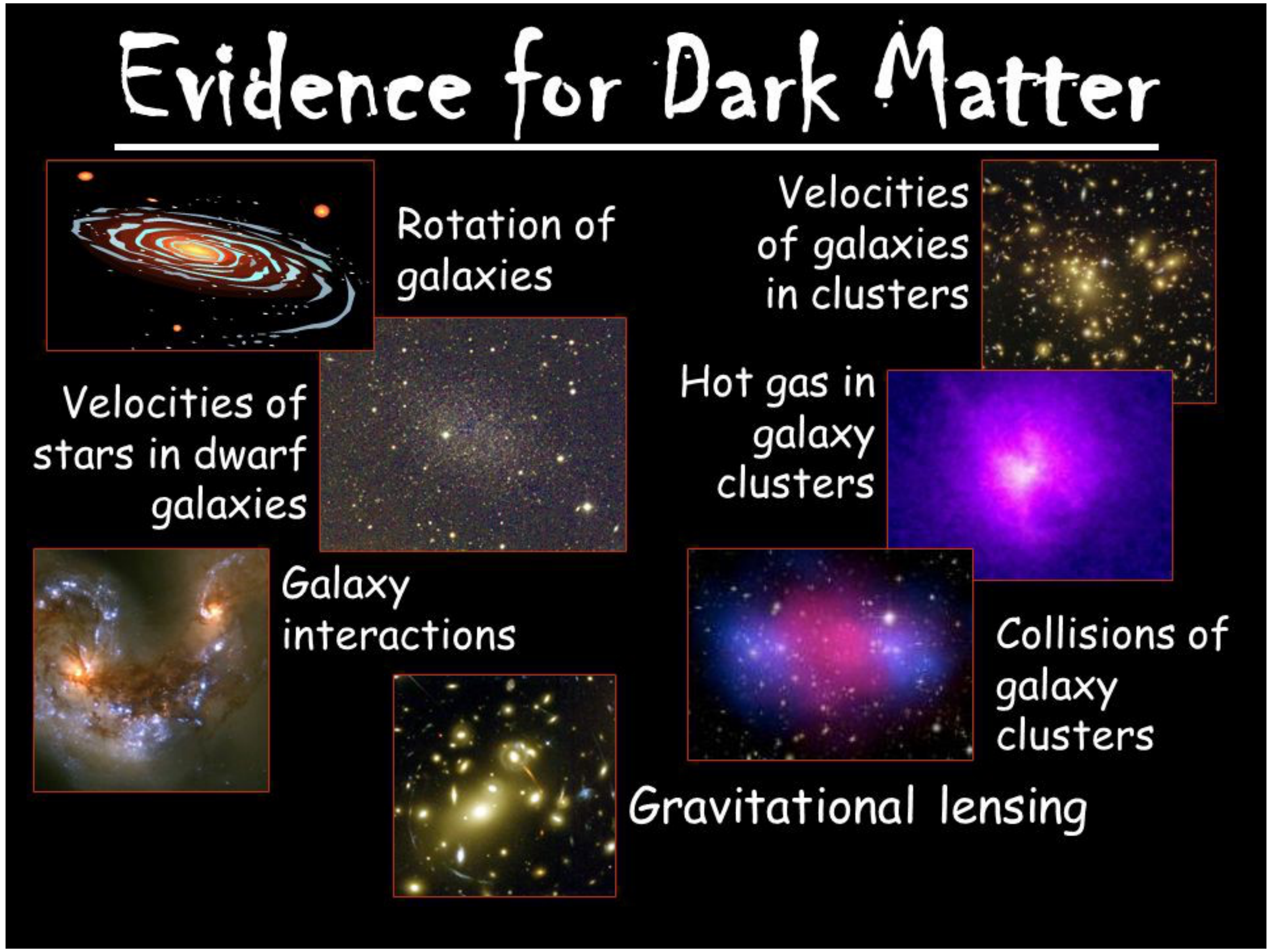
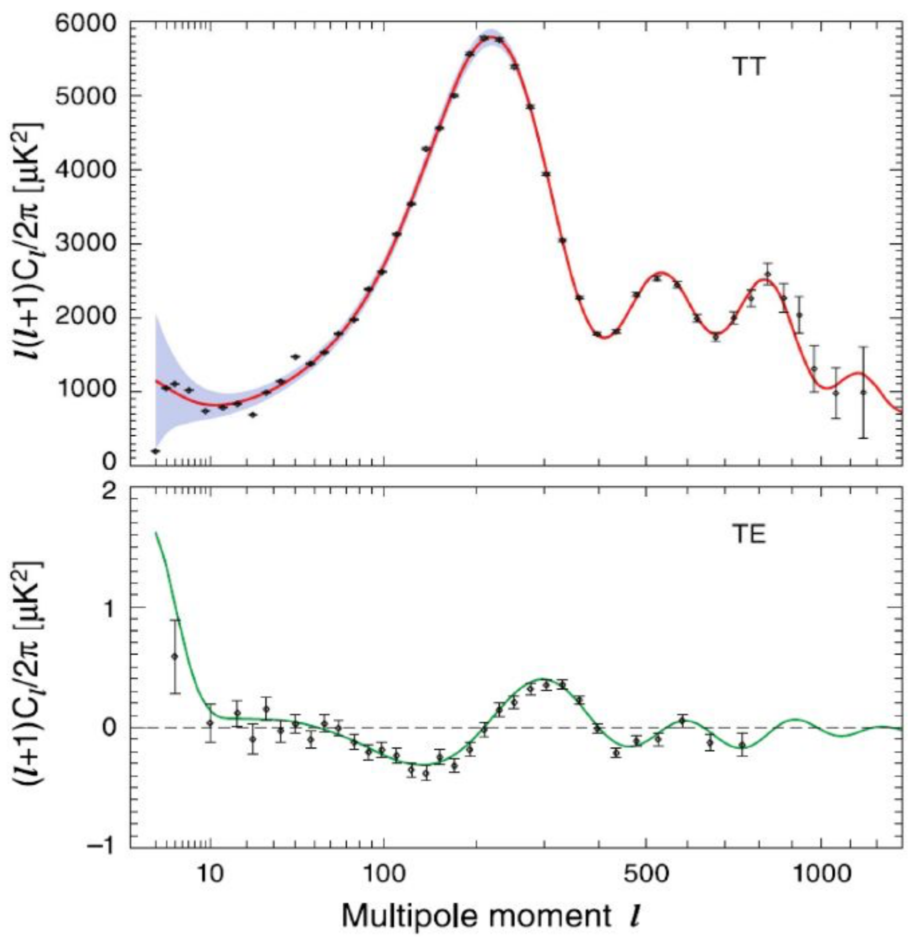
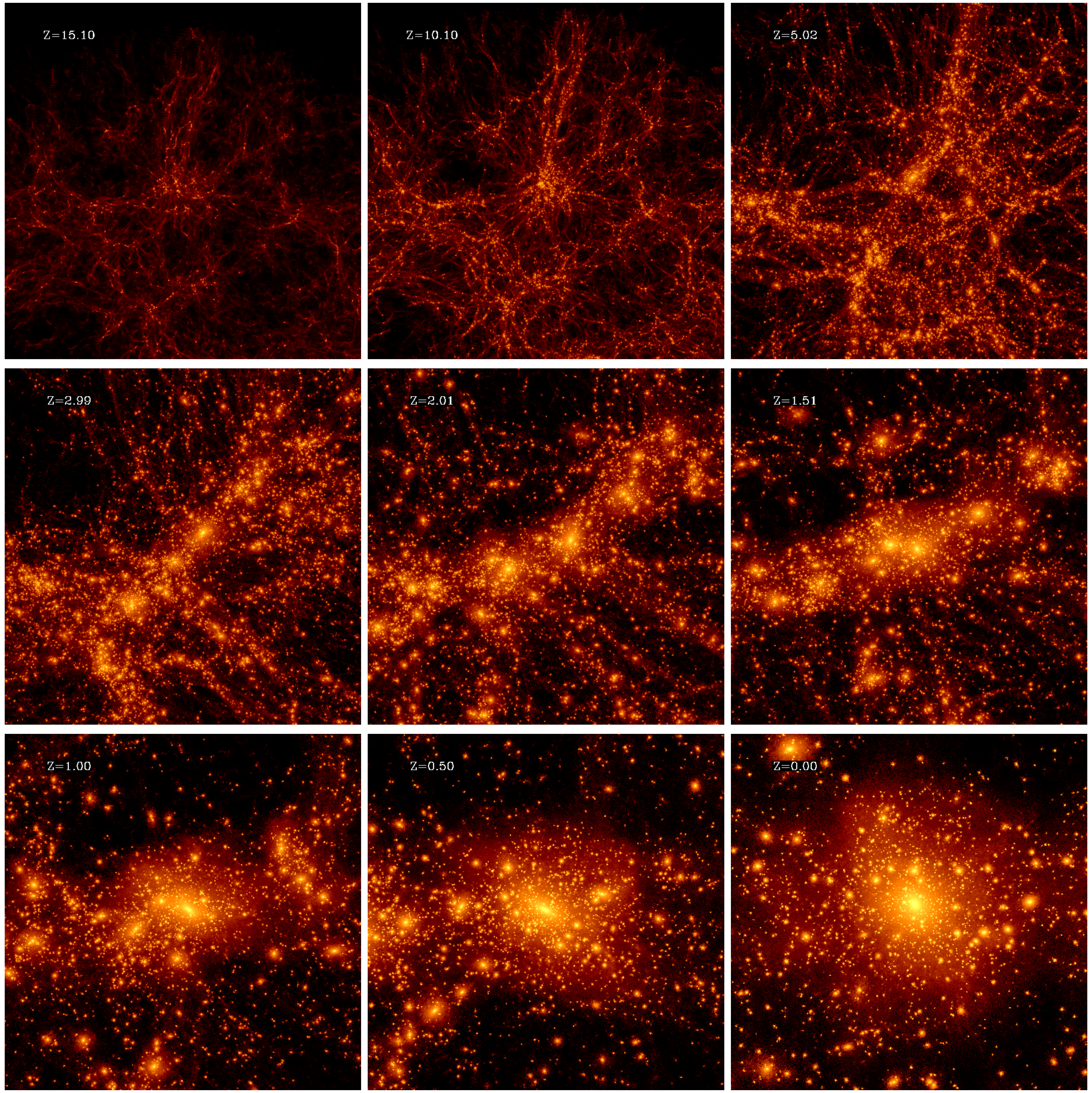
Signatures of Freeze-in and SuperWIMP Dark Matter at Colliders and Cosmology

Dipan Sengupta

Dark Matter in “Heaven”

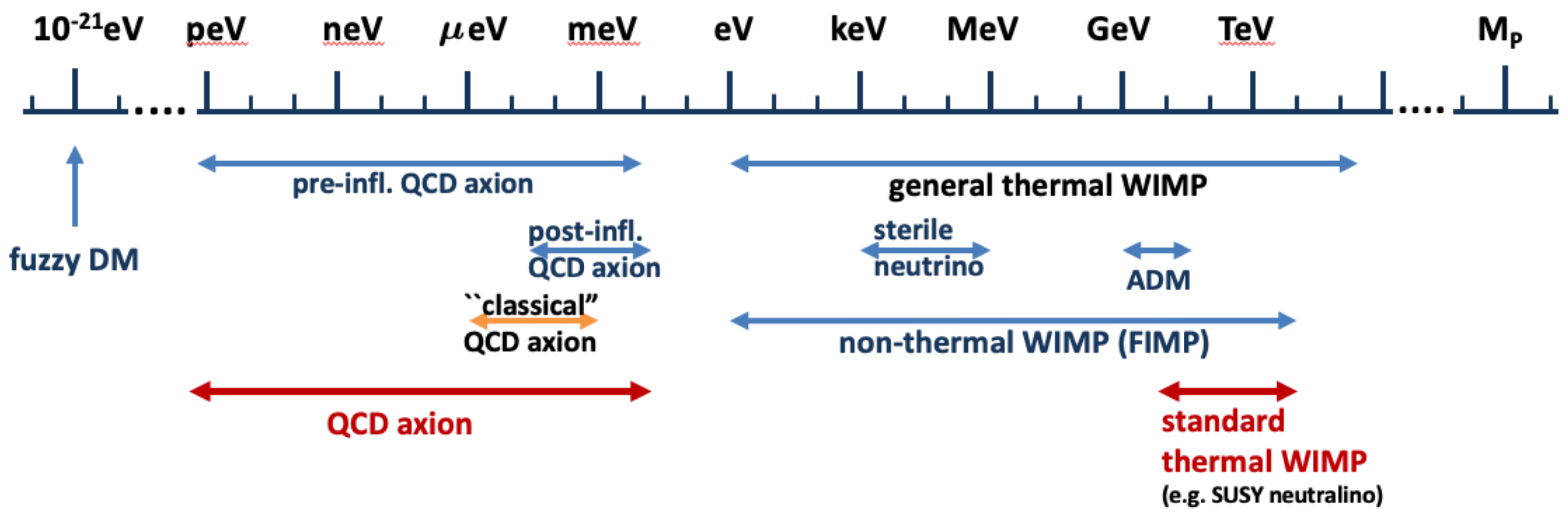


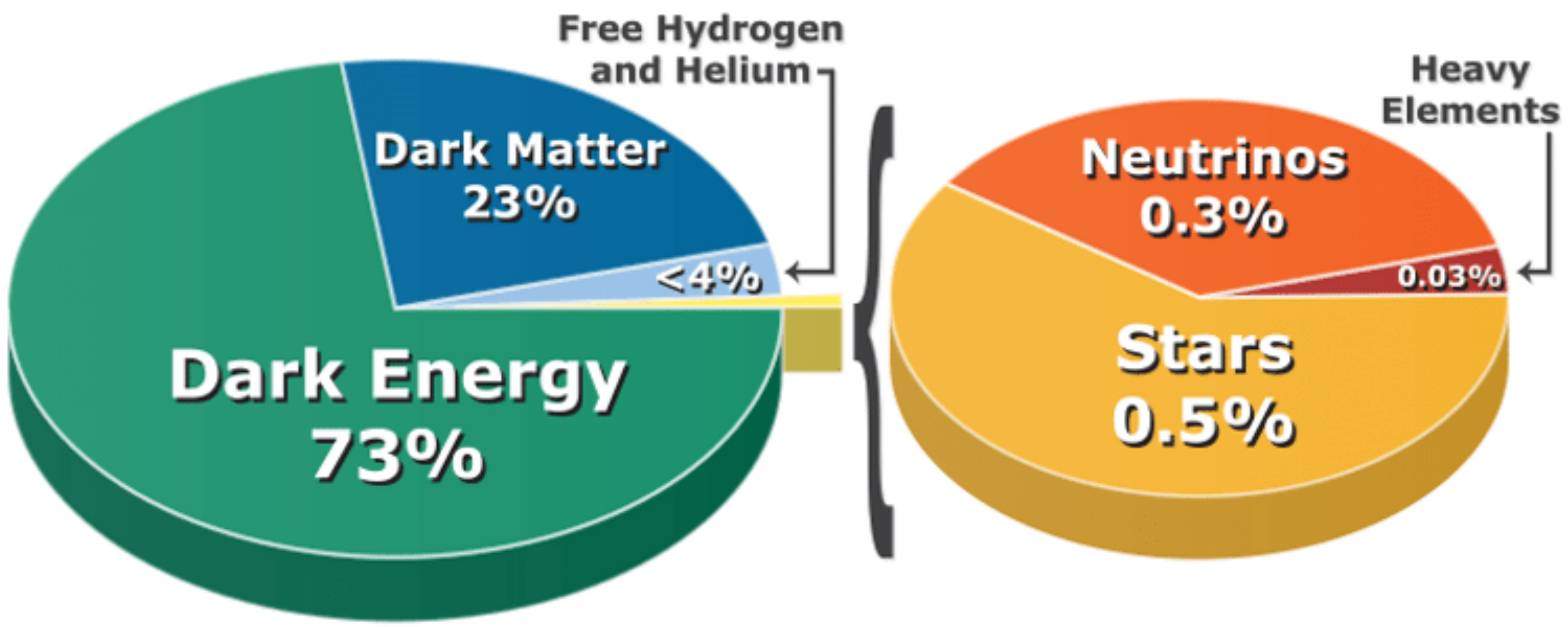




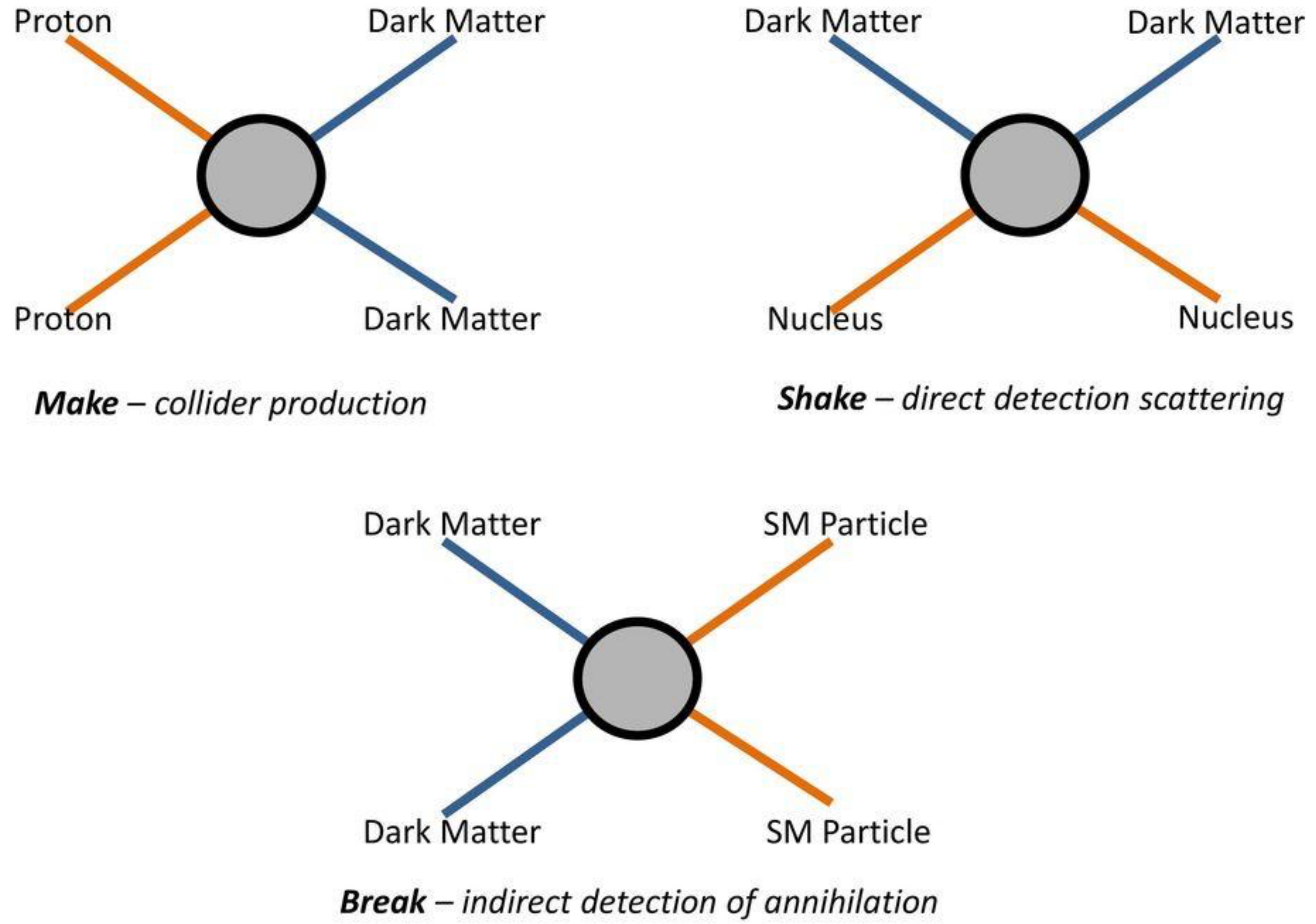
A Milky Way sized dark matter halo
with CDM cosmology

