11 June 2014

Strategy Workshop on AstroParticle in Switzerland (SWAPS 2014)

Cartigny, Switzerland

Complementarities

between Dark Matter searches

Marco Cirelli

(CNRS IPhT Saclay)

11 June 2014
Strategy Workshop on AstroParticle in Switzerland (SWAPS 2014)
Cartigny, Switzerland

Complementarities
between Dark Matter searches

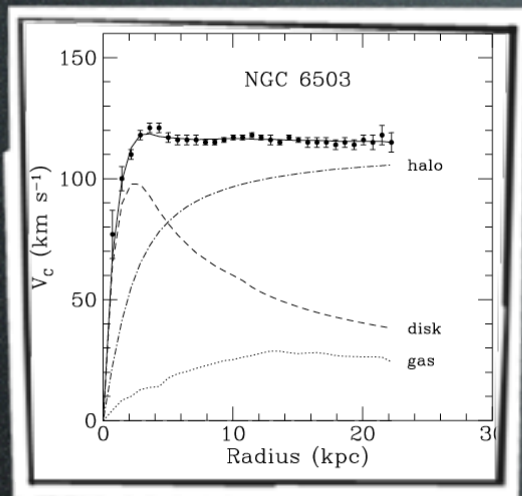
Marco Cirelli
(CNRS IPhT Saclay)

Introduction

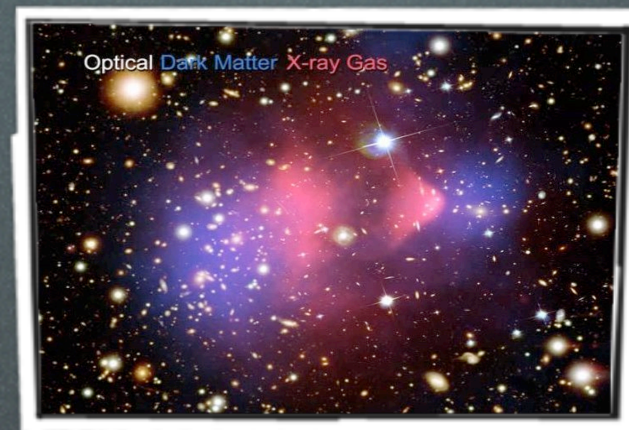
DM exists

Introduction

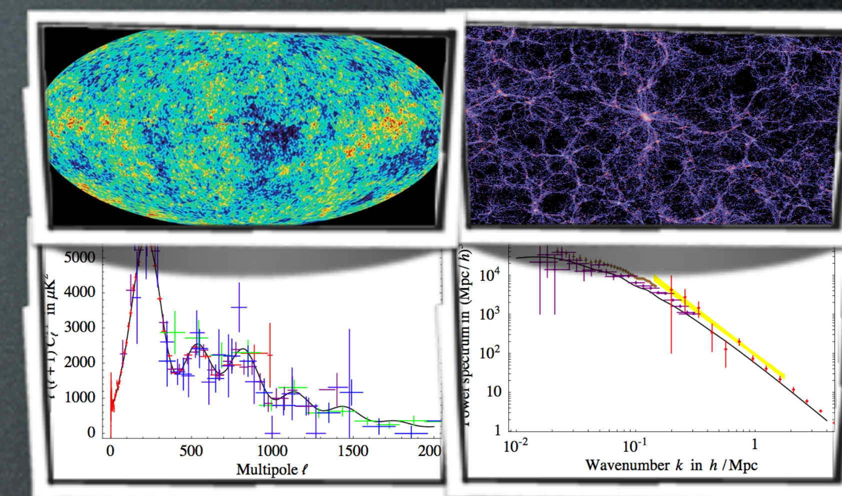
DM exists



galactic rotation curves



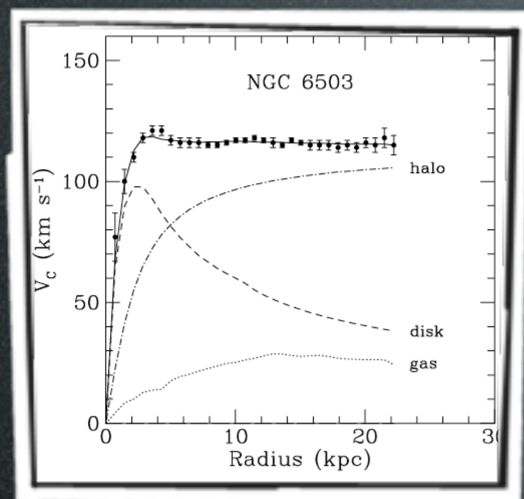
weak lensing (e.g. in clusters)



'precision cosmology' (CMB, LSS)

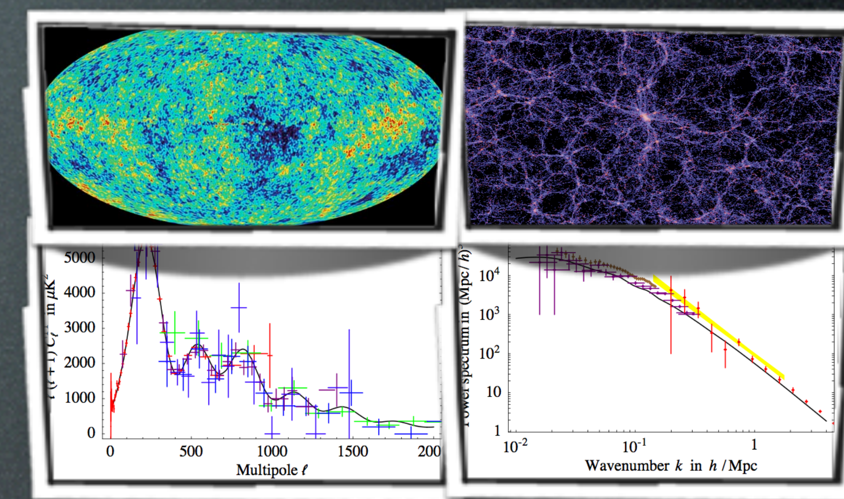
Introduction

DM exists



galactic rotation curves

weak lensing (e.g. in clusters)

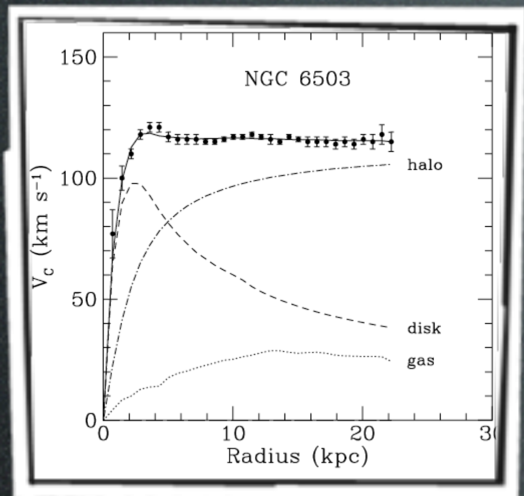


'precision cosmology' (CMB, LSS)

DM is a neutral, very long lived, feebly- interacting corpuscle.

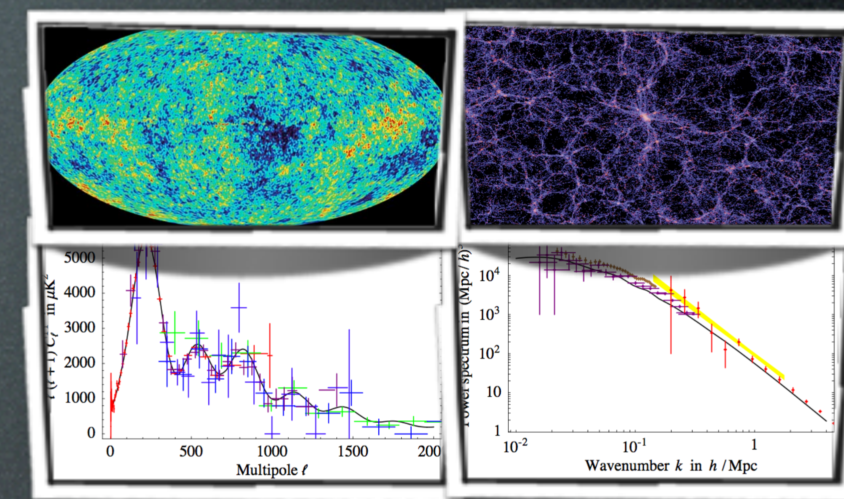
Introduction

DM exists



galactic rotation curves

weak lensing (e.g. in clusters)

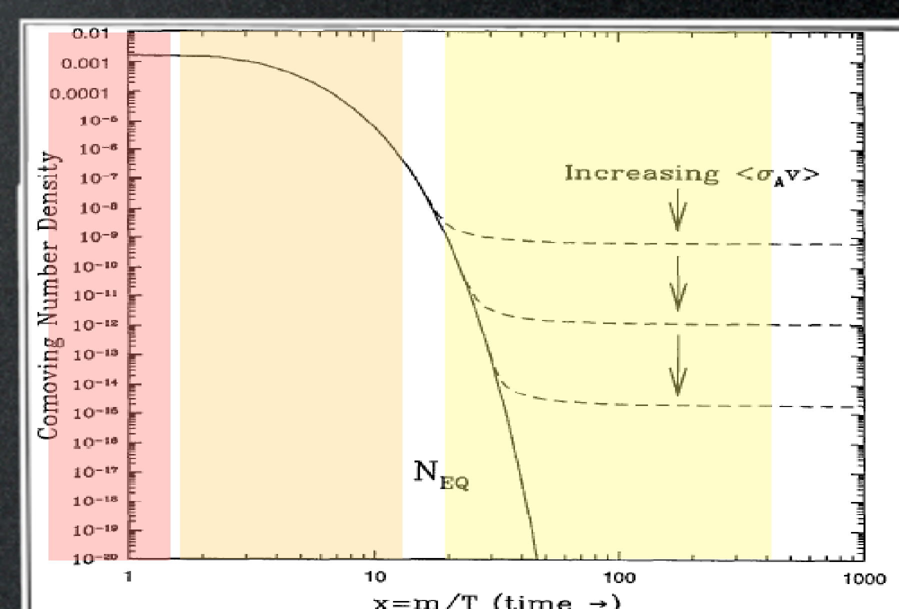


'precision cosmology' (CMB, LSS)

DM is a neutral, very long lived, weakly interacting particle.

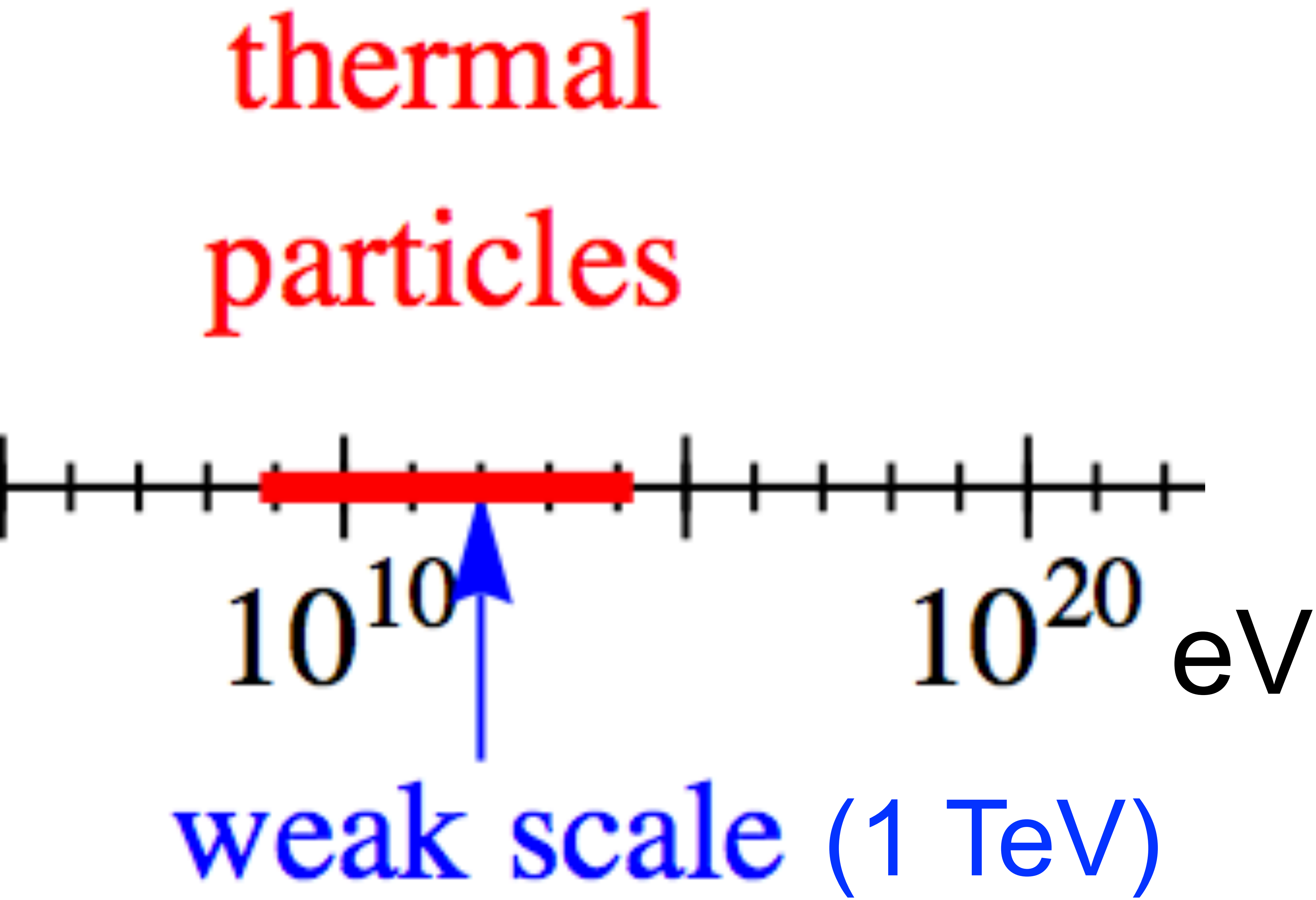
Some of us believe in the WIMP miracle.

- *weak*-scale mass (10 GeV - 1 TeV)
- *weak* interactions $\sigma v = 3 \cdot 10^{-26} \mathrm{cm}^3/\mathrm{sec}$
- give automatically correct abundance



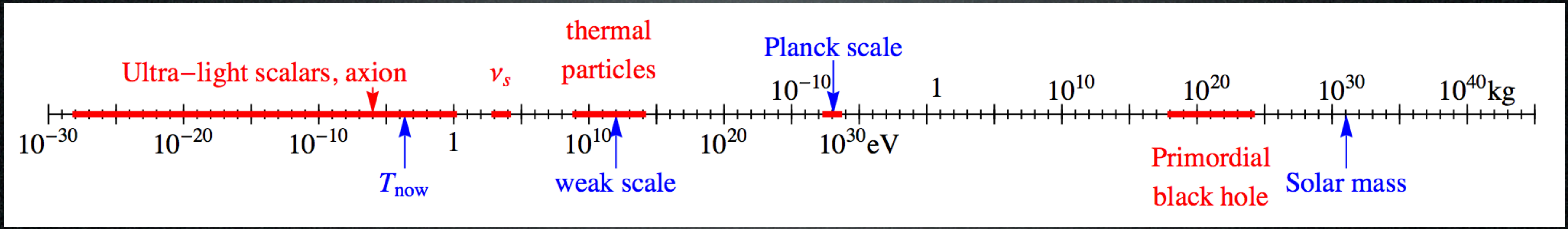
DM Candidates

A matter of perspective: plausible mass ranges



DM Candidates

A matter of perspective: plausible mass ranges



‘only’ 90 orders of magnitude!

DM Candidates

A matter of perspective: plausible mass ranges

Color code: ID, DD

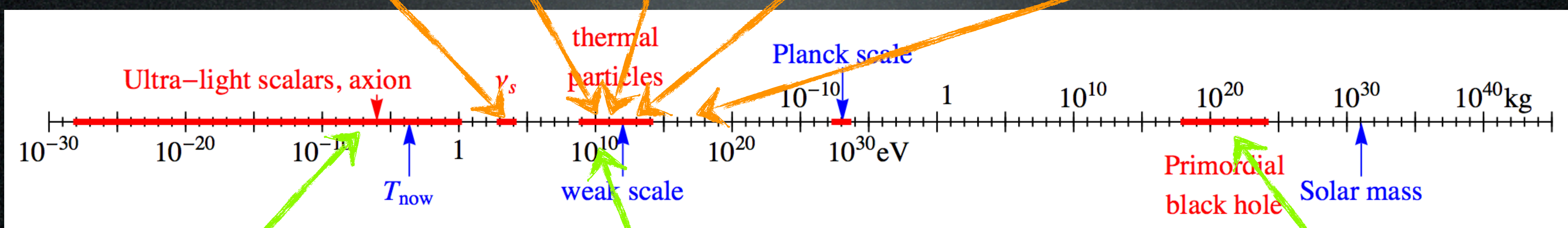
Fermi 135 GeV line

GeV gamma excess at GC

3.5 KeV line

PAMELA, Fermi, HESS excesses

PeV neutrinos Icecube



some activity recently

Light DM ('Dama') anomaly

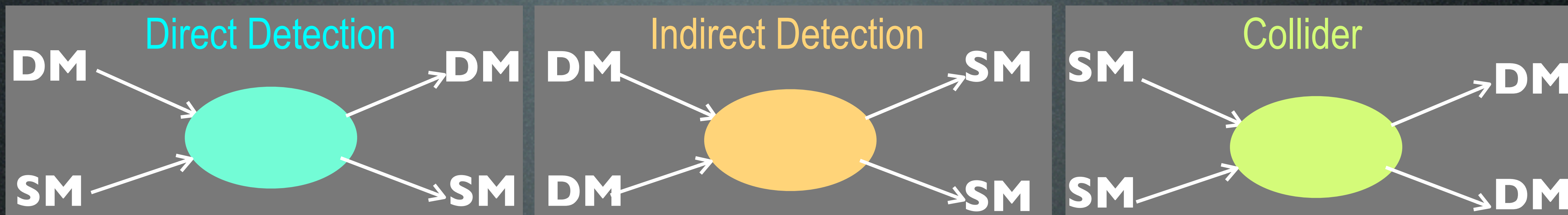
lots of activity recently

'only' 90 orders of magnitude!

DM detection

- direct detection
  - Xenon, CDMS, Lux, Dama/Libra...
- production at colliders
  - LHC
- indirect
  - γ from annihil in galactic center or halo and from secondary emission
    - Fermi, HESS, CTA, radio telescopes
  - e^+ from annihil in galactic halo or center
    - PAMELA, Fermi, AMS02
  - $\bar{p}$ from annihil in galactic halo or center
  - $\bar{d}$ from annihil in galactic halo or center
    - GAPS, AMS02
  - $\nu, \bar{\nu}$ from annihil in halo or massive bodies
    - Icecube, Antares, Km3Net

Complementarities



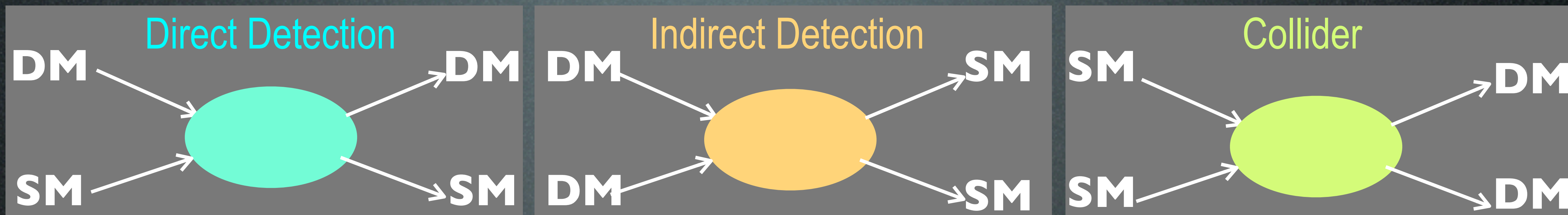
Regimes:

$q \sim \text{few KeV}$ | $\sqrt{s} \sim 2\, m_X$ | $\sqrt{s} \sim \text{few TeV}$

Basic quantities:

σ_{scatt} | $\langle \sigma_{\text{ann}} v \rangle$ | σ_{prod}

Complementarities



Regimes:

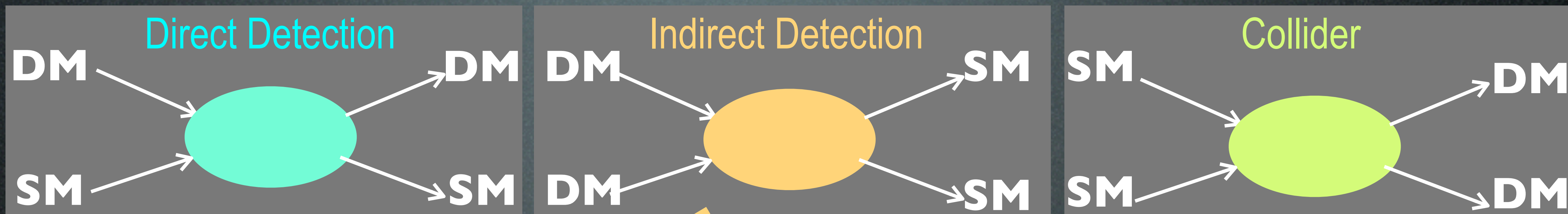
$q \sim \text{few KeV}$ $\sqrt{s} \sim 2\, m_X$ $\sqrt{s} \sim \text{few TeV}$

Basic quantities:

σ_{scatt} $\langle \sigma_{\text{ann}} v \rangle$ σ_{prod}

Can one trespass?

Complementarities



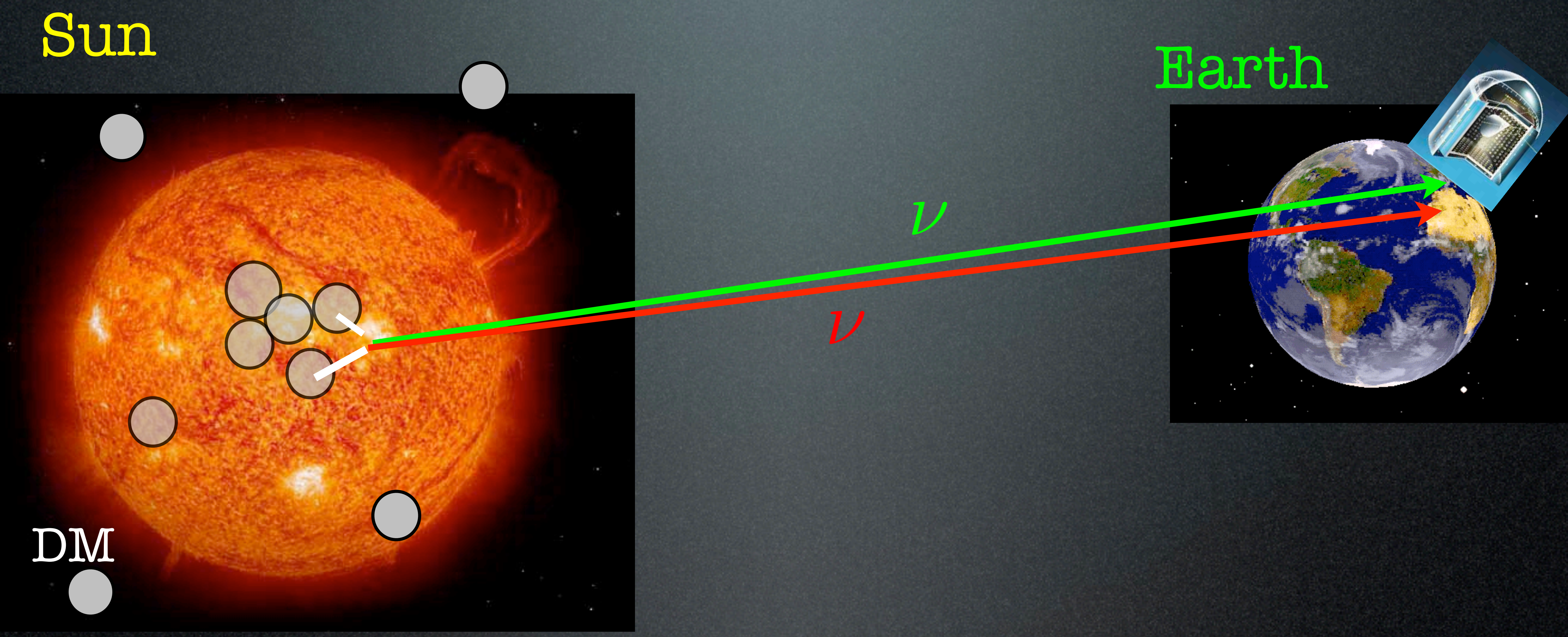
Regimes: $q \sim \text{few KeV}$ $\sqrt{s} \sim 2\, m_X$ $\sqrt{s} \sim \text{few TeV}$

Basic quantities: σ_{scatt} $\langle \sigma_{\text{ann}} v \rangle$ σ_{prod}

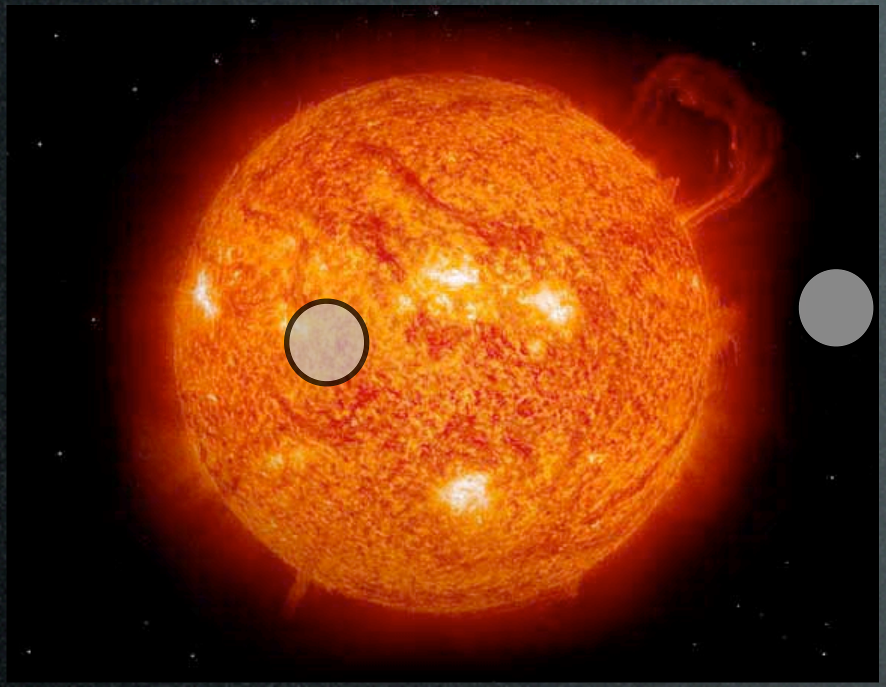
Can one trespass?

ID with neutrinos

ν from DM annihilations in the Sun



1. Capture & annihilation

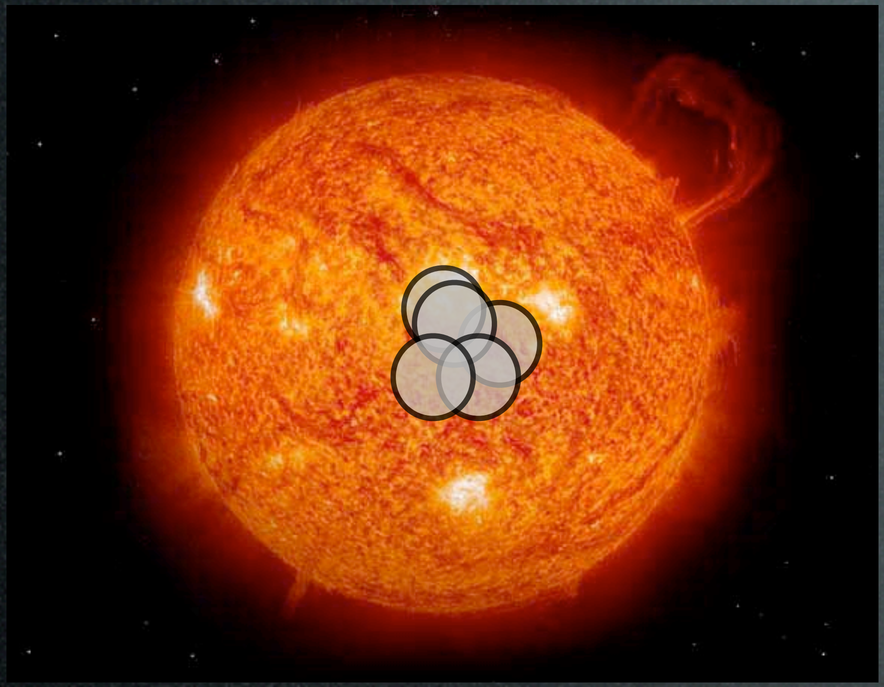


basics: DM particle scatters with nuclei and loses energy
if $v_f < v_{\rm esc}$ particle is gravitationally trapped
it spirals to center of body and accumulates
annihilates

$v_{\rm halo} \simeq 270$ km/s
$v_{{\rm esc},\odot} \simeq 620$ km/s
$v_{{\rm esc},\oplus} \simeq 12$ km/s

J. Silk, K. A. Olive and M. Srednicki, Phys. Rev. Lett. 55 (1985) 257

1. Capture & annihilation

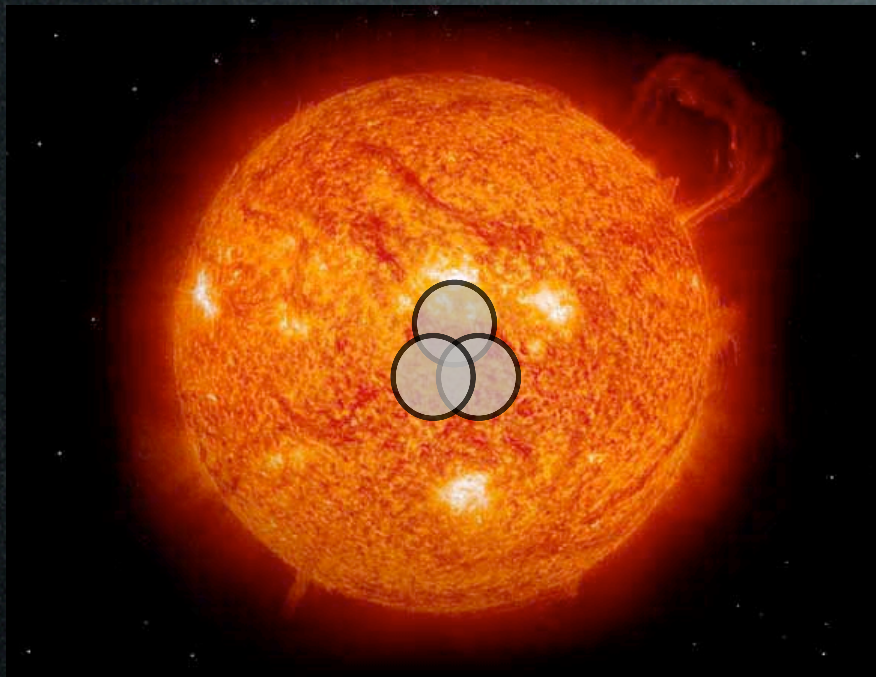


basics: DM particle scatters with nuclei and loses energy
if $v_f < v_{\rm esc}$ particle is gravitationally trapped
it spirals to center of body and accumulates
annihilates

$$v_{\rm halo} \simeq 270 \text{ km/s}$$
$$v_{{\rm esc},\odot} \simeq 620 \text{ km/s}$$
$$v_{{\rm esc},\oplus} \simeq 12 \text{ km/s}$$

J. Silk, K. A. Olive and M. Srednicki, Phys. Rev. Lett. 55 (1985) 257

1. Capture & annihilation



basics: DM particle scatters with nuclei and loses energy

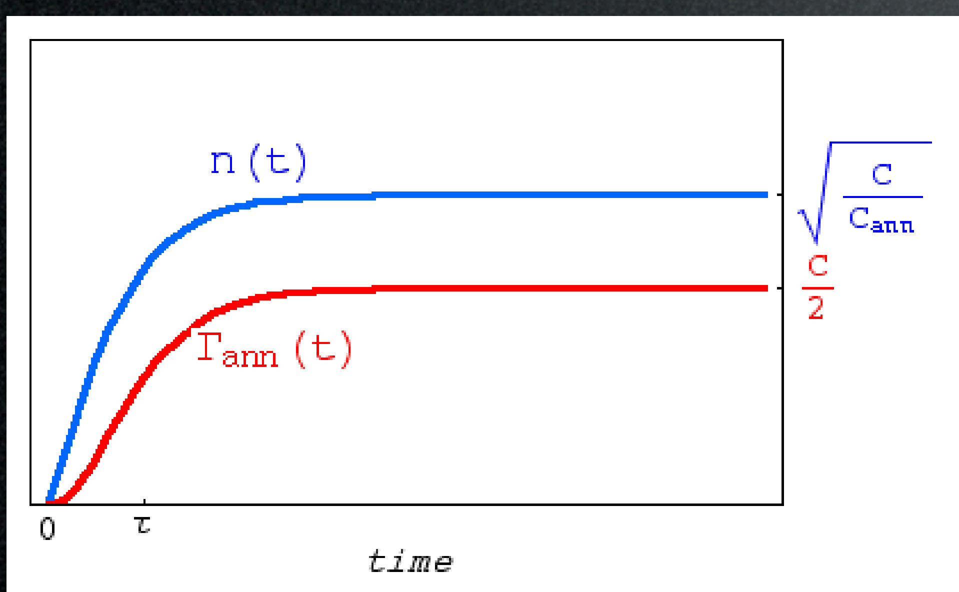
if $v_f < v_{\rm esc}$ particle is gravitationally trapped

it spirals to center of body and accumulates

annihilates

$$v_{\rm halo} \simeq 270 \text{ km/s}$$
$$v_{{\rm esc},\odot} \simeq 620 \text{ km/s}$$
$$v_{{\rm esc},\oplus} \simeq 12 \text{ km/s}$$

equilibrium attained:



σ_N (→ $\Gamma_{\rm capt}$) $\quad \langle \sigma_{\rm ann} v \rangle$ (→ $C_{\rm ann}$)

$$\dot{n} = \Gamma_{\rm capt} - C_{\rm ann}\, n^2$$

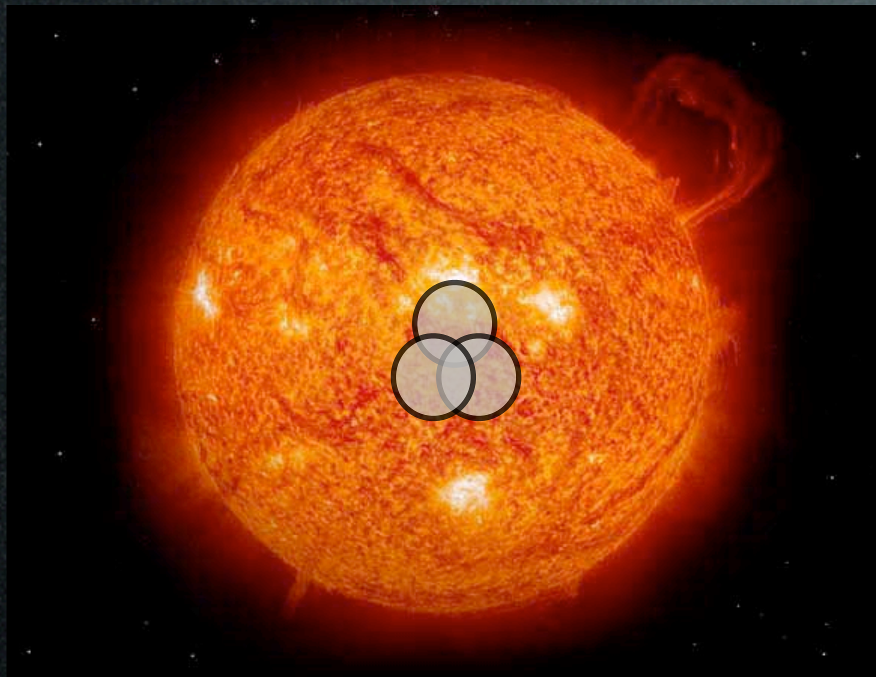
$$C_{\rm ann} = \langle \sigma v \rangle \left(\frac{G_N M_{\rm DM} \rho_\odot}{3 T_\odot} \right)^{3/2}$$

$$n(t) = \sqrt{\frac{\Gamma_{\rm capt}}{C_{\rm ann}}} \tanh\left(\frac{t}{\tau}\right)$$

$$\tau = \frac{1}{\sqrt{\Gamma_{\rm capt} C_{\rm ann}}}$$

$$\Gamma_{\rm ann}(t) = \frac{\Gamma_{\rm capt}}{2} \tanh^2\left(\frac{t}{\tau}\right)$$

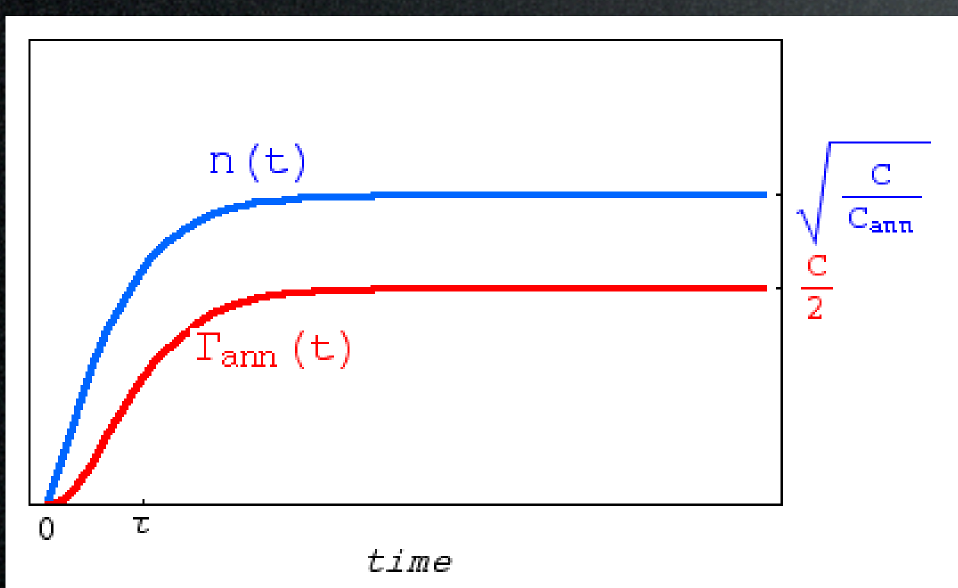
1. Capture & annihilation



basics: DM particle scatters with nuclei and loses energy
if $v_f < v_{\rm esc}$ particle is gravitationally trapped
it spirals to center of body and accumulates
annihilates

$v_{\rm halo} \simeq 270$ km/s
$v_{\rm esc,\odot} \simeq 620$ km/s
$v_{\rm esc,\oplus} \simeq 12$ km/s

equilibrium attained:



σ_N → $\Gamma_{\rm capt}$; $\langle\sigma_{\rm ann} v\rangle$ → $C_{\rm ann}$

$$\dot{n} = \Gamma_{\rm capt} - C_{\rm ann}\, n^2$$

$$C_{\rm ann} = \langle\sigma v\rangle \left(\frac{G_N M_{\rm DM}\,\rho_\odot}{3 T_\odot}\right)^{3/2}$$

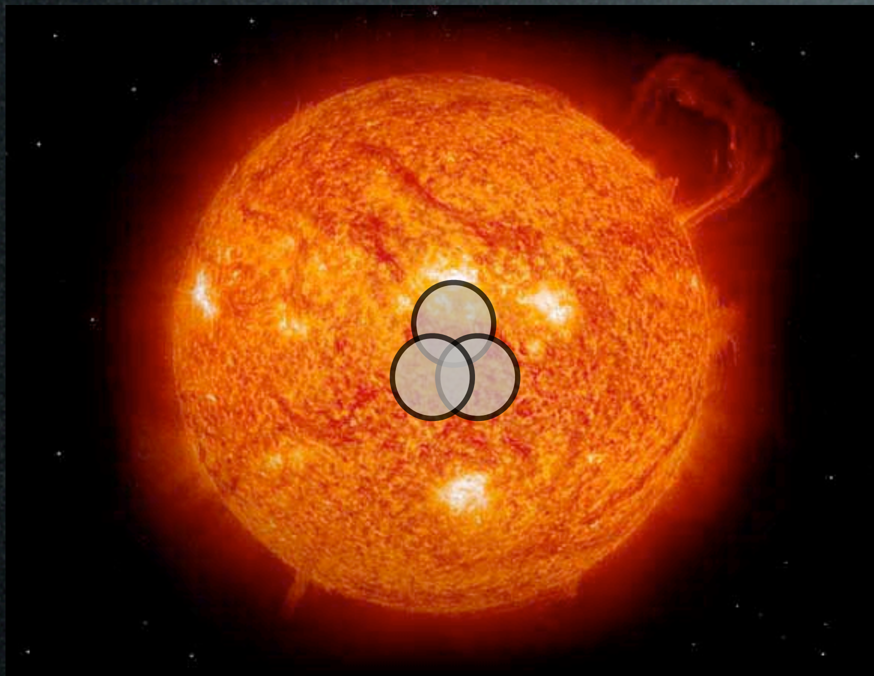
$$n(t) = \sqrt{\frac{\Gamma_{\rm capt}}{C_{\rm ann}}}\tanh\left(\frac{t}{\tau}\right)$$

$$\tau = \frac{1}{\sqrt{\Gamma_{\rm capt} C_{\rm ann}}}$$

$$\Gamma_{\rm ann}(t) = \frac{\Gamma_{\rm capt}}{2}\tanh^2\left(\frac{t}{\tau}\right)$$

