11 April 2013
Roma Tre

DM Indirect and Direct Detection phenomenology:

some anomalies and a status assessment

Marco Cirelli

(CNRS IPhT Saclay)

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Introduction

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DM exists

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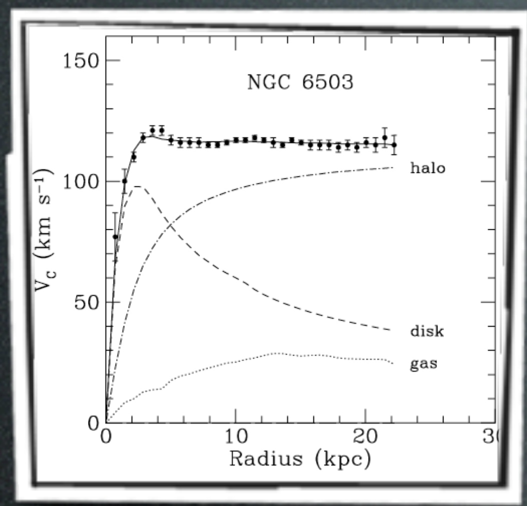
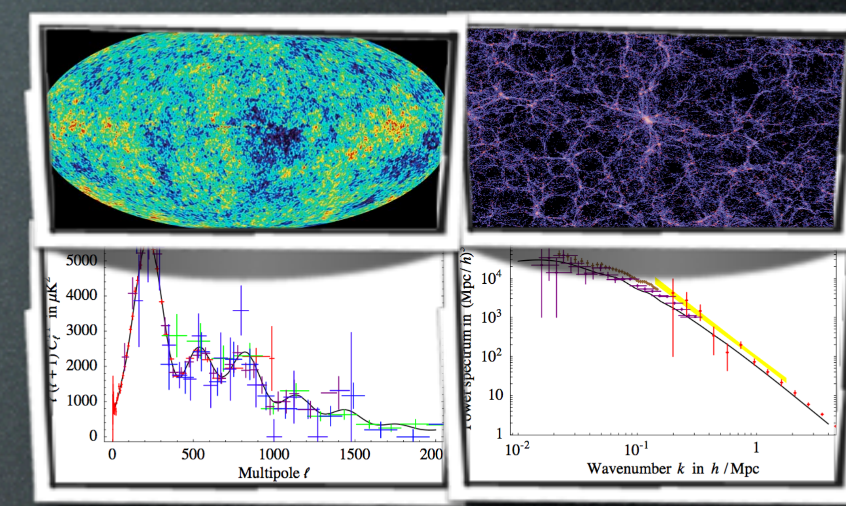


galactic rotation curves

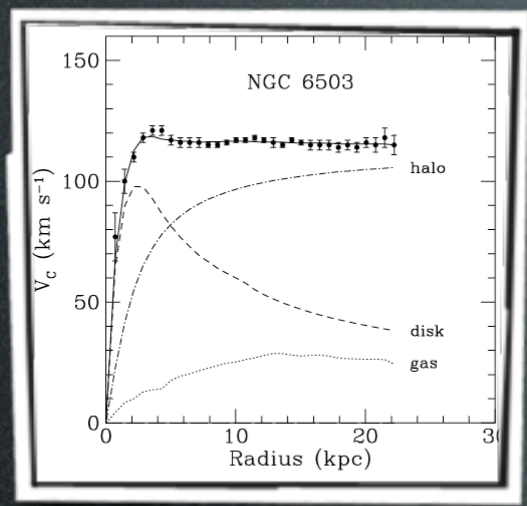
weak lensing (e.g. in clusters)



‘precision cosmology’ (CMB, LSS)

Introduction

DM exists



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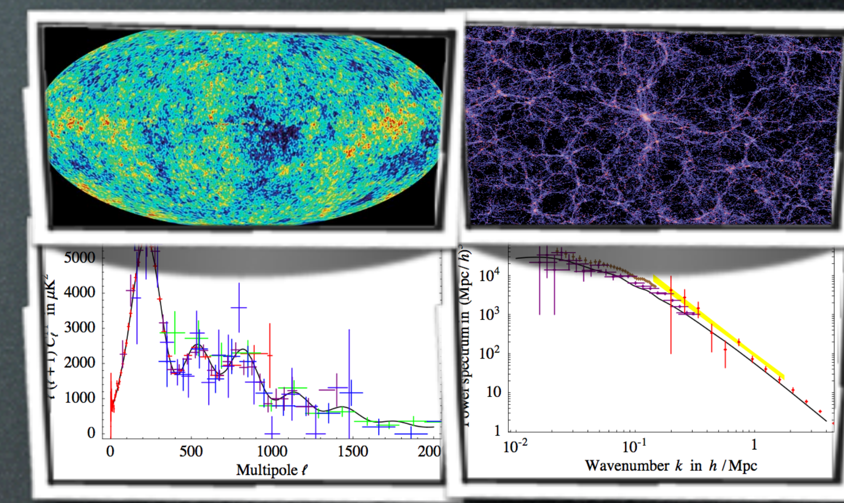
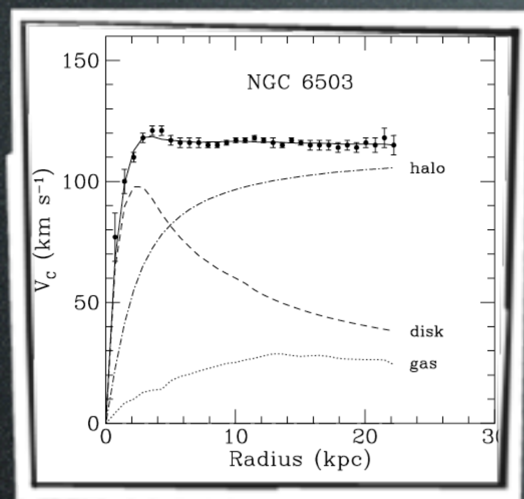


'precision cosmology' (CMB, LSS)

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

Introduction

DM exists



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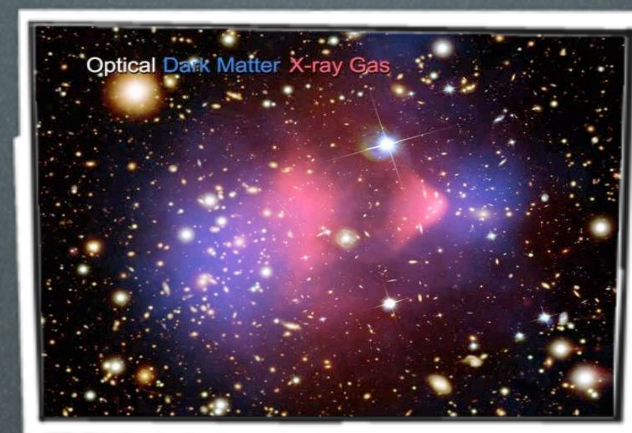
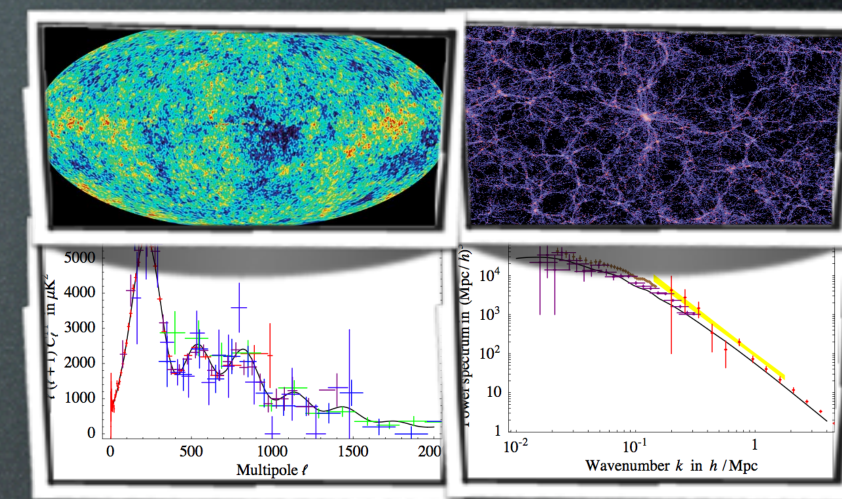


weak lensing (e.g. in clusters)

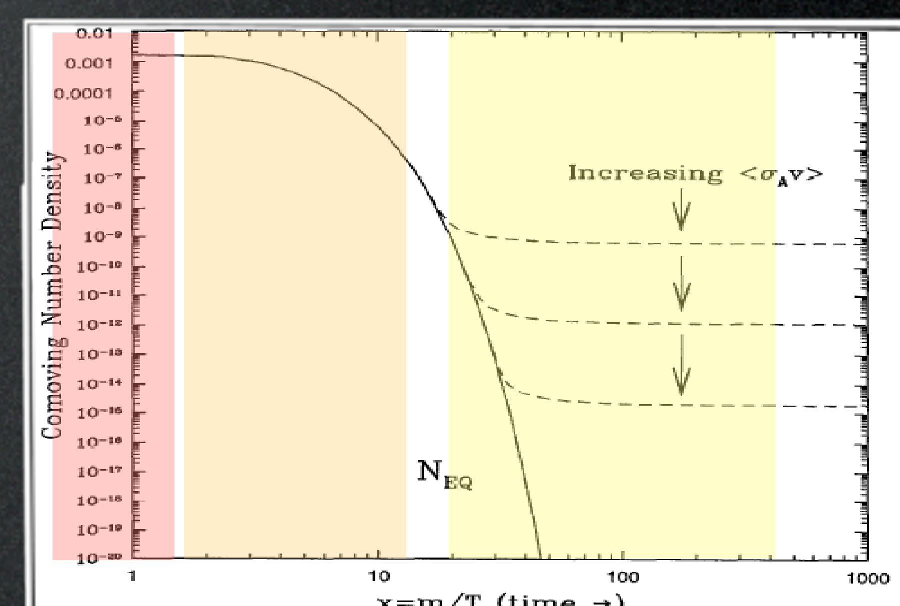


'precision cosmology' (CMB, LSS)

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

Some of us believe in the WIMP miracle.

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



DM detection

- direct detection
  - Xenon, CDMS (Dama/Libra?)
- production at colliders
  - LHC
- 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, Fermi, AMS-02**
  - $\bar{p}$ from annihil in galactic halo or center
  - $\bar{d}$ from annihil in galactic halo or center
    - GAPS
  - $\nu, \bar{\nu}$ from annihil in massive bodies
    - Icecube, Km3Net

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
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DM detection

direct detection

production at colliders

indirect

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Fermi, HESS, radio telescopes

e^+ from annihil in galactic halo or center

PAMELA, Fermi, AMS-02

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

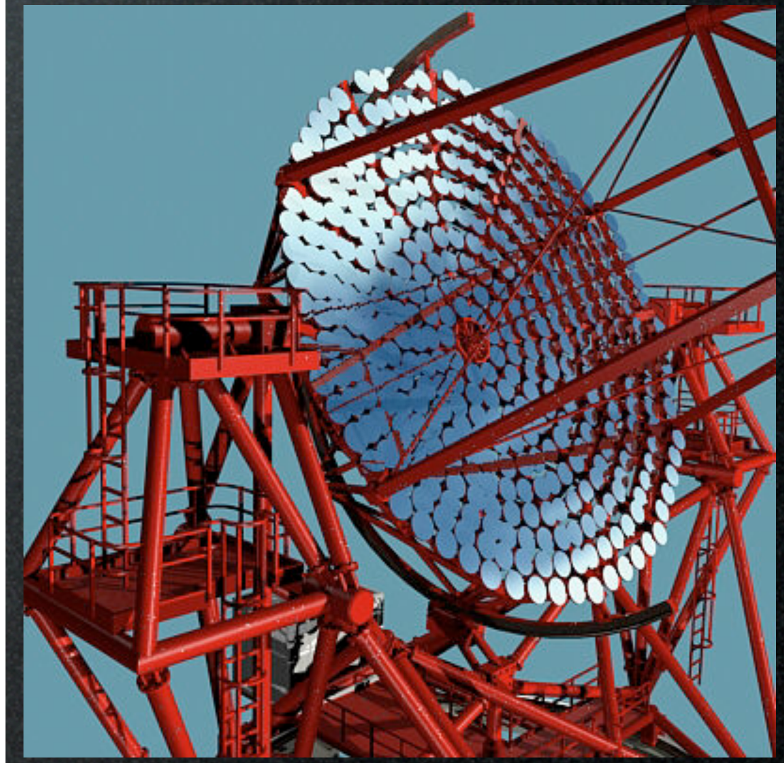
$\bar{d}$ from annihil in galactic halo or center

GAPS

$\nu, \bar{\nu}$ from annihil in massive bodies

Icecube, Km3Net

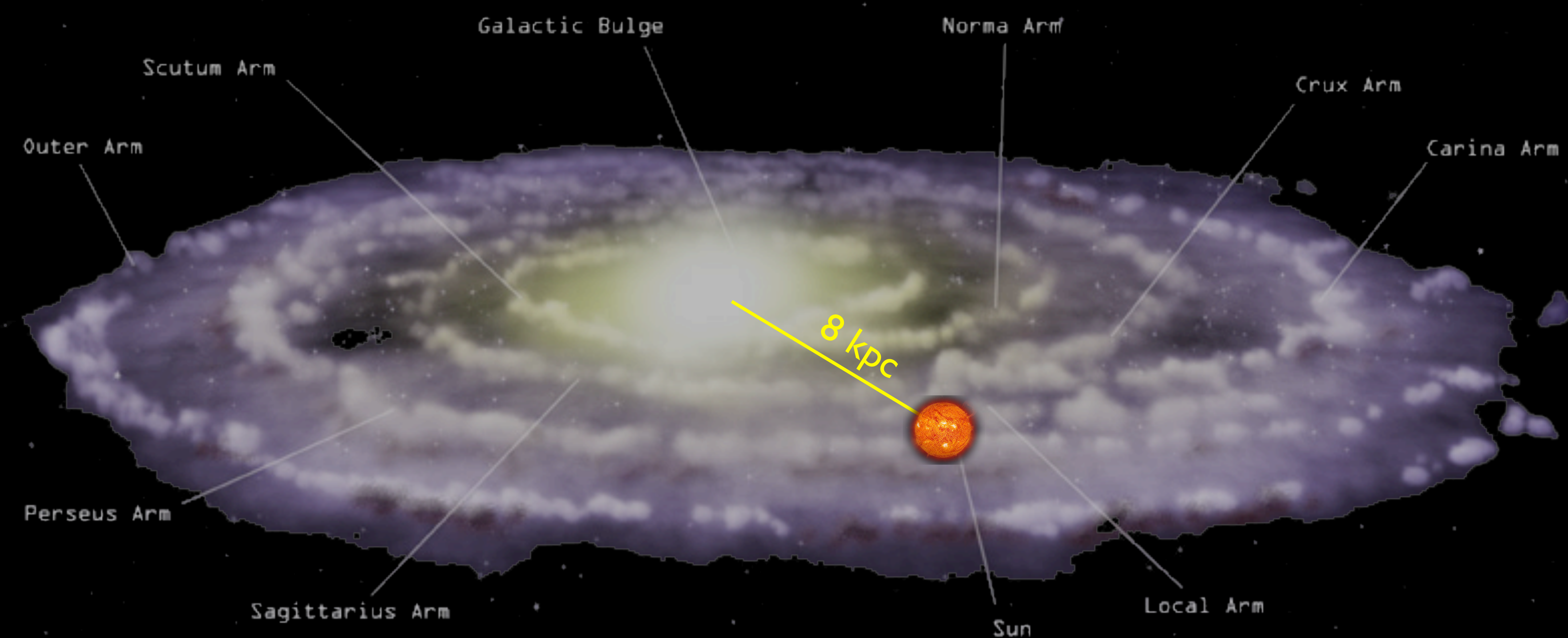
Charged CRs



1. the PAMELA/Fermi/HESS ‘excesses’