WIMPY Dark Matter





Ways to Detect Dark Matter – *Make, Shake and Break*



WIPMY Dark Matter

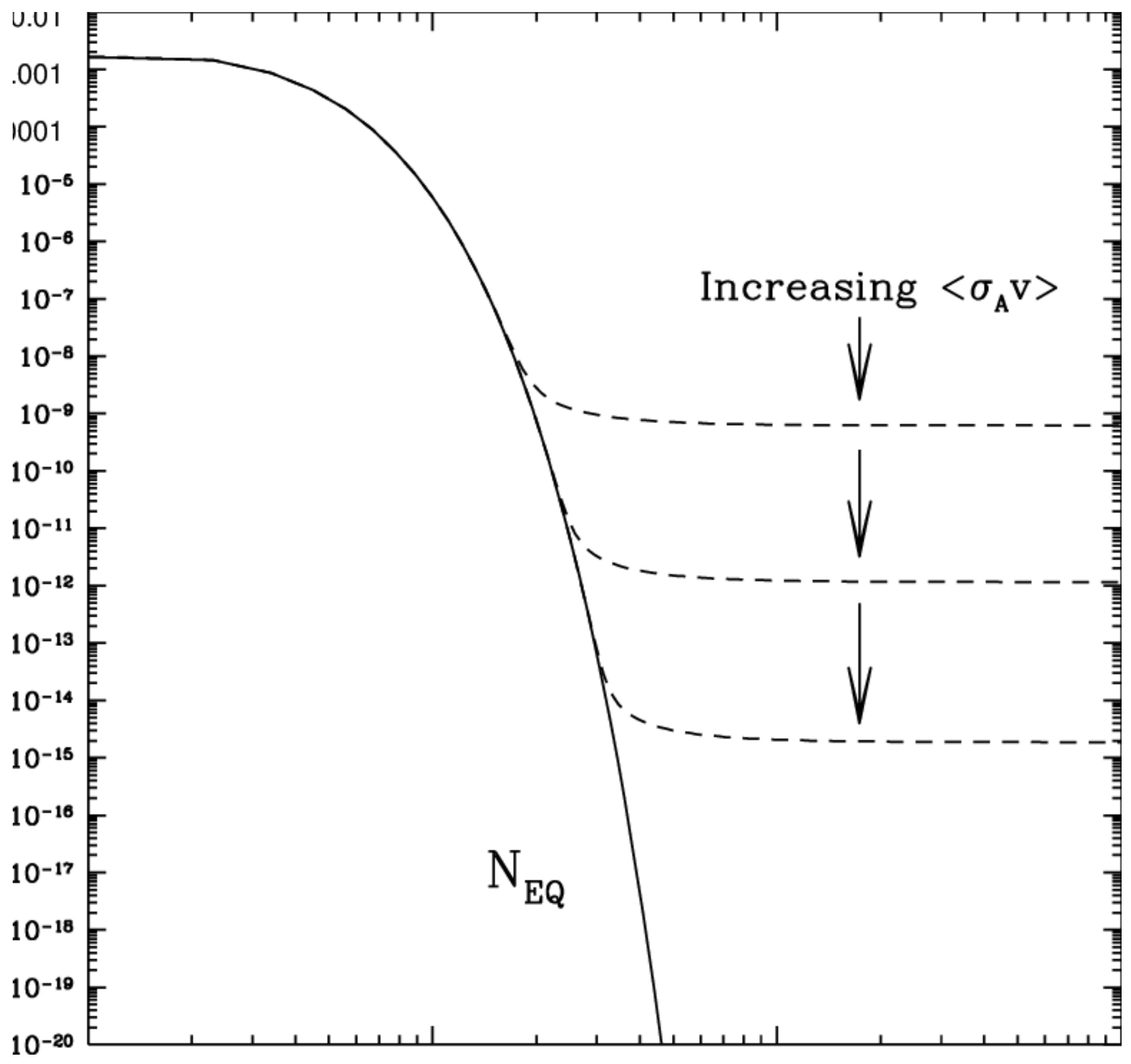
DM in thermal equilibrium with bath particles in early universe

$$n = g\left(\frac{mT}{2\pi}\right)^{3/2} e^{-m/T}$$

$$\frac{dn_\chi}{dt} + 3Hn_\chi =< \sigma v > [n_\chi^2 - n_{eq}^2]$$ → **Boltzmann equation for DM**

$$\langle\sigma_{\rm ann} v_{\rm rel}\rangle(x) = \frac{4x}{K_2(x)^2}\int_1^{+\infty} d\bar{s} \quad \sqrt{\bar{s}}\cdot(\bar{s}-1)\cdot K_1(2x\sqrt{\bar{s}})\cdot\sigma_{\rm ann}$$

$$x \equiv \frac{M_X}{T}$$

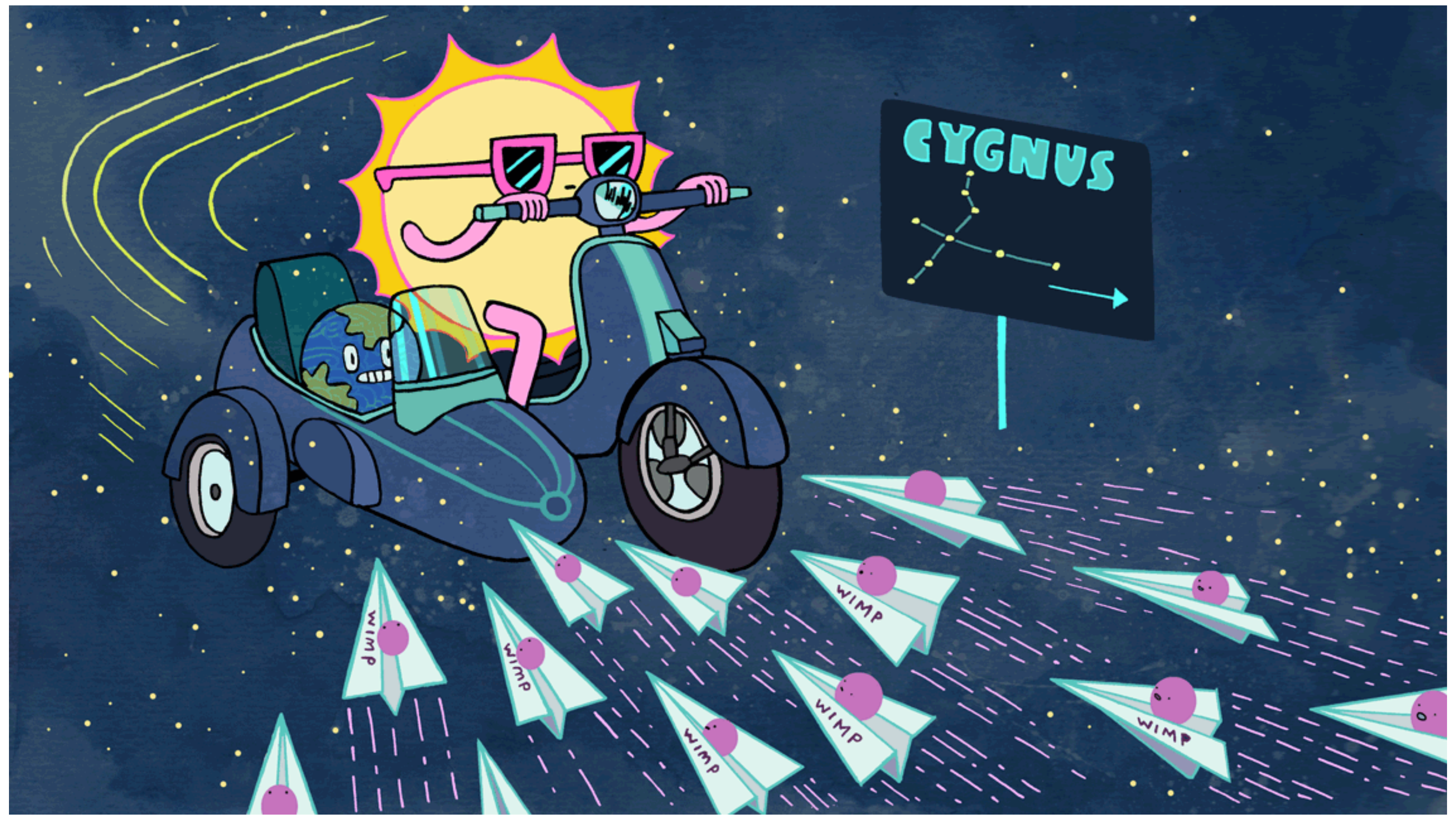


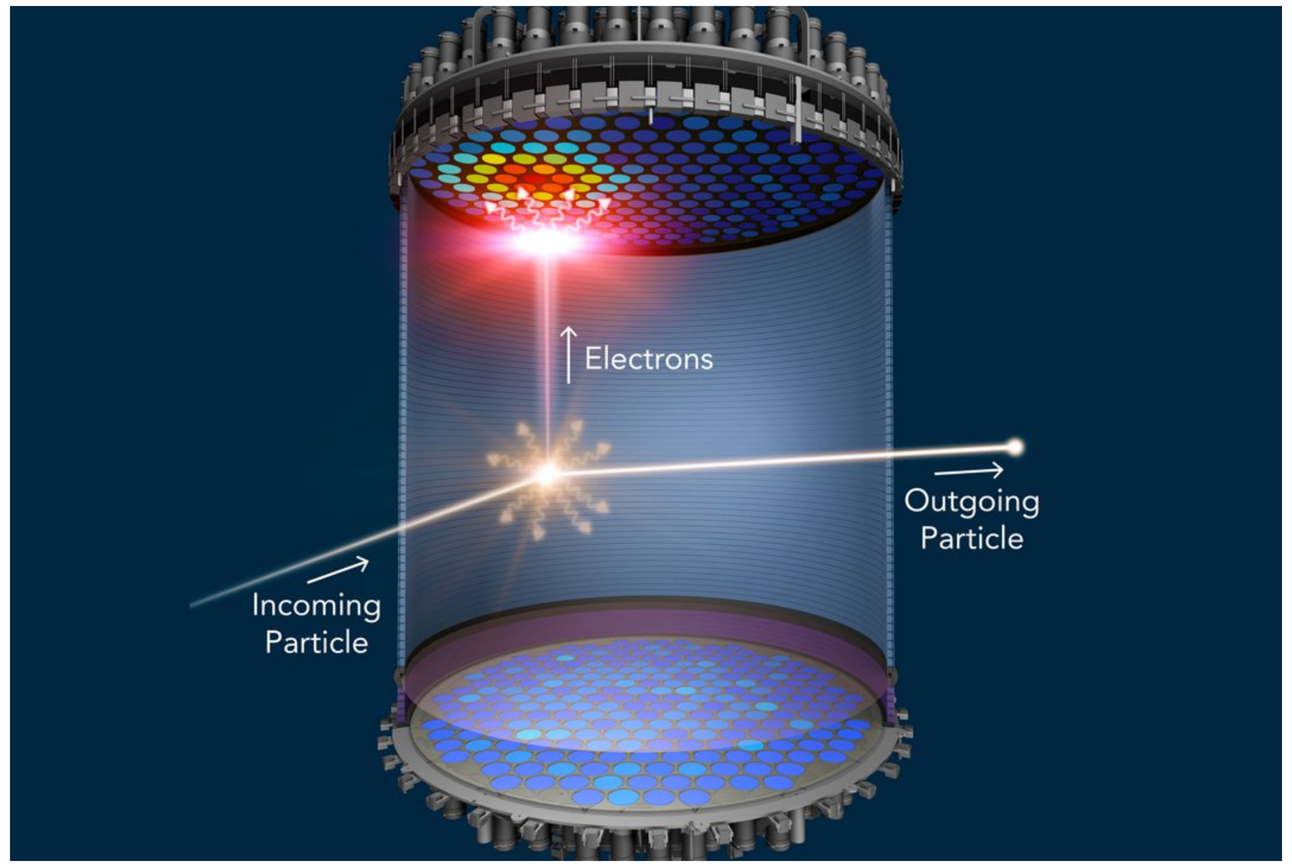
$$\Omega_X \equiv \frac{\rho_{X,0}}{\rho_{\rm crit,0}} = \frac{M_X n_{X,0}}{3M_{\rm pl}^2 H_0^2} = \frac{M_X N_{X,0} s_0}{3M_{\rm pl}^2 H_0^2} = M_X N_X^\infty \frac{s_0}{3M_{\rm pl}^2 H_0^2}$$

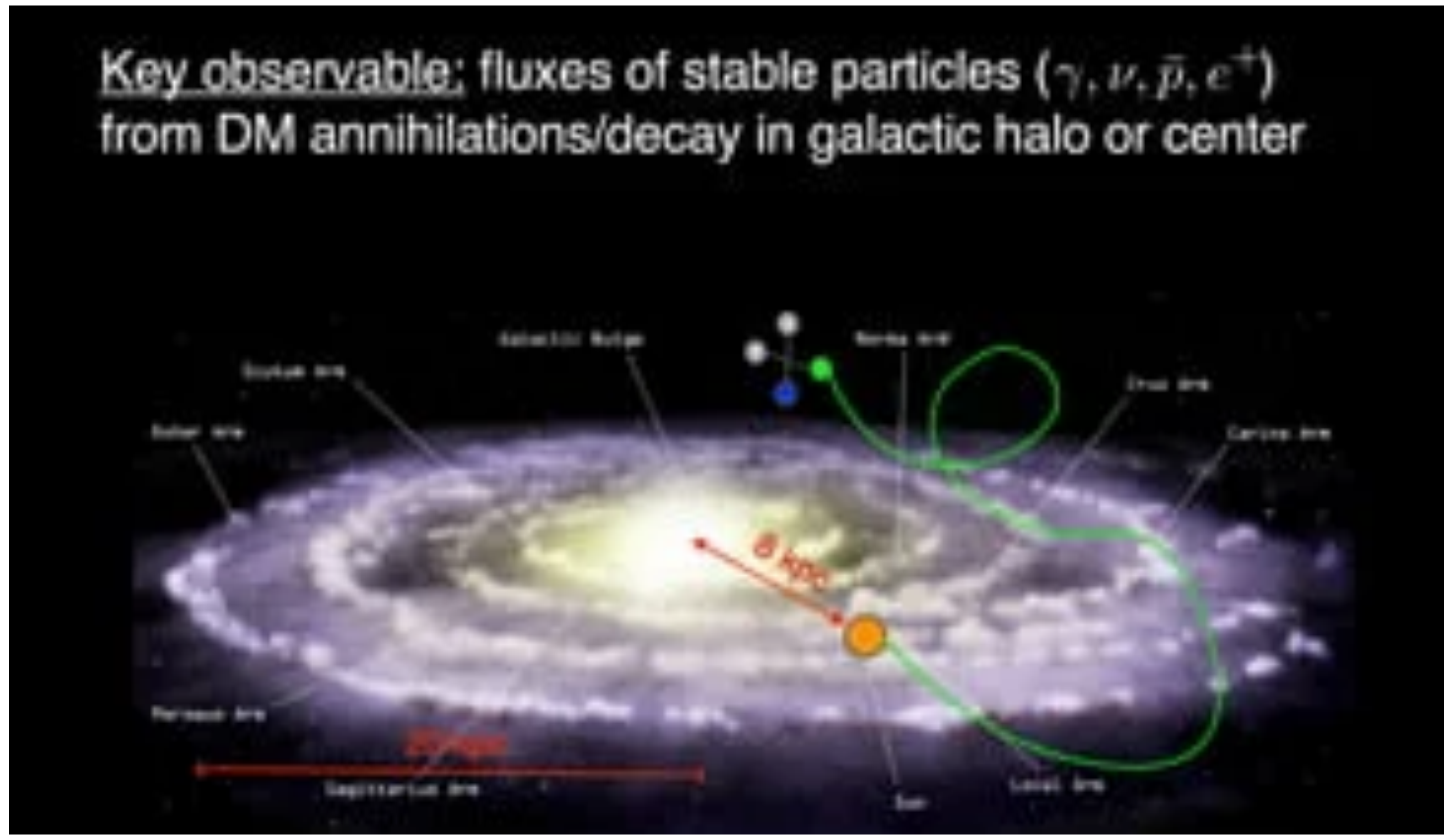
$$\Omega_\chi h^2 = 0.1\frac{x_f}{28}\frac{\sqrt{g_{eff}}}{10}\frac{2.10^{-26} cm^3 s^{-1}}{< \sigma_{\chi\chi} v_{ann} >}$$

