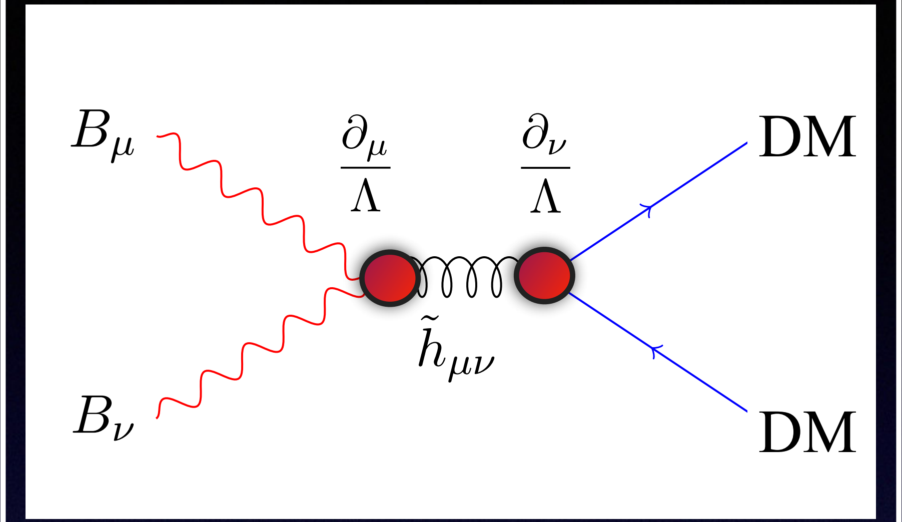
$$\mathcal{L} = \frac{\tilde{g}}{M^2} \partial^\alpha Z'_\alpha \epsilon^{\mu\nu\rho\sigma} \partial_\mu A^a_\nu \partial_\rho A^a_\sigma$$

$$\mathcal{L}_{\rm eff} = \frac{1}{\Lambda^2} \partial^\alpha Z'_\alpha \epsilon^{\mu\nu\rho\sigma} {\rm Tr}[G^a_{\mu\nu} G^a_{\rho\sigma}]$$



Spin-2 mediator

[arXiv:1803.01866]



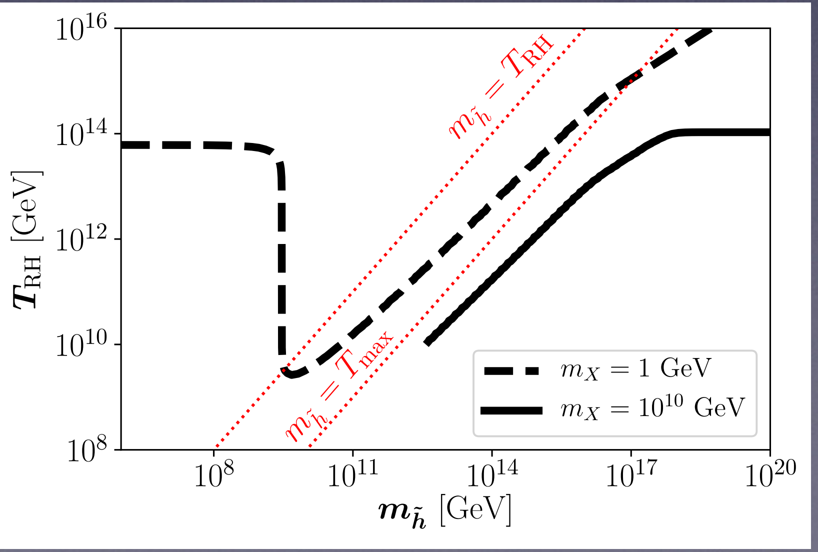
$$\mathcal{L}^1_{\rm int} = \frac{1}{2M_P} h_{\mu\nu} \left(T^{\mu\nu}_{\rm SM} + T^{\mu\nu}_{\rm X}\right)$$

$$\mathcal{L}^2_{\rm int} = \frac{1}{\Lambda} \tilde{h}_{\mu\nu} \left(g_{\rm SM} T^{\mu\nu}_{\rm SM} + g_{\rm DM} T^{\mu\nu}_{\rm X}\right)$$

$$T^0_{\mu\nu} = \frac{1}{2}\left(\partial_\mu\phi\, \partial_\nu\phi + \partial_\nu\phi\, \partial_\mu\phi - g_{\mu\nu}\partial^\alpha\phi\, \partial_\alpha\phi\right),$$

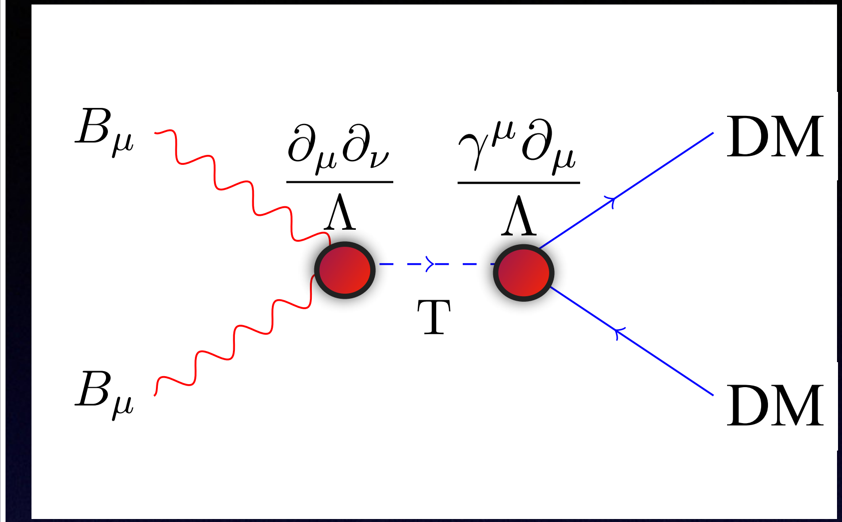
$$T^{1/2}_{\mu\nu} = \frac{i}{4}\bar{\psi}\left(\gamma_\mu\partial_\nu + \gamma_\nu\partial_\mu\right)\psi - \frac{i}{4}\left(\partial_\mu\bar{\psi}\gamma_\nu + \partial_\nu\bar{\psi}\gamma_\mu\right)\psi$$

$$T^1_{\mu\nu} = \frac{1}{2}\left[F^\alpha_\mu F_{\nu\alpha} + F^\alpha_\nu F_{\mu\alpha} - \frac{1}{2} g_{\mu\nu} F^{\alpha\beta} F_{\alpha\beta}\right].$$

