MIAPP
Munich Institute for
Astro- and Particle Physics

CAU
중앙대학교

SUSY Higgs-portal and X-ray lines

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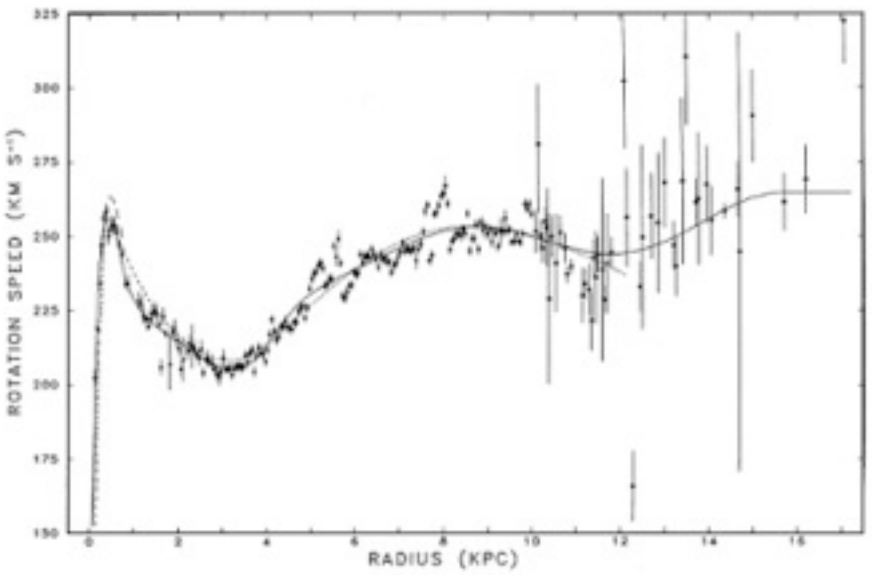
Ref. HML, C.B. Park, M. Park, 1501.05479 [hep-ph].

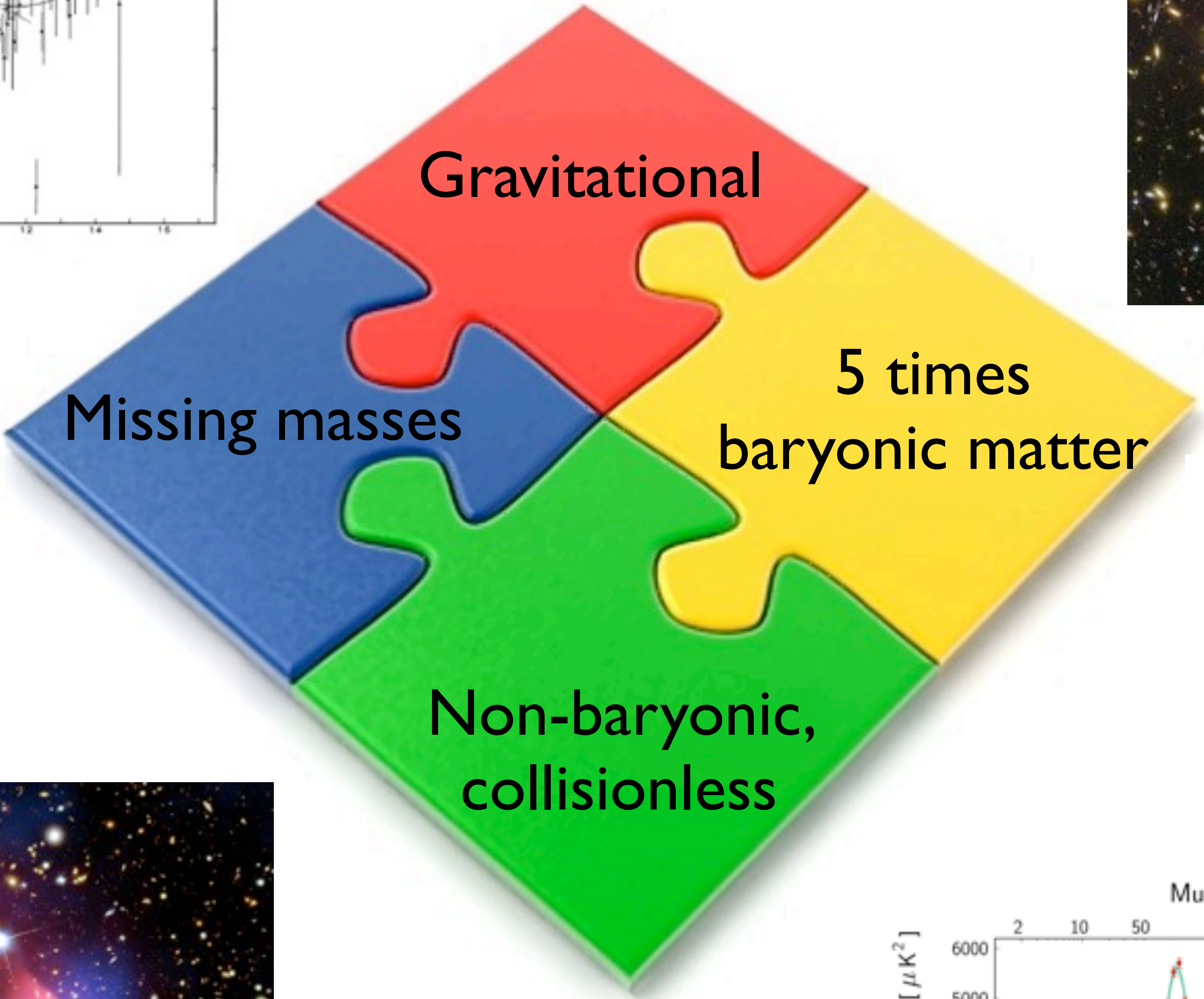
MIAPP Workshop on Dark Matter
Feb 23, 2015

Outline

- Introduction
- Magnetic dark matter and X-ray lines
- Dark matter in SUSY Higgs-portal
- Conclusions

Dark Matter



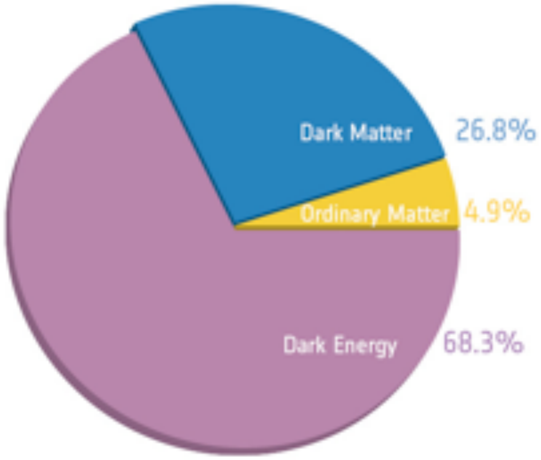


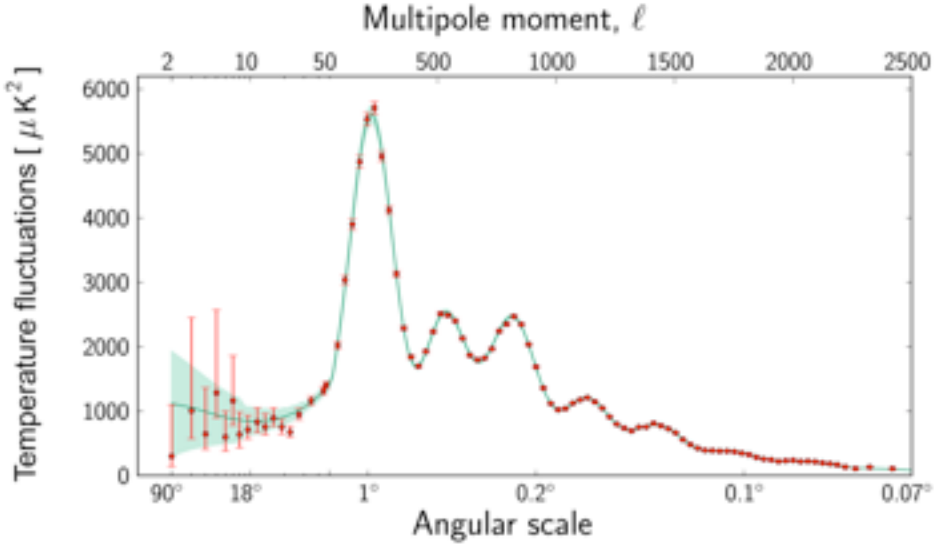
Gravitational

Missing masses

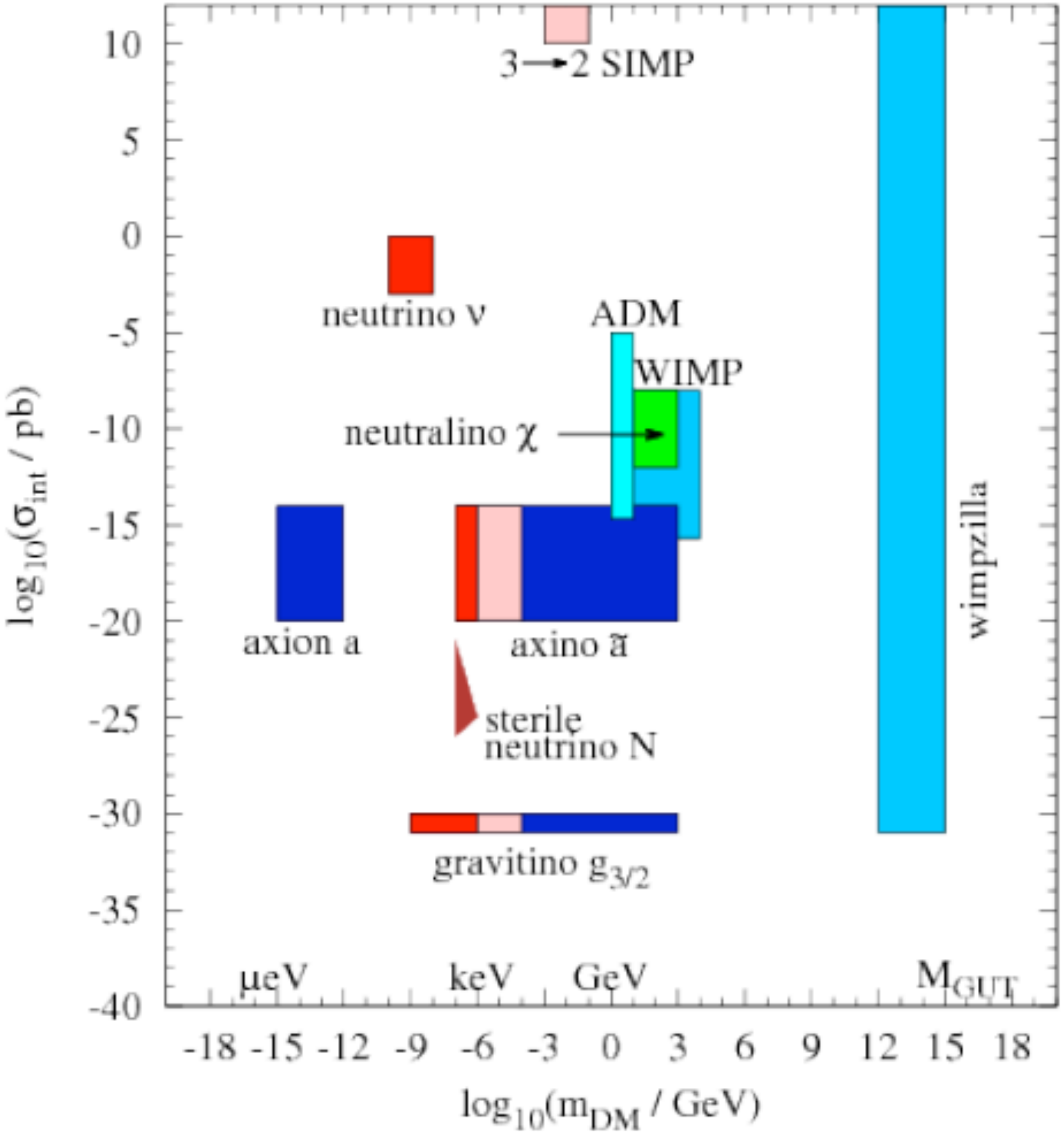
5 times
baryonic matter

Non-baryonic,
collisionless





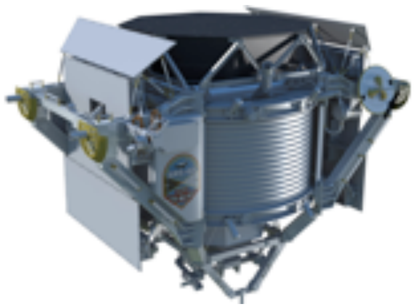
Professor DM



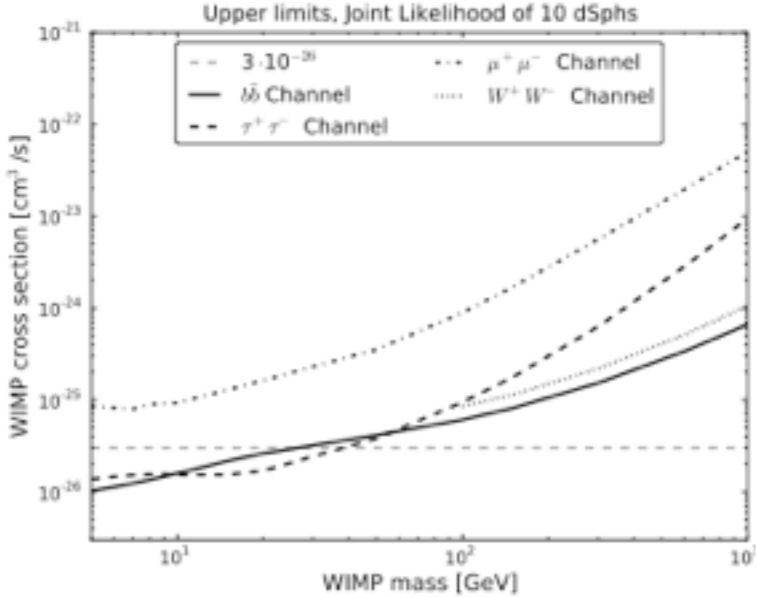
[Choi, Kim, Roszkowski, 1407.0017]

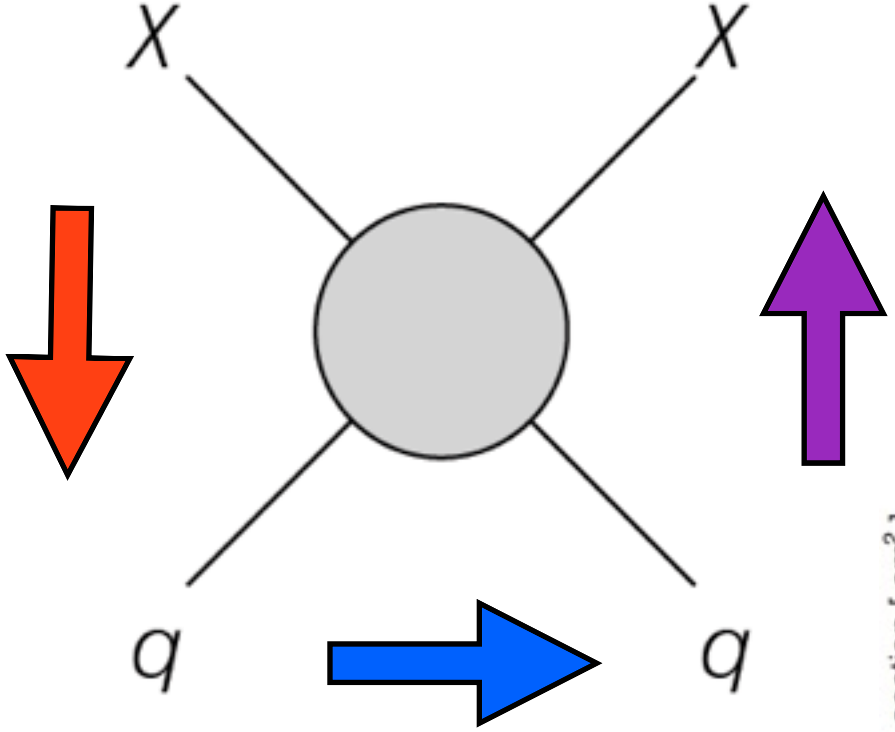
Are we simplifying it too much?

