# Pico-charged intermediate particles rescue dark matter interpretation of 511 keV line

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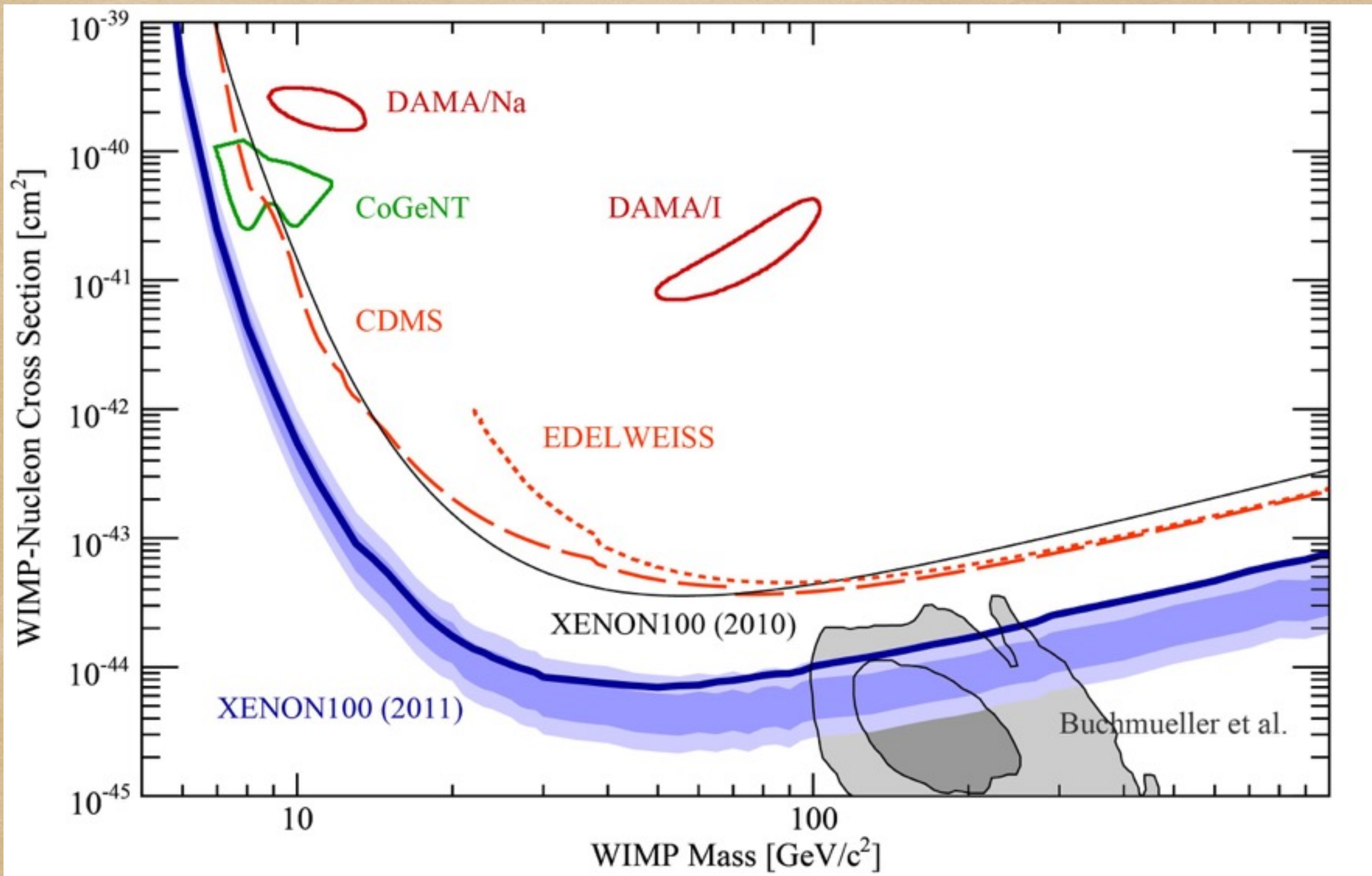
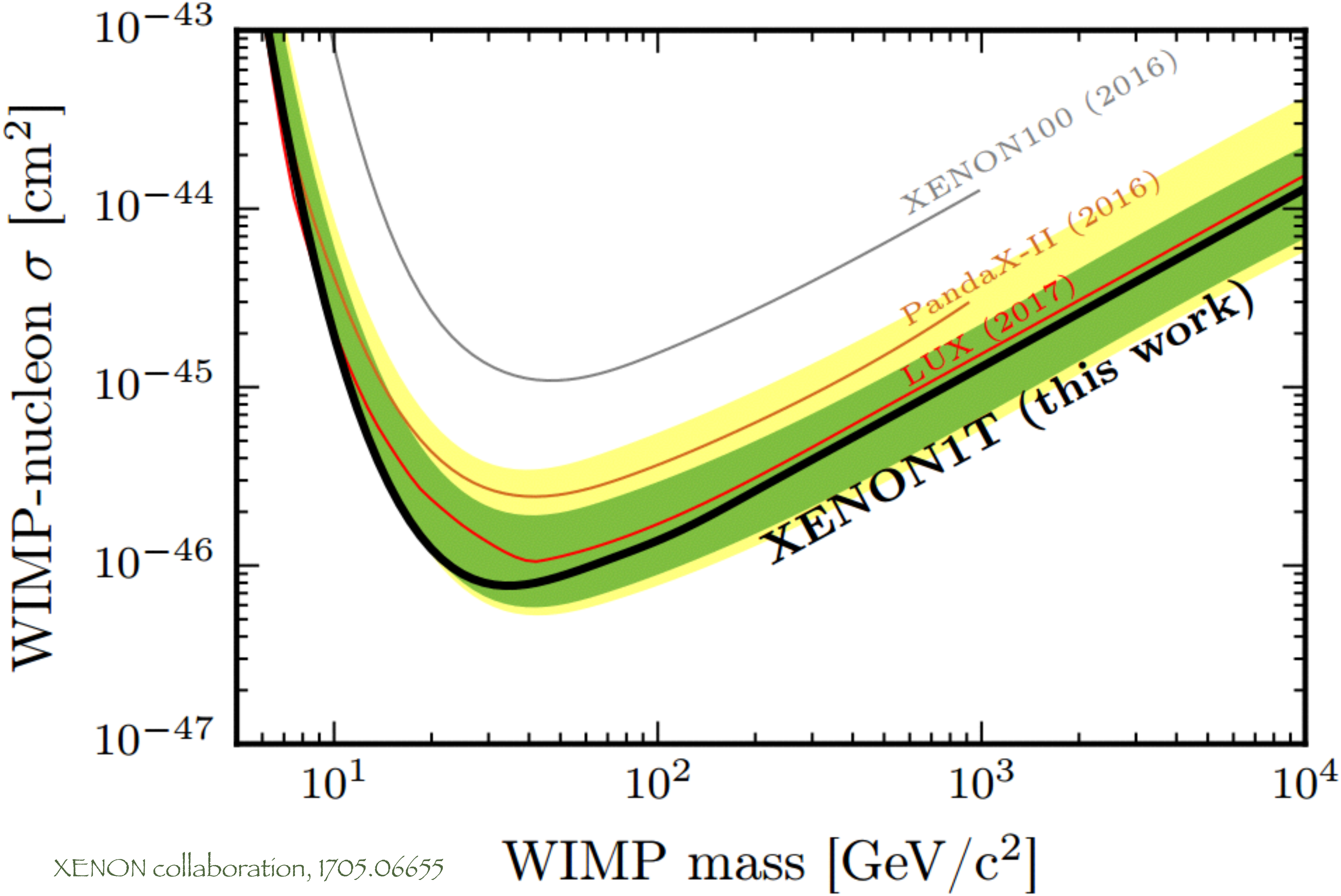
elusives
neutrinos, dark matter & dark energy physics

# Situation today

- From CMS and ATLAS: Higgs discovery but nothing more
- Some news from LHCB
- Neutrino physics: Overall picture is consistent with $3 \times 3$ oscillation paradigm
- Dark matter