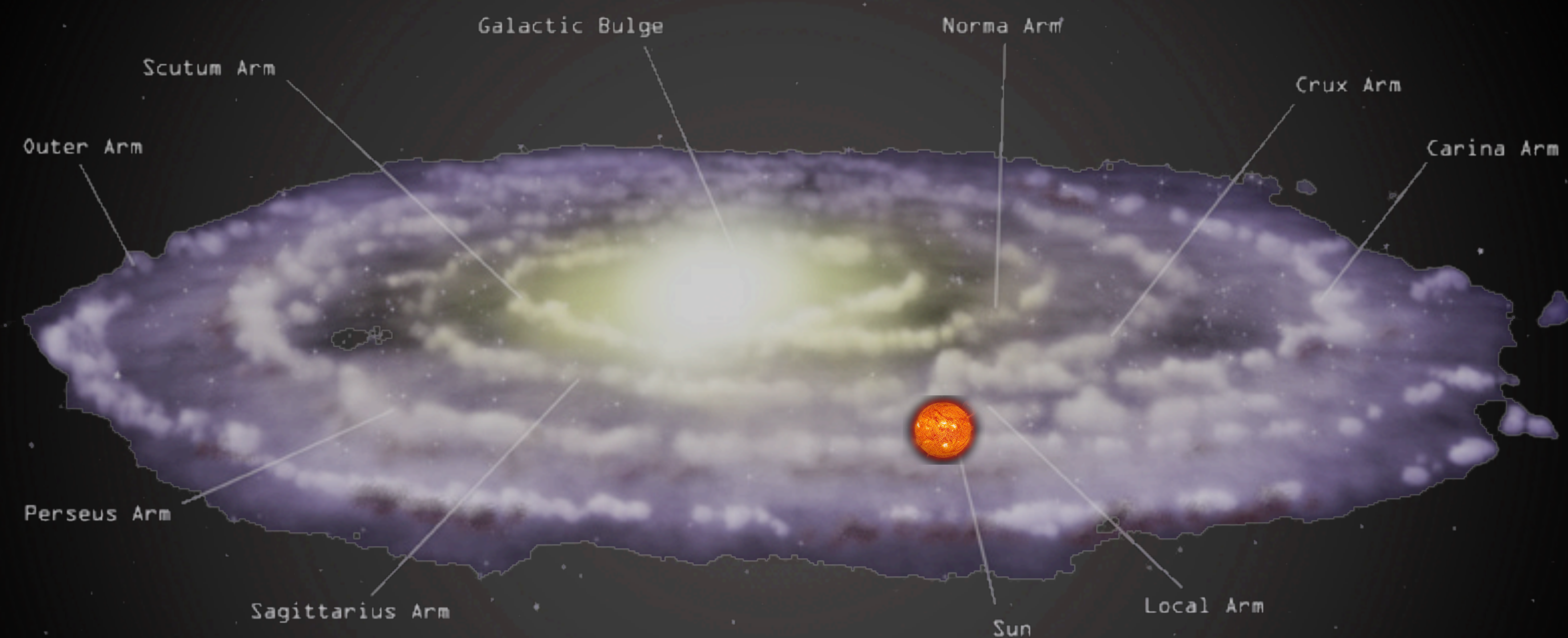
Indirect Detection: basics

$\bar{p}$ and e^+ from DM annihilations in halo



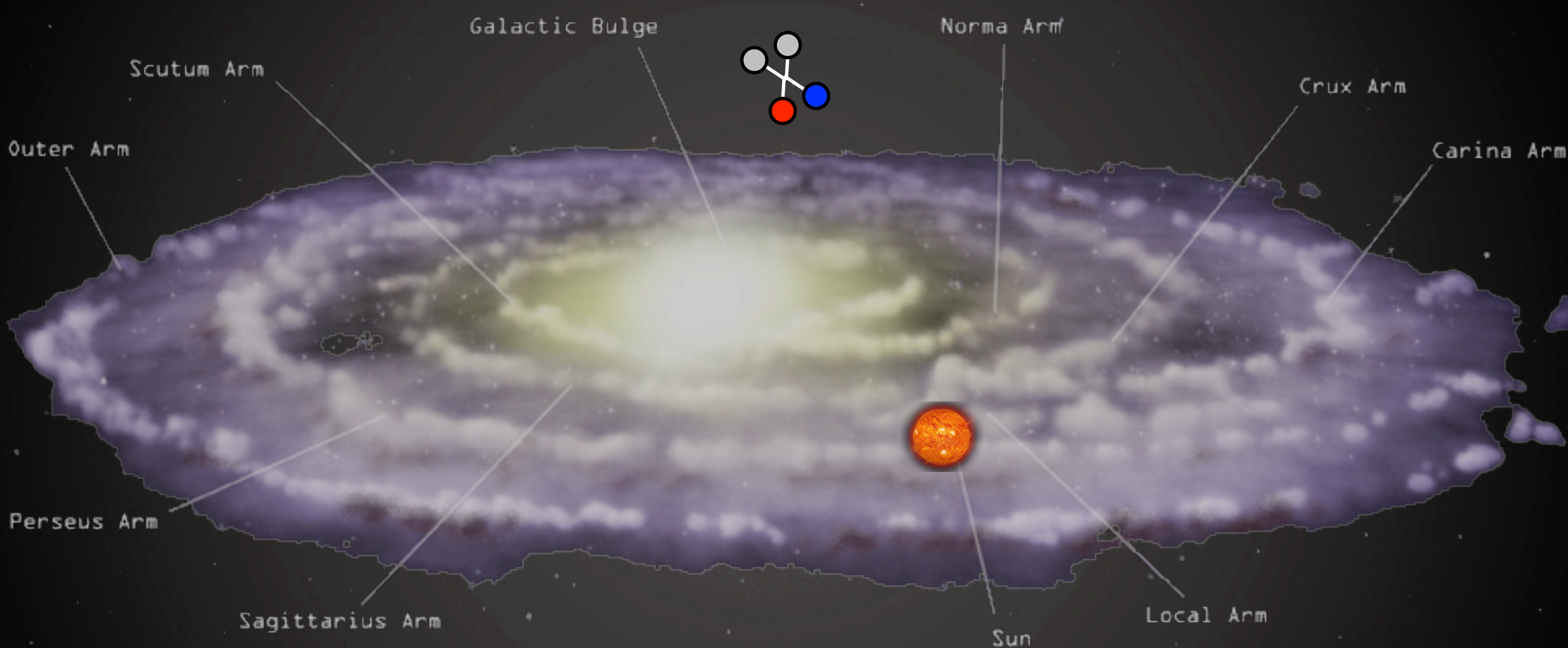
Indirect Detection: basics

$\bar{p}$ and e^+ from DM annihilations in halo



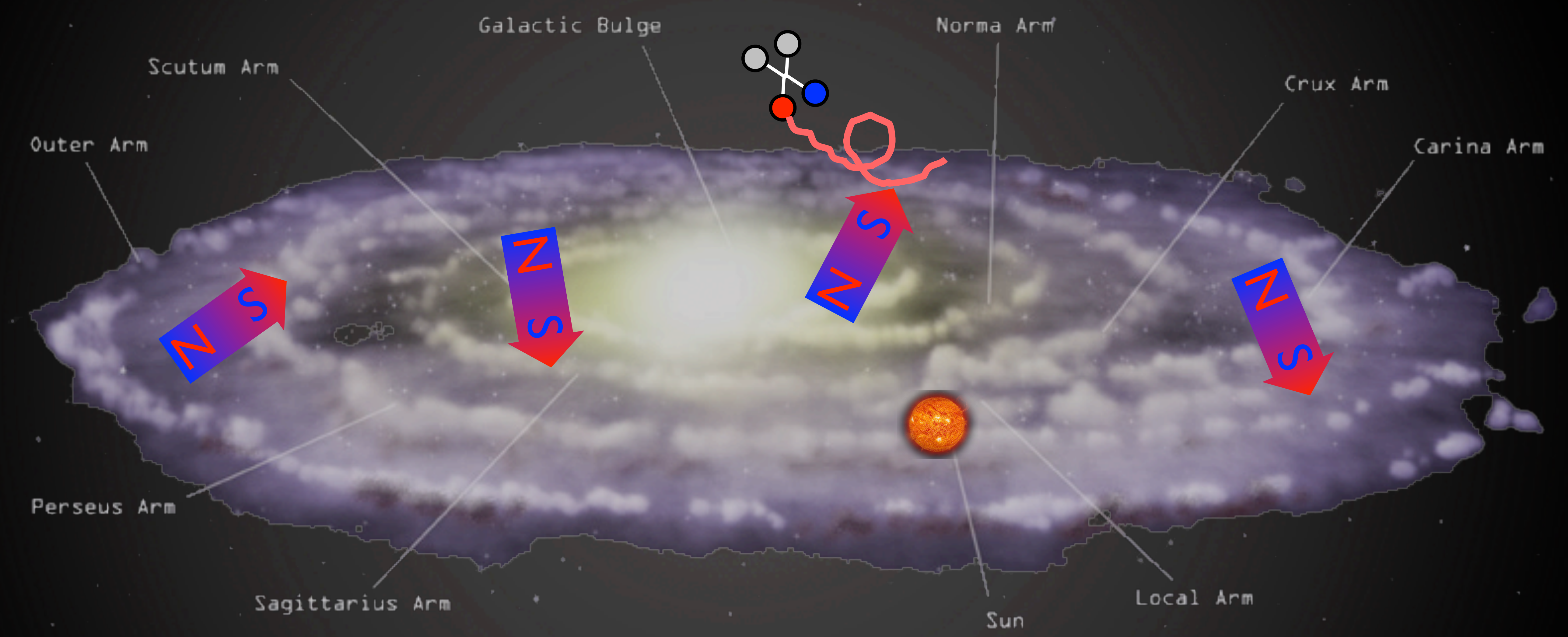
Indirect Detection: basics

$\bar{p}$ and e^+ from DM annihilations in halo



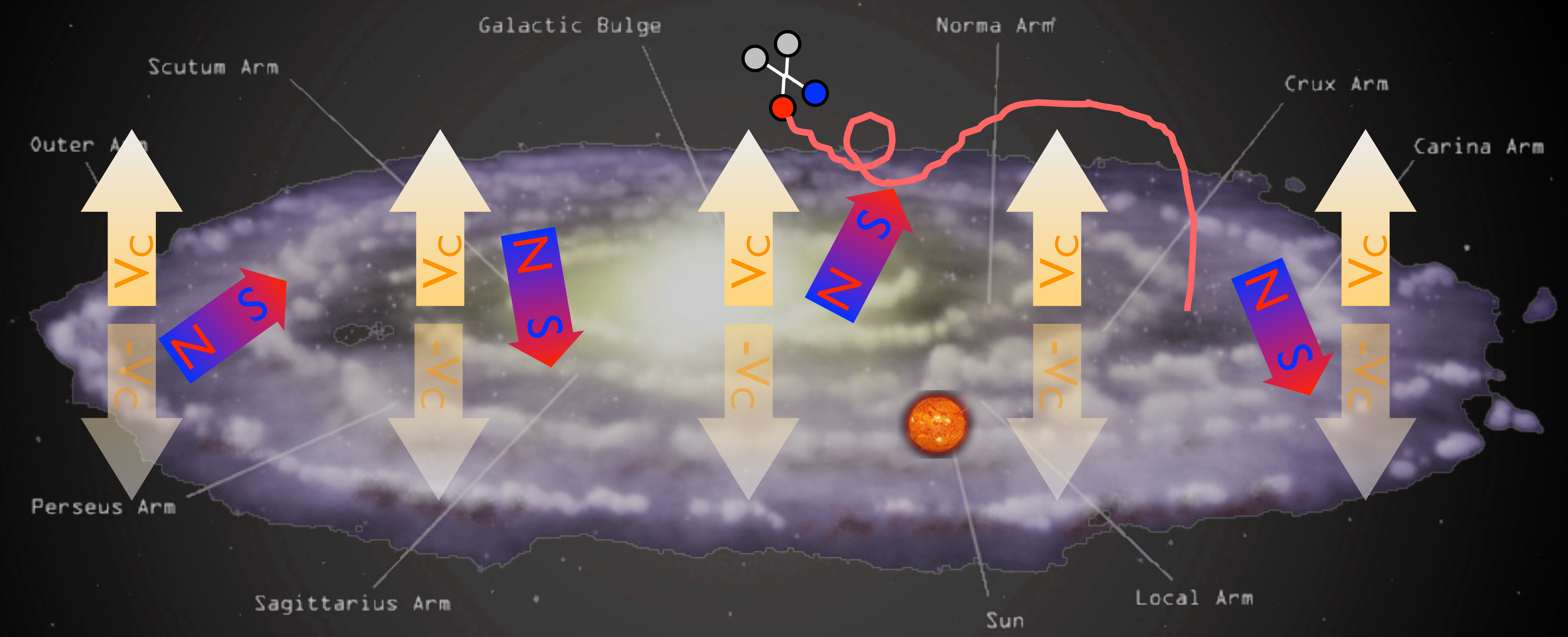
Indirect Detection: basics

$\bar{p}$ and e^{+} from DM annihilations in halo



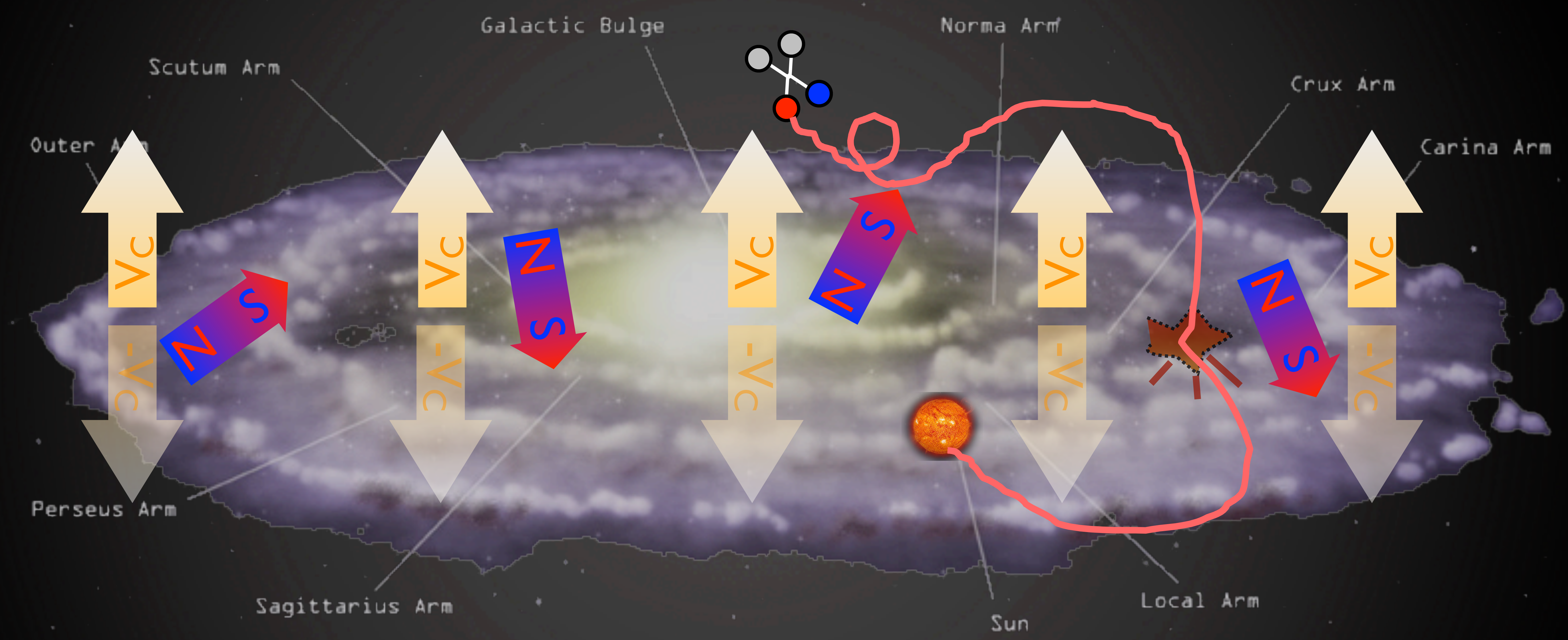
Indirect Detection: basics

$\bar{p}$ and e^+ from DM annihilations in halo



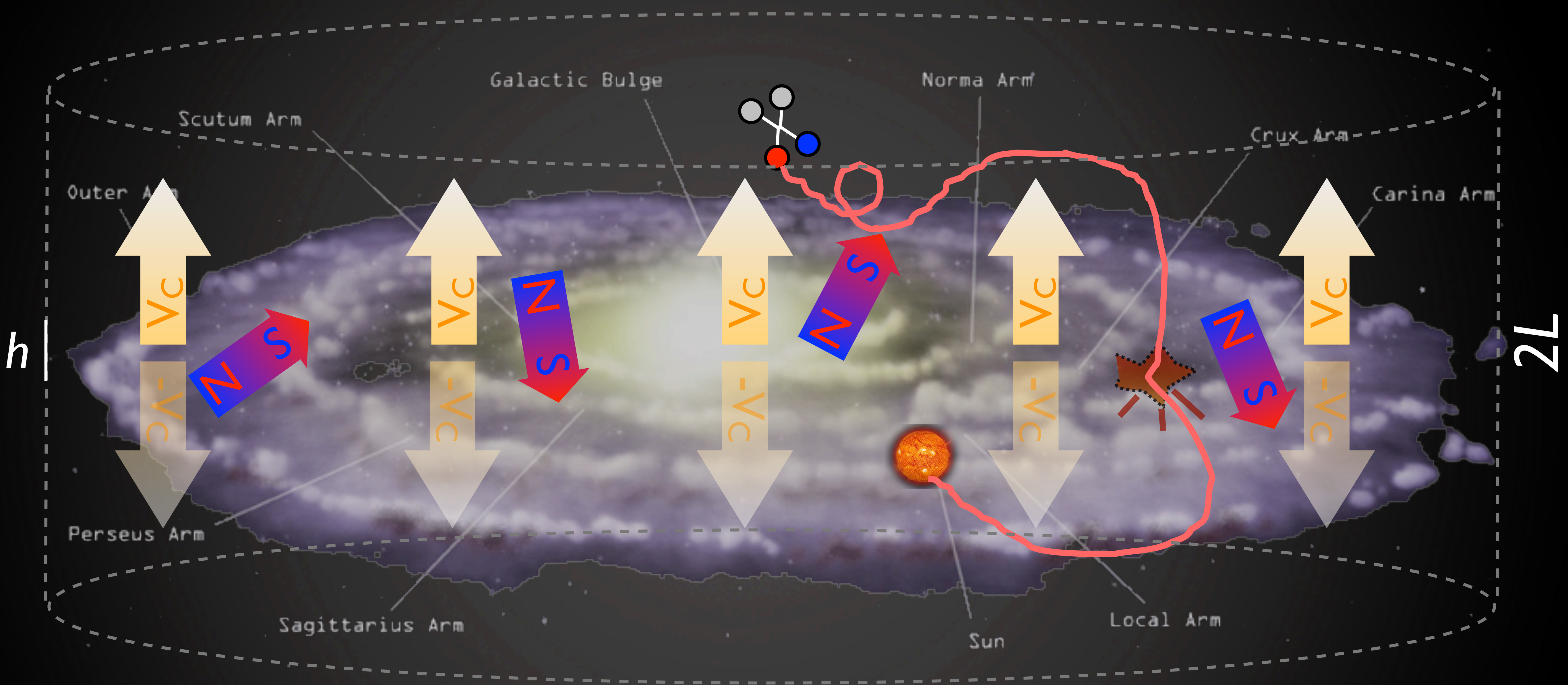
Indirect Detection: basics

$\bar{p}$ and e^{+} from DM annihilations in halo



Indirect Detection: basics

$\bar{p}$ and e^+ from DM annihilations in halo



Salati, Chardonnay, Barrau, Donato, Taillet, Fornengo, Maurin, Brun... '90s, '00s

spectrum

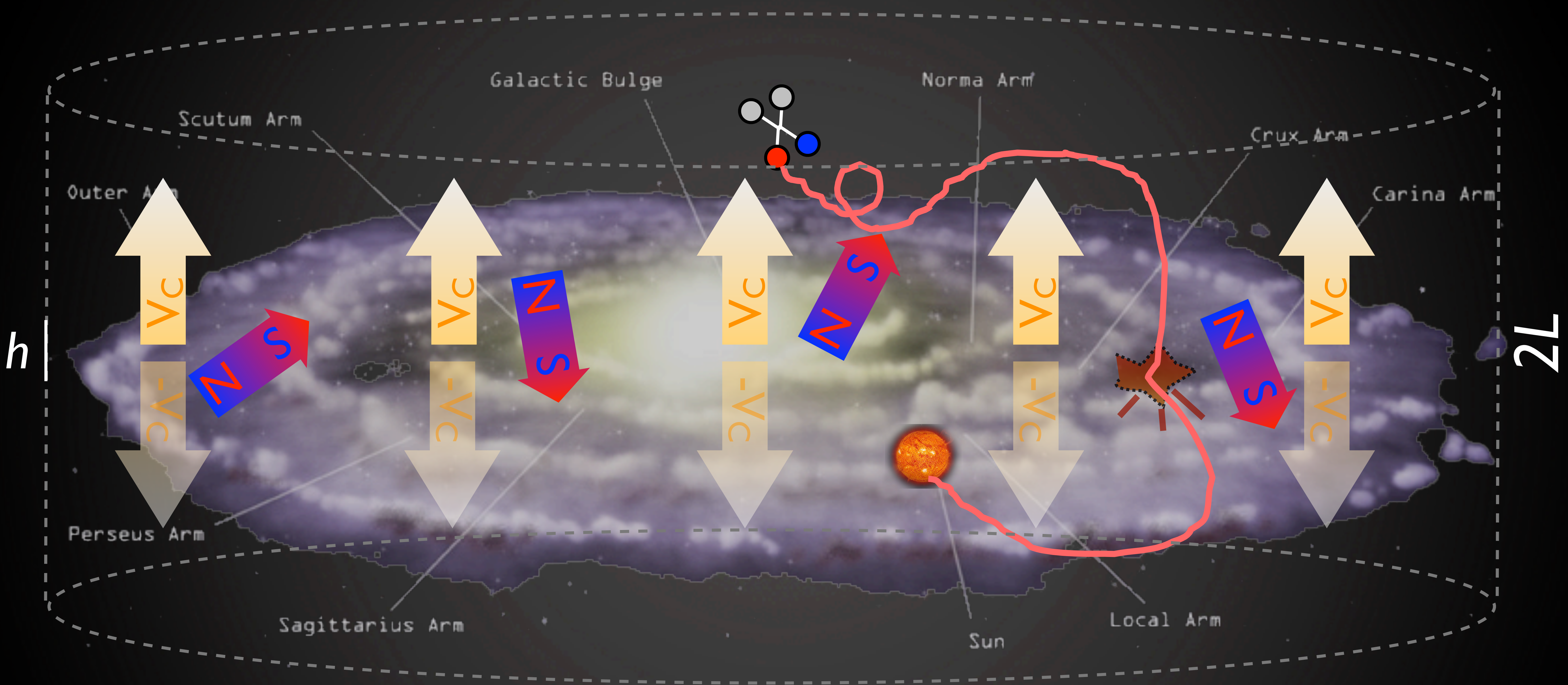
$$\frac{\partial f}{\partial t} - K(E)\cdot\nabla^2 f - \frac{\partial}{\partial E}(b(E)f) + \frac{\partial}{\partial z}(V_c f) = Q_{\rm inj} - 2h\delta(z)\Gamma_{\rm spall} f$$

diffusion energy loss convective wind source spallations

[uncert]

Indirect Detection: basics

$\bar{p}$ and e^+ from DM annihilations in halo

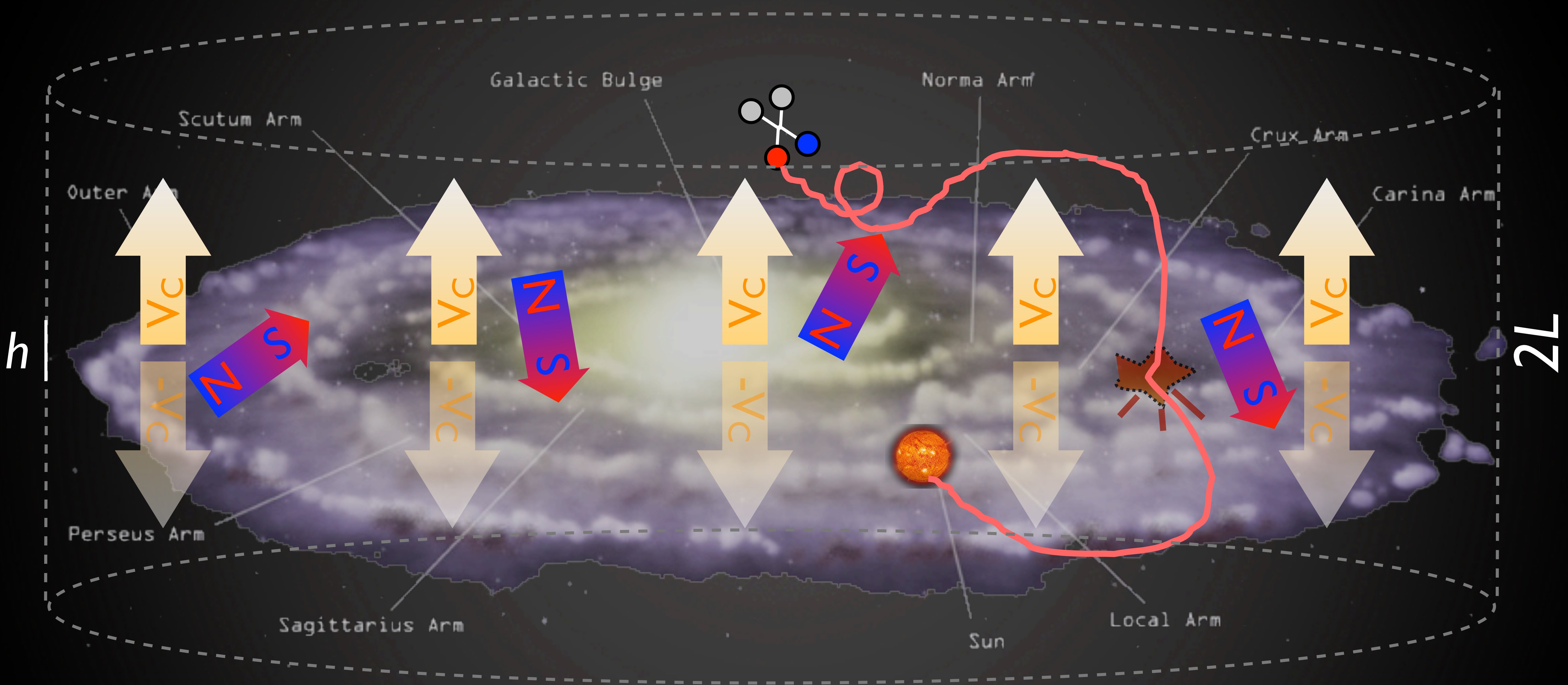


What sets the overall expected flux?

$$\text{flux} \propto n^2\,\sigma_{\text{annihilation}}$$

Indirect Detection: basics

$\bar{p}$ and e^+ from DM annihilations in halo



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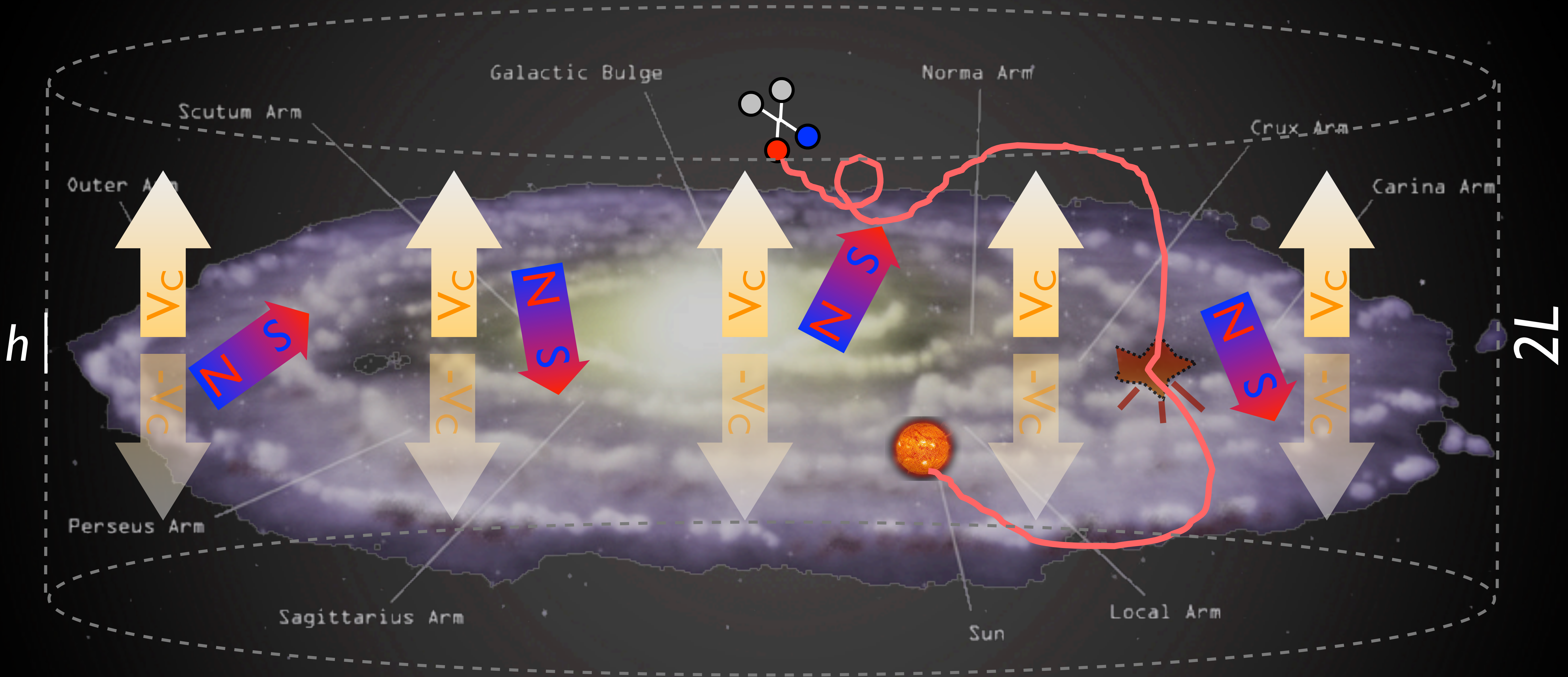
astro& cosmo

particle

Indirect Detection: basics

$\bar{p}$ and e^+ from DM annihilations in halo



What sets the overall expected flux?

$$\text{flux} \propto n^2 \, \sigma_{\text{annihilation}}$$

astro& cosmo   particle

reference cross section:

$\sigma v = 3 \cdot 10^{-26} \text{cm}^3/\text{sec}$

DM halo profiles

From N-body numerical simulations:

$$\text{NFW}: \quad \rho_{\text{NFW}}(r) = \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2}$$

$$\text{Einasto}: \quad \rho_{\text{Ein}}(r) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha}-1\right]\right\}$$

