Cosmology III

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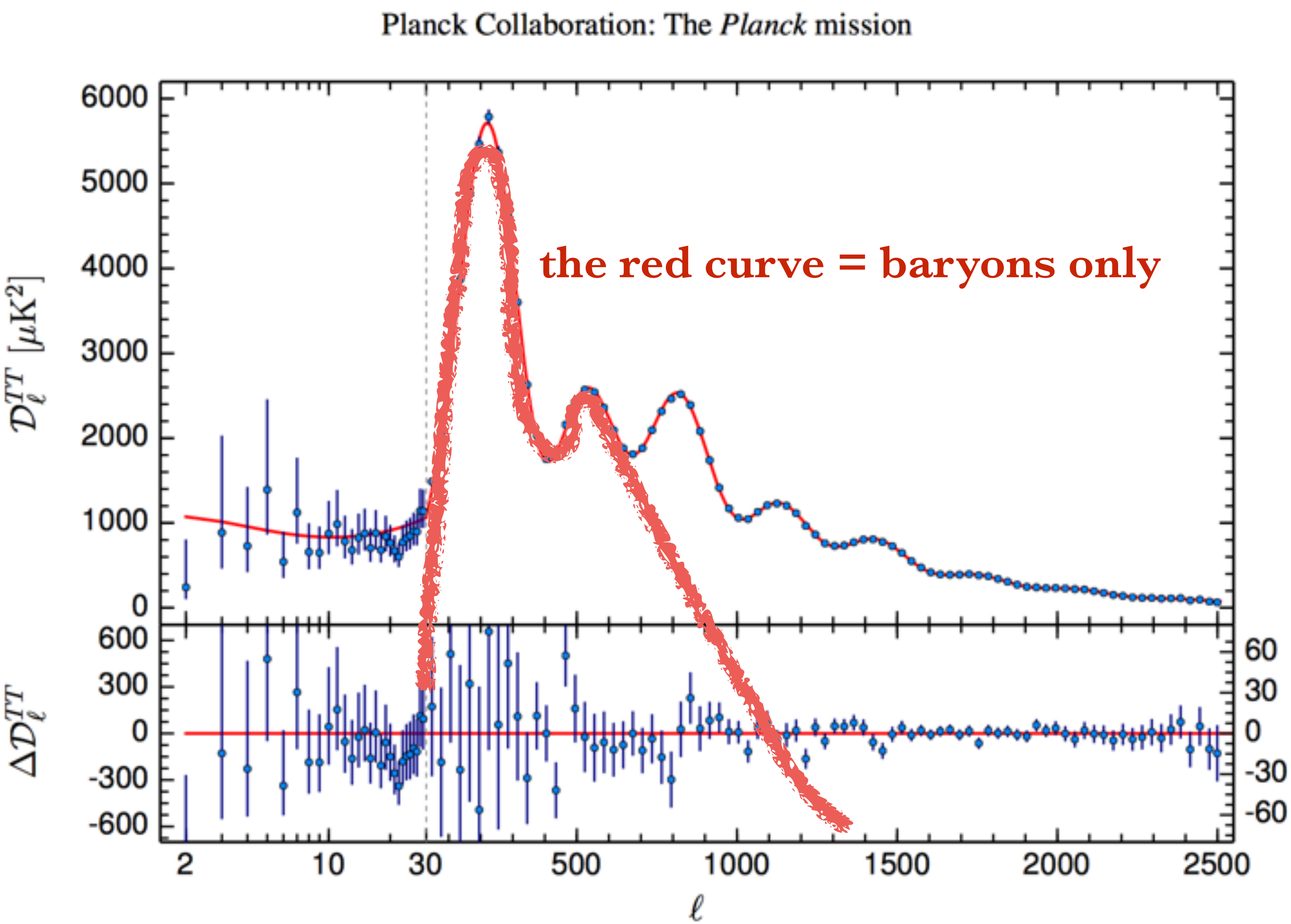
2017

Anisotropies of temperature

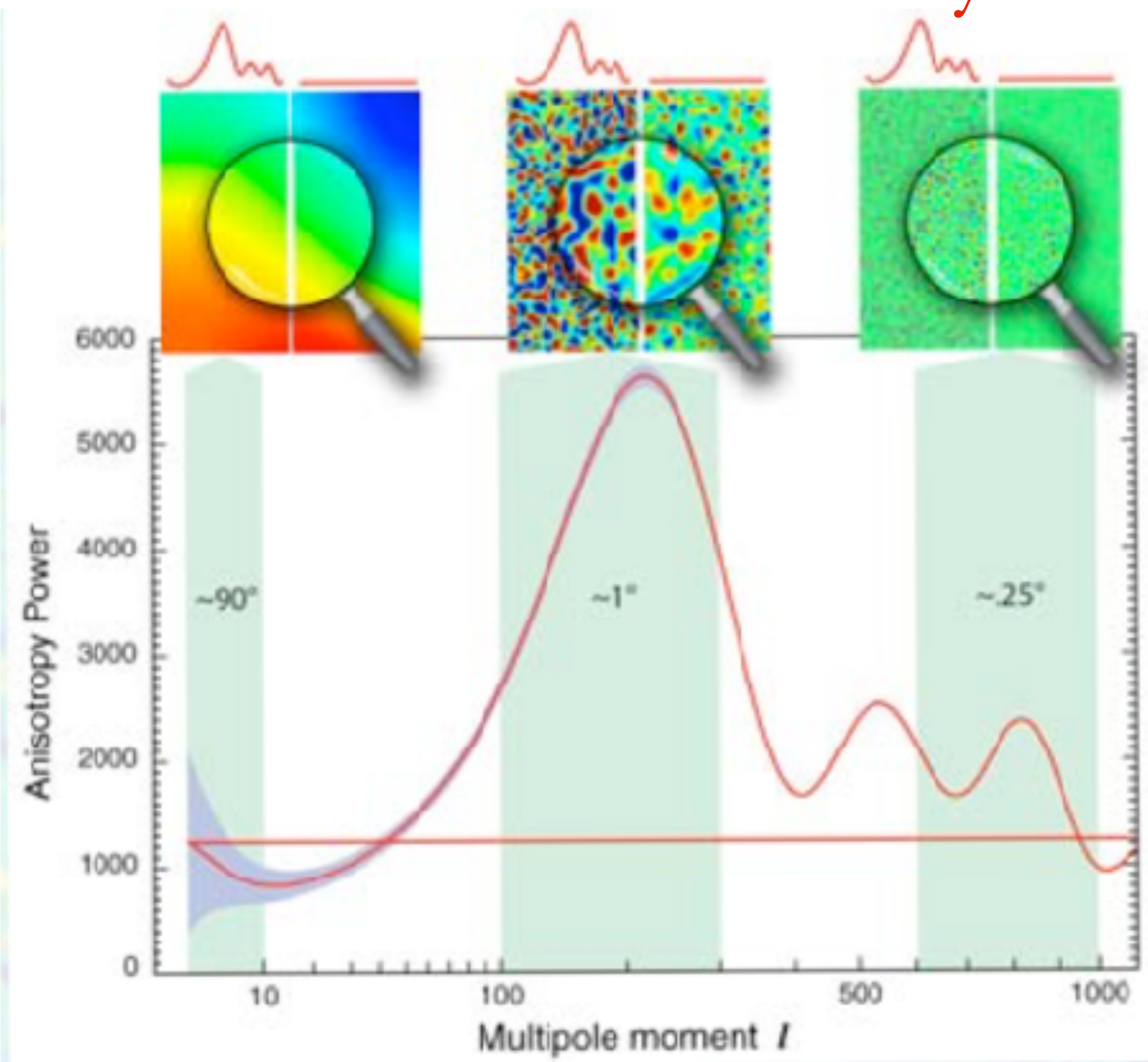


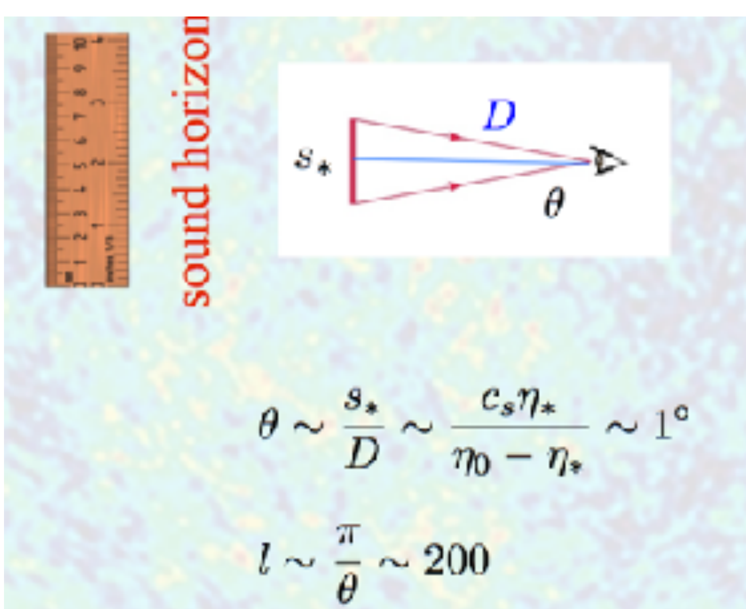
the suppression of small-scales is indicative of the presence of baryons

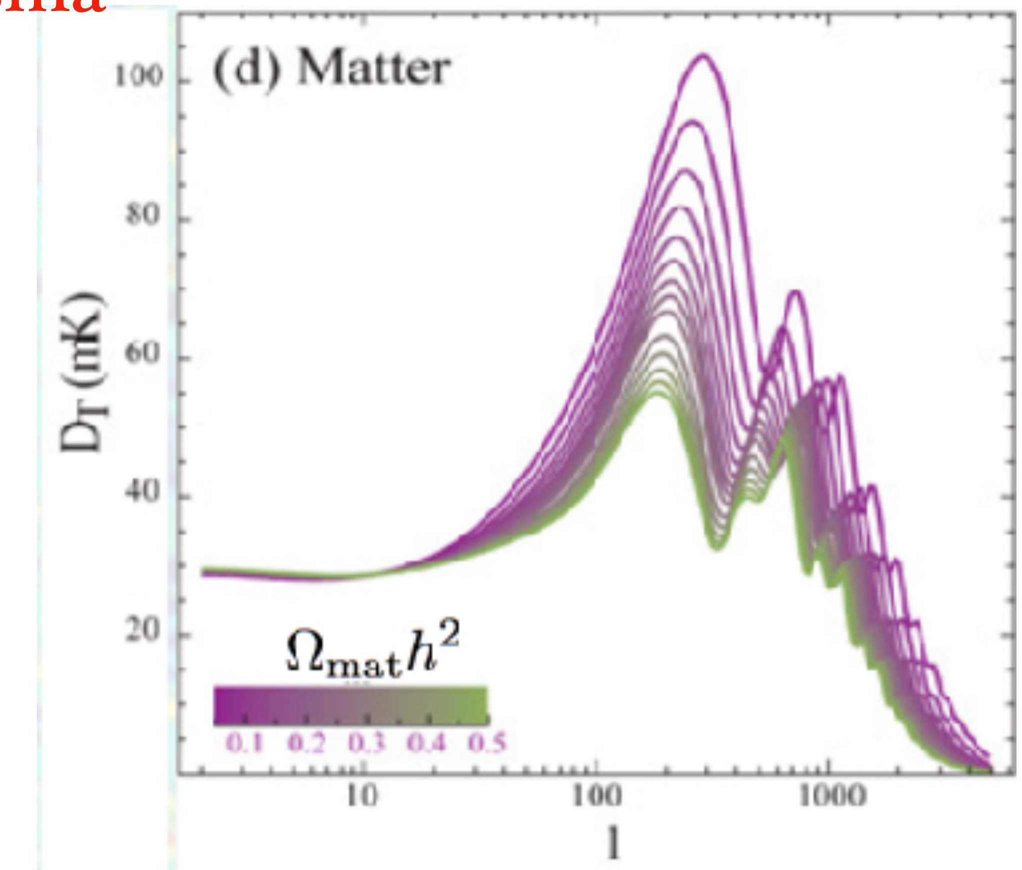
Therefore there must be more than the baryons

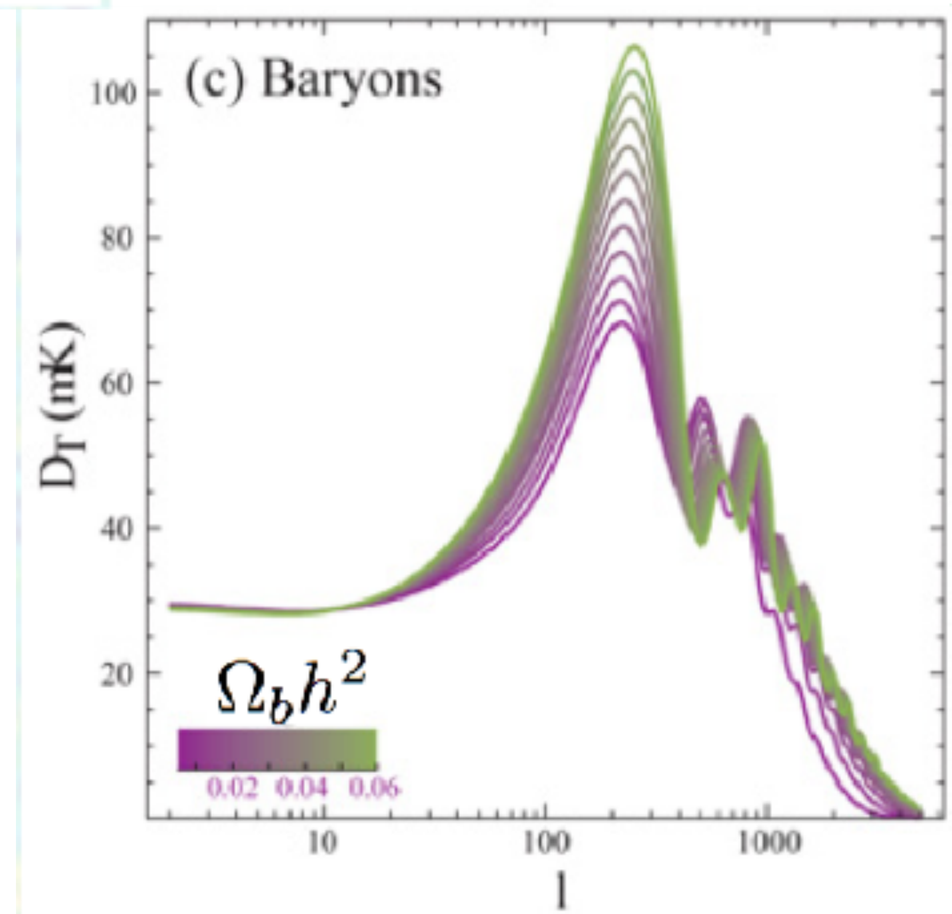
Anisotropies of temperature

Courtesy Marieke Potsma





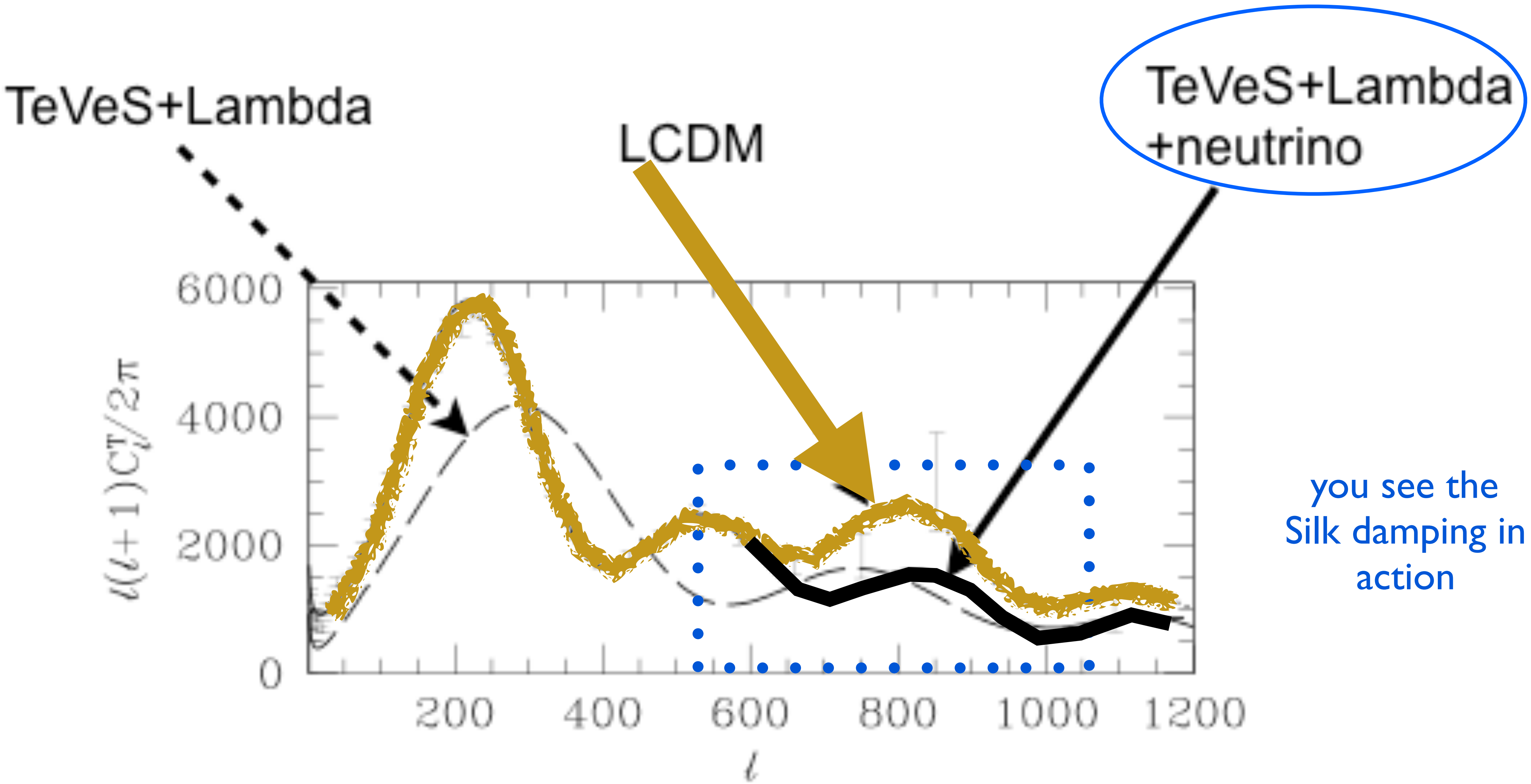




One possible theory : TeVeS (baryons only)

Bekenstein astro-ph/0403694

Silk damping unavoidable astro-ph/0505519



you see the Silk damping in action

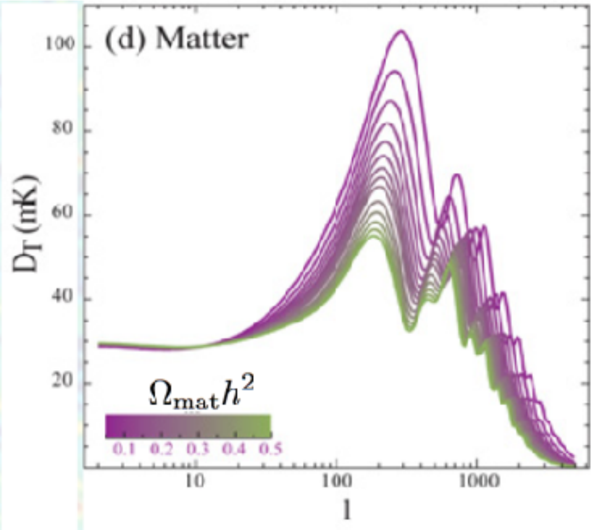
Main problem: how to reproduce the 7-8 peaks seen by Planck & ACT?

III. DM

DM

gravity

matter



massive particles

stable

neutral

not in atoms

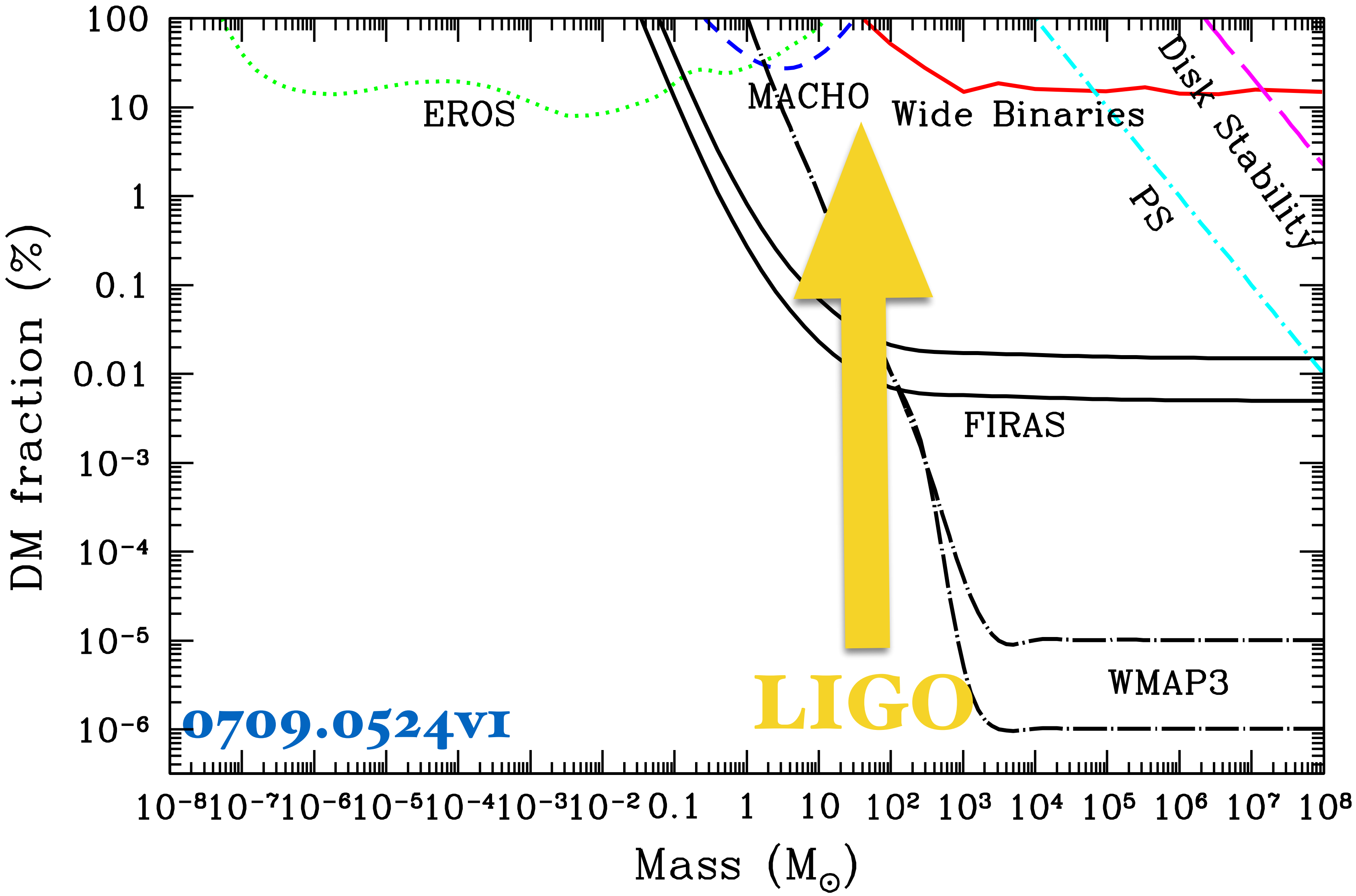
long lifetime

no electrical charge

no strong force

Weakly interacting

Can Primordial Black Holes be the DM?