The main physical parameter is: σ_N (DM-nucleon scattering cross section)

1. Capture & annihilation



basics: DM particle scatters with nuclei and loses energy

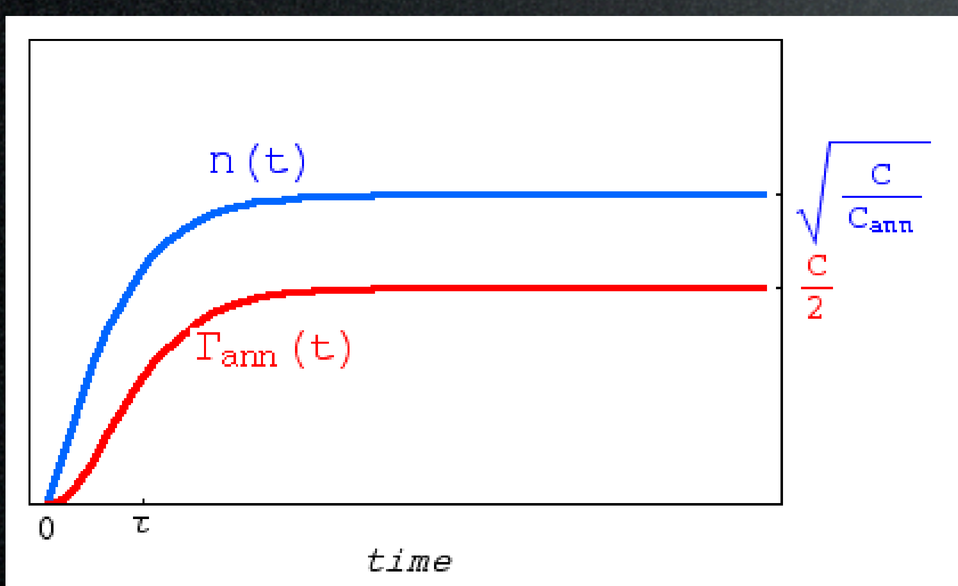
if $v_f < v_{\rm esc}$ particle is gravitationally trapped

it spirals to center of body and accumulates

annihilates

$$v_{\rm halo} \simeq 270 \text{ km/s}$$
$$v_{{\rm esc},\odot} \simeq 620 \text{ km/s}$$
$$v_{{\rm esc},\oplus} \simeq 12 \text{ km/s}$$

equilibrium attained:



σ_N → $\Gamma_{\rm capt}$; $\langle \sigma_{\rm ann} v \rangle$ → $C_{\rm ann}$

$$\dot{n} = \Gamma_{\rm capt} - C_{\rm ann}\, n^2$$

$$C_{\rm ann} = \langle \sigma v \rangle \left(\frac{G_N M_{\rm DM} \rho_\odot}{3 T_\odot} \right)^{3/2}$$

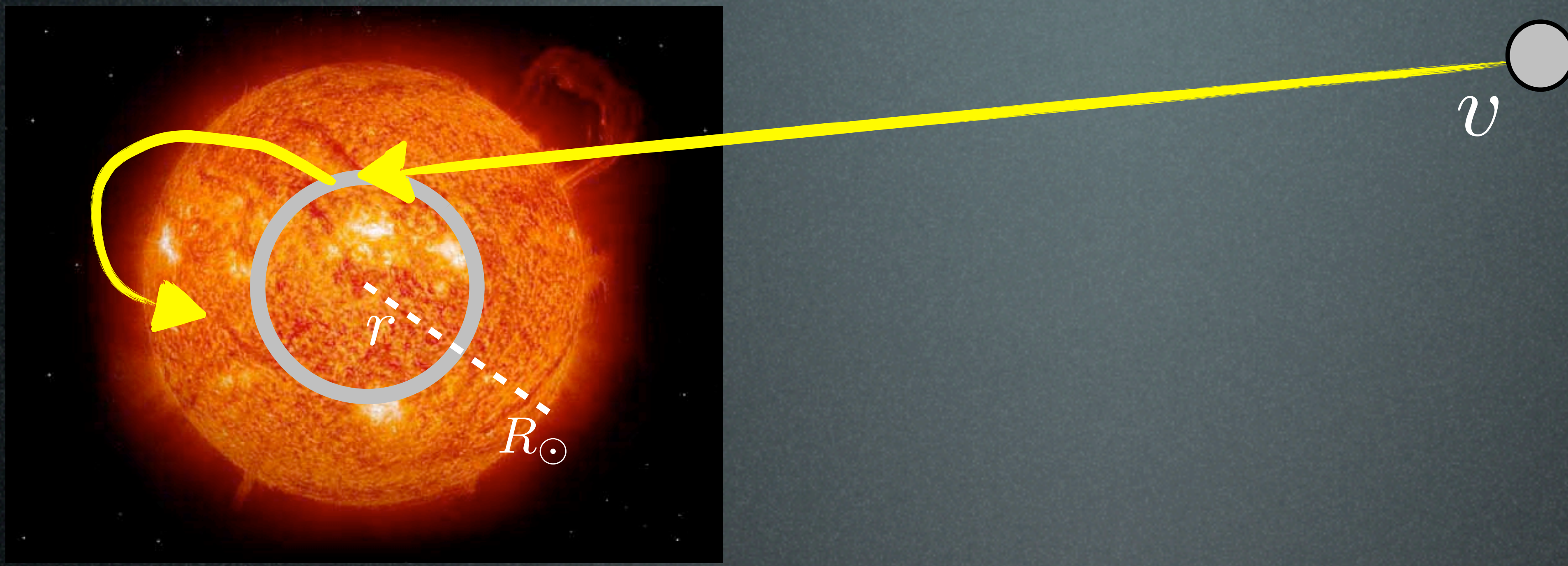
$$n(t) = \sqrt{\frac{\Gamma_{\rm capt}}{C_{\rm ann}}} \tanh\left(\frac{t}{\tau}\right)$$

$$\tau = \frac{1}{\sqrt{\Gamma_{\rm capt} C_{\rm ann}}}$$

$$\Gamma_{\rm ann}(t) = \frac{\Gamma_{\rm capt}}{2} \tanh^2\left(\frac{t}{\tau}\right) \to \frac{\Gamma_{\rm capt}}{2}$$

The main physical parameter is: σ_N (DM-nucleon scattering cross section)

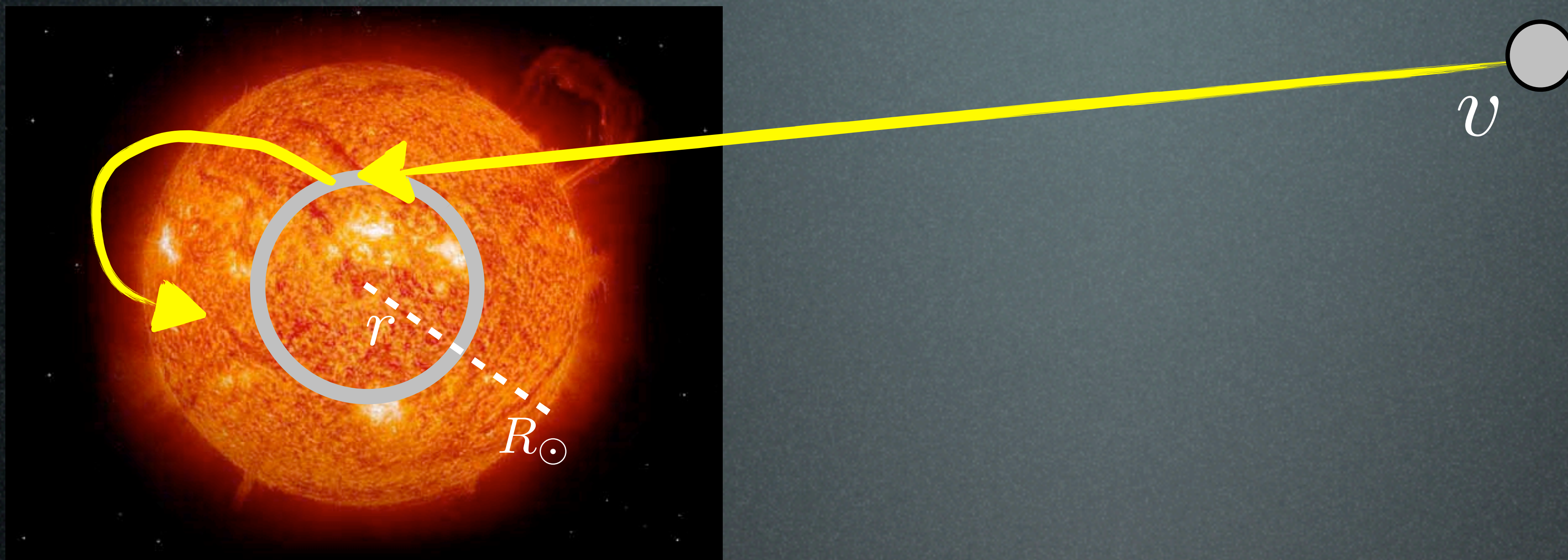
1. Capture & annihilation



A.Gould 1987, 1988, 1990

$$\Gamma_{\rm capt} = \frac{\rho_{\rm DM}}{M_{\rm DM}} \sum_i \sigma_i \int_0^{R_\odot} dr\ 4\pi r^2\ n_i(r) \int_0^\infty dv\ 4\pi v^2 f_\odot(v) \frac{v^2 + v_{\odot \rm esc}^2}{v} \wp_i(v, v_{\odot \rm esc})$$

1. Capture & annihilation

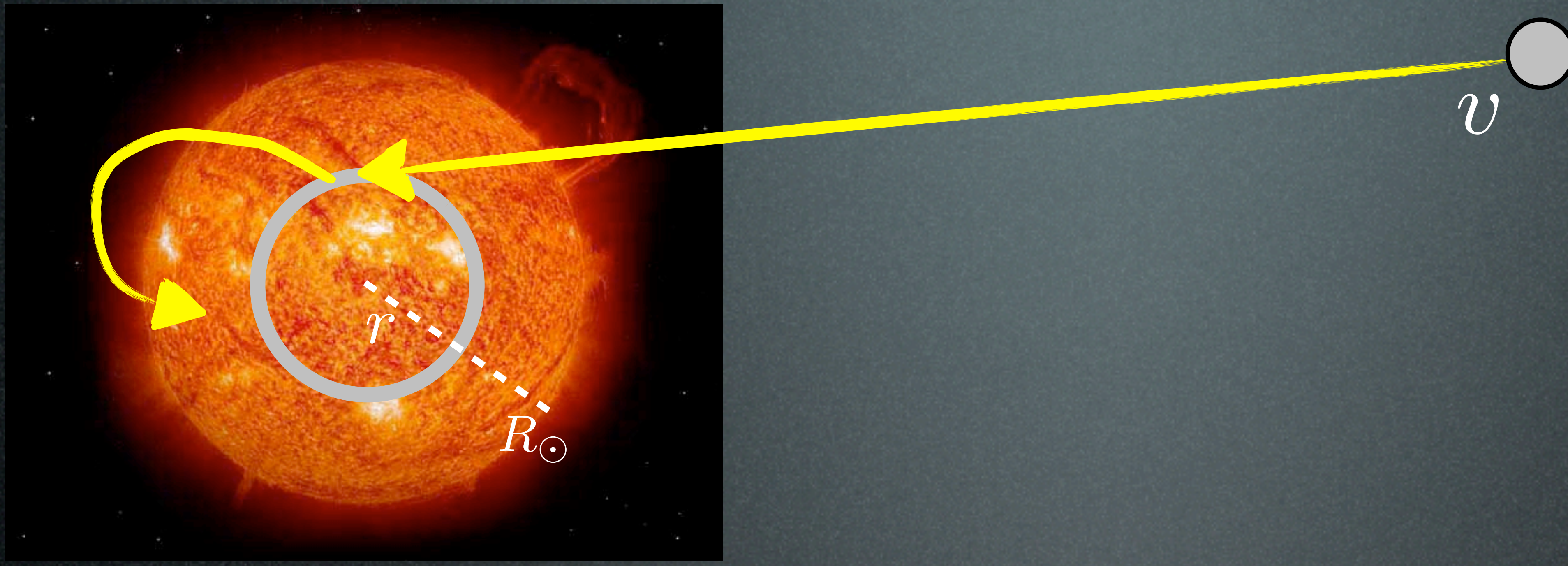


A.Gould 1987, 1988, 1990

$$\Gamma_{\rm capt} = \frac{\rho_{\rm DM}}{M_{\rm DM}} \sum_i \sigma_i \int_0^{R_\odot} dr\ 4\pi r^2\ n_i(r) \int_0^{\infty} dv\ 4\pi v^2 f_\odot(v) \frac{v^2 + v^2_{\odot{\rm esc}}}{v} \wp_i(v, v_{\odot{\rm esc}})$$

DM number density

1. Capture & annihilation



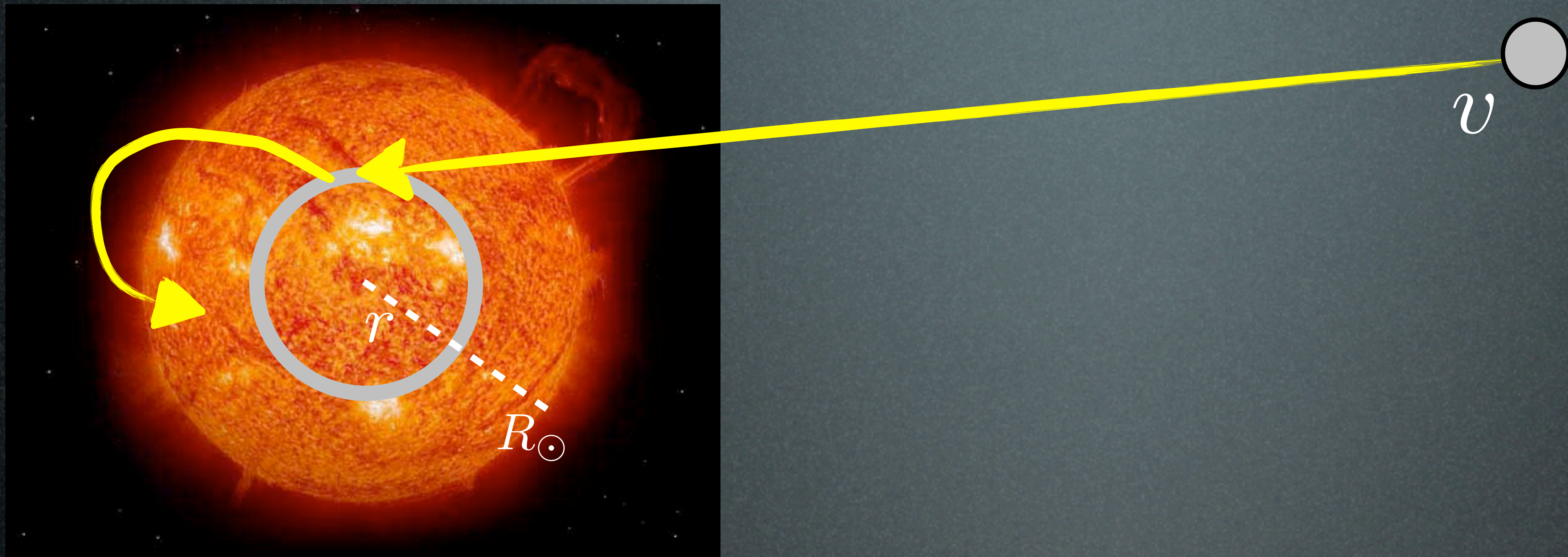
A.Gould 1987, 1988, 1990

$$\Gamma_{\rm capt} = \frac{\rho_{\rm DM}}{M_{\rm DM}} \sum_i \sigma_i \int_0^{R_\odot} dr\ 4\pi r^2\ n_i(r) \int_0^{\infty} dv\ 4\pi v^2 f_\odot(v) \frac{v^2 + v_{\odot \rm esc}^2}{v} \wp_i(v, v_{\odot \rm esc})$$

DM number density

scattering cross section on element **i**

1. Capture & annihilation



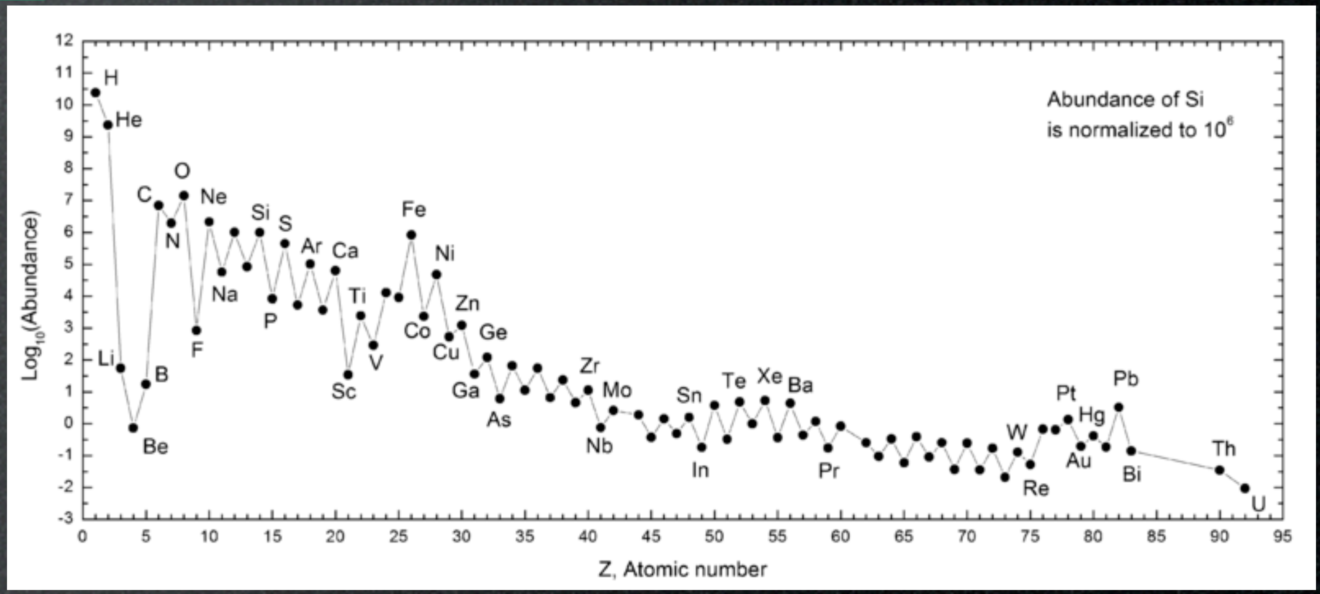
A.Gould 1987, 1988, 1990

$$\Gamma_{\rm capt} = \frac{\rho_{\rm DM}}{M_{\rm DM}} \sum_i \sigma_i \int_0^{R_\odot} dr\ 4\pi r^2\ n_i(r) \int_0^\infty dv\ 4\pi v^2 f_\odot(v) \frac{v^2 + v_{\odot \rm esc}^2}{v} \wp_i(v, v_{\odot \rm esc})$$

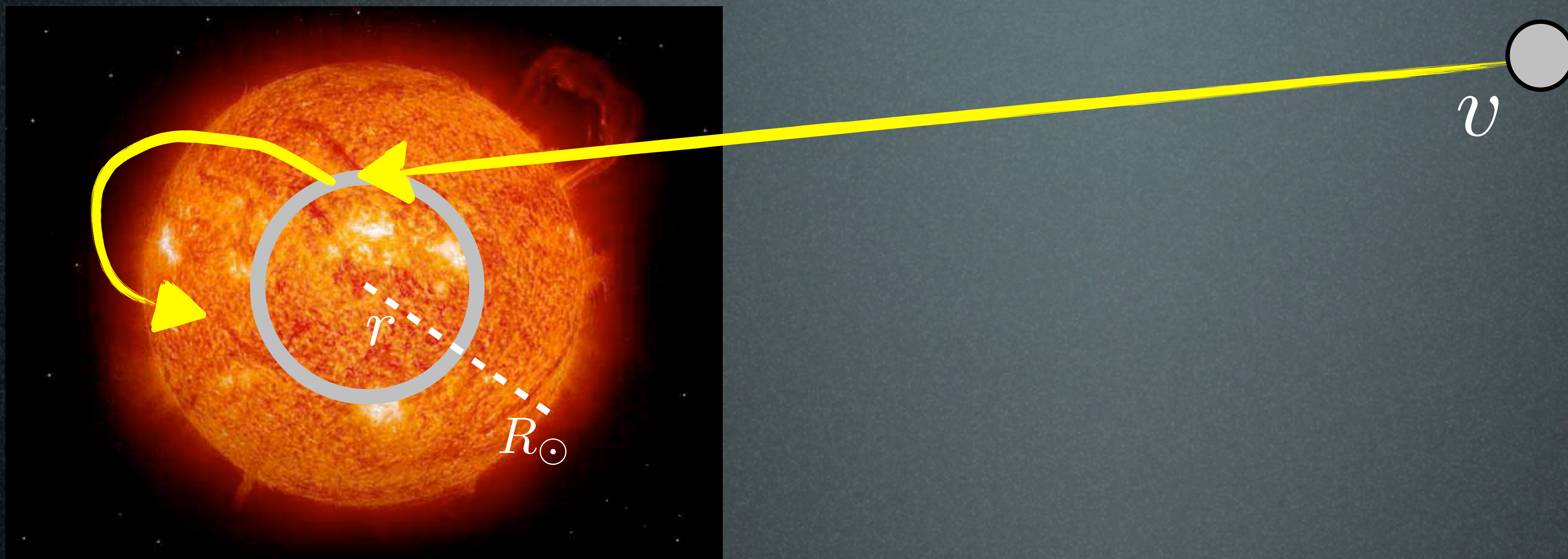
DM number density

scattering cross section on element **i**

number density of element **i**



1. Capture & annihilation



A.Gould 1987, 1988, 1990

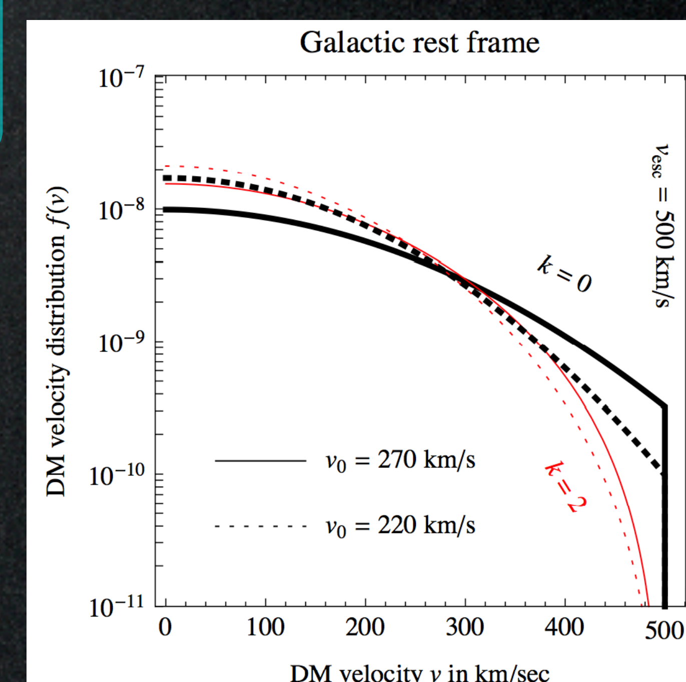
$$\Gamma_{\rm capt} = \frac{\rho_{\rm DM}}{M_{\rm DM}} \sum_i \sigma_i \int_0^{R_\odot} dr\ 4\pi r^2\ n_i(r) \int_0^\infty dv\ 4\pi v^2 f_\odot(v) \frac{v^2 + v^2_{\odot \rm esc}}{v} \wp_i(v, v_{\odot \rm esc})$$

DM number density

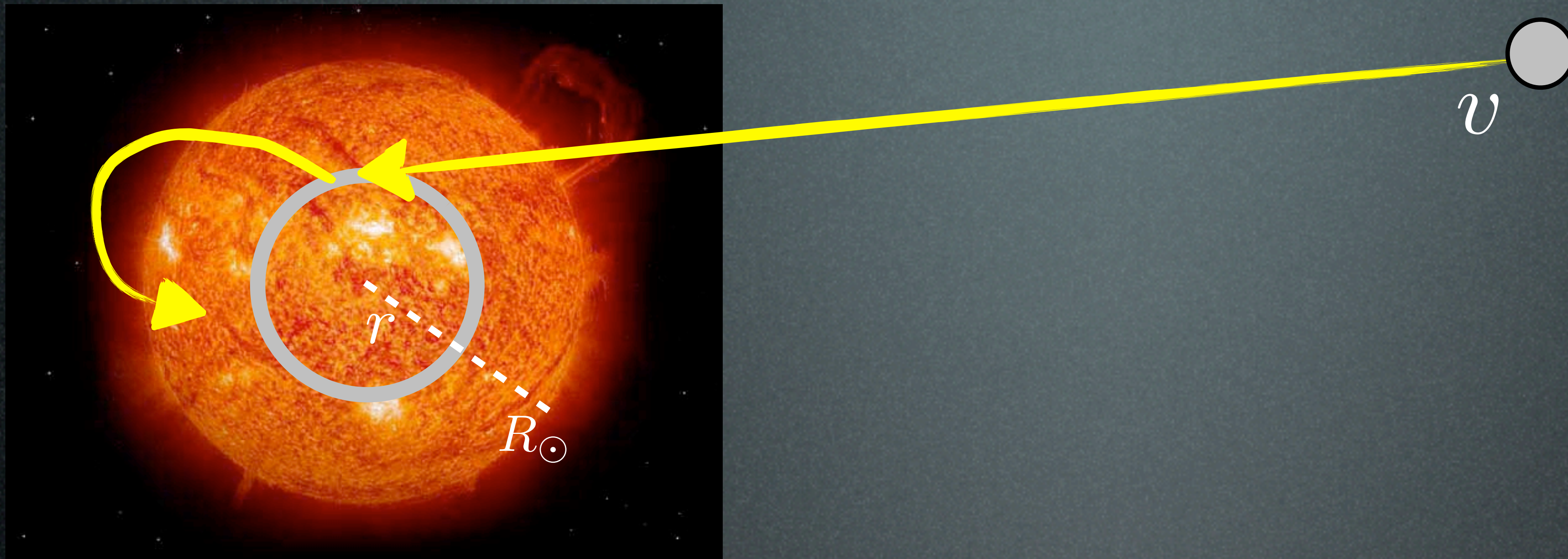
scattering cross section on element **i**

number density of element **i**

velocity distribution (in solar frame, without Sun's gravity)



1. Capture & annihilation



A.Gould 1987, 1988, 1990

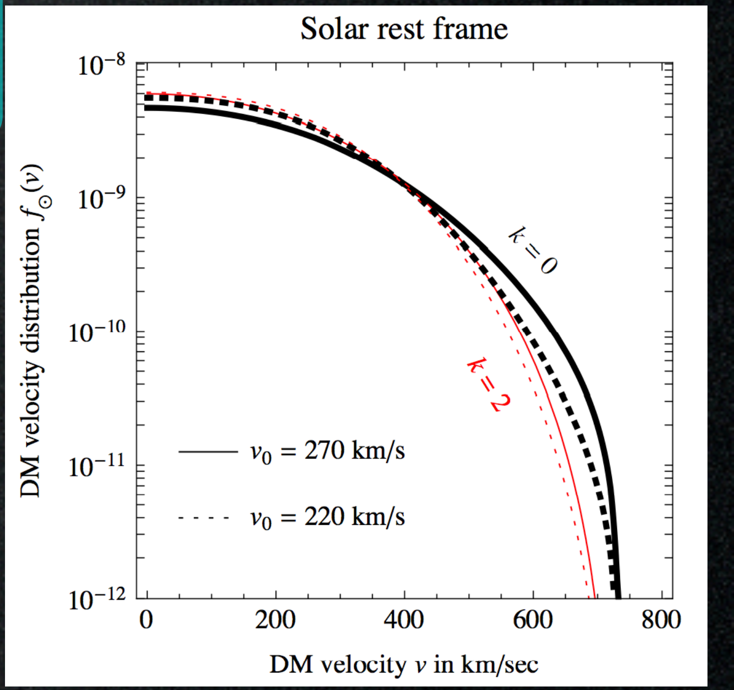
$$\Gamma_{\rm capt} = \frac{\rho_{\rm DM}}{M_{\rm DM}} \sum_i \sigma_i \int_0^{R_\odot} dr\ 4\pi r^2\, n_i(r) \int_0^\infty dv\ 4\pi v^2 f_\odot(v)\, \frac{v^2 + v_{\odot\rm esc}^2}{v}\, \wp_i(v, v_{\odot\rm esc})$$

DM number density

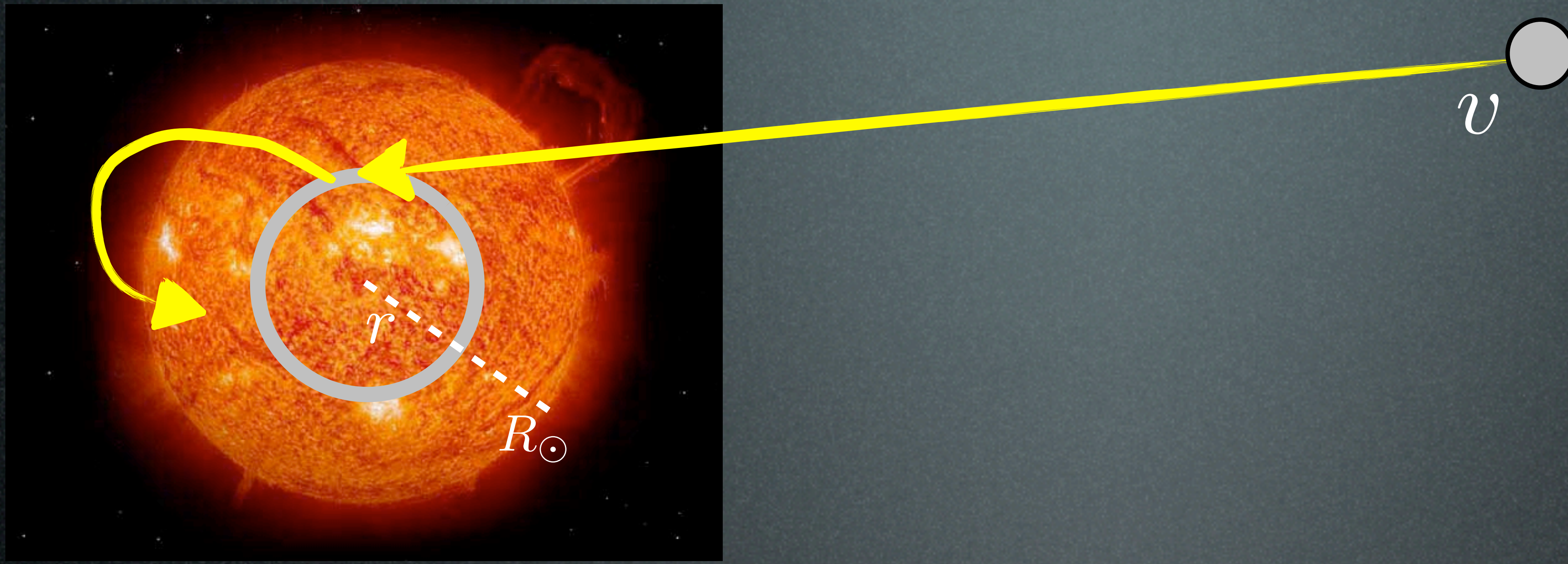
scattering cross section on element **i**

number density of element **i**

velocity distribution (in solar frame, without Sun's gravity)



1. Capture & annihilation



A.Gould 1987, 1988, 1990

$$\Gamma_{\rm capt} = \frac{\rho_{\rm DM}}{M_{\rm DM}} \sum_i \sigma_i \int_0^{R_\odot} dr\ 4\pi r^2\ n_i(r) \int_0^\infty dv\ 4\pi v^2 f_\odot(v) \frac{v^2 + v^2_{\odot \rm esc}}{v} \wp_i(v, v_{\odot \rm esc})$$

DM number density

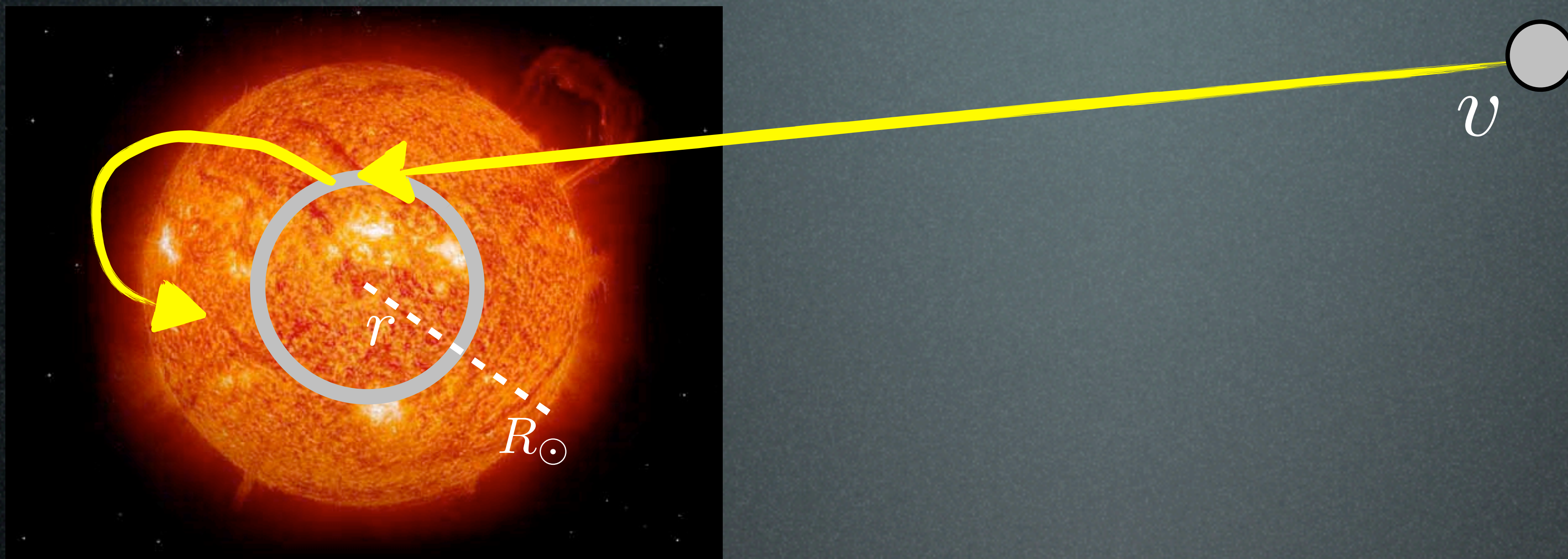
scattering cross section on element **i**

number density of element **i**

velocity distribution
(in solar frame, without Sun's gravity)

effect of solar gravity

1. Capture & annihilation



A.Gould 1987, 1988, 1990

$$\Gamma_{\rm capt} = \frac{\rho_{\rm DM}}{M_{\rm DM}} \sum_i \sigma_i \int_0^{R_\odot} dr\ 4\pi r^2\, n_i(r) \int_0^\infty dv\ 4\pi v^2 f_\odot(v) \frac{v^2 + v^2_{\odot \rm esc}}{v}\, \wp_i(v, v_{\odot \rm esc})$$

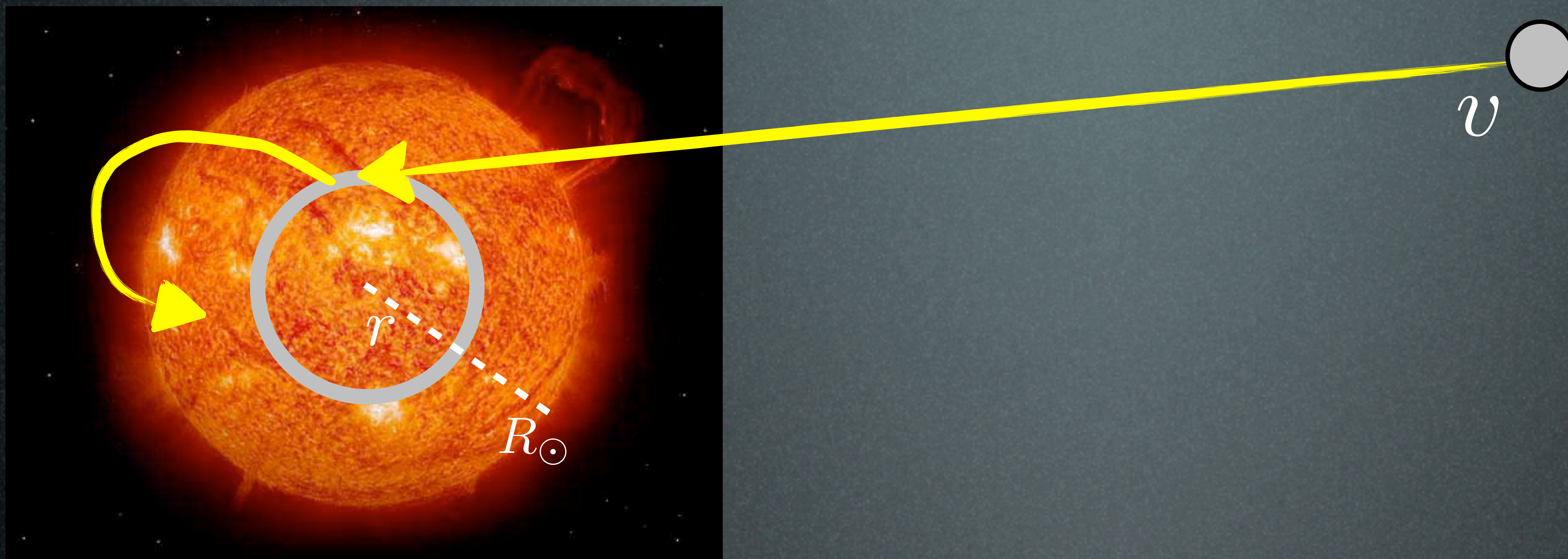
- $\frac{\rho_{\rm DM}}{M_{\rm DM}}$: DM number density
- σ_i: scattering cross section on element **i**
- $n_i(r)$: number density of element **i**
- $f_\odot(v)$: velocity distribution (in solar frame, without Sun's gravity)
- $\frac{v^2 + v^2_{\odot \rm esc}}{v}$: effect of solar gravity

scattering probability:

$$\wp_i(v, v_{\odot \rm esc}) = \max\left(0, 1 - \frac{\Delta_{\rm min}}{\Delta_{\rm max}}\right)$$

$$\Delta_{\rm max} = \frac{4\, m_i\, M_{\rm DM}}{(M_{\rm DM} + m_i)^2} \qquad \Delta_{\rm min} = \frac{v^2}{v^2 + v^2_{\odot \rm esc}}$$

1. Capture & annihilation



A.Gould 1987, 1988, 1990

$$\Gamma_{\rm capt} = \frac{\rho_{\rm DM}}{M_{\rm DM}} \sum_i \sigma_i \int_0^{R_\odot} dr\ 4\pi r^2\ n_i(r) \int_0^\infty dv\ 4\pi v^2 f_\odot(v) \frac{v^2 + v_{\odot \rm esc}^2}{v} \wp_i(v, v_{\odot \rm esc})$$

DM number density

scattering cross section on element **i**

number density of element **i**

velocity distribution (in solar frame, without Sun's gravity)

effect of solar gravity

scattering probability:

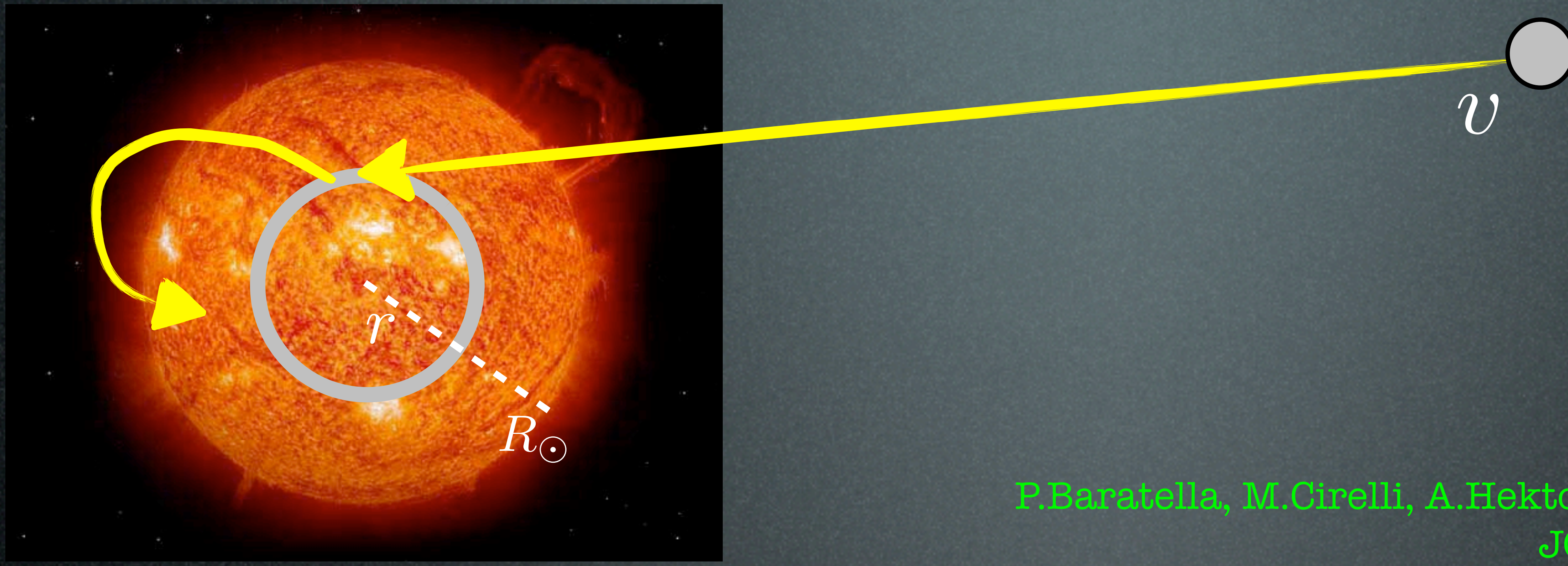
$$\wp_i(v, v_{\odot \rm esc}) = \max\left(0, 1 - \frac{\Delta_{\rm min}}{\Delta_{\rm max}}\right) \qquad \Delta_{\rm max} = \frac{4\, m_i\, M_{\rm DM}}{(M_{\rm DM} + m_i)^2} \qquad \Delta_{\rm min} = \frac{v^2}{v^2 + v_{\odot \rm esc}^2}$$

$$\wp_i(v, v_{\odot \rm esc}) = \frac{1}{E\,\Delta_{\rm max}} \int_{E\,\Delta_{\rm min}}^{E\,\Delta_{\rm max}} {\rm d}(\Delta E)\, |F_i(\Delta E)|^2 \qquad |F_i(\Delta E)|^2 = e^{-\Delta E/E_0}$$

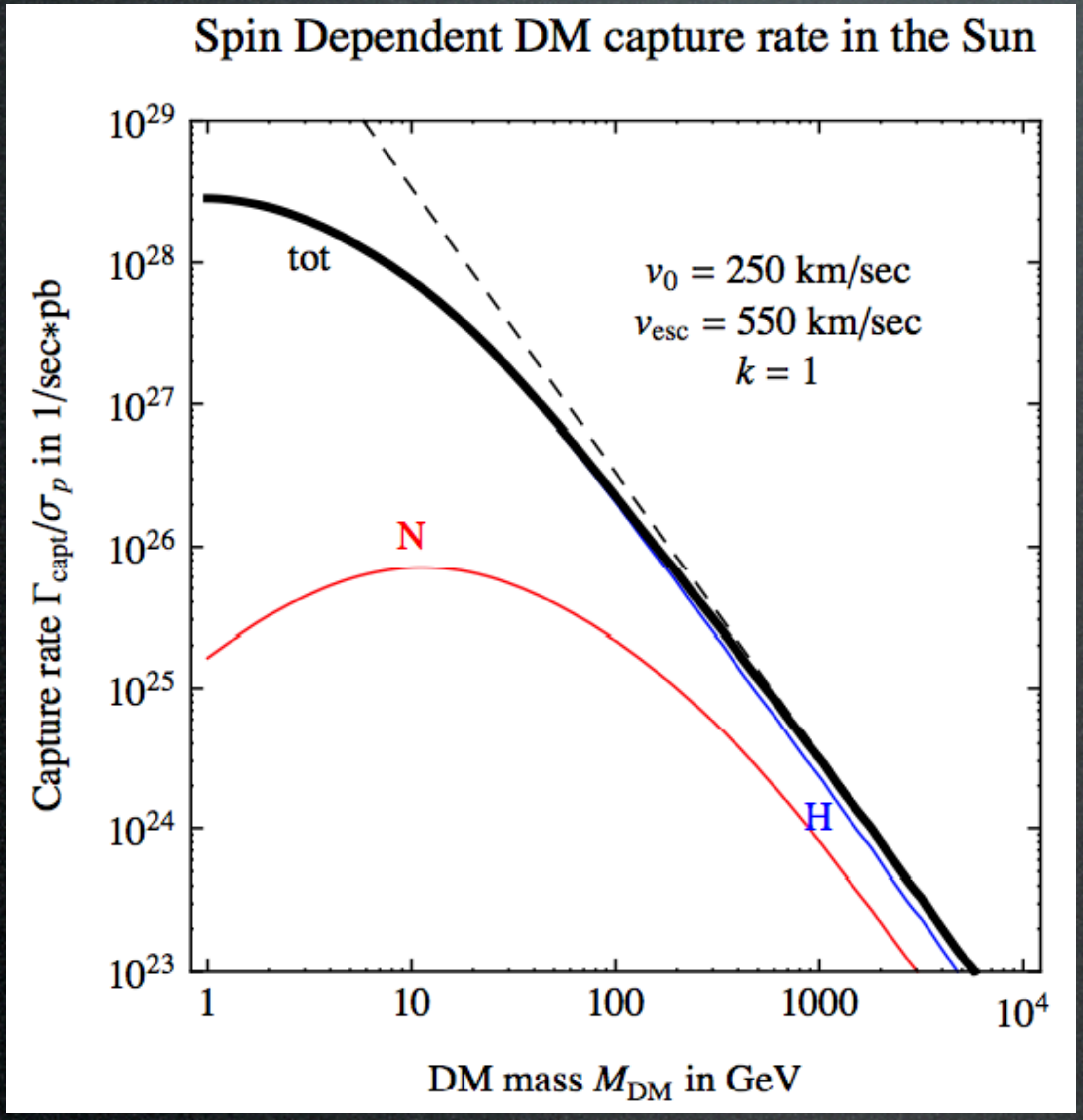
$$E_0^{\rm SI} = 5/2 m_i r_i^2$$

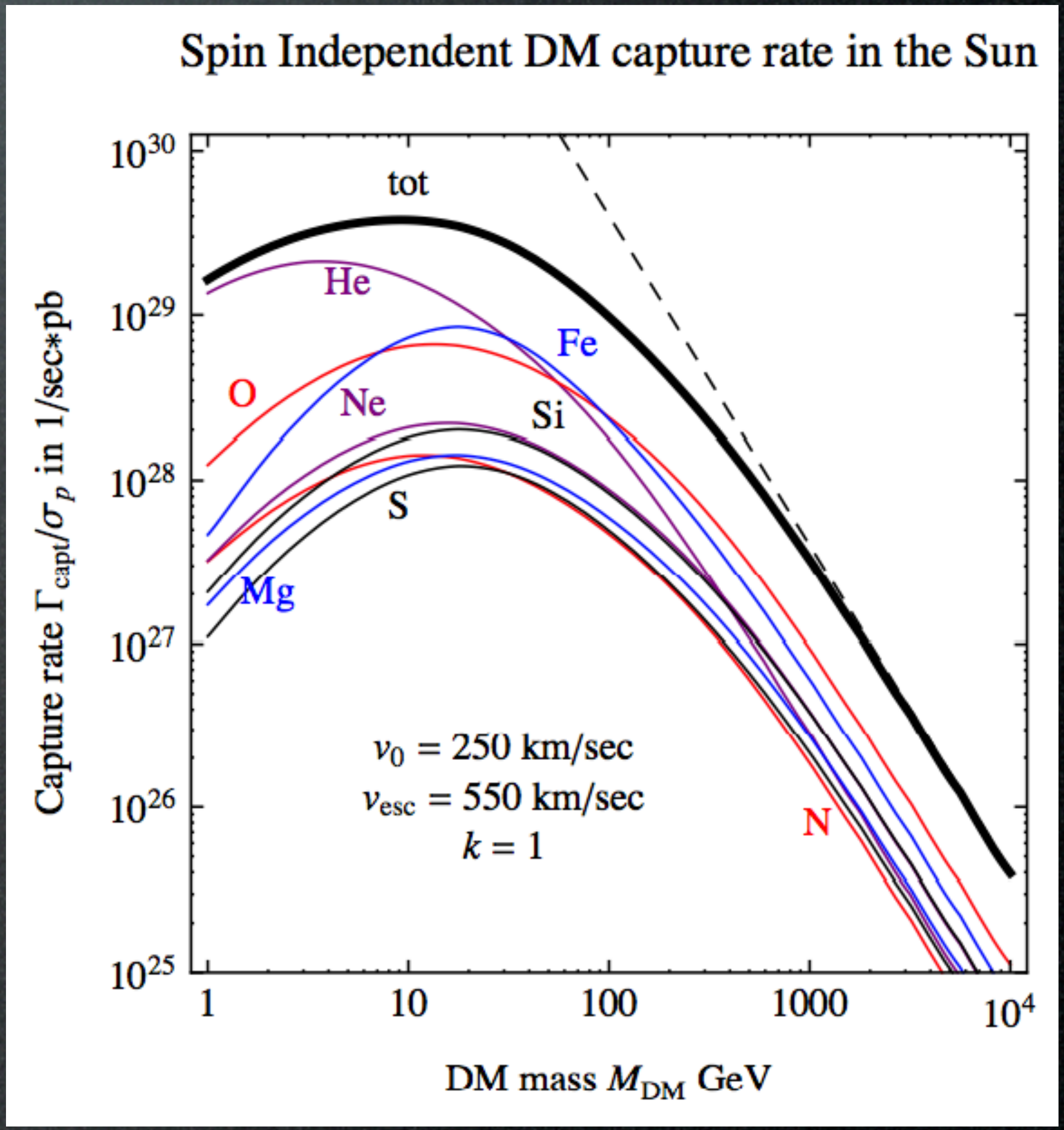
$$E_0^{\rm SD} = 3/2 m_i r_i^2$$

1. Capture & annihilation



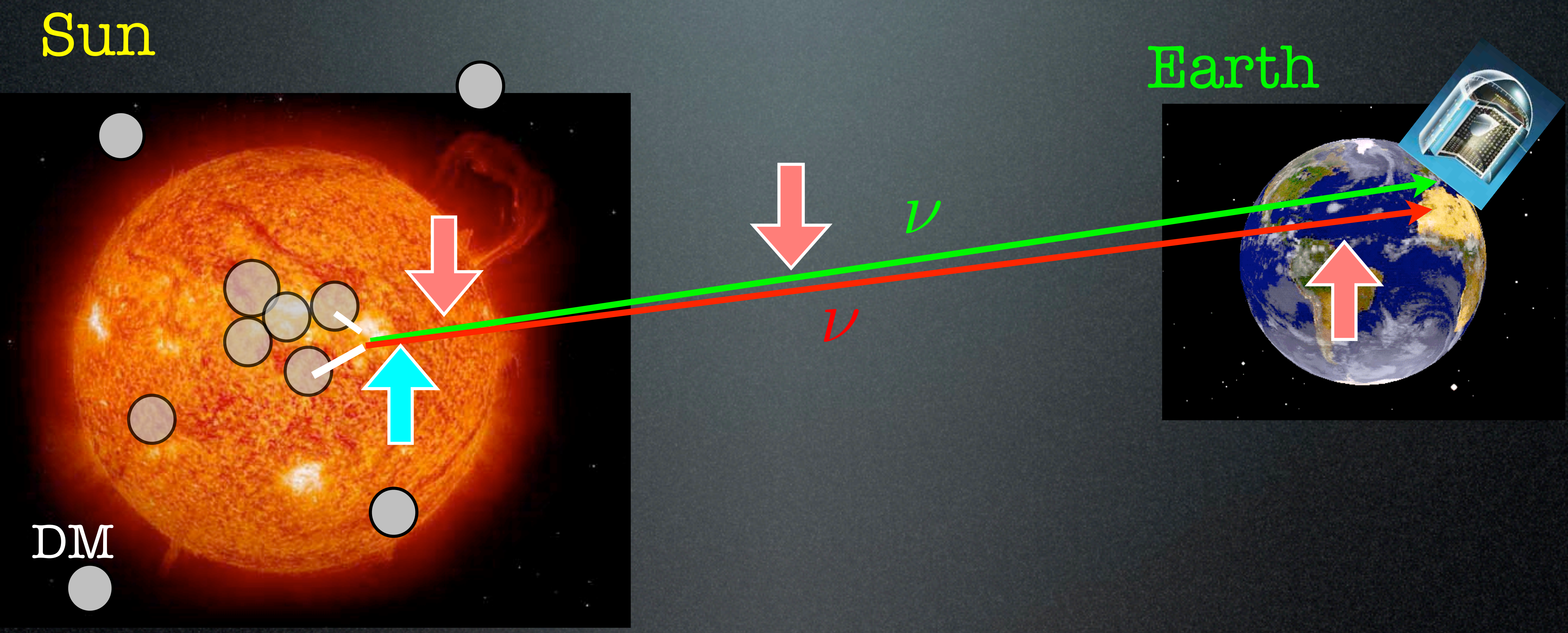
P.Baratella, M.Cirelli, A.Hektor, J.Pata, M.Piibeleht, A.Strumia,
JCAP 1403 (2014) 053, 1312.6408





ID with neutrinos

ν from DM annihilations in the Sun



Include oscillations + interactions:

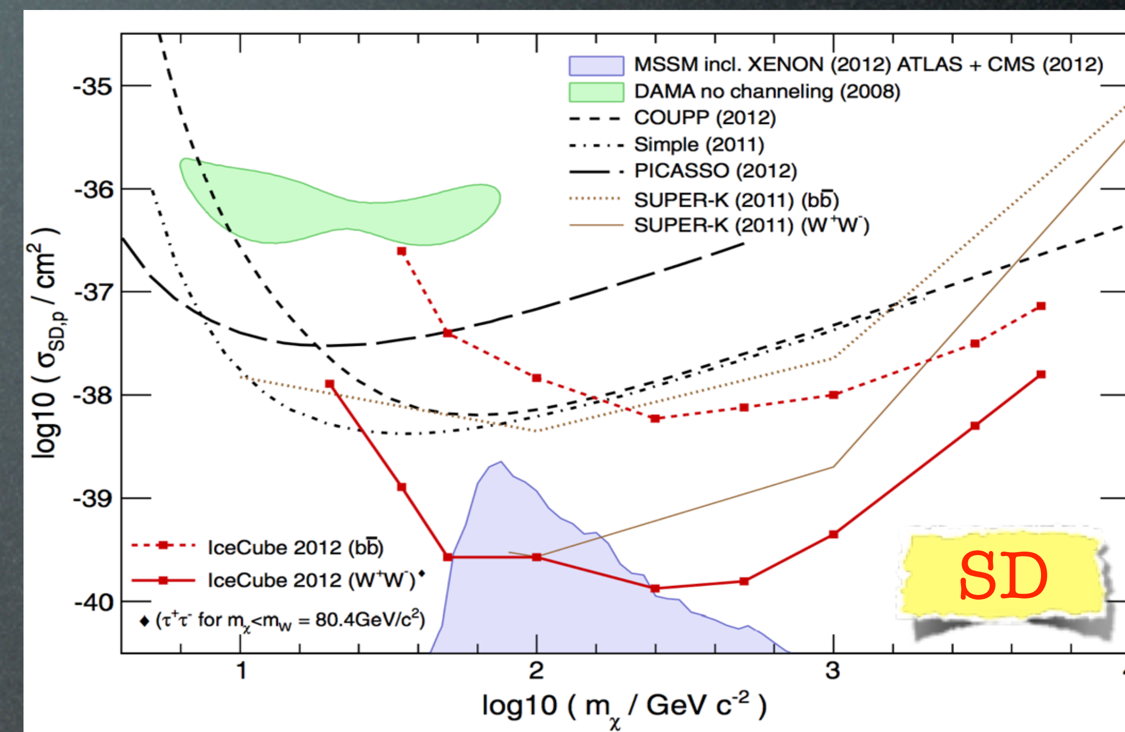
- reshuffling of the 3 flavors
- distortions the spectra
- attenuations of the fluxes

ID with neutrinos

ν from DM annihilations in the Sun

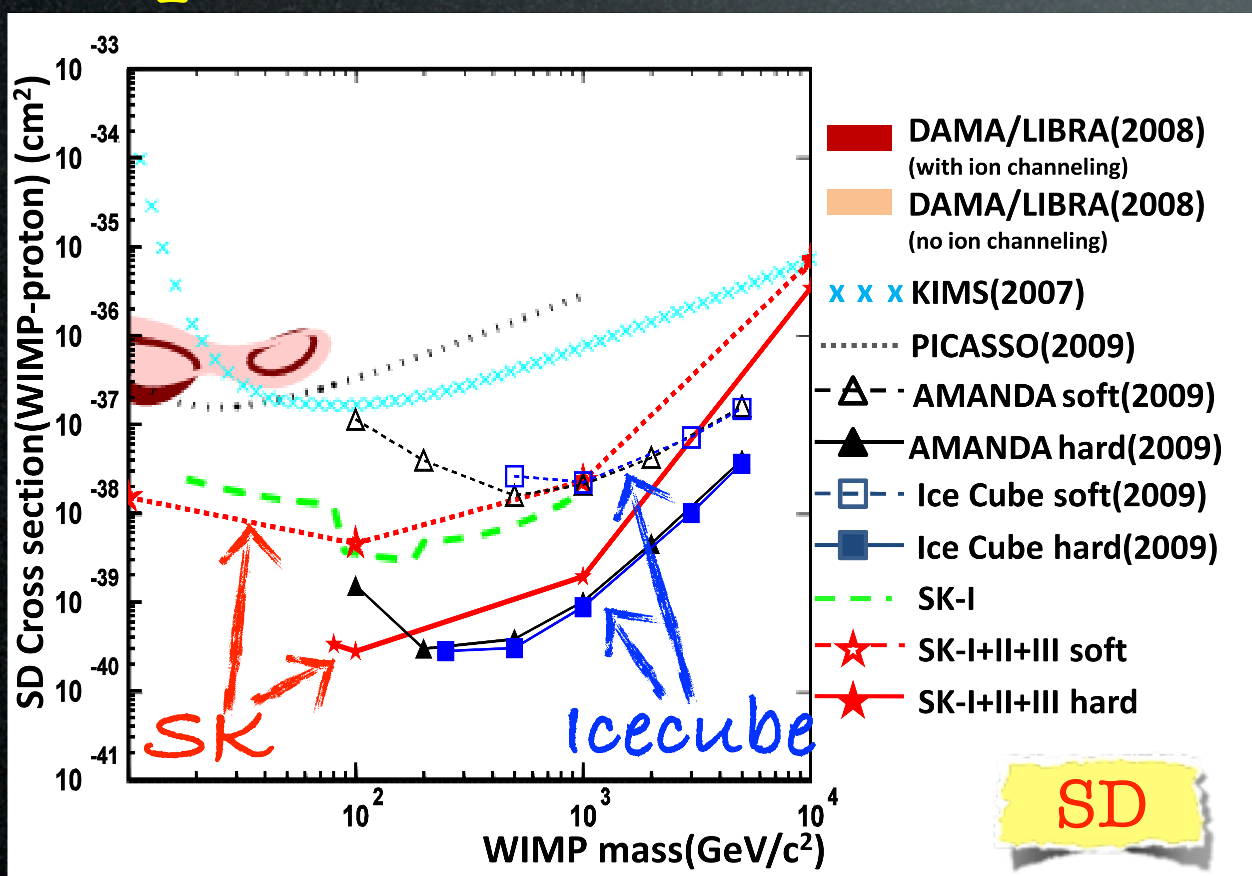
Probe the <u>scattering</u> cross section (competitively if SD).

ICECUBE



Icecube Coll., 1212.4097

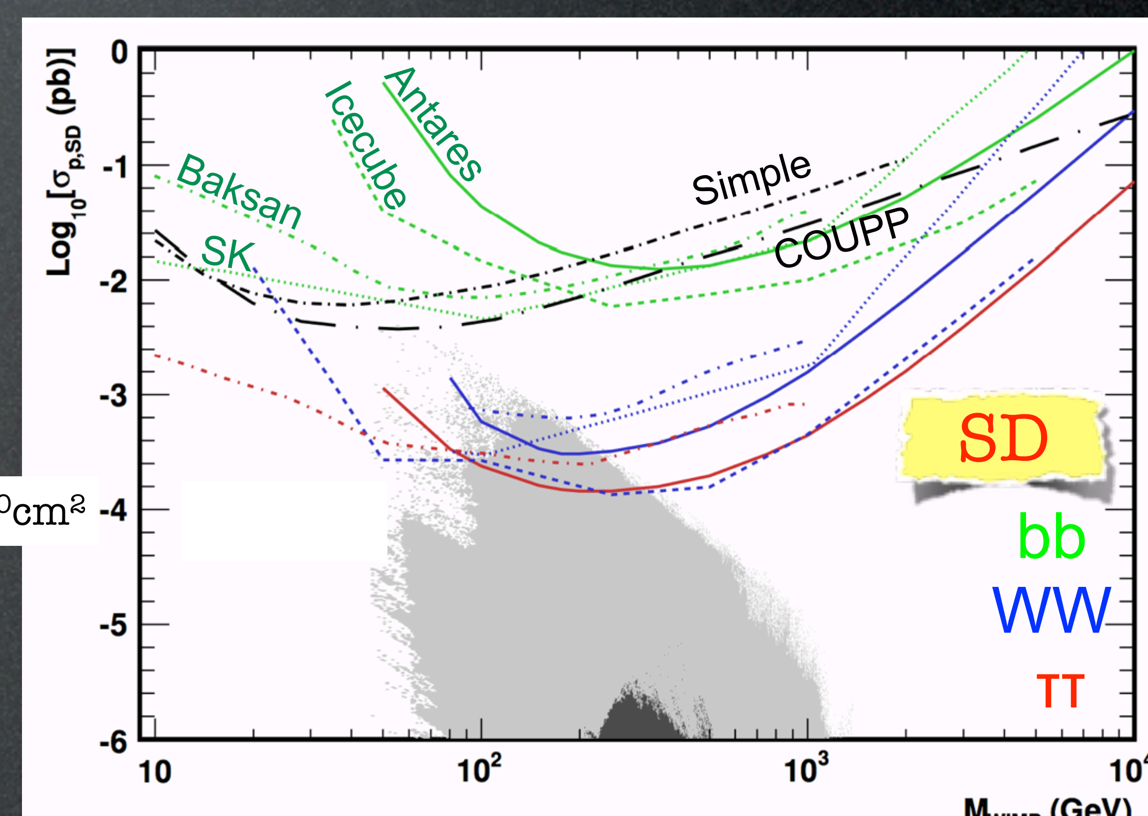
SuperKamiokande



1108.3384

3109.6 days! (now beat that)

10^{-40}cm²



Antares

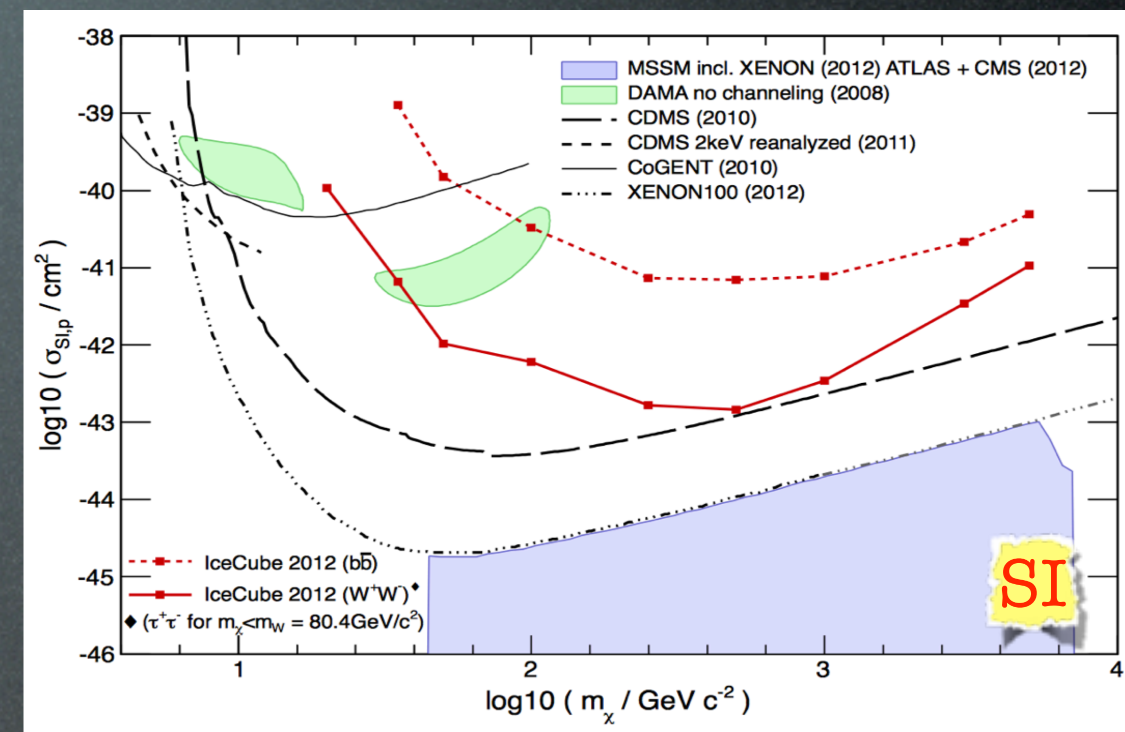
Antares coll. JCAP11 (2013) 032
1302.6516

ID with neutrinos

ν from DM annihilations in the Sun

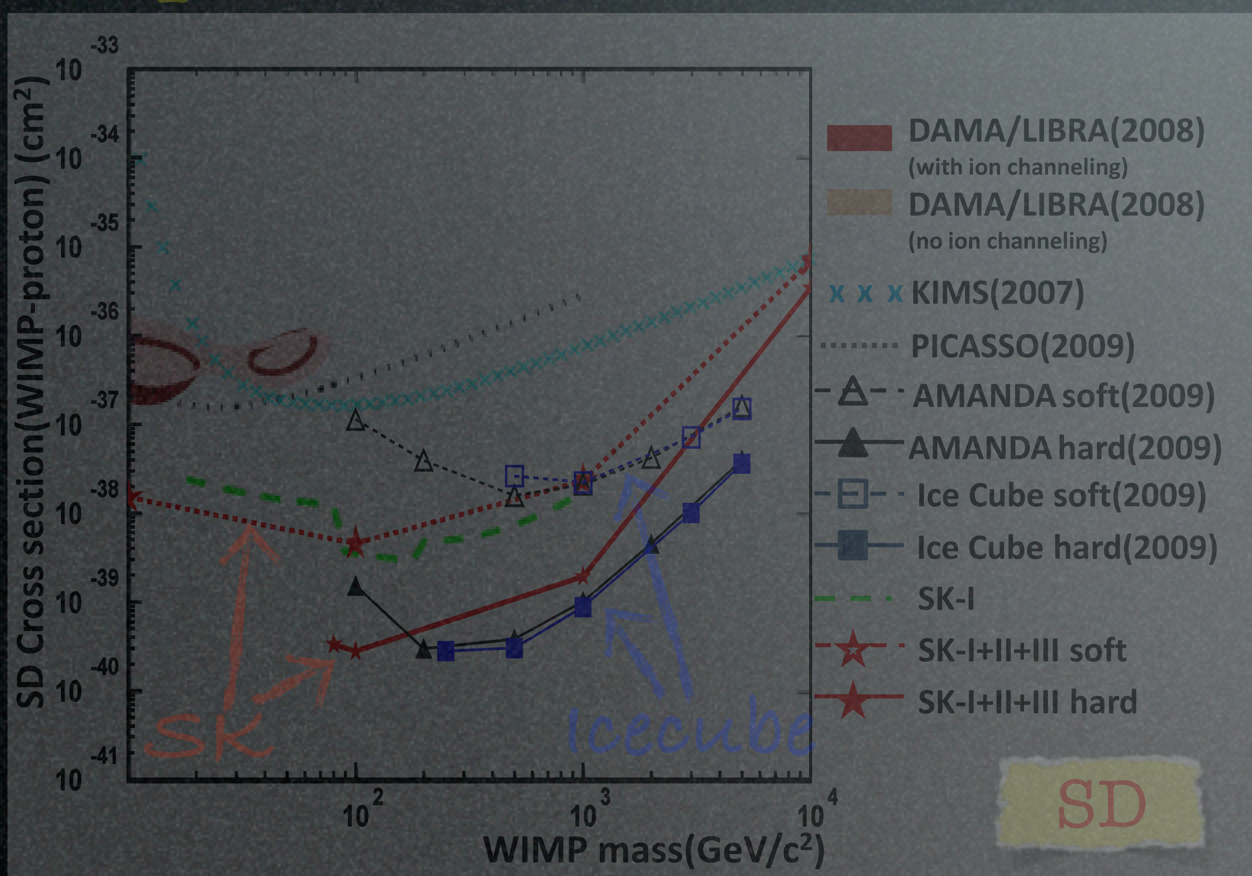
Probe the scattering cross section (competitively if SD).

ICECUBE



Icecube Coll., 1212.4097

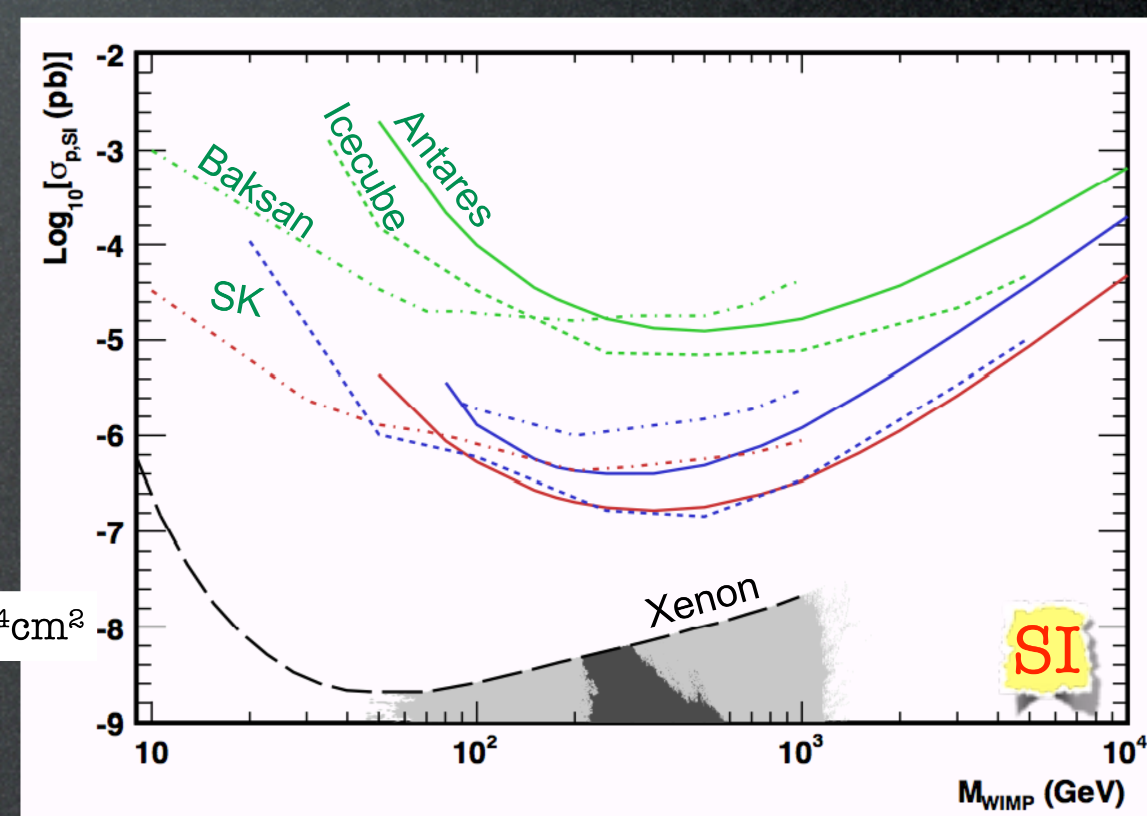
SuperKamiokande



1108.3384

3109.6 days! (now beat that)

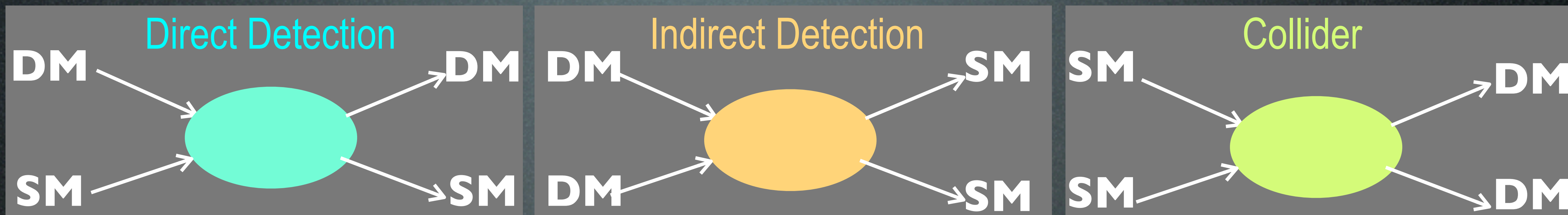
10^{-44}cm^2



Antares

Antares coll. JCAP11 (2013) 032
1302.6516

Complementarities



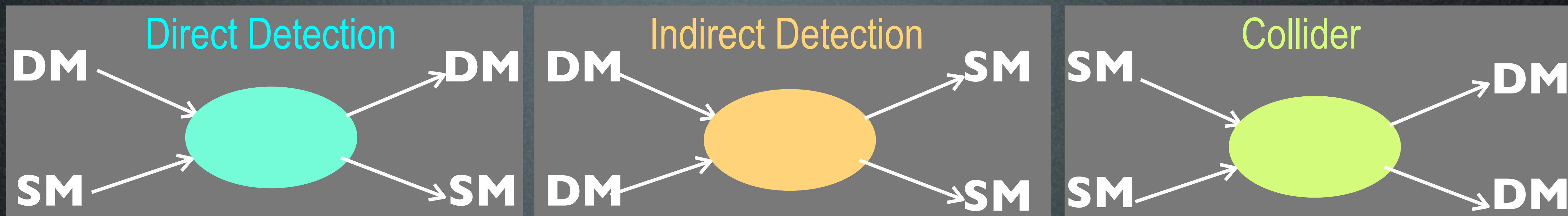
Regimes:

$q \sim \text{few KeV}$ $\sqrt{s} \sim 2\, m_X$ $\sqrt{s} \sim \text{few TeV}$

Basic quantities:

σ_{scatt} $\langle \sigma_{\text{ann}} v \rangle$ σ_{prod}

Complementarities



Regimes:

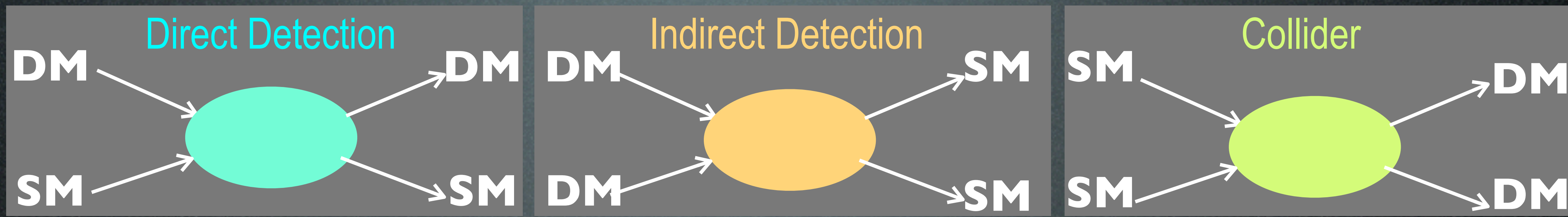
$q \sim \text{few KeV}$ $\sqrt{s} \sim 2\, m_X$ $\sqrt{s} \sim \text{few TeV}$

Basic quantities:

$\sigma_{\rm scatt}$ ⟷ $\langle \sigma_{\rm ann} v \rangle$ ⟷ $\sigma_{\rm prod}$

Can one relate?

Complementarities



Regimes:

$q \sim \text{few KeV}$ $\sqrt{s} \sim 2\, m_X$ $\sqrt{s} \sim \text{few TeV}$

Basic quantities:

σ_{scatt} ⟷ $\langle \sigma_{\text{ann}} v \rangle$ ⟷ σ_{prod}

Can one relate? - in general terms: NO

- in a specific model: YES / MAYBE

regimes are different, different uncertainties...
different parameters of your model may enter...

- in an effective operator approach: YES*

$$\frac{1}{\Lambda_1^2}[q\bar{q}][\chi\bar{\chi}] \quad \frac{1}{\Lambda_2^2}[q\gamma_\mu\bar{q}][\chi\gamma^\mu\bar{\chi}] \quad \ldots$$

* (with caveats)

Minimal DM

Minimalistic approach

On top of the SM, add only one extra multiplet $\mathcal{X} = \begin{pmatrix} \mathcal{X}_1 \\ \mathcal{X}_2 \\ \vdots \end{pmatrix}$

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \bar{\mathcal{X}}(i\not{D} + M)\mathcal{X}$$ if $\mathcal{X}$ is a fermion

$$\mathscr{L} = \mathscr{L}_{\rm SM} + |D_\mu \mathcal{X}|^2 - M^2|\mathcal{X}|^2$$ if $\mathcal{X}$ is a scalar

and systematically search for the ideal DM candidate...

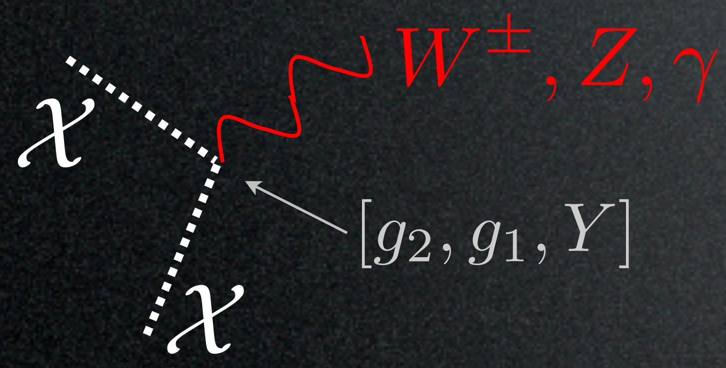
Minimalistic approach

On top of the SM, add only one extra multiplet $\mathcal{X} = \begin{pmatrix} \mathcal{X}_1 \\ \mathcal{X}_2 \\ \vdots \end{pmatrix}$

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \bar{\mathcal{X}}(i\not{D} + M)\mathcal{X}$$ if $\mathcal{X}$ is a fermion

$$\mathscr{L} = \mathscr{L}_{\rm SM} + |D_\mu \mathcal{X}|^2 - M^2|\mathcal{X}|^2$$ if $\mathcal{X}$ is a scalar

gauge interactions



the only parameter,
and will be fixed by $\Omega_{\rm DM}$.

(other terms in the scalar potential)

(one loop mass splitting)

and systematically search for the ideal DM candidate...