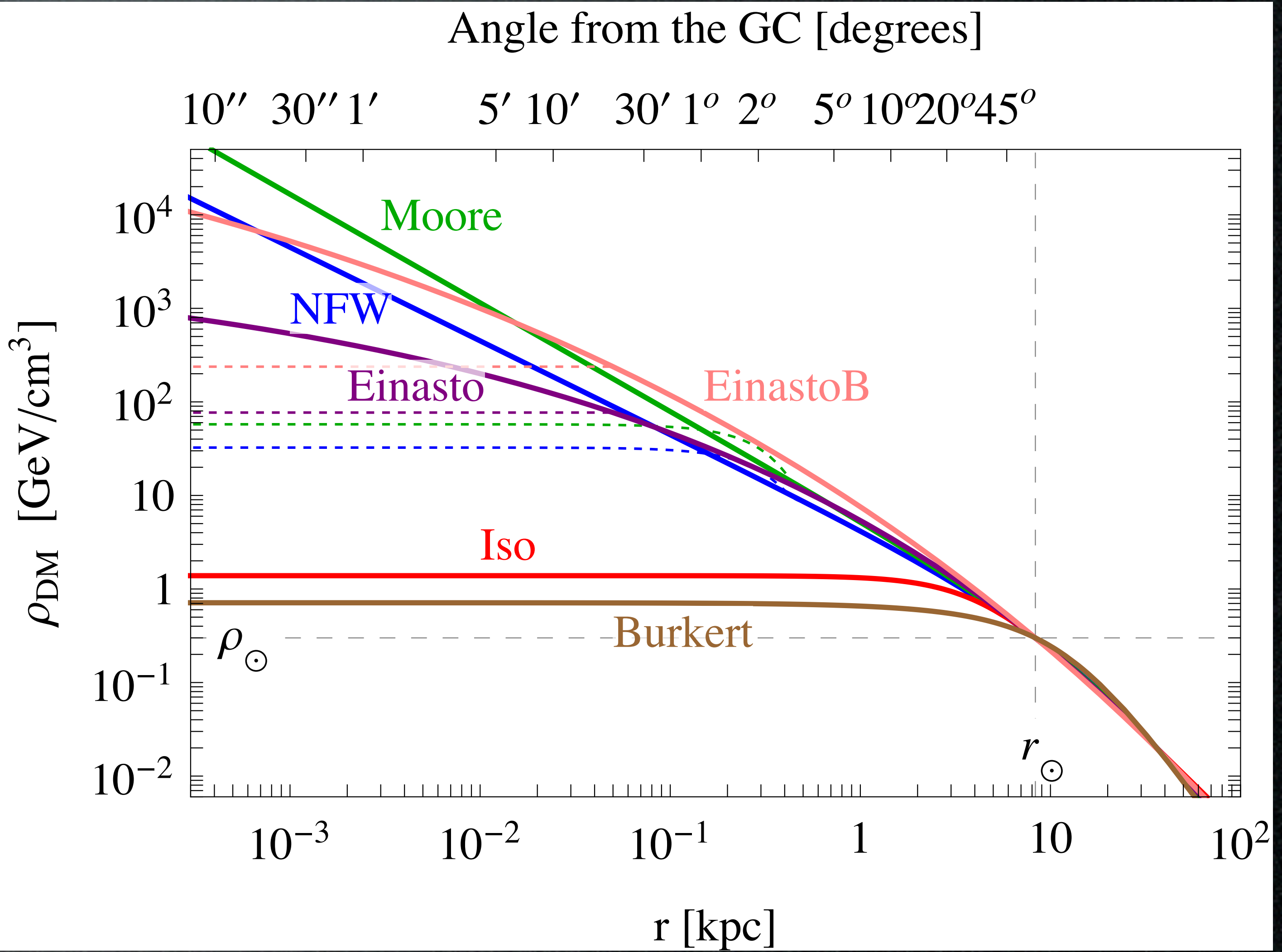
$$\text{Isothermal}: \quad \rho_{\text{Iso}}(r) = \frac{\rho_s}{1+(r/r_s)^2}$$

$$\text{Burkert}: \quad \rho_{\text{Bur}}(r) = \frac{\rho_s}{(1+r/r_s)(1+(r/r_s)^2)}$$

$$\text{Moore}: \quad \rho_{\text{Moo}}(r) = \rho_s \left(\frac{r_s}{r}\right)^{1.16}\left(1+\frac{r}{r_s}\right)^{-1.84}$$

DM halo	α	r_s [kpc]	ρ_s [GeV/cm^3]
NFW	–	24.42	0.184
Einasto	0.17	28.44	0.033
EinastoB	0.11	35.24	0.021
Isothermal	–	4.38	1.387
Burkert	–	12.67	0.712
Moore	–	30.28	0.105

At small r: $\rho(r) \propto 1/r^{\gamma}$



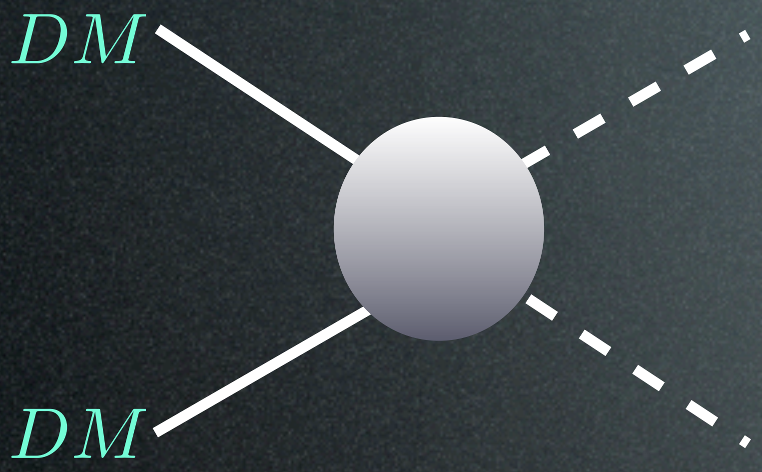
6 profiles:

- cuspy: NFW, Moore
- mild: Einasto
- smooth: isothermal, Burkert

EinastoB = steepened Einasto

(effect of baryons?)

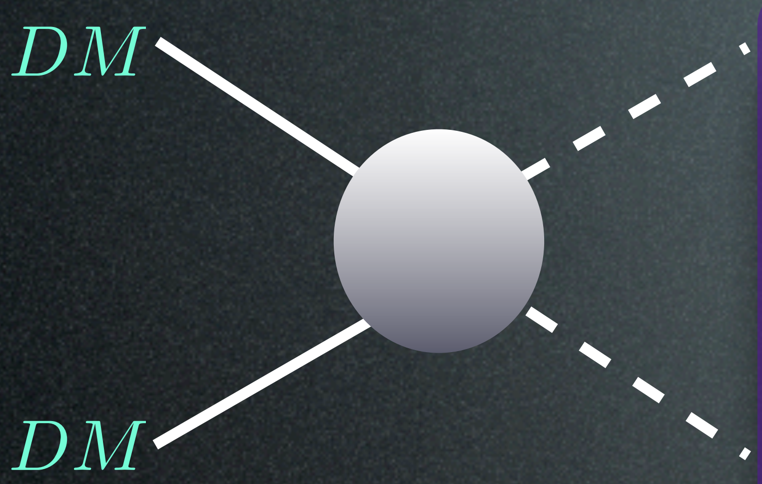
Indirect Detection: basics



$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$$

$$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$$

Indirect Detection: basics

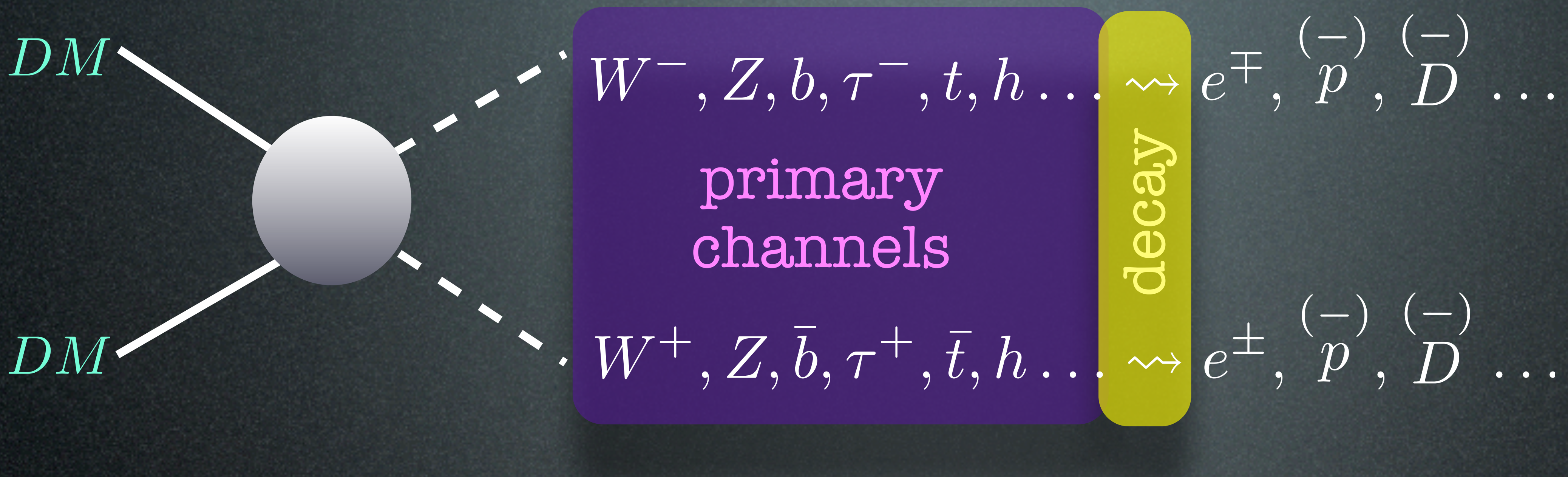


$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^{\mp}, \overset{(-)}{p}, \overset{(-)}{D} \ldots$

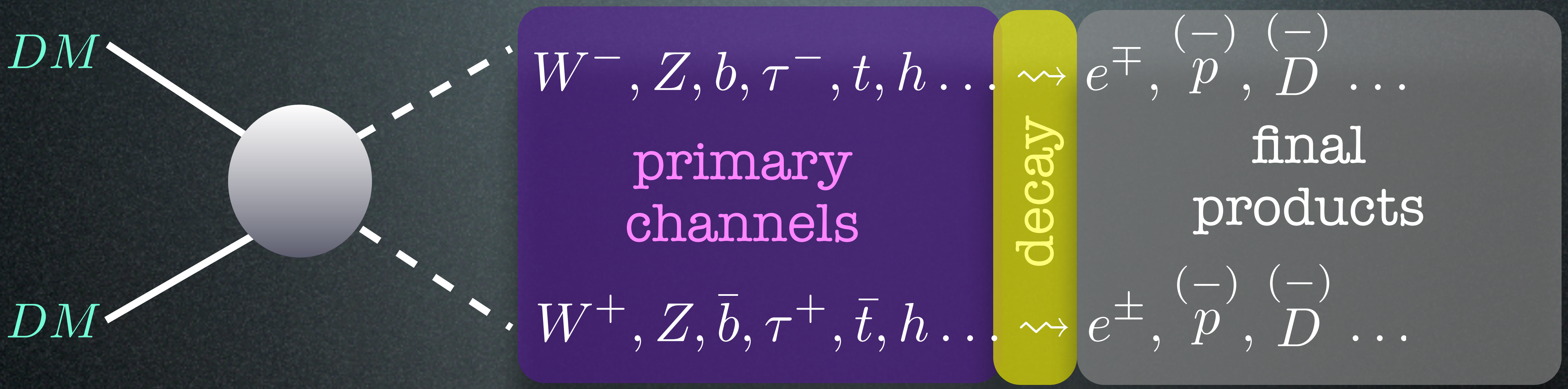
primary channels

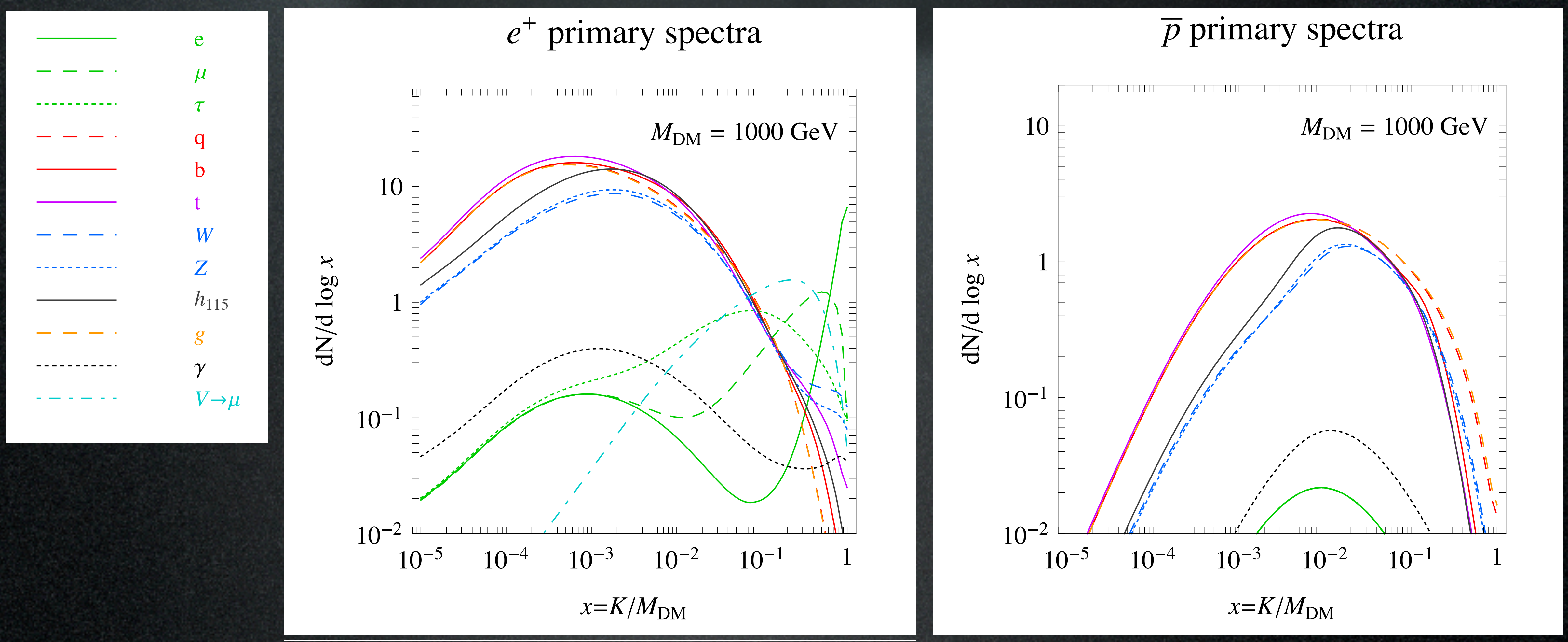
$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^{\pm}, \overset{(-)}{p}, \overset{(-)}{D} \ldots$

Indirect Detection: basics

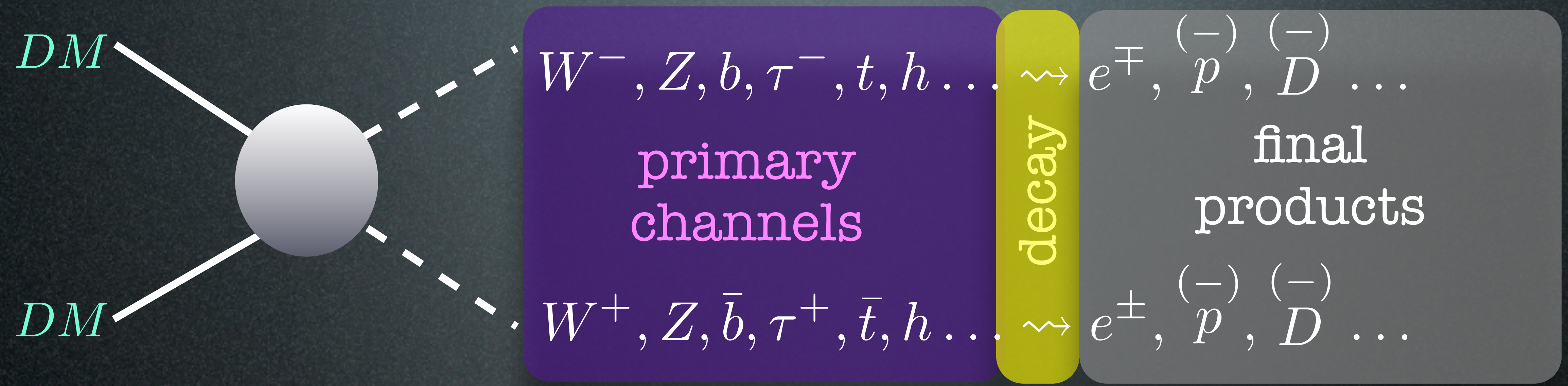


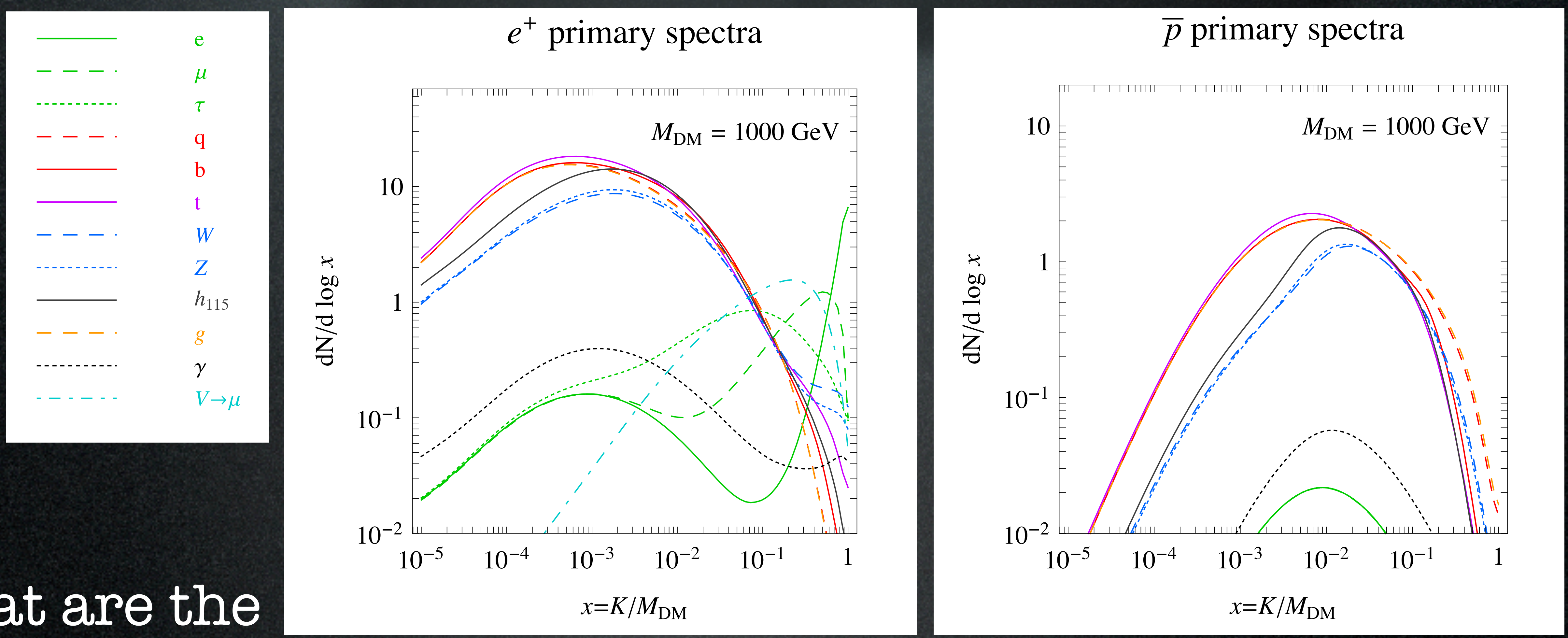
Indirect Detection: basics





Indirect Detection: basics



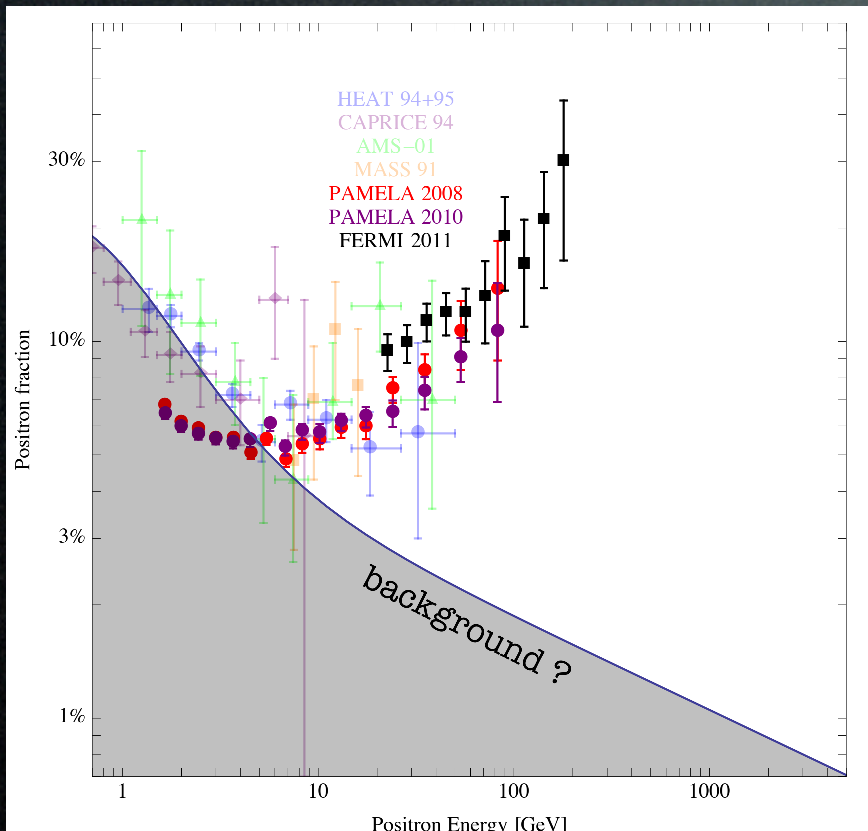


So what are the particle physics parameters?