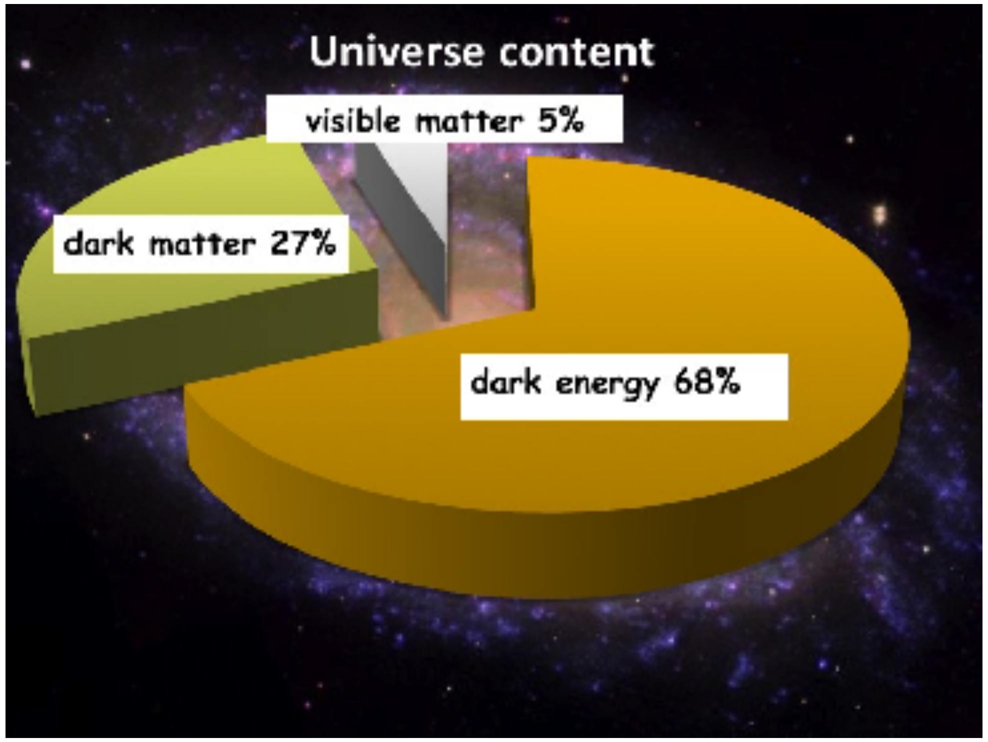


Primordial Black Holes ??? arXiv:1603.00464
arXiv:1501.07565
arXiv:1607.06077

> 100 Msol ruled out as main DM component

Ways to evade CMB limits arXiv:1612.05644

Relic density



Why 27%?

How many DM particles were produced in the Early Universe?

How much should there be today if DM was made of particles?

Does it match observations?

Relic density

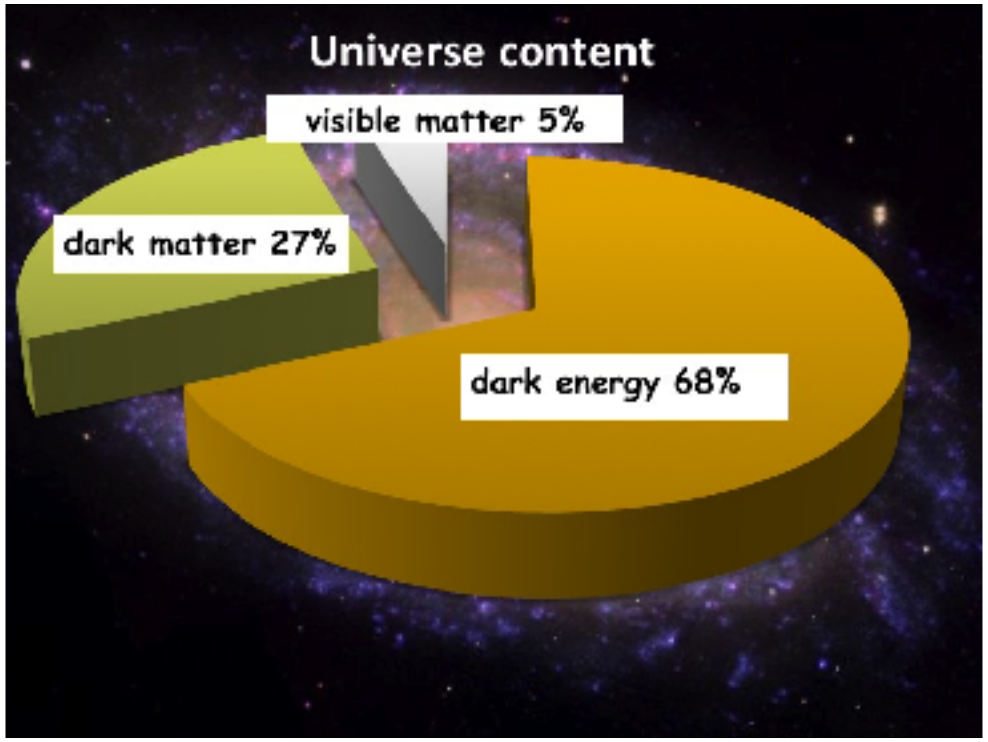
For the “baryons”

Thermal production

$$e^+e^- \to \gamma\gamma$$

$$\sigma_T \sim 6\ 10^{-25}\ \text{cm}^2$$

The annihilation process is so efficient that there would be no electrons left at all



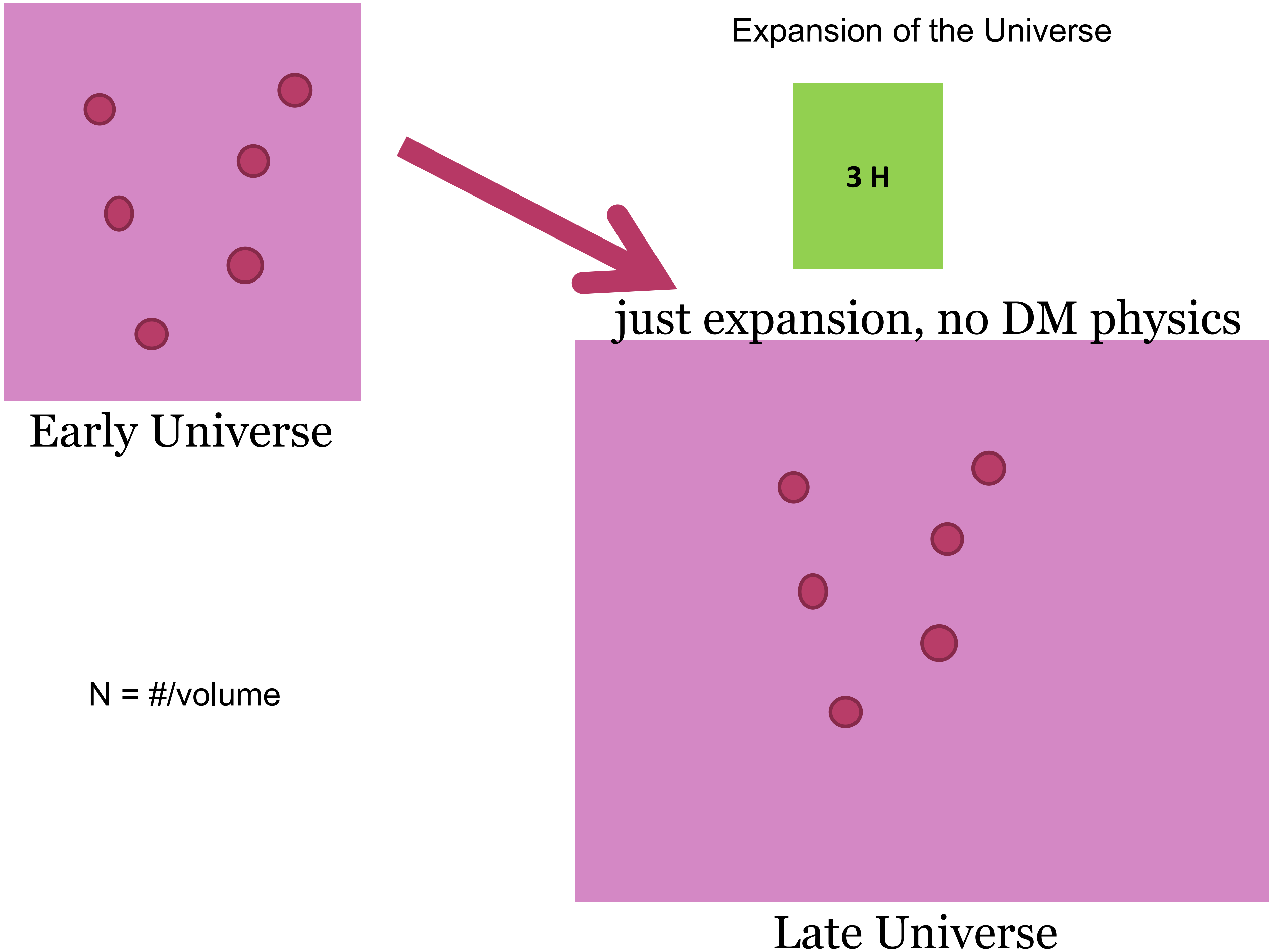
Asymmetry

For the Dark Matter

Thermal production   but …   non-thermal,freeze-in

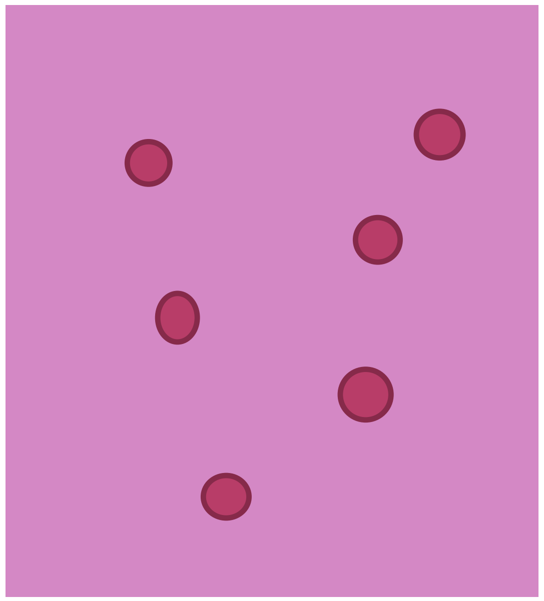
No asymmetry!   but …

Relic density



Massive DM particles can overclose the Universe!

Relic density

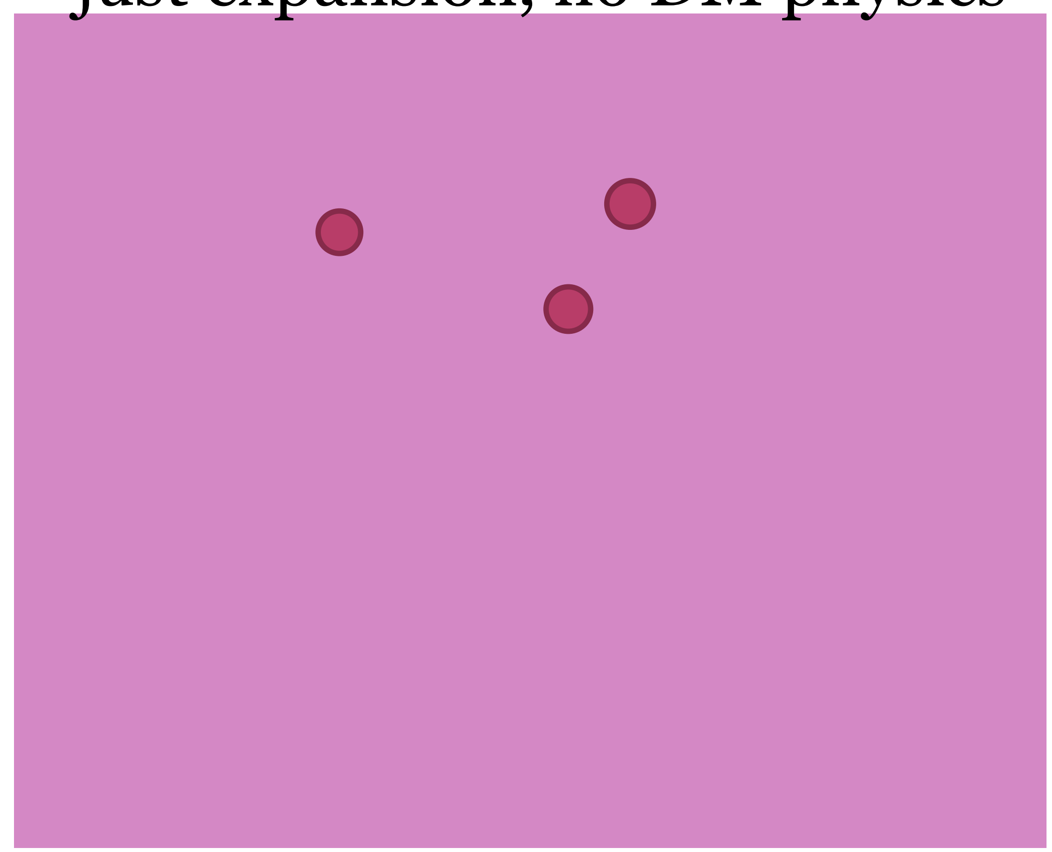


Early Universe

Expansion of the Universe

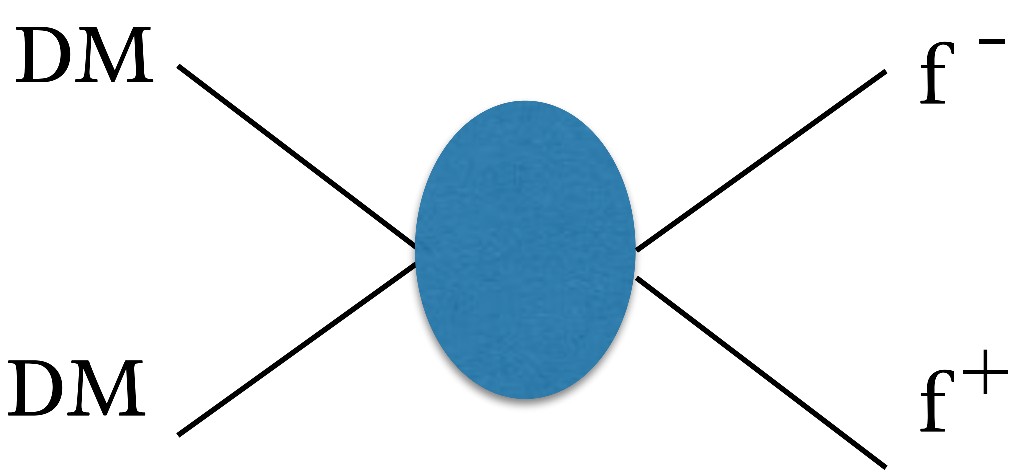
3 H

just expansion, no DM physics



Late Universe

N = #/volume



Number is reduced due to annihilations

The Boltzmann equation

Expansion of the Universe

number density of DM

(#/V)

$$\frac{dn}{dt} = -3Hn - \sigma v(n^2 - n_0^2)$$

Time evolution of the number density

Annihilations change the number density

III. DM

Deriving the Boltzmann equation

$$\frac{df}{d\lambda} = C(f)$$

$$\frac{df}{d\lambda} = \frac{\partial f}{\partial x^\mu}\frac{dx^\mu}{d\lambda} + \frac{\partial f}{\partial p^\nu}\frac{dp^\nu}{d\lambda} = p^\mu \frac{\partial f}{\partial x^\mu} - \Gamma^\nu{}_{\alpha\beta}\, p^\alpha p^\beta \frac{\partial f}{\partial p^\nu}$$

using $\frac{dp^\nu}{d\lambda} + \Gamma^\nu{}_{\alpha\beta}\, p^\alpha p^\beta = 0$

Isotropic Universe $p^i \frac{\partial f}{\partial x^i} = 0$

$$\frac{df}{d\lambda} = E\frac{\partial f}{\partial t} - \Gamma^0{}_{\alpha\beta}\, p^\alpha p^\beta \frac{\partial f}{\partial E}$$

$$E\frac{\partial f}{\partial t} - \Gamma^0{}_{\alpha\beta}\, p^\alpha p^\beta \frac{\partial f}{\partial E} = C(f)$$

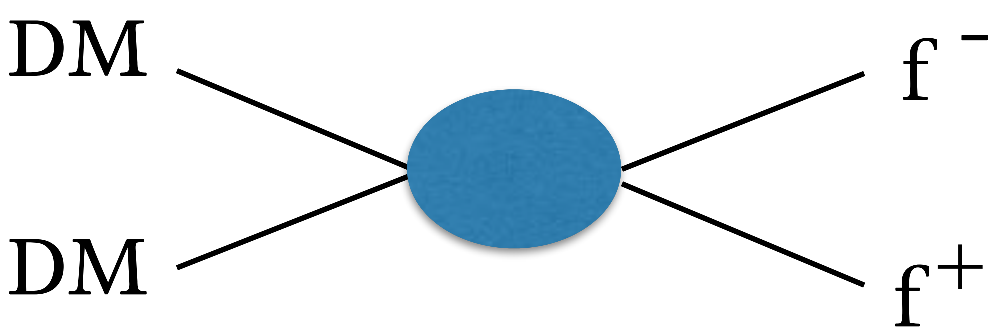
$$\frac{\partial f}{\partial t} - H\frac{E^2 - m^2}{E}\frac{\partial f}{\partial E} = \frac{1}{E}C(f)$$

$$\frac{g}{(2\pi)^3}\int\left(\frac{\partial f}{\partial t} - H\frac{E^2-m^2}{E}\frac{\partial f}{\partial E}\right)d^3p = \frac{g}{(2\pi)^3}\int \frac{1}{E}C(f)d^3p.$$

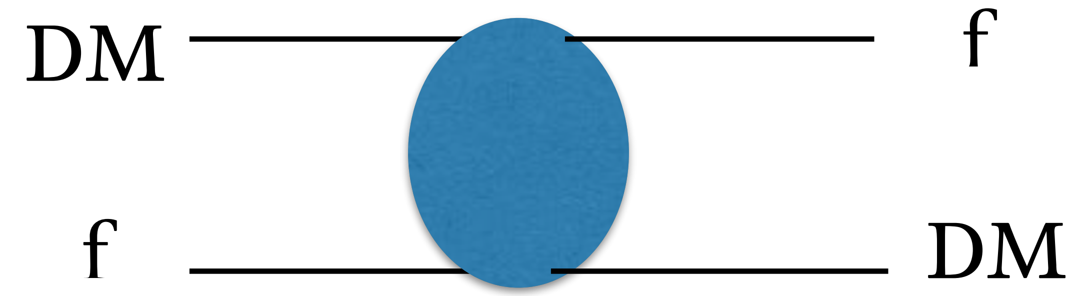
$$\frac{\partial n}{\partial t} + 3Hn = \frac{g}{(2\pi)^3}\int \frac{1}{E}C(f)d^3p.$$

Deriving the Boltzmann equation

$$\frac{\partial n}{\partial t} + 3Hn = \frac{g}{(2\pi)^3}\int \frac{1}{E} C(f)\, d^3 p.$$



annihilations; change the number density



elastic scattering; do not change density

$$C(f) = -\frac{1}{2}\sum_{spins}\int \left[f f_2 (1 \pm f_3)(1 \pm f_4) \left|\mathcal{M}_{12\to 34}\right|^2 - f_3 f_4 (1 \pm f)(1 \pm f_2) \left|\mathcal{M}_{34\to 12}\right|^2 \right]$$

$$(2\pi)^4 \delta^4 (p + p_2 - p_3 - p_4) \frac{d^3 p_2}{(2\pi)^3 2E_2} \frac{d^3 p_3}{(2\pi)^3 2E_3} \frac{d^3 p_4}{(2\pi)^3 2E_4}$$

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

III. DM

Boltzmann equation caught in the act

number of particles

(reverse) annihilation

expansion

$$\mathrm{DM}\ \mathrm{DM} \rightarrow \mathrm{f}\ \bar{\mathrm{f}}$$
$$f\ \bar{f} \rightarrow \mathrm{DM}\ \mathrm{DM}$$

1-way annihilation

$$\mathrm{DM}\ \mathrm{DM} \rightarrow \mathrm{f}\ \bar{\mathrm{f}}$$

Expansion wins but annihilations were too efficient

Non-relativistic transition

today

number of particles

(reverse) annihilation

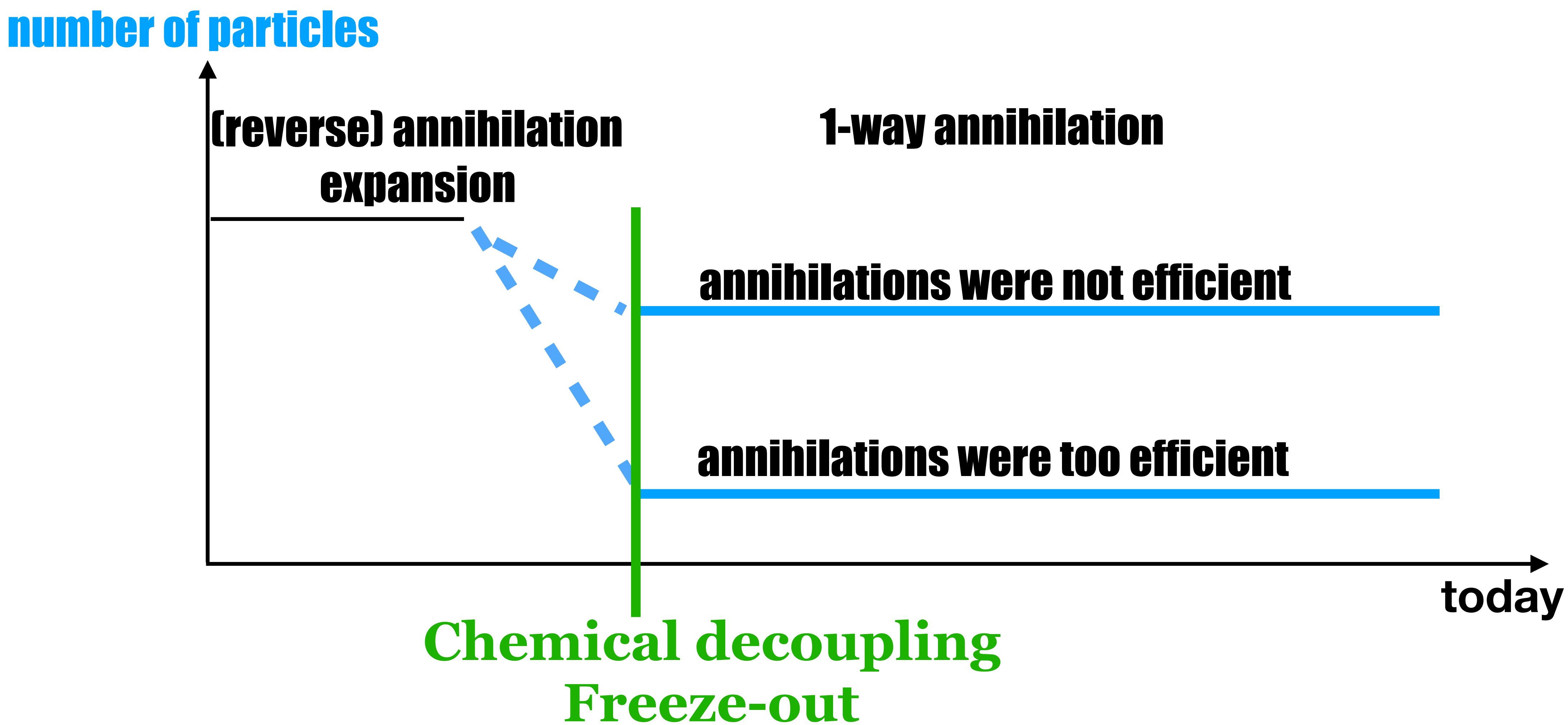
expansion

Expansion wins but annihilations were not efficient

Non-relativistic transition

today

Boltzmann equation caught in the act



Only one cross section gives the observed number of DM particles!

