Some Topics in Dark Sector Physics

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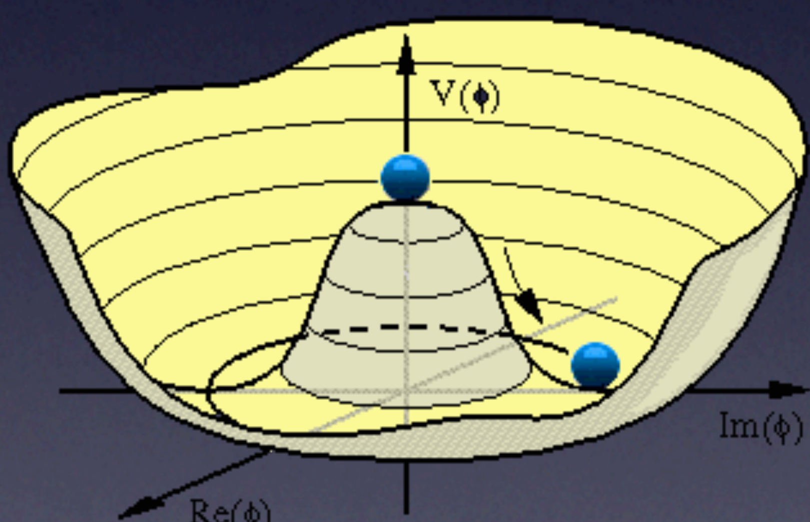
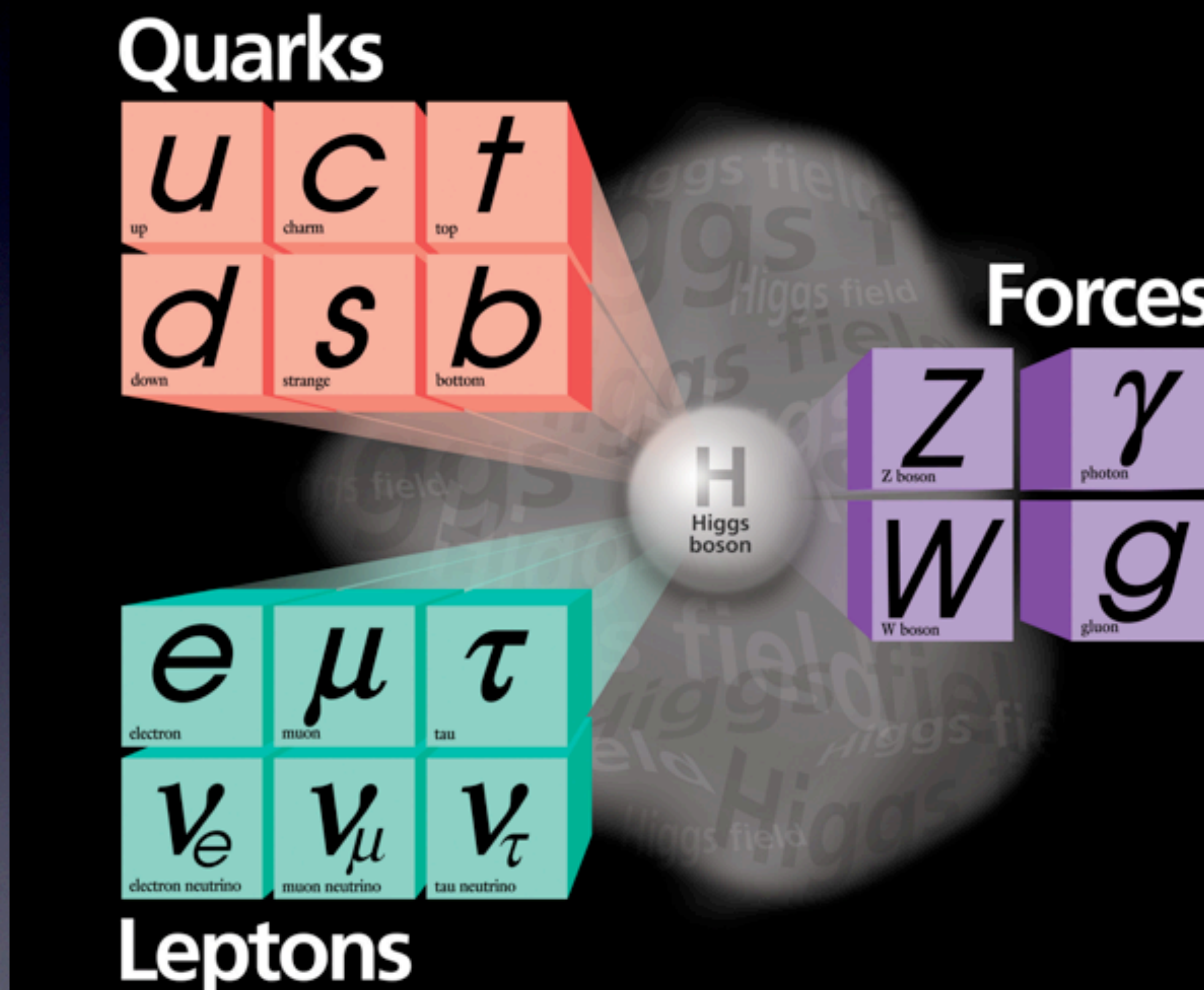
Standard Model/Theory

- SM is a gauge theory
- BEH particle responsible to spontaneously electroweak symmetry breaking

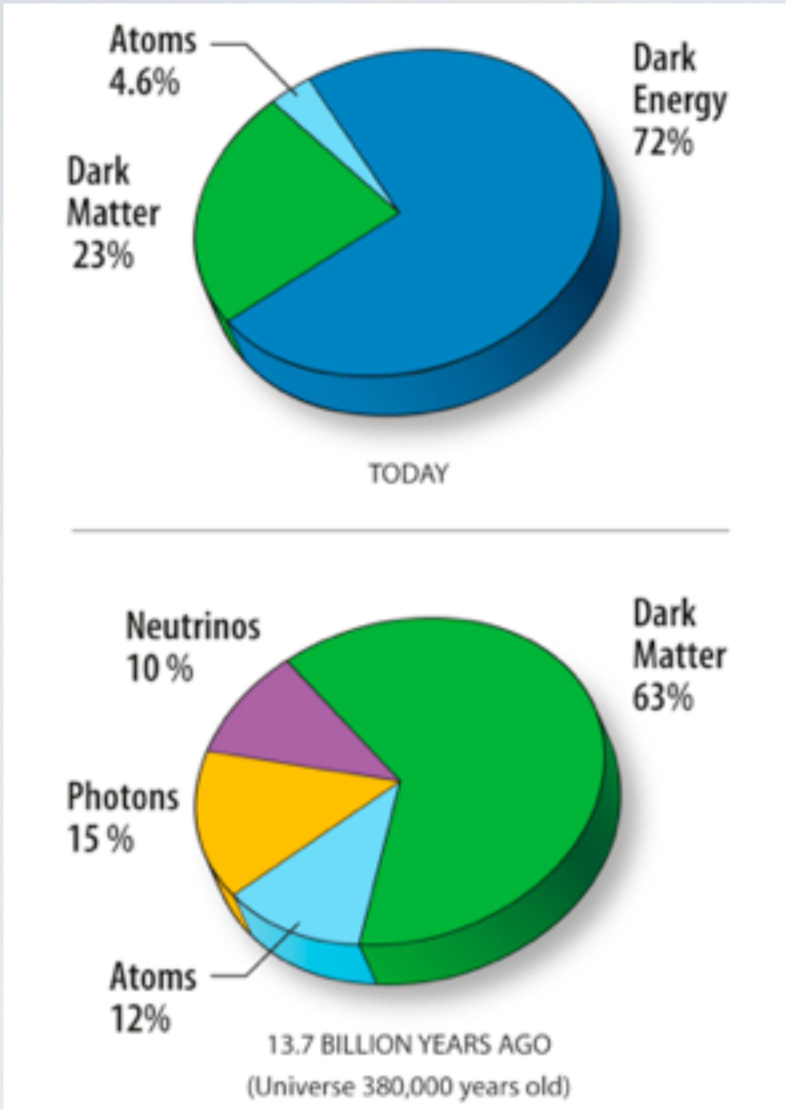


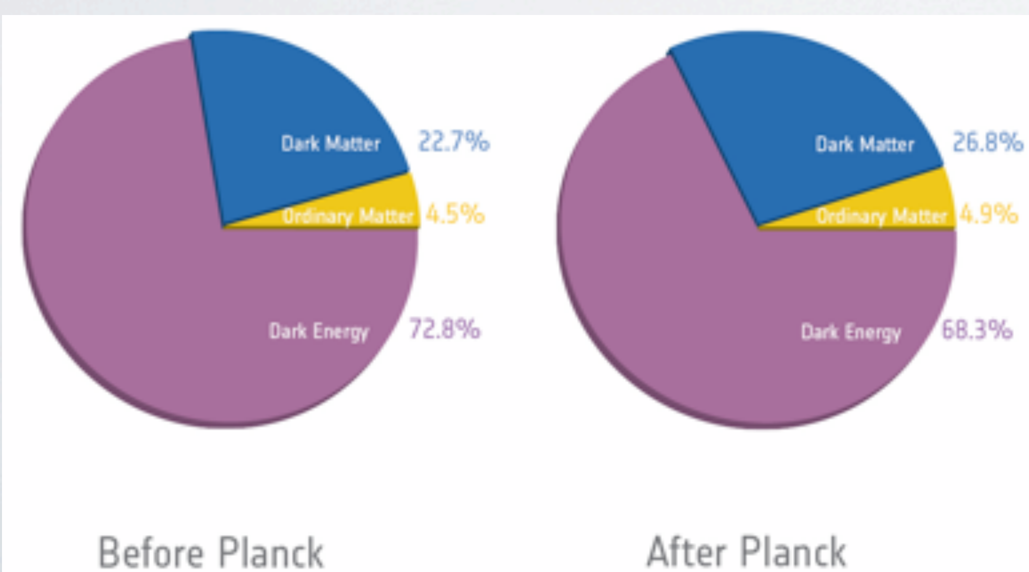
- Provide masses to quarks, leptons, and gauge bosons



The Concordance Model of Cosmology (ΛCDM)