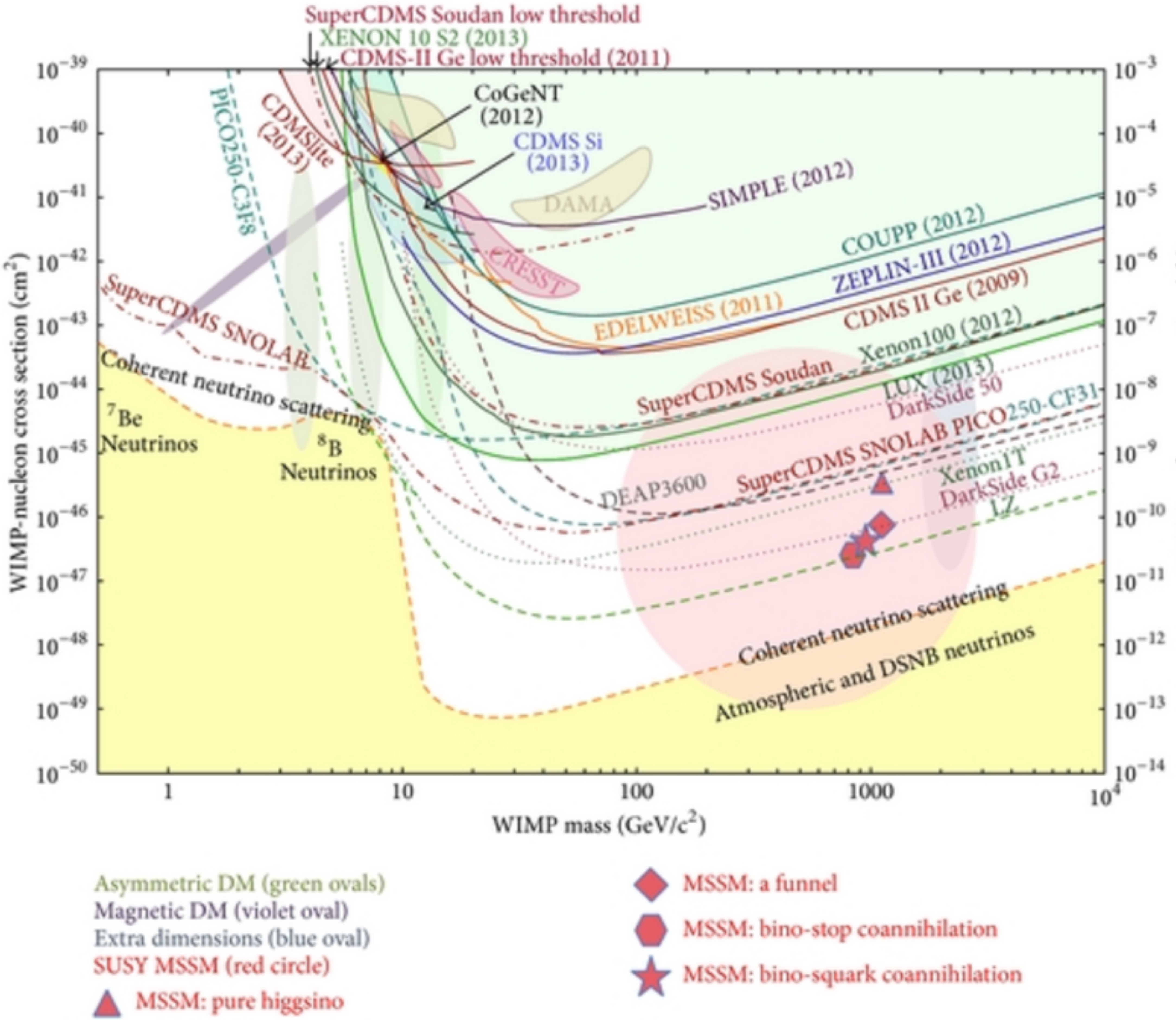


DAMA/Na
CoGeNT
DAMA/I
CDMS
EDELWEISS
XENON100 (2010)
XENON100 (2011)
Buchmueller et al.
WIMP-Nucleon Cross Section [cm$^2$]
$10^{-39}$
$10^{-40}$
$10^{-41}$
$10^{-42}$
$10^{-43}$
$10^{-44}$
$10^{-45}$
10
100
WIMP Mass [GeV/c$^2$]




XENON collaboration, 1705.06655

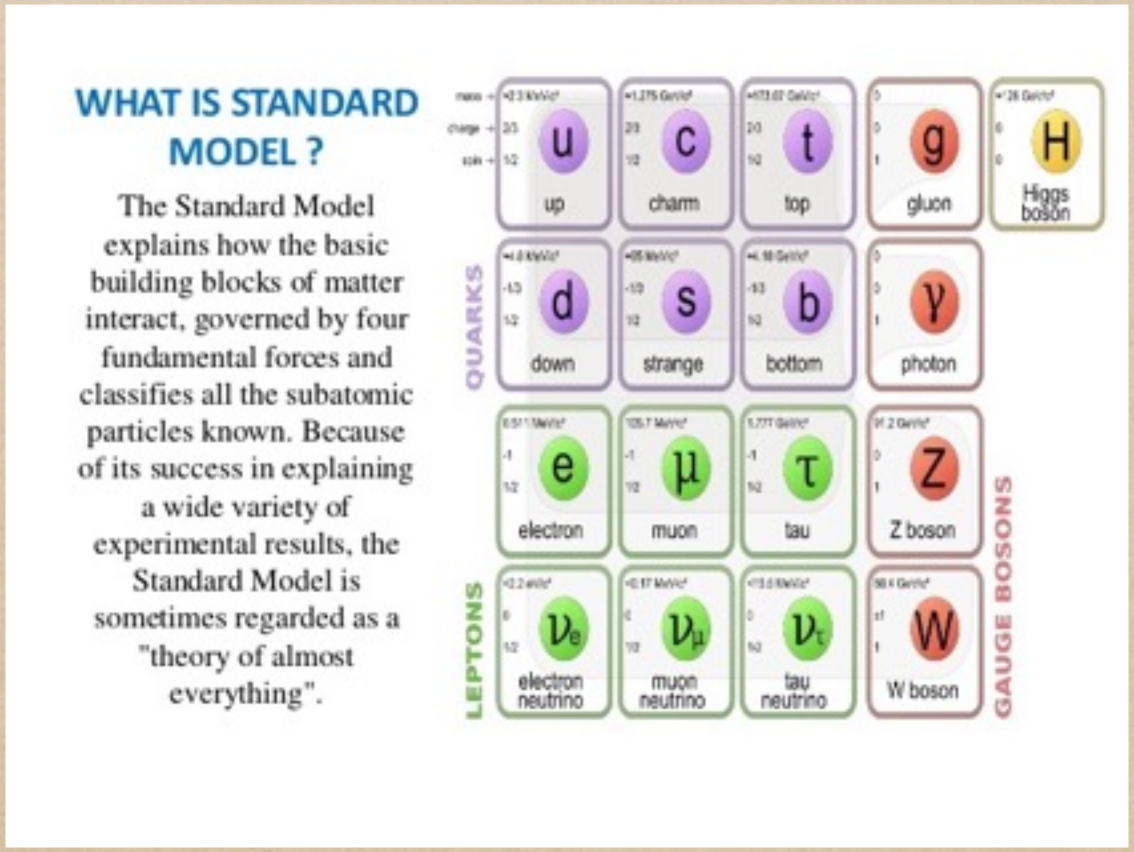
Competitive resultt from PANDAXII, 1708.06917


SuperCDMS Soudan low threshold
XENON 10 S2 (2013)
CDMS-II Ge low threshold (2011)
PICO250-C3F8
CDMSlite (2013)
CoGeNT (2012)
CDMS Si (2013)
DAMA
CRESST
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
Xenon100 (2012)
LUX (2013)
DarkSide 50
SuperCDMS Soudan
SuperCDMS SNOLAB
PICO250-CF3I
Xenon1T
DarkSide G2
LZ
DEAP3600
SuperCDMS SNOLAB
Coherent neutrino scattering
$^7$Be Neutrinos
$^8$B Neutrinos
Coherent neutrino scattering
Atmospheric and DSNB neutrinos
WIMP-nucleon cross section (cm$^2$)
WIMP-nucleon cross section (pb)
WIMP mass (GeV/c$^2$)
Asymmetric DM (green ovals)
Magnetic DM (violet oval)
Extra dimensions (blue oval)
SUSY MSSM (red circle)
MSSM: pure higgsino
MSSM: a funnel
MSSM: bino-stop coannihilation
MSSM: bino-squark coannihilation

- Why simplest dark paradigm should be true?

# SM as clue

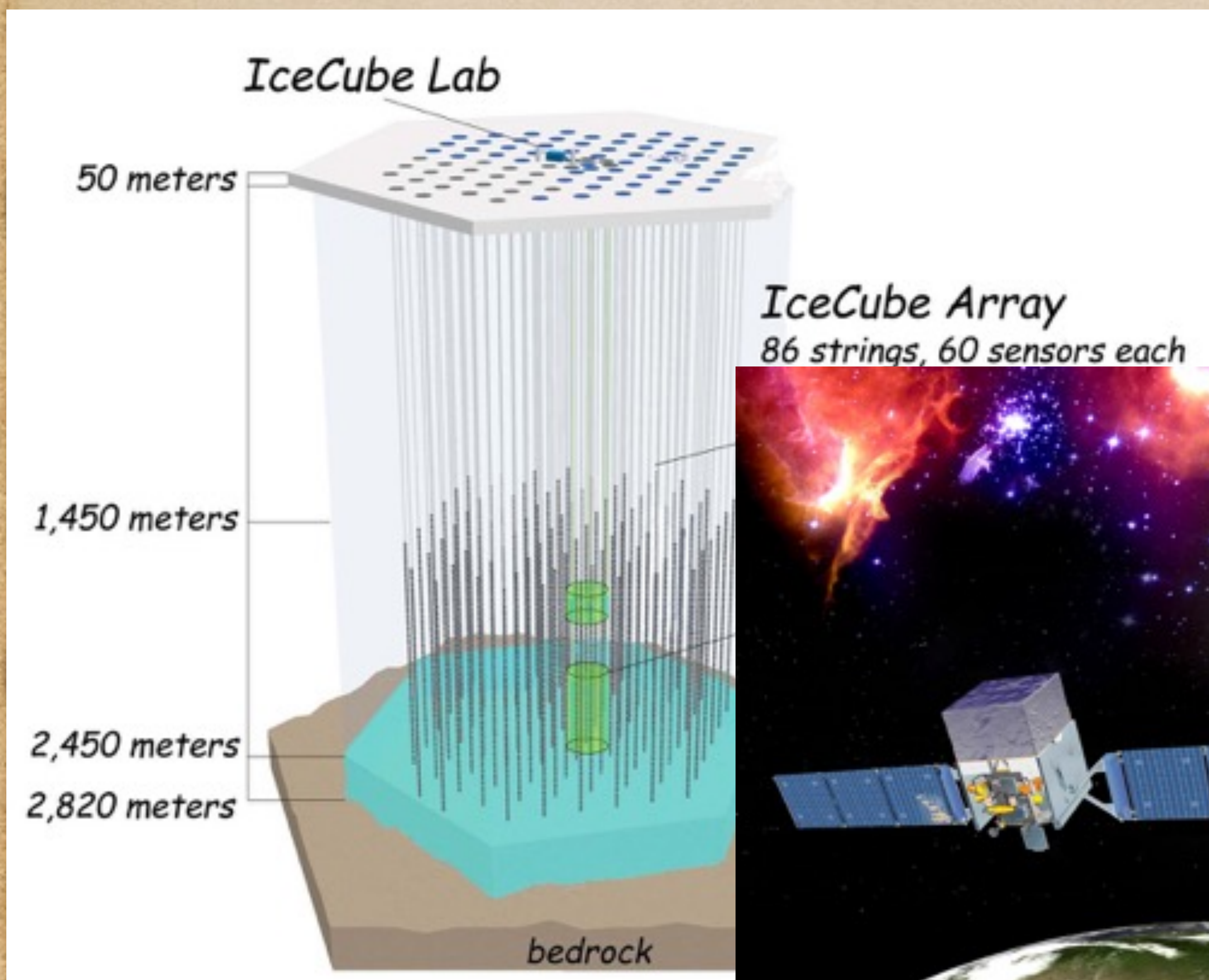
- SM sector is sophisticated and non-trivial with a very rich phenomenology