Interactions maintaining the thermal equilibrium can continue

$$\frac{dn}{dt} = -3Hn - \sigma v (n^2 - n_0^2) \qquad \sigma v \, n_{DM}^2 \simeq H \, n_{DM} \Rightarrow \sigma v \, n_{DM} \simeq H$$

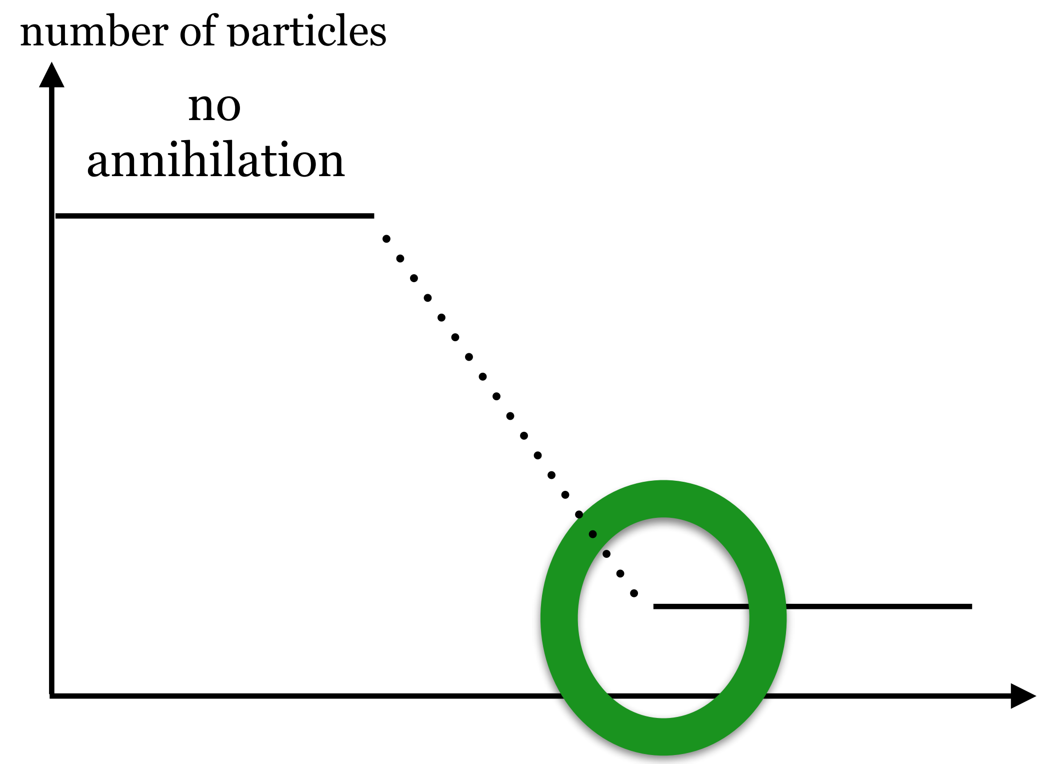
Analytical solution

$$\langle \sigma v \rangle n_{\rm DM} = H$$

$$n_{\rm DM} a^3 = n_{\rm DM,0}\ a_0^3$$

$$a(T) = \frac{T_0}{T} \quad \text{and} \quad H = H_r T^2$$

$$n_{\rm DM,0} = \frac{H_r}{\langle \sigma v \rangle} \frac{T_0}{T_{fo}}$$



$$\Omega_0 = \frac{\rho_{\rm DM,0}}{\rho_{c,0}} \rightarrow \Omega_0 = \frac{n_{\rm DM,0}}{\rho_{c,0}} m_{\rm DM} \rightarrow \boxed{\Omega_0 = \frac{H_r}{\rho_{c,0}} \frac{T_0}{\langle \sigma v \rangle} \frac{m_{\rm DM}}{T_{fo}}}$$

x_{fo}

At freeze-out, the density obeys Boltzmann statistics

$$n(T) \propto (m_{\rm DM} T)^{3/2}\ e^{-\frac{m_{\rm DM}}{T}} \qquad n_{\rm DM,0} = \frac{H_r}{\langle \sigma v \rangle} \frac{T_0}{T_{fo}} \qquad x_{fo}^{-1} \simeq \ln \frac{\langle \sigma\ v \rangle\ T_0^2\ m}{H_\alpha\ (2\pi)^{3/2}\ \sqrt{x_{fo}}}.$$

$$x_{fo} \approx 12 + (\approx 2) \log\left(\frac{m_{dm}}{MeV} \times \frac{\sigma v}{3.10^{-26} cm^3/s} \right)$$

Numerical solution

Numerically: re-write Boltzmann to remove T^3 factors in number density by using n = y T^3

$$\frac{dy}{dt} = -\sigma v \times (y^2 - y_0^2) \times T^3$$

solve dy/dT instead of dy/dt

$$\frac{dy}{dT} = \frac{\sigma v}{2 t_r T_0^2} \times (y^2 - y_0{}^2)$$

Tempted to use:

$$\frac{y_{i+1} - y_i}{\Delta T} = \Lambda \times (y^2 - y_0{}^2)$$

???

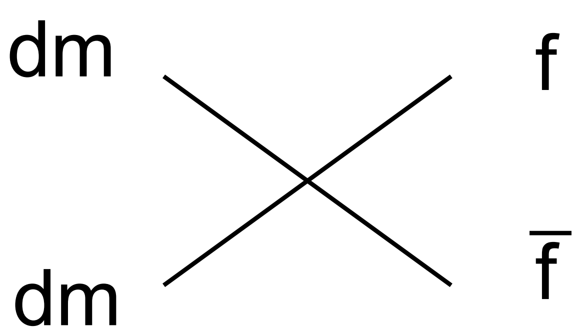
$$\frac{y_{i+1} - y_i}{\Delta T} = \frac{\Lambda}{2} \times \left[(y_i{}^2 - y_{0_i}{}^2) + (y_{i+1}{}^2 - y_{0_{i+1}}{}^2) \right]$$

The Hut, Lee&Weinberg argument

$$\frac{dn}{dt} = -3Hn - \sigma v(n^2 - n_0^2)$$

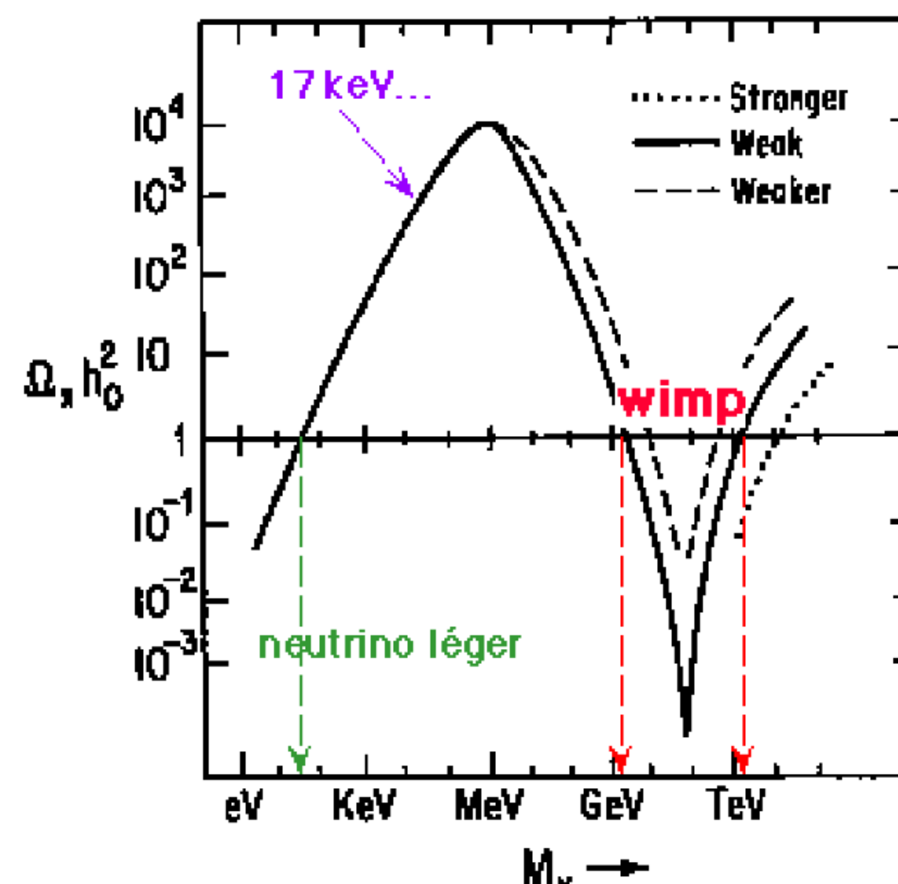
$$\Omega h^2 \simeq \frac{3 \times 10^{-27} \mathrm{cm}^3/\mathrm{s}}{\langle \sigma v \rangle}$$

$$\sigma v \sim 3\ 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$$



$$\sigma\ \mathrm{v} \propto \frac{\mathrm{m}_{\mathrm{dm}}^{2}}{\mathrm{m}_{\mathrm{w}}^{4}}$$

$$\Omega_{\mathrm{DM}} h^2 \propto m_{\mathrm{DM}}^{-2}$$



Dark Matter needs to be heavier than a proton to not over close the Universe

Particle physics examples

The supersymmetric case

N=1 : 1 operator of supersymmetry
Each operator change the spin of particles by 1/2
SUSY operator applied on SM spectrum leads to new particles with different spin

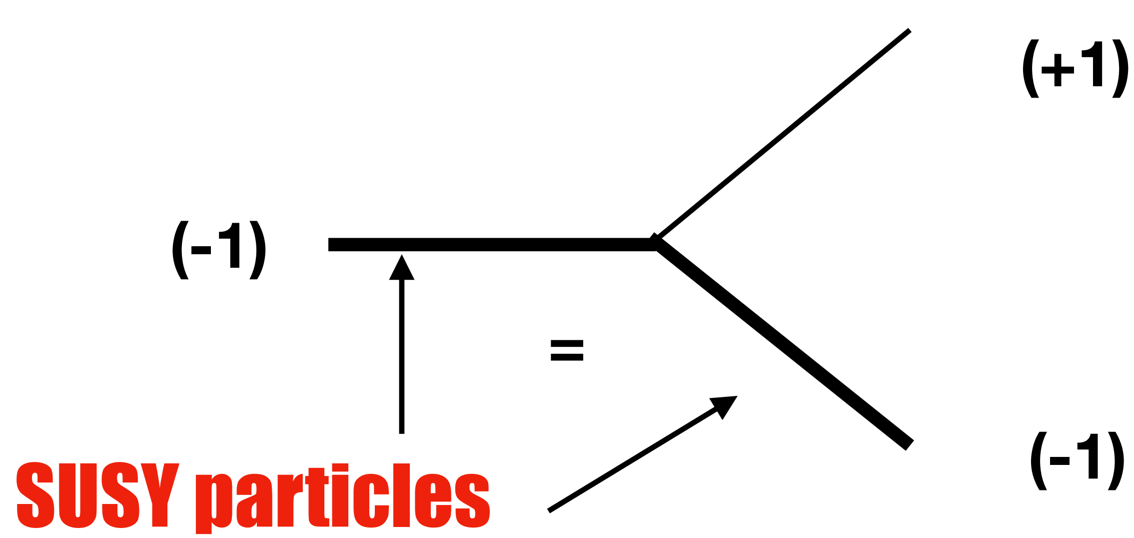
~ double SM spectrum

+ SM fermions + spin-0 particles   sfermions
+ Higgs/Gauge boson spin-1/2 particles   fermions neutralinos

R-parity

$$R_p = (-1)^{3B+L+2s}$$

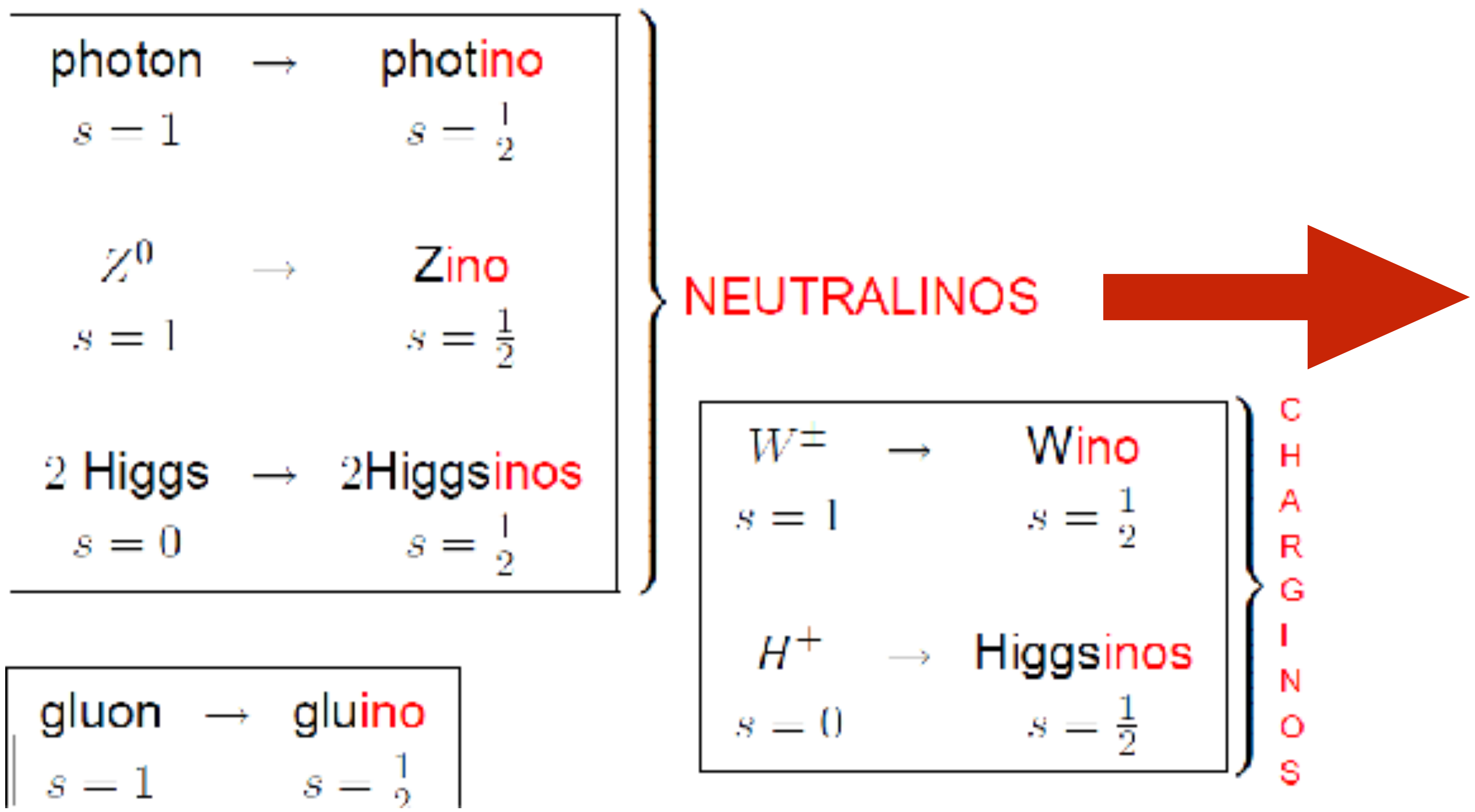
Initial realisation:
all masses the same as SM



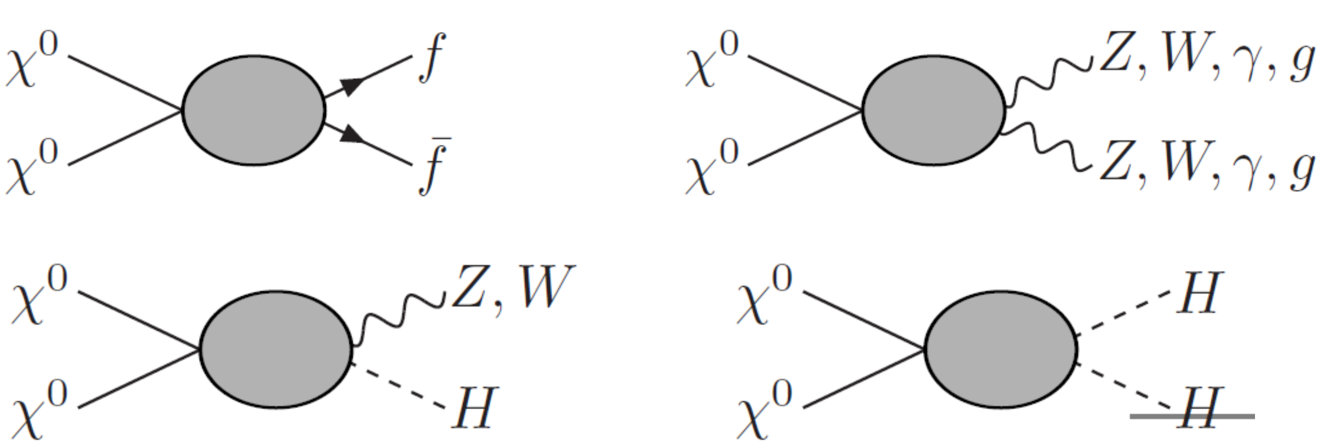
Nothing at LEP, LHC
so masses can't be the same!

The supersymmetric case

SUSY



+R-parity = stable DM



All cross sections are

$$\sigma v \propto m_\chi^2$$

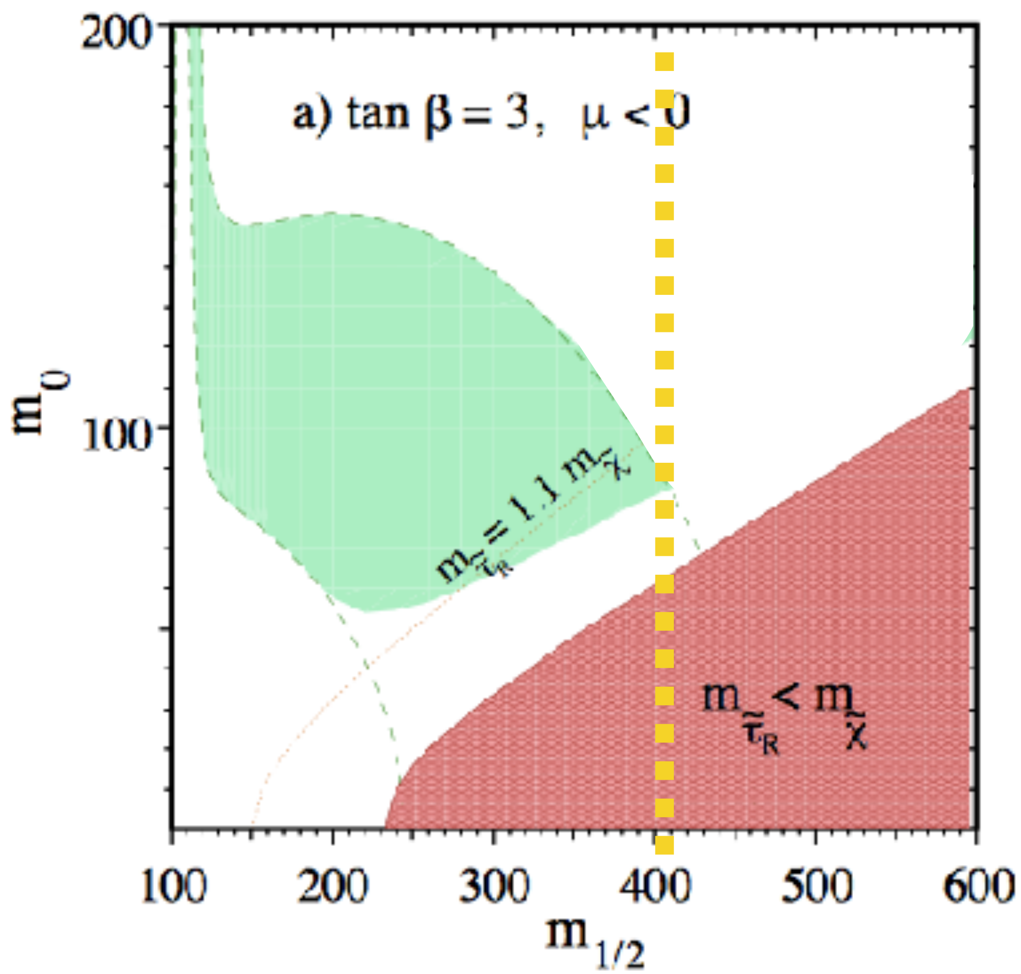
Lee-Weinberg limit applies!

III. DM

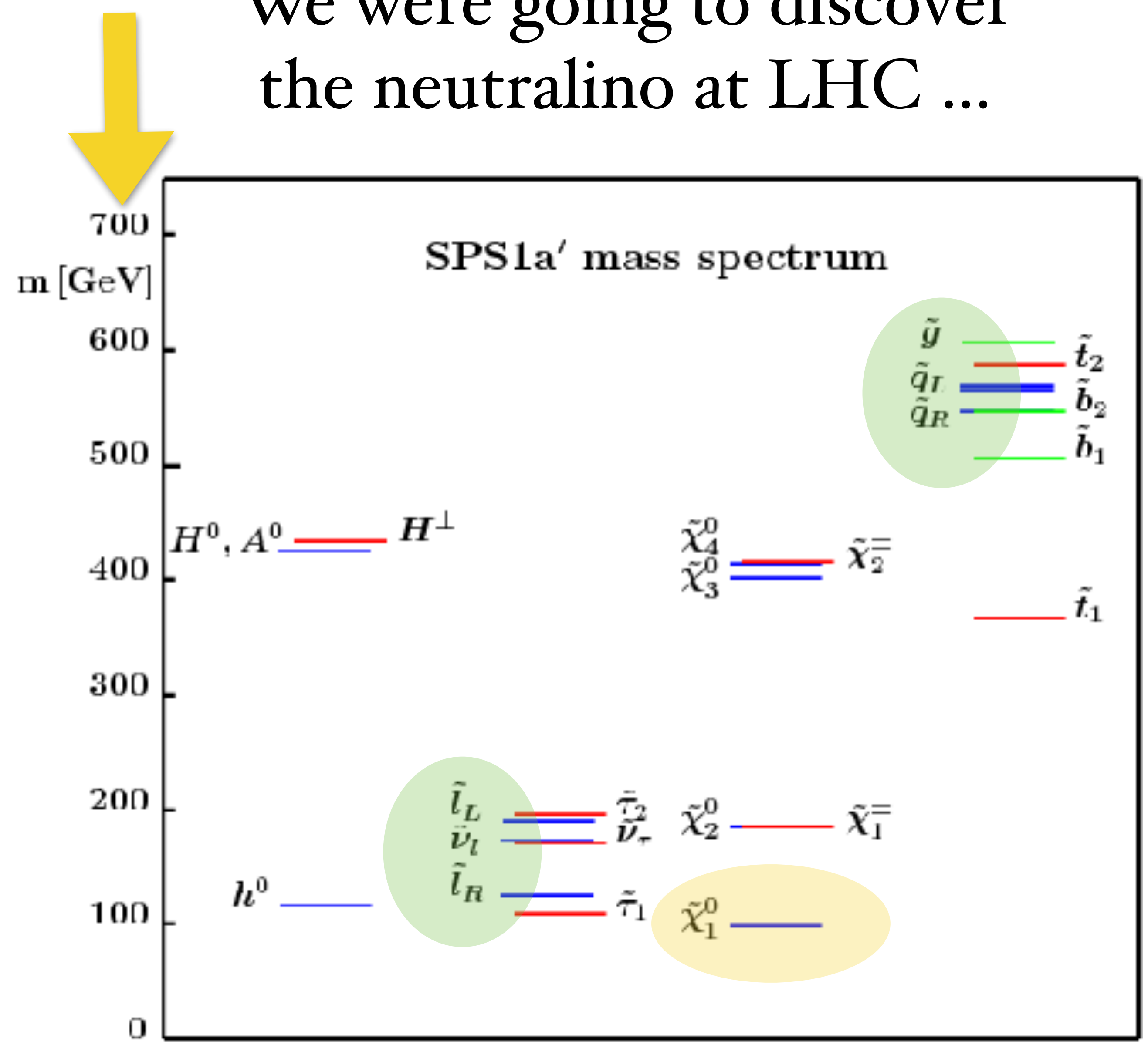
Supersymmetric and relic density

Before 1998

mDM <200 GeV



We were going to discover the neutralino at LHC ...