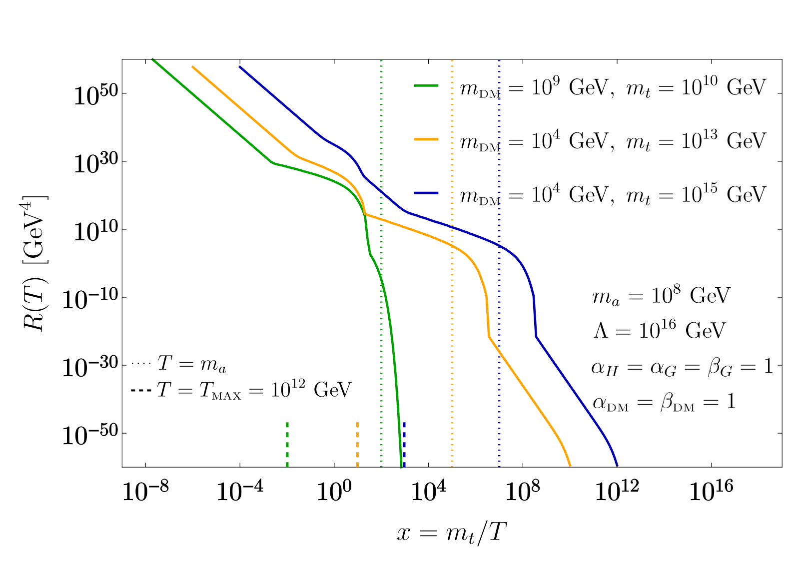


Moduli mediator

[arXiv:1811.01947]



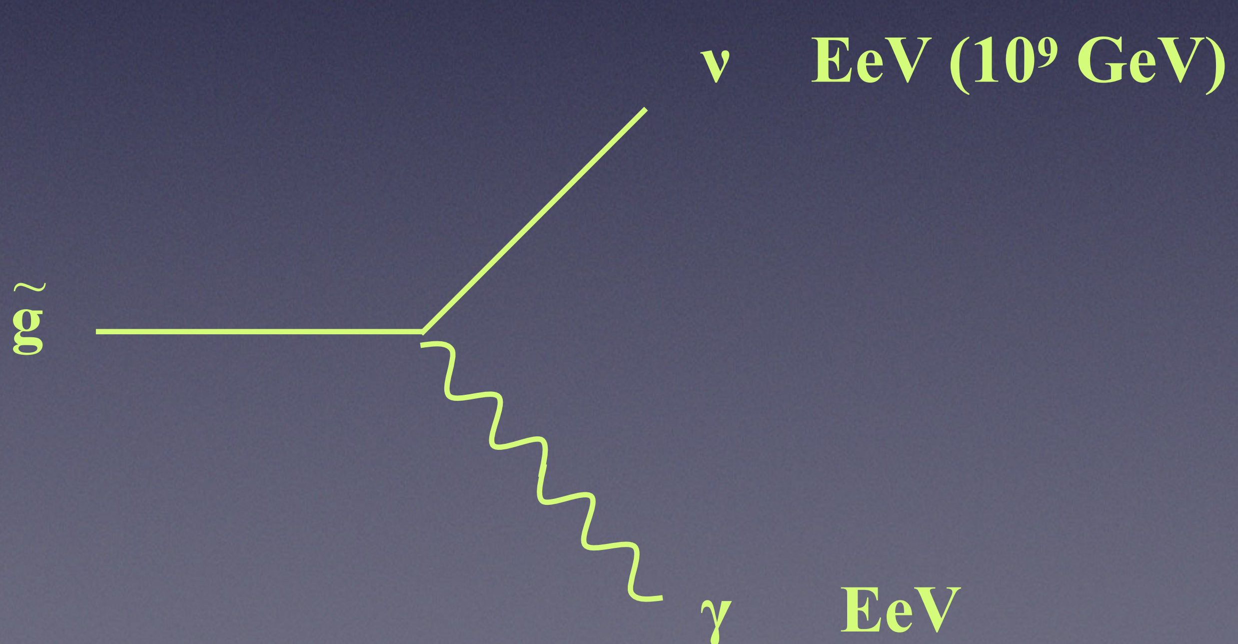
$$\begin{aligned}\mathcal{L}^{SM}_T \supset & \frac{\alpha_H}{\Lambda}\, t\, |D_\mu H|^2 - \frac{\alpha_H}{\Lambda}\, \mu_0^2\, t\, |H|^2 \\ & + \left(\frac{1}{2\Lambda}\, t\, \bar{f} i\gamma^\mu(\alpha^f_{\rm V} - \alpha^f_{\rm A}\gamma_5) D_\mu f + {\rm h.c.}\right) \\ & + \frac{1}{2\Lambda}\partial_\mu a\, \bar{f}\gamma^\mu(\beta^f_{\rm V} - \beta^f_{\rm A}\gamma_5) f \\ & - \frac{1}{4}\frac{\alpha_G}{\Lambda}\, t\, G_{\mu\nu}G^{\mu\nu} + 2\frac{\beta_G}{\Lambda}\, \partial_\mu a\, \epsilon^{\mu\nu\rho\sigma} G_\nu \partial_\rho G_\sigma\end{aligned}$$



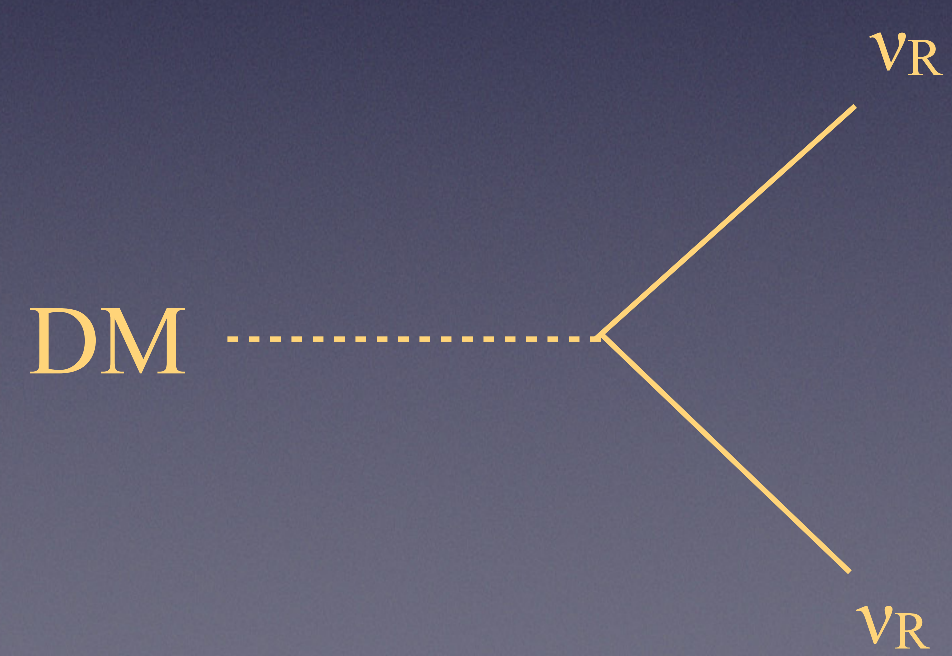
« And what is the signature of such models? »