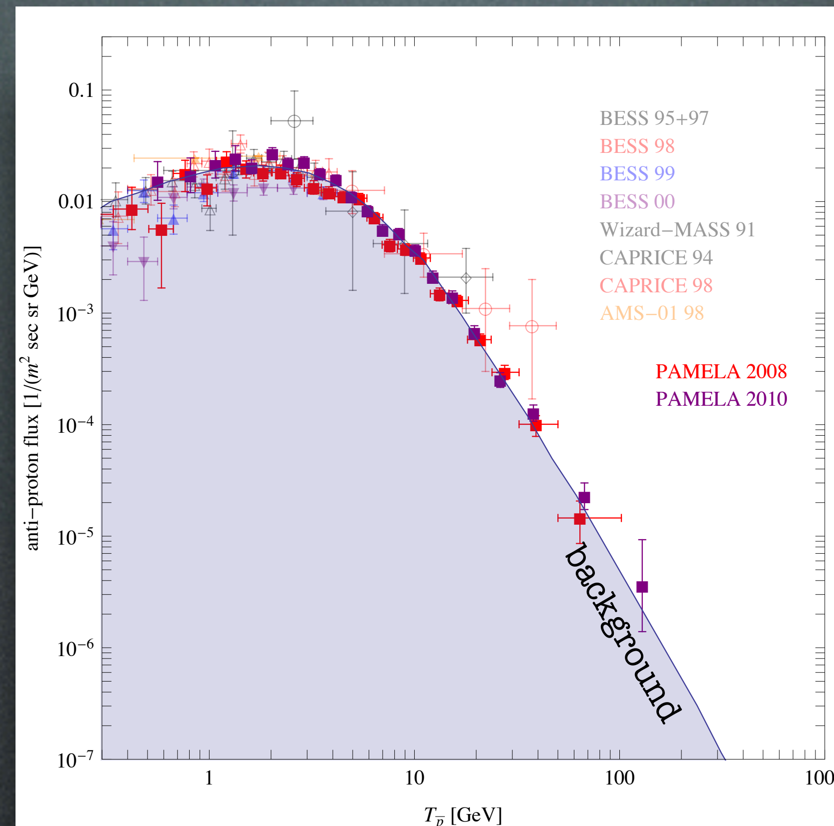
1. Dark Matter mass
2. primary channel(s)

Positrons & Electrons

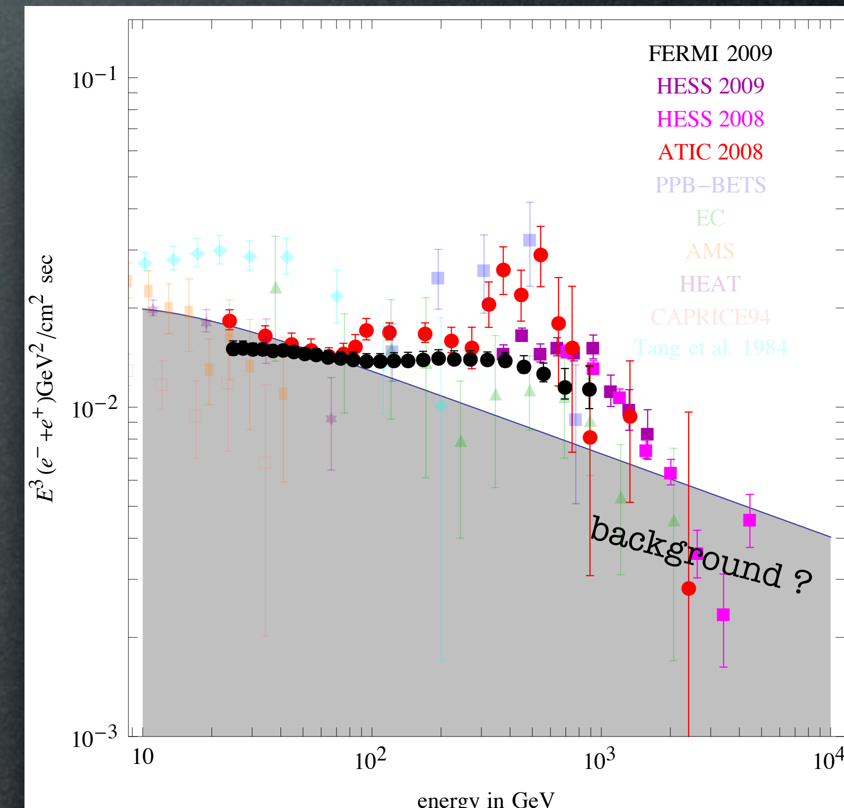
positron fraction



antiprotons



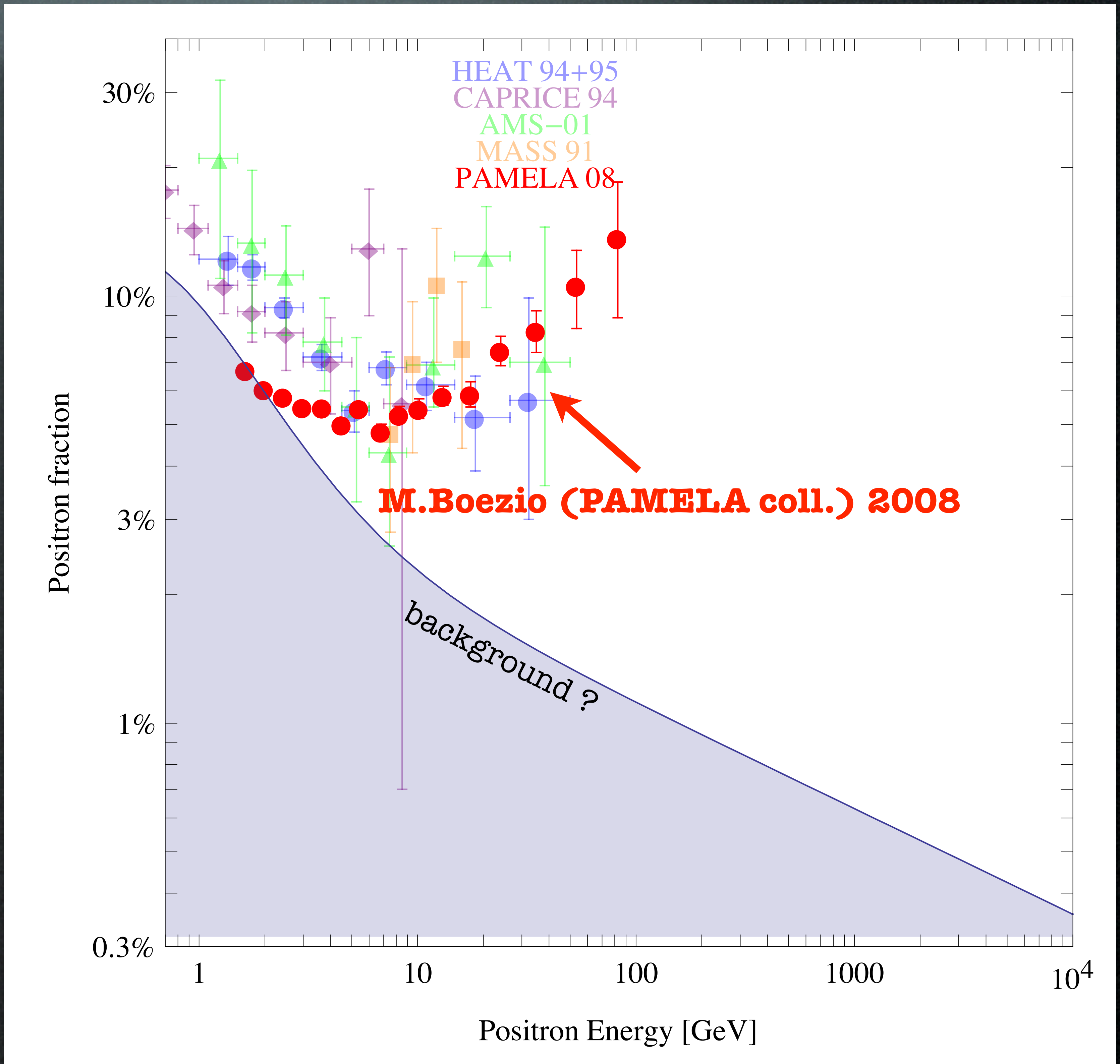
electrons + positrons



Positrons & Electrons

Positrons from PAMELA:

- steep e^+ excess above 10 GeV!
- very large flux!



positron fraction: $\frac{e^+}{e^+ + e^-}$

(9430 e^+ initially collected)

(errors statistical only in this plot, that's why larger at high energy)

Adriani et al., Nature 458 (2009) 607; ApP 34 (2010) 1

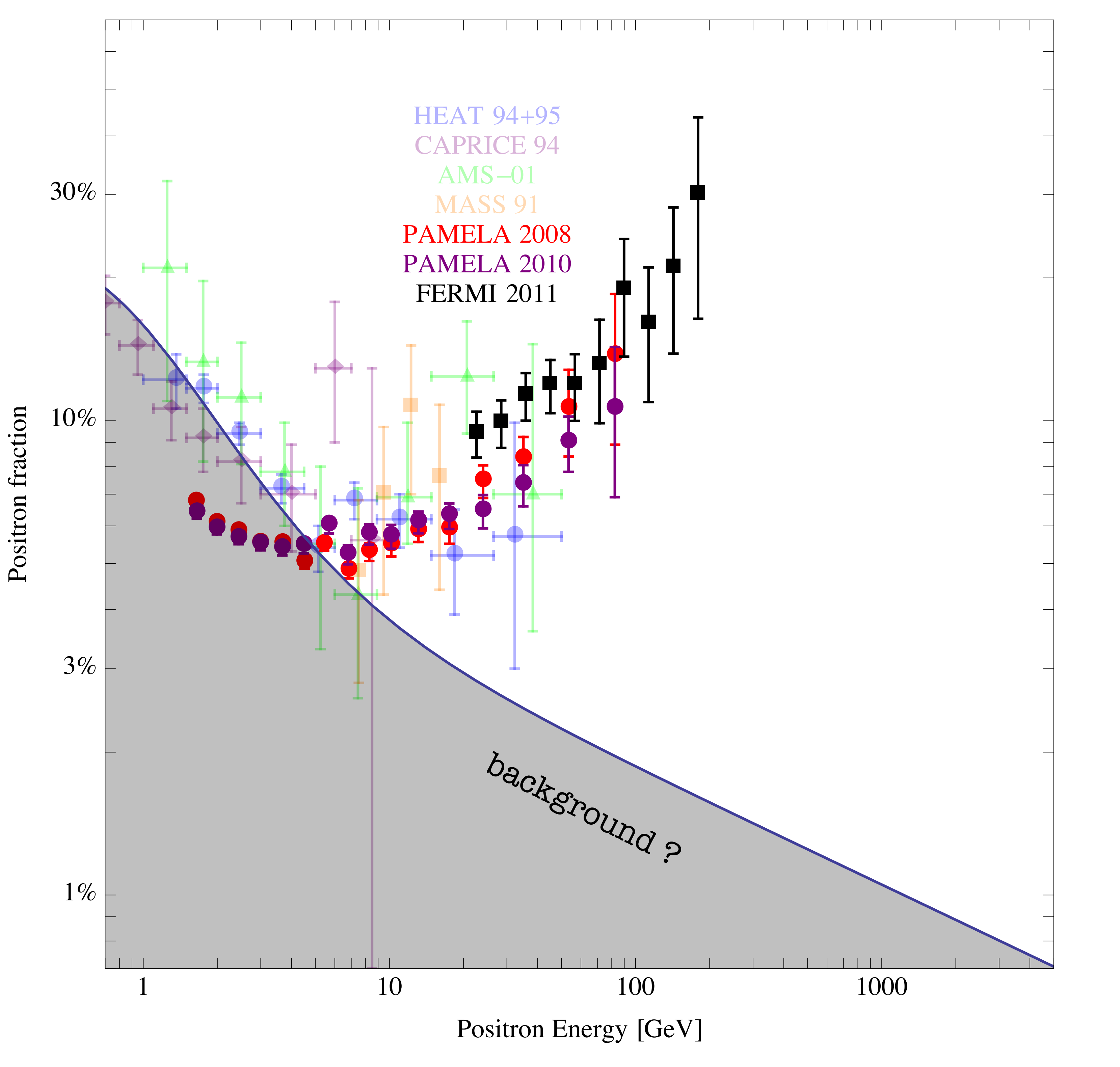
[backgnd]

Positrons & Electrons

Positrons from PAMELA and FERMI:

- steep e^+ excess above 10 GeV!
- very large flux!

positron fraction: $\frac{e^+}{e^+ + e^-}$



Adriani et al., Nature 458 (2009) 607; ApP 34 (2010) 1

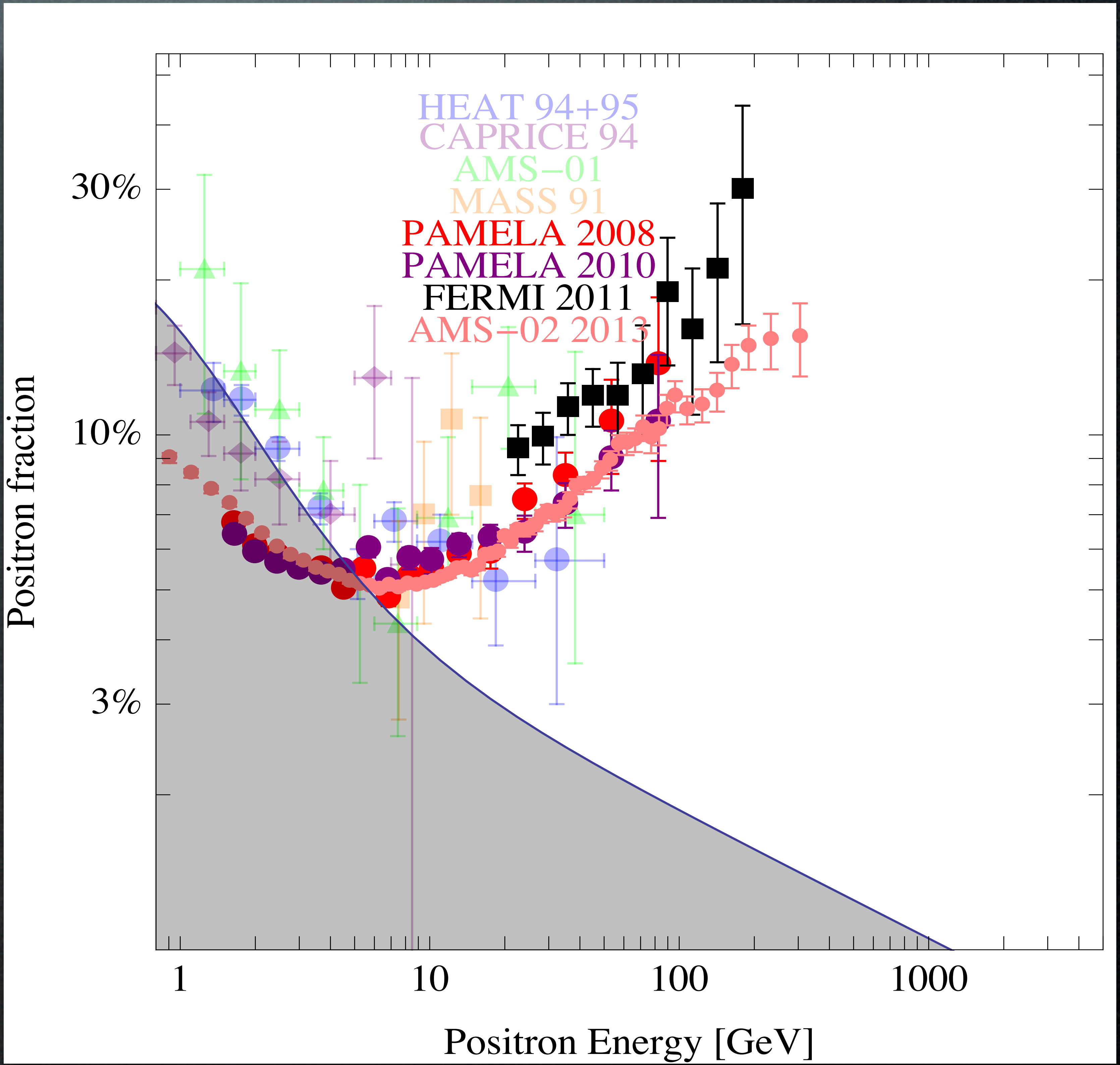
Fermi coll., 1109.0521

Positrons & Electrons

Positrons from PAMELA and FERMI and AMS-02:

- steep e^+ excess above 10 GeV!
- very large flux!

positron fraction: $\frac{e^+}{e^+ + e^-}$



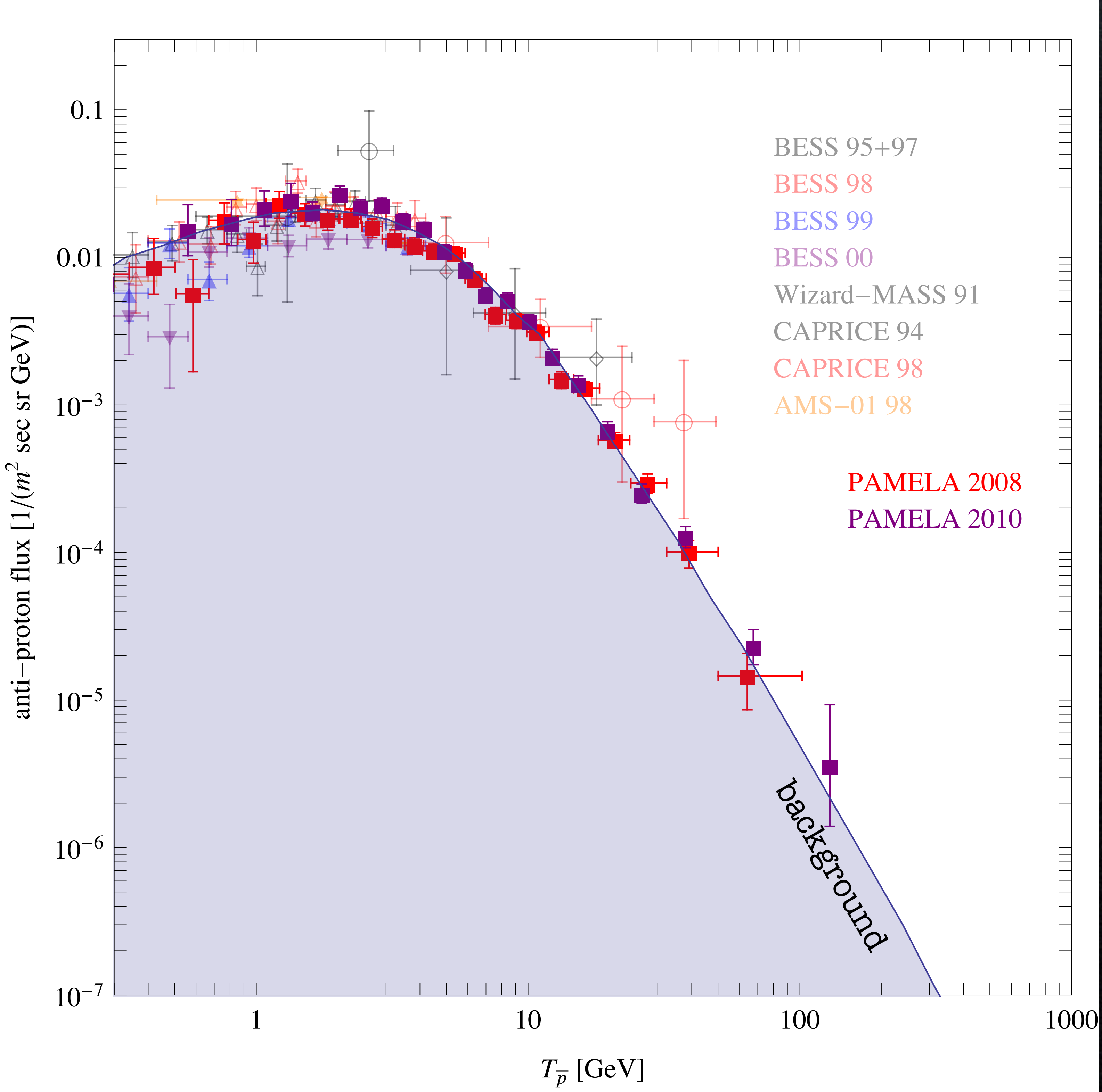
Adriani et al., Nature 458 (2009) 607; ApP 34 (2010) 1

Fermi coll., 1109.0521 **AMS-02 coll., PRL 110, 141102 (2013)**

Antiprotons

Antiprotons from PAMELA:

- consistent with the background



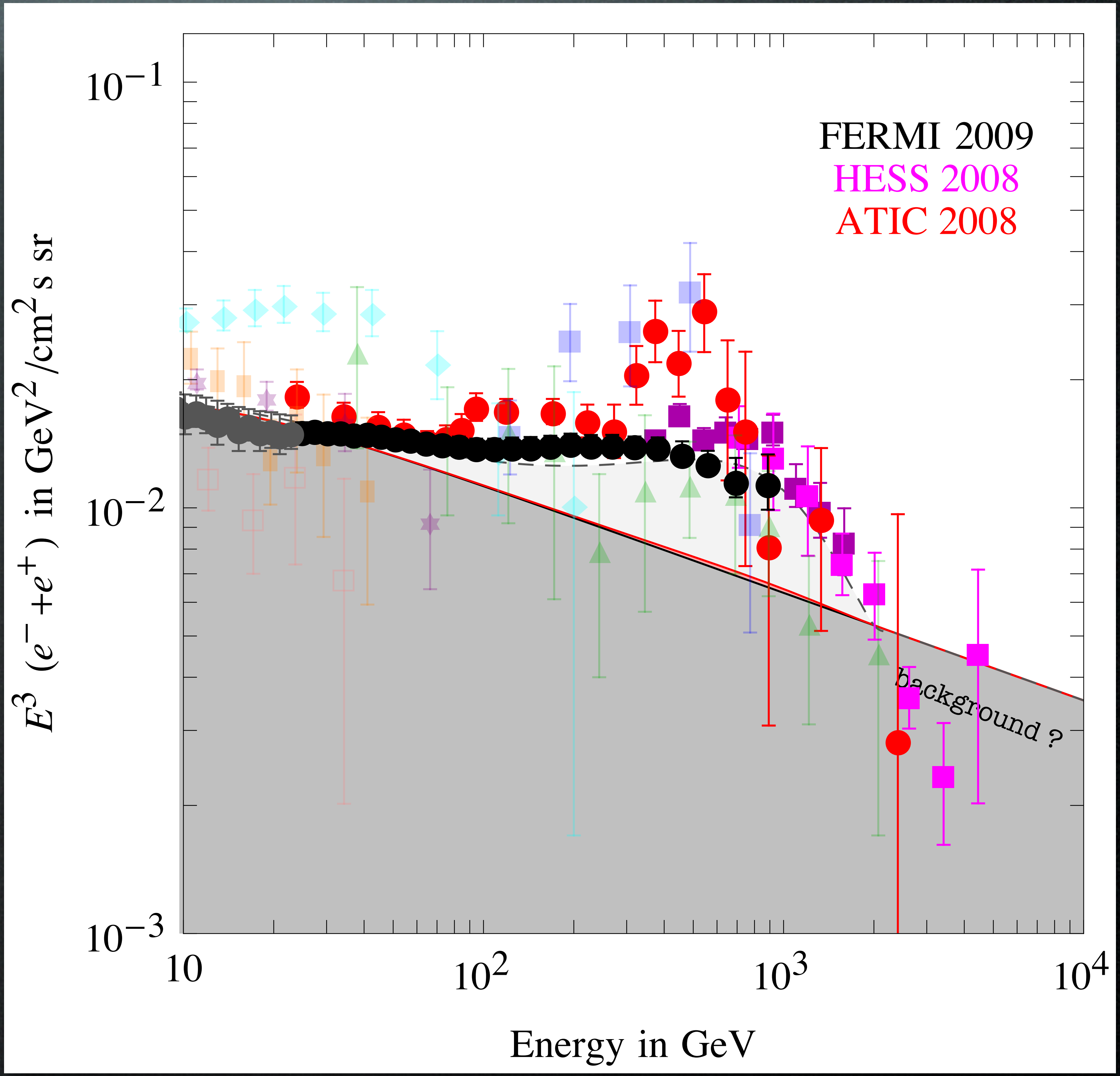
(about 1000 $\bar{p}$ collected initially)

Adriani et al., PRL 105 (2010) 121101, 1007.0821

Indirect Detection: hints

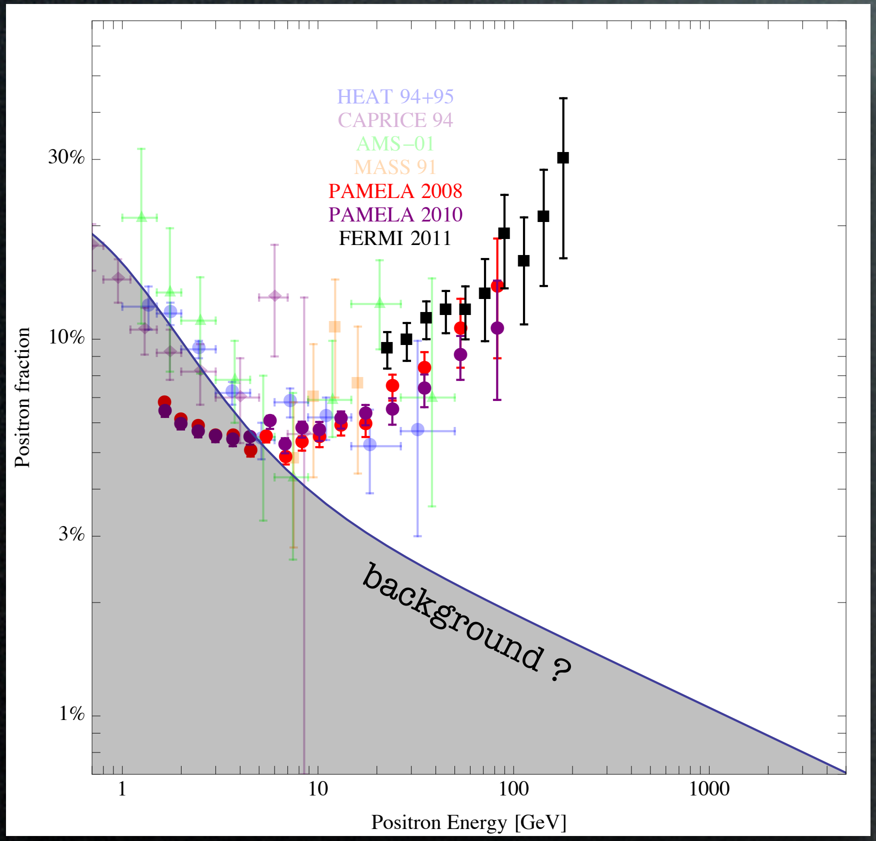
Electrons + positrons adding FERMI and HESS:

- no $e^+ + e^-$ excess
- spectrum $\sim E^{-3.04}$
- a (smooth) cutoff?