Energy Budget





$$H_0 = 100\,h\,\mathrm{km\,sec^{-1}\,Mpc^{-1}}$$
$$h = 0.6780 \pm 0.0077$$
$$\rho_{\rm cr} = \frac{3H_0^2}{8\pi G}$$
$$\rho_{\rm cr} = 1.9 \cdot 10^{-29}\,h^2 \mathrm{g\,cm^{-3}}$$

$$\rho = \rho_{\rm rad} + \rho_{\rm mat} + \rho_\Lambda$$

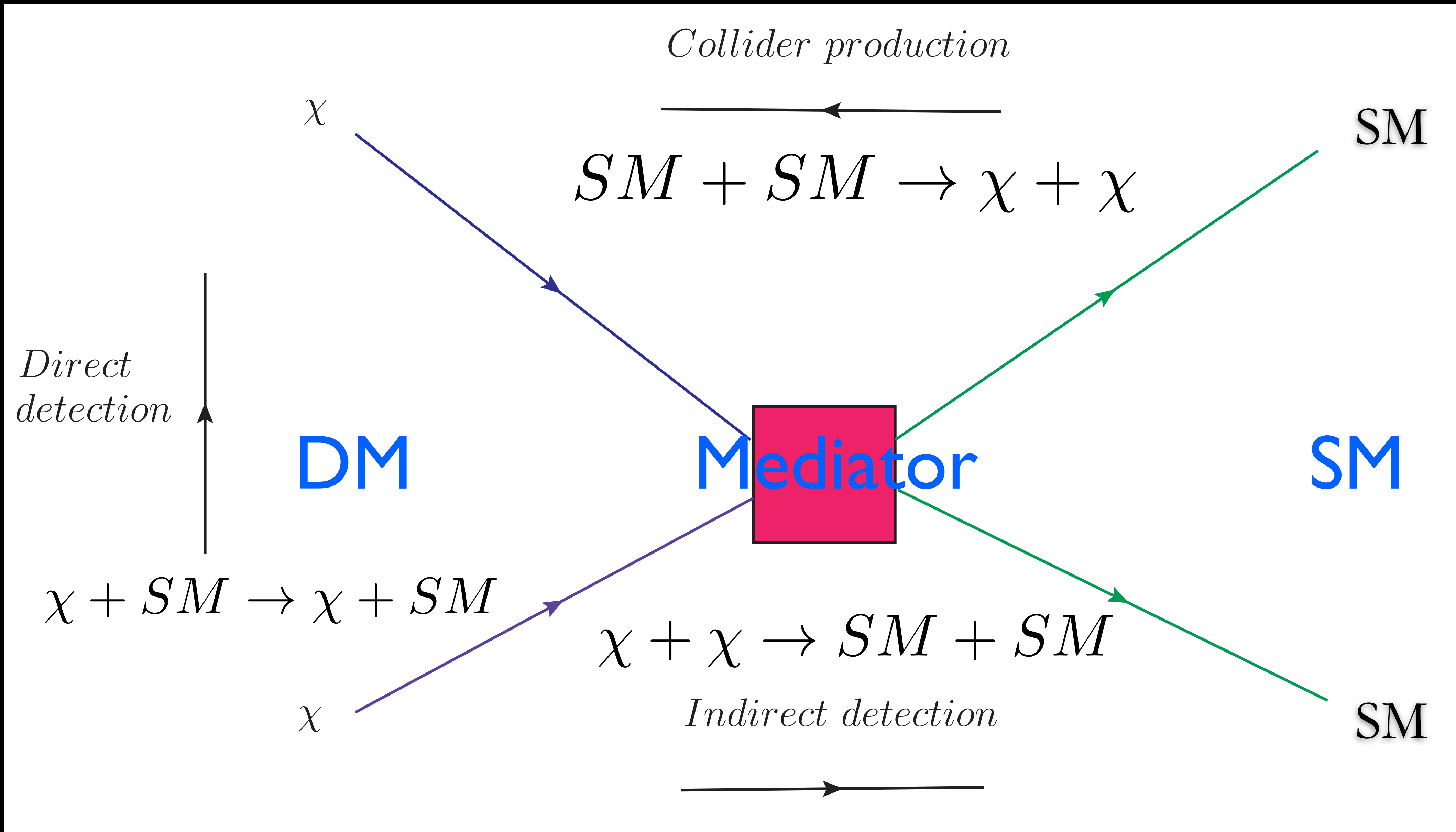
$$\Omega_b h^2 = 0.02214 \pm 0.00024$$
$$\Omega_{\rm CDM} h^2 = 0.1187 \pm 0.0017$$
$$\Omega_\Lambda = 0.692 \pm 0.010$$
$$\mathrm{Age/Gyr} = 13.798 \pm 0.037$$

$$\Omega_i = \frac{\rho_i}{\rho_{\rm cr}} \qquad \left(\sum_i \Omega_i\right) - 1 = \frac{k}{H^2 a^2}$$

Few Clouds Shadow over the SM

- Neutrino Masses (Favor Problem)
- Baryogenesis/Leptogenesis (Matter-Antimatter Asymmetry)
- Dark Matter (Missing Mass Problem)
- Dark Energy (Accelerating Universe, Cosmological Constant Problem)

Dark Crossing
(4 Pillars of Complementary DM Search)



RELIC DENSITY OF A PARTICLE SPECIES

Freeze-out condition : $n\langle\sigma_A v\rangle \leq \dot{a}/a \equiv H$

$$\Omega_X h^2 \approx \frac{3\times10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma_A v\rangle} \approx \frac{0.1\ \mathrm{pb}}{\langle\sigma_A v\rangle}$$

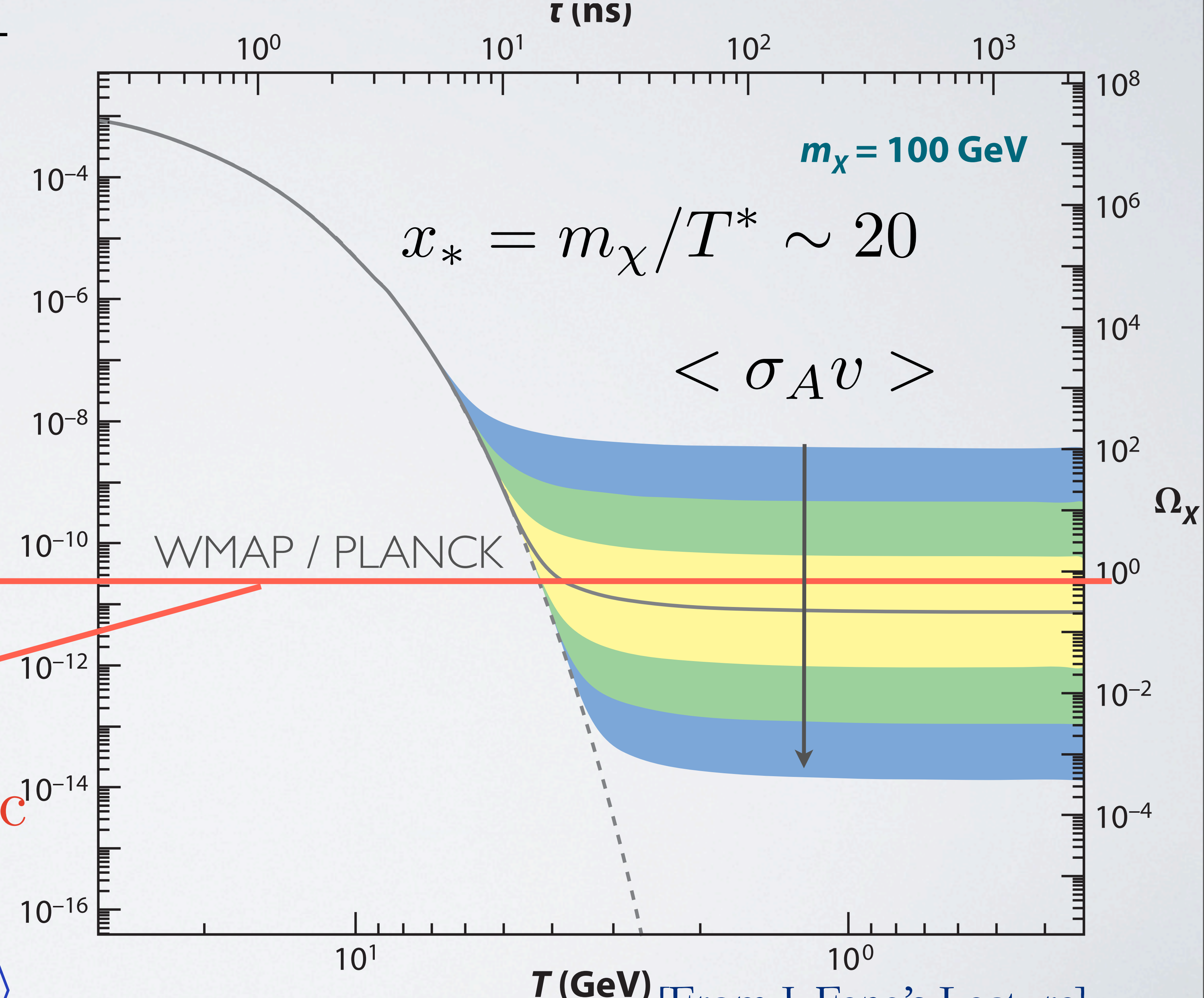
WIMP miracle:

$\langle\sigma_A v\rangle \sim \sigma_{\mathrm{weak}} \sim 1\,\mathrm{pb}$

$\Omega_{CDM}h^2(\mathrm{WMAP}) = 0.1123 \pm 0.0035$

$\Omega_{CDM}h^2(\mathrm{PLANCK}) = 0.1199 \pm 0.0027$

$\langle\sigma_A v\rangle = 3\times10^{-26}\mathrm{cm}^3/\mathrm{sec}$

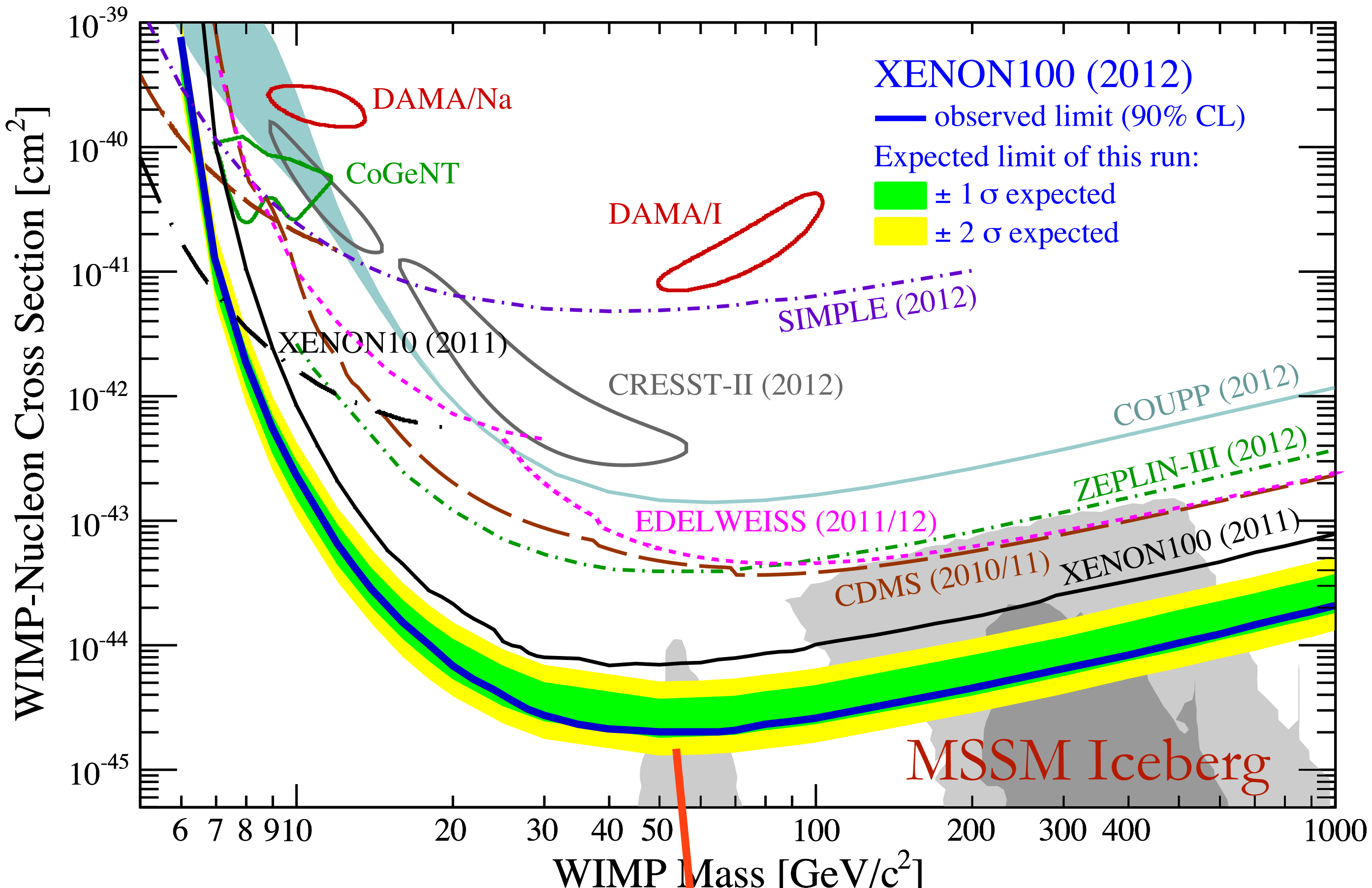


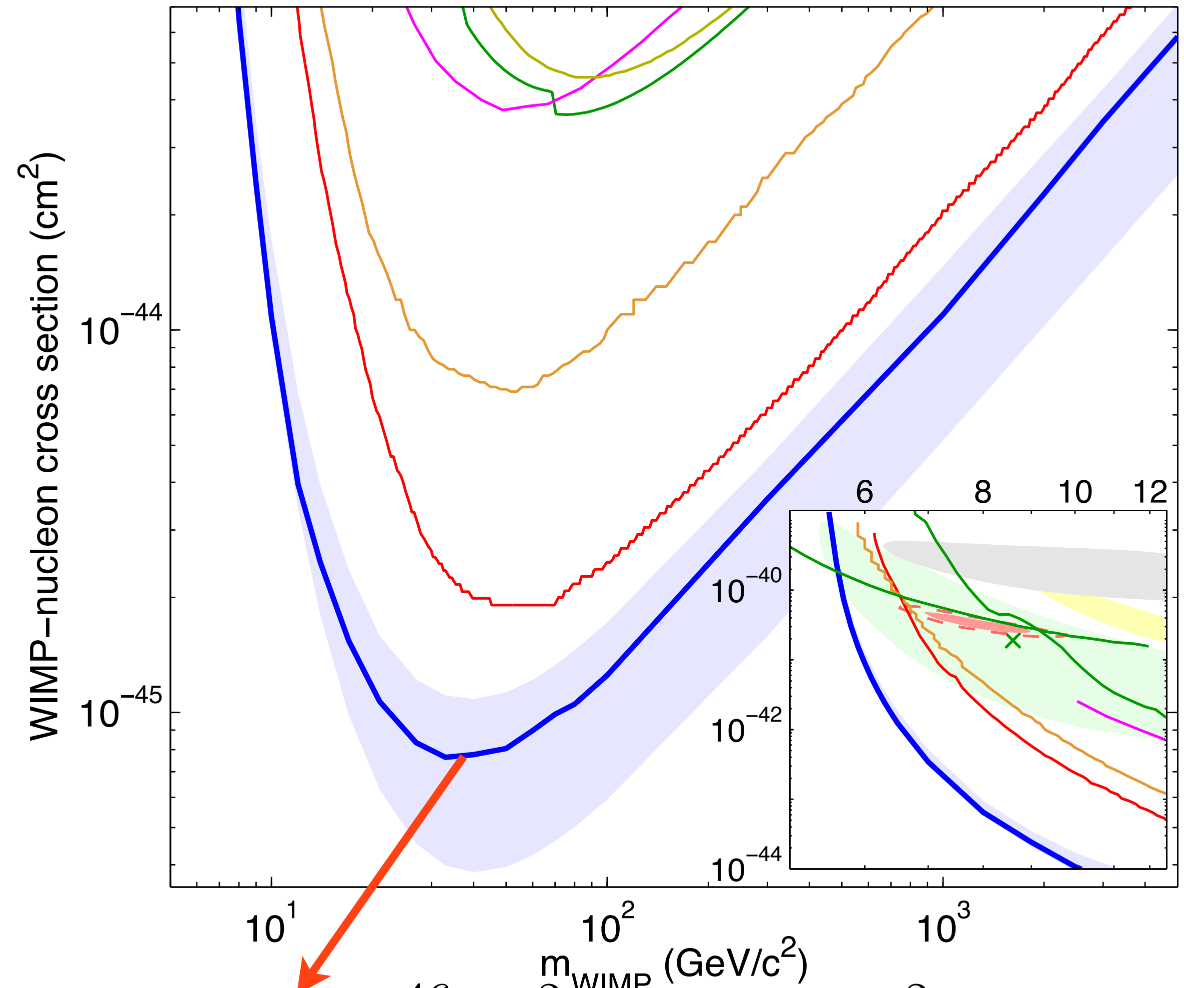
[From J. Feng's Lecture]

Put lower limits on $\langle\sigma_A v\rangle$

225 Live Days of XENON100 Data PRL 109, 181301 (2012), [1207.5988/astro-ph.CO]

LUX Oct. 31 2013





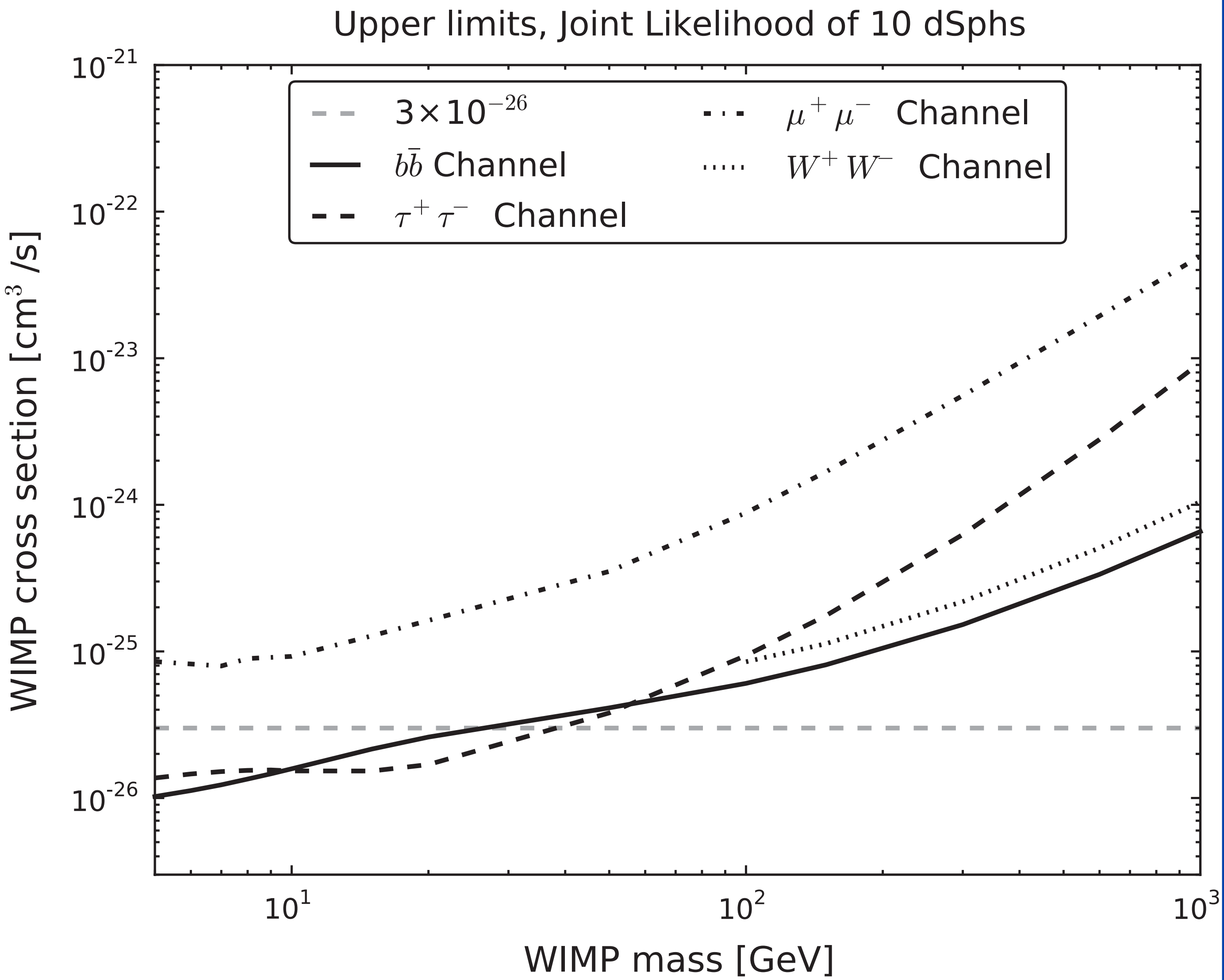
$7.6 \times 10^{-46} \mathrm{cm}^2$ at $33\,\mathrm{GeV}/c^2$ (90%CL)

FIG. 5. The LUX 90% confidence limit on the spin-independent elastic WIMP-nucleon cross section (blue), together with the $\pm 1\sigma$ variation from repeated trials, where trials fluctuating below the expected number of events for zero BG are forced to 2.3 (blue shaded). We also show Edelweiss II [41] (dark yellow line), CDMS II [42] (green line), ZEPLIN-III [43] (magenta line) and XENON100 100 live-day [44] (orange line), and 225 live-day [45] (red line) results. The inset (same axis units) also shows the regions measured from annual modulation in CoGeNT [46] (light red, shaded), along with exclusion limits from low threshold re-analysis of CDMS II data [47] (upper green line), 95% allowed region from CDMS II silicon detectors [48] (green shaded) and centroid (green x), 90% allowed region from CRESST II [49] (yellow shaded) and DAMA/LIBRA allowed region [50] interpreted by [51] (grey shaded).

b=1.0±0.2, o=2

$2 \times 10^{-45} \mathrm{cm}^2$ at $55\,\mathrm{GeV}/c^2$ (90%CL)

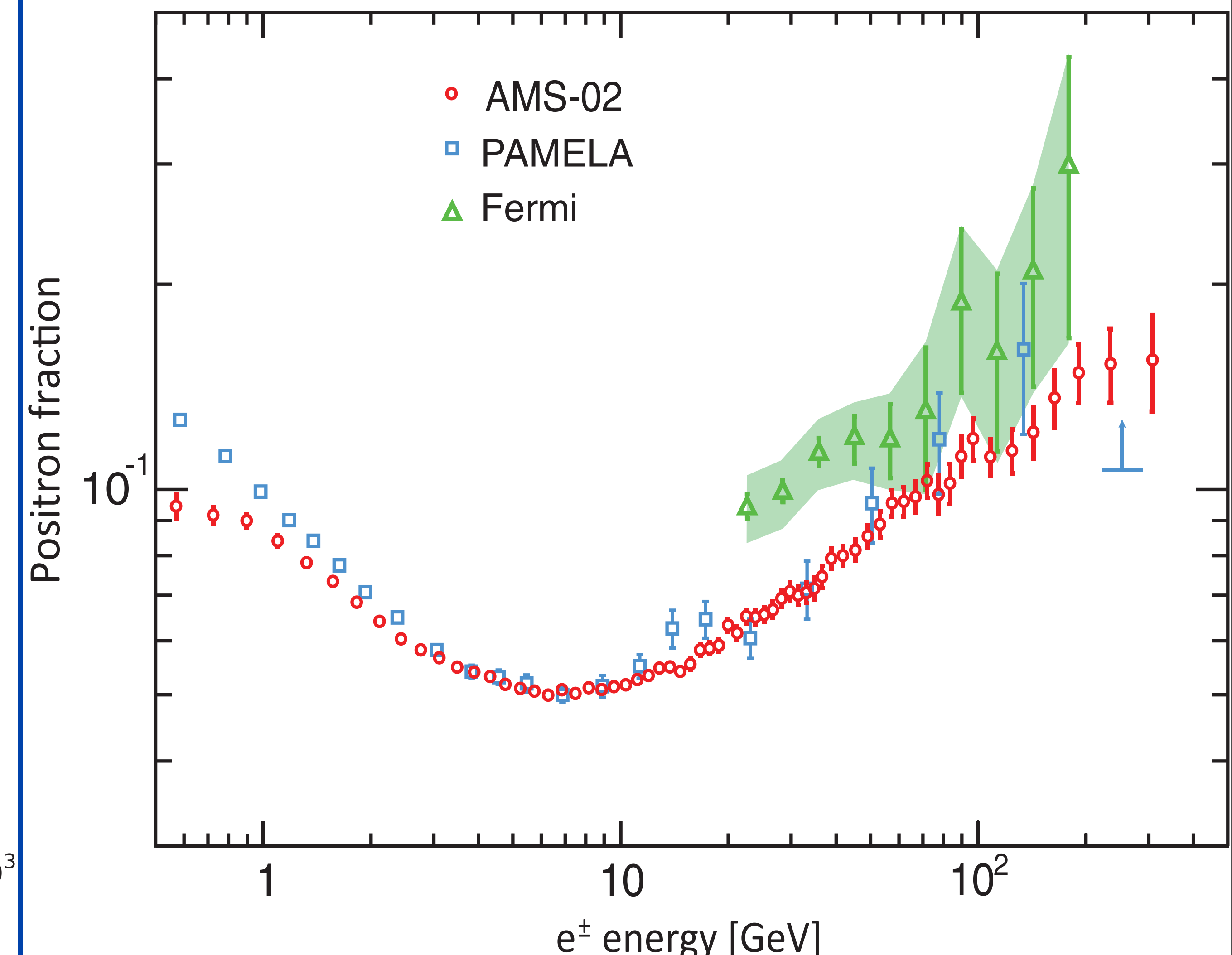
Diffuse γ Rays from Satellite Galaxies Fermi-LAT



- No signals were found → upper limits for <σ$_{A}$v> from FermiLAT data while relic density provides lower limit. We can use these upper and lower limits to constrain DM model
- At face value: 25 or 40 GeV DM can be excluded by combining indirect detection using dSphs and relic density. First limits for DM cross section from gamma ray using dSphs!