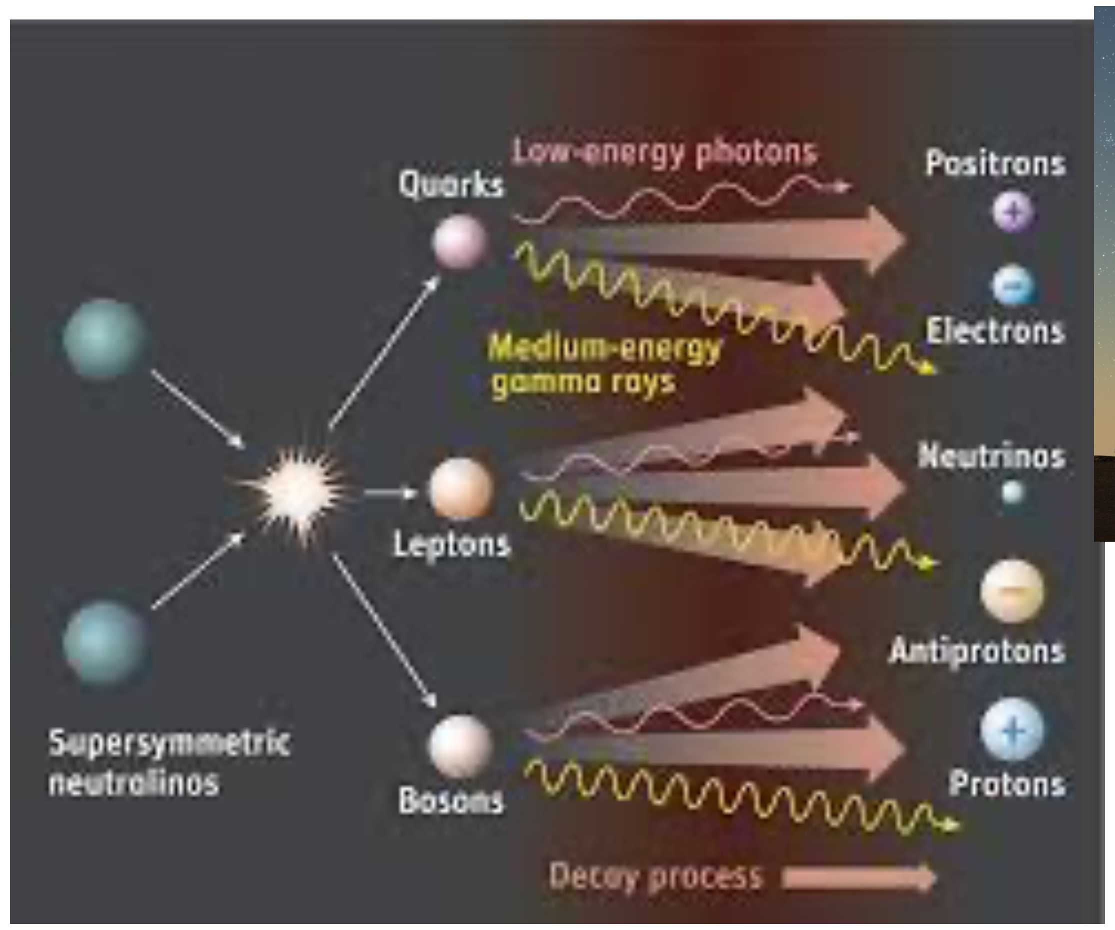
Interaction Strength : Weak Scale -> A BSM theory that also solves Hierarchy problem

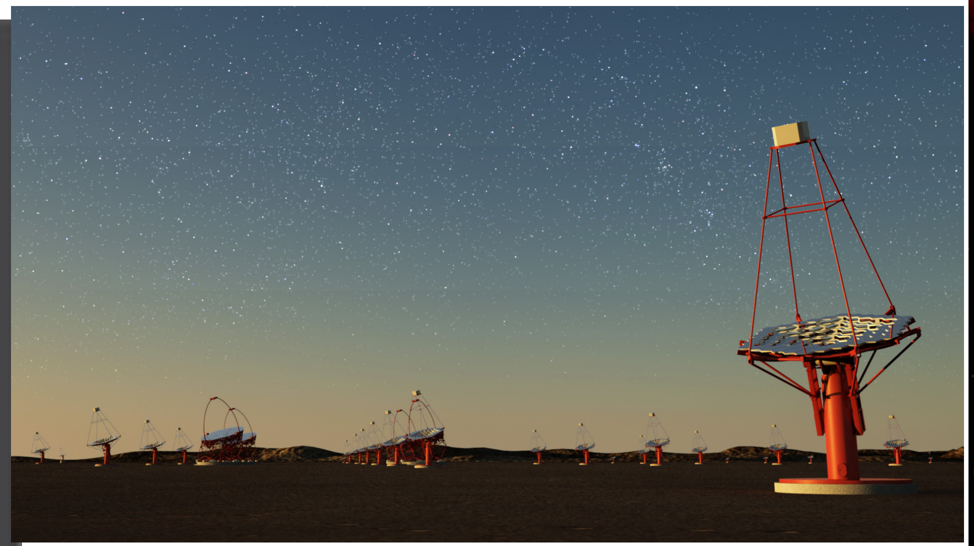
WIMPY Dark Matter

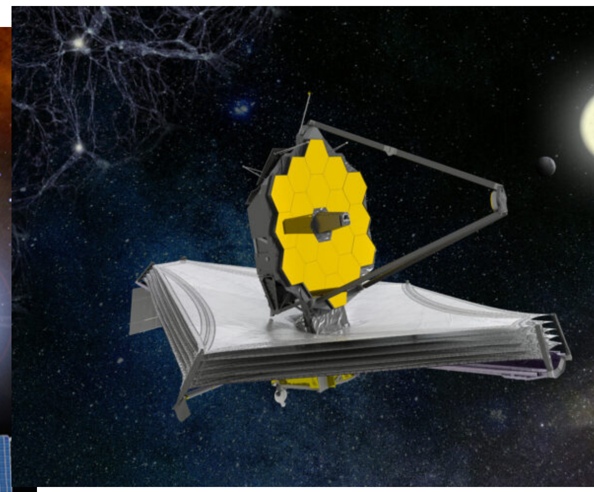


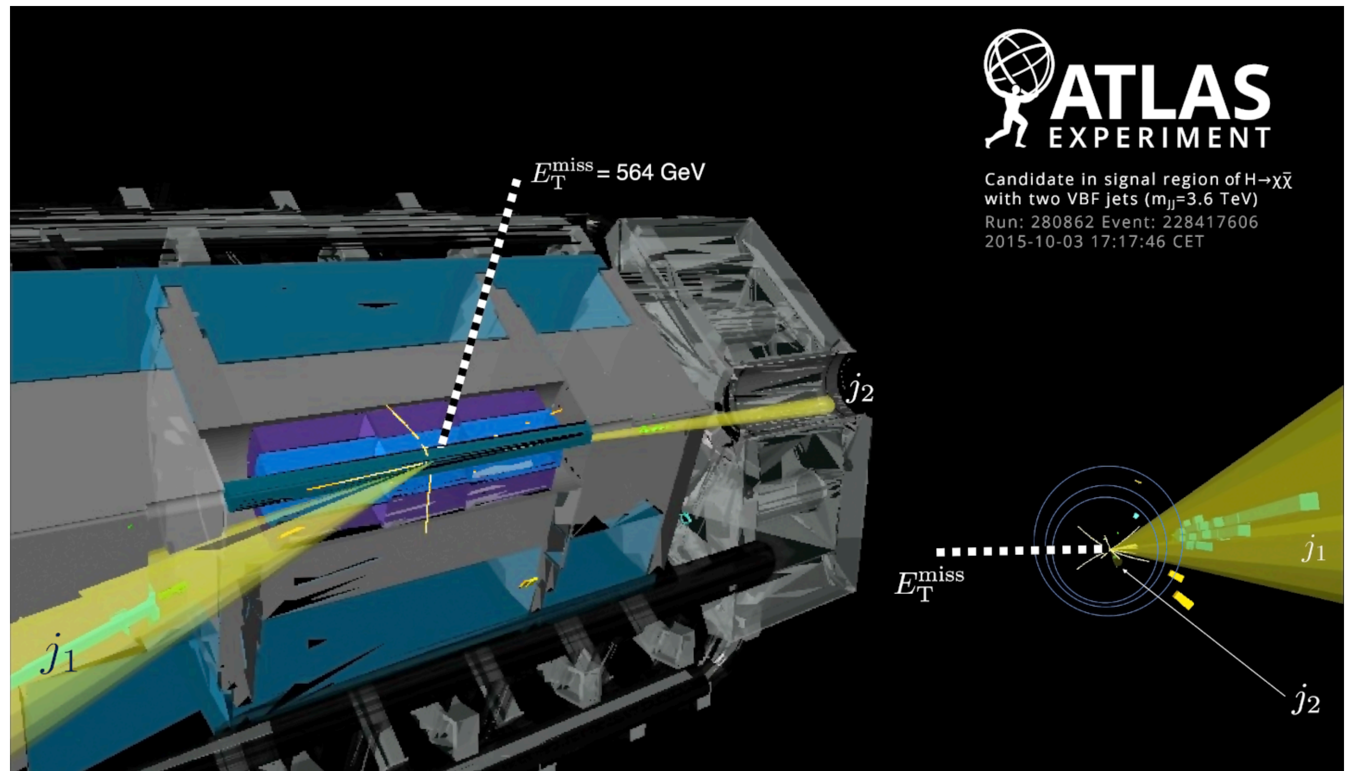




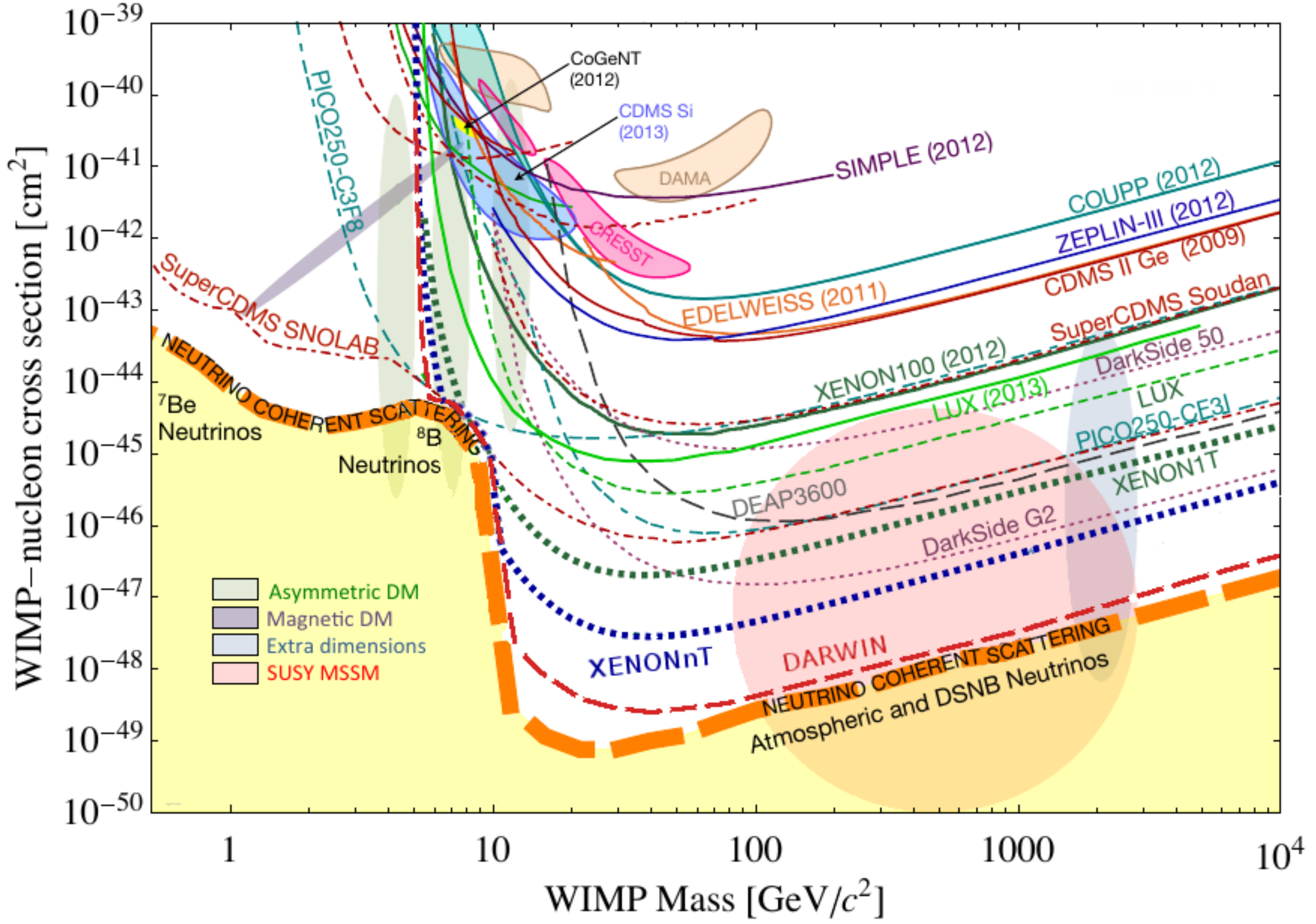








WIMPY Dark Matter



Alternative ideas for MeV - TeV dark matter

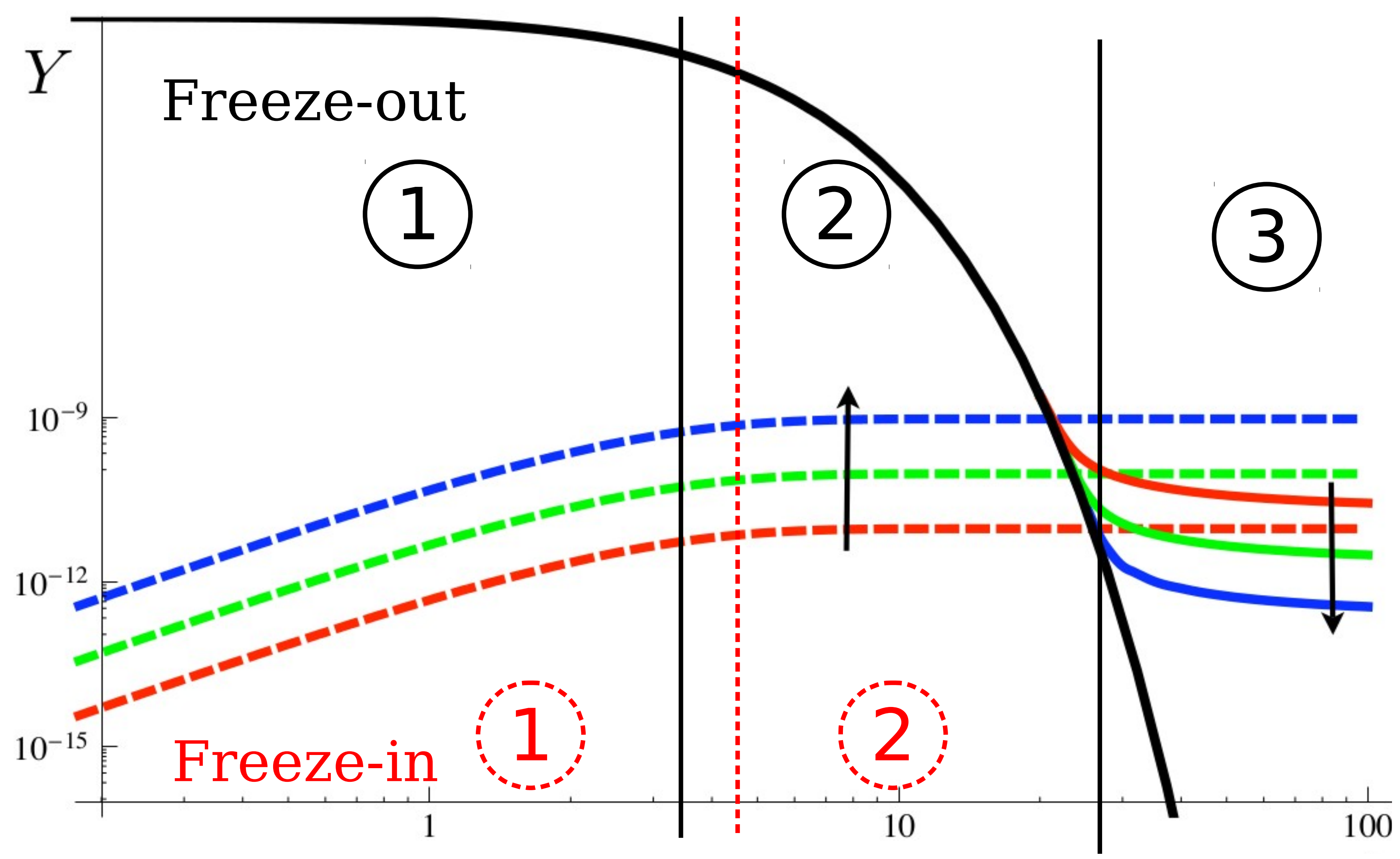
Freeze-in (FIMP) and Super WIMPS (SWIMPS)