# Indirect dark matter searches

- Searching for stable product from dark matter annihilation or decay such as
- photons
- positrons
- antiproton
- antihydrogen
- neutrinos
- ….

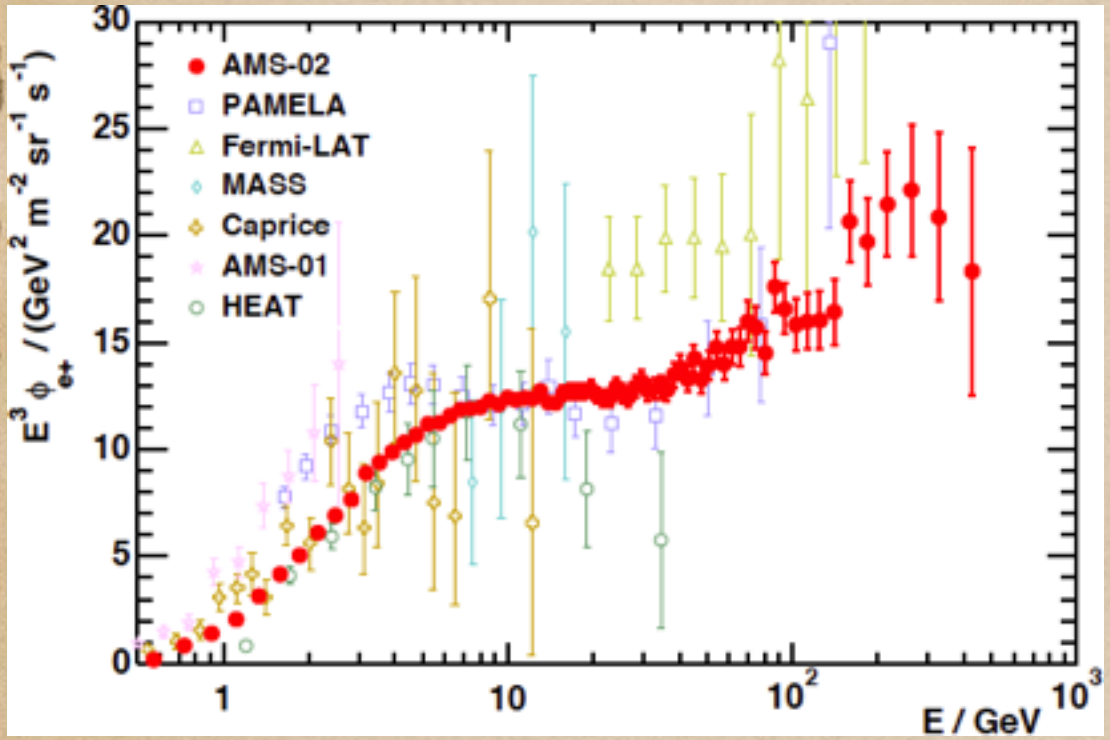
# Indirect dark matter searches

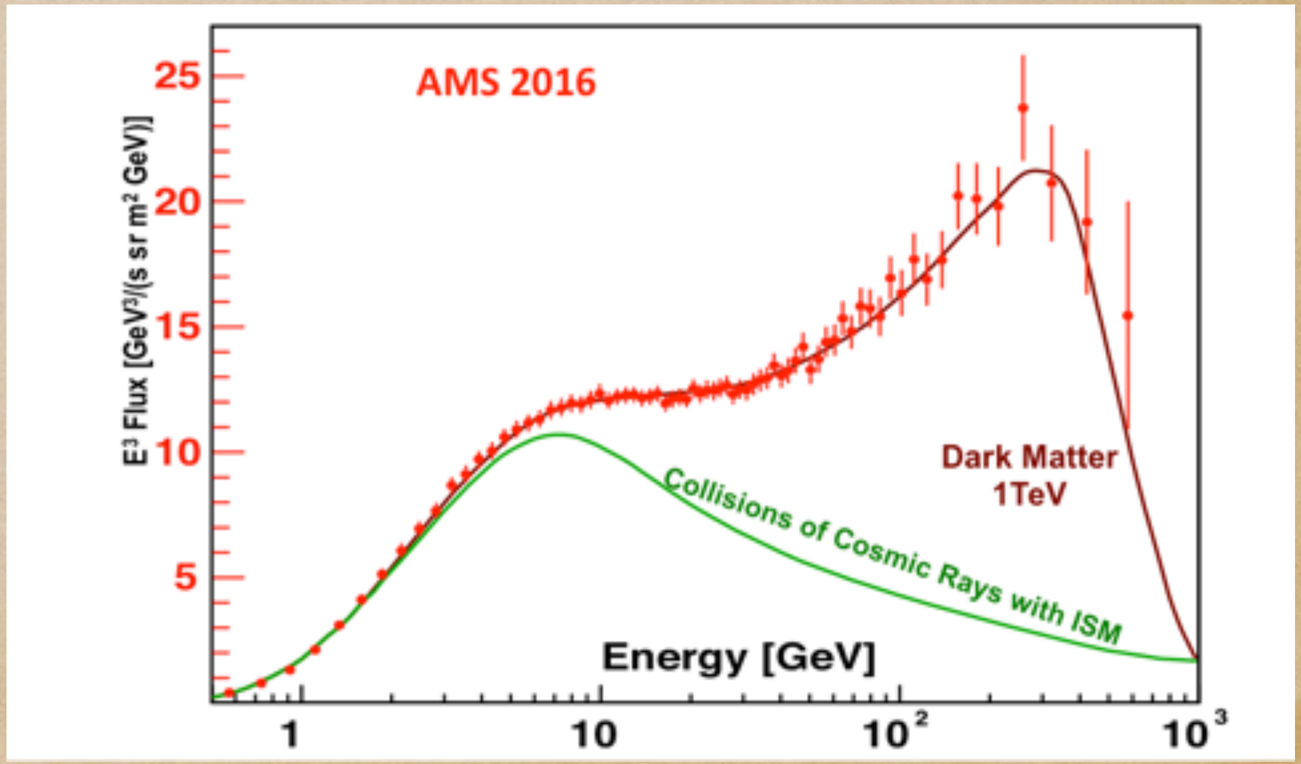



# Hints for DM from indirect search

- Signals that went away with further data: 130 GeV line observed by Fermi-LAT
- Signals that stay robust but go "out of fashion": PAMELA Signal, INTEGRAL 511 keV line

# PAMELA and AMS02 positron excess



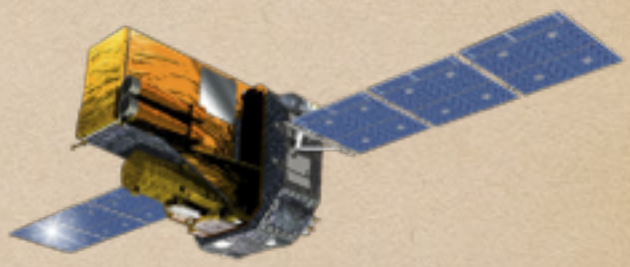
# 511 keV

- It has been observed for more than 40 years
- Leventhal et al., 1978
- $e^-e^+$ annihilation