Positron Fraction AMS-02

AMS-02, PRL 110, 141102 (2013)



Positron excess is confirmed!
No solid explanation yet for the rise.
More important results coming soon: proton flux, electron flux, positron flux, helium flux, and B/C.

Outline

- Introduction ✔
- Effective Dark Matter Theory
- Scalar Dark Matter Models
- Dark $U(1)_D$ Sector
- Summary

Particle DM Theoretical Candidates

- MSSM/NMSSM DM - LSP from R-Parity
- Kaluza-Klein DM in UED - K-Parity (LKP)
- Little Higgs DM - T-Parity (LTP)
- Scalar Phantom Model (Darkon Model) - Z_2 Parity
- Inert Higgs Doublet Model, Triplet Higgs Model, ...
- Hidden Sector Fermion, Extra Generation, ...
- Axions, right-handed neutrinos, gravitino, axinos, cosmic strings, quintessinos, Q-balls, ...
- Decaying Dark Matter (with lifetime longer than the age of the universe)
- Asymmetric Dark Matter (ADM)
- Primordial Black Holes (PBH) proposed by Hawking in 1974

DM Effective Operators

$$O_1 = \sum_f \frac{C_1^f}{\Lambda_1^2} (\bar\chi\gamma^\mu\chi)(\bar f\gamma_\mu f) \,,$$

$$O_2 = \sum_f \frac{C_2^f}{\Lambda_2^2} (\bar\chi\gamma^\mu\gamma^5\chi)(\bar f\gamma_\mu f) \,,$$

$$O_3 = \sum_f \frac{C_3^f}{\Lambda_3^2} (\bar\chi\gamma^\mu\chi)(\bar f\gamma_\mu\gamma^5 f) \,,$$

$$O_4 = \sum_f \frac{C_4^f}{\Lambda_4^2} (\bar\chi\gamma^\mu\gamma^5\chi)(\bar f\gamma_\mu\gamma^5 f) \,,$$

$$O_5 = \sum_f \frac{C_5^f}{\Lambda_5^2} (\bar\chi\sigma^{\mu\nu}\chi)(\bar f\sigma_{\mu\nu} f) \,,$$

$$O_6 = \sum_f \frac{C_6^f}{\Lambda_6^2} (\bar\chi\sigma^{\mu\nu}\gamma^5\chi)(\bar f\sigma_{\mu\nu} f) \,,$$

$$O_7 = \sum_f \frac{C_7^f m_f}{\Lambda_7^3} (\bar\chi\chi)(\bar f f) \,,$$

$$O_8 = \sum_f \frac{iC_8^f m_f}{\Lambda_8^3} (\bar\chi\gamma^5\chi)(\bar f f) \,,$$

$$O_9 = \sum_f \frac{iC_9^f m_f}{\Lambda_9^3} (\bar\chi\chi)(\bar f\gamma^5 f) \,,$$

$$O_{10} = \sum_f \frac{C_{10}^f m_f}{\Lambda_{10}^3} (\bar\chi\gamma^5\chi)(\bar f\gamma^5 f) \,.$$

$$O_{11} = \frac{C_{11}}{\Lambda_{11}^3} (\bar\chi\chi)\left(-\frac{\alpha_s}{12\pi} G^{\mu\nu}G_{\mu\nu}\right) \,,$$

$$O_{12} = \frac{iC_{12}}{\Lambda_{12}^3} (\bar\chi\gamma^5\chi)\left(-\frac{\alpha_s}{12\pi} G^{\mu\nu}G_{\mu\nu}\right) \,,$$

$$O_{13} = \frac{C_{13}}{\Lambda_{13}^3} (\bar\chi\chi)\left(\frac{\alpha_s}{8\pi} G^{\mu\nu}\tilde G_{\mu\nu}\right) \,,$$

$$O_{14} = \frac{iC_{14}}{\Lambda_{14}^3} (\bar\chi\gamma^5\chi)\left(\frac{\alpha_s}{8\pi} G^{\mu\nu}\tilde G_{\mu\nu}\right) \,.$$

$$O_{15} = \sum_f \frac{iC_{15}^f}{\Lambda_{15}^2} \left(\chi^\dagger \overleftrightarrow{\partial_\mu} \chi\right)(\bar f\gamma^\mu f) \,,$$

$$O_{16} = \sum_f \frac{iC_{16}^f}{\Lambda_{16}^2} \left(\chi^\dagger \overleftrightarrow{\partial_\mu} \chi\right)(\bar f\gamma^\mu\gamma^5 f) \,,$$

$$O_{17} = \sum_f \frac{C_{17}^f m_f}{\Lambda_{17}^2} (\chi^\dagger\chi)(\bar f f) \,,$$

$$O_{18} = \sum_f \frac{iC_{18}^f m_f}{\Lambda_{18}^2} (\chi^\dagger\chi)(\bar f\gamma^5 f) \,,$$

$$O_{19} = \frac{C_{19}}{\Lambda_{19}^2} (\chi^\dagger\chi)\left(-\frac{\alpha_s}{12\pi} G^{\mu\nu}G_{\mu\nu}\right) \,,$$

$$O_{20} = \frac{C_{20}}{\Lambda_{20}^2} (\chi^\dagger\chi)\left(\frac{\alpha_s}{8\pi} G^{\mu\nu}\tilde G_{\mu\nu}\right) \,.$$

Cheung, Tseng, Tsai, Yuan, JCAP 1205 (2012) 001, arXiv:1201.3402;
see also Tait et al, 1005.1286, 1008,1783,1108.1196,1307.6277; ...

NR Reduction

Kurylov and Kamionkowski, PRD 69, 063503 (2004);
Cheung, Tseng, Tsai, and Yuan, JCAP05 (2012) 001.

- At present epoch, $v/c \sim 10^{-3}$, NR limit is applicable
- Only 8 operators survive under NR reduction: $O_1, O_4, O_5, O_7, O_{11}, O_{16}, O_{17}$ and O_{19}
- Furthermore, only O_1, O_4 and O_7 are independence because

$$O_5 \longrightarrow O_4$$
$$O_{11} \longrightarrow O_7$$
$$O_{15} \longrightarrow O_1$$
$$O_{17} \longrightarrow O_7$$
$$O_{19} \longrightarrow O_7$$

- SI: O_1 and O_7; SD : O_4

O_1 and O_7 $\quad (\overline{\chi}\gamma^\mu\chi)(\overline{f}\gamma_\mu f) \quad (\overline{\chi}\chi)(\overline{f}f)$

- Coherent spin-independent cross section

$$\sigma^{\rm SI}_{\chi\mathcal{N}}(0) = \frac{\mu^2_{\chi\mathcal{N}}}{\pi}|b_\mathcal{N}|^2$$

$$b_\mathcal{N} = Z\,b_p + (A-Z)\,b_n$$

$$b_p = 2\,\frac{C_1^u}{\Lambda_1^2} + \frac{C_1^d}{\Lambda_1^2}\,,$$

$$b_n = \frac{C_1^u}{\Lambda_1^2} + 2\,\frac{C_1^d}{\Lambda_1^2}\,.$$

$$\sigma^{\rm SI}_{\chi\mathcal{N}}(0) = \frac{\mu^2_{\chi\mathcal{N}}}{\pi}|f_\mathcal{N}|^2$$

$$f_{p,n} = \frac{m_{p,n}}{\Lambda_7^3}\left\{\sum_{q=u,d,s} C_7^q\,f_{Tq}^{(p,n)} + \frac{2}{27}f_{TG}^{(p,n)}\sum_{Q=c,b,t} C_7^Q\right\}$$

$$f_\mathcal{N} = Z\,f_p + (A-Z)\,f_n$$

$$f_{TG}^{(p,n)} \equiv 1 - \sum_{q=u,d,s} f_{Tq}^{(p,n)}\,.$$

O_4 $\quad (\overline{\chi}\gamma^\mu\gamma^5\chi)\,(\overline{f}\gamma_\mu\gamma^5 f)$

- Spin-dependent cross section (for Dirac DM)

$$\sigma^{\mathrm{SD}}_{\chi\mathcal{N}}(0) = \frac{8\mu^2_{\chi\mathcal{N}}}{\pi} G_F^2 \bar{\Lambda}^2 J(J+1)$$

$$\bar{\Lambda} = \frac{1}{J}\left(a_p\langle S_p\rangle + a_n\langle S_n\rangle\right)$$

$$a_{p,n} = \sum_{q=u,d,s} \frac{1}{\sqrt{2}G_F}\frac{C_4^q}{\Lambda_4^2}\Delta q^{(p,n)}$$

$$a_0 = a_p + a_n \ ,$$

$$a_1 = a_p - a_n \ .$$

Constraints on Effective Interactions

- Our approach (adopted by other several groups as well):
  (1) assumption: the connector sector must be heavy and integrated out
  (2) DM can be (real/complex) scalar or (Majorana/Dirac) fermionic; vector and spin 3/2 DM not considered
  (3) effective interaction of WIMP DM with SM particles
  (4) model independent study for a large class of models
- Direct detection experiments can place upper limits on cross sections hence lower limits on effective scales Λ
- On the other hand, relic density will place upper limits on effective scales Λ
- See for example, Cheung et al, JCAP 1205 (2012) 001.

CDMS-II

In April 2013, CDMS-II reported 3 events were observed for a DM mass ~8.6 GeV and SI cross section of 1.9×10^{-41} cm^2.

LHC-8 Monojet Events

- CMS monojet events:

$$p_{T_j} > 110 \text{ GeV}, \quad |\eta_j| < 2.4, \quad \not{E}_T > 250 - 550 \text{ GeV} \ ,$$

- For DM search:

$$\not{E}_T > 400 \text{ GeV}$$

- Observed upper limit (19.5 fb^{-1}): $N^{\rm obs} < 434$.

From CDMS-II to Monojet (Spin Independent)

Kingman Cheung, Chih-Ting Lu, Po-Yan Tseng, and TCY, [arXiv:1308.0067] **(See Tseng's talk)**

TABLE I. The fitted values Λ_i for the operators $O_{1,7,11,15,17,19}$, which contribute to the spin-independent scattering between DM and nucleon. The corresponding predictions for the number of monojet events for each operator at LHC-8 for an integrated luminosity of 19.5 fb^{-1} are also shown.

