Review on Cosmology : Dark matter and radiation

Kazunori Nakayama
(University of Tokyo)

2012/3/20, Kyoto University

- 宇宙観測

  Dark matter, Dark energy, Baryon asymmetry

  Inflation, ...

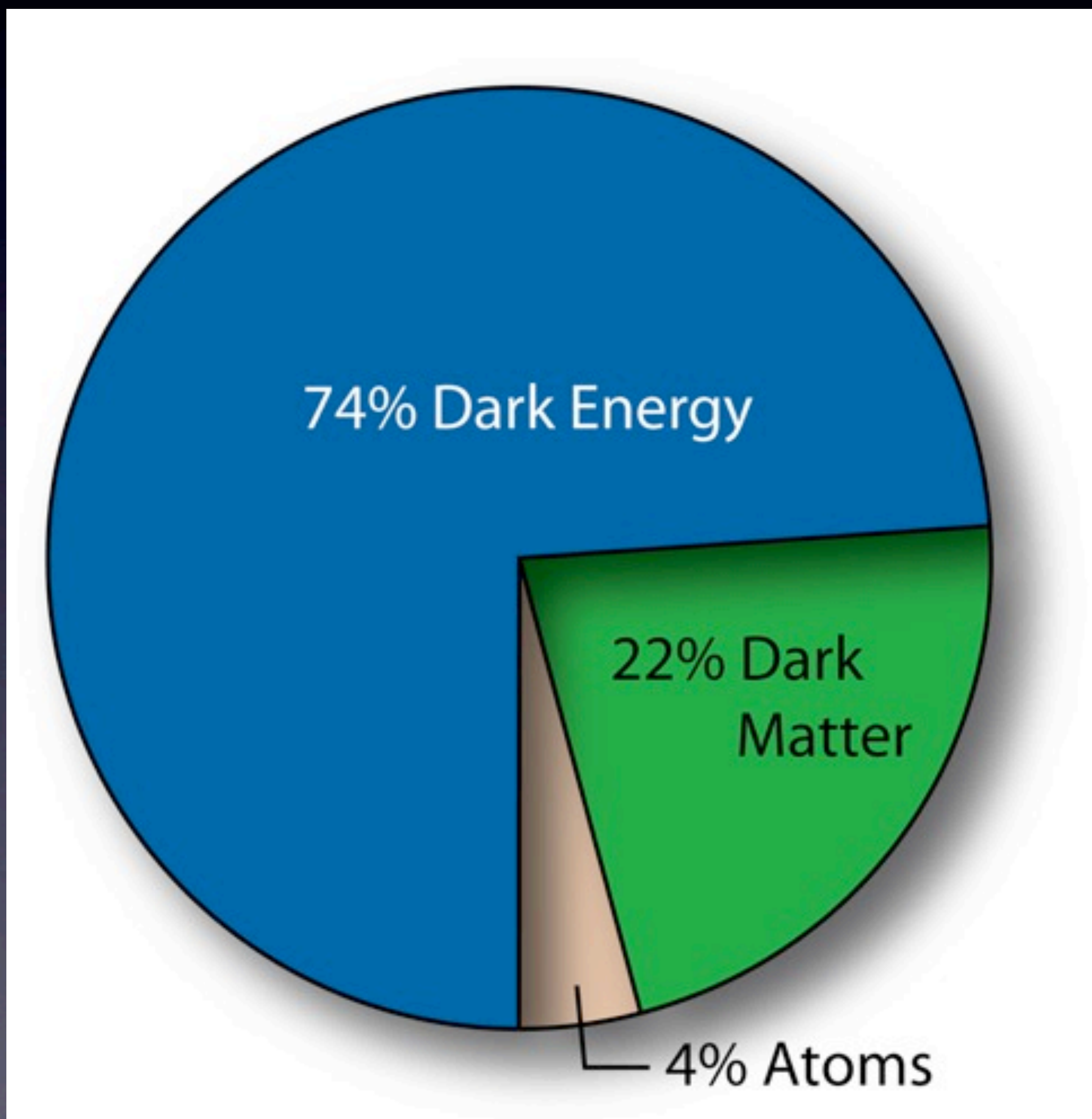
  100% New Physics はある

  (必ずしもTeVの物理と関係するとは限らない)

- 比較的最近の話題 (anomaly?) から
  - CMB：特にdark radiation
  - DM direct detection
  - DM indirect detection

Dark radiation

Energy content



74% Dark energy

22% Dark matter

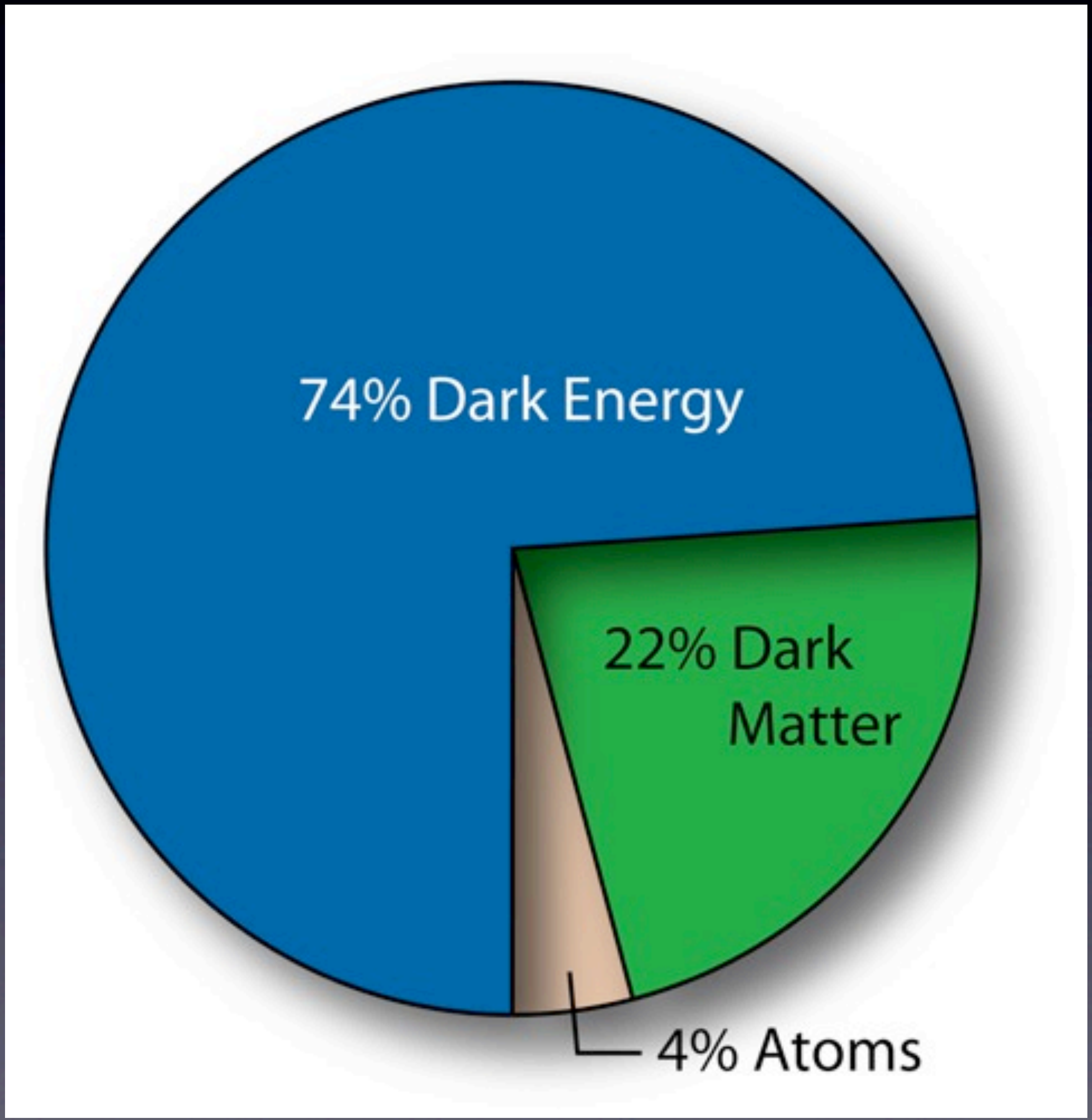
4% Baryon

0.1% Radiation

Photon

Neutrino

Energy content



74% Dark energy

22% Dark matter

4% Baryon

0.1% Radiation

Photon

Neutrino

Dark radiation?

Neff

- Parametrize radiation energy in the Universe

$$\rho_{\rm rad} = \left[1 + N_{\rm eff}\frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\right]\rho_\gamma \qquad \rho_\gamma = \frac{\pi^2}{15}T_\gamma^4$$

$N_{\rm eff}$: effective number of neutrinos

$N_{\rm eff} = 3$ in the standard model

$N_{\rm eff} \neq 3$ if extra radiation component exists

- Observational constraints on Neff : BBN and CMB

Neff from BBN

- T~1MeV $p + e \leftrightarrow n + \nu$ freezeout

$$\Gamma \sim G_F^2 T^5 \longleftrightarrow H \sim T^2/M_P$$

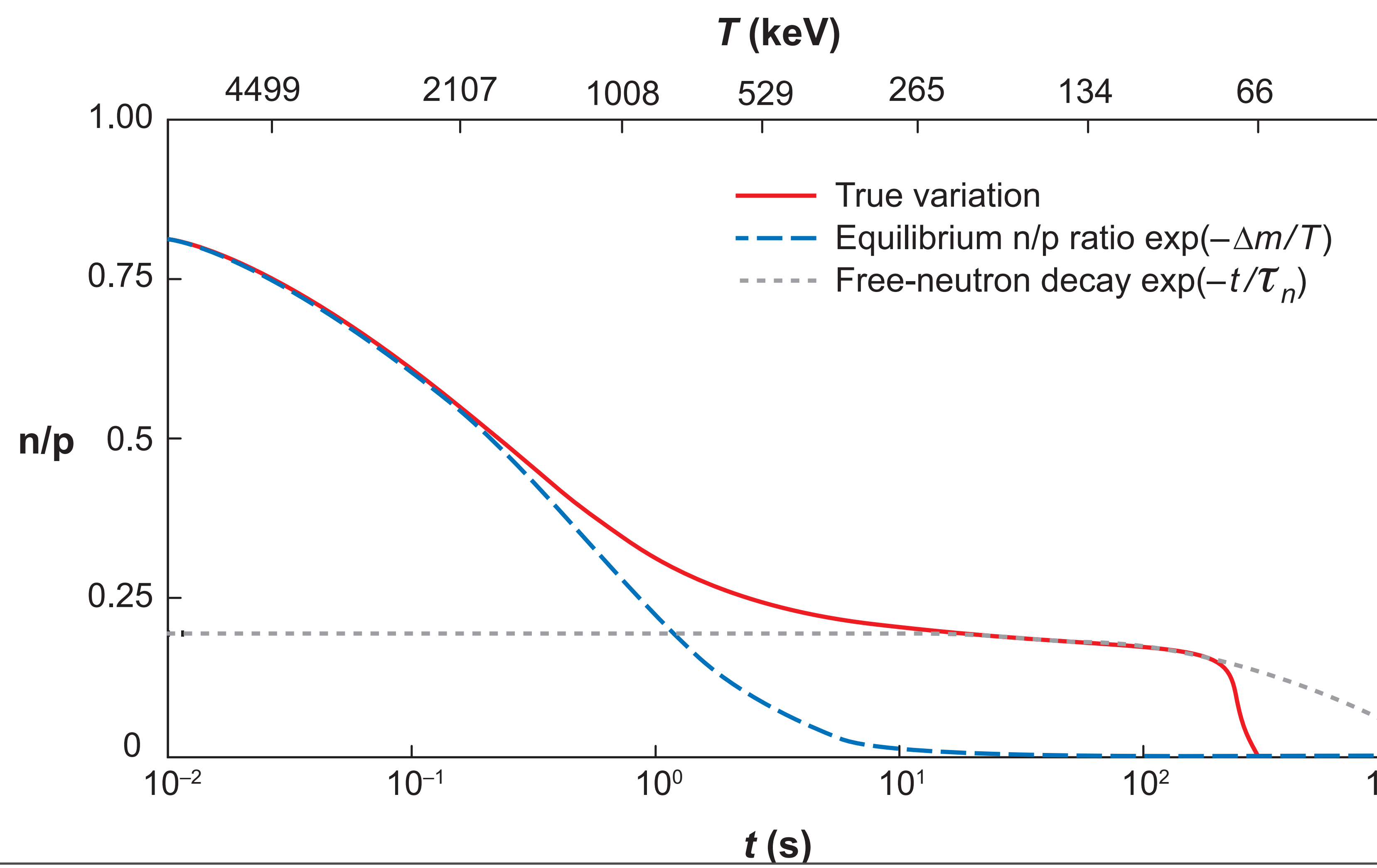
$\Rightarrow$ n/p ratio fix $\Rightarrow$ 4He

- Extra radiation :

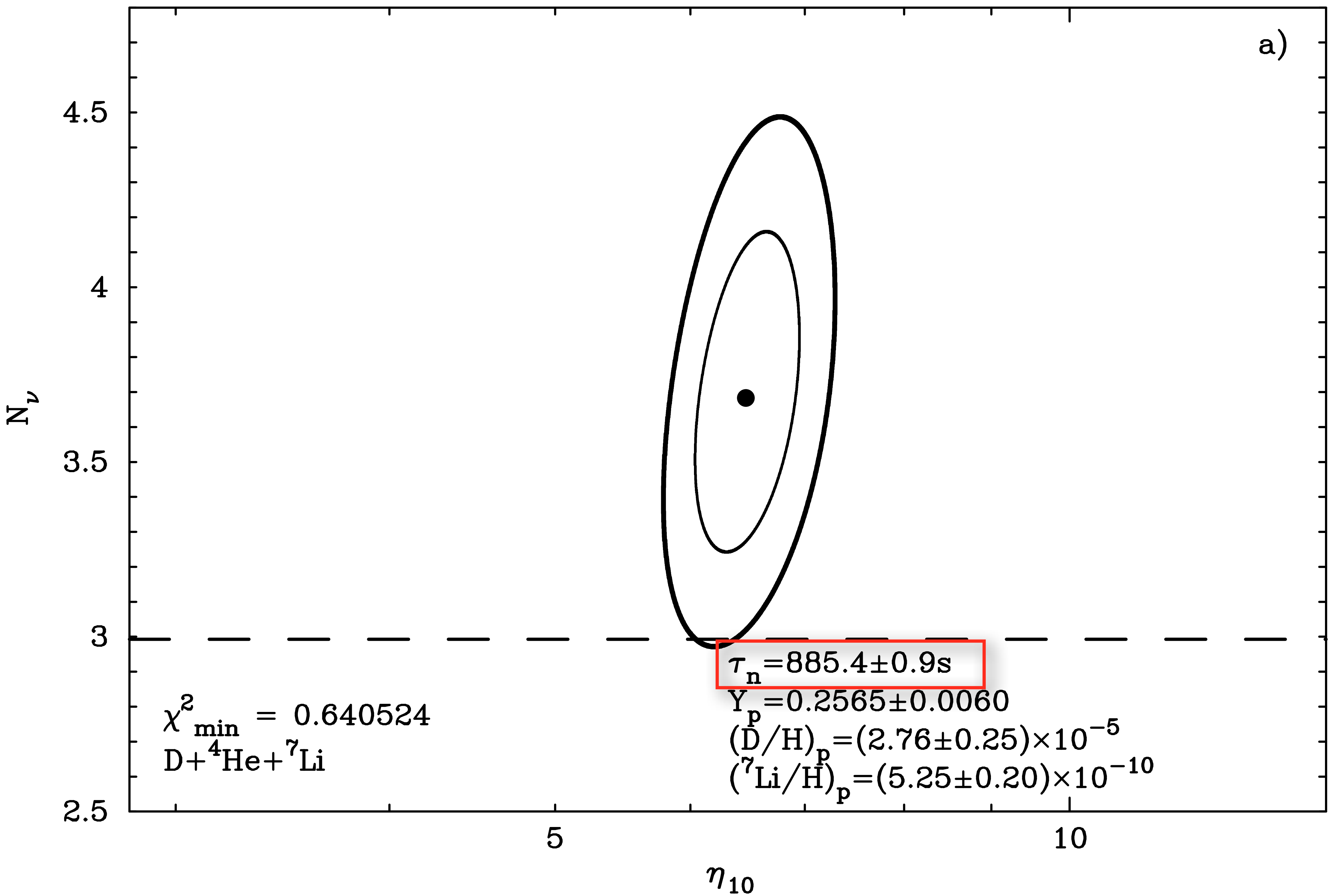
$H \nearrow \Rightarrow T_f \nearrow$

$\Rightarrow n/p$ ratio $\nearrow$

$\Rightarrow$ 4He $\nearrow$

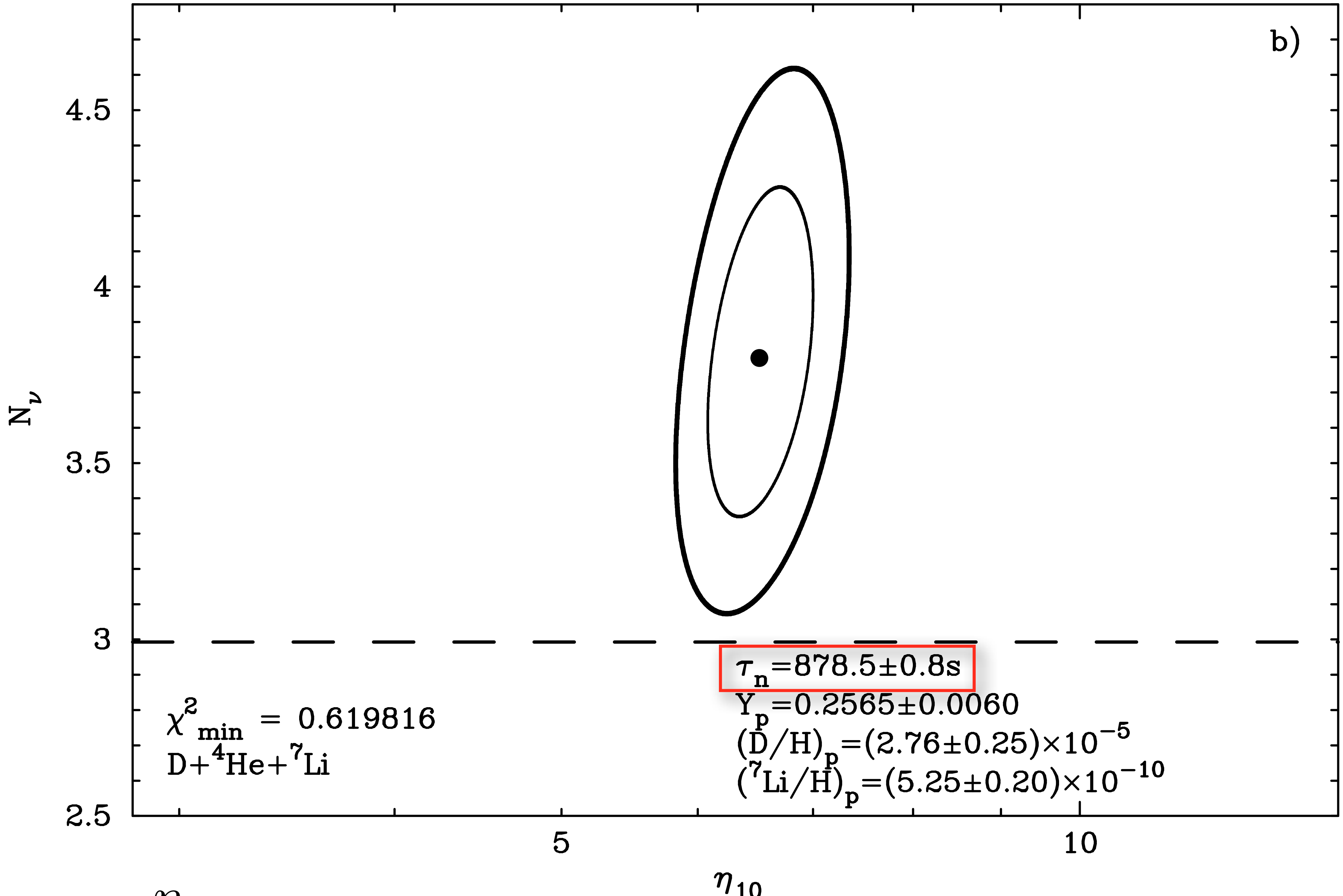


Izotov, Thuan, 1001.4440



$$\eta_{10} = \frac{n_B}{n_\gamma} \times 10^{10}$$

$$N_{\rm eff} = 3.68^{+0.80}_{-0.70}\ (2\sigma)$$

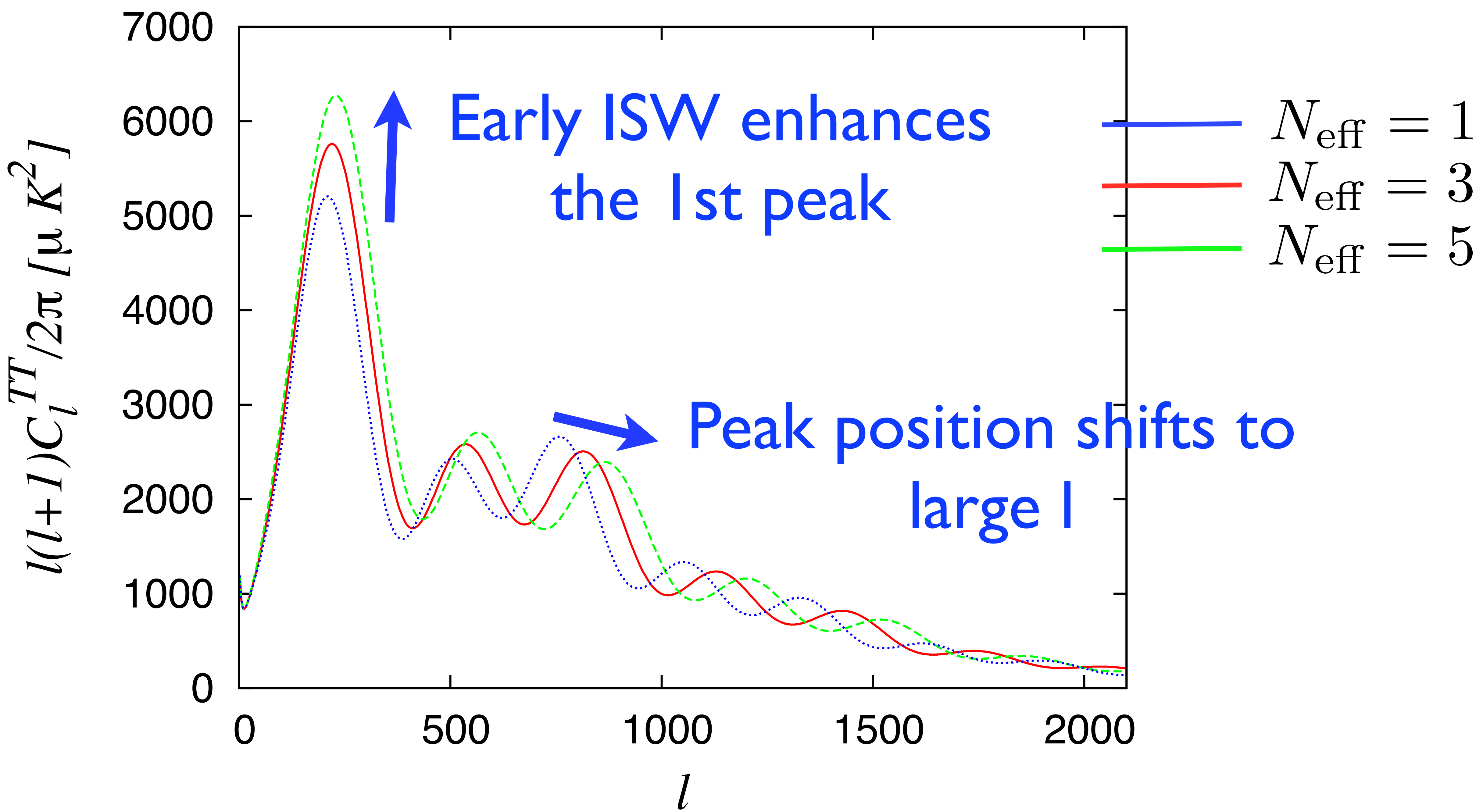


$$\eta_{10} = \frac{n_B}{n_\gamma} \times 10^{10}$$

$$N_{\rm eff} = 3.80^{+0.80}_{-0.70}\ (2\sigma)$$

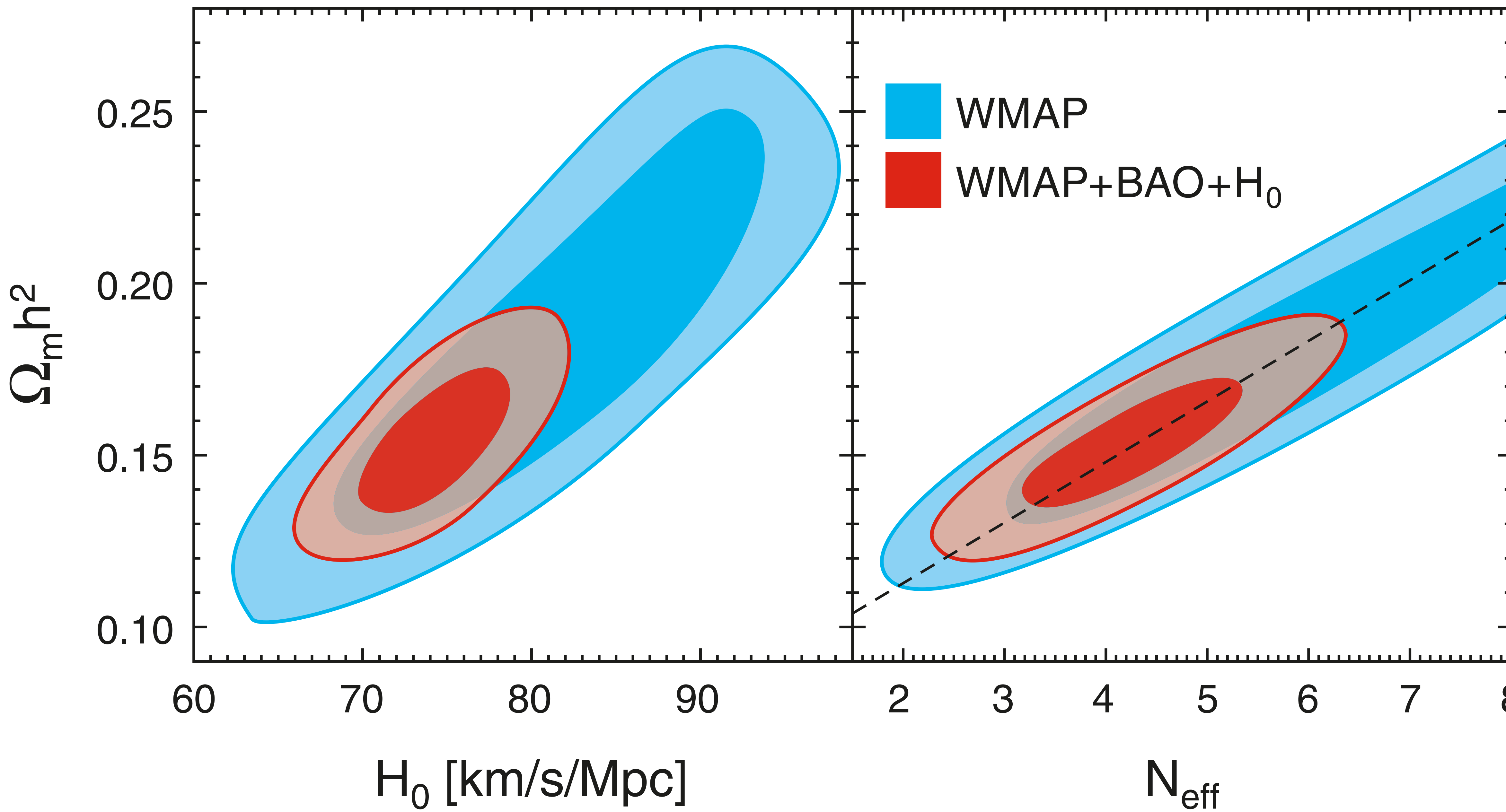
Neff from CMB

- Extra radiation → 1. Shift of the peak position
  2. Early ISW

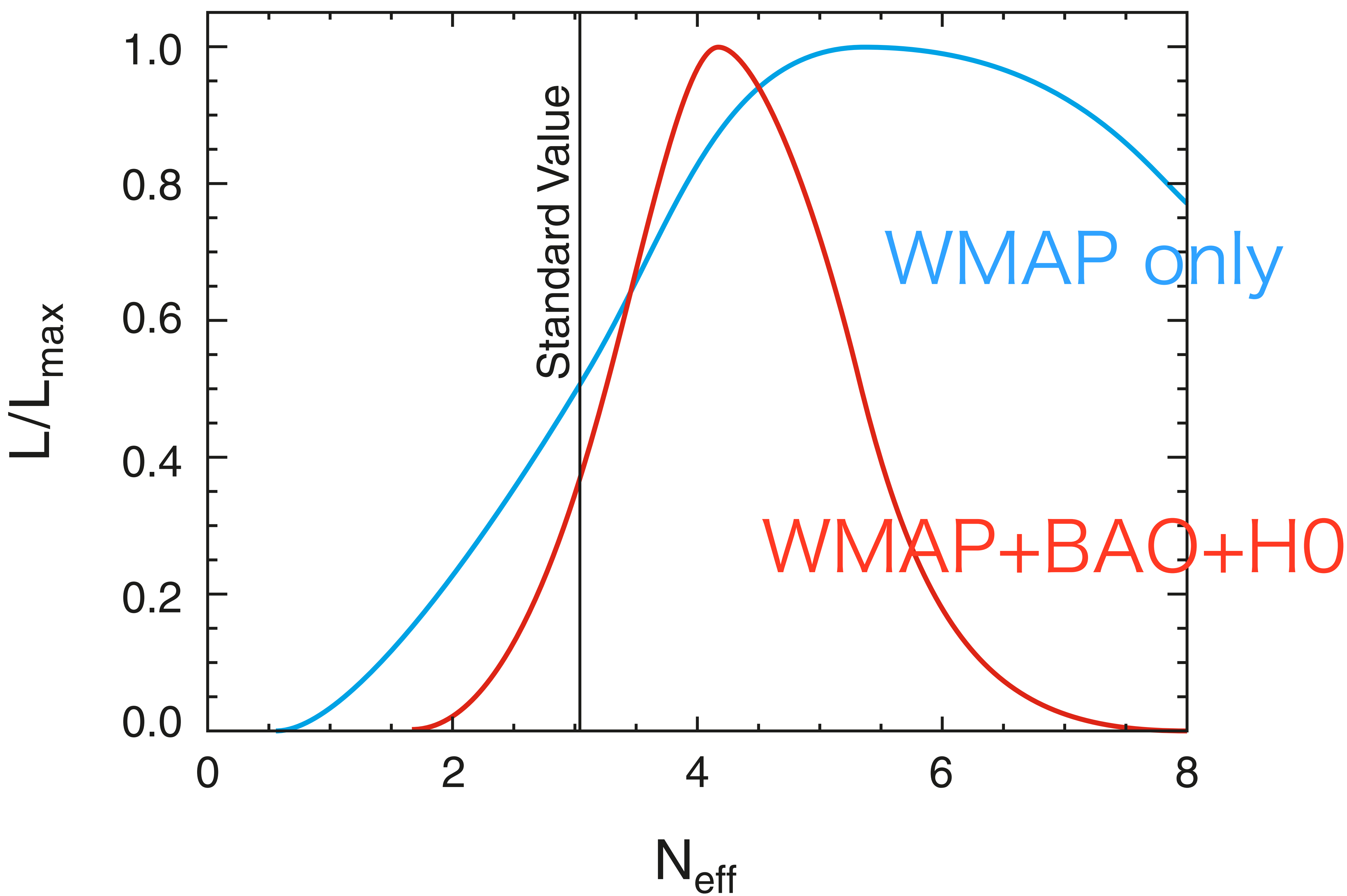


Ichikawa, Sekiguchi, Takahashi, 2008

WMAP 7yr

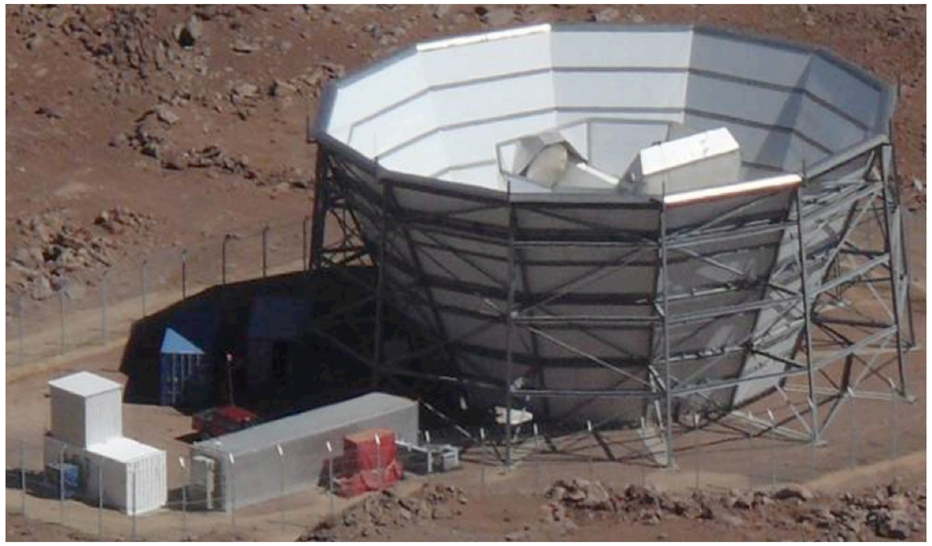


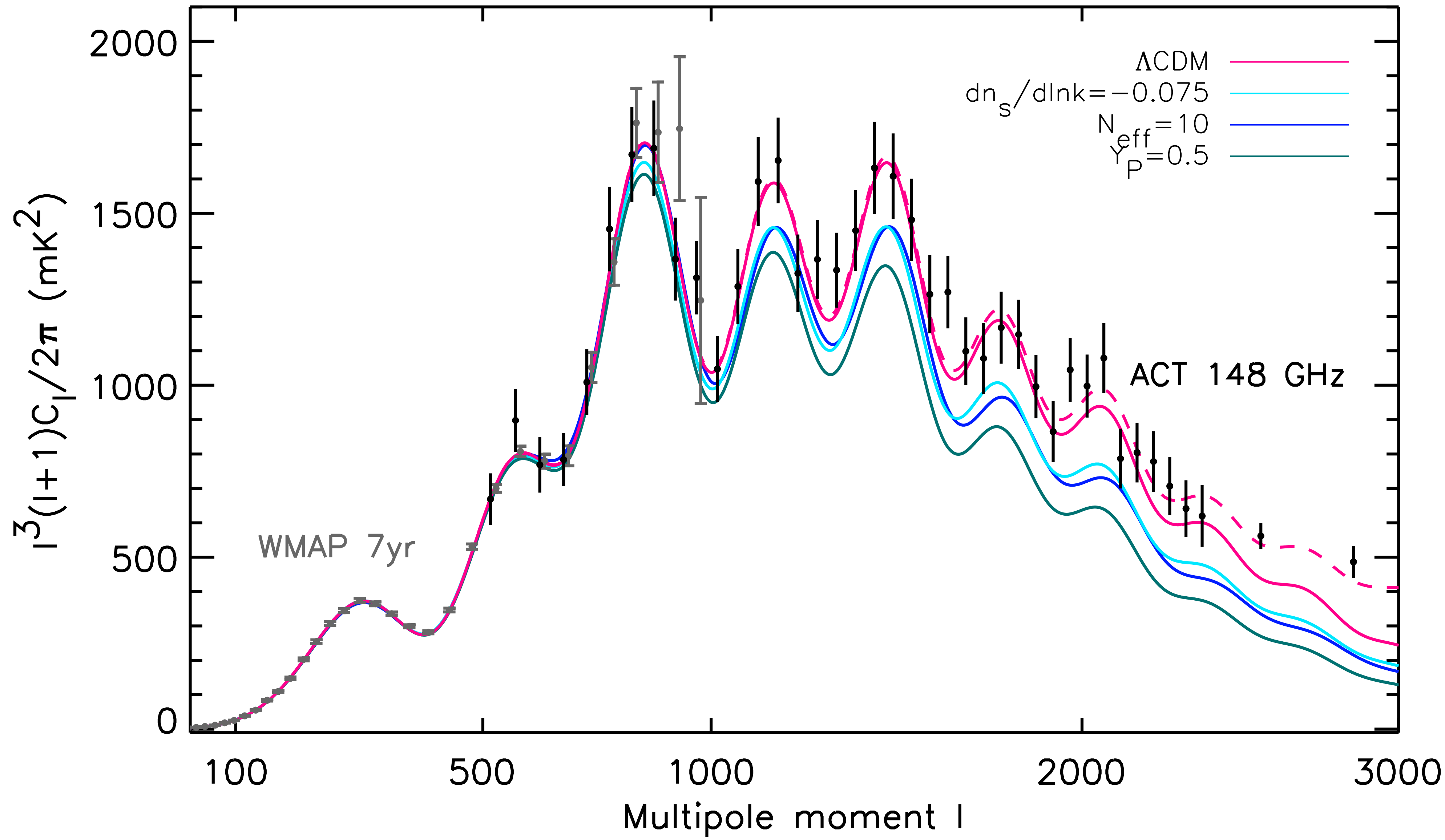
Komatsu et al, 2010



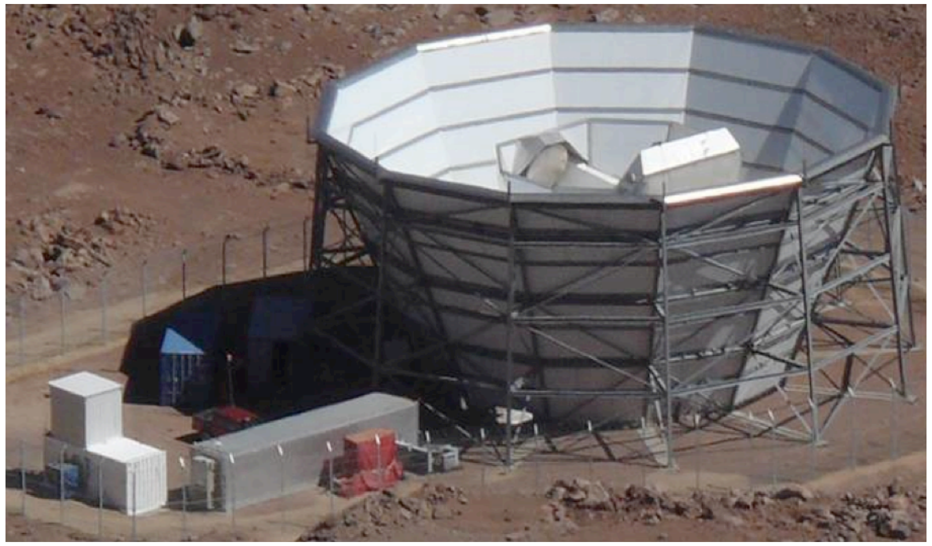
$N_{\rm eff} = 4.32^{+0.86}_{-0.88}$ **(68%CL) WMAP+BAO+H0**

ACT



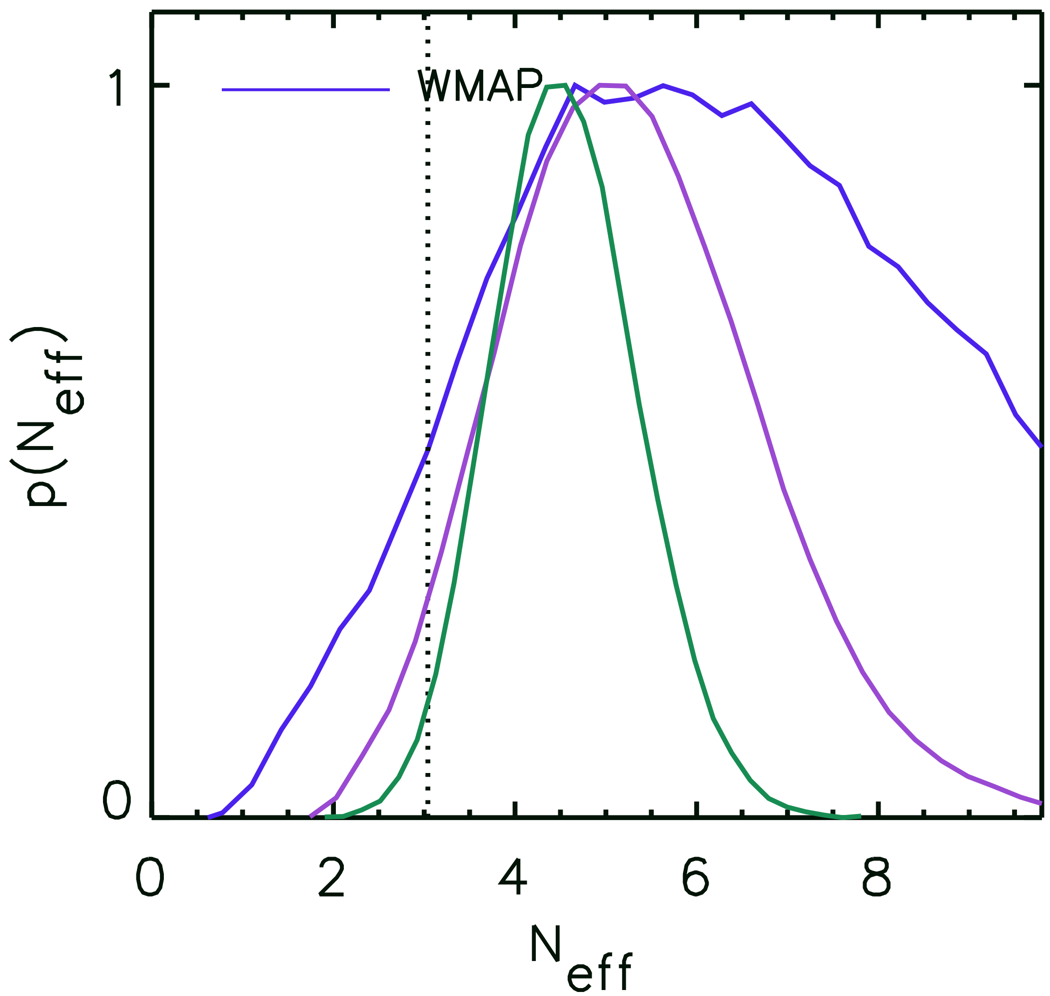


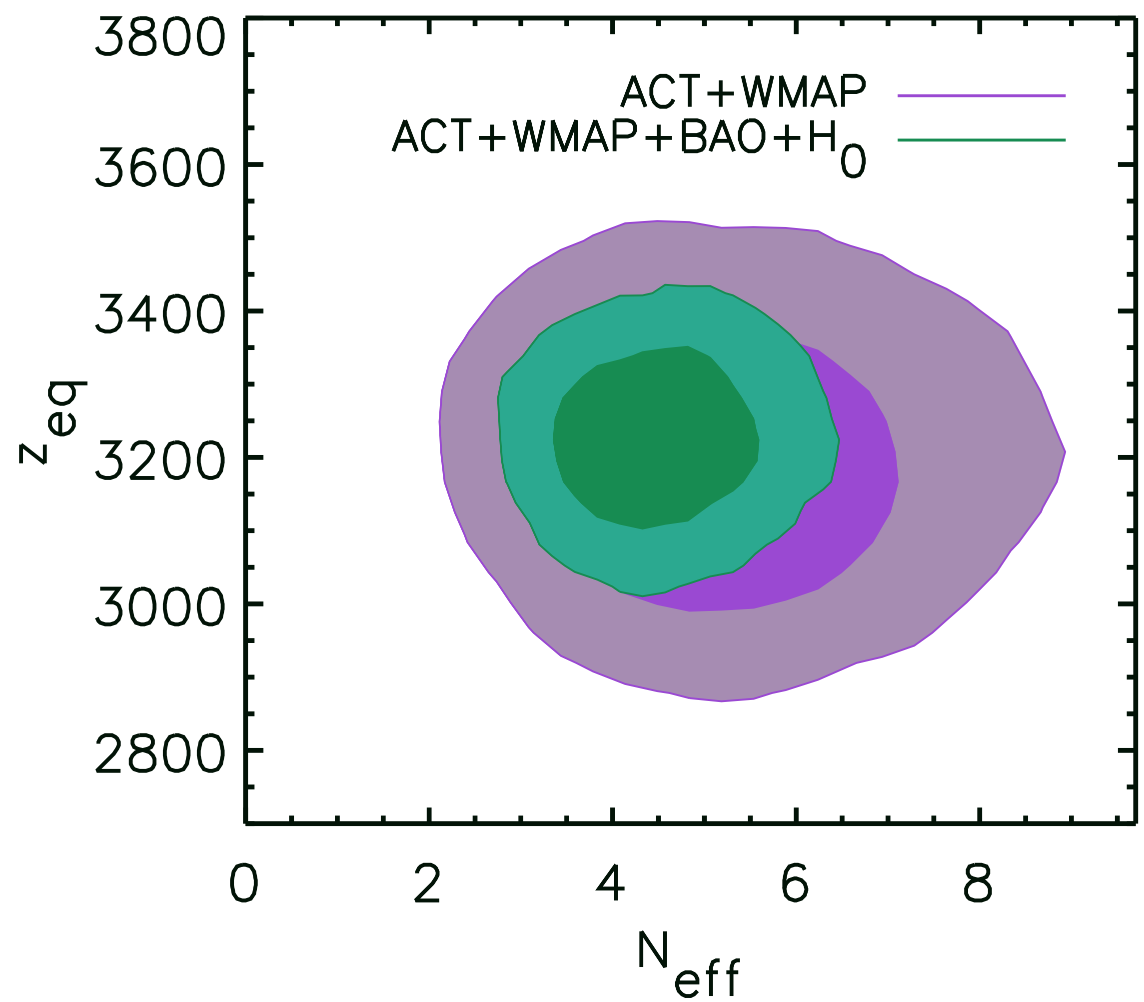
Dunkley et al., 1009.0866



ACT

Dunkley et al., 1009.0866



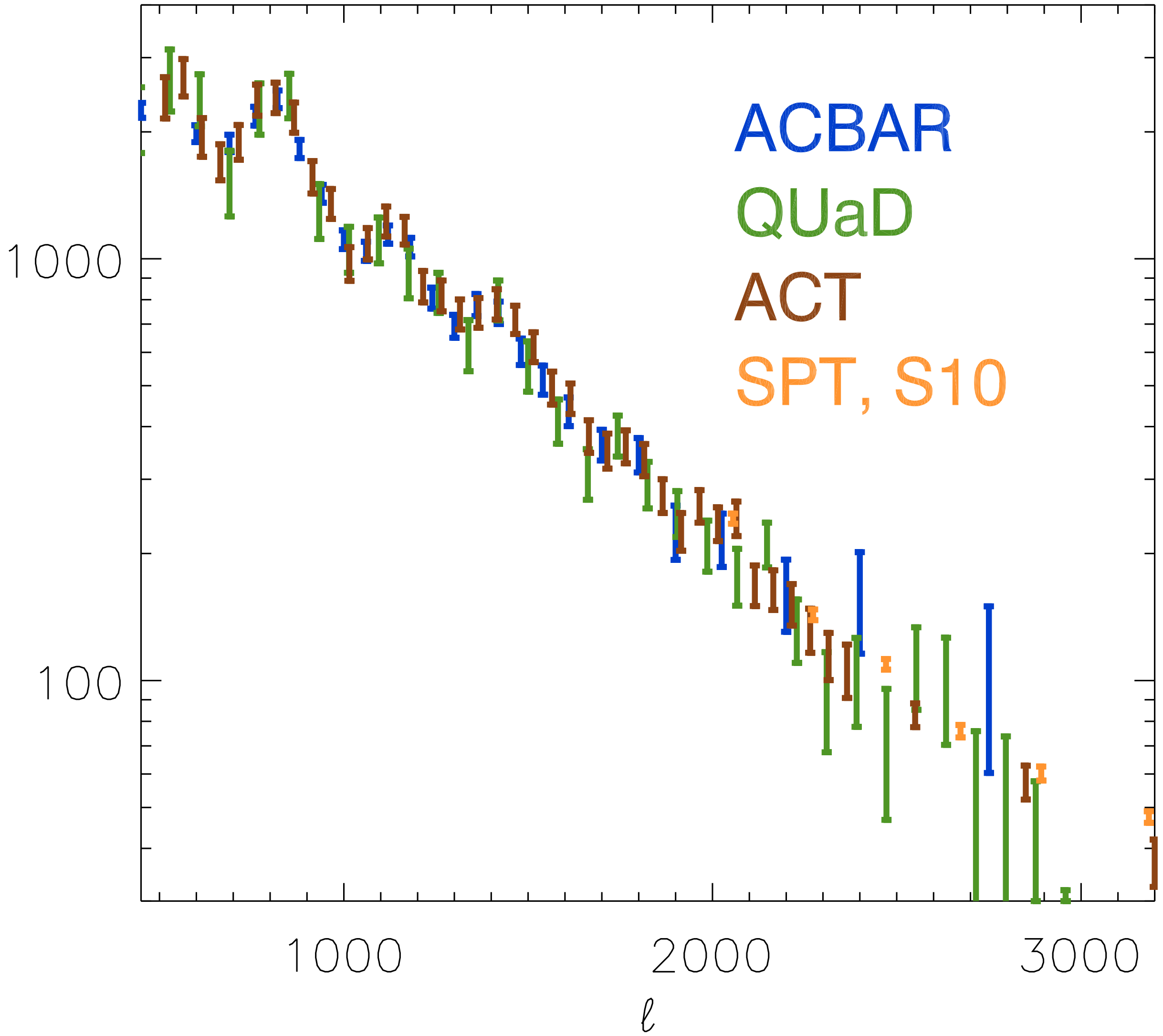


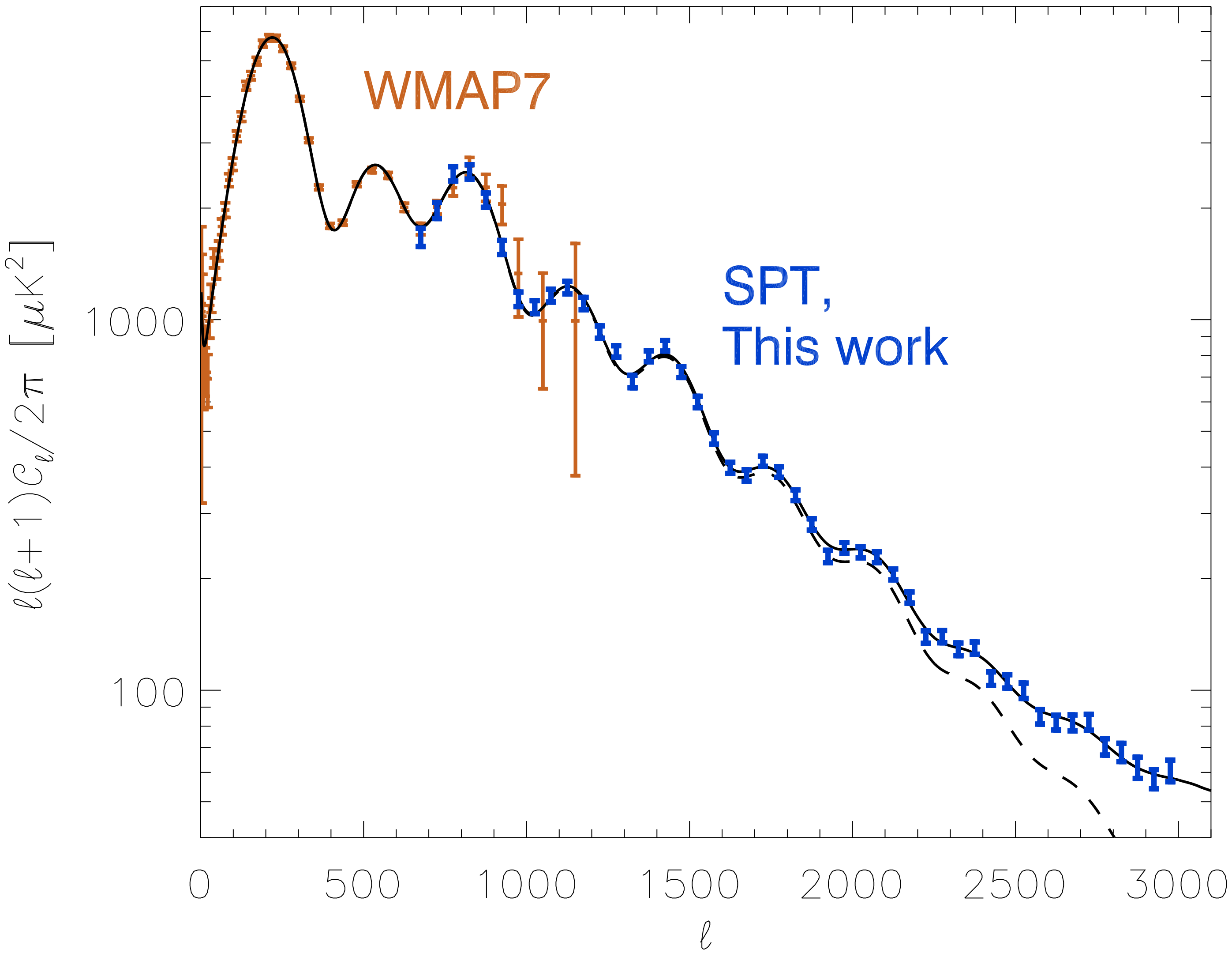
$$N_{\rm eff} = 5.3 \pm 1.3 \ (68\% \ \rm CL)$$ WMAP+ACT