Testing dark matter

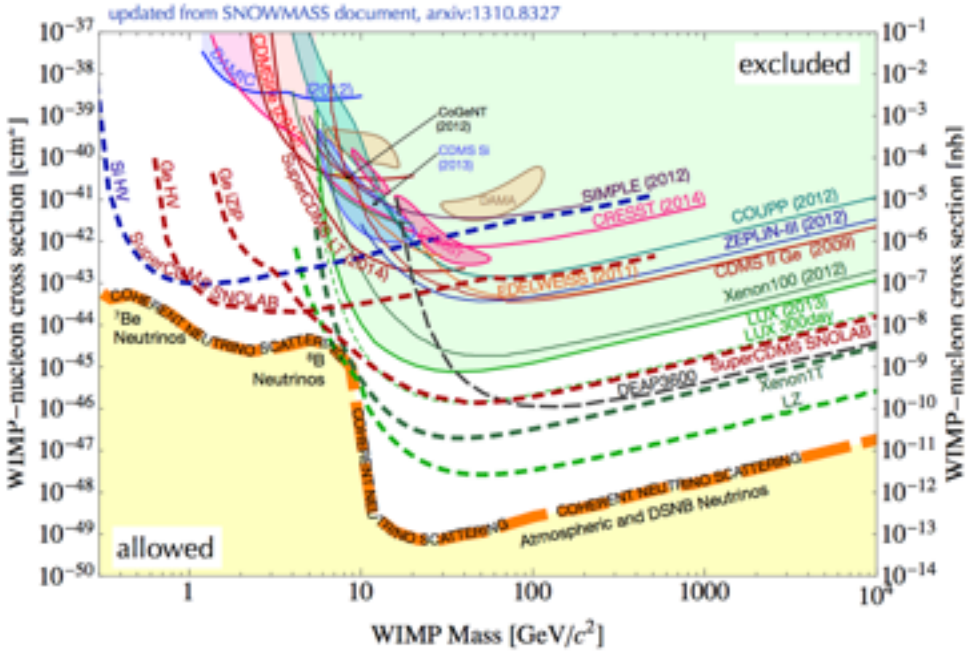


Indirect detection

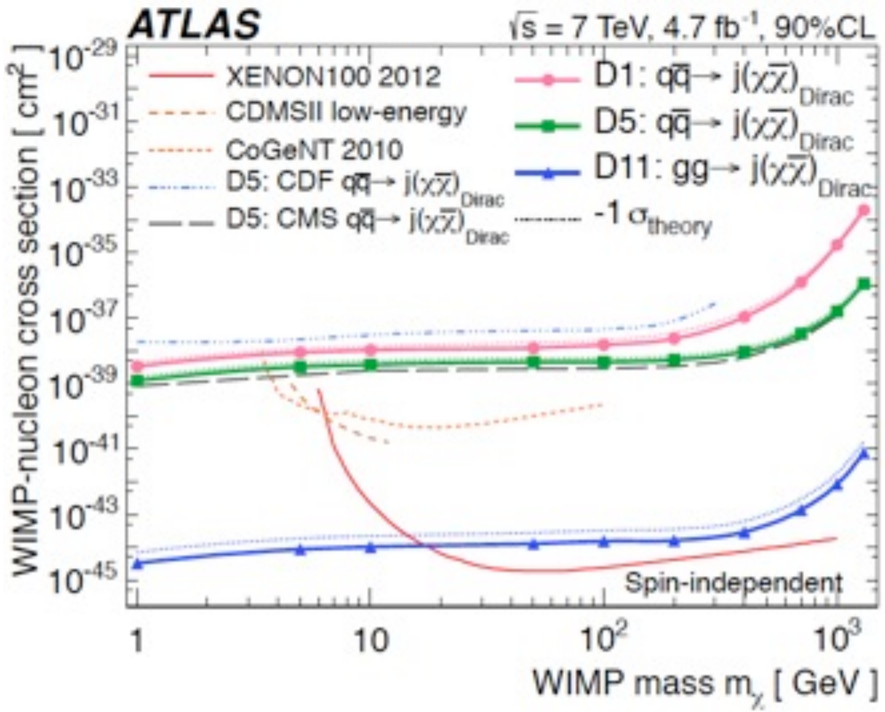




Direct detection

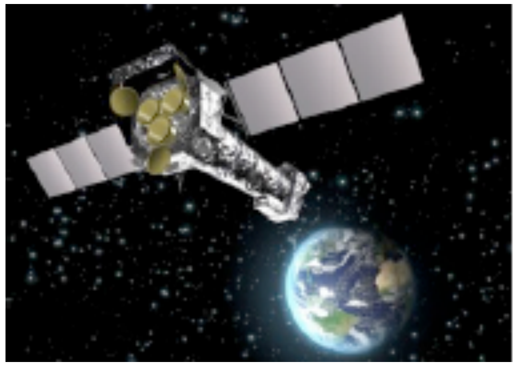


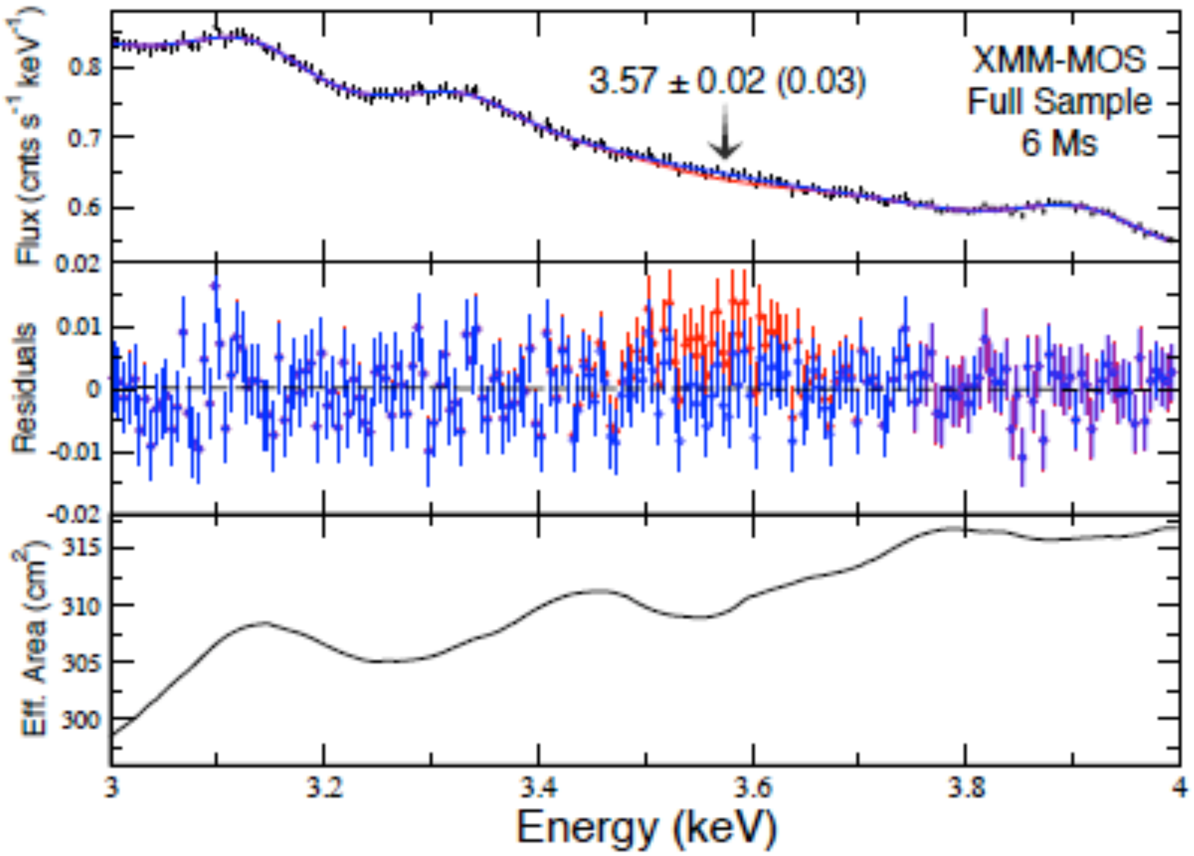
Particle colliders



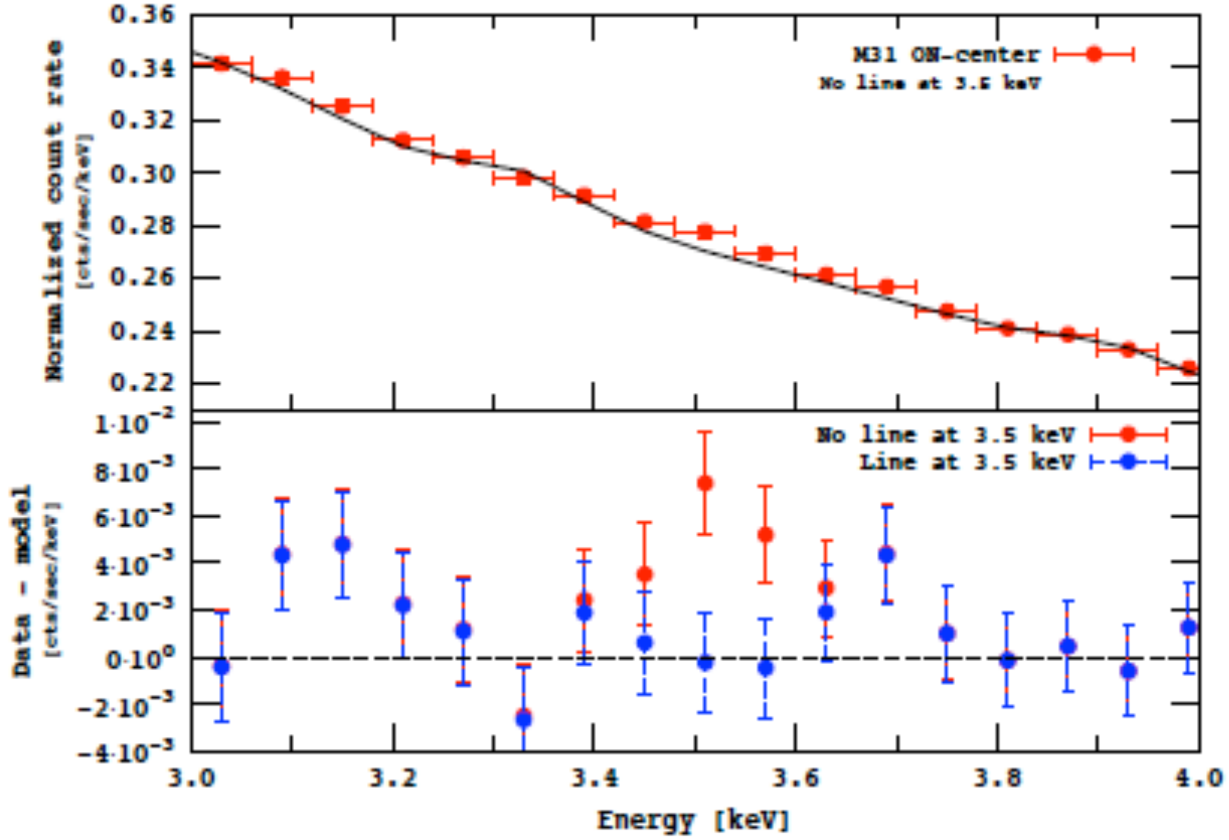
X-ray line from galaxies

- Monochromatic photon lines probe well indirect signals of dark matter due to directional information.
- X-ray spectra (XMM-Newton) of various galaxy clusters and Andromeda show an unidentified line signal at 3.55 keV at ~4σ.

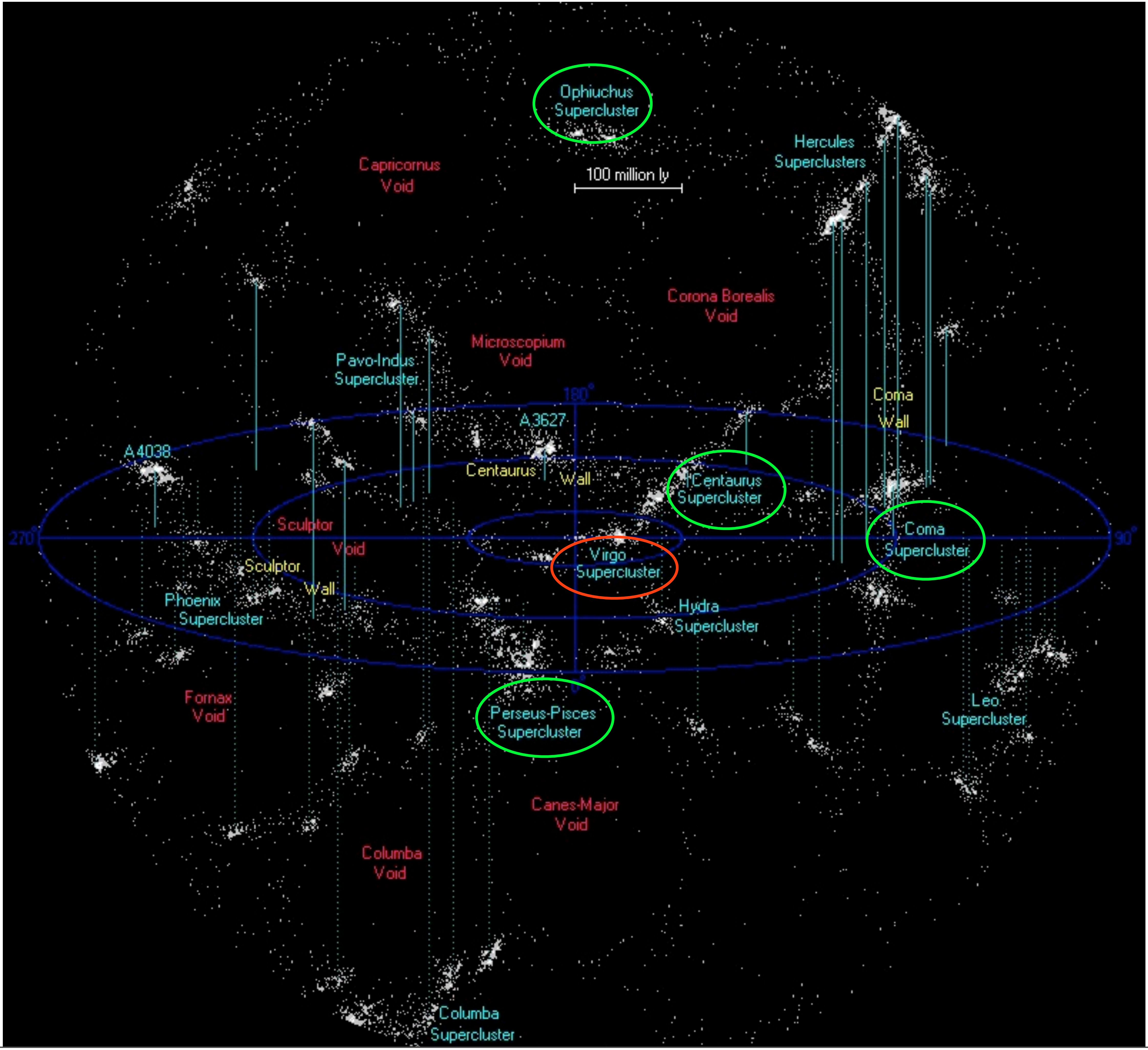




[Bulbul et al, 1402.2301]

