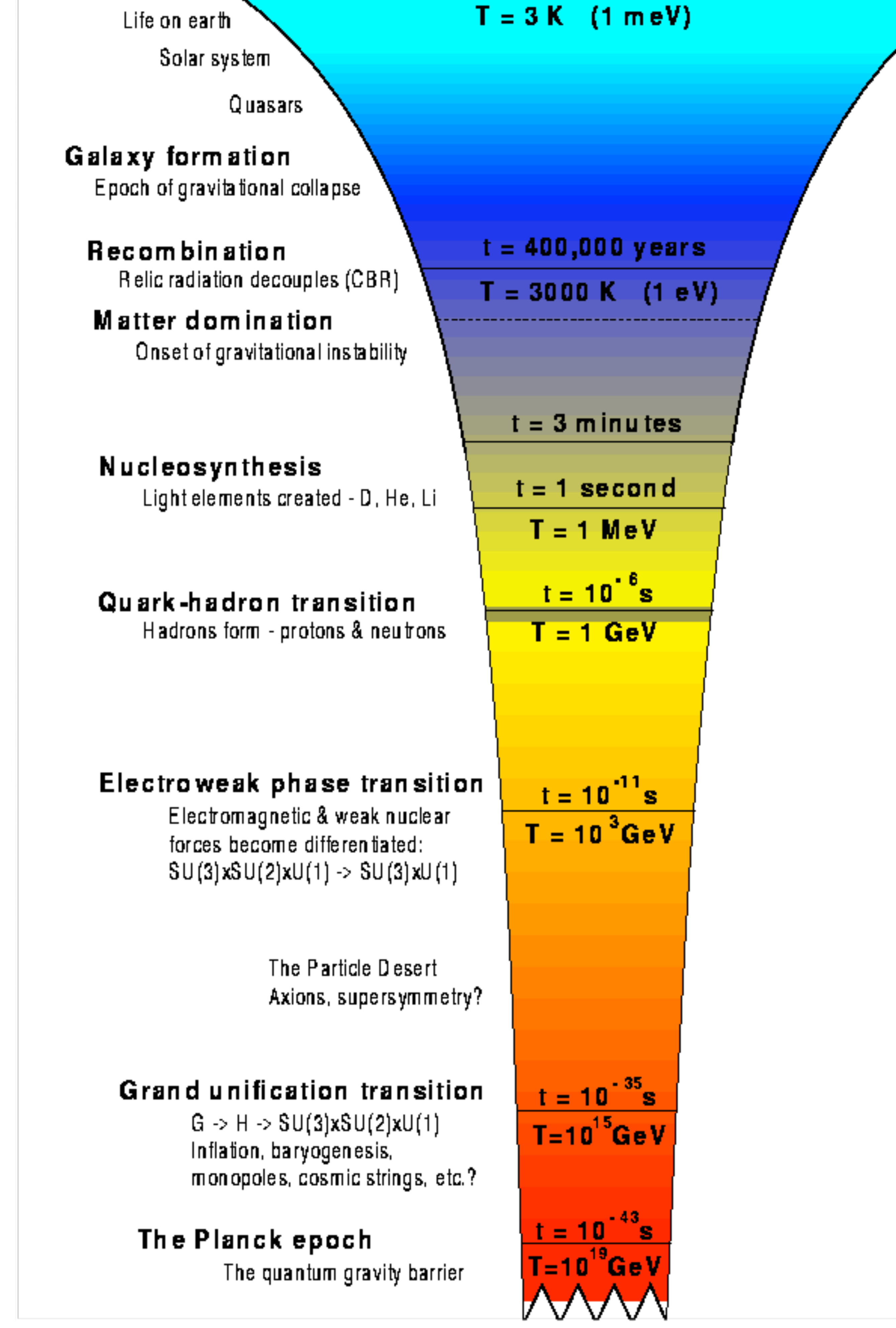
Dark Matter

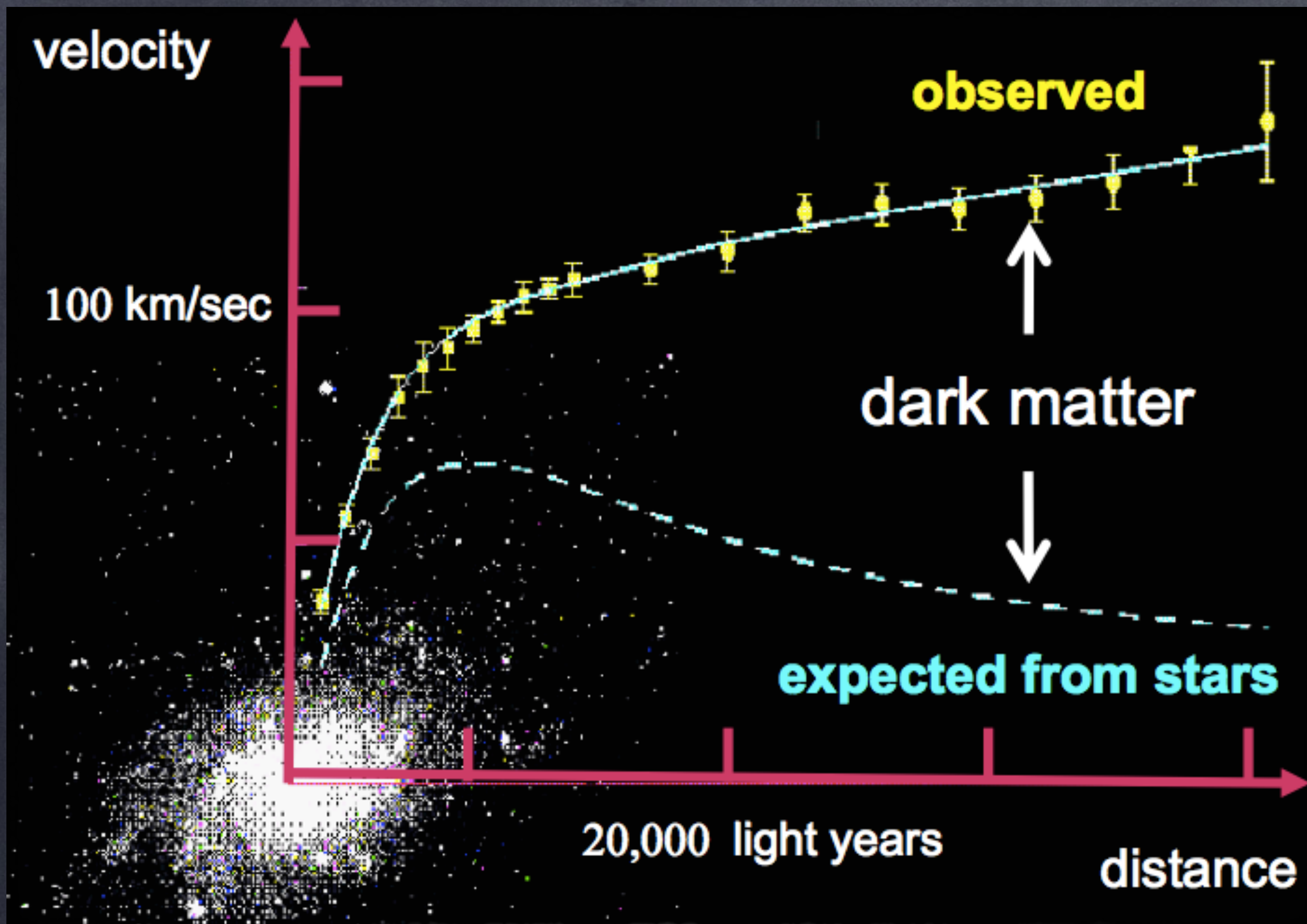
Overview

Generation

Constraints



DARK MATTERS!



$$\frac{M}{L} \sim 300h\frac{M_\odot}{L_\odot} \implies \Omega_m \simeq 0.2 - 0.3$$

$$v_{cir} = \sqrt{\frac{GM(r)}{r}}, \quad M(<r) = M_{tot}$$

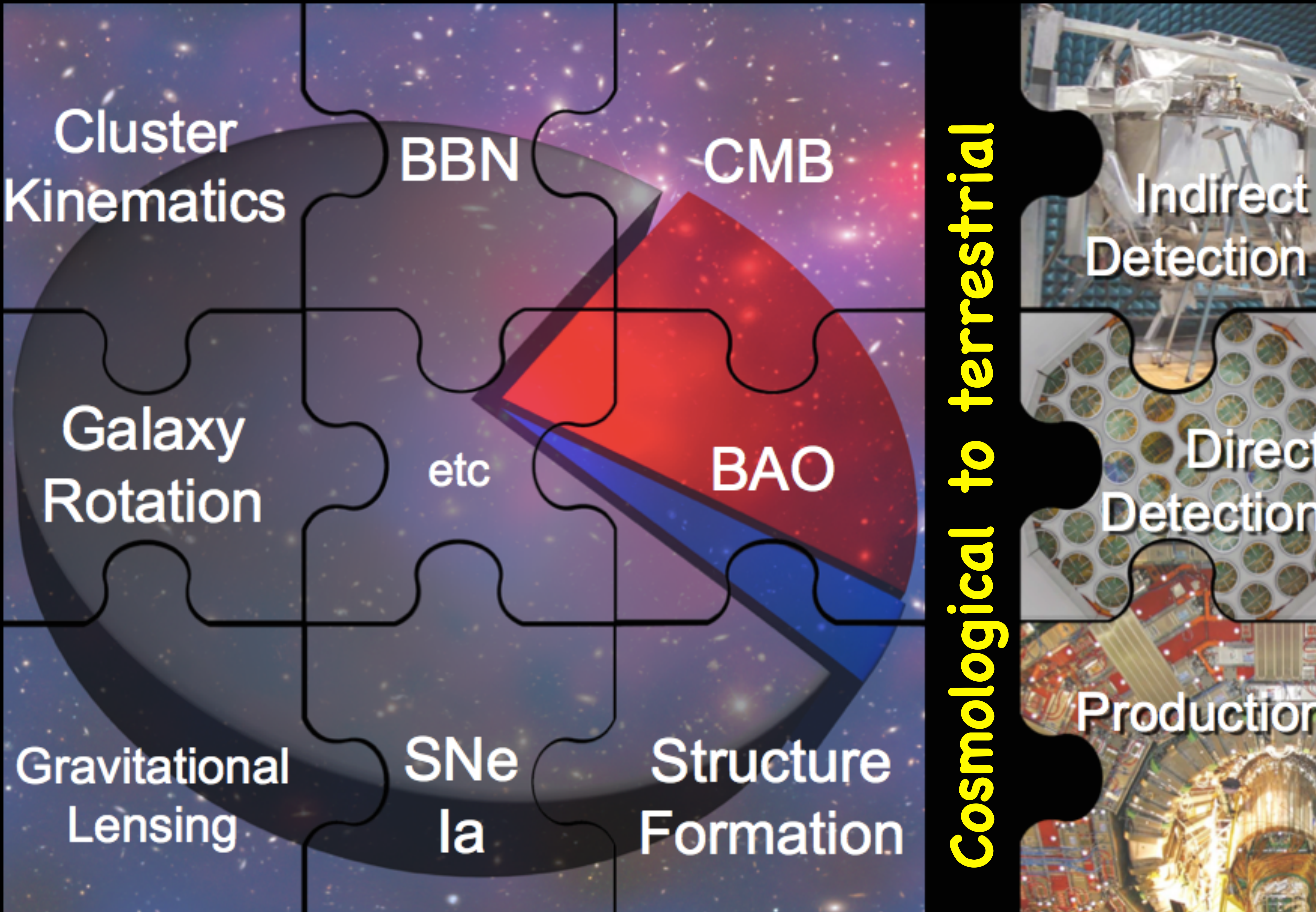
$$v_{cir} \sim \text{const.} \implies M_{DM} \propto r \implies \rho_{DM} \propto \frac{1}{r^2}$$

$$\bar{\rho}_\chi \sim 0.2 \times \rho_c = \Omega_\chi \frac{3H_0^2}{8\pi G} \sim 0.3\text{GeV}/\text{cm}^3$$

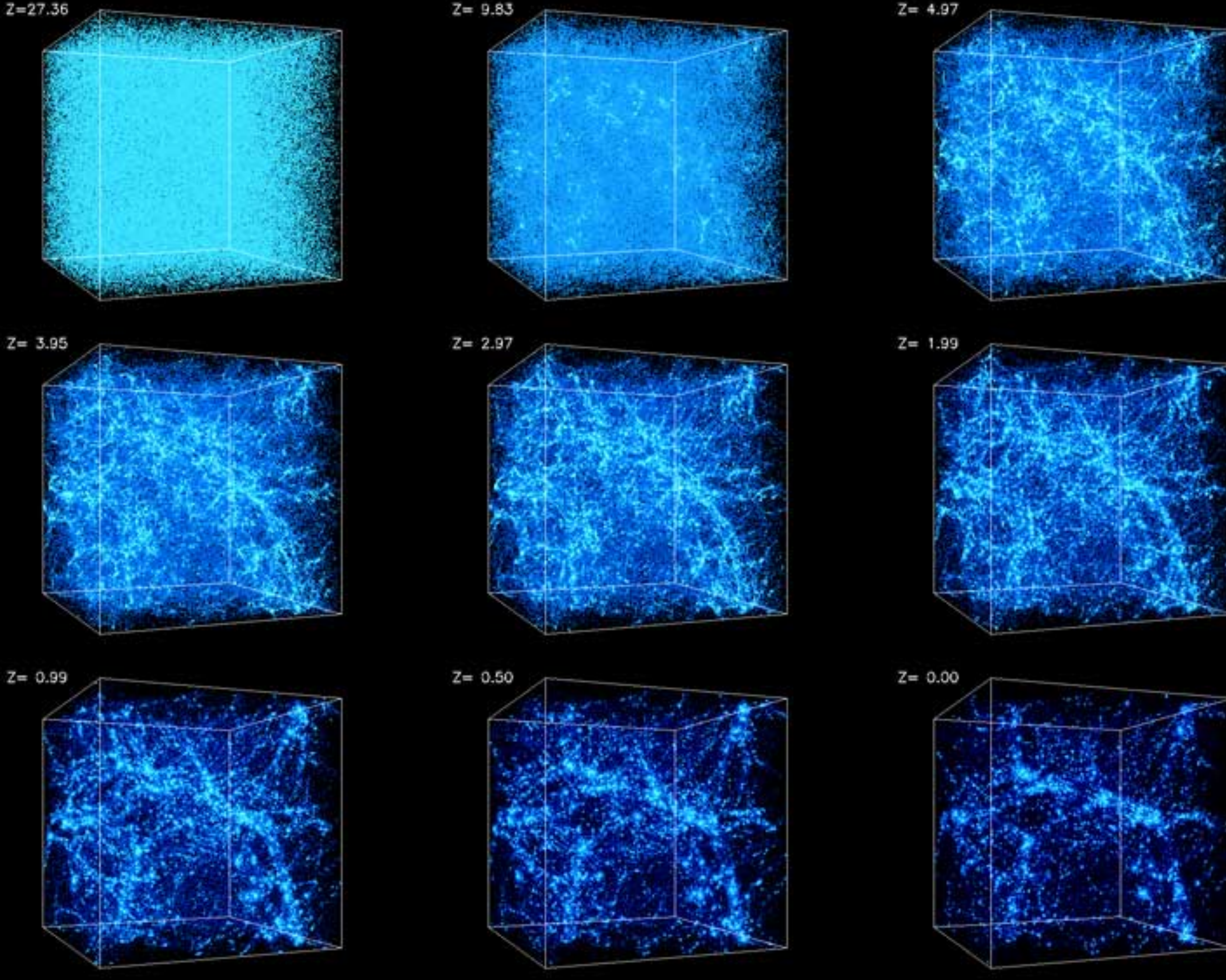
$$1\text{Mpc} = 3 \times 10^{24}\text{cm} \;\&\; 1M_\odot = 1.12 \times 10^{57}\text{GeV}$$

$$\rho_c \sim 10^{10}\frac{M_\odot}{\text{Mpc}^3} \sim 10^{-6}\text{GeV}/\text{cm}^3$$

Many probes of Dark Matter



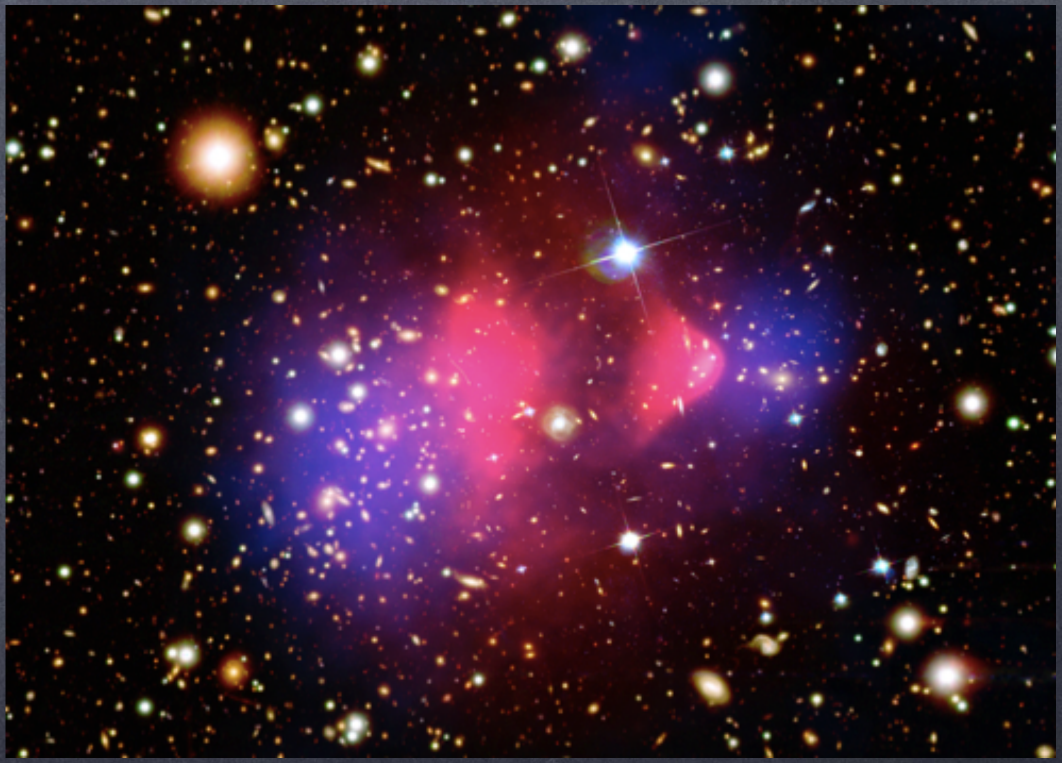
Hierarchical Structure formation



Properties of Dark matter

(1) Optically dark : does not couple to photons prior to recombination, does not cool radiatively like baryons do, dissipation-less, tight limits on charged dark matter, but it also depends on magnetic field (089.0436)

$$100(q_\chi/e)^2 \leq m_\chi \leq 10^8(q_\chi/e)\ \text{TeV}$$



(2) Collision-less :

$$\sigma/m < 1.25\text{cm}^2\text{g}^{-1}\ \text{Randall, et.al.2007}$$

$$\sigma/m < 0.5 - 5\text{cm}^2\text{g}^{-1}\ \text{Spergel + Steinhardt2000}$$

No discreteness in the DM distribution, MACHOS in the galaxy have been ruled out $(10^{-7} - 10)M_\odot$

Properties of Dark matter

(3) Classical: Confined within $1Kpc$, with density $\mathrm{GeV/cm^3}$, with velocities $100\mathrm{Km/s}$

Boson : we can estimate the mass from De Broglie wavelength

Hu, Barkana, Gruzinov, 2000

$$\lambda \sim \frac{h}{p} \leq 1\mathrm{Kpc} \implies m_\chi \geq 10^{-22} eV$$

Fermion : Pauli exclusion principle set the max occupation number and sets the phase space density

Gunn-Tremaine bound (1979)

$$f \sim 1 \sim \frac{g}{h^3} \sim \frac{\rho_0}{m_\chi^4} \frac{1}{(2\pi\sigma^2)^{3/2}} \implies m_\chi \geq 35eV$$

↗ Iso-thermal sphere

$\rho_0 \sim 1\mathrm{GeVcm^{-3}},\ \sigma \sim 100\mathrm{Kms^{-1}}$

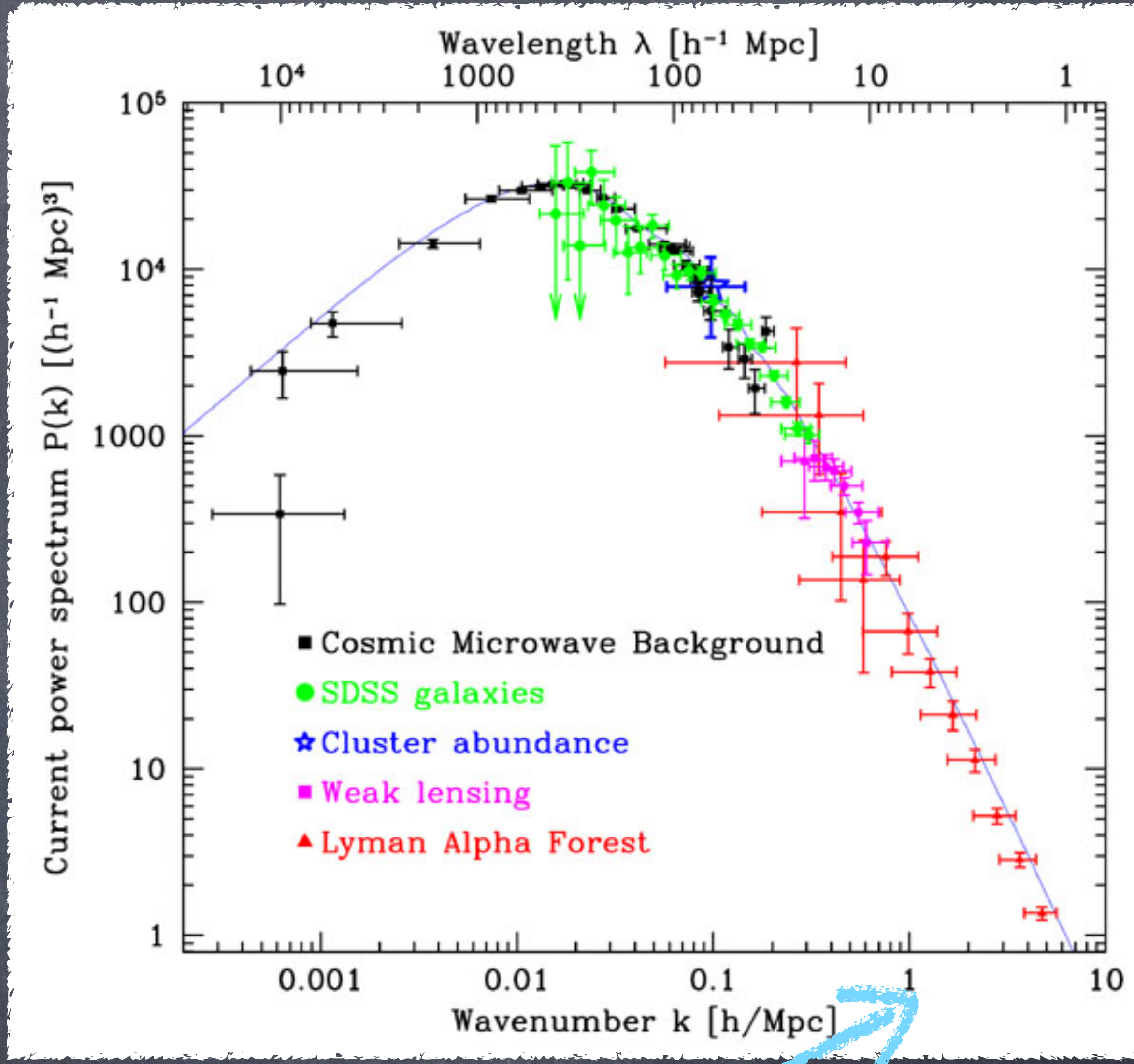
Properties of Dark matter

(3) Cold, Warm, but not Hot:

Free streaming will erase power from large scales

$$\lambda_{FS}(t) = \int_{t_i}^{t} \frac{v(t')}{a(t')} dt' \sim 2\frac{t_{NR}}{a_{NR}}$$

Largest contribution $v(t) \sim 1$, up to $t \sim t_{NR}$ (non – relativistic), for radiation domination, $t \propto a^2$



$$T^2 \propto 1/t \implies a_{NR} \propto m_\chi^{-1}, \text{ since } T \sim m_\chi v_\chi \sim m_\chi/3$$

$$\lambda_{FS} \simeq 0.4 \text{ Mpc}(m_\chi/\text{KeV})^{-1}(T_\chi/T)$$

$$\lambda_{FS}^{\nu} \simeq 40 \text{ Mpc}(m_\nu/30 \text{ KeV})^{-1}$$

KeV mass range for Warm DM

Thermal relic

Properties of Dark matter

Warm DM created from the decay of inflaton/moduli

$$v_\chi(t) = \frac{|\mathbf{p}_\chi|}{E_\chi} \simeq \frac{\frac{m_\phi}{2}\frac{a(t_D)}{a(t)}}{\sqrt{m_\chi^2 + \left[\frac{m_\phi}{2}\frac{a(t_D)}{a(t)}\right]^2}}$$

$$T_R \gtrsim 5 \times 10^4 \text{ GeV} \left(\frac{g}{200}\right)^{-1/4} \left(\frac{1 \text{ GeV}}{m_\chi}\right) \left(\frac{m_\phi}{10^{12} \text{ GeV}}\right)$$

Non-thermal nature of WDM, large initial momentum due to decay from heavy fields

$$\lambda_{\rm fs}(z) = (1.4 \times 10^{-2} \text{ Mpc}) g^{-1/3} \sqrt{\frac{1+z}{I_0}} \left(\frac{1 \text{ keV}}{m_\chi}\right) \qquad I_0 = [\int_0^\infty f^{(0)}(y)dy]/[\int_0^\infty y^2 f^{(0)}(y)dy]$$

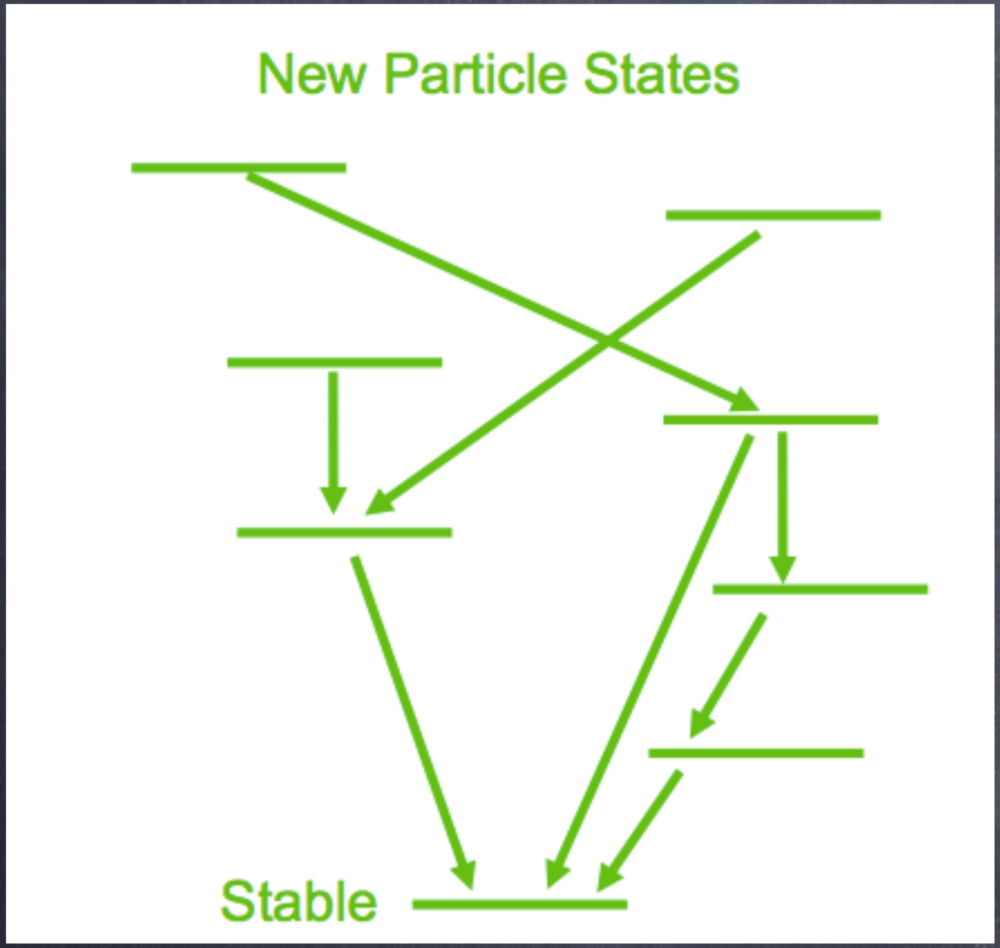
$$x = m_\chi/T \qquad f(y) = 1/\exp[\sqrt{y^2+x^2}+1]$$