$$N_{\rm eff} = 4.56 \pm 0.75 \ (68\% \ \rm CL)$$ WMAP+ACT+BAO+H0

SPT

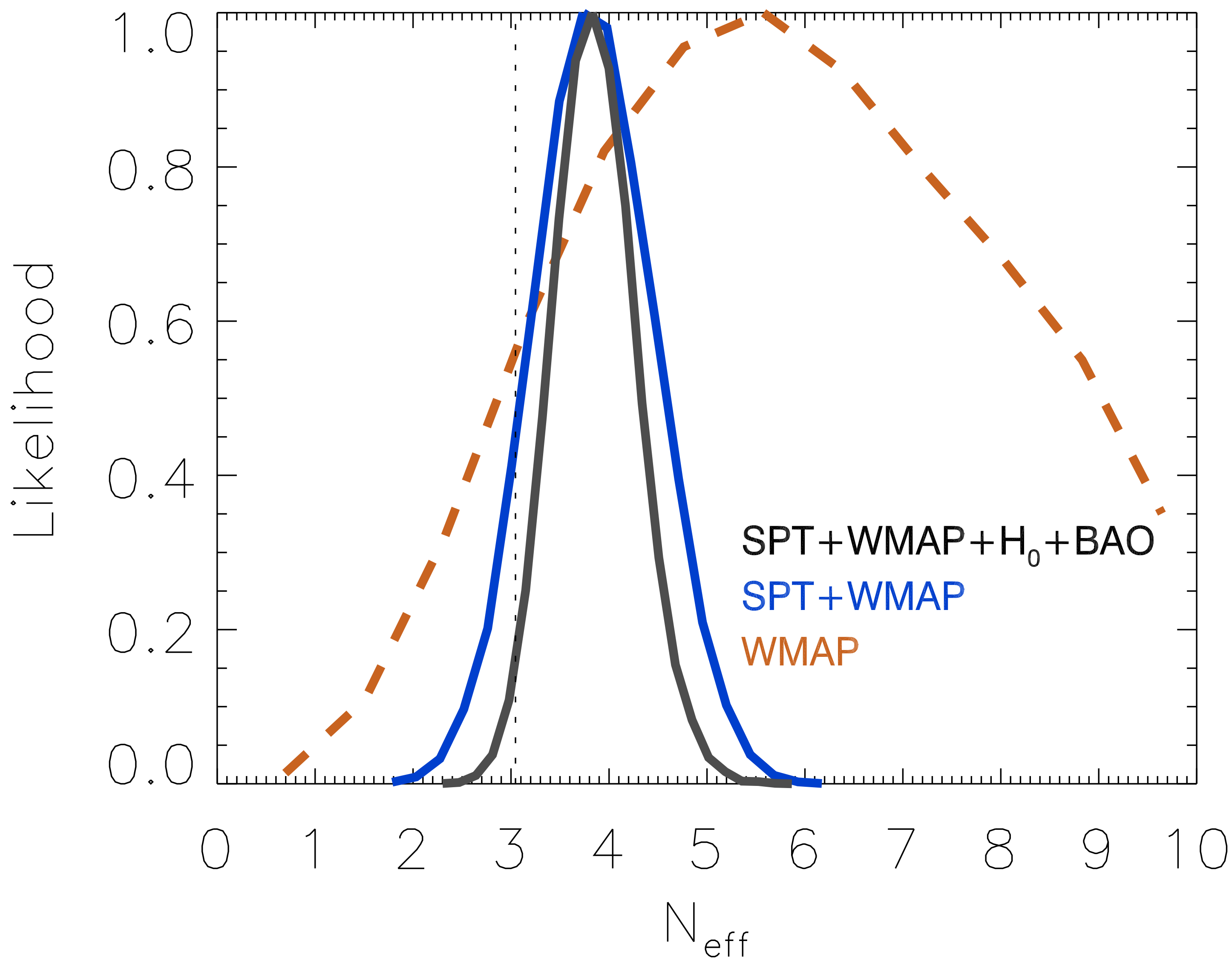
Keisler et al., 1105.3182





SPT

Keisler et al., 1105.3182

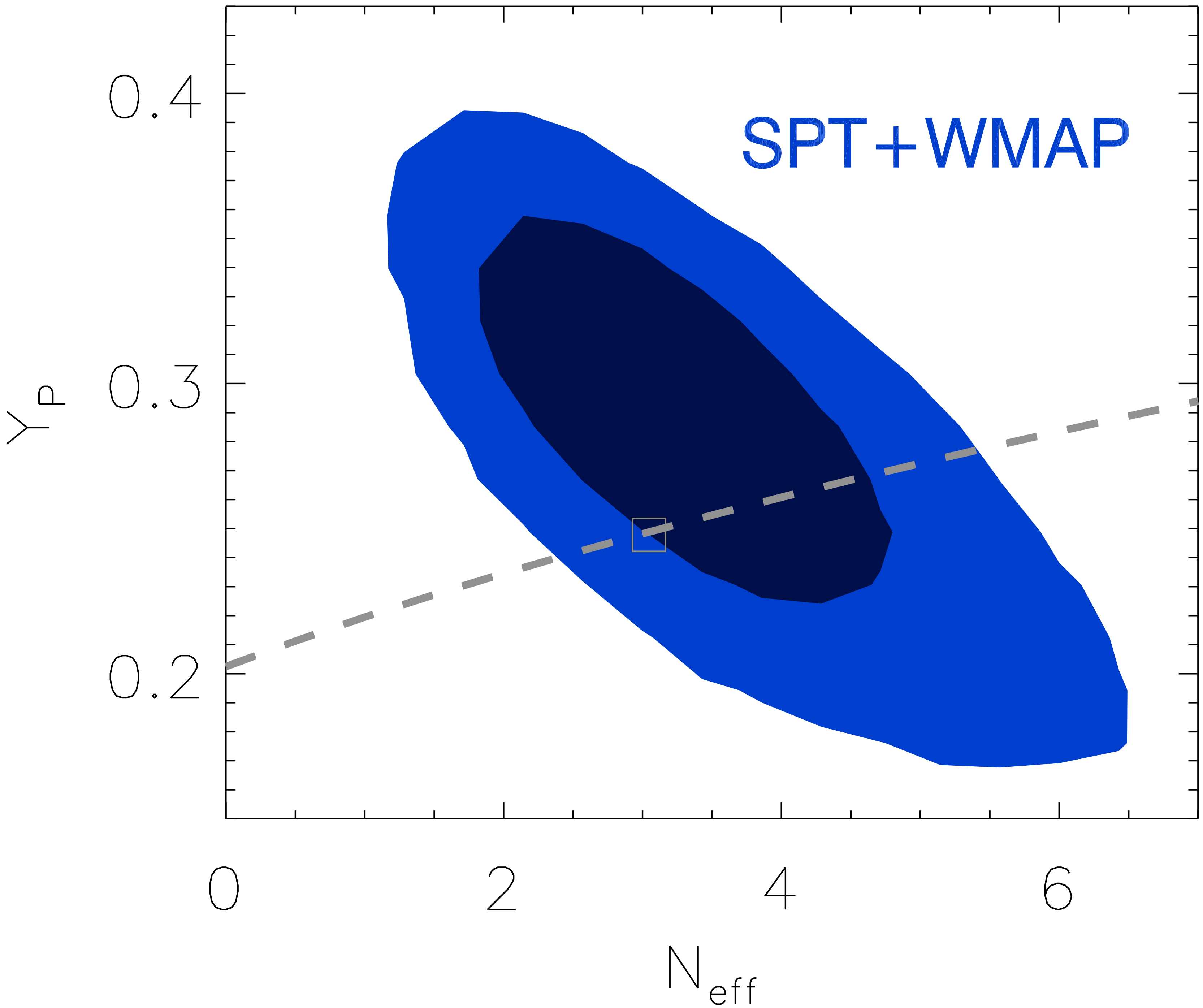


$$N_{\rm eff} = 3.85 \pm 0.62 \ (1\sigma) \ \ : \ \ {\rm WMAP + SPT}$$

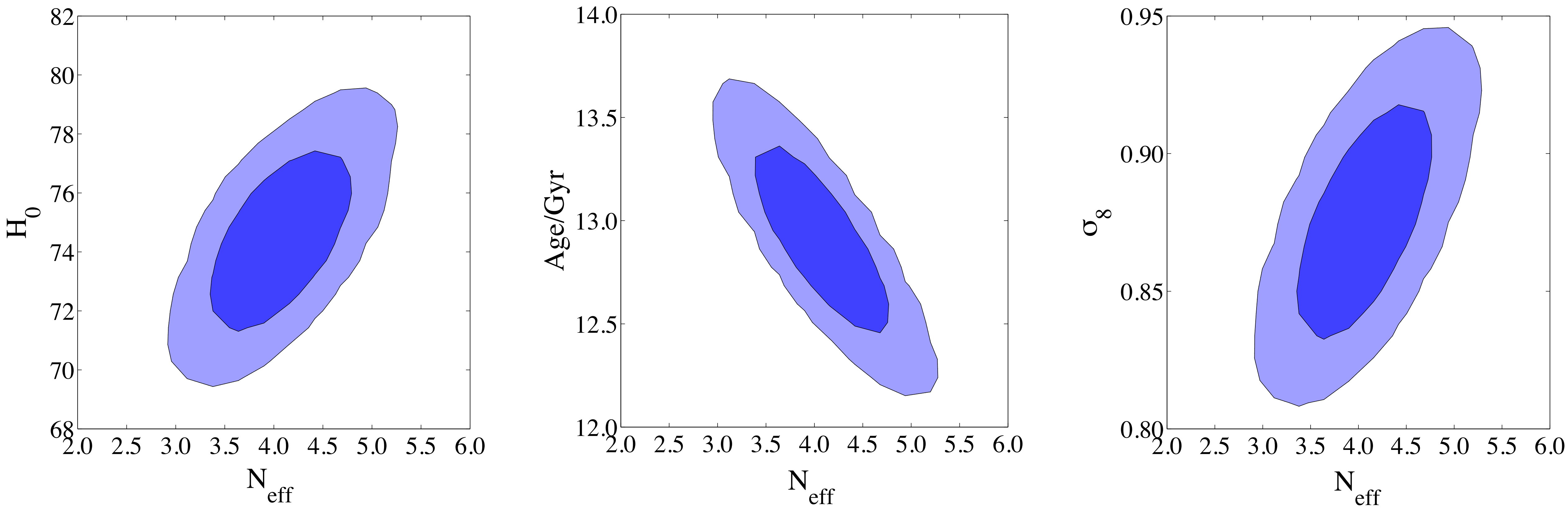
$$N_{\rm eff} = 3.86 \pm 0.42 \ (1\sigma) \ \ : \ \ {\rm WMAP + SPT + BAO + H_0}$$

SPT

Keisler et al., 1105.3182



WMAP+ACT+SPT+SDSS-DR7+H0



$$N_{\rm eff} = 4.08^{+0.71}_{-0.68} \text{ at } 95\% \text{ c.l.}$$

Archidiacono, Calabrese, Melchiorri, 1109.2767

Dark radiation mass

WMAP+ACBAR+QuAD+SDSS-DR7+SN

Framework	Neutrino sector	$\Delta\chi^2_{\rm eff}$	$\Delta N_{\rm ml}$	w	$\omega_{\rm cdm}$
ΛCDM	3 massless	0	–	–	$0.1132^{+0.0036}_{-0.0082}$
	3 massless + 1 sterile (0 eV)	-3.16	–	–	$0.1299^{+0.0069}_{-0.0066}$
	3 massless + 1 sterile (1 eV)	4.20	–	–	$0.1398^{+0.0061}_{-0.0074}$
	3 massless + 1 sterile (2 eV)	21.41	–	–	$0.1473^{+0.0075}_{-0.0064}$
ΛCDM+ΔN	3+$\Delta N_{\rm ml}$ massless + 1 sterile (0 eV)	-3.54	$0.01^{+1.12}_{-0.01}$	–	$0.133^{+0.023}_{-0.005}$
	3+$\Delta N_{\rm ml}$ massless + 1 sterile (1 eV)	2.26	$1.49^{+1.11}_{-0.73}$	–	$0.166^{+0.026}_{-0.017}$
	3+$\Delta N_{\rm ml}$ massless + 1 sterile (2 eV)	12.82	$2.57^{+1.24}_{-0.59}$	–	$0.192^{+0.031}_{-0.015}$
wCDM+ΔN	3+$\Delta N_{\rm ml}$ massless + 1 sterile (0 eV)	-5.38	$0.09^{+1.61}_{-0.09}$	$-1.00^{+0.18}_{-0.12}$	$0.132^{+0.032}_{-0.006}$
	3+$\Delta N_{\rm ml}$ massless + 1 sterile (1 eV)	-0.78	$1.23^{+1.61}_{-0.75}$	$-1.11^{+0.18}_{-0.21}$	$0.164^{+0.035}_{-0.015}$
	3+$\Delta N_{\rm ml}$ massless + 1 sterile (2 eV)	7.80	$2.48^{+1.71}_{-0.79}$	$-1.17^{+0.23}_{-0.22}$	$0.198^{+0.032}_{-0.019}$

$$m \ll 1\text{eV}$$

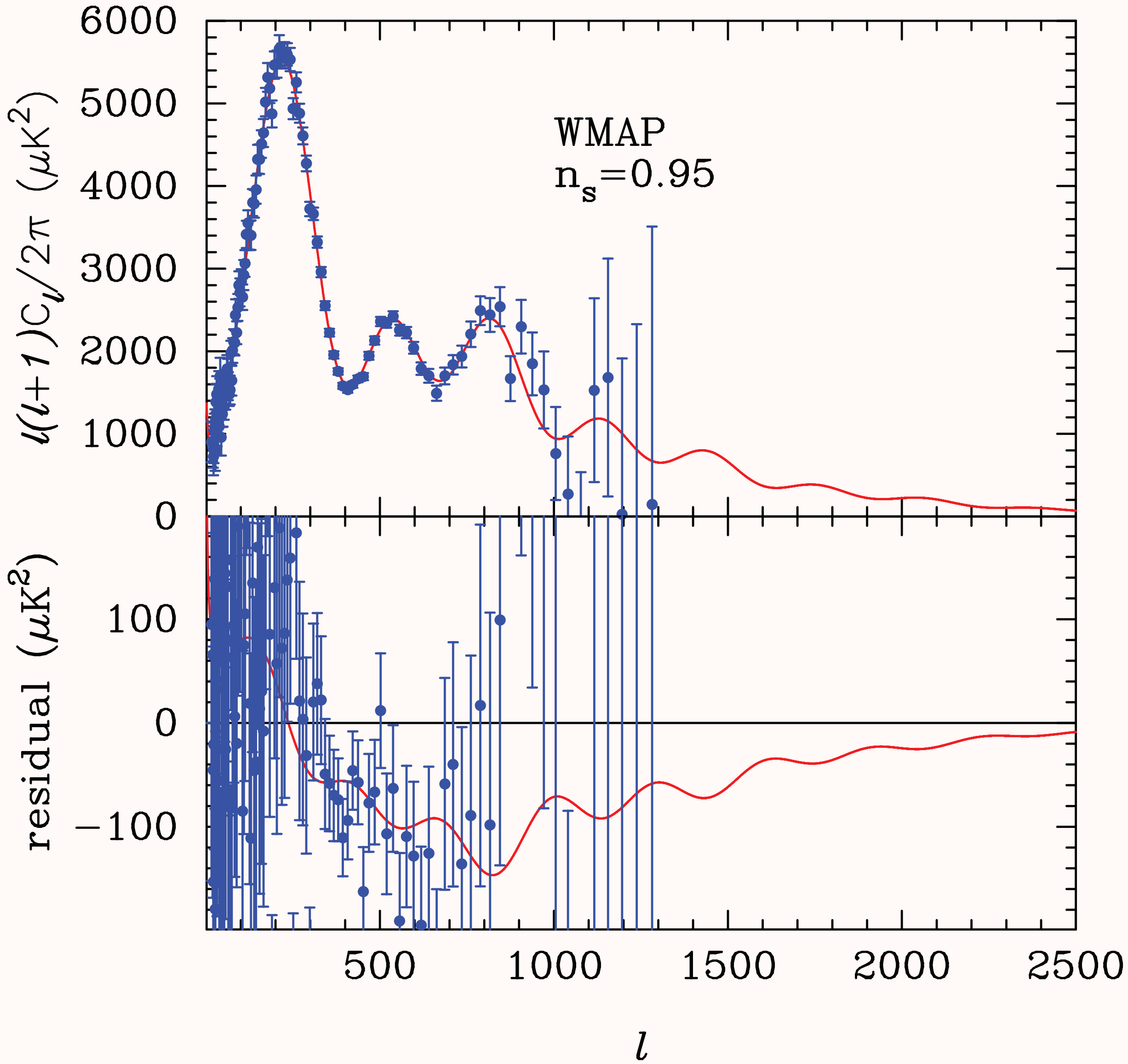
Hamann, Hannestad, Raffelt, Wong, 1108.4136

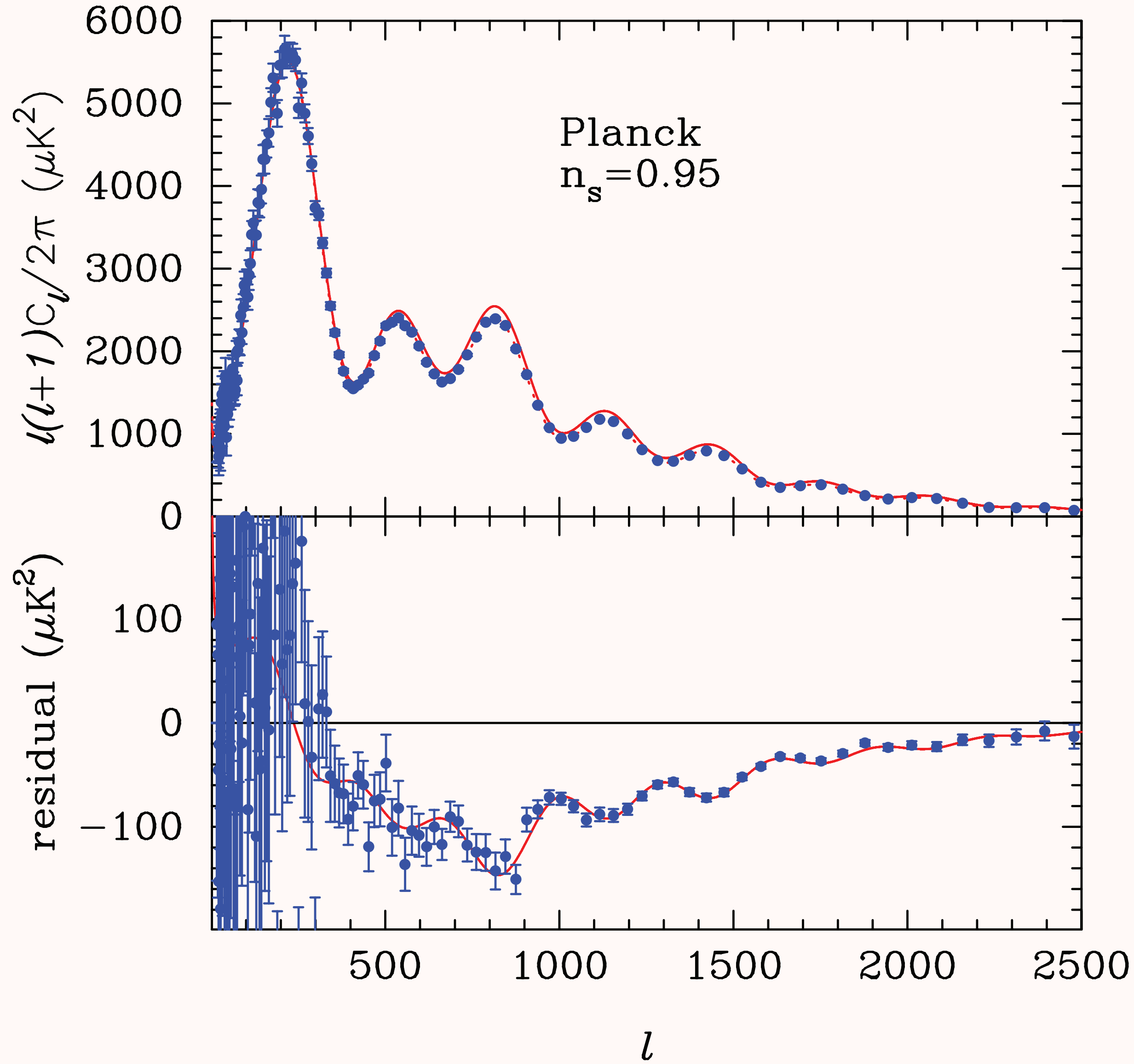
Future constraint

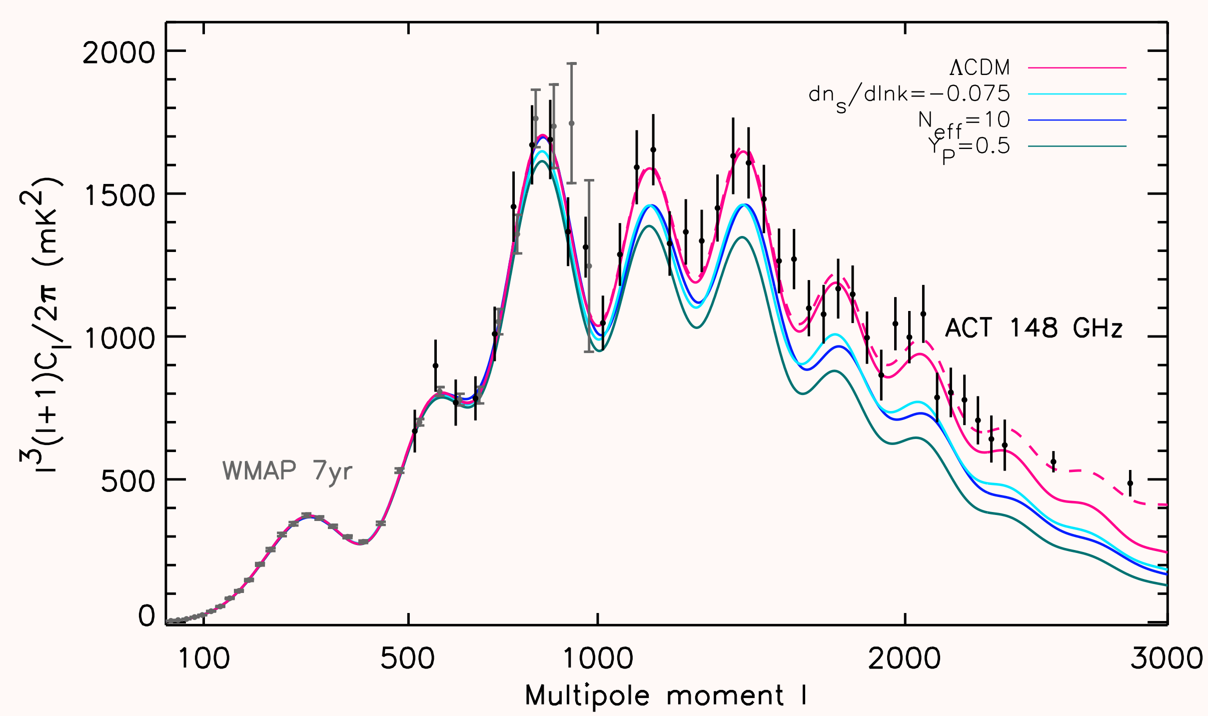
parameters	Planck (Y_p: free)	Planck (Y_p: BBN relation)	Planck ($Y_p = 0.24$)
ω_b	$0.02275^{+0.00025}_{-0.00028}$	$0.02275^{+0.00026}_{-0.00027}$	$0.02273^{+0.00027}_{-0.00026}$
ω_c	$0.1108^{+0.0046}_{-0.0056}$	$0.1101^{+0.0028}_{-0.0028}$	$0.1120^{+0.0033}_{-0.0036}$
θ_s	$1.0404^{+0.0014}_{-0.0014}$	$1.04060^{+0.00044}_{-0.00049}$	$1.04000^{+0.00055}_{-0.00062}$
τ	$0.0881^{+0.0050}_{-0.0064}$	$0.0881^{+0.0053}_{-0.0063}$	$0.0880^{+0.0056}_{-0.0059}$
n_s	$0.964^{+0.009}_{-0.010}$	$0.964^{+0.010}_{-0.010}$	$0.963^{+0.010}_{-0.009}$
$\ln(10^{10}A_s)$	$3.066^{+0.016}_{-0.016}$	$3.065^{+0.014}_{-0.015}$	$3.068^{+0.015}_{-0.015}$
Y_p	$0.246^{+0.020}_{-0.018}$	$0.2488^{+0.0027}_{-0.0027}$	—
N_ν	$3.11^{+0.33}_{-0.39}$	$3.06^{+0.20}_{-0.19}$	$3.19^{+0.24}_{-0.24}$
Ω_m	$0.256^{+0.010}_{-0.010}$	$0.256^{+0.009}_{-0.010}$	$0.255^{+0.009}_{-0.010}$
Age[Gyr]	$13.63^{+0.34}_{-0.31}$	$13.67^{+0.20}_{-0.21}$	$13.56^{+0.22}_{-0.25}$
H_0	$72.3^{+2.2}_{-2.4}$	$72.0^{+1.7}_{-1.6}$	$72.7^{+1.8}_{-1.9}$

K.Ichikawa, T.Sekiguchi, T.Takahashi (2008)

Planck : $\Delta N_{\rm eff} \sim 0.2 - 0.3$

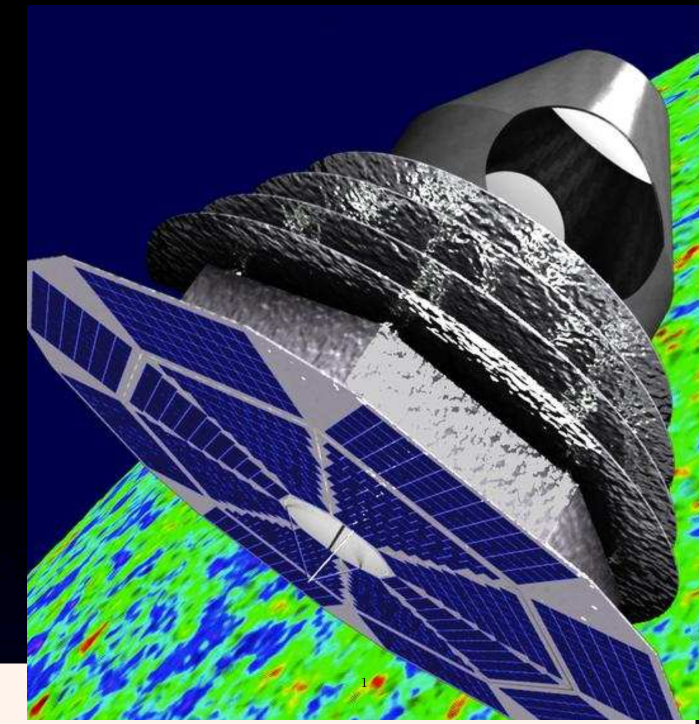






PLANCK bluebook

(Far) Future



Parameter uncertainty	Planck	COrE		Planck	COrE		Planck	COrE	
$\sigma(\Omega_b h^2)$	0.00011	0.000034	(3.3)	0.00017	0.000049	(3.6)	0.00016	0.000048	(3.3)
$\sigma(\Omega_c h^2)$	0.00087	0.00037	(2.4)	0.0022	0.00073	(3.1)	0.0009	0.00036	(2.5)
$\sigma(H_0)$	0.0039	0.0014	(2.8)	0.011	0.0034	(3.3)	0.0046	0.0016	(3.1)
$\sigma(\tau)$	0.0040	0.0022	(1.8)	0.004	0.0022	(1.8)	0.0040	0.0023	(1.8)
$\sigma(n_s)$	0.0027	0.0014	(1.9)	0.0056	0.0025	(2.3)	0.0053	0.0024	(2.3)
$\sigma(10^{10}A_s)$	0.18	0.10	(1.8)	0.23	0.11	(2.1)	0.19	0.10	(1.9)
$\sigma(N_{\rm eff})$	–	–	–	0.14	0.044	(3.3)	–	–	–
$\sigma(Y_p)$	–	–	–	–	–	–	0.0083	0.0027	(3.1)

COrE, arXiv:1102.2181

COrE : $\Delta N_{\rm eff} \sim 0.04$

Origin of dark radiation

- Observations : $\Delta N_{eff} \sim 1$

$\longrightarrow$ The presence of dark radiation ?

What's the candidate ?

- "Thermal" dark radiation

Once they were in thermal equilibrium

- "Nonthermal" dark radiation

They are produced by
decay of heavy particles

Recent Model

- Thermal relic
  - Jaeckel, Redondo, Ringwald, 0804.4157
  - KN, F.Takahashi, Yanagida, 1010.5693
  - de Holanda, Smirnov, 1012.5627
- Nonthermal relic
  - Ichikawa, Kawasaki, KN, Senami, F.Takahashi (2007)
  - Kawasaki, Kitajima, KN, 1104.1262
  - Fischler, Meyers, 1011.3501
  - J.Hasenkamp, 1107.4319
  - Menestrina, Scherrer, 1111.0605
  - Kobayashi, F.Takahashi, T.Takahashi, Yamaguchi, 1111.1336
  - K.S.Jeong, F.Takahashi, 1201.4816

“Thermal”dark radiation

Assumption : It is once in thermal equilibrium

Condition :

- (1) Extremely light ($m << 1$eV)
- (2) As abundant as neutrino

(1) ⟶ Some kind of symmetry

(2) ⟶ Sizable interaction with SM particles

What kind of particles naturally satisfy these conditions?

- Assume 4-fermi interaction $\mathcal{L}_{\rm eff} = \frac{1}{\Lambda^2}(\bar{f}\gamma^\mu f)(\bar{\psi}\gamma_\mu\psi)$
- Decoupling temperature $T_d \sim 10{\rm MeV}\left(\frac{\Lambda}{1{\rm TeV}}\right)^{4/3}$
- Effective number of neutrinos $\Delta N_{\rm eff} = \left(\frac{10.75}{g_*(T_d)}\right)^{4/3}$
- Constraint from SN cooling

  $\Lambda \gtrsim 6{\rm TeV}$ G.G.Raffelt (1999)

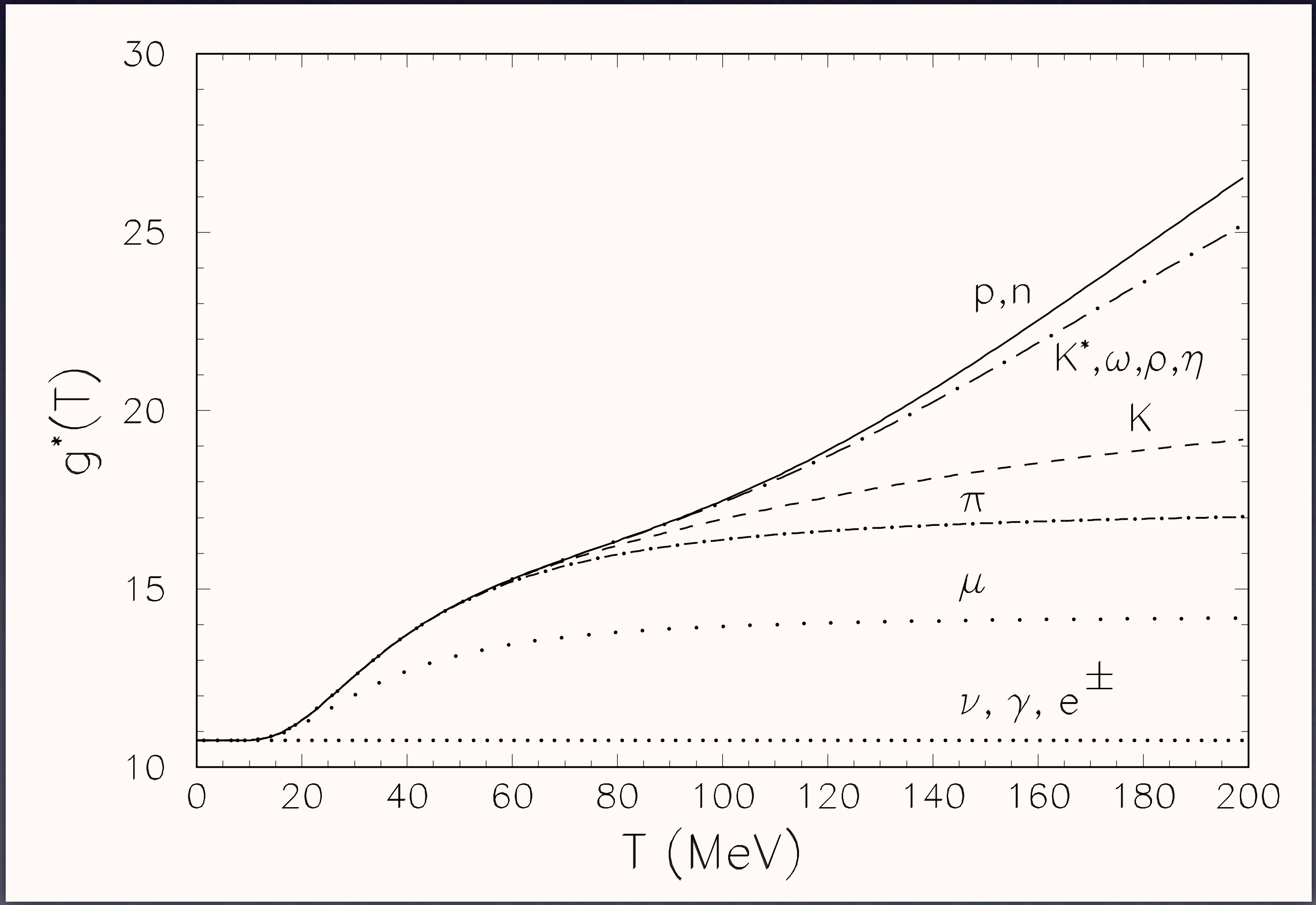
- cf. LHC bound

  $\Lambda_{qq} \gtrsim 4-5{\rm TeV}$

  CMS, 1202.5535

  $\Lambda_{ql} \gtrsim 4-5{\rm TeV}$

  ATLAS, 1112.4462



A model

anomaly-free U(1)

E_6	$SO(10) \times U(1)_\psi$	$SU(5) \times U(1)_\psi \times U(1)_\chi$
$\Psi_{\mathbf{27}}$	$\Psi_{\mathbf{16}}(1)$	$\psi^{(\mathrm{SM})}_{\mathbf{10}}(1,1)$ $\psi^{(\mathrm{SM})}_{\bar{\mathbf{5}}}(1,-3)$ $\psi^{(\mathrm{SM})}_{\mathbf{1}}(1,5) = \nu_{\mathrm{R}}$
	$\Psi_{\mathbf{10}}(-2)$	$\psi^{(\mathbf{10})}_{\mathbf{5}}(-2,-2)$ $\psi^{(\mathbf{10})}_{\bar{\mathbf{5}}}(-2,2)$
	$\Psi_{\mathbf{1}}(4)$	$\psi_{\mathbf{1}}(4,0)$
$\Phi_{\mathbf{27}}$	$\Phi_{\mathbf{16}}(1)$	$\phi^{(\mathbf{16})}_{\mathbf{10}}(1,1)$ $\phi^{(\mathbf{16})}_{\bar{\mathbf{5}}}(1,-3)$ $\phi^{(\mathbf{16})}_{\mathbf{1}}(1,5)$
	$\Phi_{\mathbf{10}}(-2)$	$\phi_{\mathbf{5}}(-2,-2) \supset$ SM Higgs $\phi_{\bar{\mathbf{5}}}(-2,2) \supset$ SM Higgs
	$\Phi_{\mathbf{1}}(4)$	$\phi_{\mathbf{1}}(4,0) = \phi_X$

A model

anomaly-free U(1)

E_6	$SO(10)\times U(1)_\psi$	$SU(5)\times U(1)_\psi\times U(1)_\chi$
$\Psi_{\mathbf{27}}$	$\Psi_{\mathbf{16}}(1)$	$\psi^{(\mathrm{SM})}_{\mathbf{10}}(1,1)$ $\psi^{(\mathrm{SM})}_{\bar{\mathbf{5}}}(1,-3)$ $\psi^{(\mathrm{SM})}_{\mathbf{1}}(1,5)=\nu_{\mathrm{R}}$
	$\Psi_{\mathbf{10}}(-2)$	$\psi^{(\mathbf{10})}_{\mathbf{5}}(-2,-2)$ $\psi^{(\mathbf{10})}_{\bar{\mathbf{5}}}(-2,2)$
	$\Psi_{\mathbf{1}}(4)$	$\psi_{\mathbf{1}}(4,0)$
$\Phi_{\mathbf{27}}$	$\Phi_{\mathbf{16}}(1)$	$\phi^{(\mathbf{16})}_{\mathbf{10}}(1,1)$ $\phi^{(\mathbf{16})}_{\bar{\mathbf{5}}}(1,-3)$ $\phi^{(\mathbf{16})}_{\mathbf{1}}(1,5)$
	$\Phi_{\mathbf{10}}(-2)$	$\phi_{\mathbf{5}}(-2,-2)\supset$ SM Higgs $\phi_{\bar{\mathbf{5}}}(-2,2)\supset$ SM Higgs
	$\Phi_{\mathbf{1}}(4)$	$\phi_{\mathbf{1}}(4,0)=\phi_X$

SM particles

A model

anomaly-free U(1)

E_6	$SO(10)\times U(1)_\psi$	$SU(5)\times U(1)_\psi \times U(1)_\chi$
$\Psi_{\mathbf{27}}$	$\Psi_{\mathbf{16}}(1)$	$\psi^{(\mathrm{SM})}_{\mathbf{10}}(1,1)$ $\psi^{(\mathrm{SM})}_{\bar{\mathbf{5}}}(1,-3)$ $\psi^{(\mathrm{SM})}_{\mathbf{1}}(1,5)=\nu_{\mathrm{R}}$
	$\Psi_{\mathbf{10}}(-2)$	$\psi^{(\mathbf{10})}_{\mathbf{5}}(-2,-2)$ $\psi^{(\mathbf{10})}_{\bar{\mathbf{5}}}(-2,2)$
	$\Psi_{\mathbf{1}}(4)$	$\psi_{\mathbf{1}}(4,0)$
$\Phi_{\mathbf{27}}$	$\Phi_{\mathbf{16}}(1)$	$\phi^{(\mathbf{16})}_{\mathbf{10}}(1,1)$ $\phi^{(\mathbf{16})}_{\bar{\mathbf{5}}}(1,-3)$ $\phi^{(\mathbf{16})}_{\mathbf{1}}(1,5)$
	$\Phi_{\mathbf{10}}(-2)$	$\phi_{\mathbf{5}}(-2,-2)\supset$ SM Higgs $\phi_{\bar{\mathbf{5}}}(-2,2)\supset$ SM Higgs
	$\Phi_{\mathbf{1}}(4)$	$\phi_{\mathbf{1}}(4,0)=\phi_X$

SM particles

U(1) Higgs

A model

anomaly-free U(1)

E_6	$SO(10)\times U(1)_\psi$	$SU(5)\times U(1)_\psi \times U(1)_\chi$
$\Psi_{\mathbf{27}}$	$\Psi_{\mathbf{16}}(1)$	$\psi^{(\mathrm{SM})}_{\mathbf{10}}(1,1)$ $\psi^{(\mathrm{SM})}_{\bar{\mathbf{5}}}(1,-3)$ $\psi^{(\mathrm{SM})}_{\mathbf{1}}(1,5)=\nu_{\mathrm{R}}$
	$\Psi_{\mathbf{10}}(-2)$	$\psi^{(\mathbf{10})}_{\mathbf{5}}(-2,-2)$ $\psi^{(\mathbf{10})}_{\bar{\mathbf{5}}}(-2,2)$
	$\Psi_{\mathbf{1}}(4)$	$\psi_{\mathbf{1}}(4,0)$
$\Phi_{\mathbf{27}}$	$\Phi_{\mathbf{16}}(1)$	$\phi^{(\mathbf{16})}_{\mathbf{10}}(1,1)$ $\phi^{(\mathbf{16})}_{\bar{\mathbf{5}}}(1,-3)$ $\phi^{(\mathbf{16})}_{\mathbf{1}}(1,5)$
	$\Phi_{\mathbf{10}}(-2)$	$\phi_{\mathbf{5}}(-2,-2)\supset$ SM Higgs $\phi_{\bar{\mathbf{5}}}(-2,2)\supset$ SM Higgs
	$\Phi_{\mathbf{1}}(4)$	$\phi_{\mathbf{1}}(4,0)=\phi_X$

SM particles

Extra radiation

U(1) Higgs

Light fermion

- Fermion mass $\mathcal{L} \sim \frac{\phi_X \phi_X \psi\psi}{M}$

$$m_\psi \sim \frac{\langle \phi_X \rangle^2}{M} \sim 10^{-3}\mathrm{eV} \quad \text{for} \quad \langle \phi_X \rangle \sim 1\mathrm{TeV}$$

- U(1) boson mass $m_A = g_A \phi_X \sim 1\mathrm{TeV}$

- ψ has weak scale interaction

→ ψ has desired properties for extra radiation !

KN, F.Takahashi, T.T.Yanagida, Phys.Lett.B 697, 275 (2011)

Signatures at LHC

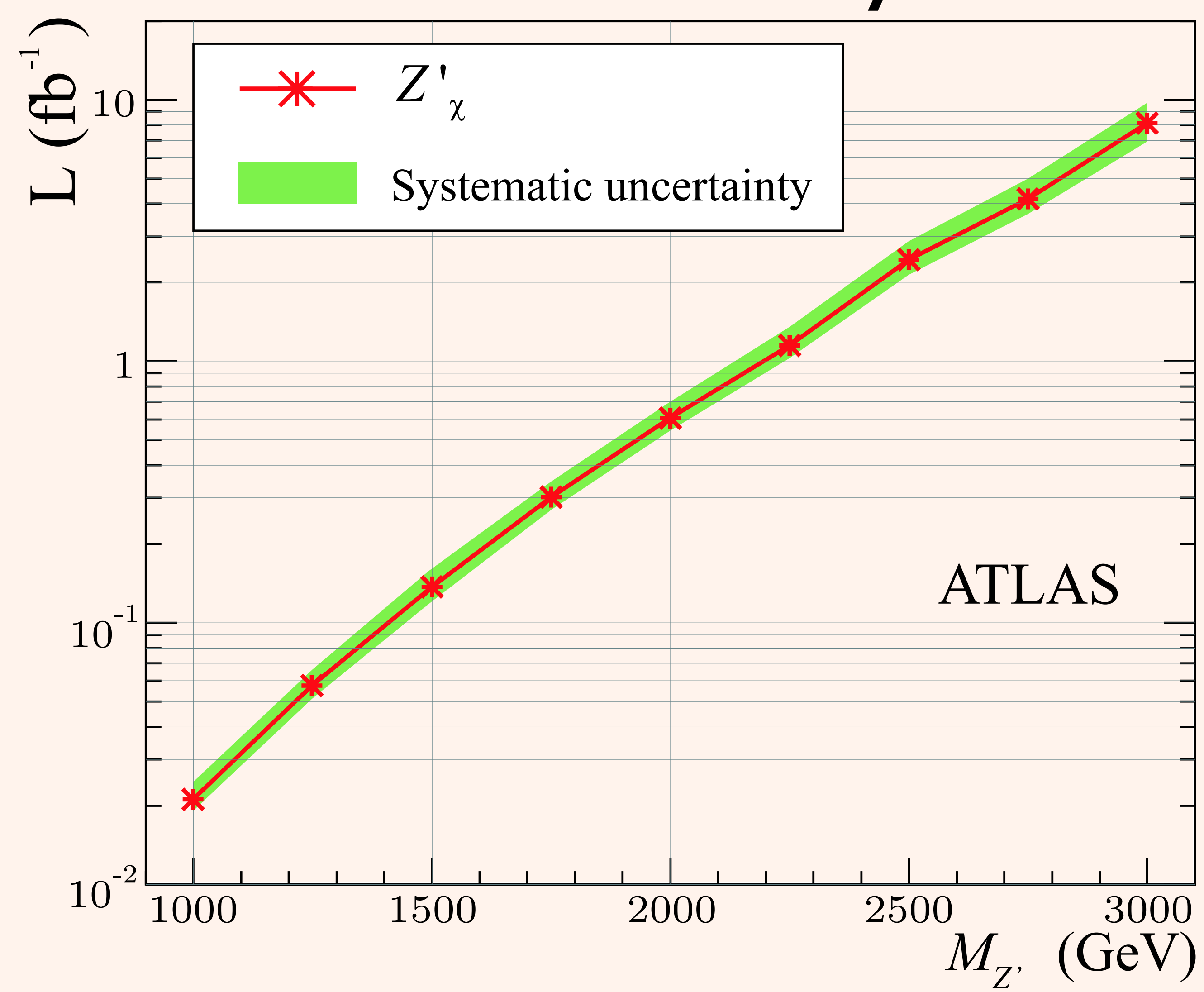
- U(1) boson with TeV

  $\longrightarrow$ Z' search at LHC

- Within the reach for int. luminosity of 10fb^{-1}

- LHC may be able to exclude some DR model

5σ discovery



arXiv:0901.0512

“Nonthermal” dark radiation

- The condition for dark radiation
  - It is relativistic before recombination
  - Its interaction is very weak

    $\longrightarrow$ same effect on CMB as neutrinos

- They do not need to have thermal distribution

  $\longrightarrow$ They may be produced by decay of heavy particles

Basic idea

- Consider the process $\phi \to XX$

  ϕ : scalar field having non-negligible energy

  X : light particles with very weak interaction

$$\Delta N_{\rm eff} = \frac{43}{7}\frac{\rho_X}{\rho_{\rm tot}} = \frac{43}{7}\frac{B_{\phi\to X}\rho_\phi}{\rho_{\rm tot}}$$

- Neff ~ 1 for $\rho_\phi \sim \rho_{\rm tot}$ at the ϕ decay
- X is relativistic until CMB epoch if $m_\phi \gg m_X$

Nonthermal axion

- Supersymmetric axion model

Axion supermultiplet

Axion a			
	$\longleftrightarrow$	Axino $\tilde{a}$	
Saxion s			

- Saxion has mass of gravitino $(1\mathrm{eV} - 100\mathrm{TeV})$
- Saxion decays into axions $s \to 2a$

$$\tau_s = \left(\frac{1}{64\pi} \frac{m_s^3}{f_a^2} \right)^{-1} \simeq 1.3 \times 10^2 \mathrm{sec} \left(\frac{1\mathrm{GeV}}{m_s} \right)^3 \left(\frac{f_a}{10^{12}\mathrm{GeV}} \right)^2$$

- Hadronic axion

Saxion mainly decays into axions $s \to 2a$

$$R = (3\rho_\sigma/4\rho_{\rm tot})_d \simeq 0.2 \qquad \Delta N_{\rm eff} = \frac{43}{7}\frac{R}{1-R}\left(\frac{10.75}{g_*(T_d)}\right)^{1/3}$$

Ichikawa, Kawasaki, KN, Senami, F.Takahashi (2007)

- DFSZ axion

Saxion mainly decays into higgs $s \to hh$
If the saxion dominates the universe,

$$B_r(s \to aa) = \frac{1}{8}\left(\frac{m_s}{\mu}\right)^4 \qquad \Delta N_{\rm eff} = \frac{43}{7}\frac{B_r}{1-B_r}\left(\frac{10.75}{g_*(T_d)}\right)^{1/3}$$

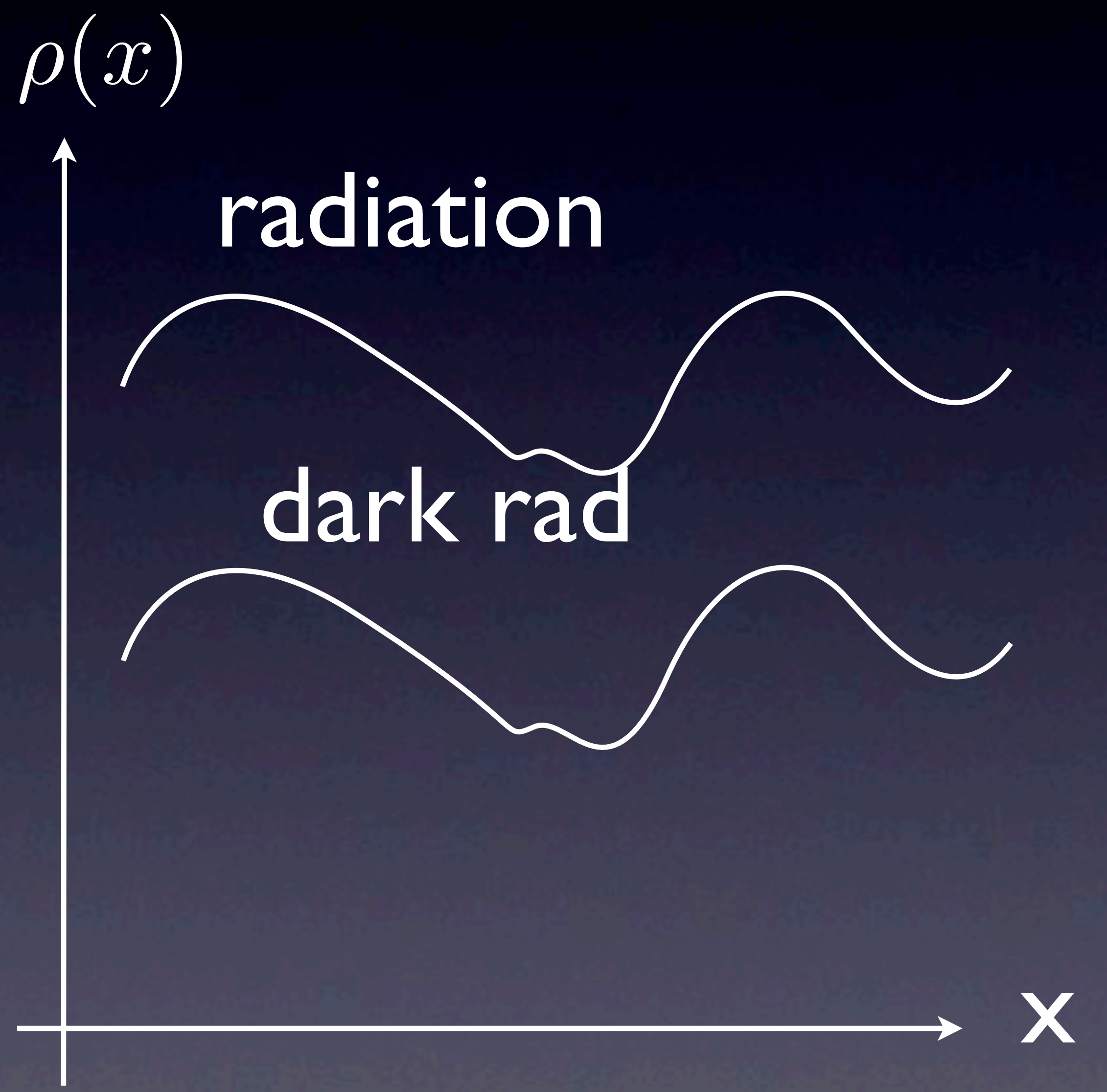
Kawasaki, Kitajima, KN, 1104.1262; K.S.Jeong, F.Takahashi, 1201.4816

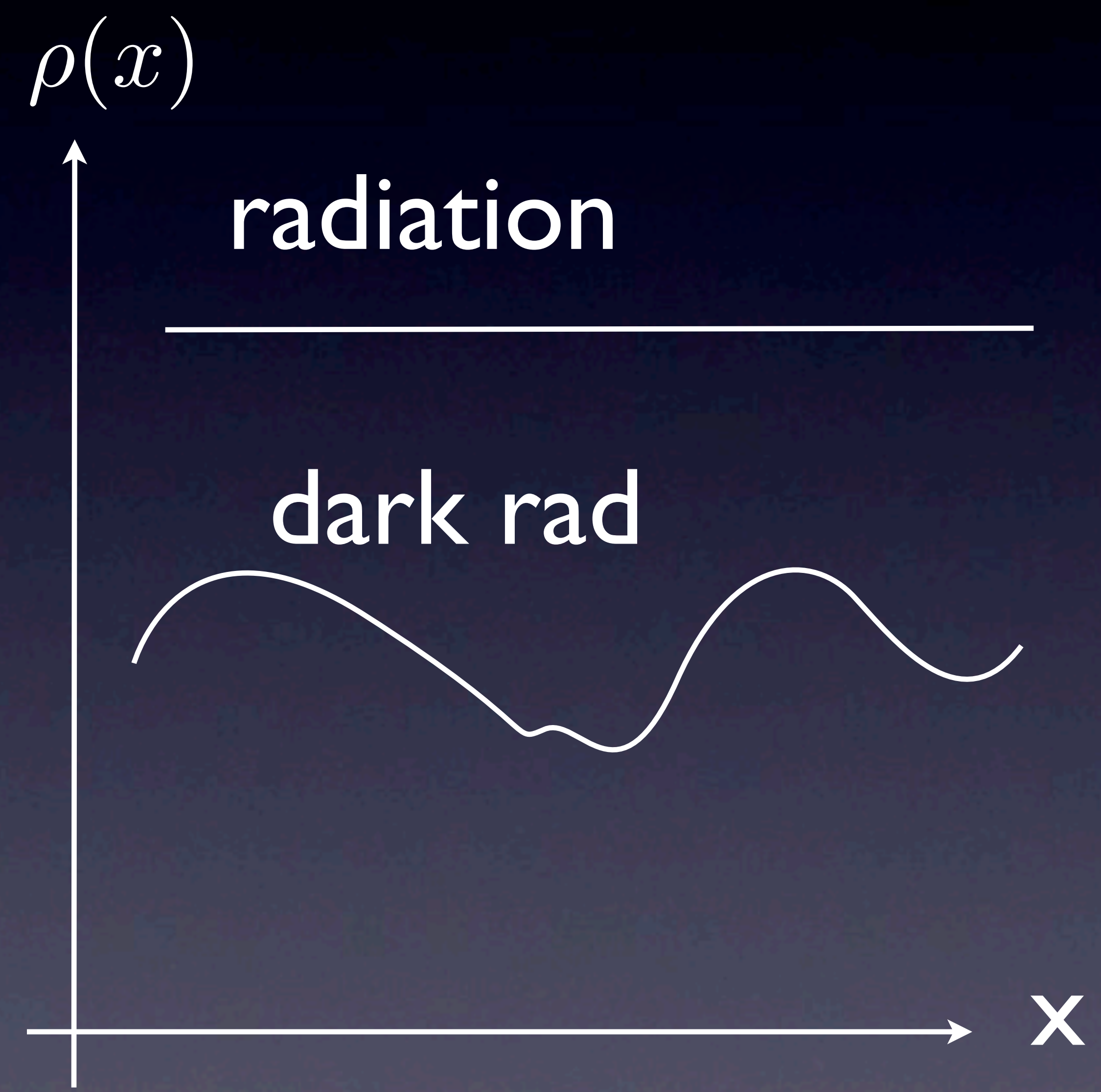
Isocurvature perturbation in dark radiation

- Can we distinguish nonthermal scenario from thermal scenario?
- If the decaying scalar has isocurvature fluctuation, dark radiation also does.
- This "dark radiation isocurvature mode" may be useful to prove the scenario.