Exceptions to relic calculations

Nucl.Phys. B237 (1984) 285-306 Phys.Rev. D43 (1991) 3191-3203

Coannihilations

$$\frac{dn_i}{dt} = -3Hn_i - \sigma v_{ann}(n_i^2 - n_{i,0}^2) - \sigma v_{co-ann}(n_i n_j - n_{i,0} n_{j,0})$$

$$\frac{dn_j}{dt} = -3Hn_j - \sigma v_{ann}(n_j^2 - n_{j,0}^2) - \sigma v_{co-ann}(n_i n_j - n_{i,0} n_{j,0}) - \Gamma_j (n_j - n_{j,0})$$

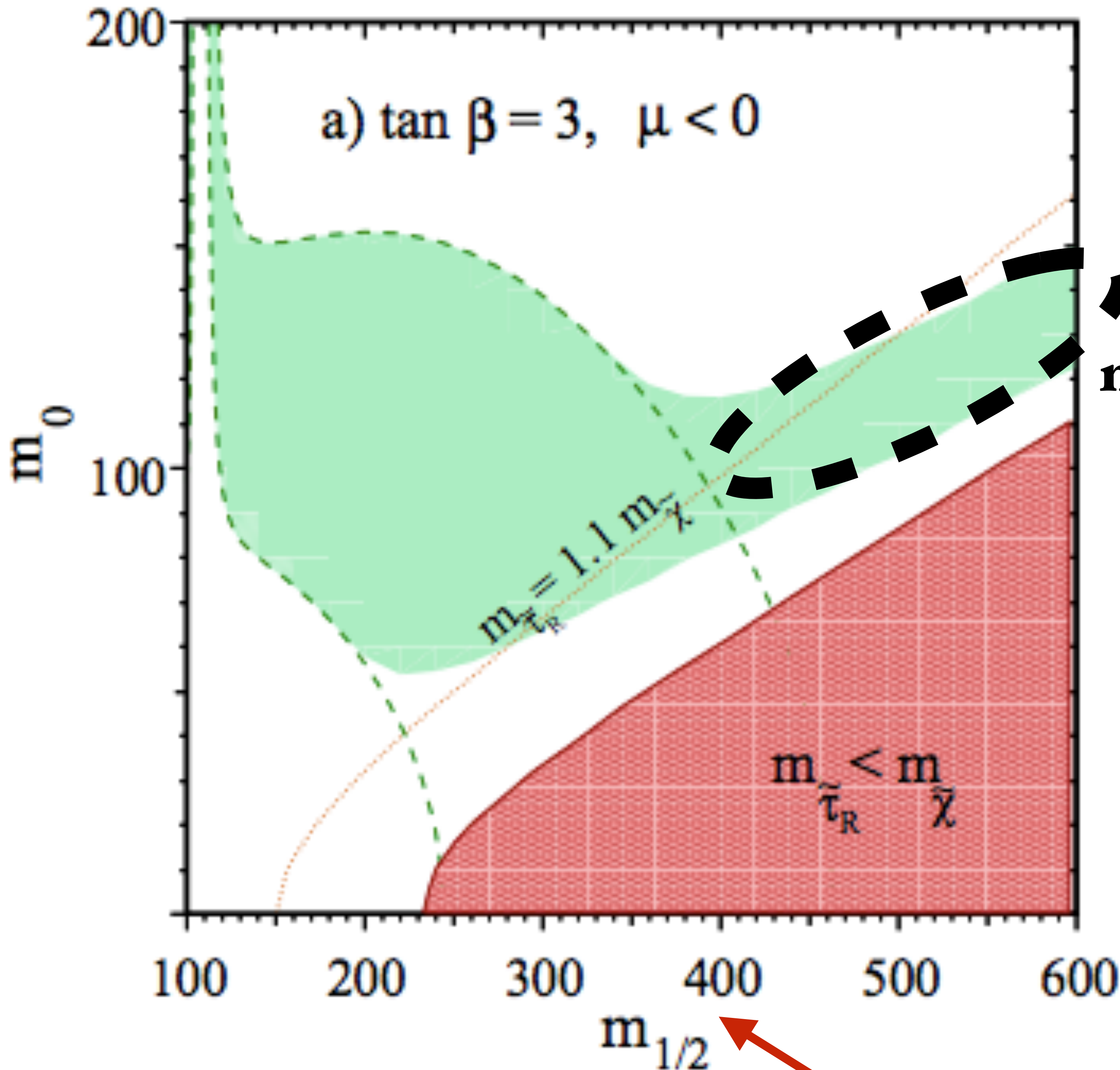
$$\begin{aligned}\frac{\Gamma_{ann}}{\Gamma_{coann}} &= \frac{\langle \sigma v \rangle_{ann}}{\langle \sigma v \rangle_{coa}} \frac{n_1}{n_2} \\ &= \frac{\langle \sigma v \rangle_{ann}}{\langle \sigma v \rangle_{coa}} \frac{m_{d_1}}{m_{d_2}} \, e^{-\beta(m_{d_2} - m_{d_1})}\end{aligned}$$

The mass difference is critical

Exceptions to relic calculations

hep-ph/9810360

Neutralino relic abundance?



coannihilations

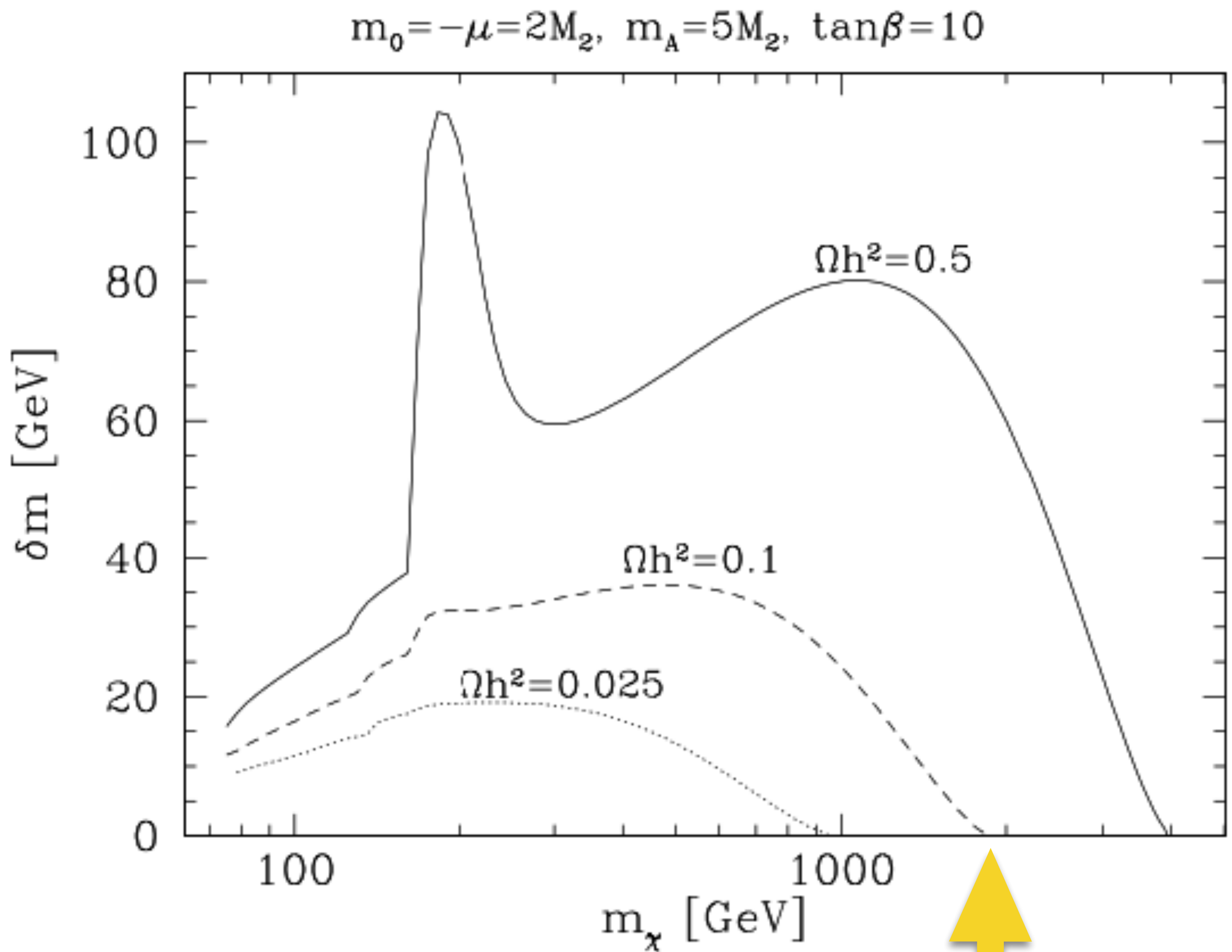
mDM > 200 GeV

neutralino mass < 200 GeV

Exceptions to relic calculations

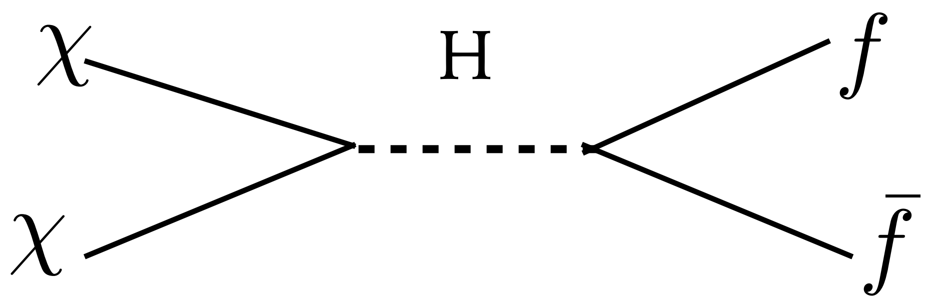
hep-ph/9911496

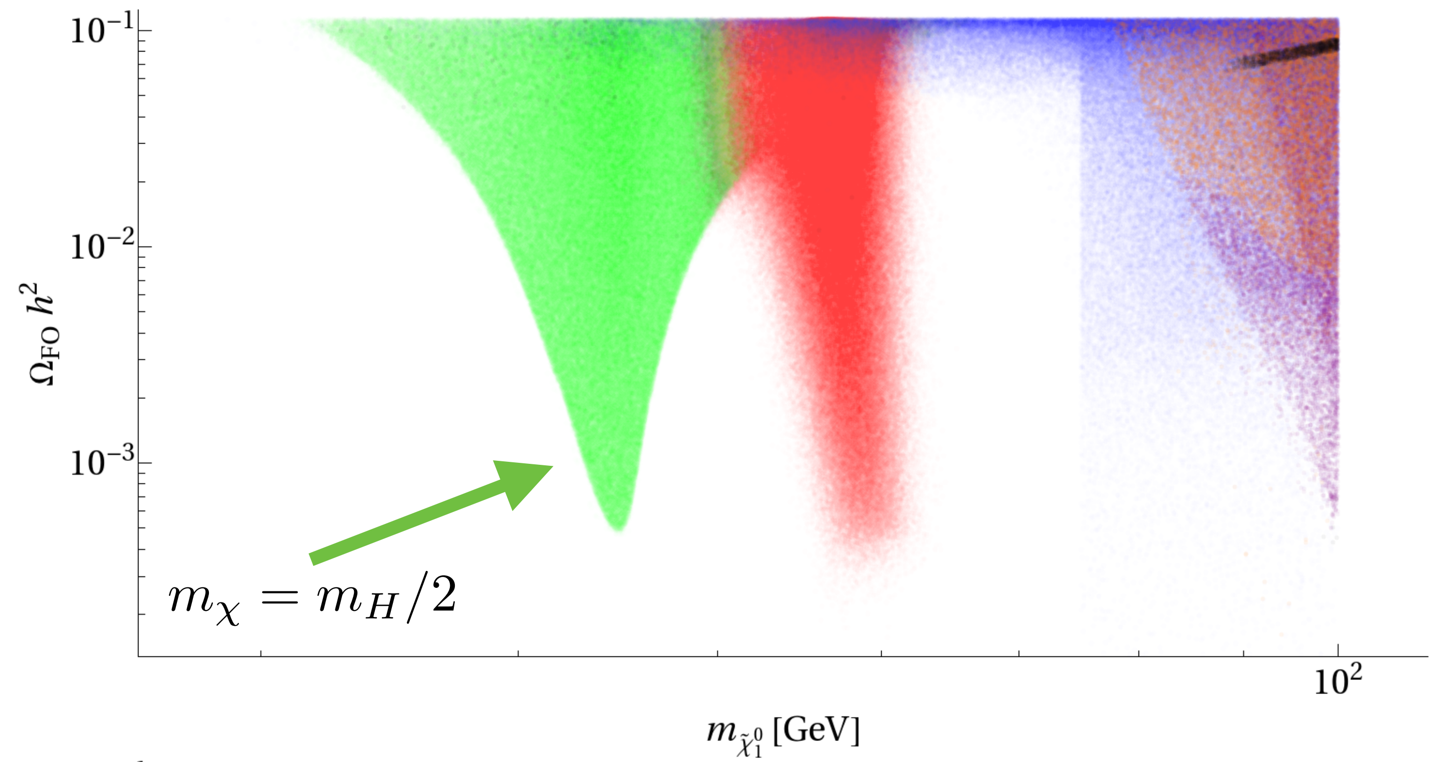
DM co-annihilations with “stops”

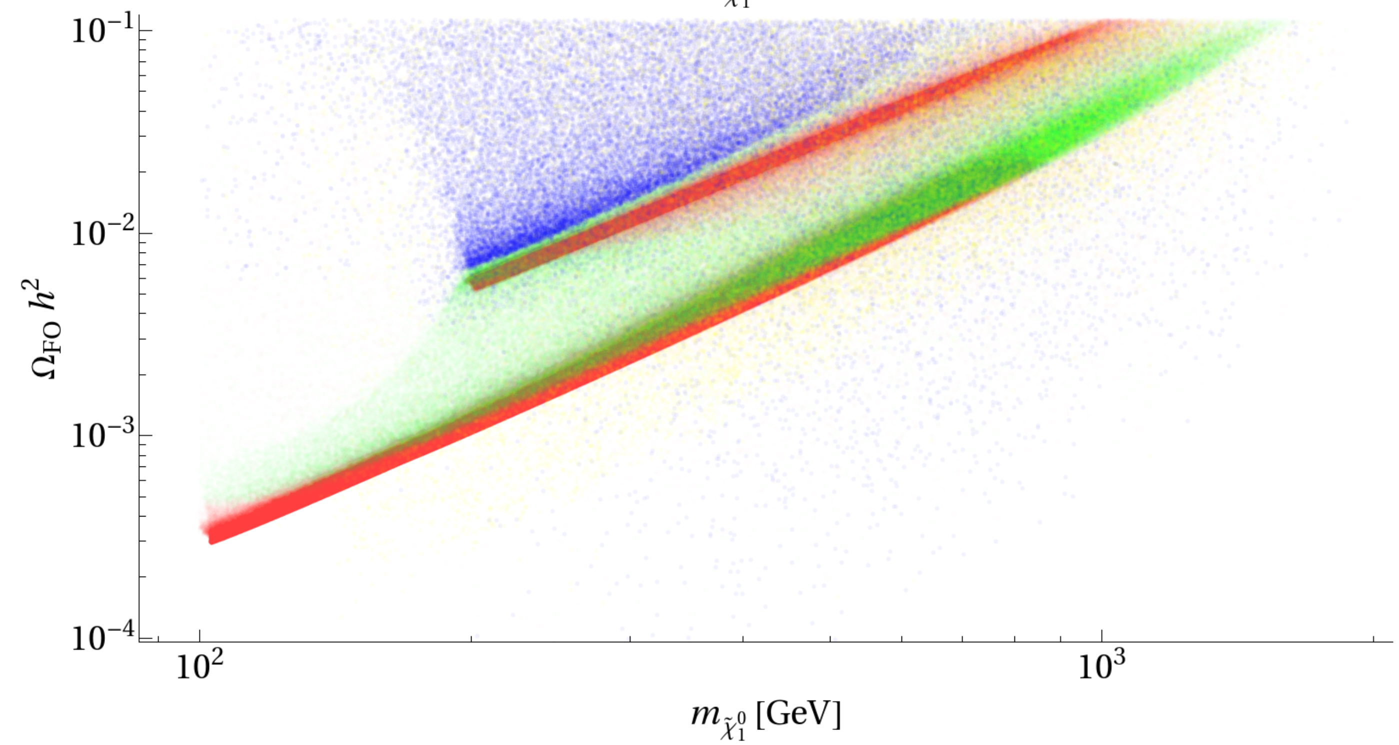


mDM > TeV

Exceptions to relic calculations







Different couplings probe different nature of the neutralino

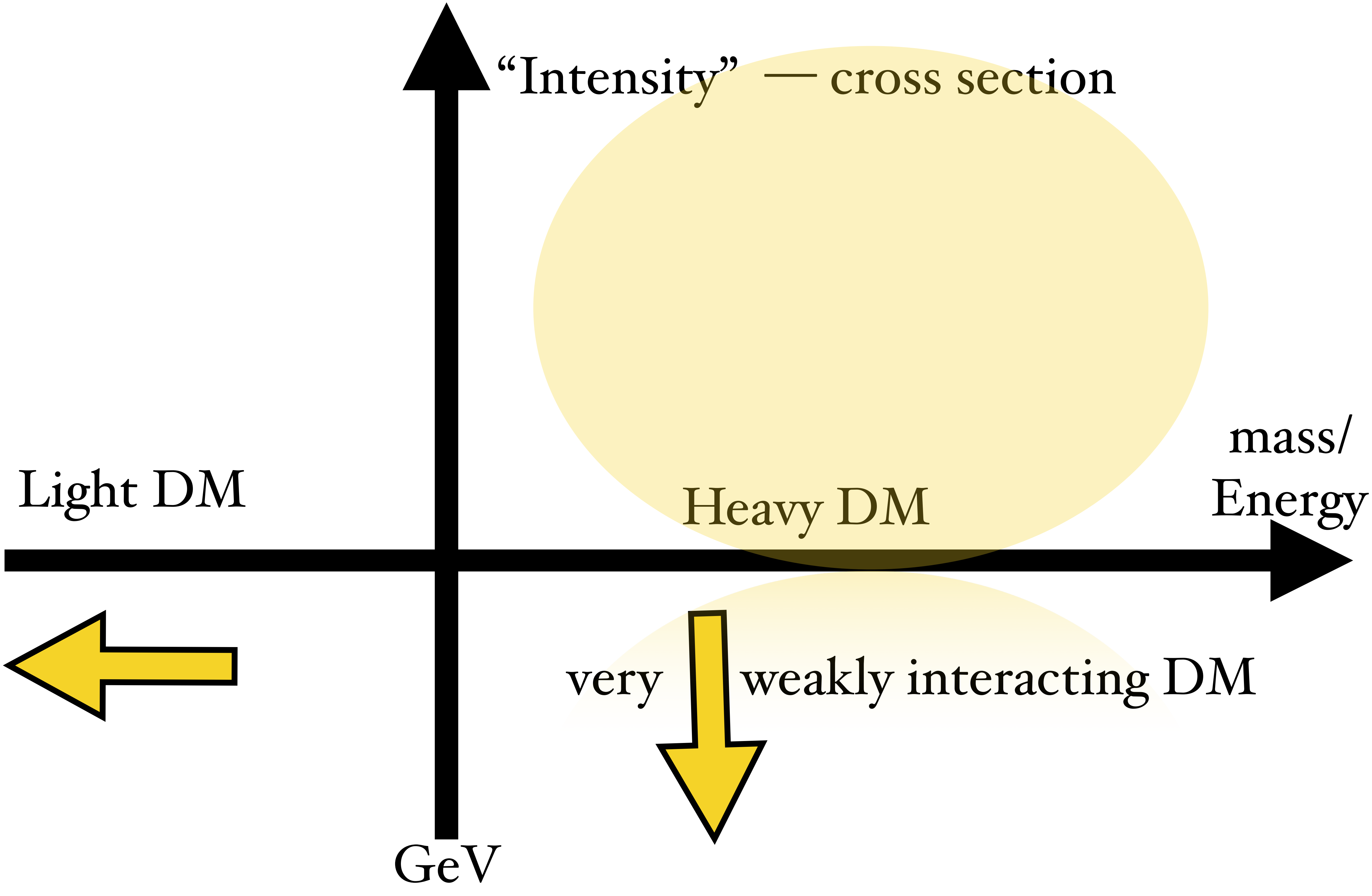
$$\chi_i^0 = N_{i1}\tilde{B}^0 + N_{i2}\tilde{W}^3 + N_{i3}\tilde{H}_1^0 + N_{i4}\tilde{H}_2^0$$

$$i = 1, \ldots, 4$$

The resonance implies smaller couplings are needed for the neutrinos to be the DM

Where else could DM be?

following the dark matter path

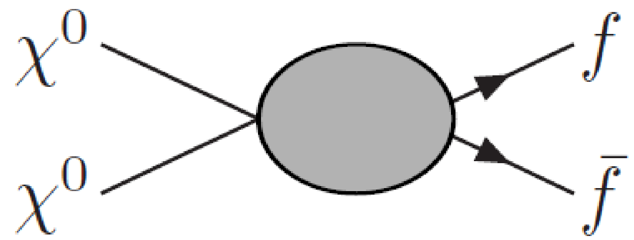


Beyond SUSY

Particle physics examples

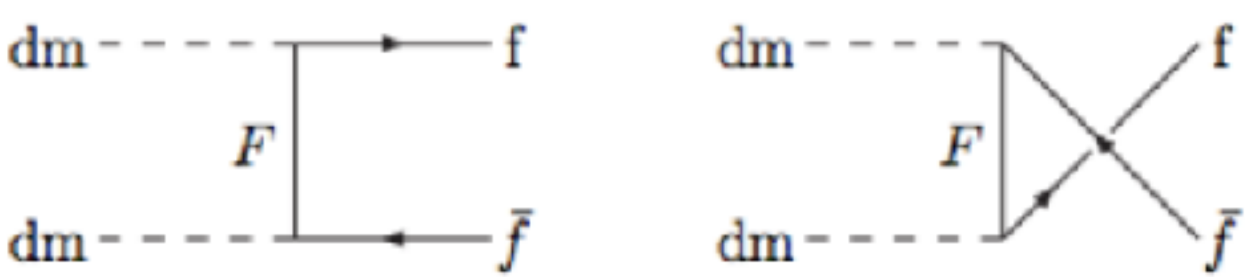
Light DM candidates

$$\frac{dn}{dt} = -3Hn - \sigma v(n^2 - n_0^2)$$



What kind of mediator?

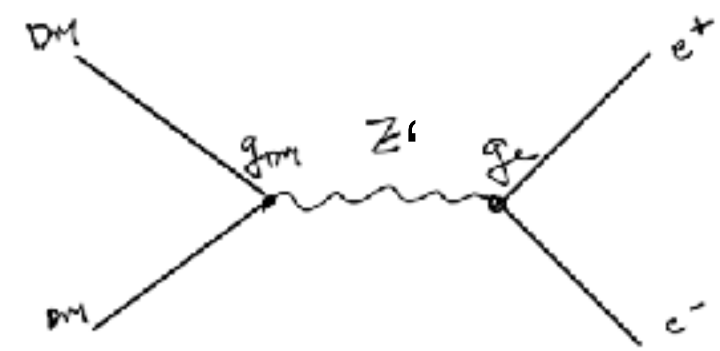
vector-like fermions



$$\sigma v \propto \frac{1}{m_F^4} \left((C_l^2 + C_r^2)\ m_f + 2 C_l\ C_r\ m_F \right)^2$$

$$\sigma v \propto \frac{1}{m_F^2}$$

dark photons/Z’



$$\sigma v \propto v^2\ \frac{m_{\rm DM}^2}{m_{Z'}^4}\ g_{\rm DM}^2\, g_e^2$$

$$m_{\rm DM} \simeq m_{Z'}$$

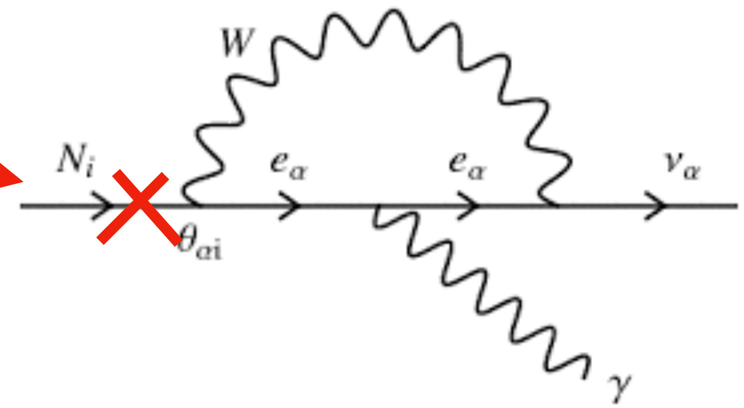
DM can be light!

astro-ph/0208458v3
hep-ph/0305261

Non-thermal DM candidates

sterile neutrinos

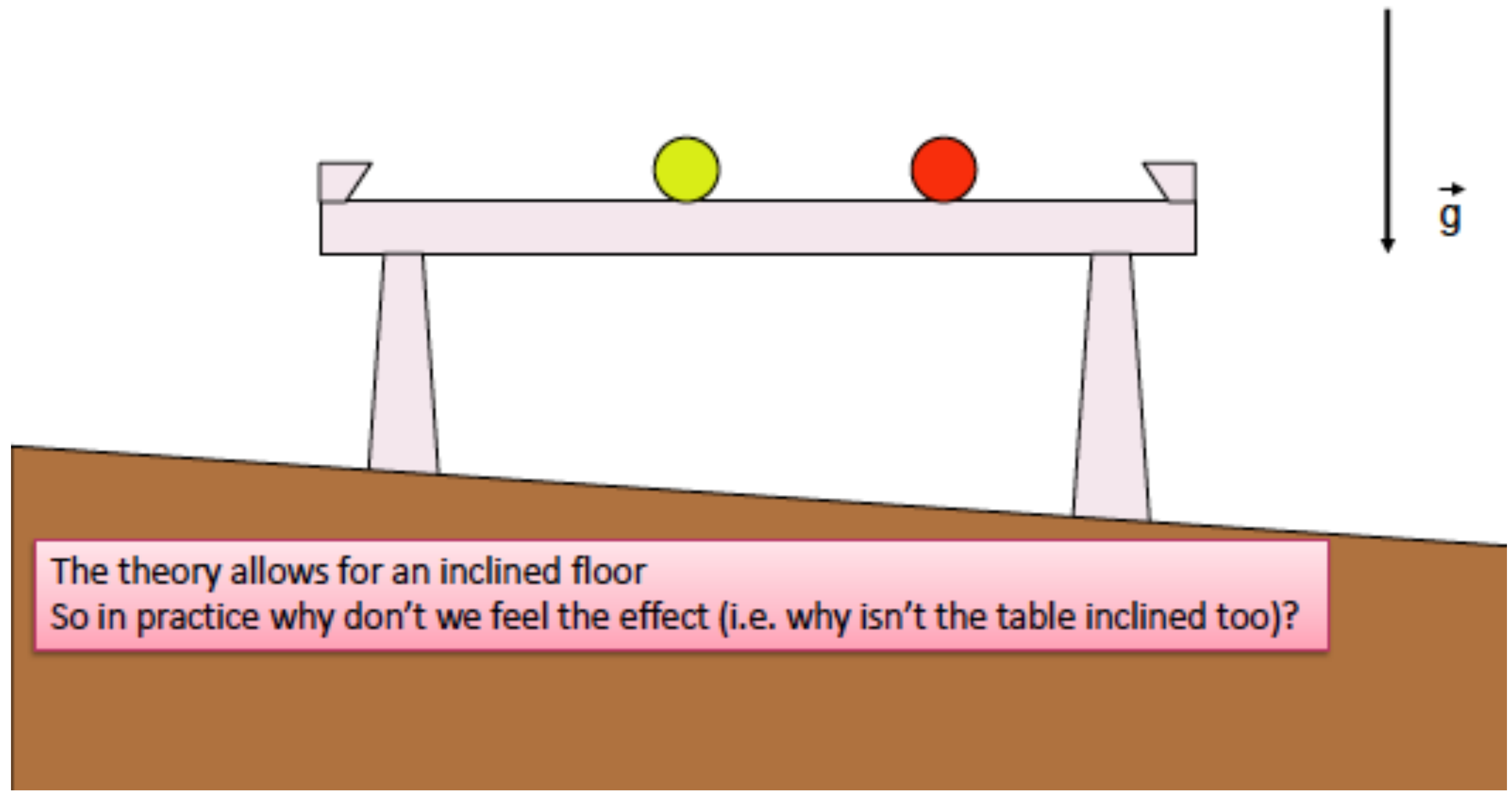
mixing angle



axions

$$L_{QCD} = \; \ldots + \boxed{\theta \frac{g^2}{32\pi^2} G^a{}_{\mu\nu} \tilde{G}^{a\mu\nu}}$$