The ideal DM candidate is

weakly int., massive, neutral, stable

The ideal DM candidate is

weakly int., massive, neutral, stable

$SU(2)_L$	$U(1)_Y$	spin
$\underline{2}$		
$\underline{3}$		
$\underline{4}$		
$\underline{5}$		
$\underline{7}$		

← ($\underline{6}$ is similar to $\underline{4}$)

$$\chi = \begin{pmatrix} \chi_1 \\ \chi_2 \\ \vdots \\ \chi_n \end{pmatrix}$$

these are all possible choices:

$n \leq 5$ for fermions

$n \leq 7$ for scalars

to avoid explosion in the running coupling

$$\alpha_2^{-1}(E') = \alpha_2^{-1}(M) - \frac{b_2(n)}{2\pi} \ln \frac{E'}{M}$$

The ideal DM candidate is

weakly int., massive, neutral, stable

$SU(2)_L$	$U(1)_Y$	spin
$\underline{2}$	$1/2$	
$\underline{3}$	0	
	1	
$\underline{4}$	$1/2$	
	$3/2$	
$\underline{5}$	0	
	1	
	2	
$\underline{7}$	0	

Each multiplet contains a neutral component with a proper assignment of the hypercharge, according to

$$Q = T_3 + Y \equiv 0$$

e.g. for $n = 2$: $T_3 = \begin{pmatrix} +\frac{1}{2} \\ \\ -\frac{1}{2} \end{pmatrix} \Rightarrow |Y| = \frac{1}{2}$

e.g. for $n = 3$: $T_3 = \begin{pmatrix} +1 \\ 0 \\ -1 \end{pmatrix} \Rightarrow |Y| = 0 \text{ or } 1$

etc.

The ideal DM candidate is
weakly int., massive, neutral, stable

$SU(2)_L$	$U(1)_Y$	spin
$\underline{2}$	$1/2$	S
		F
$\underline{3}$	0	S
		F
	1	S
		F
$\underline{4}$	$1/2$	S
		F
	$3/2$	S
		F
$\underline{5}$	0	S
		F
	1	S
		F
	2	S
		F
$\underline{7}$	0	S

Each multiplet contains a neutral component with a proper assignment of the hypercharge, according to

$$\boxed{Q = T_3 + Y} \equiv 0$$

e.g. for $n = 2$: $T_3 = \begin{pmatrix} +\frac{1}{2} \\ \\ -\frac{1}{2} \end{pmatrix} \Rightarrow |Y| = \frac{1}{2}$

e.g. for $n = 3$: $T_3 = \begin{pmatrix} +1 \\ 0 \\ -1 \end{pmatrix} \Rightarrow |Y| = 0 \text{ or } 1$

etc.

The ideal DM candidate is

weakly int., massive, neutral, stable

$SU(2)_L$	$U(1)_Y$	spin	M (TeV)
$\underline{2}$	$1/2$	S	0.43
		F	1.2
$\underline{3}$	0	S	2.0
		F	2.6
	1	S	1.4
		F	1.8
$\underline{4}$	$1/2$	S	2.4
		F	2.5
	$3/2$	S	2.4
		F	2.5
$\underline{5}$	0	S	5.0
		F	4.5
	1	S	3.5
		F	3.2
	2	S	3.5
		F	3.2
$\underline{7}$	0	S	8.5

The mass M is determined by the relic abundance:

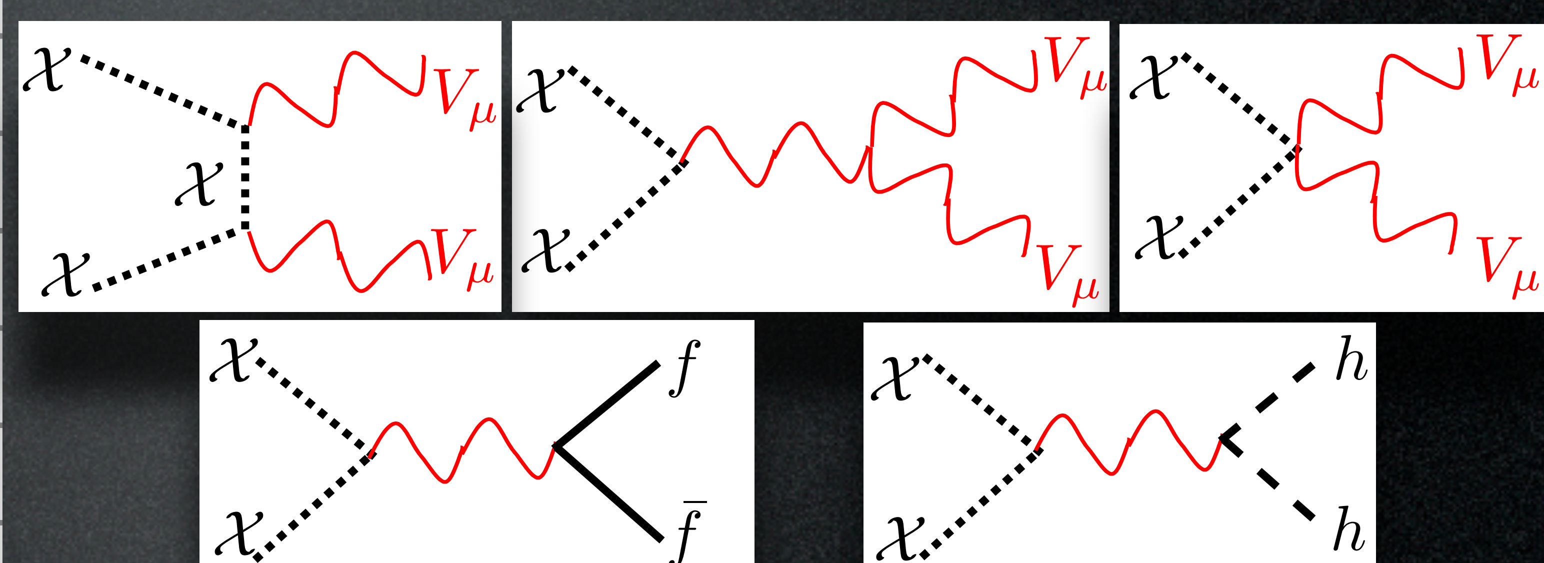
$$\Omega_{\rm DM} = \frac{6\ 10^{-27}{\rm cm}^3{\rm s}^{-1}}{\langle \sigma_{\rm ann} v\rangle} \simeq 0.24$$

for $\mathcal{X}$ scalar

$$\langle \sigma_A v\rangle \simeq \frac{g_2^4\ (3 - 4n^2 + n^4) + 16\ Y^4 g_Y^4 + 8 g_2^2 g_Y^2 Y^2 (n^2-1)}{64\pi\ M^2\ g_{\mathcal{X}}}$$

for $\mathcal{X}$ fermion

$$\langle \sigma_A v\rangle \simeq \frac{g_2^4\ (2n^4 + 17n^2 - 19) + 4Y^2 g_Y^4 (41 + 8Y^2) + 16 g_2^2 g_Y^2 Y^2 (n^2-1)}{128\pi\ M^2\ g_{\mathcal{X}}}$$



(- include co-annihilations)
(- computed for $M \gg M_{Z,W}$)

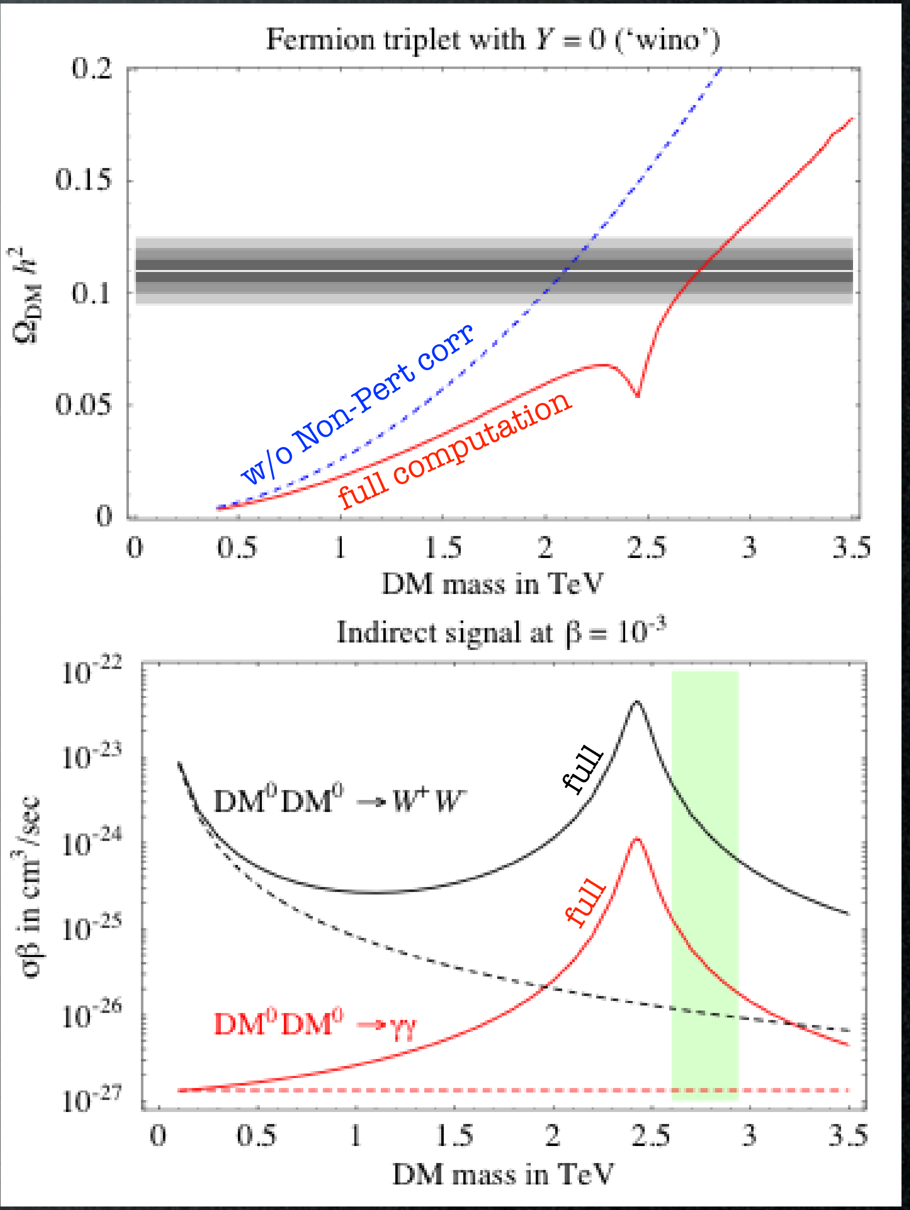
The ideal DM candidate is
weakly int., massive, neutral, stable

$SU(2)_L$	$U(1)_Y$	spin	M (TeV)
$\underline{2}$	$1/2$	S	
		F	1.0
$\underline{3}$	0	S	2.5
		F	2.7
	1	S	
		F	
$\underline{4}$	$1/2$	S	
		F	
	$3/2$	S	
		F	
$\underline{5}$	0	S	9.4
		F	10
	1	S	
		F	
	2	S	
		F	
$\underline{7}$	0	S	25

Non-perturbative corrections
(and other smaller corrections)
induce modifications:

$$\langle \sigma_{\rm ann} v \rangle \rightsquigarrow R \cdot \langle \sigma_{\rm ann} v \rangle + \langle \sigma_{\rm ann} v \rangle_{p-{\rm wave}}$$

with $R \sim \mathcal{O}(\text{few}) \to \mathcal{O}(10^2)$



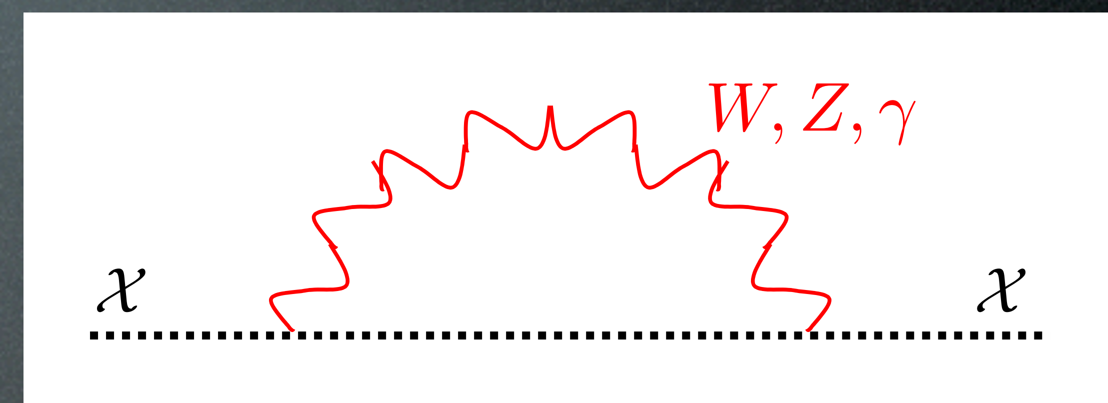
The ideal DM candidate is

weakly int., massive, neutral, stable

$SU(2)_L$	$U(1)_Y$	spin	M (TeV)	ΔM(MeV)
2	1/2	S		348
		F	1.0	342
3	0	S	2.5	166
		F	2.7	166
	1	S		540
		F		526
4	1/2	S		353
		F		347
	3/2	S		729
		F		712
5	0	S	9.4	166
		F	10	166
	1	S		537
		F		534
	2	S		906
		F		900
7	0	S	25	166

EW loops induce a mass splitting ΔM inside the n-uplet:

tree level



$$M_Q - M_{Q'} = \frac{\alpha_2 M}{4\pi}\left\{(Q^2 - Q'^2)s_W^2 f(\tfrac{M_Z}{M}) + (Q-Q')(Q+Q'-2Y)\left[f(\tfrac{M_W}{M}) - f(\tfrac{M_Z}{M})\right]\right\}$$

with $f(r) \overset{r\to 0}{\longrightarrow} -2\pi r$

The neutral component is the lightest

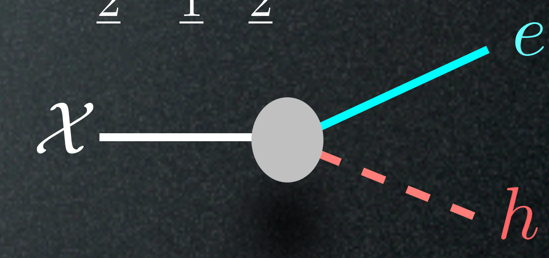
The ideal DM candidate is

weakly int., massive, neutral, stable

$SU(2)_L$	$U(1)_Y$	spin	M (TeV)	ΔM(MeV)	decay ch.
$\underline{2}$	$1/2$	S		348	EL
		F	1.0	342	EH
$\underline{3}$	0	S	2.5	166	HH^*
		F	2.7	166	LH
	1	S		540	HH, LH
		F		526	LH
$\underline{4}$	$1/2$	S		353	HHH^*
		F		347	(LHH^*)
	$3/2$	S		729	HHH
		F		712	(LHH)
$\underline{5}$	0	S	9.4	166	(HHH^*H^*)
		F	10	166	—
	1	S		537	$(HH^*H^*H^*)$
		F		534	—
	2	S		906	$(H^*H^*H^*H^*)$
		F		900	—
$\underline{7}$	0	S	25	166	—

List all allowed SM couplings:

← e.g. $\underset{\underline{2}}{\overset{1/2}{\chi}}\,\underset{\underline{1}}{\overset{-1}{E}}\,\underset{\underline{2}}{\overset{1/2}{H}}$



← e.g. $\underset{\underline{4}}{\overset{1/2}{\chi}}\,\underset{\underline{2}}{\overset{-1/2}{L}}\,\underset{\underline{2}}{\overset{1/2}{H}}\,\underset{\underline{2}}{\overset{-1/2}{H^*}}$

dim=5 operator, induces

$\tau \sim \Lambda^2 \mathrm{TeV}^{-3} \ll t_{\mathrm{universe}}$

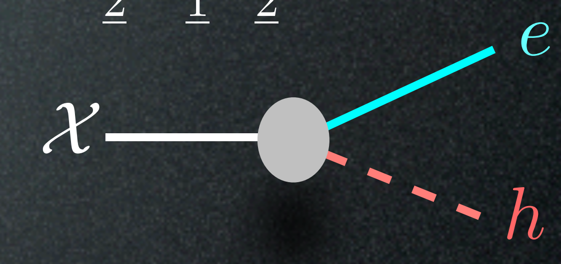
for $\Lambda \sim M_{\mathrm{Pl}}$

The ideal DM candidate is
weakly int., massive, neutral, stable

$SU(2)_L$	$U(1)_Y$	spin	M (TeV)	ΔM(MeV)	decay ch.
$\underline{2}$	$1/2$	S		348	EL
		F	1.0	342	EH
$\underline{3}$	0	S	2.5	166	HH^*
		F	2.7	166	LH
	1	S		540	HH, LH
		F		526	LH
$\underline{4}$	$1/2$	S		353	HHH^*
		F		347	(LHH^*)
	$3/2$	S		729	HHH
		F		712	(LHH)
$\underline{5}$	0	S	9.4	166	(HHH^*H^*)
		F	10	166	—
	1	S		537	$(HH^*H^*H^*)$
		F		534	—
	2	S		906	$(H^*H^*H^*H^*)$
		F		900	—
$\underline{7}$	0	S	25	166	—

List all allowed SM couplings:

e.g. $\overset{1/2}{\underset{\underline{2}}{\chi}}\,\overset{-1}{\underset{\underline{1}}{E}}\,\overset{1/2}{\underset{\underline{2}}{H}}$



e.g. $\overset{1/2}{\underset{\underline{4}}{\chi}}\,\overset{-1/2}{\underset{\underline{2}}{L}}\,\overset{1/2}{\underset{\underline{2}}{H}}\,\overset{-1/2}{\underset{\underline{2}}{H^*}}$

dim=5 operator, induces

$\tau \sim \Lambda^2 \mathrm{TeV}^{-3} \ll t_{\rm universe}$

for $\Lambda \sim M_{\rm Pl}$

No allowed decay!

Automatically stable!

The ideal DM candidate is

weakly int., massive, neutral, stable

$SU(2)_L$	$U(1)_Y$	spin	M (TeV)	ΔM(MeV)	decay ch.
$\underline{2}$	$1/2$	S		348	EL
		F	1.0	342	EH
$\underline{3}$	0	S	2.5	166	HH^*
		F	2.7	166	LH
	1	S		540	HH, LH
		F		526	LH
$\underline{4}$	$1/2$	S		353	HHH^*
		F		347	(LHH^*)
	$3/2$	S		729	HHH
		F		712	(LHH)
$\underline{5}$	0	S	9.4	166	(HHH^*H^*)
		F	10	166	—
	1	S		537	$(HH^*H^*H^*)$
		F		534	—
	2	S		906	$(H^*H^*H^*H^*)$
		F		900	—
$\underline{7}$	0	S	25	166	—

and **not excluded** by direct searches!

The ideal DM candidate is

weakly int., massive, neutral, stable

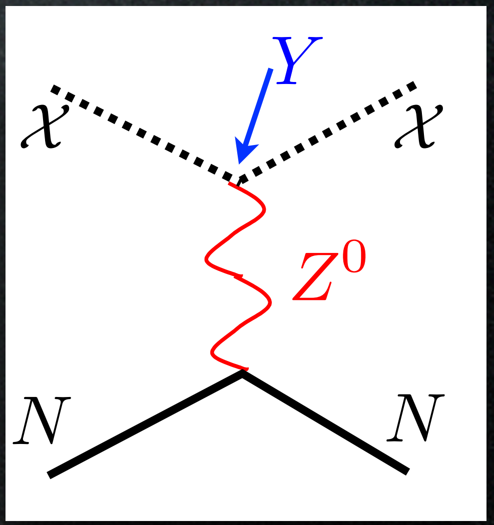
$SU(2)_L$	$U(1)_Y$	spin	M (TeV)	ΔM(MeV)	decay ch.
$\underline{2}$	$1/2$	S		348	EL
		F	1.0	342	EH
$\underline{3}$	0	S	2.5	166	HH^*
		F	2.7	166	LH
	1	S		540	HH, LH
		F		526	LH
$\underline{4}$	$1/2$	S		353	HHH^*
		F		347	(LHH^*)
	$3/2$	S		729	HHH
		F		712	(LHH)
$\underline{5}$	0	S	9.4	166	(HHH^*H^*)
		F	10	166	—
	1	S		537	$(HH^*H^*H^*)$
		F		534	—
	2	S		906	$(H^*H^*H^*H^*)$
		F		900	—
$\underline{7}$	0	S	25	166	—

and

not excluded

by direct searches!

Candidates with $Y \neq 0$ interact as



$\sigma \simeq G_F^2 M_N^2 Y^2$ Goodman Witten 1985

$\gg$ present bounds

e.g. Lux

need $Y = 0$

The ideal DM candidate is

weakly int., massive, neutral, stable

and

not excluded

by direct searches!

$SU(2)_L$	$U(1)_Y$	spin	M (TeV)	ΔM(MeV)	decay ch.
$\underline{2}$	$1/2$	S		348	EL
		F	1.0	342	EH
$\underline{3}$	0	S	2.5	166	HH^*
		F	2.7	166	LH
	1	S		540	HH, LH
		F		526	LH
$\underline{4}$	$1/2$	S		353	HHH^*
		F		347	(LHH^*)
	$3/2$	S		729	HHH
		F		712	(LHH)
$\underline{5}$	0	S	9.4	166	(HHH^*H^*)
		F	10	166	—
	1	S		537	$(HH^*H^*H^*)$
		F		534	—
	2	S		906	$(H^*H^*H^*H^*)$
		F		900	—
$\underline{7}$	0	S	25	166	—

The ideal DM candidate is

weakly int., massive, neutral, stable and not excluded

$SU(2)_L$	$U(1)_Y$	spin	M (TeV)	ΔM(MeV)	decay ch.
$\underline{2}$	$1/2$	S		348	EL
		F	1.0	342	EH
$\underline{3}$	0	S	2.5	166	HH^*
		F	2.7	166	LH
	1	S		540	HH, LH
		F		526	LH
$\underline{4}$	$1/2$	S		353	HHH^*
		F		347	(LHH^*)
	$3/2$	S		729	HHH
		F		712	(LHH)
$\underline{5}$	0	S	9.4	166	(HHH^*H^*)
		F	10	166	—
	1	S		537	$(HH^*H^*H^*)$
		F		534	—
	2	S		906	$(H^*H^*H^*H^*)$
		F		900	—
$\underline{7}$	0	S	25	166	—

The ideal DM candidate is

weakly int., massive, neutral, stable

and

not excluded

$SU(2)_L$	$U(1)_Y$	spin	M (TeV)	ΔM(MeV)	decay ch.
$\underline{2}$	$1/2$	S		348	EL
		F	1.0	342	EH
$\underline{3}$	0	S	2.5	166	HH^*
		F	2.7	166	LH
	1	S		540	HH, LH
		F		526	LH
$\underline{4}$	$1/2$	S		353	HHH^*
		F		347	(LHH^*)
	$3/2$	S		729	HHH
		F		712	(LHH)
$\underline{5}$	0	S	9.4	166	(HHH^*H^*)
		F	10	166	—
	1	S		537	$(HH^*H^*H^*)$
		F		534	—
	2	S		906	$(H^*H^*H^*H^*)$
		F		900	—
$\underline{7}$	0	S	25	166	—

The ideal DM candidate is
weakly int., massive, neutral, stable and not excluded

$SU(2)_L$	$U(1)_Y$	spin	M (TeV)	ΔM(MeV)	decay ch.
2	1/2	S		348	EL
		F	1.0	342	EH
3	0	S	2.5	166	HH^*
		F	2.7	166	LH
	1	S		540	HH, LH
		F		526	LH
4	1/2	S		353	HHH^*
		F		347	(LHH^*)
	3/2	S		729	HHH
		F		712	(LHH)
5	0	S	9.4	166	(HHH^*H^*)
		F	10	166	—
	1	S		537	$(HH^*H^*H^*)$
		F		534	—
	2	S		906	$(H^*H^*H^*H^*)$
		F		900	—
7	0	S	25	166	—

← We have a winner!

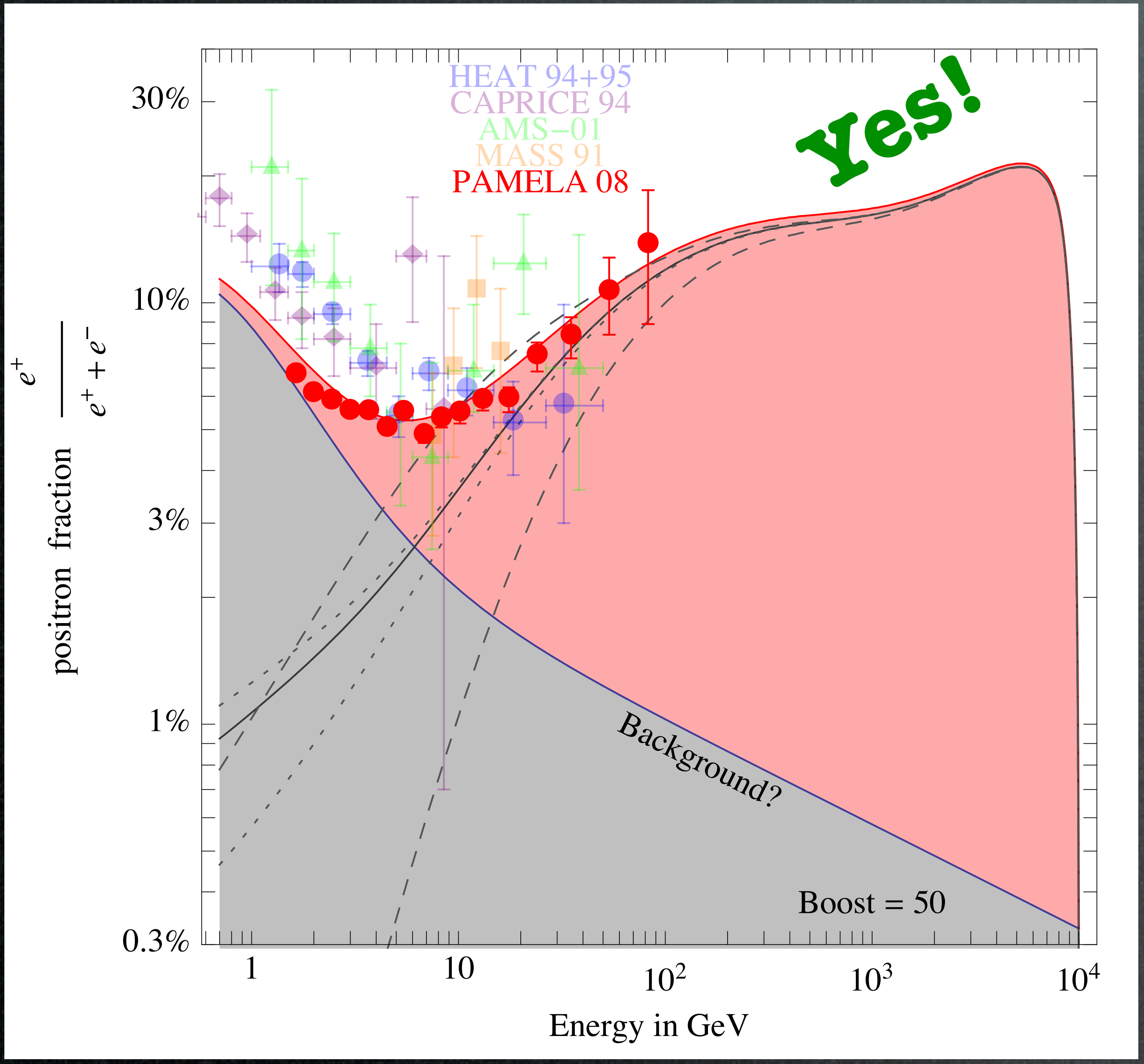
← and a 2° place

(other terms in the scalar potential)

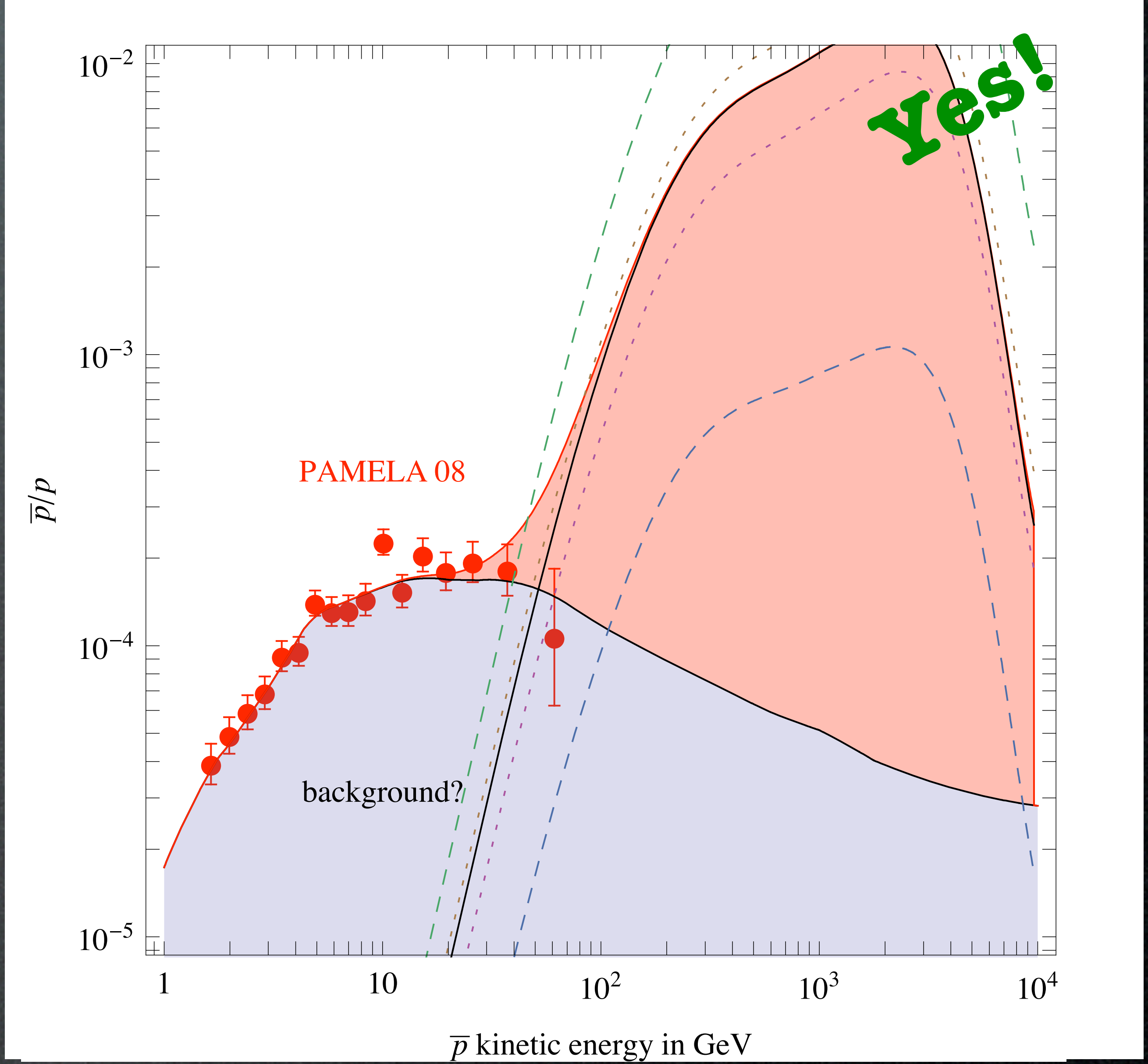
1. Indirect Detection

E.g. Minimal DM: -mass $M_{\rm DM} = 9.7\,\text{TeV}$
[Cirelli, Strumia, Fornengo 2006]
-annihilation $\text{DM DM} \to W^+W^-$
-boost $B \simeq 30$ Yes!
[thanks to **Sommerfeld** enhancement]

Positrons:



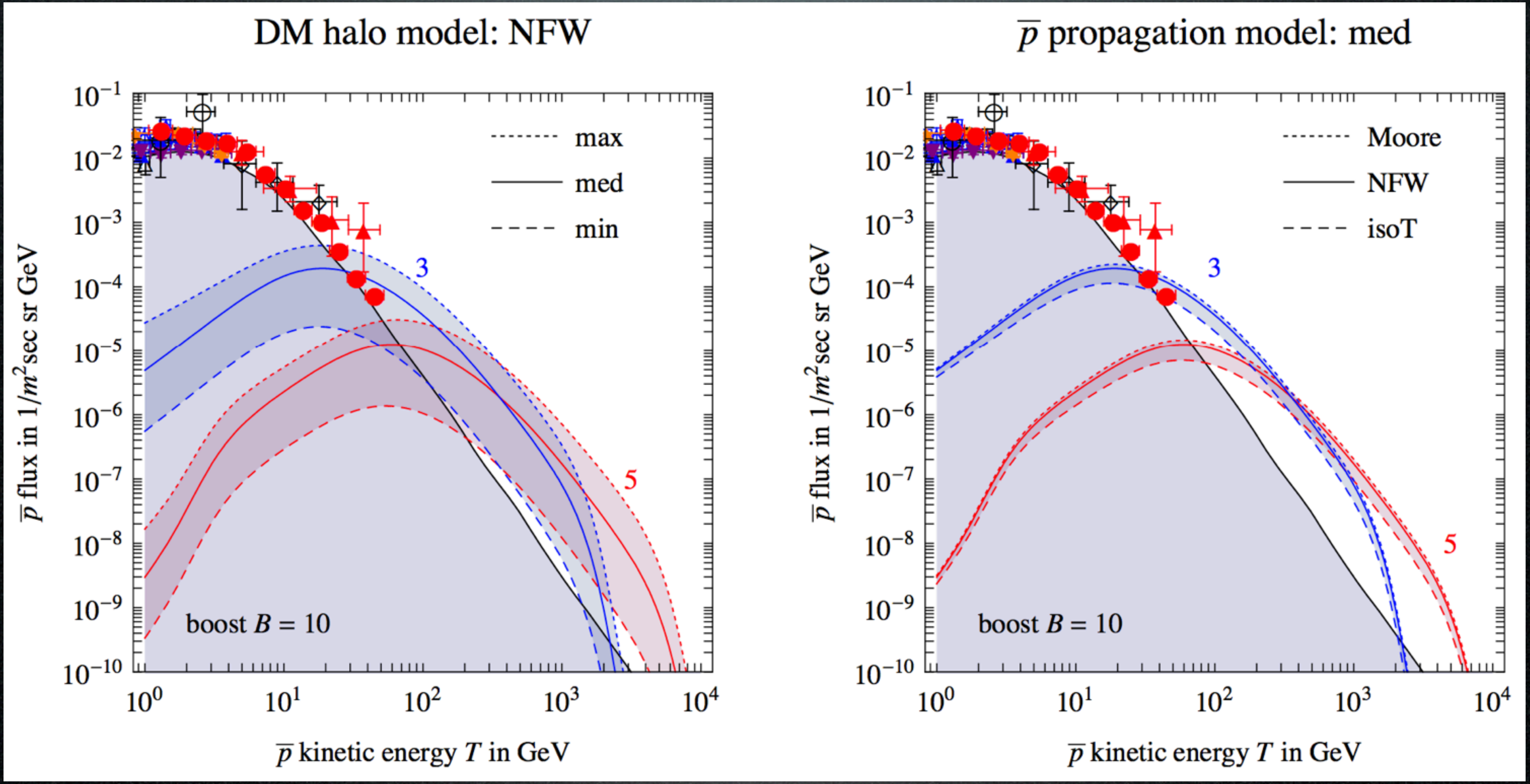
Anti-protons:



1. Indirect Detection

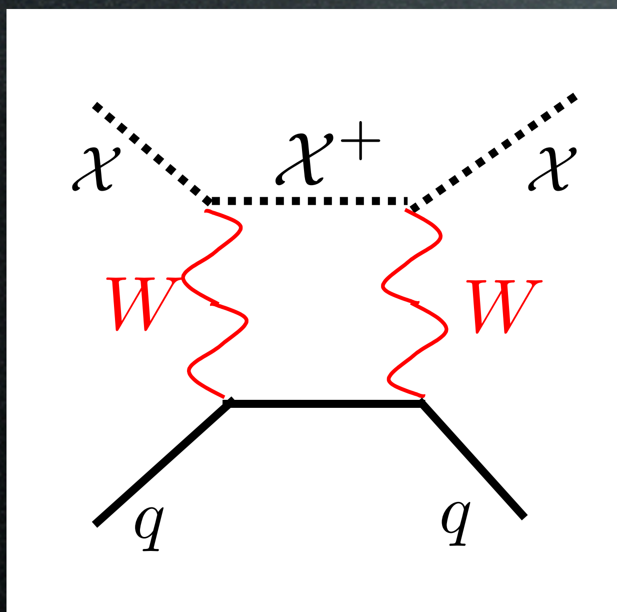
E.g. Minimal DM: triplet or quintuplet

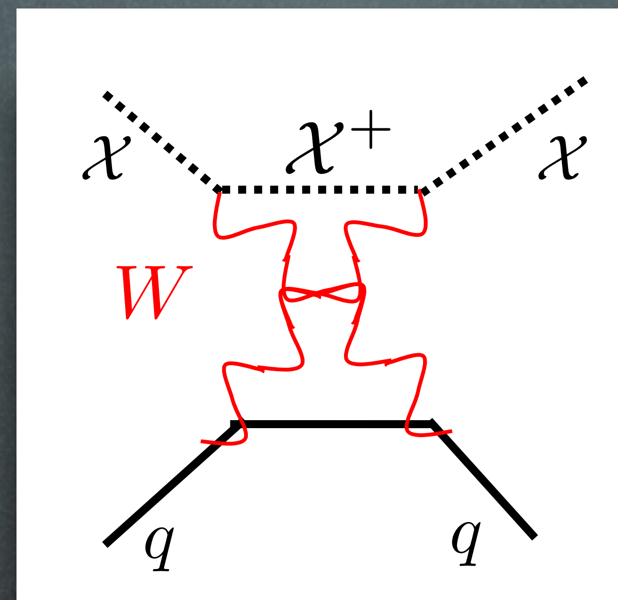
[Cirelli, Strumia, Fornengo 2006]

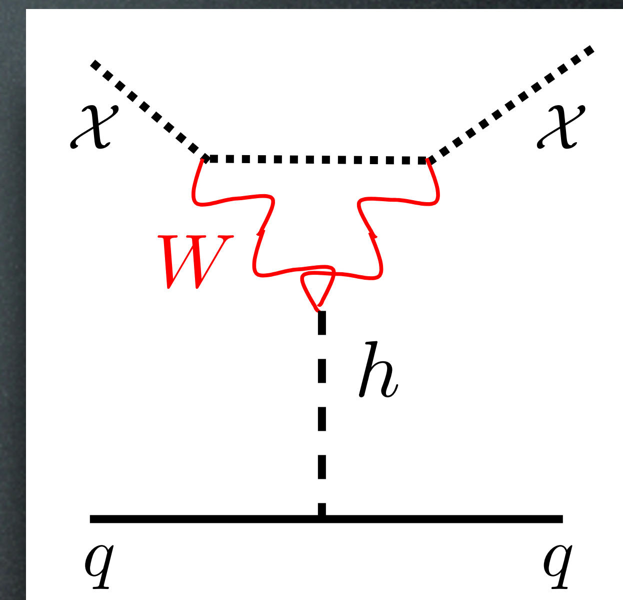


2. Direct Detection

one-loop interactions







$$\mathscr{L}_{\rm eff}^{W} = (n^2-(1-2Y)^2)\frac{\pi\alpha_2^2}{16M_W}\sum_q\left[\left(\frac{1}{M_W^2}+\frac{1}{m_h^2}\right)[\bar{\mathcal{X}}\mathcal{X}]m_q[\bar{q}q] - \frac{2}{3M}[\bar{\mathcal{X}}\gamma_\mu\gamma_5\mathcal{X}][\bar{q}\gamma_\mu\gamma_5 q]\right]$$

larger for higher n

Spin-Independent

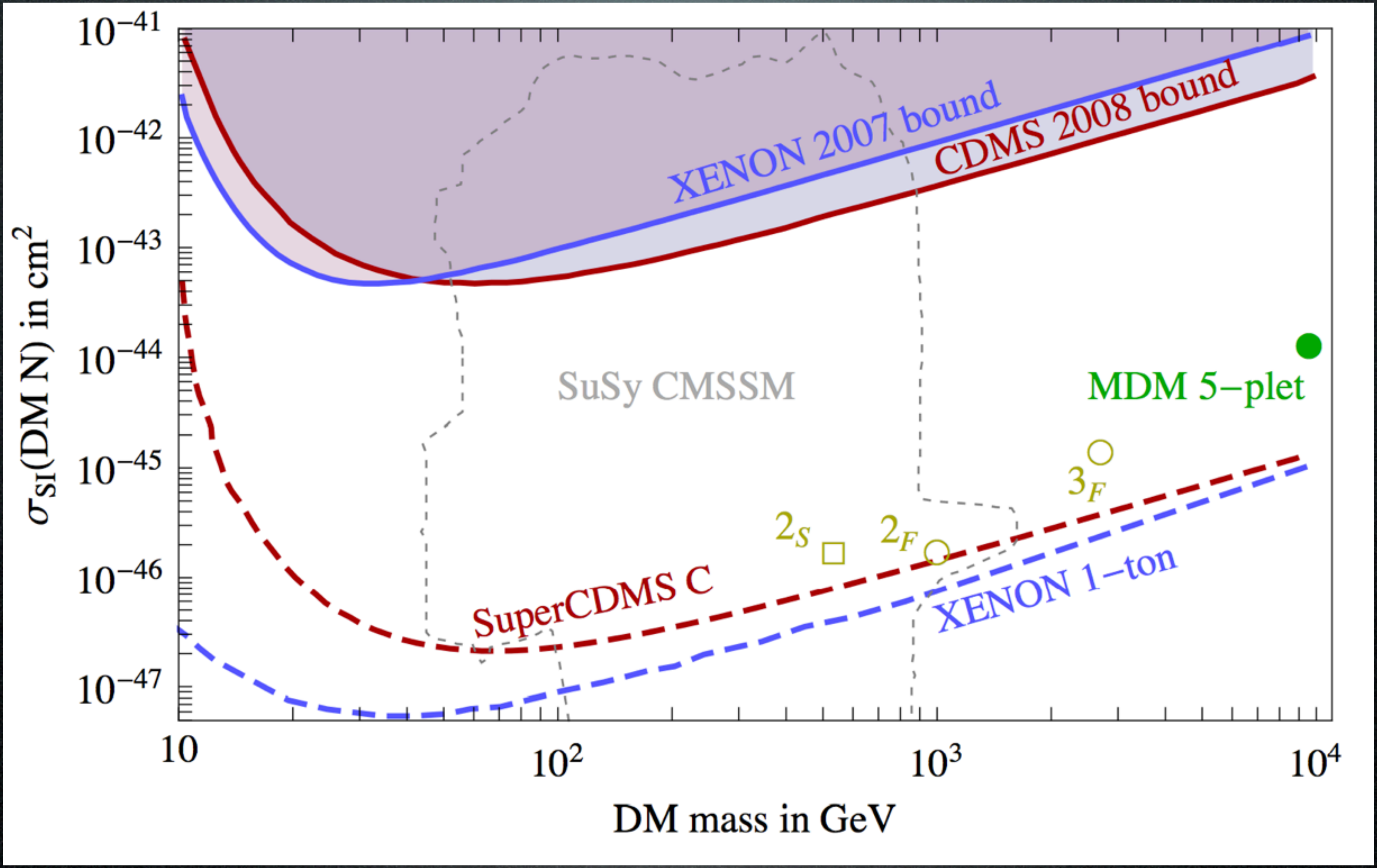
$$\propto \frac{m_q}{M_W^3}$$

Spin-Dependent

$$\propto \frac{1}{M M_W}$$

$$\langle N|\sum_q m_q\bar{q}q|N\rangle \equiv f m_N \quad \left(f \simeq \frac{1}{3}\right)$$

2. Direct Detection



(NB: no free parameters => one predicted point per candidate)

[skip to conclusions]

3. Production at colliders

$$\hat{\sigma}_{u\bar{d}} = \frac{g_{\mathcal{X}} g_2^4 (n^2-1)}{13824\ \pi \hat{s}} \beta \cdot \begin{cases} \beta^2 \\ 3-\beta^2 \end{cases}$$

if $\mathcal{X}$ is a fermion
if $\mathcal{X}$ is a scalar

(similarly $\hat{\sigma}_{u\bar{u}}$, $\hat{\sigma}_{d\bar{d}}$, $\hat{\sigma}_{d\bar{u}}$) $\qquad \beta = \sqrt{1 - 4M^2/\hat{s}}$

Large production for small M.