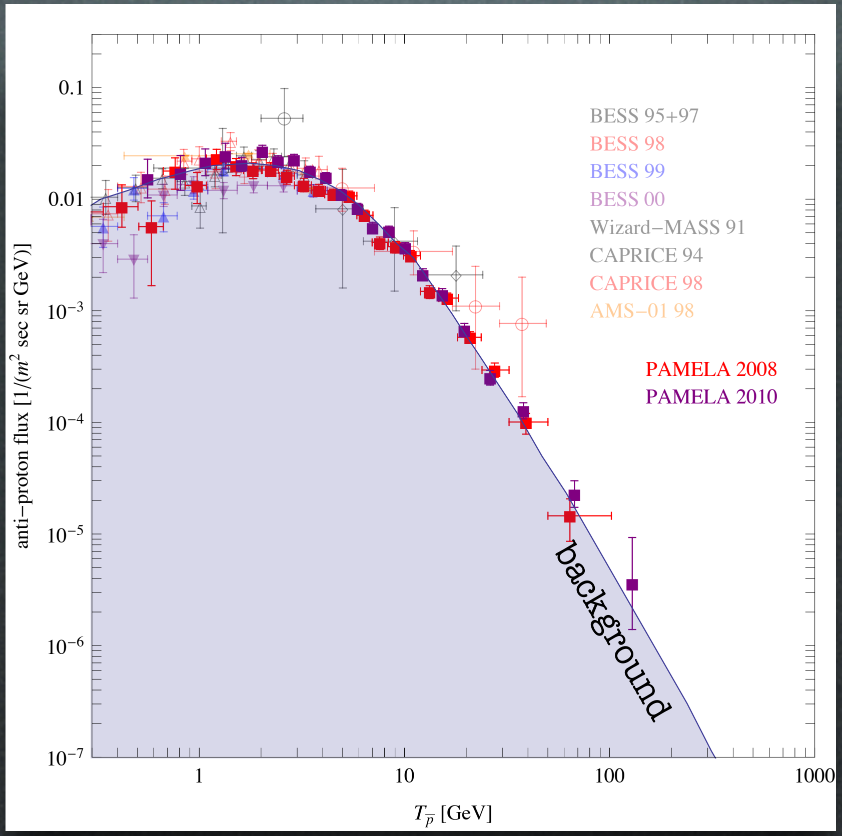


Positrons & Electrons

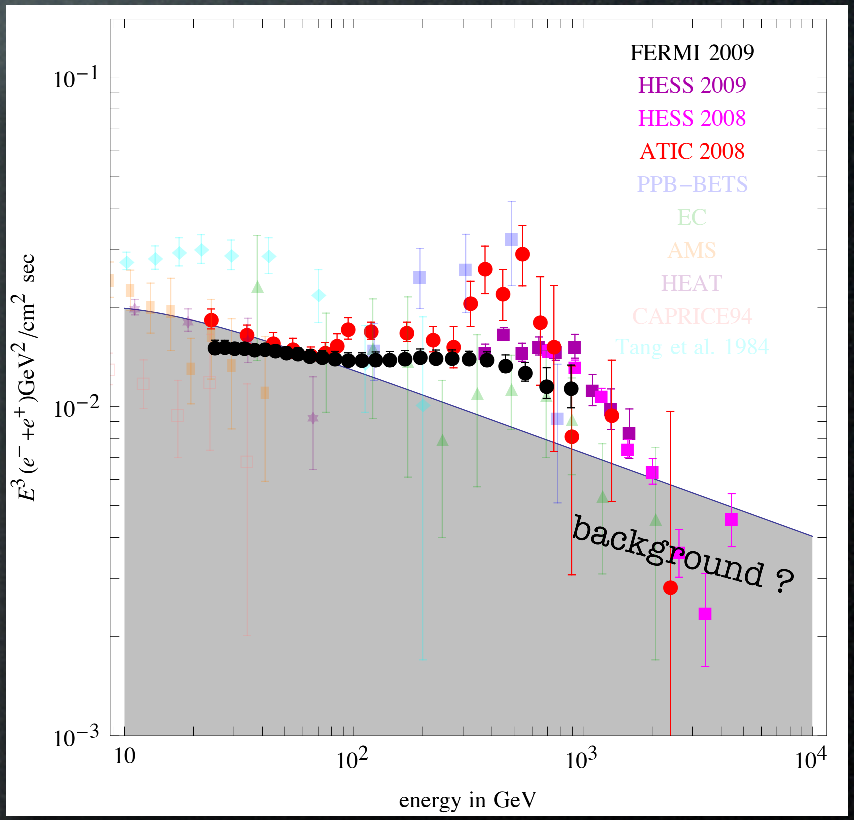
positron fraction



antiprotons



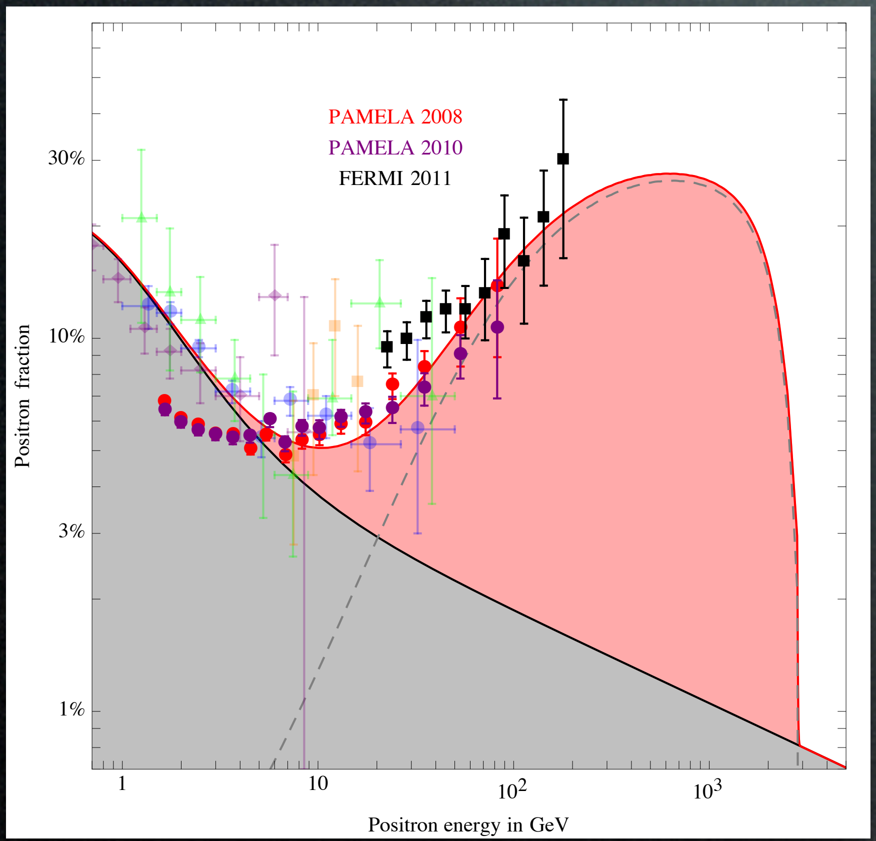
electrons + positrons



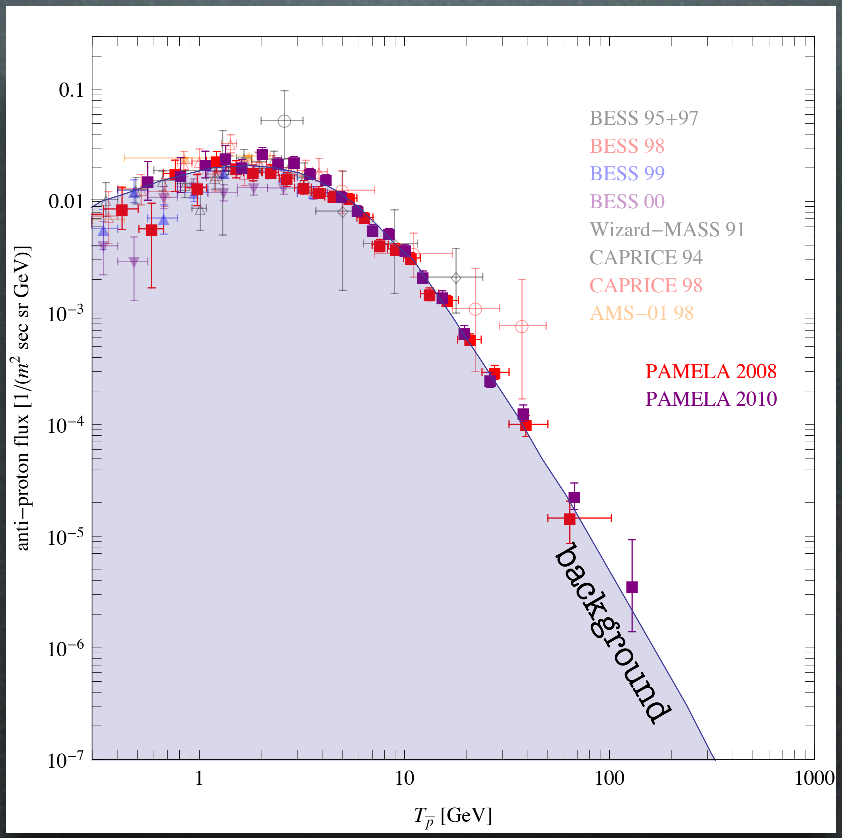
Are these signals of Dark Matter?

Positrons & Electrons

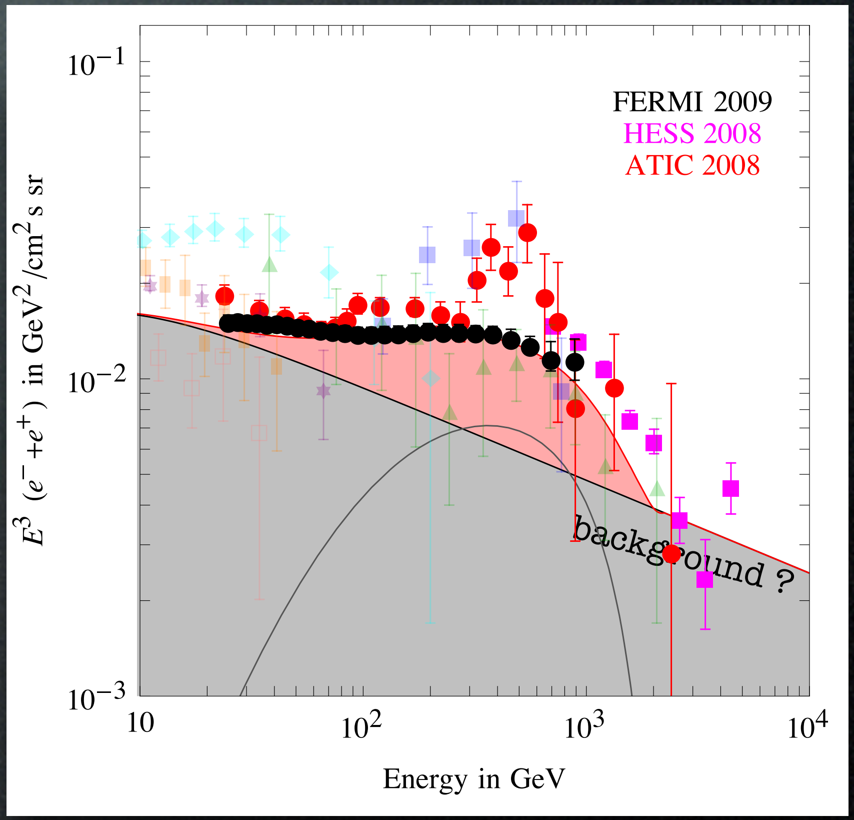
positron fraction



antiprotons



electrons + positrons

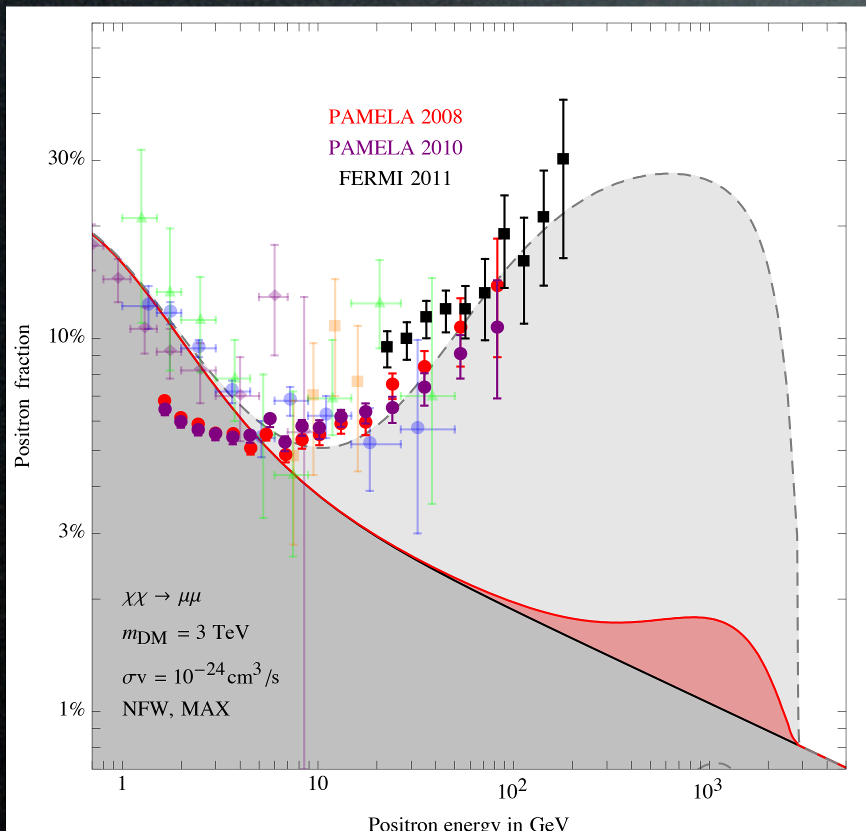


Are these signals of Dark Matter?

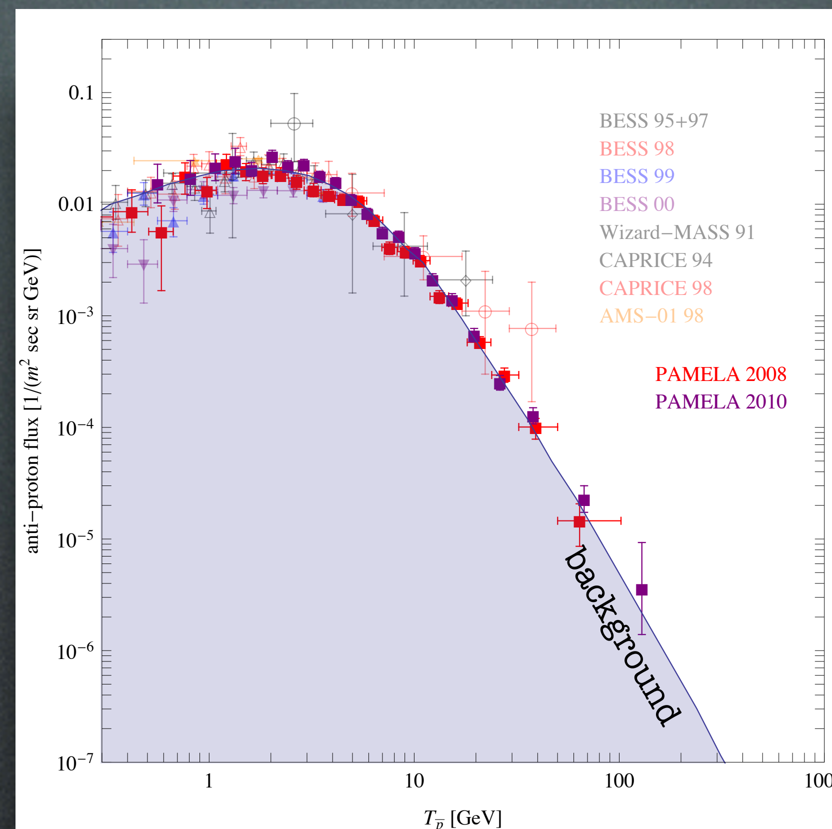
YES: few TeV, leptophilic DM
with huge $\langle\sigma v\rangle \approx 10^{-23}\,\mathrm{cm}^3/\mathrm{sec}$

Positrons & Electrons

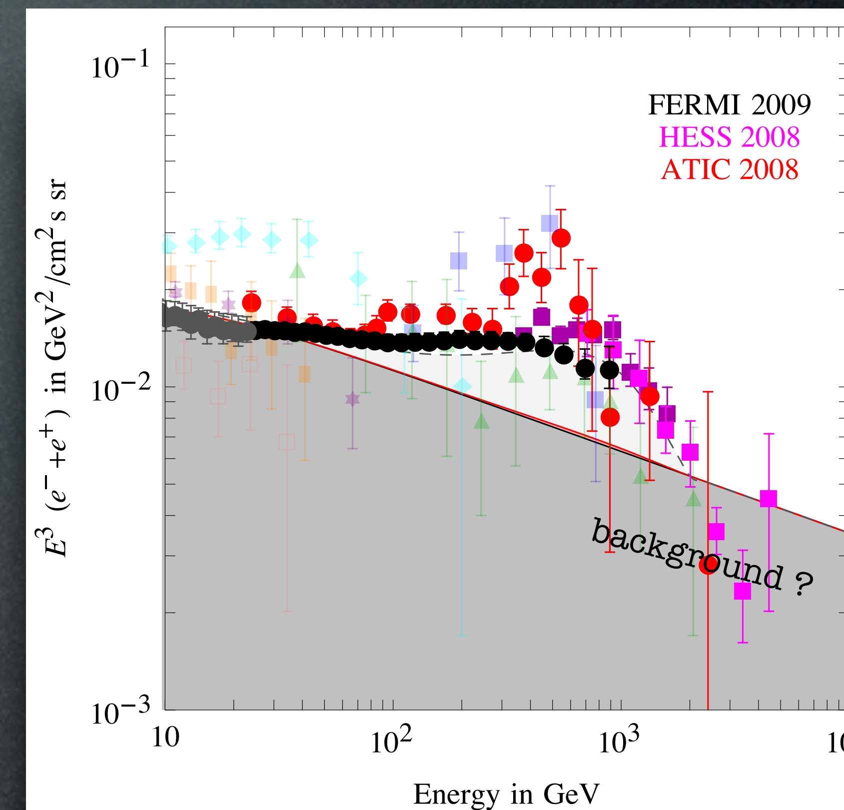
positron fraction



antiprotons



electrons + positrons



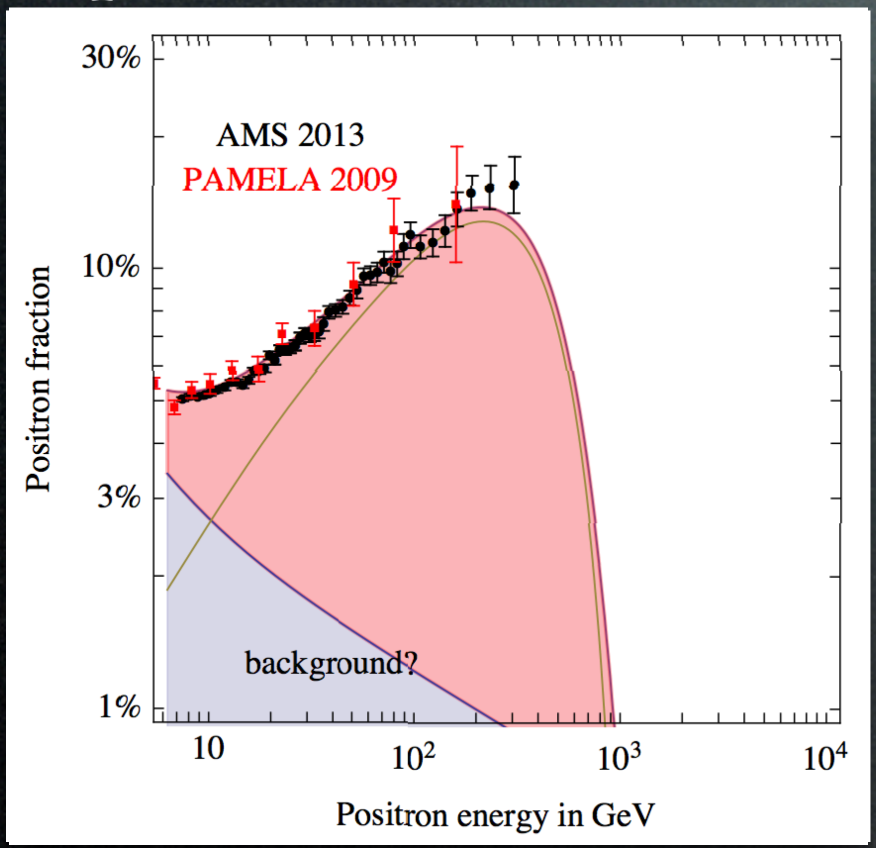
Are these signals of Dark Matter?