A smoking gun signal

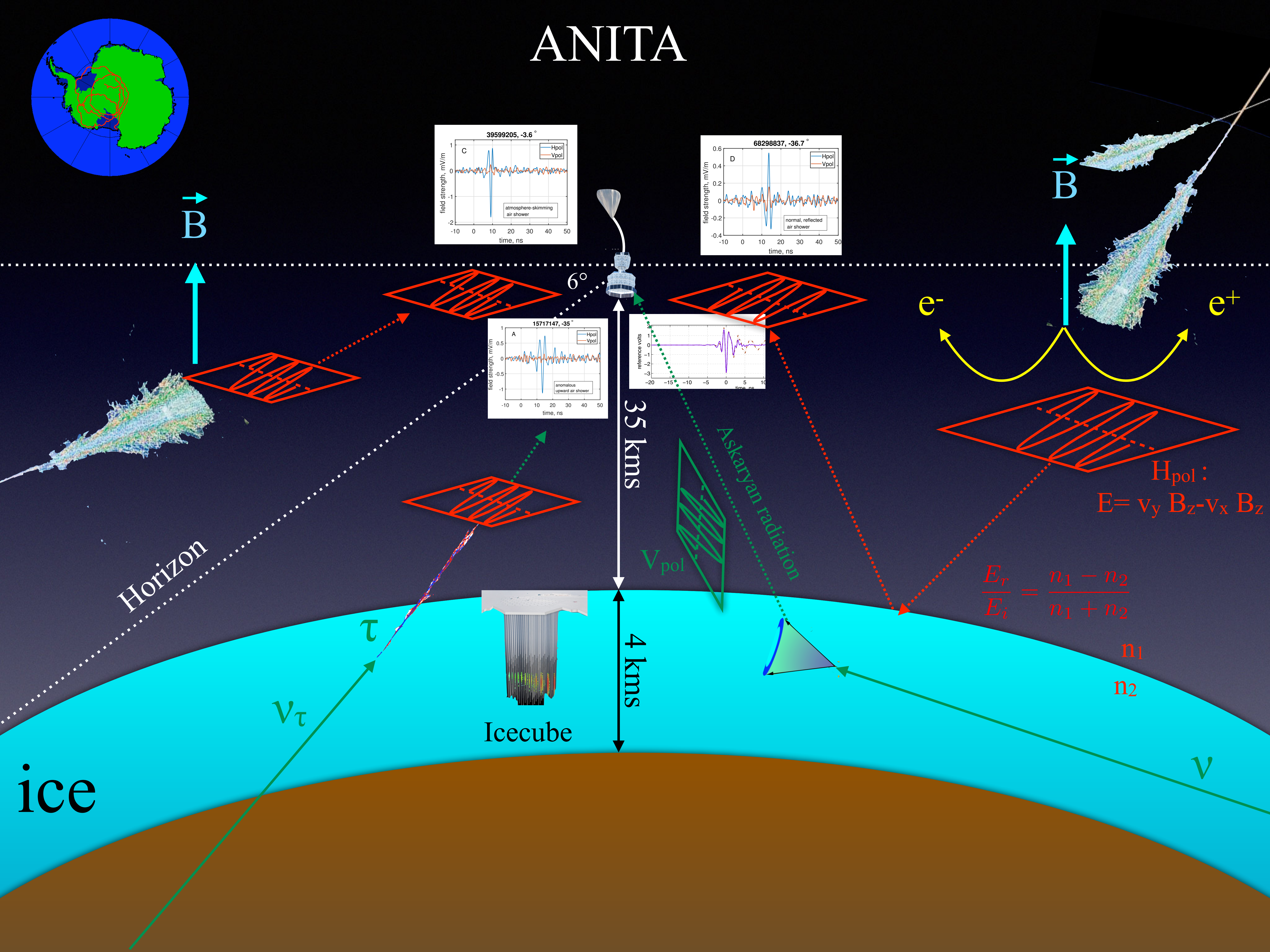
Gravitino DM



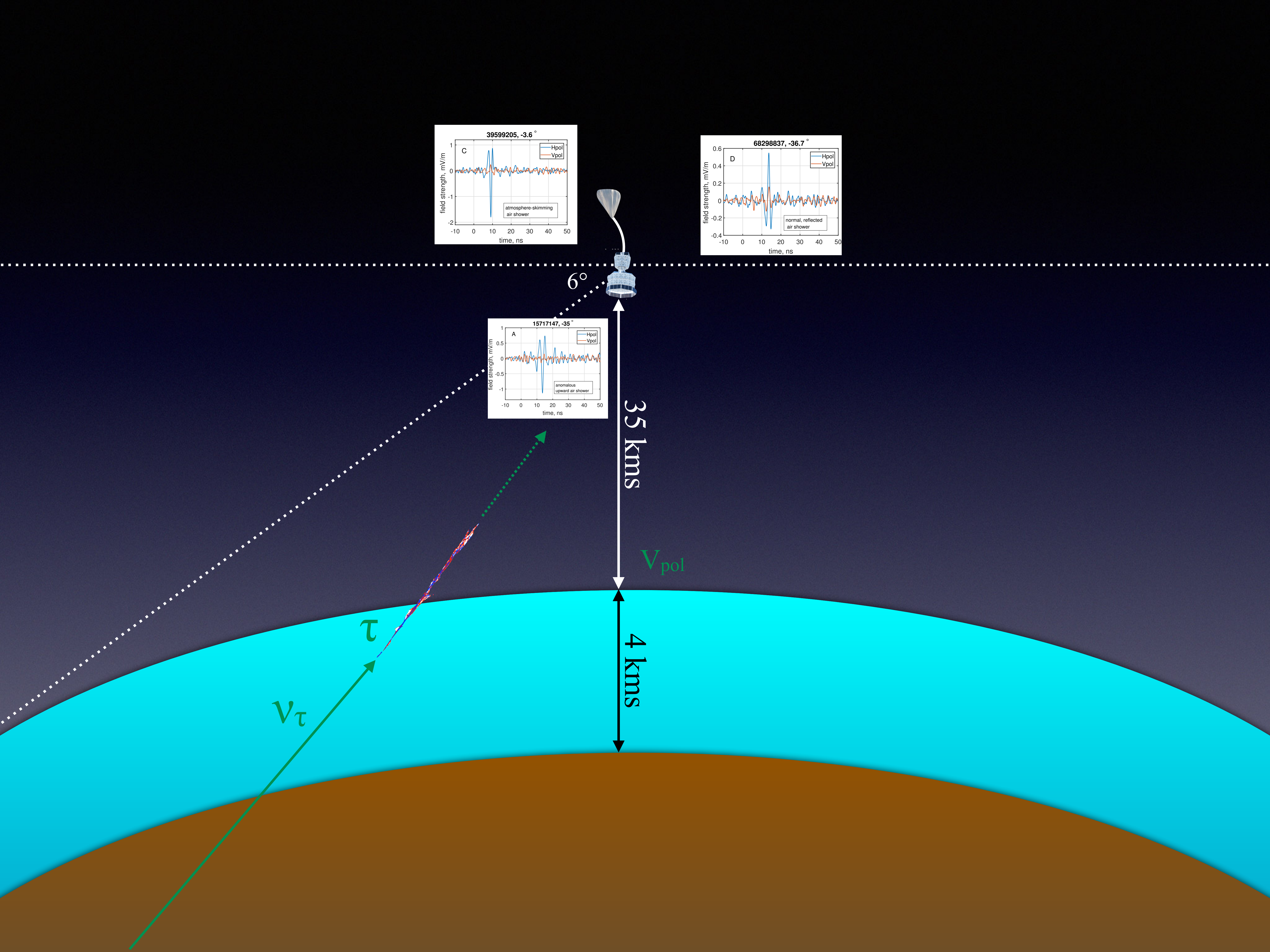
Scalar DM



EeV events?

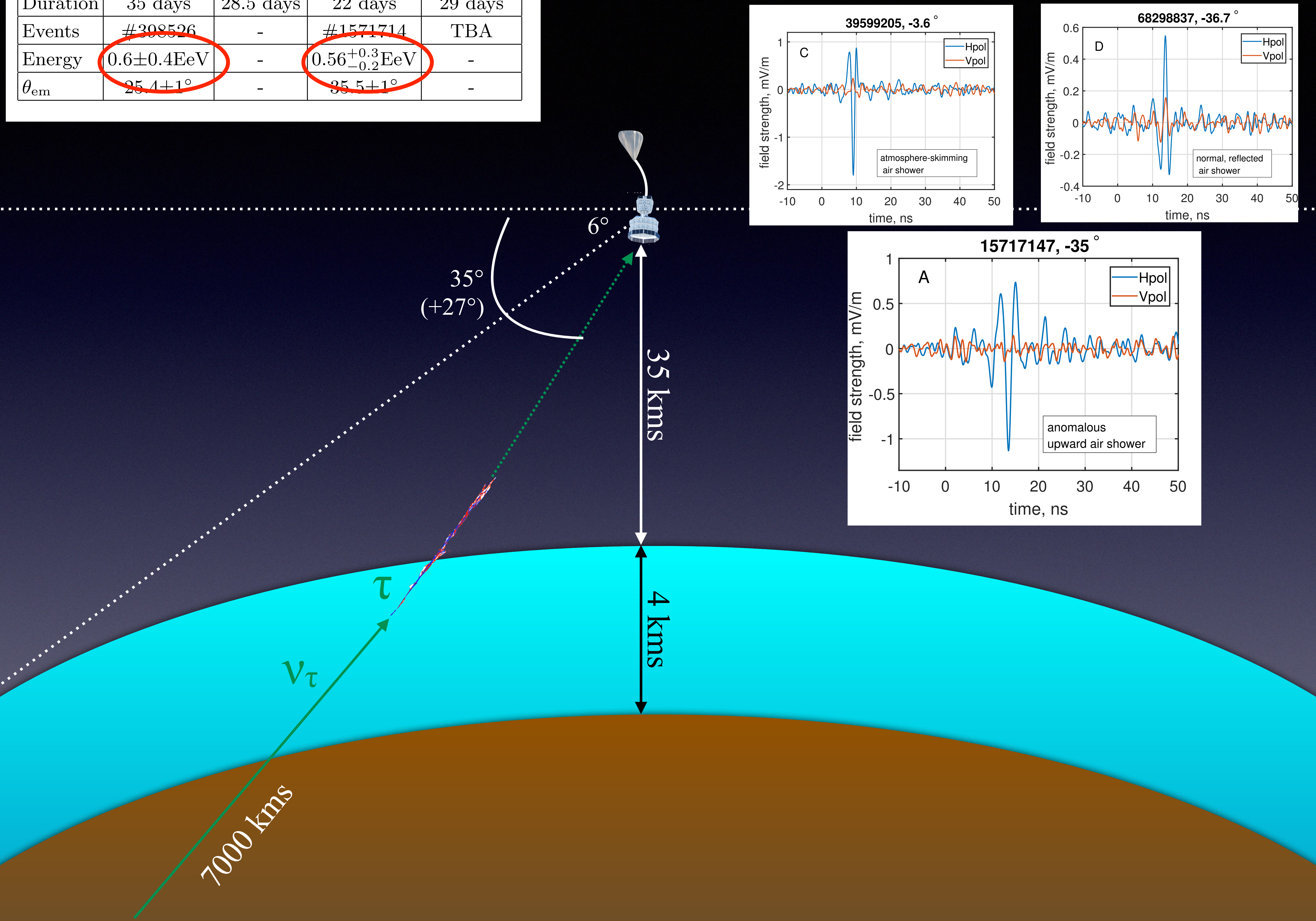


ANITA
39599205, -3.6°
atmosphere-skimming air shower
68298837, -36.7°
normal, reflected air shower
15717147, -35°
anomalous upward air shower
6°
35 kms
4 kms
Askaryan radiation
V_{pol}
H_{pol} :
$E= v_y B_z - v_x B_z$
$\frac{E_r}{E_i} = \frac{n_1 - n_2}{n_1 + n_2}$
n_1
n_2
$\vec{B}$
$\vec{B}$
e^-
e^+
Horizon
τ
ν_τ
ν
Icecube
ice



39599205, -3.6 °
C
Hpol
Vpol
field strength, mV/m
atmosphere-skimming air shower
time, ns
68298837, -36.7 °
D
normal, reflected air shower
15717147, -35 °
A
anomalous upward air shower
6°
35 kms
4 kms
V_{pol}
τ
ν_τ