# INTEGRAL

INTErnational Gamma-Ray Astrophysics Laboratory

Launched in 2002

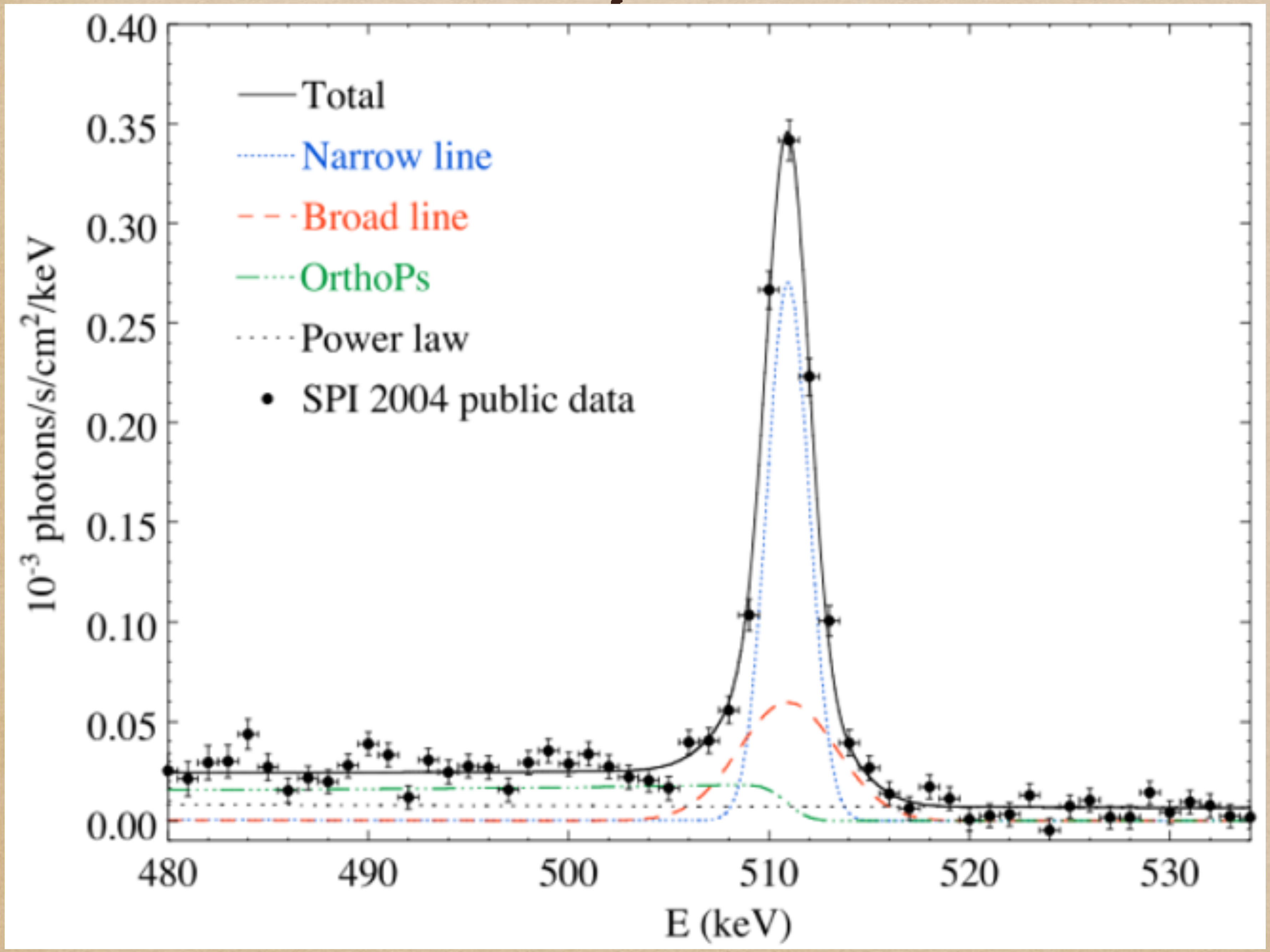


SPI at INTEGRAL of ESA

Angular resolution: $2°$

Energy resolution: 2 keV

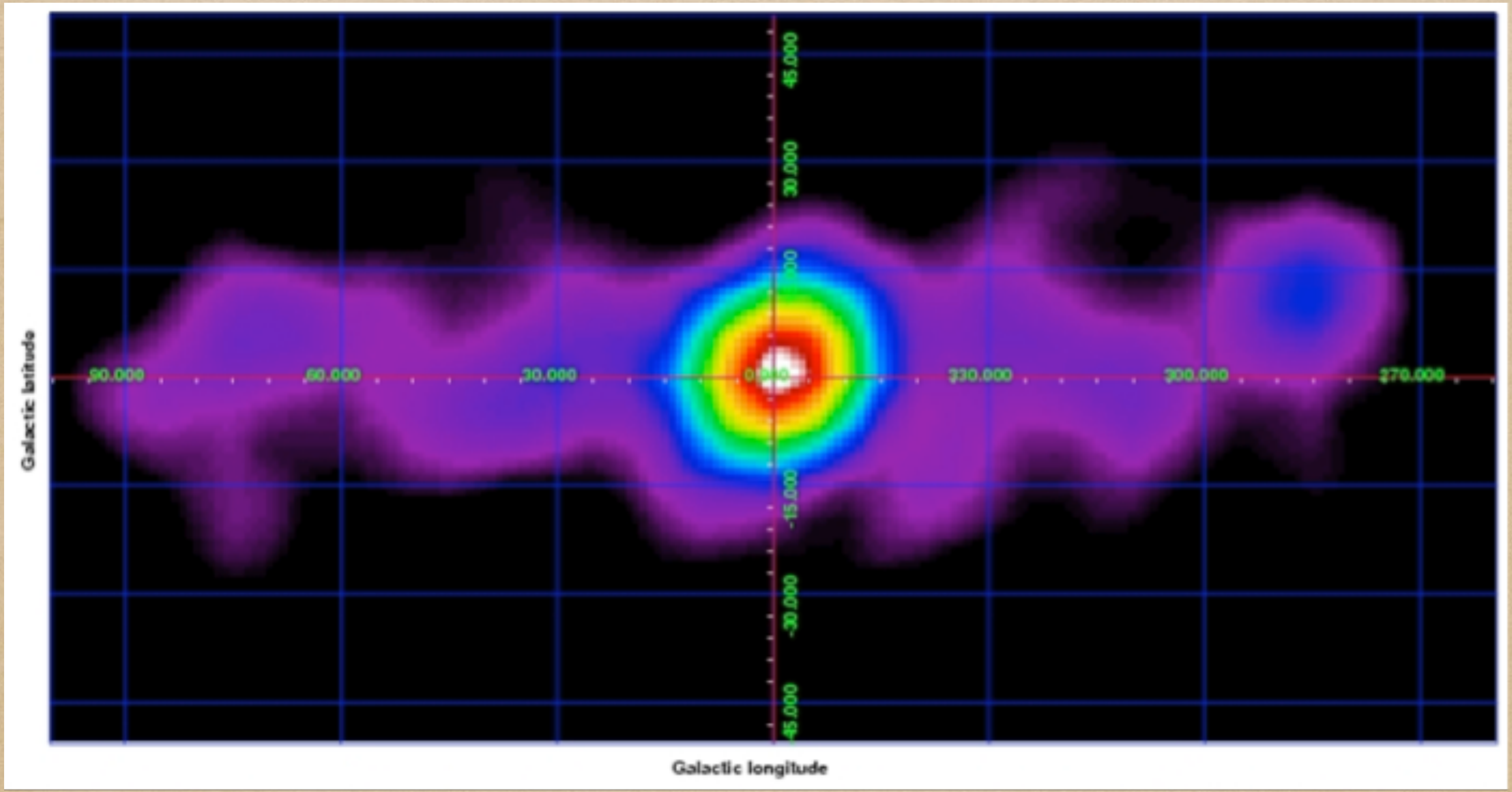
# Spectrum




$58\sigma\ C.L.$

Va'vra, 1304.0833

# Morphology of the line




Distribution of the line as observed by INTEGRAL/SPI: ESA/Bouchet et al.

# Flux

Siegert et al., arXiv:1512.00325

$$(0.96 \pm 0.07) \times 10^{-3} \mathrm{ph}\ \mathrm{cm}^{-2} sec^{-1}$$

# Some alternative scenarios

- Radioactive decay: $^{56}\mathrm{Ni}$ $^{44}\mathrm{Ti}$ $^{13}N$ $^{26}Al$
- Accreting binary sources
- pulsars
- supermassive blackhole