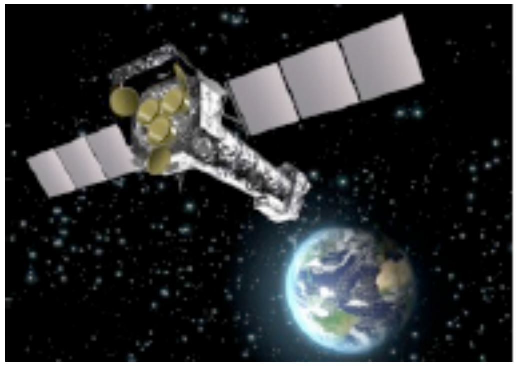


[Boyarsky et al, 1402.4119; 1408.2503 (also Milky way)]


Ophiuchus Supercluster
Hercules Superclusters
Capricornus Void
100 million ly
Corona Borealis Void
Microscopium Void
Pavo-Indus Supercluster
180°
Coma Wall
A3627
A4038
Centaurus Wall
Centaurus Supercluster
Sculptor Void
270°
90°
Coma Supercluster
Virgo Supercluster
Sculptor Wall
Phoenix Supercluster
Hydra Supercluster
0°
Fornax Void
Perseus-Pisces Supercluster
Leo Supercluster
Canes-Major Void
Columba Void
Columba Supercluster

Signal samples

- Bulbul et al **XMM-Newton**



Perseus cluster
Nearby clusters: Coma, Centaurus, Ophiuchus
All stacked 73 galaxy clusters

→ $E = 3.55 - 3.57 \pm 0.03\,\mathrm{keV}$ at $\gtrsim 3\sigma.$

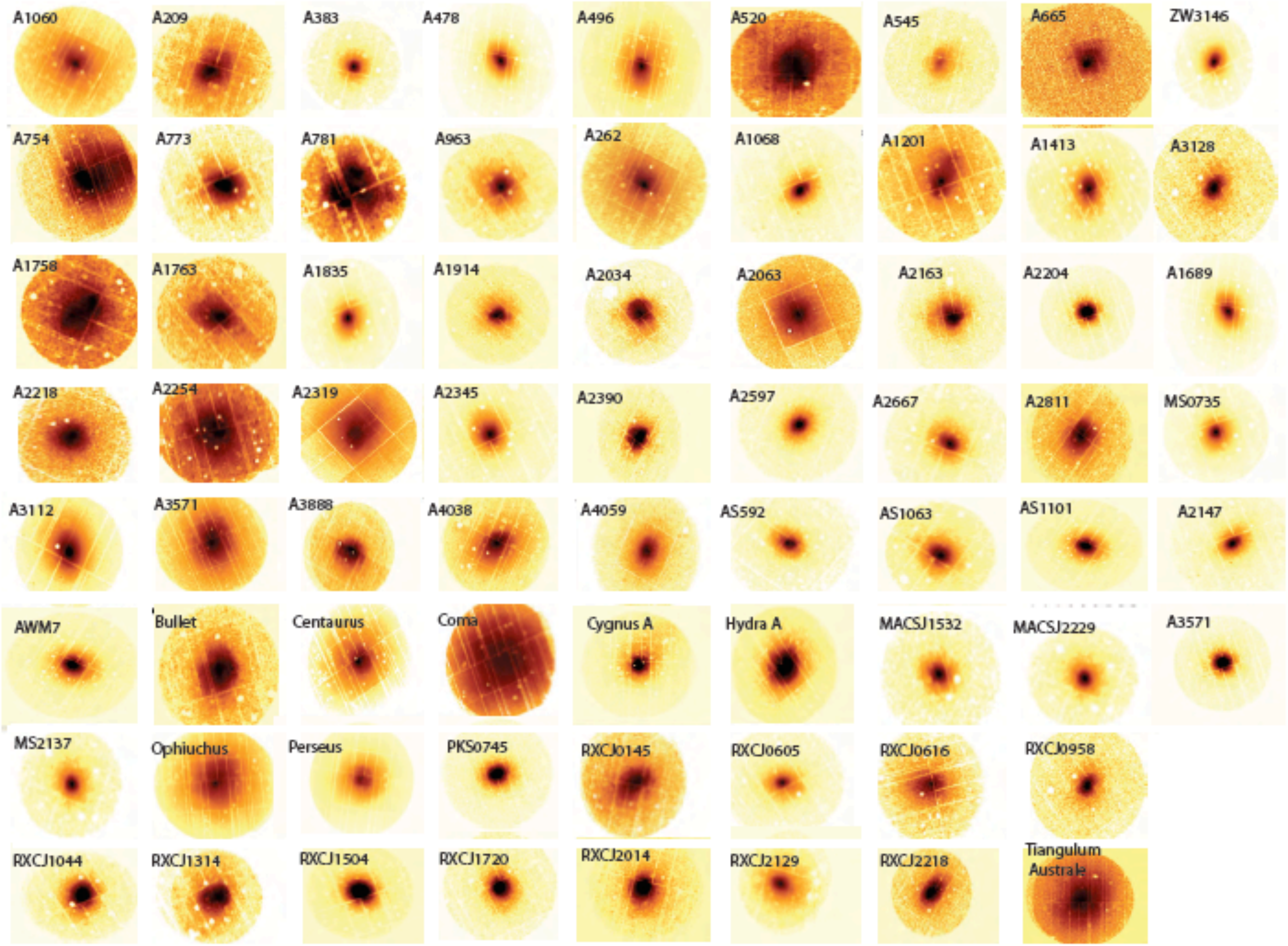
Chandra excess from Perseus,
no line from Virgo cluster.

- Boyarsky et al **XMM-Newton**

Perseus cluster
Andromeda galaxy (M31)

→ $E \sim 3.5\,\mathrm{keV}$

Sample Selection



Taken from Randall Smith’s talk (April 2014)

73 galaxy clusters for z=0.01-0.35

Sample		(1) Inst.	(2) Energy (keV)	(3) Flux (10^{-6} phts cm^{-2} s^{-1})
Full Sample	*XMM*	MOS	3.57 ± 0.02 (0.03)	$4.0^{+0.8}_{-0.8}$ $(^{+1.8}_{-1.2})$
		PN	3.51 ± 0.03 (0.05)	$3.9^{+0.6}_{-1.0}$ $(^{+1.0}_{-1.6})$
		PN	3.57^*	$2.5^{+0.6}_{-0.7}$ $(^{+1.0}_{-1.1})$
Coma + Centaurus + Ophiuchus	*XMM*	MOS	3.57^*	$15.9^{+3.4}_{-3.8}$ $(^{+6.7}_{-5.5})$
		PN	3.57^*	< 9.5
Perseus (without the core)	*XMM*	MOS	3.57^*	$21.4^{+7.0}_{-6.3}$ $(^{+11.2}_{-10.5})$
		PN	3.57^*	< 16.1
Perseus (with the core)	*XMM*	MOS	3.57^*	$52.0^{+24.1}_{-15.2}$ $(^{+37.0}_{-21.3})$
		PN	3.57^*	< 17.7
All Other Clusters	*XMM*	MOS	3.57^*	$2.1^{+0.4}_{-0.5}$ $(^{+0.8}_{-0.8})$
		PN	3.57^*	$2.0^{+0.3}_{-0.5}$ $(^{+0.5}_{-0.8})$
Perseus	*Chandra*	ACIS-S	3.56 ± 0.02 (0.03)	$10.2^{+3.7}_{-3.5}$ $(^{+4.8}_{-4.7})$
		ACIS-I	3.56^*	$18.6^{+7.8}_{-8.0}$ $(^{+12.3}_{-16.1})$
Virgo ?	*Chandra*	ACIS-I	3.56^*	< 9.1

Perseus + Andromeda

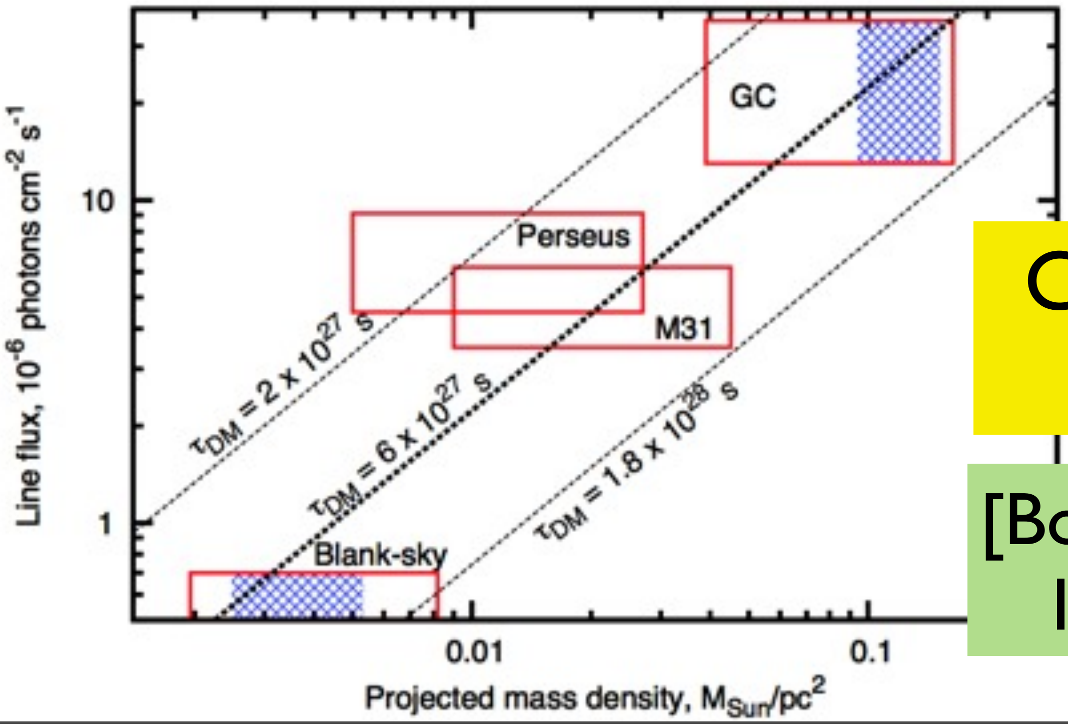
Dataset	Exposure [ksec]	χ^2/d.o.f.	Line position [keV]	Flux 10^{-6} cts/sec/cm^2	$\Delta\chi^2$
M31 ON-CENTER	978.9	97.8/74	3.53 ± 0.025	$4.9^{+1.6}_{-1.3}$	13.0
M31 OFF-CENTER	1472.8	107.8/75	3.53 ± 0.03	< 1.8 (2σ)	...
PERSEUS CLUSTER (MOS)	528.5	72.7/68	$3.50^{+0.044}_{-0.036}$	$7.0^{+2.6}_{-2.6}$	9.1
PERSEUS CLUSTER (PN)	215.5	62.6/62	3.46 ± 0.04	$9.2^{+3.1}_{-3.1}$	8.0
PERSEUS (MOS) + M31 ON-CENTER	1507.4	191.5/142	$3.518^{+0.019}_{-0.022}$	$8.6^{+2.2}_{-2.3}$ (Perseus) $4.6^{+1.4}_{-1.4}$ (M31)	25.9 (3 dof)
BLANK-SKY	15700.2	33.1/33	3.53 ± 0.03	< 0.7 (2σ)	...

$$F_{\rm DM} \approx 2.0 \times 10^{-6} \frac{\rm cts}{\rm cm^2 \cdot sec} \left(\frac{\Omega_{\rm fov}}{500\ \rm arcmin^2}\right) \times \left(\frac{\mathcal{S}_{\rm DM}}{500\ M_\odot/{\rm pc}^2}\right) \frac{10^{29}\ \rm s}{\tau_{\rm DM}} \left(\frac{\rm keV}{m_{\rm DM}}\right).$$

: DM flux

$$\mathcal{S}_{DM} = \int_{l.o.s.} \rho_{DM}(r) dr$$

: DM column density



Consistent signals!

[Boyarsky et al, 1408.2503]

15년 2월 22일 일요일

Line backgrounds

- K-shell excitation of ions leads to X-ray plasma emissions near 3.5 keV (K XVIII: 3.476 and 3.515 keV).
- Expected flux for thermal emission lines is smaller by factor 10-20.