Operators	Λ_i (GeV)	$\sigma^{SI}_{\chi N}$ ($\times 10^{-41}$ cm^2) proton	neutron	Number of Monojet events with 19.5 fb^{-1} LHC-8	Allowed/Ruled out
O_1^D	2500	2.10	2.11	7.2	allowed
O_7^D	85	2.00	2.00	2.3	allowed
O_7^M	106.4	2.12	2.13	1.3	allowed
O_{11}^D	50.7	1.88	1.88	8.6×10^5	ruled out
O_{11}^M	63.8	1.88	1.88	4.4×10^5	ruled out
O_{15}^C	2500	2.10	2.11	1.7	allowed
O_{17}^C	175	2.00	2.01	1.8×10^{-3}	allowed
O_{17}^R	250	1.84	1.88	8.7×10^{-4}	allowed
O_{19}^C	117	1.89	1.90	332	allowed
O_{19}^R	147.3	1.89	1.90	166	allowed

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Simplest Scalar Phantom DM Model

(Silveira and Zee, PLB161 (1985), 136)

$$\mathcal{L}_{\text{scalar}} = (D^\mu \Phi)^\dagger (D_\mu \Phi) - \lambda \left(\Phi^\dagger \Phi - \frac{\mu^2}{2\lambda} \right)^2 + \frac{1}{2} \partial^\mu \chi \partial_\mu \chi - \frac{1}{2} m^2 \chi^2 - \frac{1}{4!} \eta \chi^4 - \frac{1}{2} \rho \chi^2 \Phi^\dagger \Phi$$

- Φ is Higgs doublet, χ is a real singlet
- Discrete Z_2 symmetry: $\chi \to -\chi$, others stay same
- Higgs-Singlet coupling $\varrho \Rightarrow$ All SM fields interact with DM χ through Higgs exchange
- Self-interacting coupling η, i.e. collisional DM
- Three new parameters: m_χ, ϱ, η

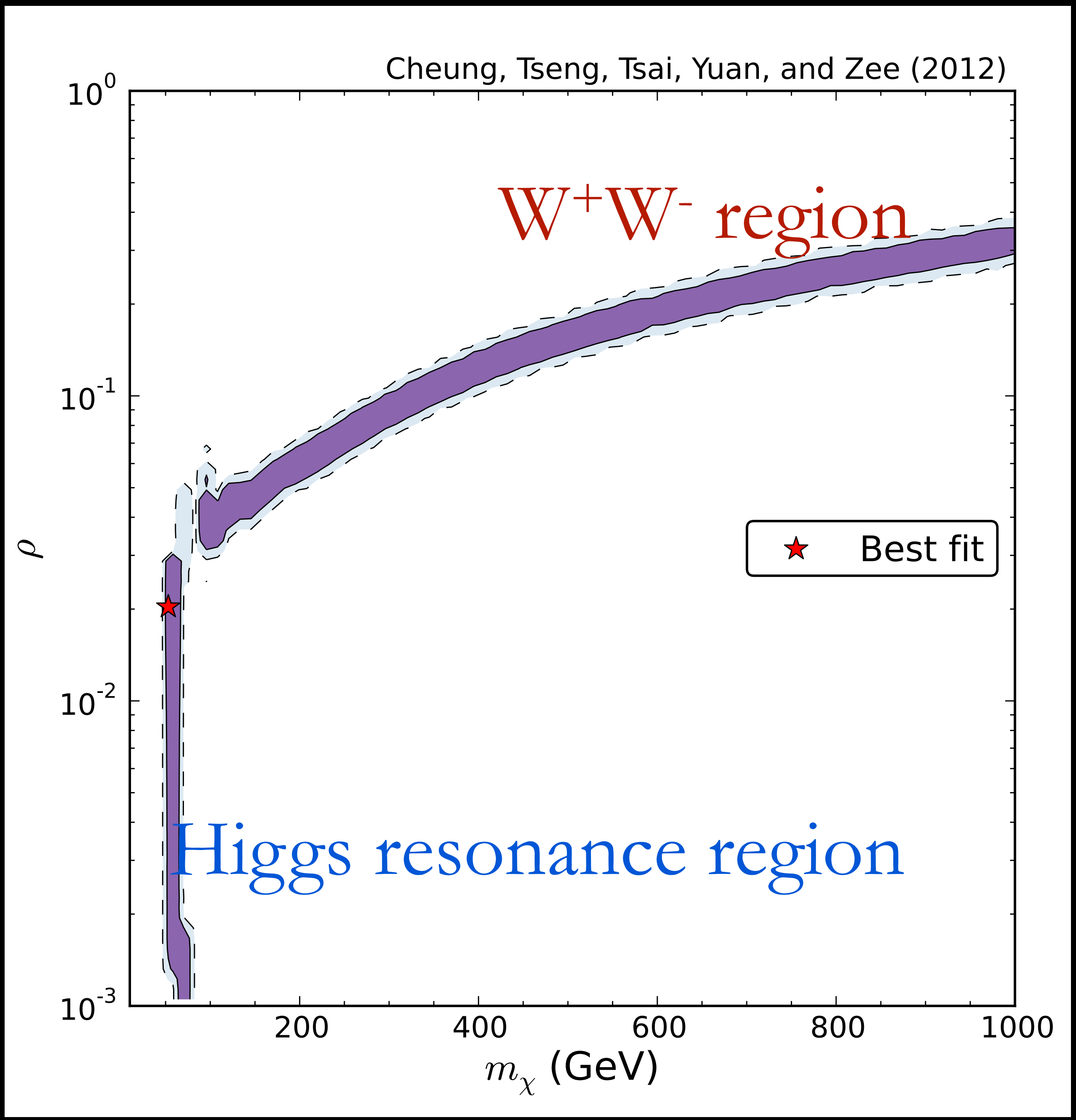
Others:

J. McDonald, PRD50 (1994) 3637;
C.P. Burgess, M. Pospelov and T. ter Veldhuis, NPB619, 709 (2001);
Y. Cai, X.-G. He and B. Ren, PRD83, 083524 (2011);
X.-G. He and J. Tandean, PRD, 88, 013020 (2013). $\Leftarrow$ **Darkon**

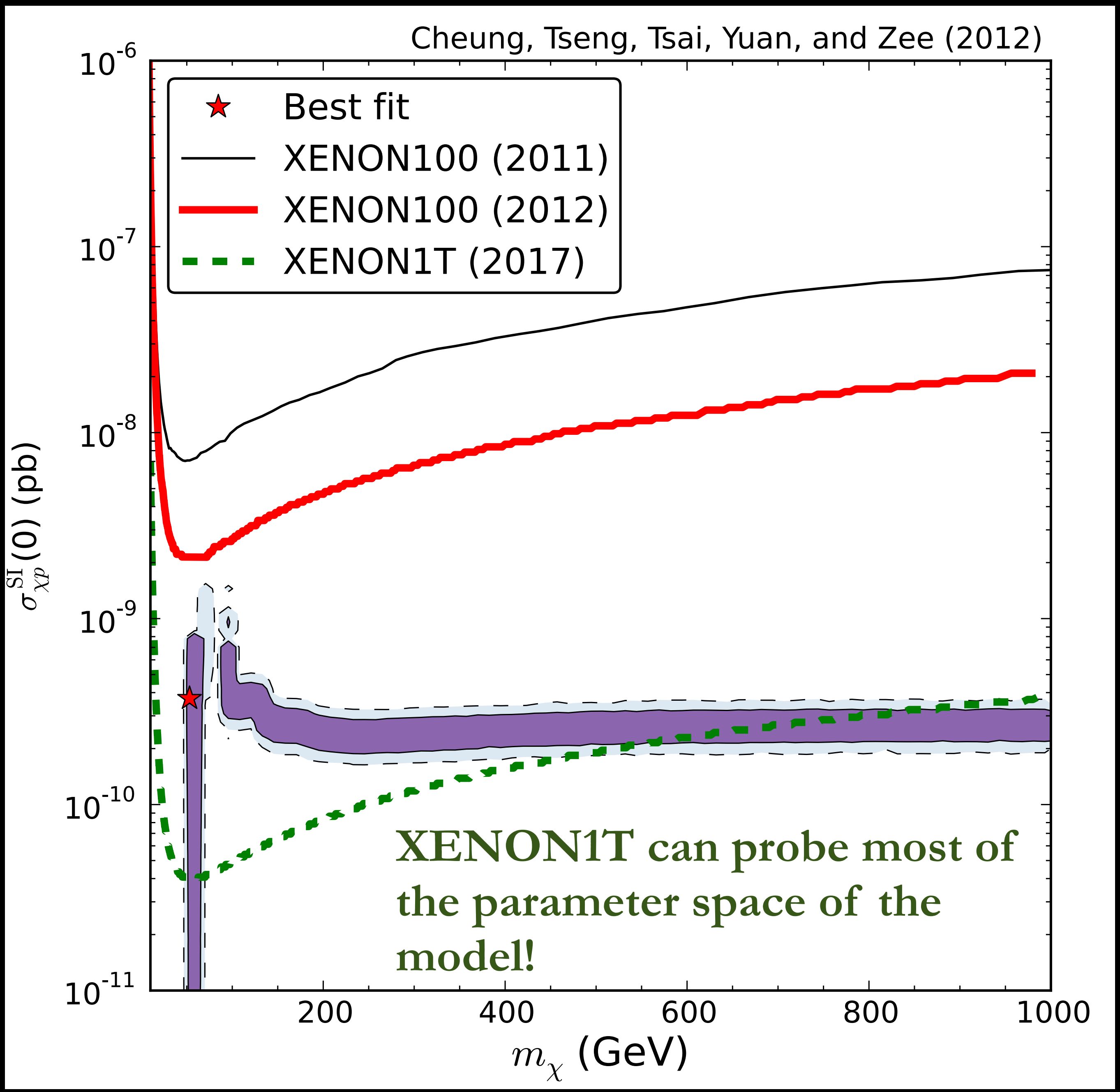
Global Analysis on SZ Model

- Relic Density (WMAP)
- XENON100 (2011,2012)
- Fermi-LAT diffuse γ-rays from 10 dSphs
- Invisible Higgs width
- Higgs mass