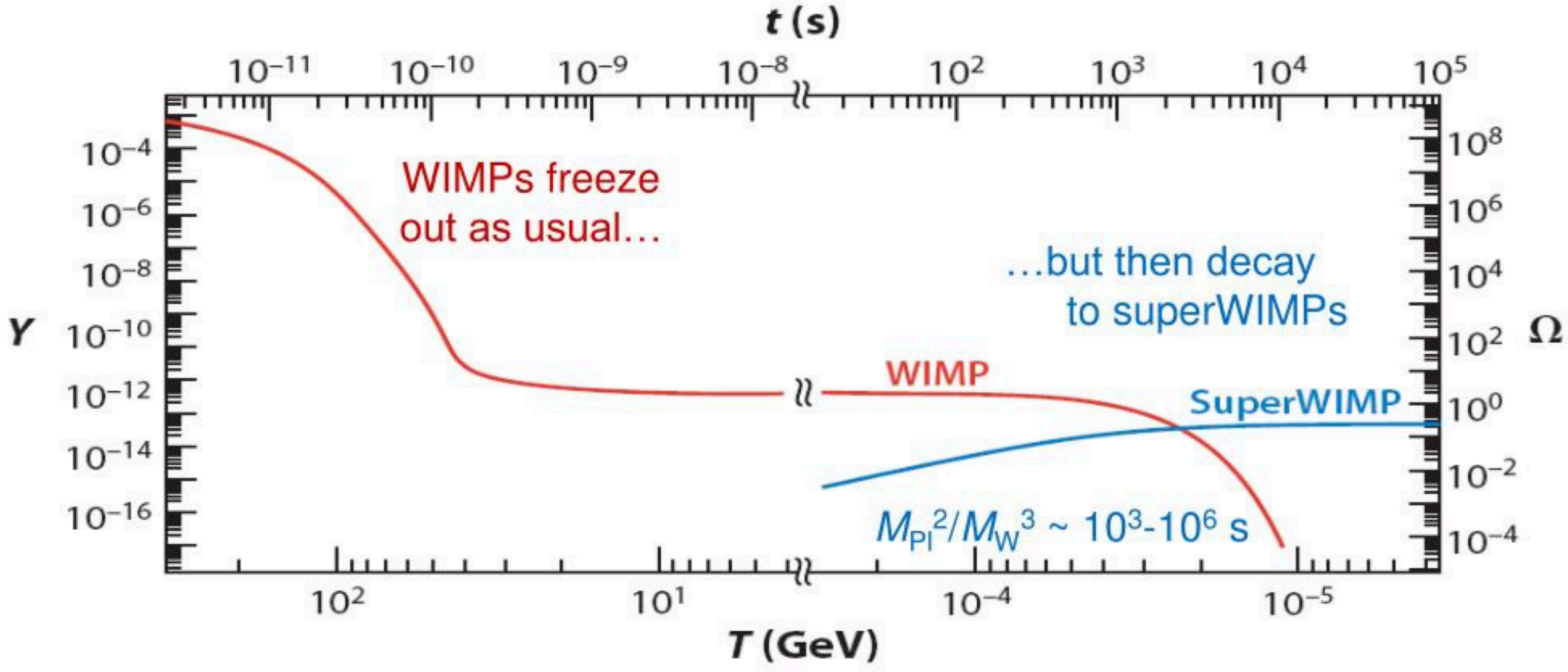
(Non-) Thermal mechanisms

Freeze-In

Super WIMPS

Tweaked from arXiv:0911.1120





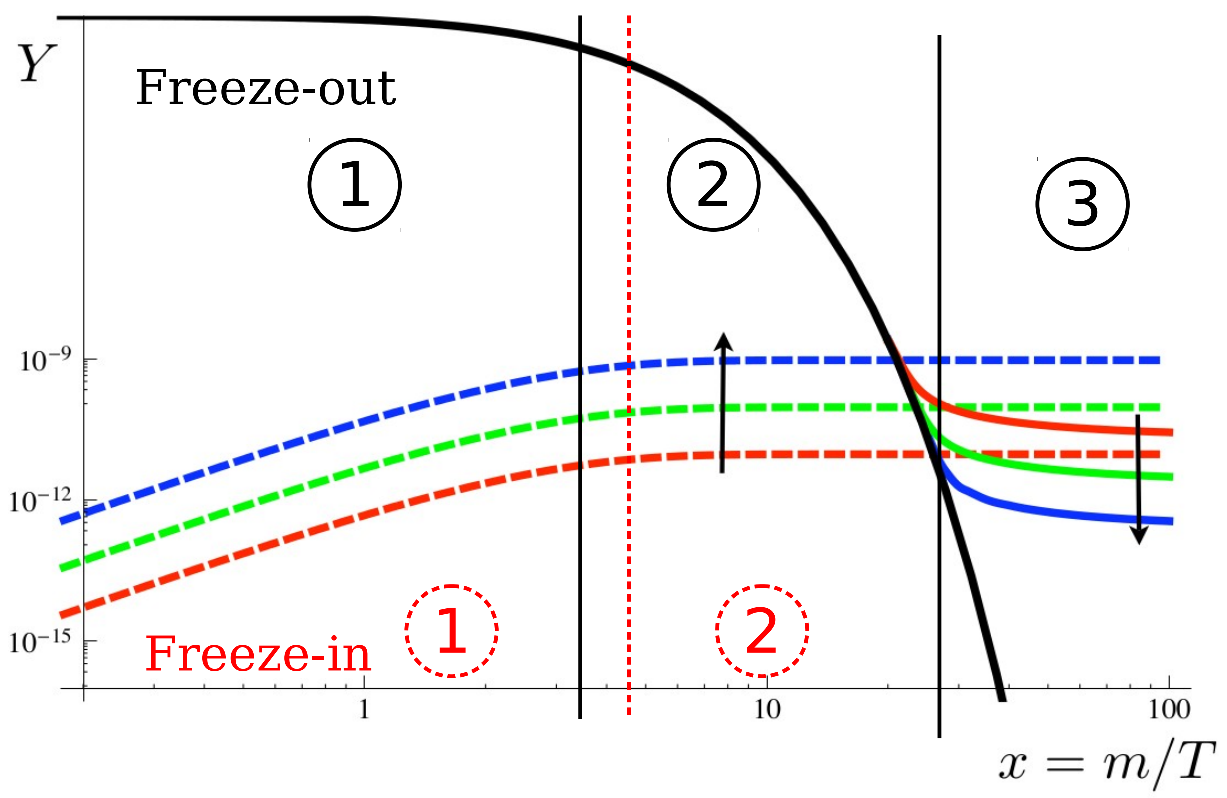
Both set ups characterised by extremely weakly interacting particles

Freeze-in (FIMP)

Freeze-in: general idea

arXiv:hep-ph/0106249
arXiv:0911.1120
arXiv:1706.07442...

Tweaked from arXiv:0911.1120



Two basic premises :

· DM interacts *very* weakly with the SM.

· DM has a negligible initial density.

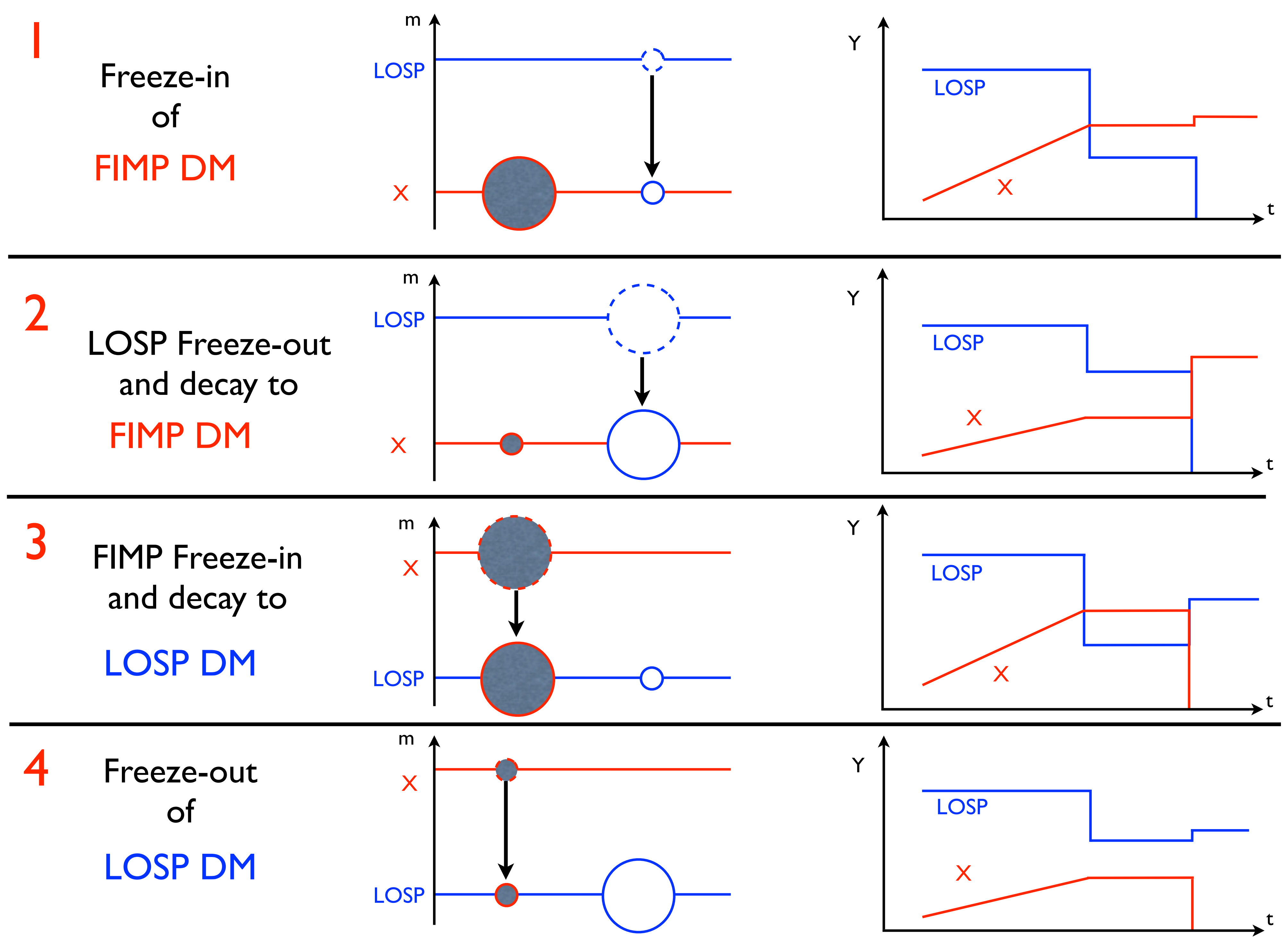
Assume that in reaction $A \to B$, ξ_A/ξ_B particles of type χ are destroyed/created.
Integrated Boltzmann equation :

$$\dot{n}_\chi + 3Hn_\chi = \sum_{A,B}(\xi_B - \cancel{\xi_A})\mathcal{N}(A \to B)$$

$$\mathcal{N}(in \to out) = \int \prod_{i=in}\left(\frac{d^3p_i}{(2\pi)^3 2E_i} f_i\right) \prod_{j=out}\left(\frac{d^3p_j}{(2\pi)^3 2E_j}(1 \mp f_j)\right) \times (2\pi)^4 \delta^4\left(\sum_{i=in} P_i - \sum_{j=out} P_j\right) C_{in} |\mathcal{M}|^2$$

1 DM produced from decays/annihilations of other particles.

2 DM production disfavoured → Abundance freezes-in



If there is a lightest observable sector particle (LOSP)

Freeze-in vs freeze-out

Naively, the freeze-in BE is simpler than the freeze-out one. However :

Initial conditions:

· FO: equilibrium erases all memory.

· FI: Ωh^2 depends on the initial conditions.

Heavier particles:

· FO: pretty irrelevant (exc. coannihilations/late decays).

· FI: their decays can dominate DM production.

$\boxed{\text{Need to track the evolution of heavier states}}$

In equilibrium? Relics? FIMPs?

Need dedicated Boltzmann eqs

Relevant temperature:

· FO: around $m_\chi/20$.

· FI: several possibilities ($m_\chi/3$, $m_{\text{parent}}/3$, T_R or higher), depending on nature of underlying theory.

Dedicated Codes to perform the integrations
MicrOmegas 5 + Belanger, Boudjema, Goudelis
Pukhov, Zaldivar

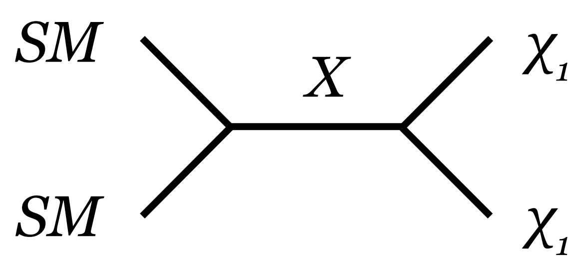
- Statistics/early Universe physics can become important.

Freeze-in (FIMP)

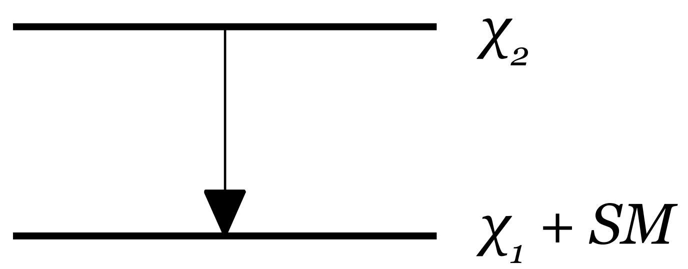
Model-building issues

What kind of couplings do we need for successful freeze-in?

Annihilation:



Decay:



· Requires $\lambda_1 \lambda_2 \sim 10^{-10} - 10^{-12}$

· Requires $\lambda \sim 10^{-13}$ x $(m_{\chi 2}/m_{\chi 1})^{1/2}$

How can we justify such small numbers?

Two main ways so far:

- Scale suppression **UV dominated**
- Symmetries **Potentially IR dominated**

How to dynamically and "naturally" generate such small couplings with order 1 numbers ?

Freeze-in (FIMP) : Some Examples

Higgs Portal

$$V(\Phi, s) = \mu_{\rm h}^2|\Phi|^2 + \lambda_{\rm h}(\Phi^\dagger\Phi)^2 + \frac{\mu_{\rm s}^2}{2}s^2 + \frac{\lambda_{\rm s}}{4}s^4 + \frac{\lambda_{\rm hs}}{2}|\Phi|^2 s^2$$

$\boxed{h \to ss}$

$\lambda_{\rm hs} \lesssim 10^{-7}$

$$\frac{\Omega_{\rm s}h^2}{0.12} \simeq 5.3\times 10^{21}\,\lambda_{\rm hs}^2\left(\frac{m_{\rm s}}{\rm GeV}\right)$$

Blenow-Martinez-Zaldivar. 1309.7348
Bernal et al. 1706.07442 ++

Pseudo-Scalar Portal

$$\mathcal{L}_\psi = \bar\psi\,(i\,\gamma^\mu\partial_\mu - m_\psi)\,\psi + i\,g\,s\,\bar\psi\,\gamma_5\,\psi$$

$$\frac{\Omega_{\rm DM}h^2}{0.12} = 5.3\times 10^{21}\,\lambda_{\rm hs}^2\,N\left(\frac{m_{\rm DM}}{\rm GeV}\right)$$

Heikinhemmo et al. 1604.02401 ++

Kinetic Portal

$$\mathcal{L} \supset \epsilon\, F_Y^{\mu\nu}\, F_{D\,\mu\nu}$$

Can also be produced by Quantum Fluctuations during Inflation

$$\frac{\Omega_A h^2}{0.12} \simeq \left(\frac{m_A}{1\,\rm keV}\right)^{1/2}\left(\frac{H_*}{10^{12}\,\rm GeV}\right)$$

Pospelov, Ritz, Voloshin 0807.3279
Redondo et al. 0811.0326
Graham, Mardon Rajendran 1504.0210

Sterile Neutrinos

$$\mathcal{L} \supset y\,\bar L\,\tilde\Phi^\dagger\,\nu_{\rm R} + m\,\bar\nu_{\rm R}^c\,\nu_{\rm R} + s\,\bar\nu_{\rm R}^c\,(y_S + i\,y_P)\,\nu_{\rm R} + {\rm h.c.} + V(\Phi, s)$$

Shakya 2015
Coy ,Schmidt 2022
+++

Freeze-in (FIMP) : Exotic Stuff

How the clockwork works (made easy)

Based on the simple observation that:

$1/2 \quad \times \quad 1/2 \quad \times \quad 1/2 \quad \times \quad 1/2 \quad \times \quad \ldots \quad \times \quad 1/2$ can **easily** be **tiny**

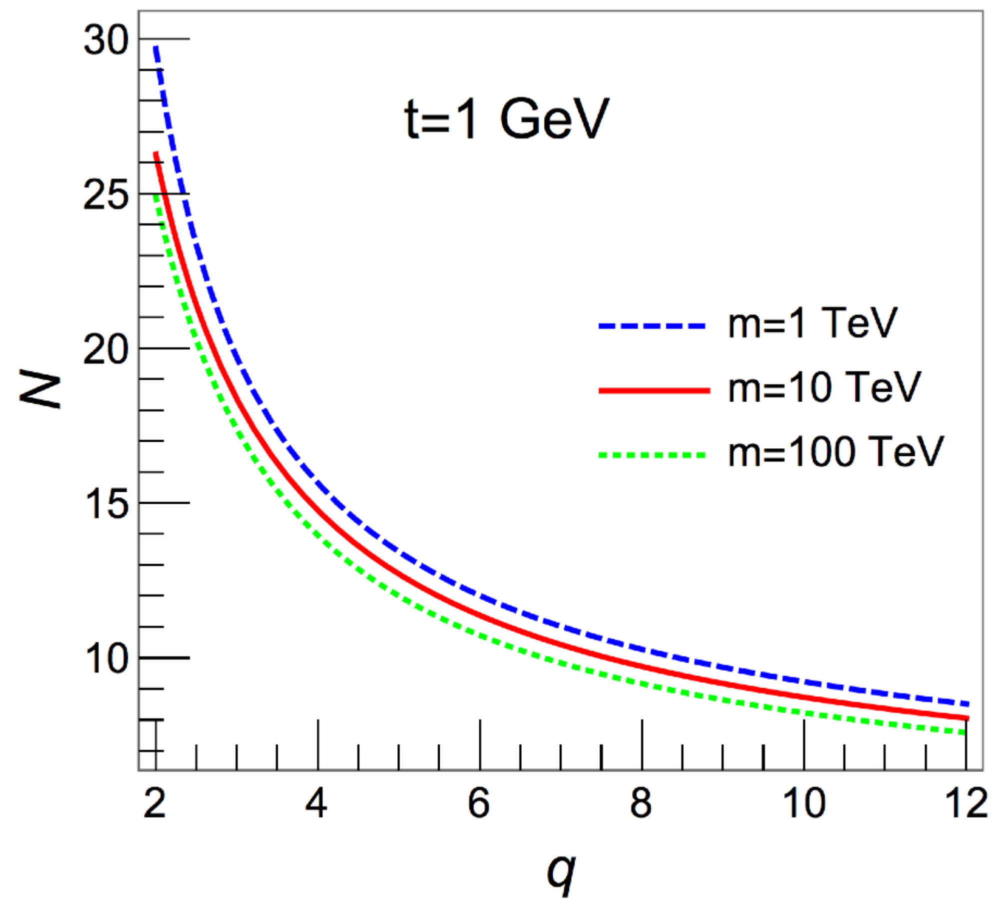
Use a **chain** of N fields

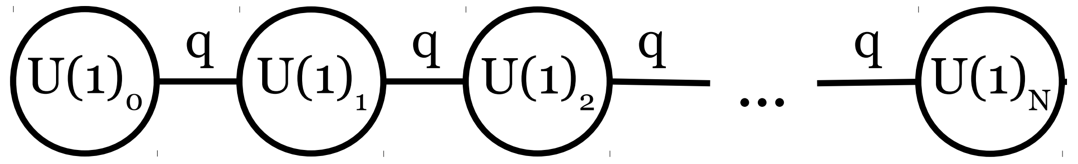
$$\phi_0 \;\overset{1/q}{\text{———}}\; \phi_1 \;\overset{1/q}{\text{———}}\; \phi_2 \;\overset{1/q}{\text{———}}\; \phi_3 \;\overset{1/q}{\text{———}}\; \ldots \;\overset{1/q}{\text{———}}\; \phi_{\mathcal{N}} \;\text{———}\; \mathbf{SM}$$