Kawasaki, Miyamoto, KN, Sekiguchi, 1107.4962

Isocurvature mode



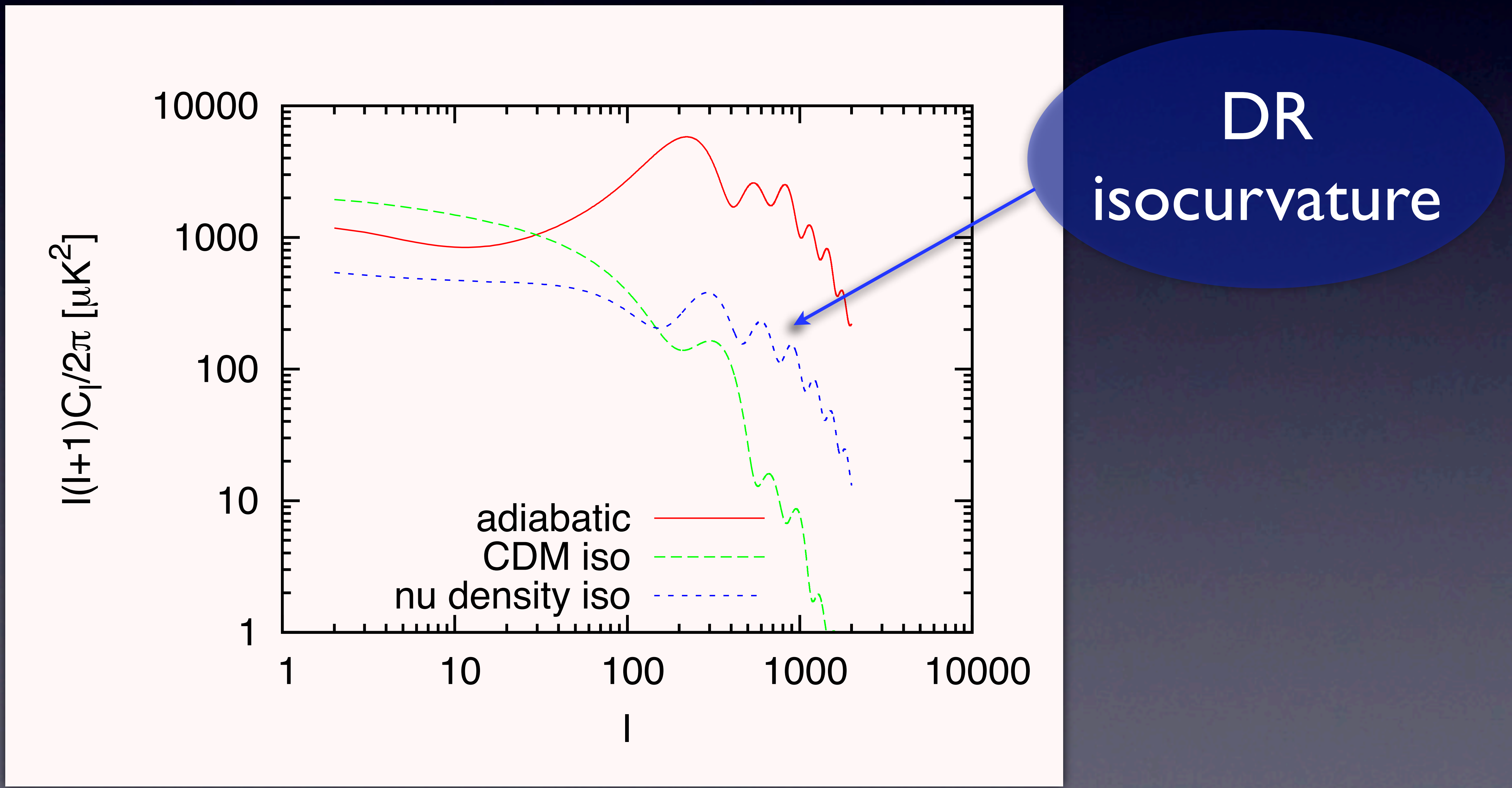


Adiabatic fluctuation

Isocurvature fluctuation

Effects on CMB

- Including the effect of DR isocurvature = Standard cosmology + Neff + neutrino isocurvature



Setup

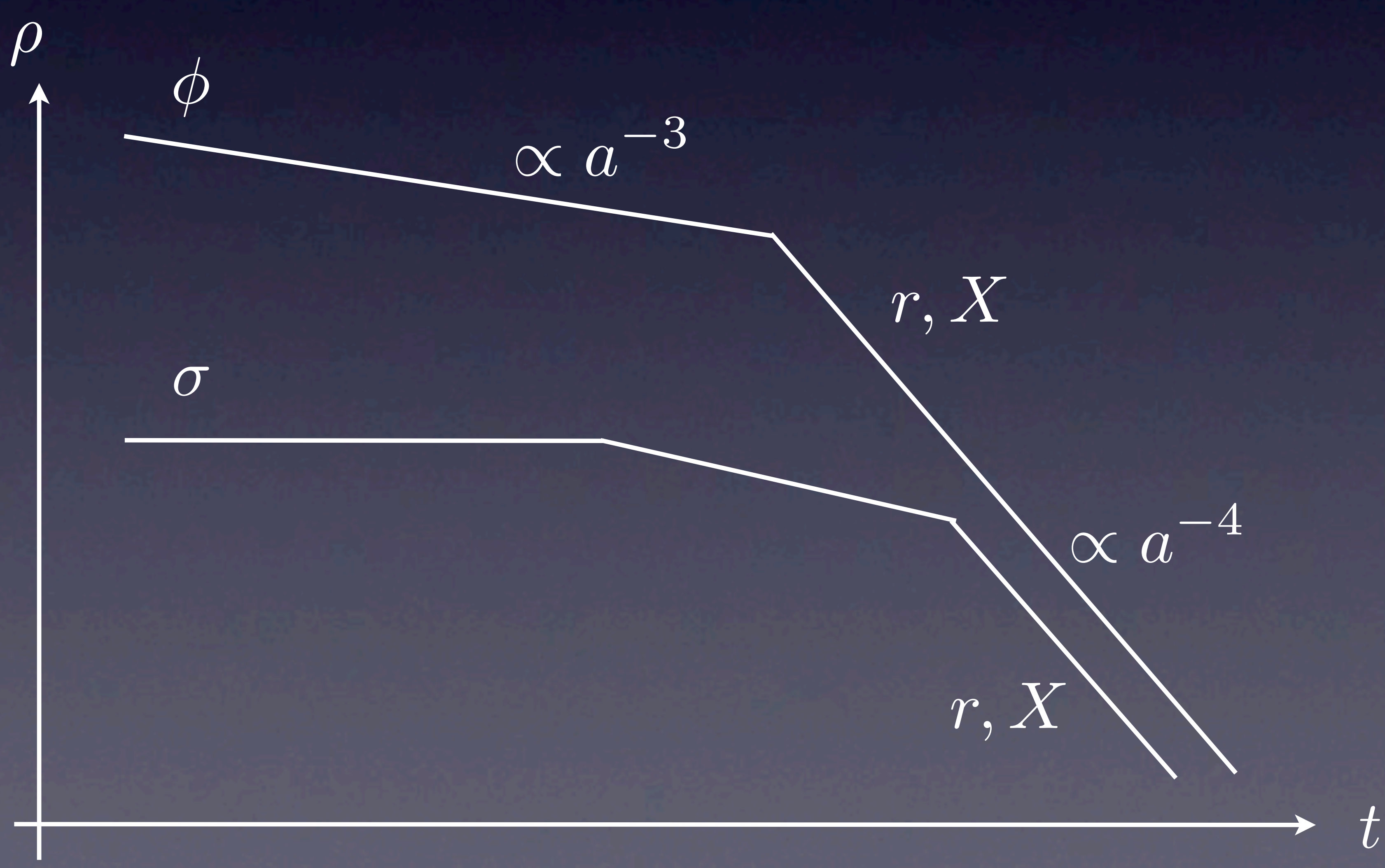
- Inflaton + light scalar

ϕ : inflaton

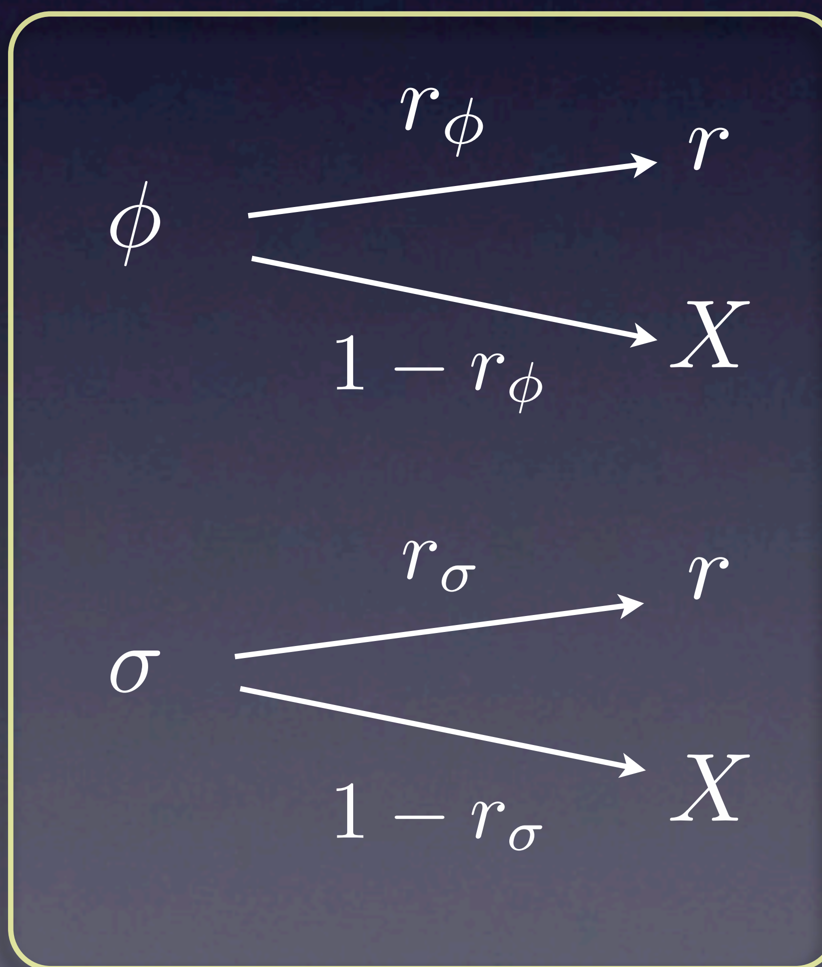
σ : curvaton like scalar

X : dark radiation

r : radiation



decay pattern



Setup

time ↑

epoch	component	energy transfer
$H < \Gamma_{e^\pm}$	$X,\ \nu,\ \gamma$ (DR $= X + \nu$)	
$\Gamma_{e^\pm} < H < \Gamma_\nu$	$X,\ \nu,\ r_e$ (DR $= X + \nu$)	$e^\pm \to \gamma$
$\Gamma_\nu < H < \Gamma_\sigma$	$X,\ r$	$r \to \nu + r_e$
$\Gamma_\sigma < H < \Gamma_\phi$	$X^{(\phi)},\ r^{(\phi)},\ \sigma$	$\sigma \to X^{(\sigma)} + r^{(\sigma)}$
$\Gamma_\phi < H$	$\phi,\ \sigma$	$\phi \to X^{(\phi)} + r^{(\phi)}$

X : dark radiation

ϕ : inflaton

σ : curvaton like scalar

Γ_ν : neutrino freezeout

$\Gamma_{e^\pm}$: $e^\pm$ annihilation

Γ_ϕ : inflaton decay rate

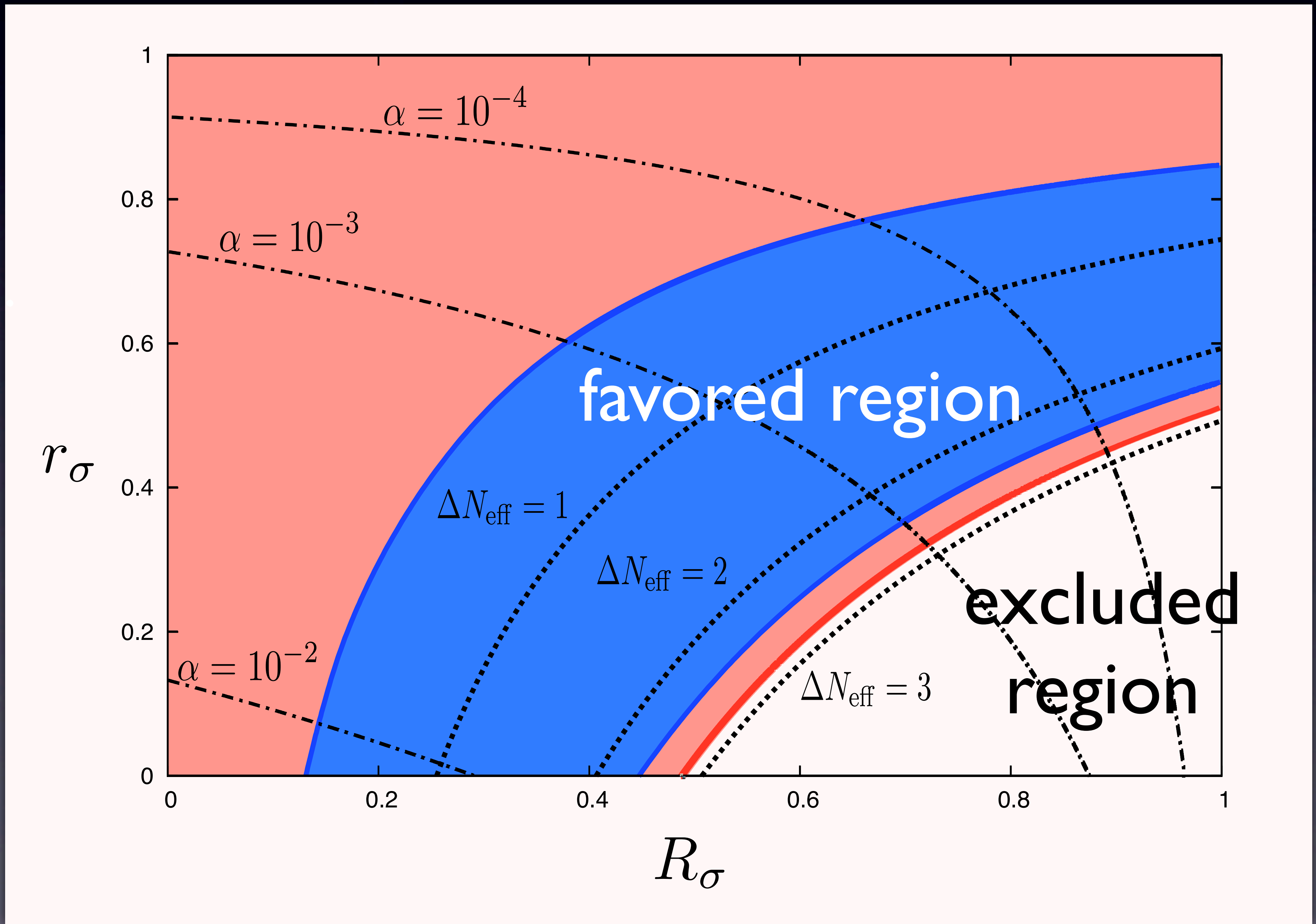
Γ_σ : curvaton decay rate

Uncorrelated cases

- Inflaton $\zeta = \zeta_\phi$ $\quad \mathrm{Br}(\sigma \to \mathrm{X}) = 1 - r_\sigma$ $\quad \mathrm{Br}(\phi \to \mathrm{X}) = 0$

$$\alpha = \left| \frac{S_{\mathrm{DR}}}{\zeta} \right|$$

WMAP
+
ACT

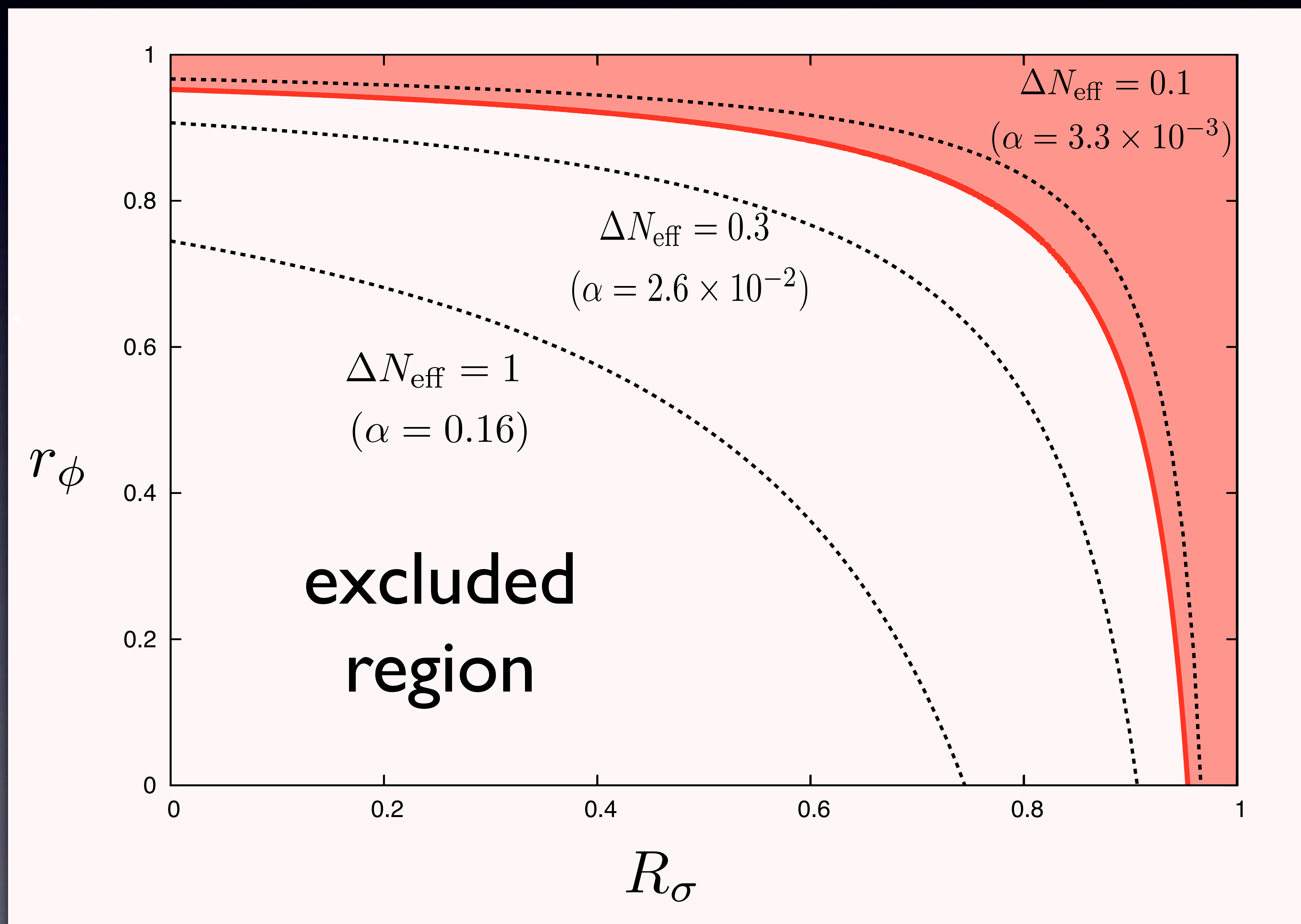


Anti-correlated case

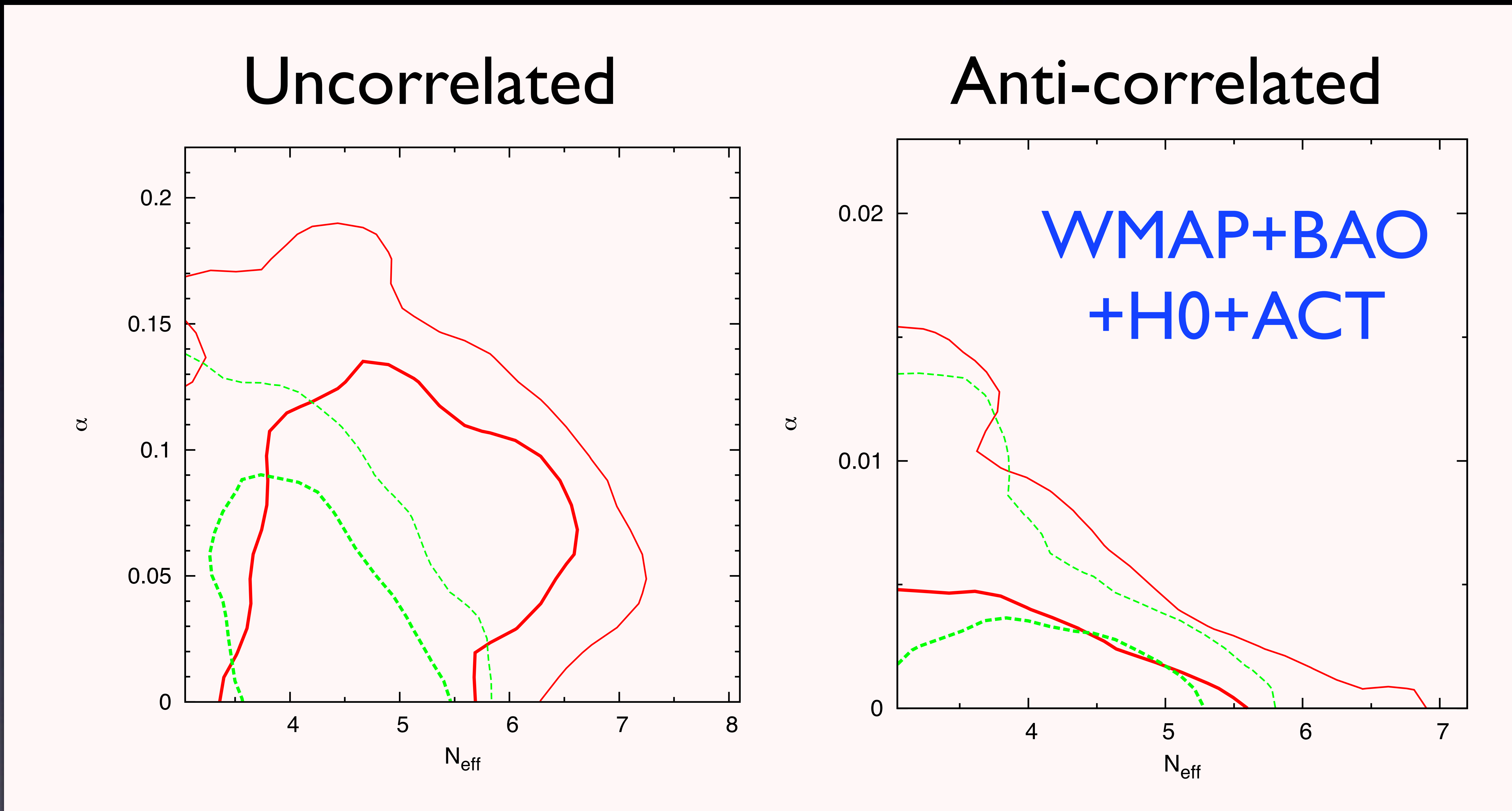
- Curvaton $\zeta = \zeta_\sigma$ $\mathrm{Br}(\phi \to \mathrm{X}) = 1 - r_\phi$ $\mathrm{Br}(\sigma \to \mathrm{X}) = 0$

$$\alpha = \left| \frac{S_{\mathrm{DR}}}{\zeta} \right|$$

WMAP
+
ACT



Constraint



$\alpha \equiv P_{S_{\rm DR}}/P_\zeta$ Kawasaki, Miyamoto, KN, Sekiguchi, 1107.4962

Non-Gaussianity

E.Kawakami, M.Kawasaki, K.Miyamoto, KN, T.Sekiguchi 1202.4890

Bispectrum : $B^{abc}(k_1, k_2, k_3) = f_{\rm NL}^{a,bc} P_\zeta(k_2) P_\zeta(k_3) + ({\rm cyclic})$

$$f_{\rm NL}^{(1)} \equiv f_{\rm NL}^{\zeta,\zeta\zeta}$$

$$f_{\rm NL}^{(2)} \equiv f_{\rm NL}^{S,\zeta\zeta}$$

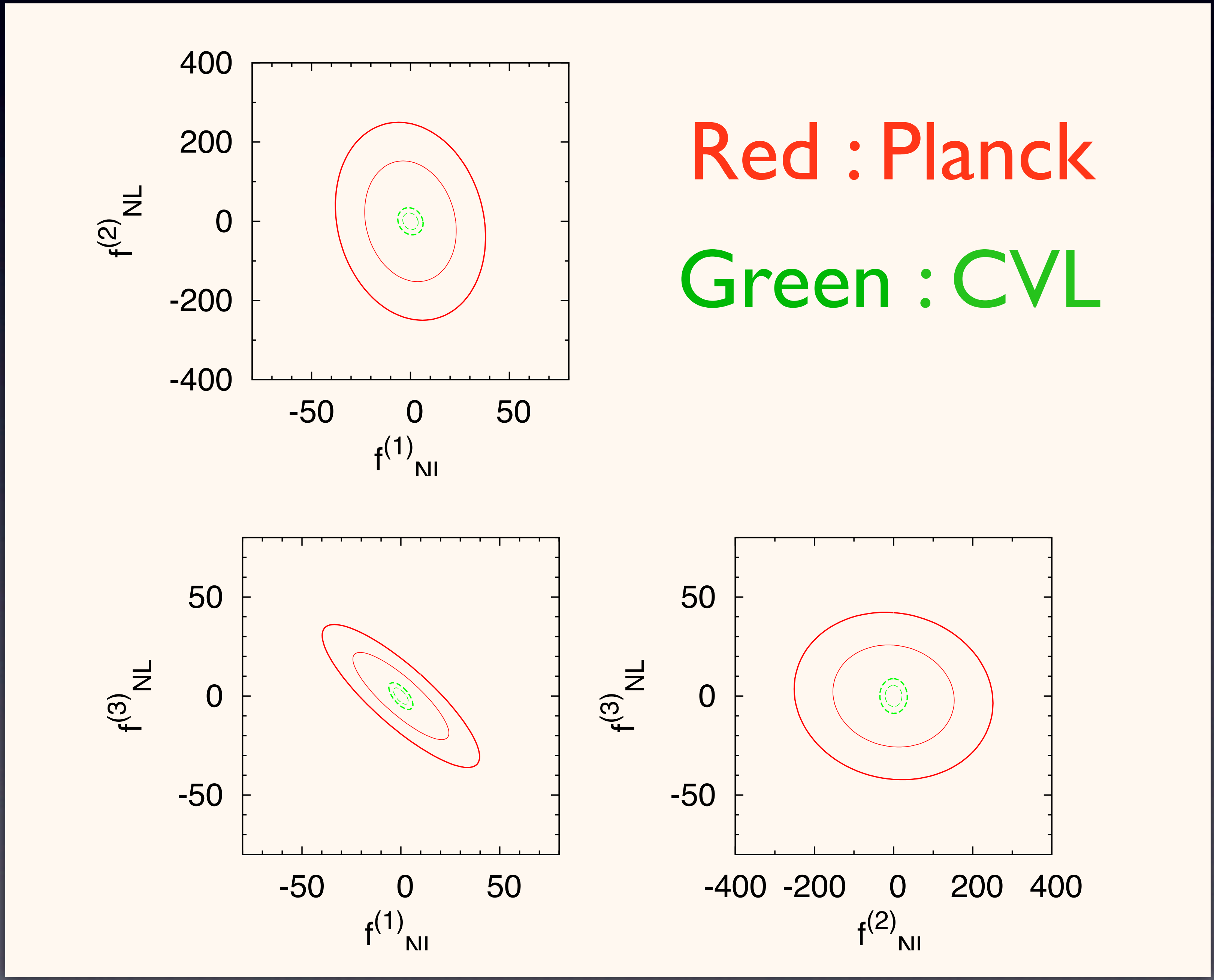
$$\cdots$$

$$f_{\rm NL}^{(6)} \equiv f_{\rm NL}^{S,SS}$$

$$f_{\rm NL}^{(1)} = \frac{N_{\phi_i} N_{\phi_j} N_{\phi_i \phi_j}}{(N_{\phi_i}^2)^2}$$

$$f_{\rm NL}^{(2)} = \frac{S_{\phi_i} N_{\phi_j} N_{\phi_i \phi_j}}{(N_{\phi_i}^2)^2}$$

$$\cdots$$



Summary on DR

- There are increasing evidence for the existence of dark radiation (DR).
- “Thermal” DR may be related to TeV-scale physics. It may be tested/excluded by LHC.
- “Nonthermal” DR models also exist.
  A good example is SUSY axion model.
- DR is adiabatic. Isocuvature component is small. Some constraint on DR production.

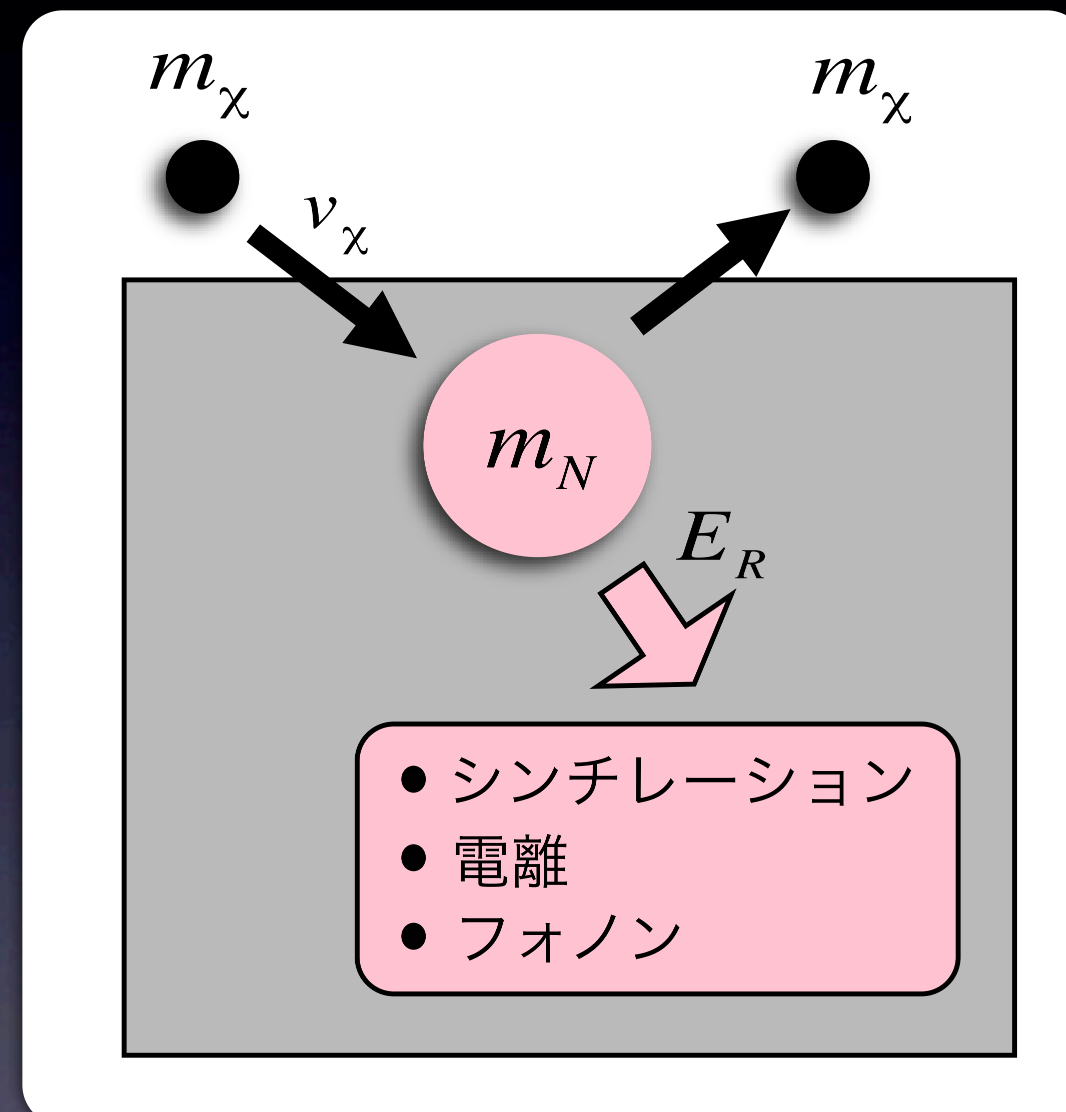
Dark matter direct detection

Direct detection

"DM wind"

$v \sim 10^{-3}c$

$\rho_\chi \sim 0.3\ \mathrm{GeV/cm^3}$



Typical recoil energy

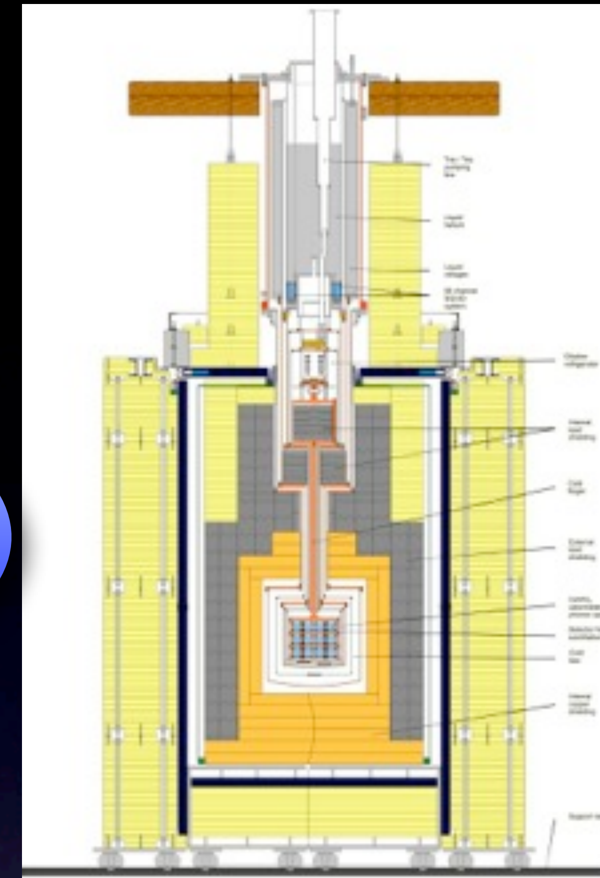
$$E \simeq \frac{m_\chi^2 m_N}{(m_\chi + m_N)^2} v^2 \sim \mathcal{O}(10)\mathrm{keV}$$

Event rate :

$$R \simeq 3 \times 10^{-4}/\mathrm{day/kg} \left(\frac{\sigma_{\chi N}}{10^{-40}\mathrm{cm}^2}\right)\left(\frac{100\mathrm{GeV}}{m_\chi}\right)\left(\frac{1\mathrm{GeV}}{m_N}\right)$$

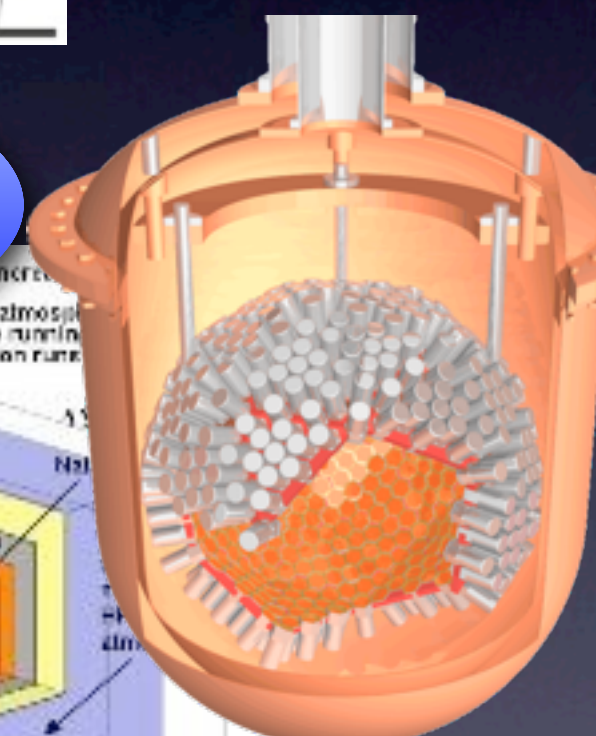
CDMS

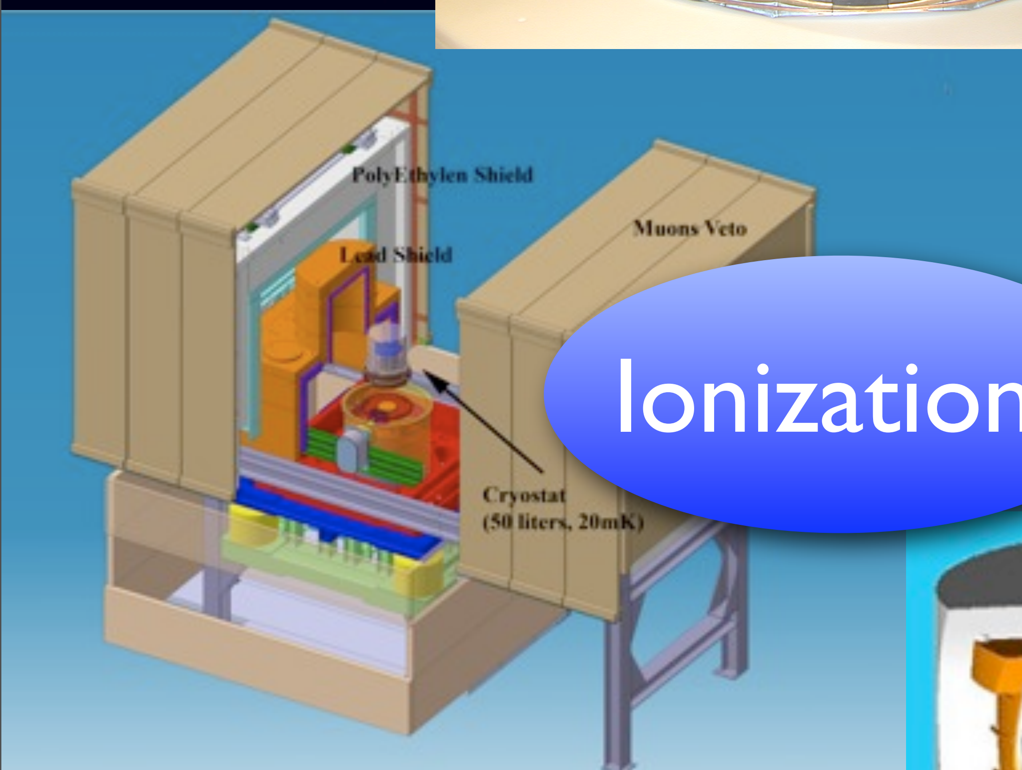
CRESST



Phonon

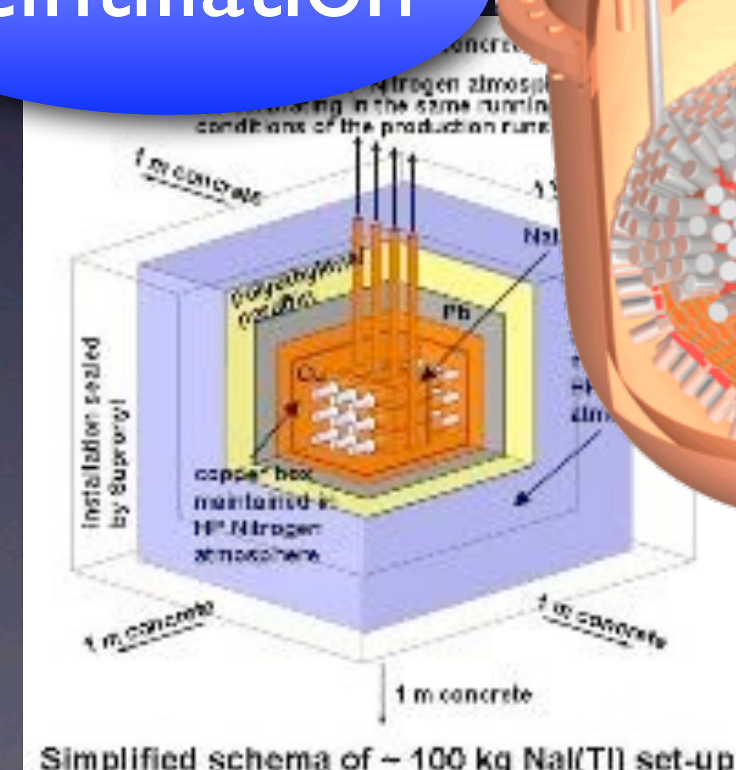
XMASS





Ionization

Scintillation



EDELWEISS

XENON

DAMA

- Low-BG analysis

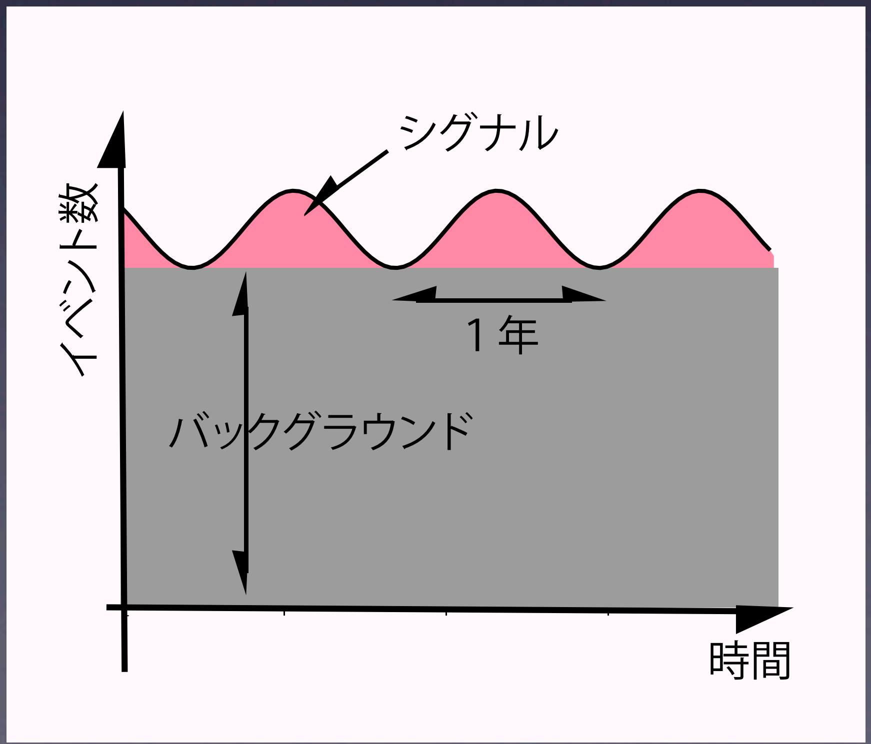
Event discrimination by combining two signals

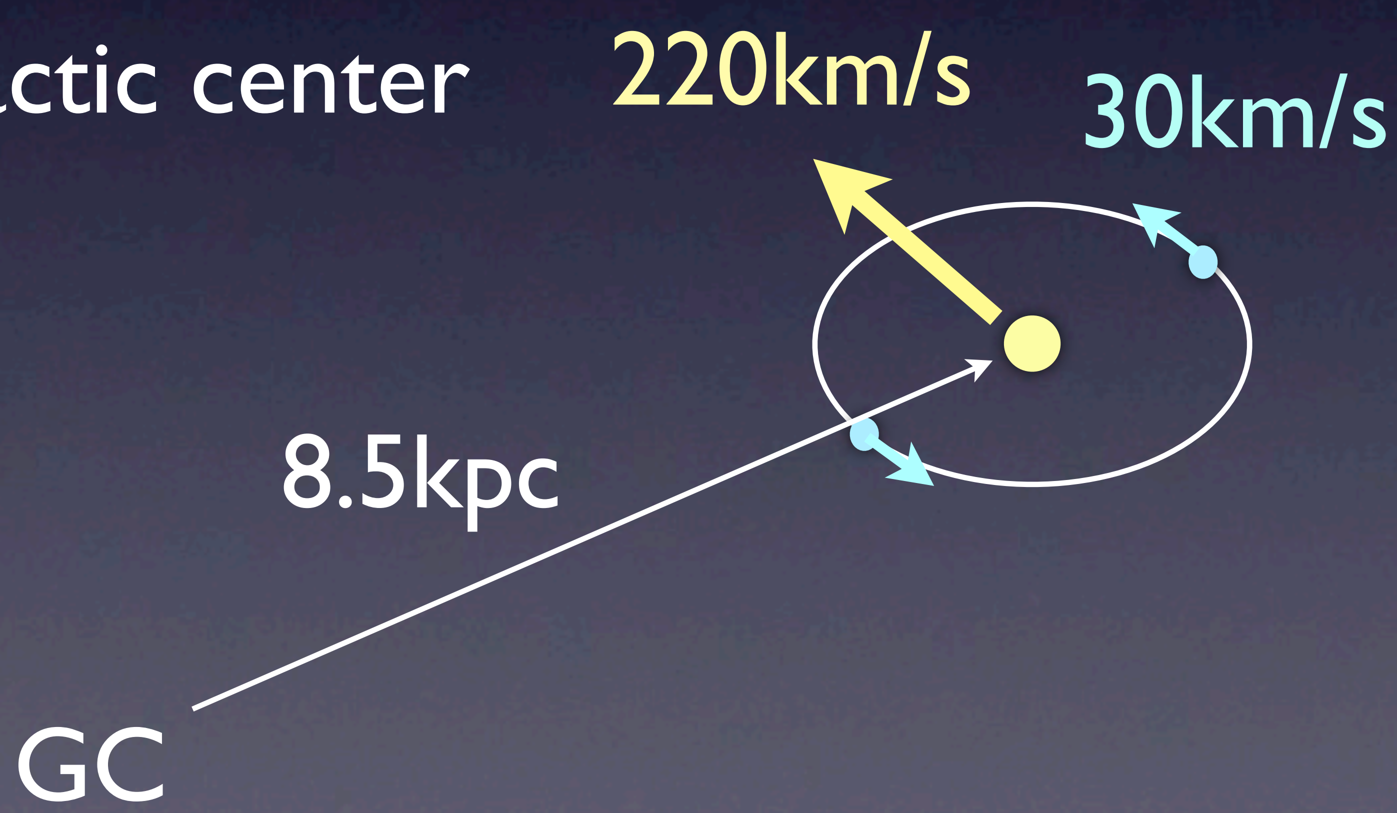
CDMS : Ionization + Phonon

XENON : Ionization + Scintillation

- Annual modulation analysis

DM flux depends on the Earth motion relative to Galactic center





Current situation

- Constraint on WIMP DM model

  CDMS, EDELWEISS, XENON,...