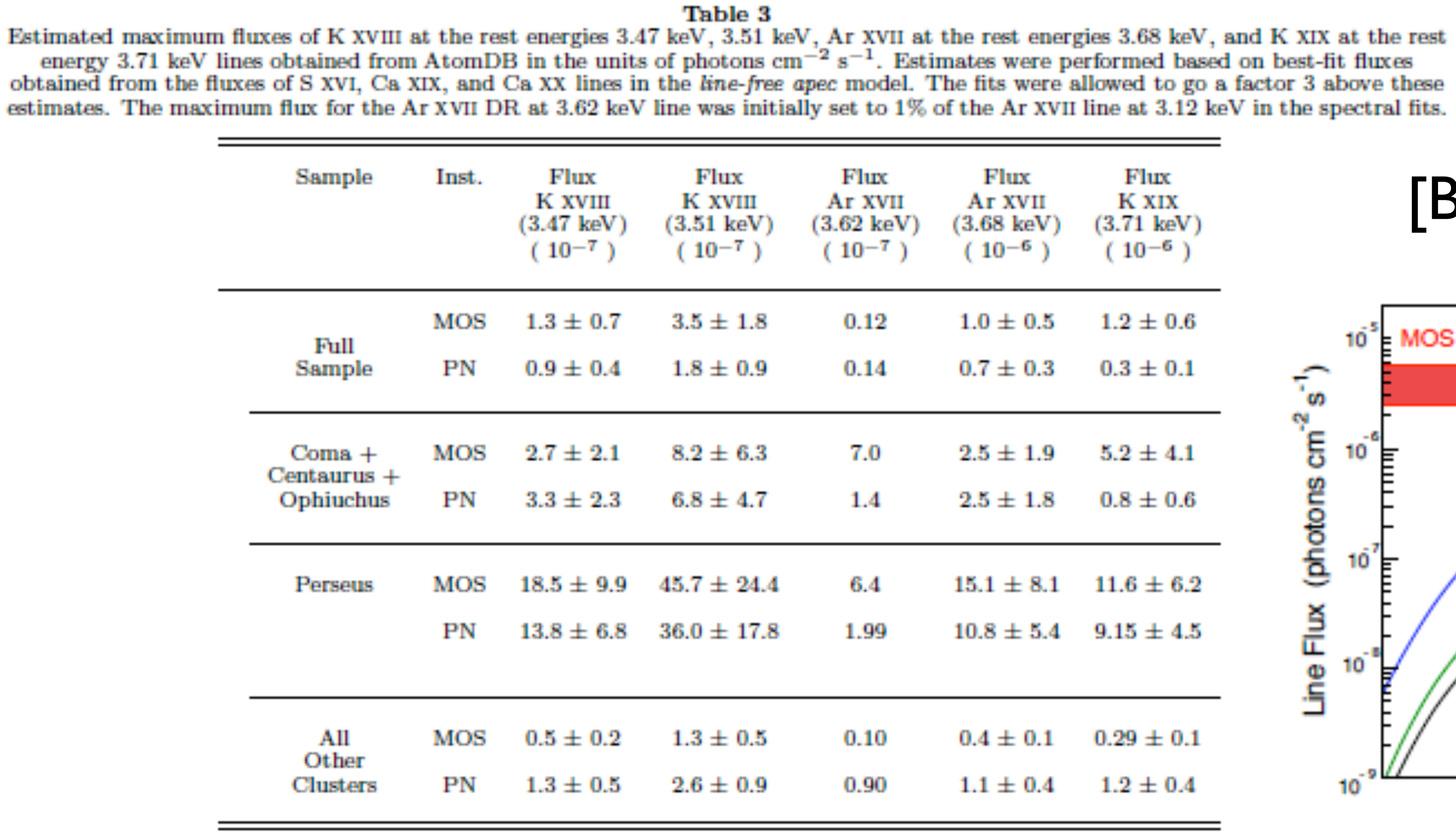
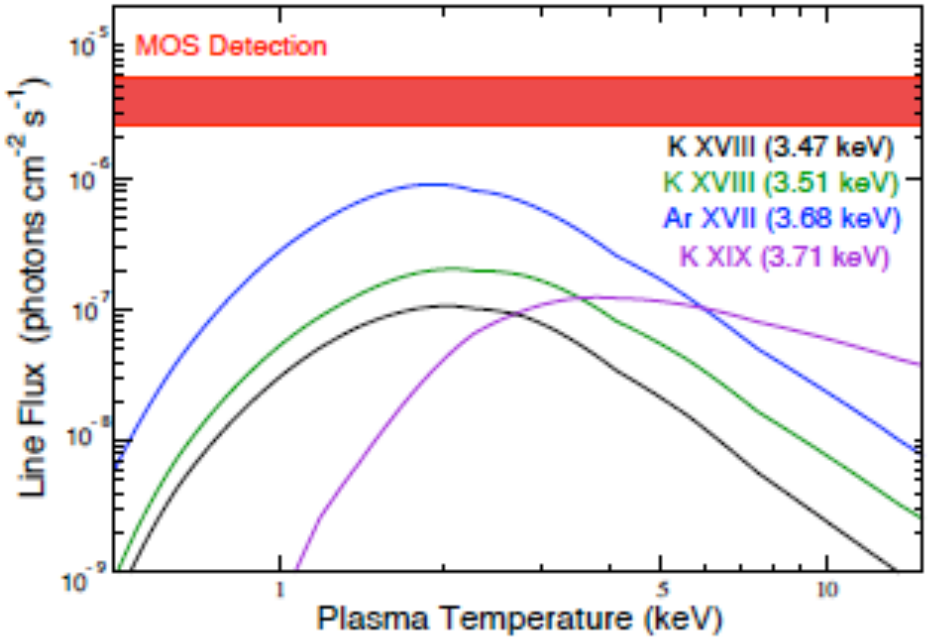


Table 3

Estimated maximum fluxes of K XVIII at the rest energies 3.47 keV, 3.51 keV, Ar XVII at the rest energies 3.68 keV, and K XIX at the rest energy 3.71 keV lines obtained from AtomDB in the units of photons cm^{-2} s^{-1}. Estimates were performed based on best-fit fluxes obtained from the fluxes of S XVI, Ca XIX, and Ca XX lines in the *line-free apec* model. The fits were allowed to go a factor 3 above these estimates. The maximum flux for the Ar XVII DR at 3.62 keV line was initially set to 1% of the Ar XVII line at 3.12 keV in the spectral fits.

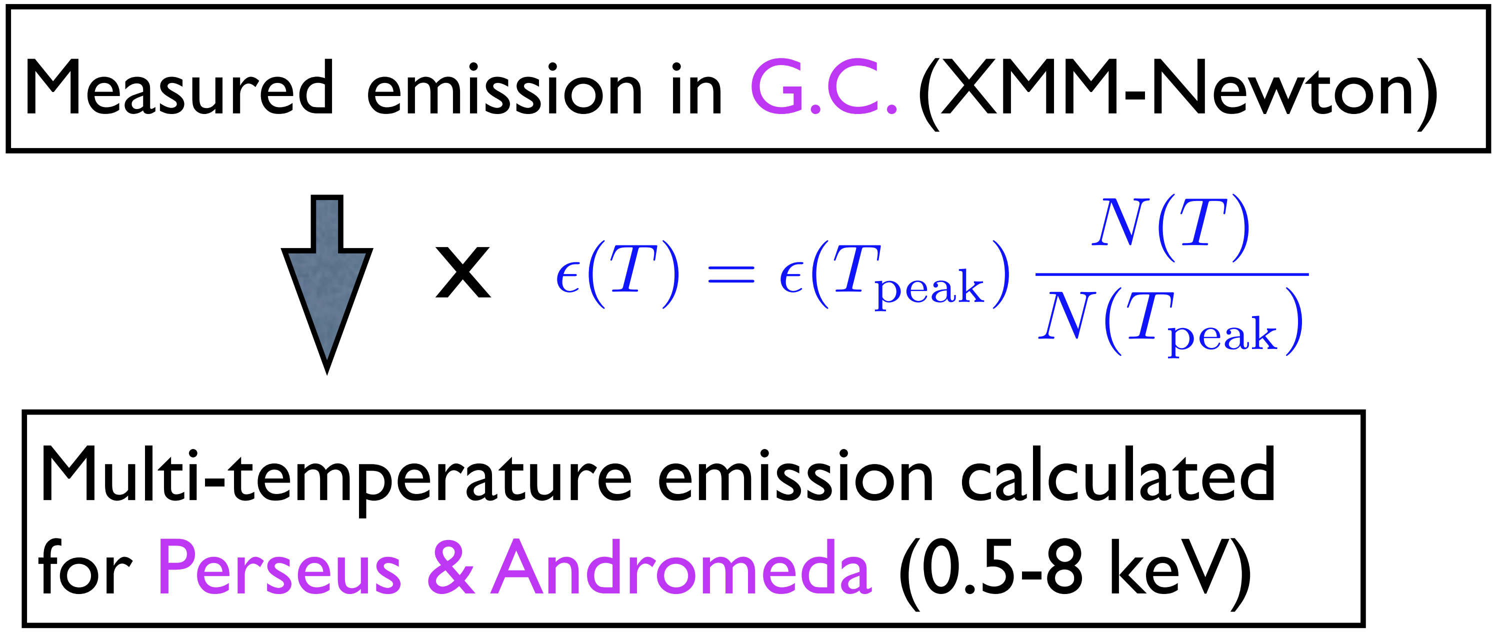
Sample	Inst.	Flux K XVIII (3.47 keV) (10^{-7})	Flux K XVIII (3.51 keV) (10^{-7})	Flux Ar XVII (3.62 keV) (10^{-7})	Flux Ar XVII (3.68 keV) (10^{-6})	Flux K XIX (3.71 keV) (10^{-6})
Full Sample	MOS	1.3 ± 0.7	3.5 ± 1.8	0.12	1.0 ± 0.5	1.2 ± 0.6
	PN	0.9 ± 0.4	1.8 ± 0.9	0.14	0.7 ± 0.3	0.3 ± 0.1
Coma + Centaurus + Ophiuchus	MOS	2.7 ± 2.1	8.2 ± 6.3	7.0	2.5 ± 1.9	5.2 ± 4.1
	PN	3.3 ± 2.3	6.8 ± 4.7	1.4	2.5 ± 1.8	0.8 ± 0.6
Perseus	MOS	18.5 ± 9.9	45.7 ± 24.4	6.4	15.1 ± 8.1	11.6 ± 6.2
	PN	13.8 ± 6.8	36.0 ± 17.8	1.99	10.8 ± 5.4	9.15 ± 4.5
All Other Clusters	MOS	0.5 ± 0.2	1.3 ± 0.5	0.10	0.4 ± 0.1	0.29 ± 0.1
	PN	1.3 ± 0.5	2.6 ± 0.9	0.90	1.1 ± 0.4	1.2 ± 0.4

[Bulbul et al, 1402.2301]



Debates on thermal emission

- Jeltima & Profumo I: Pottasium & Chlorine lines?
  [1408.1699]

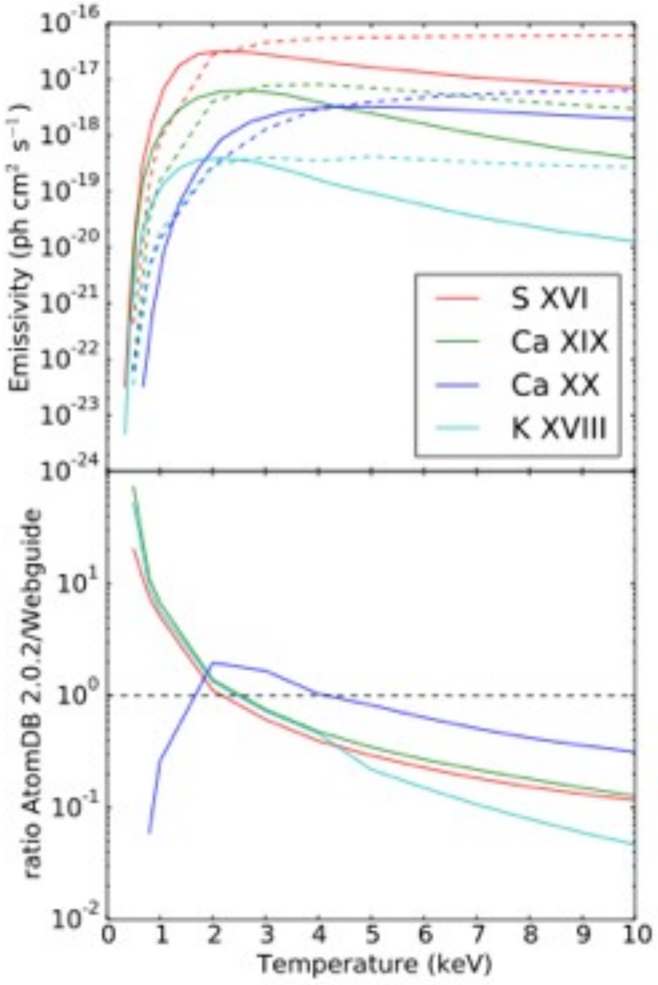


Measured emission in G.C. (XMM-Newton)

× $\epsilon(T) = \epsilon(T_{\rm peak})\,\dfrac{N(T)}{N(T_{\rm peak})}$

Multi-temperature emission calculated for Perseus & Andromeda (0.5-8 keV)

$\epsilon(T)$: emissivities $N(T)$: number of ions



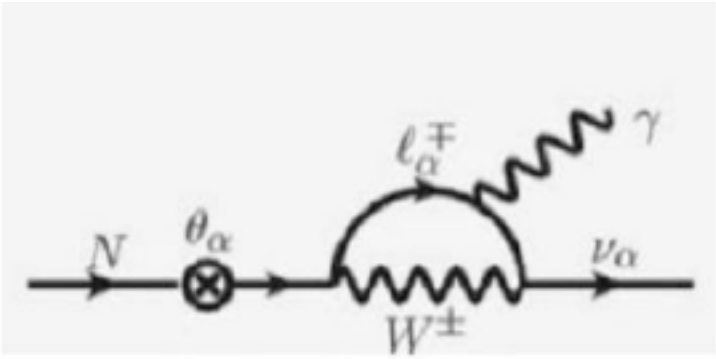
- Bulbul et al: incorrect spectral modeling away from peaks ? [1409.4143]

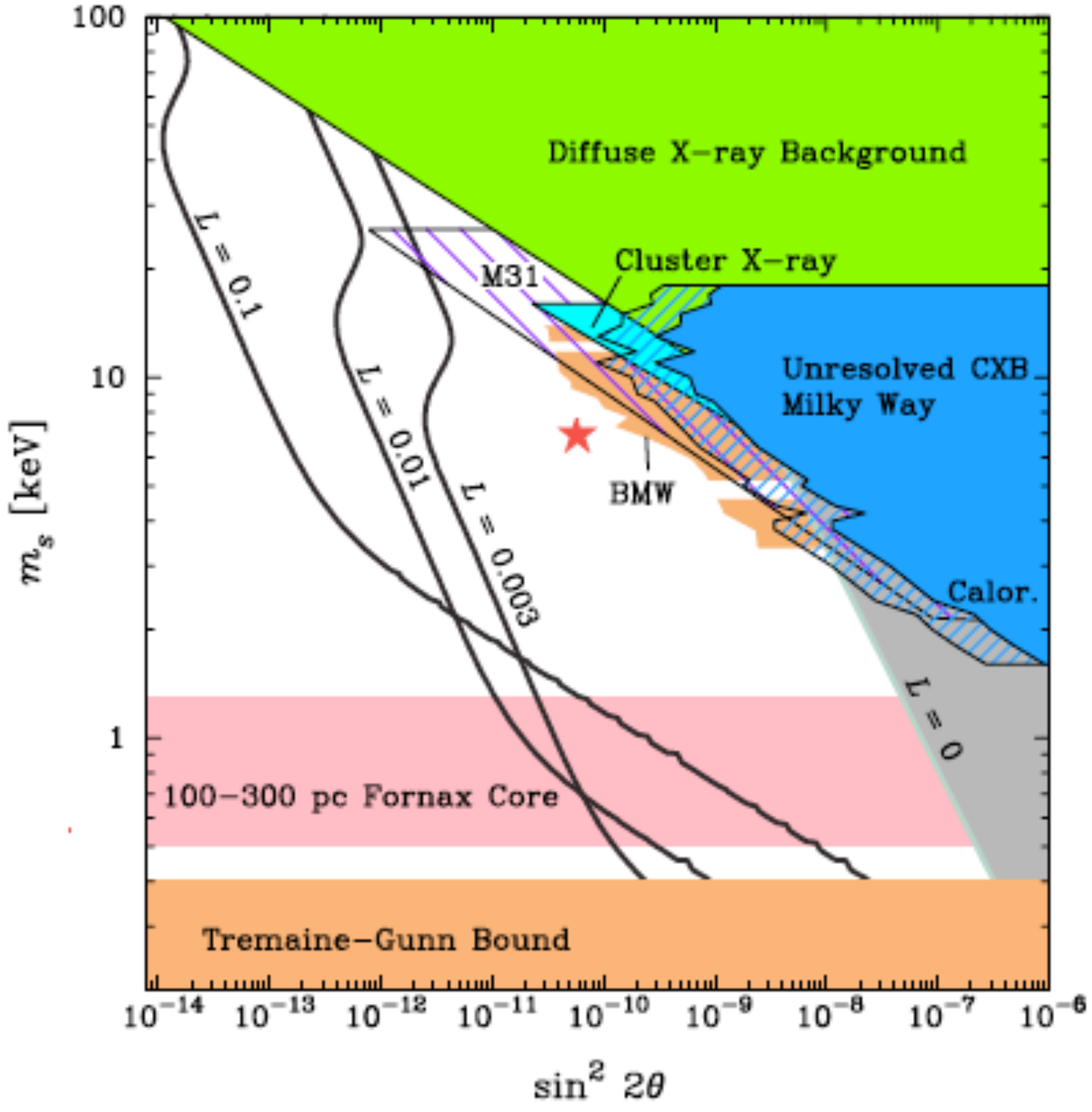
- Jeltima & Profumo II: line ratios for similar peak energies are only relevant and temperature-independent.