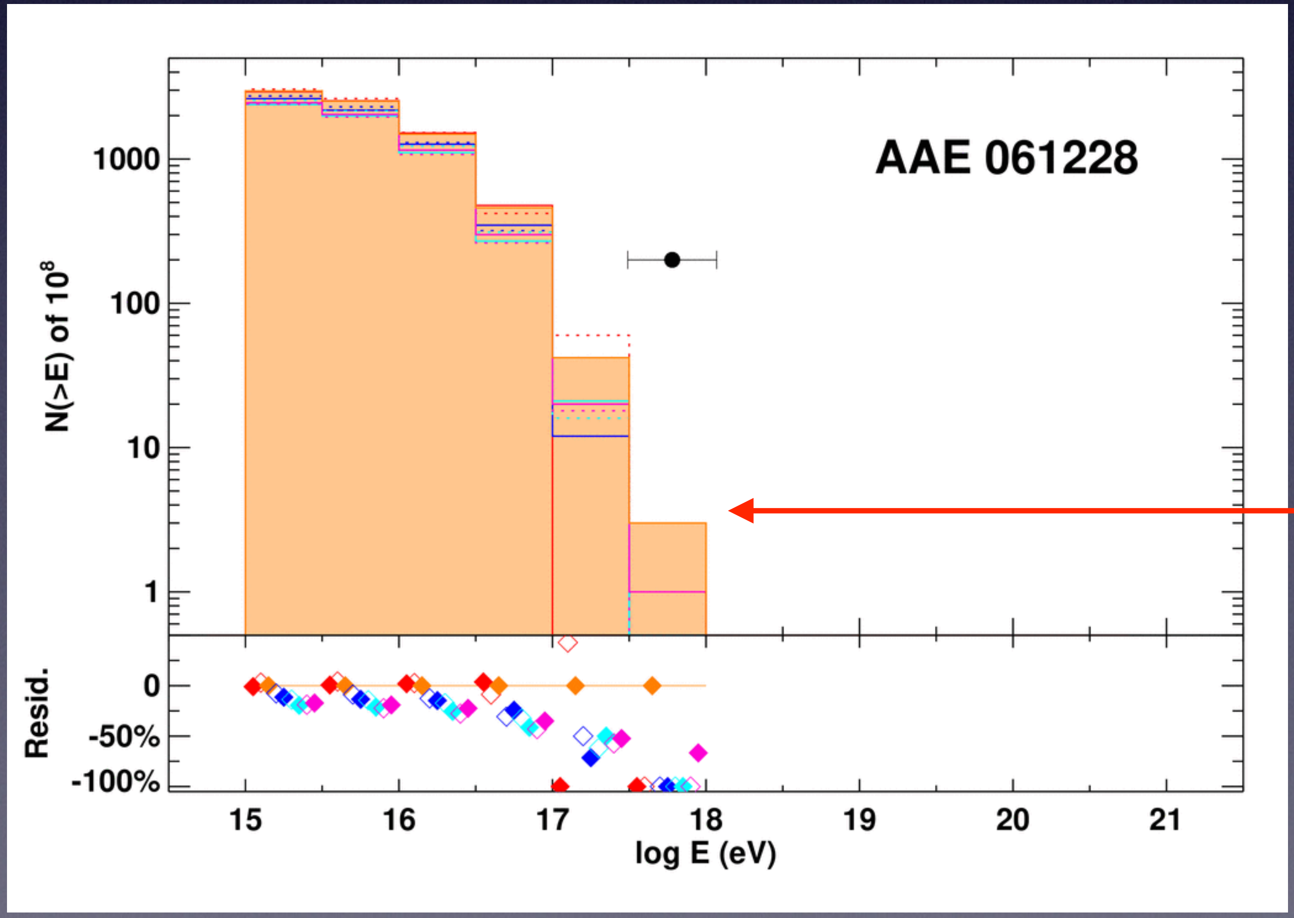
Flight	ANITA I	ANITA II	ANITA III	ANITA IV
Duration	35 days	28.5 days	22 days	29 days
Events	#398526	-	#1571714	TBA
Energy	0.6±0.4EeV	-	$0.56^{+0.3}_{-0.2}$EeV	-
θ_{em}	25.4±1°	-	35.5±1°	-



2 Anomalous events at 0.5 EeV

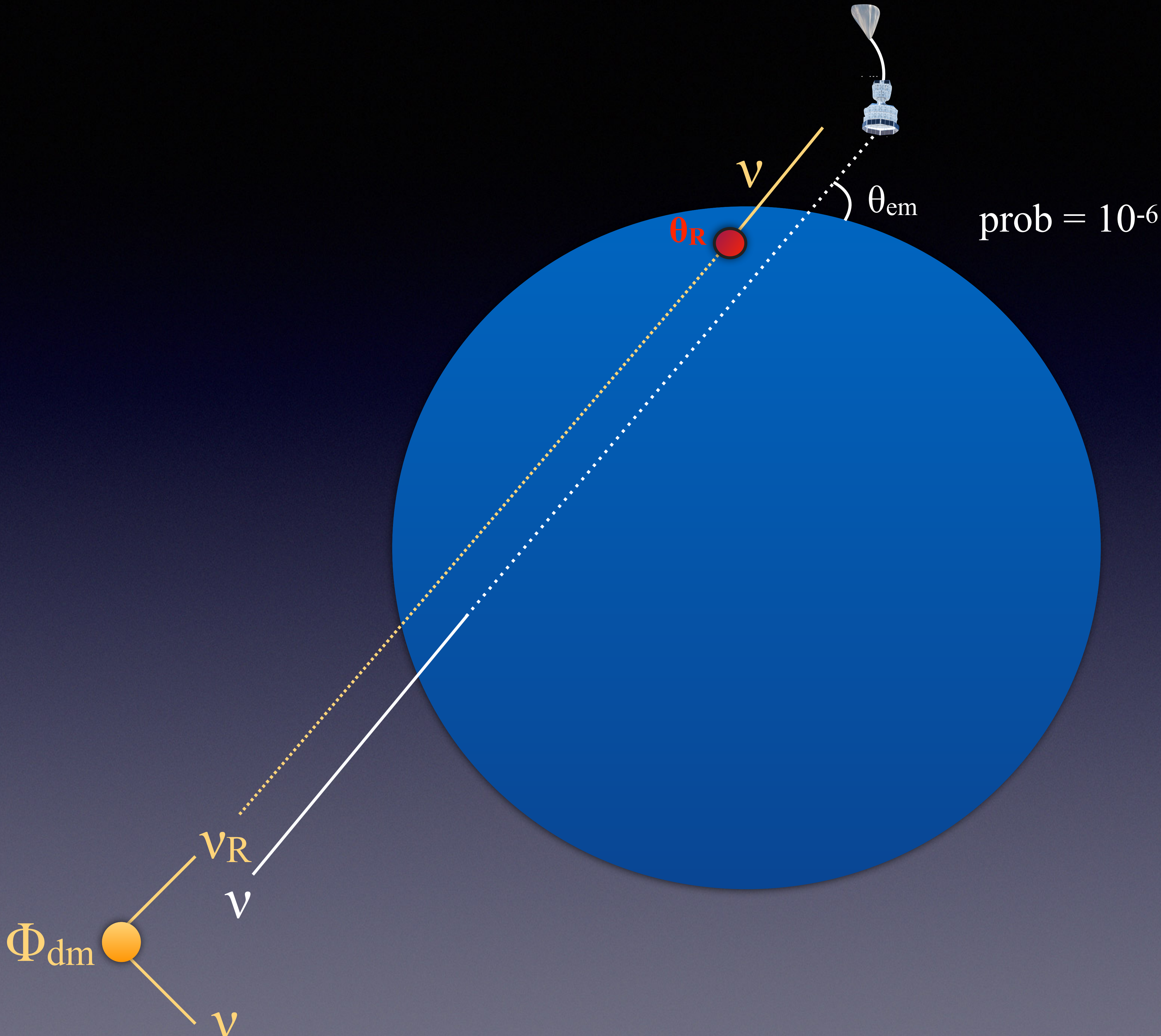
- Mean free path for an EeV neutrino in the earth crust is ~100 kms