For **fermions** use chiral symmetries

$$R_0 \;\overset{m}{\text{——}}\; \underbrace{L_1 \quad R_1}_{qm} \;\overset{m}{\text{——}}\; \underbrace{L_2 \quad R_2}_{qm} \;\overset{m}{\text{——}}\; \underbrace{L_3 \quad R_3}_{qm} \;\overset{m}{\text{——}}\; \ldots \;\overset{m}{\text{——}}\; \underbrace{L_{\mathcal{N}} \quad R_{\mathcal{N}}}_{qm} \;\text{——}\; L_{SM}$$

light $N \approx R_0 \quad \Longrightarrow \quad N — L_{SM} \sim \mathbf{1/q}^{\mathcal{N}}$





N+1 copies of U(1) global symmetry in theory space spontaneously broken down to a single U(1) at a scale f

Below f, N+1 massless Goldstones $\quad U_j = e^{i\phi_j/f} \qquad j = 0, \ldots, N$

Explicit soft N spurion mass parameters

$$\mathcal{L} = -\frac{f^2}{2}\sum_{j=0}^{N} \partial_\mu U_j^\dagger \, \partial^\mu U_j + \frac{m^2 f^2}{2}\sum_{j=0}^{N-1}\left(U_j^\dagger \, U_{j+1}^q + \text{h.c.}\right)$$

$$\boxed{\begin{aligned} V(\phi) &= \sum_{j=0}^{N-1} \frac{m^2}{2}(\phi_j - q\phi_{j+1})^2 + \sum_{j=0}^{N-1}\frac{m^2}{24 f^2}(\phi_j - q\phi_{j+1})^4 + \mathcal{O}(\phi_6) \\ &= \frac{1}{2}\sum_{i,j=0}^{N} \phi_i M_{ij}^2 \phi^j + \frac{m^2}{24 f^2}\sum_{i,j=0}^{N}(\phi_i M_{ij}^2 \phi^j)^2 + \mathcal{O}(\phi_6) \end{aligned}}$$

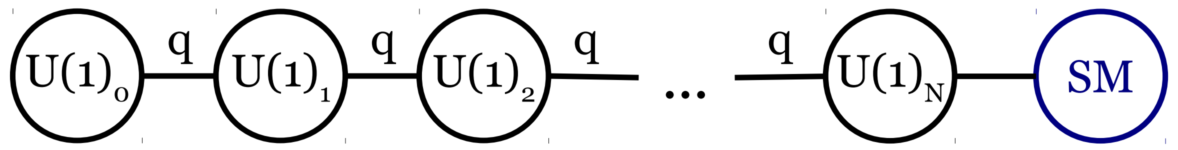
Goudelis-Mohan-DS $\quad$ *JHEP* 10 (2018) 014

Freeze-in (FIMP) : Exotic Stuff

A model of scalar FIMP

$$\mathcal{L}_{sFIMP} = -\frac{1}{2}\sum_{j=0}^{N}\partial_\mu\phi_j^\dagger\partial^\mu\phi_j - \frac{1}{2}\sum_{i,j=0}^{N}\phi_i M_{ij}^2\phi^j - \frac{m^2}{24f^2}\sum_{i,j=0}^{N}(\phi_i\tilde{M}_{ij}^2\phi^j)^2$$
$$-\kappa|H^\dagger H|\phi_n^2 + \sum_{i=0}^{n}\frac{t^2}{2}\phi_i^2 \;;$$

Diagonal mass term for every site

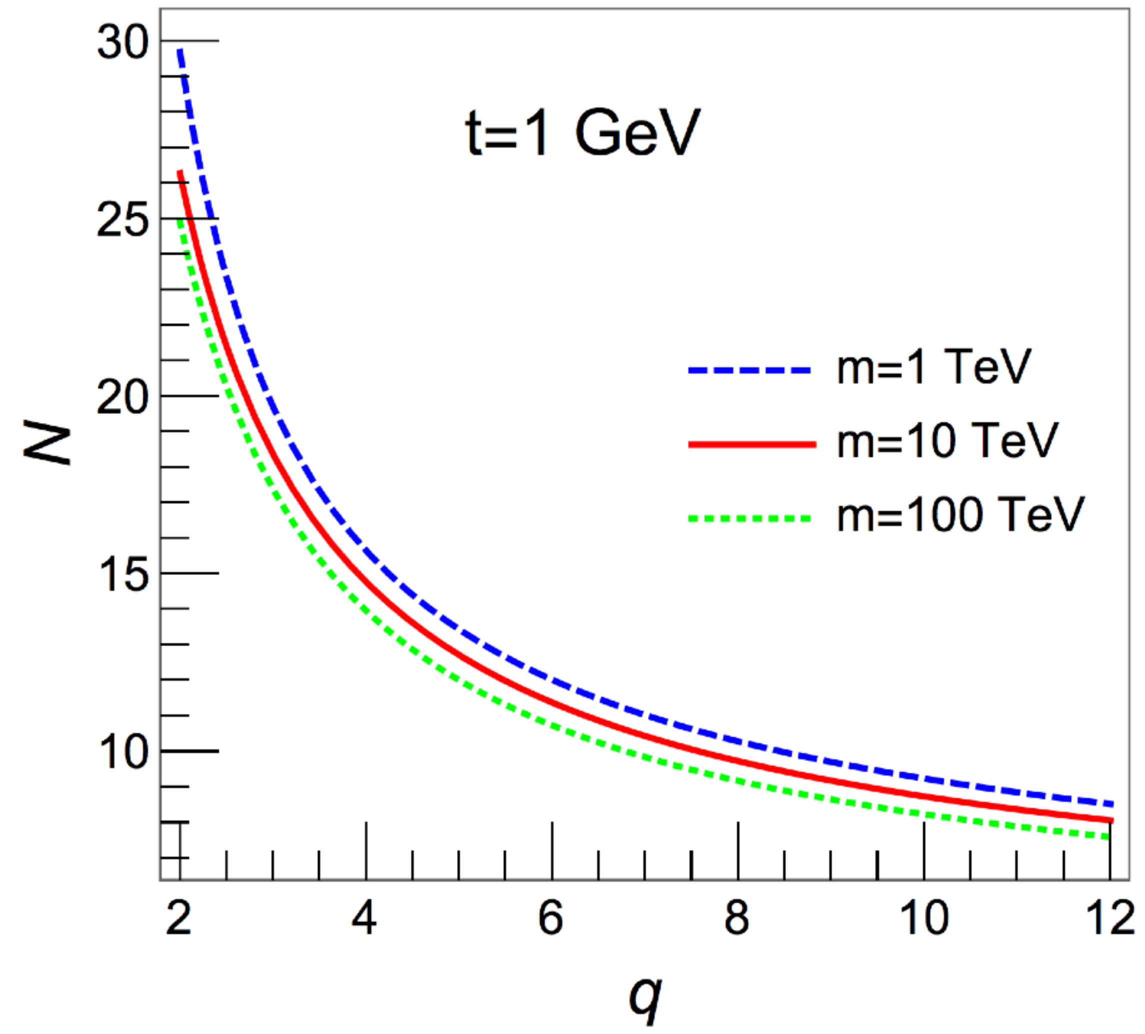


SM coupled to the nth site

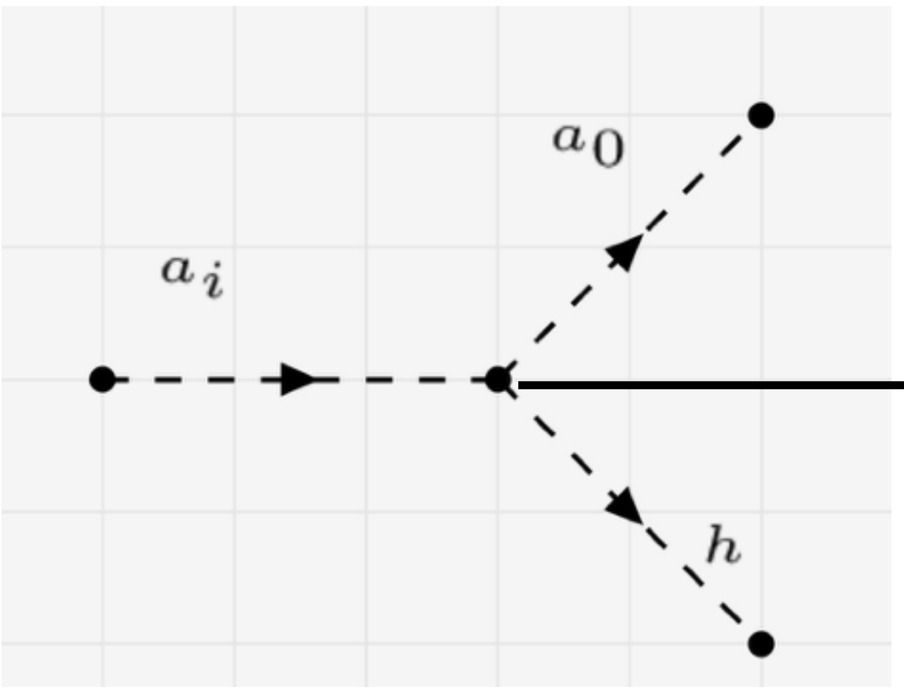
Expand the gears in the basis of Eigen-states