Sterile neutrino

- Minimal extension for neutrino masses needs three right-handed neutrinos.

$$\tau_{\rm DM} = \frac{1024\pi^4}{9\alpha G_F^2 \sin^2(2\theta) m_{\rm DM}^5} 7.2\times 10^{29}\,{\rm sec}\left[\frac{10^{-8}}{\sin^2(2\theta)}\right]\left[\frac{1\,{\rm keV}}{m_{\rm DM}}\right]^5$$





Neutrino masses:

$$m_\nu \sim \frac{\lambda_N v^2}{M_N} \sim 0.05\,{\rm eV},$$

X-ray line:

$$\theta^2 \sim \frac{\lambda_N^2 v^2}{M_N^2} \sim 10^{-11},$$

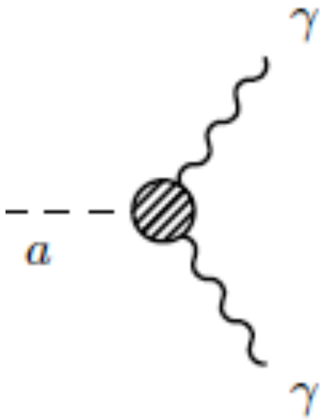
$$m_s \simeq M_N = 7.1\,{\rm keV}.$$

Flavor structure is needed for suppressing a mixing angle smaller than $\theta^2 \sim 10^{-5}$.

Axion-like scalar

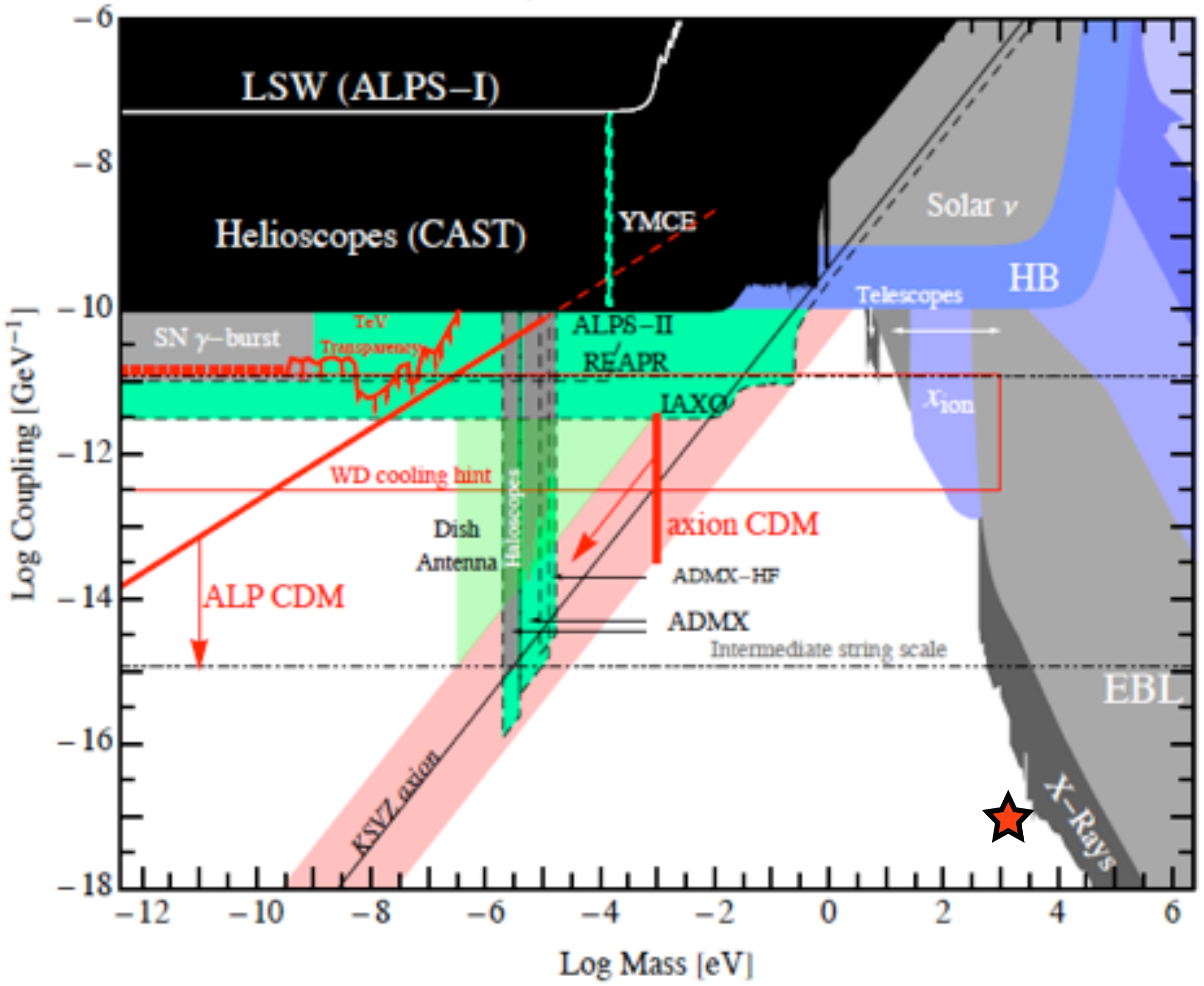
- Axion-like scalar decay:

[Higaki et al; HML, Park, Park; Jaeckel et al (2014)]



$$\Gamma(a \to \gamma\gamma) = \frac{\alpha m_a^3}{64\pi f_a^2}$$

$$\boxed{m_a = 7.1\,\mathrm{keV}, \quad f_a = 4\times 10^{14}\,\mathrm{GeV}.}$$



- Cold axion (misalignment)

$$Y_a \simeq 6.9\times 10^{-5}\left(\frac{7\,\mathrm{keV}}{m_a}\right) = \frac{1}{8}\frac{T_{\rm R}}{m_a}\theta_{\rm osc}^2\left(\frac{f_a}{M_{\rm Pl}}\right)^2$$

$$\Rightarrow \quad \boxed{T_R \lesssim 1\,\mathrm{GeV}\left(\frac{0.4}{\theta_{\rm osc}}\right)^2}$$

- Hot axion (inflaton decay)

$$Y_a \simeq 6.9\times 10^{-5}\left(\frac{7\,\mathrm{keV}}{m_a}\right) = \frac{3}{4}\frac{T_{\rm R}}{m_I}\frac{\mathrm{Br}_{I\to aa}}{\mathrm{Br}_{I\to \rm SM}}$$

Structure formation: $\frac{T_R}{m_I} \gtrsim 0.2$

$$\Rightarrow \quad \boxed{\mathrm{Br}_{I\to aa} \lesssim 4\times 10^{-4}}$$

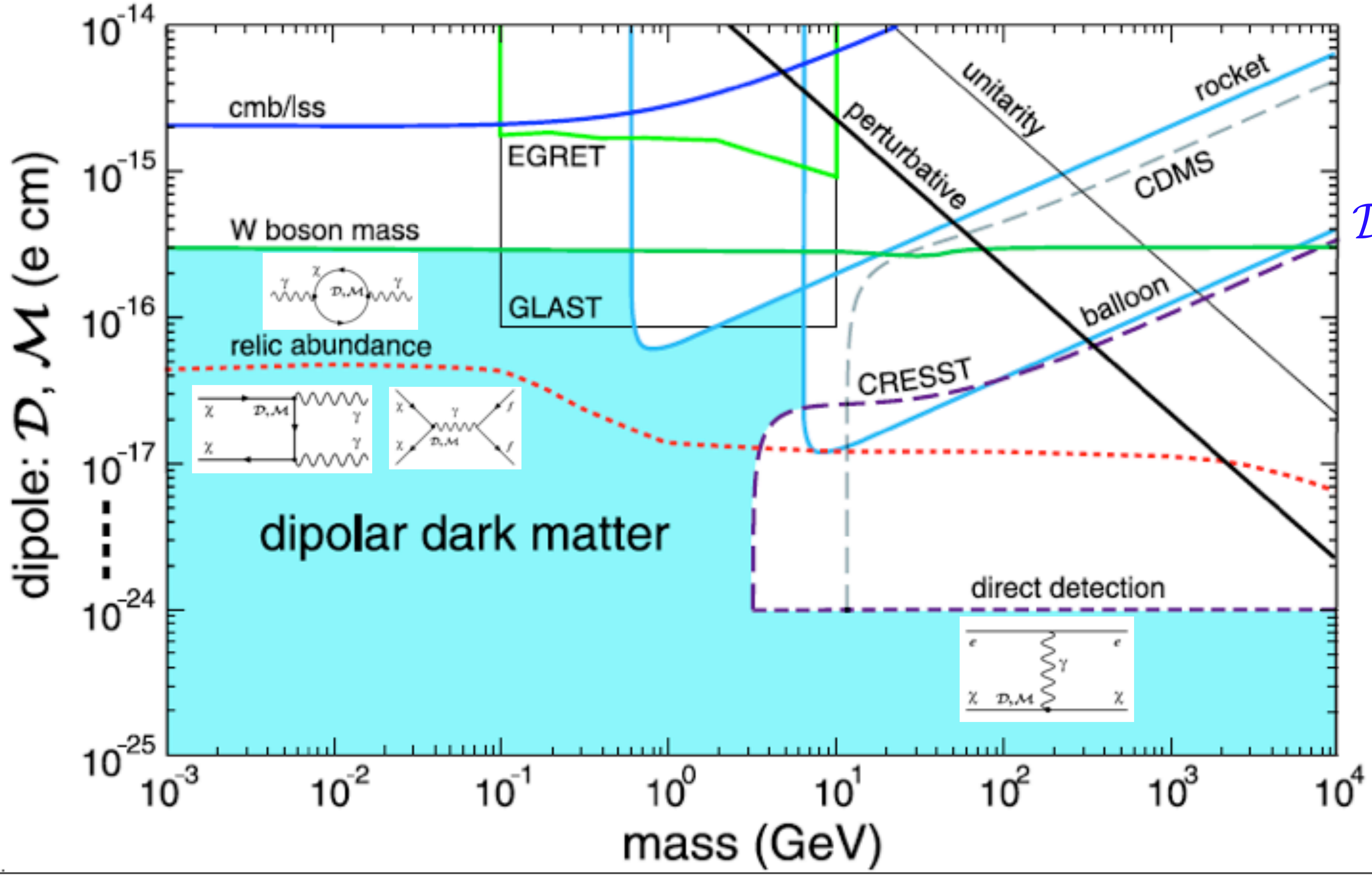
cf. CMB (isocurvature mode) $\Rightarrow$ $H_I \lesssim 4.6\times 10^{9}\,\mathrm{GeV}\left(\frac{\theta_{\rm osc}}{0.4}\right)$

Magnetic dark matter (MDM) and X-ray lines

Dipolar dark matter

- Dark matter is usually assumed neutral but it can have a small E/M dipole moment.

$$\mathcal{L}_{\gamma\chi} = -\frac{i}{2}\bar{\chi}\sigma_{\mu\nu}(\mathcal{M}+\gamma_5\mathcal{D})\chi F^{\mu\nu}, \qquad \mathcal{D} \lesssim e\, m_\chi^{-1} \simeq 2\times10^{-14}\,(m_p/m_\chi)\, e \text{ cm}$$



$$\mathcal{D} \sim \mathcal{M} \lesssim 3\times10^{-16} e\,\text{cm}$$

$$\sim 1.6\times10^{-5}\mu_B.$$

[Sigurdson et al, astro-ph/0406355]

X-ray line from MDM

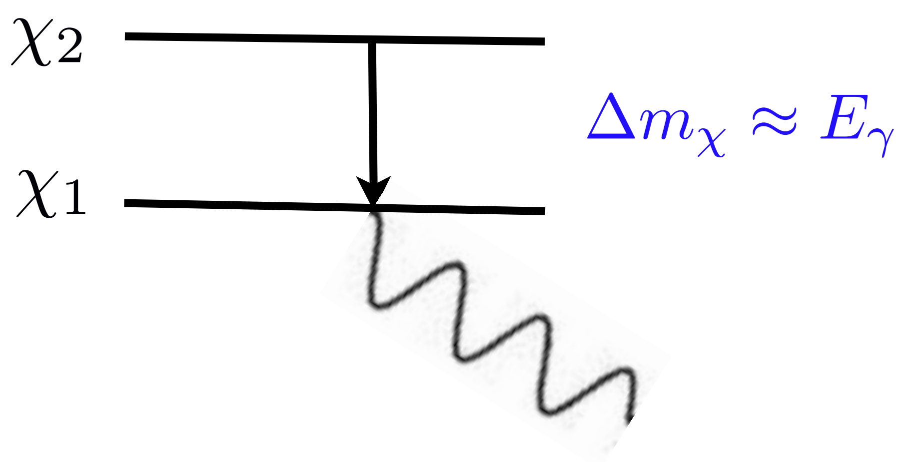
- Majorana fermion mdm vanishes. We consider a magnetic transition moment of Majorana fermion dark matter to another.

e.g. sterile-active neutrino transition, inelastic dark matter

$$\mathcal{L} = \frac{m_{\chi_2}}{\Lambda^2}\,\bar{\chi}_2 i\sigma^{\mu\nu}\chi_1 F_{\mu\nu}$$

$$\Rightarrow\quad \Gamma(\chi_2 \to \chi_1 + \gamma) = \frac{4m_{\chi_2}^2}{\pi\Lambda^4}E_\gamma^3\,, \qquad E_\gamma = \frac{1}{2}m_{\chi_2}\left(1 - \frac{m_{\chi_1}^2}{m_{\chi_2}^2}\right)$$

X-ray line @ $E_\gamma = 3.55\,\mathrm{keV}$



$$\Gamma_{\chi_2} = (0.36 - 3.3)\times 10^{-52}\,\mathrm{GeV}\left(\frac{m_{\chi_2}}{7.1\,\mathrm{keV}}\right)$$

or $$\tau_{\chi_2} = (0.20 - 1.8)\times 10^{28}\,\mathrm{s}\left(\frac{7.1\,\mathrm{keV}}{m_{\chi_2}}\right)$$

$$\Rightarrow\quad m_{\chi_2} \simeq 10\,\mathrm{GeV}:\quad \Lambda = (5.0 - 8.7)\times 10^7\,\mathrm{GeV}.$$

$$\mathcal{D} \sim 10^{-28}\,e\ \mathrm{cm}$$

Fermion-portal model

Two singlet Majorana fermions, distinguished by Z_2, have different Yukawa couplings to SM RH fermion and charged scalar.