- Probability $p \sim 10^{-6}$ of crossing 7000 kms

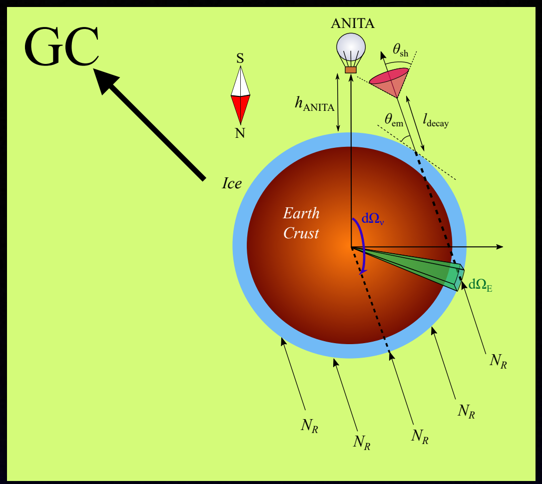


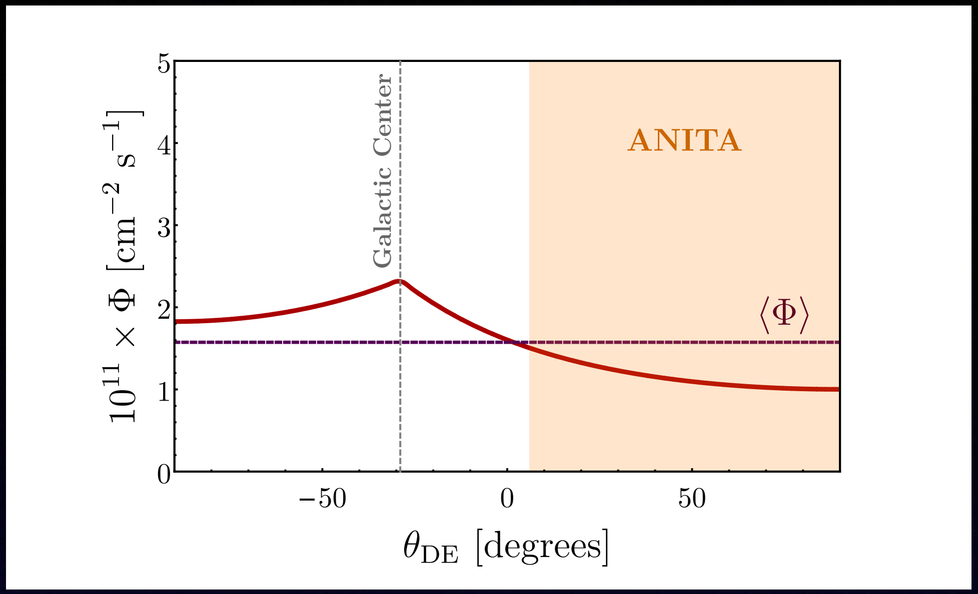
3 events left
from 100 million generated