Identify the zero mode as the FIMP candidate

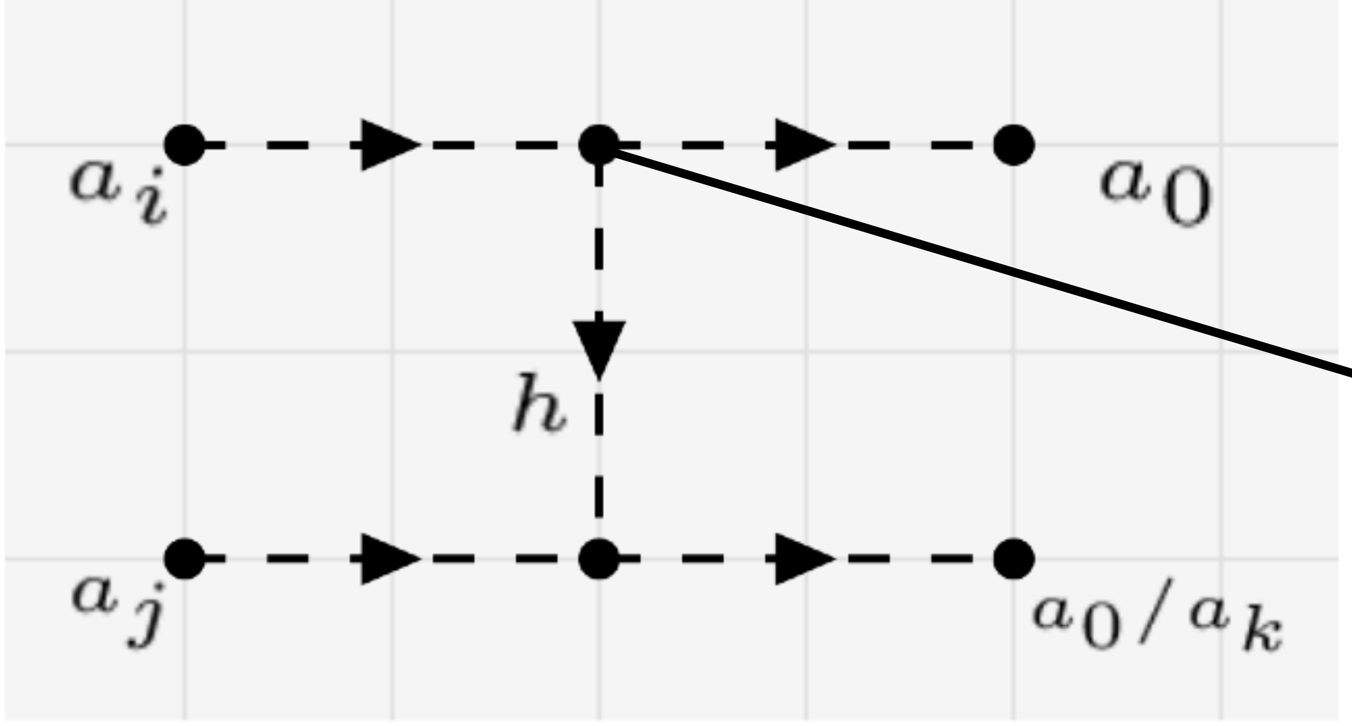
Goudelis-Mohan-DS *JHEP* 10 (2018) 014



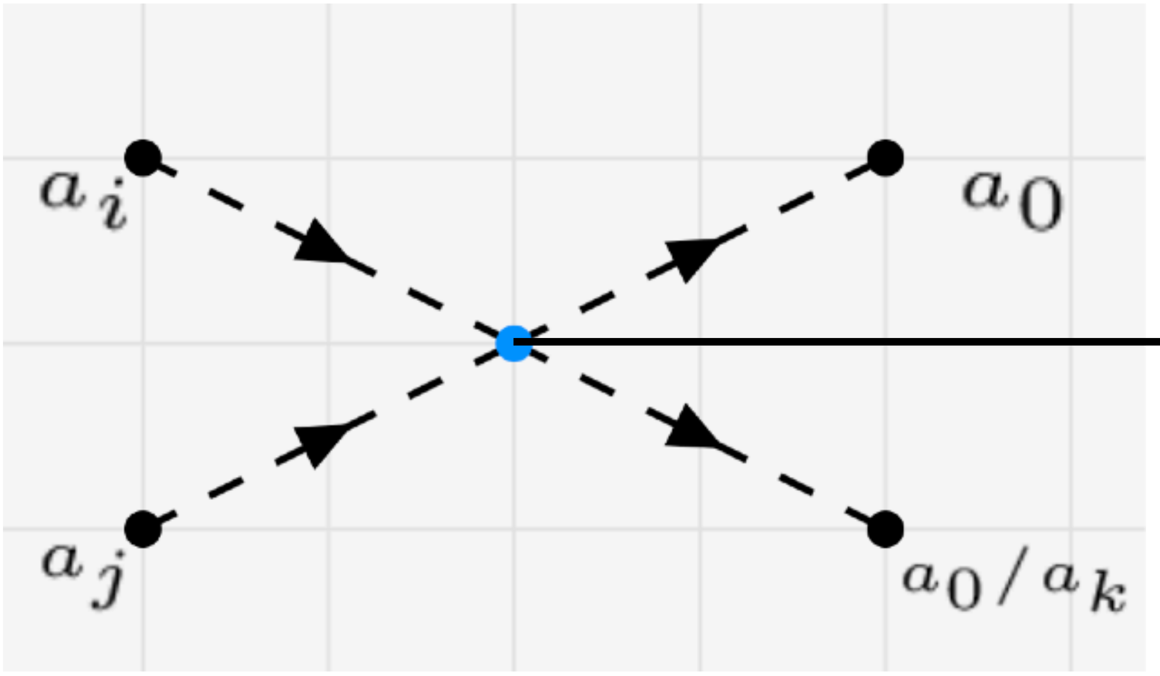
FIMP production



$\frac{\kappa}{q^n}O_{jn}$



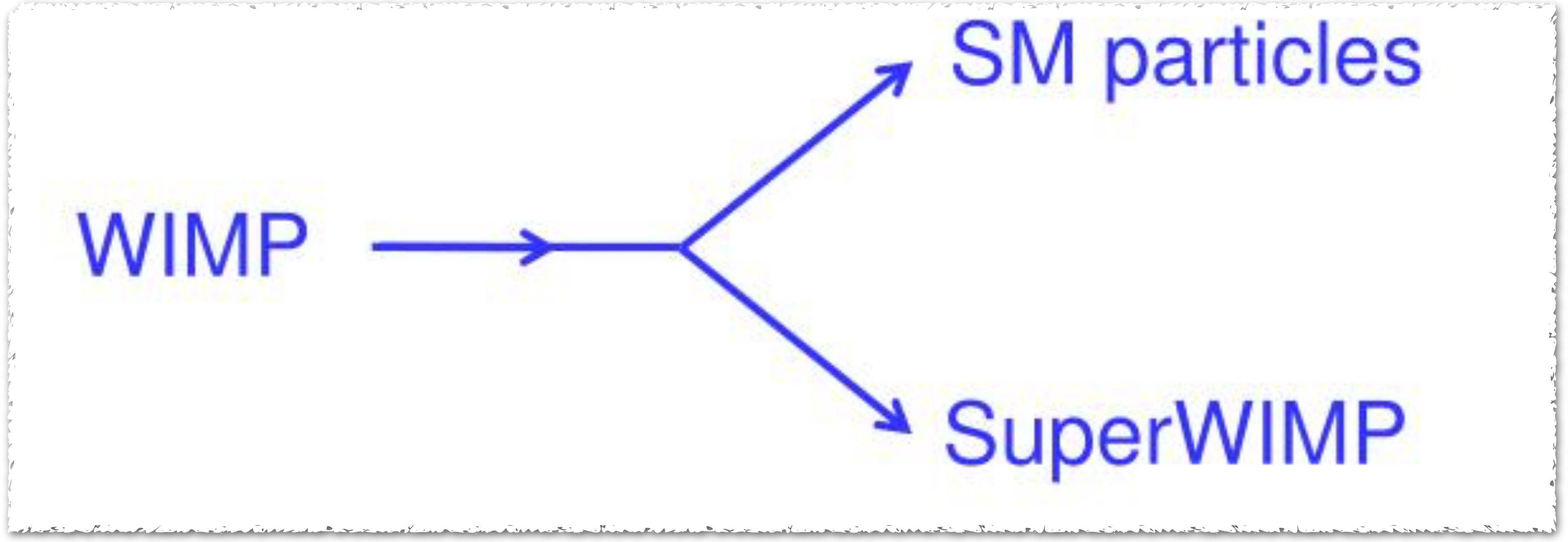
$\frac{\kappa}{q^n}O_{jn}$

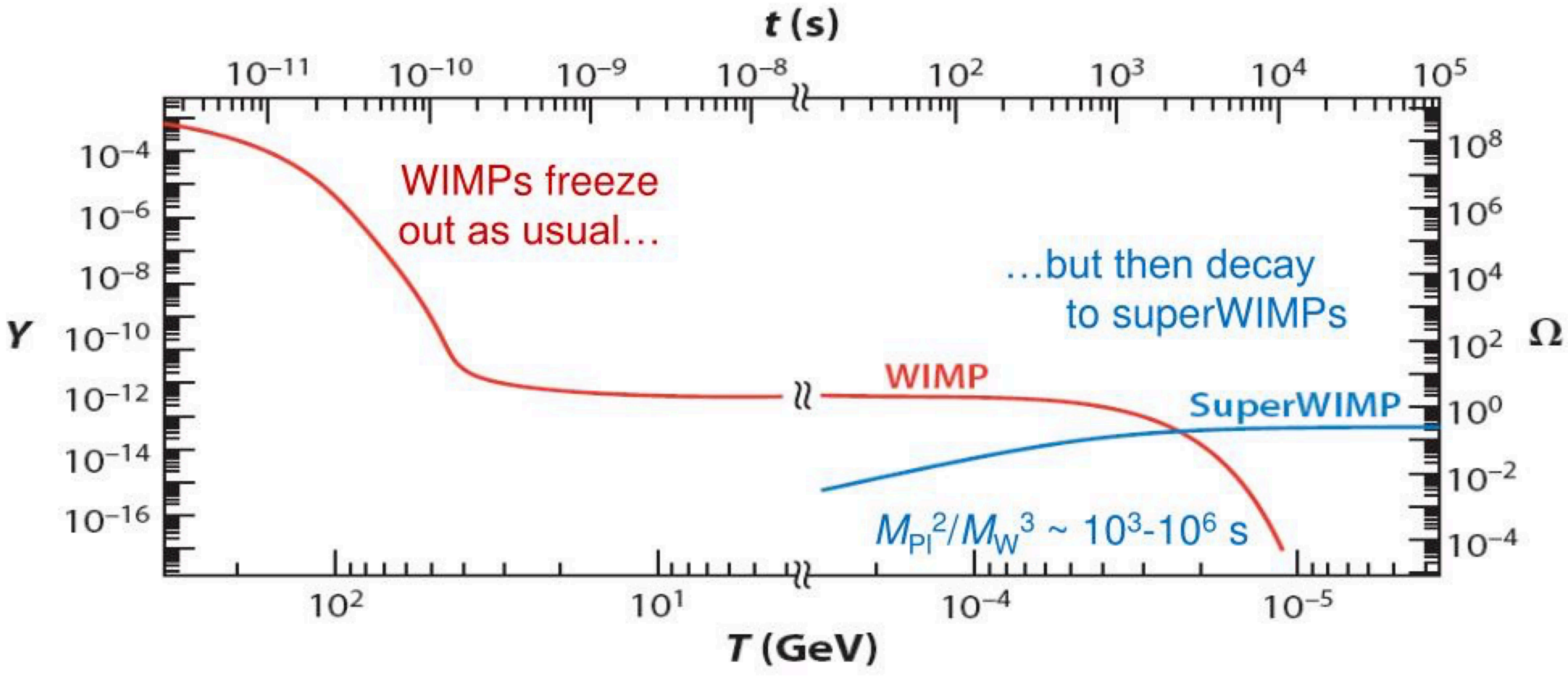


$\frac{\kappa}{q^n}O_{jn}$

Super-WIMPs

Late decay of frozen out WIMPs





Motivated by Gravitinos , the original SUSY dark matter

Similar considerations for axinos, KK gauge bosons ++

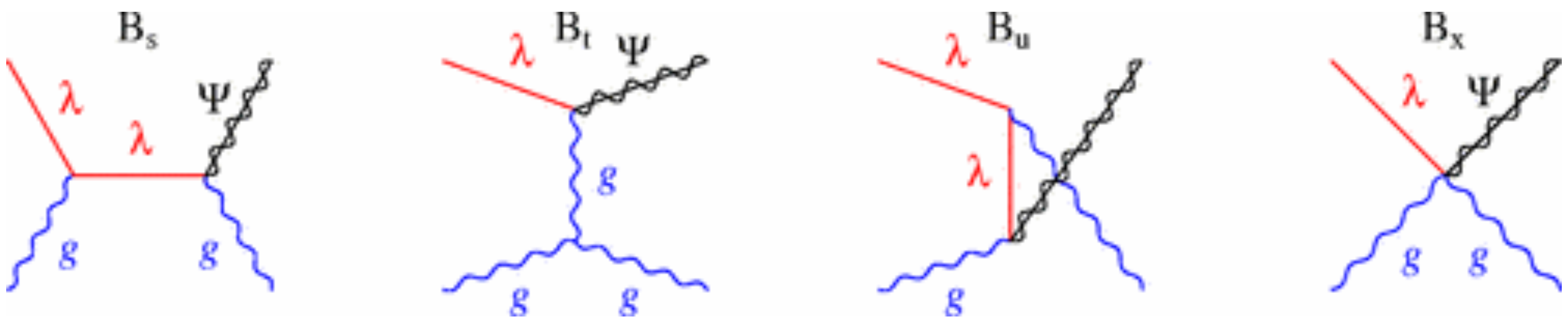
Pagels, Primack (1982)
Weinberg (1982)
Krauss (1983)
Nanopoulos, Olive, Srednicki (1983)

Khlopov, Linde (1984)
Moroi, Murayama, Yamaguchi (1993)
Bolz, Buchmuller, Plumacher (1998)

Feng, Rajaraman , Takayama 2003 +++
Feng 2003 +
Kumar, Feng 2008 +++

SuperWimps.

Consider a gravitino CDM populated thermally in the early universe through scatterings



$$\Omega_{3/2}h^2 = 0.217 \left(\frac{T_{\rm RH}}{10^7 \rm GeV}\right)\left(\frac{100 \rm GeV}{m_{3/2}}\right)\left(\frac{m_{\tilde g}(\mu)}{10 \rm TeV}\right)^2$$

$$\boxed{m_{3/2} = \frac{|F|}{\sqrt{3} M_P}}$$

Generally needs a very large reheating temperature to satisfy the relic density

Gluino Scattering dominate in the hard thermal loop approximation Rychkov, Strumia 2003

Cosmological constraints on SuperWimps.

What if the reheating temperature is low ? Thermal processes are suppressed

Gravitino abundance is populated non thermally through decays

$$\Gamma(\chi_1^0 \to \tilde{G}\gamma) \equiv \frac{\cos^2\theta_W m_{\chi_1^0}^5}{48 M_P^2 m_{\tilde{G}}^2}\left[1-\frac{m_{\tilde{G}}^2}{m_{\chi_1^0}^2}\right]^3\left(1+3\frac{m_{\tilde{G}}^2}{m_{\chi_1^0}^2}\right)$$

$$\tau \equiv 2.3 \times 10^7 \left(\frac{100\ \mathrm{GeV}}{\Delta m}\right)^3 \mathrm{s}$$

Non-thermal relic

$$\begin{aligned}\Omega_{3/2}^{\mathrm{NTP}} h^2 &= m_{3/2} Y_{\tilde{B}}\left(T_0\right) s\left(T_0\right) h^2/\rho_c \\ &= \frac{m_{3/2}}{m_{\tilde{B}}}\Omega_{\tilde{B}} h^2,\end{aligned}$$

Total Relic Density : $\Omega_{3/2}h^2 = (\Omega_{3/2}^{\mathrm{TP}}h^2 + \Omega_{3/2}^{\mathrm{NTP}}h^2)$

Energy released in Photons

$$E_\gamma = \frac{m_{\chi_1^0}^2 - m_{\tilde{G}}^2}{2m_{\chi_1^0}}$$

Fractional energy

$$E_{\mathrm{SM}} = E_\gamma / m_{\chi_1^0}$$

Primary constraints studied so far : BBN, $\mathbf{N_{eff}}$ Covi et al. 2003 ++

Synergy between experiments and observations

Dark Matter populated through extremely weakly coupled systems are difficult to probe

Cosmology

Primordial nucleosynthesis

Lyman-α

Spectral Distortions of CMB

Most promising

Collider

Displaced objects

HSCPs

Mono-X

Disappearing tracks

Some parts of the parameter space

Astro and Ground Based Detection

Direct detection

Indirect detection

Very difficult

A Simplified Freeze-in Model

Consider an extension of the SM by a Z_2-odd real singlet scalar *s* (DM) along with a Z_2-odd vector-like SU(2)-singlet fermion *F* (parent).

contribution in arXiv:1803.10379
and arXiv:1811.05478

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \partial_\mu s\, \partial^\mu s - \frac{\mu_s^2}{2} s^2 + \frac{\lambda_s}{4} s^4 + \lambda_{sh} s^2 \left(H^\dagger H\right)$$
$$+ \bar{F}\left(i\not{D}\right) F - m_F \bar{F} F - \sum_f y_s^f \left(s\bar{F}\left(\frac{1+\gamma^5}{2}\right) f + \text{h.c.}\right)$$

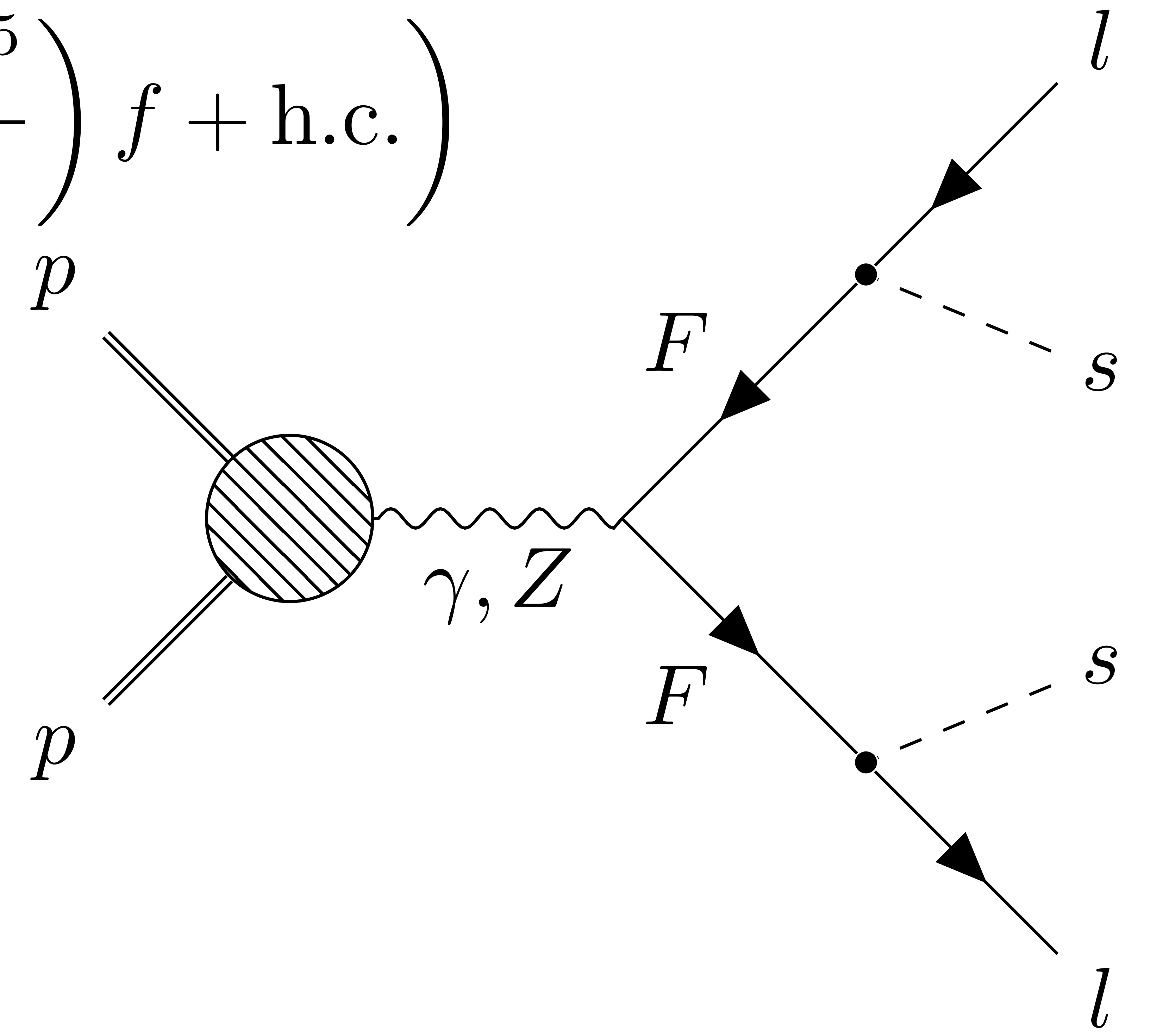
Distinguish three cases:

- $f = \{e,\mu,\tau\} \rightarrow F$ transforms as (**1, 1, -1**)
  "Heavy lepton"
- $f = \{u,c,t\} \rightarrow F$ transforms as (**3, 1, -2/3**)
  "Heavy *u*-quark"
- $f = \{d,s,b\} \rightarrow F$ transforms as (**3, 1, 1/3**)
  "Heavy *d*-quark"

Belanger, DS et al, 2018, 2019 ++

A Simplified Freeze-in Model

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \partial_\mu s\, \partial^\mu s - \frac{\mu_s^2}{2} s^2 + \frac{\lambda_s}{4} s^4 + \lambda_{sh} s^2 \left(H^\dagger H\right)$$
$$+ \bar{F}\,(iD)\,F - m_F \bar{F} F - \sum_f y_s^f \left(s\bar{F}\left(\frac{1+\gamma^5}{2}\right) f + \text{h.c.}\right)$$



For simplicity :

· Study three cases separately.

i.e. add a single pair of F fermions at a time

· Only couple F to the first two generations.

The collider pheno of 3rd generation fermions is a bit more tricky

· Set Higgs portal to zero → Only relevant coupling: y_s^f.

Non-LLP constraints: earth-bound

Focus on the first two models (heavy lepton, heavy u-quark).

Heavy lepton model

· LEP2: $m_F > 104$ GeV

Actually slightly weaker, depending on lifetime

· No EWPT constraints

arXiv:1404.4398

· Muon lifetime: $\mu \to ess$

Checked, irrelevant

· LFV processes, in particular $\mu \to e\gamma$

$$Br(\mu \to e\gamma) \sim \frac{2v^4 (y_s^e)^2 (y_s^\mu)^2}{3m_F^4 (16\pi)^2} \sim 10^{-46}$$

i.e. tiny

Heavy quark model

· Direct collider bounds subleading

Require prompt jets

· Running of α_s : $m_F >$ few hundred GeV

· Rare decays, e.g. $K^+ \to \pi^+ ss$

NA62 can reach down to $y_s \sim 10^{-5}$

· Meson mixing: similarly to $\mu \to e\gamma$, tiny

Globally: still lots of room for interesting phenomenology

A Simplified Freeze-in Model

Assuming that DM is mostly populated by F decays, we can relate the relic abundance with the parent particle lifetime:

$$c\tau \approx 4.5\,\mathrm{m}\,\xi g_F \left(\frac{0.12}{\Omega_s h^2}\right)\left(\frac{m_s}{100\mathrm{keV}}\right)\left(\frac{200\mathrm{GeV}}{m_F}\right)^2\left(\frac{102}{g_*(m_F/3)}\right)^{3/2}\left[\frac{\int_{m_F/T_R}^{m_F/T_0} dx\; x^3 K_1(x)}{3\pi/2}\right]$$

Freeze-in favours long lifetimes, unless

- Dark matter is very light
- The reheating temperature is low

Cosmological constraints

- **Big-Bang Nucleosynthesis**

  we consider 1cm < cτ < 10^4m → T~150 MeV
  → heavy fermions decay well before onset of BBN

- **Lyman-α forest**

$$m_{\mathrm{DM}} \gtrsim 12\ \mathrm{keV}\left(\frac{\sum_i \mathrm{BR}_i \Delta_i^\eta}{\sum_i \mathrm{BR}_i}\right)^{1/\eta} \gtrsim 12\ \mathrm{keV}$$

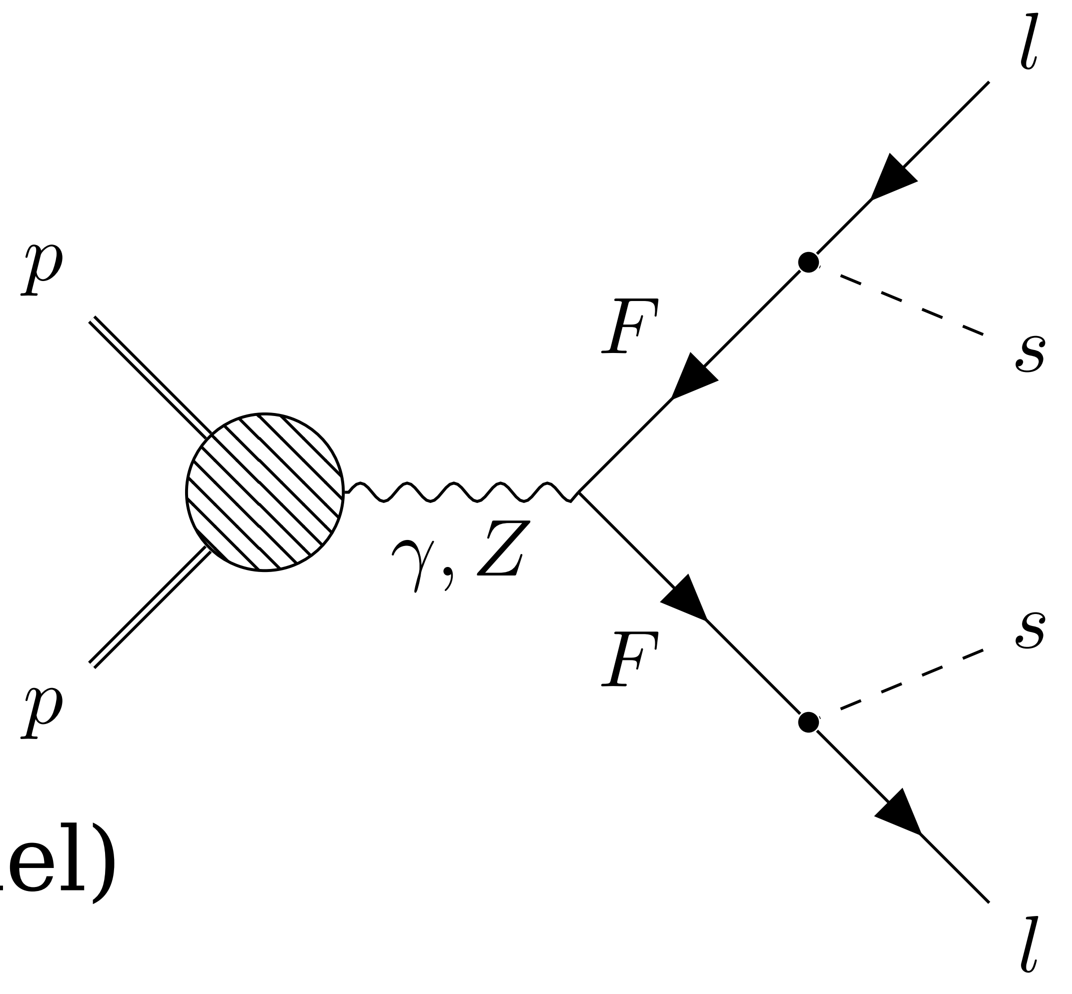
$$\eta = 1.9$$

$$\Delta_i = 1 - m^2_{X^i_{\mathrm{SM}}}/m^2_Y$$

Boulebnane, Heeck, Nguyen, Teresi, 1709.07283

A Simplified Freeze-in Model

So what are the model's signatures at the LHC?