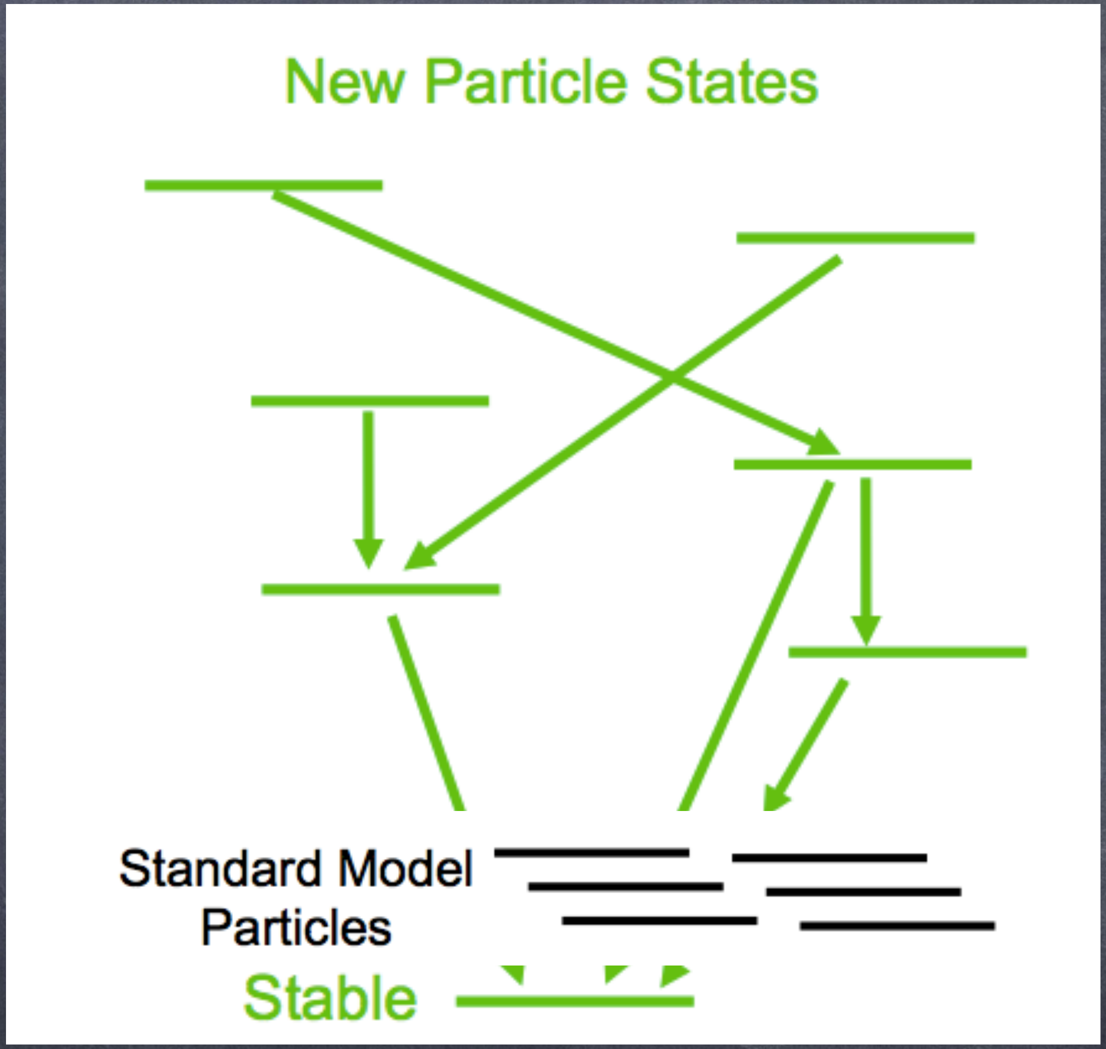
Examples: Sterile Neutrino, Gravitino, etc. can be produced in the early Universe right from the inflaton decay

0711.0470[astro-ph]

Properties of Dark matter

(4) Stability : Within SM there is no DM candidate





DM can be absolutely stable

or

Long lived

$$\Gamma_5 \sim \frac{m_\chi^3}{M^2}$$

$$\tau_5 \sim \left(\frac{1\mathrm{TeV}}{m_\chi}\right)^3 \left(\frac{M}{10^{16}\mathrm{GeV}}\right)^2 \mathrm{sec.}$$

$$\Gamma_6 \sim \frac{m_\chi^5}{M^4}$$

Right longevity

$$\tau_6 \sim 10^{27} \left(\frac{1\mathrm{TeV}}{m_\chi}\right)^5 \left(\frac{M}{10^{16}\mathrm{GeV}}\right)^4 \mathrm{sec.}$$

DM's mass range: 90 orders of magnitude

(Bulbulon)

3.5 KeV

(Wenigon)

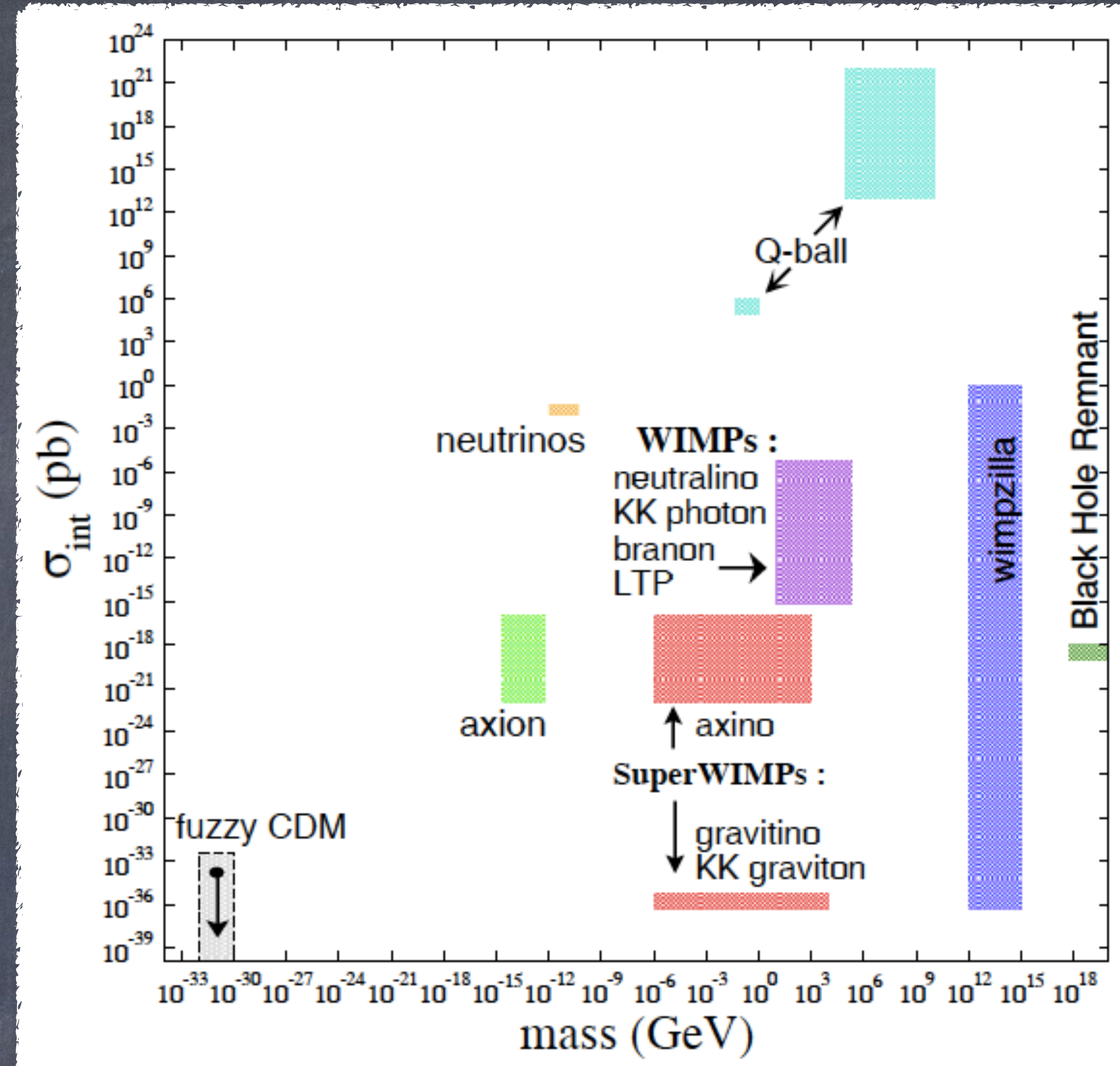
Fermi 135 GeV excess

GeV gamma-ray excess

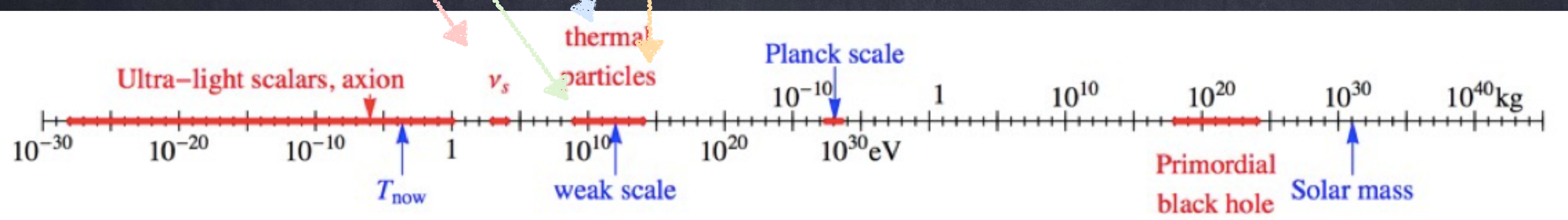
(Hooperon)

Pamela, Fermi, Hess excess

(Pamelon)



"Indirect Detection claims" — all of them have caveats & question marks



Interactive vs. Non-interactive

Any SUSY parter of matter multiplet, e.g. Neutralino

Right handed neutrinos, etc.

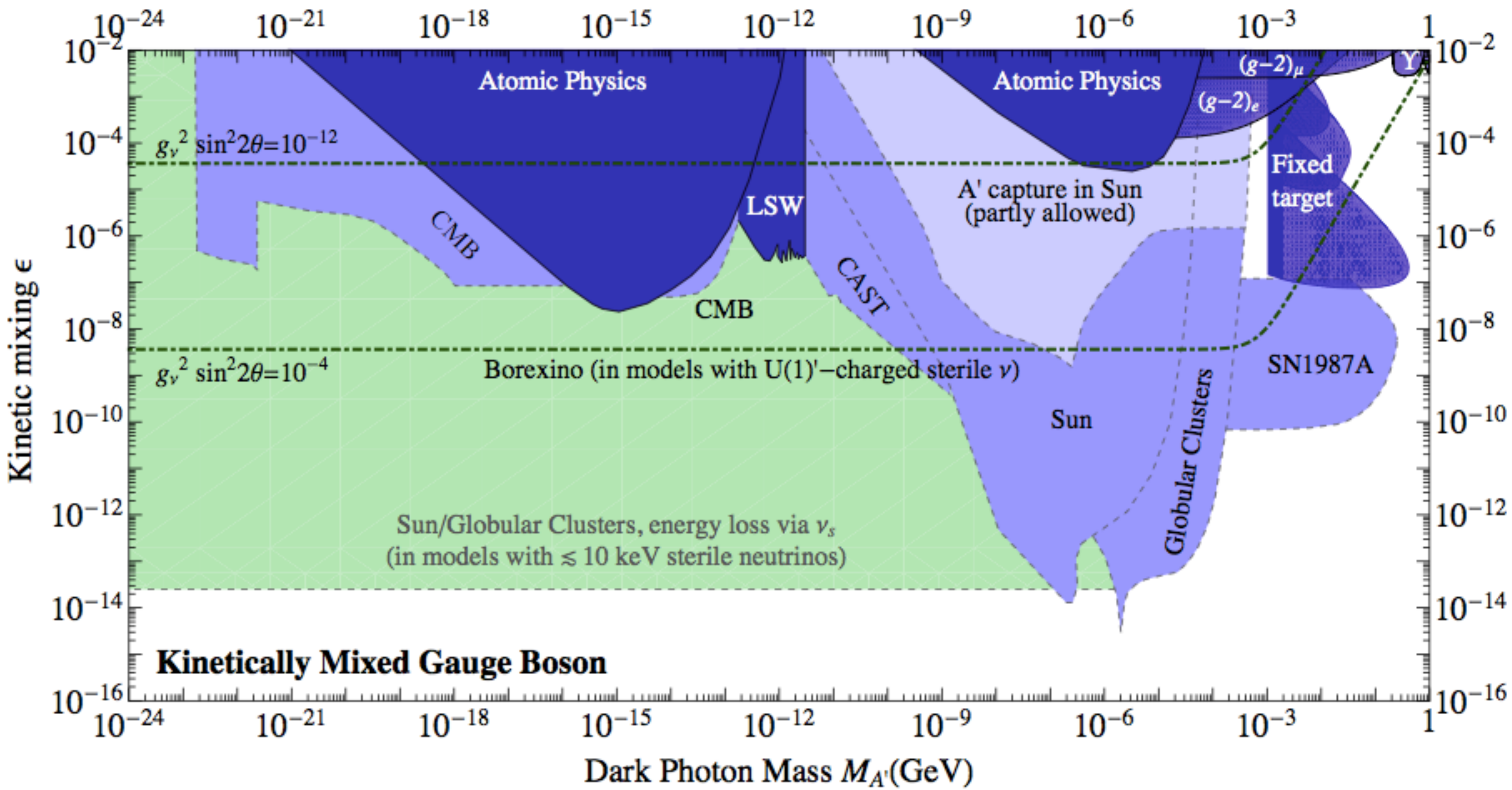
There is a hope for their detection

Gravitino, dilaton, modulino, Mirror Dark Matter, Hidden baryons/photons, Massive graviton, etc.

It will be hard to detect them, although Cosmological bounds can be placed

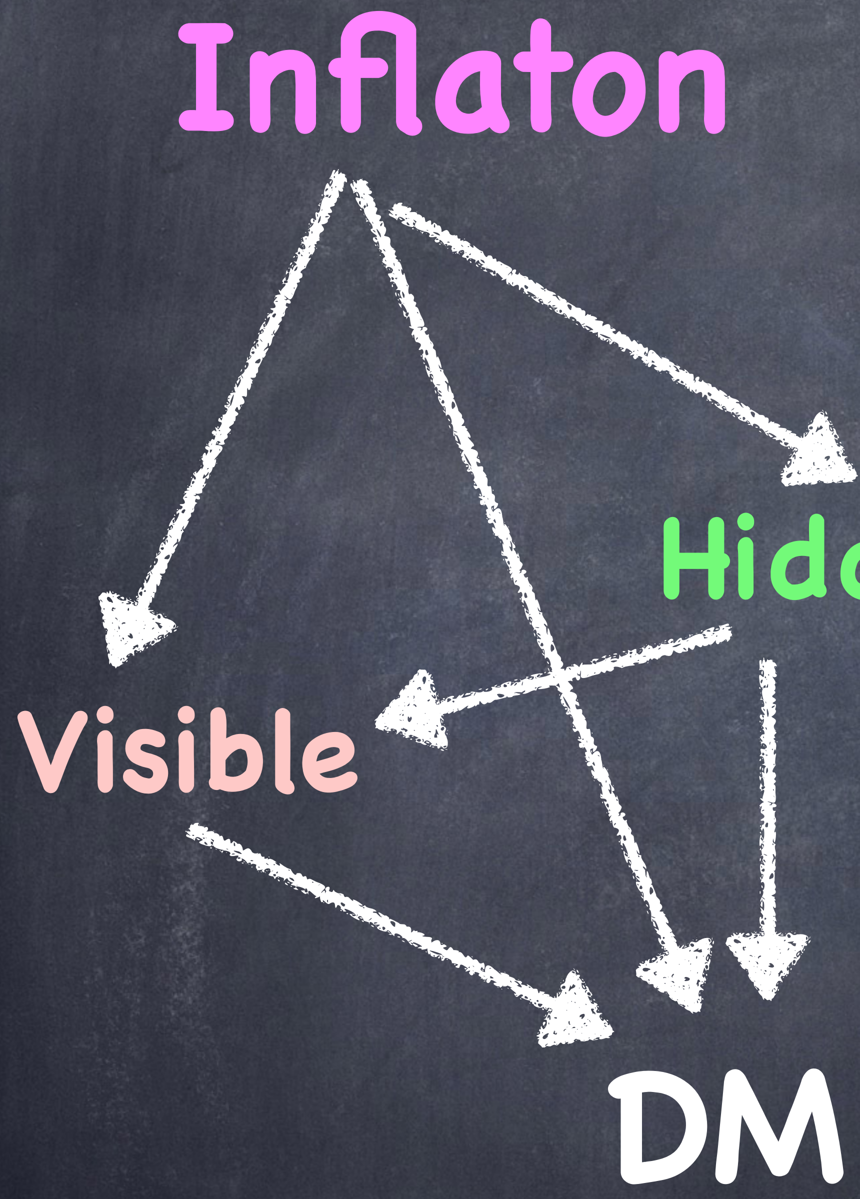
Massive photon as DM

$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}\epsilon F'_{\mu\nu}F^{\mu\nu} + \bar{\nu}_s i\partial\!\!\!/ \nu_s + g'\bar{\nu}_s\gamma^\mu\nu_s A'_\mu$$



Constraints from Jaeckel Ringwald 1002.0329, Redondo 0801.1527,
Bjorken Essig Schuster Toro 0906.0580, Dent Ferrer Krauss 1201.2683, Harnik JK Machado 1202.6073

Dark matter production



(1) DM as a thermal relic

(2) DM as a non-thermal relic

(3) DM as a scalar condensate

Unlike baryons DM can be over populated very easily

Overclosure bound is the most trivial and often provides the stringent limit

(3) DM as a (pseudo)scalar condensate

$$\mathcal{L}_{QCD} = \cdots + \theta \frac{g^2}{32\pi^2} G^a_{\mu\nu} \widetilde{G}^{a\ \mu\nu}$$

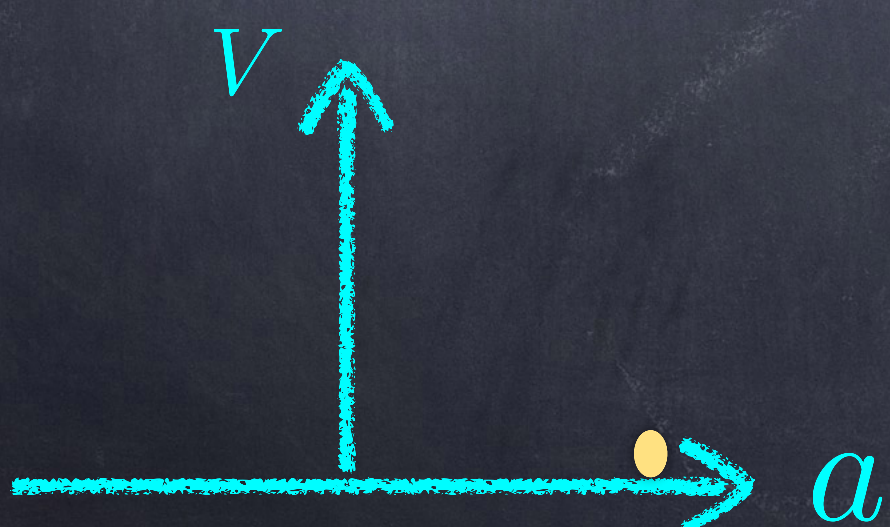
Strong interactions conserve P and CP,

$\theta \leq 10^{-10}$ (neutron electirc dipole moment)

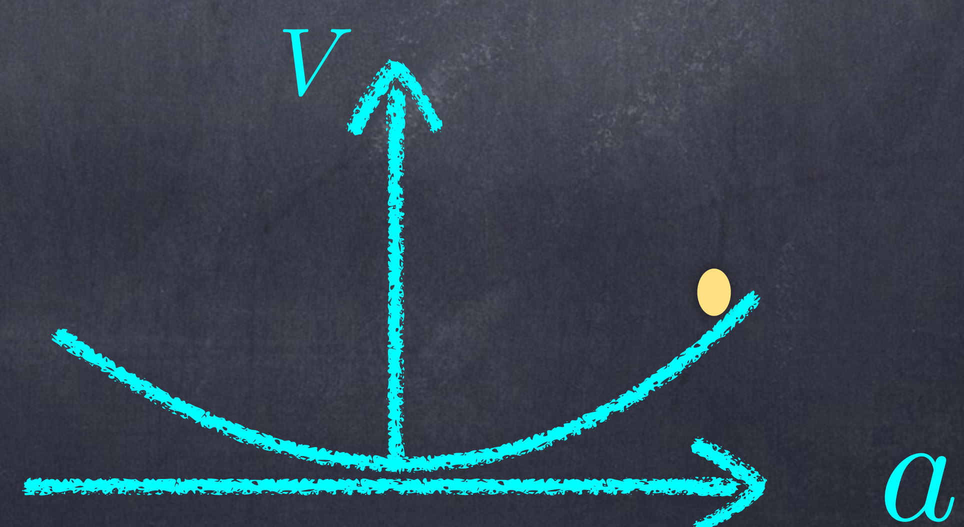
If we assume $U(1)_{PQ}$ Symmetry

$$\mathcal{L}_{QCD} = \cdots + \frac{a}{f_a^2} \frac{g^2}{32\pi^2} G^a_{\mu\nu} \widetilde{G}^{a\ \mu\nu} + \frac{1}{2}\partial_\mu a \partial^\mu a$$

$\theta = \frac{a}{f_a}$ **relaxes to** $0.$



$T \geq 1$ GeV



$T \leq 1$ GeV

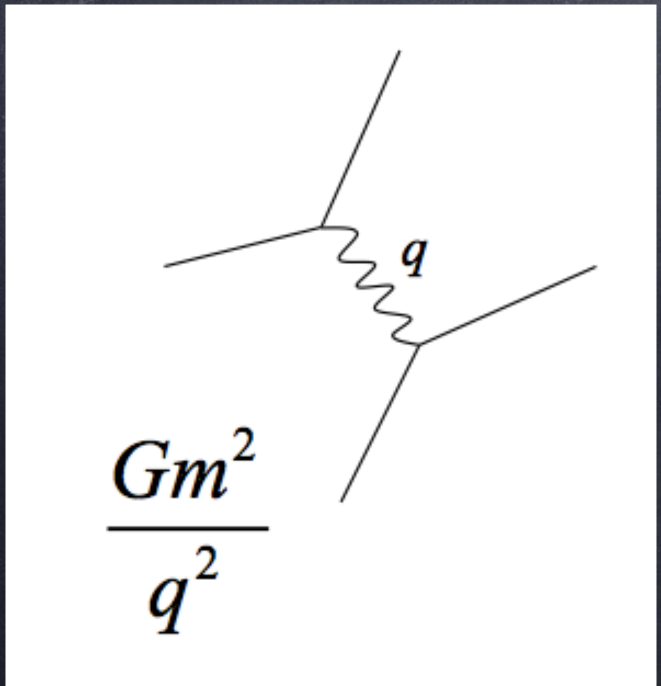
Axion condensate as a DM candidate

$$n_a(t) \simeq \frac{1}{2} m_a(t) a^2(t) \simeq \frac{1}{2t} f_a^2 \alpha(t)^2$$ → initial misalignment angle

$$\rho_a(t_0) \simeq m_a n_a(t) \left(\frac{a(t)}{a_0}\right)^3$$

$$m_a \approx 6 \times 10^{-6} \mathrm{eV} \frac{10^{12}\ \mathrm{GeV}}{f_a}$$

Coherent oscillations of the axion can act as a Bose-Einstein Condensate

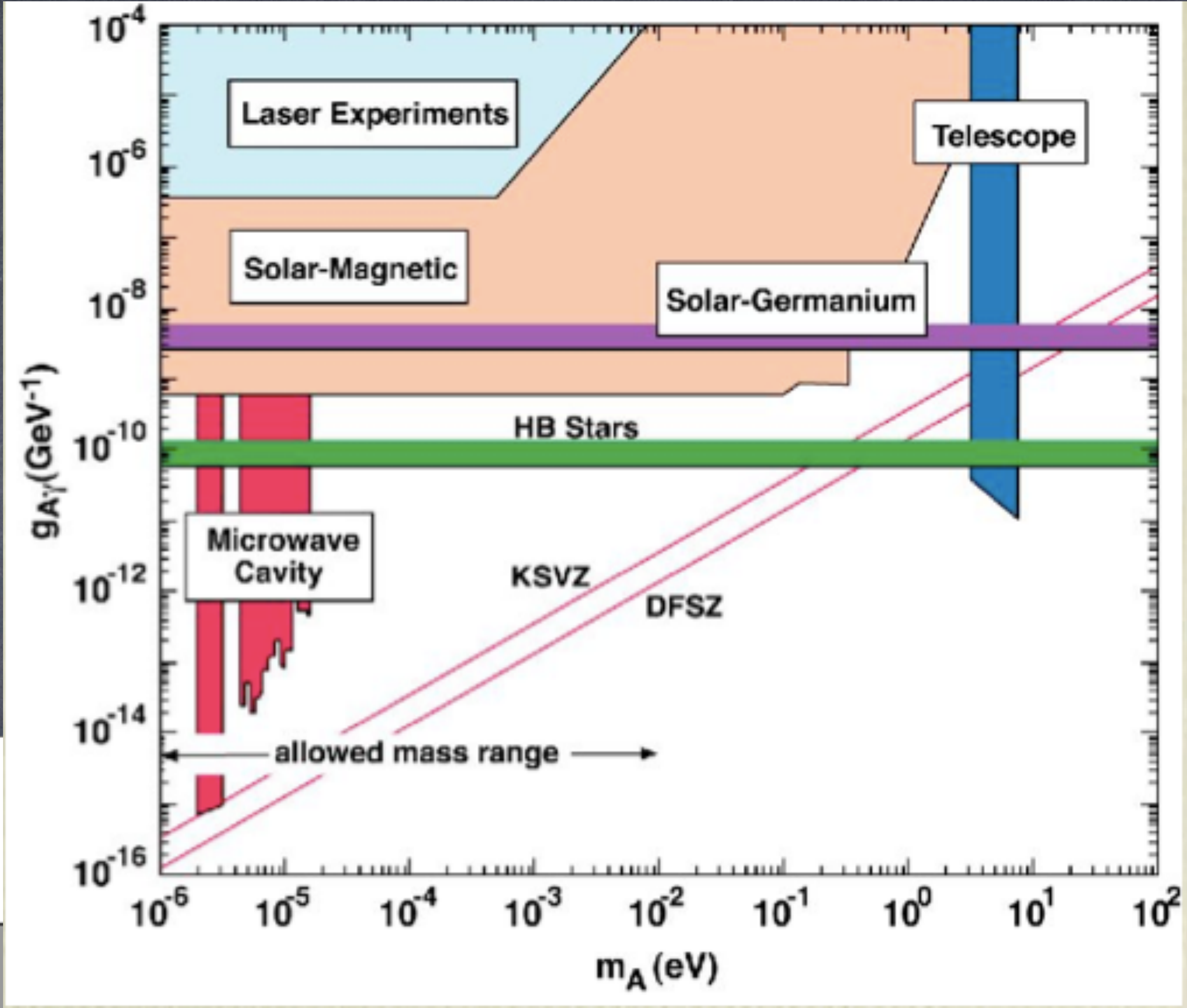


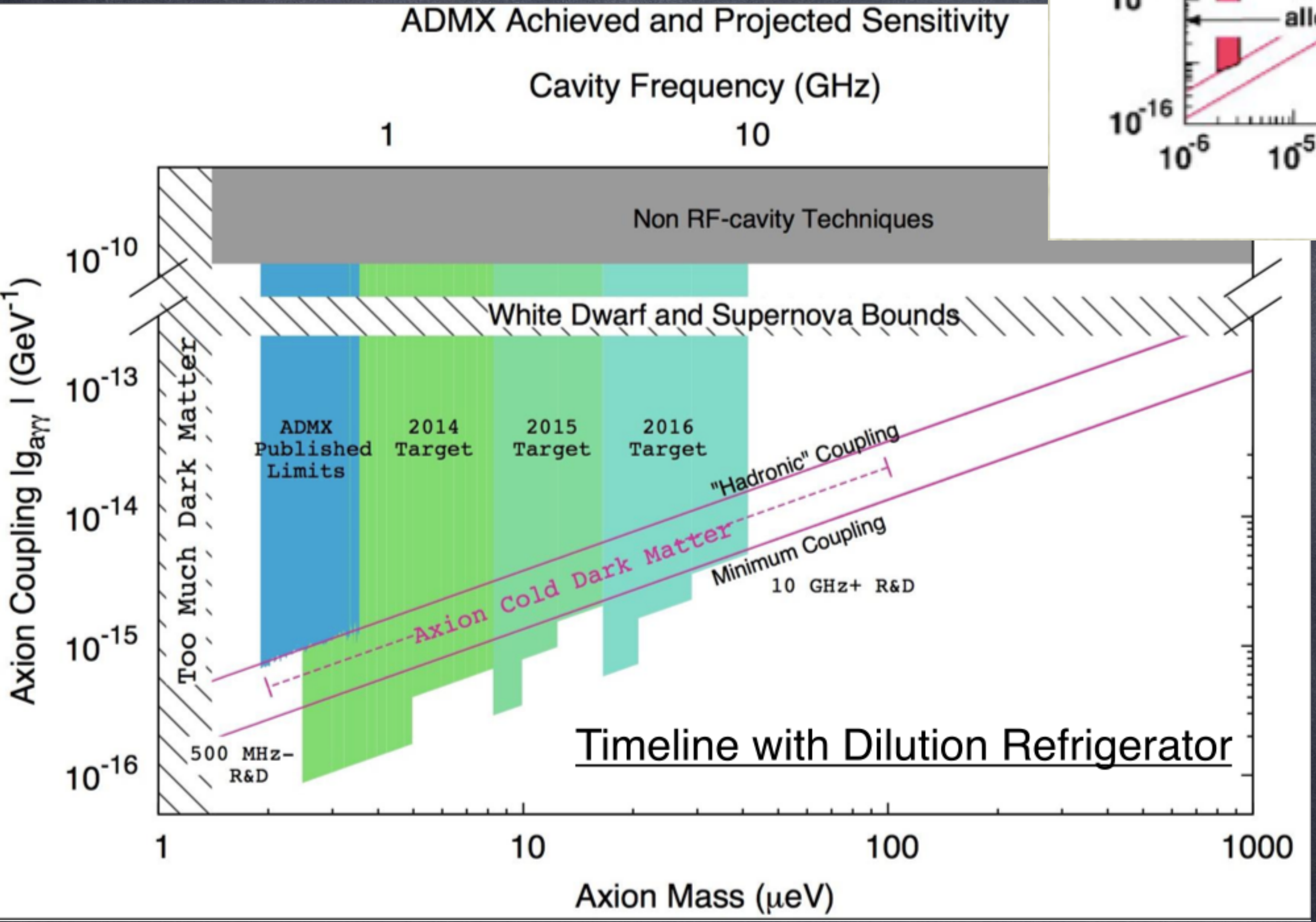
$$T_\gamma \sim 500\ \mathrm{eV} \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{1/2}$$