Fox et al.; arXiv:1806.09615



L. Heurtier, Y. Mambrini and M. Pierre, Phys. Rev. D **99** (2019) no.9, 095014 [arXiv:1902.04584].



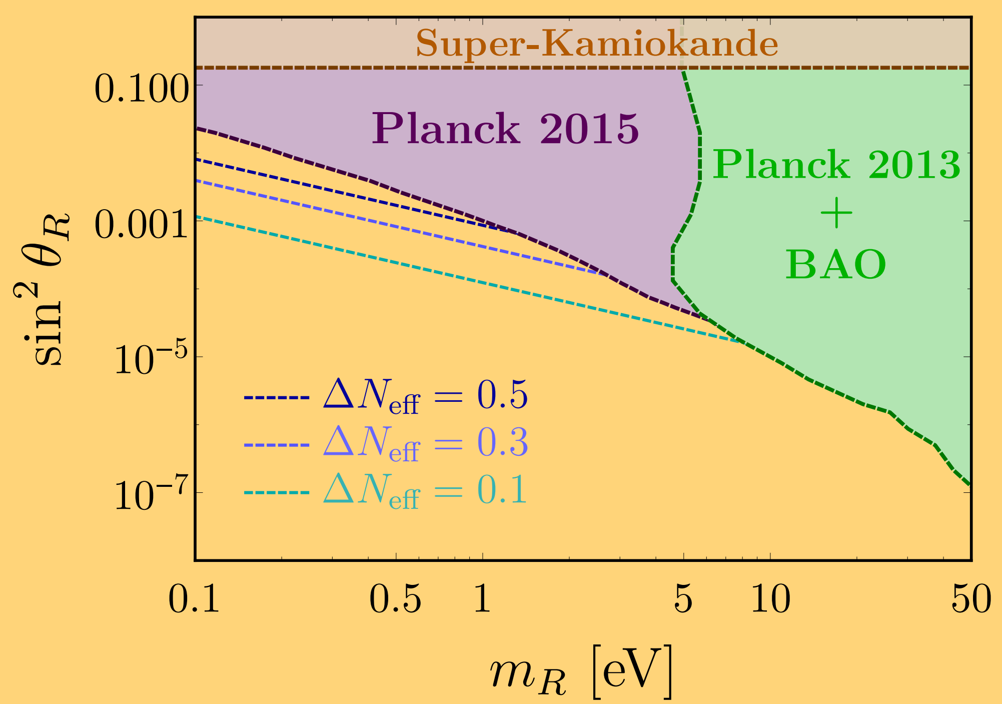


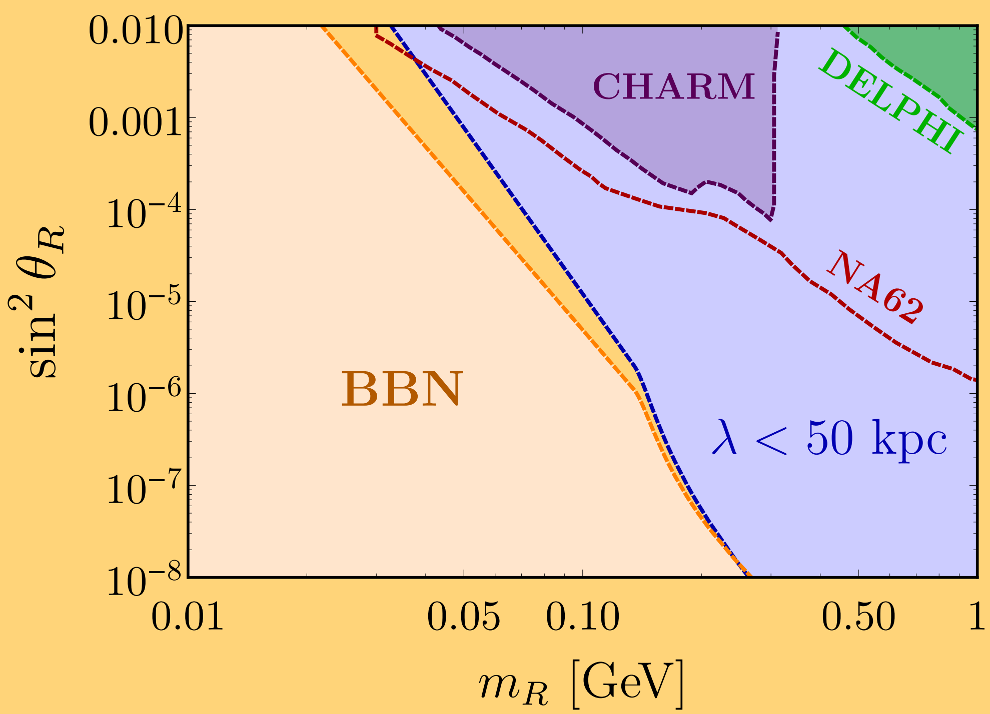
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_\nu + \frac{y_\phi}{\sqrt{2}}\phi\bar{\nu}_R^c\nu_R - \frac{1}{2}m_{\rm DM}^2\phi^2$$

$$\rho_{\rm DM}(r) \propto \frac{1}{\left(\frac{r}{r_s}\right)\left[1+\left(\frac{r}{r_s}\right)^2\right]}$$

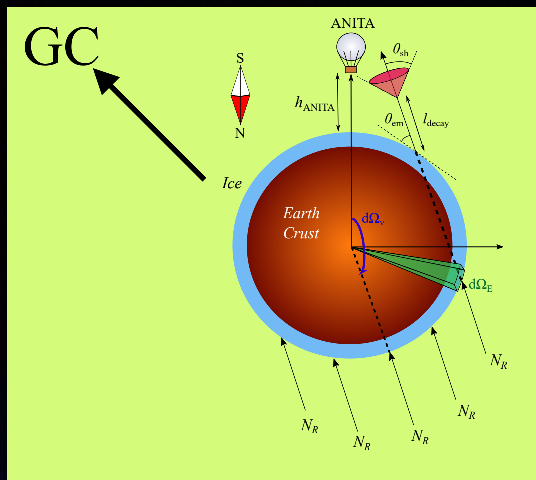
Taking into account constraints from $N_{\rm eff}$ + BAO + relic abundance + CHARM + mean free path..

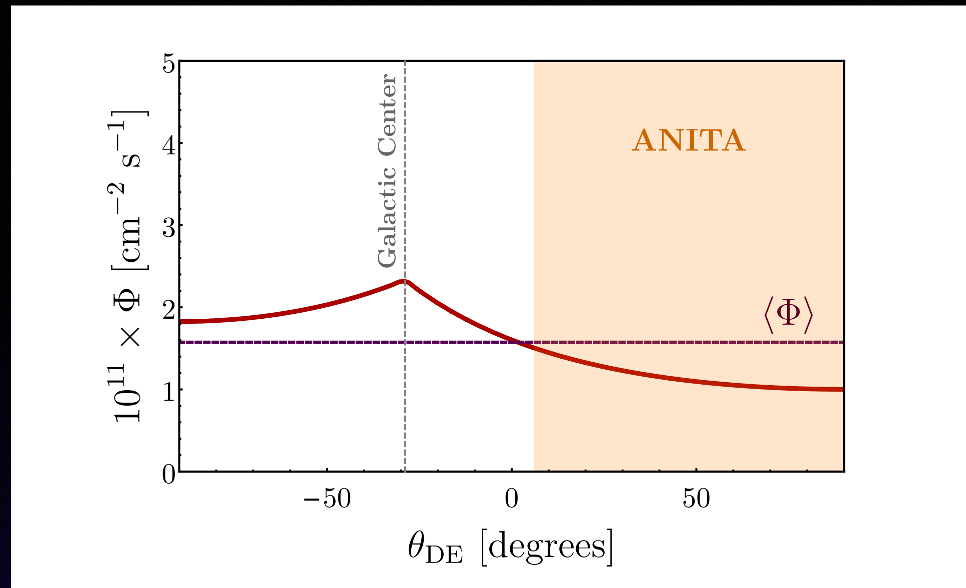
2 regions are left: **ν_R < 50 eV and 10 MeV < ν_R < 0.5 GeV**