YES: few TeV, leptophilic DM with huge $\langle \sigma v \rangle \approx 10^{-23}\,\mathrm{cm}^3/\mathrm{sec}$

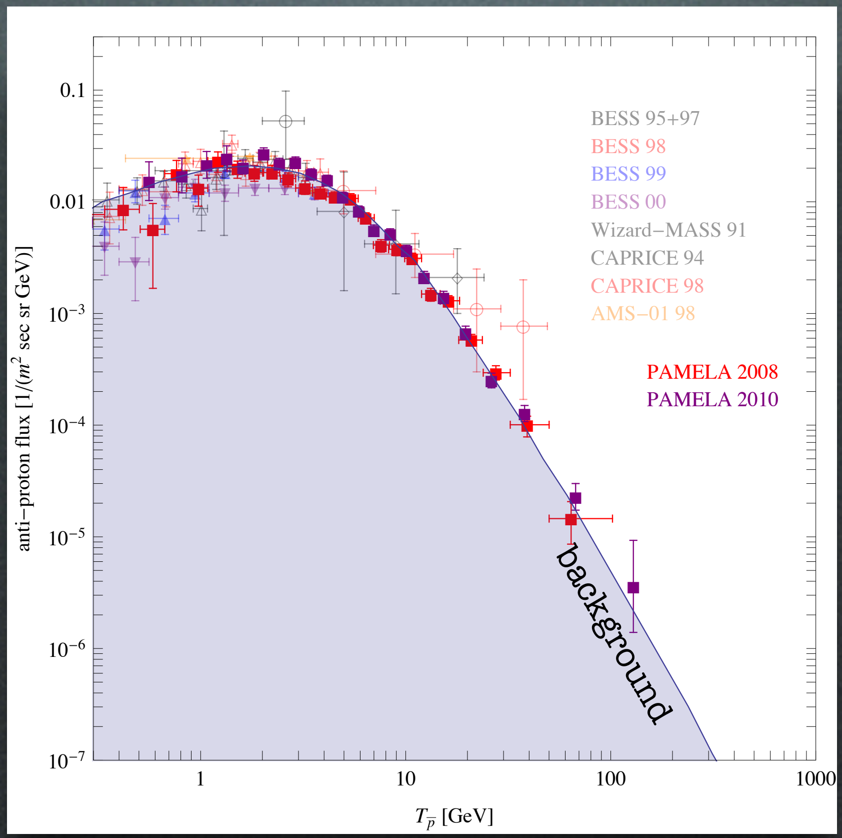
NO: a formidable ‘background’ for future searches

PS: post AMS 2013

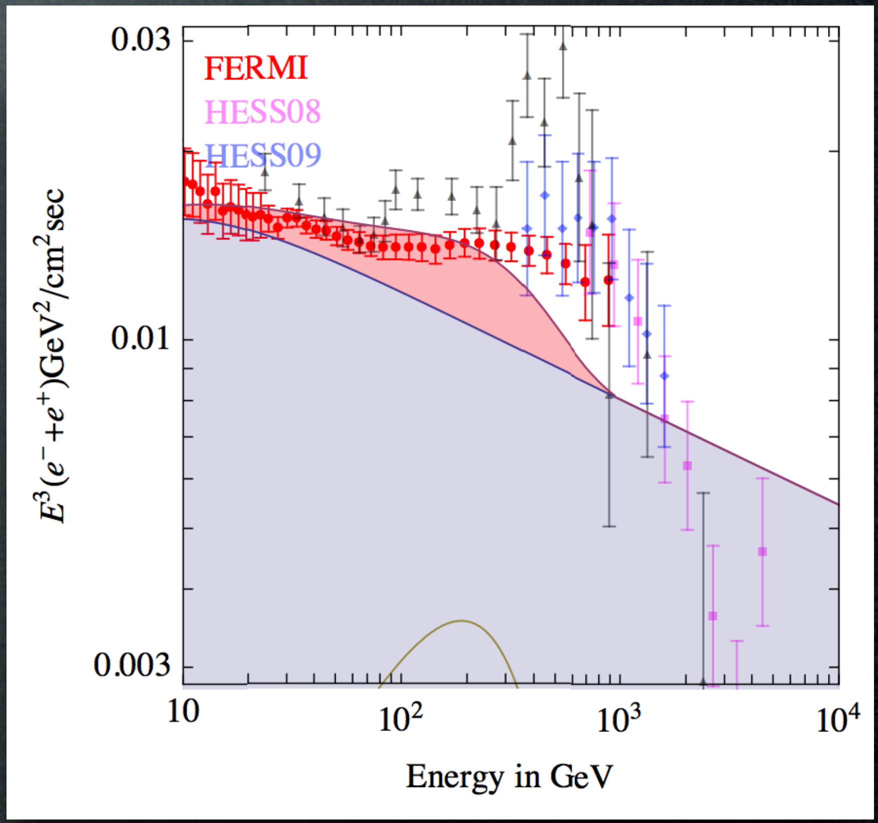
positron fraction



antiprotons



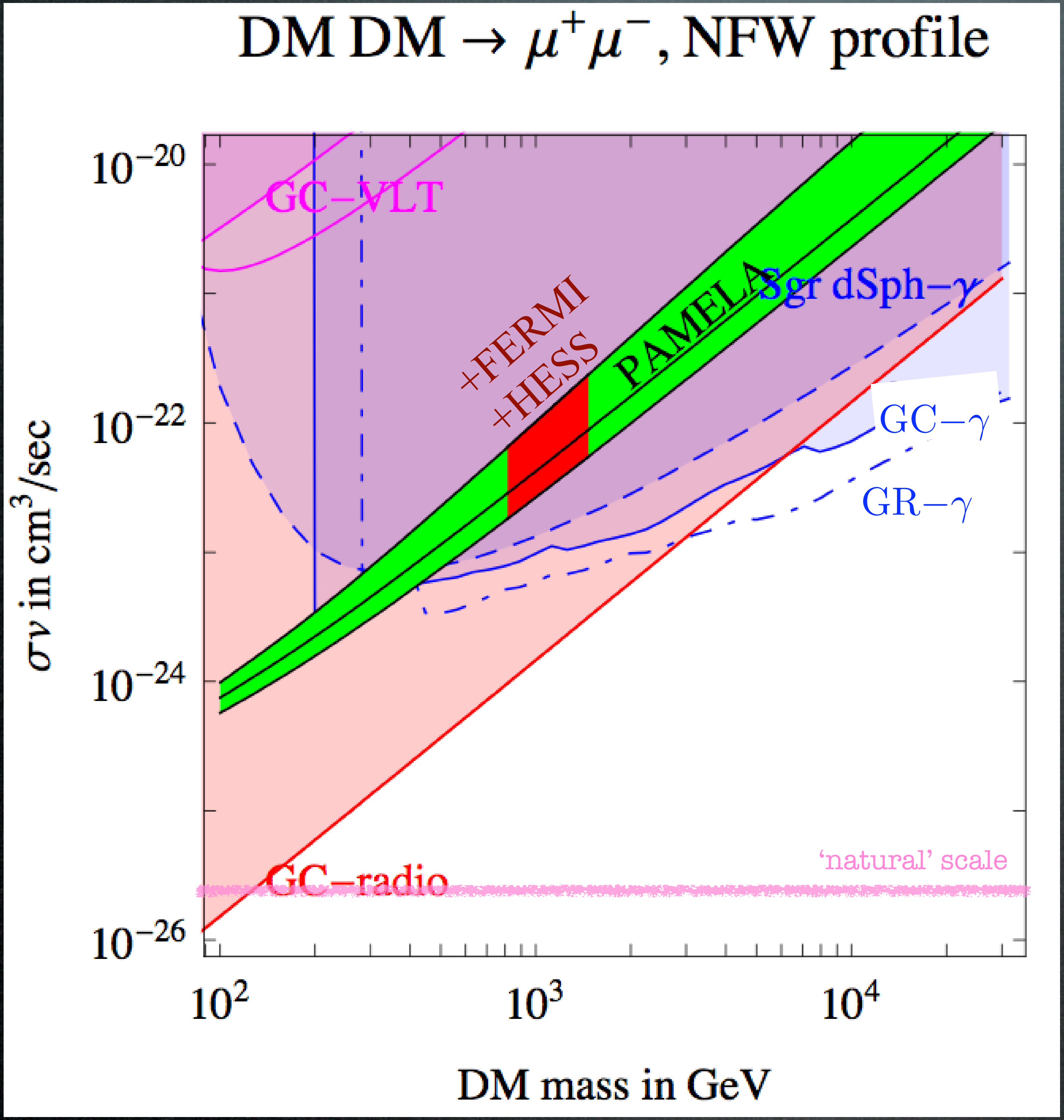
electrons + positrons



Are these signals of Dark Matter?

YES: one TeV, leptophilic DM
with huge $\langle \sigma v \rangle \approx 10^{-23}\, \mathrm{cm}^3/\mathrm{sec}$
'tension' between positron frac and $e^+ + e^-$

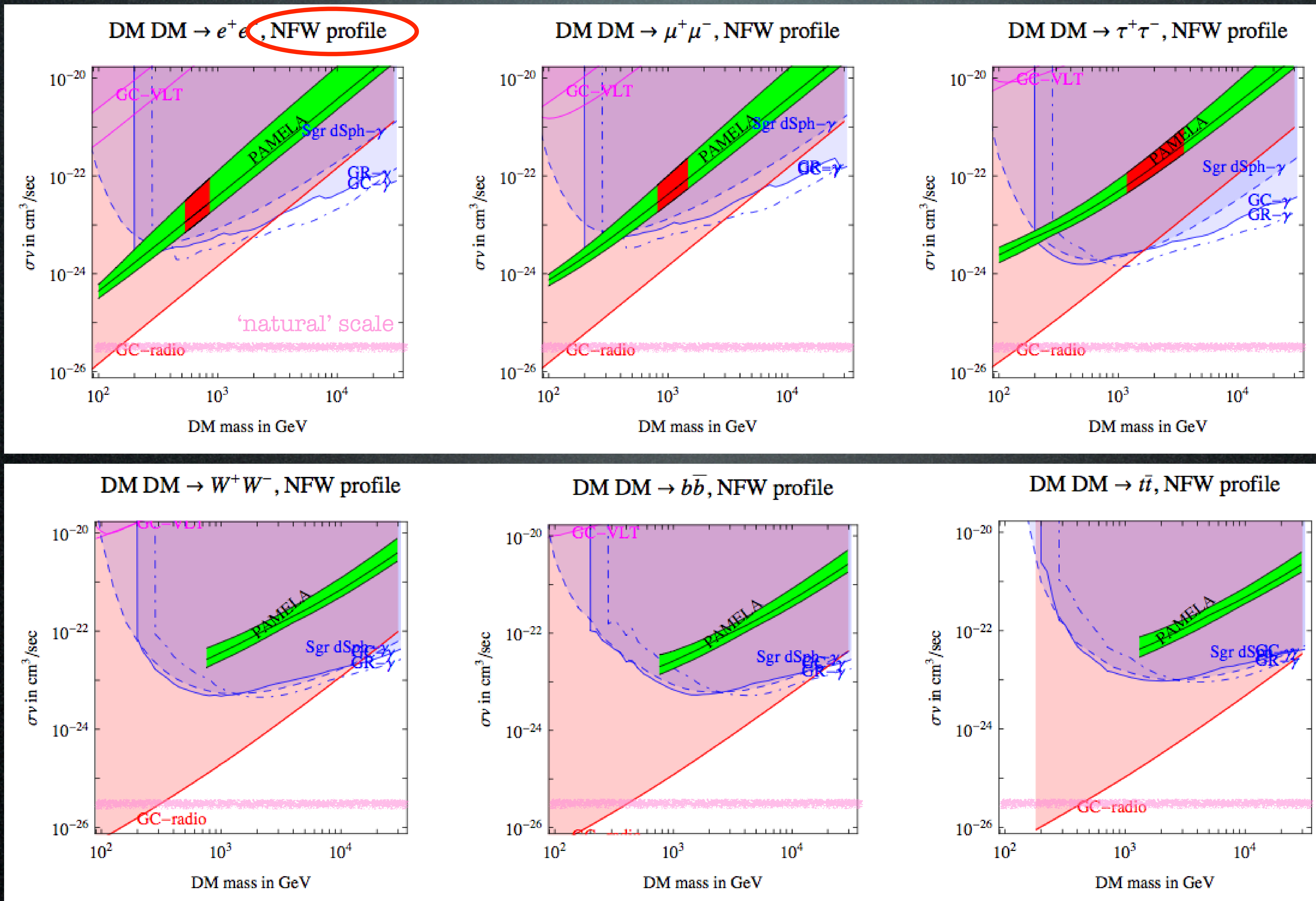
Gamma constraints



Bertone, Cirelli, Strumia, Taoso 0811.3744

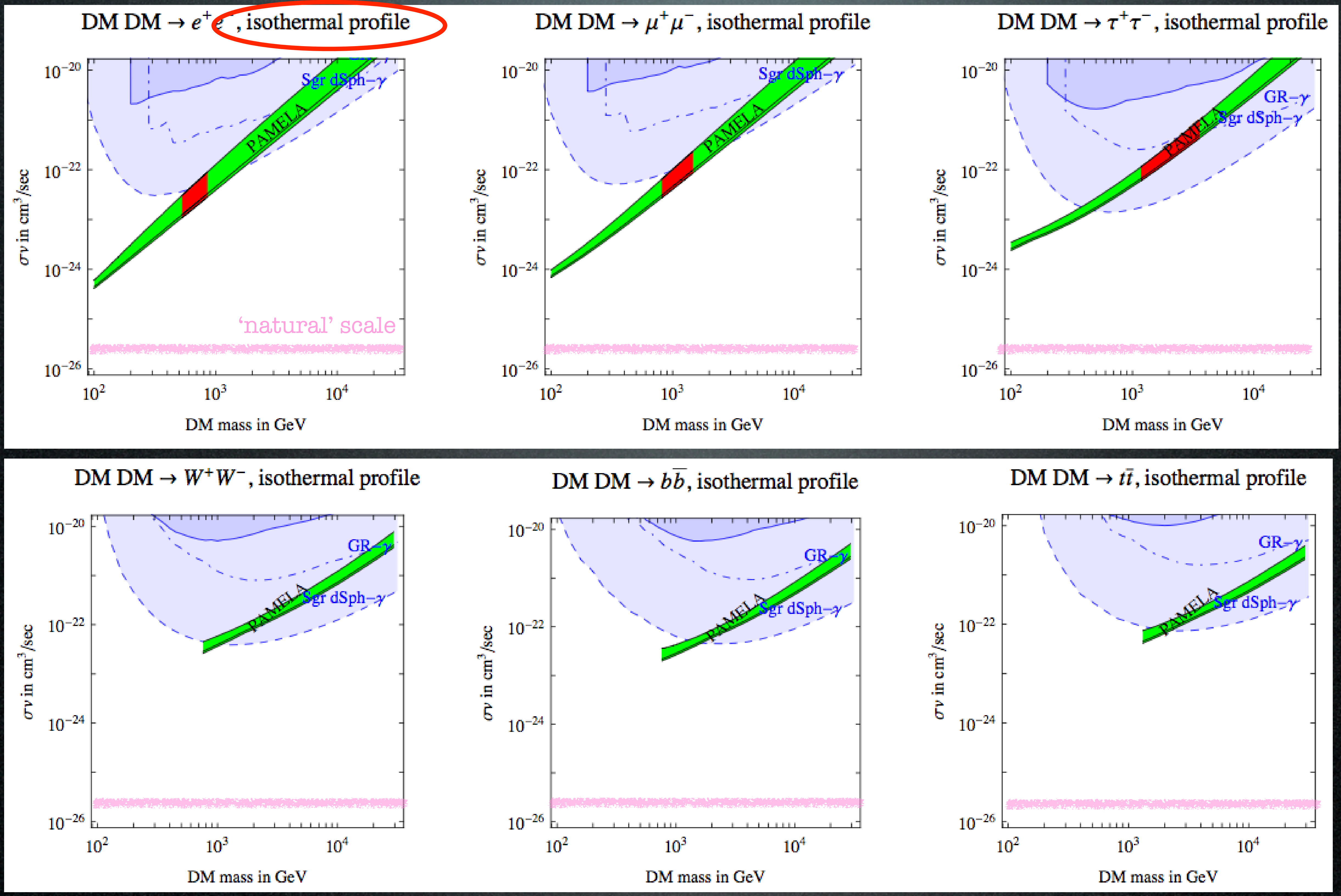
The PAMELA +FERMI regions are in conflict with gamma constraints, unless...

Gamma constraints



Bertone, Cirelli, Strumia, Taoso 0811.3744

Gamma constraints

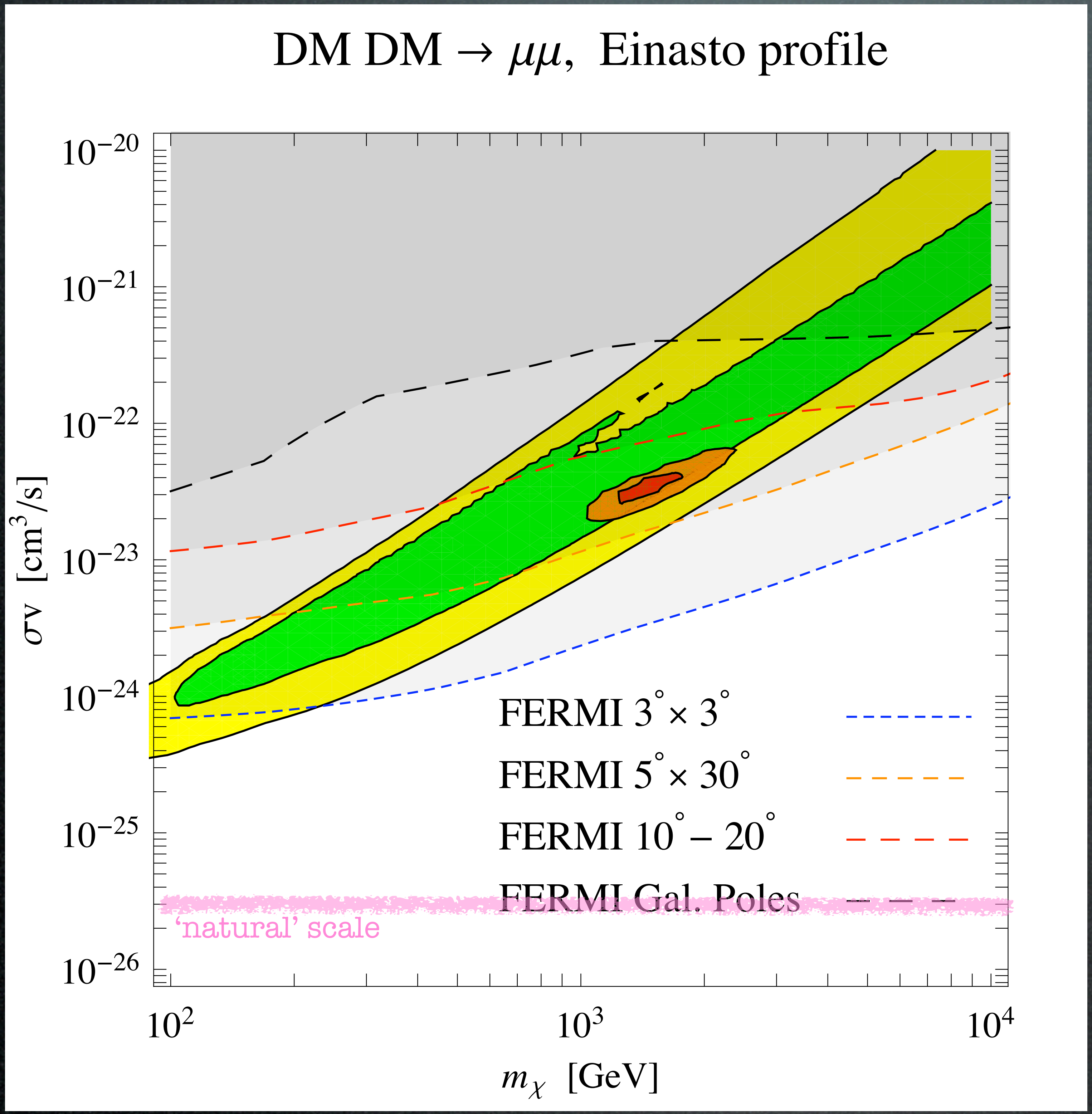


...not-too-steep profile needed.

Bertone, Cirelli, Strumia, Taoso 0811.3744

Gamma constraints

γ from Inverse Compton on $e^{\pm}$ in halo

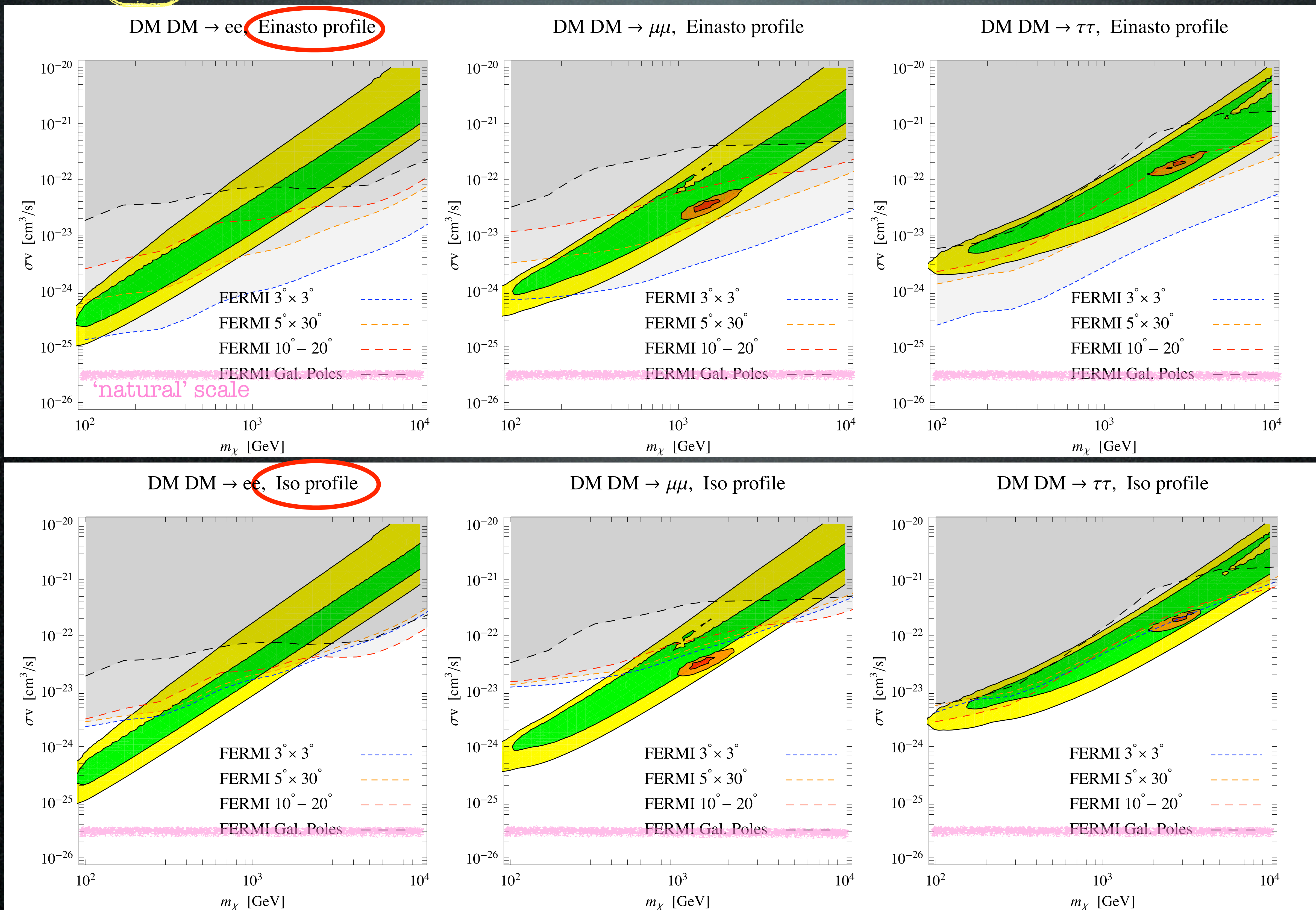


Cirelli, Panci, Serpico 0912.0663

The PAMELA and FERMI regions are in conflict with these gamma constraints, and here...