  Exclude some parameter regions
  for SUSY neutralino or other DM models

- Event excesses for low mass (1-10GeV) DM

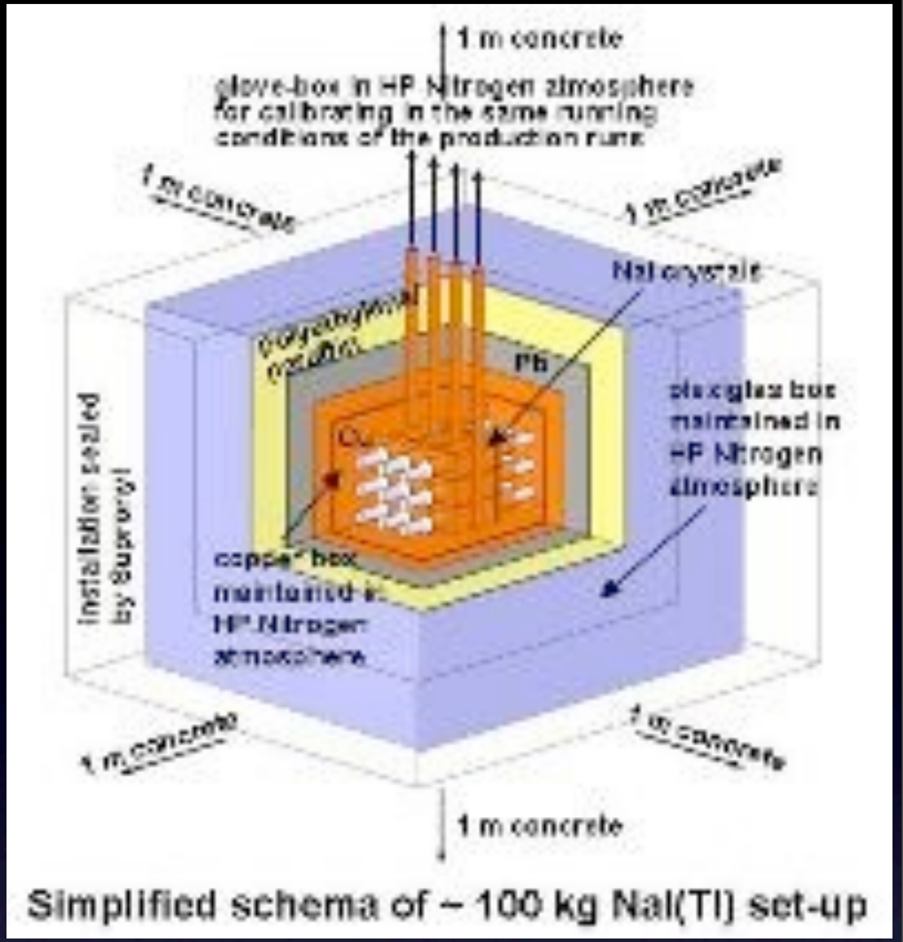
  DAMA, CoGeNT, CRESST

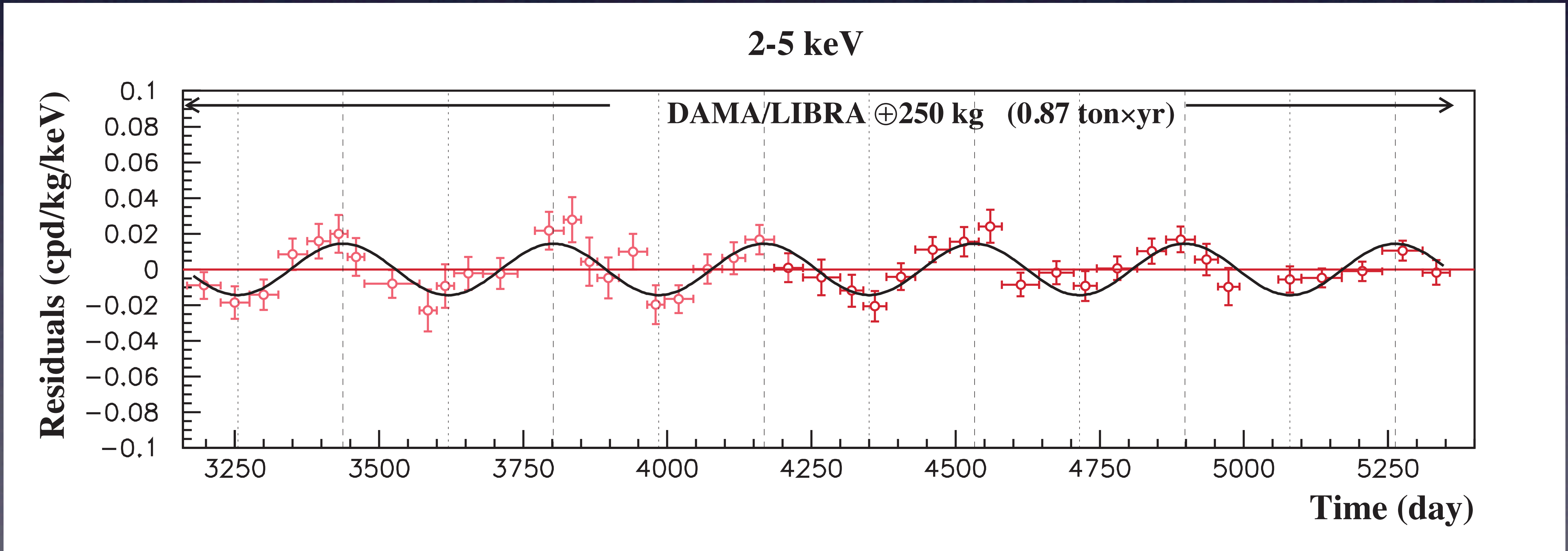
  Consistency with other experiments ?

(1) DAMA @ Gran Sasso

NaI scintillation ~1 ton yr

Huge constant BG events +
Small annual modulation DM events
DM evidence more than 8 sigma
in 2-6 keV



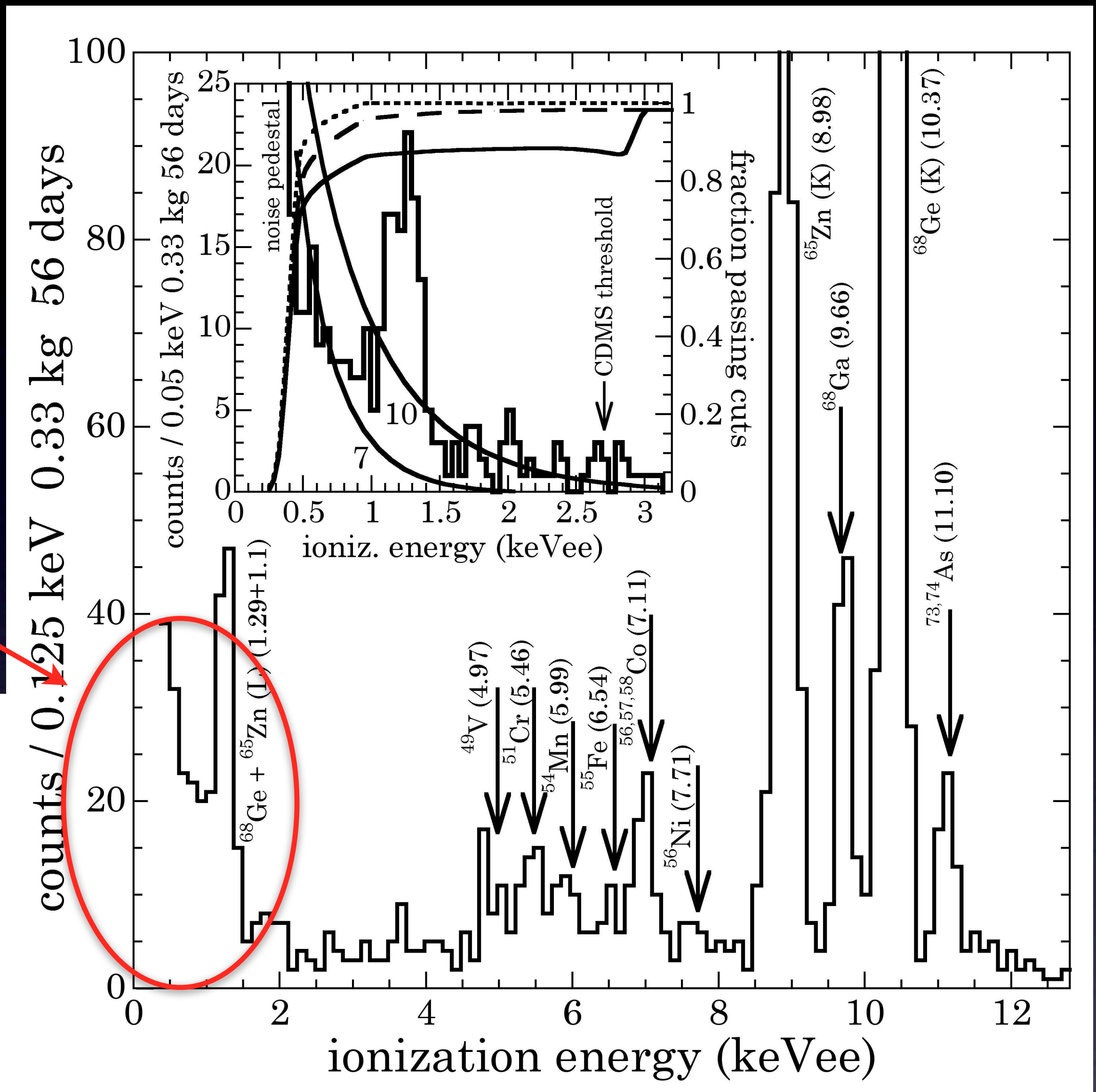


DAMA/LIBRA, 1002.1028

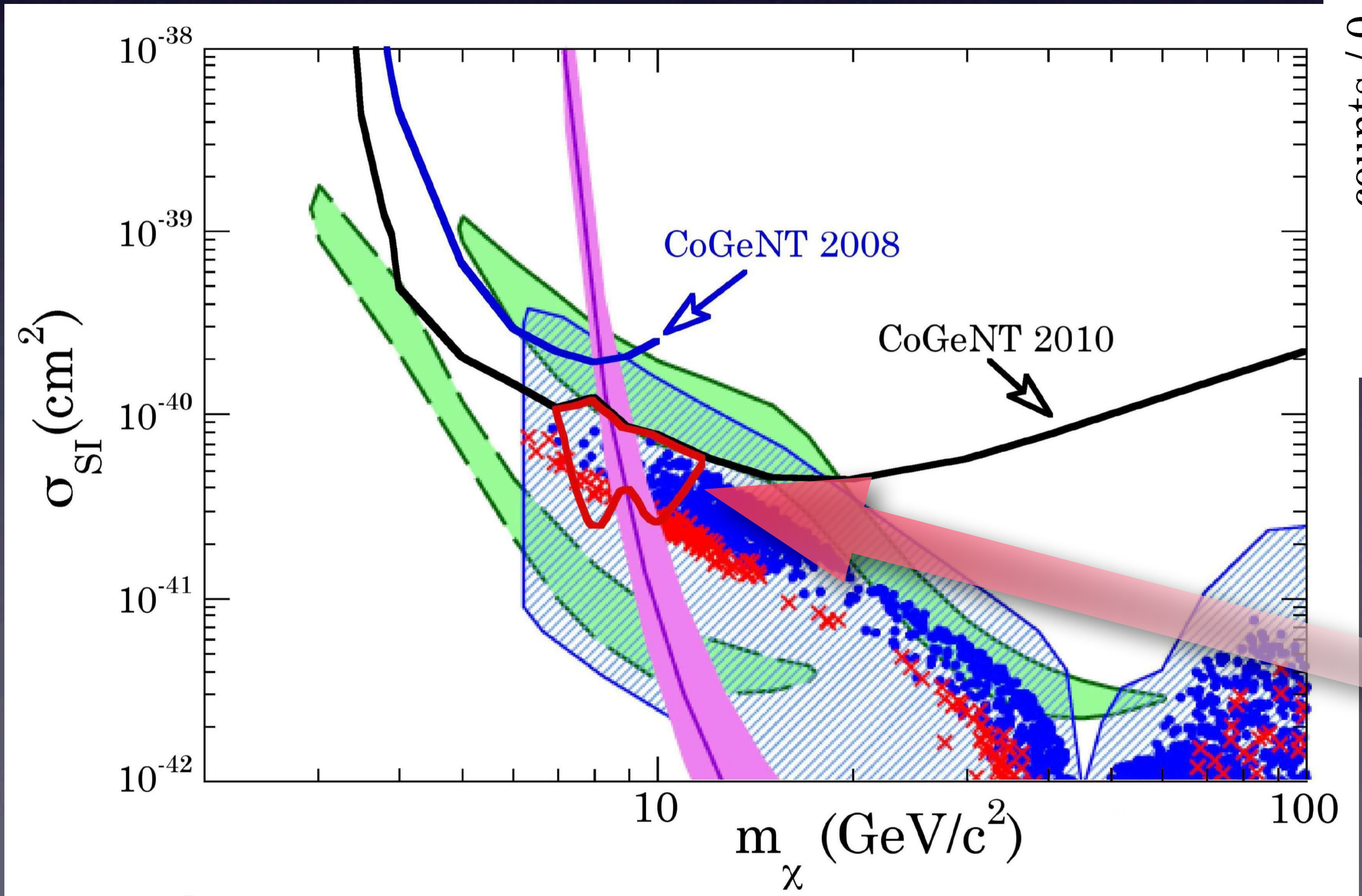
(2) CoGeNT @ Soudan

CoGeNT, 1002.4703

- Ge
- Ionization



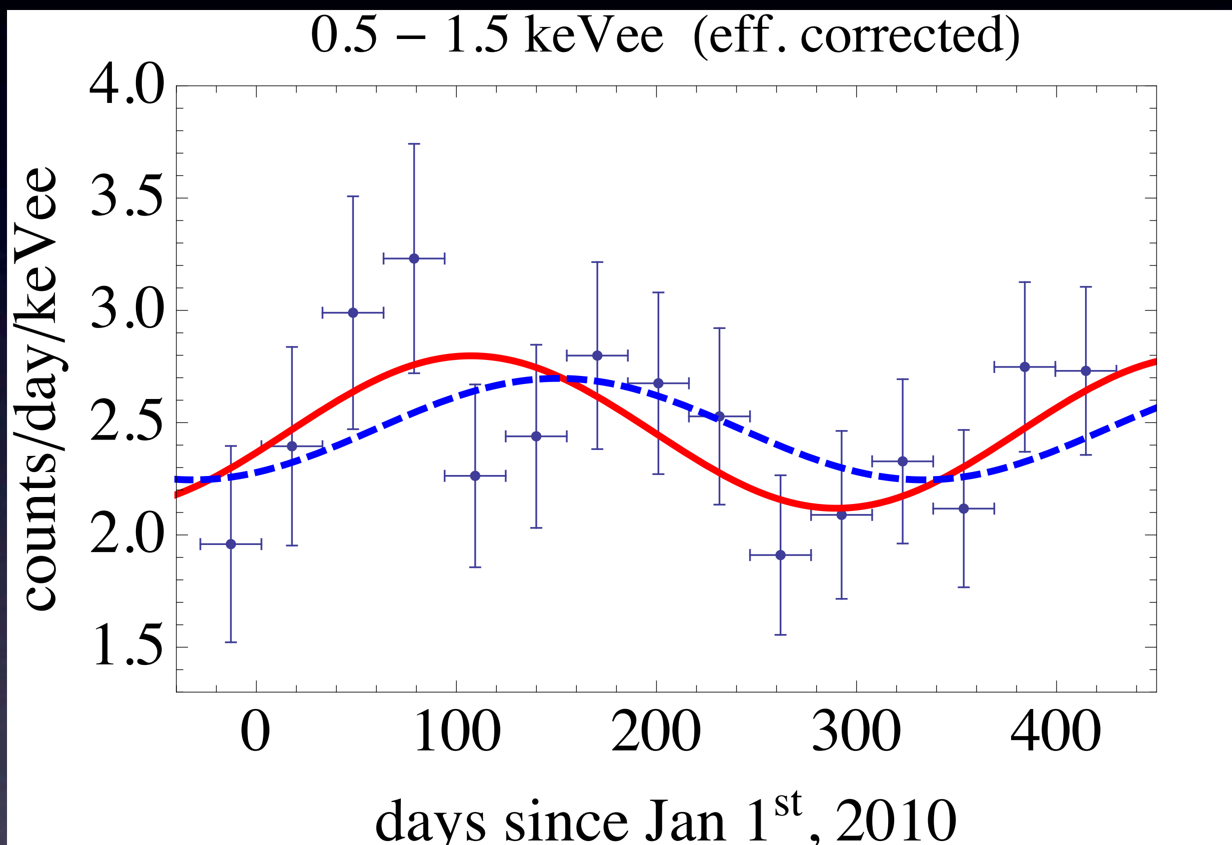
Excess caused by DM?

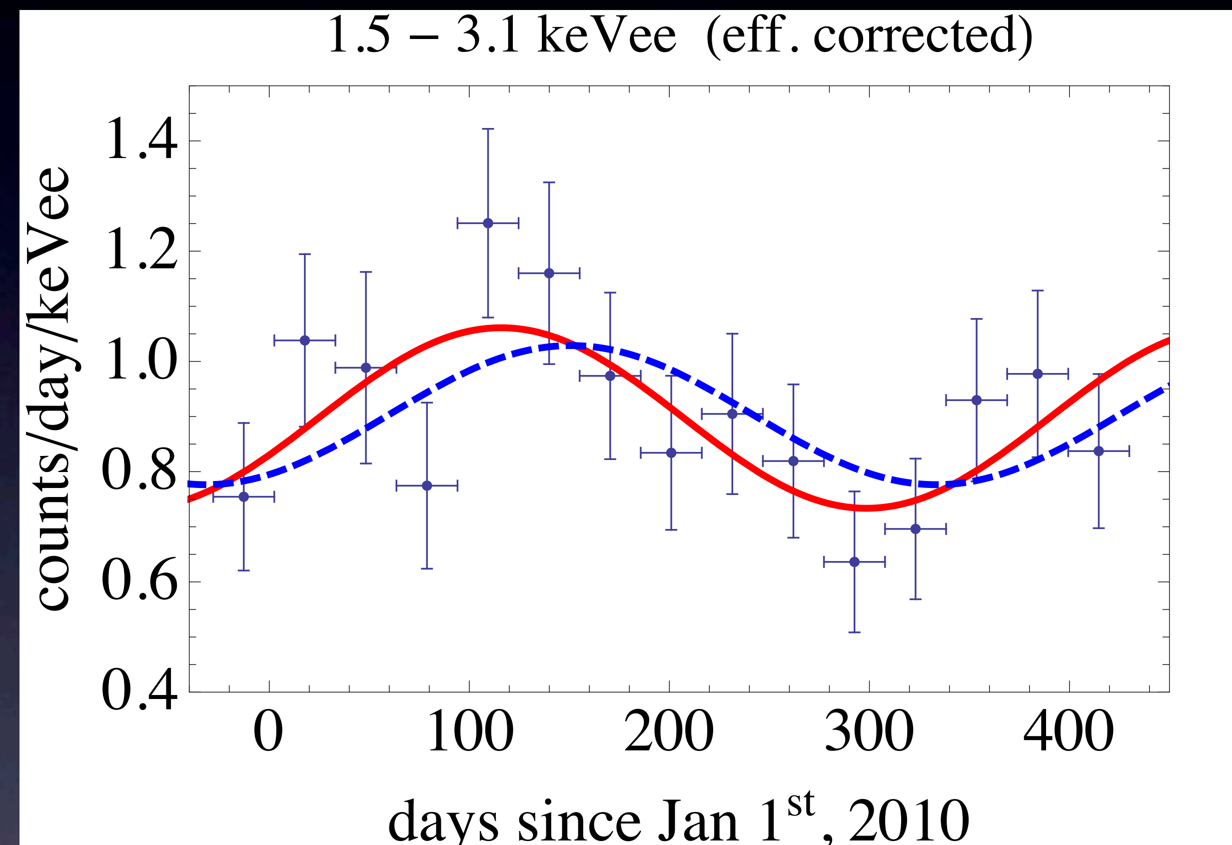


DAMA & CoGeNT suggest light DM? (m~10GeV)

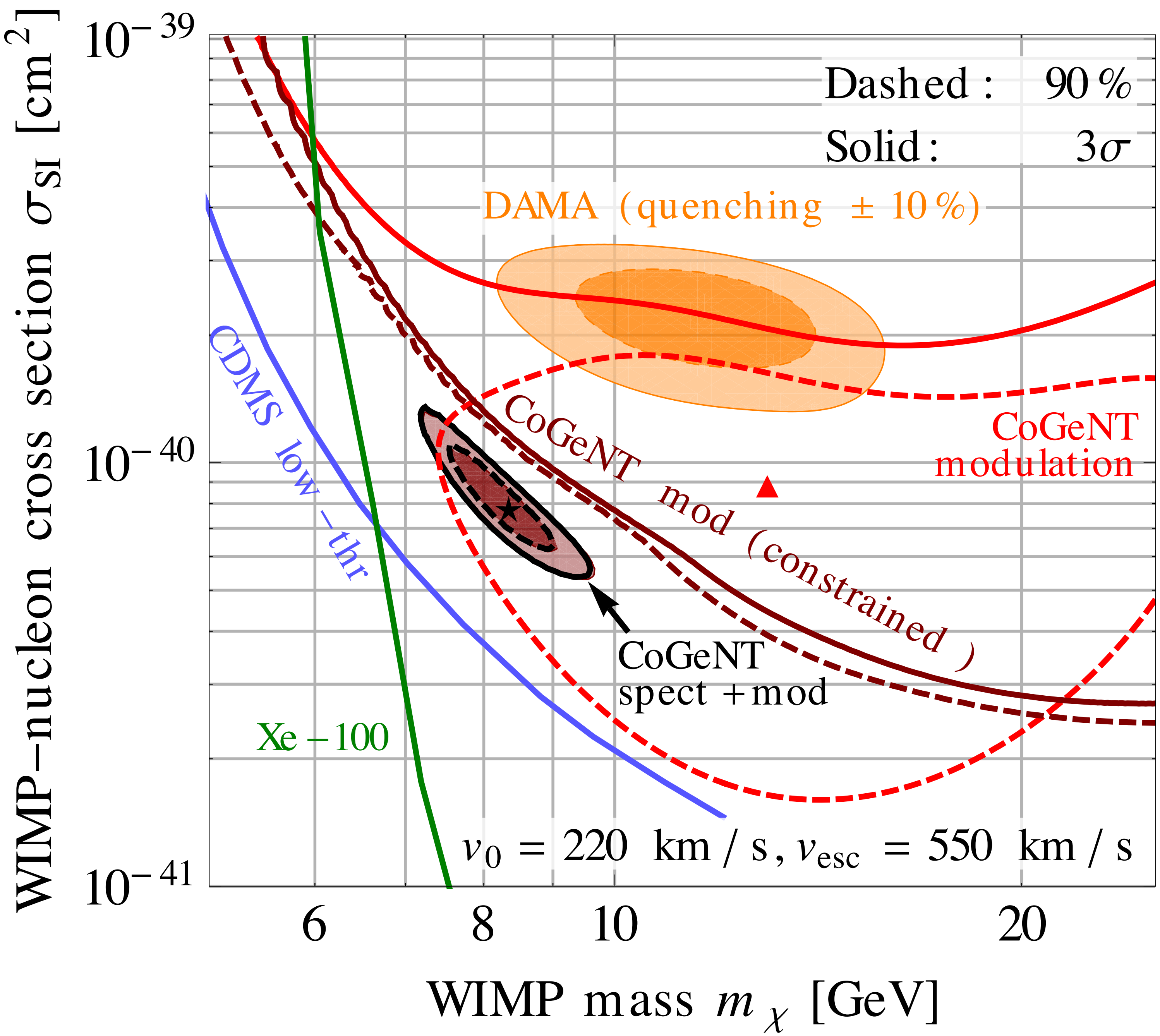
CoGeNT modulation analysis

CoGeNT, 1107.0717





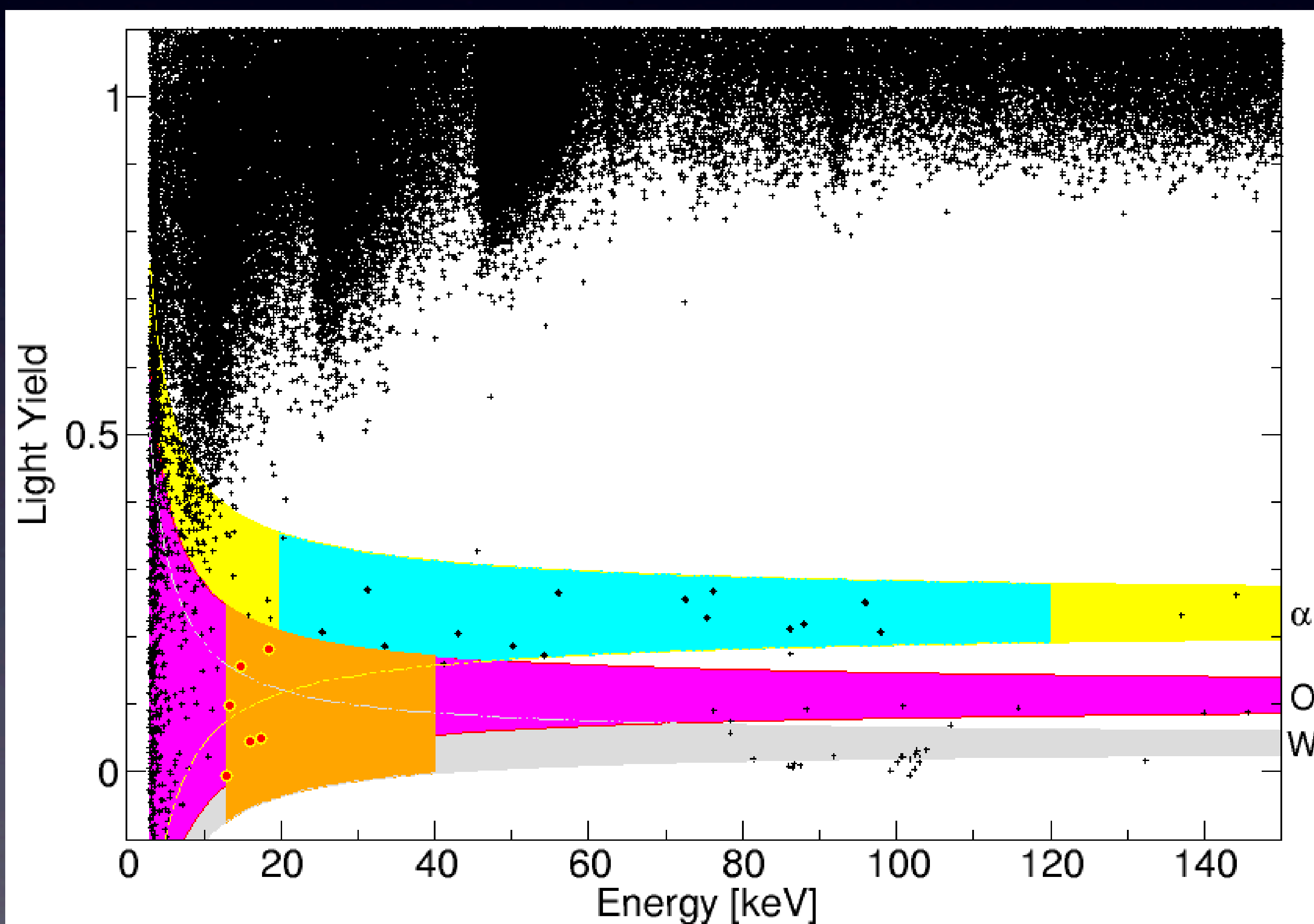
Evidence of annual modulation

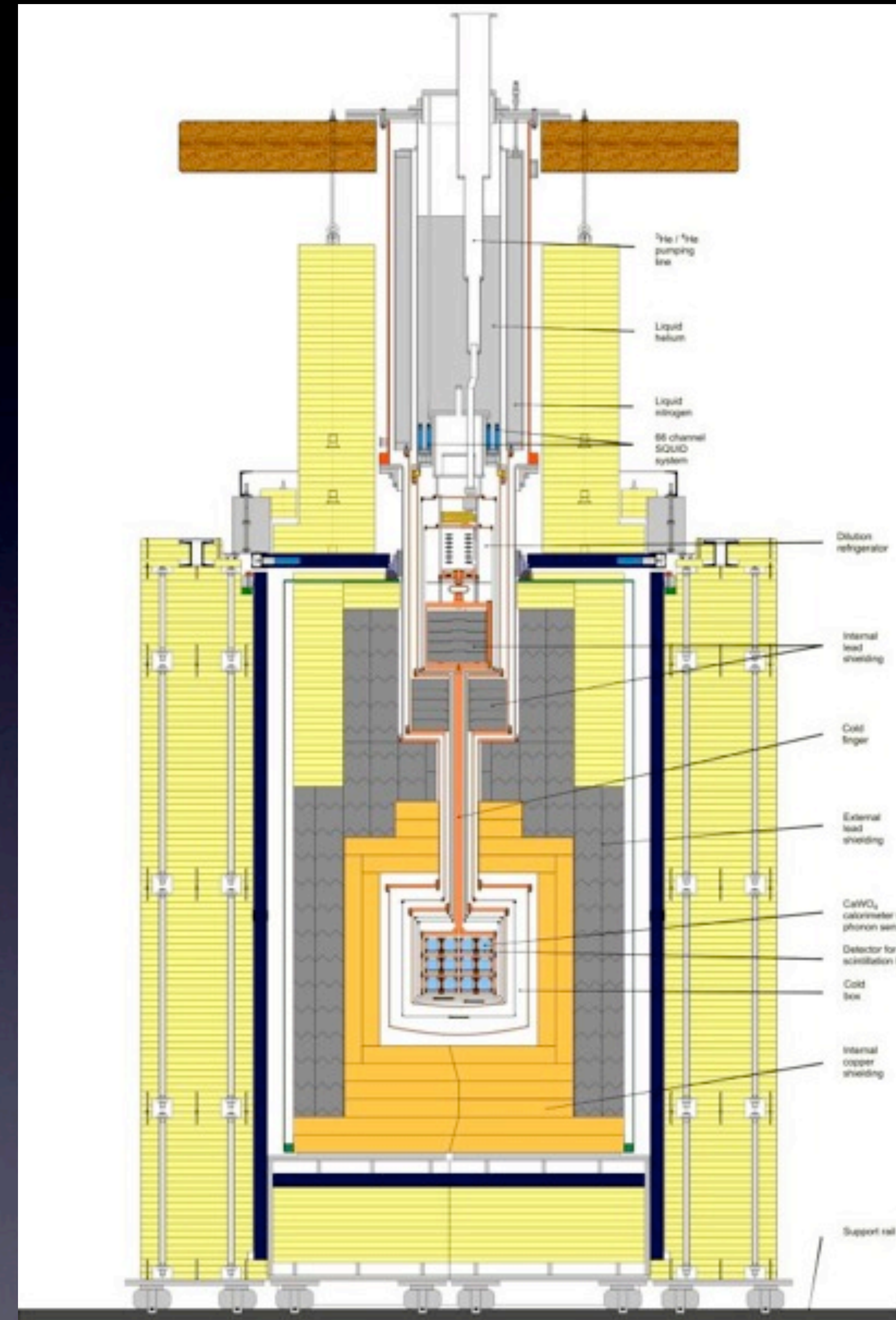


12年3月21日水曜日

(3) CRESST @ Gran Sasso

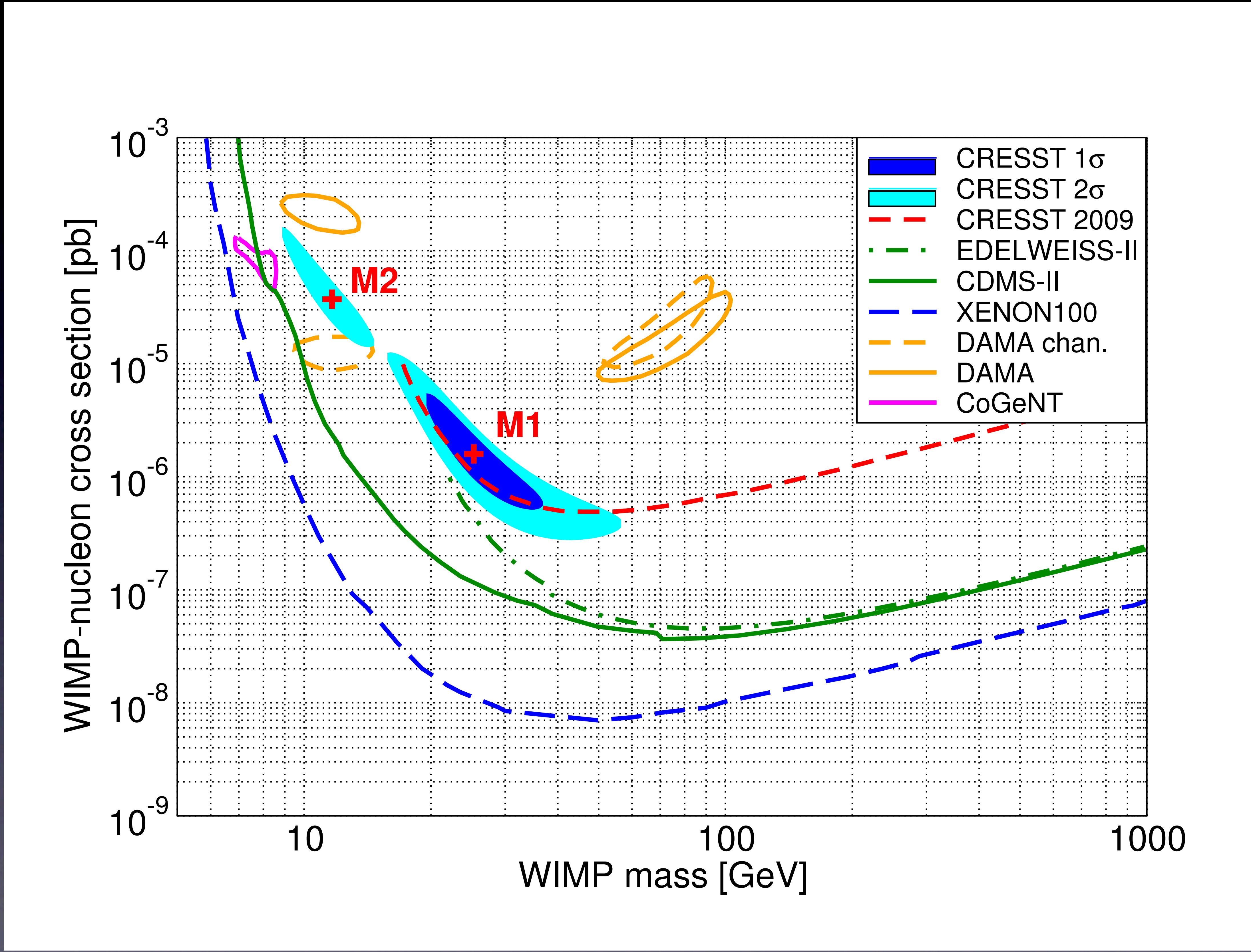
- CaWO4
- Scintillation + Phonon
- ~730 kg day





CRESST, 1109.0702

67 events observed in signal region

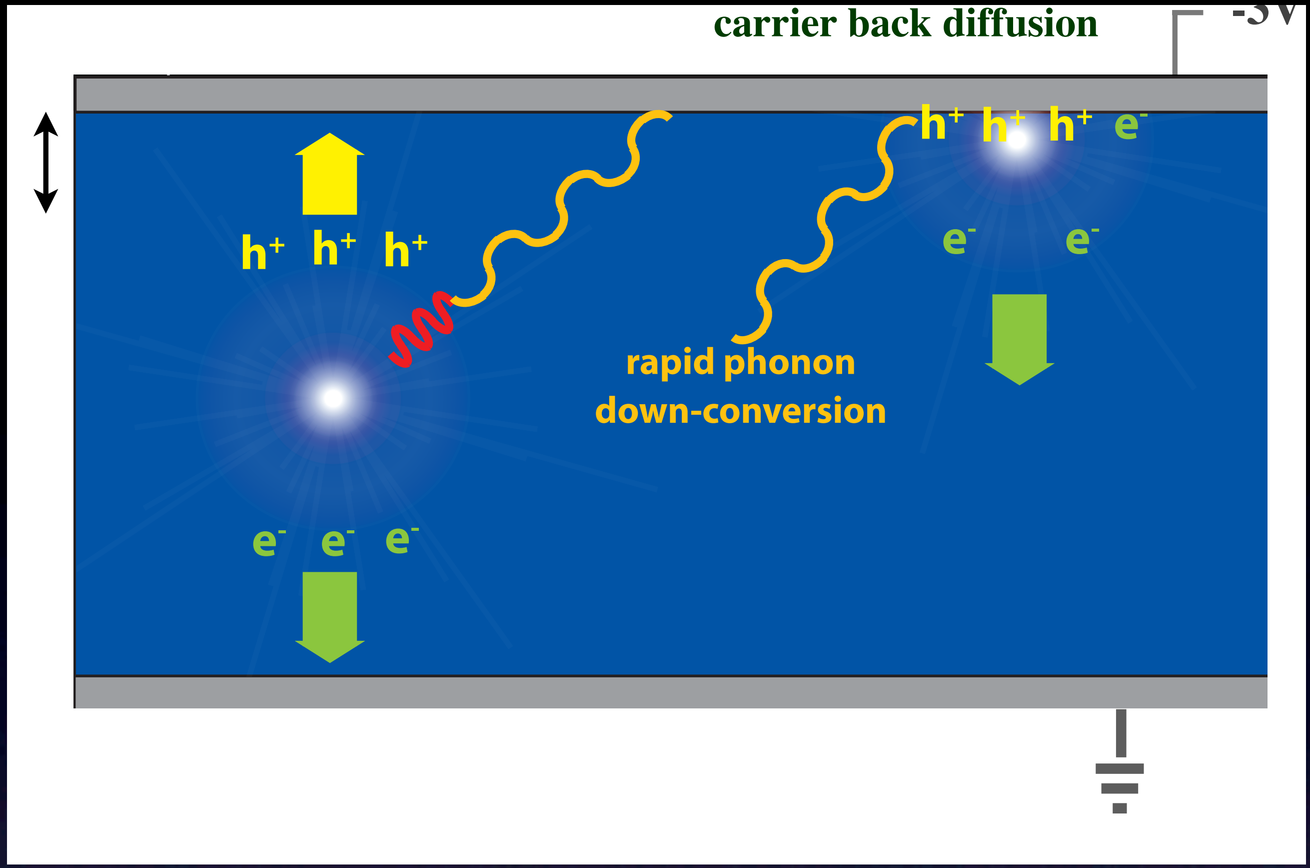


CRESST, 1109.0702

(4) CDMS II @ Soudan

- Ge
- Ionization+Phonon
- ~194 kg day

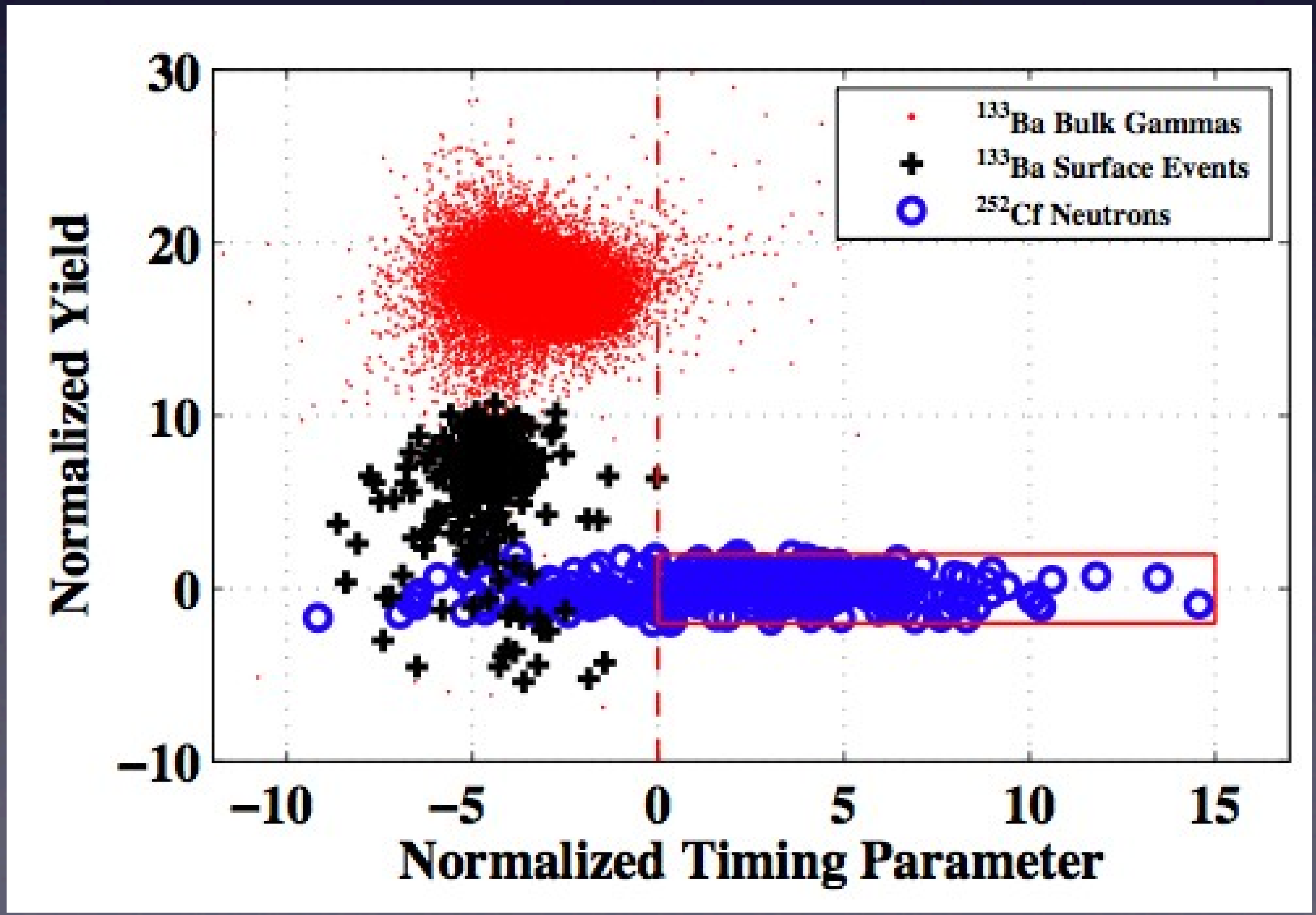
E_th = 10keV



Recoil energy : phonon

Ionization/Phonon ratio

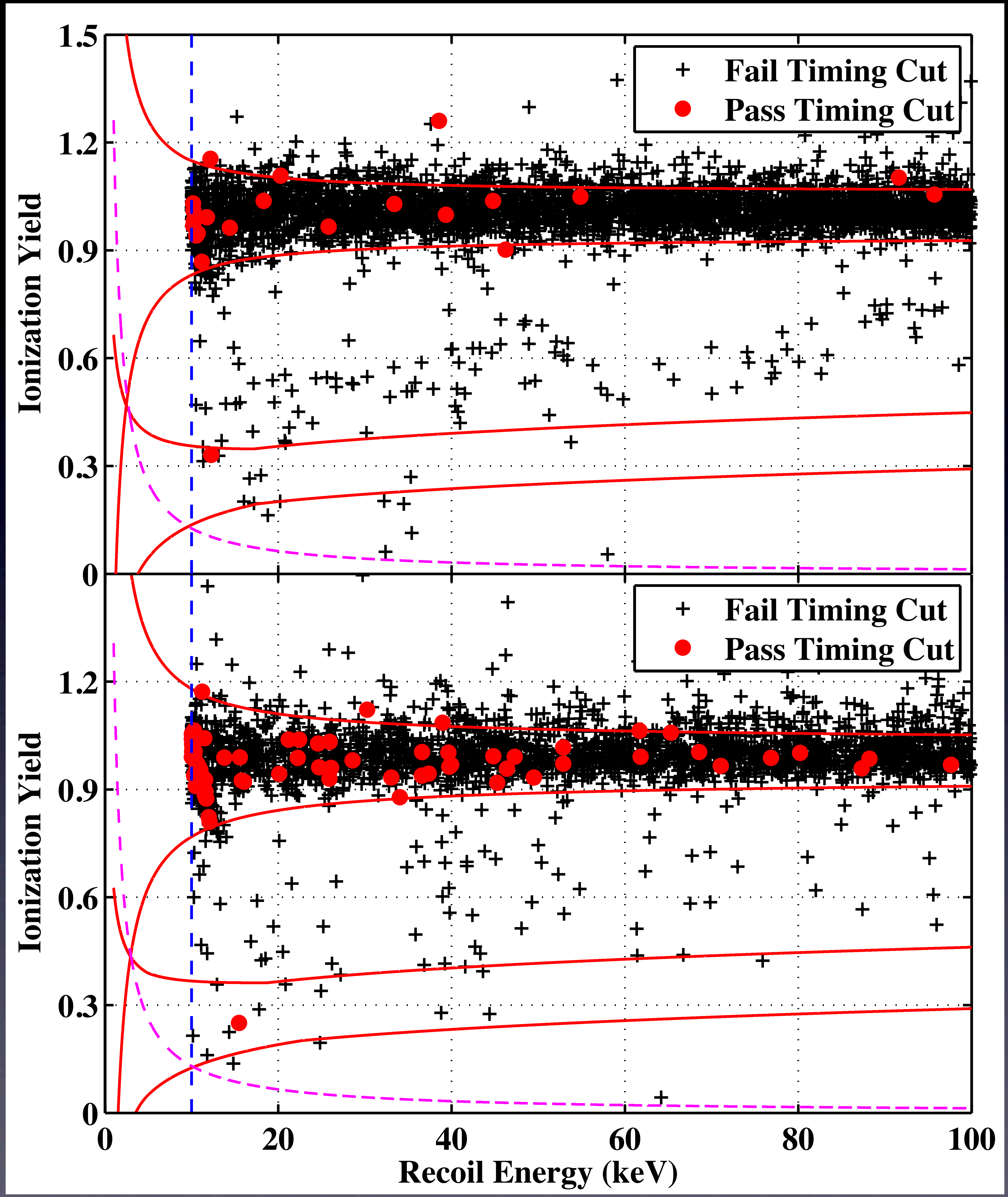
Timing of both signals



Z.Ahmed et al. 0912.3592

2 DM like events

However, expected BG is ~0.8 event



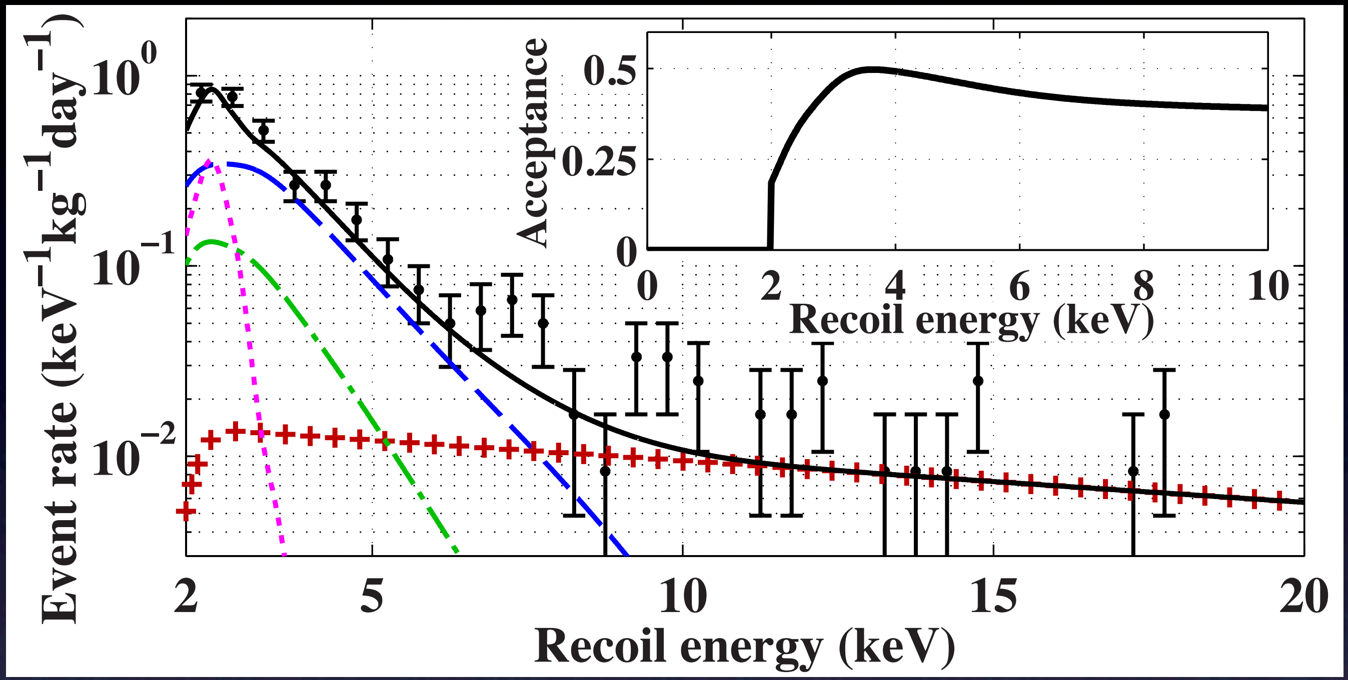
Z.Ahmed et al. 0912.3592

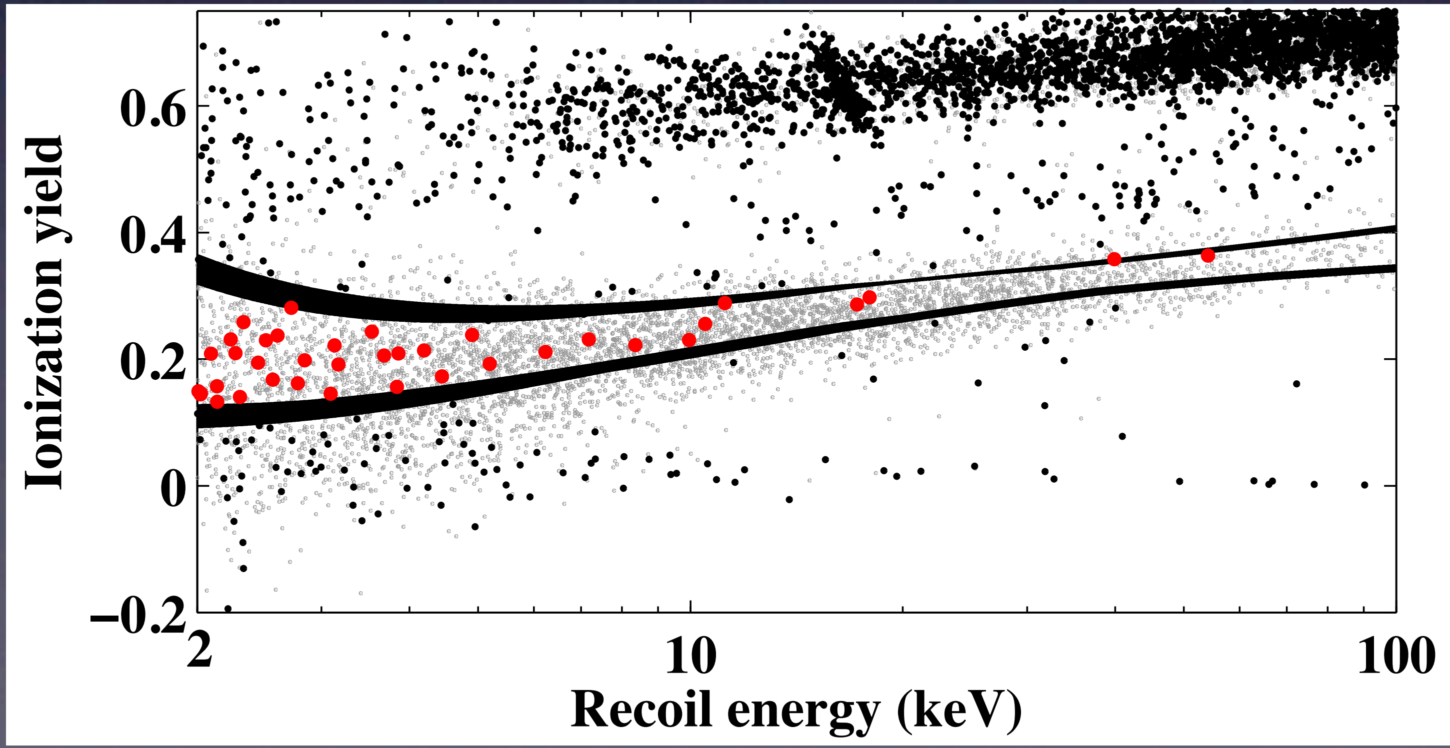
CDMS low-energy analysis

CDMS, 1011.2482

Oct.2006 - Sep.2008

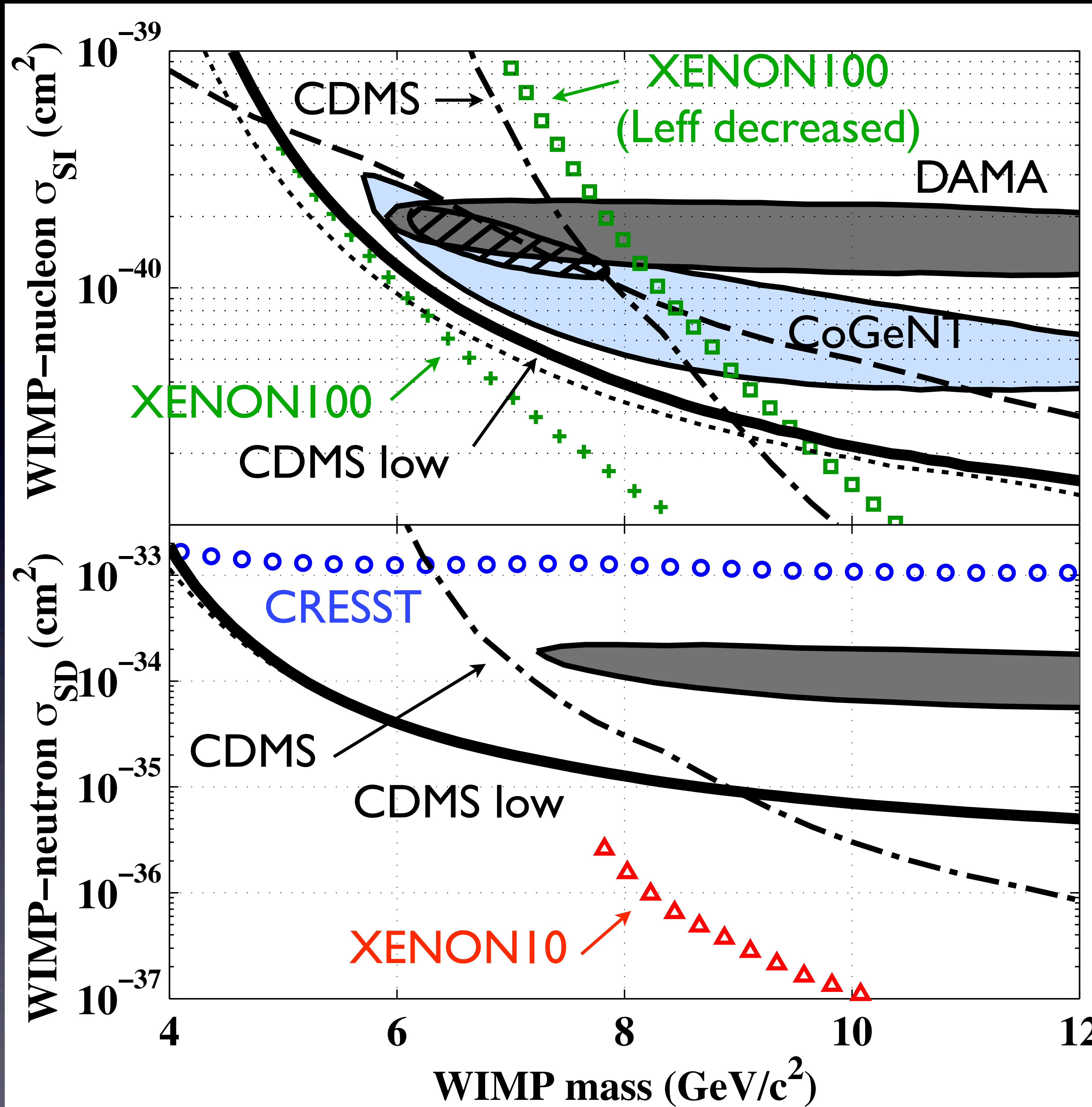
- Energy threshold 10keV --> 2keV
- Signal from low mass WIMP
- Electron BG