Sikivie, Yang, PRL (2009), 111301

Axion constraints

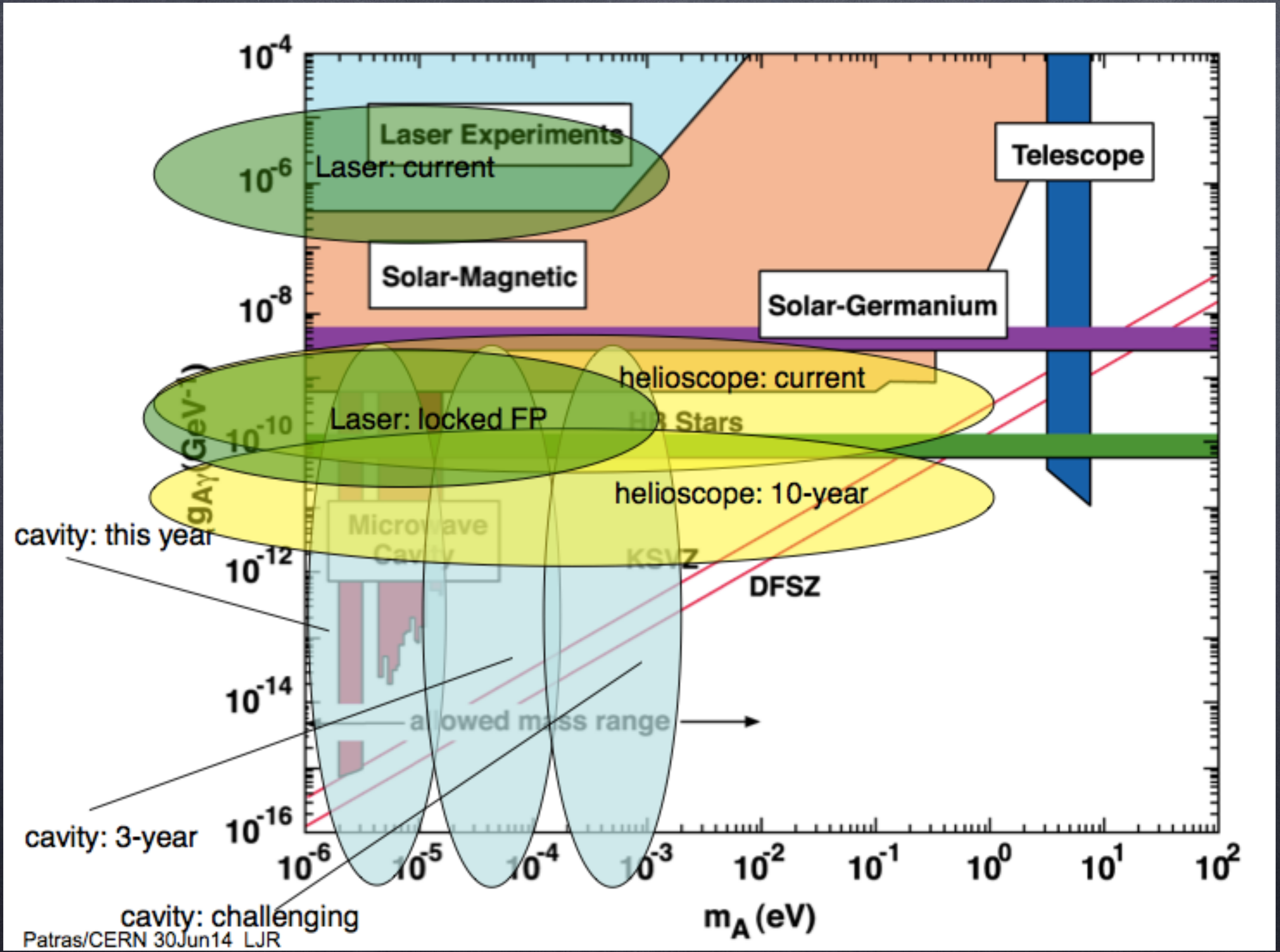
$$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma}\ aE.B$$



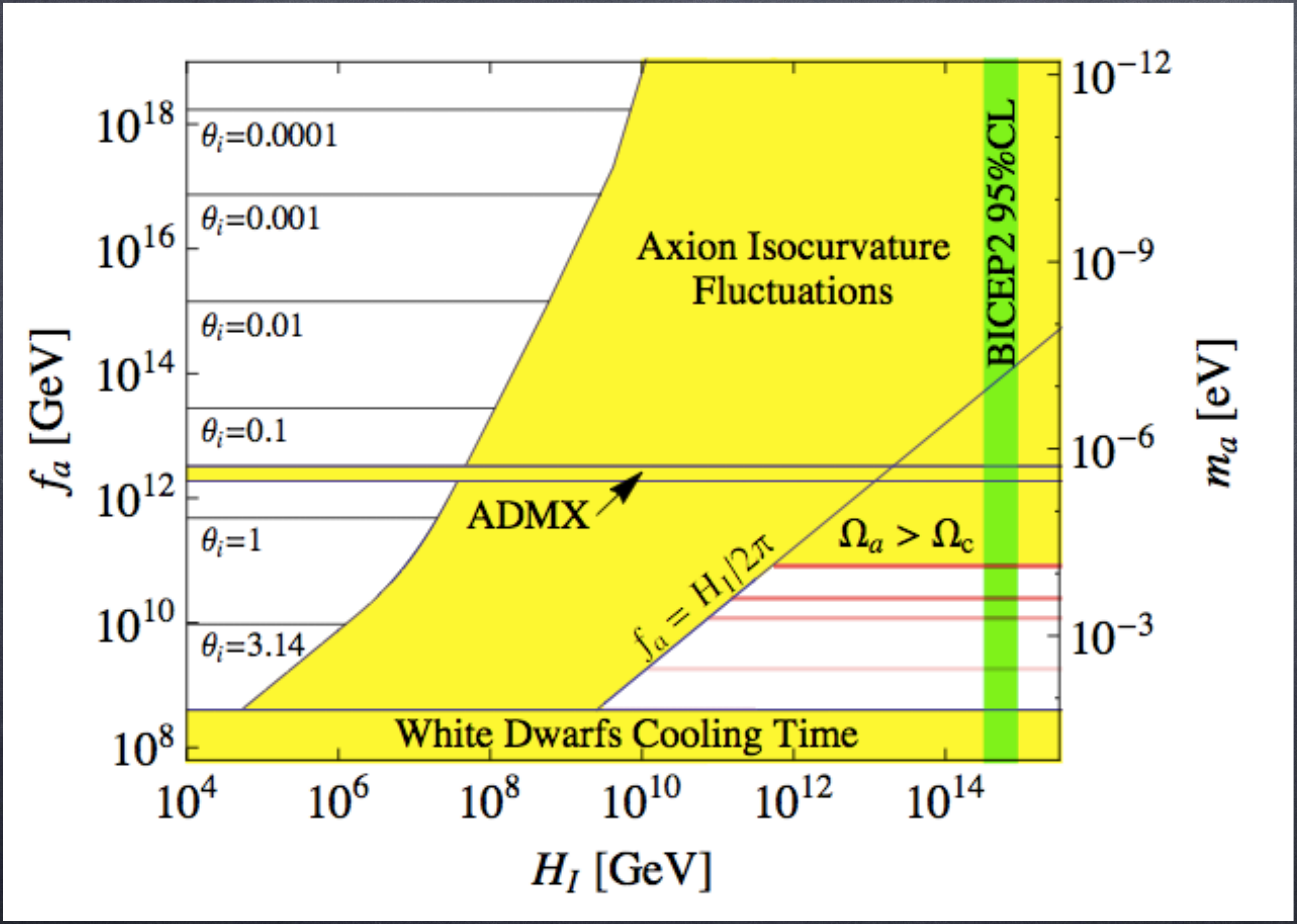


Duffy, et. al (2006)

Axion projected constraints



Axion iso-curvature constraints



Visinelli, Gondolo, PRL (2014)

(1) WIMP freeze-out paradigm

(1) Assume a new (heavy) particle χ is initially in thermal equilibrium:

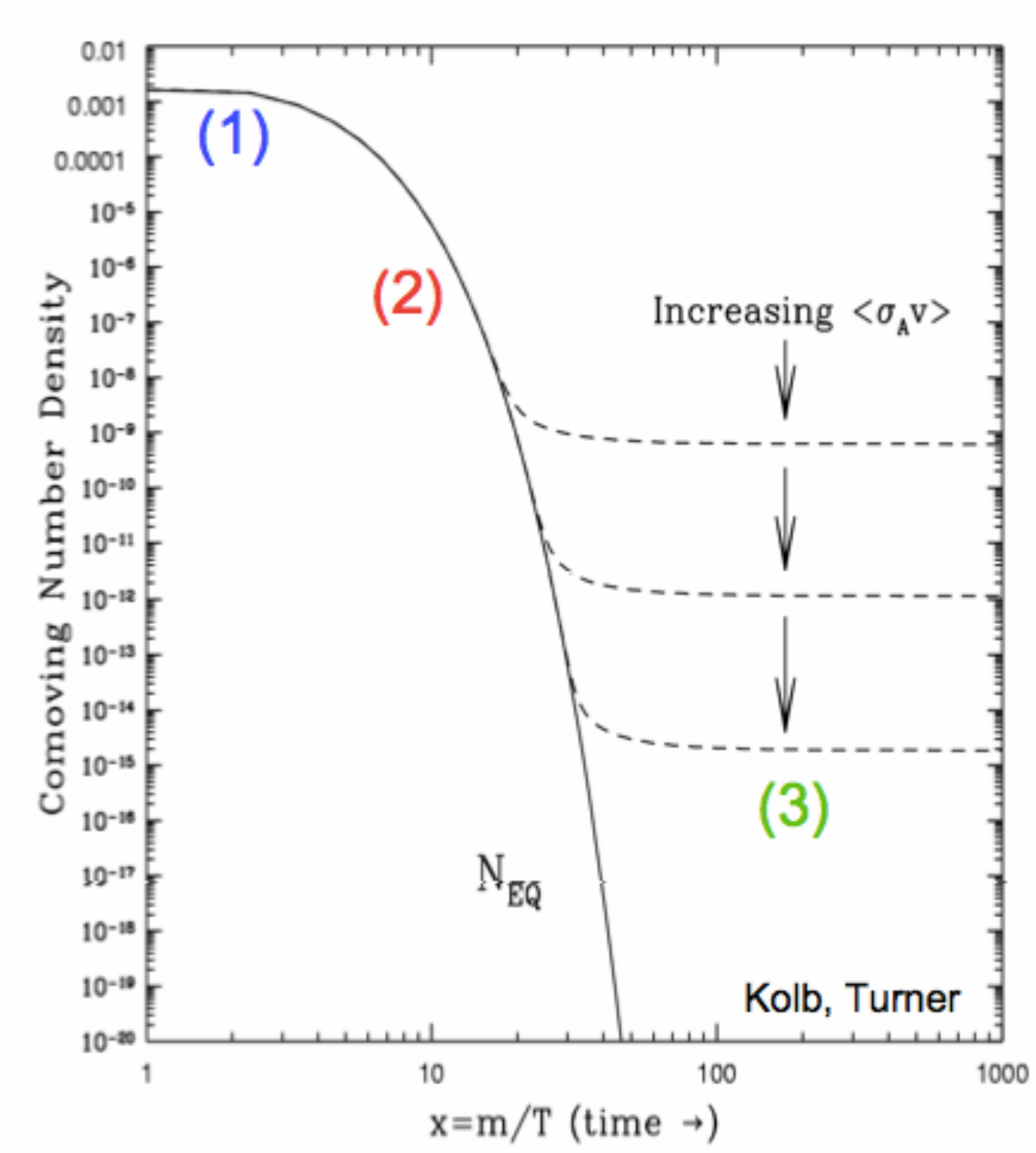
$$\chi\chi \leftrightarrow \bar{f} f$$

(2) Universe cools:

$$\chi\chi \rightleftarrows\!\!\!\!\!/\;\; \bar{f} f$$

(3) χs "freeze out":

$$\chi\chi \;\not\rightleftarrows\; f f$$



$$\Omega_\chi \approx 0.2 \left(\frac{3 \times 10^{-26}\ \mathrm{cm}^3\mathrm{s}^{-1}}{\langle \sigma v \rangle} \right)$$

CDM as a thermal relic

$f\bar{f} \leftrightarrow \chi\bar{\chi}$

Boltzmann Code:

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle \left(n_\chi^2 - n_{\chi,\mathrm{eq}}^2\right)$$

$f\bar{f} \rightarrow \chi\bar{\chi}$

$\chi\bar{\chi} \rightarrow f\bar{f}$

$\langle\sigma v\rangle = a + b\langle v^2\rangle + \cdots$

Thermally averaged cross section

$$n_\chi = g_\chi \int \frac{d^3\mathbf{p}}{(2\pi)^3} \exp\left[-\left(\sqrt{|\mathbf{p}|^2 + m_\chi^2} - \mu_\chi\right)/T\right]$$

$n_\chi^{eq} \propto T^3$ iff $T \gg m_\chi$

$n_\chi^{eq} \propto (m_\chi T)^{3/2} \exp(-m_\chi/T)$ iff $T \ll m_\chi$

Select a new variable: $Y_\chi \equiv \dfrac{n_\chi}{s}$, $\quad s \propto g_{eff}(T)T^3$

$sa^3 = \mathrm{const.} \quad \Longrightarrow \quad \dot{s} = -3sH$

CDM as a thermal relic

$$\frac{x}{Y_\chi^{eq}}\frac{dY_\chi}{dx} = -\frac{\langle\sigma v\rangle n_\chi^{eq}}{H}\left[\left(\frac{Y_\chi}{Y_\chi^{eq}}\right)^2 - 1\right]$$

$$x \equiv m_\chi/T$$

$$\Gamma(T_f) = n_\chi^{eq}(T_f)\langle\sigma v\rangle_{T=T_f} \simeq H(T_f)$$

$$\text{After freeze-out, when } \Gamma \ll H, \quad Y_\chi \simeq Y_\chi^{eq}(T_f)$$

The relic abundance freezes

$$\Omega_\chi = \frac{\rho_\chi}{\rho_c} = \frac{m_\chi n_0}{\rho_c} = \frac{m_\chi s_0 Y_0}{\rho_c} \simeq \frac{m_\chi s_0 Y_\chi^{eq}(T_f)}{\rho_c}$$

$$\text{With } s_0 \simeq 3000\text{cm}^{-3}$$

Freeze out of relativistic species:

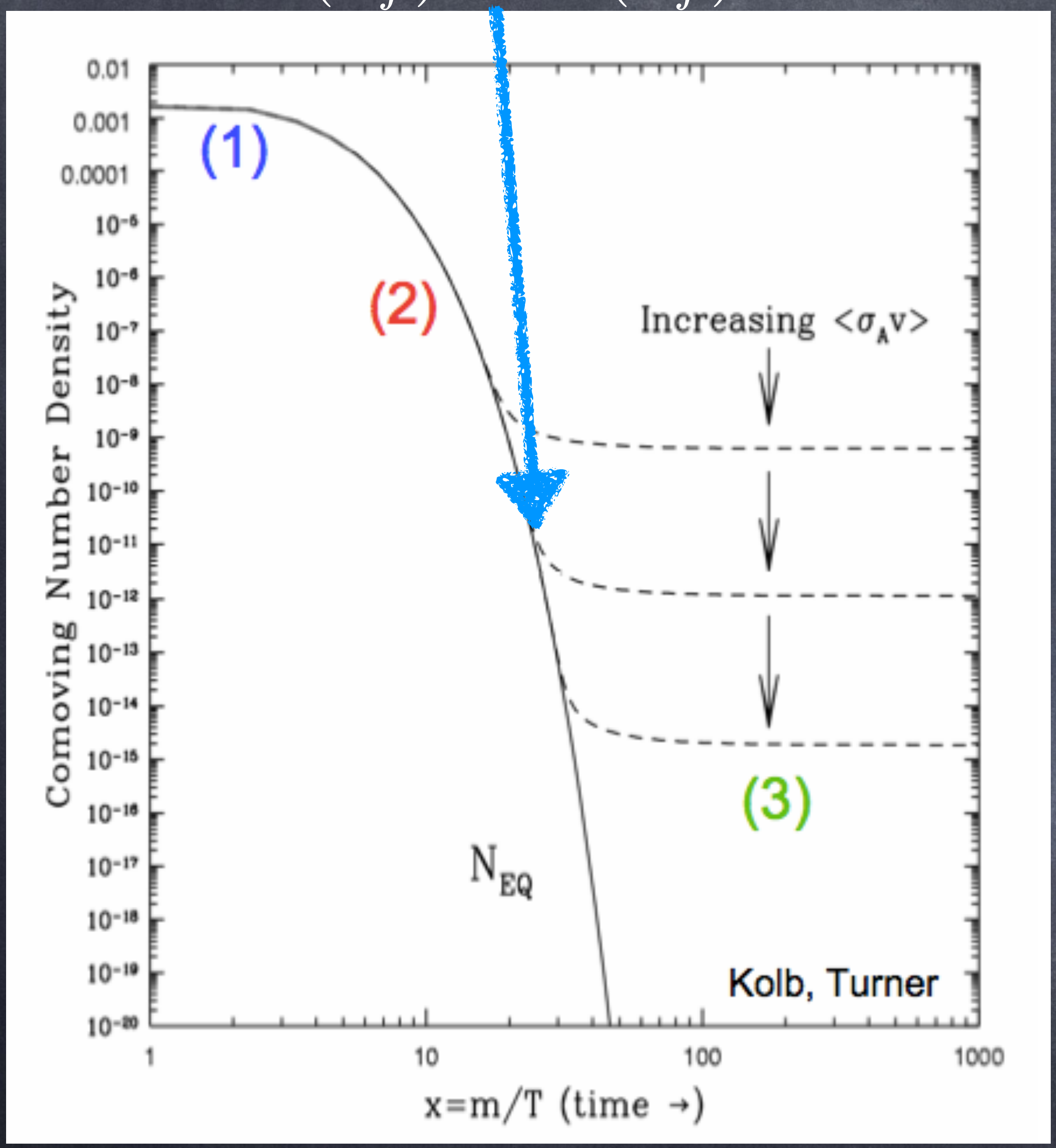
$$x_{f.o} \ll 1, \quad Y_{\chi,eq}(x_{f.o.}) = \frac{n_{\chi,eq}}{s}$$

$$\Omega_\chi h^2 = 7.62 \times 10^{-2}\frac{g_{eff}}{g(x_{f.o.})}\frac{m_\chi}{1\text{eV}} \qquad g_{eff} = g_\chi\ (boson),\ (3g_\chi/4)\ (fermion)$$

Bhupal DeV, AM, Qutub: 1311.5297[hep-ph]

Freeze out of CDM

$$\Gamma(T_f) \simeq H(T_f)$$



Entropy conserved

$$\Omega_\chi h^2 \simeq \frac{m_\chi s_0 Y_\chi^{eq}(T_f)}{\rho_c/h^2}$$

$$\simeq \frac{m_\chi s_0}{\rho_c/h^2} \frac{H(T_f)}{s(T_f)\langle\sigma v\rangle_{T_f}}$$

$$\simeq \frac{m_\chi}{T_f} \frac{g(x_f)}{g_{eff}} \frac{1\times 10^{-27}\text{cm}^3\text{s}^{-1}}{\langle\sigma v\rangle_{T_f}}$$

$$m_\chi/T_f \sim 20$$

$$\Omega_\chi h^2 \simeq \frac{3\times 10^{-27}\text{cm}^3\text{s}^{-1}}{\langle\sigma v\rangle_{T_f}} \simeq \frac{10^{-10}\text{GeV}^{-2}}{\langle\sigma v\rangle_{T_f}}$$

$$1\text{GeV}^{-1} = 1.9\times 10^{-14}\text{cm}$$

$$1\text{GeV}^{-1} = 6.5\times 10^{-25}\text{Sec}$$

$$1pb = 10^{-36}\ \text{cm}^2$$

This is the bench mark number - must remember

WIMP scenario

Unitarity bound => Upper bound on mass :

$$\Omega_\chi h^2 \simeq \frac{3\times 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma v\rangle_{T_f}} \simeq \frac{10^{-10}\mathrm{GeV}^{-2}}{\langle\sigma v\rangle_{T_f}} \sim 0.1$$

$$\sigma \leq \frac{4\pi}{m_\chi^2} \qquad \Longrightarrow \left(\frac{m_\chi}{120\ \mathrm{TeV}}\right)^2 \leq 1$$

Griest + kamionkowski PRL(1990)

Lower bound on mass :

$$\sigma \sim G_{EW}^2 m_\chi^2 \Longrightarrow \Omega_\chi h^2 \sim 0.1 \frac{10^{-8}}{GeV^{-2}} \left(\frac{1}{G_{EW}^2 m_\chi^2}\right) \sim 0.1 \left(\frac{10\ GeV}{m_\chi}\right)^2$$

Co-annihilation

Assume there are N states $\chi_1,\ \chi_2, \cdots, \chi_N$ sharing a quantum number, with $m_1 \leq m_2 \cdots \leq m_N$. The Boltzmann equation can be traced simultaneously

$$\frac{dn_i}{dt} = -3Hn_i - \Sigma_j \langle \sigma_{ij} v_{ij} \rangle (n_i n_j - n_i^{eq} n_j^{eq})$$

$$\chi_i \chi_j \leftrightarrow X_a^f$$

$$-\Sigma_{j \neq i} \langle \sigma_{i \to j} v_{i \to j} \rangle \left(n_i - n_j \frac{n_i^{eq}}{n_j^{eq}} \right)$$

$$\chi_i X_b^i \leftrightarrow \chi_j X_b^f$$

$$+\Sigma_{j>i} \Gamma_{j \to i} \left(n_j - n_i \frac{n_j^{eq}}{n_i^{eq}} \right)$$

$$-\Sigma_{j<i} \Gamma_{i \to j} \left(n_i - n_j \frac{n_i^{eq}}{n_j^{eq}} \right)$$

$$\chi_j \leftrightarrow \chi_i X_c^f$$

Co-annihilation

All freeze out almost simultaneously, and decay to χ_1.
It is easy to trace $n = \Sigma_i n_i$, rather than n_i :

$$\frac{dn}{dt} = -3Hn - \langle \sigma_{eff} v \rangle \left[n^2 - (n^{eq})^2 \right]$$

$$\text{with } \langle \sigma_{eff} v \rangle = \Sigma_{i,j} \langle \sigma_{ij} v_{ij} \rangle \frac{n_i^{eq}}{n^{eq}} \frac{n_j^{eq}}{n^{eq}}$$

Dominant: Annihilation is large, decrease in DM density

Parasite: Annihilation is small, increase in DM density

Kinetic Decoupling

Chemical decoupling to kinetic decoupling

$$\chi f \leftrightarrow \chi f$$

$$\chi\chi \leftrightarrow ff \quad \rightarrow \quad \Gamma = n_{\rm non-rel} \cdot \sigma$$
$$\chi f \leftrightarrow \chi f \quad \rightarrow \quad \Gamma = n_{\rm rel} \cdot \sigma$$

Relativistic & Non-relativistic scattering rates are very different

Stochastic Process

Dark matter is undergoing several scatterings

$$\sigma_{\chi f \leftrightarrow \chi f} \sim G_F^2 T^2$$

$$N = \left(\frac{\delta p}{p}\right)^2 \sim \frac{T^2}{m_\chi T} = \frac{T}{m_\chi} \qquad \delta p \sim T \qquad \frac{p^2}{2m} \sim T$$

$$n_{\rm rel} \cdot \sigma_{\chi f \leftrightarrow \chi f} \left(\frac{\delta p}{p}\right)^2 \sim T^3 \cdot G_F^2 T^2 \cdot \frac{T}{m_\chi} \sim H \sim \frac{T^2}{M_P}$$

$$T_{\rm k.d.} \sim \left(\frac{m_\chi}{M_P \cdot G_F^2}\right)^{1/4} \sim 30 \text{ MeV} \left(\frac{m_\chi}{100 \text{ GeV}}\right)^{1/4}$$

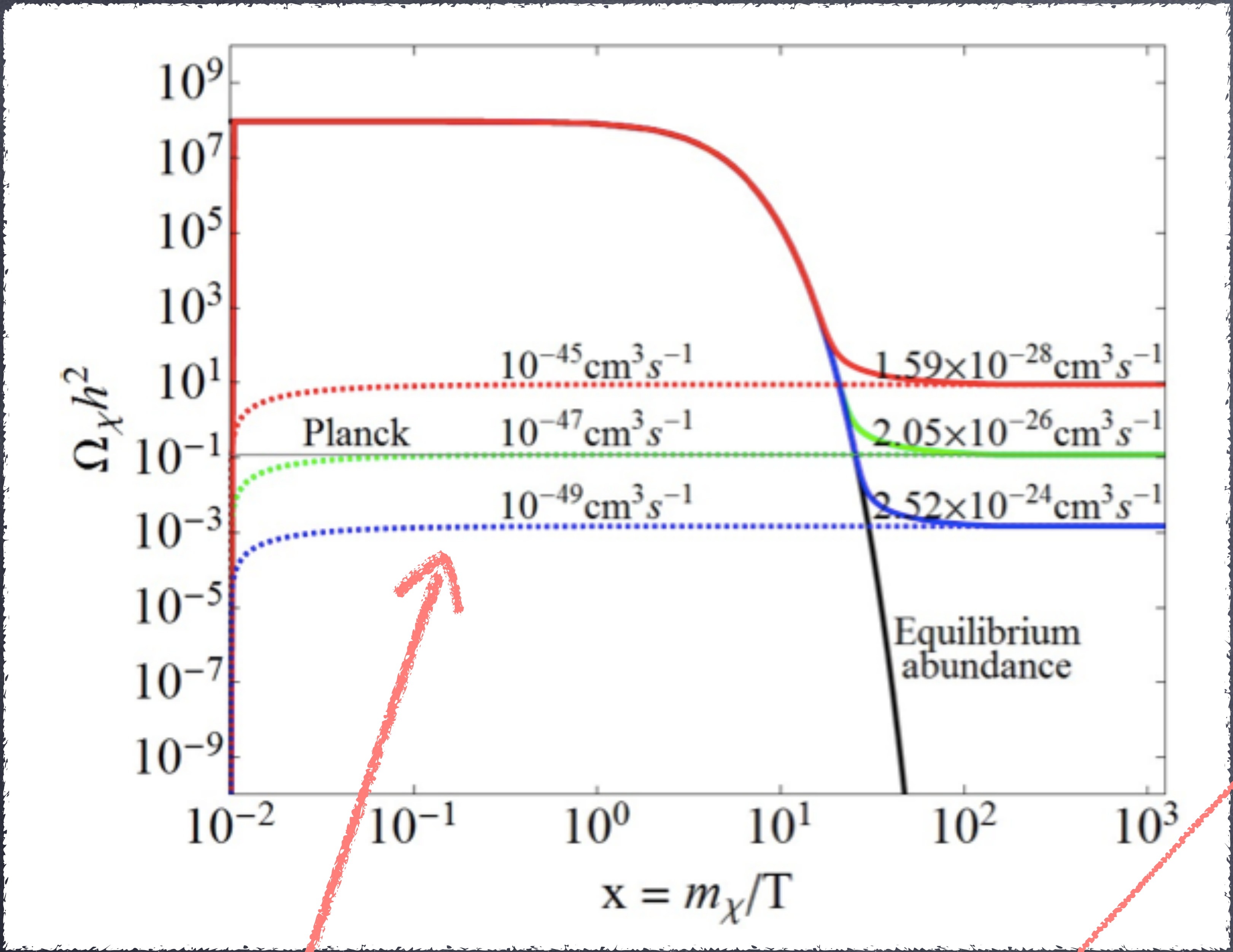
$$M_{\rm cutoff} \sim \frac{4\pi}{3}\left(\frac{1}{H(T_{\rm kd})}\right)^3 \rho_{\rm DM}(T_{\rm kd}) \sim 30\, M_\oplus \left(\frac{10 \text{ MeV}}{T_{\rm kd}}\right)^3$$