QCD field strength

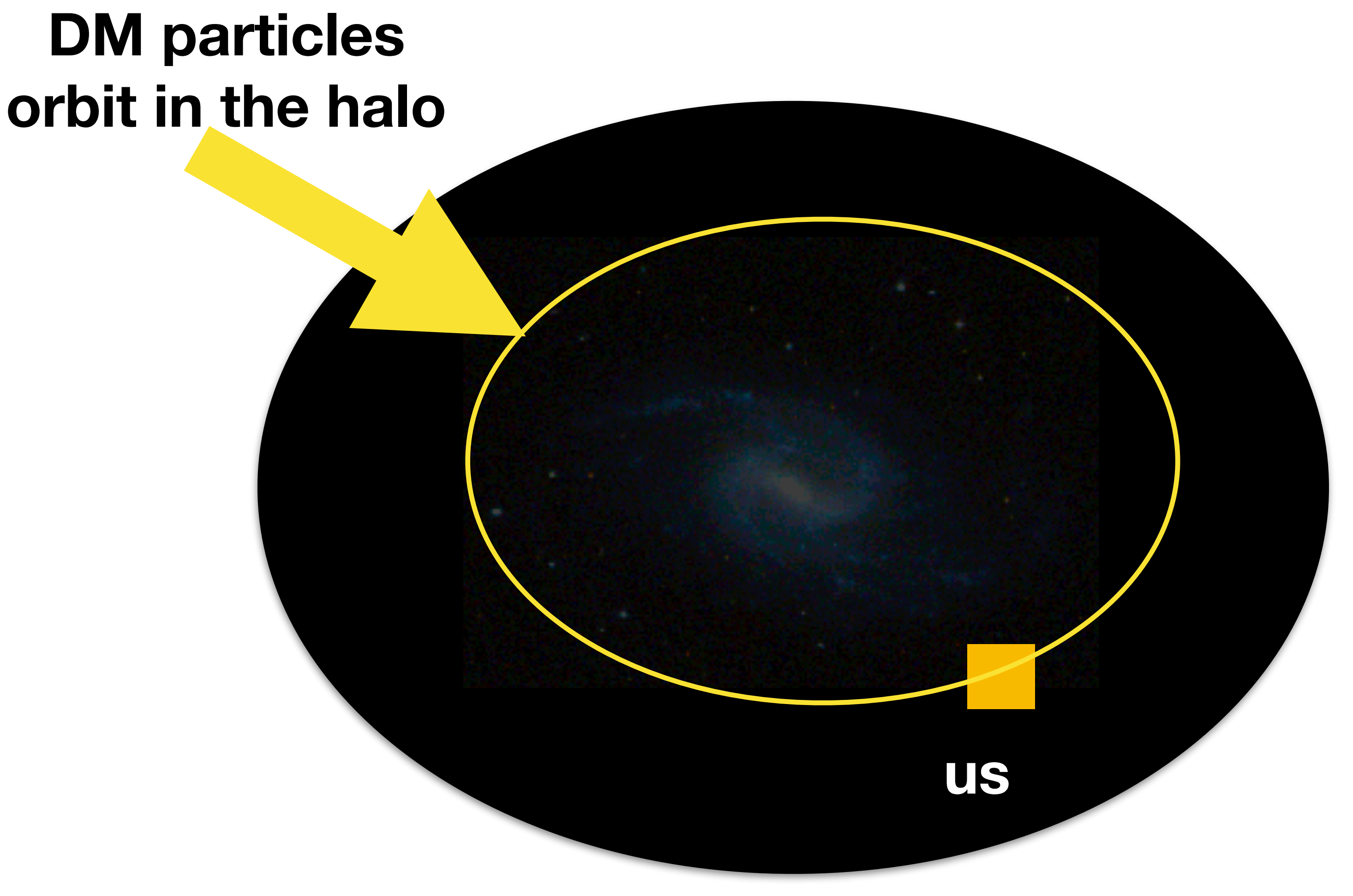


P. Sikivie's cartoon

III. Signatures

* Direct Detection
* Indirect Detection
* LHC

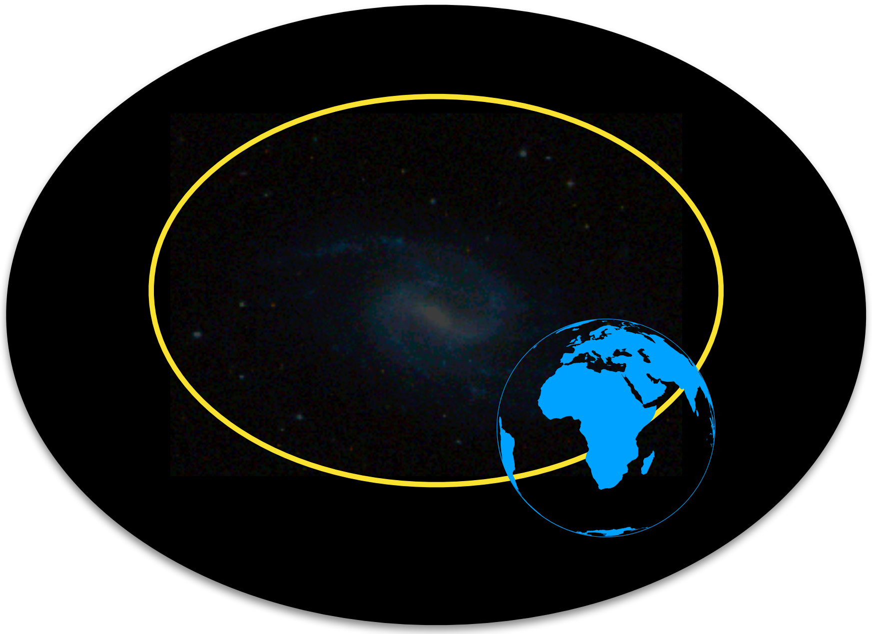
III. A. Direct detection



DM particles cross through the Earth

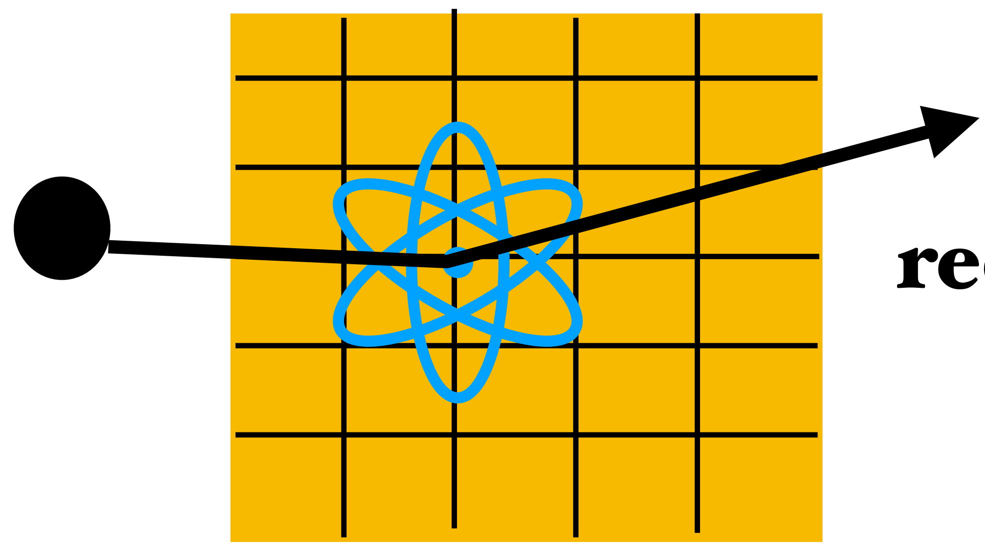
Principle of direct detection

Make a detector, wait, hope for an interaction within



Assuming that

DM interacts with SM particles
We are able to detect the interaction

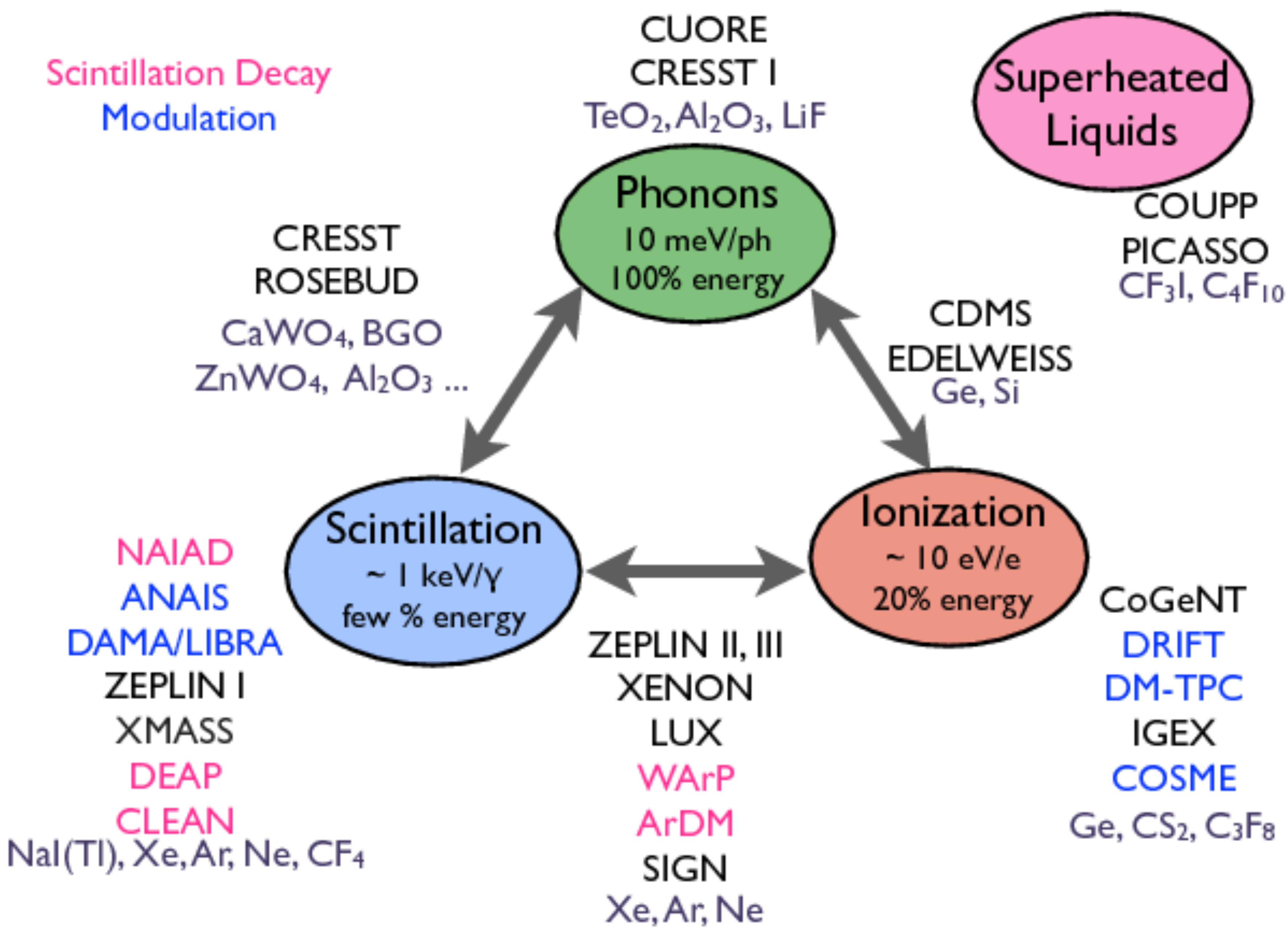


What kind of signatures do we expect?

ionisation
scintillation
phonons
heat

Principle of direct detection

arXiv:1203.2566 + many presentations



Principle of direct detection

How do we know we have detected DM?

We **don't** know unless we understand the background sources!

- * radioactivity produces neutrons
- * neutrons behave like WIMPs
- * electrons, photons are also polluting experiments

To understand the background,
we need to reduce it to its minimum

We need shielding

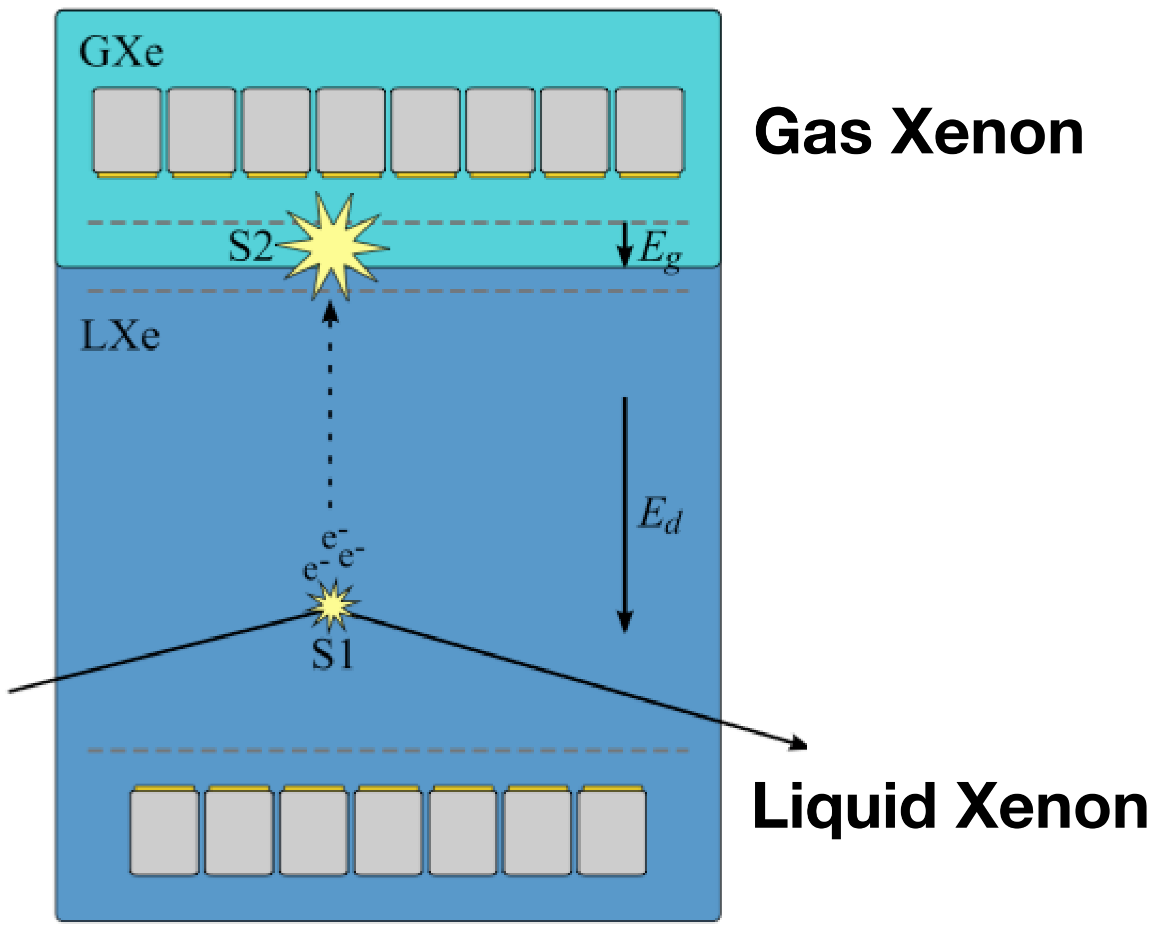
mountain
or dig deep into mines

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

No dark matter direct detection experiments in the Southern Hemisphere !

Principle of direct detection

XENON100 experiment
now 1T and nT

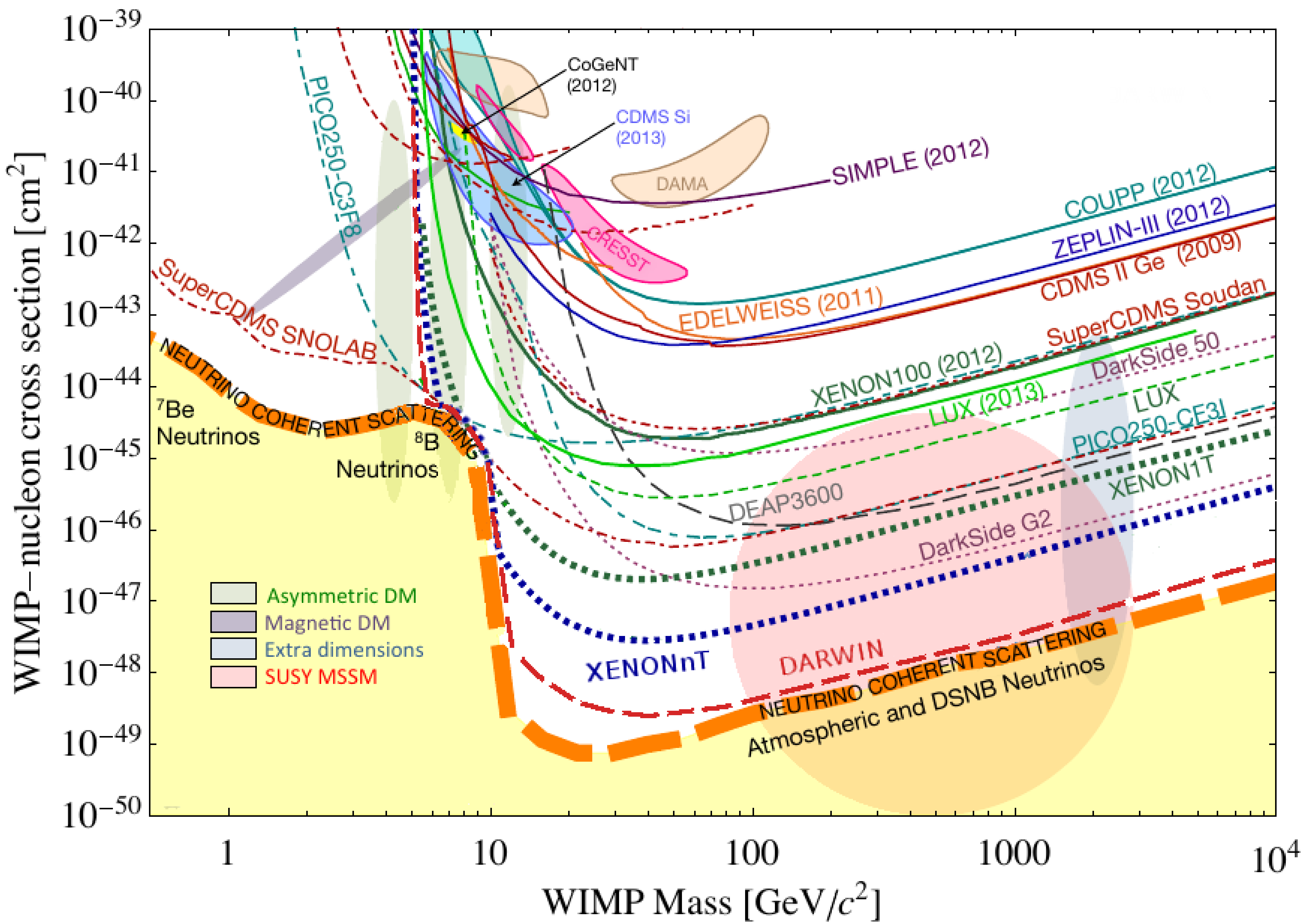


S1 = primary scintillation signal

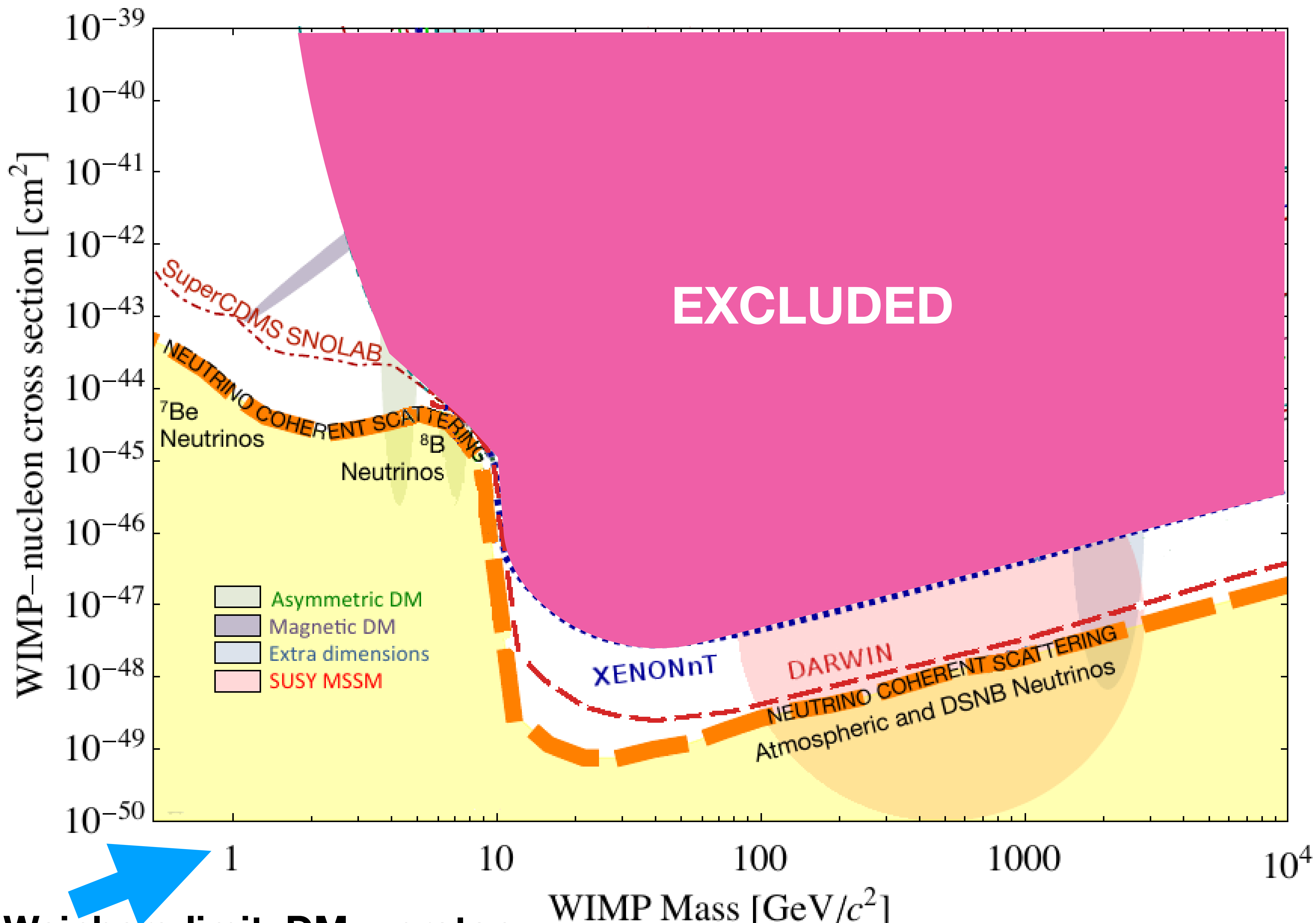
S2 = secondary scintillation signal (from the drift of electrons from ionised Xenon)

Xenon 10 (10 kg Xenon)

Principle of direct detection



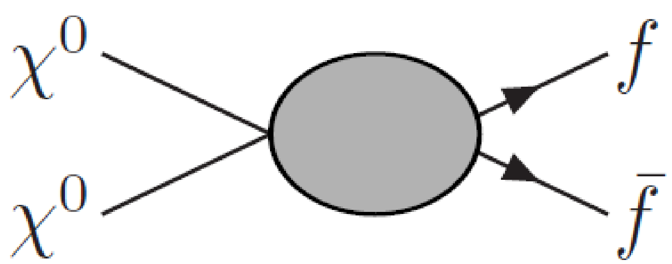
Principle of direct detection



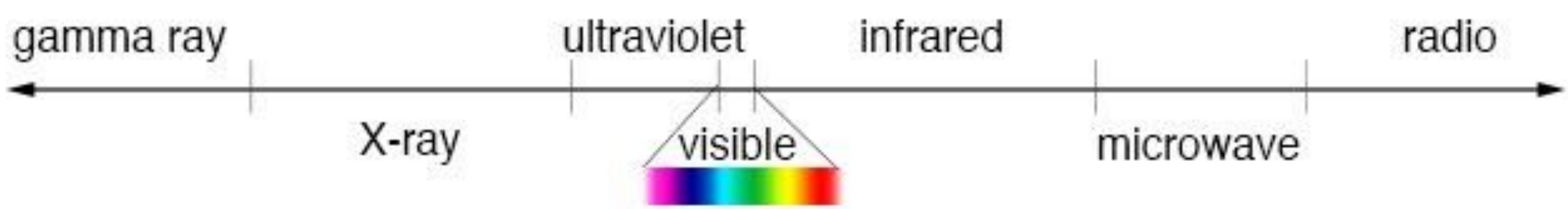
Lee&Weinberg limit: DM > proton but light DM OK so experiments need to be extended.