# Dark matter explanation

- C Boehm, D Hooper, Silk, Casse and Paul, Phys. Rev. Lett. 92 (2004) 101301
- Dark matter mass ~ few MeV

$$\sigma(X + X \to e^- e^+) \sim 10^{-4} pb$$

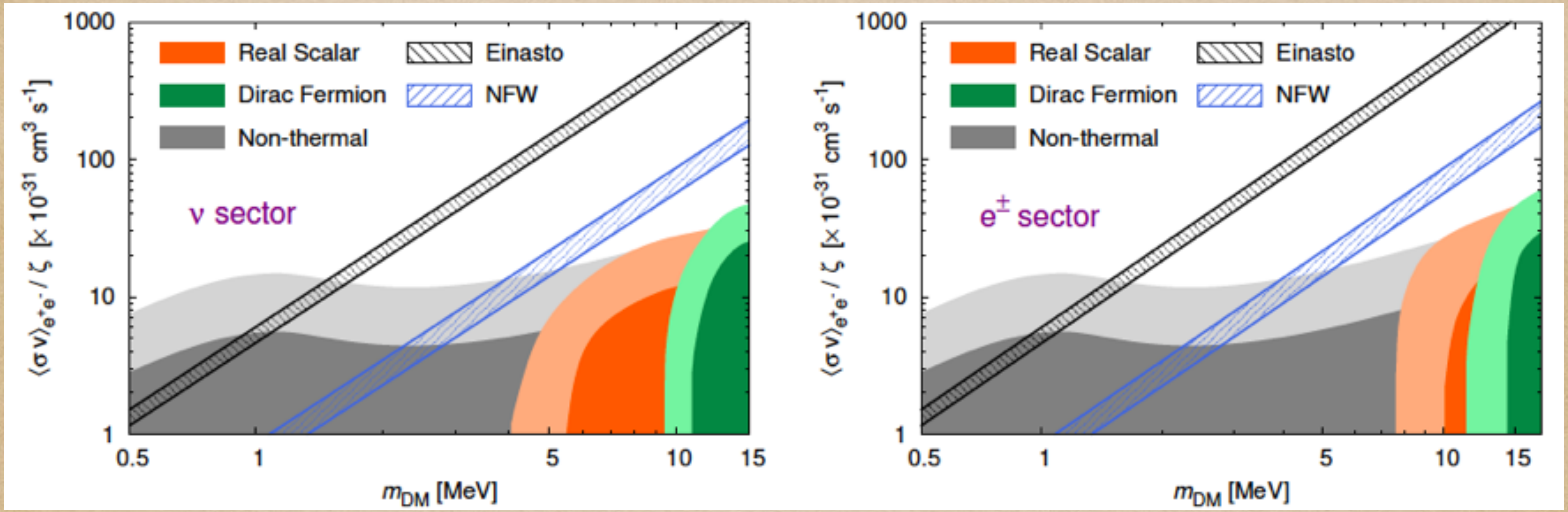
# Delayed recombination

- Reionization → rescattering CMB photons
→ Broadening last scattering surface

- Suppression of temperature and polarization correlation on small scales (large multipoles)

- Late time Thompson scattering → enhanced polarization correlation at large scales

# Bounds from CMB




Wilkinson, Vincent, Boehm and McCabe, PRD 94 (2016)

Can p-wave annihilation rescue the DM explanation?

$$\sigma(X + X \to e^- e^+) = (10^{-4}\ pb)v^2$$

- At galaxy: $10^{-3} >>$ velocity at recombination

At freeze-out time:

$$\sigma(X + X \to e^- e^+) = 10 - 100\ pb$$

suppressed relic density

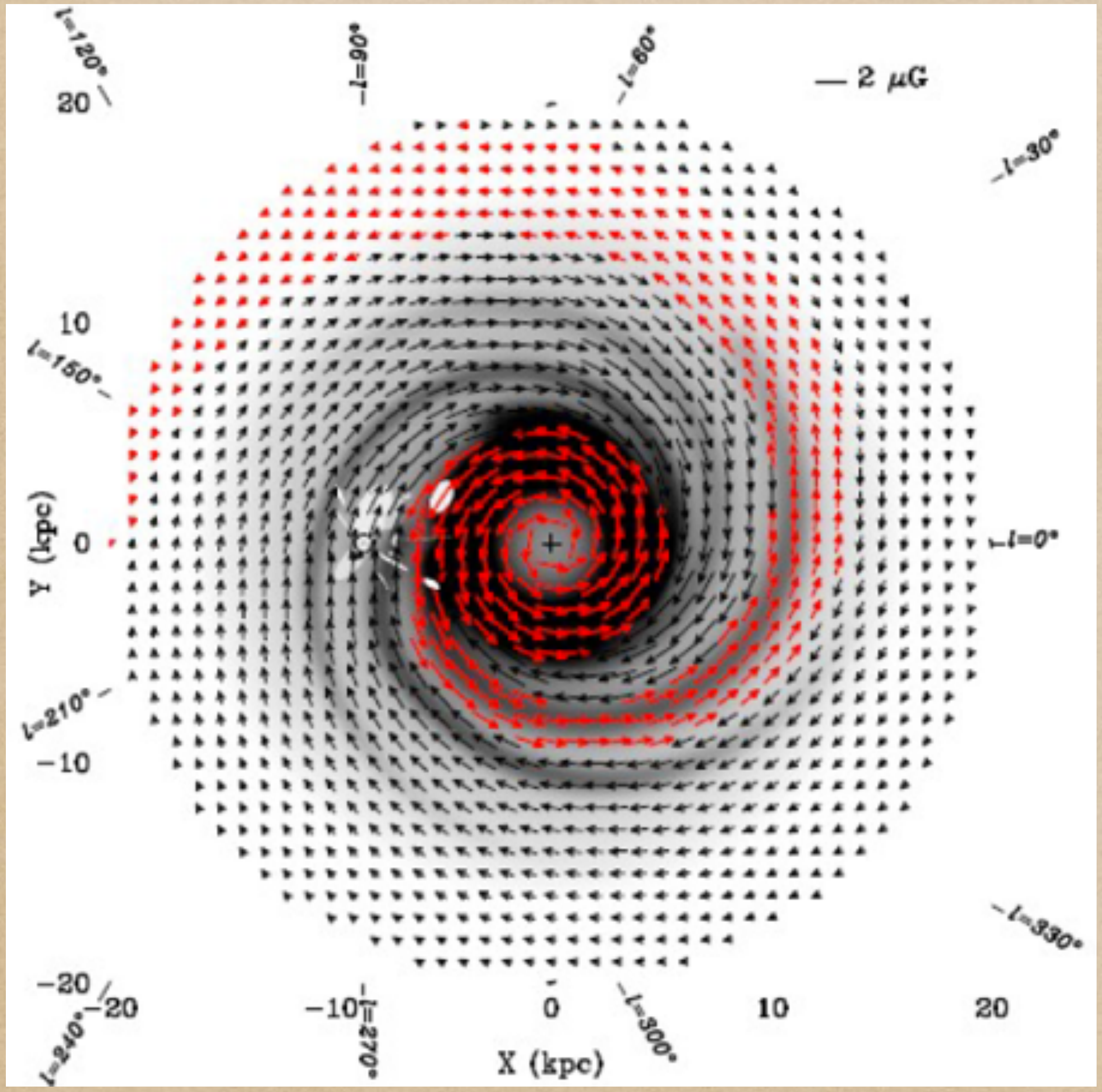
# Our scenario

- YF and M Rajaee, arXiv:1708.01137

$$X \to C\bar{C} \quad C\bar{C} \to e^- e^+$$

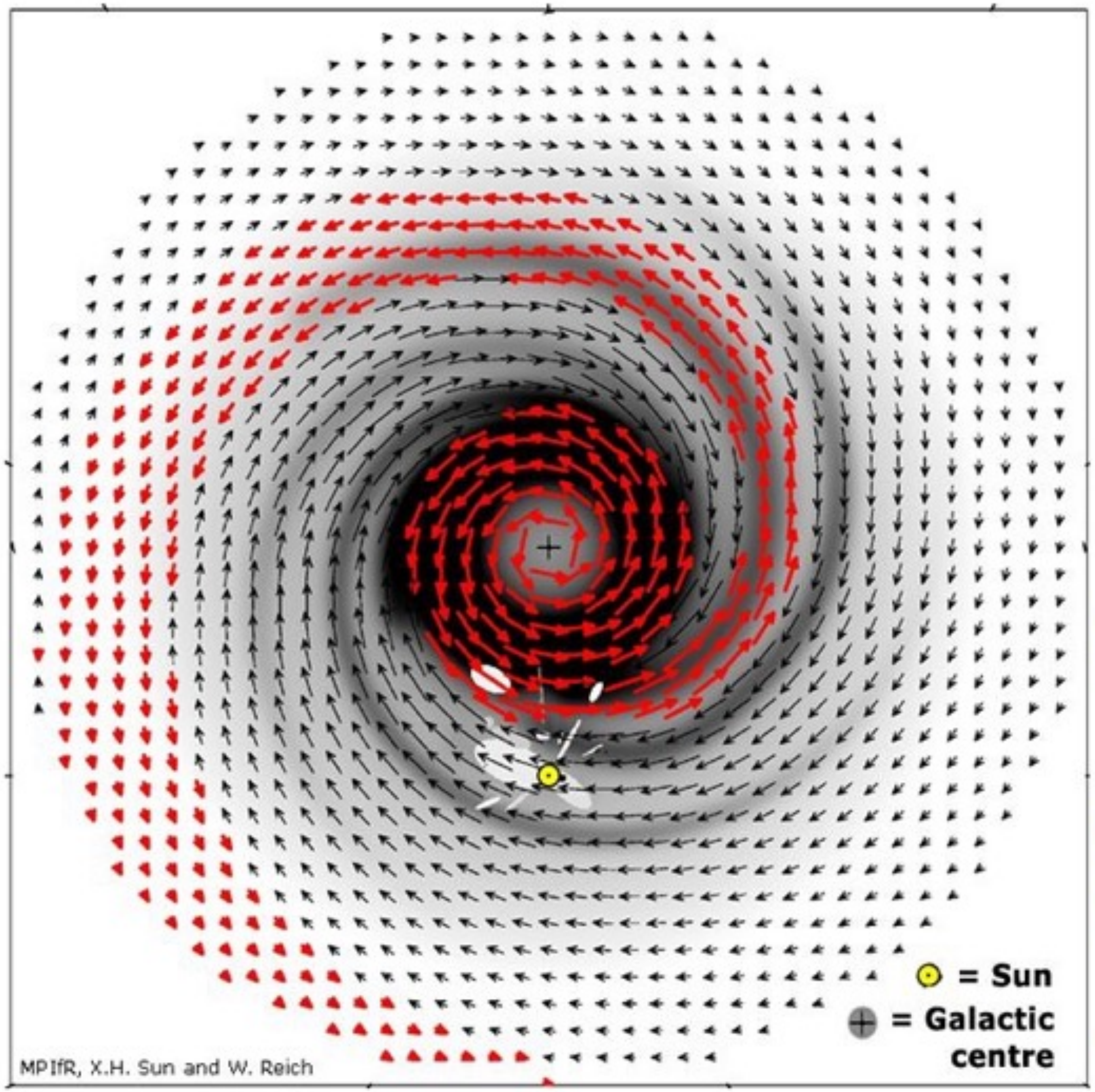
- The velocity of $C$ will be above escape velocity.