· First of all, production through :

- Drell-Yan (lepton model)
- Drell-Yan +QCD (quark model)

· Several search strategies, depending on the lifetime of the parent particle, i.e. which part of the detector it mostly decays at (if at all).

Long lifetimes

Short lifetimes

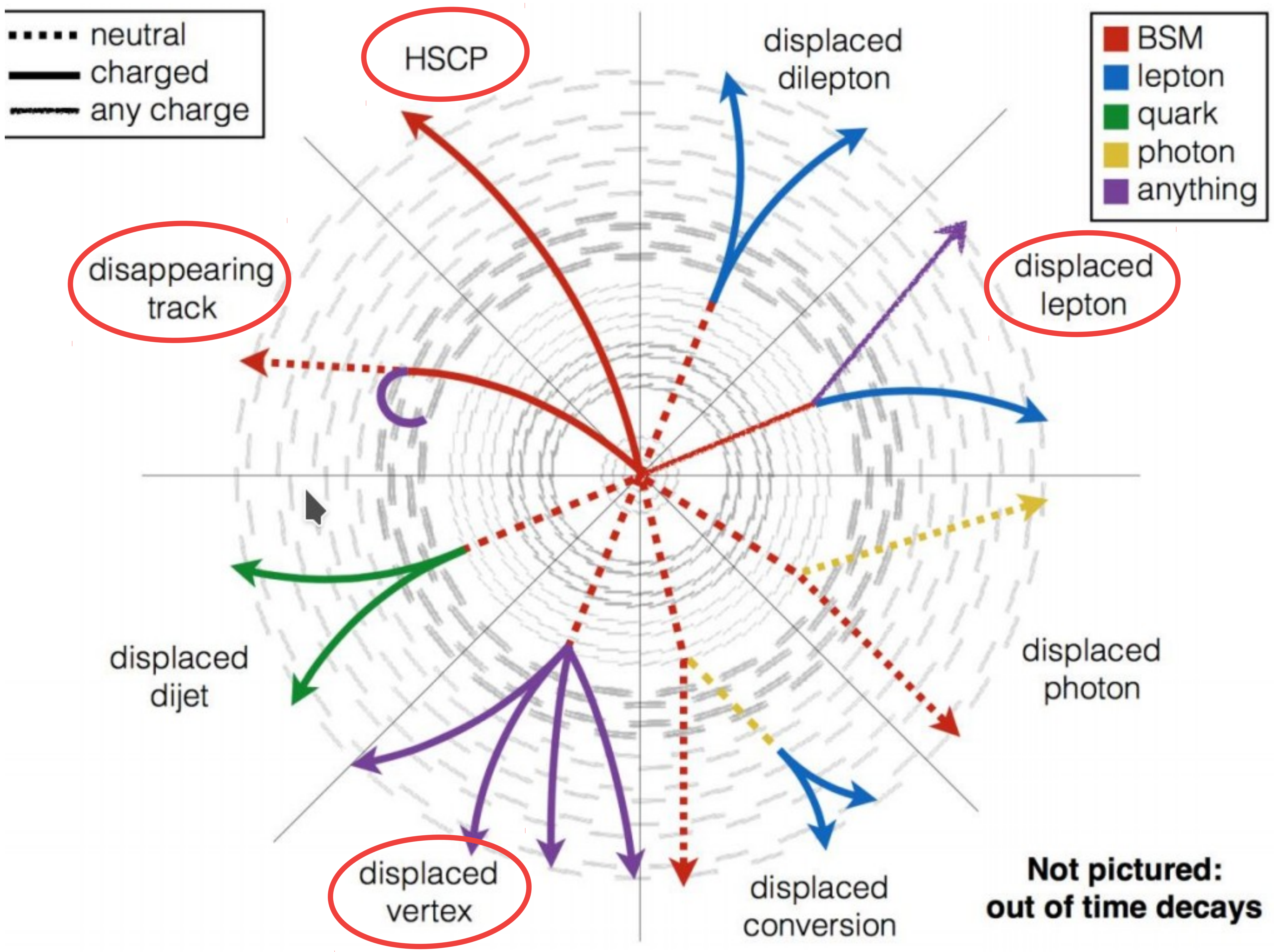
Heavy Stable Charged Particles (HSCPs)

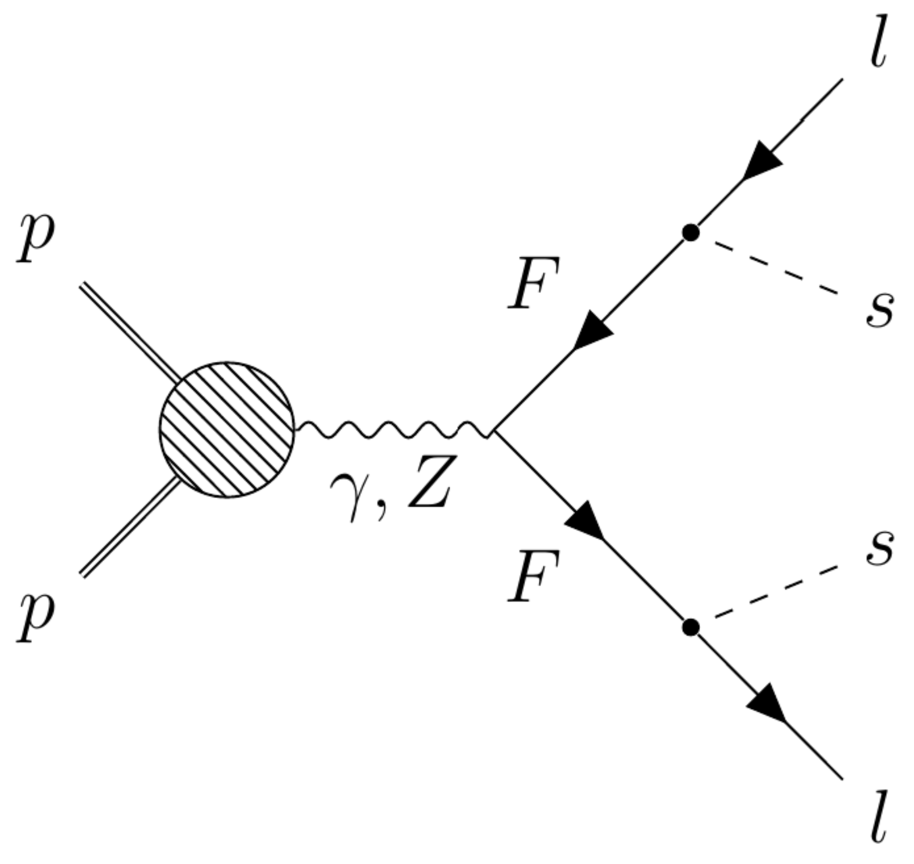
Intermediate lifetimes (for lepton model)

Displaced leptons/vertices

Disappearing/kinked tracks

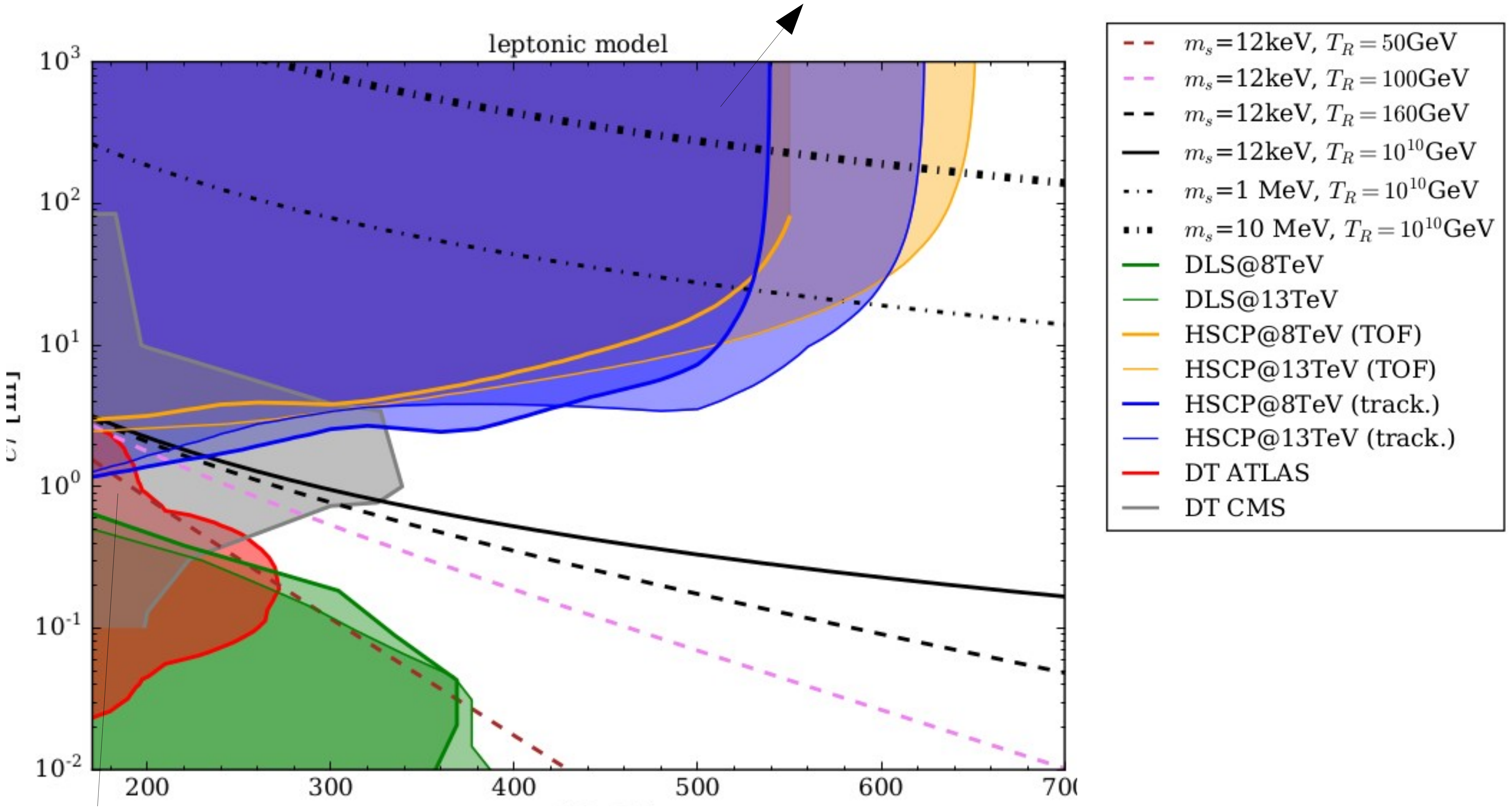
Collider constraints

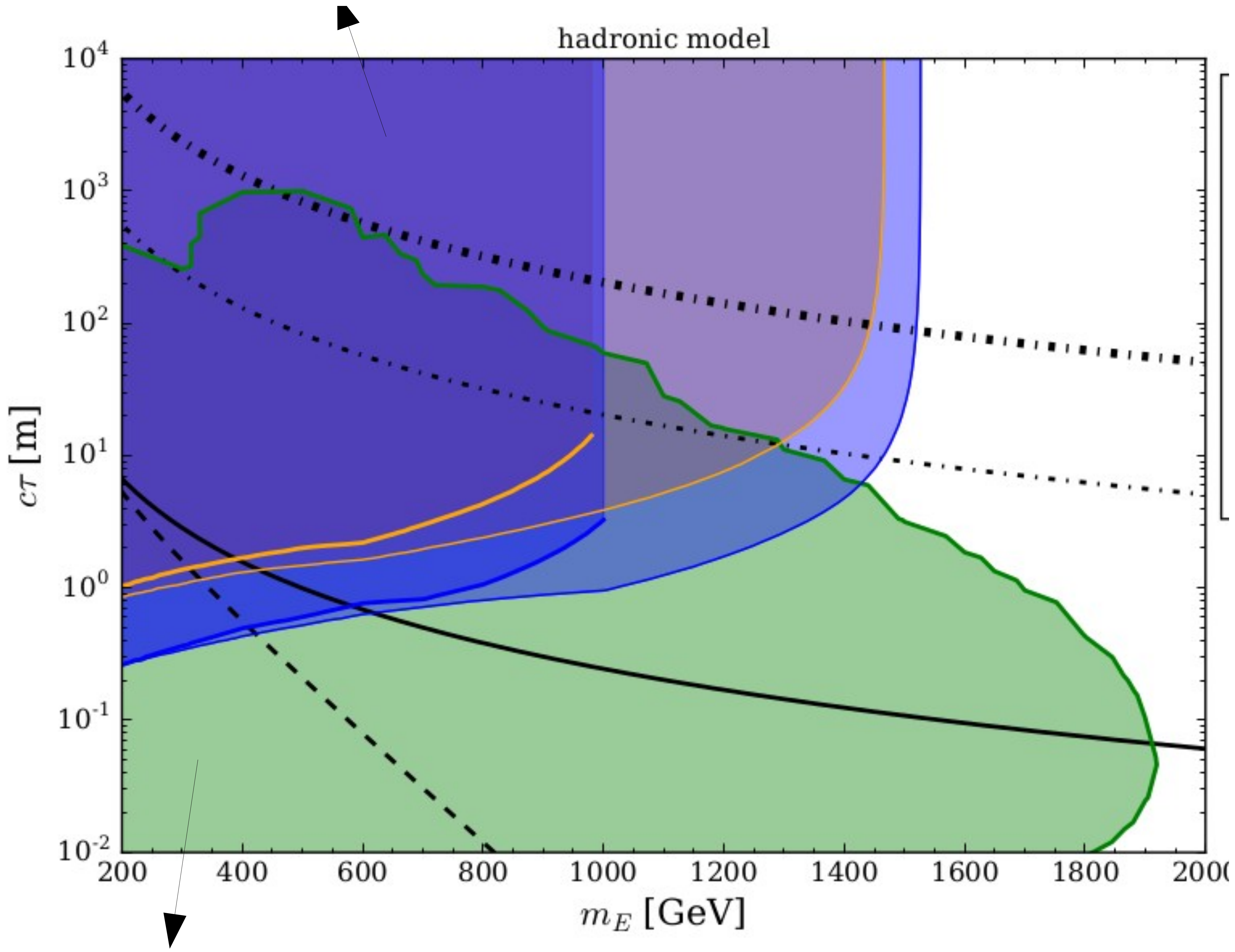




A Simplified Freeze-in Model

HSCP: Tracker + TOF analysis more powerful for larger lifetimes, tracker-only for shorter ones.

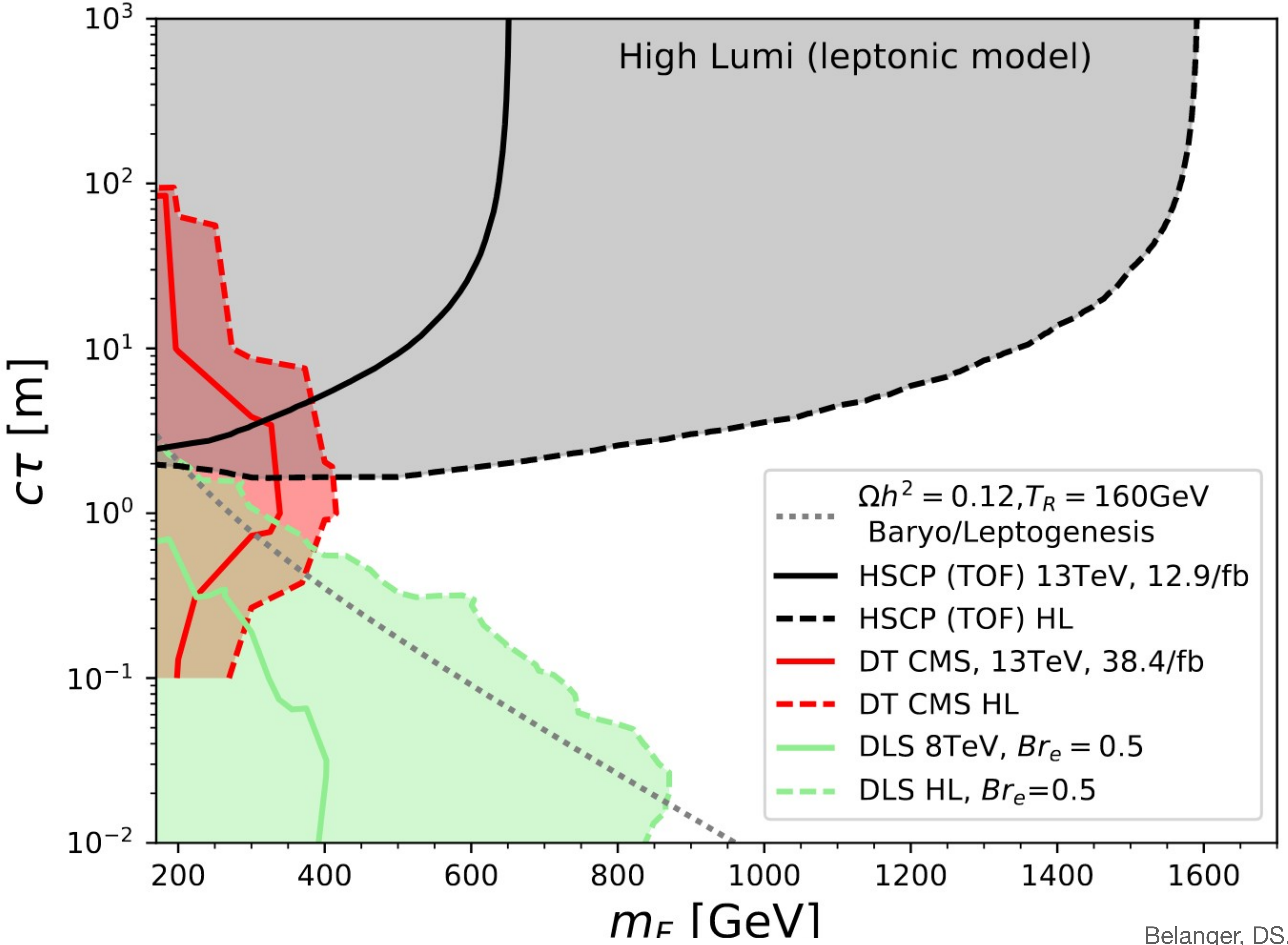




DT: Order-of-magnitude difference in peak sensitivity between ATLAS/CMS

Belanger, DS, Zurita et al, 2018, 2019 ++

A Simplified Freeze-in Model



Belanger, DS, Zurita et al, 2018, 2019 ++

High Lumi LHC could almost close the parameter space in which baryogenesis models would be in tension in case of a discovery

An interplay with baryo/leptogenesis ?