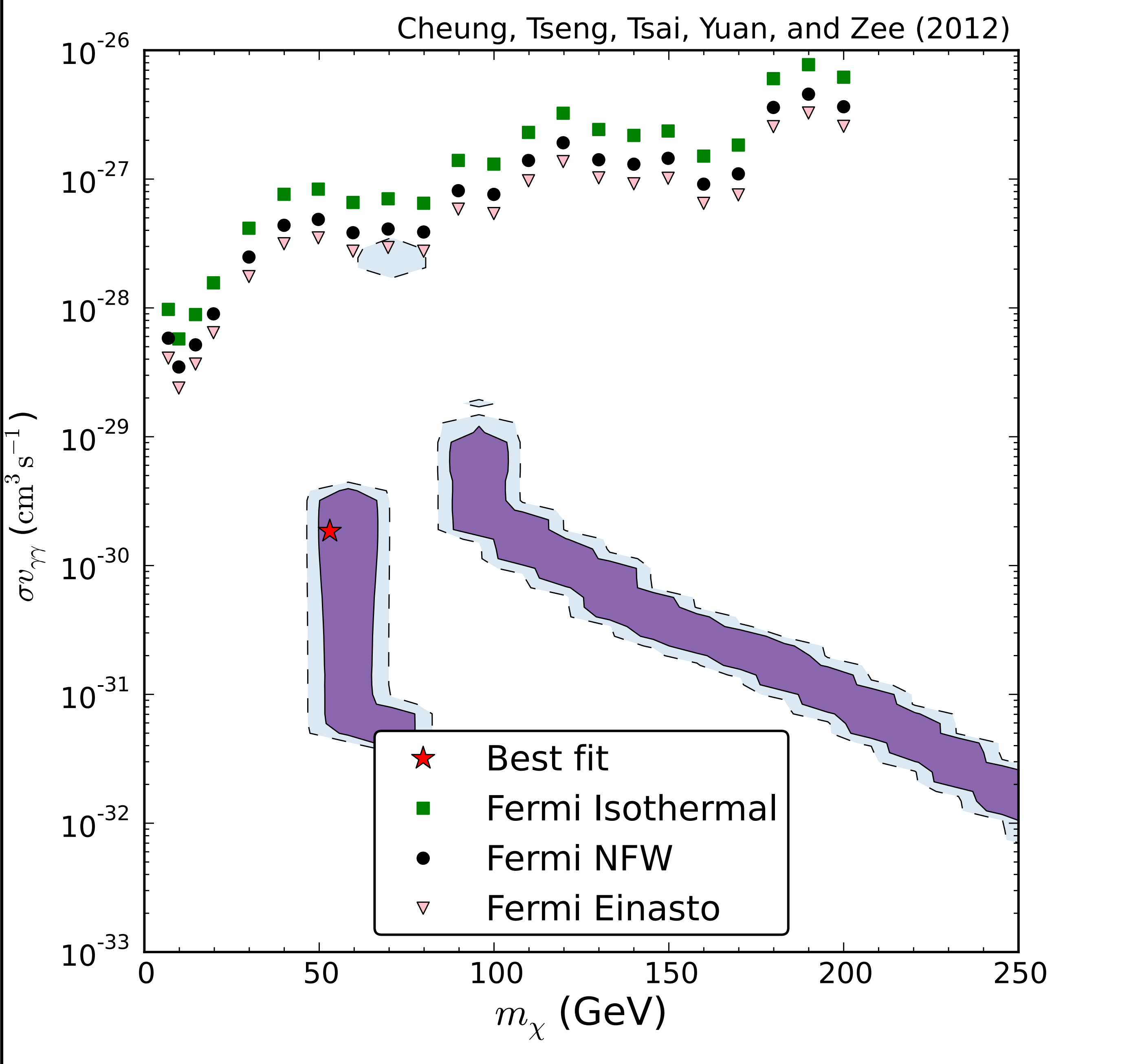
Profile Likelihood of SZ Model

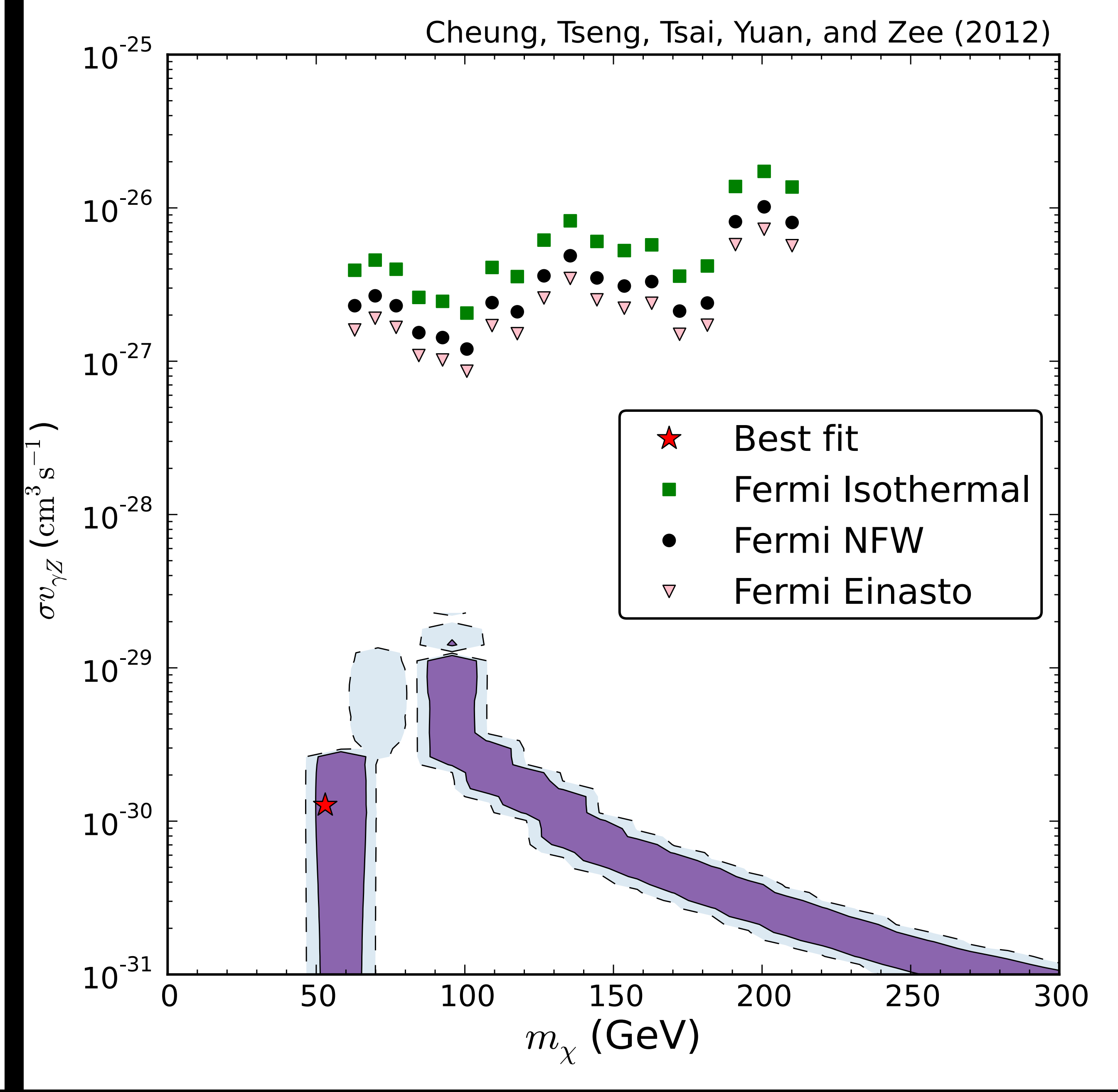


Spin-independent Elastic Cross Section



γ-Ray Line in SZ Model (1 -loop)





Fermi-LAT γ ray data is not sensitive to most of the parameter space yet.

Inert Higgs Doublet Model (IHDM)

Deshpande & Ma, 1978

- Employs two doublets with a Z_2 symmetry: All SM fields even, H_2 odd.

$$H_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + h + iG^0\right) \end{pmatrix} \quad , \quad H_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(S + iA) \end{pmatrix}$$

- Scalar Potential with Z_2 symmetry imposed

$$\begin{aligned} V &= \mu_1^2|H_1|^2 + \mu_2^2|H_2|^2 + \lambda_1|H_1|^4 + \lambda_2|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1^\dagger H_2|^2 \\ &+ \frac{\lambda_5}{2}\left\{(H_1^\dagger H_2)^2 + \text{h.c.}\right\} \quad . \end{aligned}$$

- DM candidate: S or A

- Parameter space of scalar sector

$$\mathcal{P} = \{m_h, m_S, m_A, m_{H^\pm}, \lambda_2, \lambda_L \equiv \frac{\lambda_3 + \lambda_4 + \lambda_5}{2}\}$$

Global Constraints

- **RC** (Relic Density & Colliders)
These include relic density for DM from WMAP 7 years measurement, EWPT (S and T variables), Higgs mass from LHC, invisible width for Higgs decay (if $h \to \chi\chi$ is opened), signal strength for diphoton mode, and monojet plus missing energy events from the CMS.

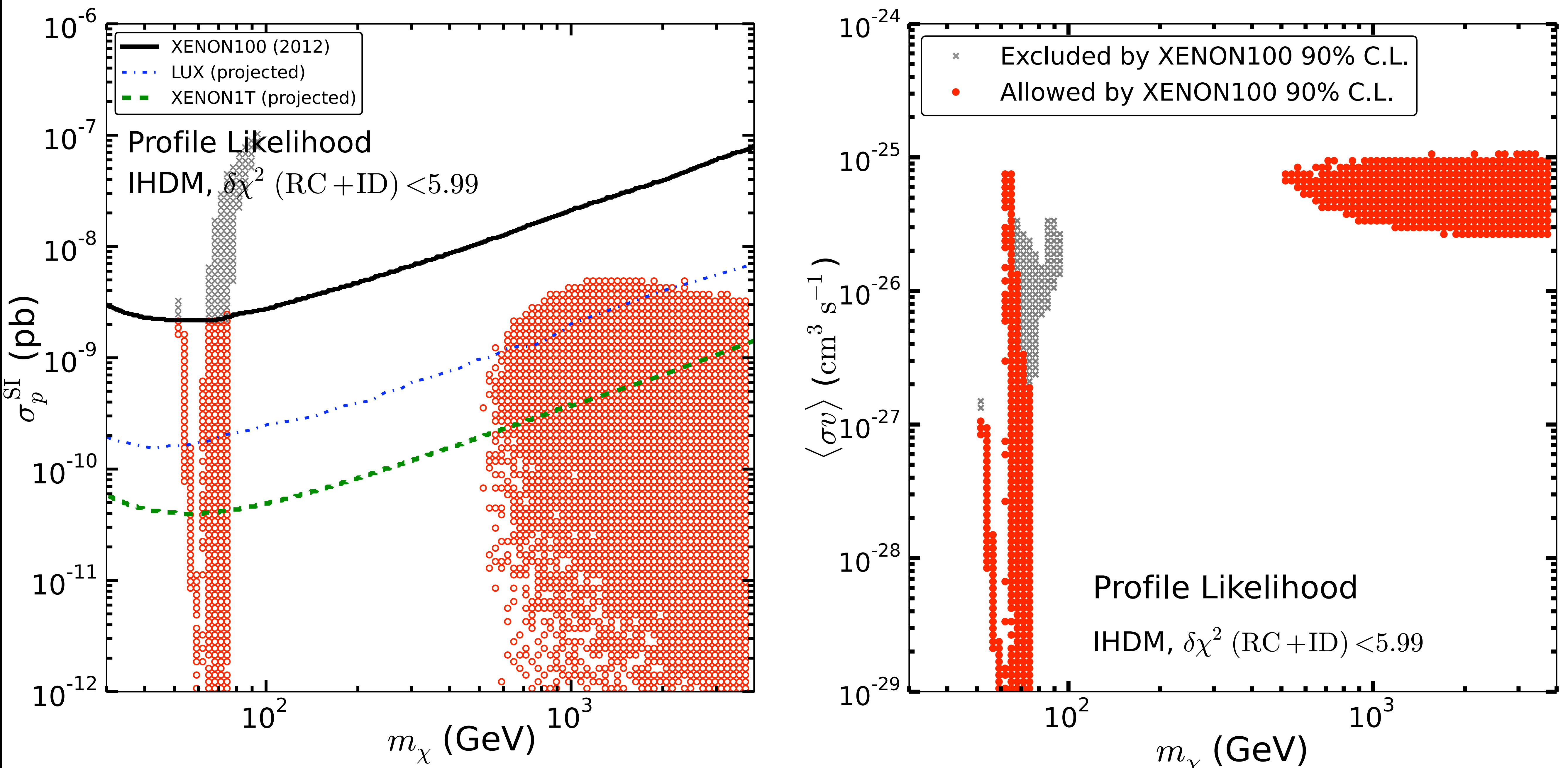
- **ID** (Indirect Detection)
The data set used in the global fittings include the Fermi-LAT γ-ray from 10 dSphs and Galaxy Center, the electron spectrum from PAMELA, the positron fraction $e^+/(e^+ + e^-)$ from AMS-02, as well as the total $(e^+ + e^-)$ flux from Fermi-LAT and HESS and the antiproton flux from PAMELA.

- **DD** (Direct Detection)
Upper limit from XENON100 (2012) for the spin-independent cross section versus DM mass.

- Theoretical Constraints
Perturbativity, unitarity, potential bounded from below, ... etc

Global Fits of IHDM

Arhrib, Tsai, Yuan, and TCY, 1310.0358



See Tsai's talk for more details.