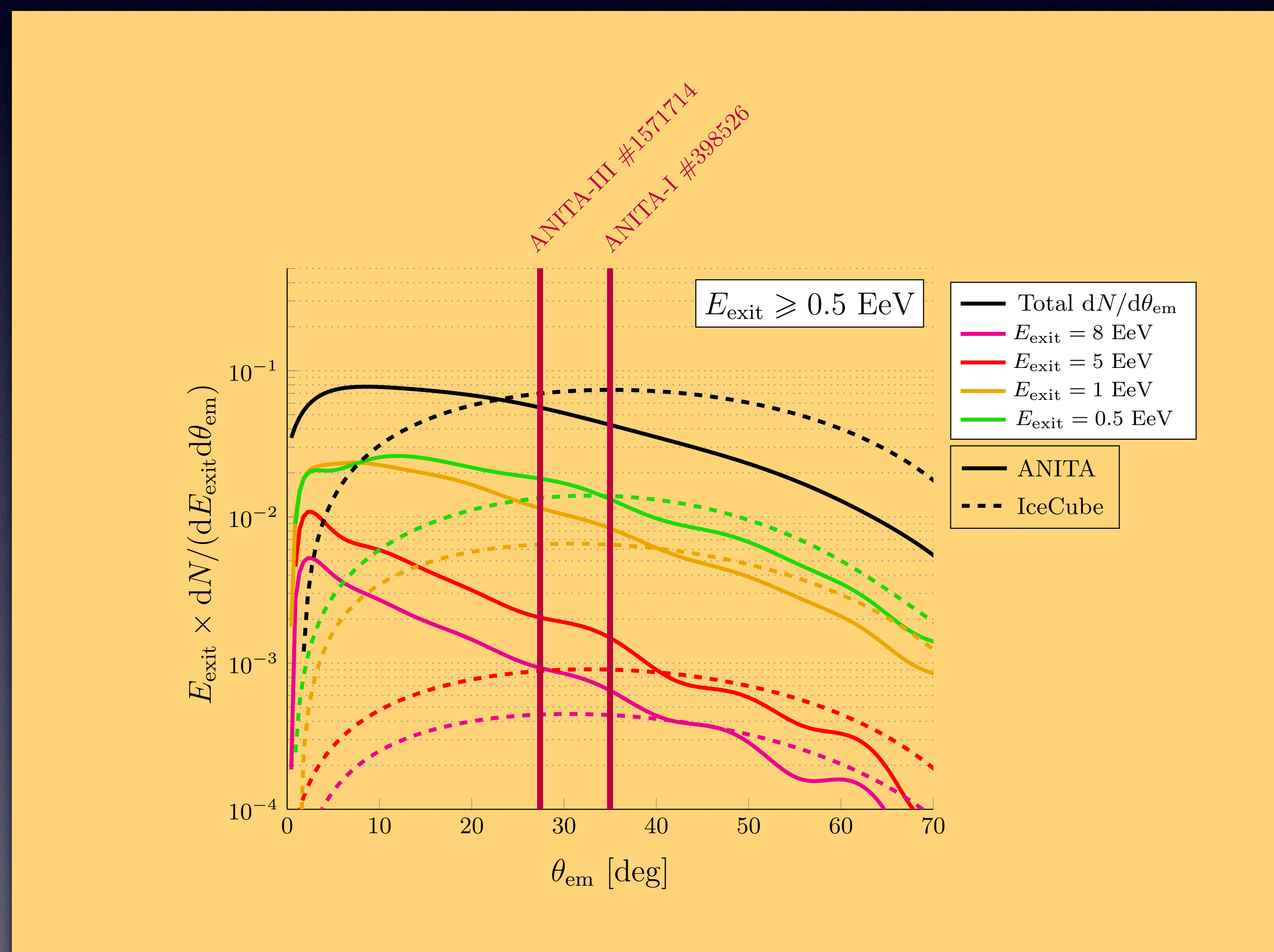
L. Heurtier, Y.M., M. Pierre; arXiv:1902.xxxxx





$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_\nu + \frac{y_\phi}{\sqrt{2}} \phi \bar{\nu}_R^c \nu_R - \frac{1}{2} m_{\rm DM}^2 \phi^2$$

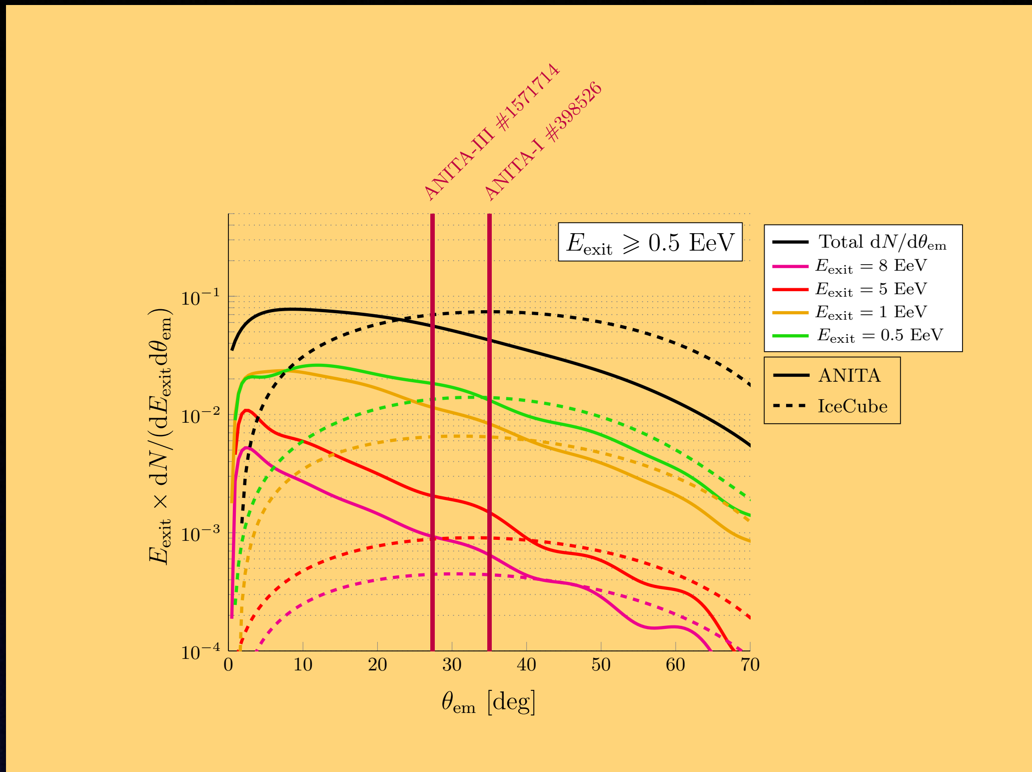
$$\rho_{\rm DM}(r) \propto \frac{1}{\left(\frac{r}{r_s}\right)\left[1 + \left(\frac{r}{r_s}\right)\right]^2}$$



$$N_{tot} \simeq 2.5 \times \left(\frac{\theta_R}{0.01}\right)^2 \left(\frac{10^{23}}{\tau_{DM}}\right) \left(\frac{T_{\rm exp}}{85.5 \text{ days}}\right) \left(\frac{20 \text{ EeV}}{m_{\rm DM}}\right)^{2/3}$$

L. Heurtier, Y.M., M. Pierre; arXiv:1902.xxxxx

IceCube



Even if the exposure of IceCube is larger than ANITA, a 20 PeV τ has a mean free path > 1 km : difficult to distinguish it from a μ (just a track, no decay)

For this reason it has been shown by Fox et al. [1809.09615] that the 2 ~PeV down-going events observed by IceCube can be misinterpreted as ~ 0.07 EeV upgoing events.
Which is also the number of events we predict…

L. Heurtier, Y.M., M. Pierre; arXiv:1902.xxxxx

Conclusions

Wimp paradigm is in question

Alternative scenarios (FIMP, reheating) can lead to EeV DM

Not independent on the initial conditions (more complex thermal scenarios)

PeV/EeV DM observable (observed?) by Icecube and/or ANITA