Free Streaming Length

Chen, Kamionkowski, Zhang PRD(2001)

Green, Hoffman, Schwarz PRD(2001)

Freeze-out and Freeze-in Scenarios



(2) Non-thermal

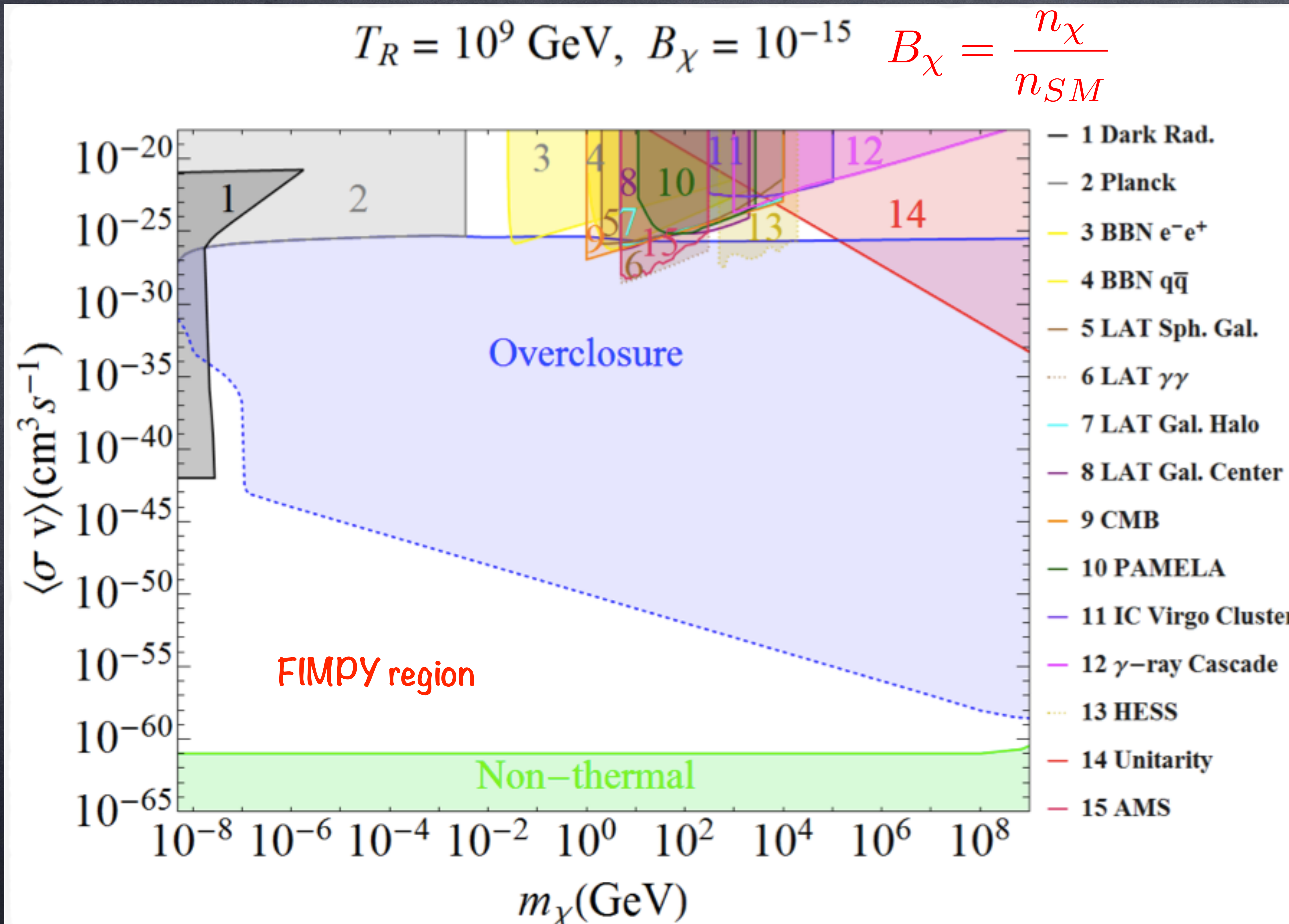
$$Y_{\chi,in} = \frac{n_{\chi,in}}{s(T_R)} \sim \frac{3}{4} B_\chi \frac{T_R}{m_\phi}$$

Thermal

$$\Omega_\chi h^2 = 2.06 \times 10^8 \, B_\chi \frac{m_\chi}{m_\phi} \left(\frac{T_R}{1 \text{ GeV}} \right) + g^{1/2} \langle \sigma v \rangle m_{\rm Pl} m_\chi \left(\frac{T_R}{1 \text{ GeV}} \right) \left(5.6 \times 10^6 \frac{g_{\rm eff}^2}{g^2} - 4.1 \times 10^7 B_\chi^2 \frac{T_R^2}{m_\phi^2} \right)$$

Bhupal-Dev, AM, Qutub, Front.Physics (1311.5297)

Constraints on Dark matter Cross Section



Main Uncertainties: DM annihilation/decay (branching fraction) + Astrophysics (propagation)

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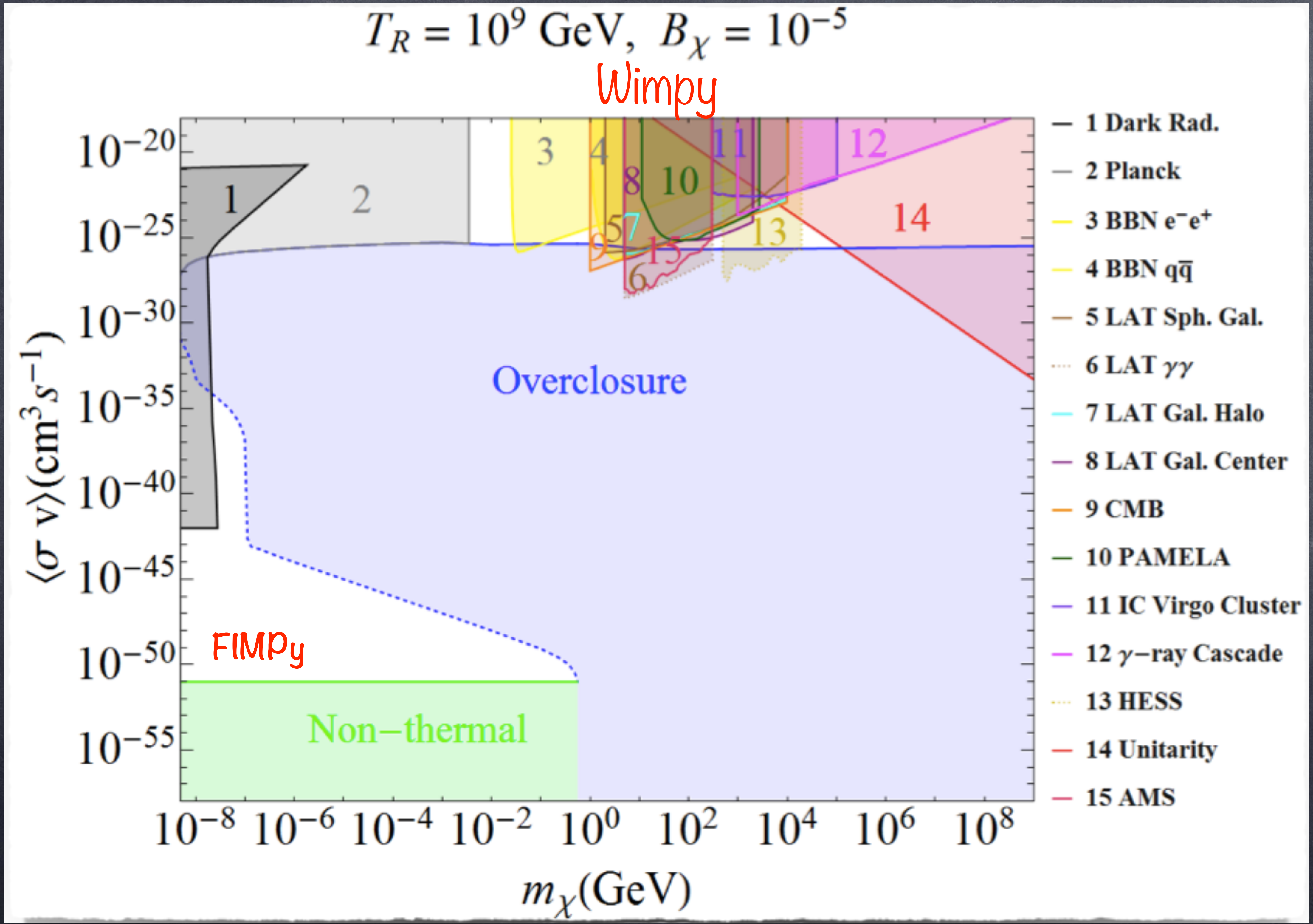

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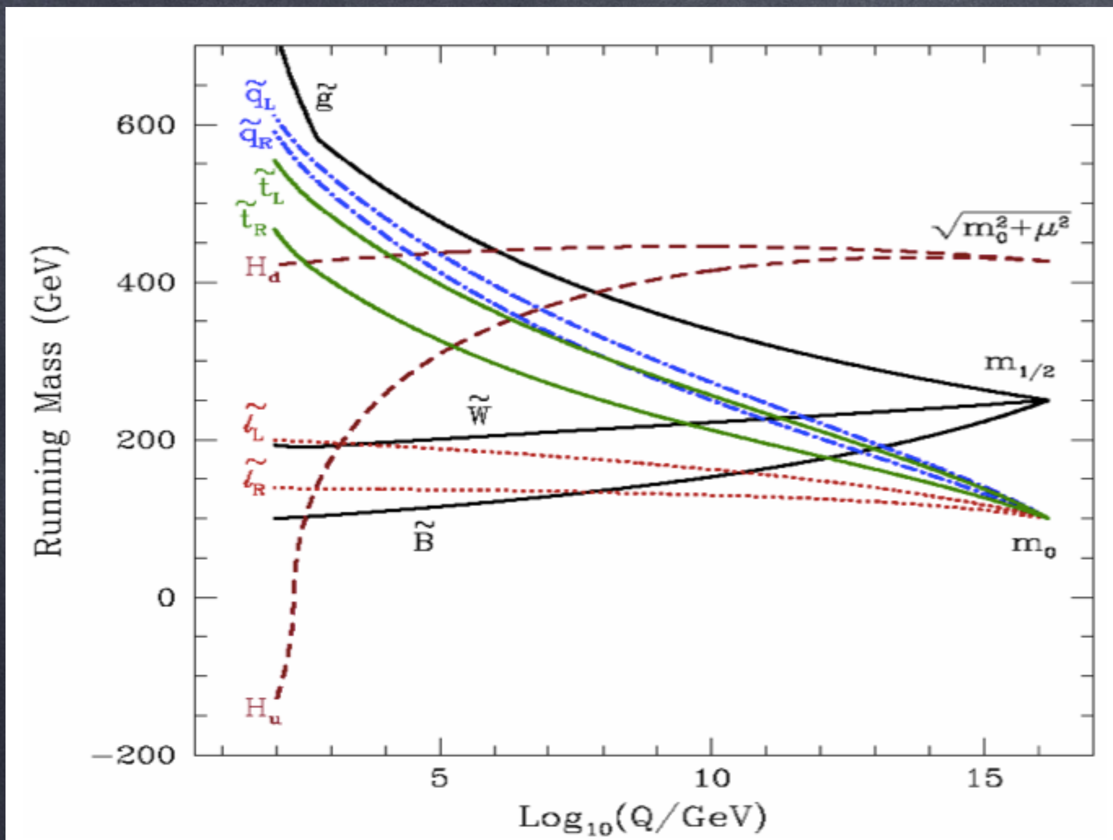
SUSY WIMP

LSP is protected by R-parity, or very light Gravitino < 1 GeV could be DM



Spin	U(1) M_1	SU(2) M_2	Up-type μ	Down-type μ	$m_{\tilde{\nu}}$	$m_{3/2}$
2						G graviton
3/2	Neutralinos: $\{\chi \equiv \chi_1, \chi_2, \chi_3, \chi_4\}$					$\tilde{G}$ gravitino
1	B	W^0				
1/2	$\tilde{B}$ Bino	$\tilde{W}^0$ Wino	$\tilde{H}_u$ Higgsino	$\tilde{H}_d$ Higgsino	ν	
0			H_u	H_d	$\tilde{\nu}$ sneutrino	

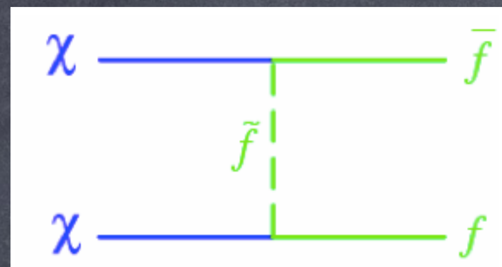
$$\mathcal{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z s_\theta c_\beta & M_Z s_\theta s_\beta \\ 0 & M_2 & M_Z c_\theta c_\beta & -M_Z c_\theta s_\beta \\ -M_Z s_\theta c_\beta & M_Z c_\theta c_\beta & 0 & -\mu \\ M_Z s_\theta s_\beta & -M_Z c_\theta s_\beta & -\mu & 0 \end{pmatrix}$$

$$\tilde{\chi}_1^0 = \underbrace{N_{11}\,\tilde{B}^0 + N_{12}\,\tilde{W}_3^0}_{\text{Gaugino content}} + \underbrace{N_{13}\,\tilde{H}_d^0 + N_{14}\,\tilde{H}_u^0}_{\text{Higgsino content}}$$

Neutralino LSP in CMSSM

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu)$$

Bulk :

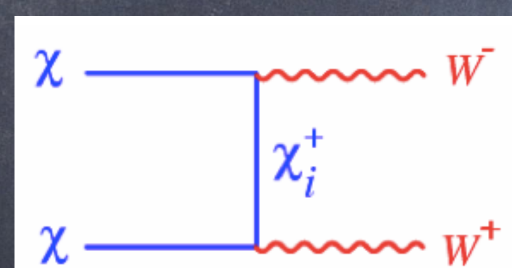


Mostly Bino, helicity suppressed annihilations, neutralino: 100-150 GeV

Funnel :

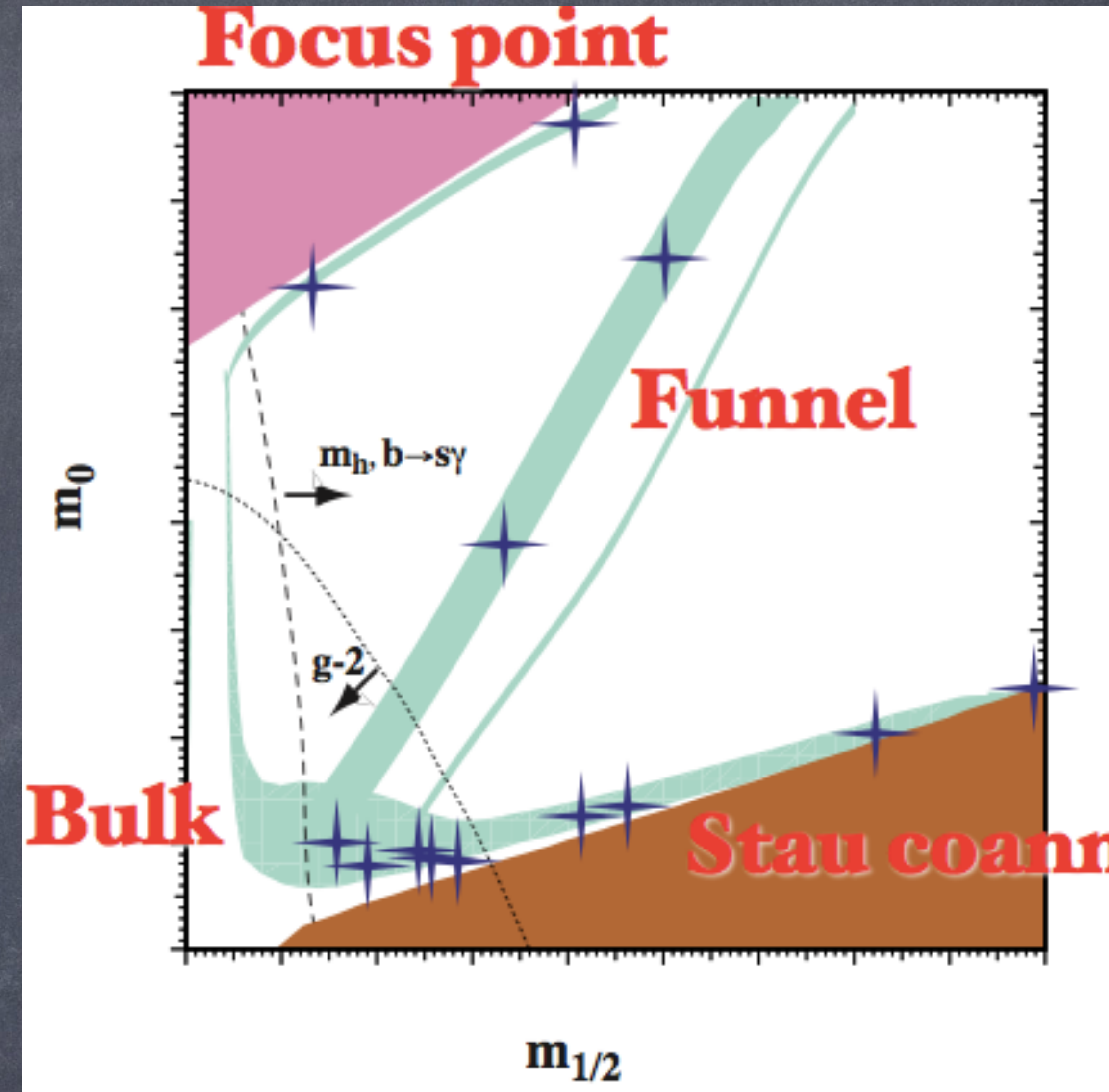
Bino type,
Resonant A0 in s-channel,
large $\tan\beta$ and neutralino mass:700 GeV

Focus point :



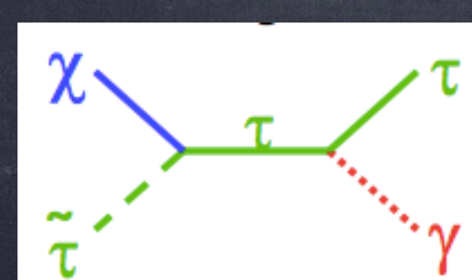
The μ parameter is close to the gaugino mass, neutralino is mostly Higgsino type, sfermions are heavy

Scalar mass



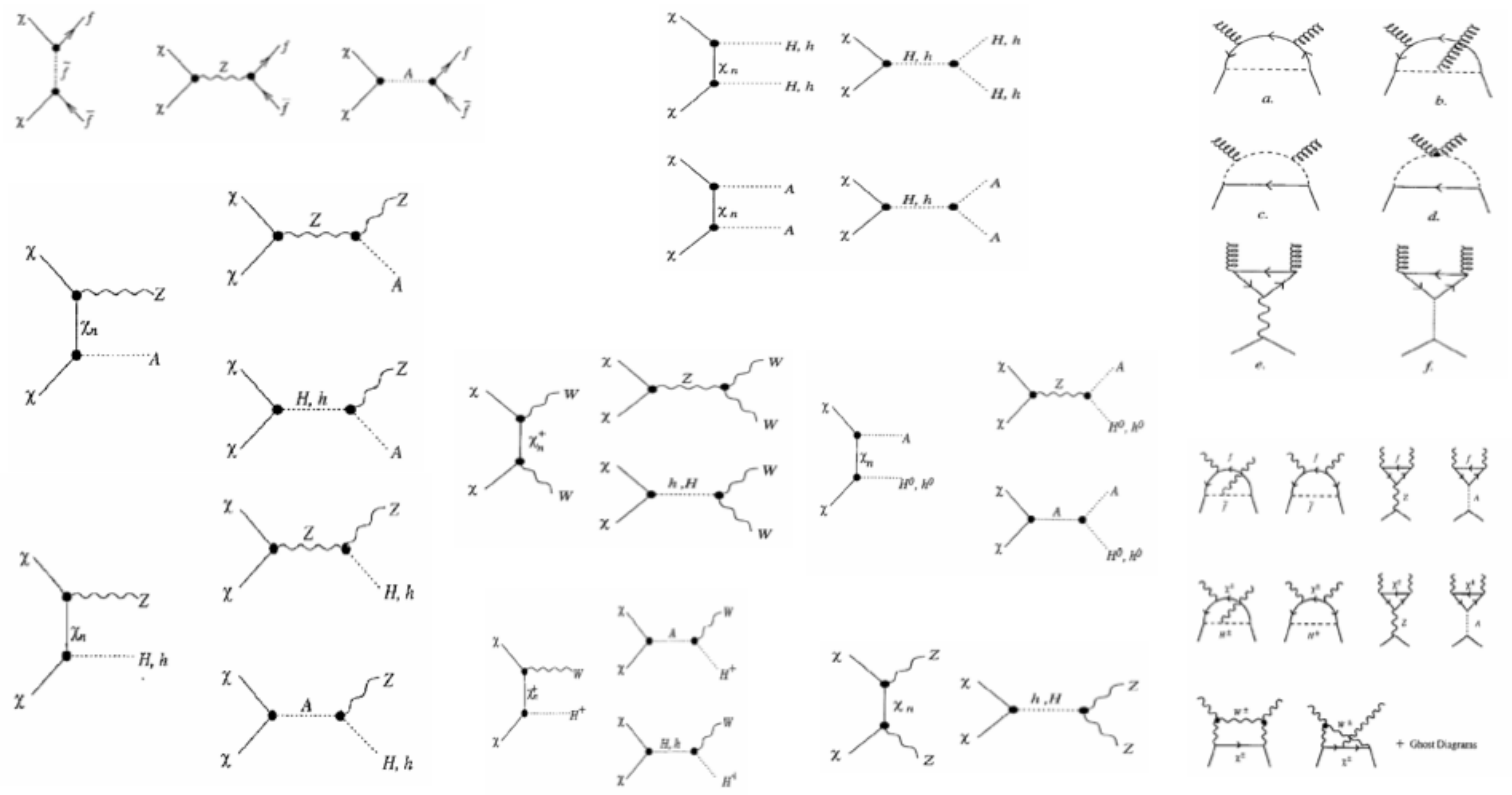
Gaugino mass

Co-annihilation :



Bino type neutralino is degenearte with stau, latter set the abundance, neutralino mass: 300-400 GeV

Neutralino interactions

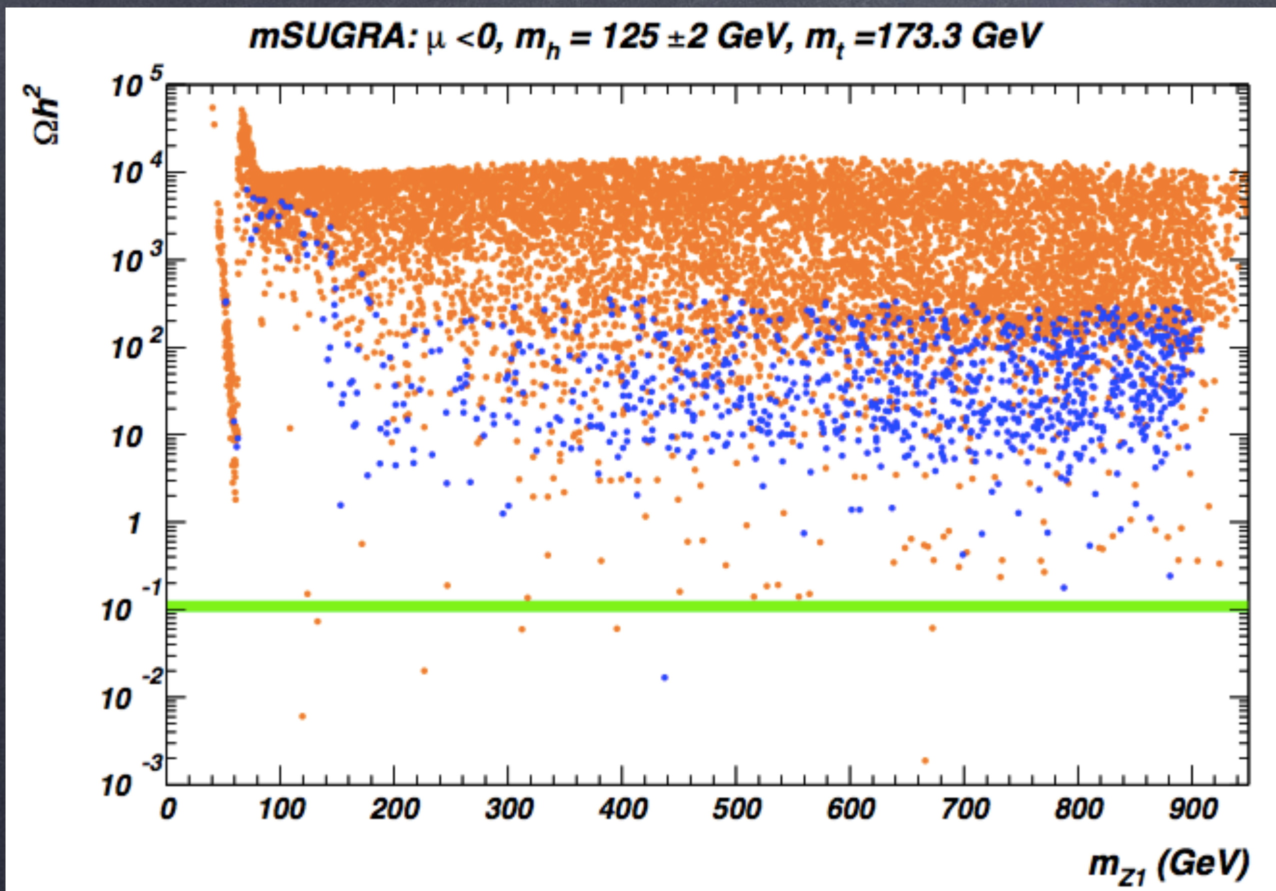


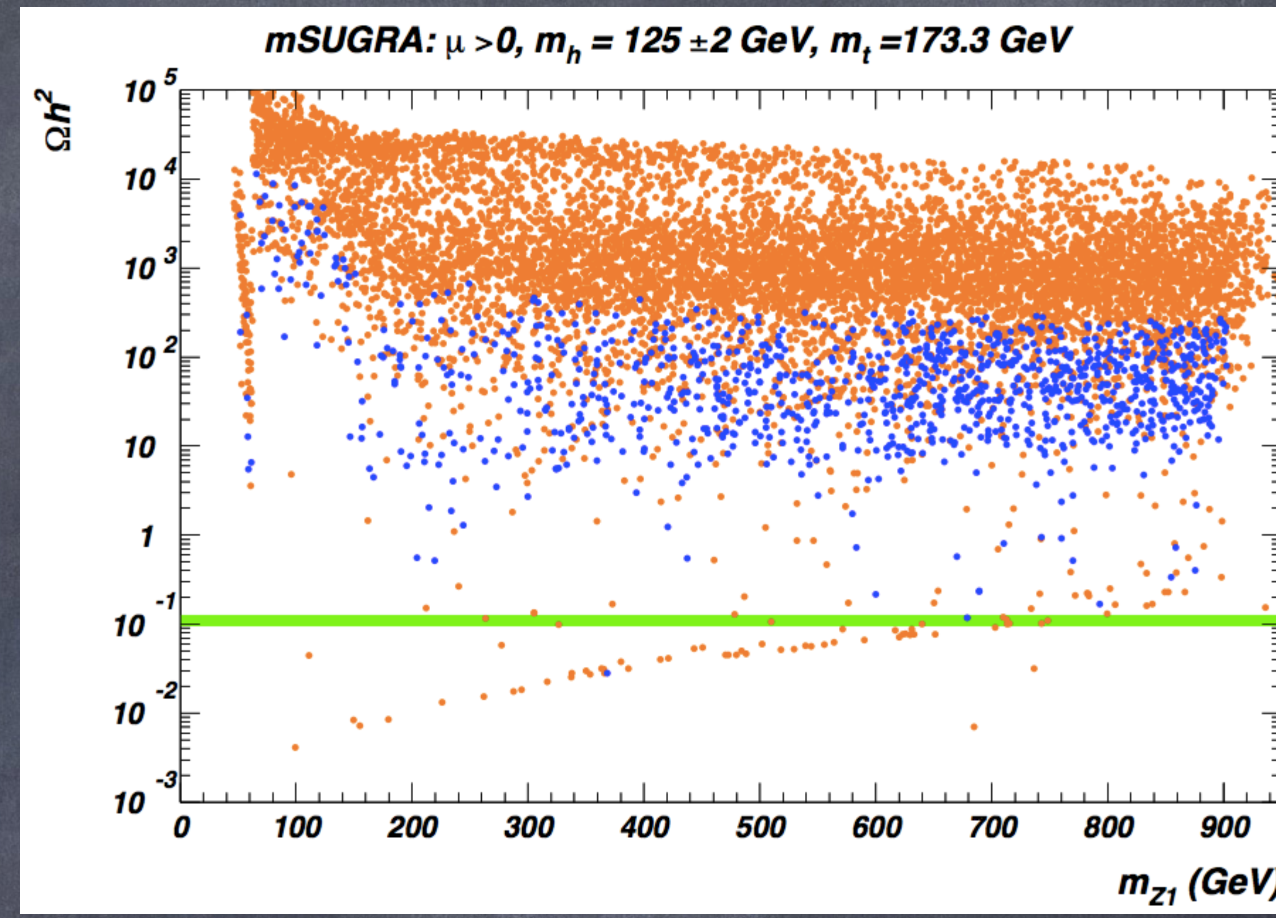
Jungman, Kamionkowski, Griest (1995)