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Original Higgs U(1) Model As Dark Sector

Chia-Feng Chang, Ernest Ma and TCY, [arXiv:1308.6071]

- The Model

Kinetic Mixing

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}\vec{W}_{\mu\nu} \cdot \vec{W}^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}C_{\mu\nu}C^{\mu\nu} - \frac{\epsilon}{4}B_{\mu\nu}C^{\mu\nu} \ ,$$

$$\mathcal{L}_{\text{scalar}} = |D_\mu \Phi|^2 + |D_\mu \chi|^2 - V_{\text{scalar}}(\Phi, \chi) \ ,$$

$$V_{\text{scalar}} = -\mu_\Phi^2 \Phi^\dagger \Phi + \lambda_\Phi \left(\Phi^\dagger \Phi\right)^2 - \mu_\chi^2 \chi^* \chi + \lambda_\chi \left(\chi^* \chi\right)^2 + \lambda_{\Phi\chi} \left(\Phi^\dagger \Phi\right) \left(\chi^* \chi\right) \ .$$

$$\Phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \ , \quad \chi(x) = \frac{1}{\sqrt{2}} \left(v_D + h_D(x)\right)$$

- SM Higgs and Dark Higgs Mixing

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ h_D \end{pmatrix} \ , \qquad \sin 2\alpha = \frac{2m_{12}^2}{m_1^2 - m_2^2} \ .$$

SM 126 GeV Higgs

Rich Higgs Phenomenology

- Higgs mixings implies non-standard Higgs decay

$$h_1 \to \gamma_D \gamma_D$$
$$h_1 \to h_2 h_2$$
$$h_1 \to h_2 h_2^* \to h_2 \gamma_D \gamma_D$$
$$h_1 \to h_2 h_2 h_2$$

- h_2 decays predominantly into two dark photons $h_2 \to \gamma_D \gamma_D$

- Dark photon may decay to light leptons through mixings $\gamma_D \to \bar{l} l \;\; (l = e, \mu)$

- This model predicts: non-standard modes of Higgs decay could be 4, 8, or even 12 leptons in the final states!

Higgs Decay Width

- SM Higgs total width contains two pieces

$$\Gamma_{h_1} = \cos^2\alpha \hat{\Gamma}_h + \Gamma_{h_1}^{NS} \ ,$$

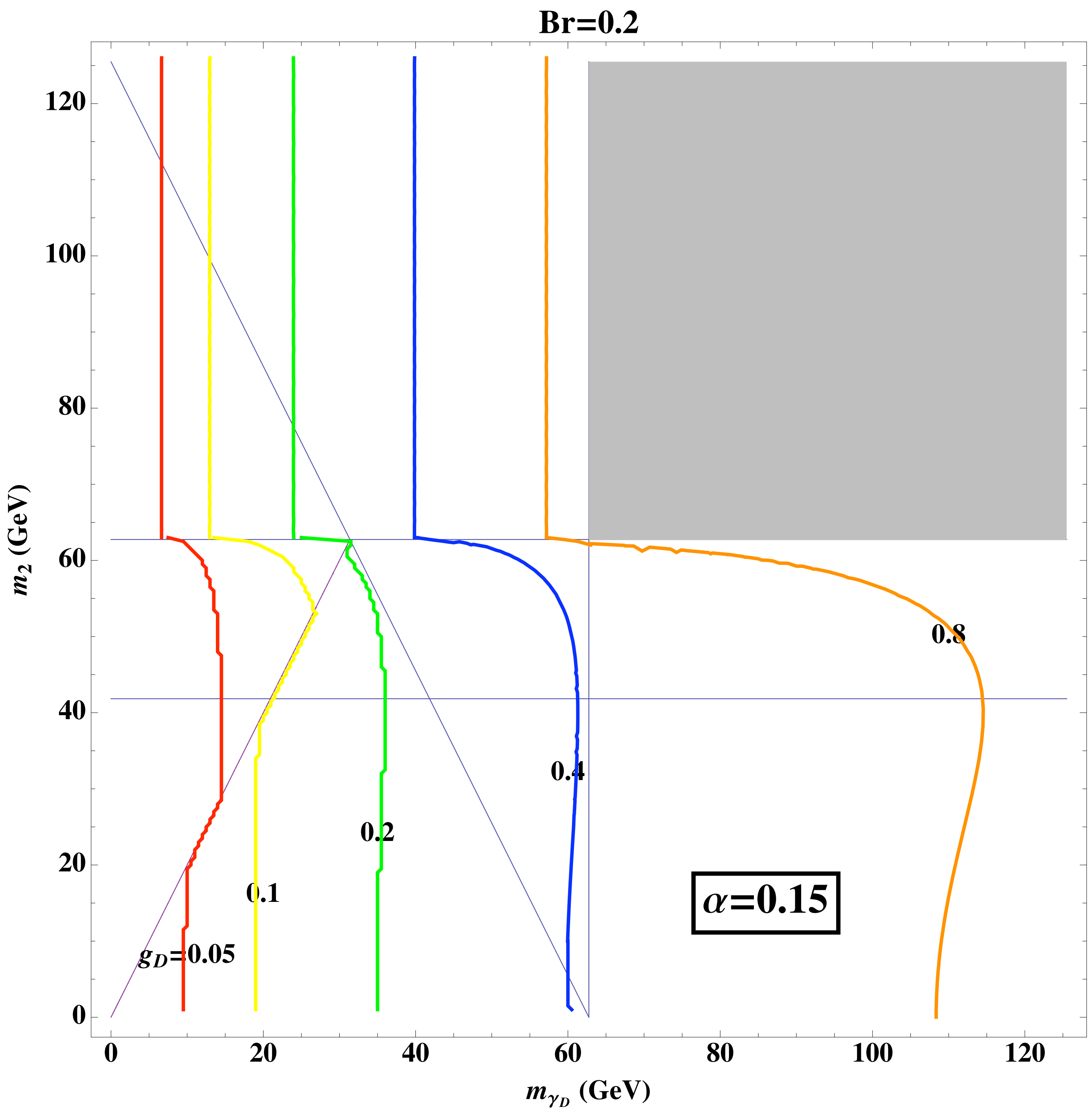
- Non-standard contributions from dark Higgs U(1) sector

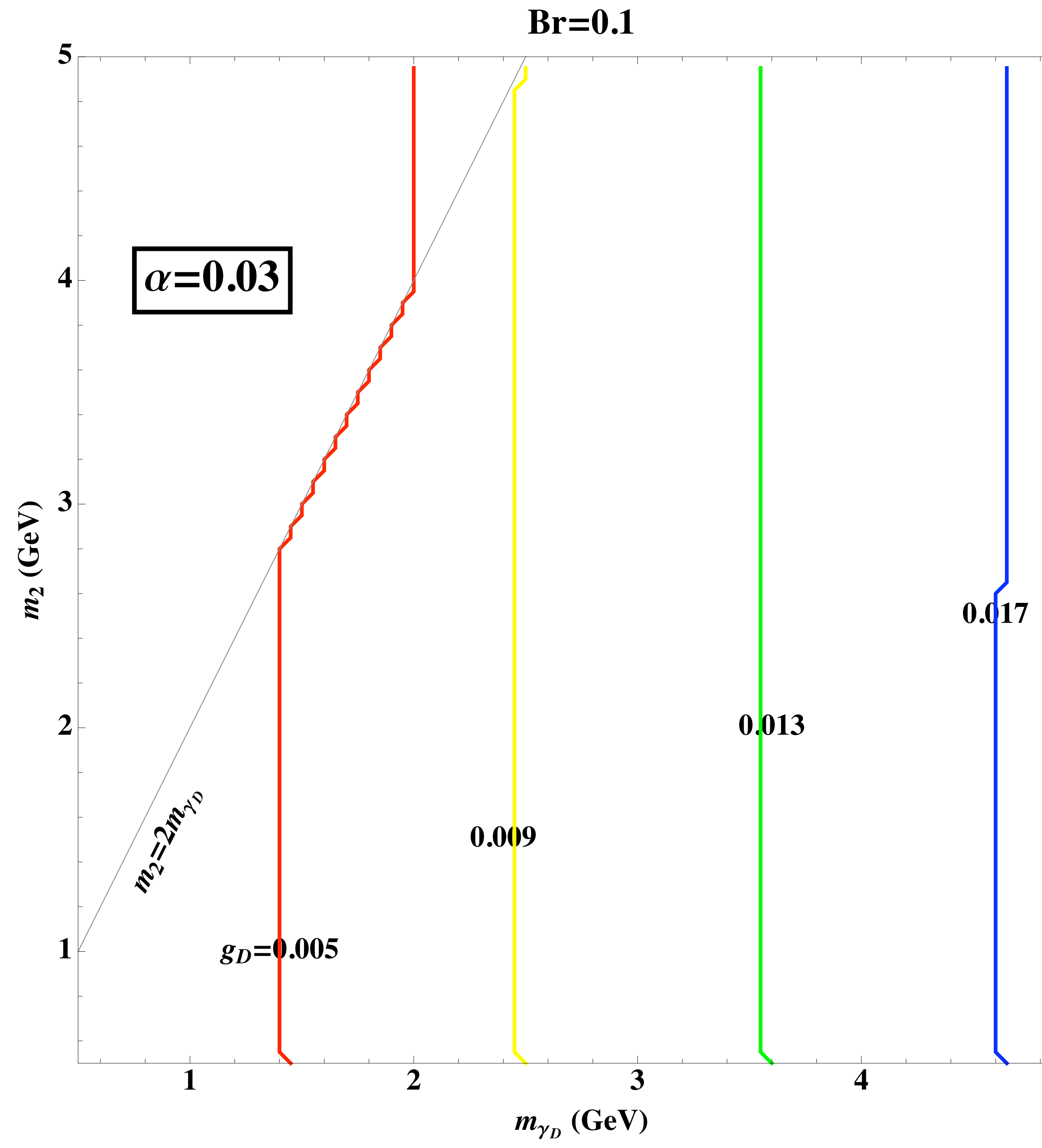
$$\Gamma_{h_1}^{NS} = \sin^2\alpha \hat{\Gamma}(h_1 \to \gamma_D \gamma_D) + \Gamma(h_1 \to h_2 h_2) + \Gamma(h_1 \to h_2 \gamma_D \gamma_D) + \Gamma(h_1 \to h_2 h_2 h_2) + \cdots$$

- The SM Higgs width is 4.03 MeV (Theory) while LHC constrains the non-standard Higgs width to be less than 1.2 MeV (20 % or so)

Contour Plots for non-standard branching ratio for standard model Higgs

Chia-Feng Chang, Ernest Ma and TCY, [arXiv:1308.6071]





Goldstone Boson (GB) as Cosmic Neutrino Impostor

- Temperature fluctuation in CMB depends on cosmic energy density hence on the effective number of neutrino species $N_{\rm eff}$
- Planck ⊕ WMAP9 Polarization ⊕ high-l ACT & SPT:

$N_{\rm eff} = 3.36 \pm 0.34$

$$\rho_\nu = N_{\rm eff}\,\frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\rho_\gamma$$

- Weinberg (PRL 110, 241301, 2014) suggested GB may be masquerading as *fractional* (0.39) cosmic neutrinos, provided that they must remain thermal equilibrium with ordinary SM particles until after the era of muon annihilation so that the Goldstone particle temperature matches with the neutrino temperature.

Why fractional 0.39?

- At equilibrium at high temperature, relative to neutrino+antineutrino, neutral GB counts effectively as follows

$$g^*=(2 + 2*7/8 + 1+ ...) = 2 (1 + 7/8 + 1/2 + ...)$$

$$\Rightarrow g_{GB}/g_\nu=(1/2) / (7/8) = 4/7!$$

- Suppose GB decoupled not far above muon annihilation, from that time on, GB is then free propagating across the Universe with constant Ta.

- Just before muon annihilation, cosmic entropy density is

$$s \sim (1 + 7/4 +7/4 + 3*7/8)T^3 \sim (57/8)\ T^3$$

Right after muon annihilation,

$$s \sim (1 + 7/4 + 0 + 3*7/8)T^3 \sim (43/8)\ T^3$$

- To remain constant sa^3, Ta must be increased by a factor $(57/43)^{1/3}$ for particles still remain equilibrium like neutrino, photon and electron/positron.