An upshot:

· In E/W baryogenesis and leptogenesis, the reheating temperature must in general be larger than both the EW phase transition temperature (T_{EW}~160 GeV) and the sphaleron freeze-out one (T^*~132 GeV).

· Assume s makes up all of dark matter.

If it doesn't, argument even stronger!

· Assume we manage to measure $c\tau_F$ and $m_F \rightarrow$ 2 free parameters: m_s and T_R.

· Difficult to access $m_s \rightarrow$ take the lowest value allowed from Lyman-α.

If it's heavier, argument even stronger!

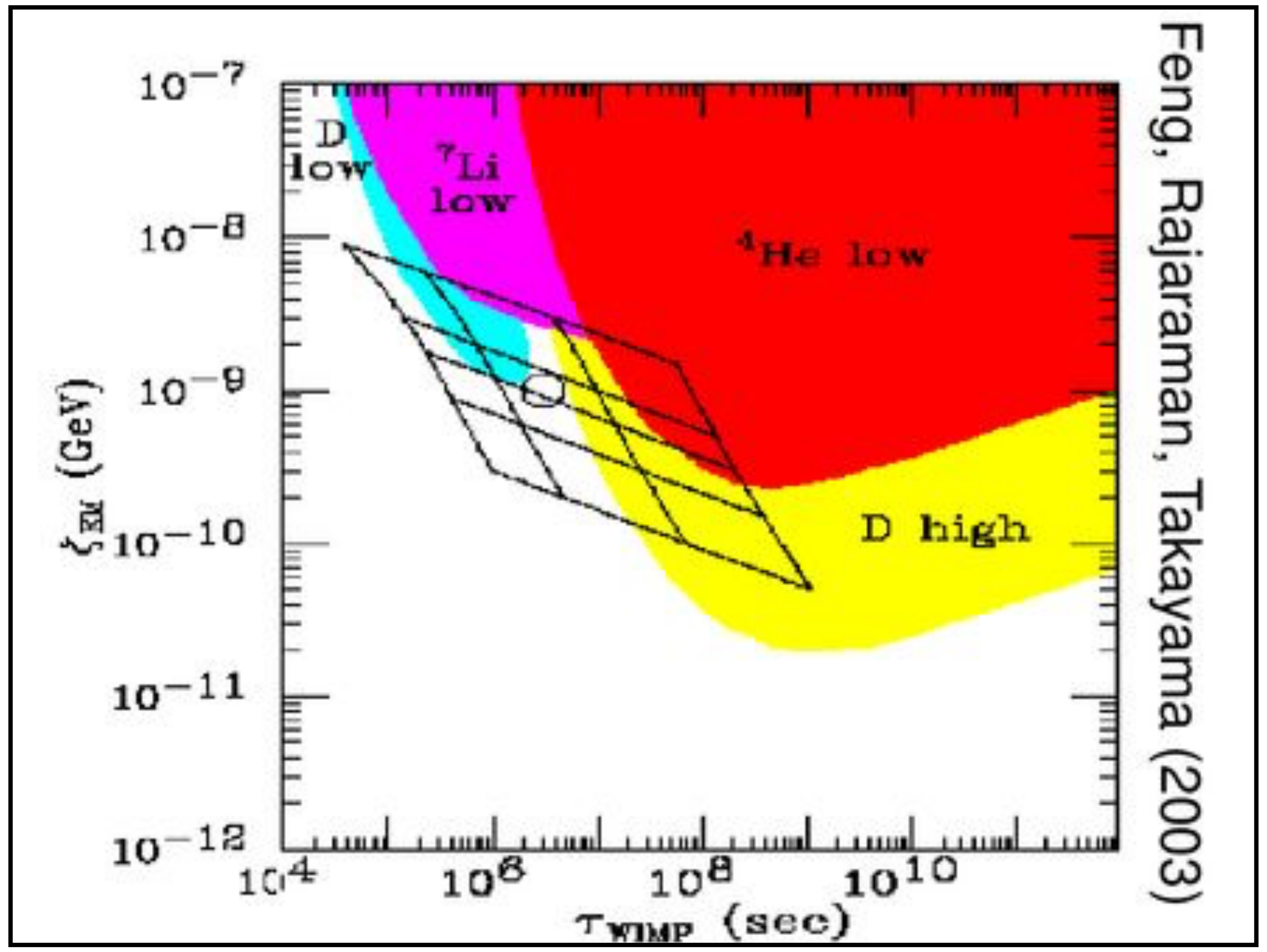
If measurements point to $T_R < T_{EW}$, T^*, we can falsify baryogenesis models that rely on efficient sphaleron transitions

Belanger, DS, Zurita et al, 2018, 2019 ++

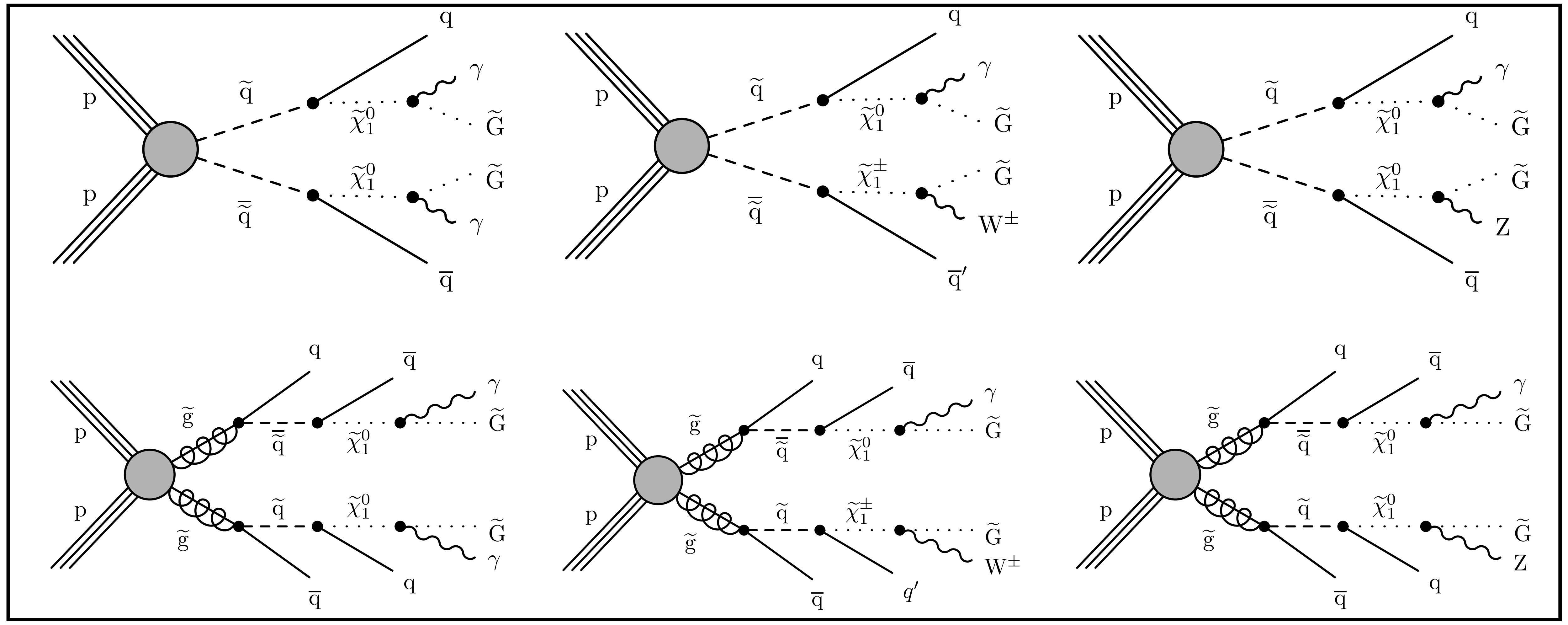
A similar story for SuperWIMPs

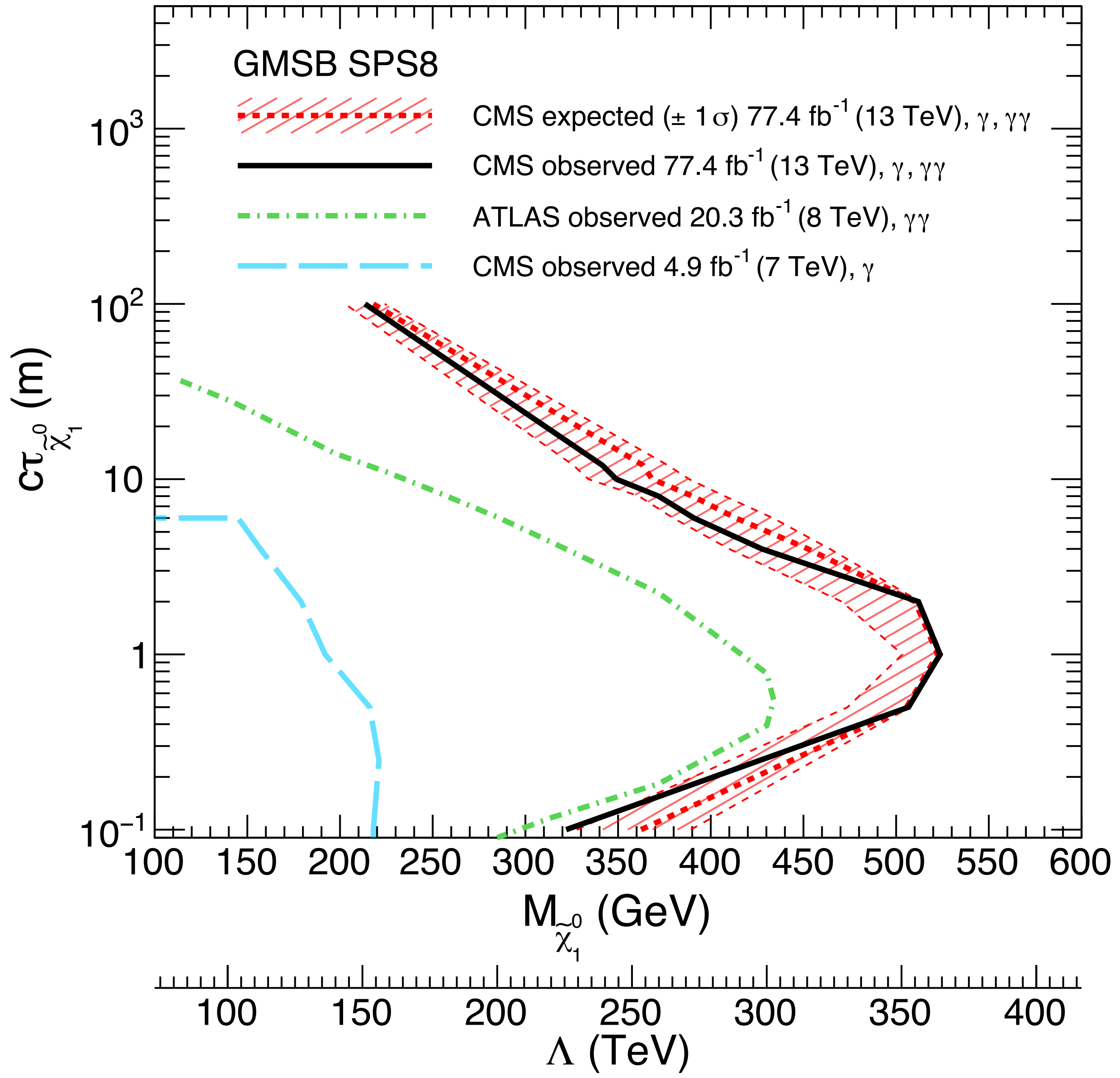
Originally used to solve the Lithium-7 problem

$$\Gamma(\chi_1^0 \to \tilde{G}\gamma) \equiv \frac{\cos^2\theta_W m_{\chi_1^0}^5}{48 M_P^2 m_{\tilde{G}}^2}\left[1-\frac{m_{\tilde{G}}^2}{m_{\chi_1^0}^2}\right]^3\left(1+3\frac{m_{\tilde{G}}^2}{m_{\chi_1^0}^2}\right)$$



At LHC one needs to provide a production model





Energy Injection Constraints

Spectral Distortions

Distortions of the Blackbody spectrum of the primordial photon bath

Energy injection and deposition into the Intergalactic Medium (IGM)

$$\frac{\mathrm{d}E}{\mathrm{d}t\mathrm{d}V}\bigg|_{\mathrm{dep,c}} = \frac{\mathrm{d}E}{\mathrm{d}t\mathrm{d}V}\bigg|_{\mathrm{inj}} f_{\mathrm{c}} = \frac{\mathrm{d}E}{\mathrm{d}t\mathrm{d}V}\bigg|_{\mathrm{inj}} f_{\mathrm{eff}}\ \chi_c \equiv \dot{\mathcal{Q}}\,\chi_c$$

injection efficiency function $f_{\mathrm{eff}}(z)$

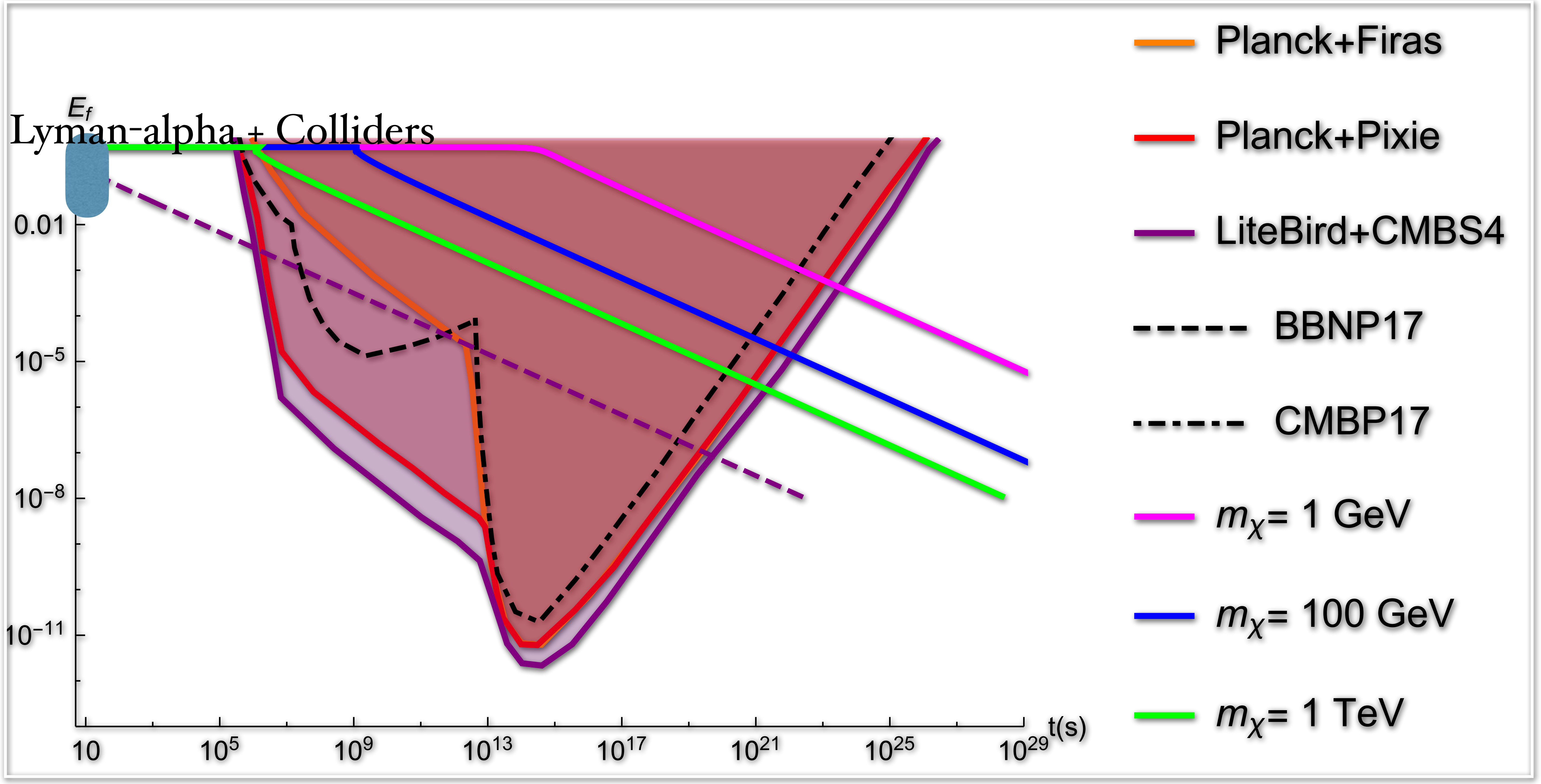
deposition *fraction* $\chi_c(z)$

Thermalisation via Compton, Double Compton and Brehmstrahlung scatterings $\longrightarrow$ Photon Phase Space Distribution

Distortions manifested in terms of temperature shifts ***g***, chemical potential distortions ***mu***, and Compton distortions ***y***

Cosmological constraints on SuperWimps.

Deshpande, Sengupta, Wong, Hamman,White, Williams (To appear)



Constraints on Gravitino SuperWIMP

Cosmological constraints on Supersymmetric SuperWimps

Meera Deshpande[a], Jan Hamann[b], Dipan Sengupta[a], Martin White[a], Anthony G. Williams[a], and Yvonne Y. Y. Wong[b]

[a]*ARC Centre of Excellence for Dark Matter Particle Physics, Department of Physics, University of Adelaide, South Australia 5005, Australia and*
[b]*Sydney Consortium for Particle Physics and Cosmology, School of Physics, The University of New South Wales, Sydney NSW 2052, Australia*

Similar considerations for axino SuperWimps : Additional freedom in decay width due to axion decay constant

In consideration : Complementarity between collider, Warm DM bounds

Future : Axino/Gravitino decays for solving Hubble/S_8 tensions consistent with constraints

Release Code to do understand general multistep process in Class/Exoclass

Other DDM scenarios

Conclusions

- Extremely weakly coupled dark matter MeV-TeV dark matter is very well motivated
- Although not in full generality, can be probed in several different experiments
- Provides a synergy between cosmology and colliders

- **Leads to a wide array of exotic signatures at the LHC and beyond.**

- **Such scenarios also have interesting cosmological implications, in particular baryogengesis and BBN**