SM RH fermion | Singlet fermions | Charged scalar | Singlet scalar

	ψ_R	χ_{1L}	χ_{2L}	ϕ	S
$U(1)_Y$	q_{ψ_R}	0	0	q_{ψ_R}	0
$U(1)_X$	0	$+1$	-1	$+1$	-2
Z_2	$+$	$+$	$-$	$-$	$+$

$$-\mathcal{L}_{\rm DM} = (\boxed{\lambda\bar{\psi}P_L\chi_2\phi} + m_\psi\bar{\psi}_R\psi_L + \text{c.c.}) + m_\phi^2|\phi|^2$$

$$+ \frac{1}{2}y_1 S\bar{\chi}_1 P_L\chi_1 + \frac{1}{2}y_2 S^*\bar{\chi}_2 P_L\chi_2 + \boxed{\frac{\kappa}{\Lambda_{UV}} S\bar{\psi}P_L\chi_1\phi} + \text{c.c.}$$

Explicit breaking of Z_2

$$\langle S\rangle \neq 0 \longrightarrow \frac{1}{2}m_{\chi_1}\overline{\chi_1}\chi_1 + \frac{1}{2}m_{\chi_2}\overline{\chi_2}\chi_2 + \boxed{\epsilon\bar{\psi}P_L\chi_1\phi}, \quad \epsilon = \frac{\kappa\langle S\rangle}{\Lambda_{UV}} \ll 1.$$

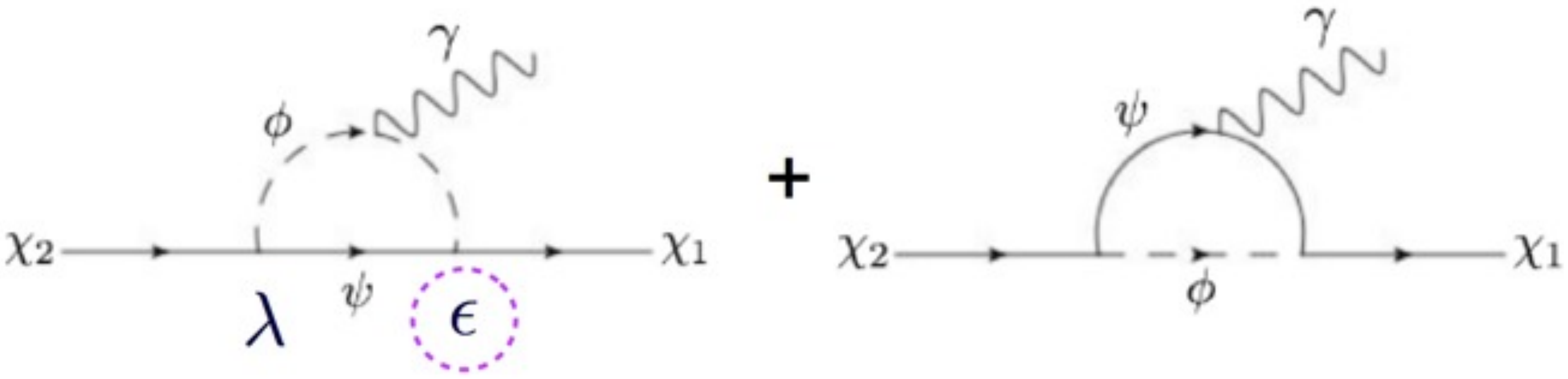
$U(1)_X$ SSB

Similar Yukawa couplings → Almost degenerate masses

$y_1 \approx y_2$ → $m_{\chi_1} \approx m_{\chi_2}$

MDM + Thermal DM

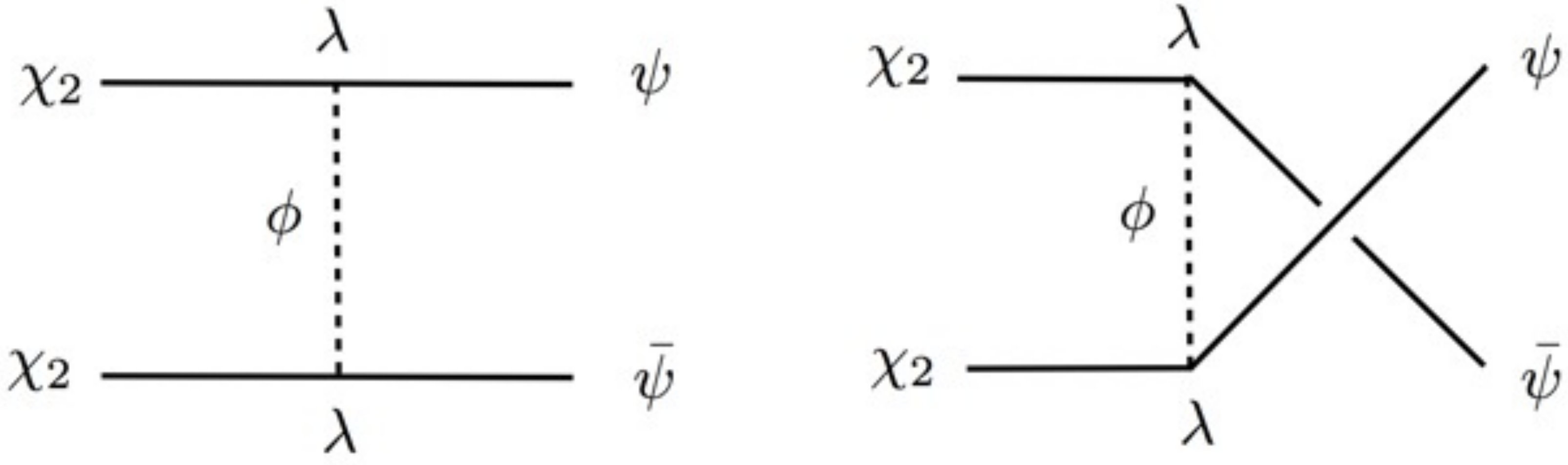
- The same fermion-portal coupling and charged scalar are responsible for DM transition and annihilation.



$$\Lambda_{UV} = \sqrt{\frac{64\pi^2}{e|q_\phi|}}\,\frac{m_\phi}{\sqrt{|\mathrm{Im}(\epsilon^*\lambda)|}}$$

+ fermion lines flipped

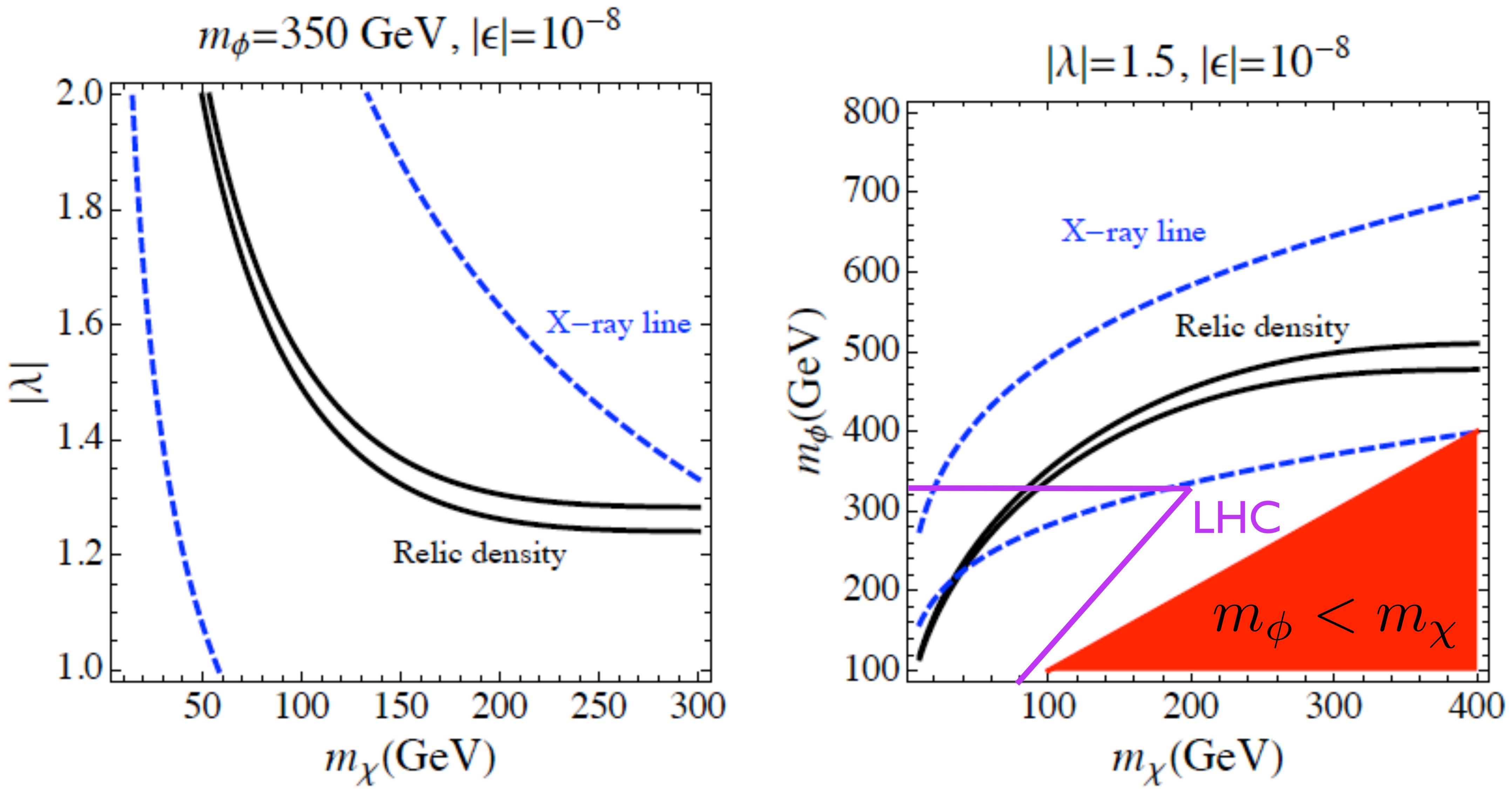
→ $\lambda = \mathcal{O}(1), \quad \epsilon = \dfrac{\alpha\langle S\rangle}{\Lambda_{UV}} \sim 10^{-9} - 10^{-7}$



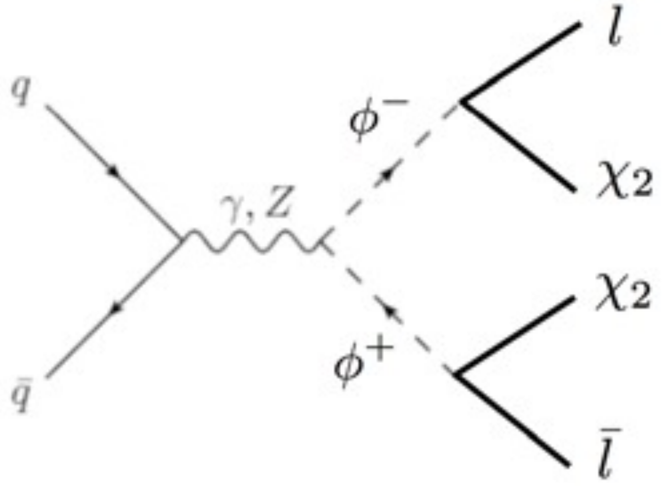
p-wave, but relevant at freeze-out.

$$\langle\sigma v\rangle = \frac{|\lambda|^4}{16\pi}\,\frac{m_{\chi_2}^2(m_{\chi_2}^4 + m_\phi^4)}{(m_{\chi_2}^2 + m_\phi^2)^4}\cdot\frac{T}{m_{\chi_2}}.$$

Relic density+X-ray line+LHC



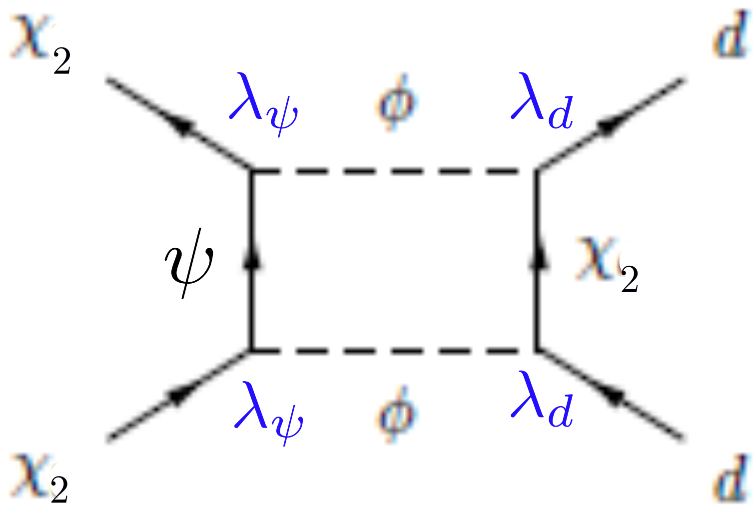
- A wide parameter space exists.
- Slepton-like charged scalar masses below 325 GeV excluded by LHC.



Bounds on DM

- For baryophilic dark matter, the WIMP-nucleon spin-independent cross section can be constrained by LUX.

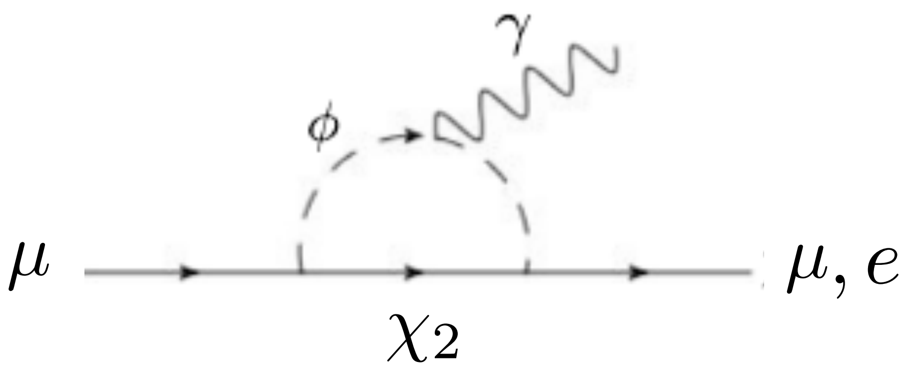
[Batell et al (2014); Nelson et al (2014)]



$$\mathcal{L}_{\rm box} \sim \frac{\lambda_d^2 \lambda_\psi^2 m_\chi m_d}{32\pi^2 m_\phi^2 (m_\chi^2 - m_\psi^2)} \bar\chi\chi\bar d d.$$

$$\boxed{\begin{array}{l} \lambda_\psi = 1.5,\ m_\phi = 400\,{\rm GeV}, m_\chi = 200\,{\rm GeV} \\ \Rightarrow \quad \lambda_d \lesssim 4.4 \end{array}}$$

- Leptophilic dark matter is bounded by muon g-2 and lepton flavor violation.