$2 \times$ LHC to produce heavy candidates.

A clean signature:

$$\mathcal{X}^\pm \to \mathcal{X}^0 \pi^\pm \quad : \quad \Gamma_\pi = (n^2-1) \frac{G_F^2 V_{ud}^2 \Delta M^3 f_\pi^2}{4\pi} \sqrt{1 - \frac{m_\pi^2}{\Delta M^2}}, \qquad \mathrm{BR}_\pi = 97.7\%$$

$$\mathcal{X}^\pm \to \mathcal{X}^0 e^\pm \overset{(-)}{\nu}_e \quad : \quad \Gamma_e = (n^2-1) \frac{G_F^2 \Delta M^5}{60\pi^3} \qquad \mathrm{BR}_e = 2.05\%$$

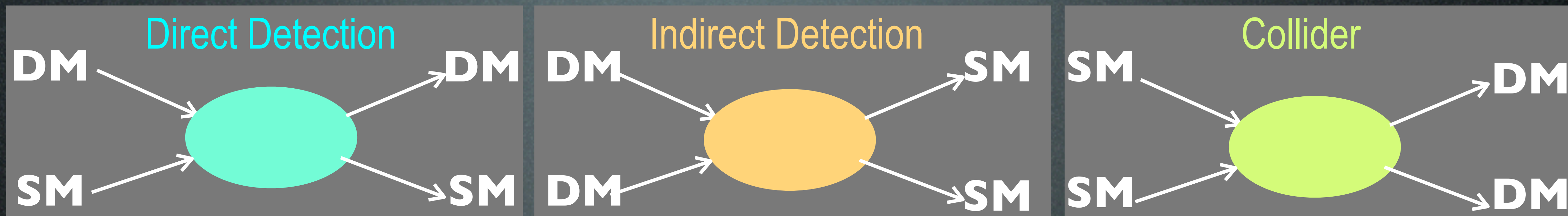
$$\mathcal{X}^\pm \to \mathcal{X}^0 \mu^\pm \overset{(-)}{\nu}_\mu \quad : \quad \Gamma_\mu = 0.12\ \Gamma_e \qquad \mathrm{BR}_\mu = 0.25\%$$

$$\tau \simeq 44\text{cm}/(n^2-1)$$

Events at LHC $\int \mathcal{L}\, dt$ =100/fb
$(0.7 \div 2) \cdot 10^3$
$120 \div 260$
$0.2 \div 1.0$
$0.4 \div 2.2$
$11 \div 33$
$26 \div 80$
$0.1 \div 0.7$
$3.6 \div 18$
$0.1 \div 0.6$
$2.7 \div 14$
$\ll 1$
$\ll 1$
$\ll 1$

[skip to conclusions]

Complementarities



Regimes:

$q \sim$ few KeV $\qquad \sqrt{s} \sim 2\, m_X \qquad \sqrt{s} \sim$ few TeV

Basic quantities:

$\sigma_{\rm scatt} \quad \longleftrightarrow \quad \langle \sigma_{\rm ann} v \rangle \quad \longleftrightarrow \quad \sigma_{\rm prod}$

Can one relate? - in general terms: NO

- in a specific model: YES / MAYBE

regimes are different, different uncertainties...
different parameters of your model may enter...

- in an effective operator approach: YES*

$$\frac{1}{\Lambda_1^2}[q\bar{q}][\chi\bar{\chi}] \qquad \frac{1}{\Lambda_2^2}[q\gamma_\mu\bar{q}][\chi\gamma^\mu\bar{\chi}] \qquad \ldots$$

* (with caveats)

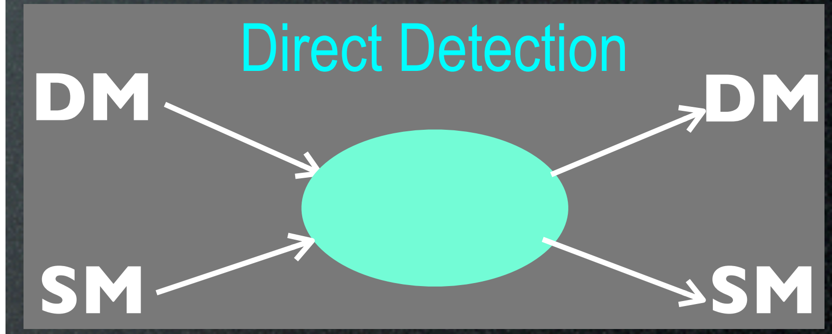
EFT approach

(a) Operators for Dirac fermion DM

Name	Operator	Dimension	SI/SD
D1	$\frac{m_q}{\Lambda^3}\bar\chi\chi\bar q q$	7	SI
D2	$\frac{im_q}{\Lambda^3}\bar\chi\gamma^5\chi\bar q q$	7	N/A
D3	$\frac{im_q}{\Lambda^3}\bar\chi\chi\bar q\gamma^5 q$	7	N/A
D4	$\frac{m_q}{\Lambda^3}\bar\chi\gamma^5\chi\bar q\gamma^5 q$	7	N/A
D5	$\frac{1}{\Lambda^2}\bar\chi\gamma^\mu\chi\bar q\gamma_\mu q$	6	SI
D6	$\frac{1}{\Lambda^2}\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu q$	6	N/A
D7	$\frac{1}{\Lambda^2}\bar\chi\gamma^\mu\chi\bar q\gamma_\mu\gamma^5 q$	6	N/A
D8	$\frac{1}{\Lambda^2}\bar\chi\gamma^\mu\gamma^5\chi\bar q\gamma_\mu\gamma^5 q$	6	SD
D9	$\frac{1}{\Lambda^2}\bar\chi\sigma^{\mu\nu}\chi\bar q\sigma_{\mu\nu} q$	6	SD
D10	$\frac{i}{\Lambda^2}\bar\chi\sigma^{\mu\nu}\gamma^5\chi\bar q\sigma_{\mu\nu} q$	6	N/A
D11	$\frac{\alpha_s}{\Lambda^3}\bar\chi\chi G^{\mu\nu}G_{\mu\nu}$	7	SI
D12	$\frac{\alpha_s}{\Lambda^3}\bar\chi\gamma^5\chi G^{\mu\nu}G_{\mu\nu}$	7	N/A
D13	$\frac{\alpha_s}{\Lambda^3}\bar\chi\chi G^{\mu\nu}\tilde G_{\mu\nu}$	7	N/A
D14	$\frac{\alpha_s}{\Lambda^3}\bar\chi\gamma^5\chi G^{\mu\nu}\tilde G_{\mu\nu}$	7	N/A

(b) Operators for Complex scalar DM

Name	Operator	Dimension	SI/SD
C1	$\frac{m_q}{\Lambda^2}\phi^\dagger\phi\bar q q$	6	SI
C2	$\frac{m_q}{\Lambda^2}\phi^\dagger\phi\bar q\gamma^5 q$	6	N/A
C3	$\frac{1}{\Lambda^2}\phi^\dagger\overleftrightarrow{\partial}_\mu\phi\bar q\gamma^\mu q$	6	SI
C4	$\frac{1}{\Lambda^2}\phi^\dagger\overleftrightarrow{\partial}_\mu\phi\bar q\gamma^\mu\gamma^5 q$	6	N/A
C5	$\frac{\alpha_s}{\Lambda^3}\phi^\dagger\phi G^{\mu\nu}G_{\mu\nu}$	6	SI
C6	$\frac{\alpha_s}{\Lambda^3}\phi^\dagger\phi G^{\mu\nu}\tilde G_{\mu\nu}$	6	N/A



Tim Tait, 2010+

and many many many others

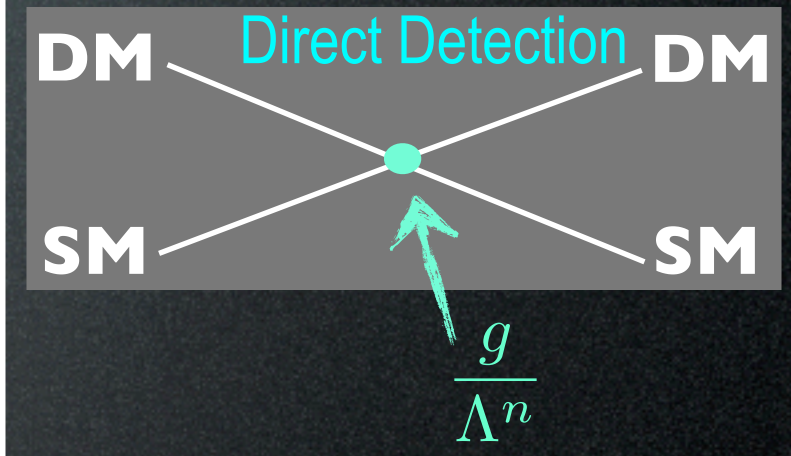
EFT approach

(a) Operators for Dirac fermion DM

Name	Operator	Dimension	SI/SD
D1	$\frac{m_q}{\Lambda^3}\bar{\chi}\chi\bar{q}q$	7	SI
D2	$\frac{im_q}{\Lambda^3}\bar{\chi}\gamma^5\chi\bar{q}q$	7	N/A
D3	$\frac{im_q}{\Lambda^3}\bar{\chi}\chi\bar{q}\gamma^5 q$	7	N/A
D4	$\frac{m_q}{\Lambda^3}\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	7	N/A
D5	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	6	SI
D6	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	6	N/A
D7	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	6	N/A
D8	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	6	SD
D9	$\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	6	SD
D10	$\frac{i}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\mu\nu}q$	6	N/A
D11	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\chi G^{\mu\nu}G_{\mu\nu}$	7	SI
D12	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\gamma^5\chi G^{\mu\nu}G_{\mu\nu}$	7	N/A
D13	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\chi G^{\mu\nu}\tilde{G}_{\mu\nu}$	7	N/A
D14	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\gamma^5\chi G^{\mu\nu}\tilde{G}_{\mu\nu}$	7	N/A

(b) Operators for Complex scalar DM

Name	Operator	Dimension	SI/SD
C1	$\frac{m_q}{\Lambda^2}\phi^\dagger\phi\bar{q}q$	6	SI
C2	$\frac{m_q}{\Lambda^2}\phi^\dagger\phi\bar{q}\gamma^5 q$	6	N/A
C3	$\frac{1}{\Lambda^2}\phi^\dagger\overleftrightarrow{\partial}_\mu\phi\bar{q}\gamma^\mu q$	6	SI
C4	$\frac{1}{\Lambda^2}\phi^\dagger\overleftrightarrow{\partial}_\mu\phi\bar{q}\gamma^\mu\gamma^5 q$	6	N/A
C5	$\frac{\alpha_s}{\Lambda^3}\phi^\dagger\phi G^{\mu\nu}G_{\mu\nu}$	6	SI
C6	$\frac{\alpha_s}{\Lambda^3}\phi^\dagger\phi G^{\mu\nu}\tilde{G}_{\mu\nu}$	6	N/A



Tim Tait, 2010+

and many many many others

EFT approach

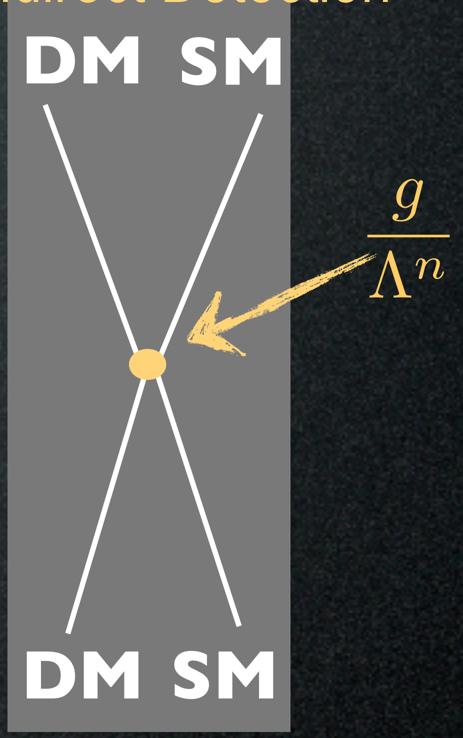
(a) Operators for Dirac fermion DM

Name	Operator	Dimension	SI/SD
D1	$\frac{m_q}{\Lambda^3}\bar{\chi}\chi\bar{q}q$	7	SI
D2	$\frac{im_q}{\Lambda^3}\bar{\chi}\gamma^5\chi\bar{q}q$	7	N/A
D3	$\frac{im_q}{\Lambda^3}\bar{\chi}\chi\bar{q}\gamma^5 q$	7	N/A
D4	$\frac{m_q}{\Lambda^3}\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	7	N/A
D5	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	6	SI
D6	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	6	N/A
D7	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	6	N/A
D8	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	6	SD
D9	$\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	6	SD
D10	$\frac{i}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\mu\nu}q$	6	N/A
D11	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\chi G^{\mu\nu}G_{\mu\nu}$	7	SI
D12	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\gamma^5\chi G^{\mu\nu}G_{\mu\nu}$	7	N/A
D13	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\chi G^{\mu\nu}\tilde{G}_{\mu\nu}$	7	N/A
D14	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\gamma^5\chi G^{\mu\nu}\tilde{G}_{\mu\nu}$	7	N/A

(b) Operators for Complex scalar DM

Name	Operator	Dimension	SI/SD
C1	$\frac{m_q}{\Lambda^2}\phi^\dagger\phi\bar{q}q$	6	SI
C2	$\frac{m_q}{\Lambda^2}\phi^\dagger\phi\bar{q}\gamma^5 q$	6	N/A
C3	$\frac{1}{\Lambda^2}\phi^\dagger\overleftrightarrow{\partial}_\mu\phi\bar{q}\gamma^\mu q$	6	SI
C4	$\frac{1}{\Lambda^2}\phi^\dagger\overleftrightarrow{\partial}_\mu\phi\bar{q}\gamma^\mu\gamma^5 q$	6	N/A
C5	$\frac{\alpha_s}{\Lambda^3}\phi^\dagger\phi G^{\mu\nu}G_{\mu\nu}$	6	SI
C6	$\frac{\alpha_s}{\Lambda^3}\phi^\dagger\phi G^{\mu\nu}\tilde{G}_{\mu\nu}$	6	N/A

Indirect Detection



Tim Tait, 2010+
and many many many others

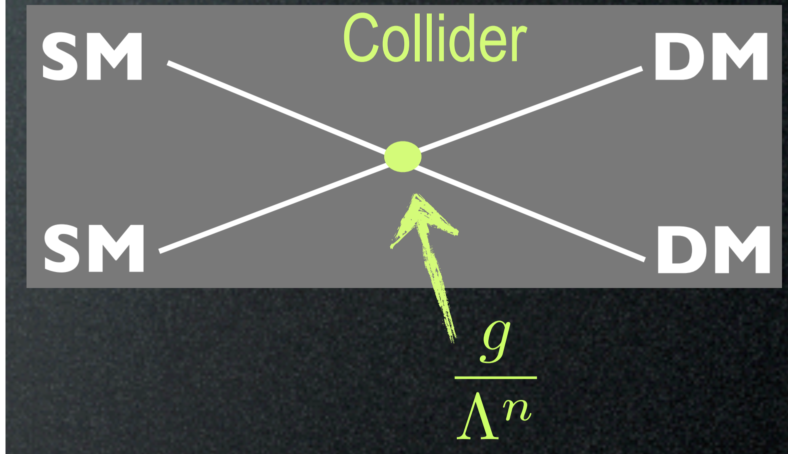
EFT approach

(a) Operators for Dirac fermion DM

Name	Operator	Dimension	SI/SD
D1	$\frac{m_q}{\Lambda^3}\bar{\chi}\chi\bar{q}q$	7	SI
D2	$\frac{im_q}{\Lambda^3}\bar{\chi}\gamma^5\chi\bar{q}q$	7	N/A
D3	$\frac{im_q}{\Lambda^3}\bar{\chi}\chi\bar{q}\gamma^5 q$	7	N/A
D4	$\frac{m_q}{\Lambda^3}\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	7	N/A
D5	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	6	SI
D6	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	6	N/A
D7	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	6	N/A
D8	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$	6	SD
D9	$\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$	6	SD
D10	$\frac{i}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\gamma^5\chi\bar{q}\sigma_{\mu\nu}q$	6	N/A
D11	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\chi G^{\mu\nu}G_{\mu\nu}$	7	SI
D12	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\gamma^5\chi G^{\mu\nu}G_{\mu\nu}$	7	N/A
D13	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\chi G^{\mu\nu}\tilde{G}_{\mu\nu}$	7	N/A
D14	$\frac{\alpha_s}{\Lambda^3}\bar{\chi}\gamma^5\chi G^{\mu\nu}\tilde{G}_{\mu\nu}$	7	N/A

(b) Operators for Complex scalar DM

Name	Operator	Dimension	SI/SD
C1	$\frac{m_q}{\Lambda^2}\phi^\dagger\phi\bar{q}q$	6	SI
C2	$\frac{m_q}{\Lambda^2}\phi^\dagger\phi\bar{q}\gamma^5 q$	6	N/A
C3	$\frac{1}{\Lambda^2}\phi^\dagger\overleftrightarrow{\partial}_\mu\phi\bar{q}\gamma^\mu q$	6	SI
C4	$\frac{1}{\Lambda^2}\phi^\dagger\overleftrightarrow{\partial}_\mu\phi\bar{q}\gamma^\mu\gamma^5 q$	6	N/A
C5	$\frac{\alpha_s}{\Lambda^3}\phi^\dagger\phi G^{\mu\nu}G_{\mu\nu}$	6	SI
C6	$\frac{\alpha_s}{\Lambda^3}\phi^\dagger\phi G^{\mu\nu}\tilde{G}_{\mu\nu}$	6	N/A

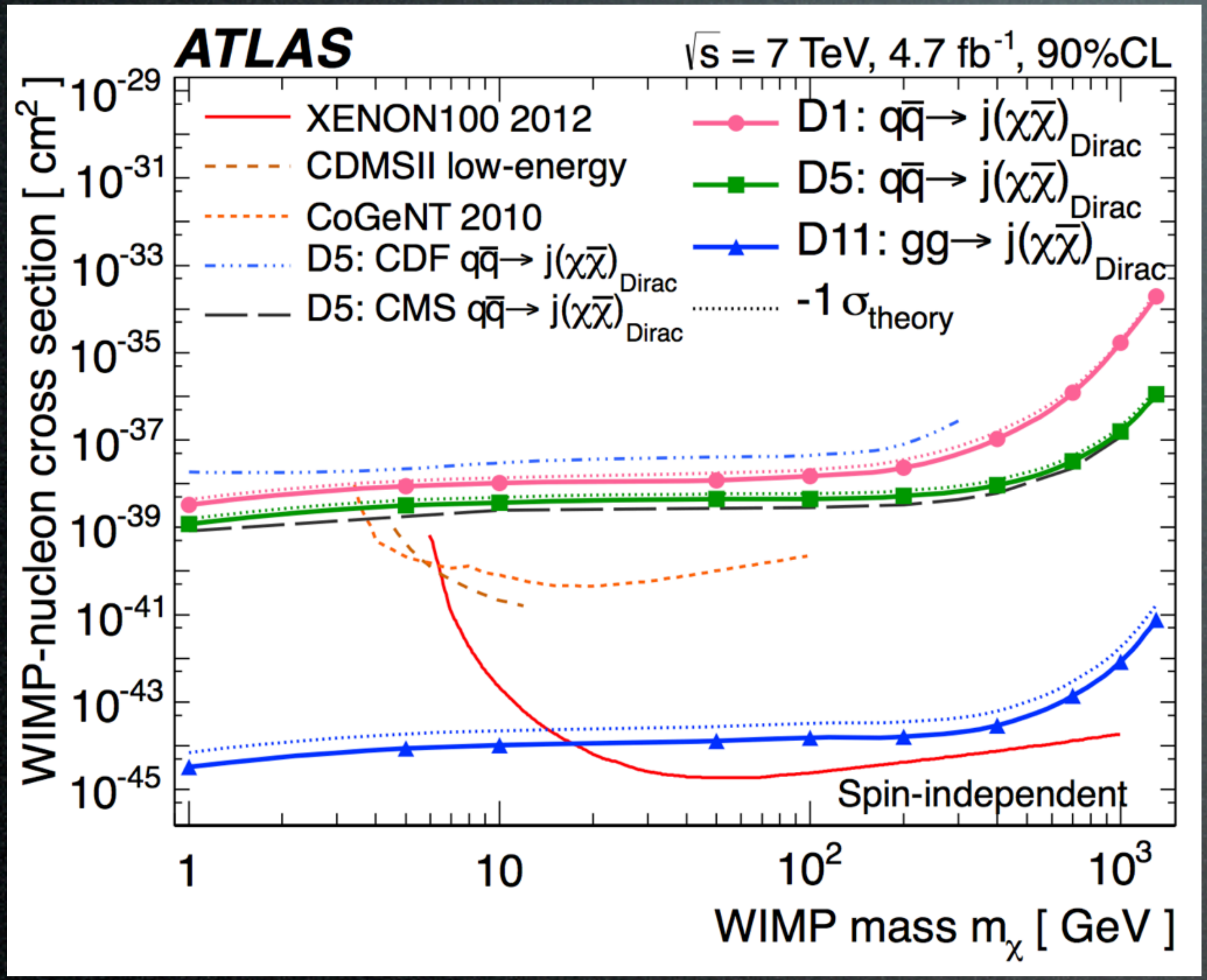


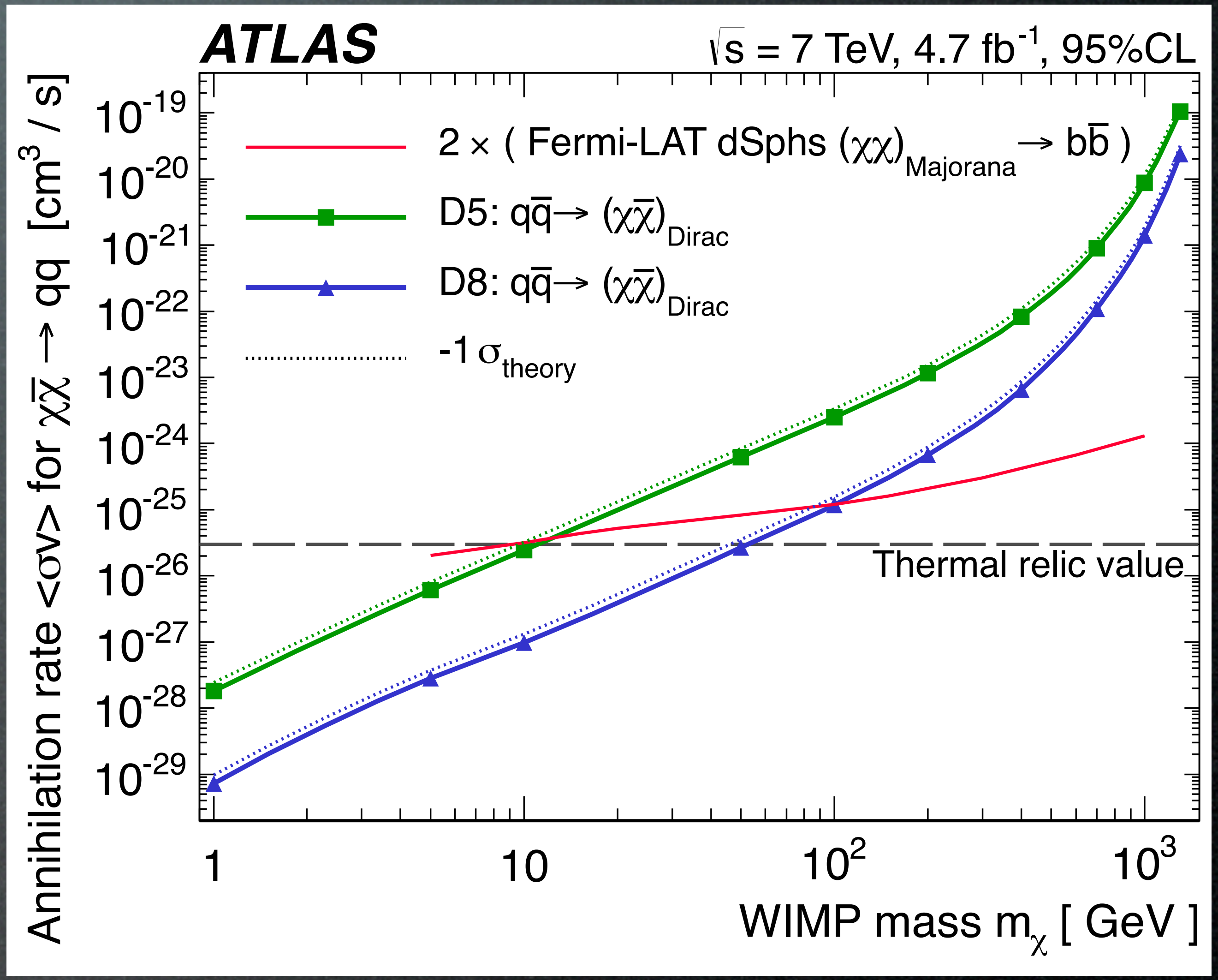
Tim Tait, 2010+

and many many many others

Complementarities

Examples:



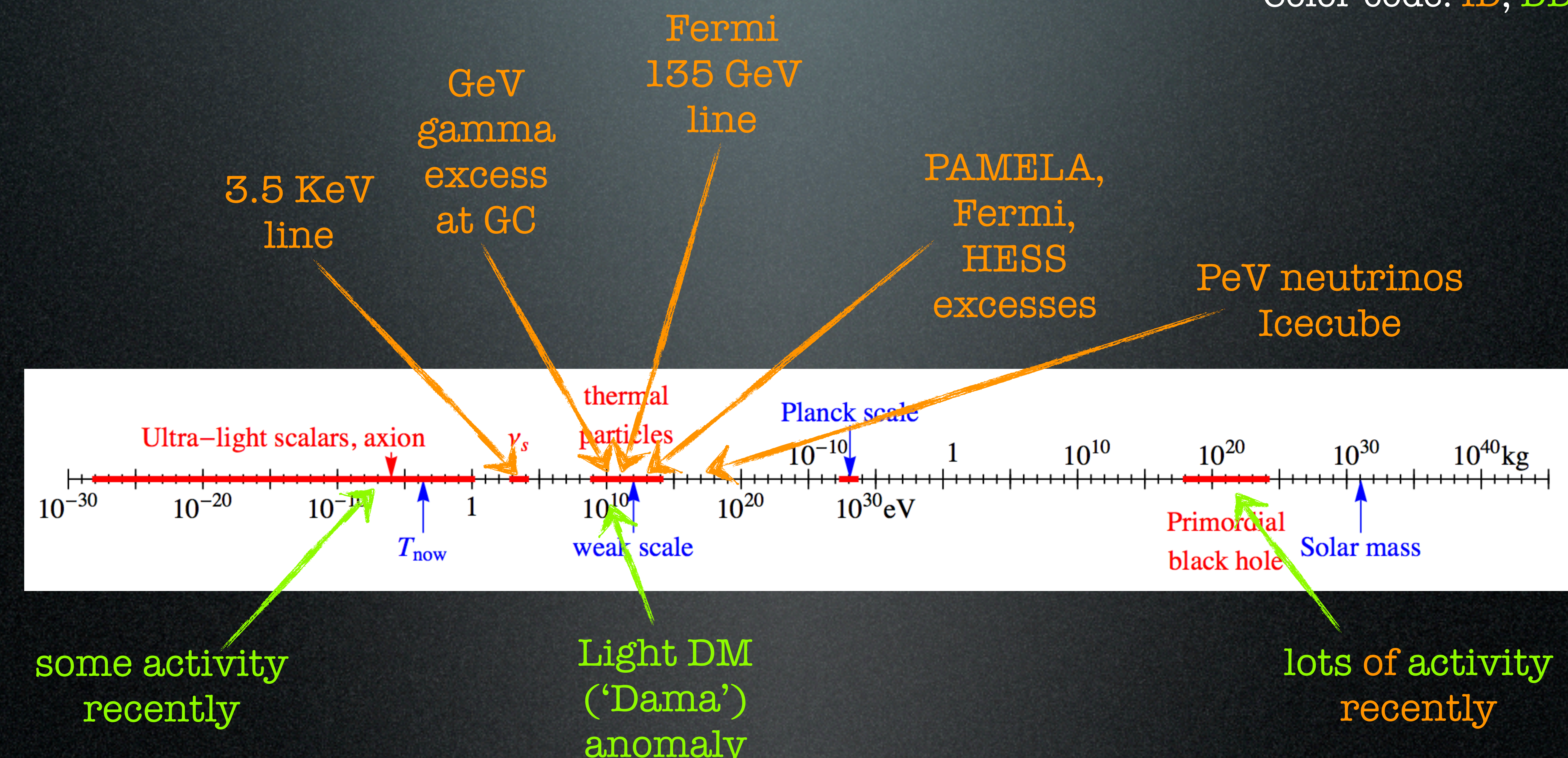


ATLAS coll., CERN-PH-EP-2012-210, arXiv:1210.4491

DM Candidates

A matter of perspective: plausible mass ranges

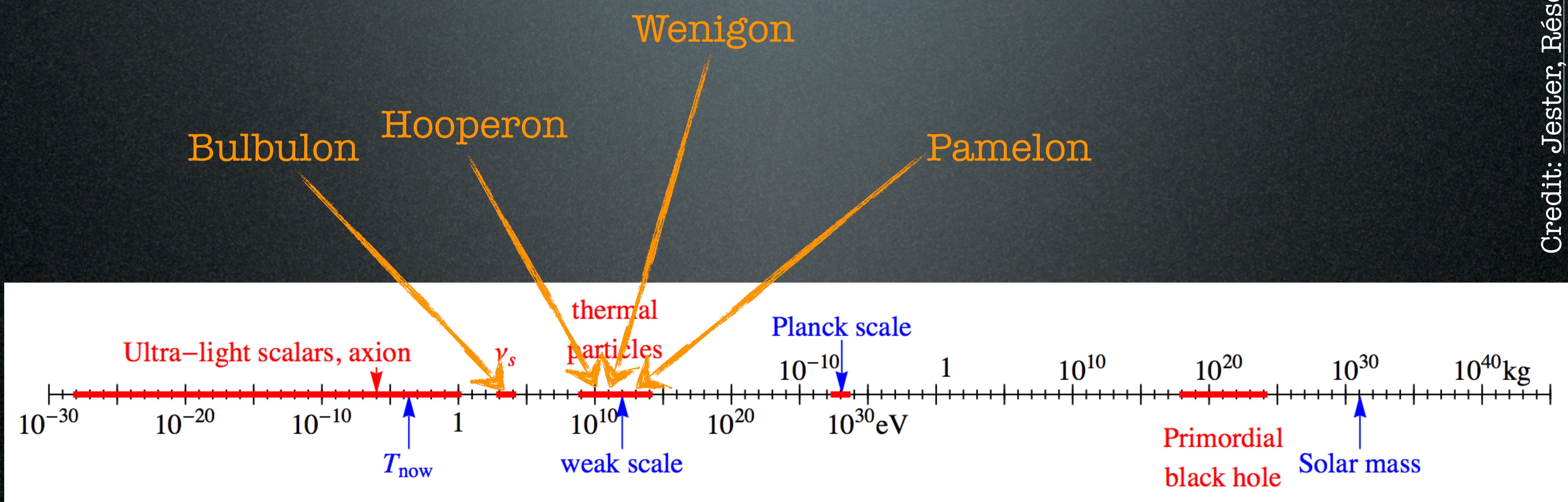
Color code: ID, DD



'only' 90 orders of magnitude!

DM Candidates

A matter of perspective: plausible mass ranges

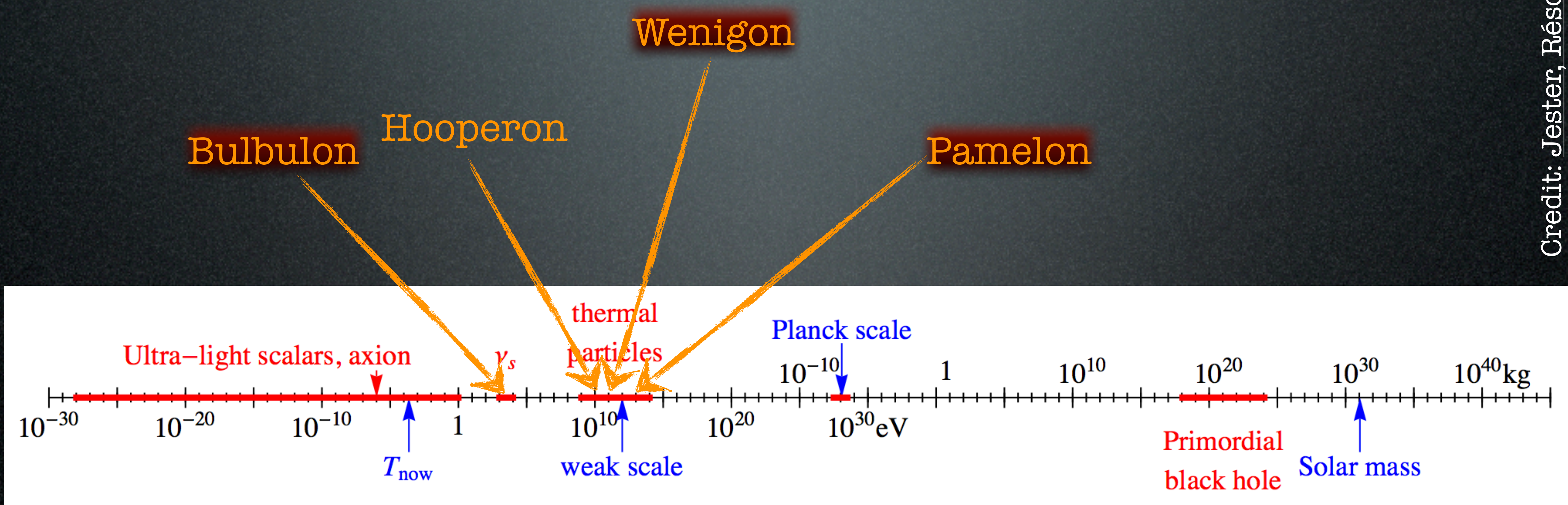


Credit: Jester, Résonaances

‘only’ 90 orders of magnitude!

DM Candidates

A matter of perspective: plausible mass ranges

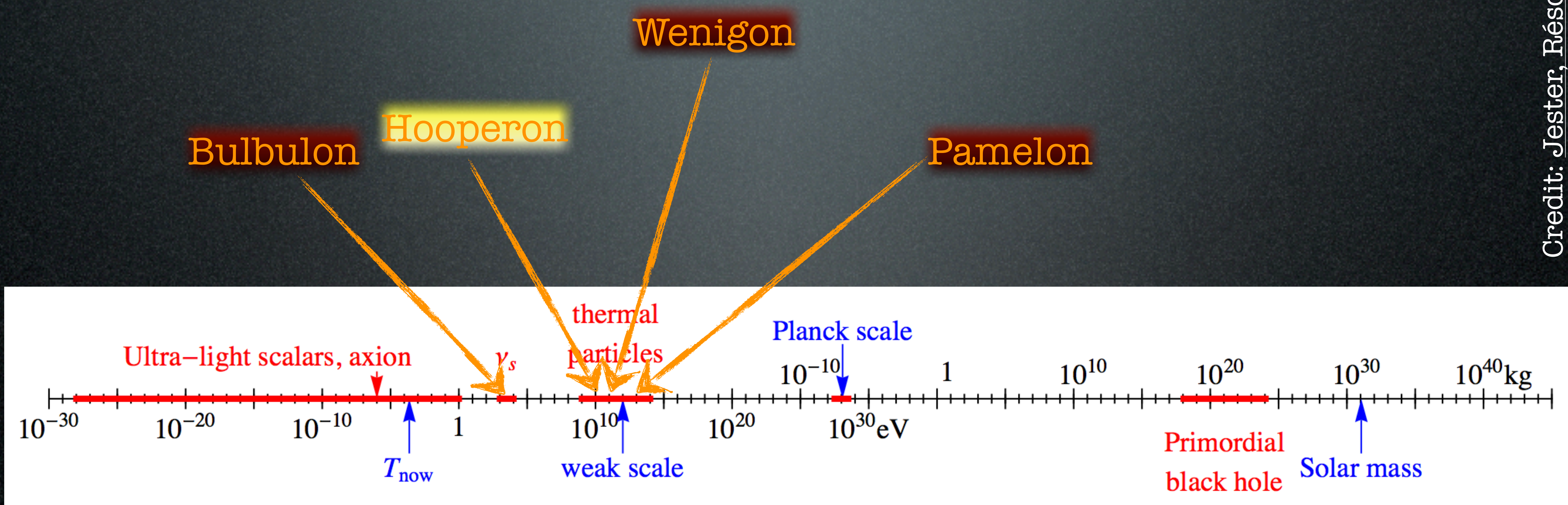


Credit: Jester, Résonaances

'only' 90 orders of magnitude!

DM Candidates

A matter of perspective: plausible mass ranges



Credit: Jester, Résonaances

'only' 90 orders of magnitude!

GeV gamma excess?