# Galactic magnetic field



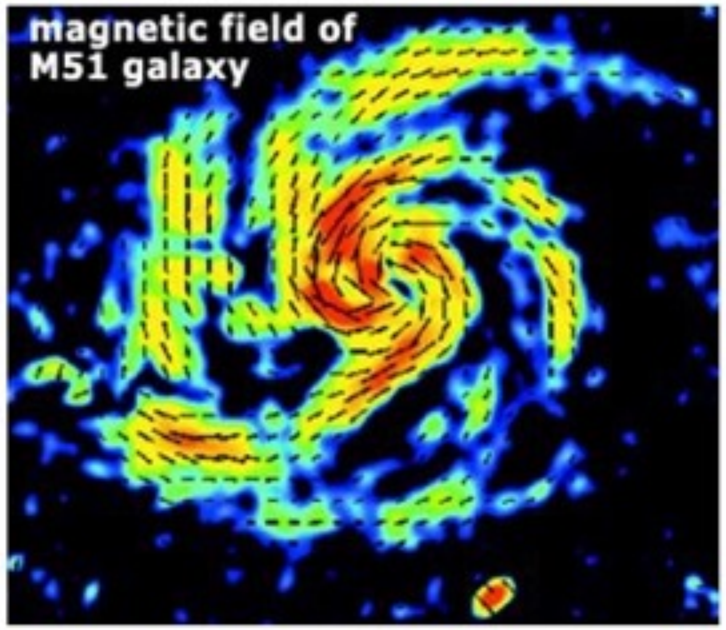

Sun et. al 2008

# The magnetic fields of our galaxy, the Milky Way




The main magnetic field structure lies *in the plane* of the disc and follows the spiral arms.

- The red arrows are in the opposite direction to the black ones – i.e. the magnetic field is reversed.
- There is also a toroidal and a poloidal magnetic field (not shown)



# Larmour radius

$$r_L = 5\ pc \times \left(\frac{3\times10^{-11}}{q}\right)\left(\frac{m_X}{5\ \mathrm{MeV}}\right)\left(\frac{10\ \mu\mathrm{Gauss}}{B}\right)$$

$$(8\ kpc) \times \sin(2^\circ) = 280\ pc$$

# Acceleration by supernova shock waves

Chuzhoy and Kolb, JCAP 0907 (2009) 014

$\tau_E^{-1} = d \log E/dt$

$(100 \ \mathrm{Myr})^{-1}$

We need a mechanism for energy loss.

The same mechanism that gives charge to C particles also provides a mechanism for cooling.

- Feldman, Liu and Nath, Phys Rev D 95 (2007)

$$U(1)_X \times SU(2) \times U(1)_Y \rightarrow U(1)_{em},$$

- Stueckelberg mechanism

$$-\frac{X_{\mu\nu}X^{\mu\nu}}{4} - \frac{\delta}{2}X_{\mu\nu}B^{\mu\nu} - (\partial_\mu\sigma + M_1 X_\mu + M_2 B_\mu)^2$$

$$\epsilon = \frac{M_2}{M_1} \ll 1 \qquad\qquad \delta \ll 1$$

Dark photon, $\gamma'$ , mainly composed of $X_\mu$

# A particularly interesting limit

- Feldman, Liu and Nath, Phys Rev D 95 (2007)

$\delta = \epsilon$ ➡ Decoupling of the sectors

$$q = \frac{g}{e}\epsilon$$

$g$ → Standard SU(2) coupling

$q$ → Electric charge of C particles

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For $\delta \neq \epsilon$ still $q \propto \max[\epsilon, \delta]$

# A particularly interesting limit

- Feldman, Liu and Nath, Phys Rev D 95 (2007)

$\delta = \epsilon$ $\rightarrow$ Decoupling of the sectors

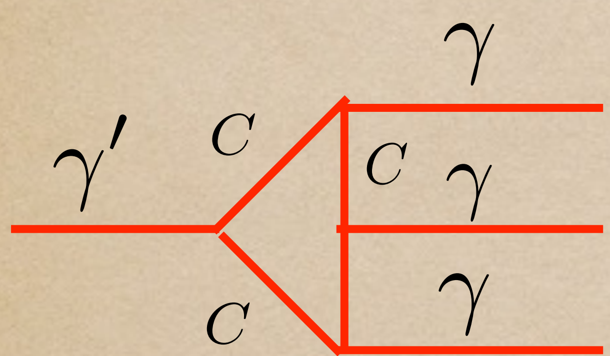
$$q = \frac{g}{e}\epsilon$$

Dark photon mass arbitrary given by $M_1$

No tree level coupling between $\gamma'$ and SM fermions

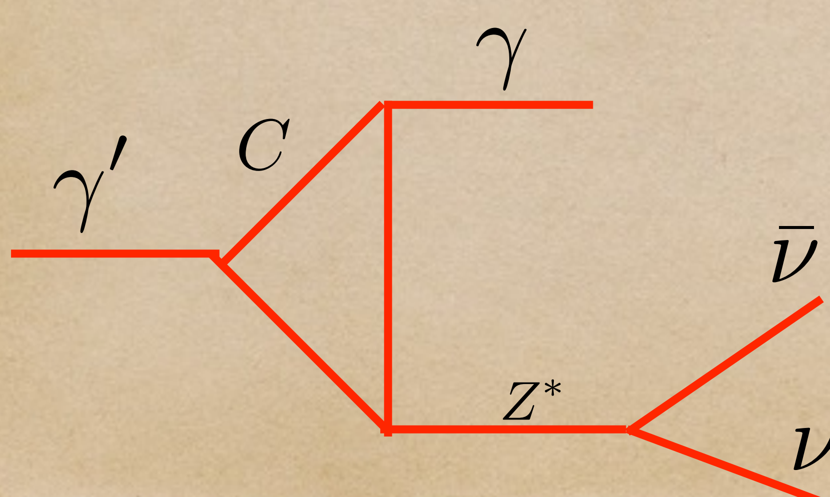
# Decay of Dark photon

- kinetically available decays modes for keV dark photons $\gamma\gamma, \gamma\gamma\gamma, \nu\bar{\nu}$
- Landau-Yang theorem $\gamma' \not\to \gamma\gamma$




$$\Gamma_{\gamma'} \sim m_{\gamma'} \frac{g_X^2 q^6}{4\pi(16\pi^2)^2}$$

$$\tau = 7 \times 10^{45}\ \text{years} \gg 10\ \text{Gyr}$$




$$\sim m_{\gamma'} \left(\frac{m_{\gamma'}}{m_{Z'}^2}\right)^2 \frac{g_X^2 q^4}{4\pi(16\pi^2)^2}$$

# $C$ and $\gamma'$ production in early Universe

$$e^+e^- \to C\bar{C}$$

$$\frac{\dot{n}_C H^{-1}}{n_\gamma} = 5 \times 10^{-5} \left(\frac{q}{10^{-11}}\right)^2$$

$$\dot{n}_C + 3Hn_C = -\langle \sigma(C\bar{C} \to \gamma'\gamma')v \rangle n_C^2$$

$$\boxed{n_C = \frac{T^3}{M_{Pl}^* \langle \sigma(C\bar{C} \to \gamma'\gamma')v \rangle m_C} \quad \text{at} \quad T \ll m_C.}$$

$$\boxed{\frac{n_{\gamma'}}{n_\gamma} = 10^{-4} \left(\frac{q}{10^{-11}}\right)^2}$$

$$\boxed{n_{\gamma'}/n_\gamma < 0.1 \text{ which implies } q < 3 \times 10^{-10}}$$

# Range

$$10^{-11} < q < 3 \times 10^{-10}$$

BBN: $\frac{n_{\gamma'}}{n_\gamma} < 0.1$

$$10 \text{ eV} < m_{\gamma'} < 10 \text{ keV}$$

Non-relativistic at recombination

Subdominant dark matter component

# Dark photon concentration in galaxy

$$n_{\gamma'}|_{GC} = \frac{\rho_{DM}|_{GC}}{\langle \rho_{DM} \rangle} \langle n_{\gamma'} \rangle.$$

$$\rho_{DM}|_{GC} \sim 3 \text{ GeV cm}^{-3}$$

$$n_{\gamma'} \sim 10^5 (q/10^{-11})^2 \text{cm}^{-3}$$

$$\Delta E_C = m_{\gamma'} \left( \frac{E_C}{m_C} \right)^2 v^2$$

$$\sigma_S \simeq 3 g_X^4 / (4\pi m_C^2)$$

$$\tau_E = \int_{m_C(1+v_f^2/2)}^{m_X/2} \frac{dE_C}{\Delta E_C} \frac{1}{\sigma_S v n_{\gamma'}} |_{GC} \simeq 100 \text{ Myr} \left( \frac{m_C}{5 \text{ MeV}} \right)^3 \left( \frac{10 \text{ keV}}{m_{\gamma'}} \right) \left( \frac{0.03}{v_f} \right) \left( \frac{0.15}{g_X} \right)^4 \left( \frac{10^5 \text{ cm}^{-3}}{n_{\gamma'}} \right)$$