- Despite GB went out of equilibrium before muon annihilation, it still contributes to cosmic energy density ($\sim T^4$) with an effective neutrino number $\Delta N_{eff} = (4/7) * ((43/57)^{1/3})^4 = 0.39!$

Global Dark U(1) Model

S. Weinberg, PRL 110, 241301 (2013)

- Add a complex U(1) scalar singlet S to SM

Higgs Portal

$$\mathcal{L} = (\partial_\mu S^\dagger)(\partial^\mu S) + \mu^2 S^\dagger S - \lambda(S^\dagger S)^2 - g(S^\dagger S)(\Phi^\dagger\Phi) + \mathcal{L}_{\rm sm}$$

$$S(x) = \frac{1}{\sqrt{2}}\left(\langle r\rangle + r(x)\right) e^{i2\alpha(x)} \qquad \Phi(x) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \langle\phi\rangle + \phi(x)\end{pmatrix}$$

Radial field   Goldstone boson   SM Higgs

- SM/Dark Higgs Mixing:

$$\begin{pmatrix} H(x) \\ \sigma(x)\end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix} \phi(x) \\ r(x)\end{pmatrix}$$

$$m_H^2 \approx 2\lambda_{\rm sm}\langle\phi\rangle^2\,, \quad m_\sigma^2 \approx 2\lambda\langle r\rangle^2\,, \quad \theta \approx \frac{g\langle r\rangle\langle\phi\rangle}{m_H^2 - m_\sigma^2}\,.$$

- New couplings

$$\mathcal{L}_{H\alpha\alpha} = \frac{\theta}{\langle r\rangle} H\,(\partial_\mu\alpha)(\partial^\mu\alpha)\,,$$

$$\mathcal{L}_{\sigma\alpha\alpha} = \frac{1}{\langle r\rangle}\sigma\,(\partial_\mu\alpha)(\partial^\mu\alpha)\,,$$

$$\mathcal{L}_{H\sigma\sigma} = -\frac{g}{2}\langle\phi\rangle\, H\,\sigma^2\,.$$

Higgs Invisible Width

- Recall non-standard Higgs width is constrained to be less than 1.2 MeV
- One can use this to constrain the parameter space of the dark global U(1) sector

Muon Decoupling

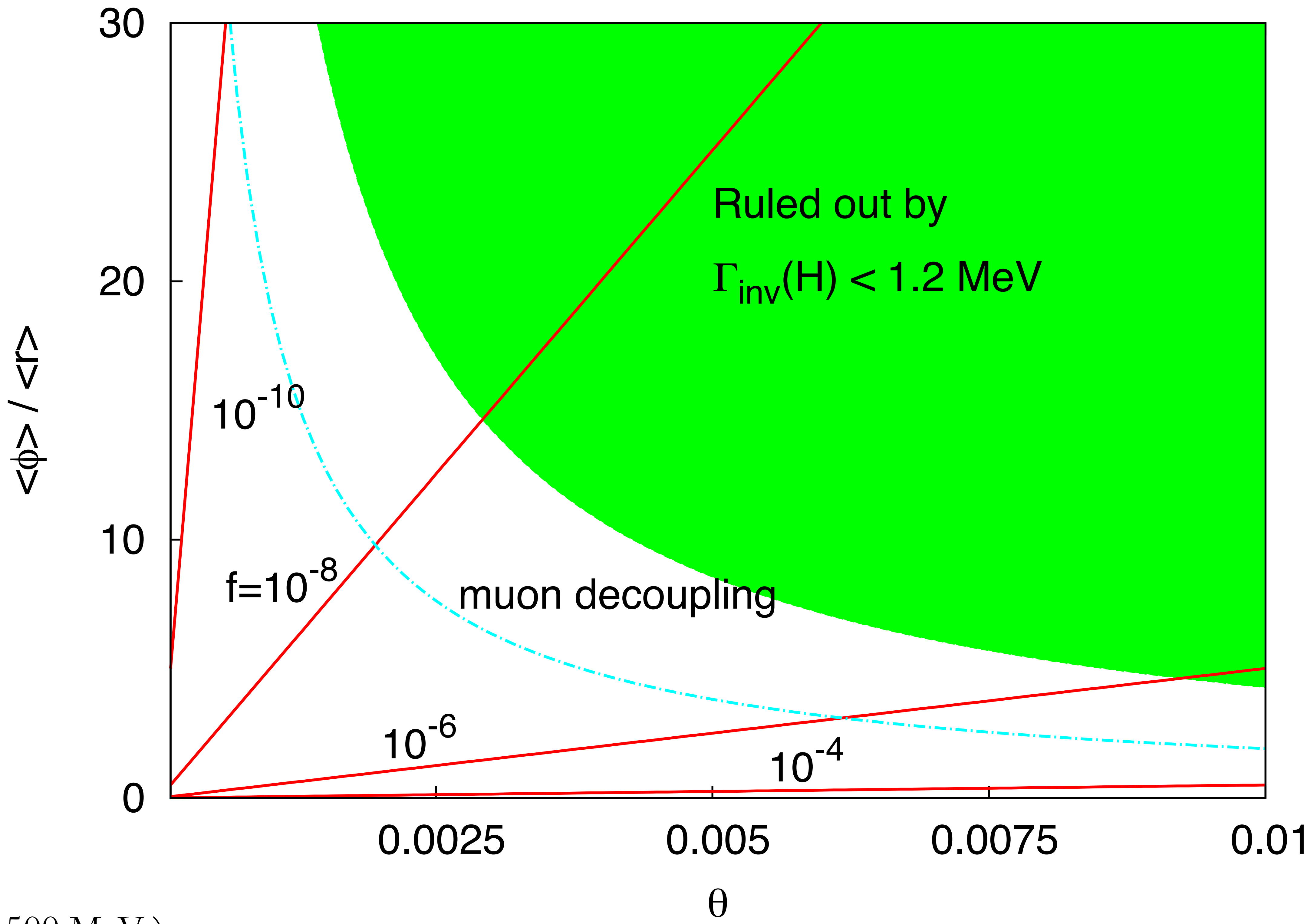
- Hubble expansion rate ~ Goldstone Boson Annihilation to muon pair through Higgs exchange

As $k_B T \approx m_\mu$; we have $\frac{g^2 m_\mu^7 m_{\rm PL}}{m_\sigma^4 m_H^4} \approx 1$

- For g = 0.005, m_H = 125 GeV, m_σ ~ 500 MeV (Weinberg). Note that one can express g^2 in terms of mixing angle θ, VEV ratio <Φ>/<r> and mass m_σ.

Constraints

$$f \equiv \frac{\Gamma(\sigma \to \pi\pi)}{\Gamma(\sigma \to \alpha\alpha)} = \theta^2 \frac{4}{27} \frac{\langle r \rangle^2}{\langle \phi \rangle^2} \left(1 - \frac{4m_\pi^2}{m_\sigma^2}\right)^{1/2} \left(1 + \frac{11 m_\pi^2}{2 m_\sigma^2}\right)^2$$

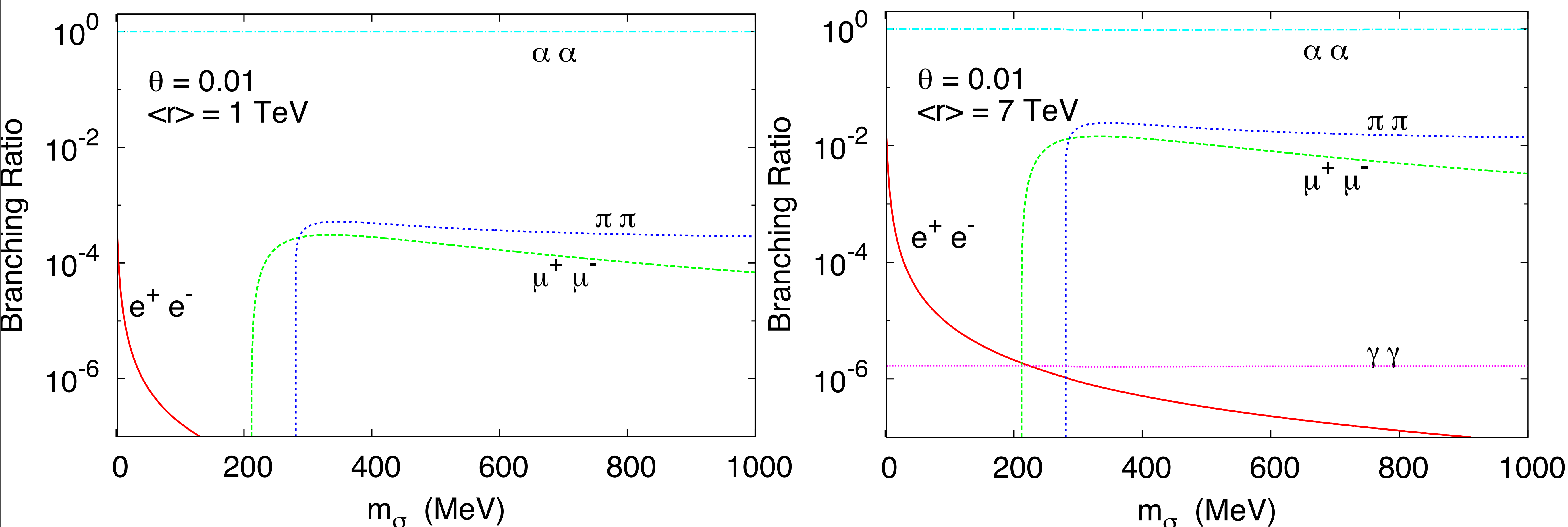


(m_σ = 500 MeV)

(Cheung, Keung, TCY, 1308.4235)

Decay of the σ field

- The dominant decay mode of σ field is the invisible Goldstone pair.
- However, through Φχ mixing, the radial field can decay into SM particles.



Collider Signature

- Higgs production: gg fusion or associated hW

$$gg \to H \to \sigma\sigma \to (\pi\pi)(\alpha\alpha)$$
$$pp \to WH \to (l\nu)(\sigma\sigma) \to (l\nu)(\pi\pi + \alpha\alpha)$$

- For light σ, the pion pair is very collimated with $M_{\pi\pi} \approx m_\sigma$, while the Goldstone boson α pair is invisible as MET.
- Possible Signals:
  - a microjet (τ jet) + MET (charged pions not resolved)
  - charged pion tracks + MET (if charged pions can be resolved)
  - 4 collimated photons + MET (neutral pions)
  - For associated WH case, additional charged lepton may be act as an efficient trigger for the event
- Detailed detector simulation may be interesting.

Cross Section

$$pp \to H \to \sigma\sigma \to (\pi\pi)(\alpha\alpha)$$

TABLE I. Cross sections in fb for the gluon fusion process $pp \to H \to \sigma\sigma \to (\pi\pi)(\alpha\alpha)$ and the associated process $pp \to WH \to (\ell\nu)(\sigma\sigma) \to (\ell\nu)(\pi\pi + \alpha\alpha)$ at the LHC-8 and LHC-14 with the selection cuts described in the text. We choose $m_\sigma = 500$ MeV.

$\langle r \rangle$	$B(\sigma \to \pi\pi)$	Cross Section (fb) LHC-8		Cross Section (fb) LHC-14	
(TeV)		gluon fusion	WH	gluon fusion	WH
3	3.72×10^{-3}	0.16	0.013	0.39	0.024
4	6.58×10^{-3}	0.27	0.022	0.68	0.043
5	1.02×10^{-2}	0.42	0.034	1.05	0.067
6	1.46×10^{-2}	0.60	0.049	1.50	0.095
7	1.97×10^{-2}	0.80	0.065	2.00	0.13

Summary

- Dark sector physics is very rich. Dark particle can be generic dark matter, dark Higgs, dark photon, dark goldstone particle, ...
- Dark matter is NOT detected yet, despite strong evidences from cosmological/astrophysical observations involved many different scales.
- Many theoretical particle dark matter models can now be probed by direct detection experiments like LUX, XENON100, CDMS, etc. by indirect detection experiments like AMS-02, FermiLAT, etc. as well as LHC.
- Non-standard Higgs decay modes (in particular multilepton+MET, pion pair + MET) are important to constrain dark Higgs, dark photon as well as dark Goldstone boson physics.
- Just like the two *clouds* of blackbody radiation and luminiferous ether over classical physics at the beginning of 20^{th} century led to the discovery of *quantum mechanics* and *relativity*, the few *clouds* presently shadow over the two standard models of particle physics and cosmology may eventually lead to revolutionary discoveries.
- Keep one's mind open for alternatives, like non-WIMP axions or pure gravity interpretation!

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