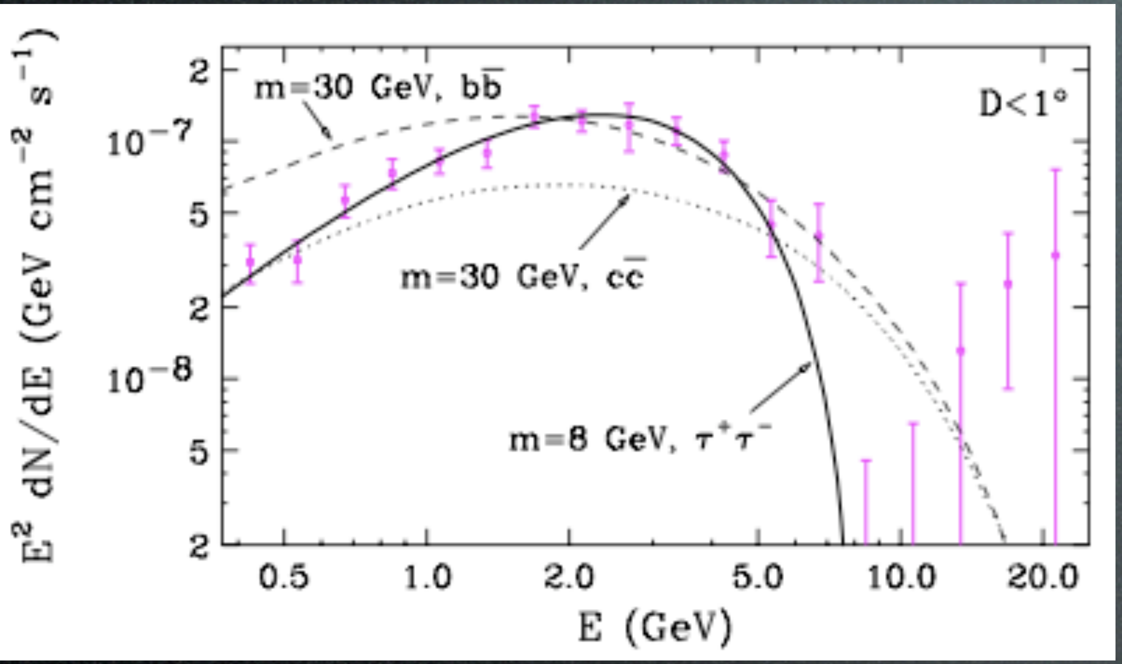
What if a signal of DM is *already* hidden in Fermi diffuse γ data from the GC?

A diffuse GeV excess from around the GC

Dan Hooper

GeV gamma excess?

What if a signal of DM is *already* hidden in Fermi diffuse γ data from the GC?



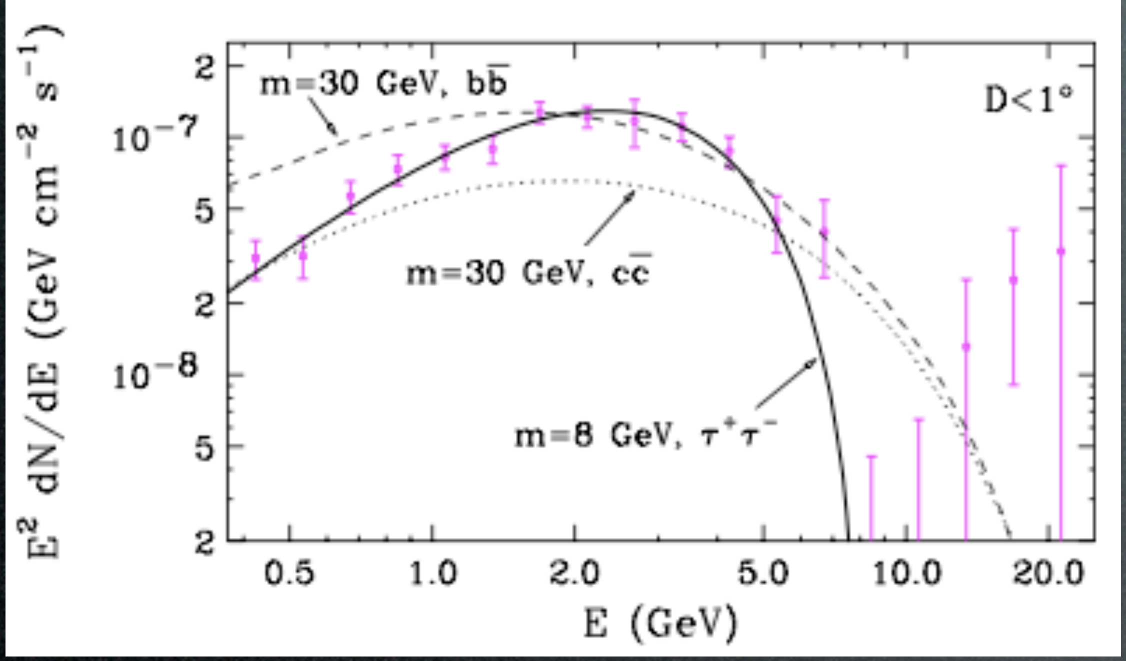
Hooper, Goodenough 1010.2752

A diffuse GeV excess from around the GC

Dan Hooper

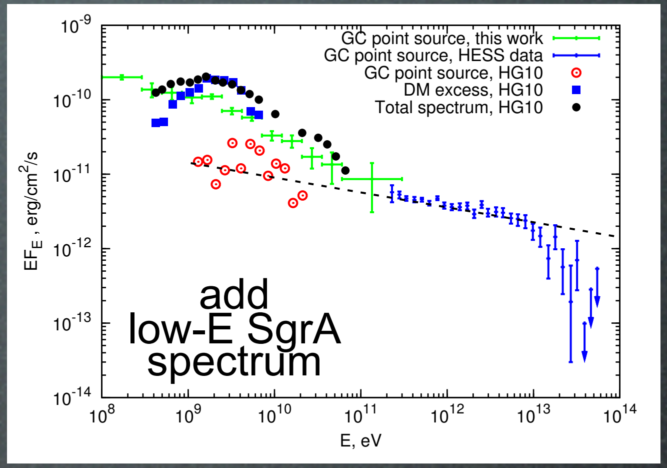
GeV gamma excess?

What if a signal of DM is *already* hidden in Fermi diffuse γ data from the GC?

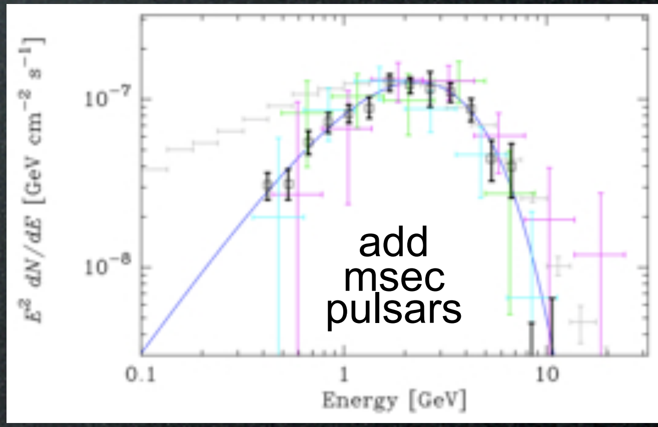


Hooper, Goodenough 1010.2752

Objection: know your backgrounds!



Boyarsky et al., 1012.5839



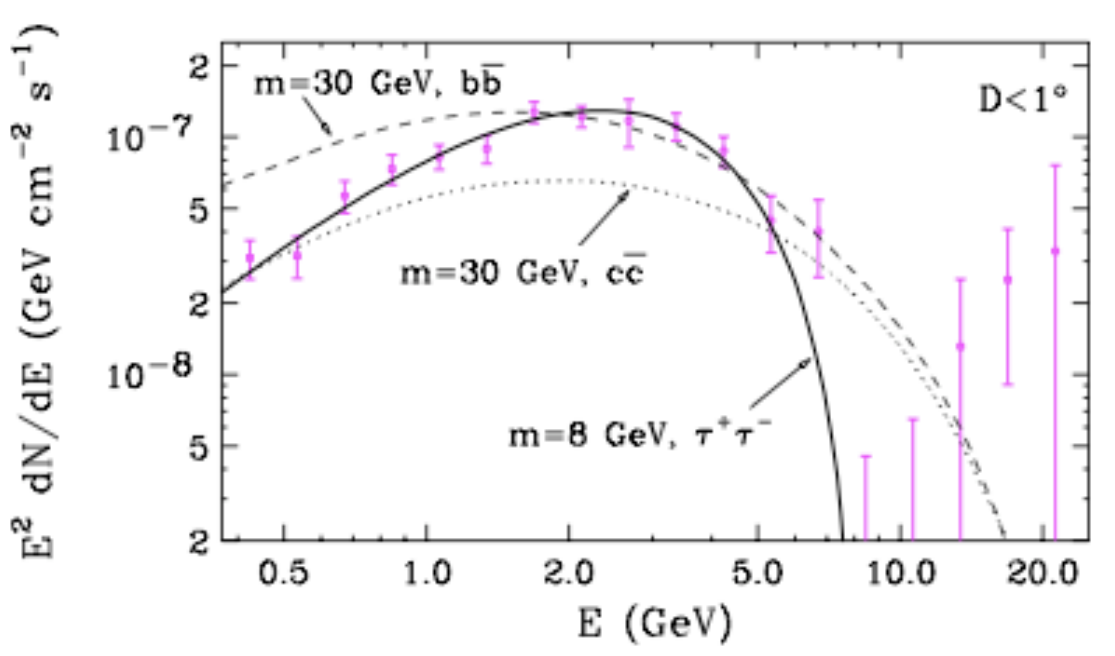
Abazajian 1011.4275

A diffuse GeV excess from around the GC

Dan Hooper

GeV gamma excess?

What if a signal of DM is *already* hidden in Fermi diffuse γ data from the GC?



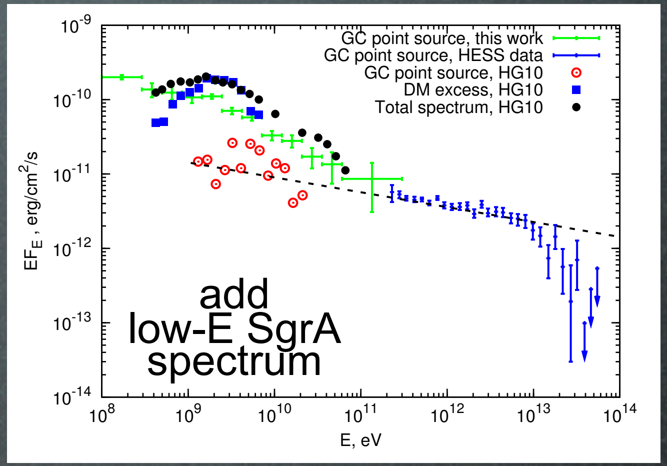
Hooper, Goodenough 1010.2752

Best fit: 8 GeV, $\tau^+ \tau^-$, ~thermal σv

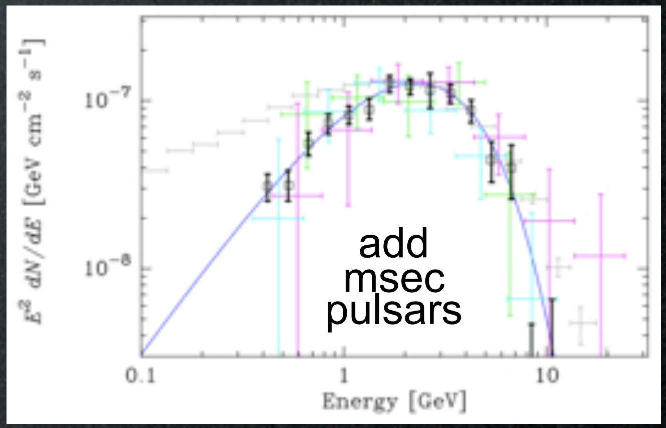
A diffuse GeV excess from around the GC

Dan Hooper

Objection: know your backgrounds!



Boyarsky et al., 1012.5839



Abazajian 1011.4275

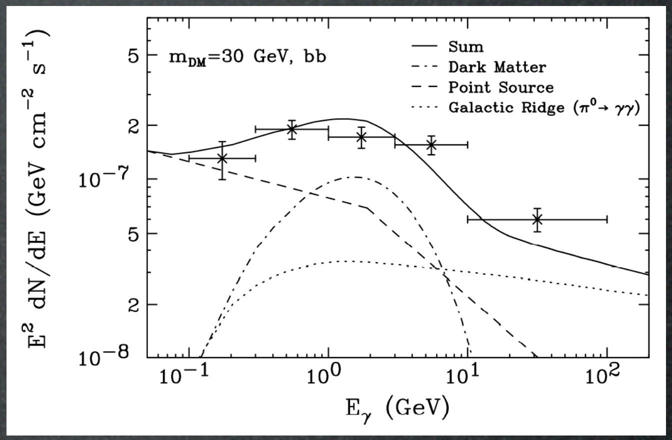
No, too few

(and we should have seen them elsewhere)

and wrong spectra

Hooper et al. 1305.0830

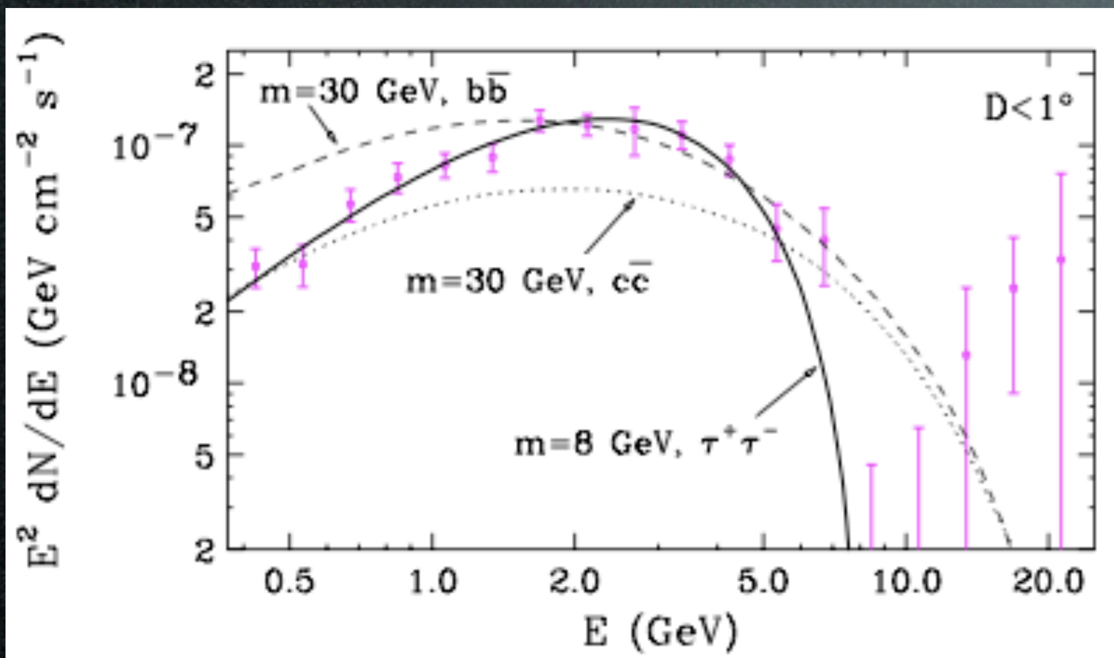
Still works...



Hooper, Linden 1110.0006

GeV gamma excess?

What if a signal of DM is *already* hidden in Fermi diffuse γ data from the GC?



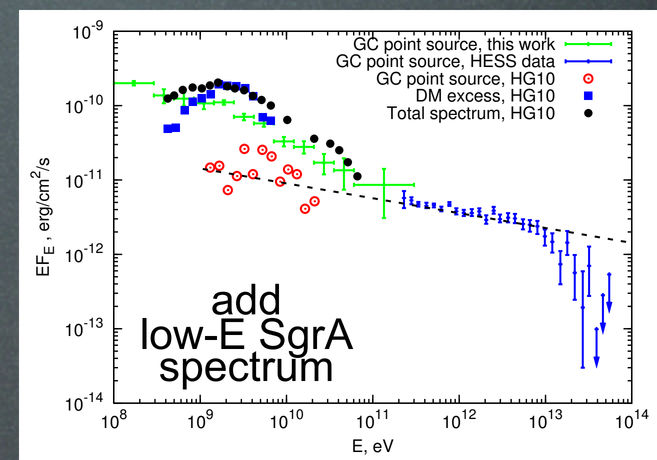
Hooper, Goodenough 1010.2752

Best fit: 8 GeV, $\tau^+ \tau^-$, ~thermal σv

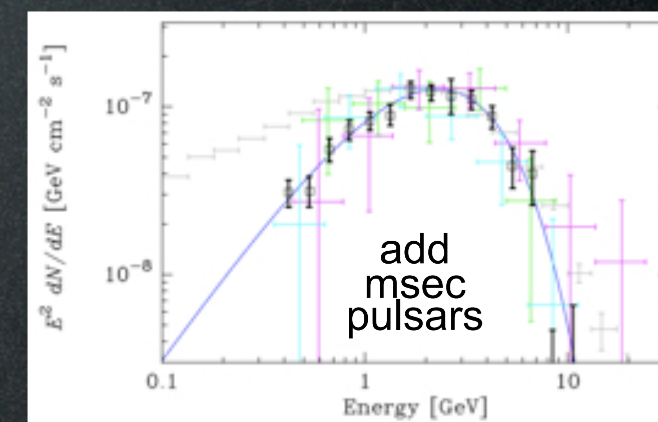
A diffuse GeV excess from around the GC

Dan Hooper

Objection: know your backgrounds!

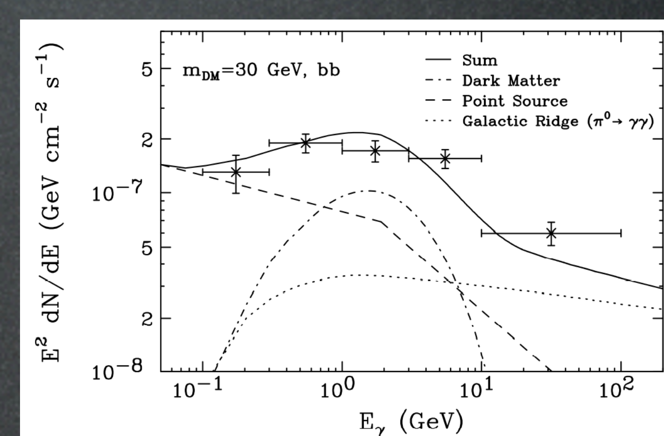


Boyarsky et al., 1012.5839



Abazajian 1011.4275

Still works...



Hooper, Linden 1110.0006

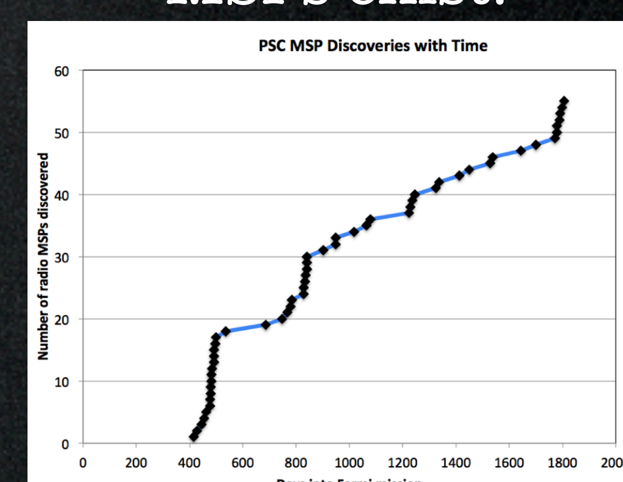
No, too few

(and we should have seen them elsewhere)

and wrong spectra

Hooper et al. 1305.0830

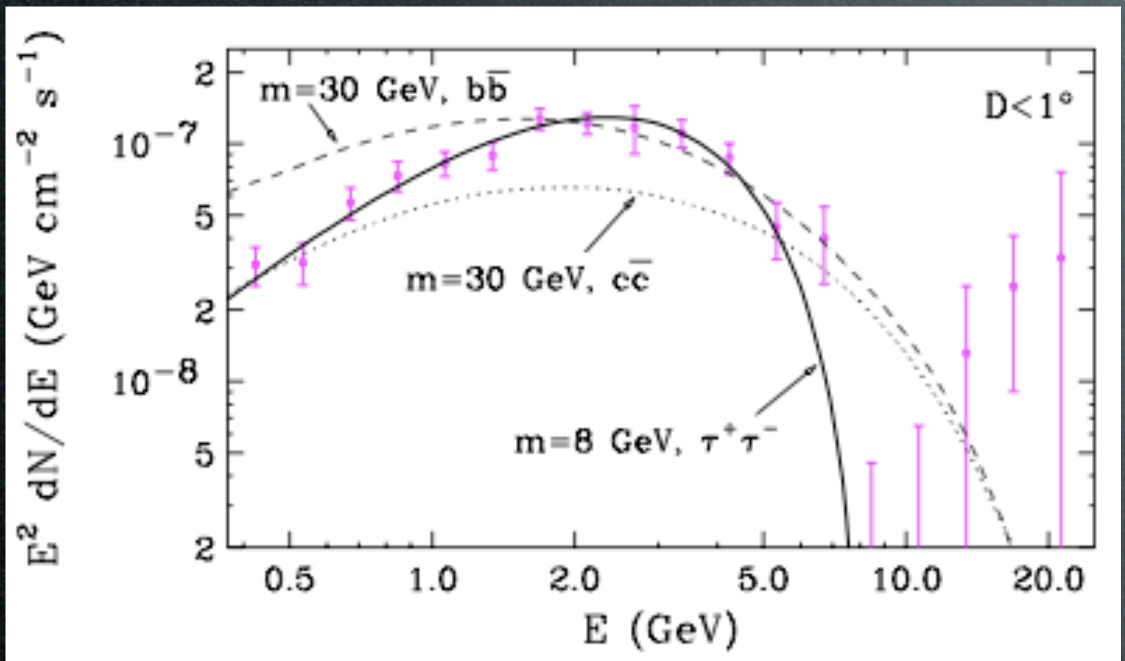
MSPs exist.



Caraveo 1312.2913

GeV gamma excess?

What if a signal of DM is *already* hidden in Fermi diffuse γ data from the GC?



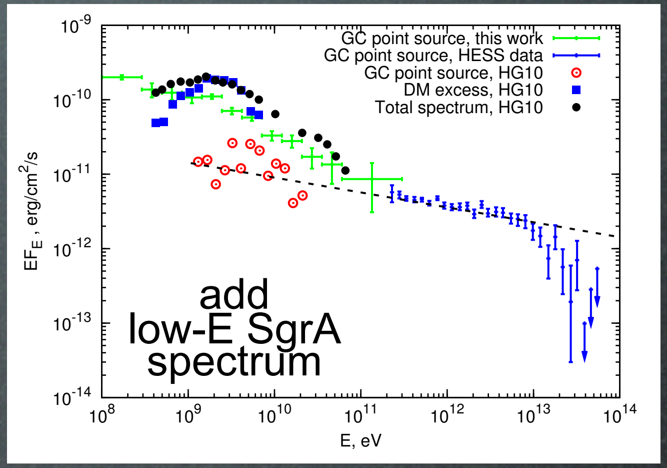
Hooper, Goodenough 1010.2752

Best fit: 8 GeV, $\tau^+ \tau^-$, ~thermal σv

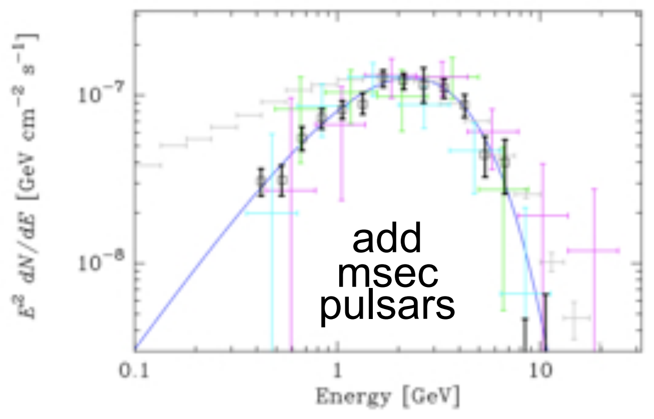
A diffuse GeV excess from around the GC

Dan Hooper

Objection: know your backgrounds!



Boyarsky et al., 1012.5839



Abazajian 1011.4275

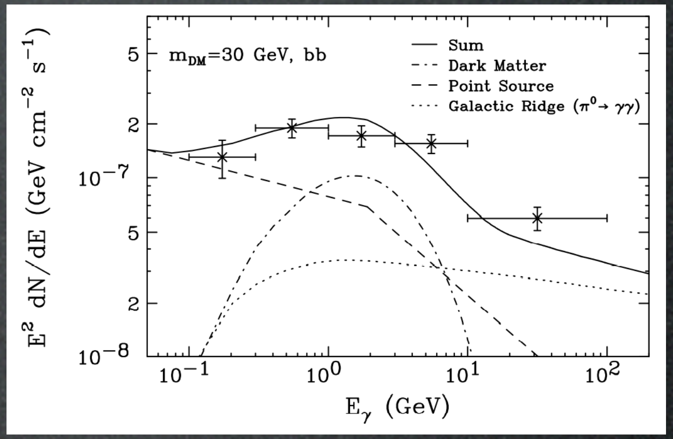
No, too few

(and we should have seen them elsewhere)

and wrong spectra

Hooper et al. 1305.0830

Still works...



Hooper, Linden 1110.0006

No no, MSPs can do.

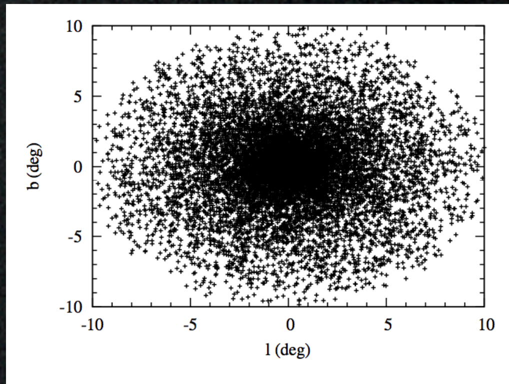


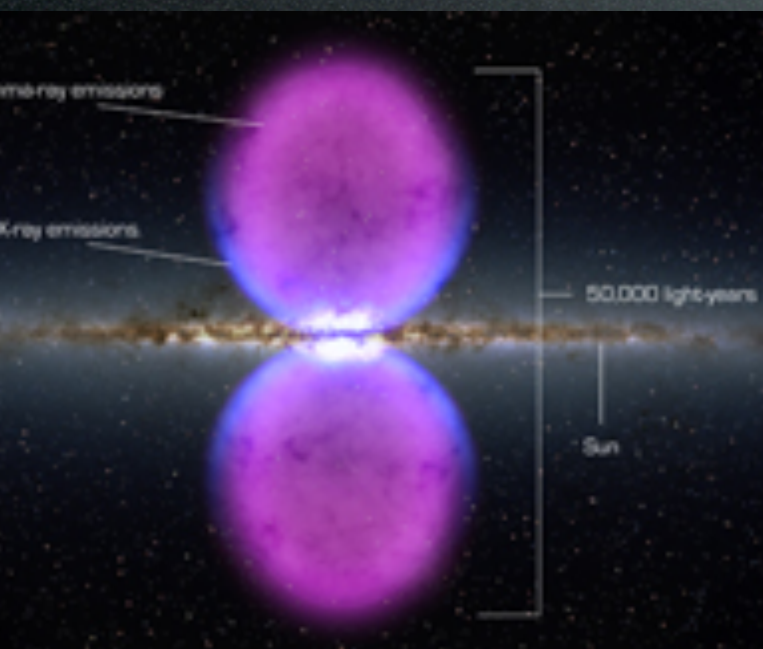
Figure 5: Simulated spatial distribution of the bulge MSPs.

Yuan, Zhang 1404.2318

(LMXB (tracers of MSP?) seen in M31 with this distribution)

GeV gamma excess?

What if a signal of DM is *already* hidden in Fermi diffuse γ data from the GC?

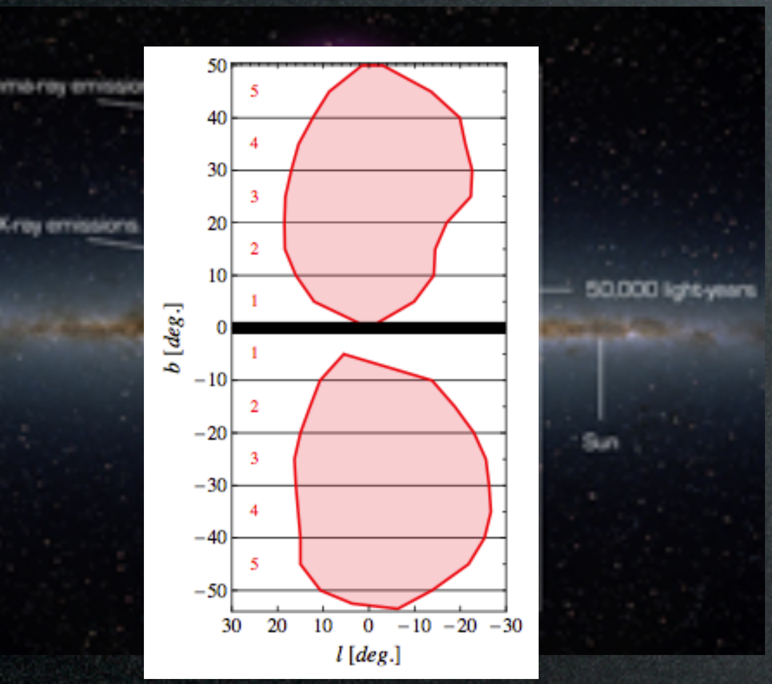


Fermi bubbles

Dan Hooper

GeV gamma excess?

What if a signal of DM is *already* hidden in Fermi diffuse γ data from the GC?

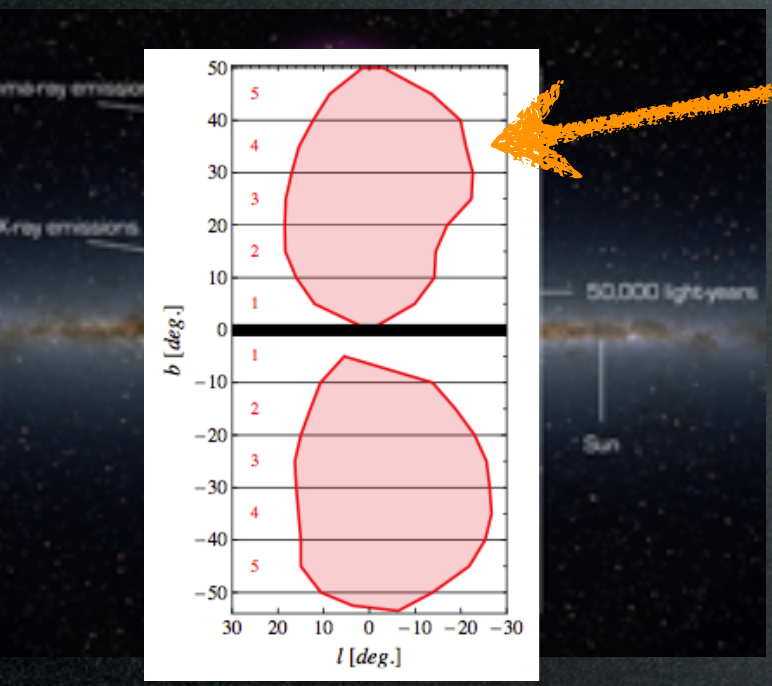


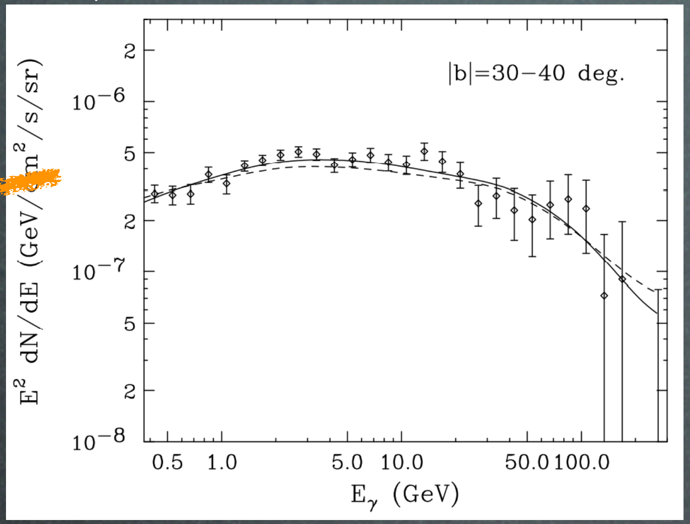
Fermi bubbles

Dan Hooper

GeV gamma excess?

What if a signal of DM is *already* hidden in Fermi diffuse γ data from the GC?





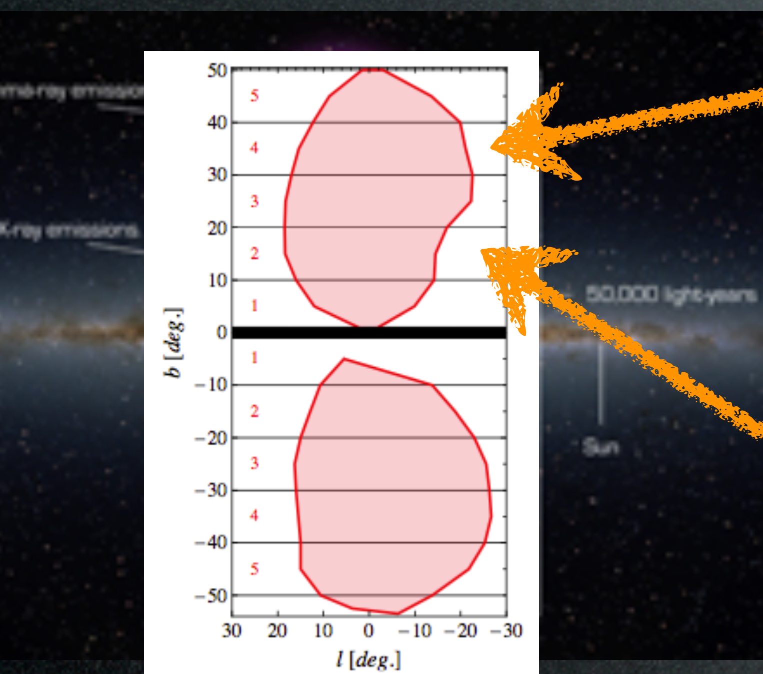
Here there's no excess which cannot be explained in terms of ordinary ICS.

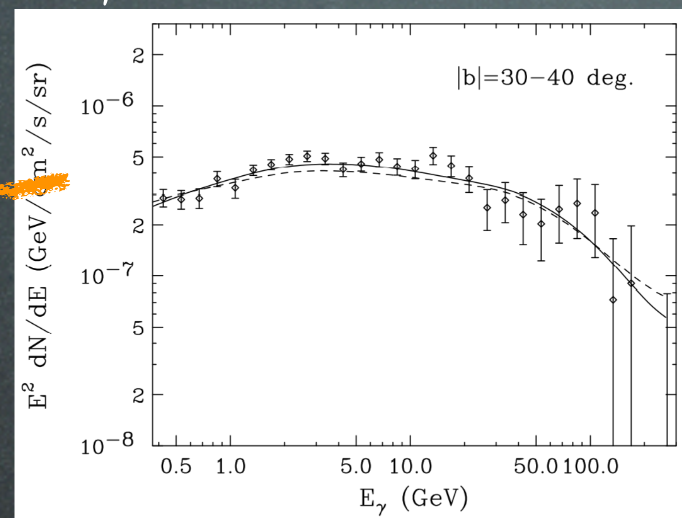
Fermi bubbles

Dan Hooper

GeV gamma excess?

What if a signal of DM is *already* hidden in Fermi diffuse γ data from the GC?



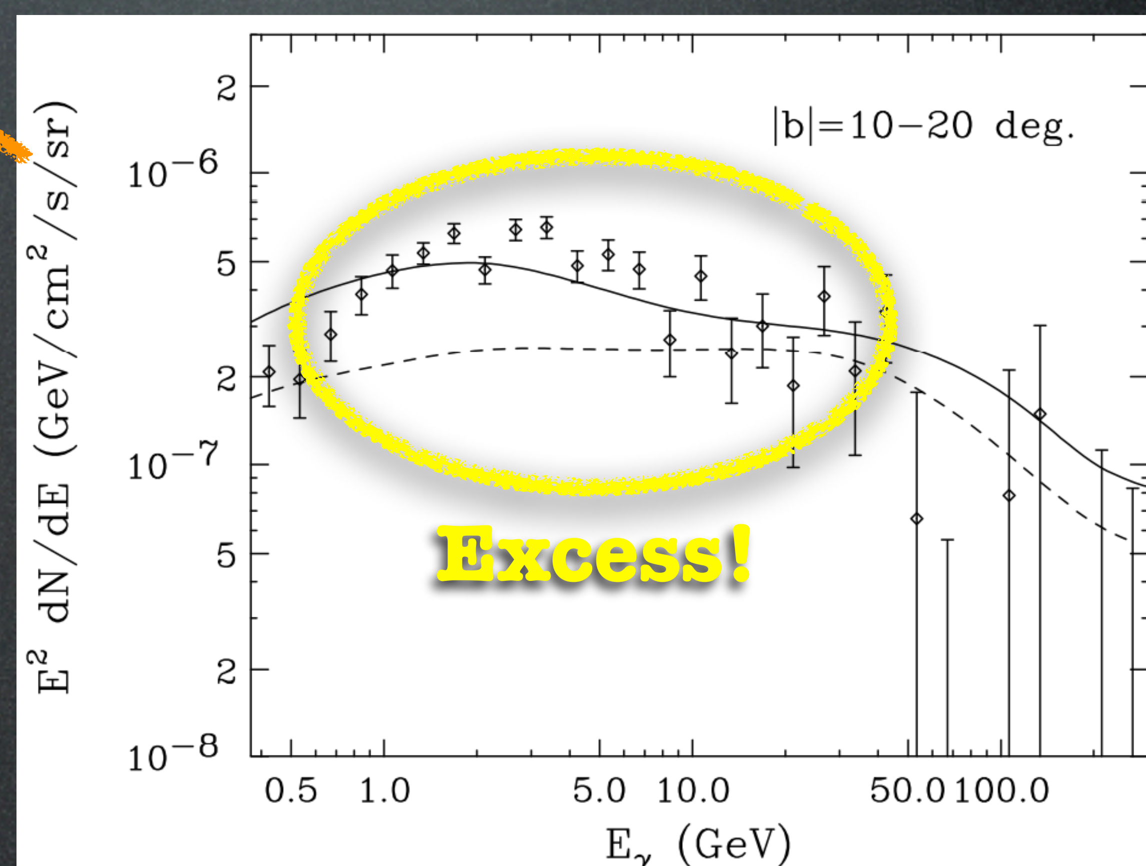


Here there's no excess which cannot be explained in terms of ordinary ICS.

Best fit:
~10 GeV, leptons, ~thermal σv

Fermi bubbles

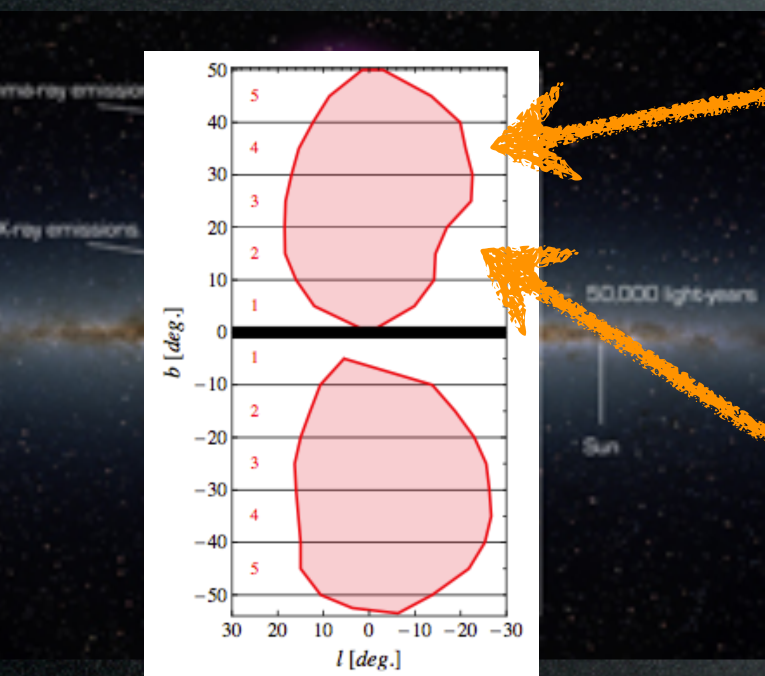
Dan Hooper

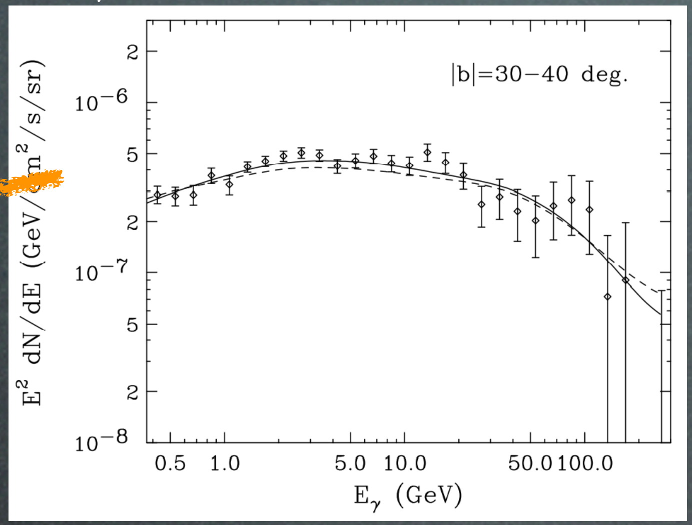


Hooper, Slatyer 1302.6589
Essentially confirmed by: Huang, Urbano, Xue 1307.6862

GeV gamma excess?