Annihilation rates are suppressed : large $\Omega_{\chi^0} h^2$

Constrained MSSM

1202.4038[hep-ph]





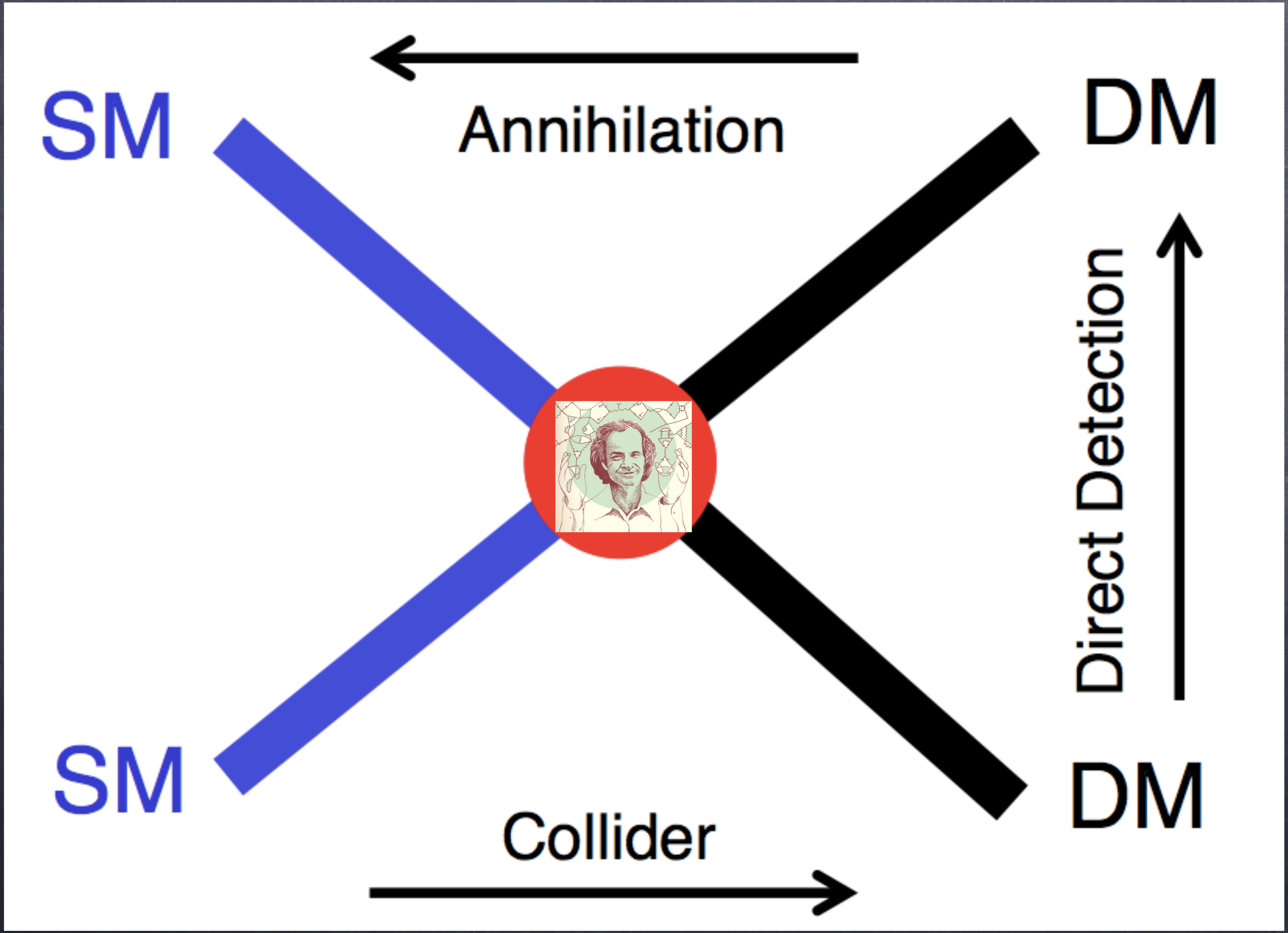
$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ sign(\mu)$$

$$m_0 : 0 \to 5\ \text{TeV}\ \ \text{(blue points)};\quad m_0 :\ 5 \to 20\ \text{TeV}\ \ \text{(orange points)}$$
$$m_{1/2} : 0 \to 2\ \text{TeV},$$
$$A_0 : -5m_0 \to\ +5m_0,$$
$$\tan\beta : 5 \to 55.$$

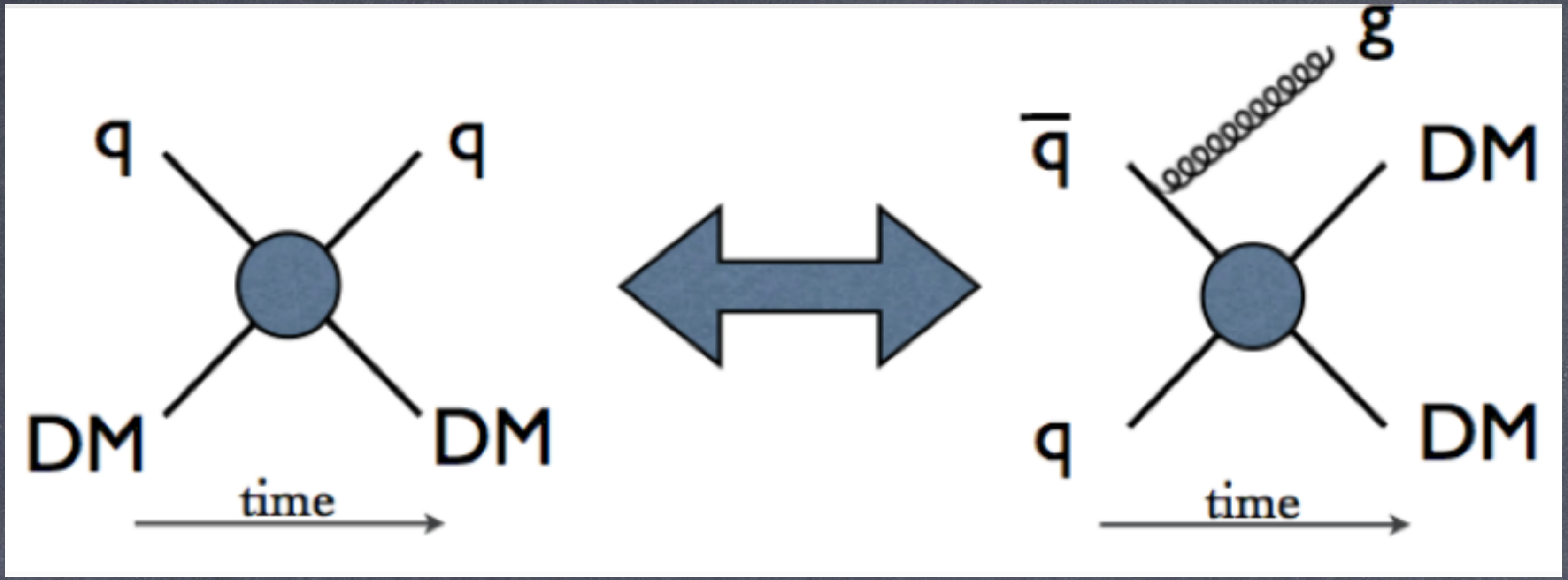
One has to look beyond CMSSM

One has to look beyond WIMP paradigm

Direct, Indirect Detection of DM

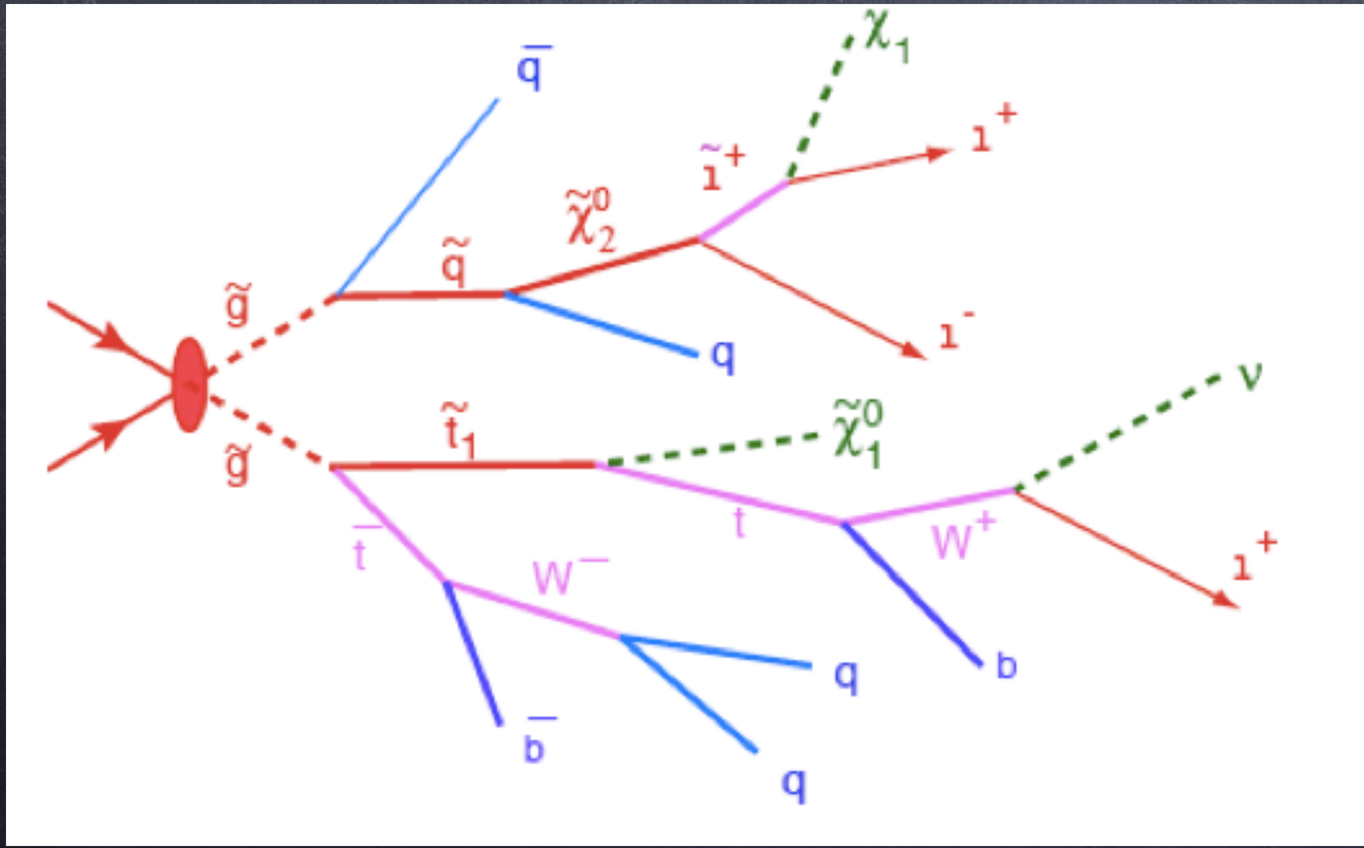


Direct detection of Dark Matter

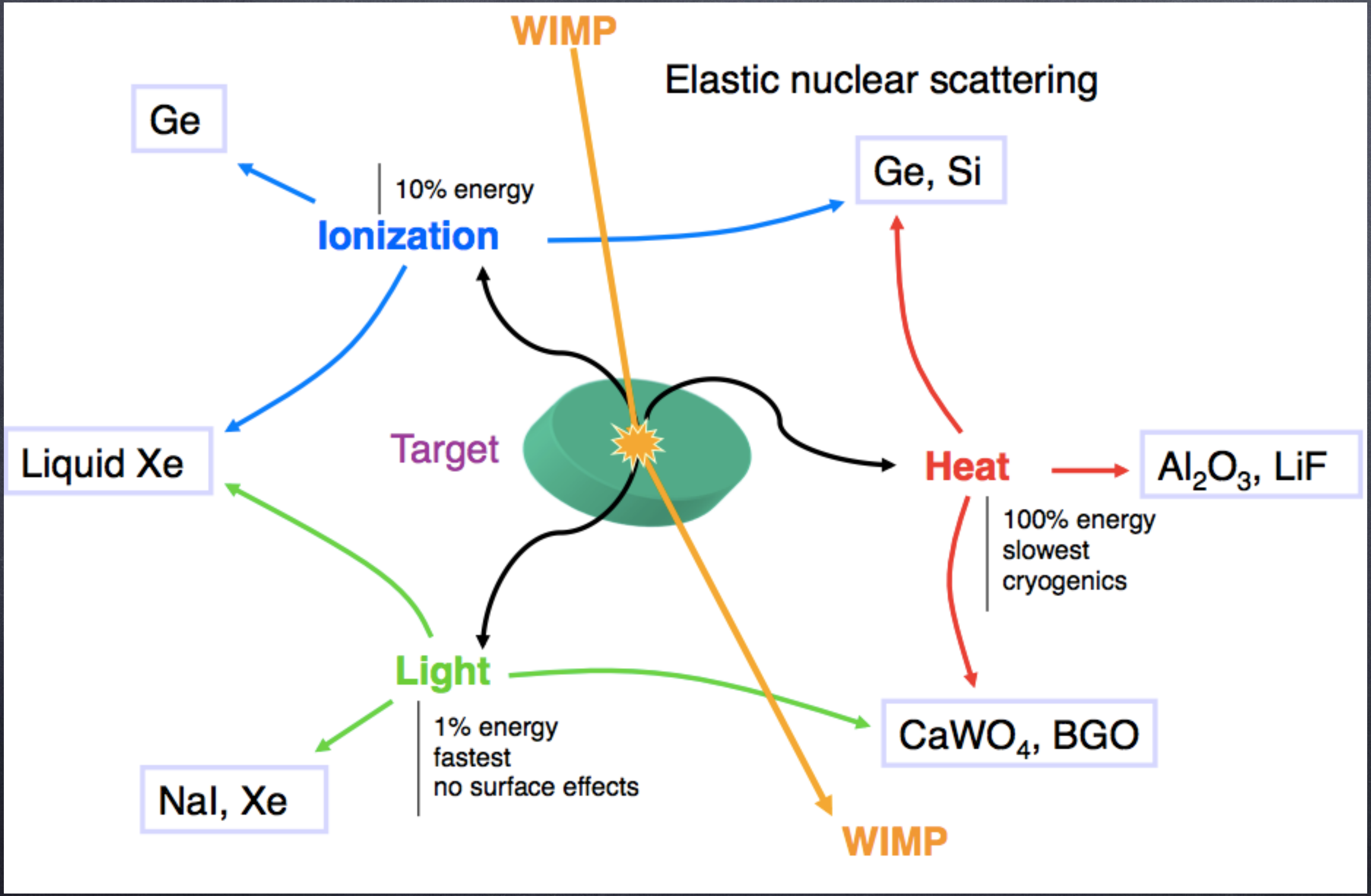


Direct production of DM

missing energy, (mono/multi) jets at LHC

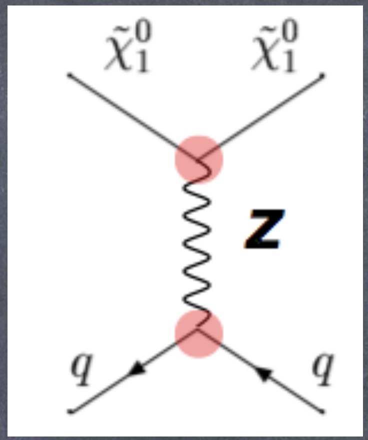


DM nucleon scattering



Direct detection of Dark Matter

Generic (fermionic) WIMP interaction with a nucleon can be understood in EFT language



Axial-Vector

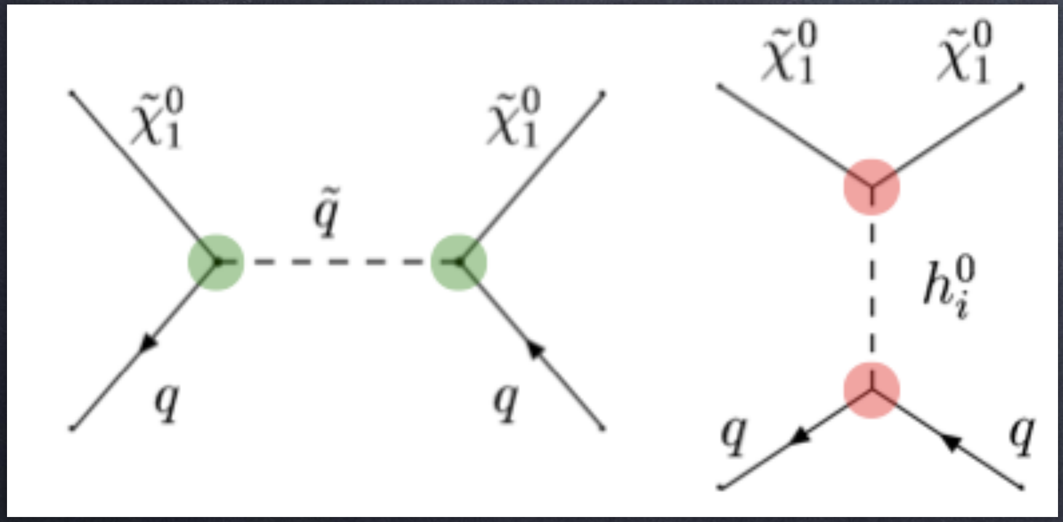
$$\mathcal{L} \supset \alpha_q^A (\bar{\chi}\gamma^\mu\gamma_5\chi)(\bar{q}\gamma_\mu\gamma_5 q) \qquad \frac{(J+1)}{J}$$

SPIN-DEPENDENT (Nucl. Angular mom)

Scalar

$$\mathcal{L} \supset \alpha_q^S \bar{\chi}\chi\bar{q}q \qquad A^2$$

SPIN-INDEPENDENT (Nucleon #)



Vector

$$\mathcal{L} \supset \alpha_q^V \bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q \qquad A^2$$

- Only for non-Majorana WIMPs

SPIN-INDEPENDENT

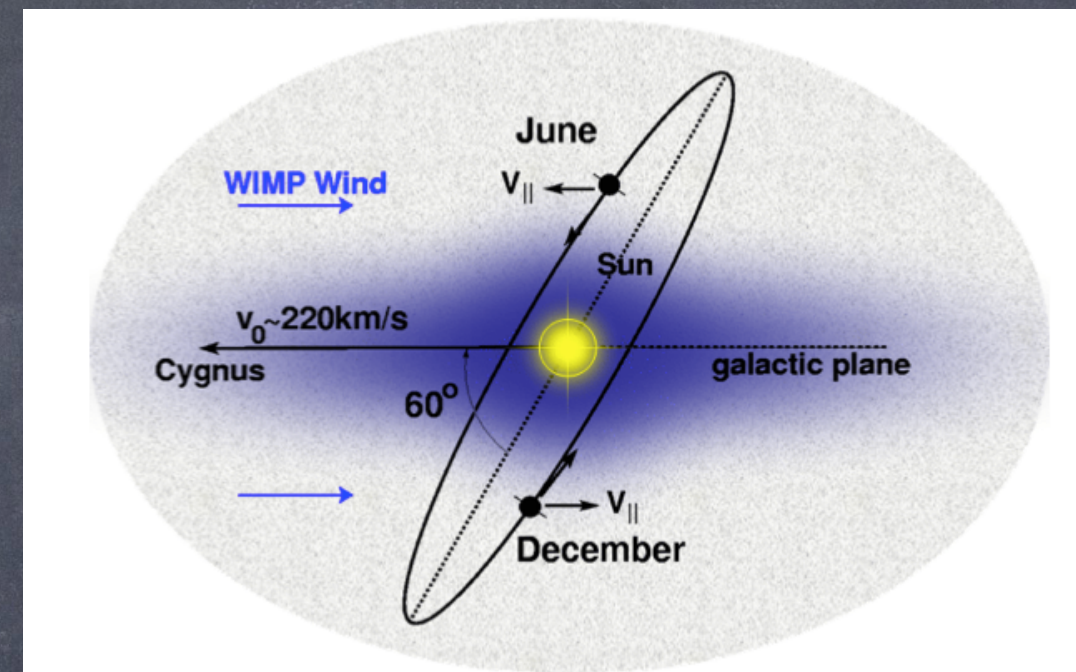
Spin independent constraints are better for Current DD experiments

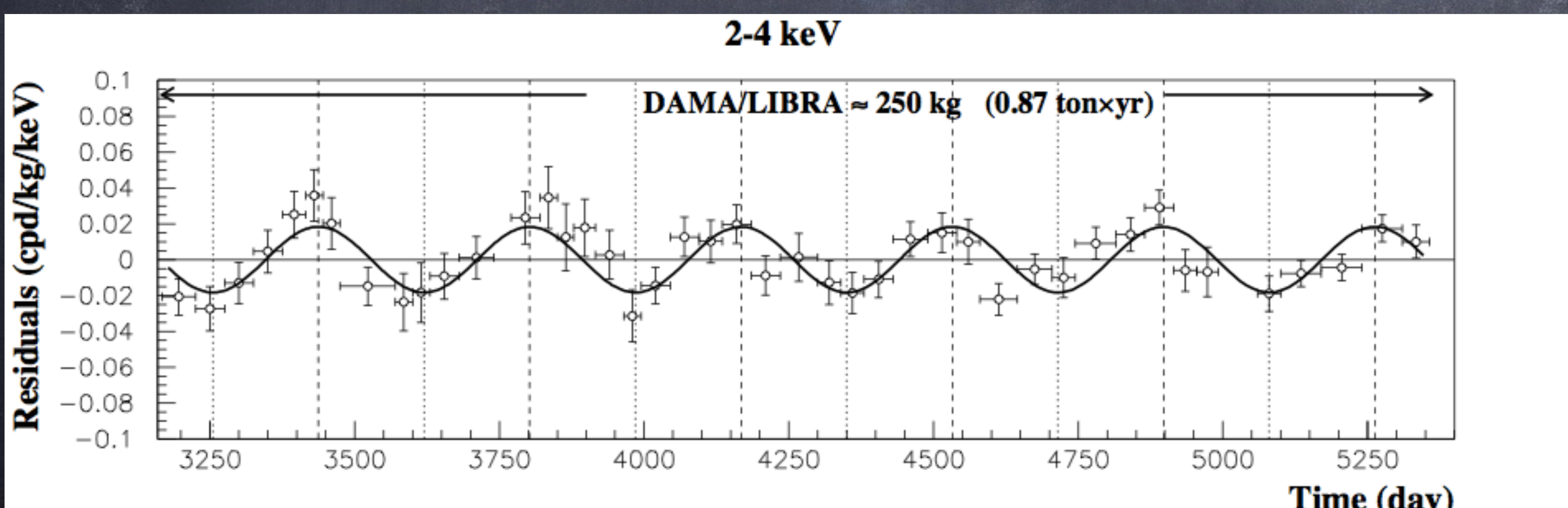
Annual modulation of scattering rates

Freese, Friemann, Gould, (1988)

$$R = \int_{E_T}^{\infty} dE_R \frac{\rho_0}{m_N \, m_\chi} \int_{v_{min}}^{\infty} v f(v) \frac{d\sigma_{WN}}{dE_R}(v, E_R)\, dv$$

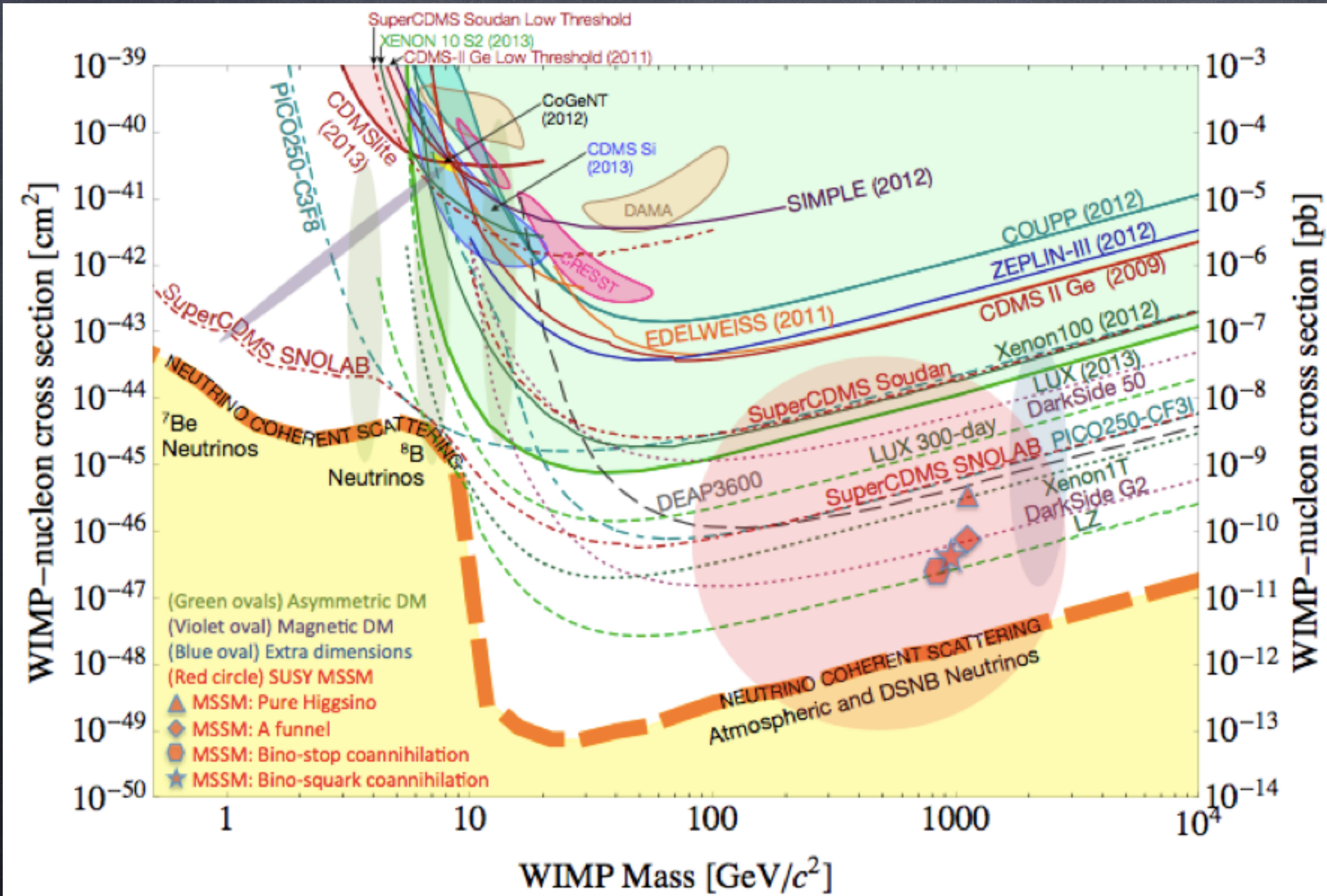
Low recoil energy, heavy DM, peak in summer
High recoil energy, light DM, peak in winter