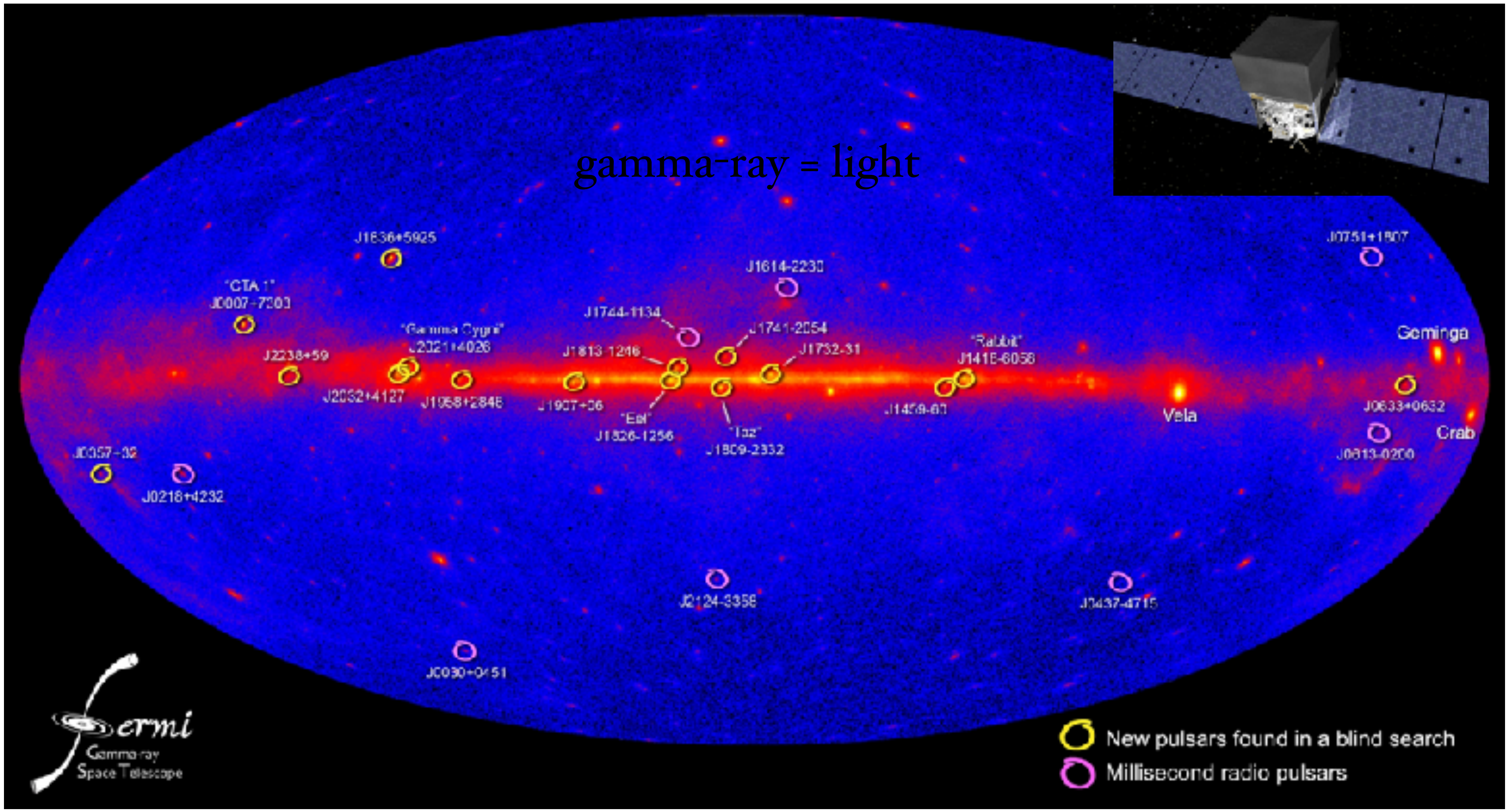
III. B Indirect detection

DM annihilates thermally or not ...



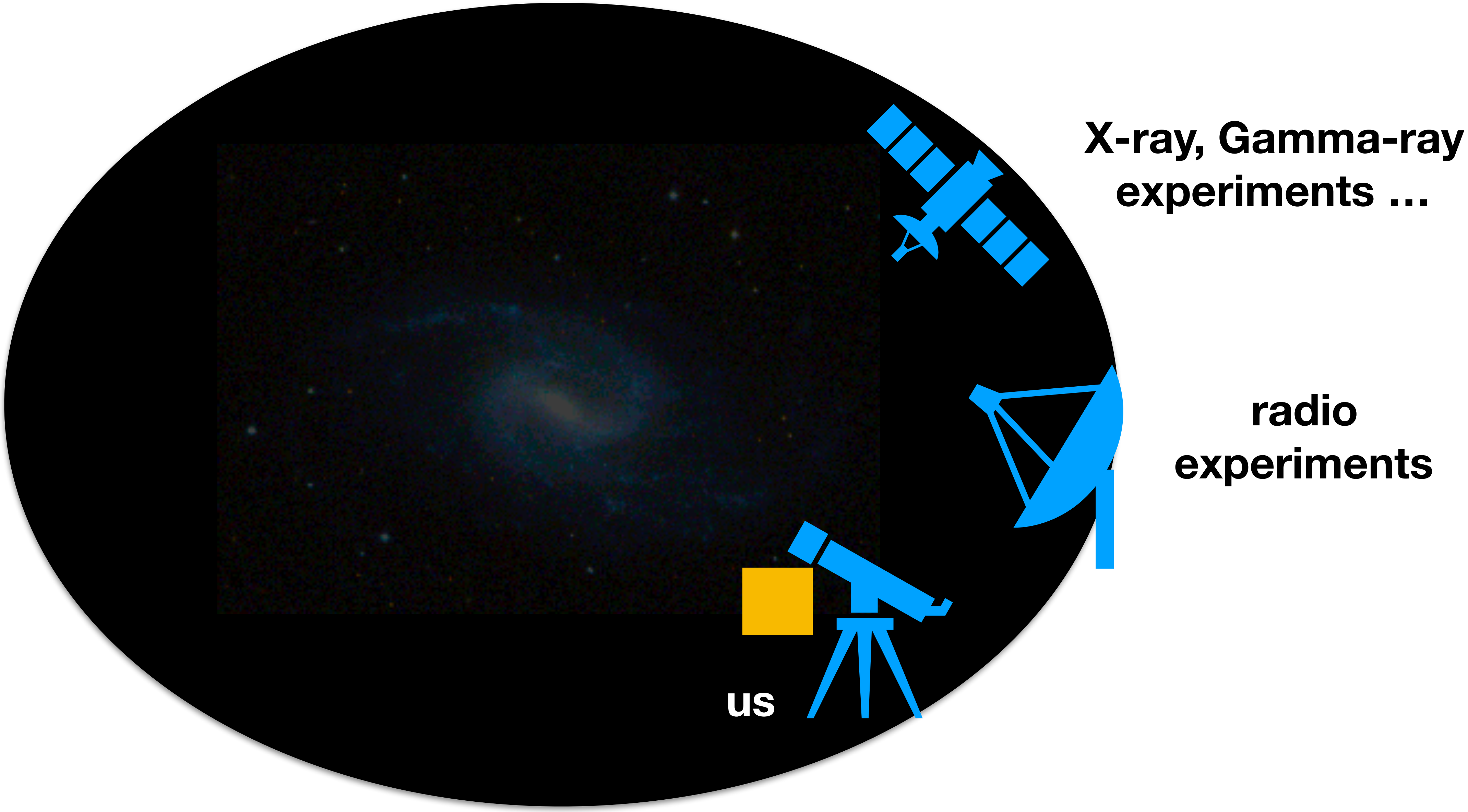
$$\frac{dn}{dt} = -3\cancel{H}n - \sigma v(n^2 - n_0^2)$$





Principle of indirect detection

DM particles orbit in the Milky Way halo

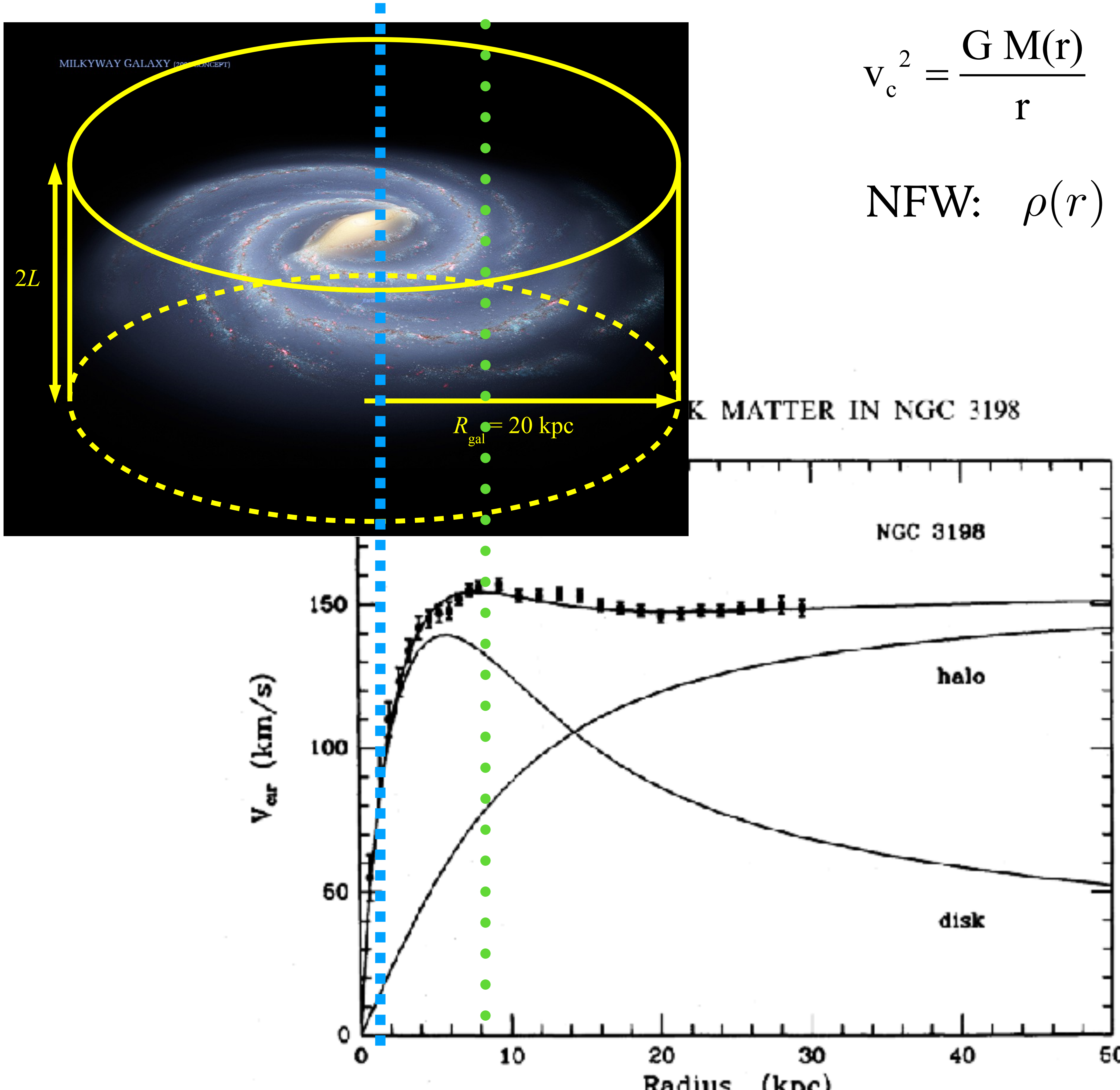


Question: is DM "concentration" everywhere the same in the halo ?

Principle of indirect detection

$$v_c^{\,2} = \frac{G\,M(r)}{r} \qquad M(r) = \int 4\pi^2 \rho(r)\, d^3r$$

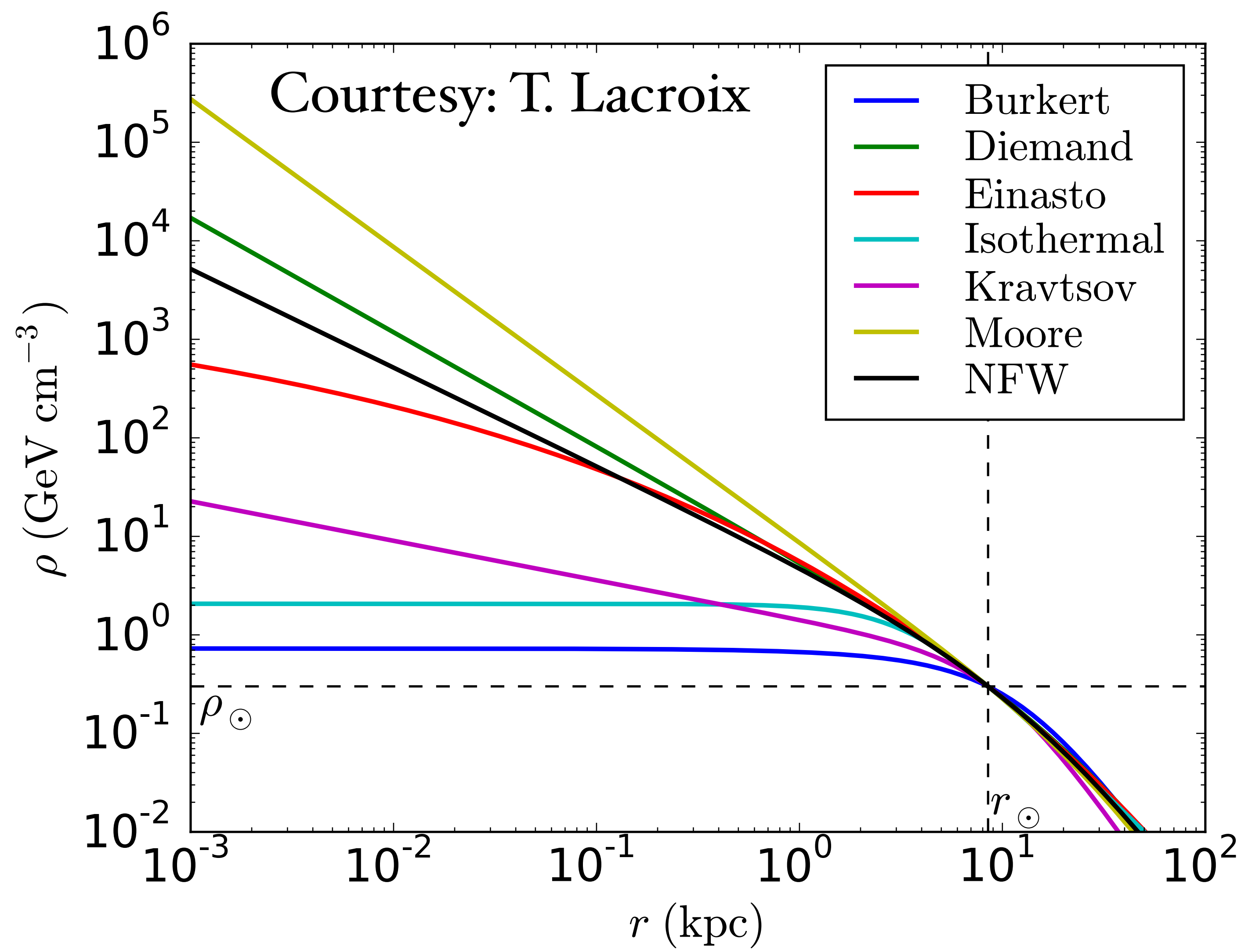
$$\text{NFW:} \quad \rho(r) \propto \frac{1}{r}$$



The DM halo profile

$$v_c^{\,2} = \frac{G\,M(r)}{r} \qquad M(r) = \int 4\pi^2 \rho(r)\, d^3r$$

$$\rho_{\mathrm{NFW_{gen}}}(r) = \rho_0 \left(\frac{r}{r_0}\right)^{-\gamma} \left[1 + \left(\frac{r}{r_0}\right)^{\alpha}\right]^{-\frac{\beta-\gamma}{\alpha}}$$

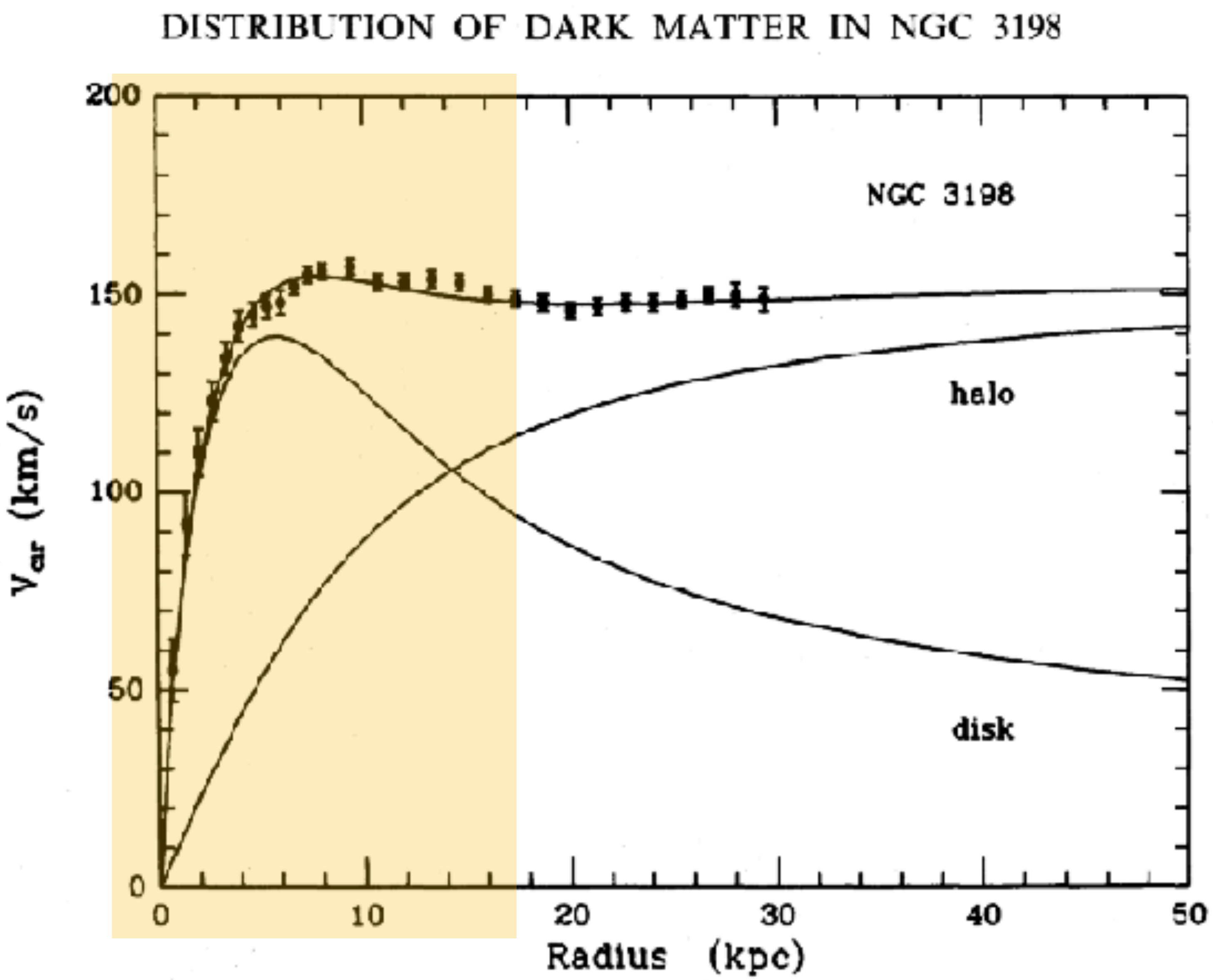


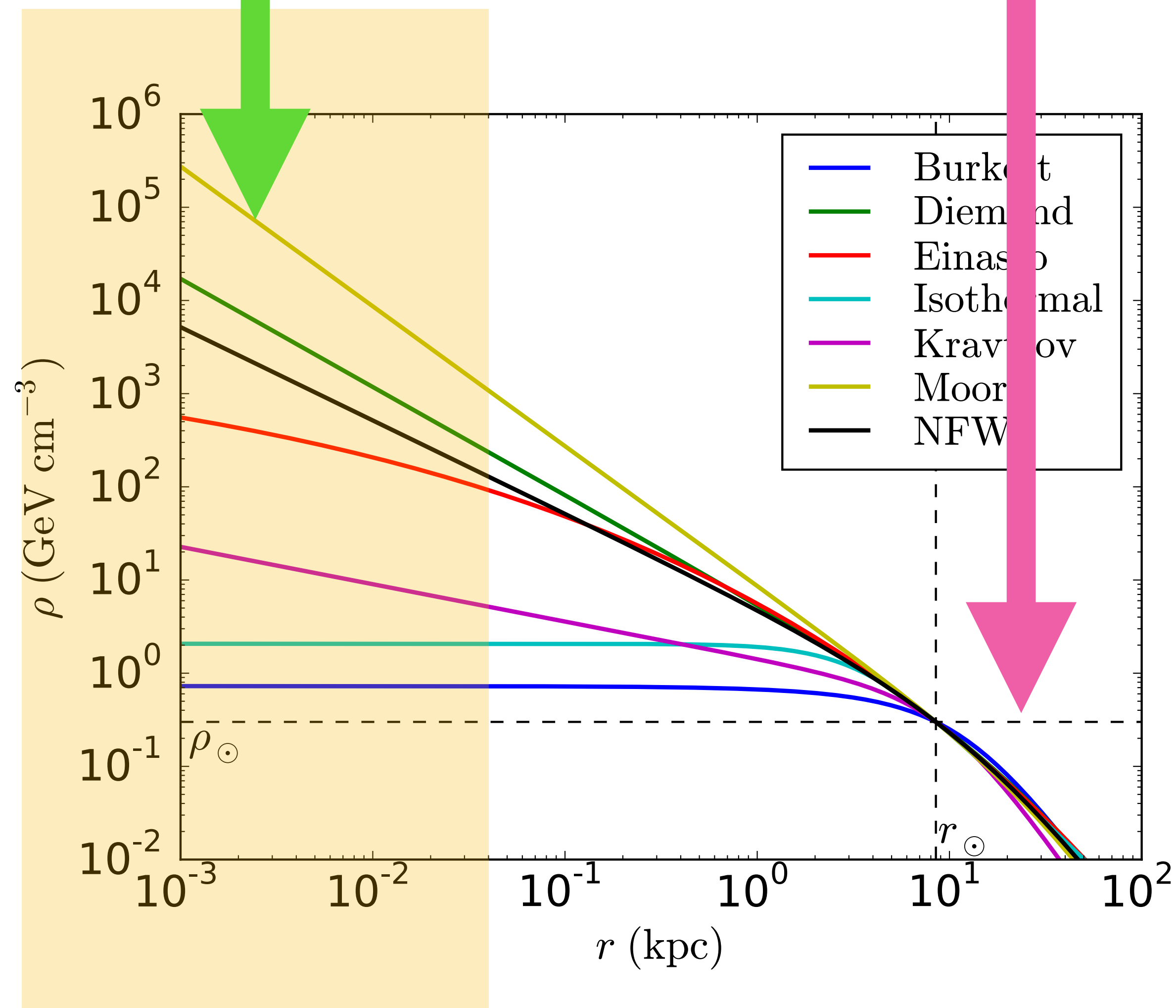
The DM number density is the highest the centre!