Candidate events consistent with e BG

12年3月21日水曜日



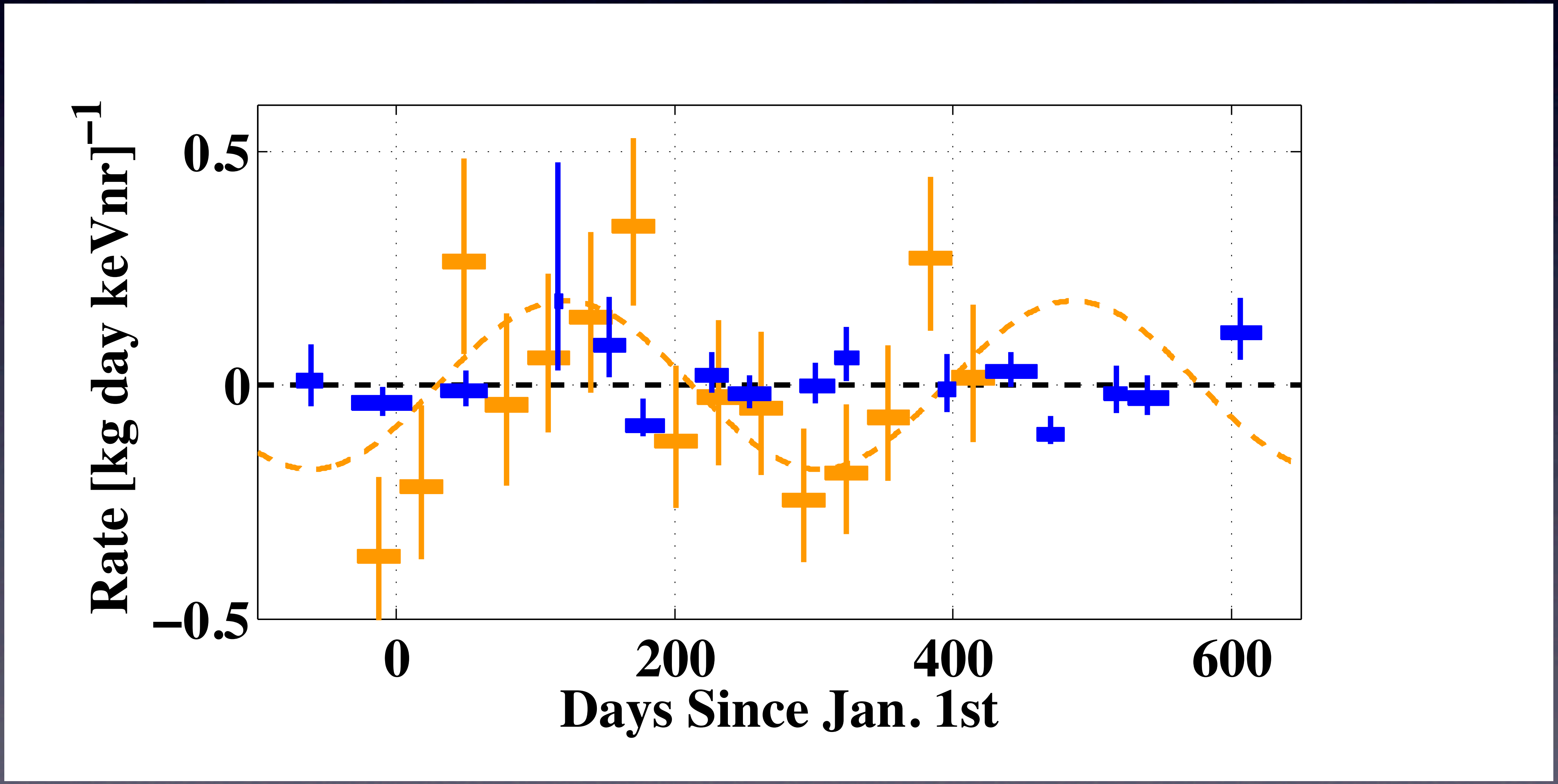
CDMS, 1011.2482

CDMS modulation analysis @ Soudan

CDMS, 1203.1309

Oct.2006 - Sep.2008

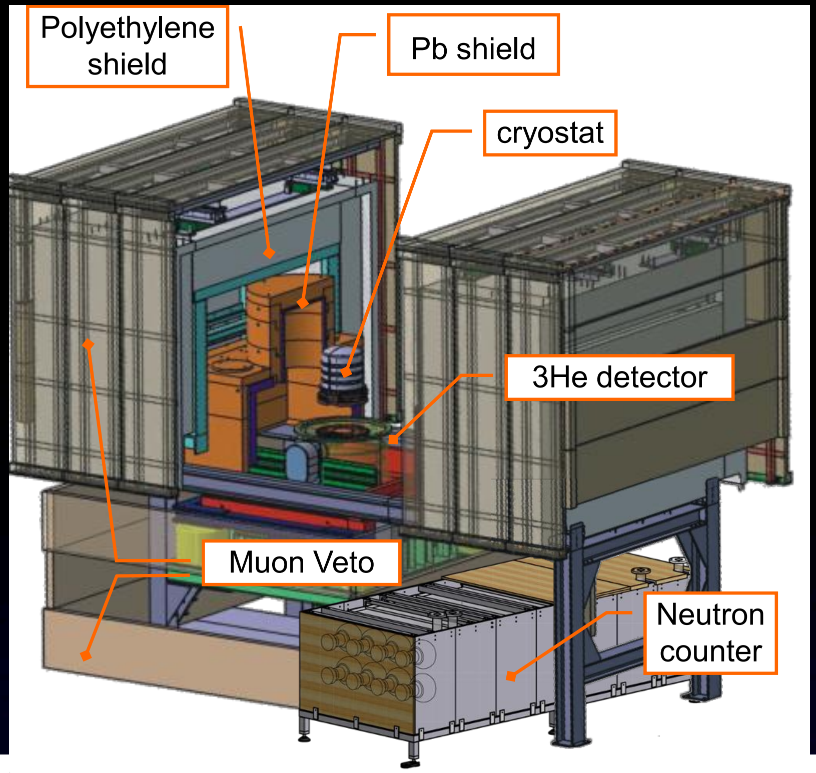
Same energy range for CoGeNT

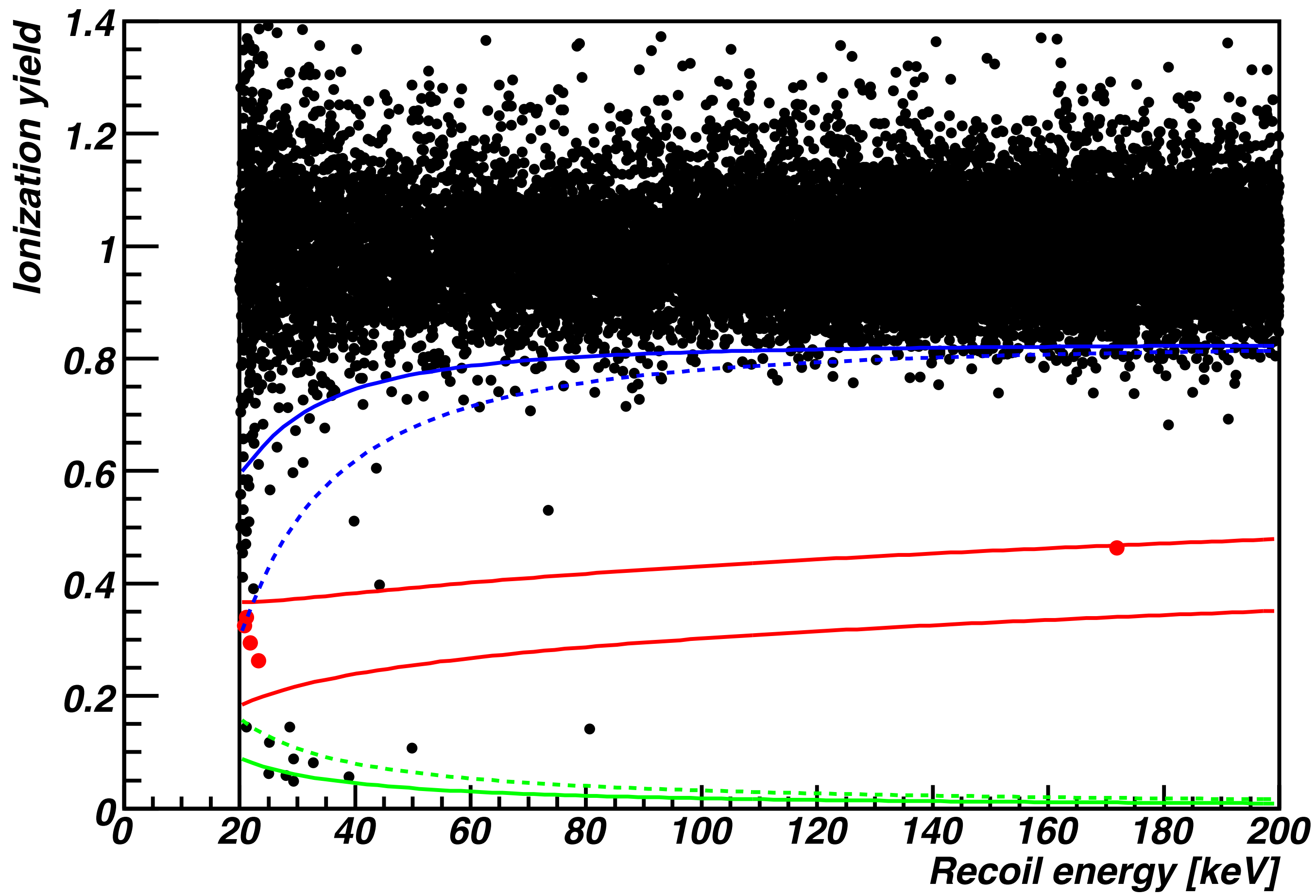


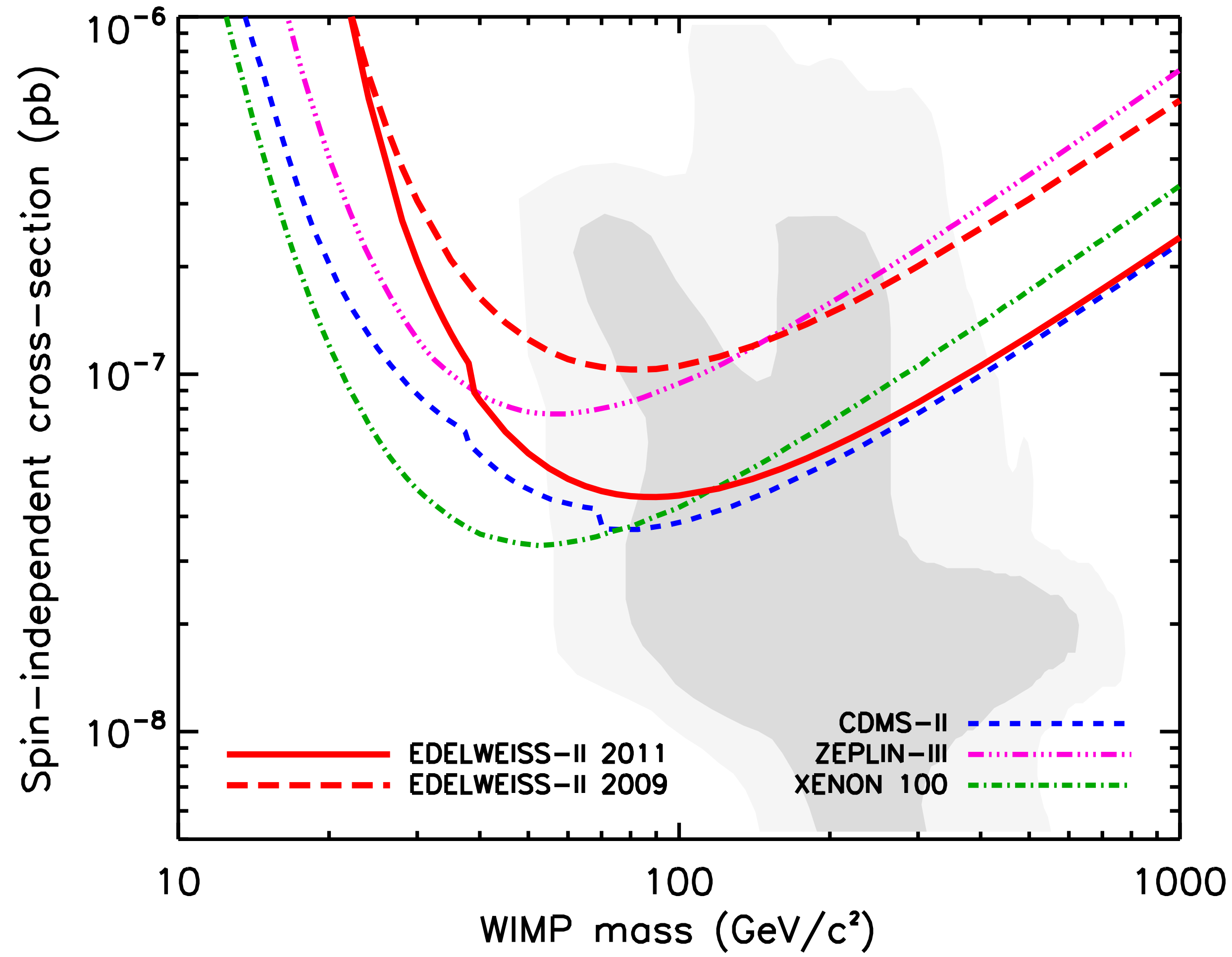
No evidence for annual modulation

(5) EDELWEISS-2 @ France

- Ge
- Phonon+Ionization
- 384 kg day data





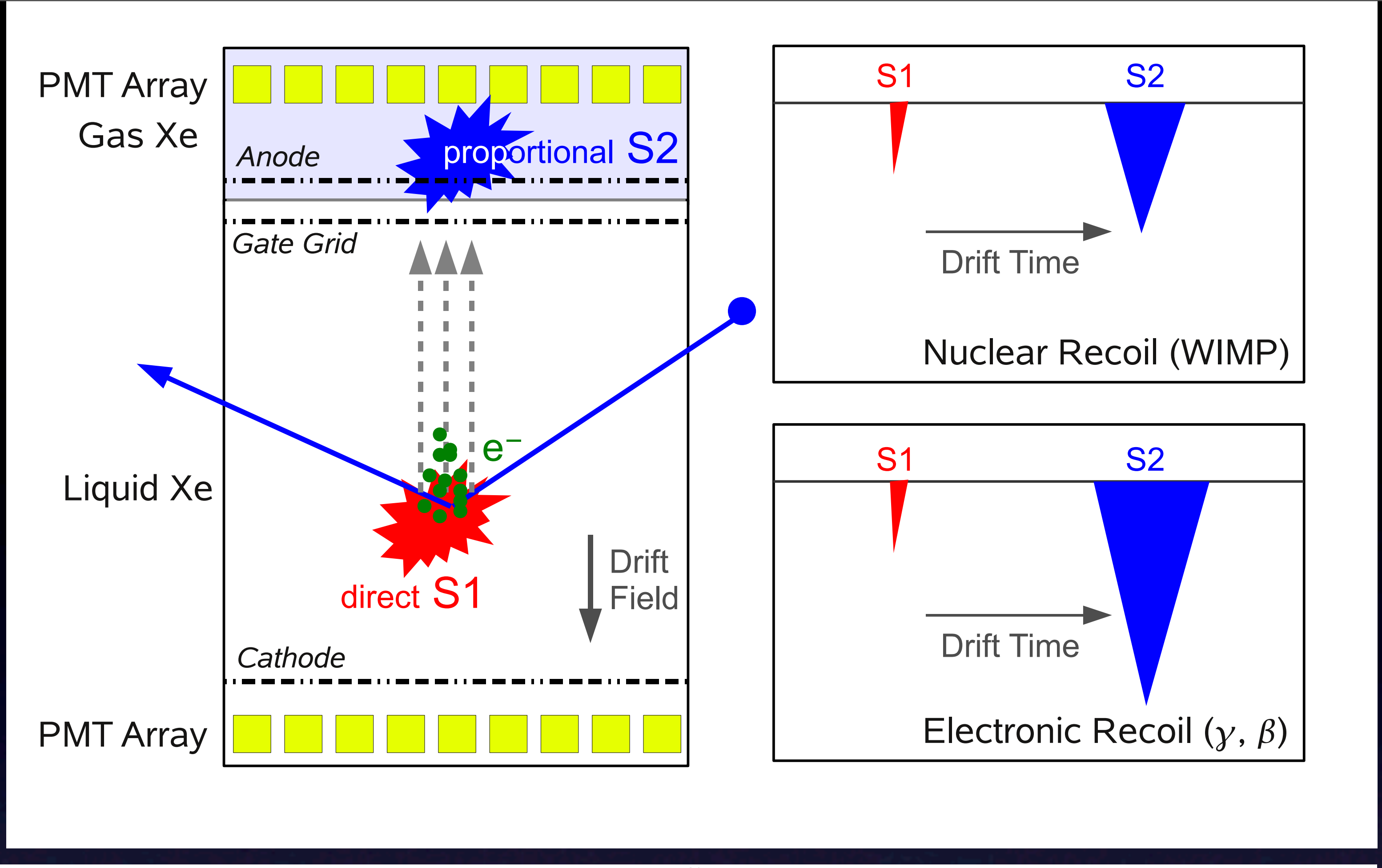


5 DM like events
expected BG ~ 3 events

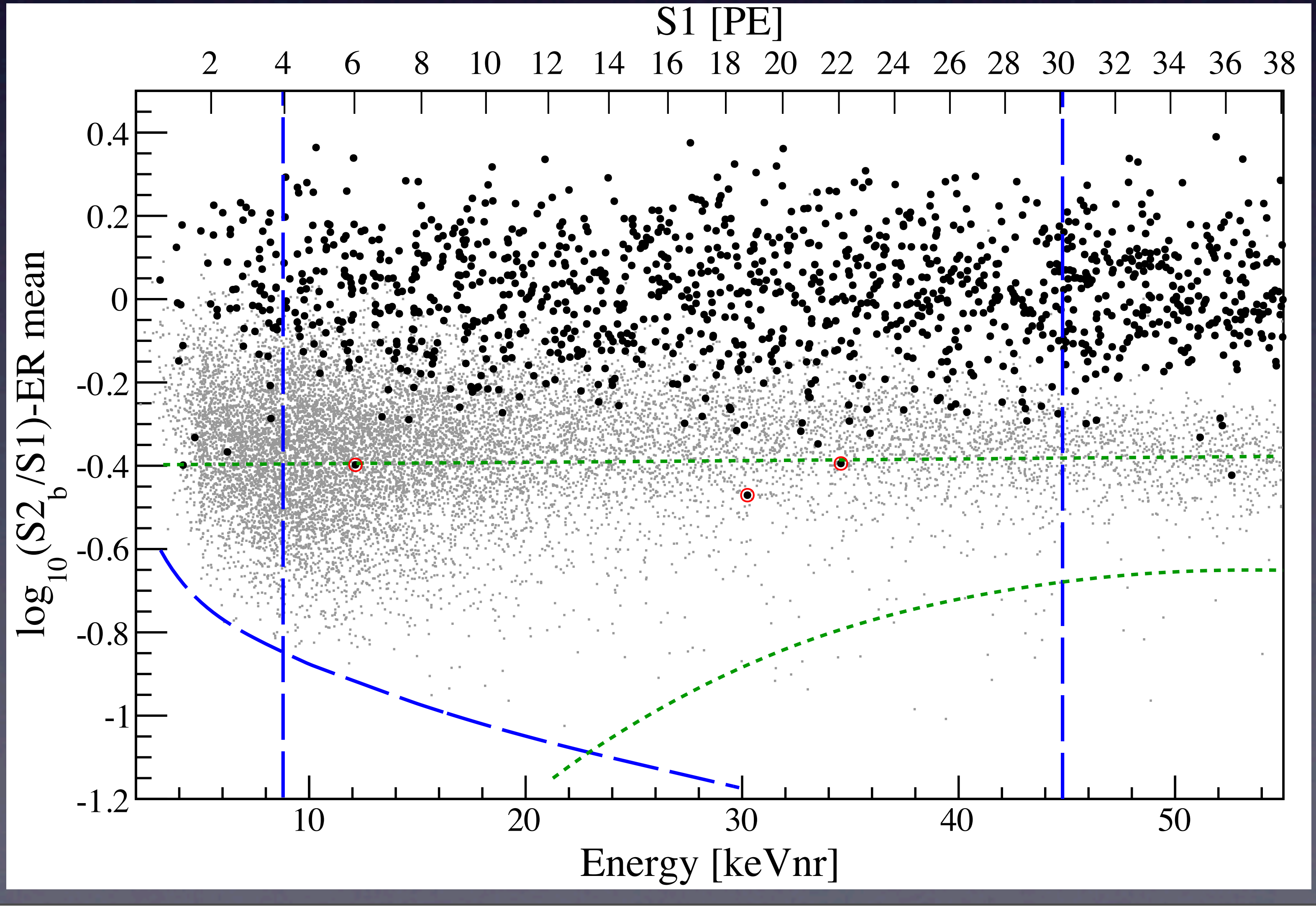
EDELWEISS, 1103.4070

(6) XENON100 @ Gran-Sasso

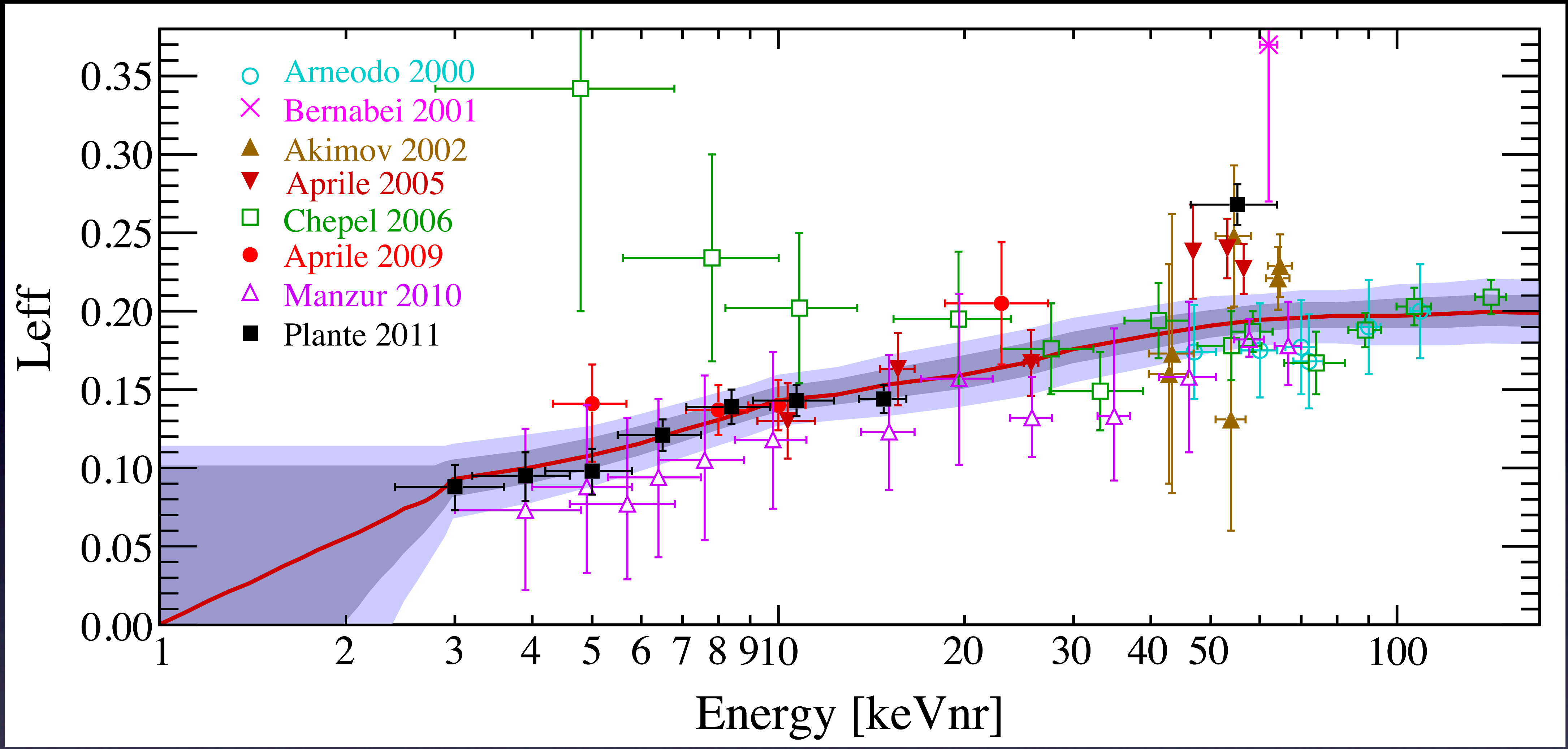
- LXe
- Scintillation + Ionization
- ~1500 kg day



- Observed 3 events after all cuts
- Expected BG : 1.8 +- 0.6 events



Scintillation efficiency at low energy



Discussions on scintillation efficiency

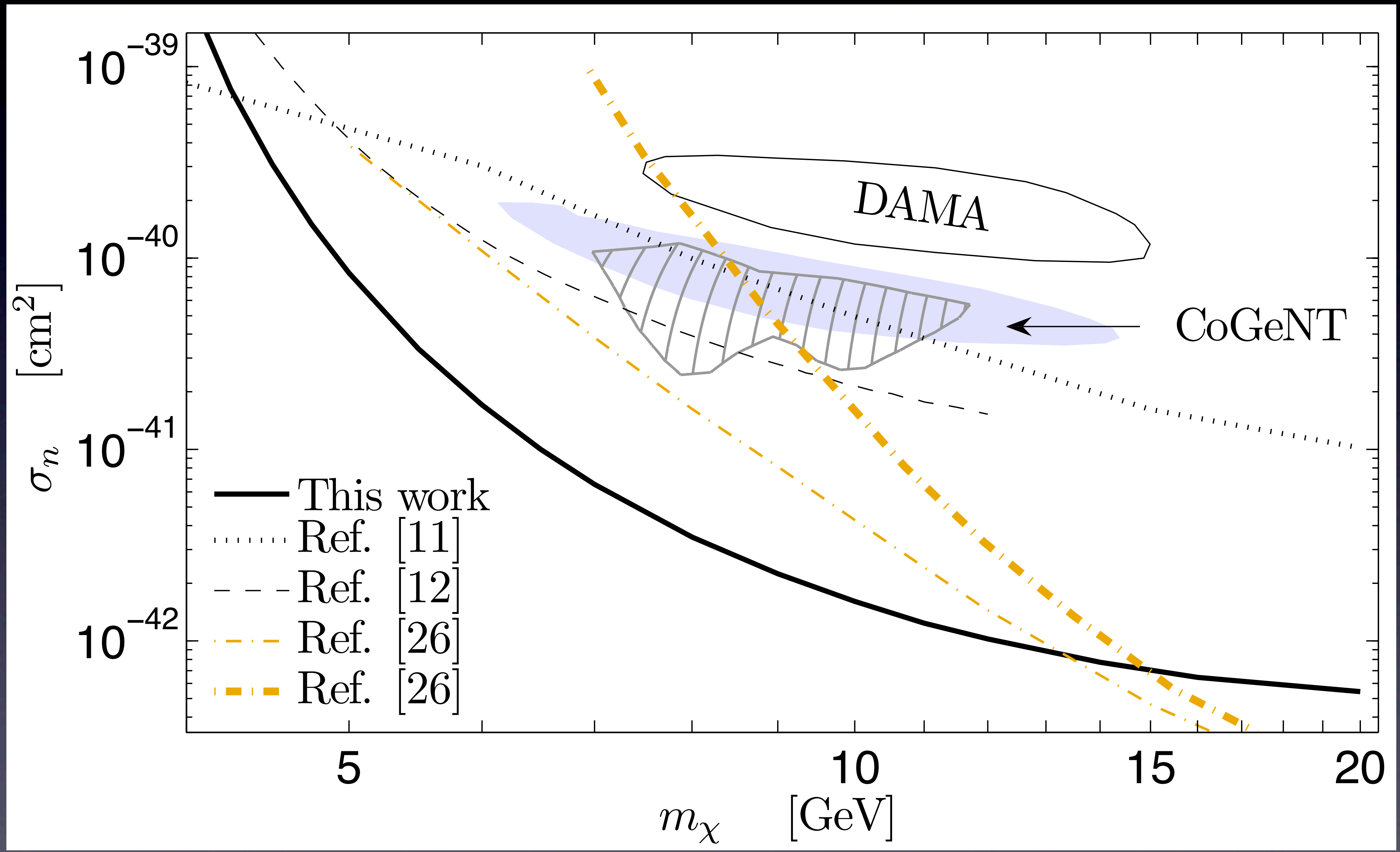
(J.I.Collar, 1005.0838, 1006.2031,XENON collab., 1005.2615)

Uncertainty below 3keVnr is negligible for m~10GeV

XENON, 1104.2549

XENON10

Lower threshold,   S2(ionized e)only

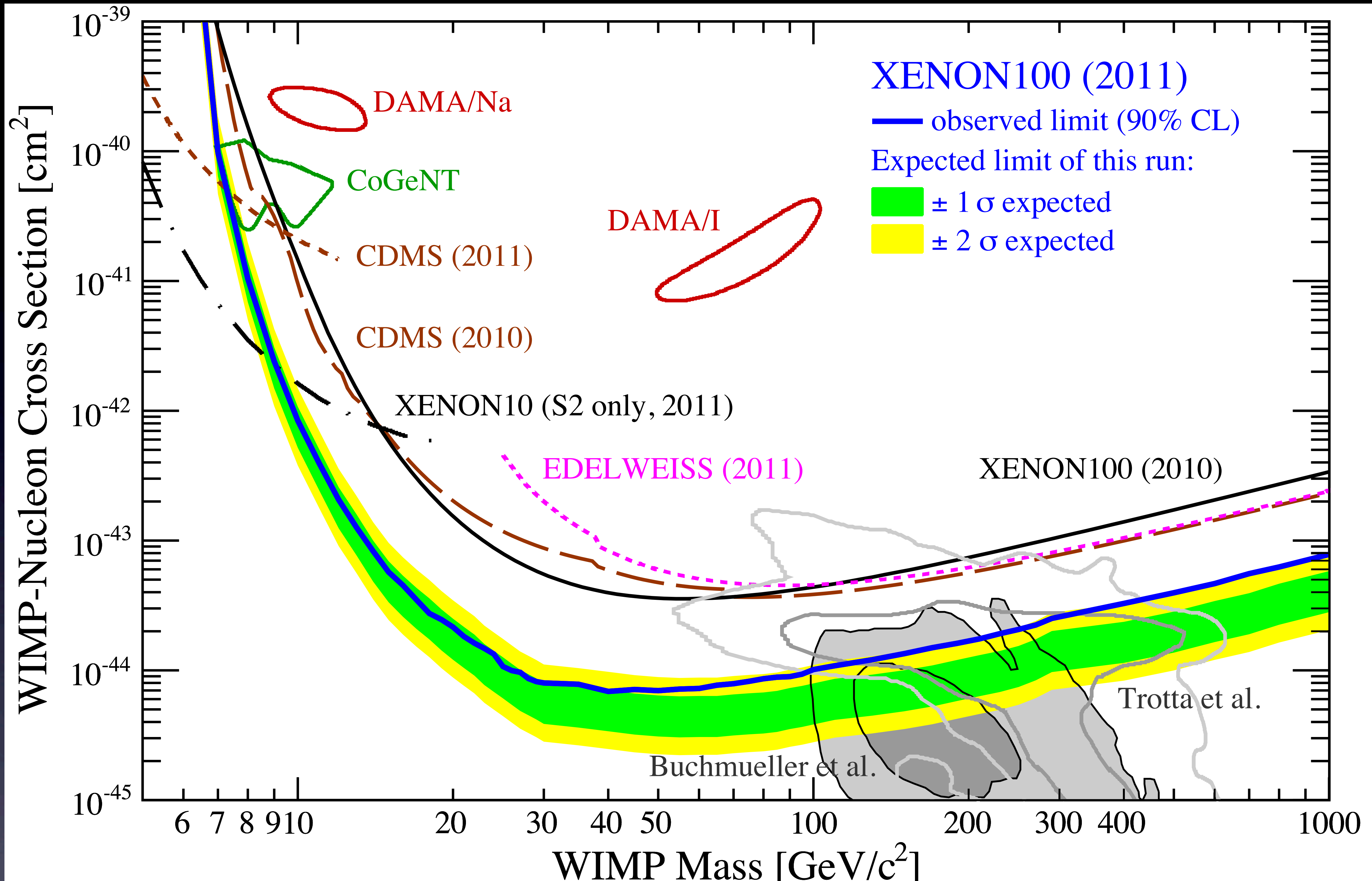


~0.2 /kg/d/keV

(5/kg/d/keV for CoGeNT)

XENON collab., 1104.3088

(See, However, J.I.Collar, 1106.0653)



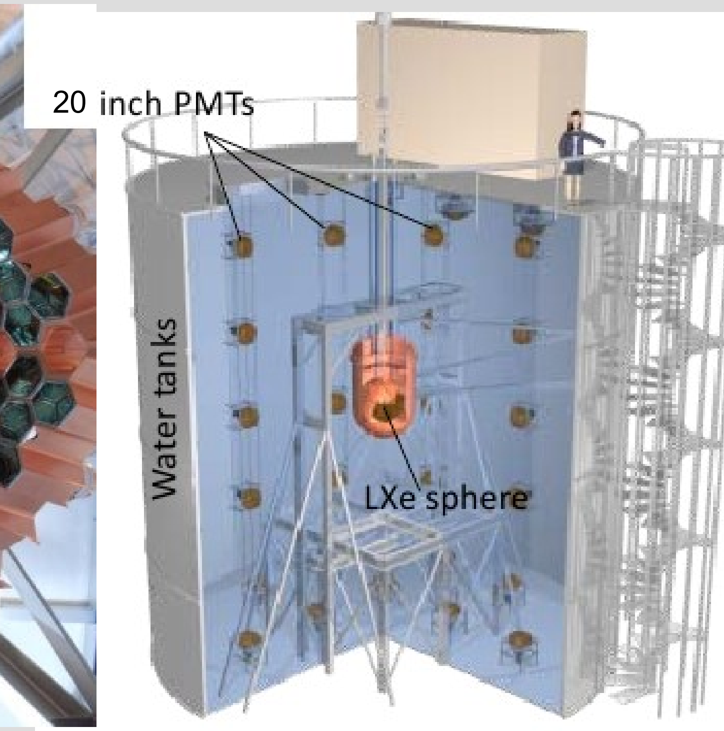
XENON, 1104.2549

Note : $\rho_\chi = 0.3 \mathrm{GeV/cm^3}$

($\rho_\chi \simeq 0.39 \mathrm{GeV/cm^3}$ Catena, Ullio, 0907.0018)

XMASS

- single phase **LXe** detector
- 800kg total, 100kg fiducial mass
- 60% of surface covered with 642 hexagonal PMTs
- very high LY (~7x higher than Xe100)
- located in Kamioka (JP)
- running since end of 2010; ultra low Kr85 background
- higher Rn background reported at TAUP2011; study on S1 PSD published (92% rej @ 50% acc)



first results will be announced at the Japanese Physical Society meeting, March 23, 2012
→ expect results from 1 year exposure

From slide by M.Schumann @ Moriond 2012

- Inelastic DM

$$\chi_- + p \to \chi_+ + p \qquad \delta m \equiv m_{\chi+} - m_{\chi-}$$

kinematical condition : $\delta m < \dfrac{v^2 m_\chi m_N}{2(m_\chi + m_N)}$

$\delta m \sim 10\mathrm{keV} \longrightarrow$ CDMS(Ge)can be suppressed, but XENON, ZEPLIN (Xe)...

White dwarf constraint McCullough, Fairbairn 1001.2737

- Isospin violating DM

$$\sigma_{\chi N} \propto [Z f_p + (A - Z) f_n]^2$$

$f_n/f_p = -0.7$: avoid XENON constraint

CoGeNT (Ge) = CDMS (Ge) ?

Farina et al., 1107.0715 Kopp, Schwetz, Zupan, 1110.2721

Constraint from LHC

- DM effective interaction

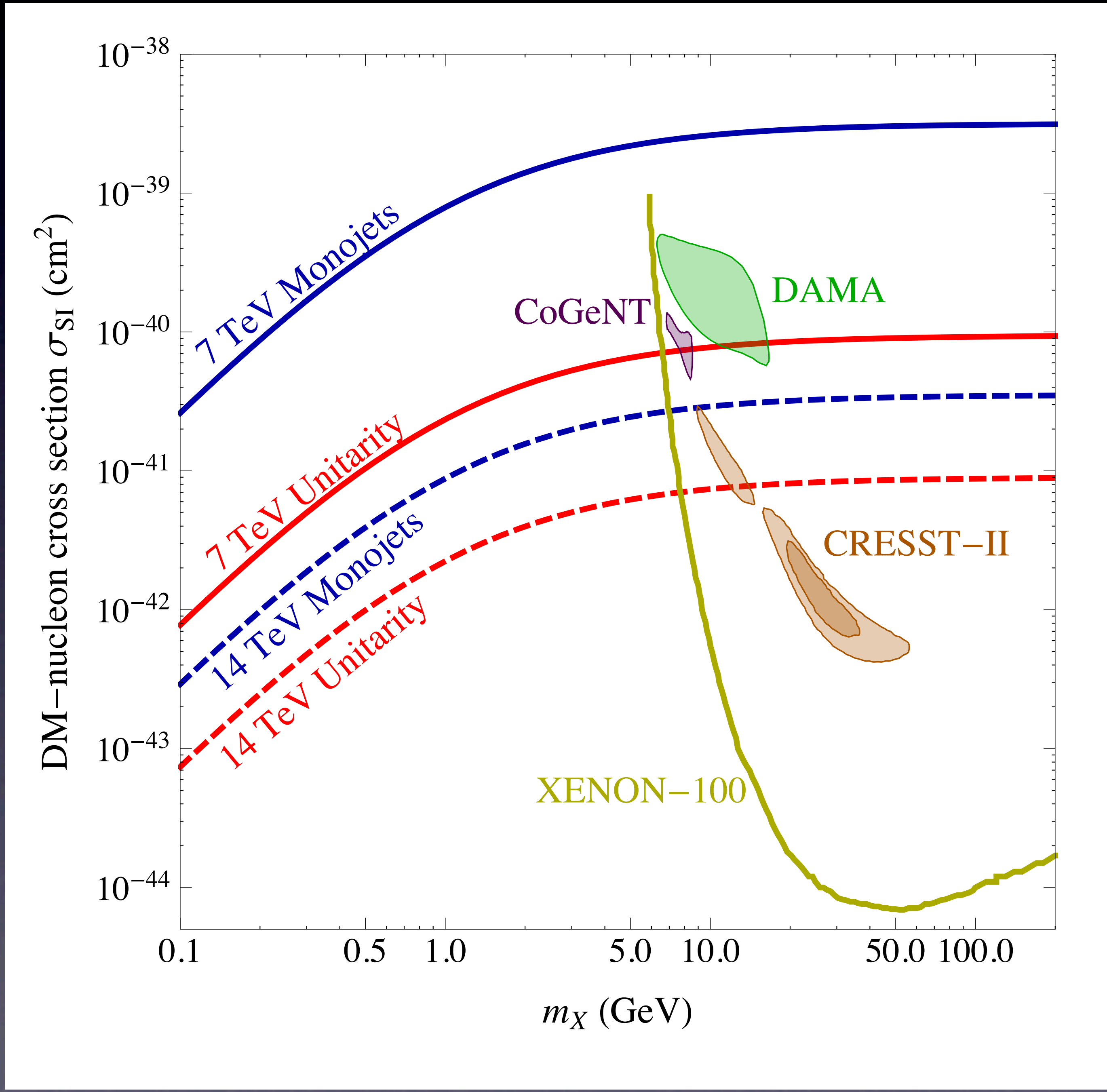
$$\mathcal{O} = \frac{\bar{q}\gamma^\mu q \, \overline{X}\gamma^\mu X}{\Lambda^2}$$

DM scatter

$$pX \to pX$$

Production at LHC

$$pp \to XX(+j)$$



Shoemaker, Vecchi, 1112.5457

Neutralino DM

Bino, Wino, Higgsino

$$(\tilde{B}, \tilde{W}, \tilde{H}_1, \tilde{H}_2)$$

→ Mass eigenstate

Neutralino

$$(\tilde{\chi}_0, \tilde{\chi}_1, \tilde{\chi}_2, \tilde{\chi}_3)$$

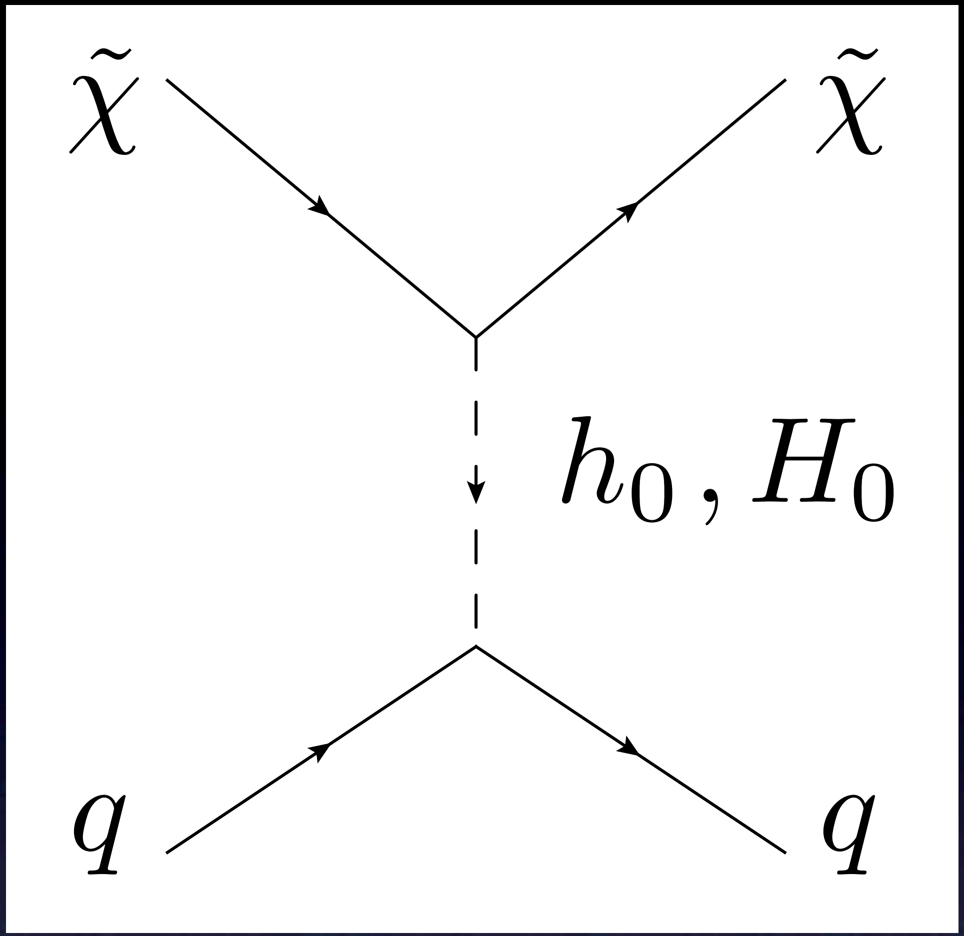
Good DM candidate
(R-parity conservation)

Effective Lagrangian

$$\mathcal{L}_{\rm eff} \simeq f_q \bar{\tilde{\chi}}\tilde{\chi}\bar{q}q + a_q(\bar{\tilde{\chi}}\gamma^\mu\gamma_5\tilde{\chi})(\bar{q}\gamma_\mu\gamma_5 q)$$

Dominant contribution : Higgs exchange diagram

$$\sigma_{\chi p}^{(\mathrm{SI})} = \frac{4}{\pi}\left(\frac{m_\chi m_N}{m_\chi + m_N}\right)^2 f_p^2$$



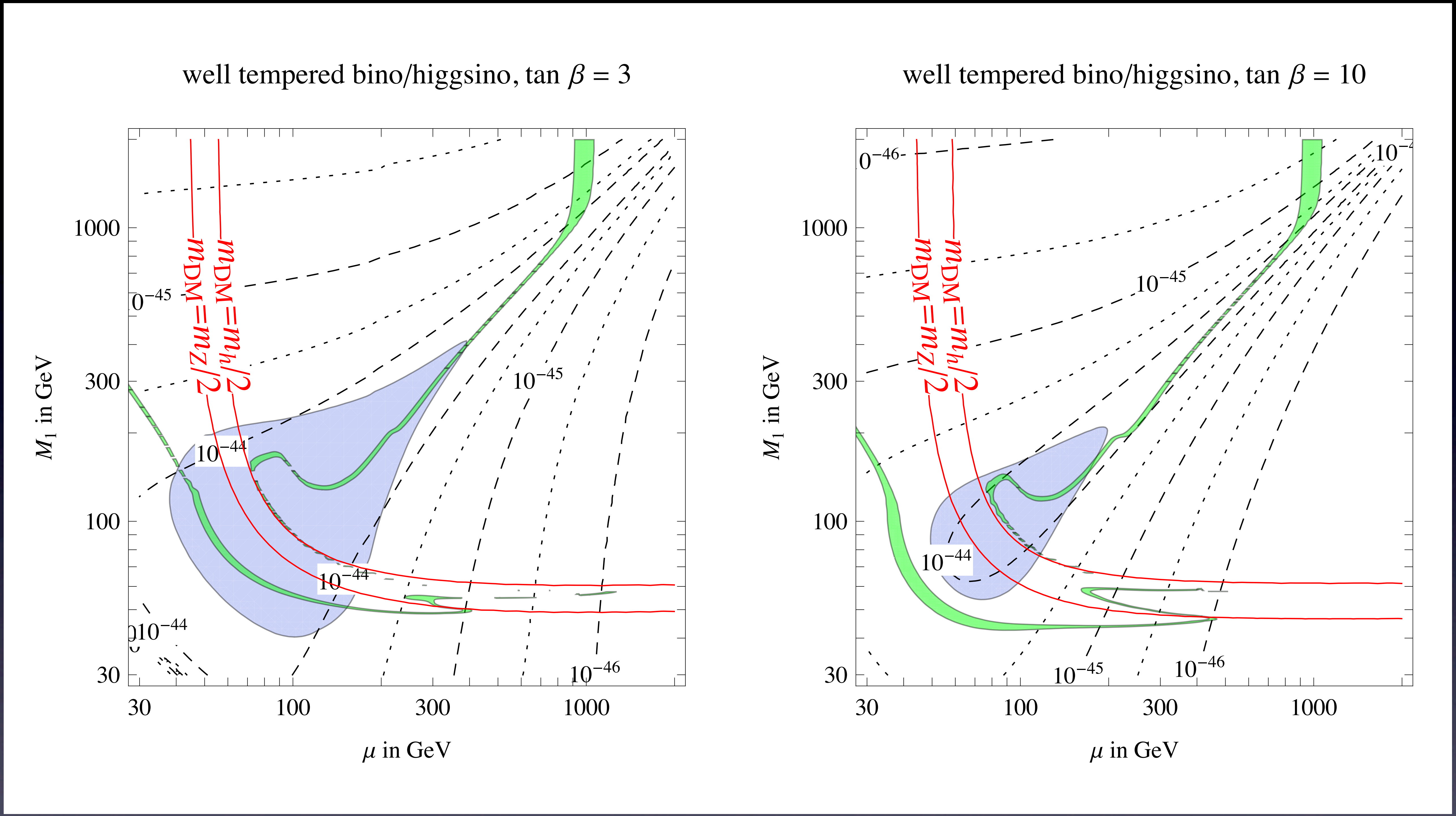
$$\frac{f_p}{m_p} = \sum_{q=u,d,s} \frac{f_q}{m_q} f_{T_q} + \frac{2}{27} f_{T_G} \sum_{q=c,b,t} \frac{f_q}{m_q}$$

$$f_q \sim \frac{C_{h\tilde{\chi}\tilde{\chi}} C_{hqq}}{m_{h^0}^2} + \frac{C_{H\tilde{\chi}\tilde{\chi}} C_{Hqq}}{m_{H^0}^2}$$

(Lattice simulation by H.Ohki et al. (08))

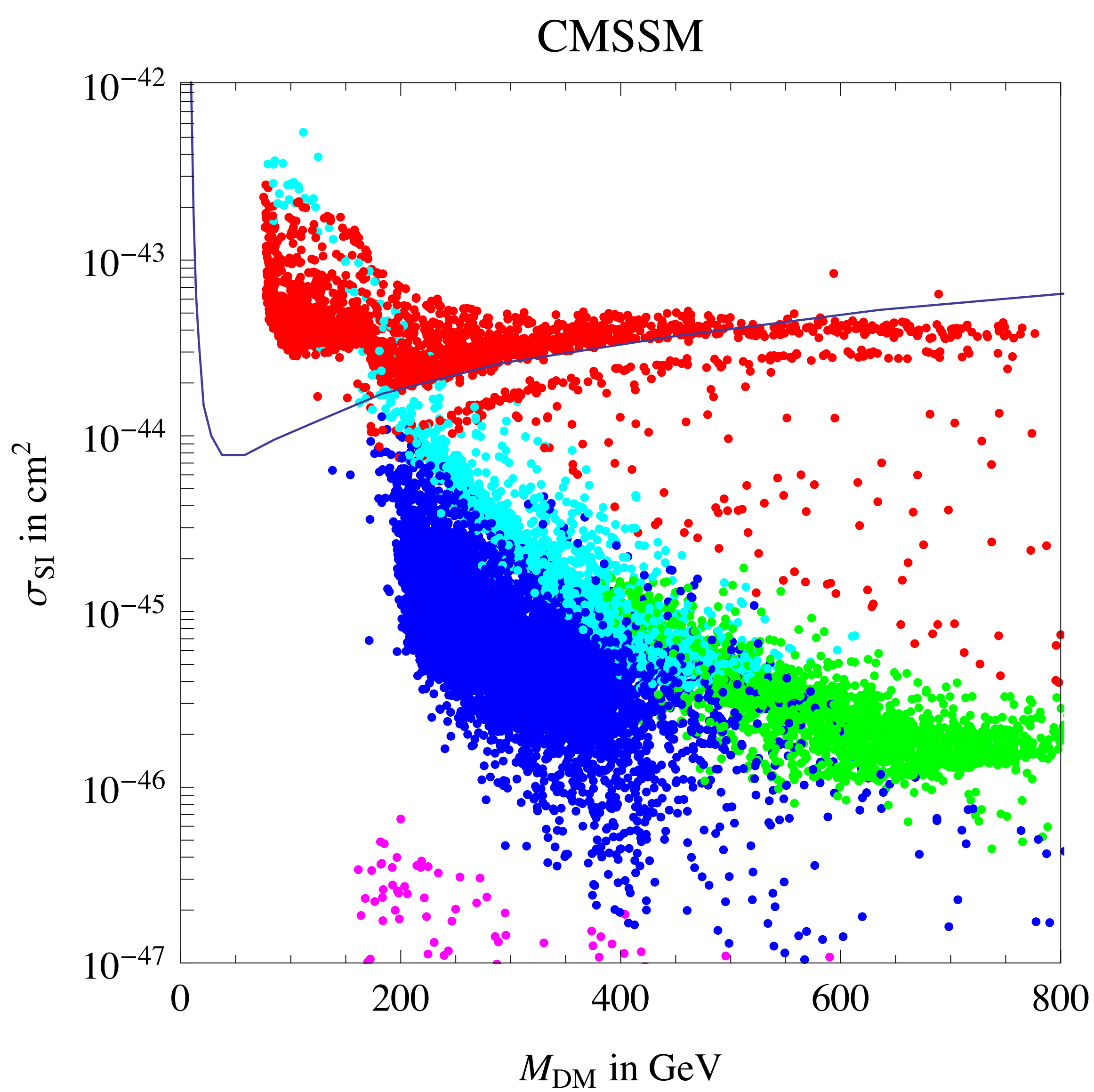
Quark content in a proton: $f_{T_u} = 0.023,\, f_{T_d} = 0.034,\, f_{T_s} = 0.025$