What if a signal of DM is *already* hidden in Fermi diffuse γ data from the GC?

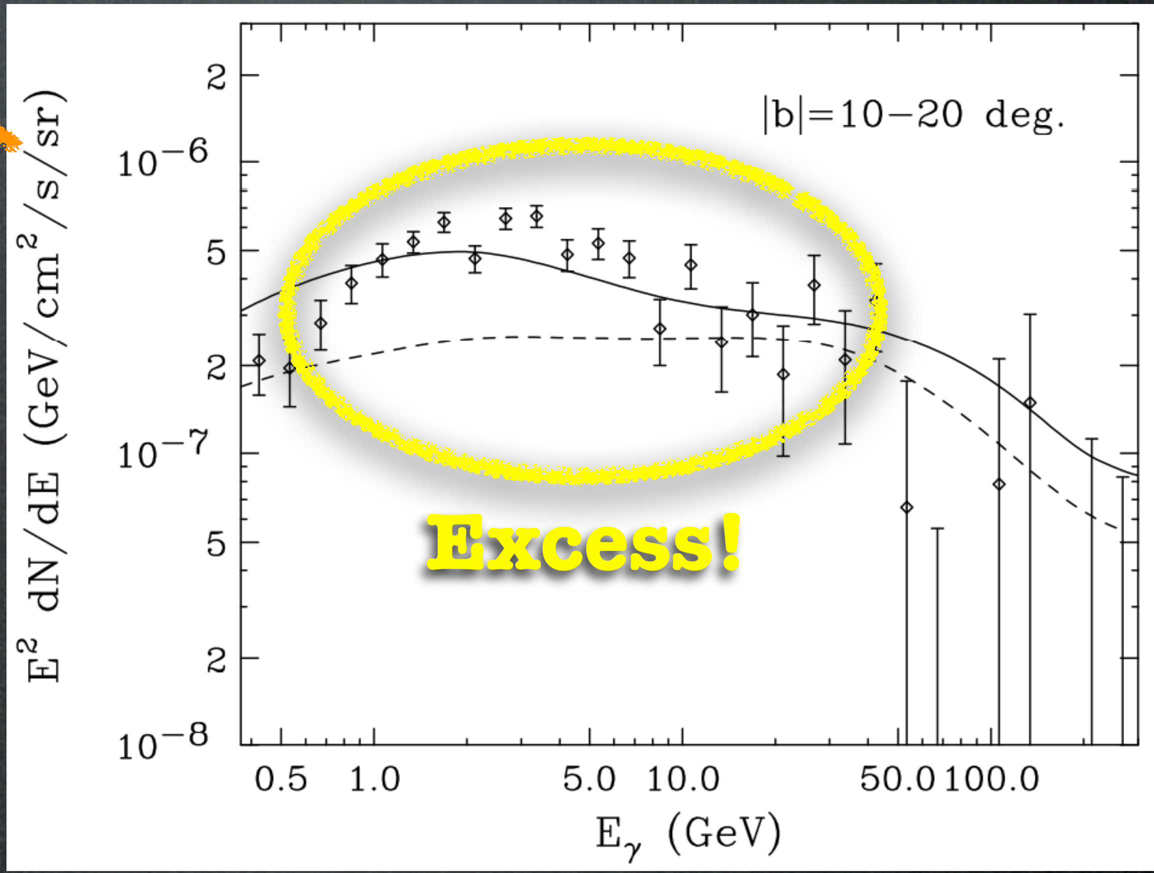




Here there's no excess which cannot be explained in terms of ordinary ICS.

Best fit:
~10 GeV, leptons, ~thermal σv

Fermi bubbles
Dan Hooper

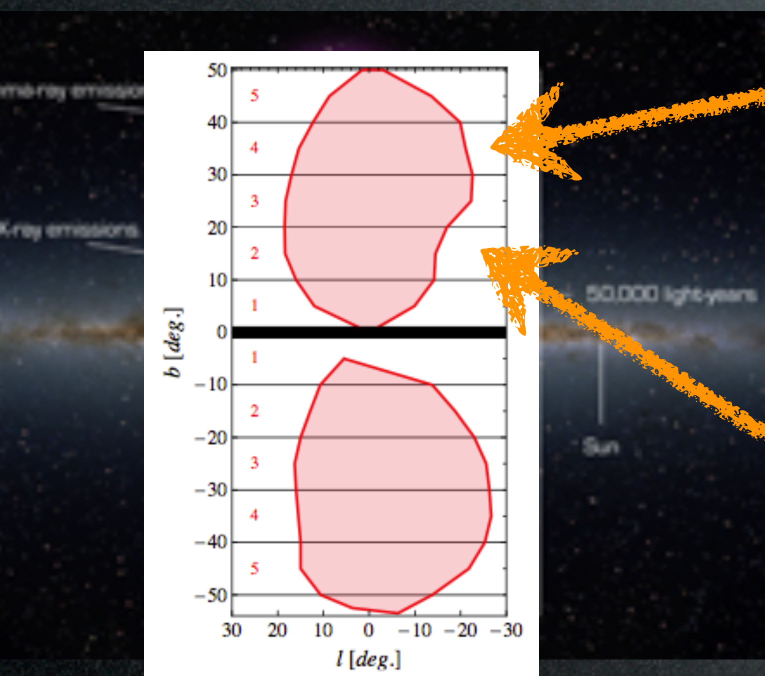


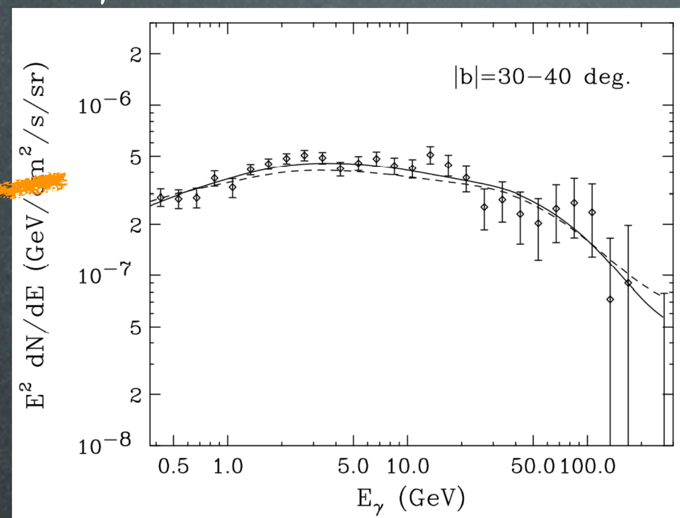
Objection:
nothing tells you that the input $e^\pm$ spectrum stays the same at high and low latitudes
(the ISRF too, but one can better model that)

Hooper, Slatyer 1302.6589
Essentially confirmed by: Huang, Urbano, Xue 1307.6862

GeV gamma excess?

What if a signal of DM is *already* hidden in Fermi diffuse γ data from the GC?





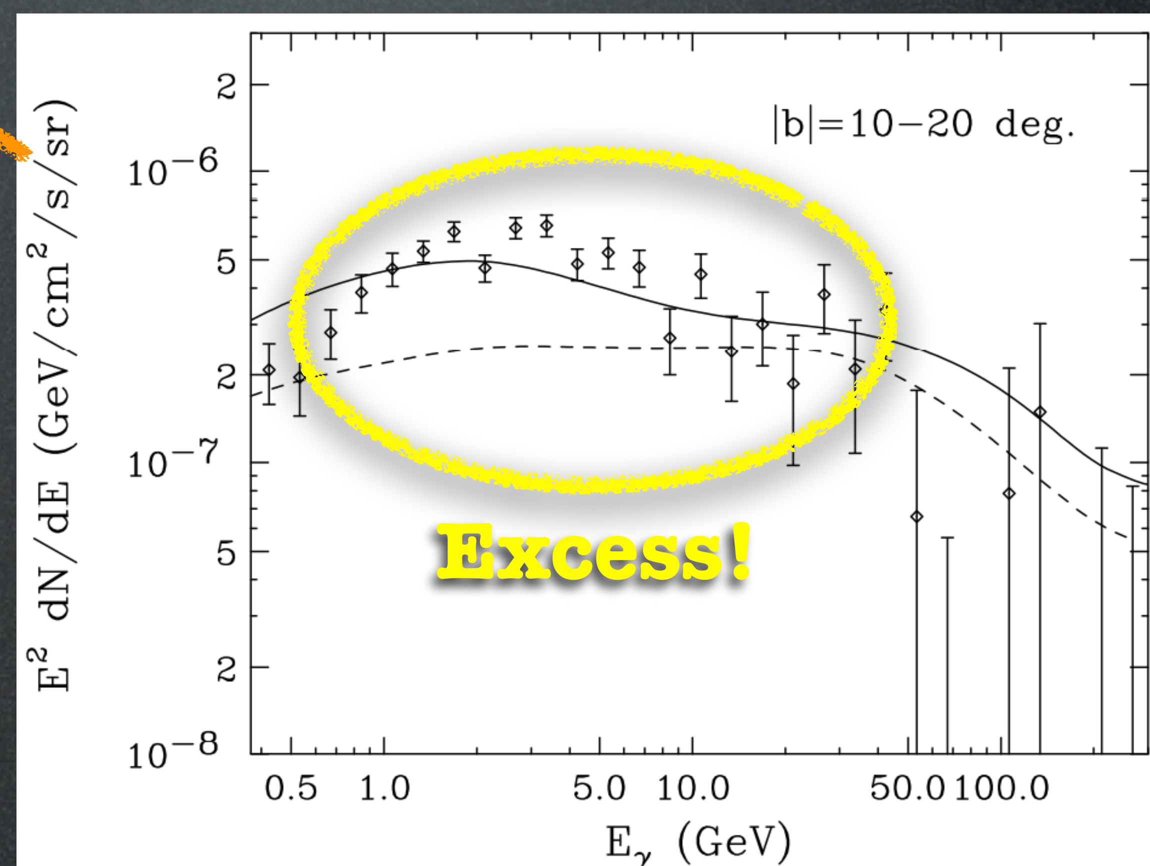
Here there's no excess which cannot be explained in terms of ordinary ICS.

Best fit:

~10 GeV, leptons, ~thermal σv

Fermi bubbles

Dan Hooper



Objection:
nothing tells you that the input $e^\pm$ spectrum stays the same at high and low latitudes
(the ISRF too, but one can better model that)

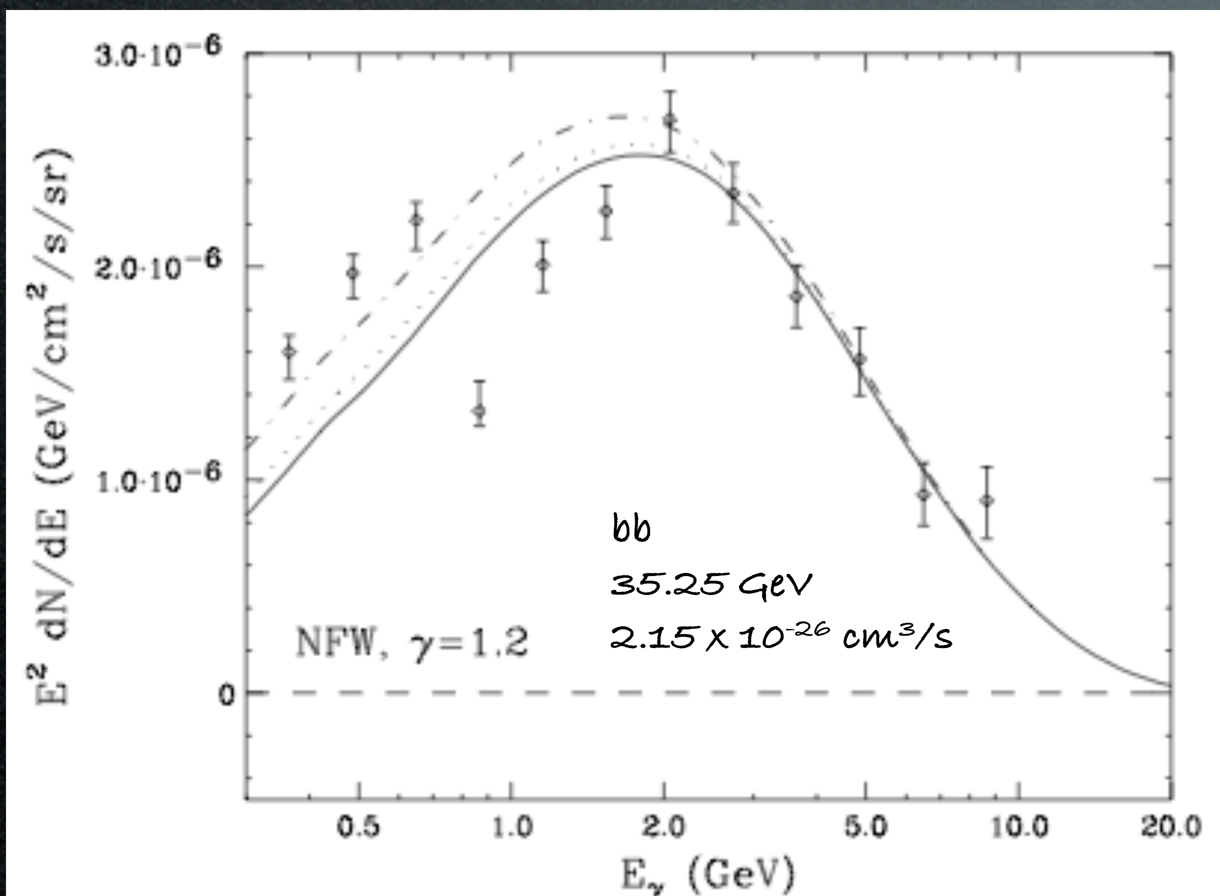
Response:
even if you try, the input $e^\pm$ spectrum has to be weird
(a δ fnct at 16 GeV?!?)

Hooper, Slatyer 1302.6589

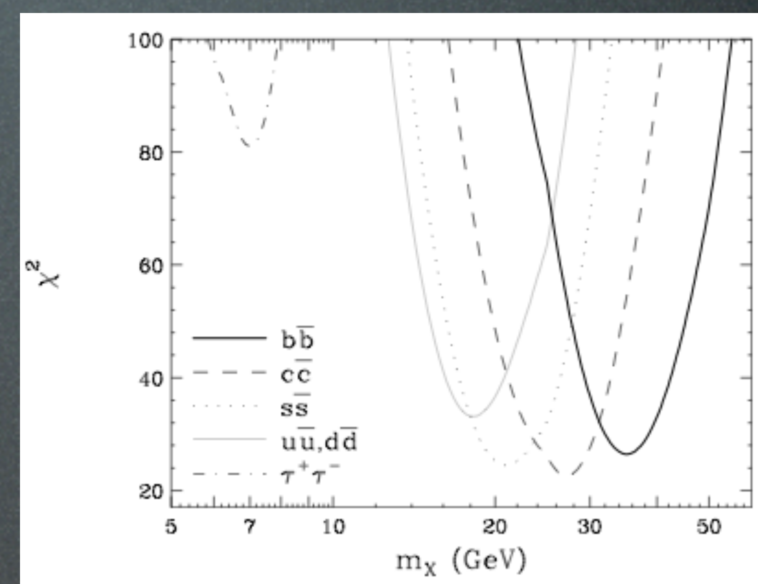
Essentially confirmed by: Huang, Urbano, Xue 1307.6862

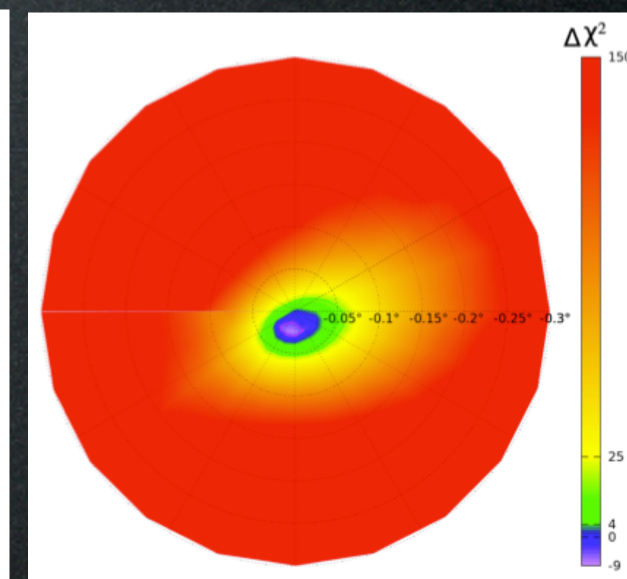
GeV gamma excess?

What if a signal of DM is *already* hidden in Fermi diffuse γ data from the GC?



Using events with accurate directional reconstruction





Best fit:

~35 GeV, quarks, ~thermal σv

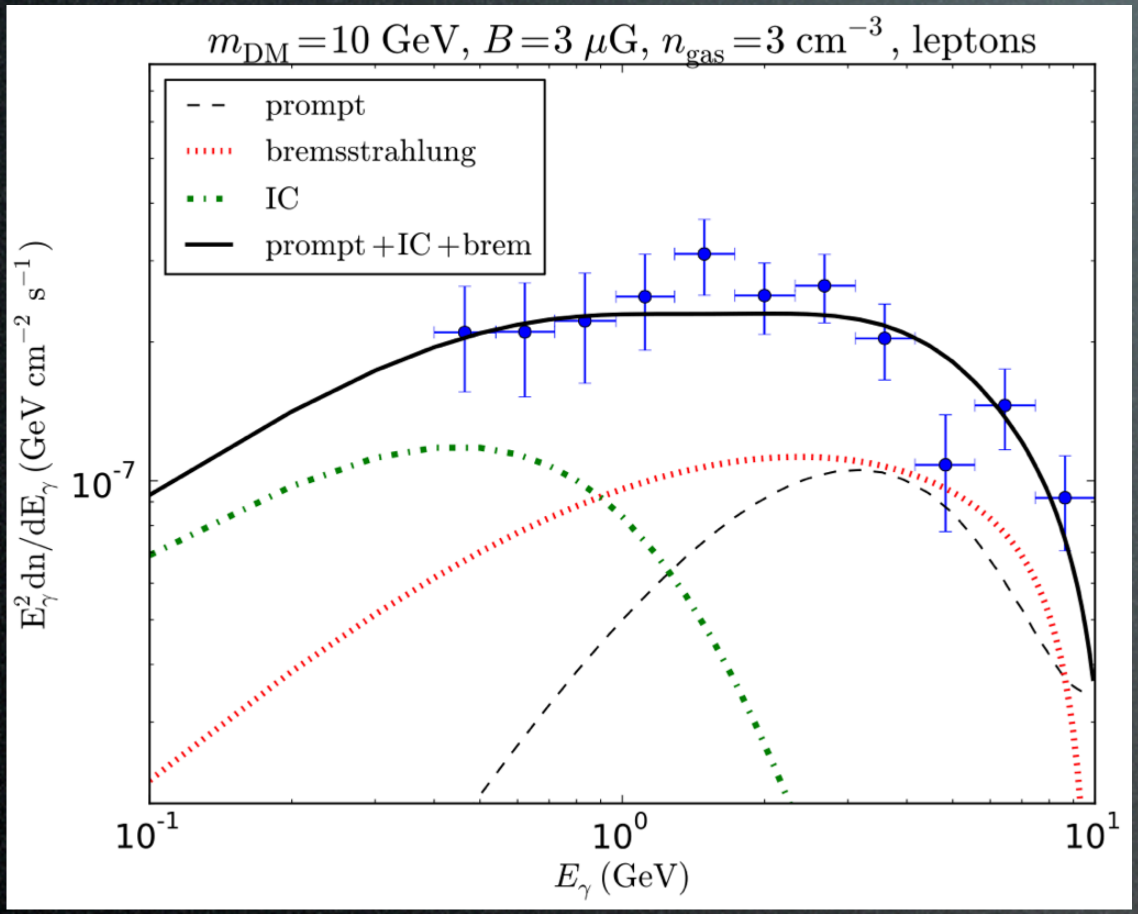
A compelling case for annihilating DM

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

As found in previous studies [8, 9], the inclusion of the dark matter template dramatically improves the quality of the fit to the *Fermi* data. For the best-fit spectrum and halo profile, we find that the inclusion of the dark matter template improves the formal fit by $\Delta\chi^2 \simeq 1672$, corresponding to a statistical preference greater than 40σ.

GeV gamma excess?

What if a signal of DM is *already* hidden in Fermi diffuse γ data from the GC?



Lacroix, Bœhm, Silk 1403.1987

Including secondary emission changes the conclusions

But: propagation is approximate

Best fit:
~10 GeV, leptons, ~thermal σv

Fermi-LAT excess

Lacroix, Bœhm, Silk 1403.1987

GeV gamma excess?

An excess with respect to **what**?
Extracting 'data points' is not trivial:

i. choose a ROI (shape, extension, masking...) and harvest Fermi-LAT data
ii. impose sensible cuts (Pass N, angles, CTBCORE...)
iii. in each energy bin, fit to a sum of spatial templates:
1. Fermi Coll. diffuse
2. isotropic
3. unresolved point sources
4. features (bubbles...)
5. AOB (molecular gas...)

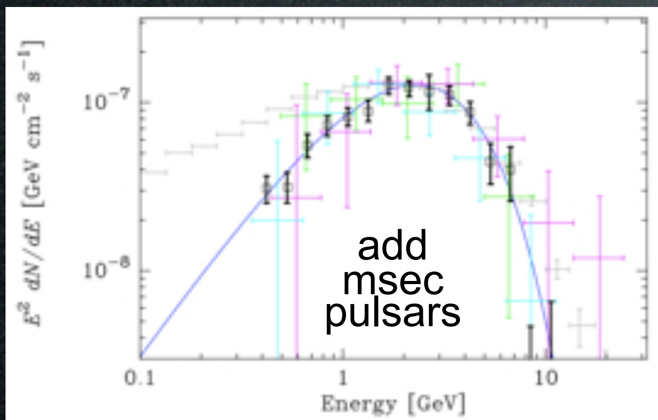
iv. repeat the same, adding a template for:
6. Dark Matter, having chosen a certain profile!

v. if iii. → iv. improves χ^2, there's evidence for DM
vi. the component fitted by 6 is the residual excess to be explained

Note:
Adding 6 will in general change the recipe of 1...5 (you'll need a bit more of x here, a bit less of y there...).
Changing the profile of 6 too.

Astrophysical interpretation

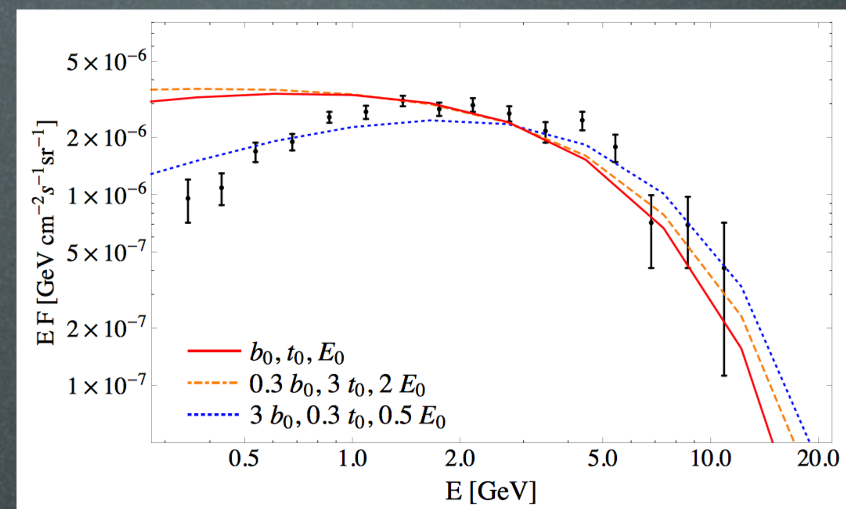
Millisec pulsars

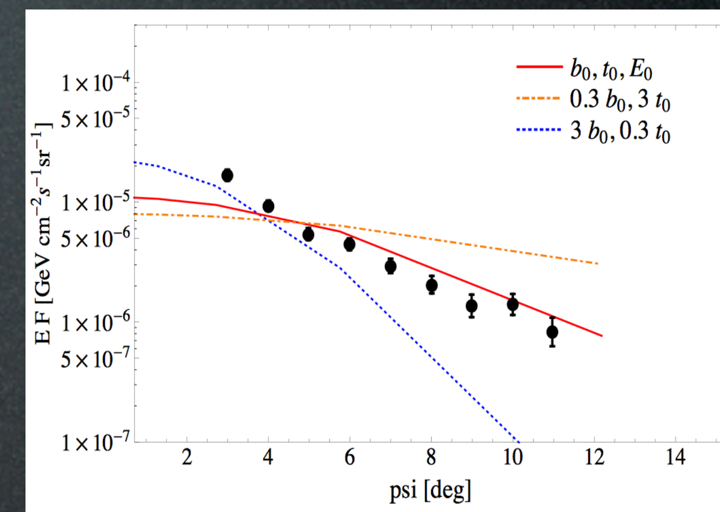


Abazajian 1011.4275
Hooper et al. 1305.0830
Yuan, Zhang 1404.2318

A transient phenomenon:

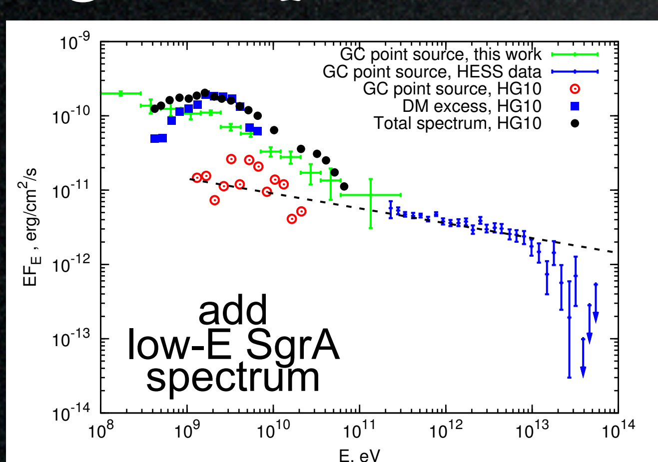
the GC spit 10^{52} ergs in $e^{\pm}$ 1 mln yrs ago and they do ICS on ambient light, 'fits' both spectrum and morphology Petrović, Serpico, Zaharijas 1405.7928





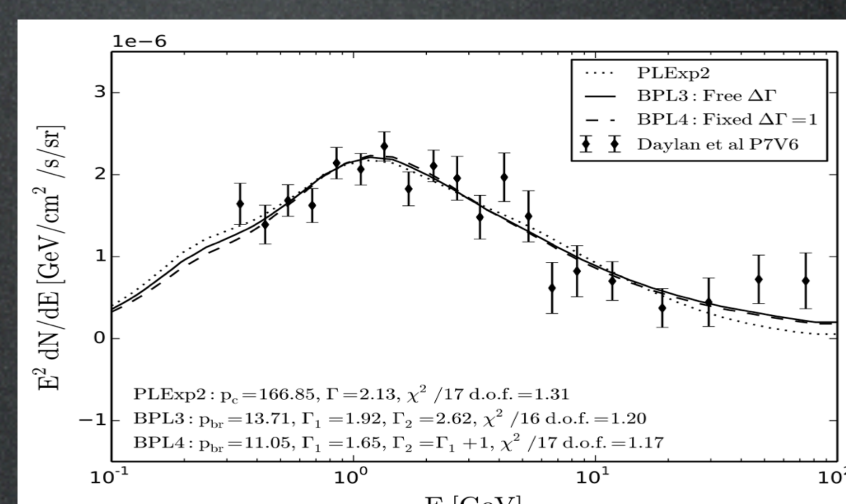
but: can one really get everything right?

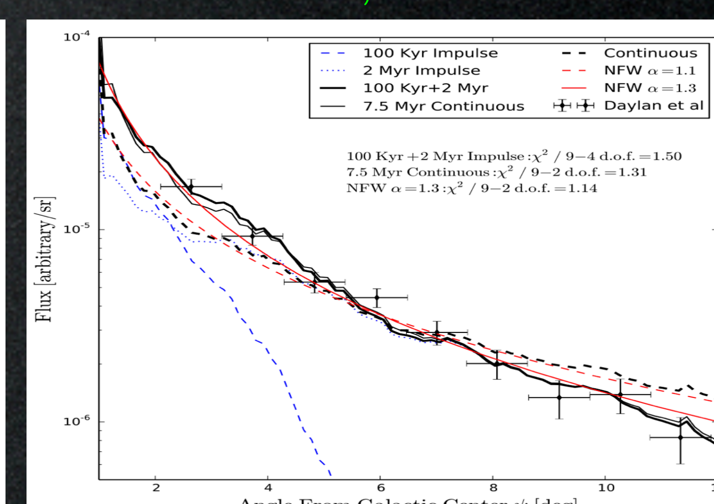
Non-trivial SgrA spectrum



Boyarsky et al., 1012.5839

a SN explosion spits protons 5000 yrs ago and they do spallations + bremsstrahlung as well as $e^{\pm}$ which do ICS... fits spectrum & morphology
Carlson, Profumo 1405.7685





but: why correlation with gas density not seen?

'The effective hooperon'

Huang, Urbano, Xue 1310.7609

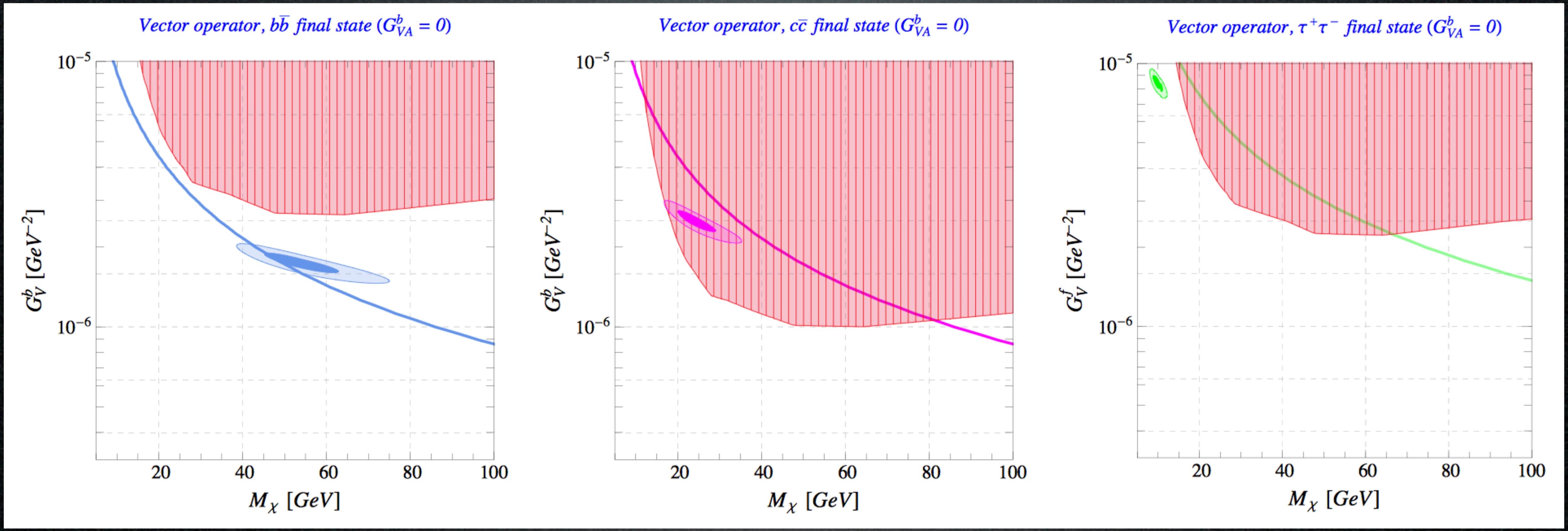
$$\text{Scalar}: \quad \mathcal{O}^f_{\rm S} \equiv \frac{m_f}{\sqrt{2}} \bar{\chi}\chi\, \bar{f}\left[G^f_{\rm S} + G^f_{\rm SA}\gamma^5\right] f\,,$$

$$\text{Pseudoscalar}: \quad \mathcal{O}^f_{\rm PS} \equiv \frac{m_f}{\sqrt{2}} \bar{\chi}\gamma^5\chi\, \bar{f}\left[G^f_{\rm PS} + G^f_{\rm PSA}\gamma^5\right] f\,,$$

$$\text{Vector}: \quad \mathcal{O}^f_{\rm V} \equiv \frac{1}{\sqrt{2}} \bar{\chi}\gamma^\mu\chi\, \bar{f}\gamma_\mu\left[G^f_{\rm V} + G^f_{\rm VA}\gamma^5\right] f\,,$$

$$\text{Pseudovector}: \quad \mathcal{O}^f_{\rm PV} \equiv \frac{1}{\sqrt{2}} \bar{\chi}\gamma^\mu\gamma^5\chi\, \bar{f}\gamma_\mu\left[G^f_{\rm PV} + G^f_{\rm PVA}\gamma^5\right] f\,,$$

$$\text{Tensor}: \quad \mathcal{O}^f_{\rm T} \equiv \frac{m_f}{\sqrt{2}} \bar{\chi}\sigma^{\mu\nu}\chi\, \bar{f}\sigma_{\mu\nu}\left[G^f_{\rm T} + G^f_{\rm TA}\gamma^5\right] f\,,$$



See also:
Profumo et al., 'The effective Hooperon', 1403.5027. Hooper et al., 1404.0022

‘The effective hooperon’

Huang, Urbano, Xue 1310.7609

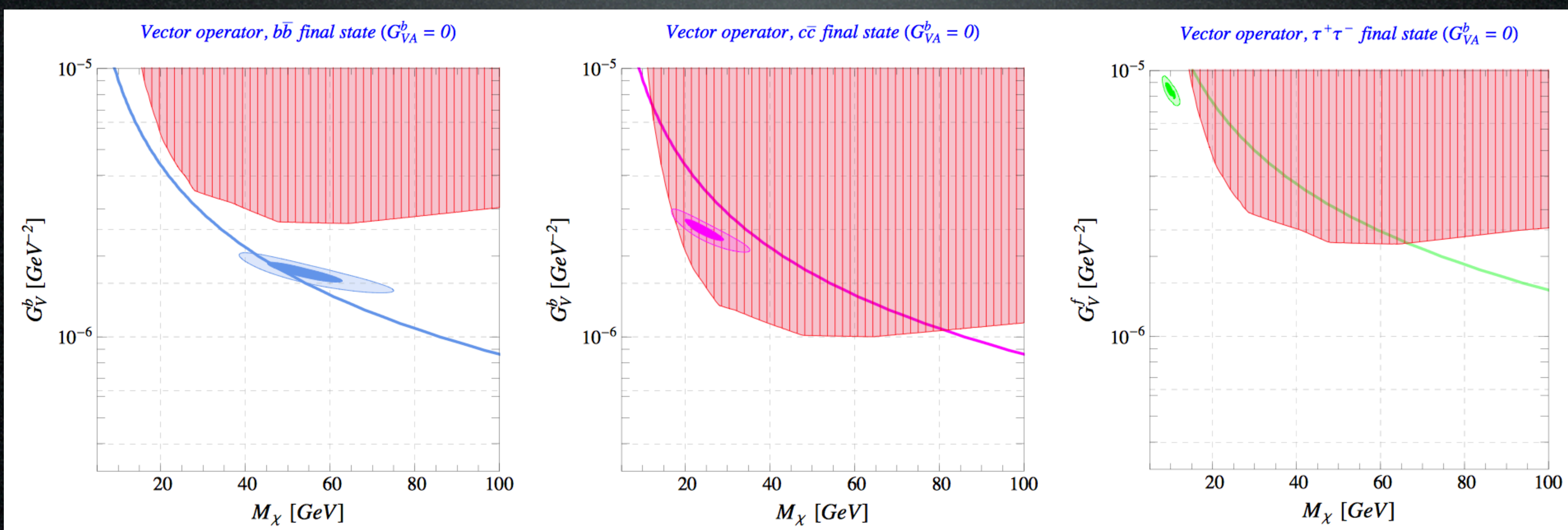
$$\text{Scalar}: \quad \mathcal{O}_S^f \equiv \frac{m_f}{\sqrt{2}} \bar{\chi}\chi \, \bar{f}\left[G_S^f + G_{SA}^f \gamma^5\right] f \,,$$

$$\text{Pseudoscalar}: \quad \mathcal{O}_{PS}^f \equiv \frac{m_f}{\sqrt{2}} \bar{\chi}\gamma^5\chi \, \bar{f}\left[G_{PS}^f + G_{PSA}^f \gamma^5\right] f \,,$$

$$\text{Vector}: \quad \mathcal{O}_V^f \equiv \frac{1}{\sqrt{2}} \bar{\chi}\gamma^\mu\chi \, \bar{f}\gamma_\mu\left[G_V^f + G_{VA}^f \gamma^5\right] f \,,$$

$$\text{Pseudovector}: \quad \mathcal{O}_{PV}^f \equiv \frac{1}{\sqrt{2}} \bar{\chi}\gamma^\mu\gamma^5\chi \, \bar{f}\gamma_\mu\left[G_{PV}^f + G_{PVA}^f \gamma^5\right] f \,,$$

$$\text{Tensor}: \quad \mathcal{O}_T^f \equiv \frac{m_f}{\sqrt{2}} \bar{\chi}\sigma^{\mu\nu}\chi \, \bar{f}\sigma_{\mu\nu}\left[G_T^f + G_{TA}^f \gamma^5\right] f \,,$$



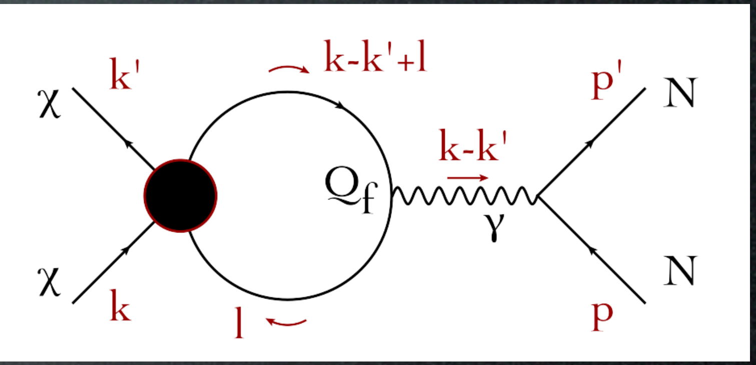
See also:
Profumo et al., ‘The effective Hooperon’, 1403.5027. Hooper et al., 1404.0022

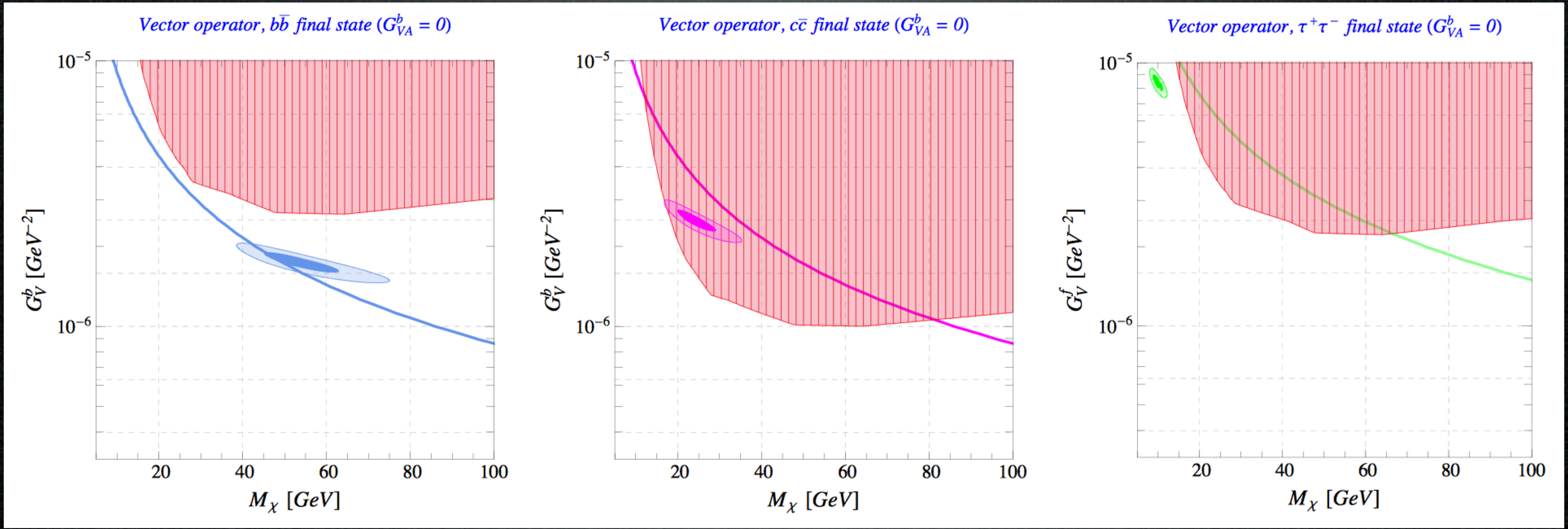
‘The effective hooperon’