Principle of indirect detection

high DM density

low DM density

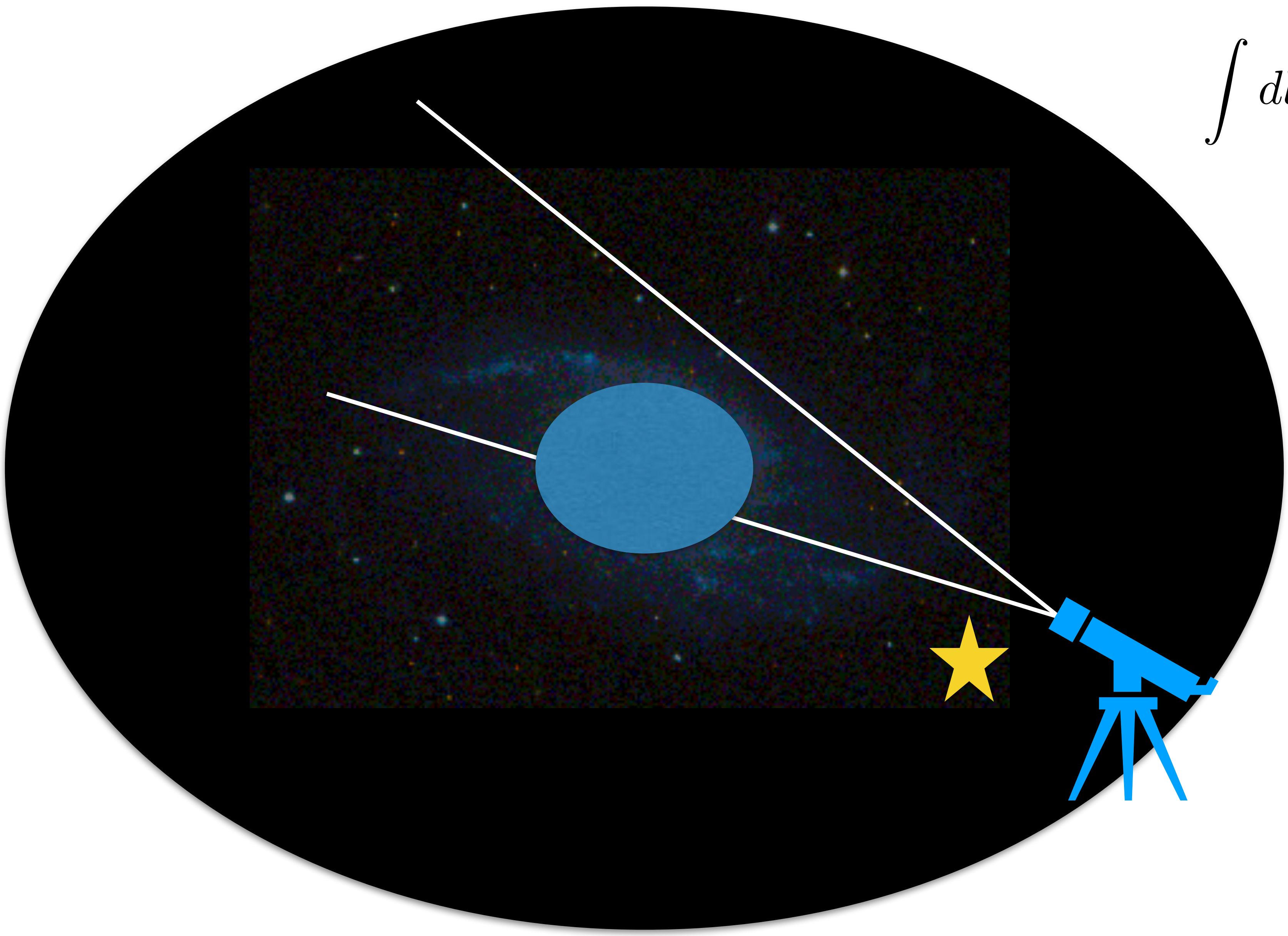




Principle of indirect detection

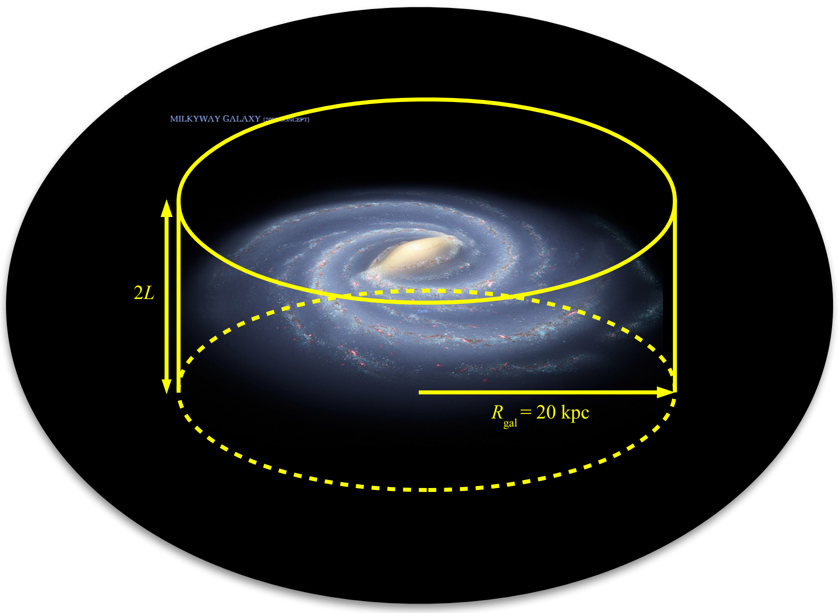
To understand where to look, we need to know where the DM density is the highest. This means reconstruct the shape of the DM profile first.

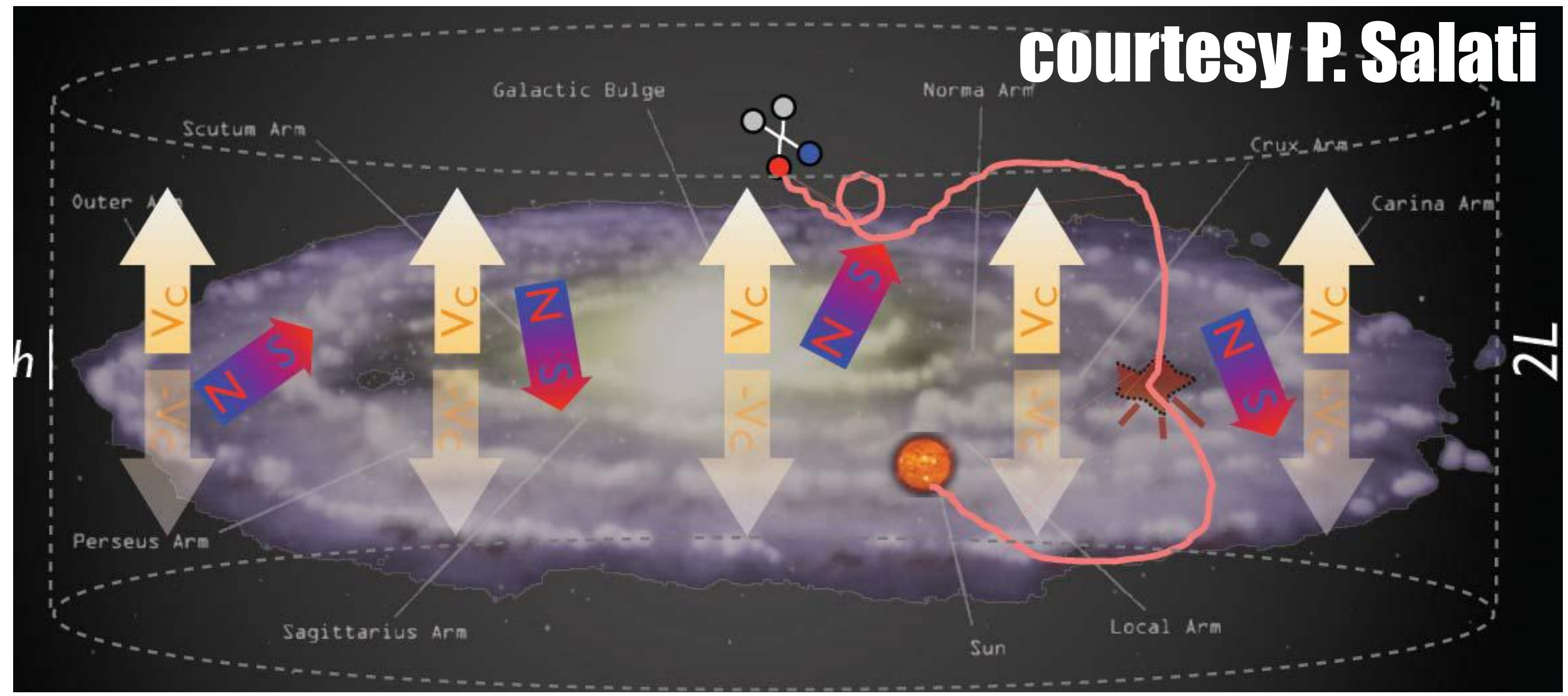
$$\int dl \; \rho(r) \propto \int dl \; \frac{1}{r}$$



$$\frac{d\phi}{dE} = \frac{1}{8\,\pi} \left(\frac{\sigma v}{m_\chi}\right)^2 \sum_i \mathrm{BR_i} \, \frac{\mathrm{dN_i}}{\mathrm{dE}} \, \xi^2 \int \mathrm{dl} \; \rho_\chi^2(\mathrm{l})$$

Principle of indirect detection





$$\frac{\partial \psi}{\partial t} = -\vec{\nabla} \cdot \vec{j}_{\rm diff} - \vec{\nabla} \cdot \vec{j}_{\rm conv} - \frac{\partial j_E}{\partial E} + q$$

$$\vec{j}_{\rm diff} = -K(E,\vec{x})\vec{\nabla}\psi \qquad \vec{j}_{\rm conv} = \psi \vec{v} \qquad j_E = \psi \frac{{\rm d}E}{{\rm d}t}$$

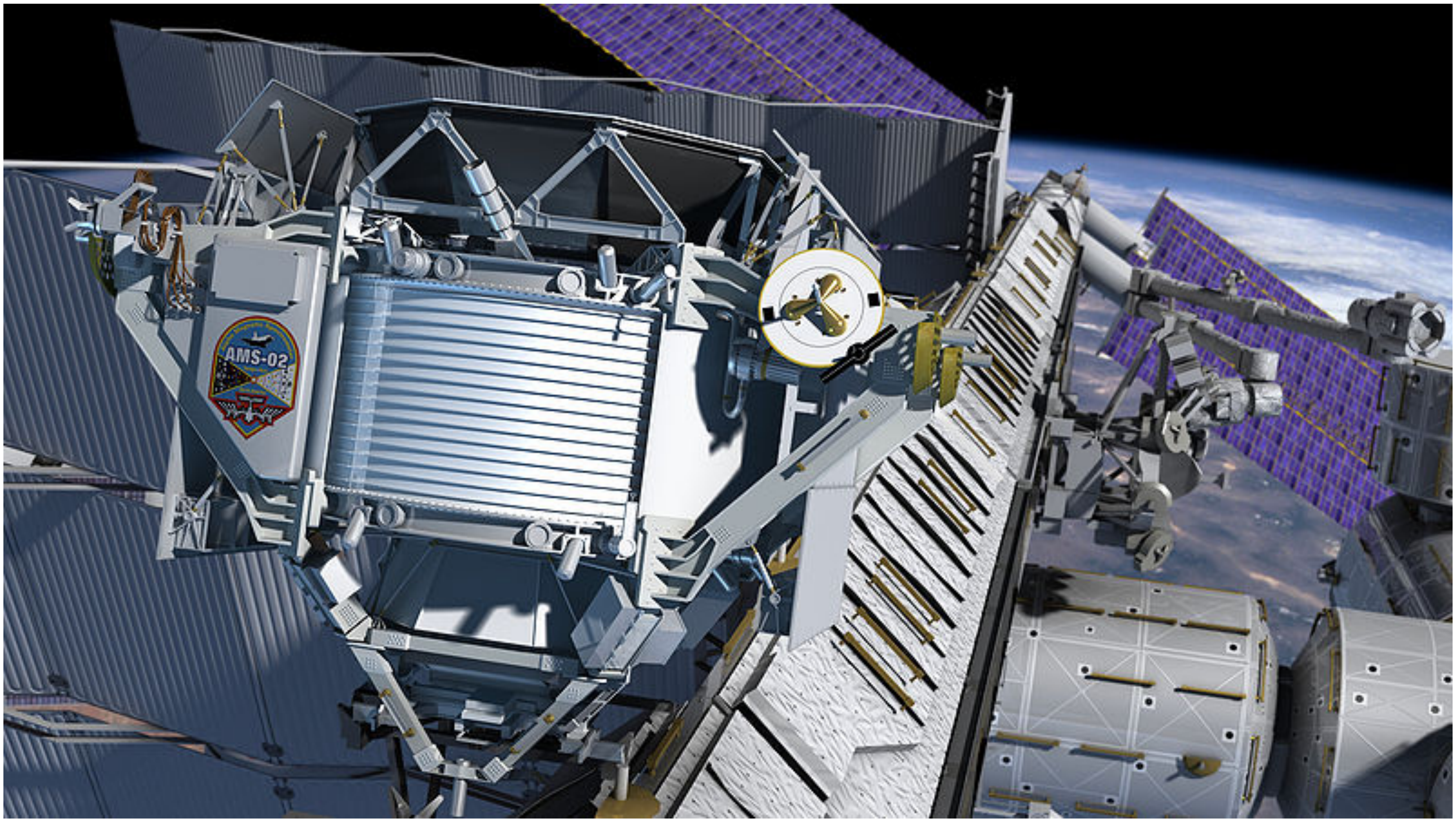
$$\boxed{K\nabla^2\psi + \frac{\partial}{\partial E}(b_{\rm tot}\psi) + q = 0.}$$

$$b_{\rm tot}(E,\vec{x}) = -\frac{{\rm d}E}{{\rm d}t} \qquad K(E) = K_0 \left(\frac{E}{1\ {\rm GeV}}\right)^{\delta}$$

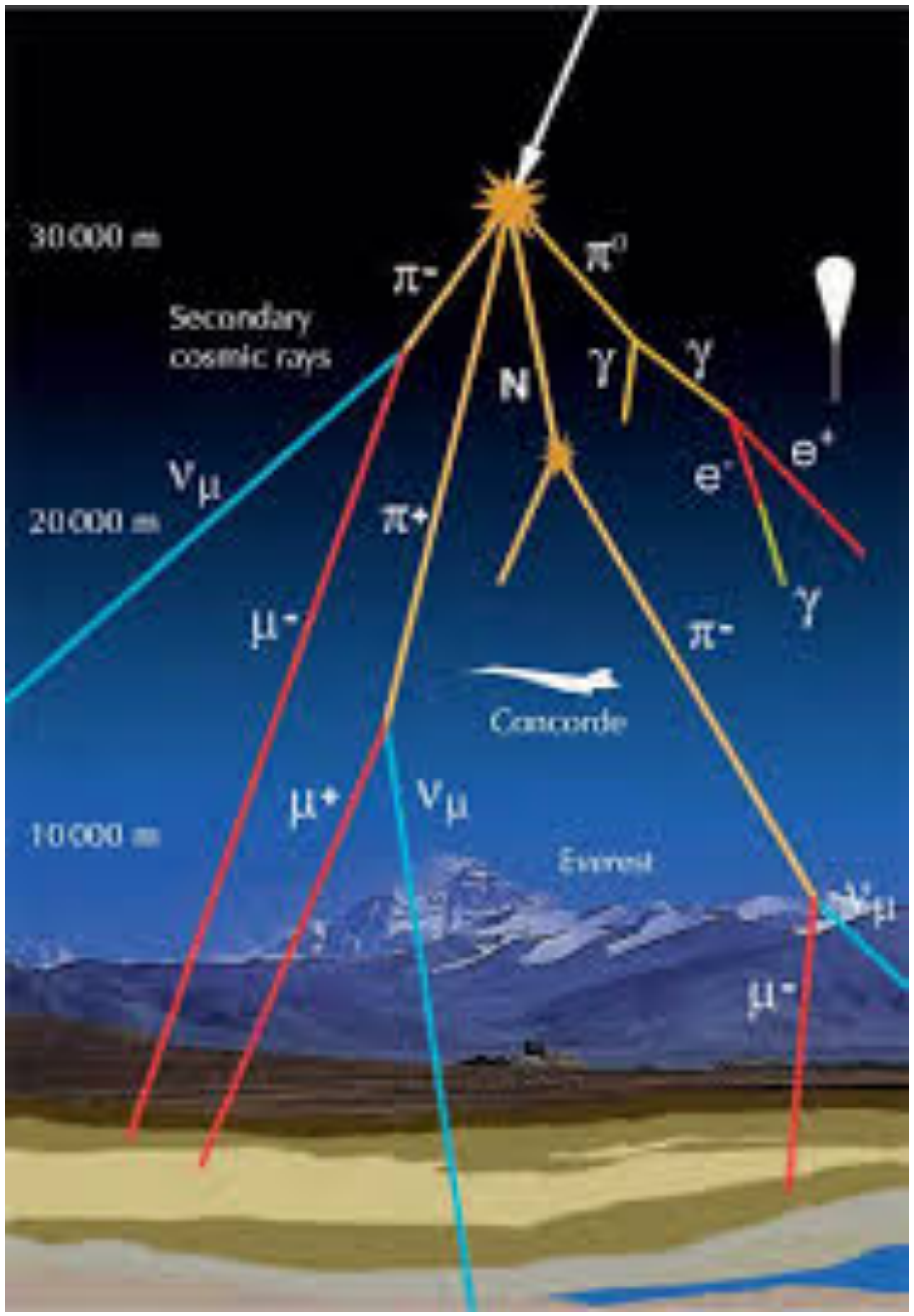
$$\frac{\partial \psi}{\partial t} = \vec{\nabla} \cdot (K\vec{\nabla}\psi - \vec{v}\psi) + \frac{\partial}{\partial E}(b_{\rm tot}\psi) + q$$

Principle of indirect detection

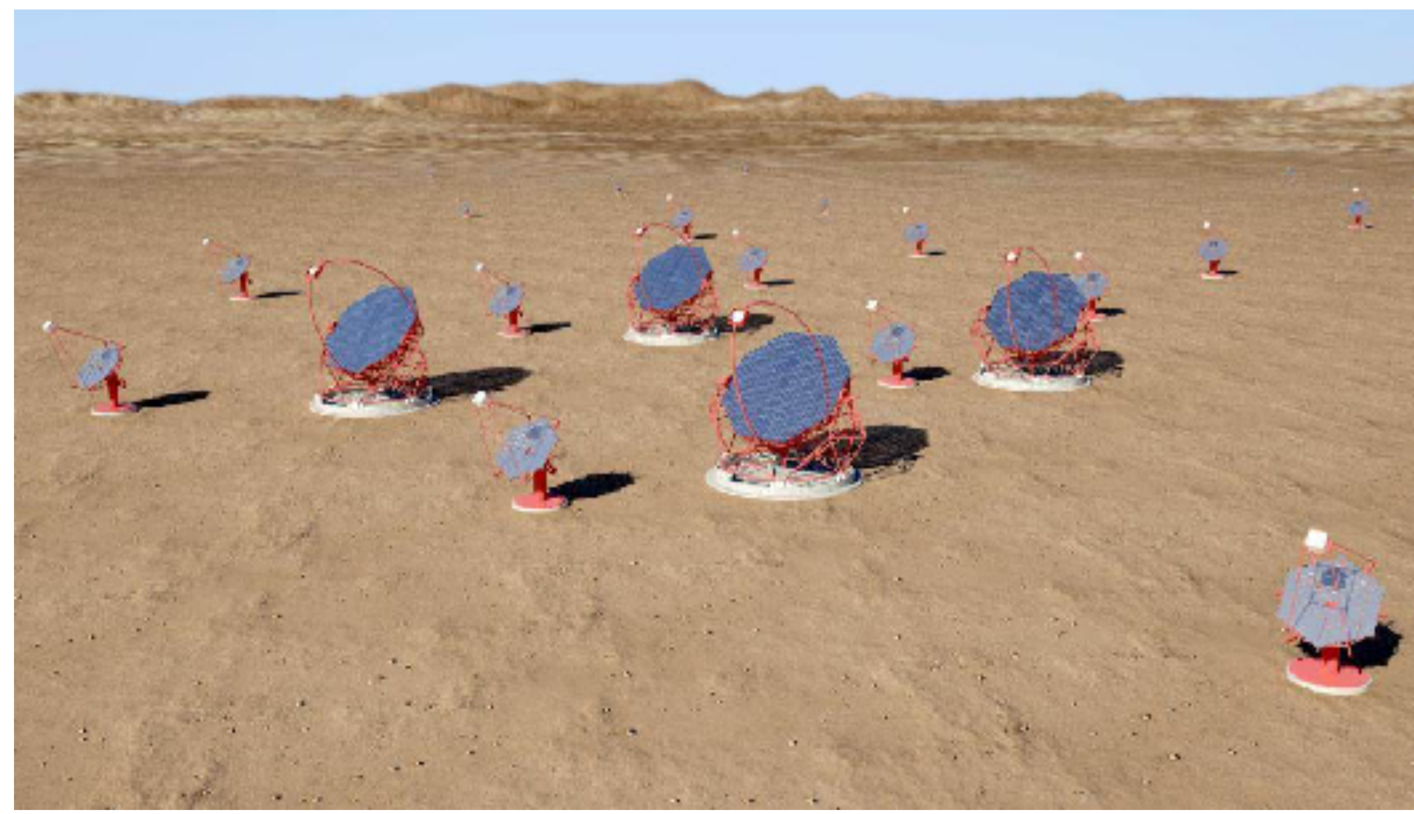
http://www.ams02.org/ams-and-iss/ AMS-02 on international space station



Principle of indirect detection



one can try to detect the annihilation products directly, i.e. detect the cosmic rays



CTA

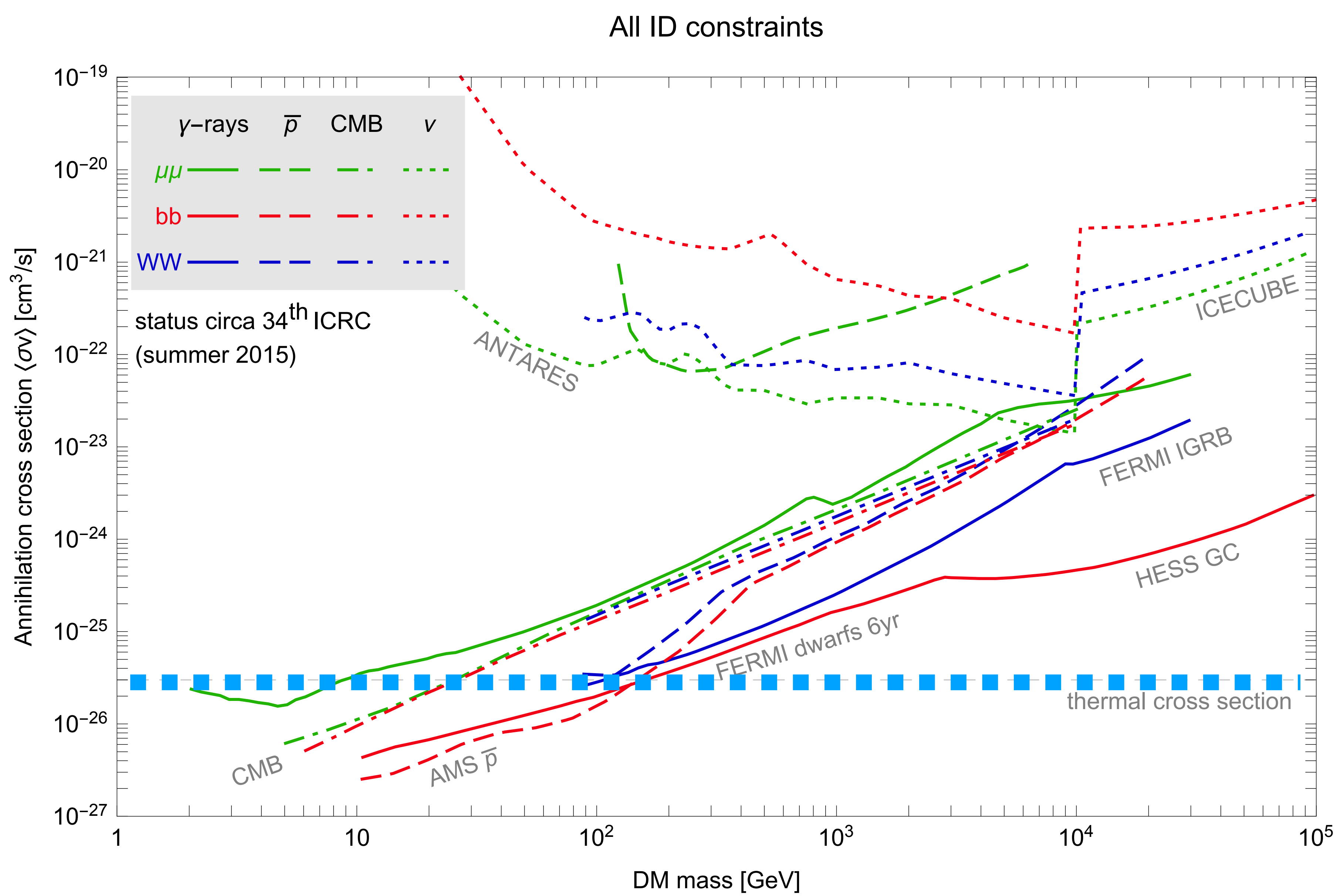
DM annihilates thermally or not ...