$|\Delta a_\mu| < 3.45 \times 10^{-12}$ (BNL821)

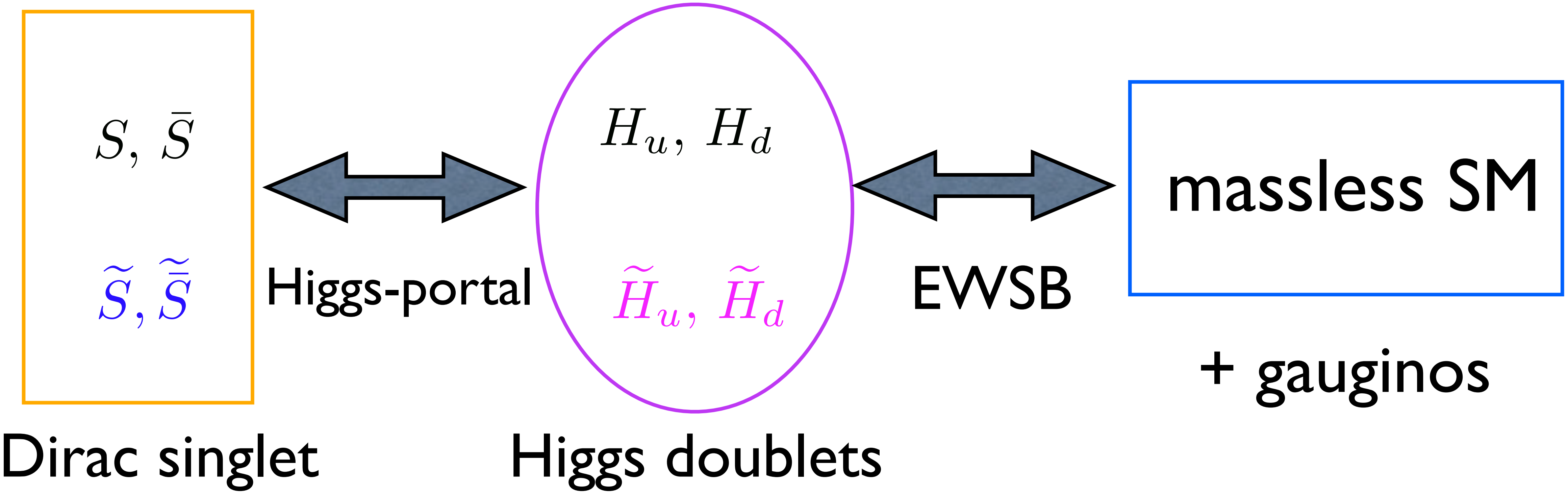
$\Rightarrow \quad |\lambda_\mu| < 0.27(m_\phi/500\,{\rm GeV}).$

${\rm BR}(\mu \to e\gamma) < 5.7 \times 10^{-13}$ (MEG)

$\Rightarrow \quad |\lambda_e| < 0.03(m_\phi/500\,{\rm GeV}).$

Dark matter in SUSY
Higgs-portal

SUSY Higgs-portal



$S,\ \bar{S}$

$\widetilde{S}, \widetilde{\bar{S}}$

Dirac singlet

Higgs-portal

$H_u,\ H_d$

$\widetilde{H}_u,\ \widetilde{H}_d$

Higgs doublets

EWSB

massless SM

+ gauginos

- SUSY and chiral (PQ) symmetry leads to light Higgsino & singlet fermions, which interact with each other by SUSY Higgs-portal.
- R symmetry can make gauginos light too, while scalar superpartners are decoupled.

→ “Split” SUSY with extra singlets

Dirac singlino

- Superpotential with approximate PQ:

$$W = \boxed{\lambda_S S H_u H_d + \lambda_{\bar{S}} \bar{S} H_u H_d}$$

PQ symmetric

$$\boxed{+\mu_H H_u H_d + M_S \bar{S} S} + \frac{1}{2} M_1 S^2 + \frac{1}{2} M_2 \bar{S}^2$$

PQ violating $\quad \text{e.g.}\, W \supset \frac{1}{M_P} P^2 H_u H_d + \frac{1}{M_P} Q^2 \bar{S} S + \cdots$

- We assume a singlet flavor symmetry (e.g. U(2)) that singlino gets Dirac mass only.

$$M_1 = M_2 = 0, \qquad \text{small} \quad \lambda_S,\, \lambda_{\bar{S}}$$

⇒ Dirac singlino gets a small mass splitting only after EWSB.

Singlino mass splitting

- Neutralino mass matrix for $(\widetilde{B}, \widetilde{W}^0, \widetilde{H}_d^0, \widetilde{H}_u^0, \widetilde{S}, \widetilde{\bar{S}})$

$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -\frac{1}{2}g'v_d & \frac{1}{2}g'v_u & 0 & 0 \\ 0 & M_2 & \frac{1}{2}gv_d & -\frac{1}{2}gv_u & 0 & 0 \\ -\frac{1}{2}g'v_d & \frac{1}{2}gv_d & 0 & -\mu_{\rm eff} & -\frac{1}{\sqrt{2}}\lambda_S v_u & -\frac{1}{\sqrt{2}}\lambda_{\bar{S}} v_u \\ \frac{1}{2}g'v_u & -\frac{1}{2}gv_u & -\mu_{\rm eff} & 0 & -\frac{1}{\sqrt{2}}\lambda_S v_d & -\frac{1}{\sqrt{2}}\lambda_{\bar{S}} v_d \\ 0 & 0 & -\frac{1}{\sqrt{2}}\lambda_S v_u & -\frac{1}{\sqrt{2}}\lambda_S v_d & 0 & M_S \\ 0 & 0 & -\frac{1}{\sqrt{2}}\lambda_{\bar{S}} v_u & -\frac{1}{\sqrt{2}}\lambda_{\bar{S}} v_d & M_S & 0 \end{pmatrix}$$

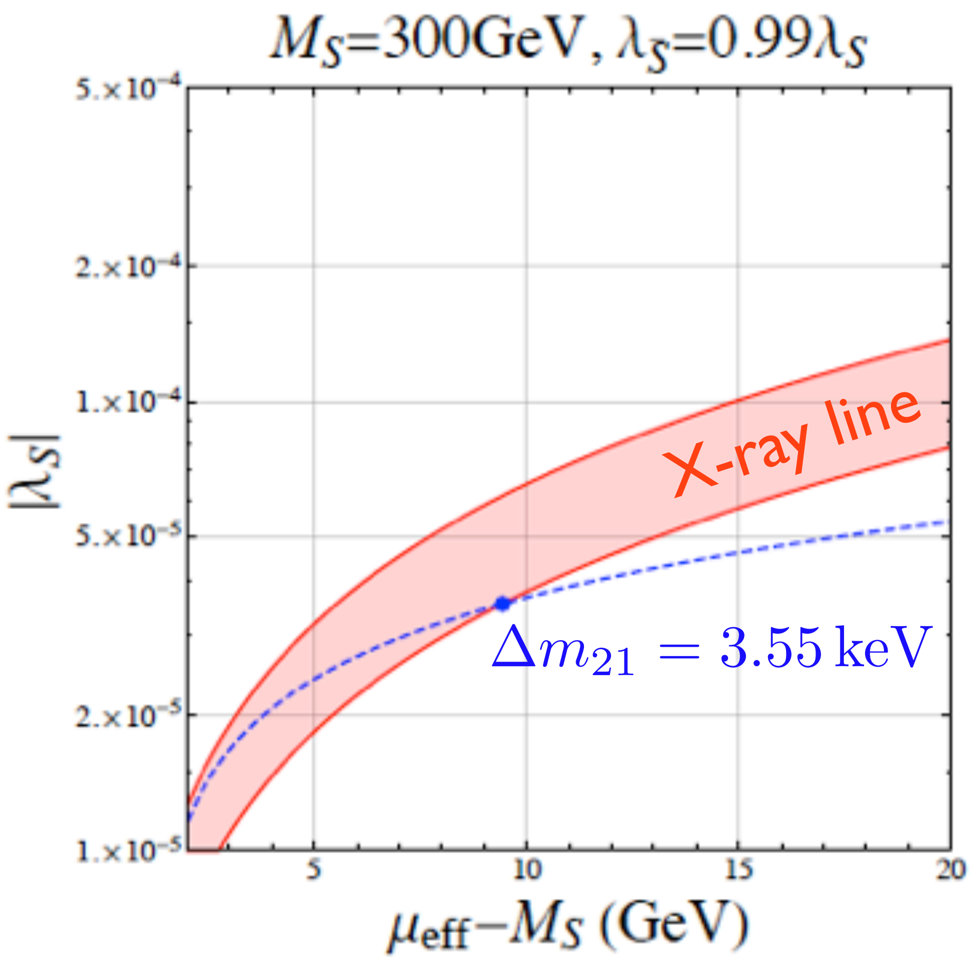
- Singlino mass splitting: $M_{1,2} \gg \mu_{\rm eff}, M_S, \quad \lambda_S, \lambda_{\bar{S}} \ll 1$

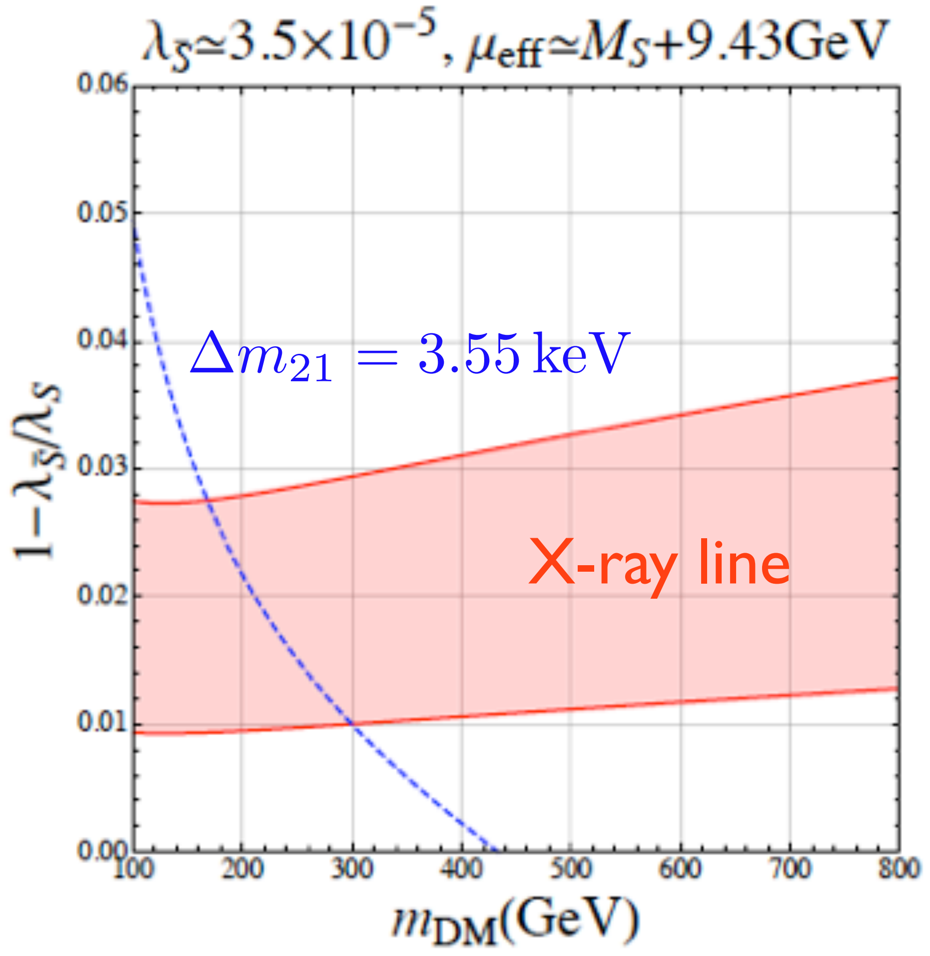
$$\Delta m_{34} \equiv m_{\tilde{\chi}_3^0} - m_{\tilde{\chi}_4^0} \approx \frac{1}{2}\frac{v^2}{\mu_{\rm eff}^2 - M_S^2}\Big((\lambda_+^2 - \lambda_-^2)M_S - (\lambda_+^2 + \lambda_-^2)\mu_{\rm eff}\sin(2\beta)\Big) + \frac{1}{8}(\lambda_+^2 + \lambda_-^2)\frac{v^4\cos^2(2\beta)\mu_{\rm eff}^2}{(\mu_{\rm eff}^2 - M_S^2)^2}\left(\frac{g'^2}{M_1} + \frac{g^2}{M_2}\right),$$

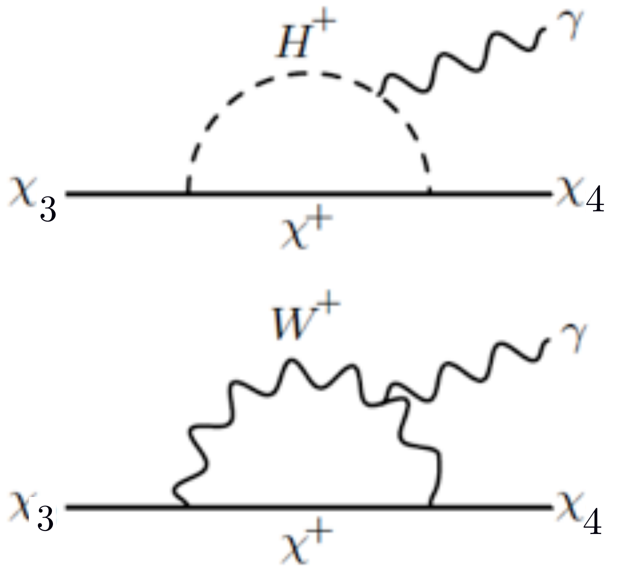
"keV-scale" mass splitting for weak-scale $\mu_{\rm eff} > M_S$.