Large gaugino-Higgsino mixing
Lighter Higgs (H0)
→ Large cross section



M.Farina et al., 1104.3572

12年3月21日水曜日



- Well-tempered (focus point)
- stau coannihilation
- Higgs exchange (resonance)
- Higgs exchange
- stop coannihilation

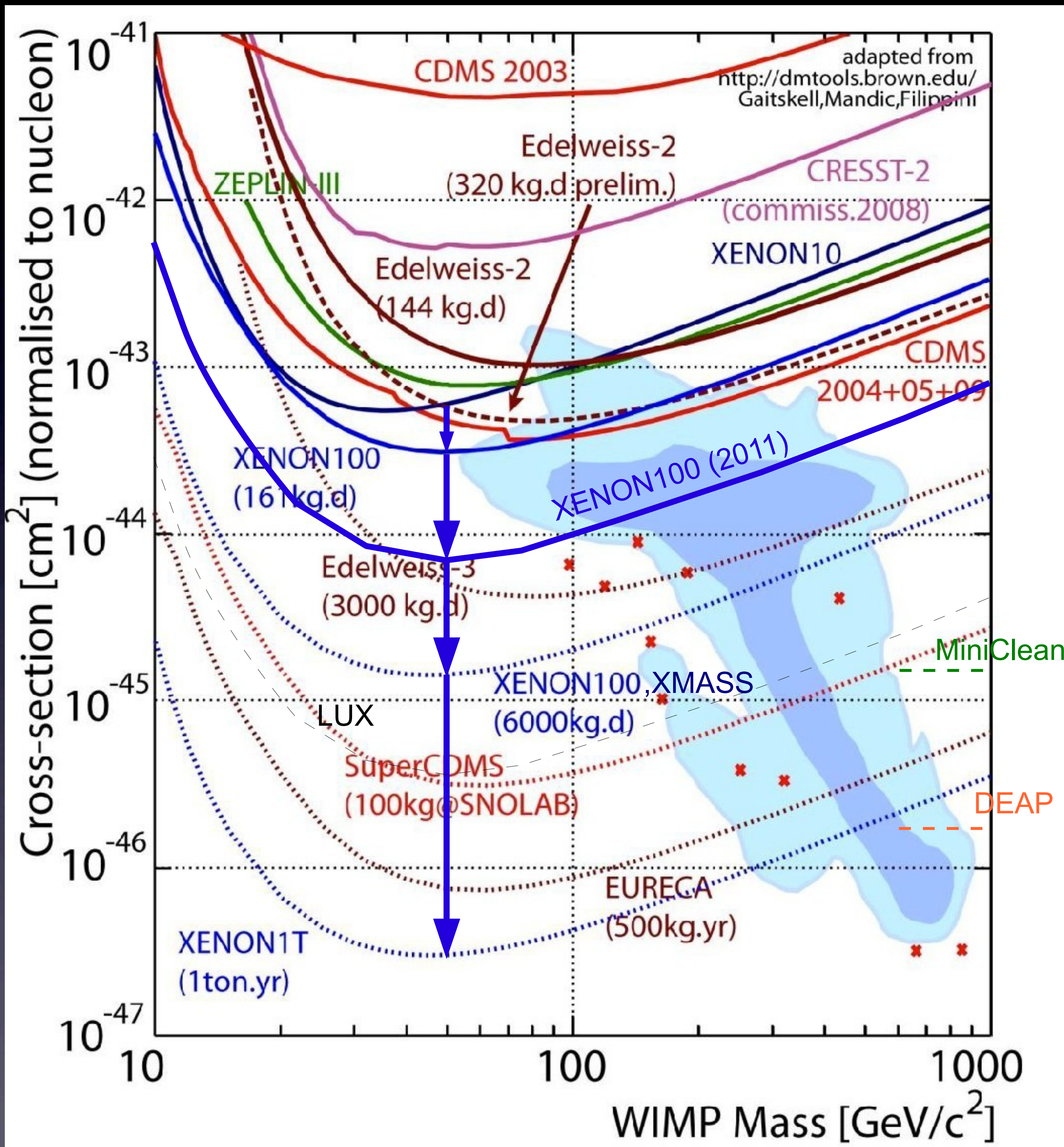
quantity	experiment	Standard Model
$\alpha_3(M_Z)$ [45]	0.1184 ± 0.0007	parameter
m_t [46]	173.1 ± 0.9	parameter
m_b [47]	4.19 ± 0.12	parameter
$\Omega_{DM}h^2$ [48]	0.112 ± 0.0056	0
δg_μ [49]	$(2.8 \pm 0.8)10^{-9}$	0
$BR(B_d \to X_s\gamma)$ [50]	$(3.50 \pm 0.17)\,10^{-4}$	$(3.15 \pm 0.23)\,10^{-4}$
$BR(B_s \to \mu^+\mu^-)$ [19]	$(0.9 \pm 0.6)\,10^{-8}$	$(0.33 \pm 0.03)\,10^{-8}$
$BR(B_u \to \tau\bar{\nu})/SM$ [51]	1.25 ± 0.40	1

+ATLAS & CMS 1.1fb-1 (July 2011)

$$(m_0, M_{1/2}) \sim (0, 4000)\ \text{GeV},\ A_0 \sim (-3m_0, 3m_0),\ \tan\beta \sim (1, 60)\ \text{and}\ \text{sign}(\mu) = \pm 1$$

M.Farina et al., 1104.3572

Sensitivity of near future experiments (~next 5 yr)



Talk by U.Overlack (2011/5)

Ton scale detector

$$\sigma_{\rm SI} \sim 10^{-45} - 10^{-46}{\rm cm}^2$$

- Cryogenic

  SuperCDMS, EURECA

- LXe

  XMASS, LUX, XENON1T

- LAr

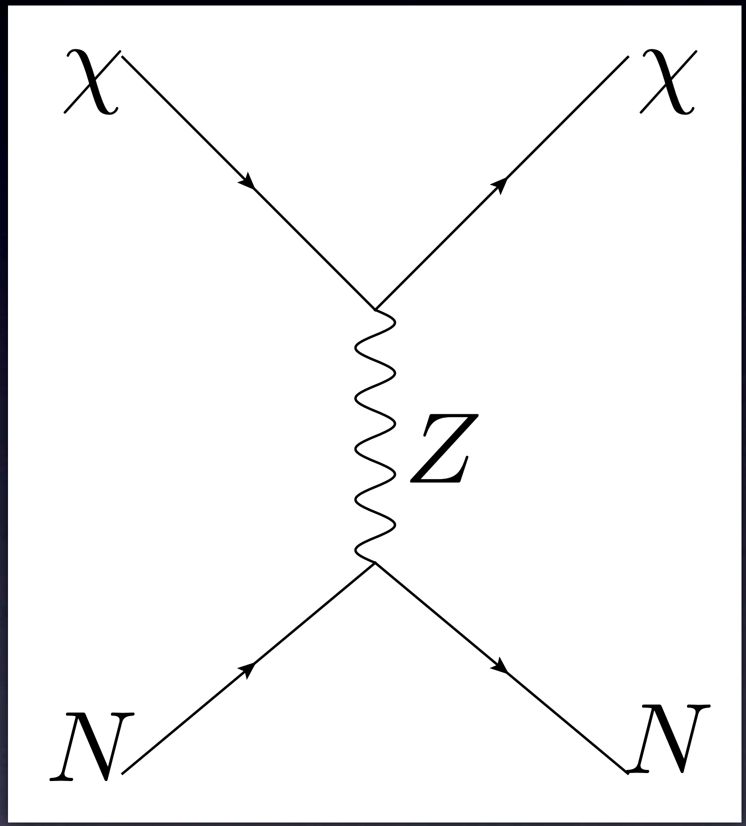
  DEAP/CLEAN, WARP, ArDM

SD cross section

- SI cross section $\propto A^2$

$(A : \text{atomic mass number})$

➡ For large target nucleus (A>30),
SI dominates.
(Most laboratory experiments.)



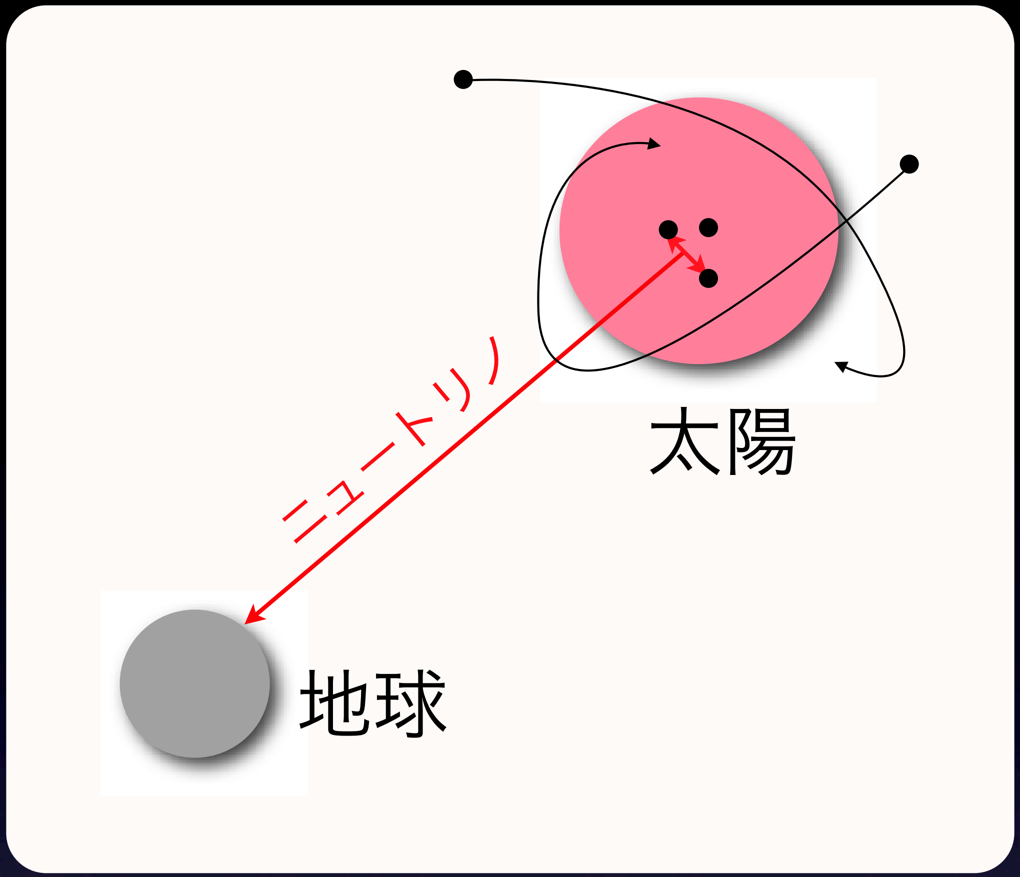
- SD cross section $\propto \text{nuclear spin}$

SD cross section is limited from interaction in the Sun through neutrino observations.

Ritz, Seckel (88), Kamionkowski (91)

DM scatters off nucleon in the Sun and loses its momentum

➡ DM is trapped by the Sun, then self-annihilates yielding high-energy neutrinos



Super-K, AMANDA, IceCube

- Capture rate

$$C_{\odot} \sim 3 \times 10^{20} \mathrm{s}^{-1} \left(\frac{\rho_\chi}{0.3\mathrm{GeV/cc}} \right) \left(\frac{100\mathrm{GeV}}{m_\chi} \right)^2 \left(\frac{270\mathrm{km/s}}{v_\chi} \right)^3 \left(\frac{\sigma_{\mathrm{SD}}}{10^{-42}\mathrm{cm}^2} \right)$$

Press, Spergel (85), Gould (87)

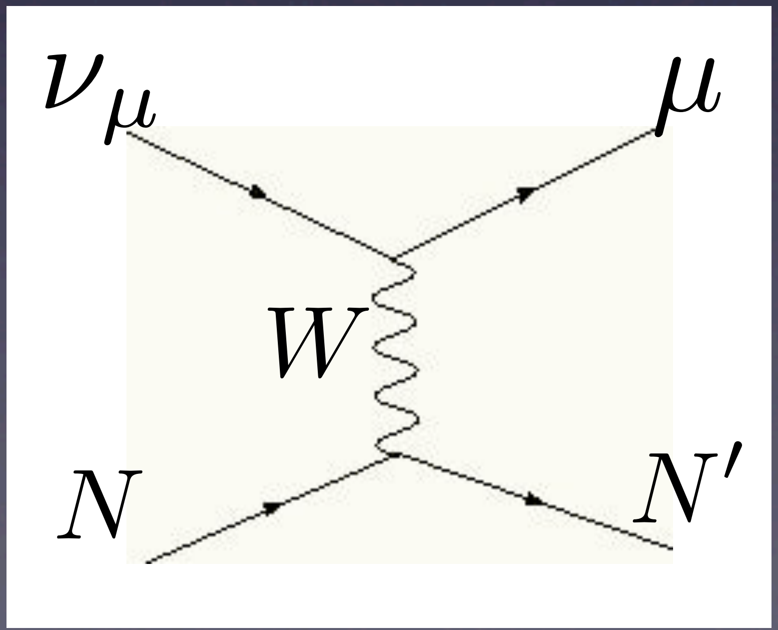
- Annihilation rate = Capture rate

  if DM reaches equilibrium in the Sun

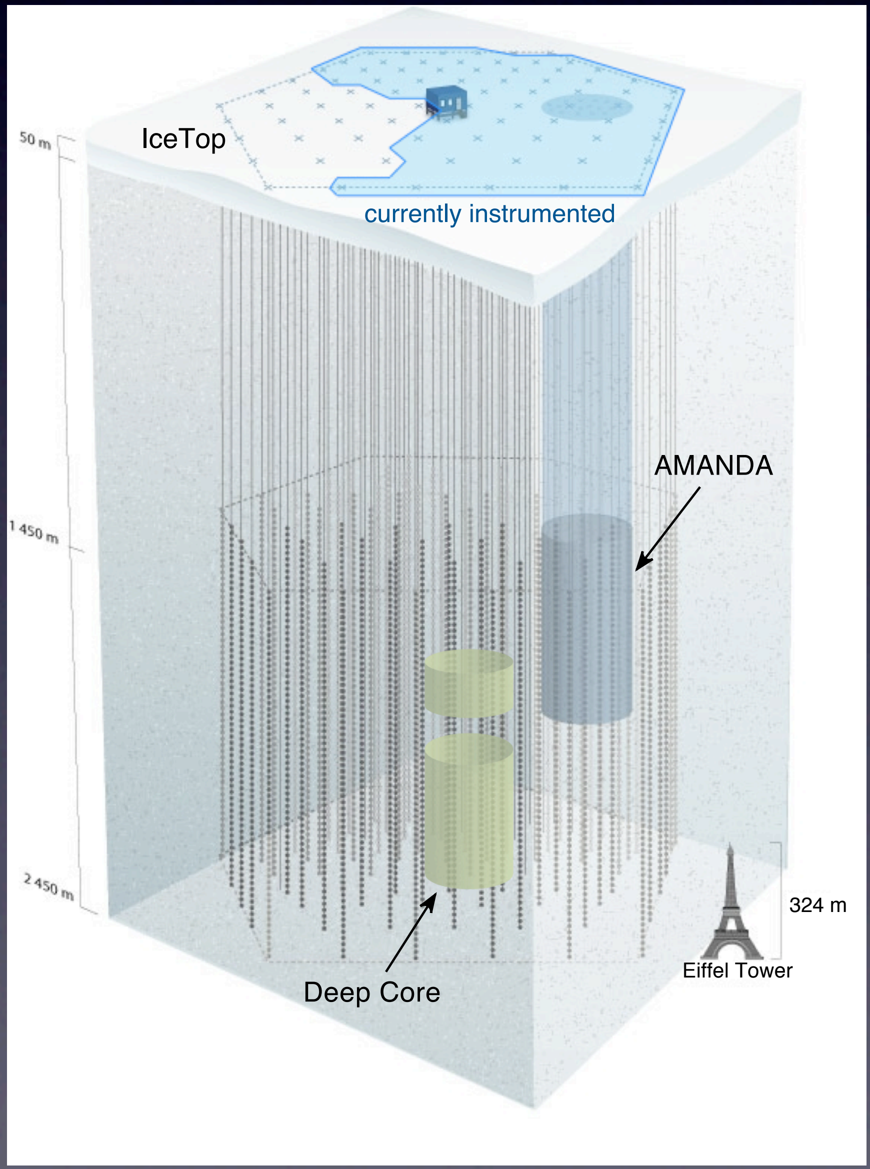
Muon event rate

$$N_{\mu^+\mu^-} = \int dE_{\nu_\mu} \int_{E_{\rm th}}^{E_{\nu_\mu}} dE_\mu \left[\frac{d\Phi_{\nu_\mu}}{dE_{\nu_\mu}} \left(\frac{d\sigma^{\rm (CC)}_{\nu_\mu p}}{dE_\mu} n_p + \frac{d\sigma^{\rm (CC)}_{\nu_\mu n}}{dE_\mu} n_n \right) + (\nu_\mu \leftrightarrow \bar{\nu}_\mu) \right] V_{\rm eff}(E_\mu),$$

- Cross section : $\sim \frac{G_F^2 s}{\pi} \propto E_{\nu_\mu}$
- Number density of proton in the ice : $n_p \sim N_A \ {\rm cm}^{-3}$

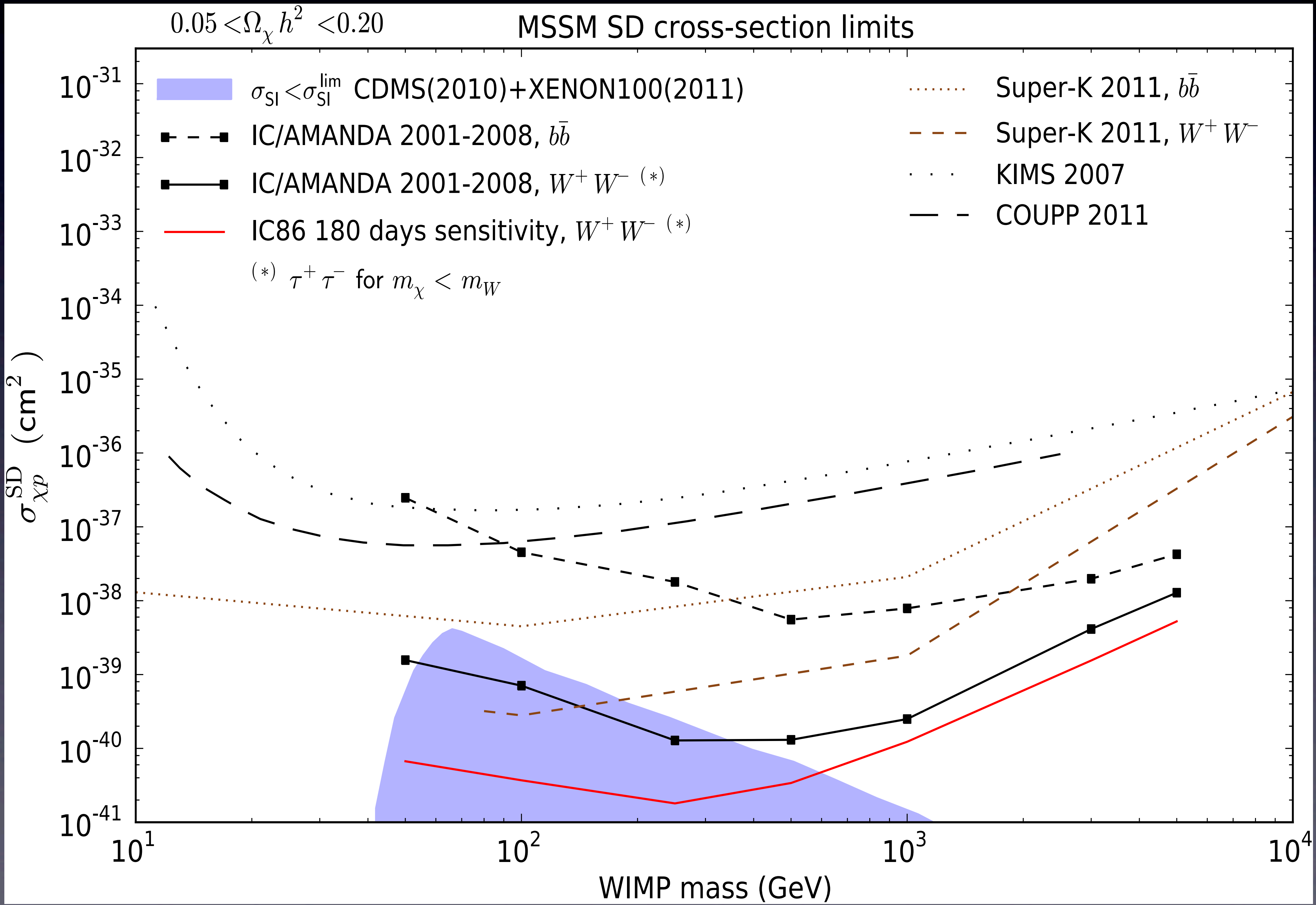


- Effective volume : $V_{\rm eff} \sim 10^{-3} {\rm km}^3$



IceCube 40string (149d)+ AMANDA II (812d)

- Best limit on SD cross section
- Limit depends on DM ann. mode.



IceCube, 1112.1840

12年3月21日水曜日

Wino LSP

- 125GeV Higgs is easily explained in O(100)TeV SUSY

$\longrightarrow$ Wino LSP

e.g. "Pure gravity-mediation"

$$W = W_{\rm MSSM} + W_0$$

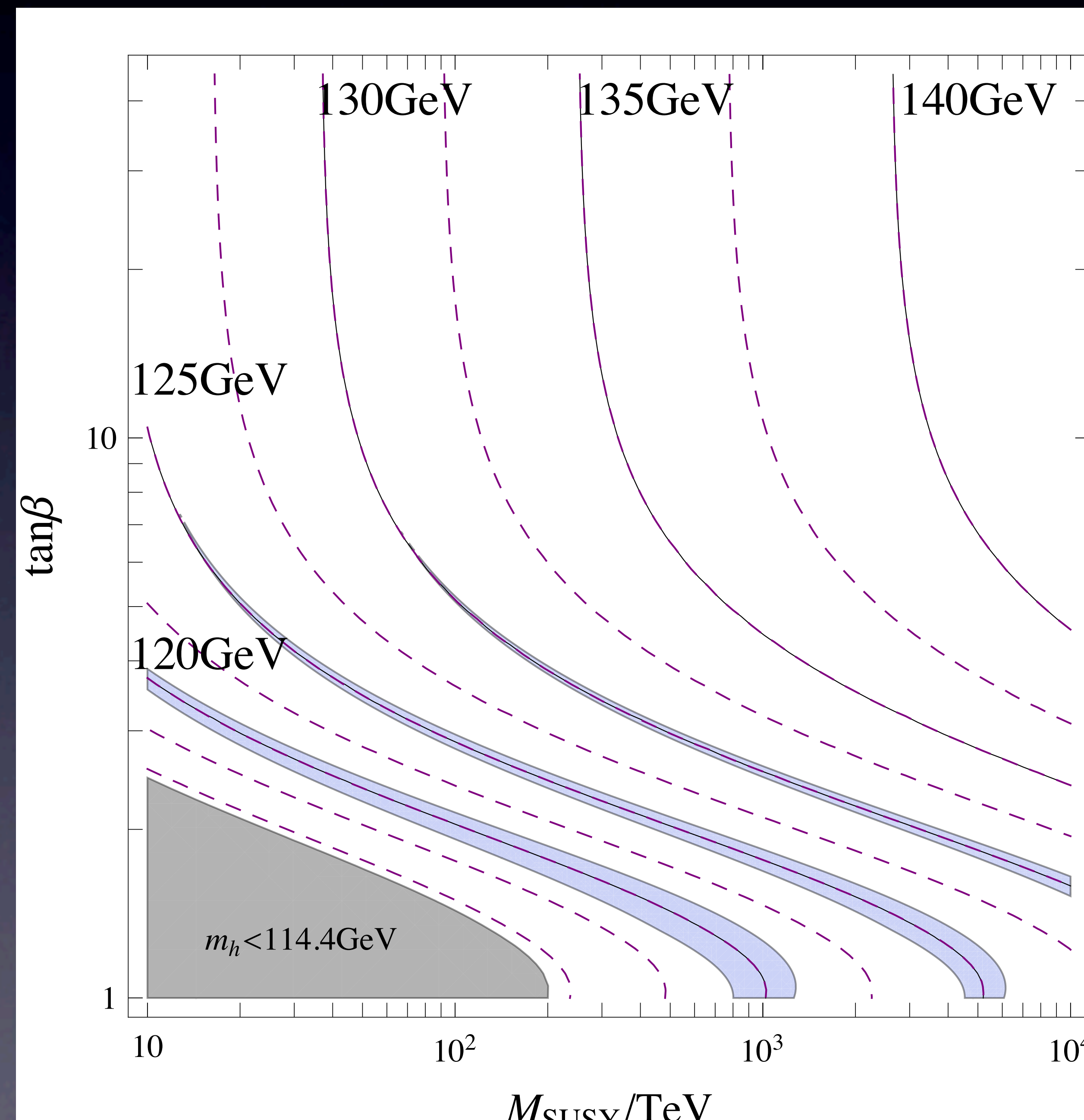
$$W_0 = m_{3/2} M_P^2$$

$$m_{\tilde{f}} \sim m_{3/2} \sim O(100)\,\mathrm{TeV}$$

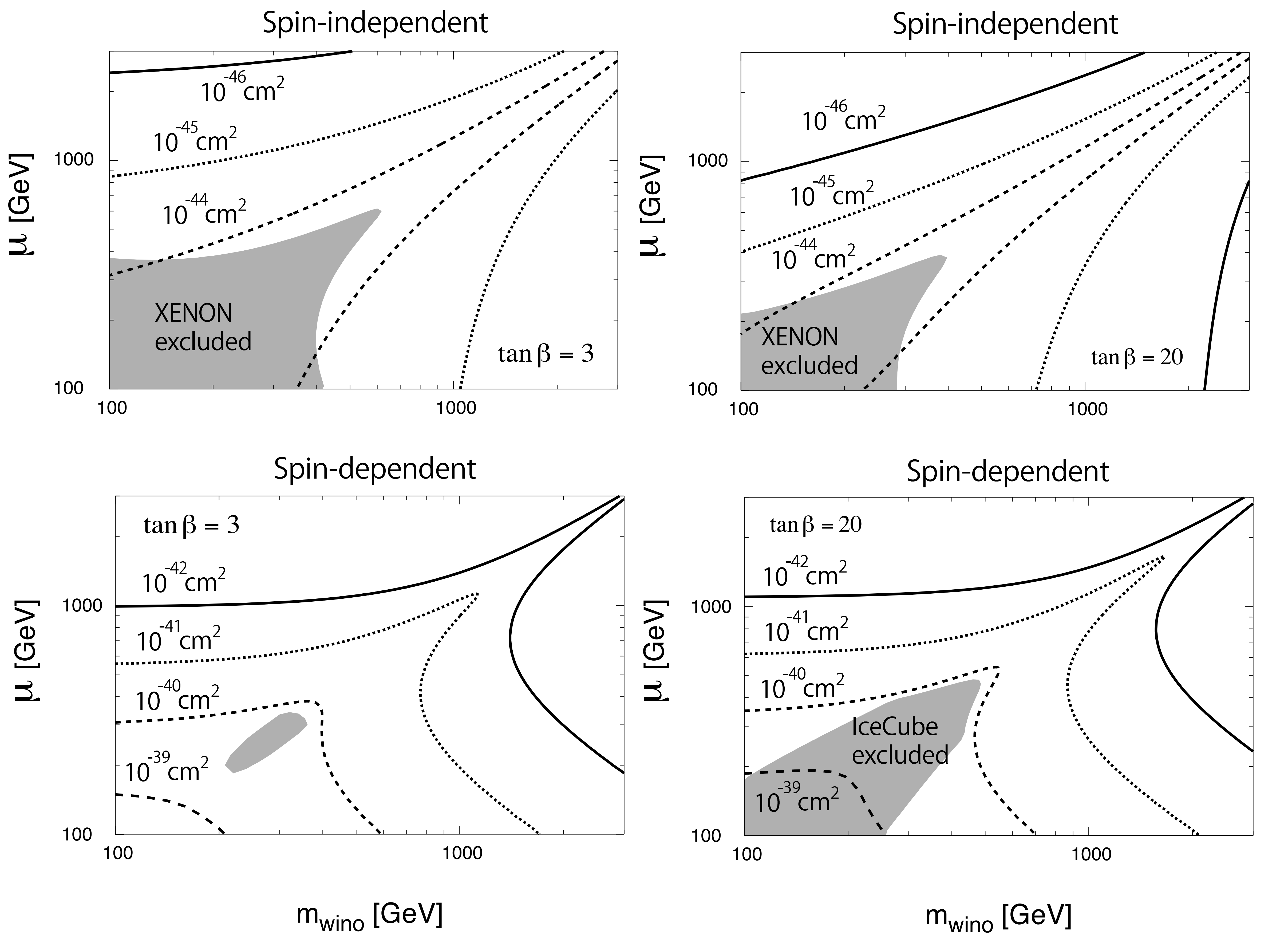
$\rightarrow$

$$m_{\tilde{g}} \sim \frac{g^2}{16\pi^2} m_{3/2} \sim O(1)\,\mathrm{TeV}$$

Direct/indirect detection may be possible

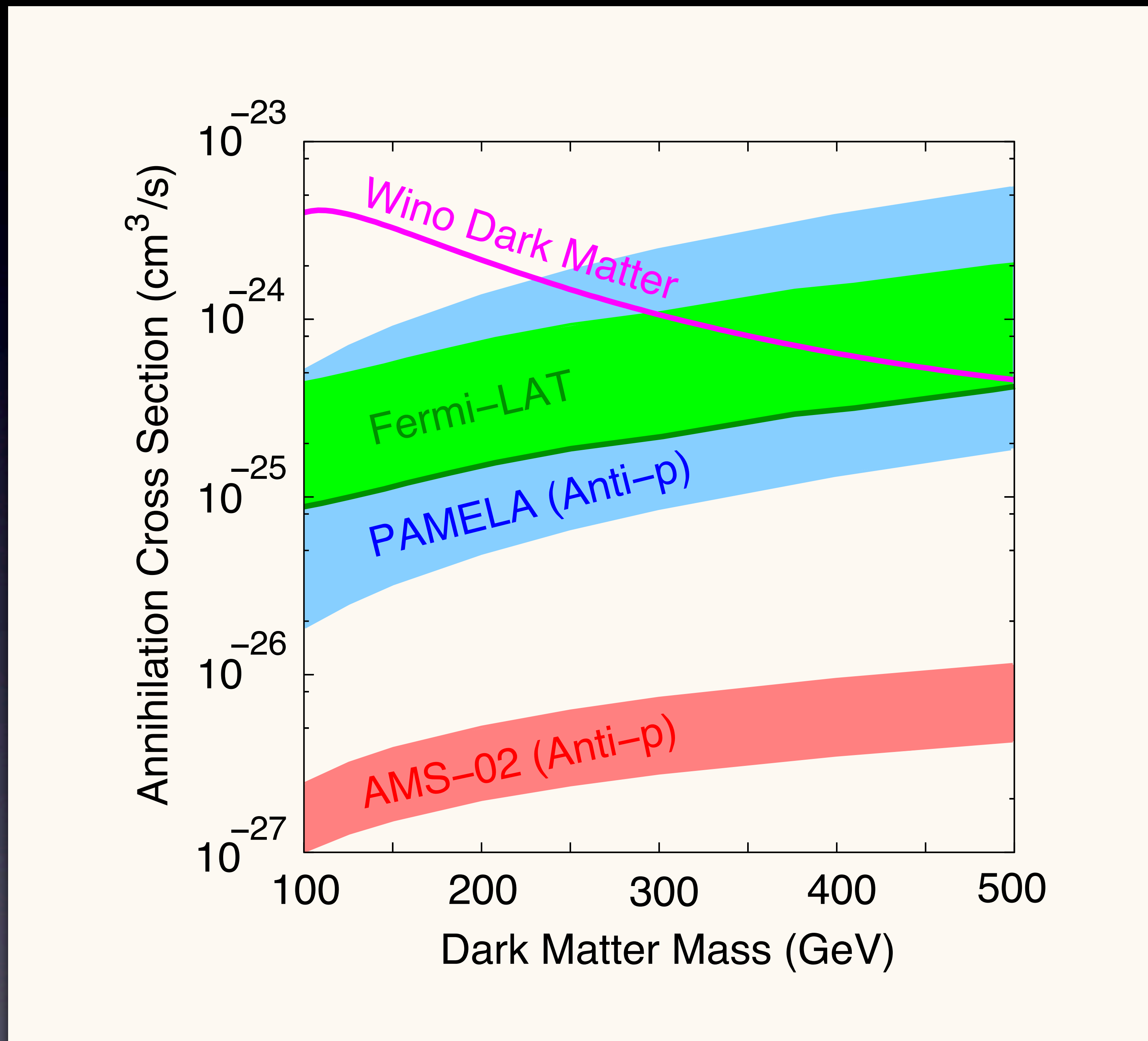


Ibe, Yanagida, 1112.2462



T.Moroi, KN, 1112.3123

- Constraint from indirect exp.



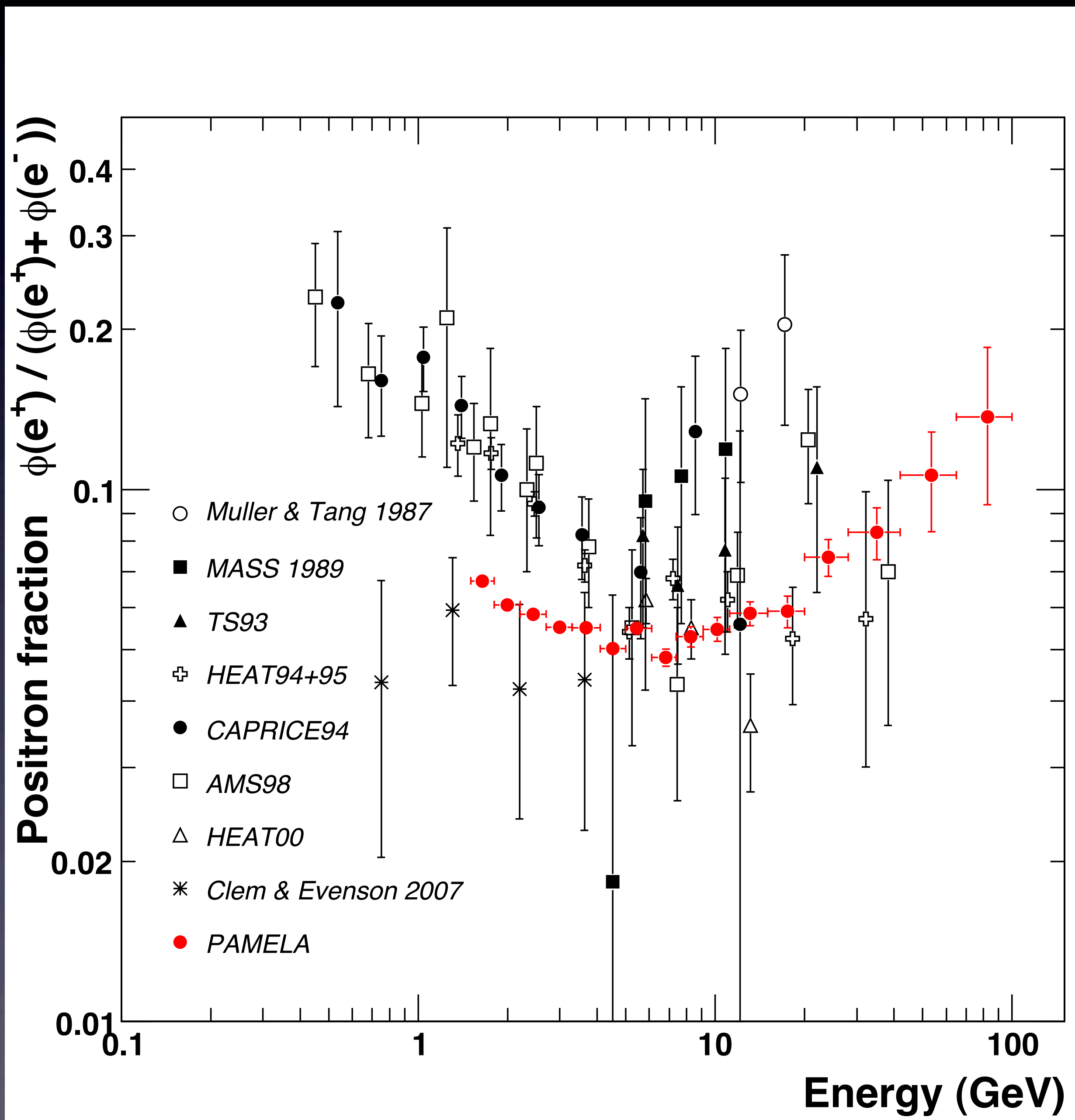
Ibe, Matsumoto, Yanagida, 1202.2253

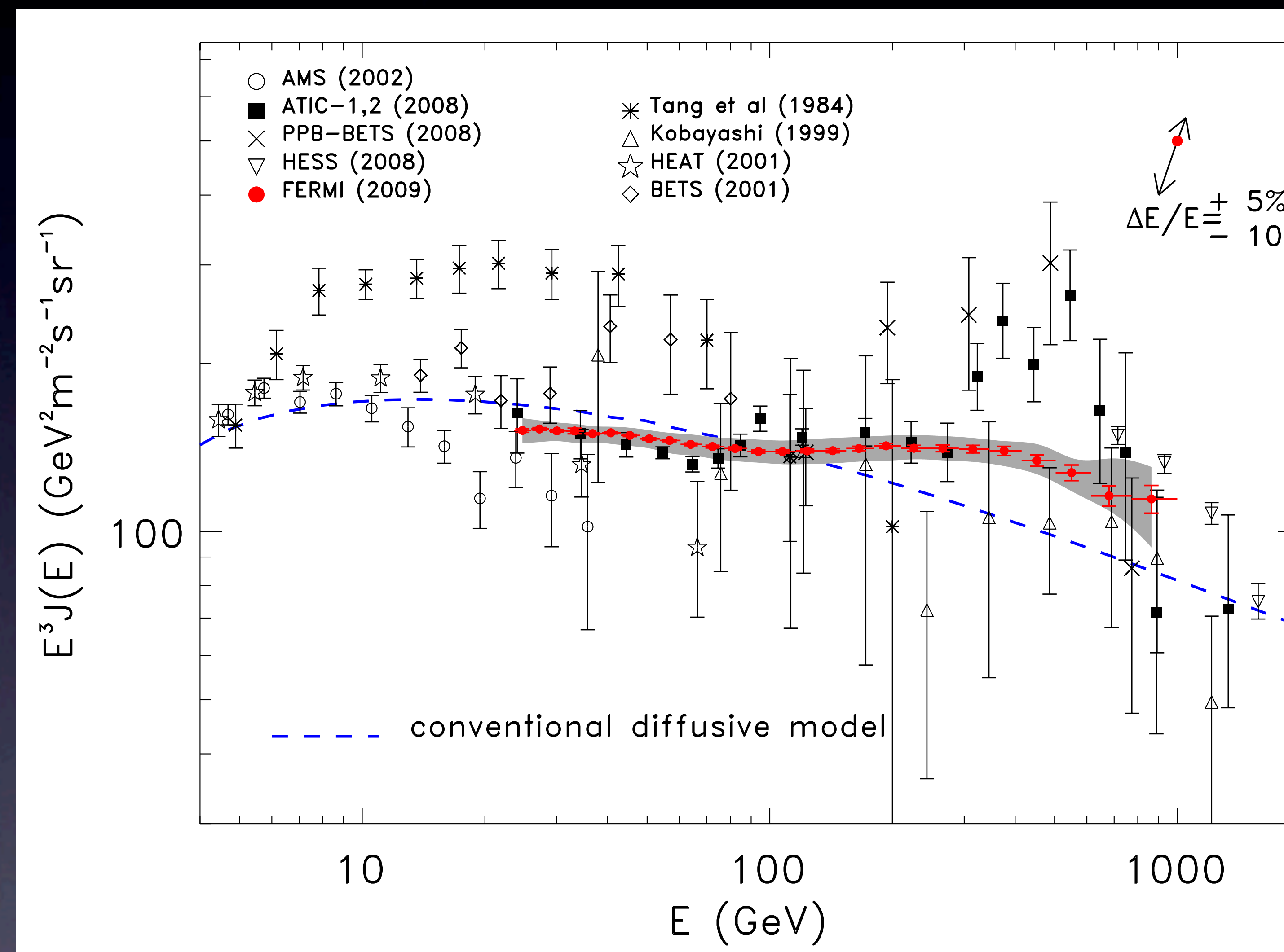
Dark matter indirect detection

Current situation

- Excess in Positron and Electron flux : PAMELA and Fermi
- No excess in gamma-rays : Fermi, HESS, ...
- No excess in neutrinos : SK, IceCube
- Strong constraint from CMB and BBN

Excess in e+ and e-



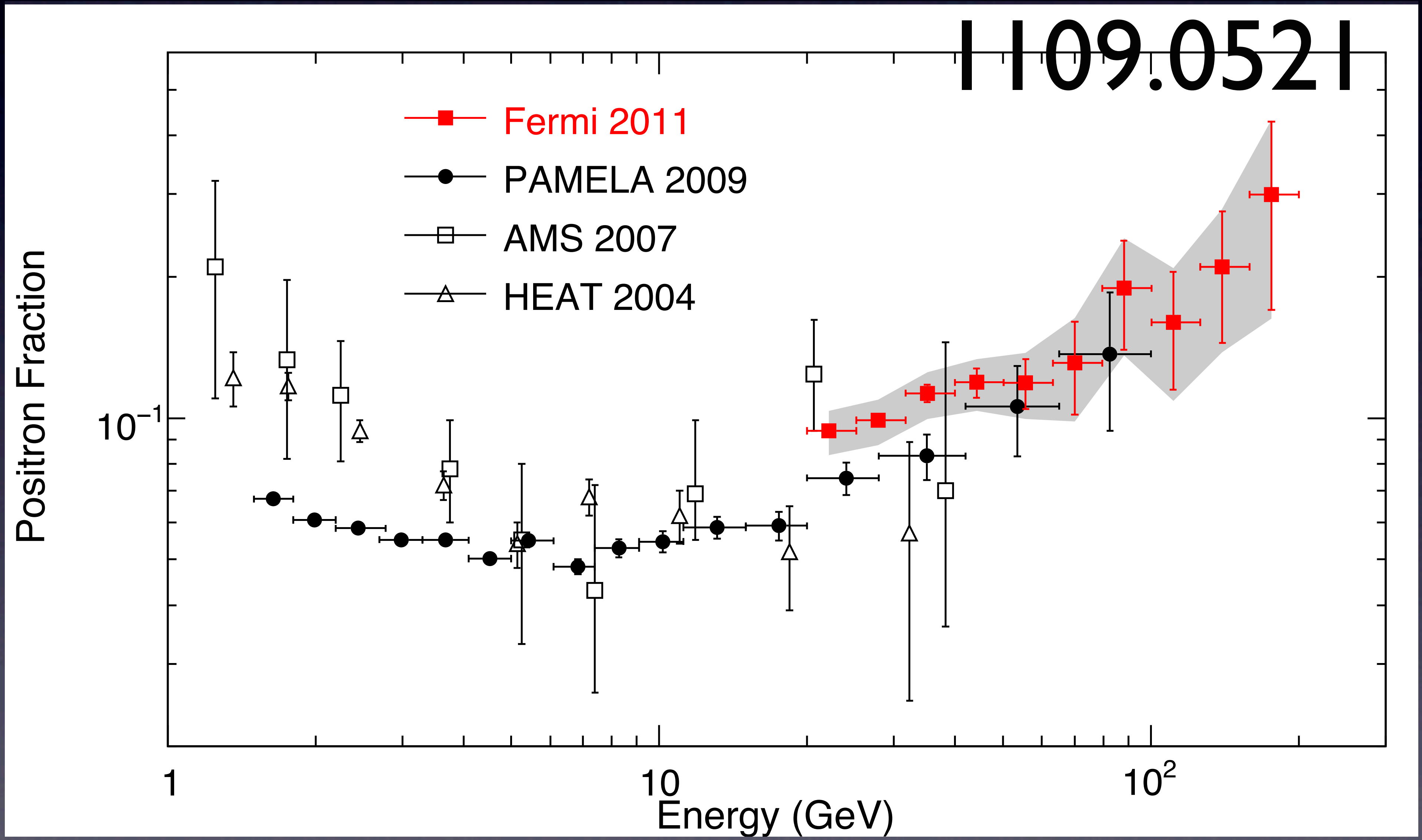


PAMELA

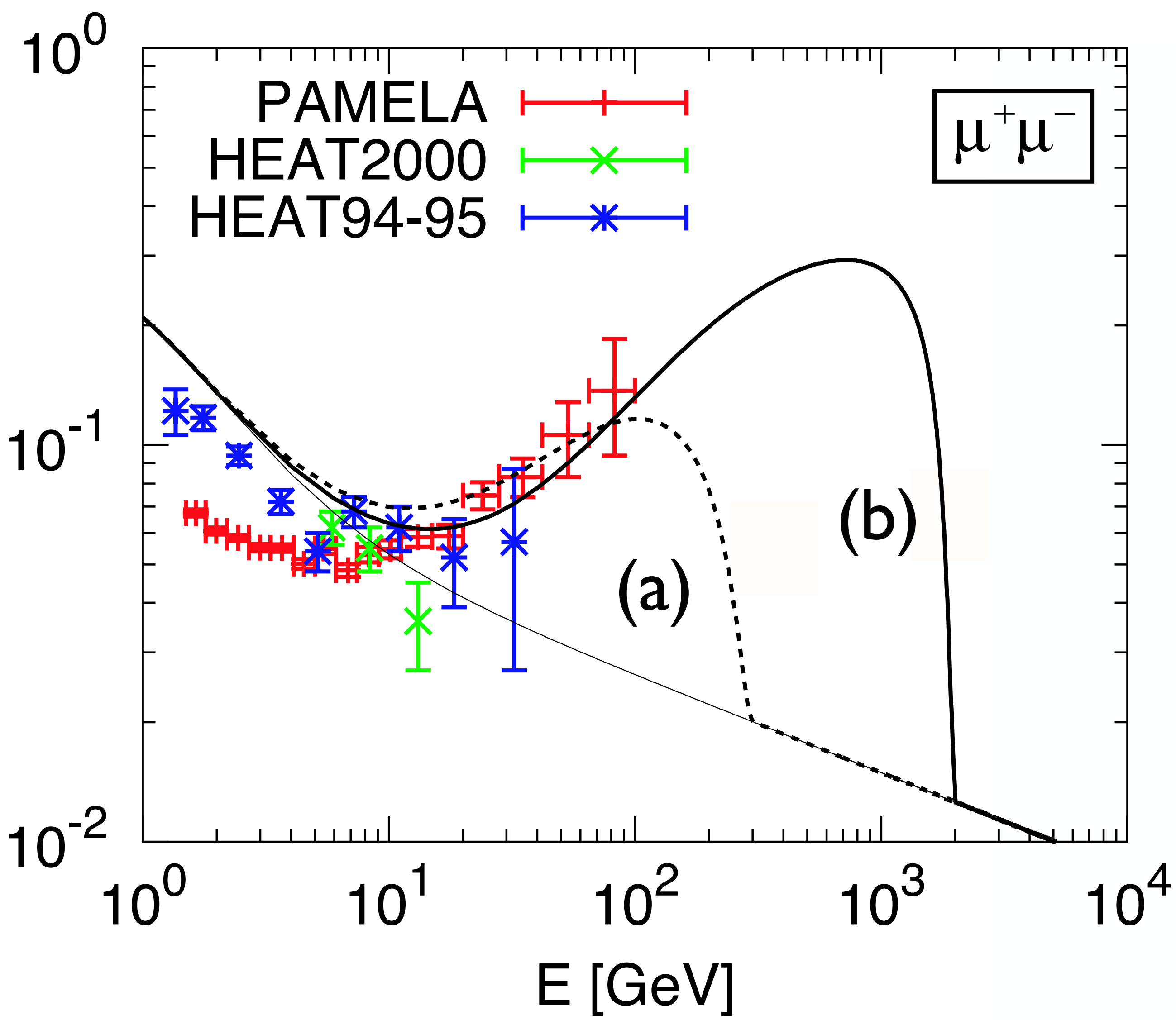
Fermi and HESS

12年3月21日水曜日

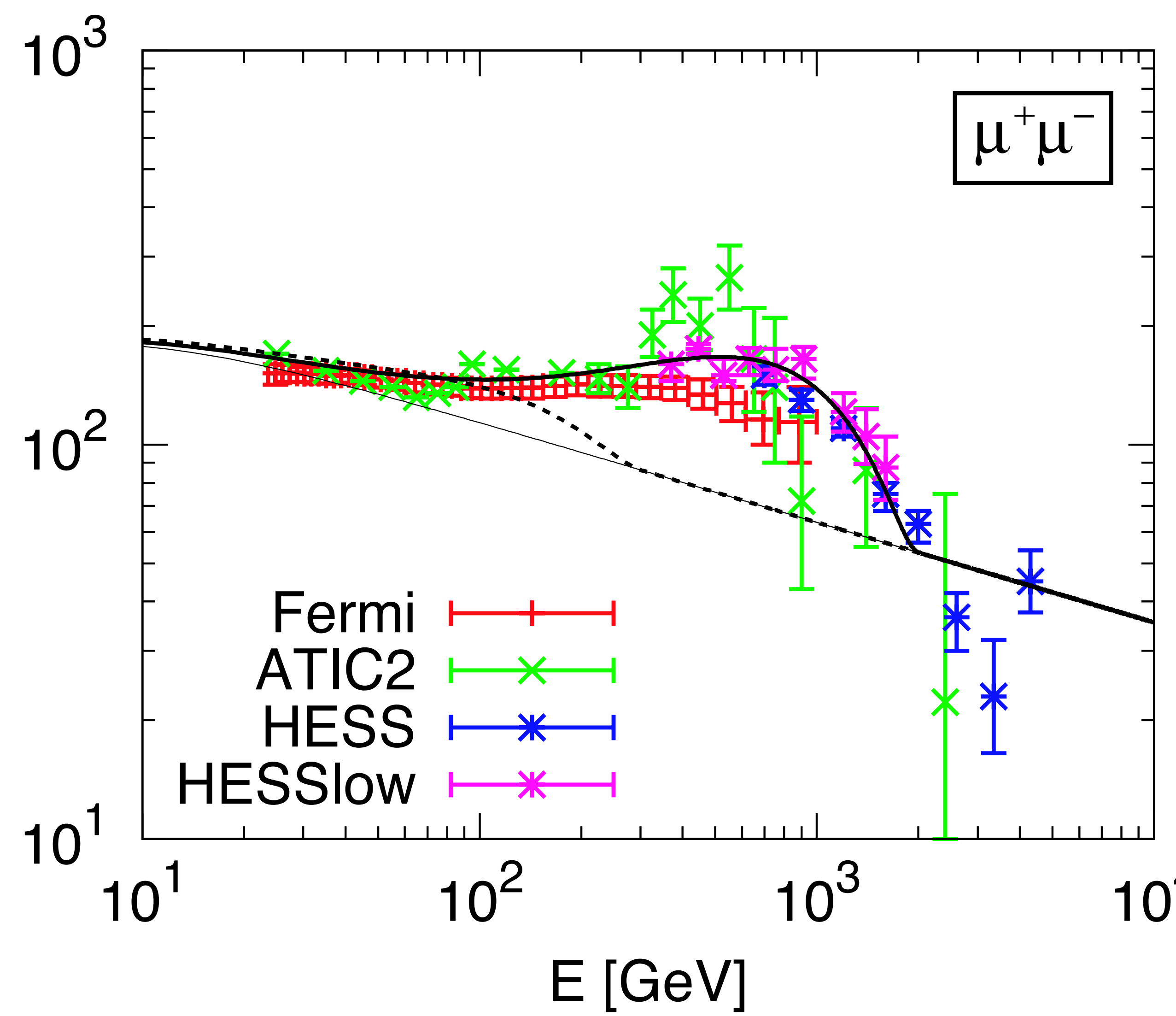
Positron by Fermi



Positron fraction

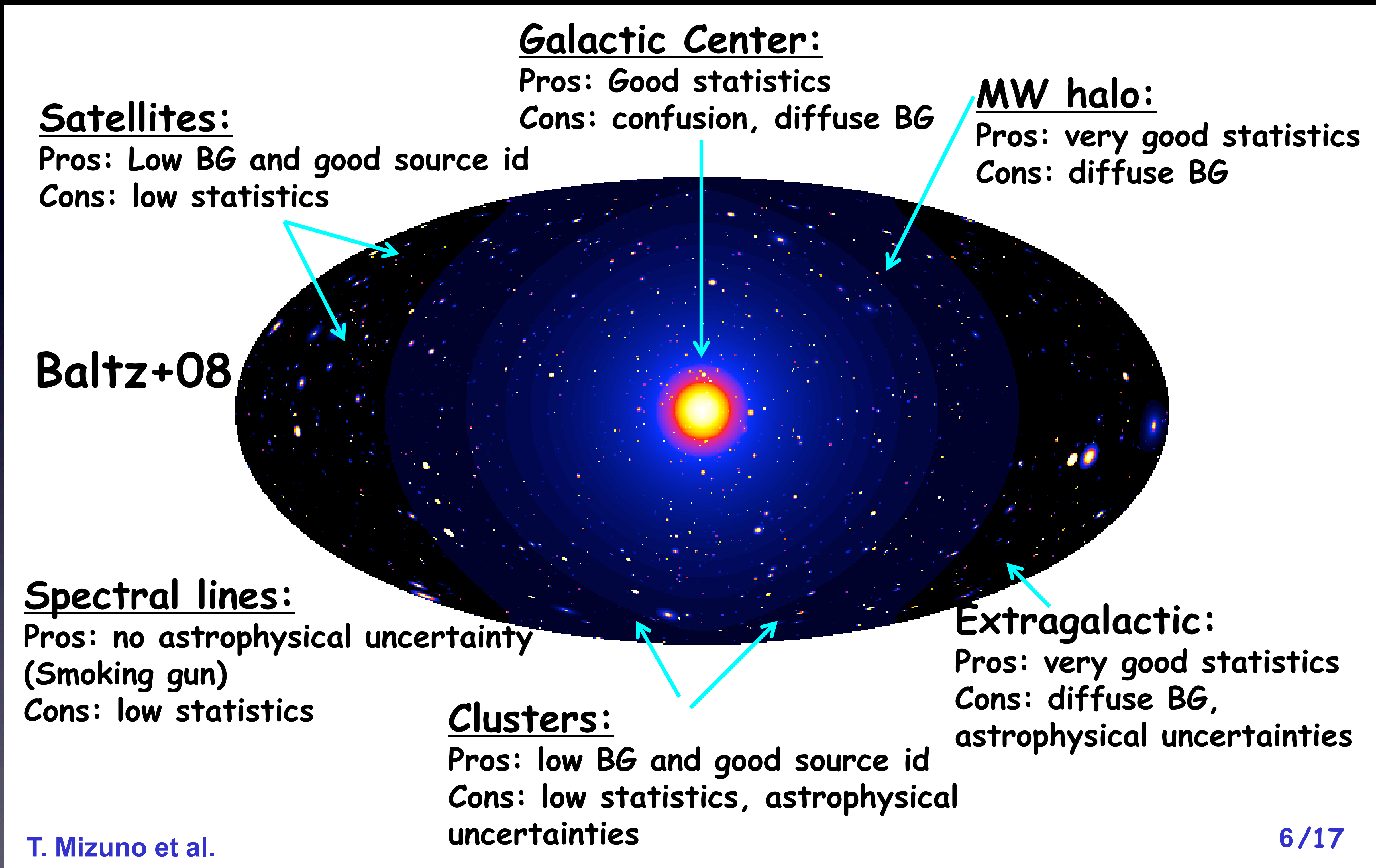


Total flux $[\mathrm{GeV^2 m^{-2} s^{-1} sr^{-1}}]$



$$\chi\chi \to \mu^+\mu^- : (a)\ m_\chi = 300\mathrm{GeV}, \langle\sigma v\rangle = 2.0 \times 10^{-24}\mathrm{cm^3 s^{-1}}$$
$$(b)\ m_\chi = 2\mathrm{TeV}, \langle\sigma v\rangle = 5.0 \times 10^{-23}\mathrm{cm^3 s^{-1}}$$