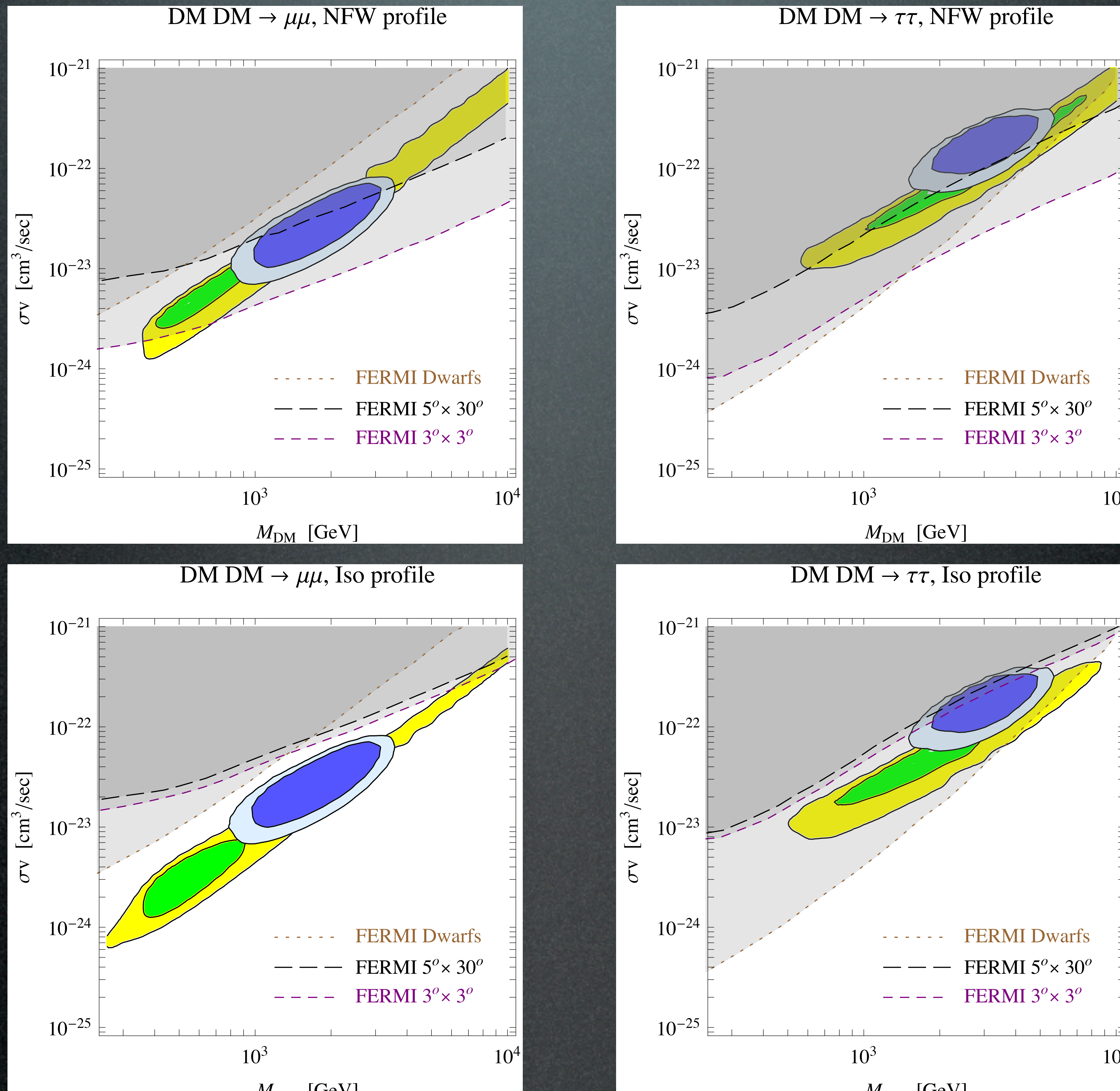
Gamma constraints

d. γ from Inverse Compton on $e^{\pm}$ in halo



Cirelli, Panci, Serpico 0912.0663

PS: post AMS 2013



Theorist's reaction

Theorist's reaction

1. the 'PAMELA frenzy'

Challenges for the ‘conventional’ DM candidates

Needs:	SuSy DM	KK DM
- TeV or multi-TeV masses	difficult	ok
- no hadronic channels	difficult	difficult
- very large flux	no	ok

for any Majorana DM,
s-wave annihilation cross section

$$\sigma_{\rm ann}({\rm DM}\,\bar{\rm DM} \to f\bar{f}) \propto \left(\frac{m_f}{M_{\rm DM}}\right)^2$$

Enhancement

How to reconcile $\sigma = 3 \cdot 10^{-26} \mathrm{cm}^3/\mathrm{sec}$ with $\sigma \simeq 10^{-23} \mathrm{cm}^3/\mathrm{sec}$?

- DM is produced non-thermally: the annihilation cross section today is unrelated to the production process

	at freeze-out	***today***
- astrophysical boost	no clumps	clumps
- resonance effect	off-resonance	on-resonance
- Sommerfeld effect	$v/c \simeq 0.1$	$v/c \simeq 10^{-3}$

+ (Wimponium)

Sommerfeld Enhancement

NP QM effect that can enhance the annihilation cross section by orders of magnitude in the regime of small velocity and relatively long range force.

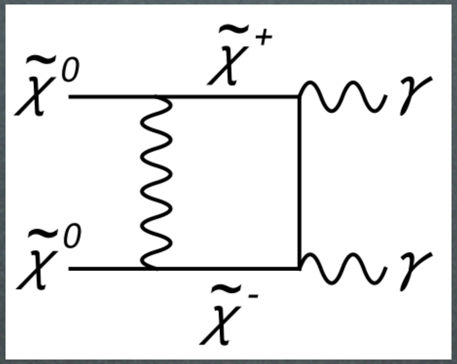
Sommerfeld Enhancement

NP QM effect that can enhance the annihilation cross section by orders of magnitude in the regime of small velocity and relatively long range force.

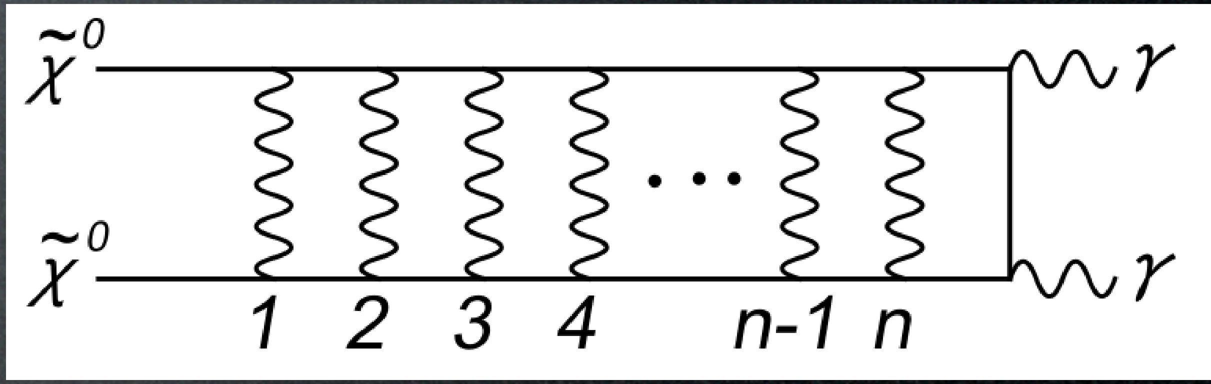
In terms of Feynman diagrams:

Hisano et al. hep-ph/0412403

First order cross section:



Adding a rung to the ladder: $\times \left(\frac{\alpha M}{m_W}\right)$



For $\alpha M/m_V \gtrsim 1$ the perturbative expansion breaks down,
need to resum all orders
i.e.: keep the full interaction potential.

Model building

- Minimal extensions of the SM:
  heavy WIMPS (Minimal DM, Inert Doublet)

  Cirelli, Strumia et al. 2005-2009 Tytgat et al. 0901.2556

- More drastic extensions:
  New models with a rich Dark sector

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- Decaying DM

  Ibarra et al., 2007-2009 Nardi, Sannino, Strumia 0811.4153

  A.Arvanitaki, S.Dimopoulos, S.Dubovsky, P.Graham, R.Harnik, S.Rajendran, 0812.2075

Decaying DM

DM need not be absolutely stable,
just $\tau_{\rm DM} \gtrsim \tau_{\rm universe} \simeq 4.3\ 10^{17}{\rm sec}$.

The current CR anomalies can be due to decay with:

$$\tau_{\rm decay} \approx 10^{26}{\rm sec}$$

Motivations from theory?

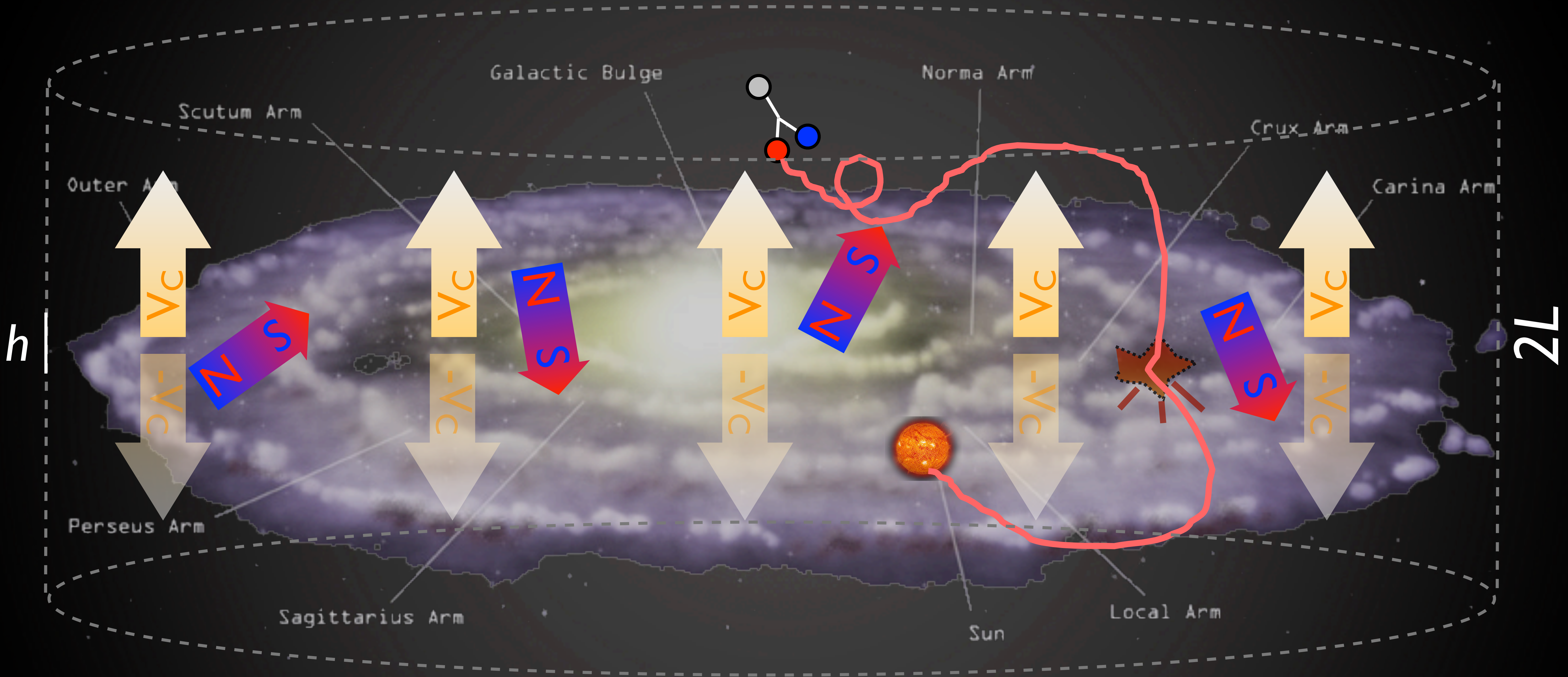
- dim 6 suppressed operator in GUT — Arvanitaki, Dimopoulos et al., 2008+09

$$\tau_{\rm DM} \simeq 3 \cdot 10^{27}{\rm sec} \left(\frac{1\ {\rm TeV}}{M_{\rm DM}}\right)^5 \left(\frac{M_{\rm GUT}}{2 \cdot 10^{16}\ {\rm GeV}}\right)^4$$

- or in TechniColor — Nardi, Sannino, Strumia 2008
- gravitino in SuSy with broken R-parity...

Indirect Detection

$\bar{p}$ and e^+ from DM decay in halo



What sets the overall expected flux?

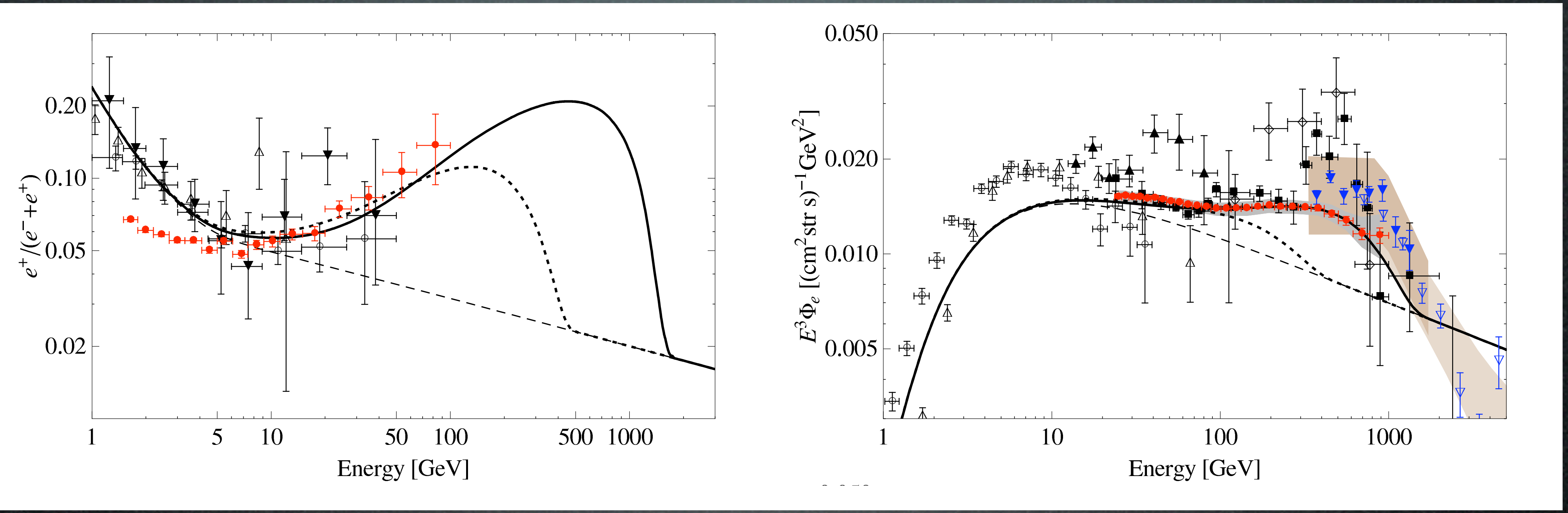
$$\text{flux} \propto n\,\Gamma_{\rm decay}$$

$$\Gamma_{\rm decay}^{-1} = \tau_{\rm decay} \approx 10^{26}\,\text{sec}$$

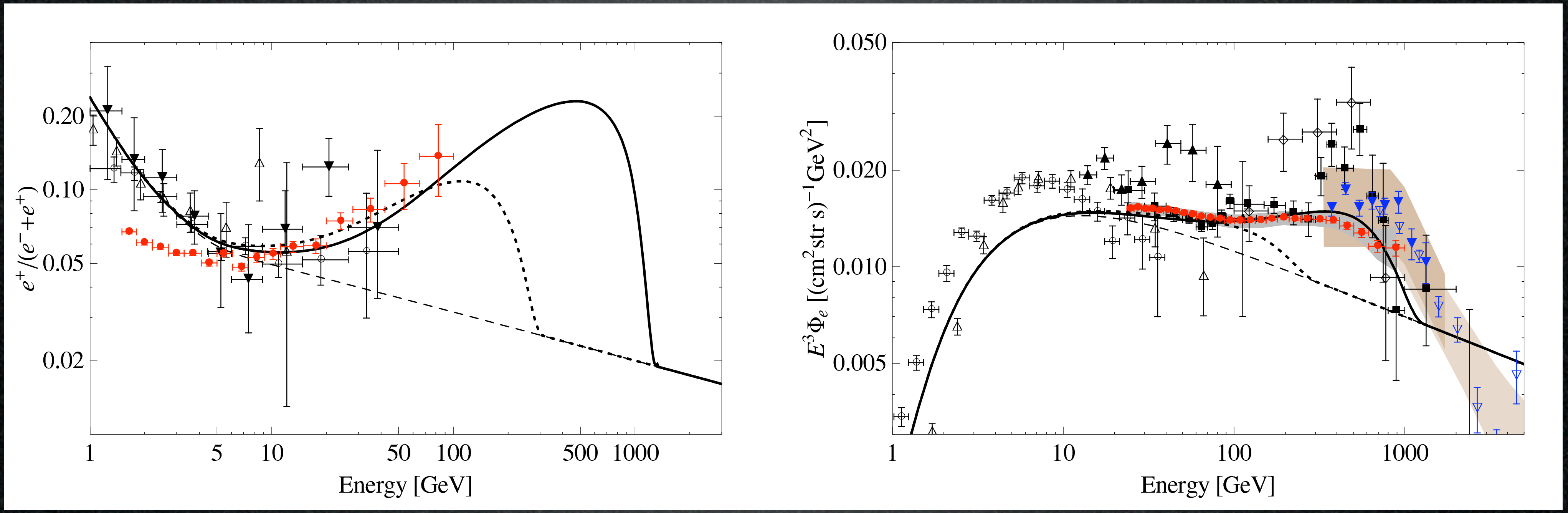
Decaying DM

Which DM spectra can fit the data?

E.g. a fermionic $\mathrm{DM} \to \mu^+\mu^-\nu$ with $M_{\mathrm{DM}} = 3.5\,\mathrm{TeV}$:



E.g. a scalar $\mathrm{DM} \to \mu^+\mu^-$ with $M_{\mathrm{DM}} = 2.5\,\mathrm{TeV}$:

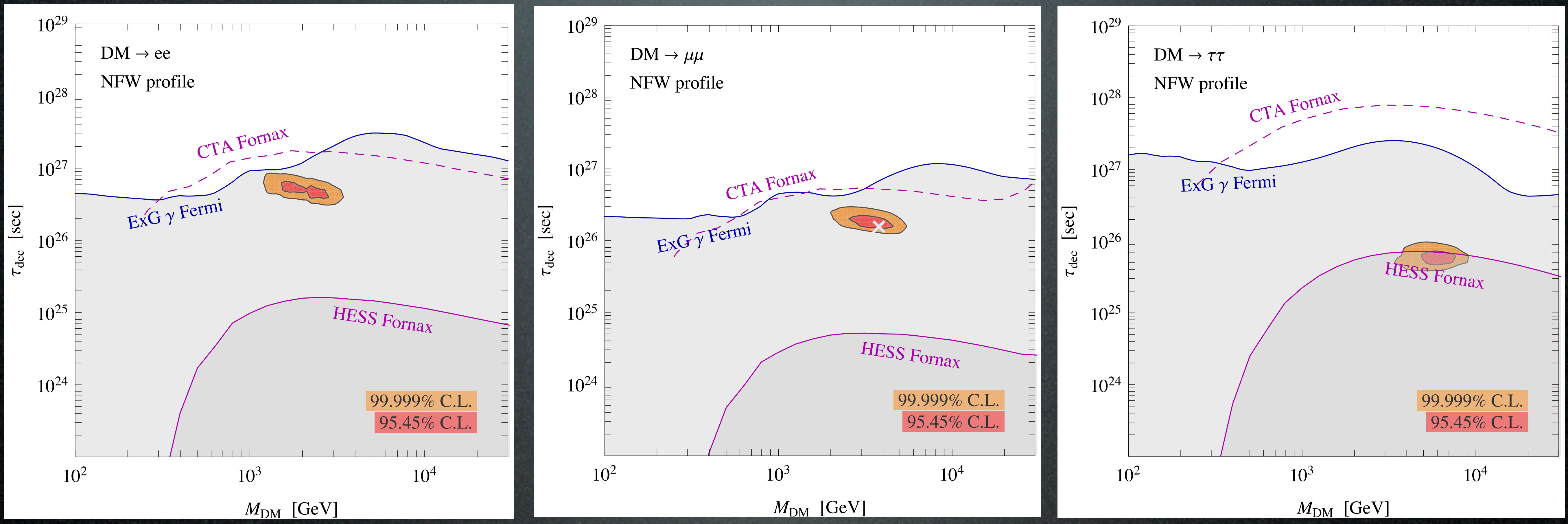


Ibarra, Tran, Weniger 2009

Decaying DM

But, again: gamma ray constraints

(although: no radio, neutrino constraints)



Cirelli, Moulin, Panci, Serpico, Viana 1205.5283

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- Decaying DM

  Ibarra et al., 2007-2009 Nardi, Sannino, Strumia 0811.4153

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- More drastic extensions:

  New models with a rich Dark sector

  - TeV mass DM
  - new forces (that Sommerfeld enhance)
  - leptophilic because: - kinematics (light mediator)

    - DM carries lepton #

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The "Theory of DM"

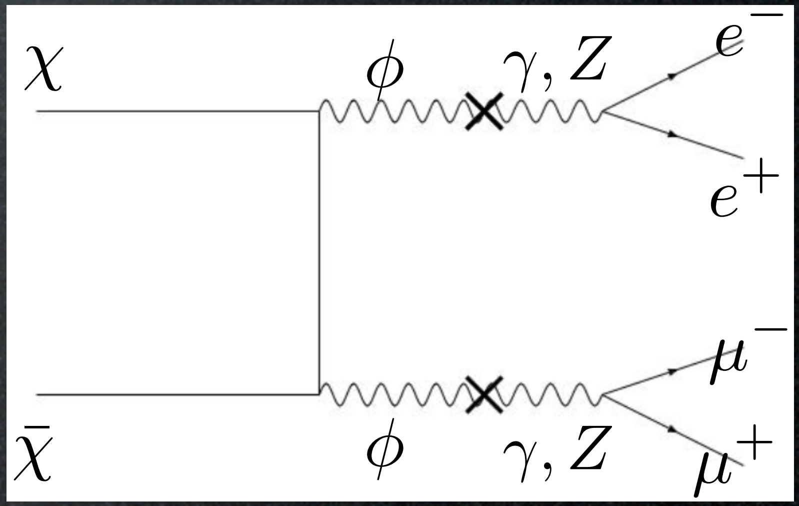
Arkani-Hamed, Weiner, Finkbeiner et al. 0810.0713
0811.3641

Basic ingredients:

χ Dark Matter particle, decoupled from SM, mass $M \sim 700+$ GeV

ϕ new gauge boson ("Dark photon"),
couples only to DM, with typical gauge strength, $m_\phi \sim$ few GeV
- mediates Sommerfeld enhancement of $\chi\bar{\chi}$ annihilation:
$\alpha M/m_V \gtrsim 1$ fulfilled