⇒ $\boxed{\lambda_S, \lambda_{\bar{S}} \sim 10^{-5}, \qquad M_{1,2} \gtrsim 1\,\text{TeV}.}$

X-ray line from singlinos







$$m_{H^\pm} = 1\,\mathrm{TeV},\ M_1 = 0.5 M_2 = 3\,\mathrm{TeV}\ \text{and}\ \tan\beta = 10.$$

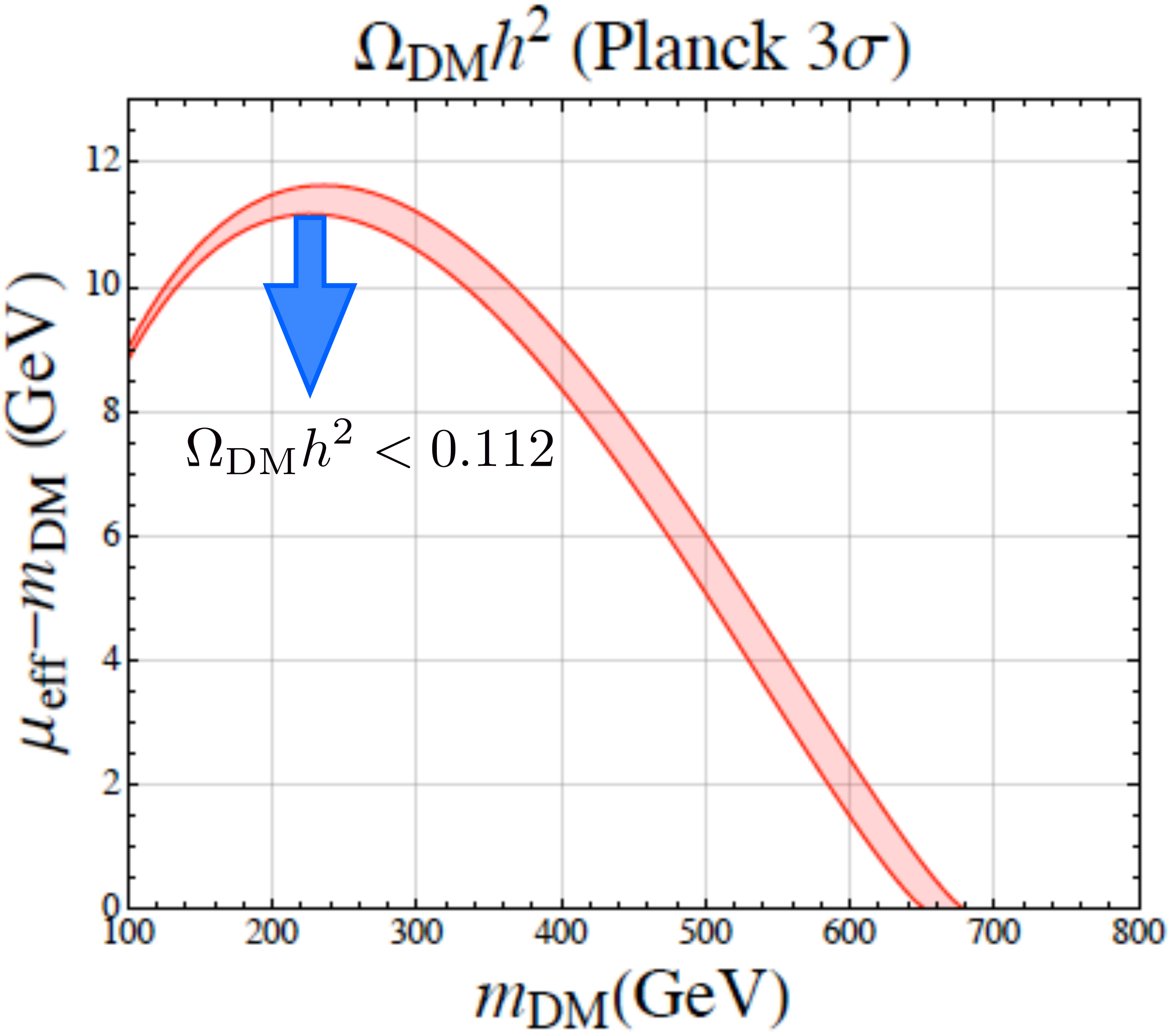
- "Charged Higgs, W-boson"-chargino loops induce magnetic transition moment for singlinos.
- X-ray line requires $\boxed{\lambda_{\bar{S}}/\lambda_S \simeq 0.97 - 0.99\ \text{ for }\ \lambda_S \gtrsim 10^{-5}.}$

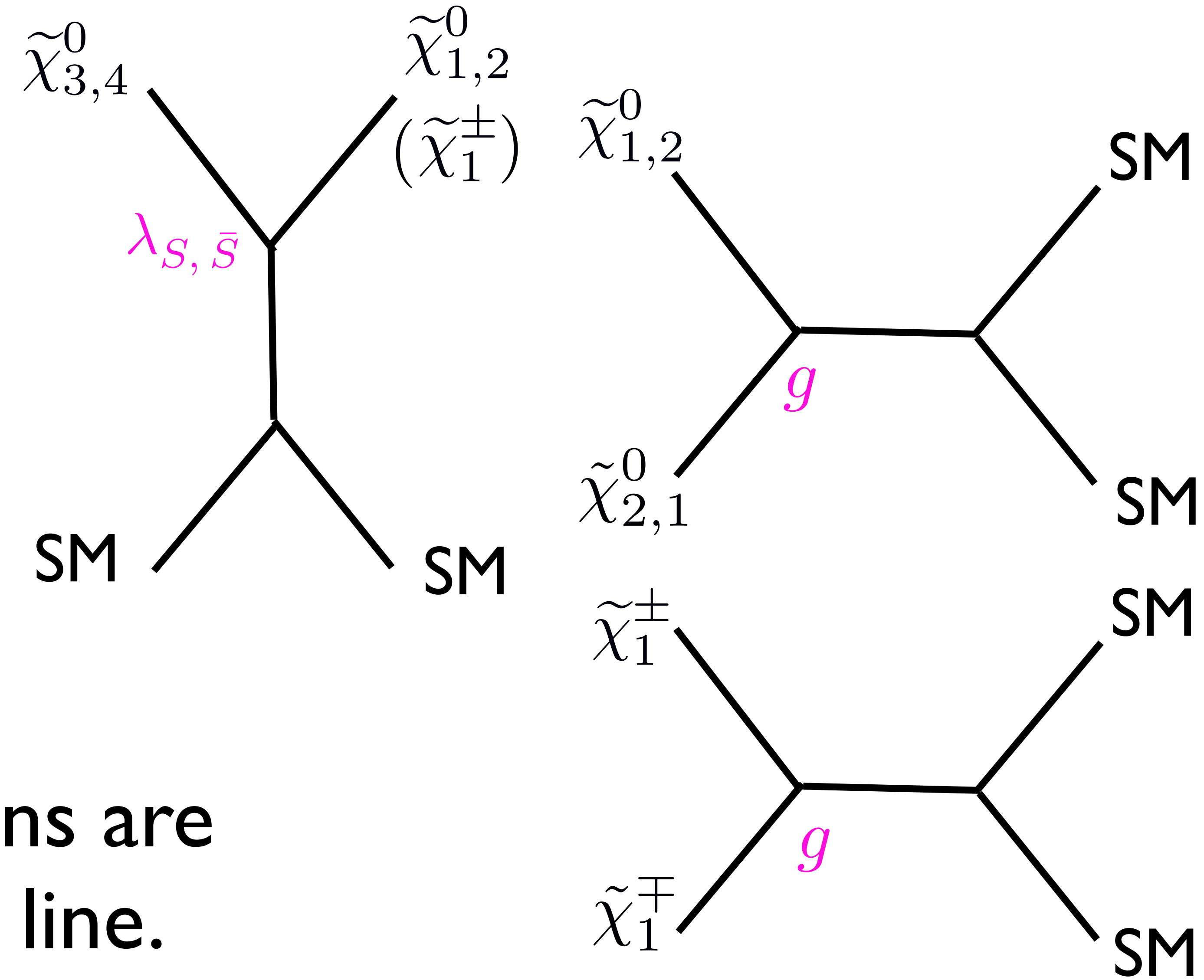
DM relic density

- Singlino DM keeps in thermal equilibrium until freeze-out, due to kinetic scattering with the SM.

$$\frac{\Gamma_{\rm kin}}{\Gamma_{\rm th}} \sim \frac{n_{SM}\langle\sigma v\rangle_{\rm kin}}{n_{DM}\langle\sigma v\rangle_{\rm th}} \sim |\lambda_{S,\bar{S}}|^2 \cdot 10^{10} \gtrsim 1.$$

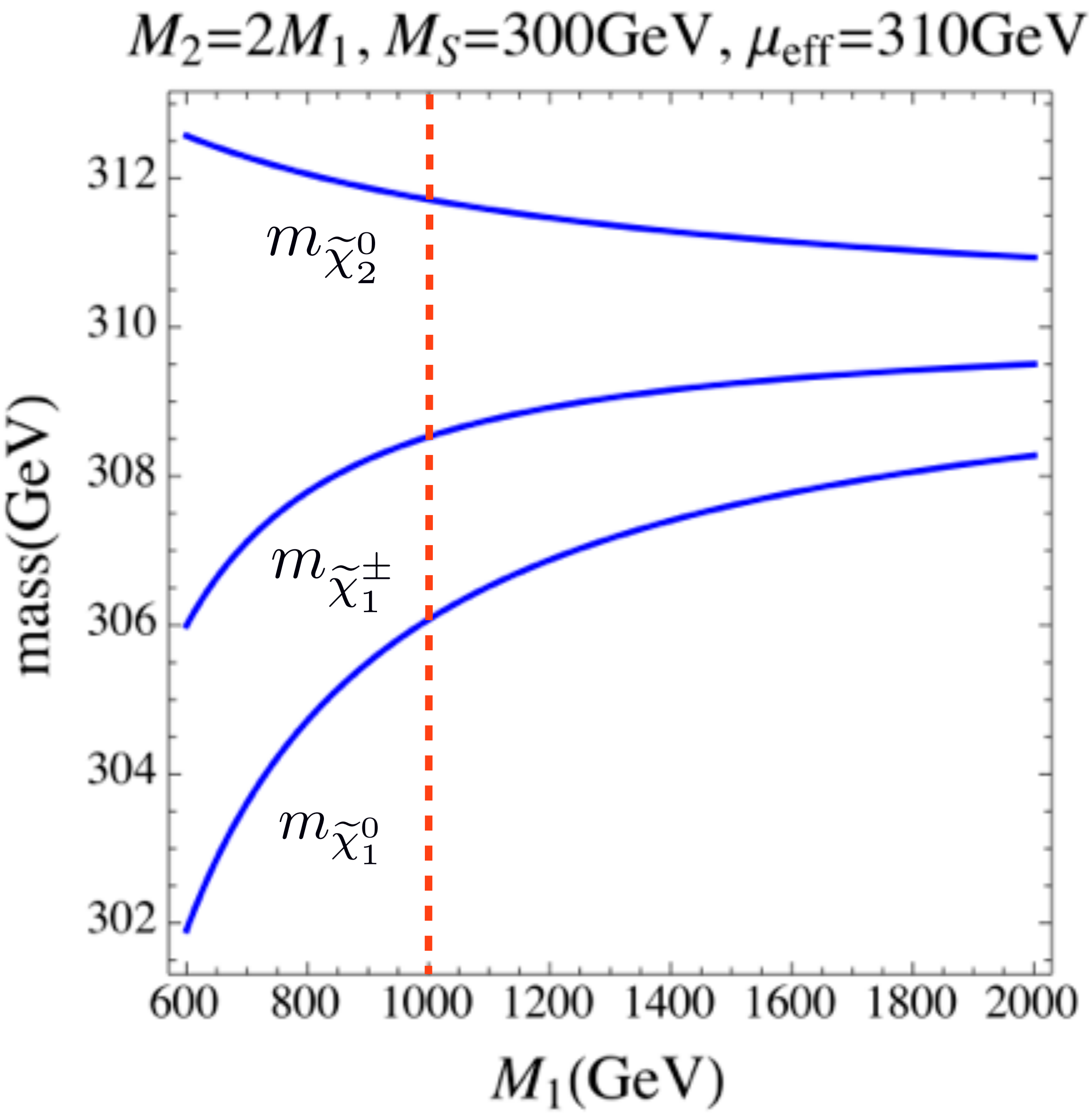
⇒ $|\lambda_{S,\bar{S}}| \gtrsim 10^{-5}.$



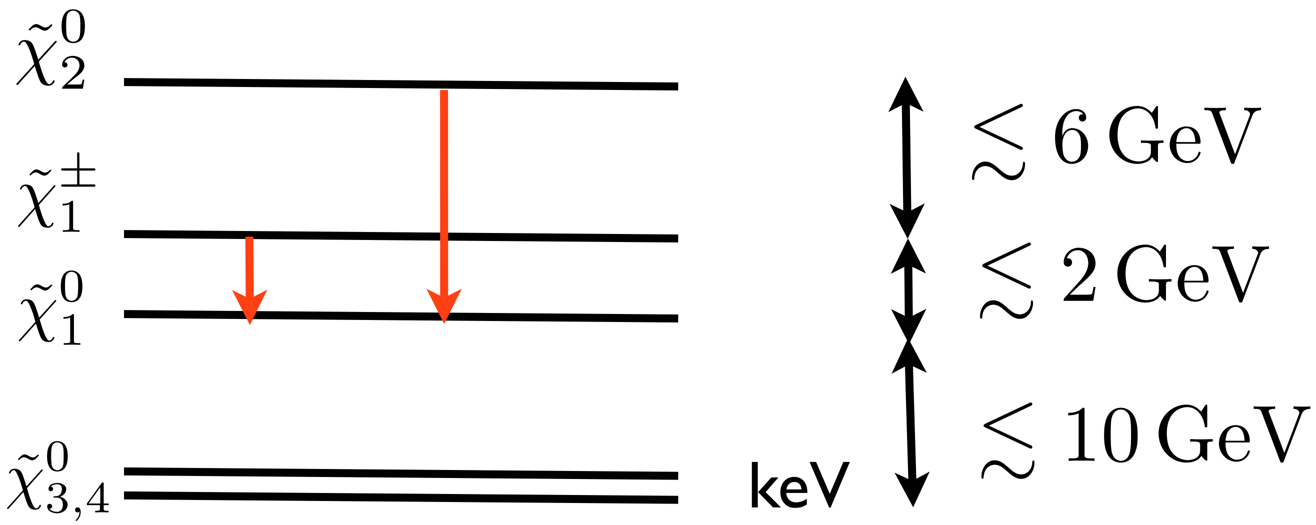


- The relic density conditions are consistent with the X-ray line.

Degenerate Higgsinos at LHC



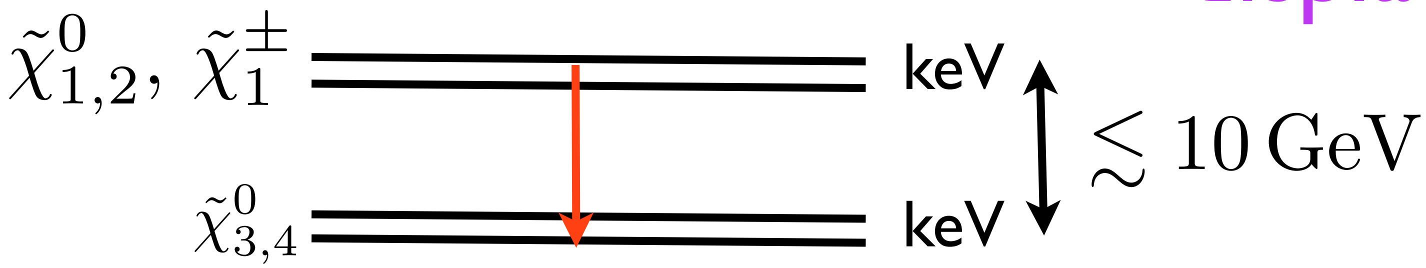
For gauginos > TeV,



3-body cascade decays (mostly prompt)

$$\tilde\chi_2^0 \to \tilde\chi_1^0 Z^*(h^*),\ \tilde\chi_1^\pm \to \tilde\chi_1^0 W^*.$$

For decoupled gauginos,



Higgsinos decay to singlinos: "displaced" vertices + MET.

$$\tilde\chi_{1,2}^0 \to \tilde\chi_{3,4}^0 Z^*(h^*),$$
$$\tilde\chi_1^\pm \to \tilde\chi_{3,4}^0 W^*.$$

Conclusions

- Dipolar dark matter can explain the X-ray line and is thermally produced due to an accompanied charged particle.
- Fermion-portal coupling of order one and charged scalar can be constrained by g-2, LFV, LHC and direct detection.
- In SUSY Higgs-portal model, Dirac singlino with a naturally small mass splitting can explain the X-ray line. But, almost degenerate Higgsinos/ singlinos would be challenging for the LHC Run II searches.

Dream Improvisation
by Wassily Kandinsky

Dark sector might be dynamic like our world!