Gamma-ray sky

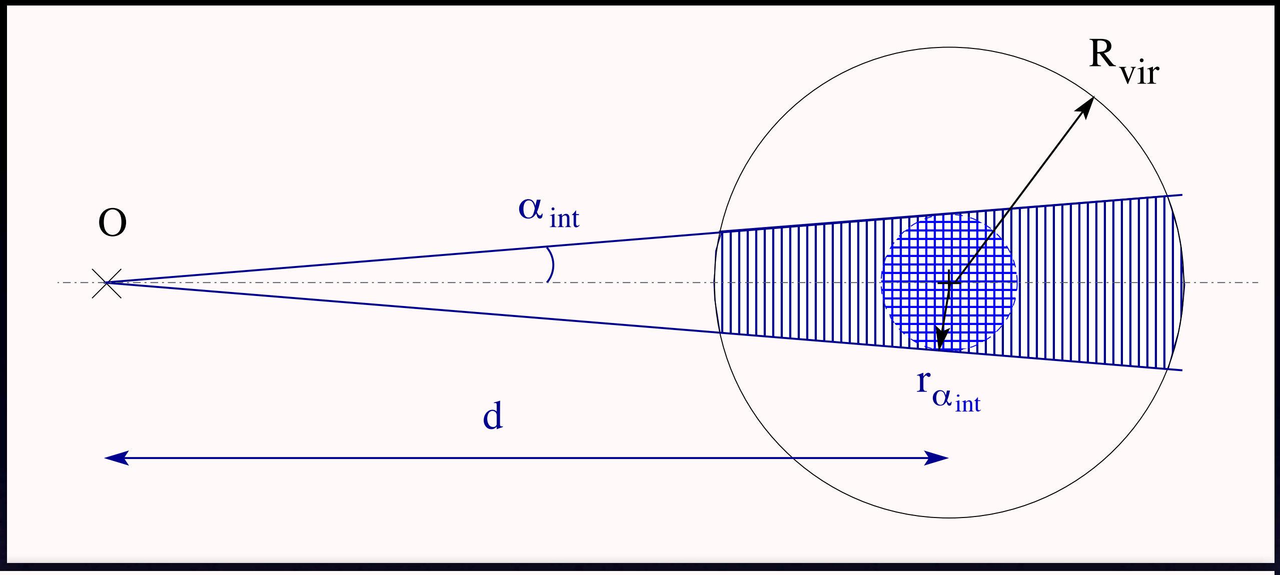


Slide from Talk by T.Mizuno

Dwarf Spheroidals

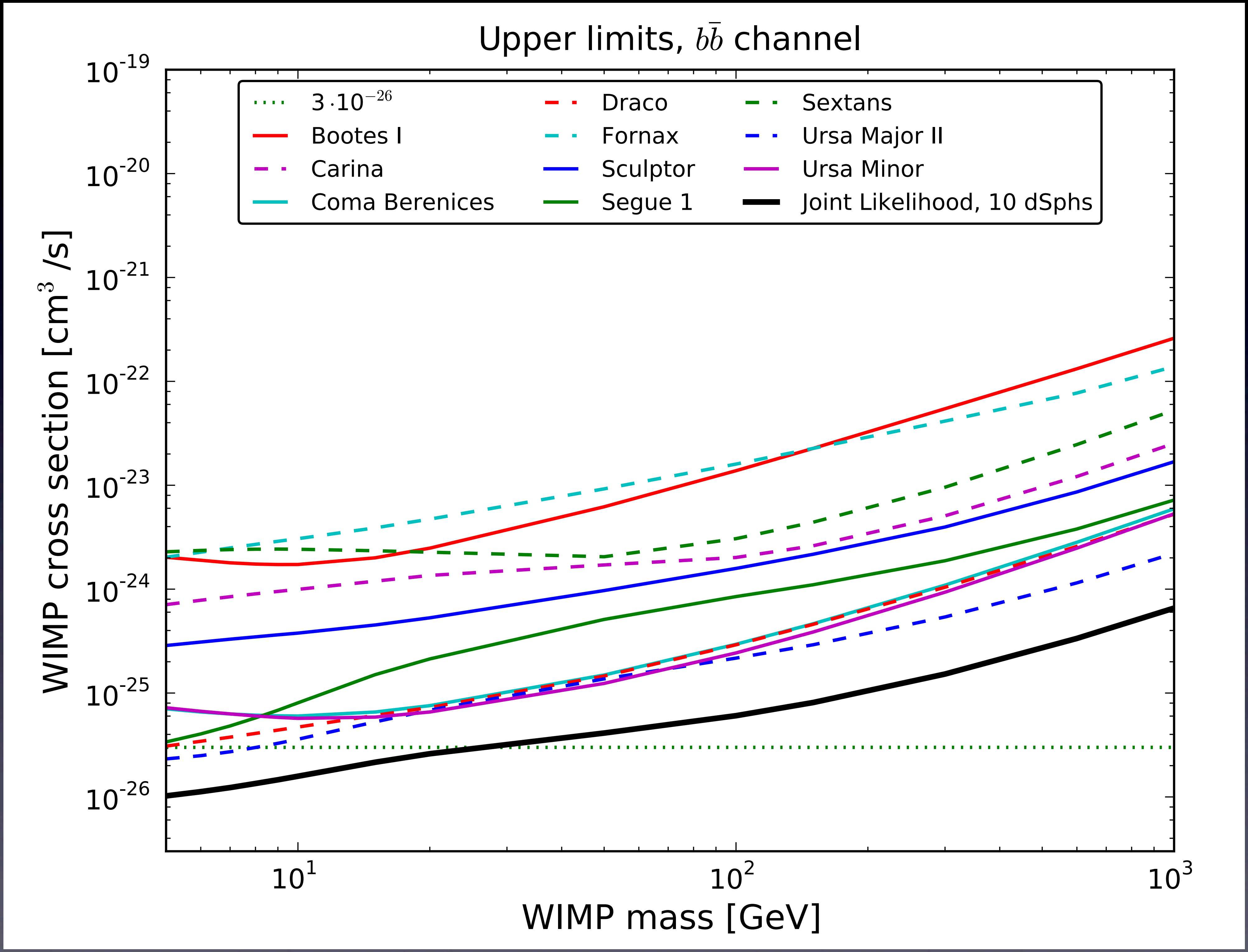
$$\frac{d\Phi_\gamma}{dE} = \frac{\langle \sigma v \rangle}{8\pi m_{\rm DM}^2} \frac{dN_\gamma}{dE} J(\Delta\Omega)$$

$$J(\Delta\Omega) = \int \rho_{\rm DM}^2 \, dl \, d\Omega$$



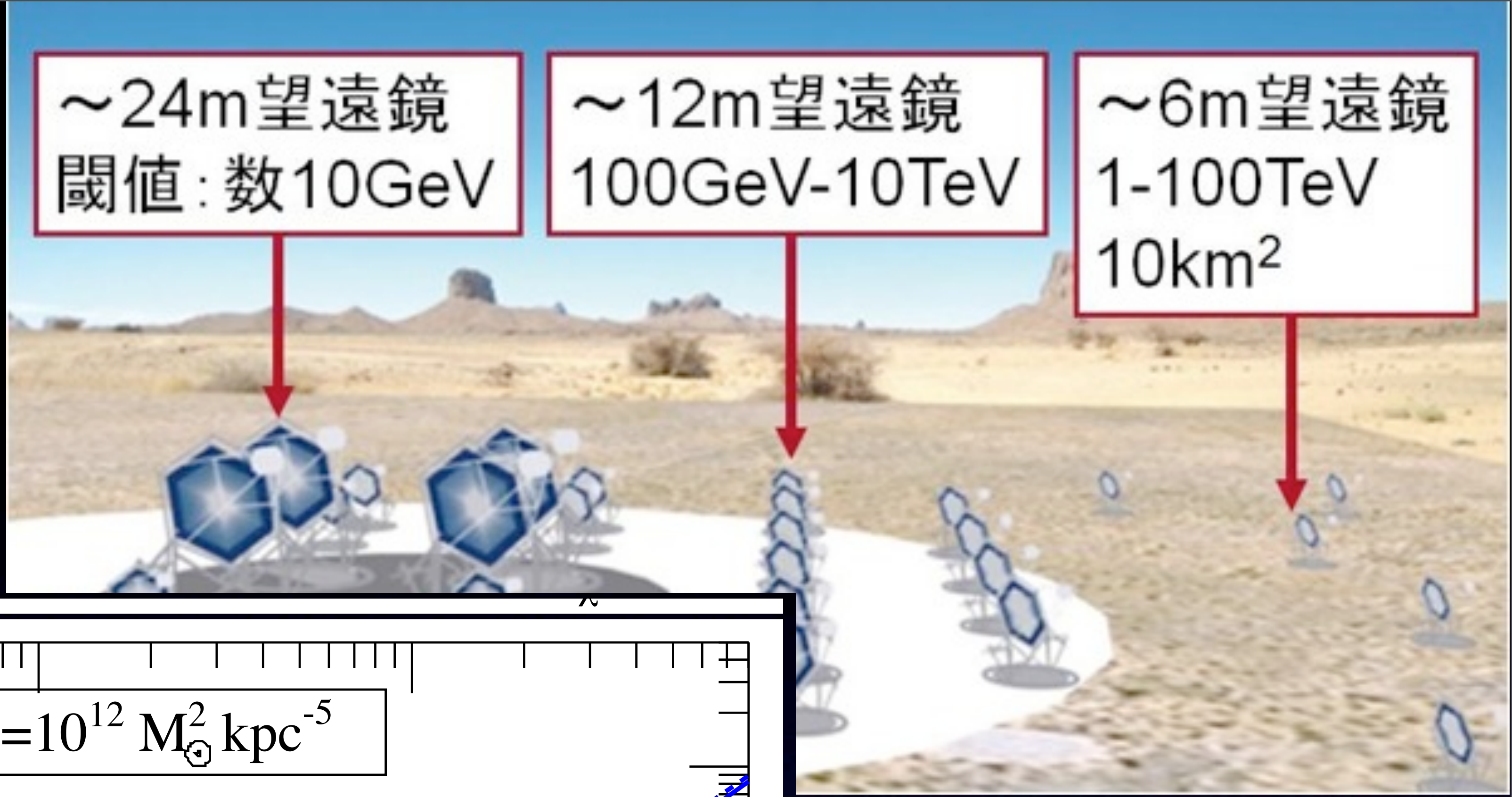
dSph	long. [deg]	lat. [deg]	d [kpc]	$2r_h$ [kpc]	ϕ [deg]	α_c [deg]	M_{300} $[10^7 M_\odot]$	$\log_{10}[J(0.01^\circ)]$	$\log_{10}[J(0.1^\circ)]$ $[M_\odot^2 \text{ kpc}^{-5}]$	$\log_{10}[J^\star(\alpha_c)]$
Ursa Minor	105.0	+44.8	66	0.56	100.6	0.49	$1.54^{+0.18(+0.33)}_{-0.21(-0.42)}$	$10.5^{+0.8(+1.5)}_{-0.6(-1.2)}$	$11.7^{+0.5(+0.8)}_{-0.3(-0.6)}$	$12.0^{+0.3(+0.5)}_{-0.1(-0.2)}$
Sculptor	287.5	-83.2	79	0.52	88.0	0.38	$1.34^{+0.12(+0.23)}_{-0.13(-0.23)}$	$10.0^{+0.5(+0.9)}_{-0.5(-0.8)}$	$11.3^{+0.2(+0.4)}_{-0.2(-0.3)}$	$11.7^{+0.1(+0.2)}_{-0.1(-0.1)}$
Draco	86.4	+34.7	82	0.40	87.0	0.28	$1.22^{+0.15(+0.28)}_{-0.14(-0.28)}$	$9.8^{+0.5(+0.9)}_{-0.5(-0.8)}$	$11.2^{+0.2(+0.4)}_{-0.2(-0.3)}$	$11.6^{+0.1(+0.2)}_{-0.1(-0.2)}$
Sextans	243.5	+42.3	86	1.36	109.3	0.91	$0.61^{+0.38(+0.96)}_{-0.31(-0.43)}$	$9.4^{+1.7(+2.9)}_{-1.2(-1.8)}$	$10.7^{+1.1(+1.9)}_{-0.8(-1.1)}$	$11.1^{+0.7(+1.5)}_{-0.4(-0.6)}$
Carina	260.1	-22.2	101	0.48	99.2	0.27	$0.59^{+0.10(+0.60)}_{-0.07(-0.14)}$	$9.3^{+0.3(+0.8)}_{-0.4(-0.8)}$	$10.5^{+0.2(+0.4)}_{-0.1(-0.2)}$	$10.9^{+0.1(+0.1)}_{-0.1(-0.1)}$
Fornax	237.1	-65.7	138	1.34	102.9	0.56	$1.01^{+0.30(+0.60)}_{-0.17(-0.28)}$	$9.5^{+0.5(+1.1)}_{-0.5(-0.8)}$	$10.8^{+0.2(+0.5)}_{-0.2(-0.3)}$	$10.5^{+0.3(+0.7)}_{-0.2(-0.4)}$
LeoII	220.2	+67.2	205	0.30	107.2	0.08	$0.94^{+0.26(+0.50)}_{-0.18(-0.29)}$	$11.6^{+0.8(+1.7)}_{-0.8(-1.5)}$	$11.7^{+0.7(+1.6)}_{-0.6(-0.9)}$	$11.7^{+0.7(+1.6)}_{-0.6(-0.9)}$
LeoI	226.0	+49.1	250	0.50	117.1	0.11	$1.22^{+0.24(+2.52)}_{-0.21(-0.36)}$	$9.7^{+0.3(+1.0)}_{-0.2(-0.5)}$	$10.7^{+0.1(+0.3)}_{-0.1(-0.2)}$	$10.7^{+0.1(+0.3)}_{-0.1(-0.2)}$

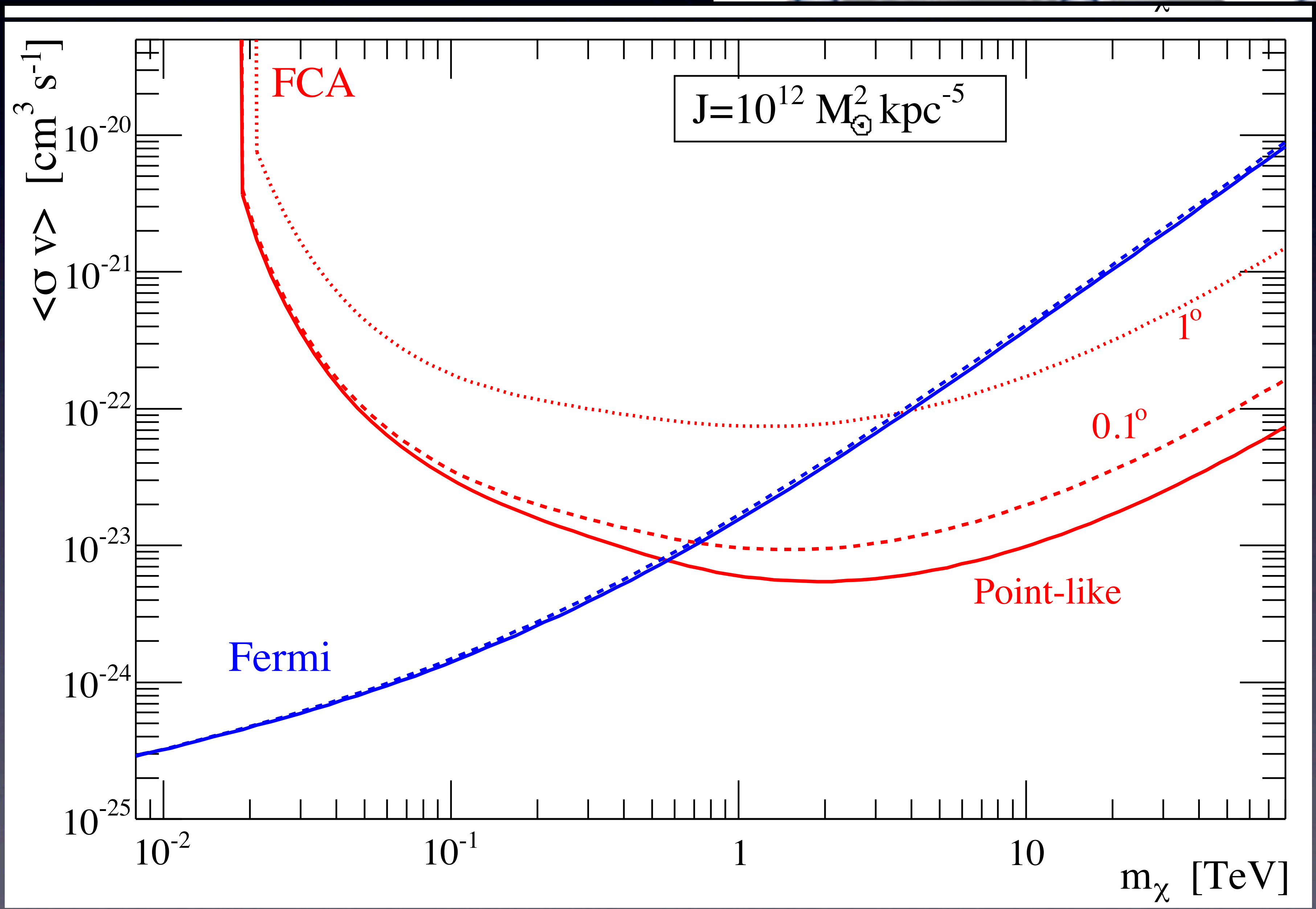
- Fermi upper limit from dSph



Fermi, 1108.3546

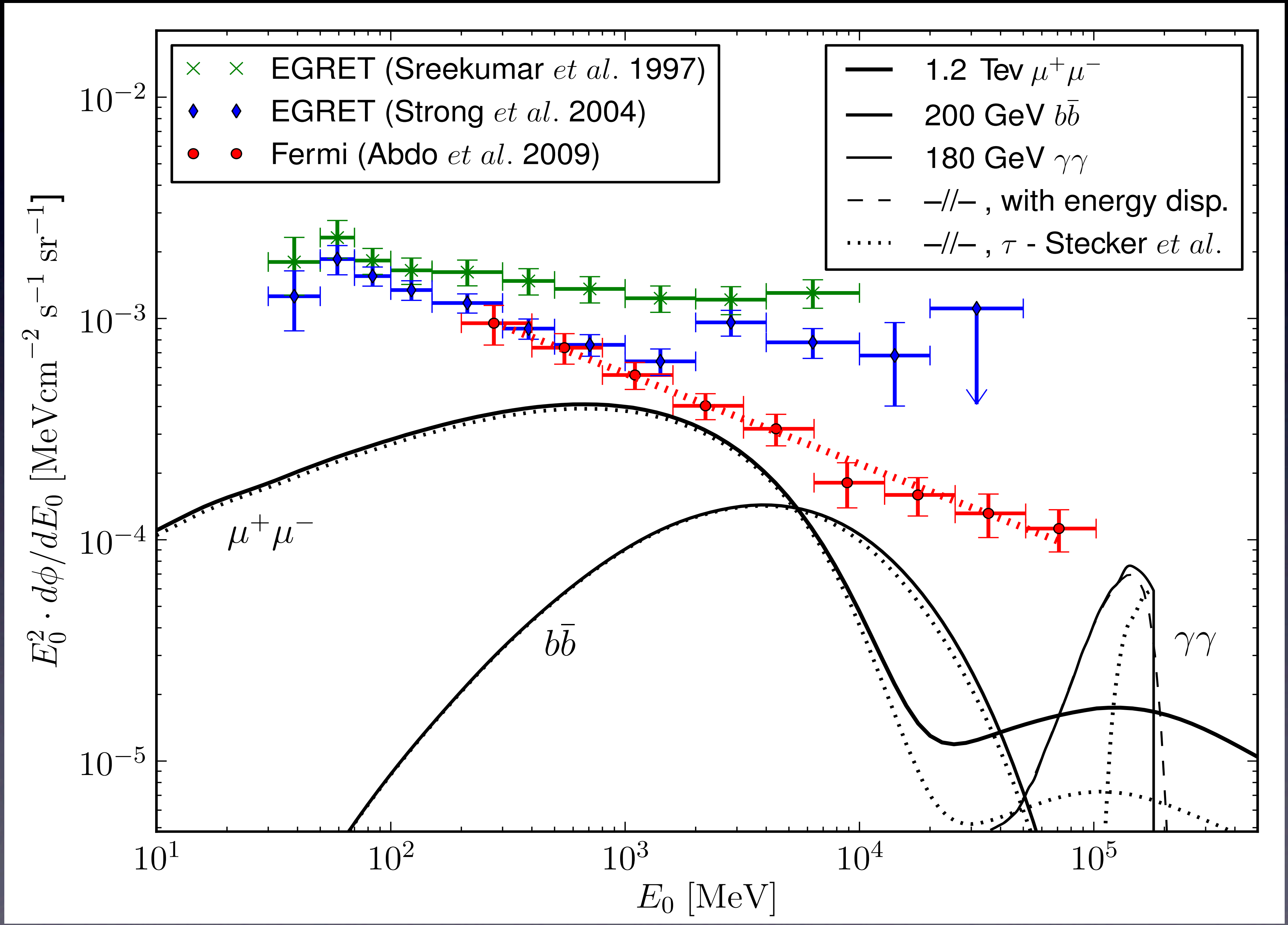
- CTA expected sensitivity





A.Charbonnier et al., 1104.0412

Diffuse gamma



Abdo et al., 1002.4415

$$\frac{d\phi_\gamma}{dE_0} = \frac{\langle\sigma v\rangle}{8\pi}\frac{c}{H_0}\frac{\bar{\rho}_0^2}{m_{DM}^2}\int dz(1+z)^3\frac{\Delta^2(z)}{h(z)}\frac{dN_\gamma(E_0(1+z))}{dE}e^{-\tau(z,E_0)},$$

$\Delta^2(z)$: enhancement from DM clustering

- (Modified) Press-Schechter

  Ellipsoidal DM collapse

  Bergstrom, Edjso, Ullio, Lacey (2002)

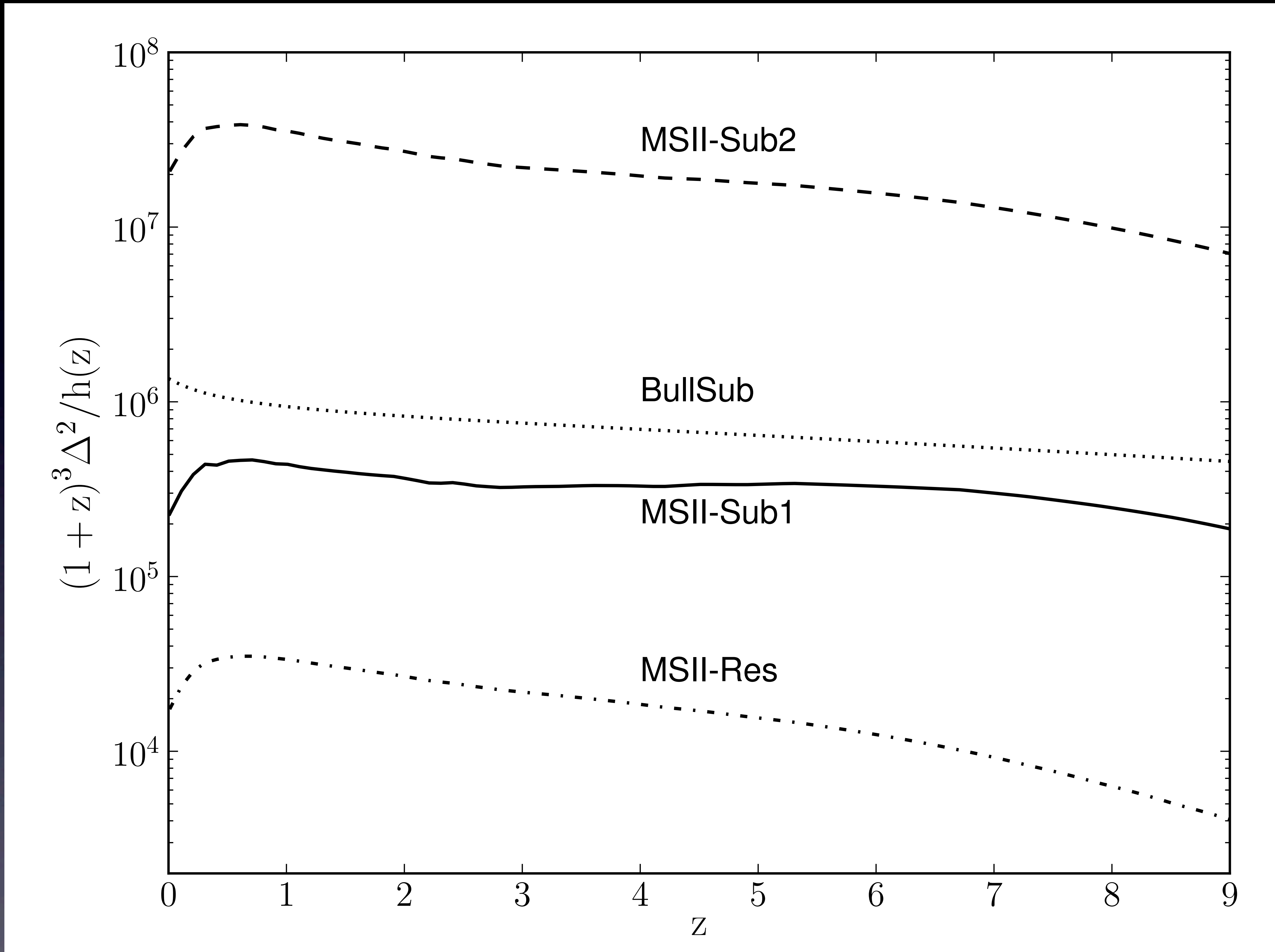
- N-body simulation

  Millennium-II

  Zavala et al. (2010)

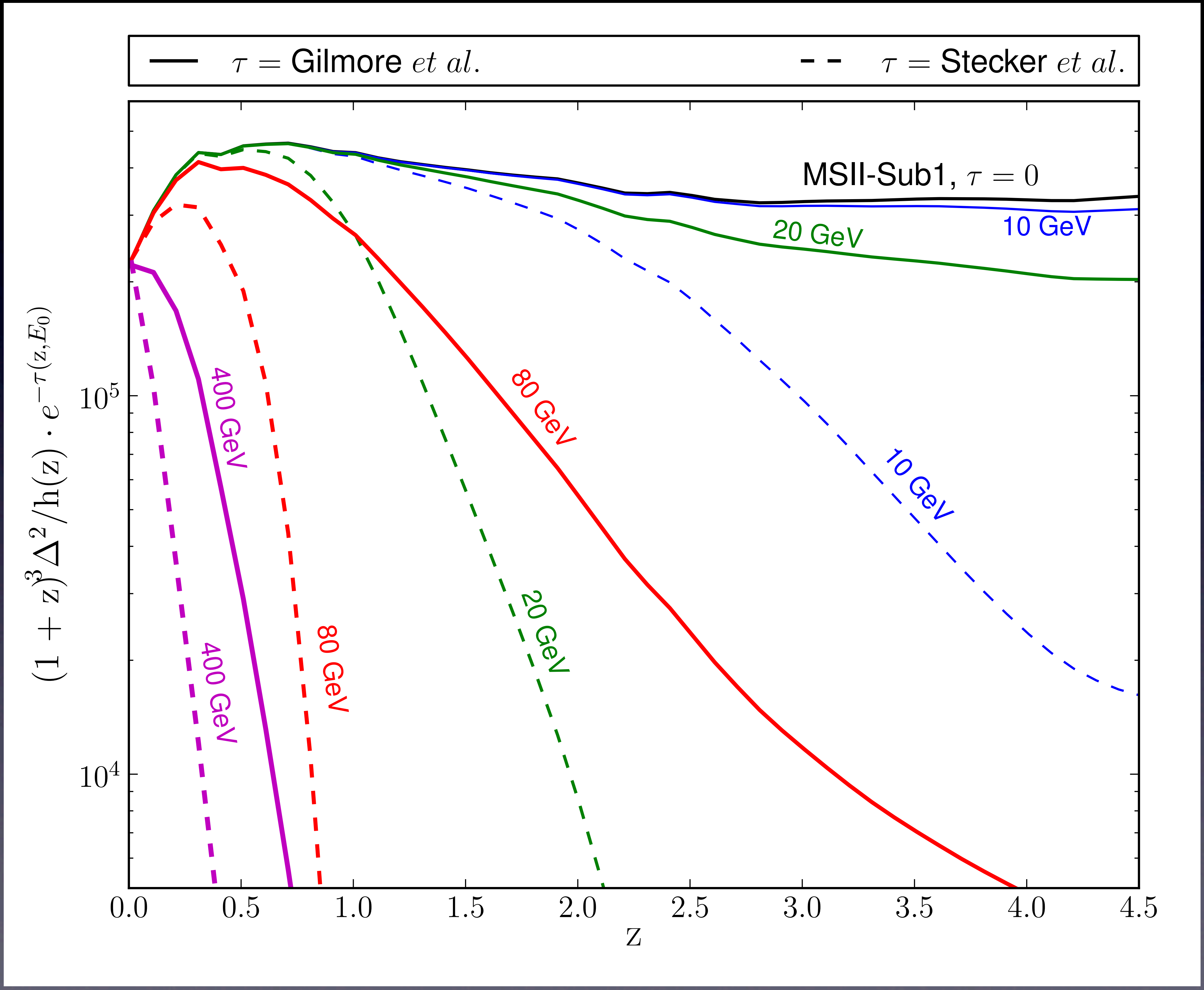
How to extrapolate to smallest (sub)halo?

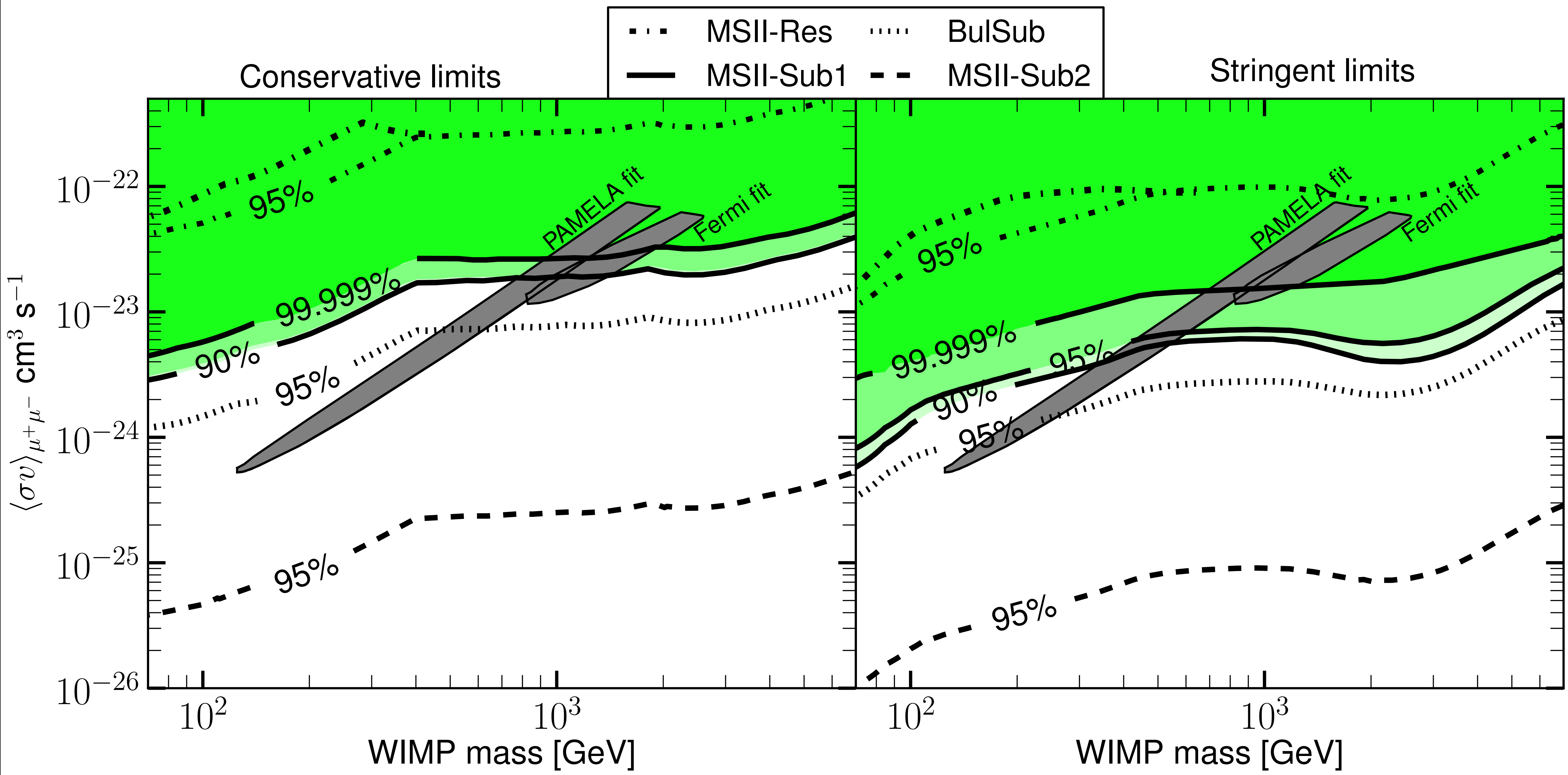
$\sim 10^{-6} M_\odot$



Abdo et al., 1002.4415

Uncertainty on the gamma-ray optical depth

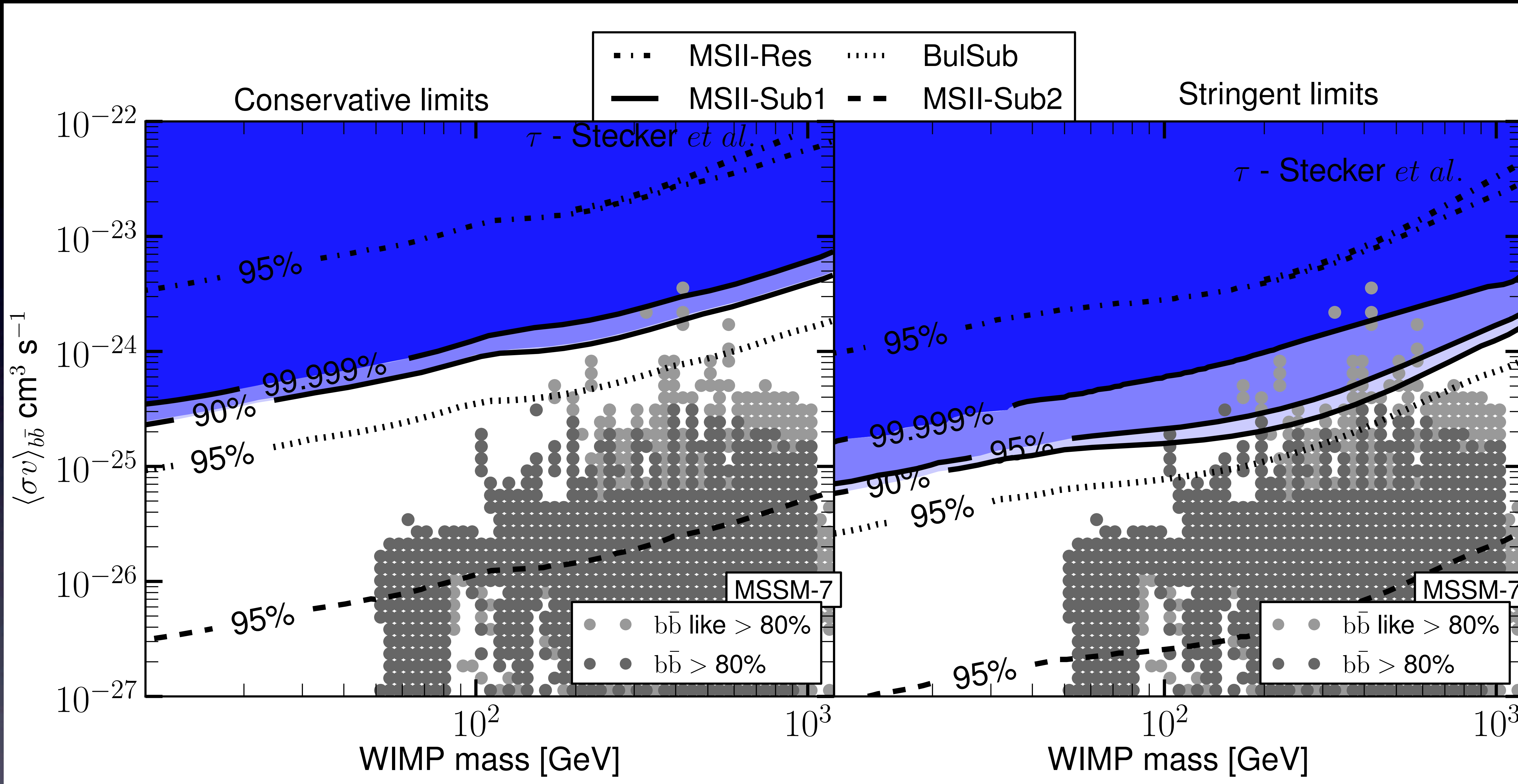




left : no astrophysical BG

right : realistic astrophysical BG

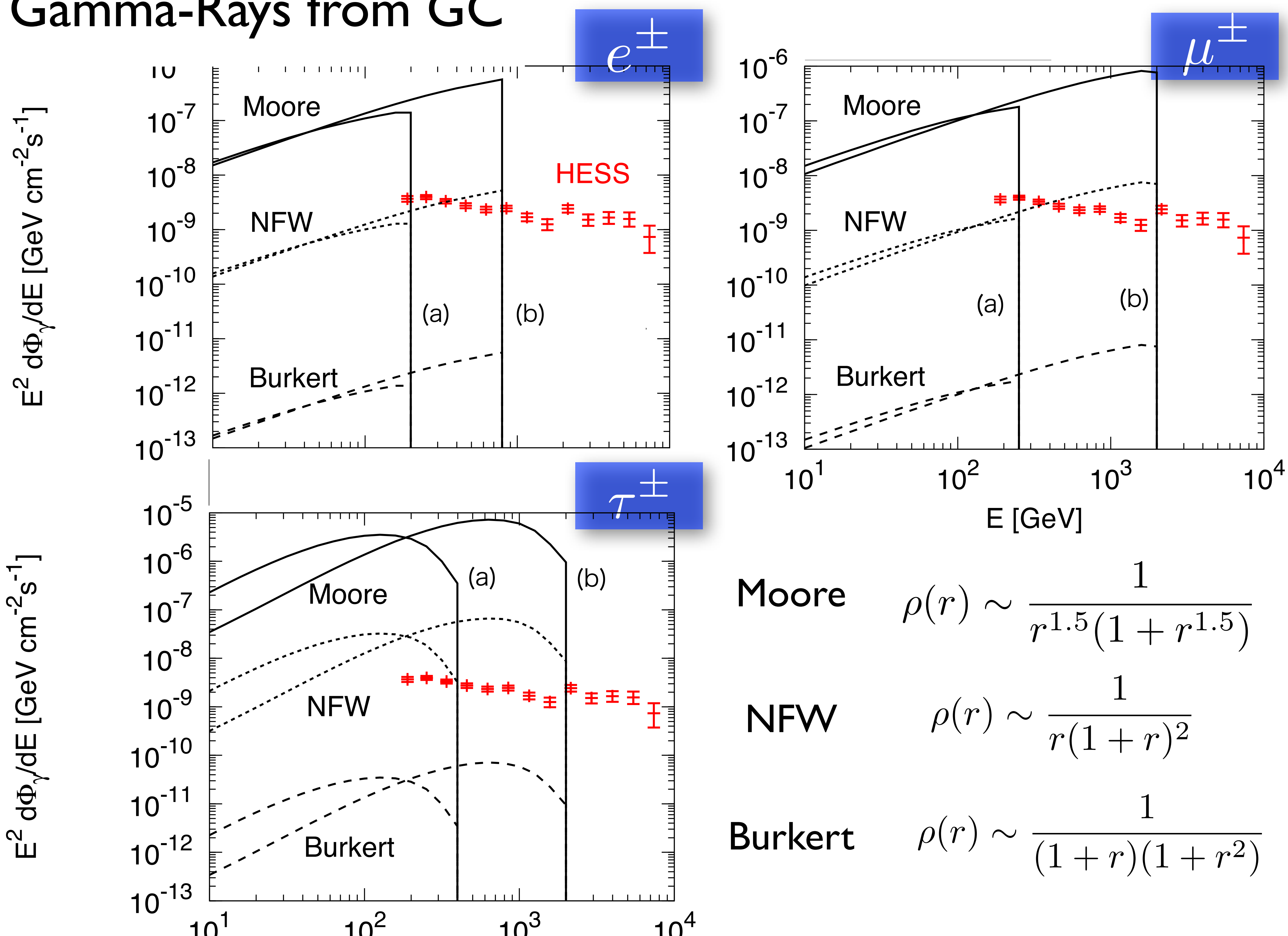
Abdo et al., 1002.4415



Abdo et al., 1002.4415

Galactic center

Gamma-Rays from GC



Moore $\rho(r) \sim \dfrac{1}{r^{1.5}(1+r^{1.5})}$

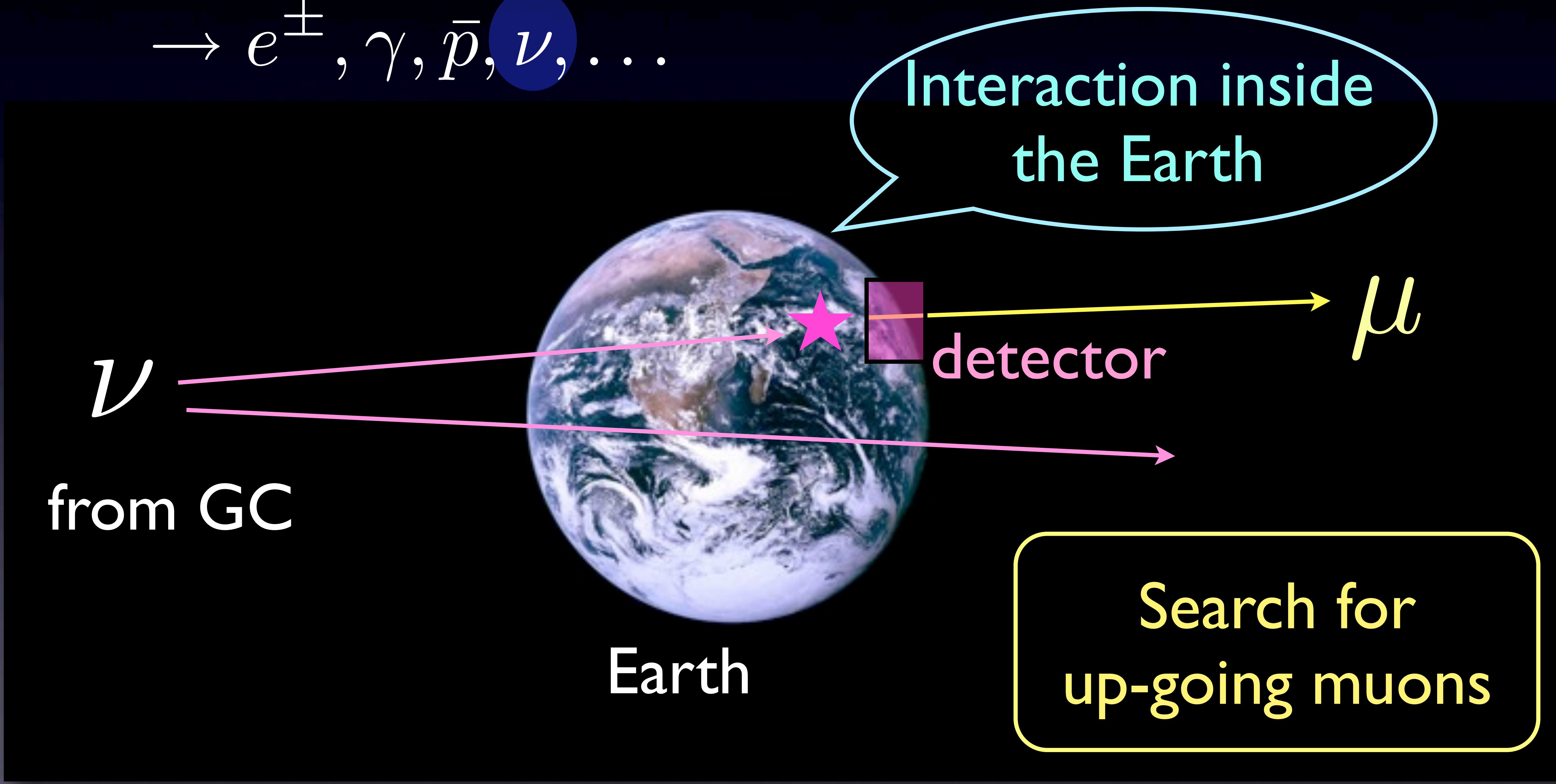
NFW $\rho(r) \sim \dfrac{1}{r(1+r)^2}$

Burkert $\rho(r) \sim \dfrac{1}{(1+r)(1+r^2)}$

Neutrino Signal from DM Annihilation

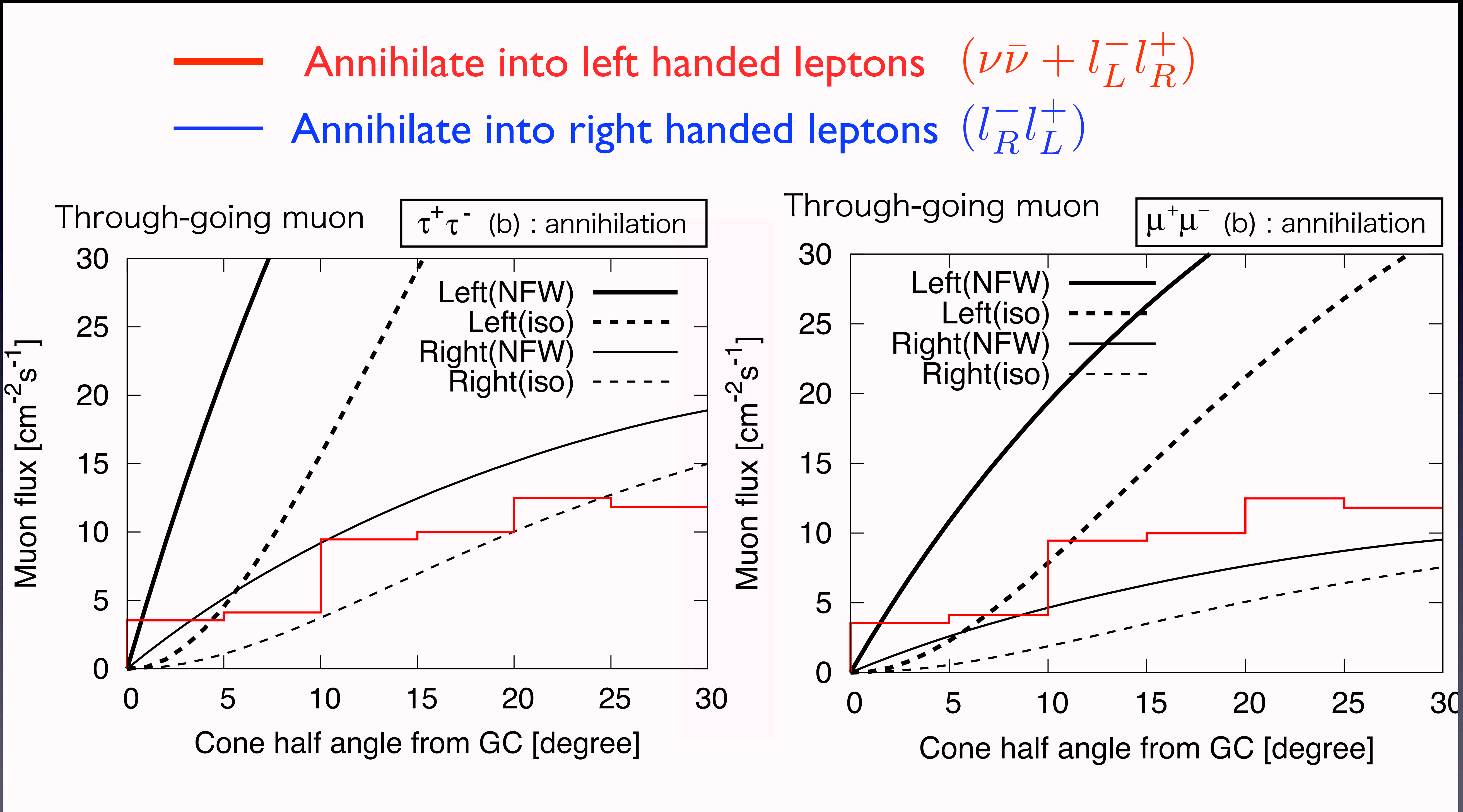
Ritz, Seckel (88),Kamionkowski (90),...
Bertone,Nezri,Orloff,Silk (04),
Yuksel,Horiuchi,Beacom,Ando(07)

$$\chi\chi \to W^+W^-, b\bar{b}, l^+l^-, \ldots$$
$$\to e^\pm, \gamma, \bar{p}, \nu, \ldots$$

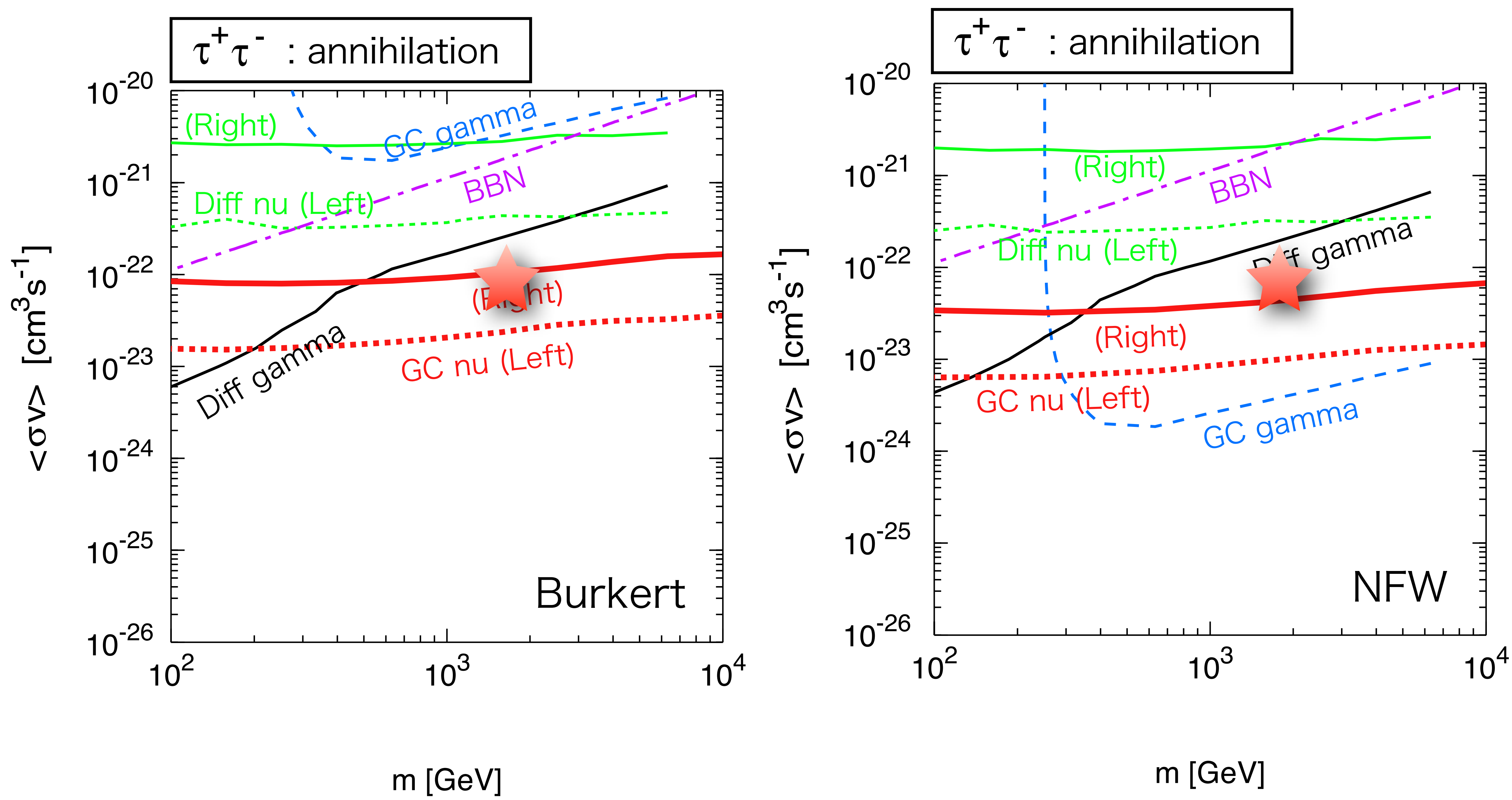


→ Limits from Super-K

- Limits from SK : Annihilation into left-handed leptons is not favored.