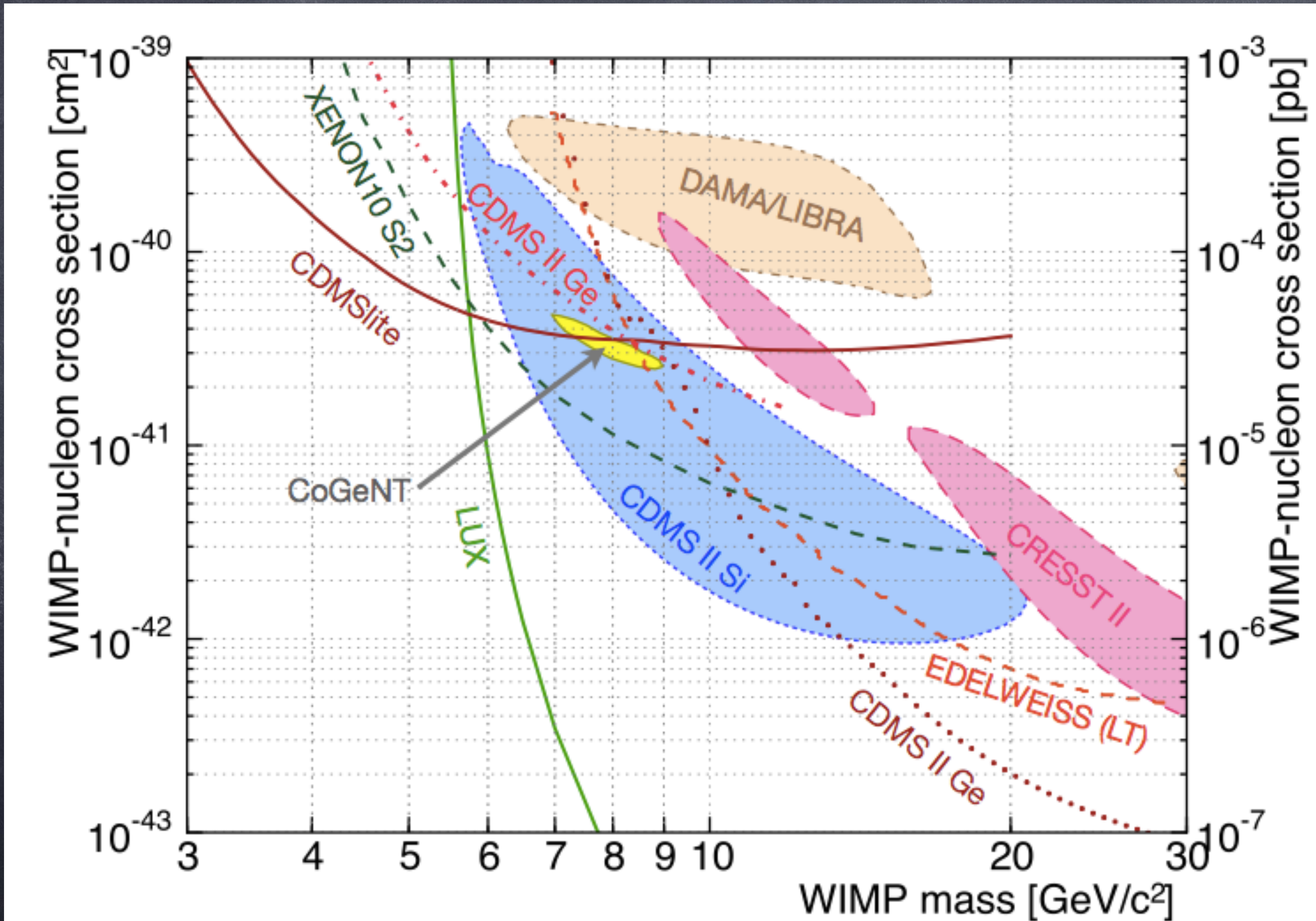


DAMA collaboration, Bernabei et al. 1002.1028

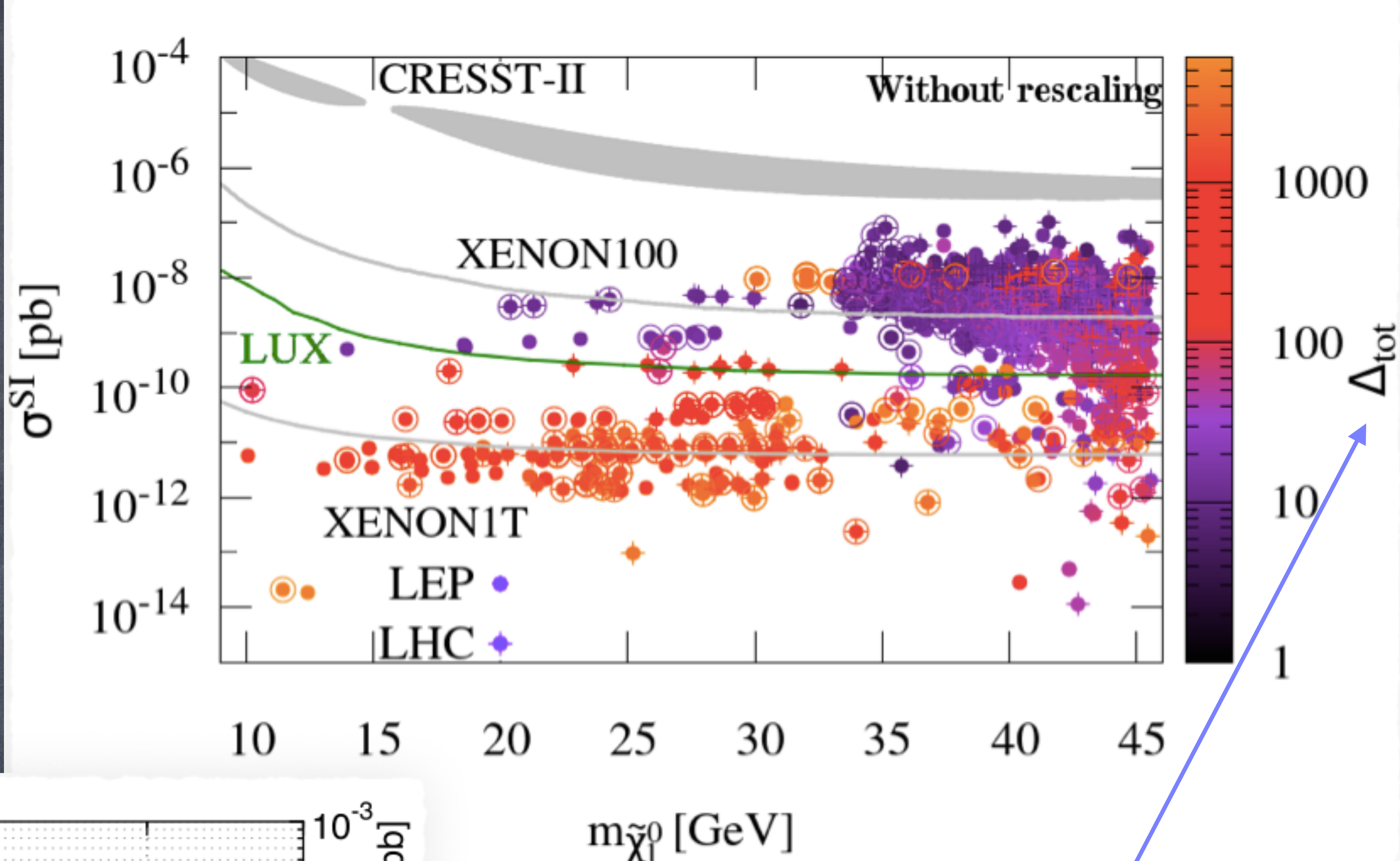
Direct Dark Matter Search Experiments

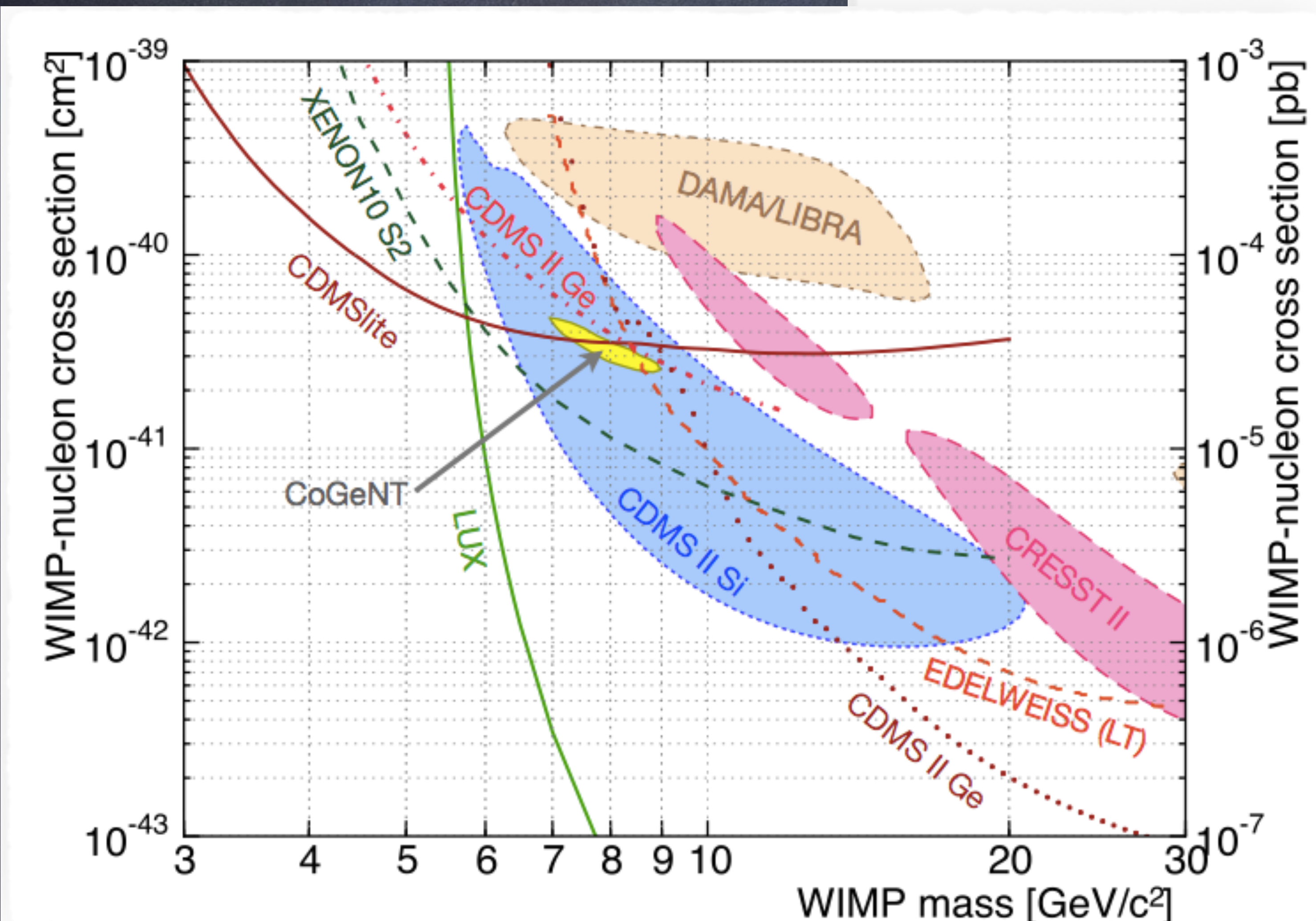


Direct detection for low mass WIMP



How Light Neutralino Could be ?





&

How Fine Tuned we are

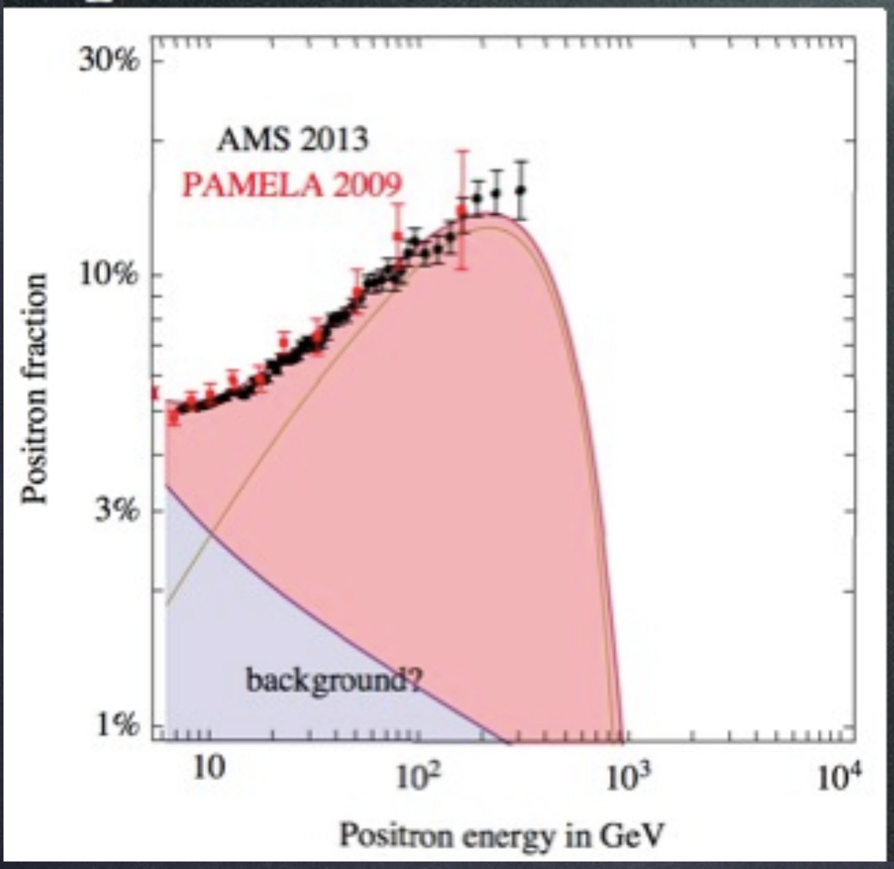
Bhupal, Celine, Mazumdar, Pukartas, JHEP (2013)

Indirect detection: Cosmic ray experiments

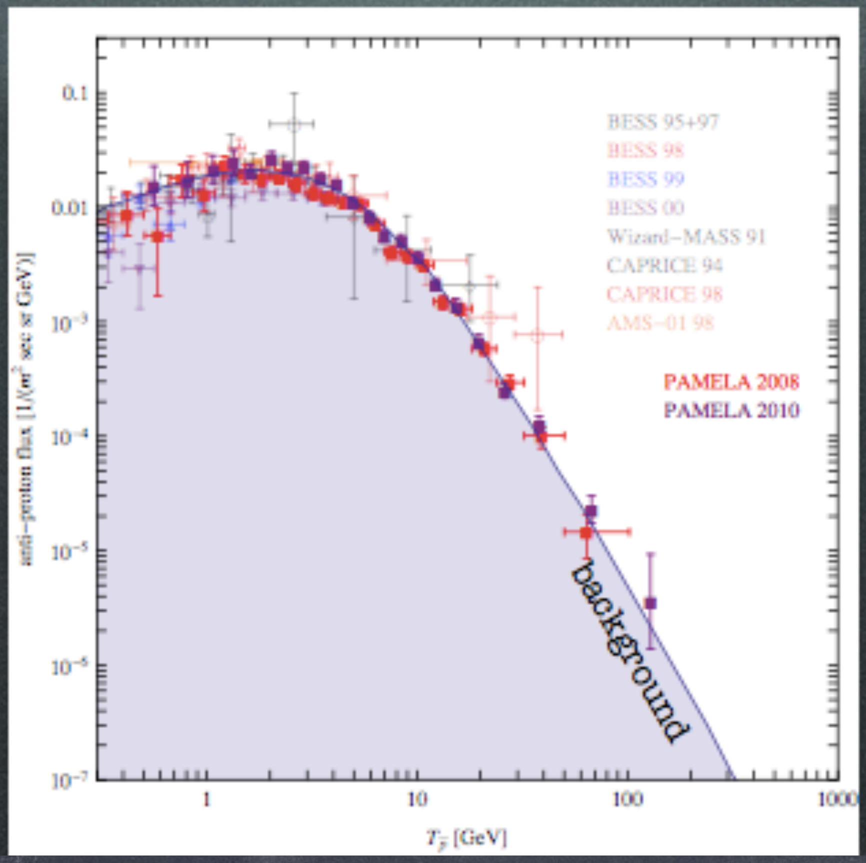
e^+ PAMELA, Fermi, HESS, AMS, Balloons ν, $\bar{\nu}$ SKA, Icecube, Km3Net

$\bar{p}$ AMS, PAMELA, Fermi $\bar{d}$ GAPS γ Fermi, ICT, Radiotelescope

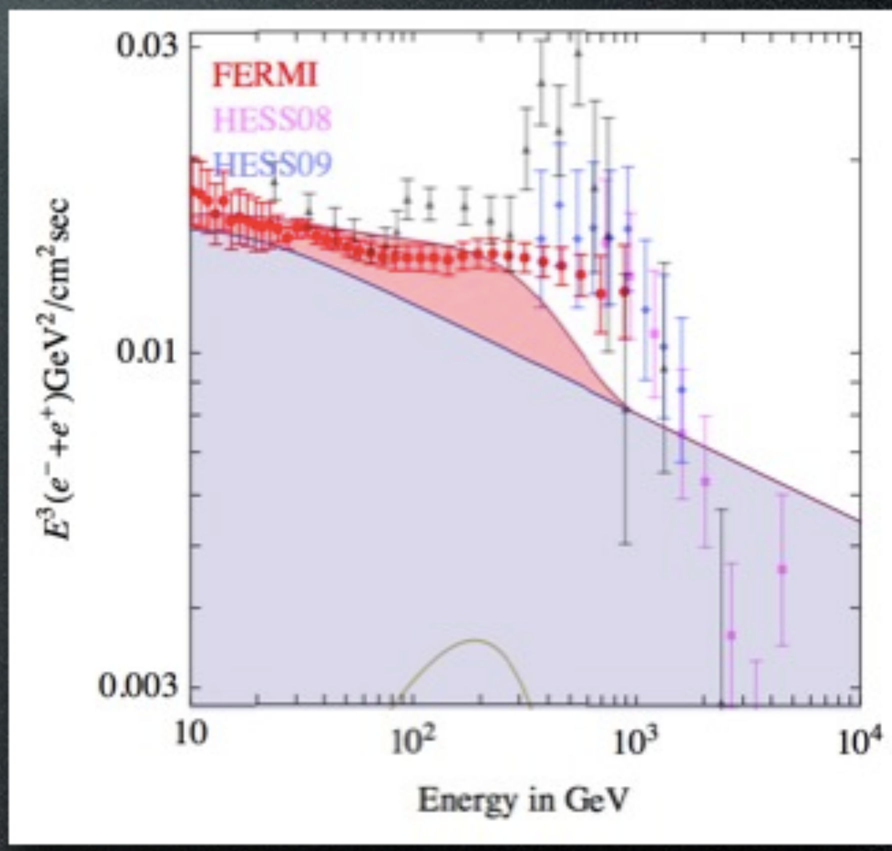
positron fraction



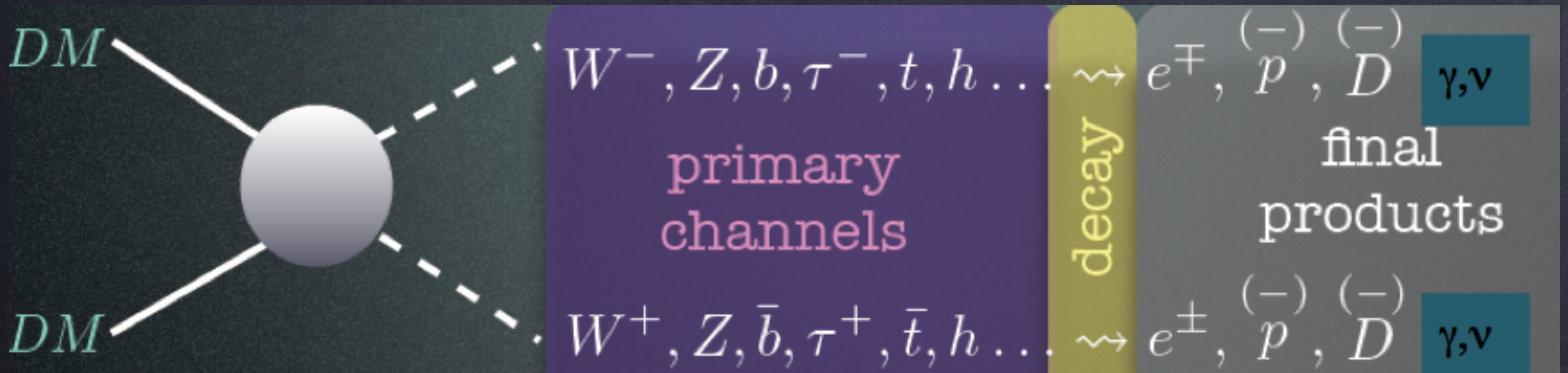
antiprotons



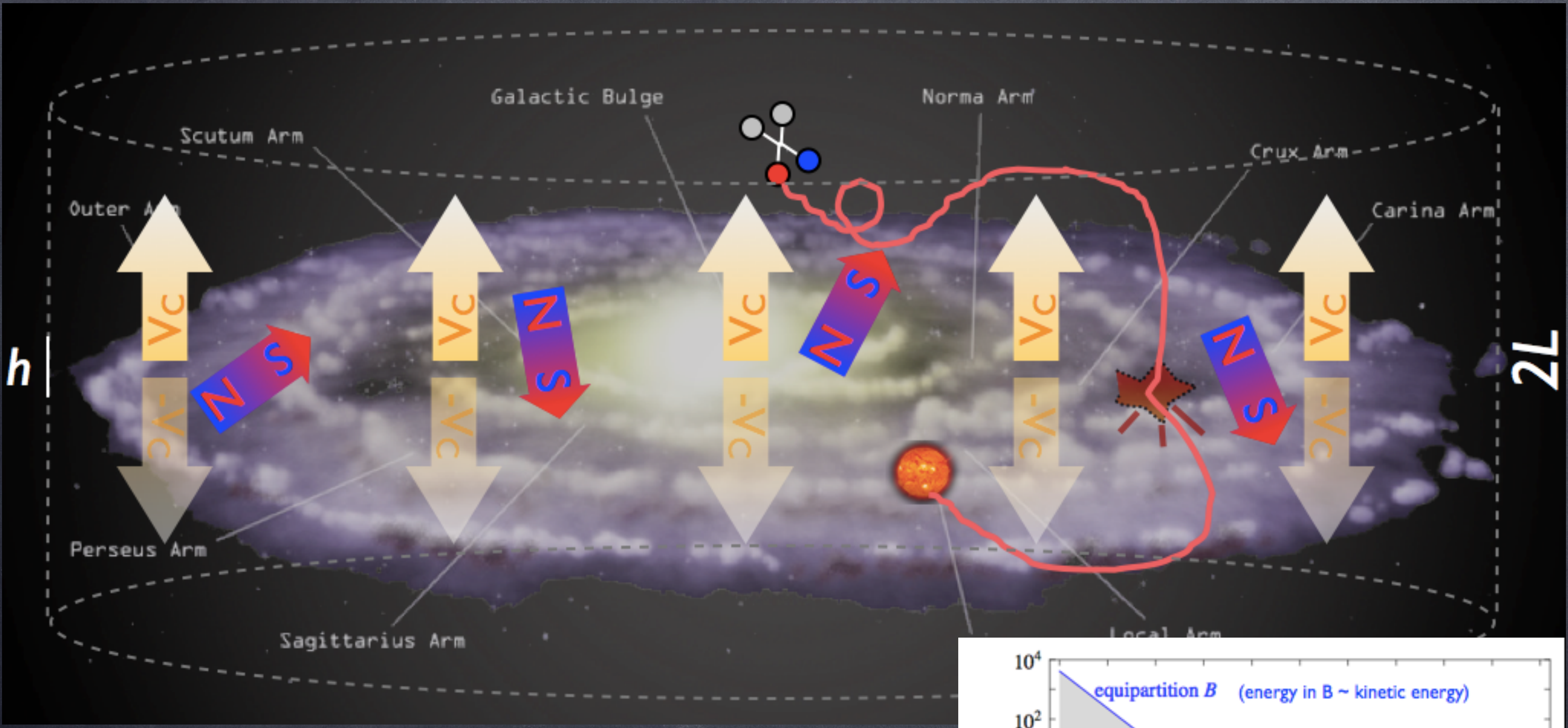
electrons + positrons

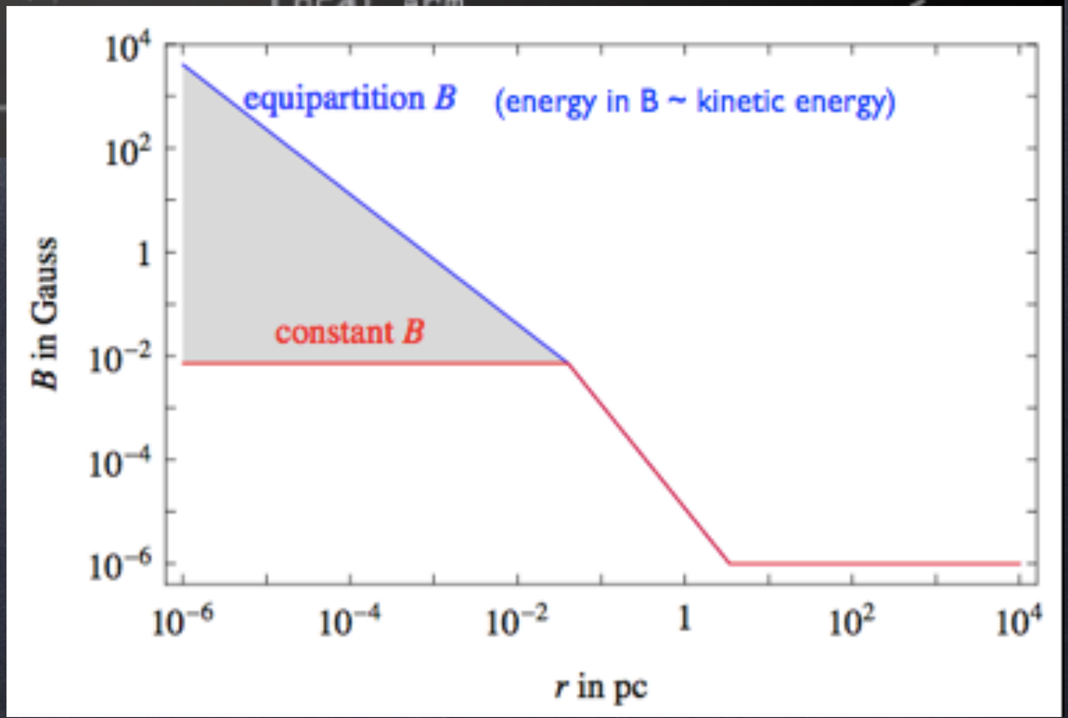


Few TeV leptophilic DM; $\langle\sigma v\rangle \approx 10^{-23}$ $\mathbf{cm^3/sec}$



Propagation of charged particles





$$Flux \propto n^2 \times \sigma_{annihilation}$$

Beware of Astrophysical uncertainties

$$\text{NFW}: \quad \rho_{\text{NFW}}(r) = \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2}$$

$$\text{Einasto}: \quad \rho_{\text{Ein}}(r) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha}-1\right]\right\}$$