Huang, Urbano, Xue 1310.7609

NB: no heavy Q nor τ in nuclei, but DD applies because of 1-loop diagrams

$$\text{Scalar}: \quad \mathcal{O}^f_{\rm S} \equiv \frac{m_f}{\sqrt{2}}\,\bar\chi\chi\,\bar f\left[G^f_{\rm S}+G^f_{\rm SA}\gamma^5\right]f\,,$$
$$\text{Pseudoscalar}: \quad \mathcal{O}^f_{\rm PS} \equiv \frac{m_f}{\sqrt{2}}\,\bar\chi\gamma^5\chi\,\bar f\left[G^f_{\rm PS}+G^f_{\rm PSA}\gamma^5\right]f\,,$$
$$\text{Vector}: \quad \mathcal{O}^f_{\rm V} \equiv \frac{1}{\sqrt{2}}\,\bar\chi\gamma^\mu\chi\,\bar f\gamma_\mu\left[G^f_{\rm V}+G^f_{\rm VA}\gamma^5\right]f\,,$$
$$\text{Pseudovector}: \quad \mathcal{O}^f_{\rm PV} \equiv \frac{1}{\sqrt{2}}\,\bar\chi\gamma^\mu\gamma^5\chi\,\bar f\gamma_\mu\left[G^f_{\rm PV}+G^f_{\rm PVA}\gamma^5\right]f\,,$$
$$\text{Tensor}: \quad \mathcal{O}^f_{\rm T} \equiv \frac{m_f}{\sqrt{2}}\,\bar\chi\sigma^{\mu\nu}\chi\,\bar f\sigma_{\mu\nu}\left[G^f_{\rm T}+G^f_{\rm TA}\gamma^5\right]f\,,$$





See also:
Profumo et al., ‘The effective Hooperon’, 1403.5027. Hooper et al., 1404.0022

‘The effective hooperon’

Huang, Urbano, Xue 1310.7609

$$\text{Scalar}: \quad \mathcal{O}^f_{\rm S} \equiv \frac{m_f}{\sqrt{2}}\,\bar{\chi}\chi\,\bar{f}\left[G^f_{\rm S} + G^f_{\rm SA}\gamma^5\right] f\,,$$

$$\text{Pseudoscalar}: \quad \mathcal{O}^f_{\rm PS} \equiv \frac{m_f}{\sqrt{2}}\,\bar{\chi}\gamma^5\chi\,\bar{f}\left[G^f_{\rm PS} + G^f_{\rm PSA}\gamma^5\right] f\,,$$

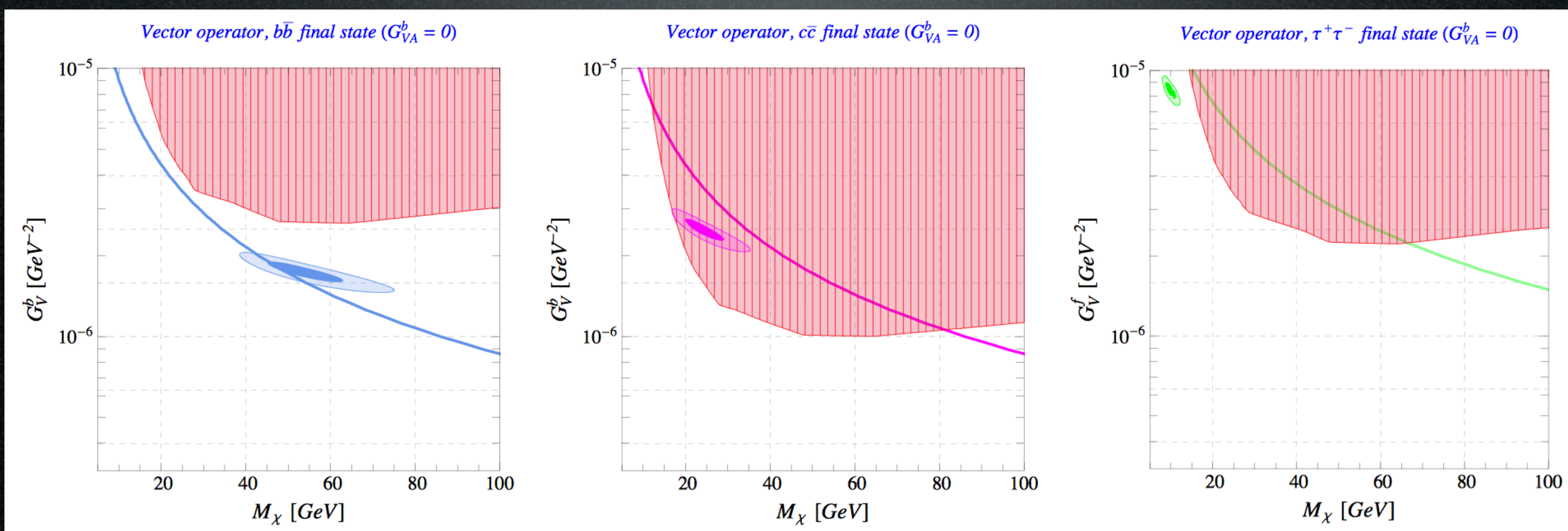
$$\text{Vector}: \quad \mathcal{O}^f_{\rm V} \equiv \frac{1}{\sqrt{2}}\,\bar{\chi}\gamma^\mu\chi\,\bar{f}\gamma_\mu\left[G^f_{\rm V} + G^f_{\rm VA}\gamma^5\right] f\,,$$

$$\text{Pseudovector}: \quad \mathcal{O}^f_{\rm PV} \equiv \frac{1}{\sqrt{2}}\,\bar{\chi}\gamma^\mu\gamma^5\chi\,\bar{f}\gamma_\mu\left[G^f_{\rm PV} + G^f_{\rm PVA}\gamma^5\right] f\,,$$

$$\text{Tensor}: \quad \mathcal{O}^f_{\rm T} \equiv \frac{m_f}{\sqrt{2}}\,\bar{\chi}\sigma^{\mu\nu}\chi\,\bar{f}\sigma_{\mu\nu}\left[G^f_{\rm T} + G^f_{\rm TA}\gamma^5\right] f\,,$$

Fermionic Dark Matter

Operator	Channel	Annihilation cross section: m_f^2 suppression	Annihilation cross section: v^2 suppression	DD cross section	s/Λ^2 (%)
S	$\tau^+\tau^-$	✓	✓	×	
	$c\bar{c}$			✓	
	$b\bar{b}$			✓	
	$q\bar{q}$			✓	
PS	$\tau^+\tau^-$ (76.3)	✓	×	×	13.7
	$c\bar{c}$ (58.2)				43.7
	$b\bar{b}$ (57.5)				78.5
	$q\bar{q}$				
V	$\tau^+\tau^-$ (76.3)	×	×	✓ (1L)	0.3
	$c\bar{c}$ (58.2)			✓ (1L)	0.6
	$b\bar{b}$ (57.5)			✓ (1L)	1.9
	$q\bar{q}$ (57.8)			✓	0.7
PV	$\tau^+\tau^-$ (76.3)	✓	×	×	2.5
	$c\bar{c}$ (58.2)				14.4
	$b\bar{b}$ (57.5)				34.6
	$q\bar{q}$				
T	$\tau^+\tau^-$ (76.3)	✓	×	×	8.3
	$c\bar{c}$ (58.2)				29.1
	$b\bar{b}$ (57.5)				49.1
	$q\bar{q}$				



See also:
Profumo et al., ‘The effective Hooperon’, 1403.5027. Hooper et al., 1404.0022

DM detection

direct detection

production at colliders

indirect

γ from annihil in galactic center or halo
and from synchrotron emission

Fermi, HESS, radio telescopes

e^+ from annihil in galactic halo or center

PAMELA, ATIC, Fermi

$\bar{p}$ from annihil in galactic halo or center

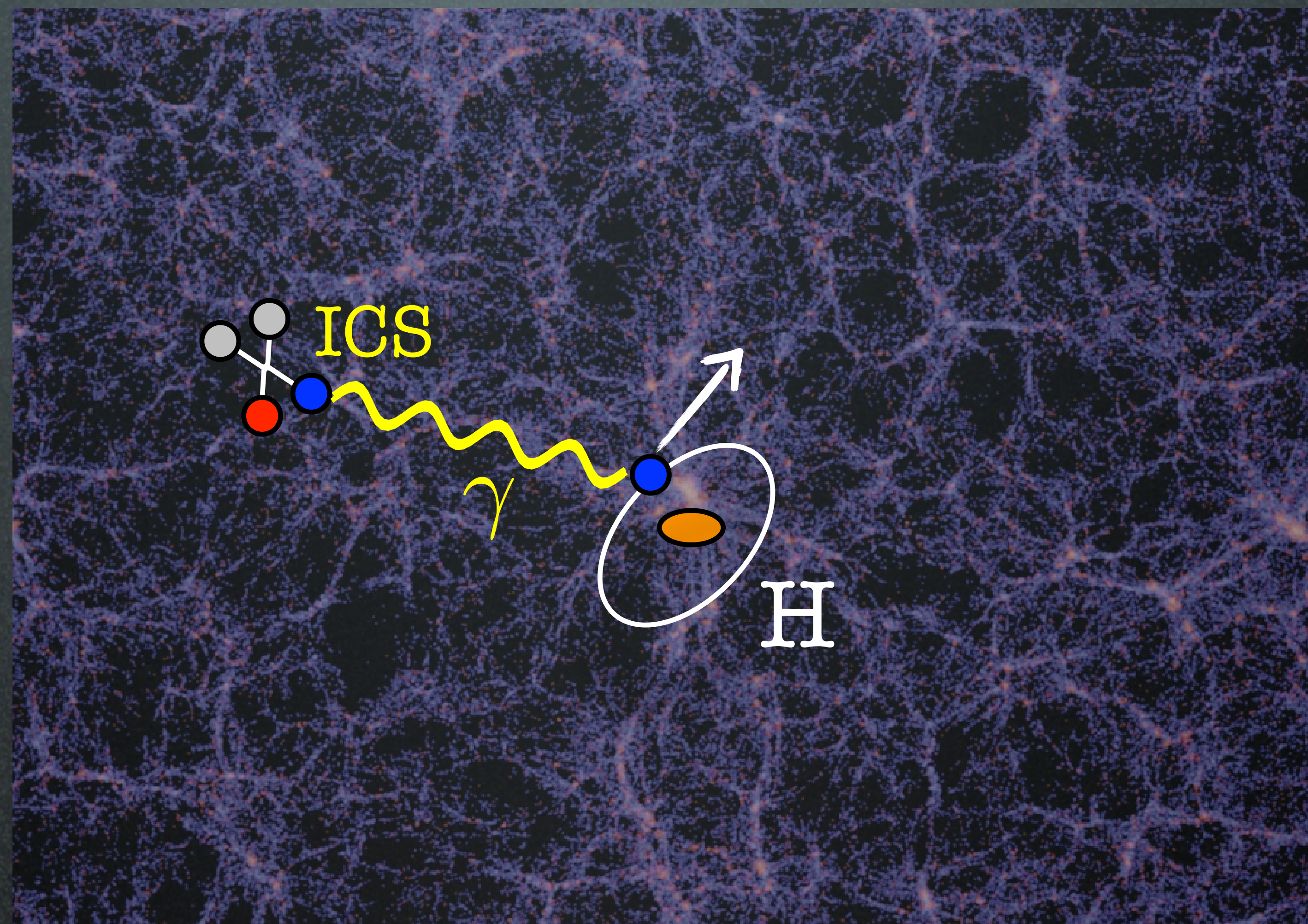
$\bar{D}$ from annihil in galactic halo or center

$\nu, \bar{\nu}$ from annihil in galactic center

bonus track: cosmology

Cosmology: bounds from reionization

DM particle annihilations produce free electrons



$$-n_{\rm A} H_0 \sqrt{\Omega_{\rm M}}(1+z)^{11/2}\frac{dx_{\rm ion}(z)}{dz} = I(z) - R(z).$$

$$I(z) = \int_{e_{\rm i}}^{m_\chi} dE_\gamma\, \frac{dn}{dE_\gamma}(z)\cdot P(E_\gamma,z)\cdot N_{\rm ion}(E_\gamma)$$

$$P(E_\gamma,z) = n_{\rm A}(1+z)^3\left[1-x_{\rm ion}(z)\right]\cdot\sigma_{\rm tot}(E_\gamma),$$

$$N_{\rm ion}(E_\gamma) = \eta_{\rm ion}(x_{\rm ion}(z))\; E_\gamma\left[\frac{n_{\rm H}}{n_{\rm A}}\frac{1}{e_{\rm i,H}} + \frac{n_{\rm He}}{n_{\rm A}}\frac{1}{e_{\rm i,He}}\right] = \eta_{\rm ion}(x_{\rm ion}(z))\;\frac{E_\gamma}{\rm GeV}\,\mu$$

$$\frac{dn}{dE_\gamma}(z) = \int_\infty^z dz'\,\frac{dt}{dz'}\,\frac{dN}{dE'_\gamma}(z')\,\frac{(1+z)^3}{(1+z')^3}\cdot A(z')\cdot\exp\left[\Upsilon(z,z',E'_\gamma)\right].$$

$$\Upsilon(z,z',E'_\gamma) \simeq -\int_{z'}^{z} dz''\,\frac{dt}{dz''}n_{\rm A}(1+z'')^3\sigma_{\rm tot}(E''_\gamma)$$

$$\frac{dT_{\rm igm}(z)}{dz} = \frac{2\,T_{\rm igm}(z)}{1+z} - \frac{1}{H_0\,\sqrt{\Omega_{\rm M}}\,(1+z)^{5/2}}\left(\frac{x_{\rm ion}(z)}{1+x_{\rm ion}(z)+0.073}\frac{T_{\rm CMB}(z)-T_{\rm igm}(z)}{t_{\rm c}(z)} + \frac{2\,\eta_{\rm heat}(x_{\rm ion}(z))\,\mathcal{E}(z)}{3\,n_{\rm A}(1+z)^3}\right).$$

$$A(z) = \frac{\langle\sigma v\rangle}{2\,m_\chi^2}\rho^2_{\rm DM,0}(1+z)^6\,(1+\mathcal{B}_i(z))\,,$$

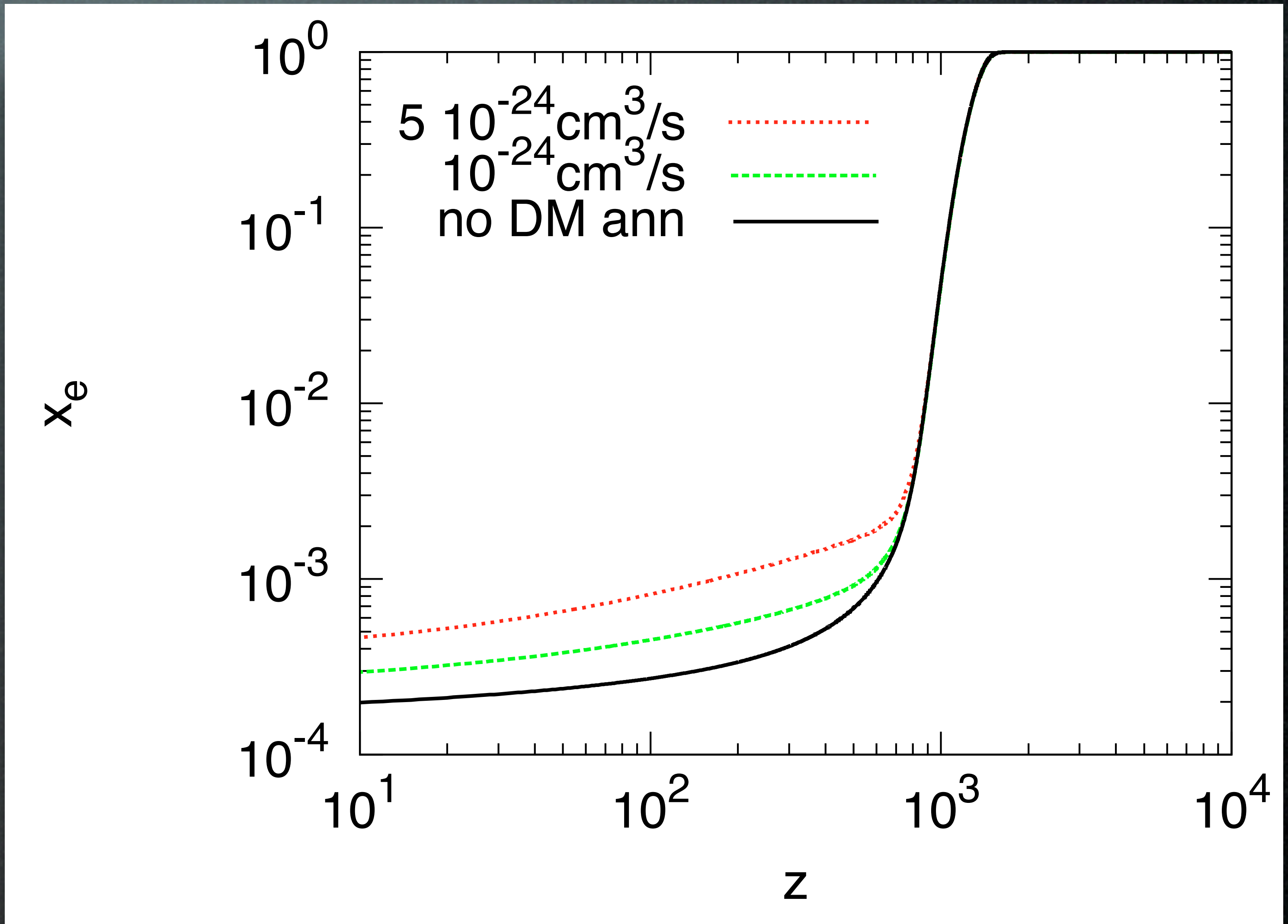
$$\mathcal{B}_i(z) = \frac{\Delta_{\rm vir}(z)}{3\,\rho_{\rm c}\Omega_{\rm M}}\int_{M_{\rm min}}^{\infty} dM\,M\frac{dn}{dM}(z,M)\,F_i(M,z),$$

$$\frac{dn}{dM}(M,z) = \sqrt{\frac{\pi}{2}}\frac{\rho_{\rm M}}{M}\,\delta_{\rm c}\,(1+z)\frac{d\sigma(R)}{dM}\frac{1}{\sigma^2(R)}\exp\left(-\frac{\delta_{\rm c}^2\,(1+z)^2}{2\sigma^2(R)}\right)$$

Cirelli, Iocco, Panci, JCAP 0910

Cosmology: bounds from reionization

DM particle annihilations produce free electrons



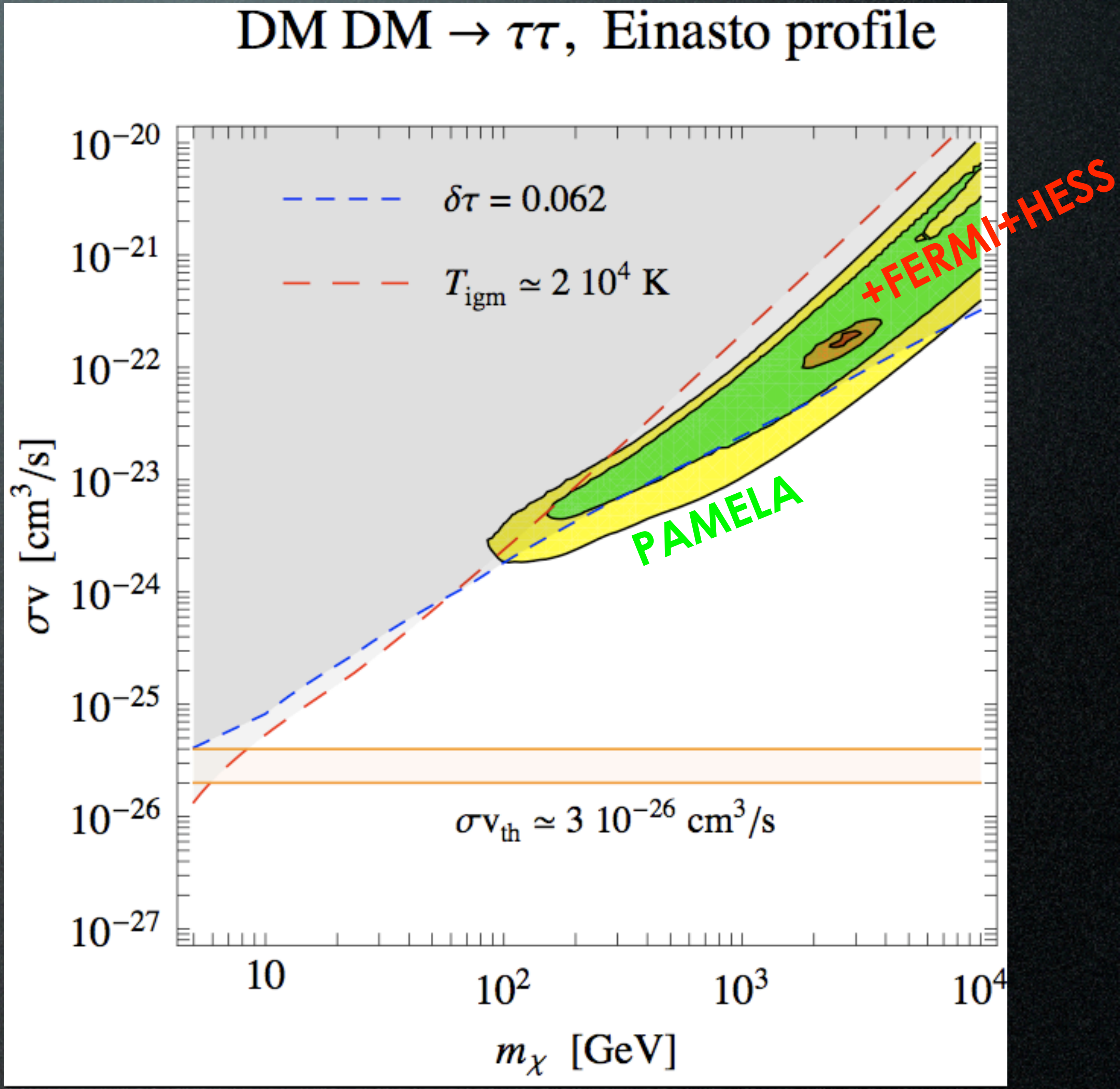
Kanzaki et al., 0907.3985

Cosmology: bounds from reionization

DM particle annihilations may produce too many free electrons

bounds on optical depth of the Universe violated

$\tau = 0.084 \pm 0.016$ (WMAP-5yr)



Cirelli, Iocco, Panci, JCAP 0910

see also:
Huetsi, Hektor, Raidal 0906.4550
Kanzaki et al., 0907.3985
Huetsi et al., 1103.2766

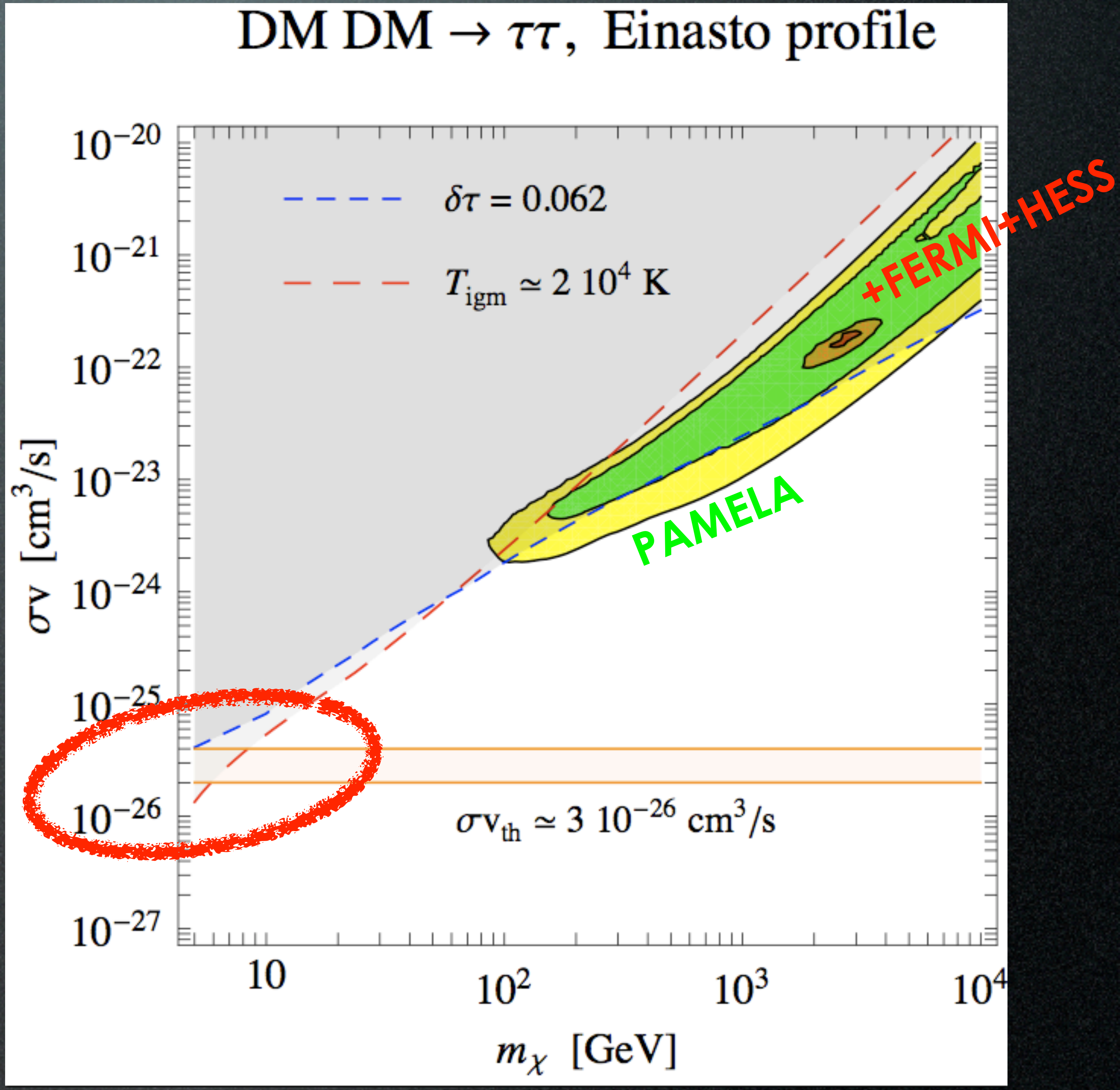
Cosmology: bounds from reionization

DM particle annihilations may produce too many free electrons

bounds on optical depth of the Universe violated

$\tau = 0.084 \pm 0.016$ (WMAP-5yr)

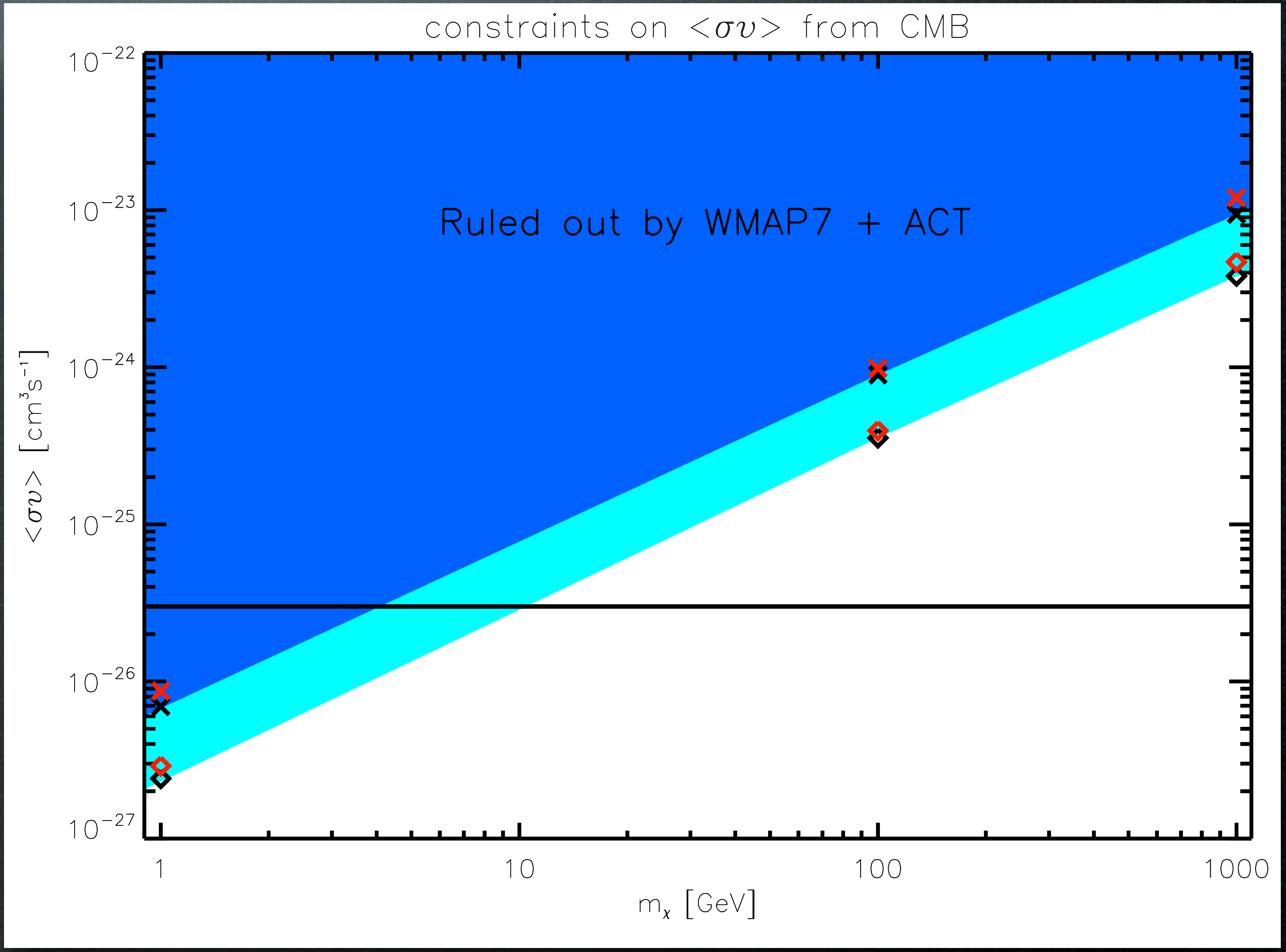
Starts constraining even thermal DM!



Cirelli, Iocco, Panci, JCAP 0910

Cosmology: bounds from CMB

Similar conclusion from global CMB fits

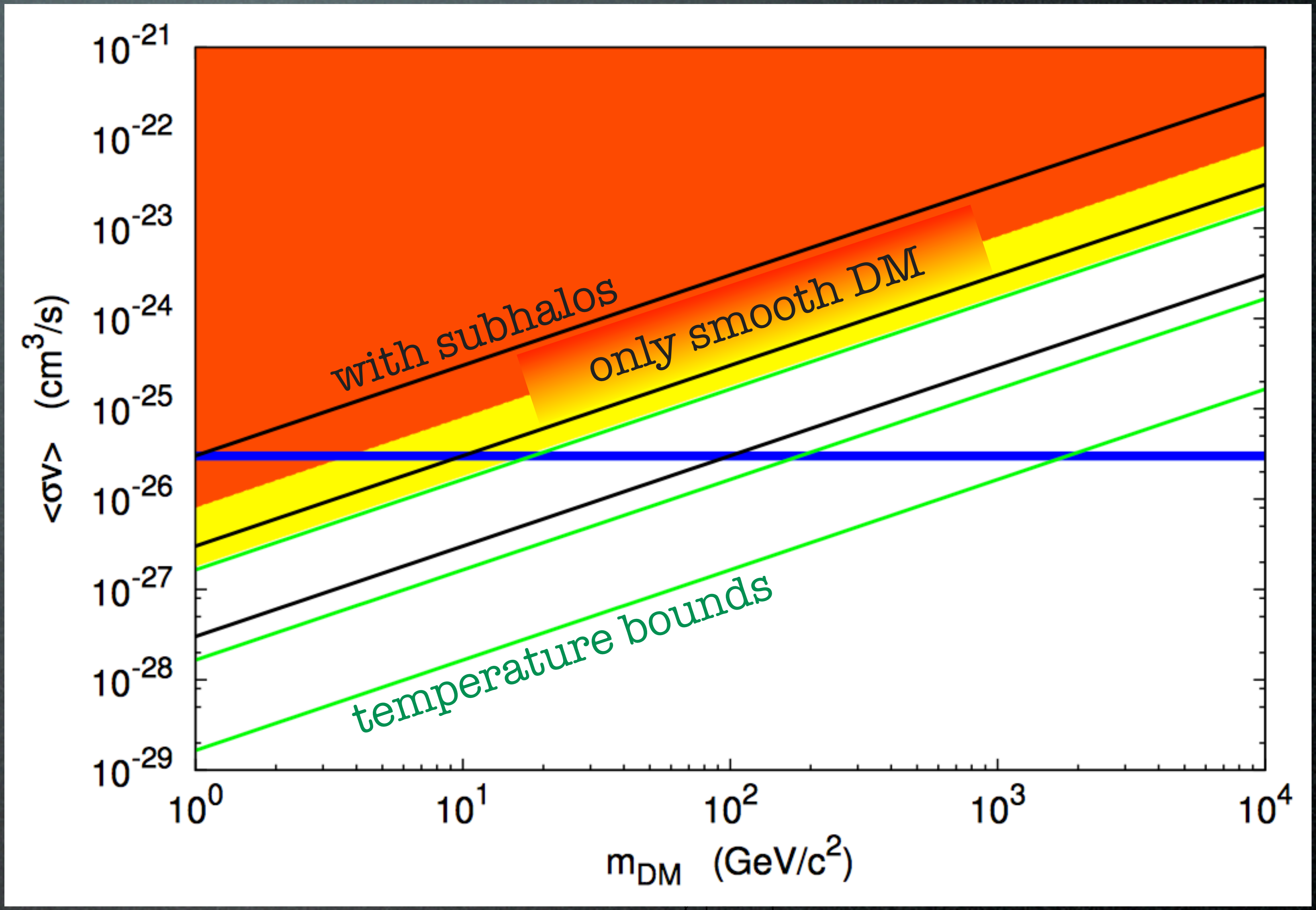


Galli, Iocco, Bertone, Melchiorri, PRD 80 (2009)
Slatyer, Padmanabahn, Finkbeiner, PRD 80 (2009)
Galli, Iocco, Bertone, Melchiorri, 1106.1528 (2011)

see also: Finkbeiner, Galli, Lin, Slatyer 1109.6322 (2011)
Galli, Slatyer, Valdes, Iocco, 1306.0563 (2013)

Cosmology: bounds from CMB

Similar conclusion from global CMB fits

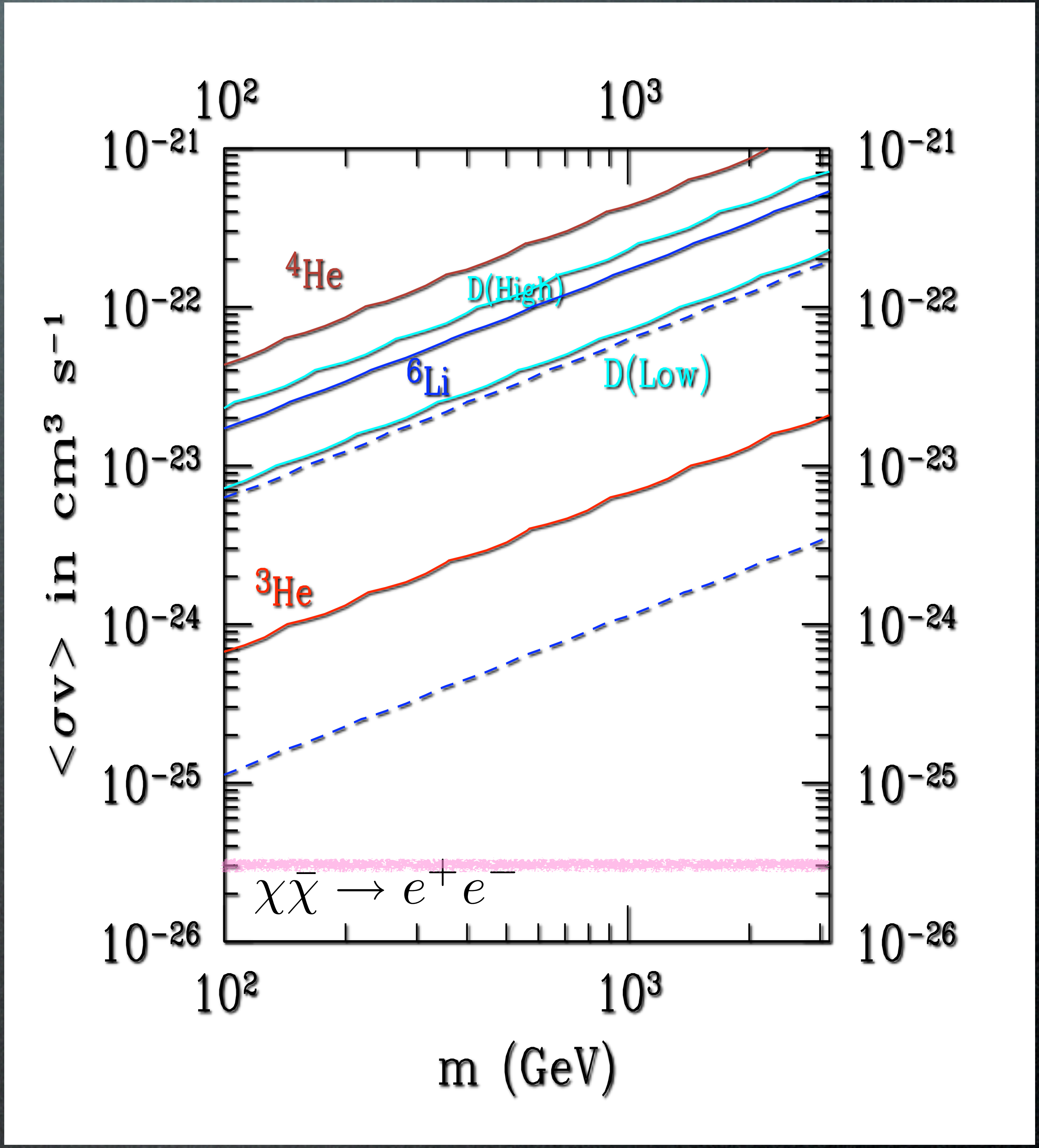


Giesen, Lesgourgues, Audren, Ali-Haïmoud (2012)

see also: Finkbeiner, Galli, Lin, Slatyer 1109.6322 (2011)
Galli, Slatyer, Valdes, Iocco, 1306.0563 (2013)

Cosmology: bounds from BBN

DM particles annihilations may inject too much energy that destroys forming nuclei: stringent bounds!



Hisano, Kohri et al., 0901.3582

Conclusions

Conclusions

DM exists

Conclusions

DM exists

DM searches are inherently multipronged: direct, indirect, collider.

Conclusions

DM exists

DM searches are inherently multipronged: direct, indirect, collider.

Complementarities are difficult:
- either in the special case of DMν from the Sun
- or in a specific model
- or in a EFT approach (with caveats)

Conclusions

DM exists

DM searches are inherently multipronged:
direct, indirect, collider.

Complementarities are difficult:
- either in the special case of DMν from the Sun
- or in a specific model
- or in a EFT approach (with caveats)

Associated signals might be more promising.

Conclusions

DM exists

DM searches are inherently multipronged: direct, indirect, collider.

Complementarities are difficult:
- either in the special case of DMν from the Sun
- or in a specific model
- or in a EFT approach (with caveats)

Associated signals might be more promising.

Beware of uncertainties and backgrounds.