$$\phi_\gamma \propto \sigma v \int dl\ n^2_{\rm DM}$$

for prompt emission

$$\boxed{K\nabla^2\psi + \frac{\partial}{\partial E}(b_{\rm tot}\psi) + q = 0.}$$

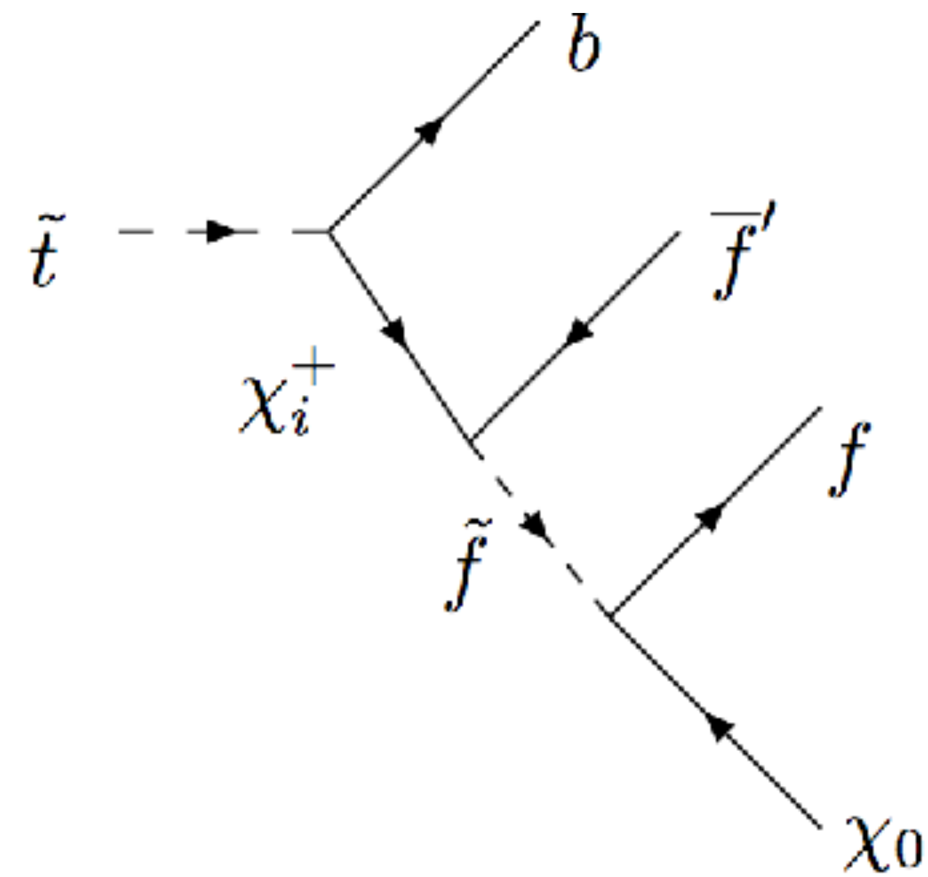
to follow the propagation of cosmic ray and the associated electromagnetic emission



III.c LHC/ collider physics

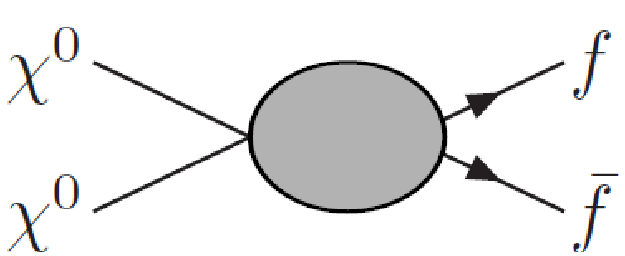
LHC physics

$$g\ g\ \to \tilde{t}\tilde{t}$$

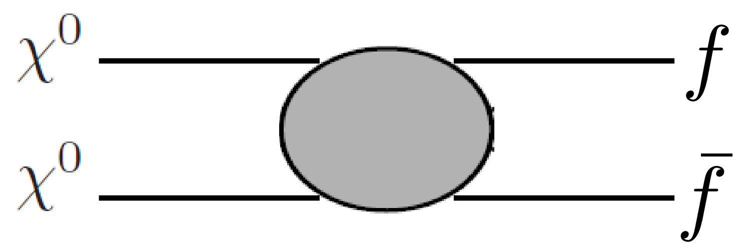


DM can be produced.
DM can be detected indirectly by looking for charged particles

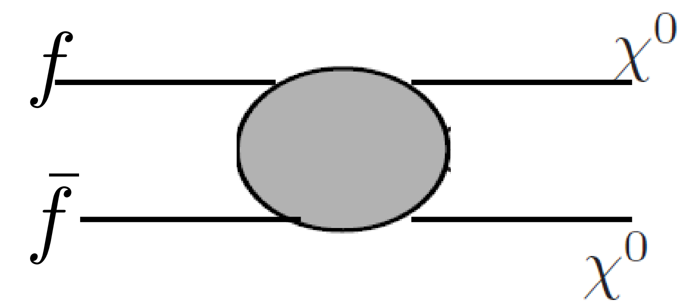
DM interacts with SM particles



Indirect Detection

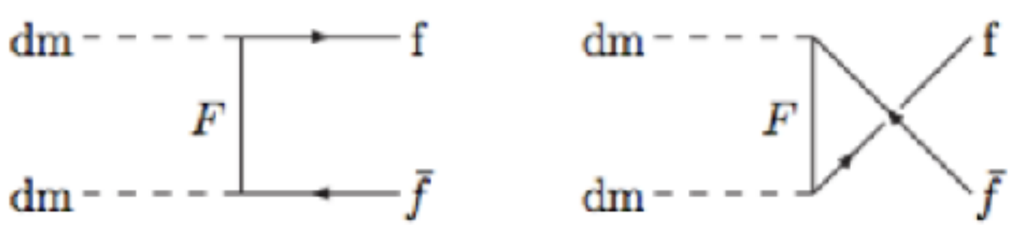


Direct Detection



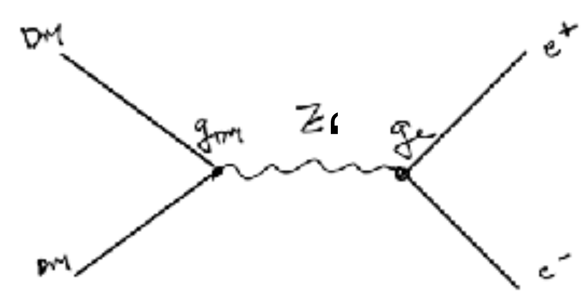
Collider

In principle we should take models by models but that is long
Can we do like I have done for Light Dark Matter?



$$\sigma v \propto \frac{1}{m_F^4} \left(\left(C_l^2 + C_r^2 \right) \, m_f + 2 C_l \, C_r \, m_F \right)^2$$

$$\sigma v \propto \frac{1}{m_F^2}$$



$$\sigma v \propto v^2 \, \frac{m_{\mathrm{DM}}^2}{m_{Z'}^4} \, g_{\mathrm{DM}}^2 \, g_e^2$$

$$m_{\mathrm{DM}} \simeq m_{Z'}$$

simplified models

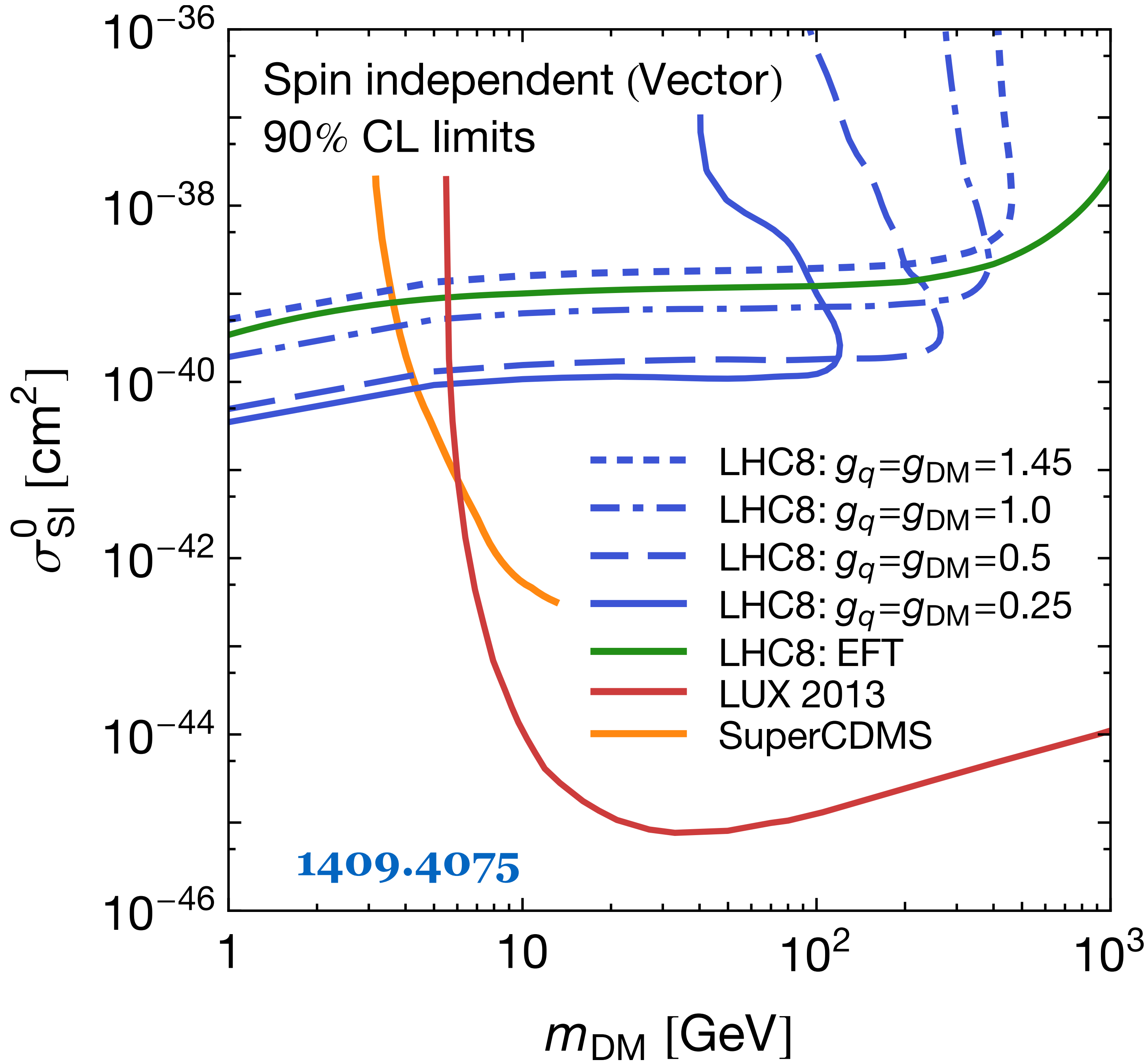
Simplified models

hep-ph/0305261

Model Number	DM	Mediator	Interactions	Elastic Scattering	Near Future Reach?	
					Direct	LHC
1	Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
1	Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}f$	$\sigma_{\rm SI} \sim (q/2m_\chi)^2$ (scalar)	No	Maybe
2	Dirac Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
2	Majorana Fermion	Spin-0	$\bar{\chi}\gamma^5\chi$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q^2/4m_n m_\chi)^2$	Never	Maybe
3	Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi$, $\bar{b}\gamma_\mu b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Maybe
4	Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\chi$, $\bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$ or $\sigma_{\rm SD} \sim (q/2m_\chi)^2$	Never	Maybe
5	Dirac Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi$, $\bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim 1$	Yes	Maybe
5	Majorana Fermion	Spin-1	$\bar{\chi}\gamma^\mu\gamma^5\chi$, $\bar{f}\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD} \sim 1$	Yes	Maybe
6	Complex Scalar	Spin-0	$\phi^\dagger\phi$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
6	Real Scalar	Spin-0	ϕ^2, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
6	Complex Vector	Spin-0	$B^\dagger_\mu B^\mu$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
6	Real Vector	Spin-0	$B_\mu B^\mu$, $\bar{f}\gamma^5 f$	$\sigma_{\rm SD} \sim (q/2m_n)^2$	No	Maybe
7	Dirac Fermion	Spin-0 (t-ch.)	$\bar{\chi}(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
7	Dirac Fermion	Spin-1 (t-ch.)	$\bar{\chi}\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
8	Complex Vector	Spin-1/2 (t-ch.)	$X^\dagger_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes
8	Real Vector	Spin-1/2 (t-ch.)	$X_\mu\gamma^\mu(1 \pm \gamma^5)b$	$\sigma_{\rm SI} \sim$ loop (vector)	Yes	Yes

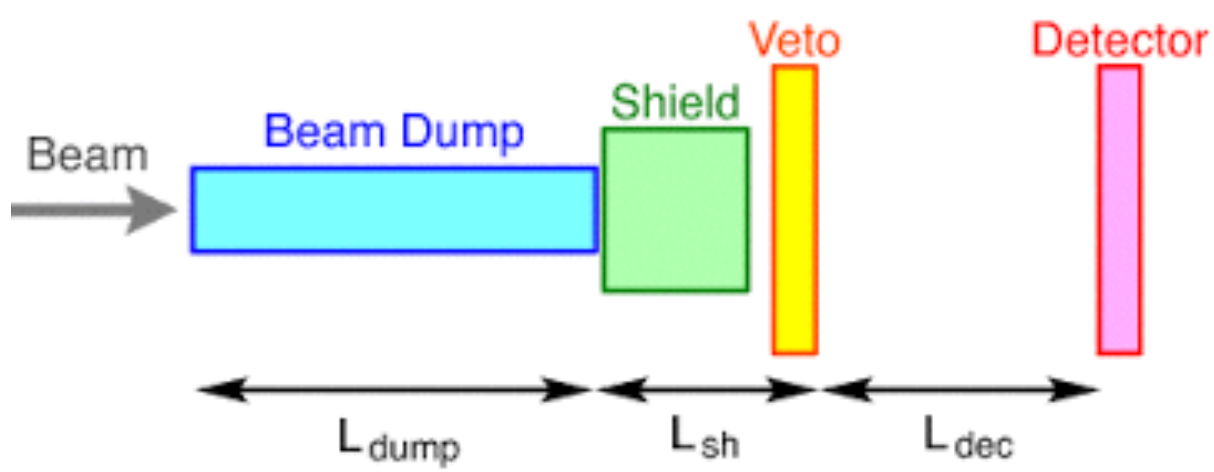
arXiv:1404.0022

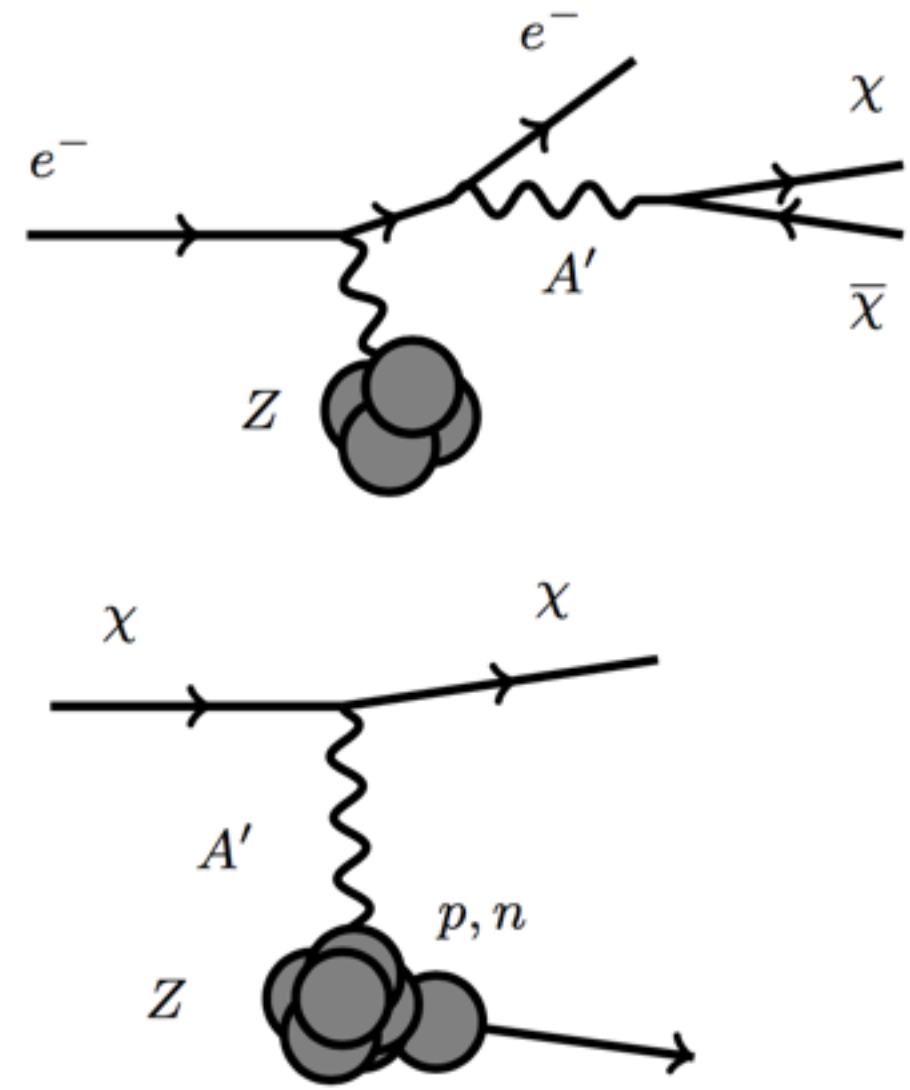
DM interacts with SM particles



If DM interacts only with the dark sector then detection depends on the interactions of this dark sector with SM

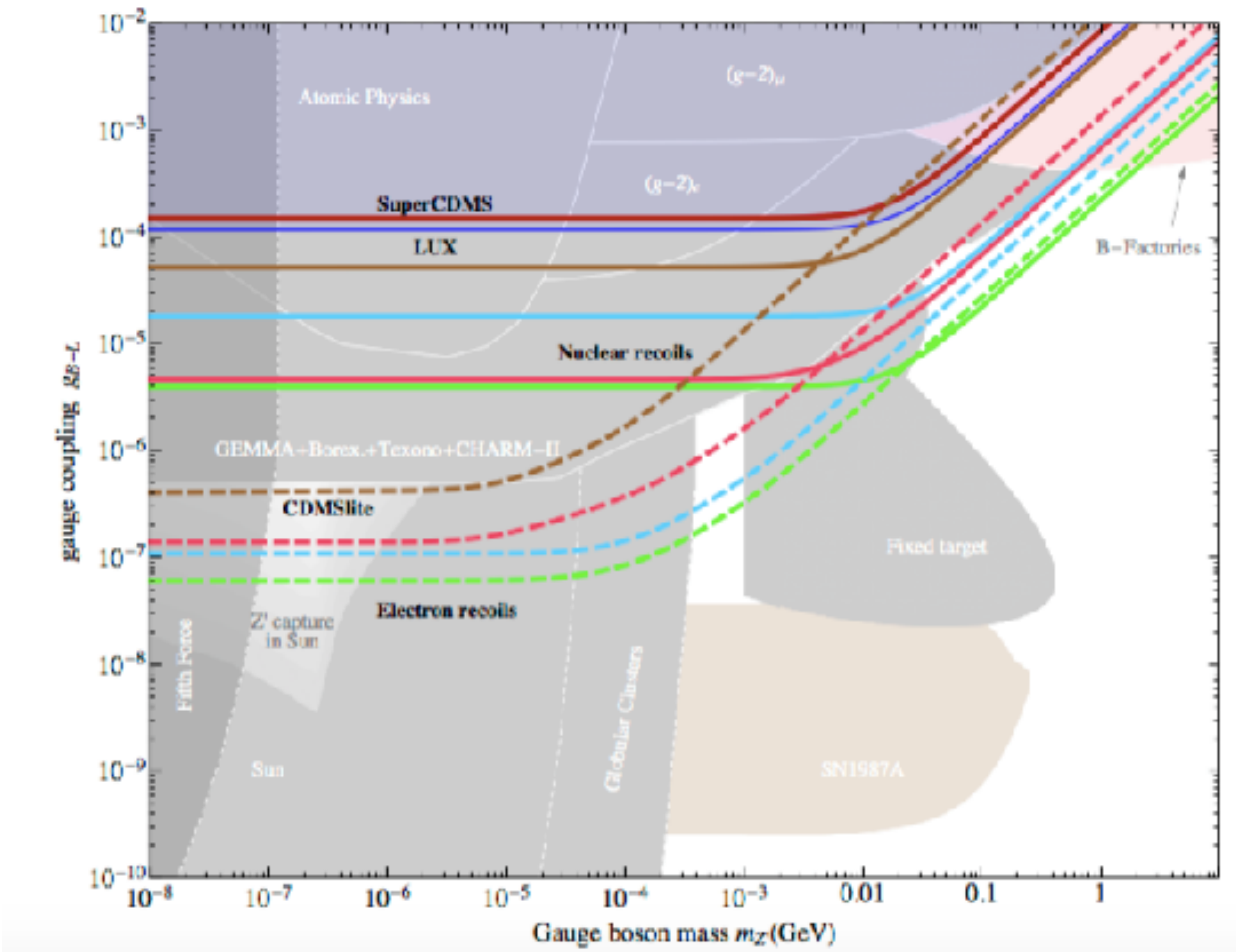
Beam dump experiments

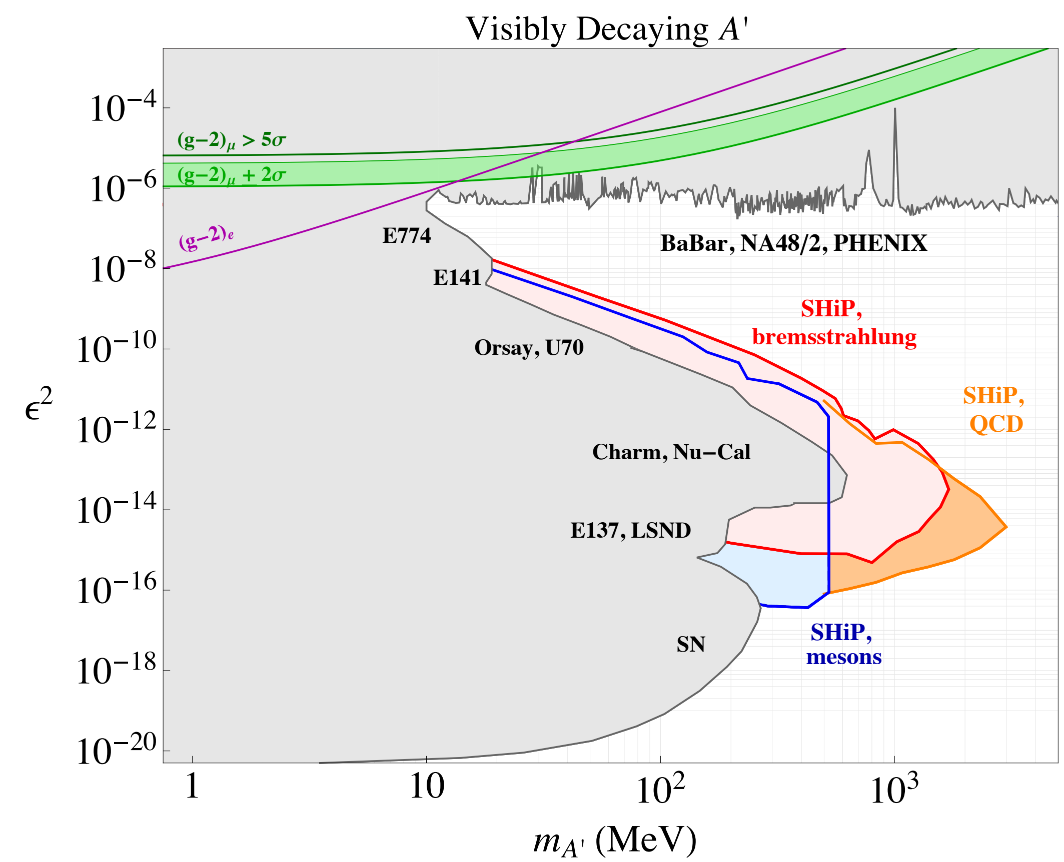




https://arxiv.org/pdf/1406.3028.pdf

Searching for Z'/dark photons





Effects of Weakly Interacting Slim Particles in Cavities with a Moving Boundary Condition

Ariel Arza

May 10, 2017

e-Print: arXiv:1705.03906 [hep-ph] | PDF

END of LECTURE 3

Thank you and good luck :)