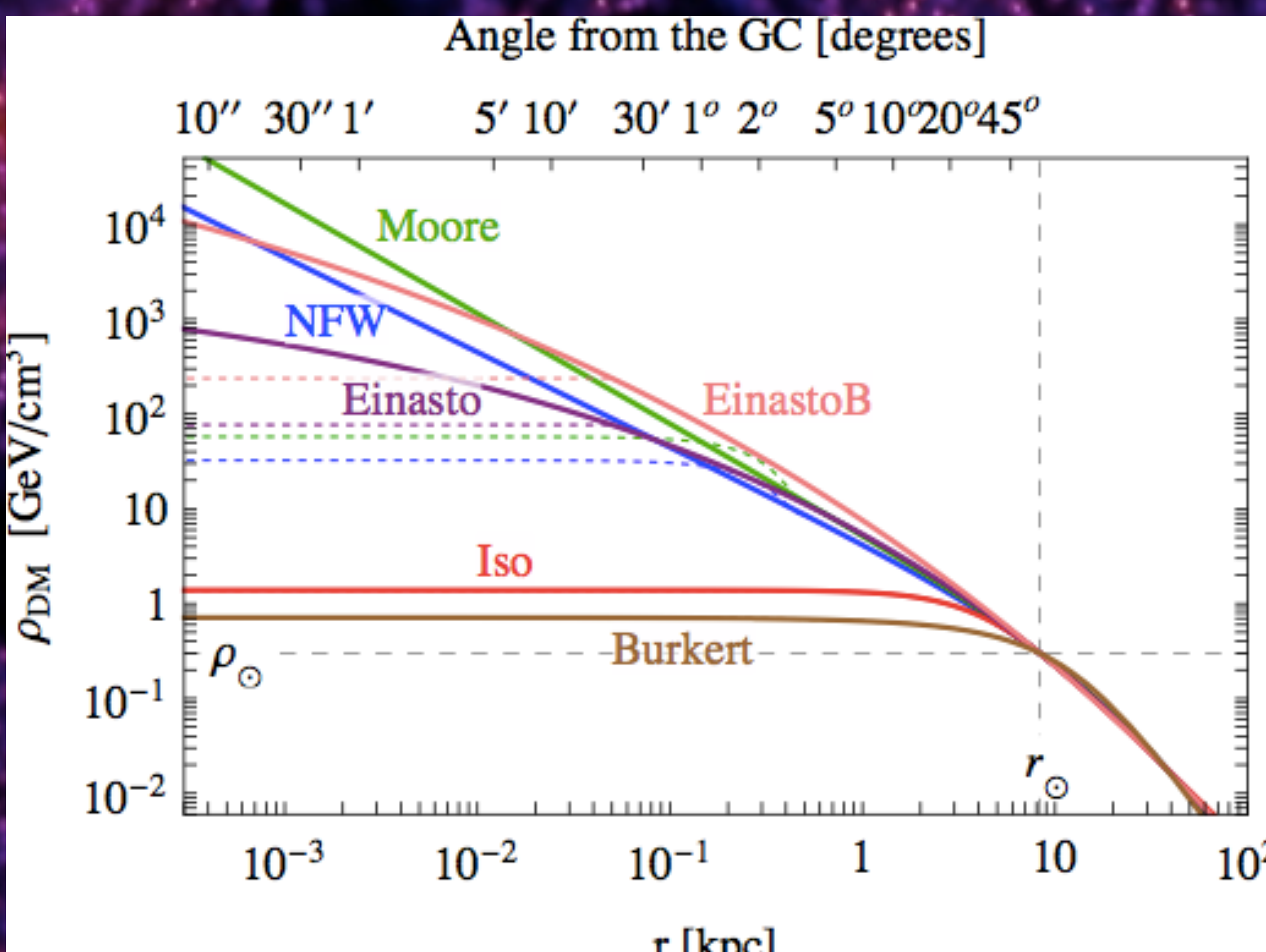
$$\text{Isothermal}: \quad \rho_{\text{Iso}}(r) = \frac{\rho_s}{1+(r/r_s)^2}$$

$$\text{Burkert}: \quad \rho_{\text{Bur}}(r) = \frac{\rho_s}{(1+r/r_s)(1+(r/r_s)^2)}$$

$$\text{Moore}: \quad \rho_{\text{Moo}}(r) = \rho_s \left(\frac{r_s}{r}\right)^{1.16}\left(1+\frac{r}{r_s}\right)^{-1.84}$$

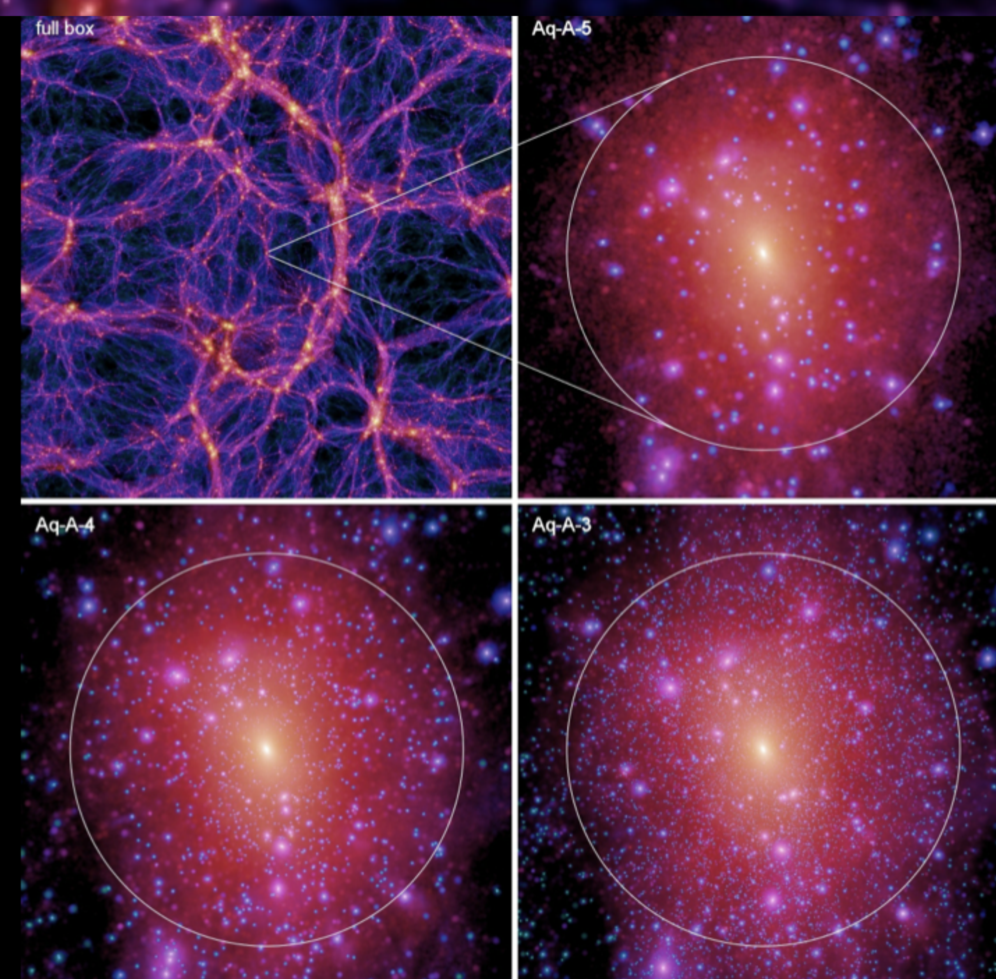
DM halo	α	r_s [kpc]	ρ_s [GeV/cm^3]
NFW	−	24.42	0.184
Einasto	0.17	28.44	0.033
EinastoB	0.11	35.24	0.021
Isothermal	−	4.38	1.387
Burkert	−	12.67	0.712
Moore	−	30.28	0.105

Small r : $\rho(r) \propto 1/r^{\gamma}$



Zooming in on dark matter halos reveals a huge abundance of dark matter substructure

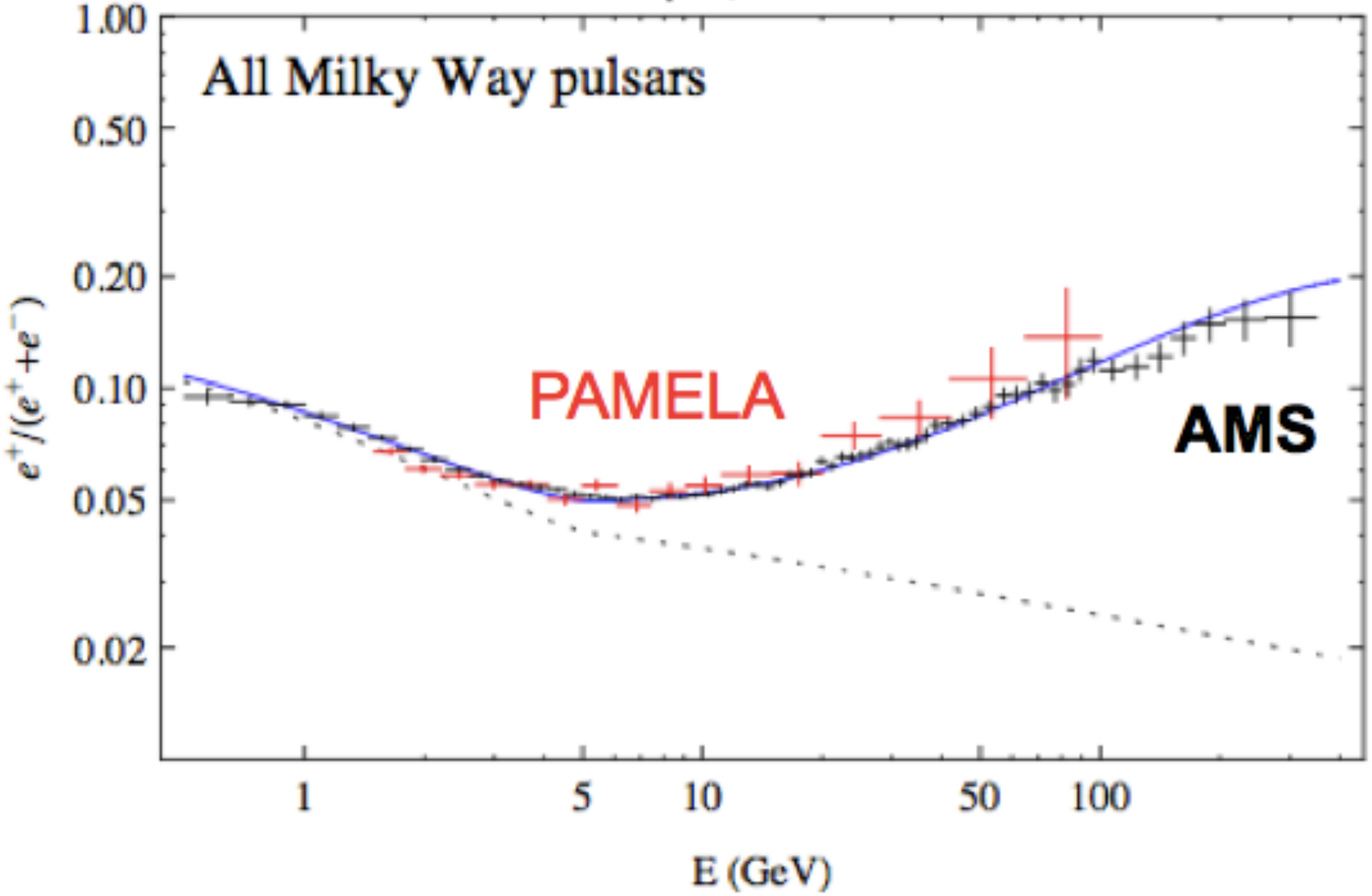
DARK MATTER DISTRIBUTION IN A MILKY WAY SIZED HALO AT DIFFERENT RESOLUTION



DM interpretation vs. pulsars

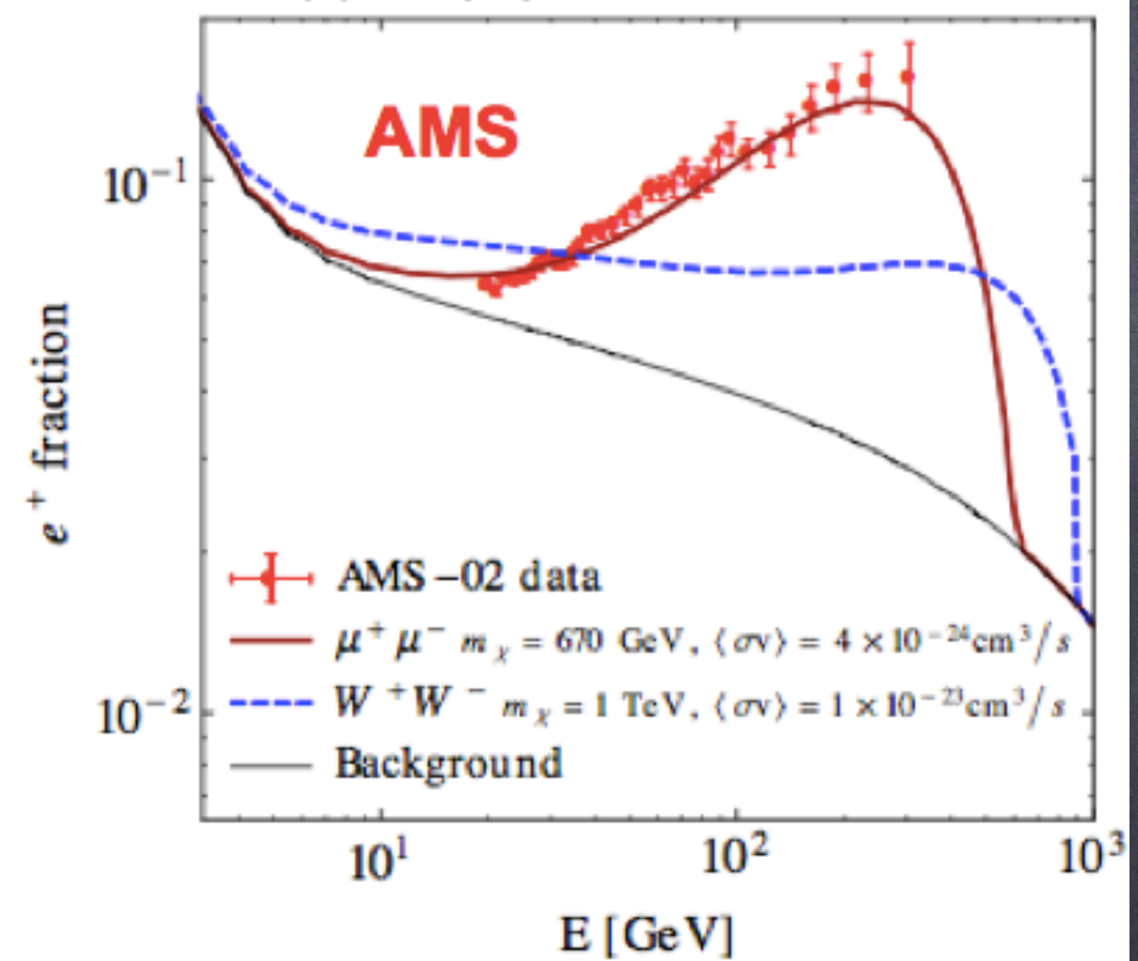
Astrophysical objects

Cholis arXiv: astro-ph/1304.1840



Dark Matter

Kopp hep-ph/1304.1184

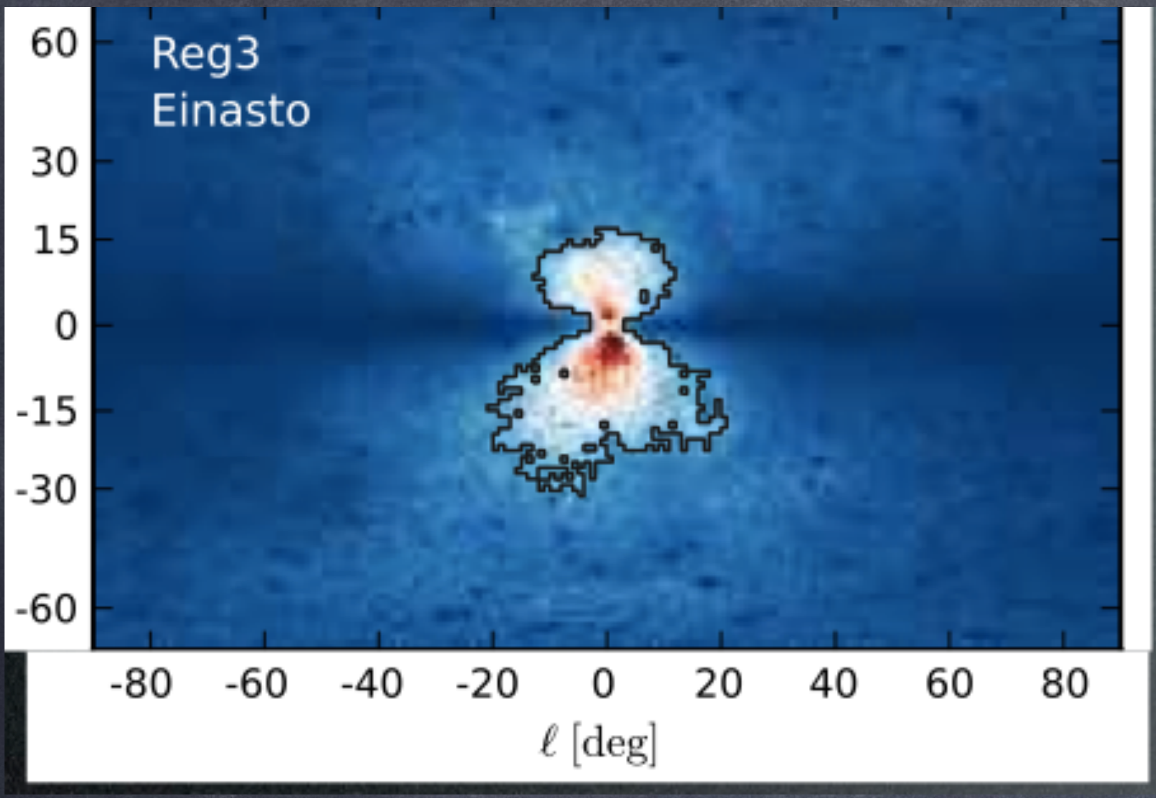


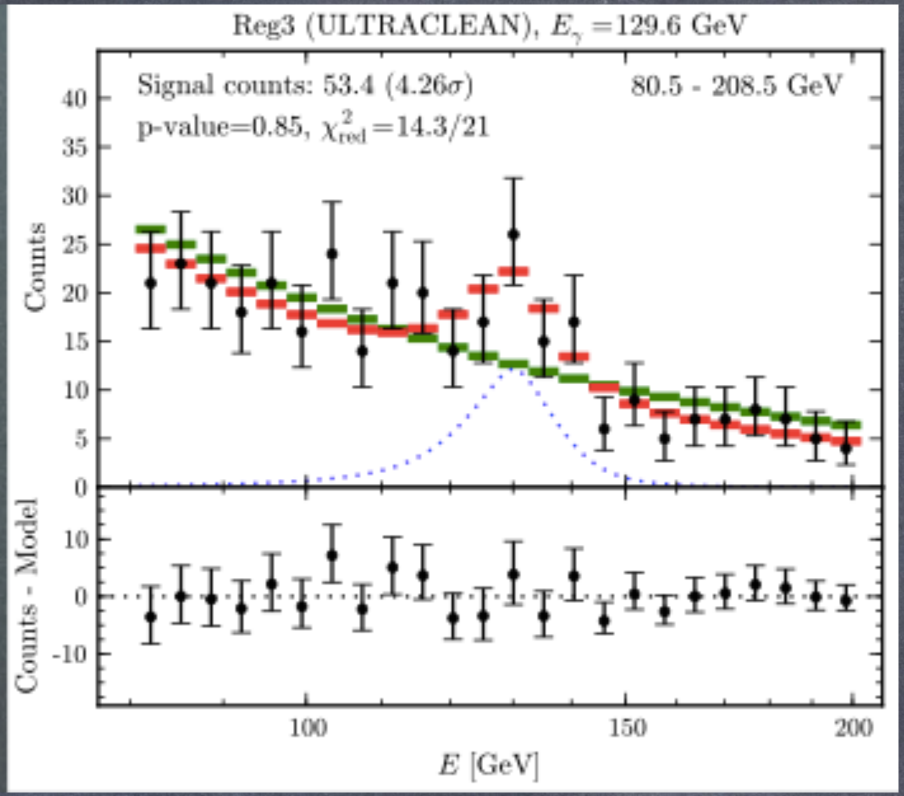
Different energy behavior of the positron fraction:

- **Pulsars predictions:**
  - **slow fall at high energies**
  - **anisotropic positron flux**
- **Dark Matter prediction:**
  - **steeper fall at high energies**
  - **isotropic positron flux**

Gamma ray line vs. background

DM signal is hiding under diffused gamma ray background



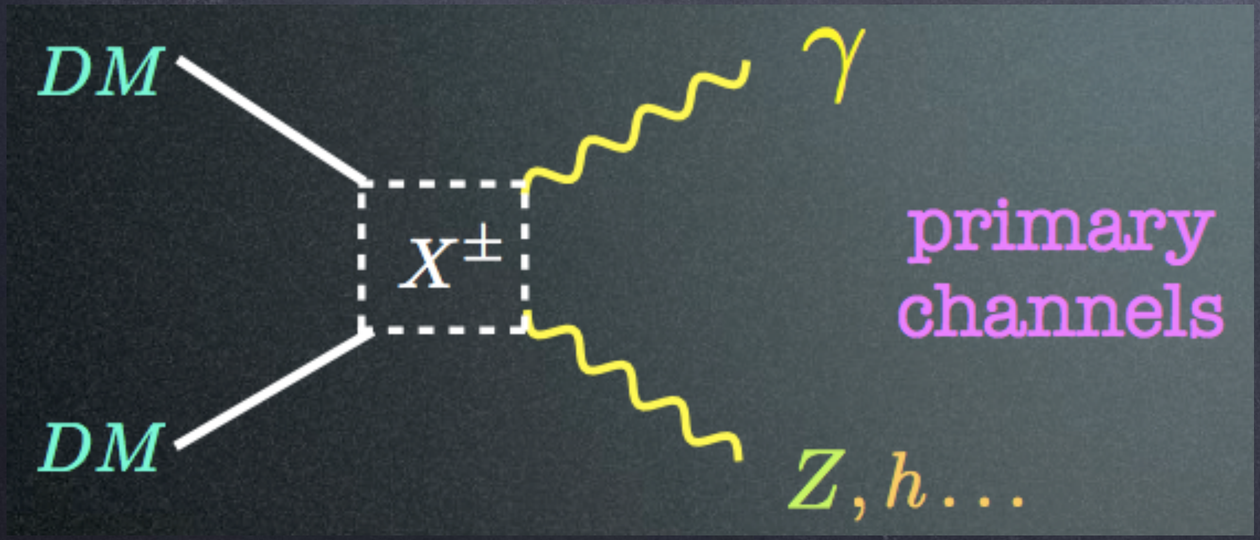


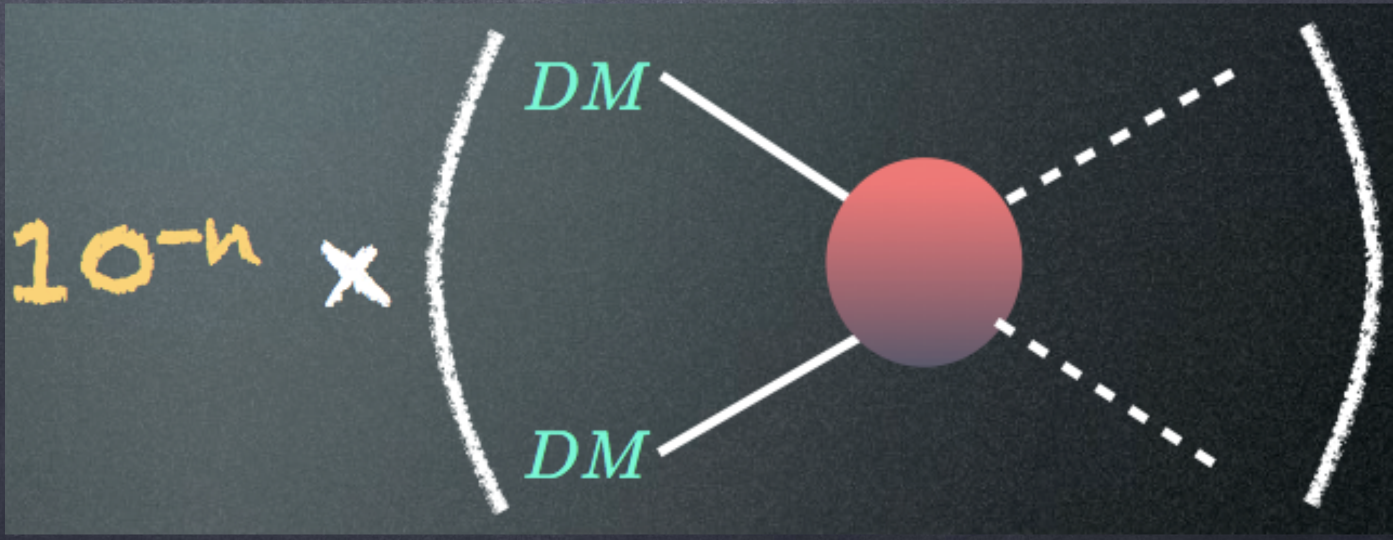
C. Weniger

1204.2797

Large cross section !

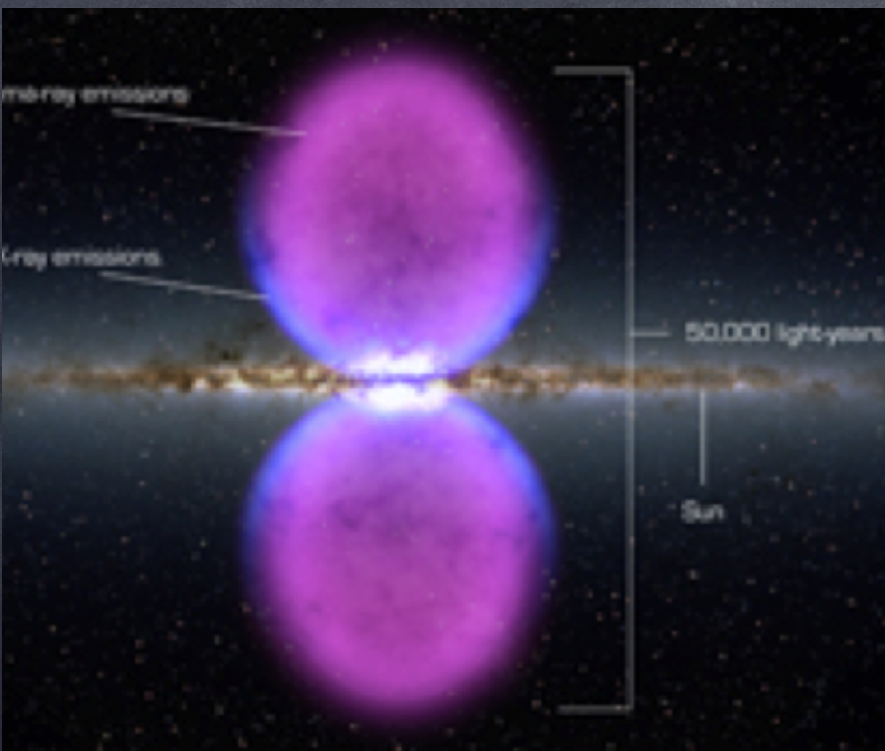
Ruled out by Fermi collab. $\langle \sigma v \rangle_{\chi\chi \to \gamma\gamma} \simeq 1.3 \times 10^{-27} \mathrm{cm}^3/\mathrm{s}$