$\tau_E$ is given by $(n_{\gamma'} m_{\gamma'})^{-1}$

$$v_f = 0.3 \left( \frac{0.15}{g_X} \right)^4 \left( \frac{10^4 \text{cm}^{-3}}{n_{\gamma'}} \right) \left( \frac{m_C}{5 \text{ MeV}} \right)^3 \left( \frac{m_{\gamma'}}{10 \text{ keV}} \right)$$

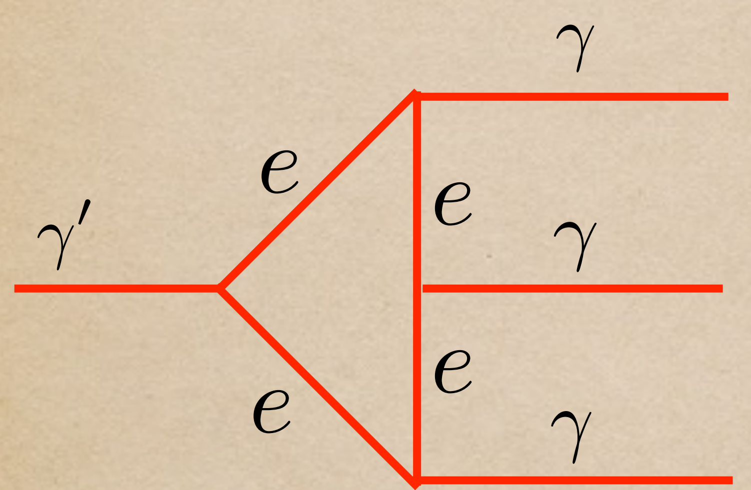
# Bounds on $\frac{n_C}{n_X}$ fraction

$$n_C = \frac{\rho_X}{m_X} f \quad \text{where} \quad f = \Gamma_X t^0.$$

- Dominant DM component cannot be relativistic [Audren, JCAP 1412 (2014)] $f < 1\ \%$
- Not all $\gamma'$ are ejected: $f < 10^{-2} \left(\frac{q}{10^{-11}}\right)^2 \left(\frac{m_{\gamma'}}{10\ \text{keV}}\right) \left(\frac{m_X}{10\ \text{MeV}}\right)$
- $C$ should be accumulated $n_C \langle \sigma(CC \to \gamma'\gamma') v \rangle t_0 \ll 1$

$$f < 6 \times 10^{-4} \left(\frac{m_X}{10\ \text{MeV}}\right) \left(\frac{0.15}{g_X}\right)^4 \left(\frac{m_C}{5\ \text{MeV}}\right)^2$$

# What if $\delta \neq \epsilon$




$$q' \sim g_X \max[\delta, \epsilon] \sim 10^{-11} - 3 \times 10^{-10}$$

$$\tau = 1000\ yr \left(\frac{3 \times 10^{-10}}{q'}\right)^2 \left(\frac{keV}{m_{\gamma'}}\right)$$

Before recombination

$$\boxed{\lambda_{C\phi'} |C|^2 (\phi')^2}$$

$$\boxed{C\bar{C} \to \phi'\phi'}$$

# Bounds

- SLAC bounds on millicharged particles; Prinz et al., PRL 81 (1998) 1175 1 MeV-100 MeV

$$q < 4.1 \times 10^{-5} e - 5.8 \times 10^{-4} e$$

- Supernova bound (energy loss) Davidson, Hannestad and Raffelt, JHEP 05 (2000) 03

$$q < 10^{-9}$$

# A few words on dark matter

$$m_X \sim O(10\ \mathrm{MeV})$$

$$\langle \sigma(X + X \to \nu + \nu, \bar{\nu} + \bar{\nu}) v \rangle |_{tot} = 1\ \mathrm{pb}$$

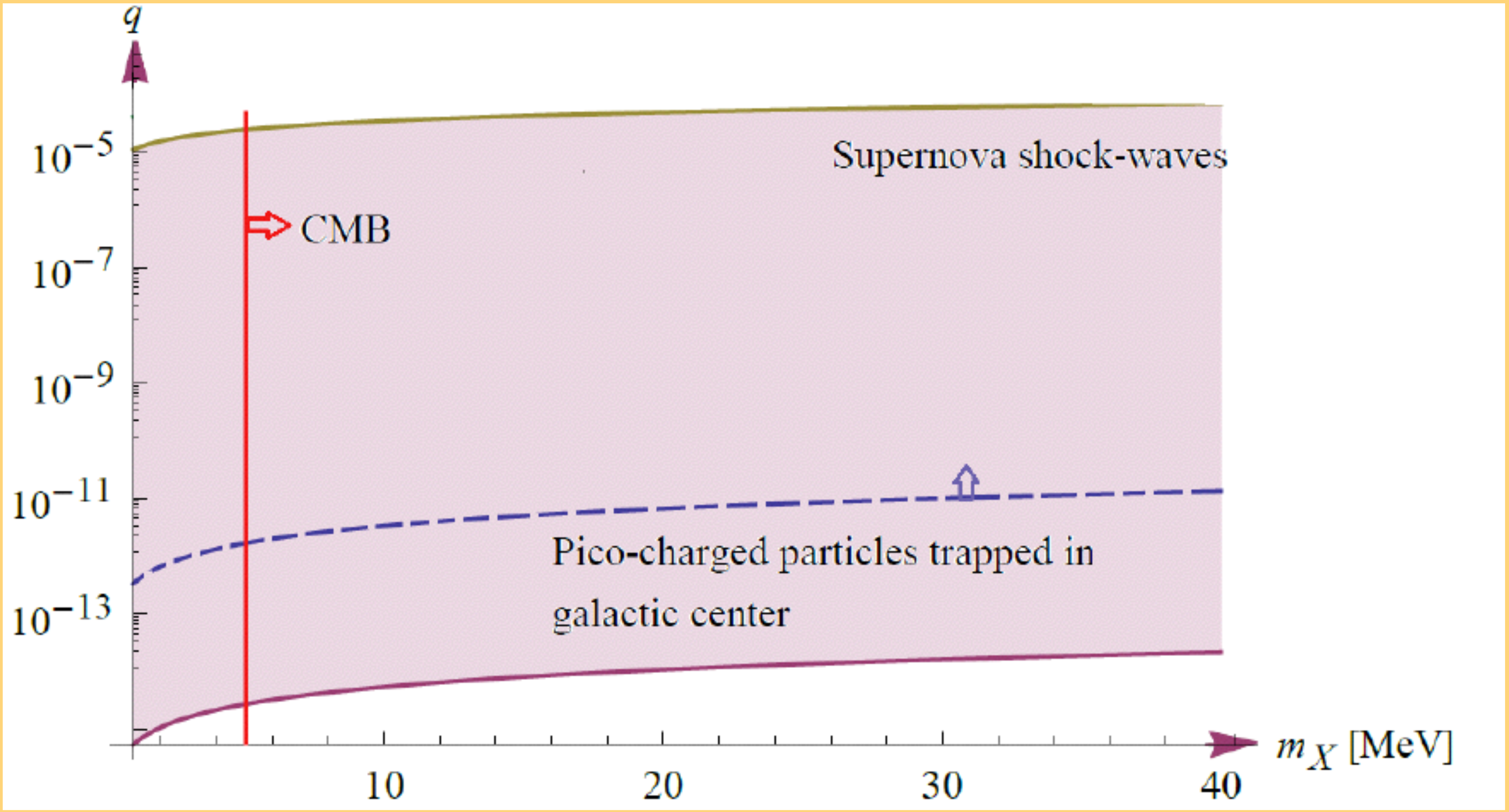
Bohm et al., PRD 77 (2008) 043516;

Farzan, PRD 80 (2009) 073009

$\boxed{\text{The bounds from CMB on } N_{eff} \text{ then implies } m_X > 5\ \mathrm{MeV}}$

Wilkinson et al., PRD 94 (2016) 103525

# Bounds on electric charge of C versus DM mass



# Positronium decay

$$\boxed{e^- e^+ \to \gamma\gamma}$$

- Decay at rest: 511 keV line
- Decay in flight:   harder and continuous spectrum