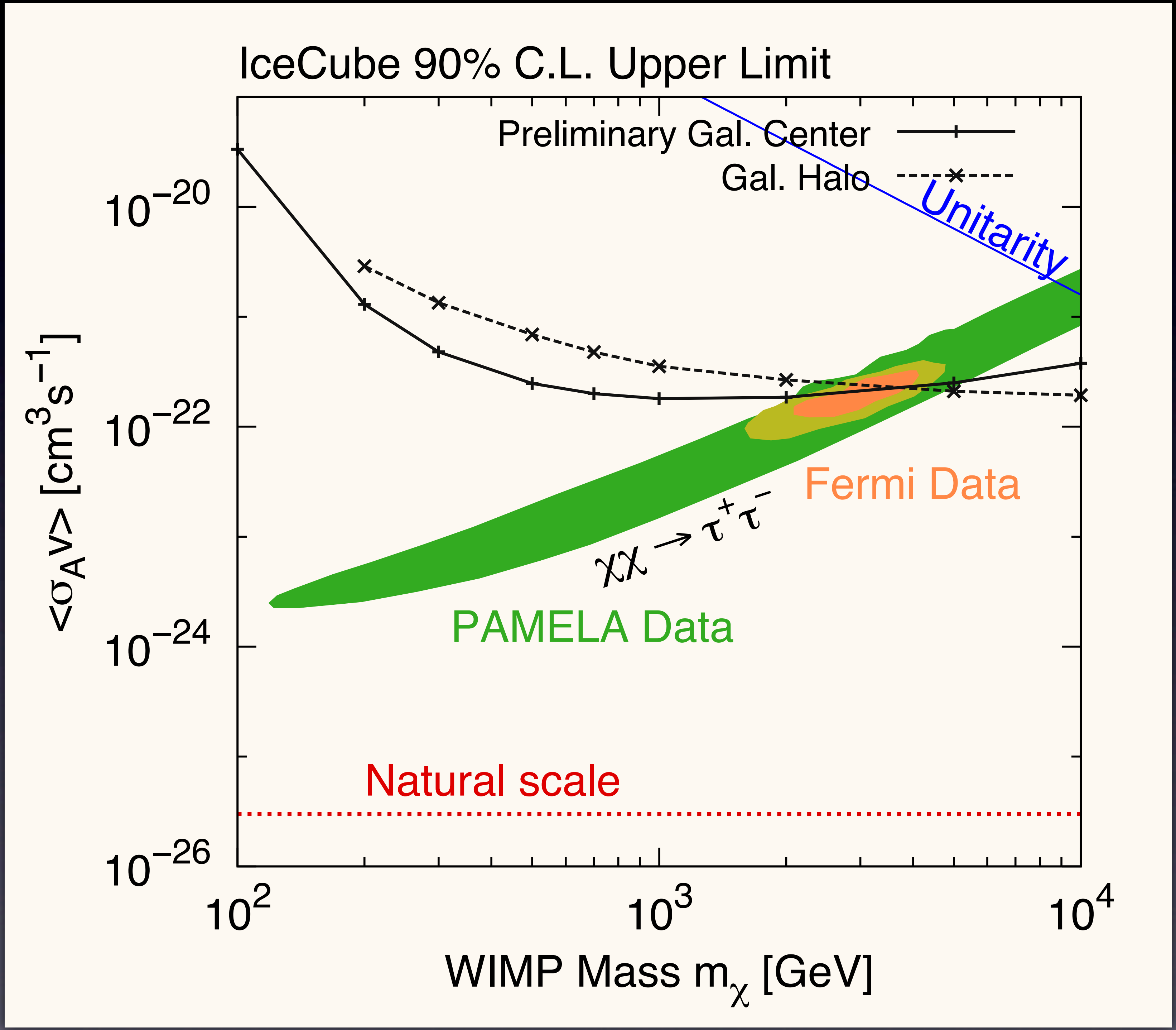
J.Hisano, M.Kawasaki, K.Kohri, KN (2008)



KN, PhD Thesis

12年3月21日水曜日

- Limit from IceCube with 22 strings



IceCube, 1111.2738

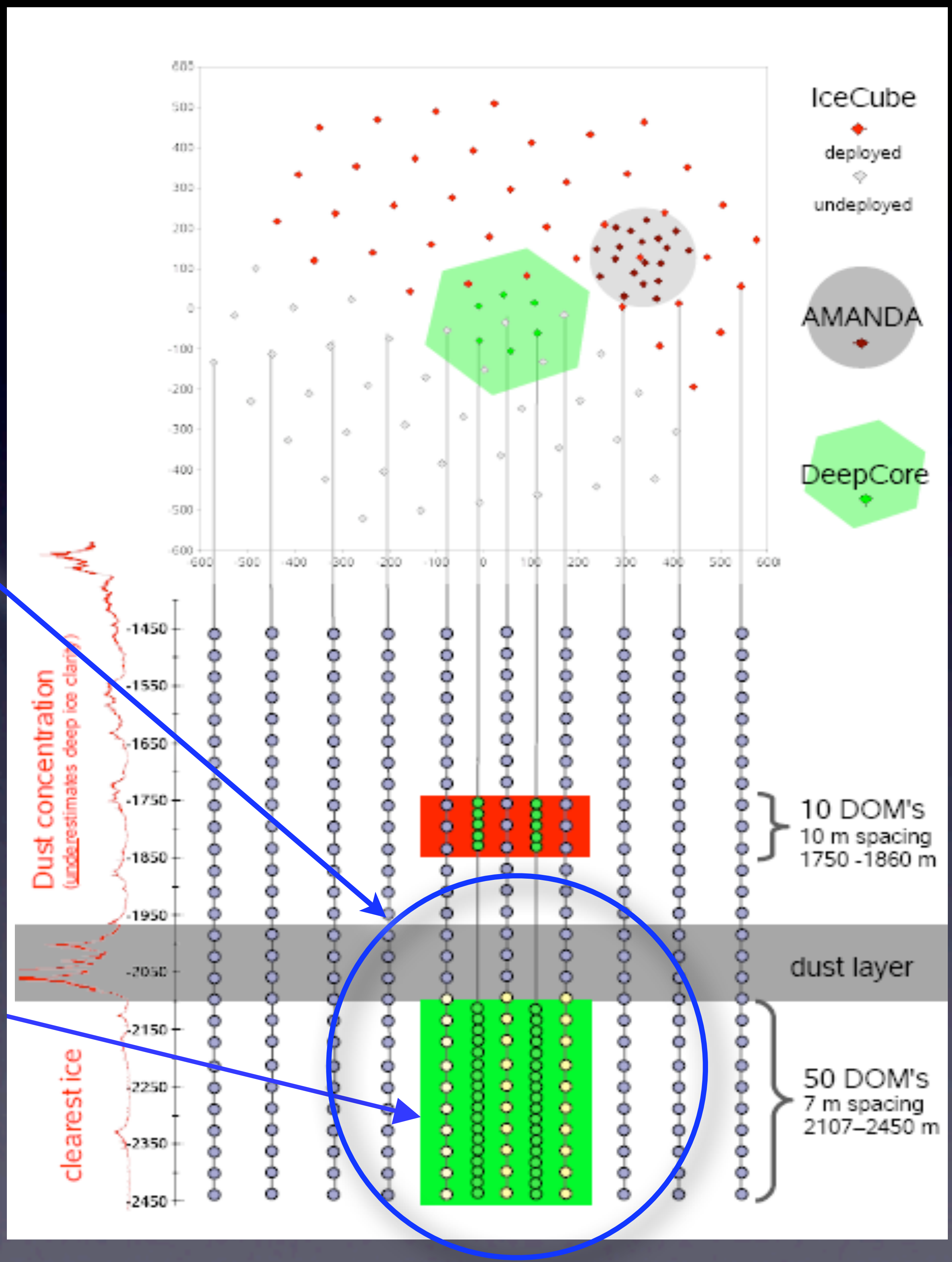
DeepCore

- Primary purpose : better sensitivity on low-energy neutrino

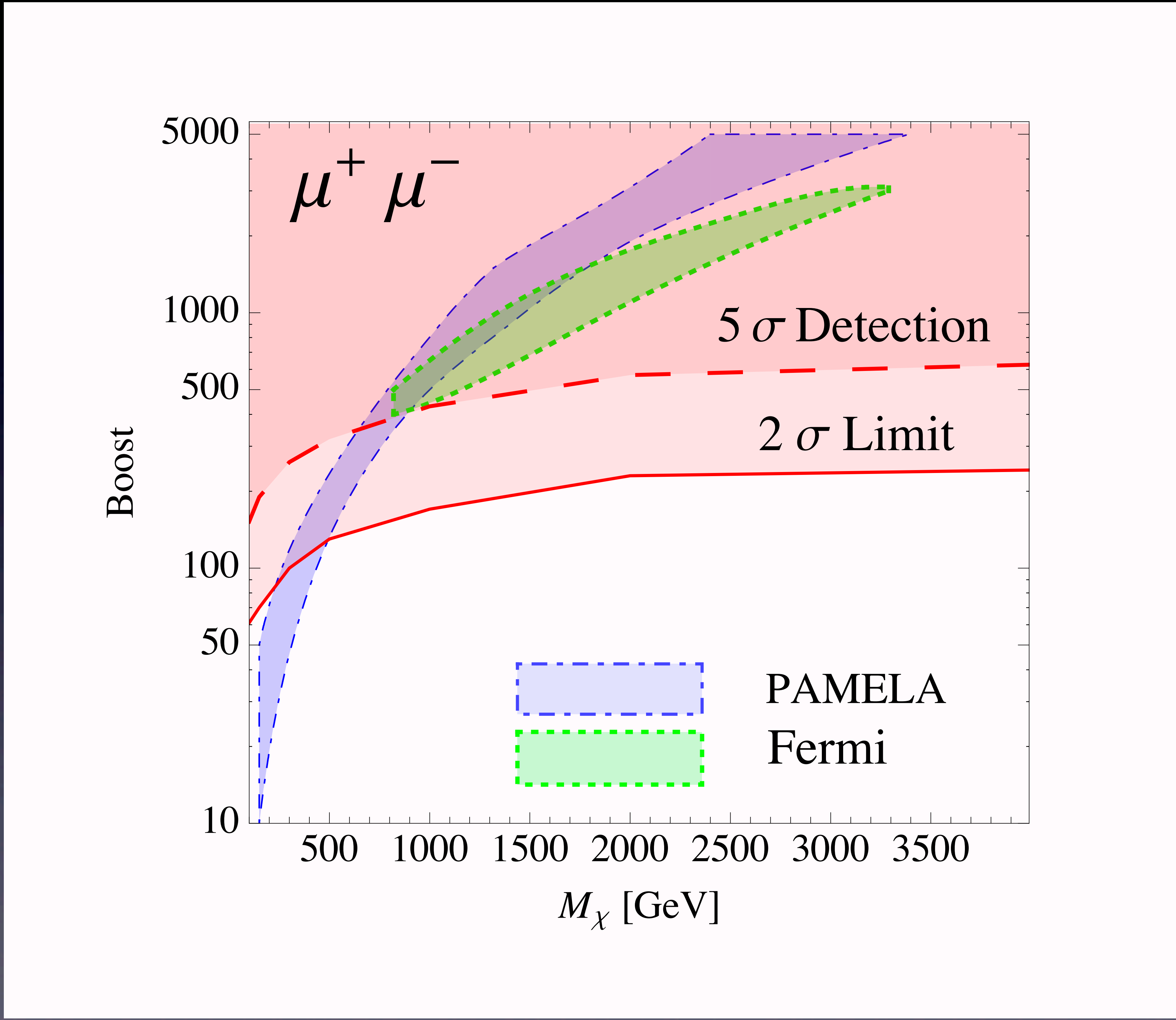
  Inner detector with denser instrumentation

- Use original detector as muon veto

→ Remove atmospheric muon BG



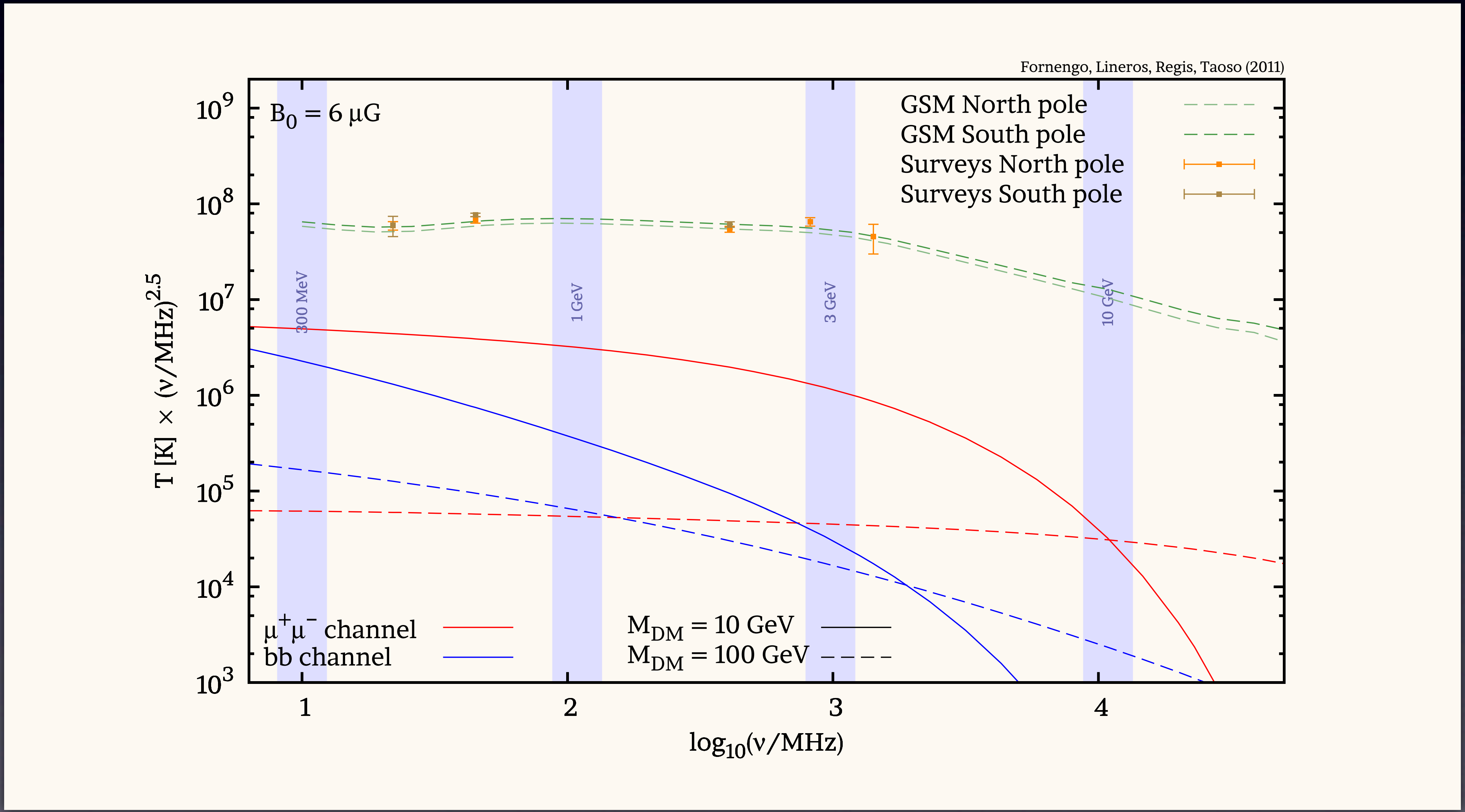
Expected sensitivity of DeepCore (5yr)



Spolyar, Buckley, Freese, Hooper, Murayama, 0905.4764

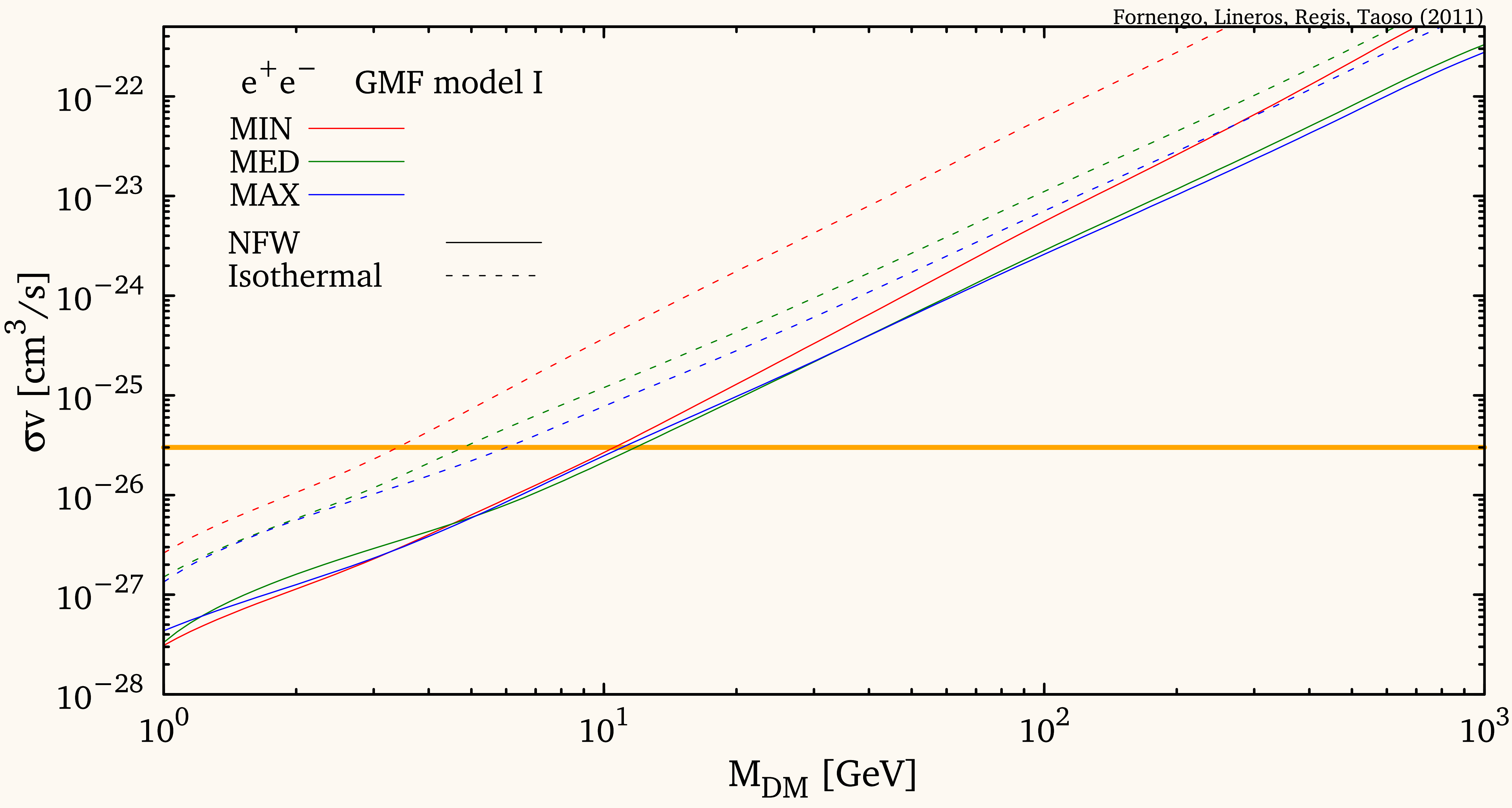
Synchrotron

- Depends on Magnetic field structure



Fornengo et al., 1110.4337

22-1420MHz Haslam MAP, etc.



Fornengo et al., 1110.4337

BBN and CMB

- DM annihilation takes place in the early Universe

  ⟶ It may affect BBN and CMB

- Energy injection in BBN epoch

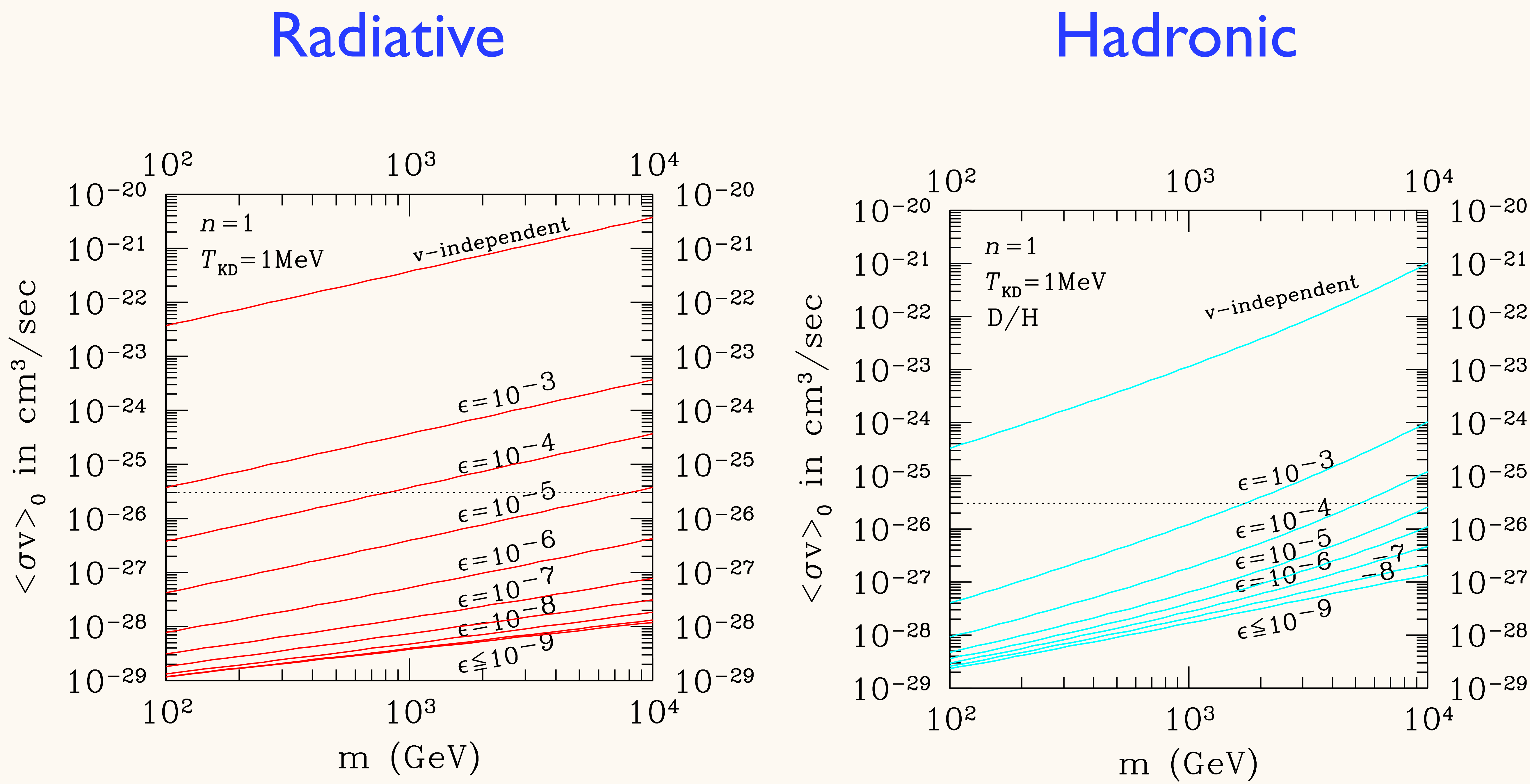
  Destroy & overproduction of light elements

- Energy injection in recombination epoch

  Increase ionization fraction of H atom

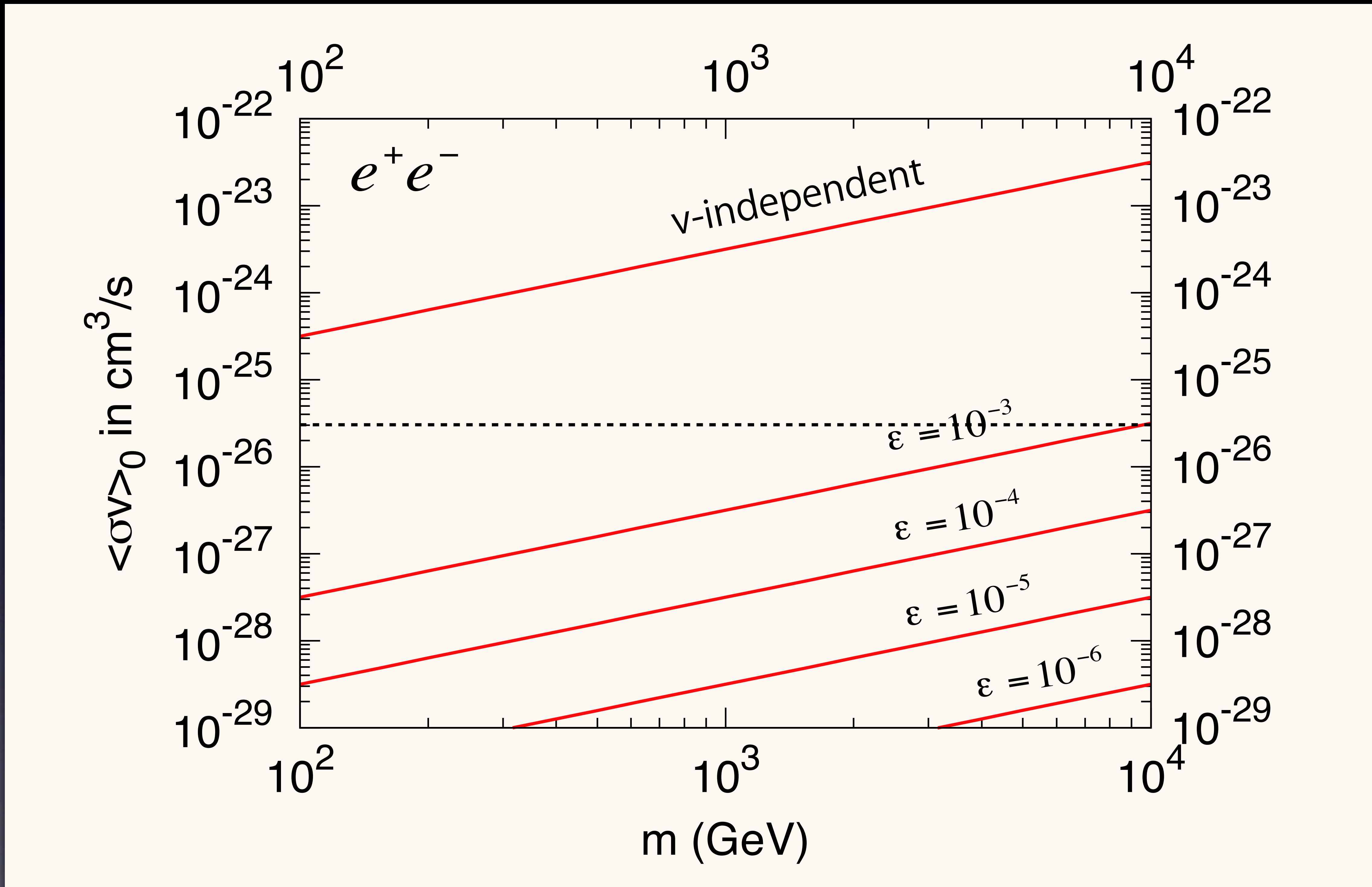
  CMB anisotropy changes

- Constraint from BBN



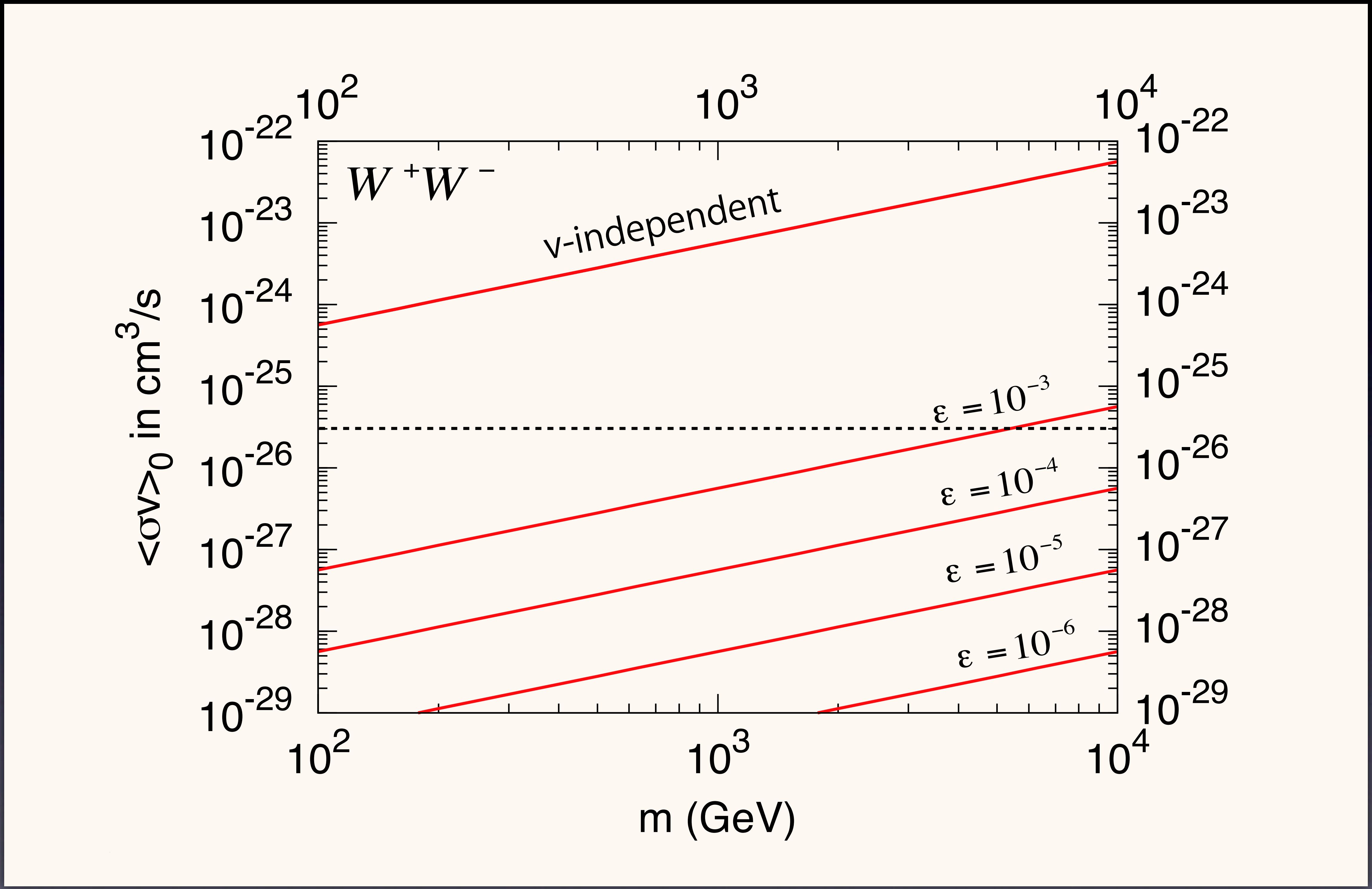
Hisano, Kawasaki, Kohri, Moroi, KN, Sekiguchi, 1102.4658

- Constraint from WMAP

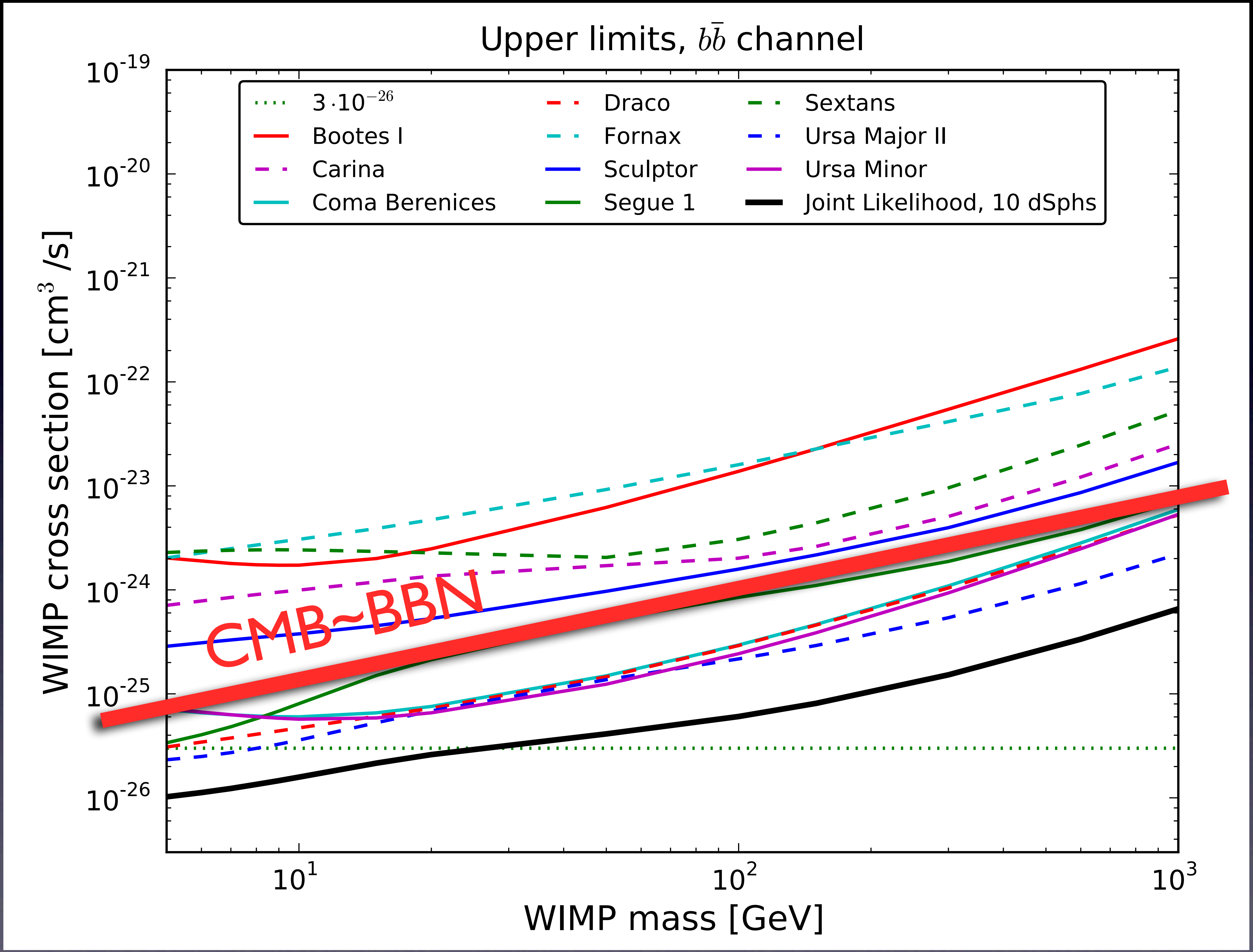


Hisano, Kawasaki, Kohri, Moroi, KN, Sekiguchi, 1102.4658

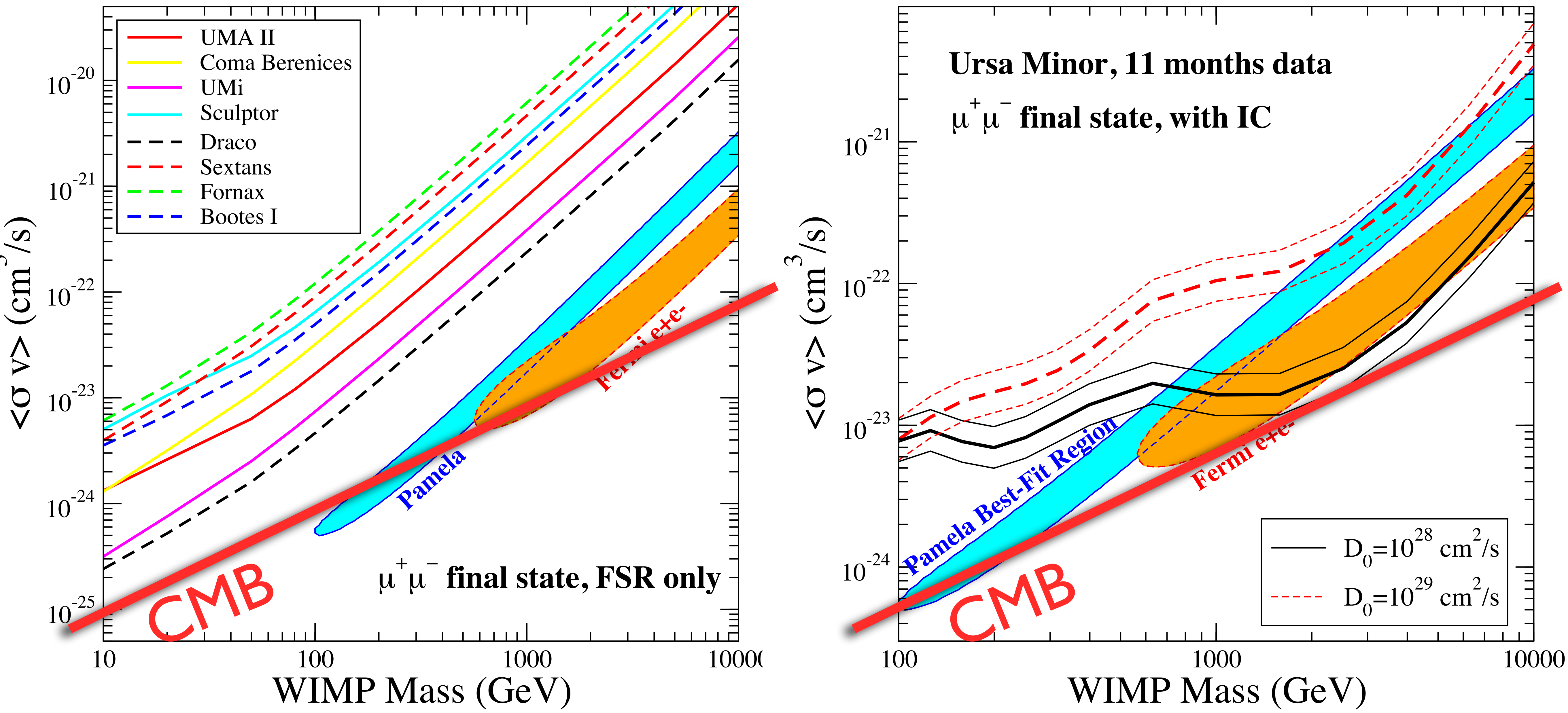
- Constraint from WMAP



Hisano, Kawasaki, Kohri, Moroi, KN, Sekiguchi, 1102.4658



Upper limits, $b\bar{b}$ channel
$3 \cdot 10^{-26}$
Bootes I
Carina
Coma Berenices
Draco
Fornax
Sculptor
Segue 1
Sextans
Ursa Major II
Ursa Minor
Joint Likelihood, 10 dSphs
WIMP cross section [cm^3 /s]
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^1
10^2
10^3
WIMP mass [GeV]
CMB~BBN



Abdo et al., 1001.4531

Backup

- Determination of Local DM density

Catena, Ullio, 0907.0018

1. Solar system data (Galactic constant)

- Galactocentric radius

Star orbit around the BH at GC

$R_0 = 8.33 \pm 0.35\text{kpc}$ S.Gillessen et al.,0810.4674

cf) RR Ly. near GC

- Oort's constants

Proper motion of Cephaid, OB stars,... (Hipparcos)

$$\Theta_0/R_0 = A - B = 29.45 \pm 0.15\text{km/s/kpc}$$

$$\longrightarrow \quad \Theta_0 = 245 \pm 10.4\text{km/s}$$

2. Galactic dynamics data

- Terminal velocity

  HI, CO line from inside solar system (>3kpc)

  ⟶ Rotation curve for inner Galaxy

- Local standard rest velocity

  (proper motion of solar)

  Outer Galaxy

  18 star formation regions by VLBI

- Total mass including dark halo

  Velocities of MW satellite

  $$M(< 50\mathrm{kpc}) = (5.4 \pm 0.25) \times 10^{11} M_\odot$$

- Surface mass density

  Star motions perp. to Galactic plane

  $$\Sigma_* = (48.8 \pm 8) M_\odot \mathrm{pc}^{-2}$$

3. Model

- Stellar disk

$$\rho_d(R,z) = \frac{\Sigma_d}{2z_d}\, e^{-\frac{R}{R_d}}\, \mathrm{sech}^2\left(\frac{z}{z_d}\right) \quad \text{with} \quad R < R_{dm}\ ,$$

- Stellar bulge

$$\rho_{bb}(x,y,z) = \rho_{bb}(0)\left[s_a^{-1.85}\, \exp(-s_a) + \exp\left(-\frac{s_b^2}{2}\right)\right]$$

$$s_a^2 = \frac{q_b^2(x^2+y^2)+z^2}{z_b^2} \qquad s_b^4 = \left[\left(\frac{x}{x_b}\right)^2 + \left(\frac{y}{y_b}\right)^2\right]^2 + \left(\frac{z}{z_b}\right)^4 .$$

- DM halo

$$\rho_h(r) = \rho' f\,(r/a_h)\ , \qquad f_E(x) = \exp\left[-\frac{2}{\alpha_E}\,(x^{\alpha_E}-1)\right]$$

$$\rho',\, a_h \rightarrow R_{\mathrm{vir}},\, M_{\mathrm{vir}}$$

Parameters	mean	σ	low 68.00%	up 68.00%	low 95.00 %	up 95.00 %
Σ_d [$M_\odot pc^{-2}$]	1154.14	427.43	683.14	1662.94	476.17	1943.67
$\rho_{bb}(0)$ [$M_\odot pc^{-3}$]	1.37	0.80	0.48	2.32	0.16	2.9
R_d [kpc]	2.45	0.21	2.24	2.65	2.07	2.90
R_0 [kpc]	8.25	0.29	7.97	8.54	7.66	8.81
M_{vir} [10^{12} $M_\odot$]	1.39	0.33	1.07	1.74	0.93	2.14
c_{vir}	18.01	3.32	14.51	21.76	12.31	24.36
α_E	0.22	0.07	0.14	0.29	0.11	0.35
β	-0.29	0.24	-0.53	-0.06	-0.80	0.13
Derived quantities	mean	σ	low 68.00%	up 68.00%	low 95.00 %	up 95.00 %
$A - B$ [km s^{-1} kpc^{-1}]	29.44	0.15	29.29	29.59	29.15	29.74
$A + B$ [km s^{-1} kpc^{-1}]	0.07	0.45	-0.38	0.51	-0.82	0.94
$v_c(R_0)$ [km s^{-1}]	243.03	8.49	234.68	251.28	225.61	259.13
Σ_* [$M_\odot$ pc^{-2}]	46.51	5.47	41.05	51.96	35.76	57.23
$\Sigma_{\|z\|<1.1\mathrm{kpc}}$ [$M_\odot$ pc^{-2}]	72.16	4.24	67.93	76.37	63.87	80.47
$M(< 50\mathrm{kpc})$ [10^{11} $M_\odot$]	5.36	0.24	5.13	5.60	4.90	5.83
$M(< 100\mathrm{kpc})$ [10^{11} $M_\odot$]	8.59	0.64	7.94	9.23	7.37	9.86
$\rho_{DM}(R_0)$ [GeV cm^{-3}]	0.386	0.027	0.359	0.413	0.333	0.439

Table 2: Means, standard deviations and confidence intervals for the model parameters and the derived quantities in the Einasto case.

Catena, Ullio, 0907.0018

- 16yr observation of stars around GCBH

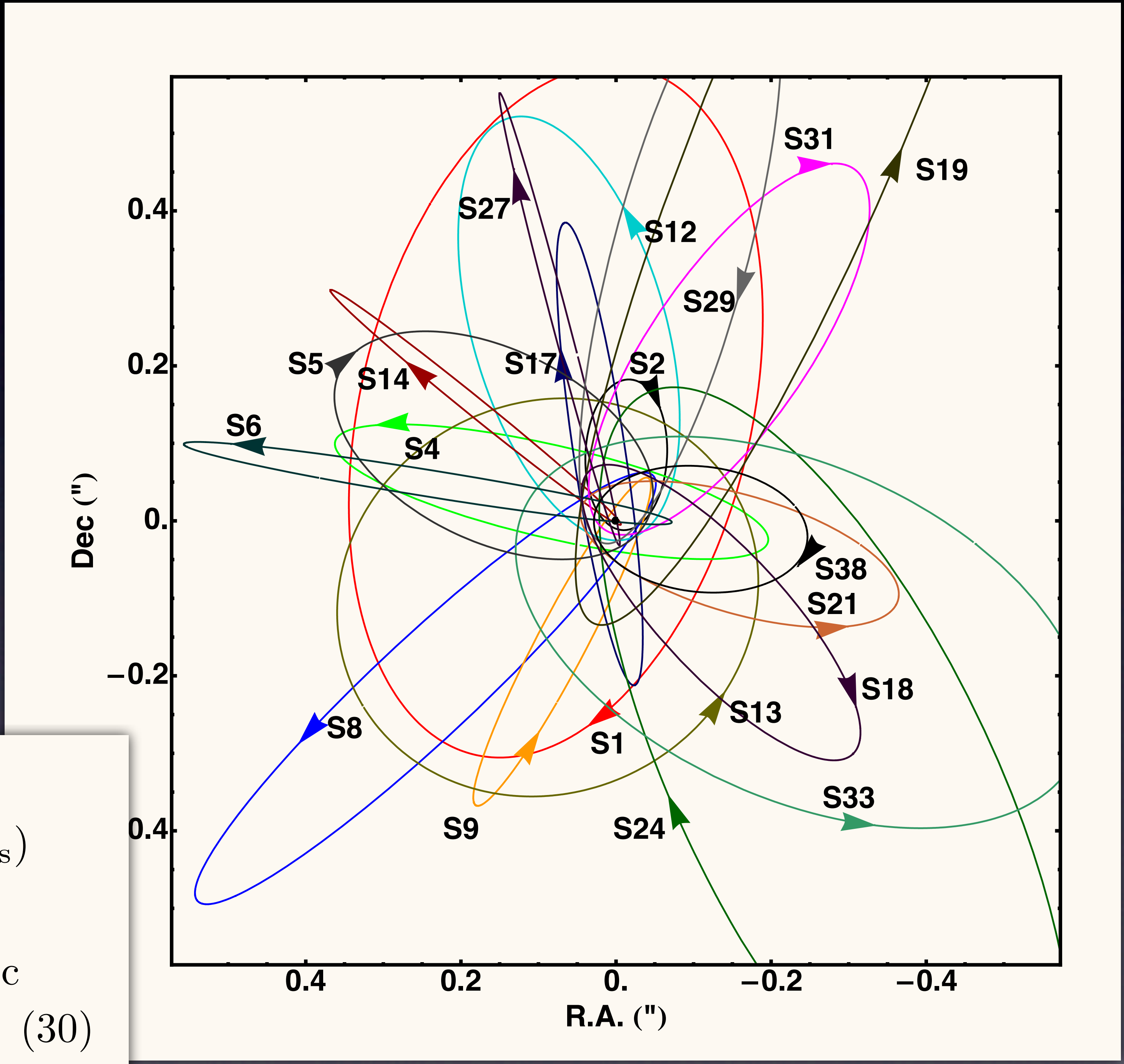
  → Period of star motion

- Spectroscopy (IR)

  → Velocity

  → Orbital radius

→ Distance to GC & Mass of BH



$$M = (3.95 \pm 0.06|_{\rm stat} \pm 0.18|_{R_0,\,{\rm stat}} \pm 0.31|_{R_0,\,{\rm sys}}) \times 10^6\,M_\odot \times (R_0/8\,{\rm kpc})^{2.19} = (4.31 \pm 0.36) \times 10^6\,M_\odot \text{ for } R_0 = 8.33\,{\rm kpc}$$

$$R_0 = 8.33 \pm 0.17|_{\rm stat} \pm 0.31|_{\rm sys}\,{\rm kpc} \qquad (30)$$

S.Gillessen et al.,0810.4674