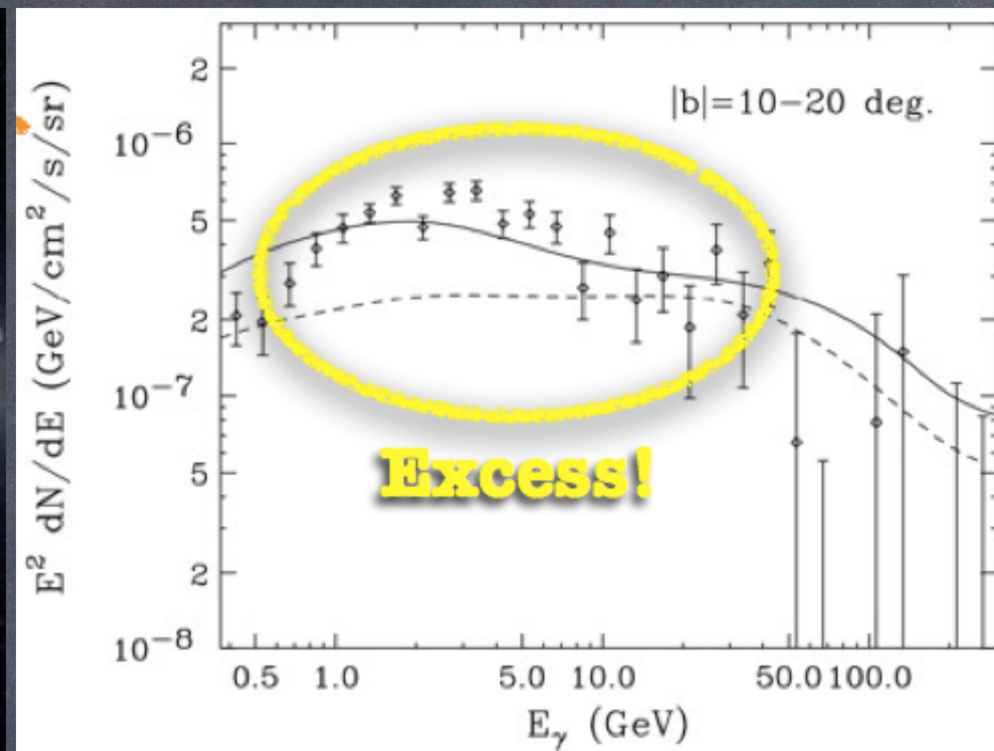




Typically suppressed

Gamma ray excess from galactic centre



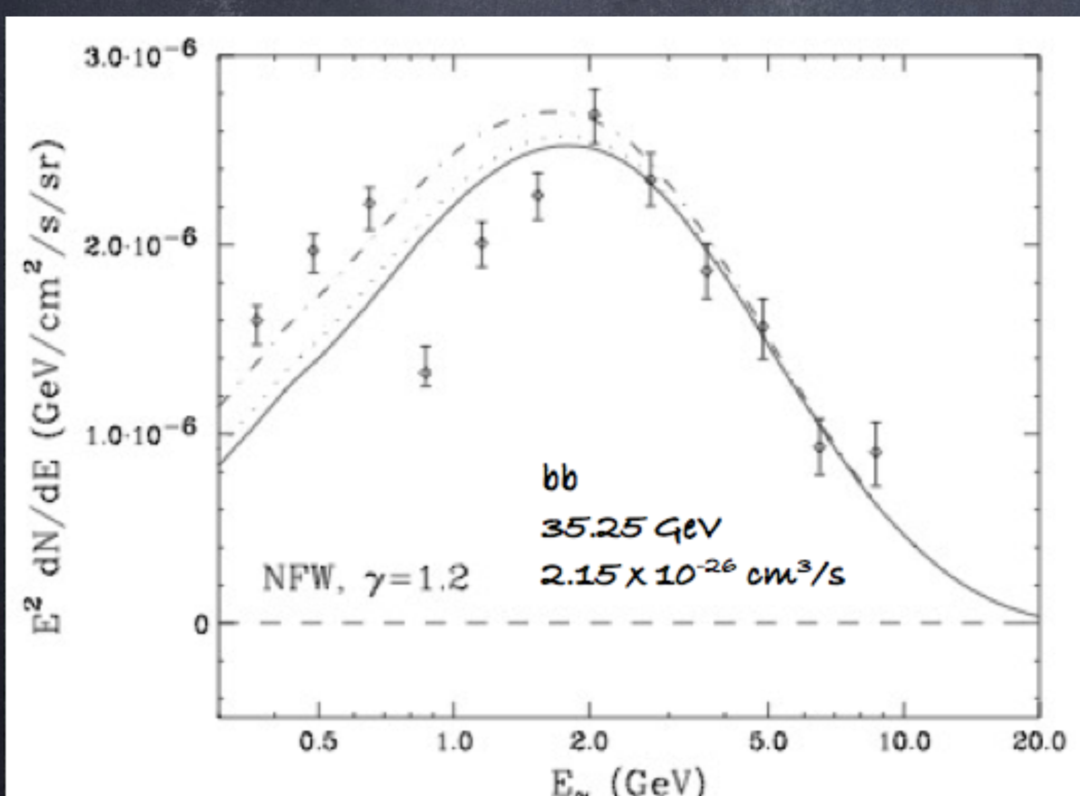


Hooper, Slatyer, 1302.6589

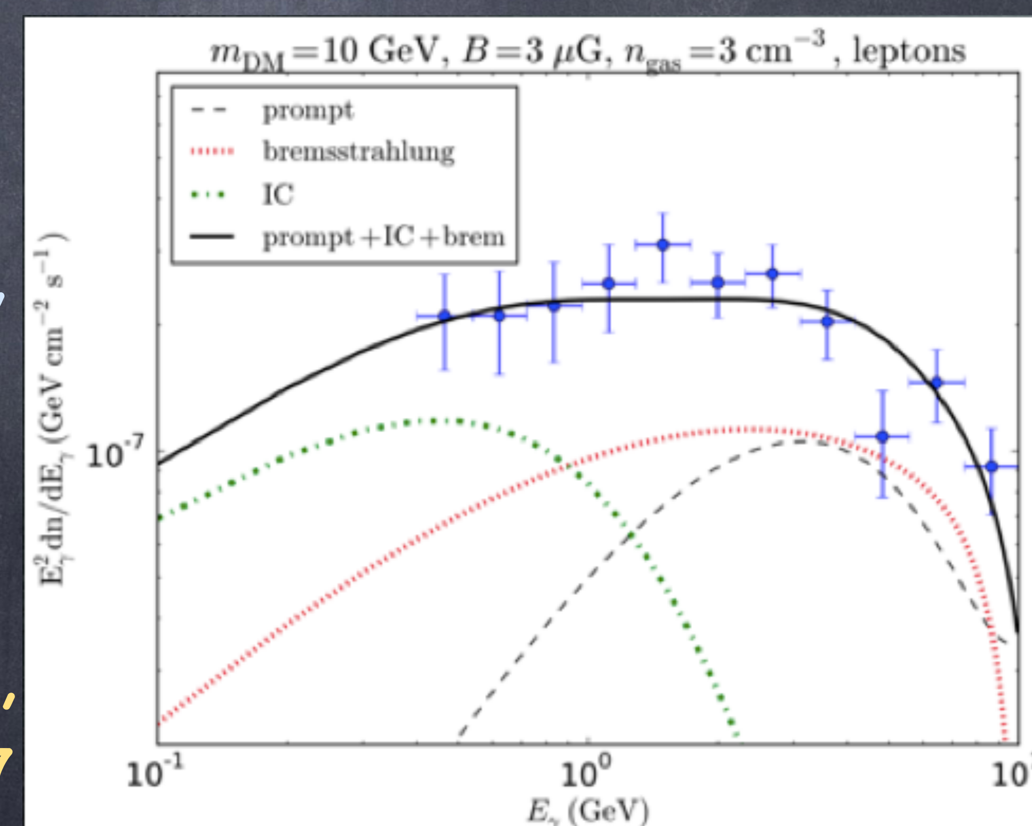
Huang, Urbano, Xue, 1307.6862

Excess goes away at higher altitudes: 30-40 deg.

10 GeV, Leptonic, thermal cross section



Dylan, Finkbeiner, Hooper, Linden, Portillo,Rodd,Slatyer, 1402.6703

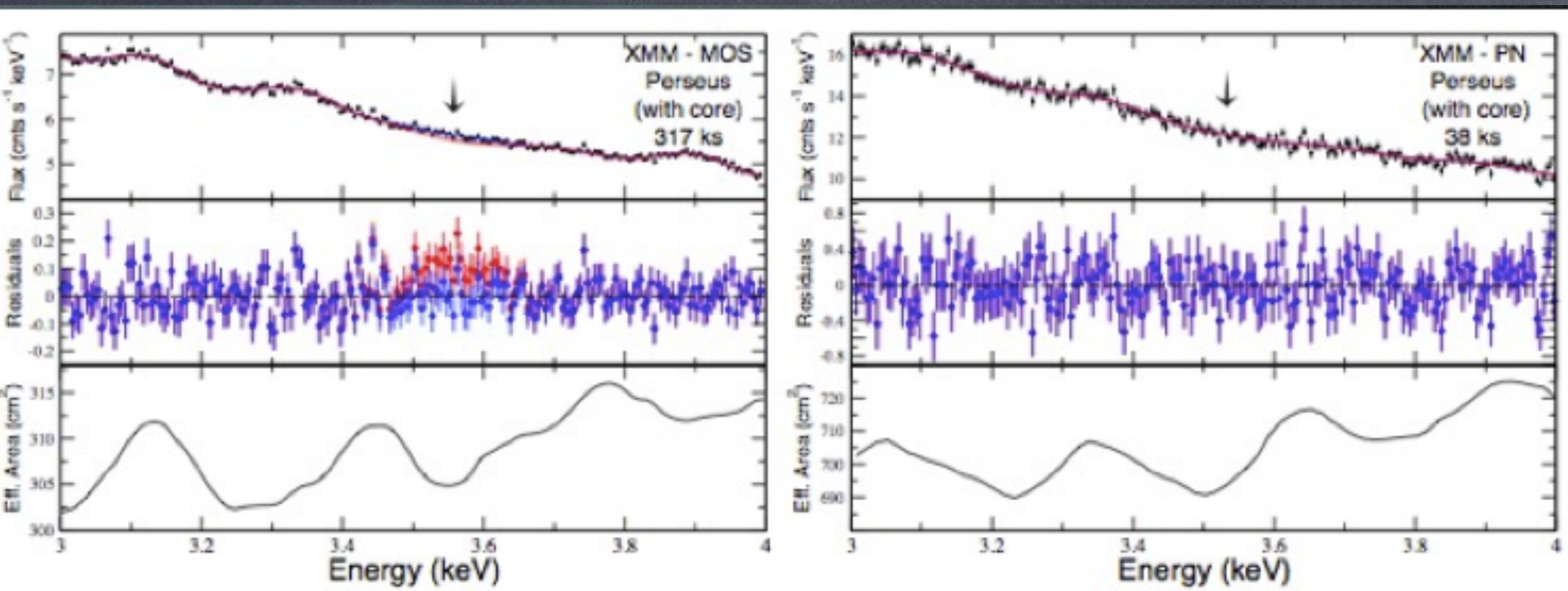


Lacroix, Boehm, Silk, 1403.1987

35 GeV, quark, thermal cross section

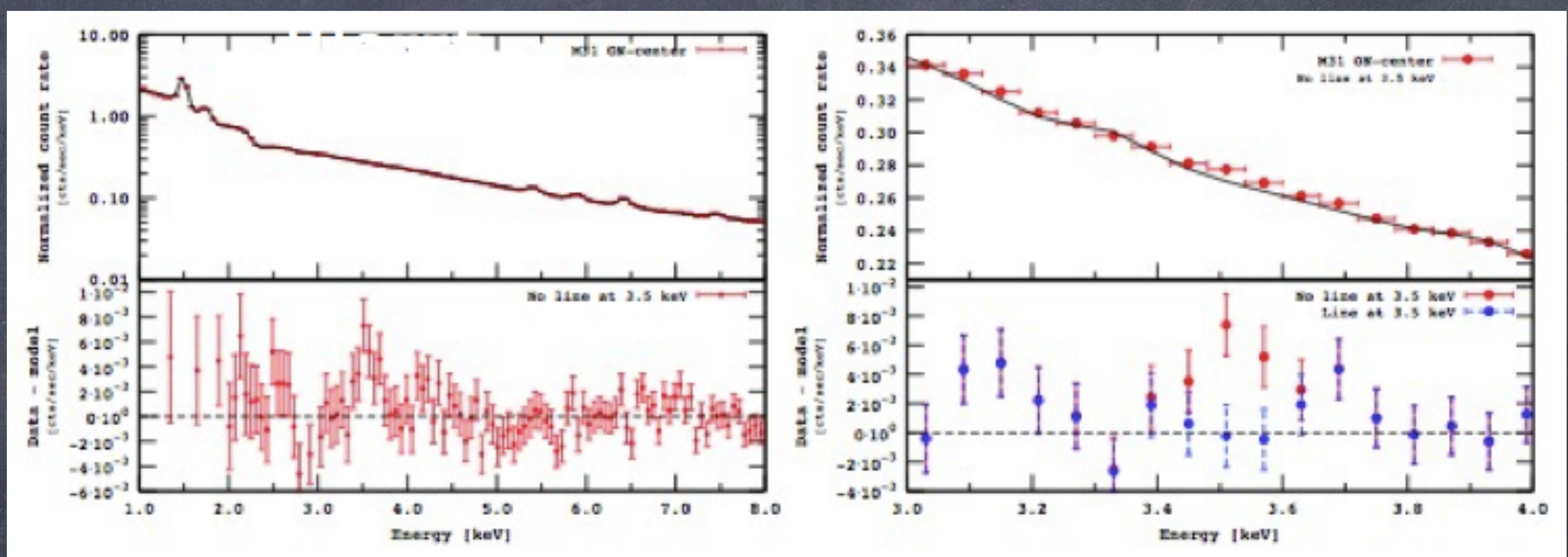
10 GeV, Leptonic, thermal cross section

X-ray line



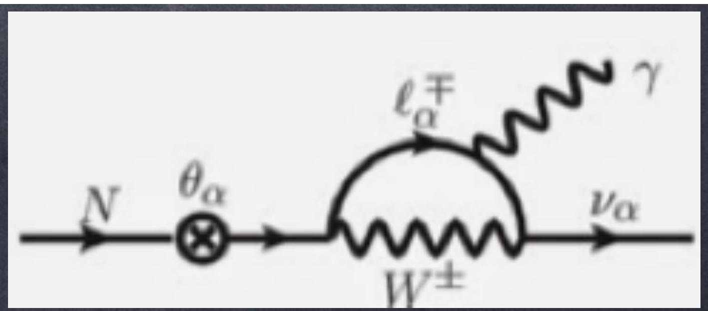
Bulbul et. al. 1402.2301
$3.55 - 3.57 \pm 0.03$KeV
73 clusters, $z = 0.01 - 0.35$

Boyarsky, Ruchayskiy, 1402.4119
3.5 KeV Andromeda
+Perseus cluster, $z = 0,\ 0.0179$



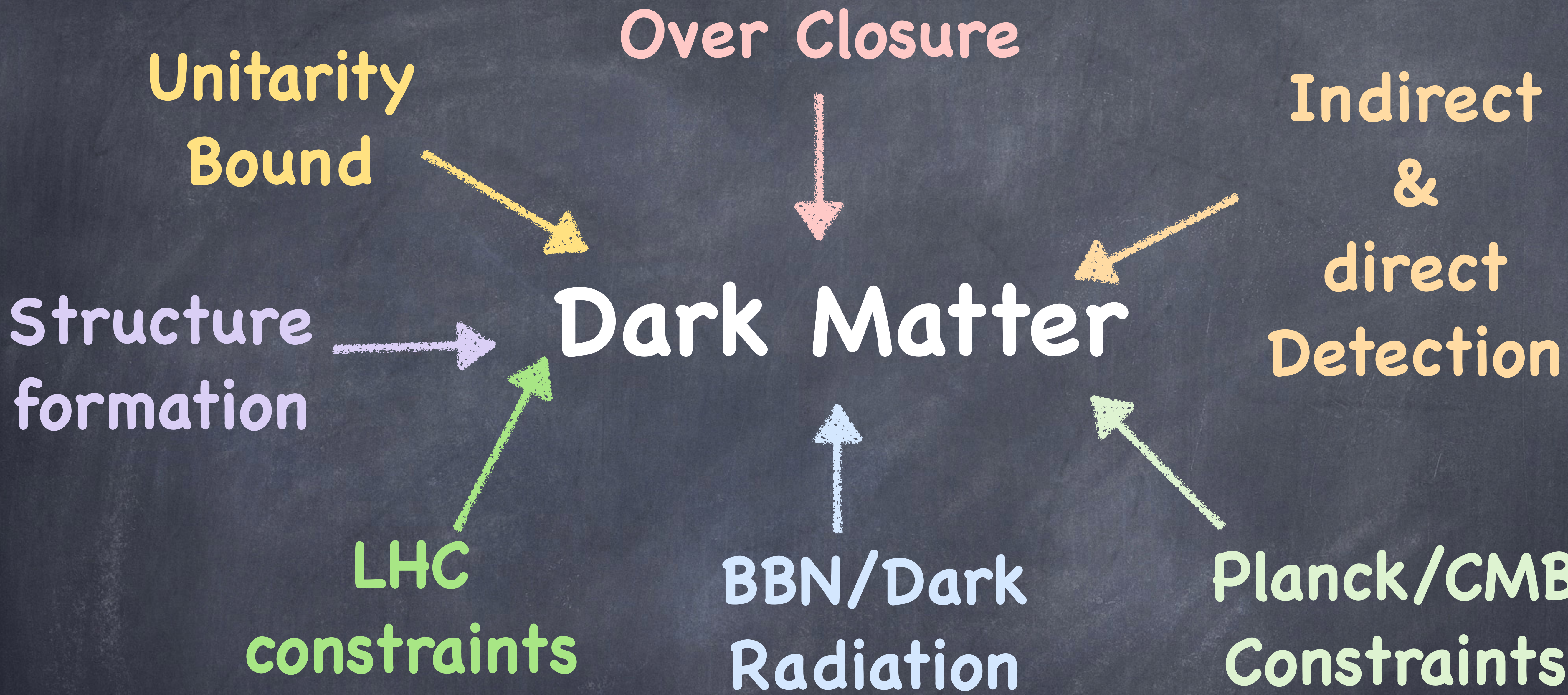
Sterile neutrino

$$m_\nu = 7.1\ \textbf{KeV},\ \tau \simeq 10^{29}\ \textbf{sec},\ \ \sin^2 2\theta \sim 10^{-11}$$



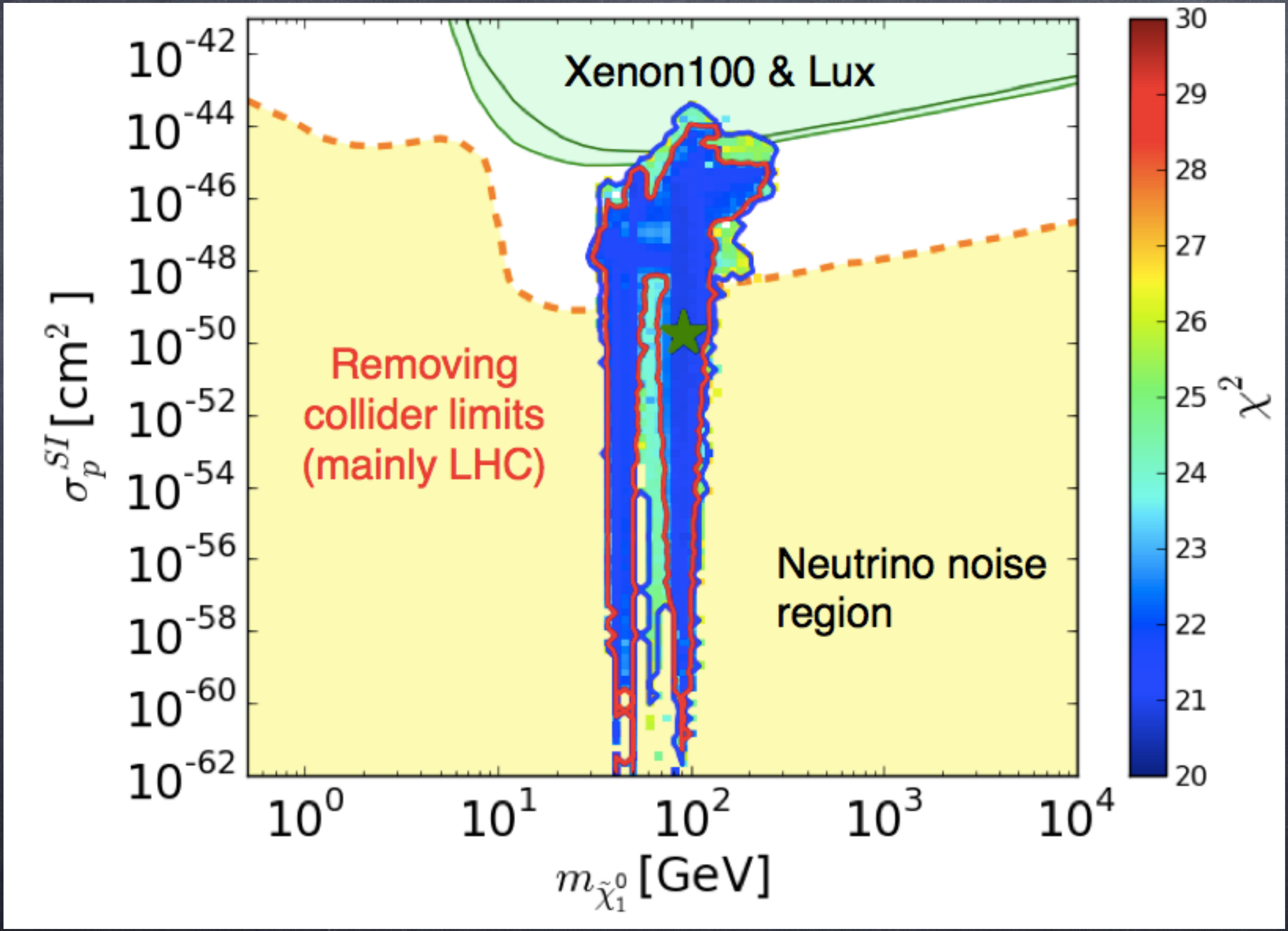
axion (1402.7335), axino (1403.1536, 1403.1782, 1403.6621), modulus (1403.1733), ALP (1403.2370) gravitino (1403.6503), excited DM (1404.4795), the good the bad and the unlikely (1403.1570), sgoldstino (1404.1339), magnetic DM (1404.5446), majoron (1404.1400), annihilating effective DM (1404.1927), 7KeV scalar DM (1404.2220)...

Various ways of constraining DM



DM need not be a WIMP/FIMP

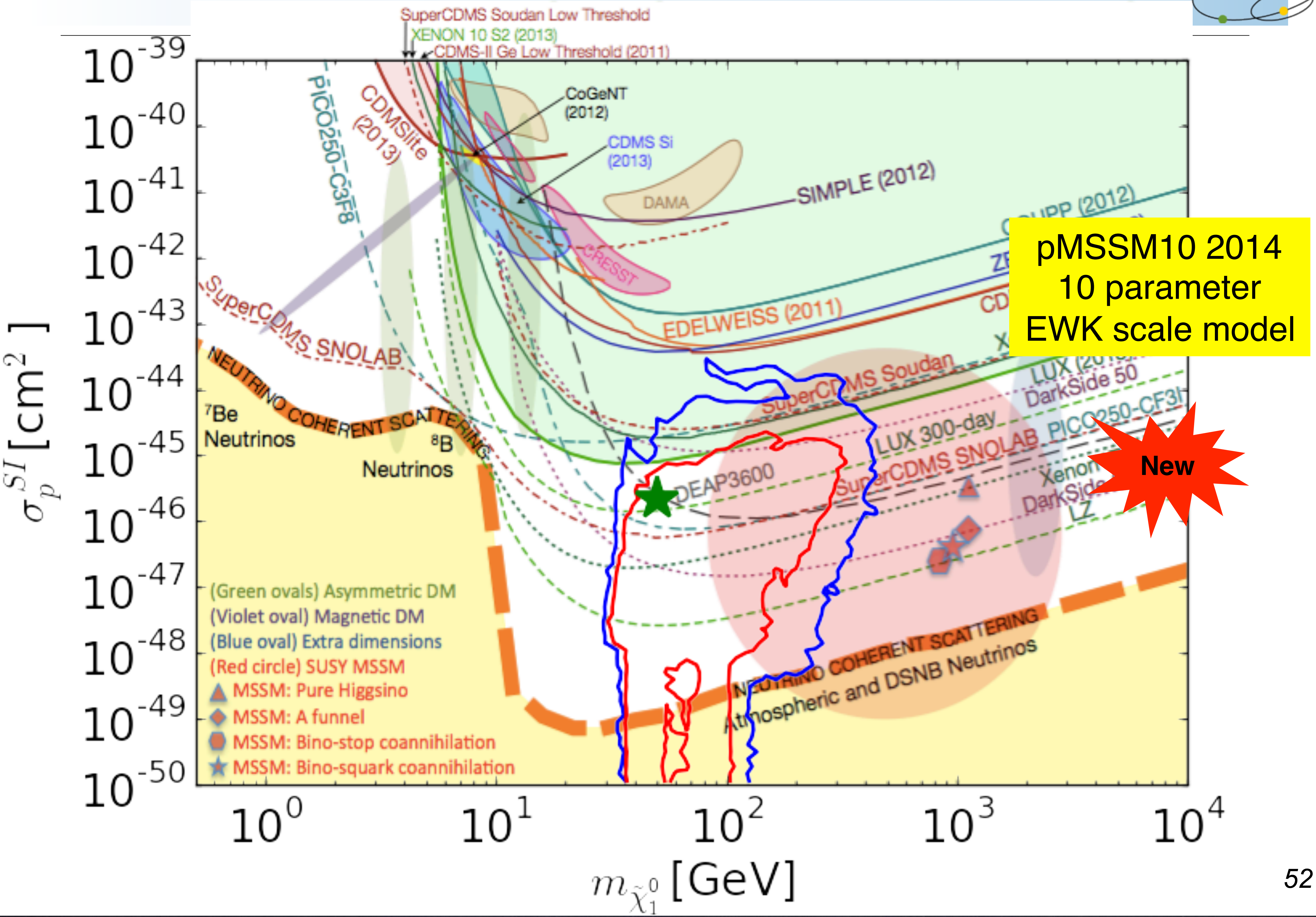
There need not be a single DM candidate, could be many…



Xenon100 & Lux
Removing
collider limits
(mainly LHC)
Neutrino noise
region
σ_p^{SI} [cm^2]
$m_{\tilde{\chi}_1^0}$ [GeV]
χ^2
10^{-42}
10^{-44}
10^{-46}
10^{-48}
10^{-50}
10^{-52}
10^{-54}
10^{-56}
10^{-58}
10^{-60}
10^{-62}
10^0
10^1
10^2
10^3
10^4
30
29
28
27
26
25
24
23
22
21
20

What to expected for SUSY?

MasterCode



CDM as a thermal relic

$$n \sim (m_\chi T)^{3/2} e^{-m_\chi/T}$$

$$\Gamma \sim n\sigma \sim H(T) \implies n_{f.o} \sim \frac{T_{f.o}^2}{M_p \sigma}$$

$$\frac{m_\chi^3}{x^{3/2}} e^{-x} = \frac{m_\chi^2}{x^2 M_p \sigma} \quad (x = m_\chi/T, \quad x \gg 1)$$

$$Rough\ estimate: \ \sqrt{x} e^{-x} = \frac{1}{m_\chi M_p \sigma} \sim \frac{1}{10^2 10^{18} 10^{-6}} \sim 10^{-14}$$

$$\sigma \sim G_F^2 m_\chi^2 \ (G_F \sim 10^{-5} GeV^2)$$

$$\sigma_{EW} \sim G_F^2 T_{f.o.}^2 \sim G_F^2 \left(m_\chi/20\right)^2 \sim 10^{-8}\ \mathrm{GeV}^{-2}$$

$$\Omega_\chi = \frac{m_\chi n_\chi (T{=}T_0)}{\rho_c} = \frac{m_\chi T_0^3}{\rho_c} \frac{n_0}{T_0^3} \quad (T_0 \sim 10^{-4} eV)$$

$$Since\ aT \sim \mathrm{const.}: \frac{n_0}{T_0^3} \approx \frac{n_{f.o.}}{T_{f.o.}^3}$$

$$\Omega_\chi = \frac{T_0^3}{\rho_c} x_{f.o.} \left(\frac{n_{f.o.}}{T_{f.o.}^2}\right) = \left(\frac{T_0^3}{\rho_c M_p}\right) \frac{x_{f.o.}}{\sigma}$$

Production Mechanisms

1311.5297[hep-ph]

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - n_{\chi,\mathrm{eq}}^2\right)$$

$$n_\chi = g_\chi \int \frac{d^3\mathbf{p}}{(2\pi)^3}\, \exp\left[-\left(\sqrt{|\mathbf{p}|^2 + m_\chi^2} - \mu_\chi\right)/T\right]$$

Non-Relativistic $\quad v_r = |\mathbf{v}_1 - \mathbf{v}_2|$

Relativistic

$$v = \bar{v}/(1 - \mathbf{v}_1 \cdot \mathbf{v}_2) = \sqrt{(p_1 \cdot p_2)^2 - m_1^2 m_2^2}/(p_1 \cdot p_2)$$

$$\bar{v} = \sqrt{(\mathbf{v}_1 - \mathbf{v}_2)^2 - (\mathbf{v}_1 \times \mathbf{v}_2)^2}$$

$$\frac{dY_\chi}{dx} = -\frac{s\langle\sigma v\rangle}{Hx}\left(1 + \frac{1}{3}\frac{d\ln g}{d\ln T}\right)\left(Y_\chi^2 - Y_{\chi,\mathrm{eq}}^2\right)$$

$$Y_\chi = n_\chi/s \qquad \rho_\chi(x_0) = m_\chi s_0 Y_\chi(x_0)$$

$$sa^3 = \mathrm{const.} \implies Y \sim na^3, \quad Y_0 = Y_{f.o.}$$

$$\Omega_\chi h^2 = 2.74 \times 10^8\, Y_\chi(x_0)\left(\frac{m_\chi}{1\ \mathrm{GeV}}\right)$$

$$\rho_c = 1.05375(13) \times 10^{-5} h^2\ \mathrm{GeV cm}^{-3}$$

$$s_0 = 2889.2\ \mathrm{cm}^{-3}(T_0/2.725\ \mathrm{K})^3$$

(1) Non-relativistic

$$\Omega_\chi h^2 = \frac{9.92 \times 10^{-28}\ \mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma v\rangle}\frac{x_*}{g_*^{1/2}}\frac{(\Gamma_\chi/H)_*}{1 + \alpha_*(\Gamma_\chi/H)_*},$$

$$\alpha_* = \int_{T_F}^{T_*} \frac{dT}{T_*}\left(\frac{g}{g_*}\right)^{1/2}\left(1 + \frac{1}{3}\frac{d\ln g}{d\ln T}\right)$$

$$\langle\sigma v\rangle = a + b\langle v_r^2\rangle + \mathcal{O}\left(\langle v_r^4\rangle\right) = a + \frac{b'}{x} + \mathcal{O}\left(\frac{1}{x^2}\right)$$

$$x_{f.o} \geq 3$$

(2) Semi Relativistic:

$$x_{f.o.} \sim 1$$

(3) Relativistic:

$$x_{f.o} \ll 1, \quad Y_{\chi,eq}(x_{f.o.}) = \frac{n_{\chi,eq}}{s}$$

$$\Omega_\chi h^2 = 7.62 \times 10^{-2}\frac{g_{eff}}{g(x_{f.o.})}\frac{m_\chi}{1\mathrm{eV}} \qquad g_{eff} = g_\chi\ (boson),\ (3g_\chi/4)\ (fermion)$$