Beacom and Yuksel, PRL 97 (2006) 071102

$E_{inj} < 3 \text{ MeV}$ Assuming zero ionization

Size, Casse and Schanne, PRD 74 (2006) 063514

$E_{inj} < 7.5 \text{ MeV}$ 51 % ionization

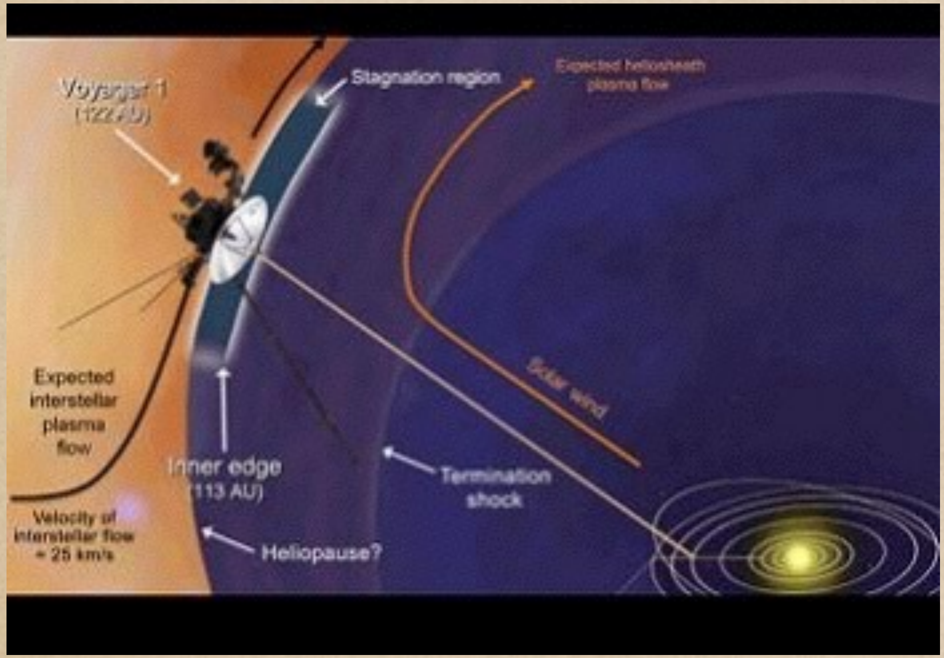
# A fun bound from Voyager

Launched on 5th of September, 1977

# A fun bound from Voyager


Containing a piece of Azarbaijani music

# Voyager out of heliopause




$$E_{inj} < 10 \text{ MeV}$$

Boudaud Lavalle and Salati, PRL 119 (2017) 021103

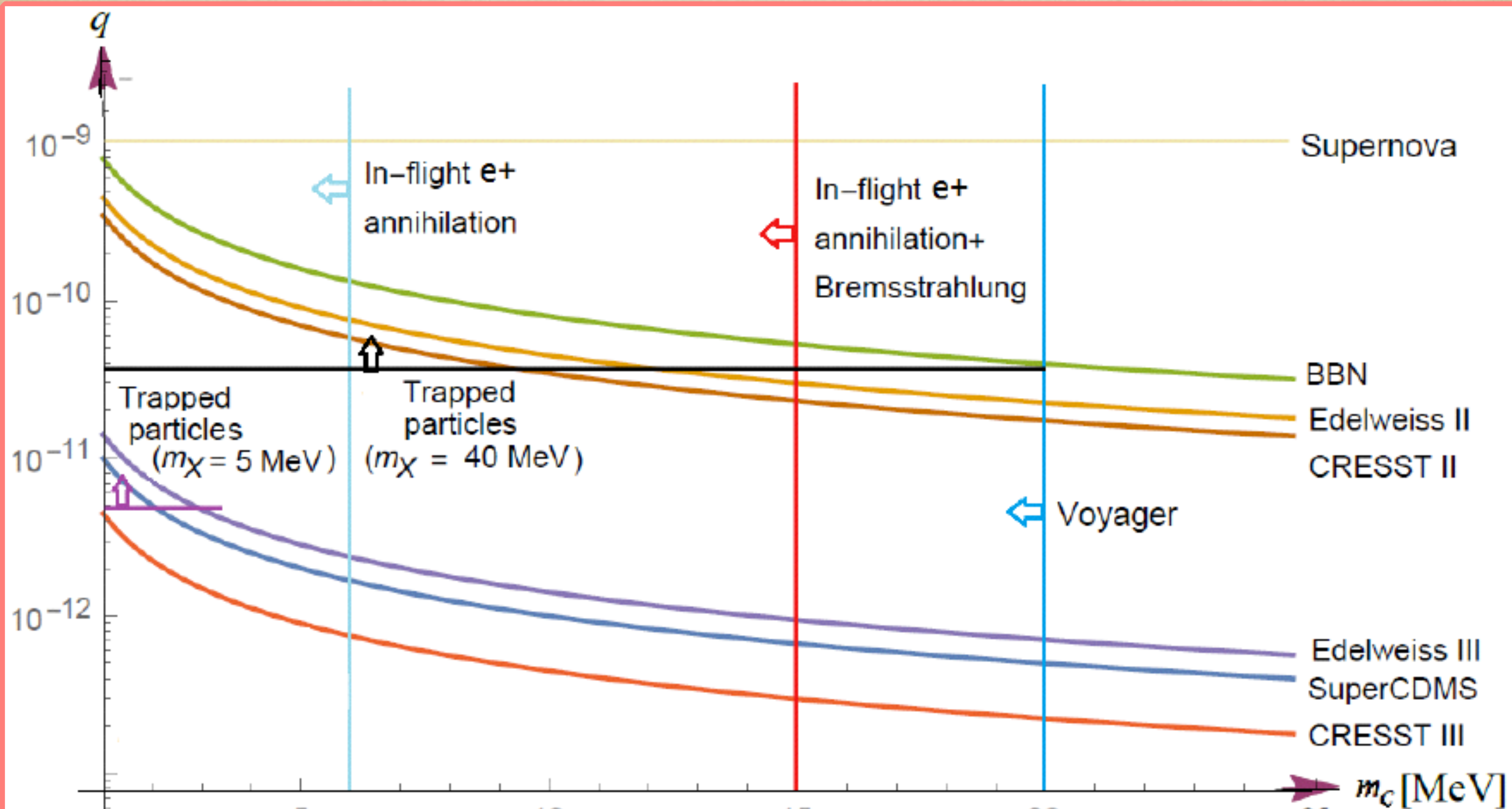
Voyager entered interstellar medium in summer 2012

# Direct detection

$C$ relativistic $\boxed{v \sim 1/3}$

$$\boxed{\langle \Delta E \rangle \sim 0.035 \text{ keV} \frac{1}{1-v^2} \left(\frac{v}{1/3}\right)^2 \left(\frac{m_C}{3 \text{ MeV}}\right)^2 \left(\frac{28 \text{ GeV}}{M_N}\right) \left(\frac{M_N}{M_N + \gamma m_C}\right)^2}$$

| Present | | Future | |
|---|---|---|---|
| LUX experiment | $E_{th} = 3$ keV | SuperCDMS | $E_{th} = 0.056$ keV |
| DAMA | $E_{th} = 2$ keV | CRESST III | $E_{th} = 0.02 - 0.06$ keV |
| CRESST II | $E_{th} = 0.3$ keV | Edelweiss III | $E_{th} < 0.1$ keV |



q
$10^{-9}$
$10^{-10}$
$10^{-11}$
$10^{-12}$
Supernova
In–flight e+
annihilation
In–flight e+
annihilation+
Bremsstrahlung
BBN
Edelweiss II
CRESST II
Trapped
particles
($m_X$ = 5 MeV)
Trapped
particles
($m_X$ = 40 MeV)
Voyager
Edelweiss III
SuperCDMS
CRESST III
5
10
15
20
25
$m_c$ [MeV]


Fig 1-b

# Dependence on recoil energy

$$\frac{dN_{events}}{dE_r} = \frac{1}{M_N}\frac{\rho_X}{m_X}(2fv)\frac{d\sigma}{dE_r}$$

$$\frac{d\sigma}{dE_r} = \mid F \mid^2 \frac{Z^2}{4\pi M_N^2} \times \frac{e^2 q^2 m_C^2}{E_r^2} \times \frac{1}{E_r^{max}}$$

Recoil energy

Distinctive behavior

Different recoil energy dependence from DM signal

Even dipole or anapole DM

# Tests of the scenario

- Direct dark matter search
- Positron search by Voyager
- Studying the correlation of 511 keV line with magnetic field in various dwarf galaxies (e.g. Reticulum II) and milky way

# Summary

- Scenario for saving DM interpretation of 511 keV signal from CMB bounds.
- Dark matter decays to a pair of pico-charged particles that stay in galaxy and eventually annihilate to create electron positron.
- Testable by low energy DM search experiments Edelweiss II, superCDMS and CRESST III with distinctive dependence on the recoil energy.
- Search for a positron signal in outer space by Voyager
- Correlation between galactic magnetic field and 511 keV signal in our galaxy and in dwarf galaxies
- General scenario applicable for the indirect DM signal other than the 511 keV line

# Direct annihilation of C pairs to electron positron pair

$$C\bar{C} \to \phi\phi \qquad \frac{\bar{e}e\bar{C}C}{\Lambda}$$

$$\sigma(C\bar{C} \to \phi\phi) \sim 100pb$$

$$\Lambda \sim 100\ GeV$$

# In two steps

$$C\bar{C} \to \phi\phi \qquad\qquad \phi \to e^- e^+$$

$$g_\phi \phi e^- e^+$$

$$\boxed{0.3 \times 10^{-15} < g_\phi < 10^{-11}}$$

decay length smaller than 100 pc

Supernova

# Model building

$$a_\phi \phi |H|^2$$

$$g_\phi = \sqrt{2}\frac{a_\phi v}{m_h^2} Y_e$$