- decays only into e^+e^- or $\mu^+\mu^-$
for kinematical limit



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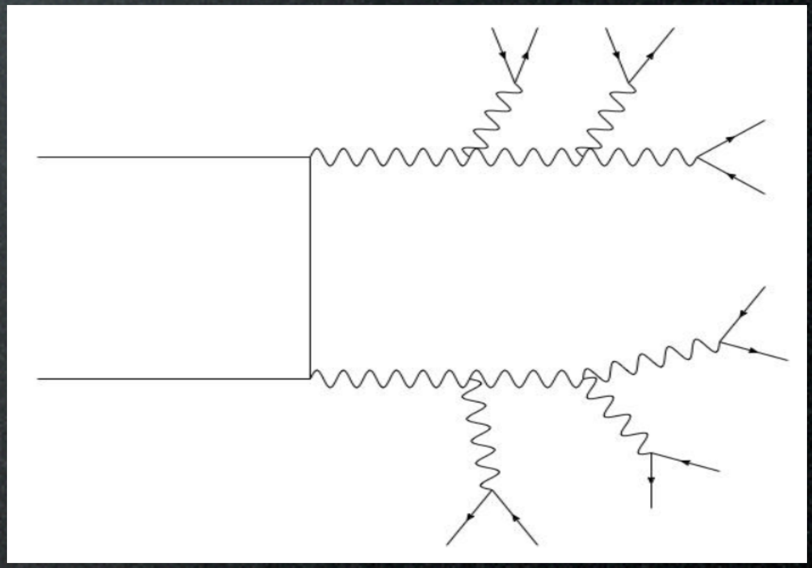
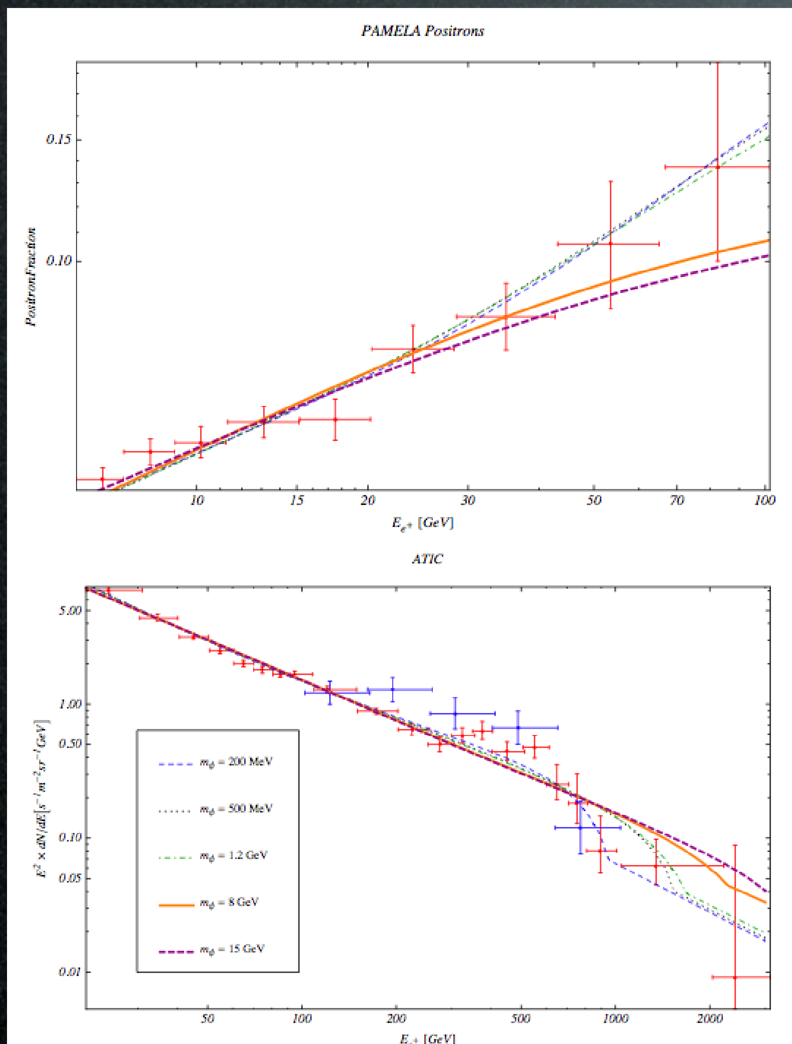


Extras:

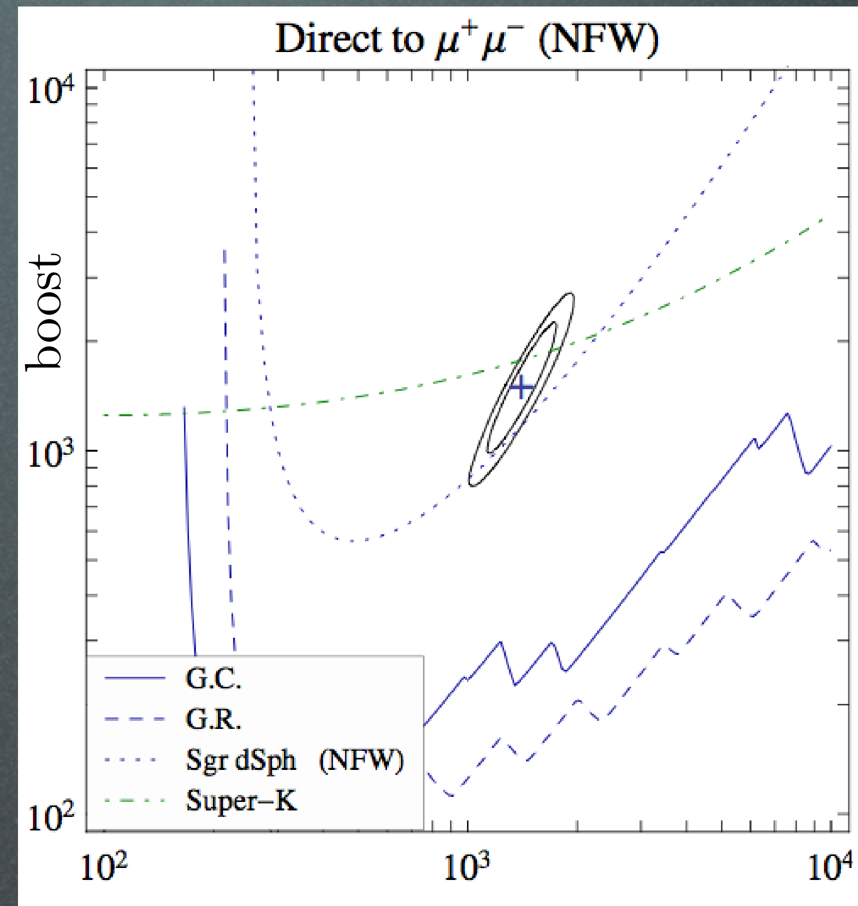
χ is a multiplet of states and ϕ is non-abelian gauge boson:
splitting $\delta M \sim 200$ KeV (via loops of non-abelian bosons)
- inelastic scattering explains DAMA
- eXcited state decay $\chi\chi \to \chi\chi^*$ explains INTEGRAL
  $\hookrightarrow e^+e^-$

The "Theory of DM"

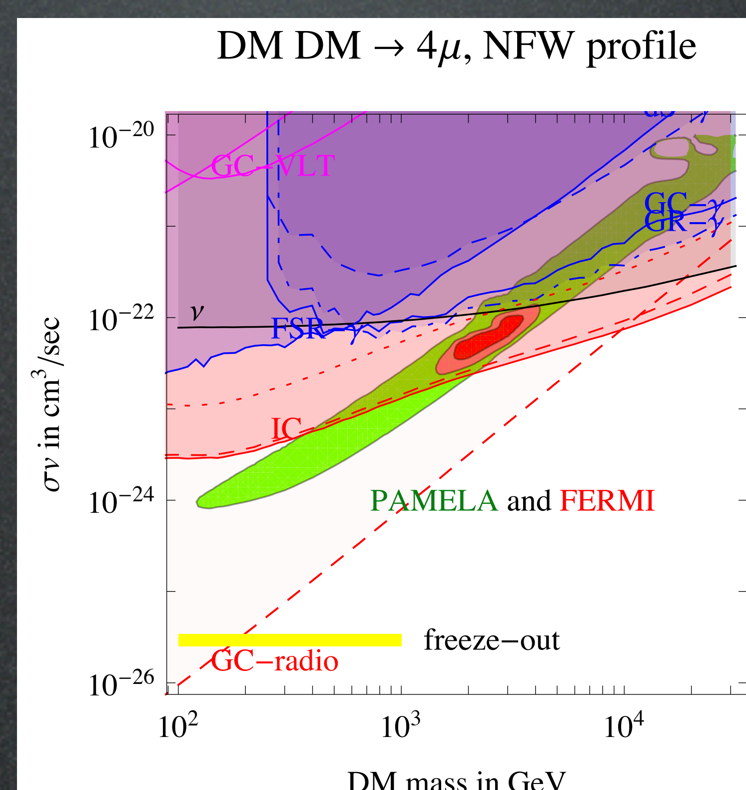
Phenomenology:

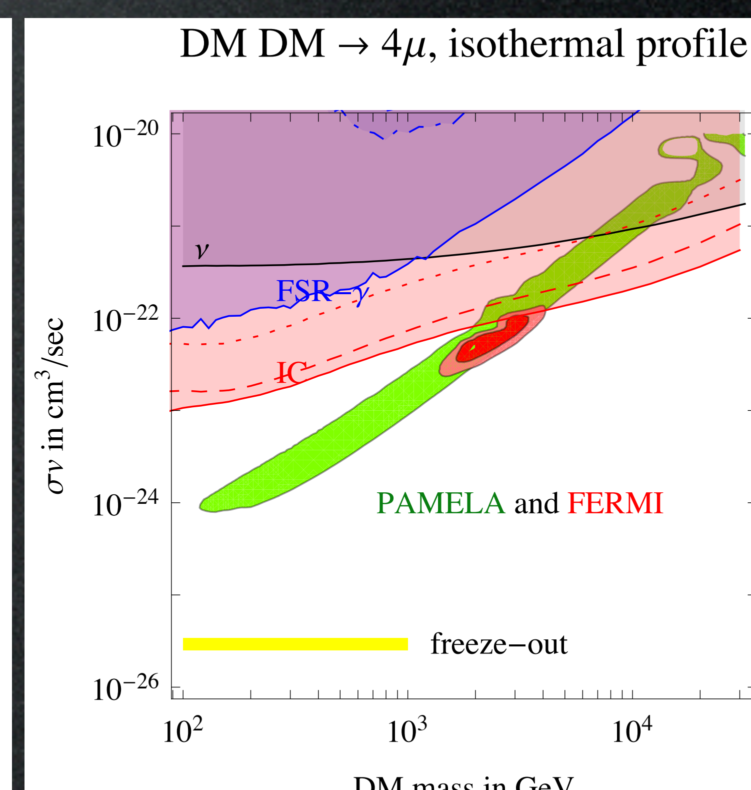


Meade, Papucci, Volanski 0901.2925



Mardon, Nomura, Stolarski, Thaler 0901.2926





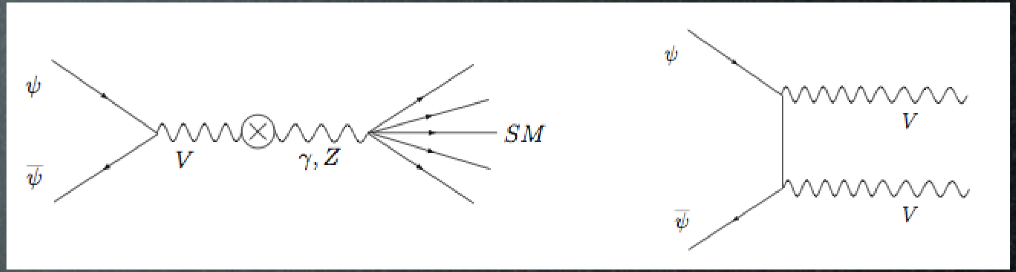
Strumia, Papucci 0912.0742

Variations

(selected)

- pioneering: Secluded DM, U(1) Stückelberg extension of SM

  Pospelov, Ritz et al 0711.4866 P.Nath et al 0810.5762



- Axion Portal: ϕ is pseudoscalar axion-like

  Nomura, Thaler 0810.5397

- singlet-extended UED: χ is KK RNnu, ϕ is an extra bulk singlet

  Bai, Han 0811.0387

- split UED: χ annihilates only to leptons because quarks are on another brane

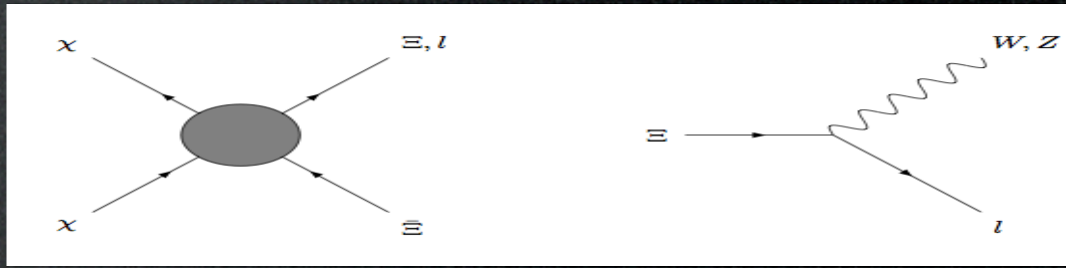
  Park, Shu 0901.0720

- DM carrying lepton number: χ charged under $U(1)_{L_\mu - L_\tau}$, ϕ gauge boson

  Cirelli, Kadastik, Raidal, Strumia 0809.2409 Fox, Poppitz 0811.0399 $(m_\phi \sim \text{tens GeV})$

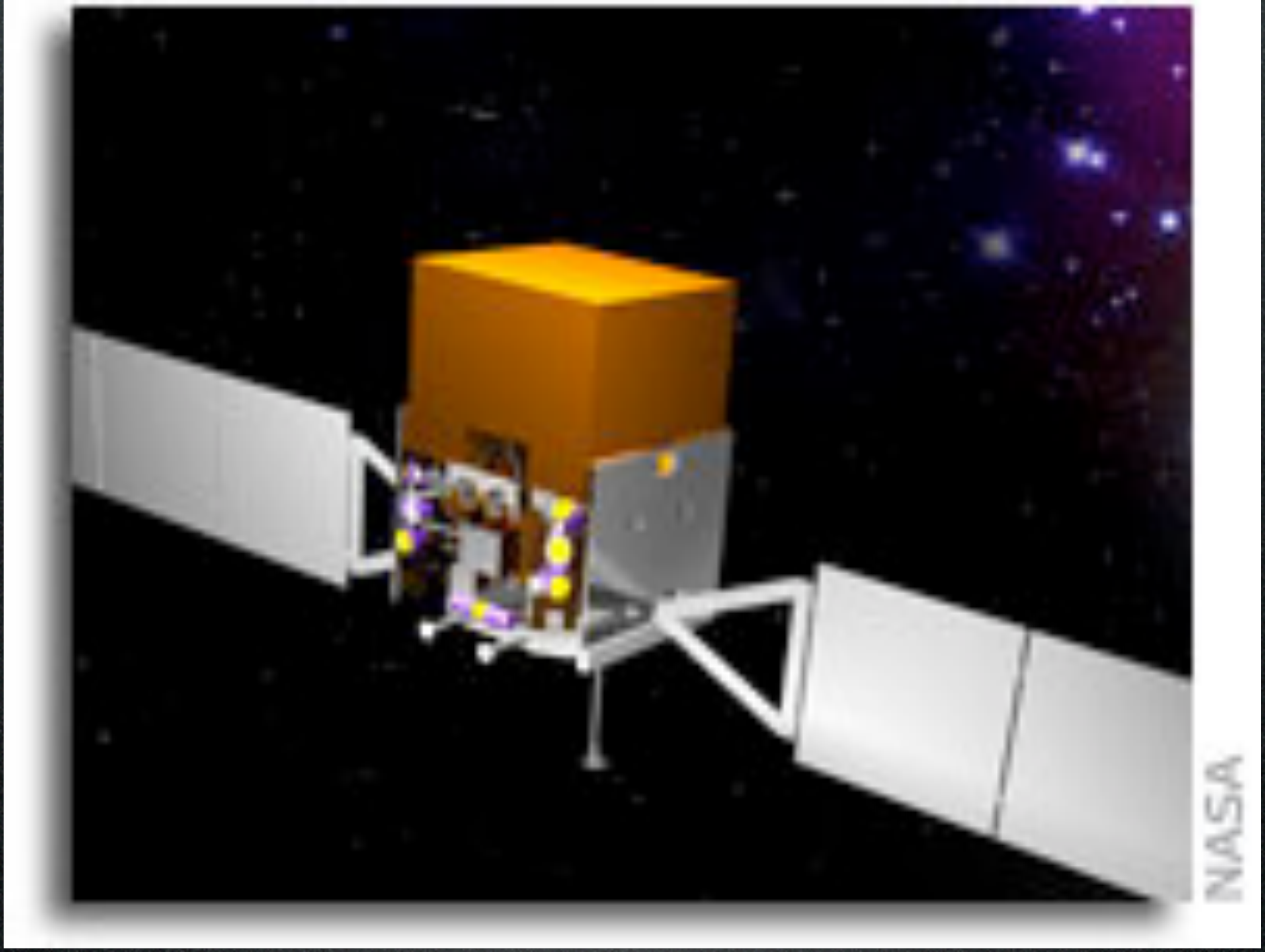
- New Heavy Lepton: χ annihilates into Ξ that carries lepton number and decays weakly $(\sim \text{TeV})$ $(\sim 100\text{s GeV})$

  Phalen, Pierce, Weiner 0901.3165



- ......

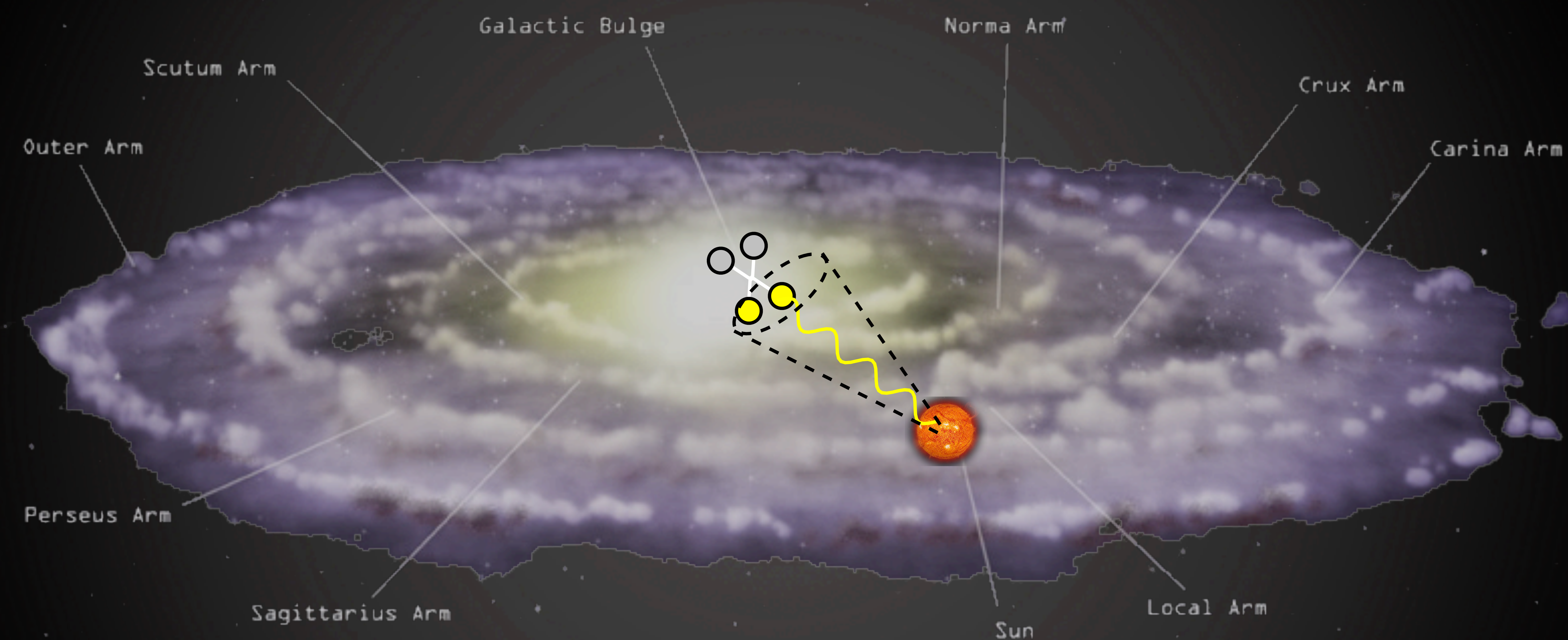
Gamma rays

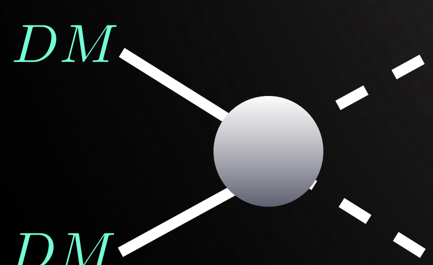


2. the '130 GeV line'

Basic picture: targets

γ from DM annihilations in galactic center



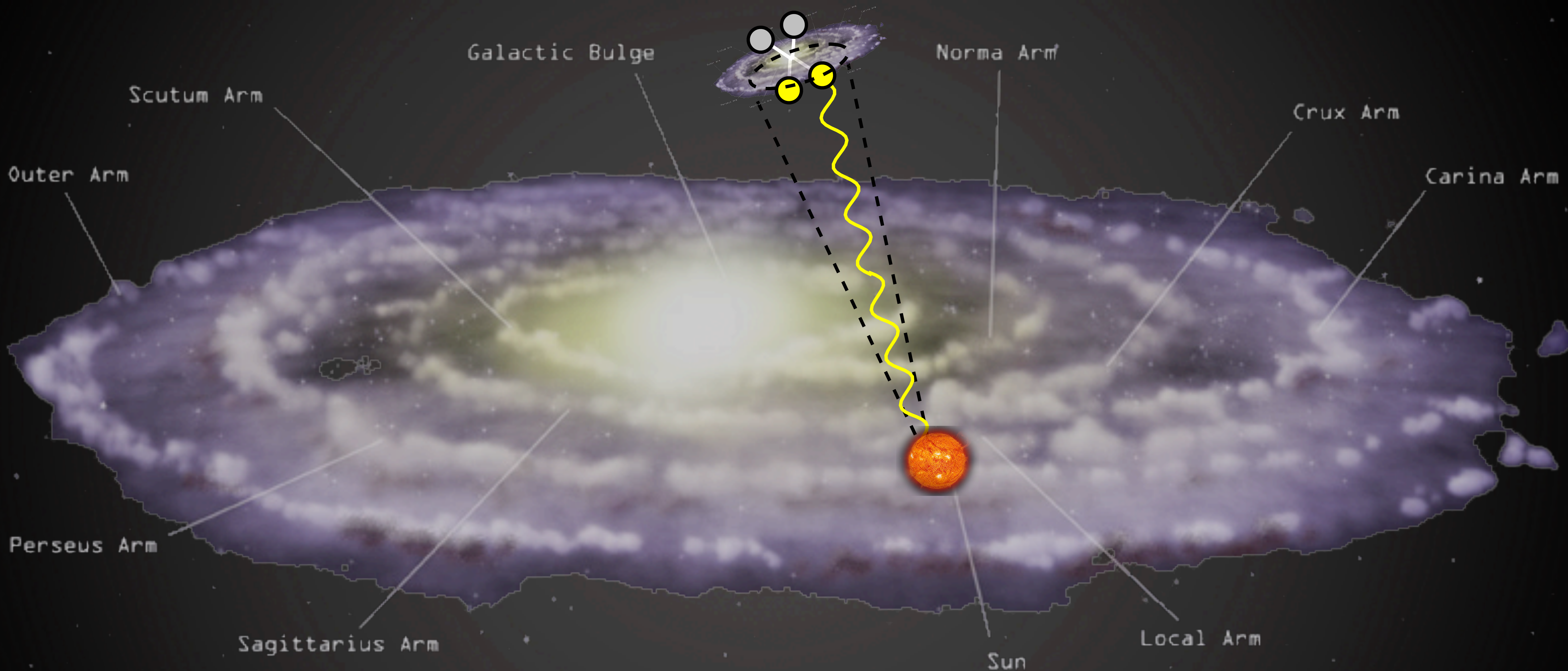


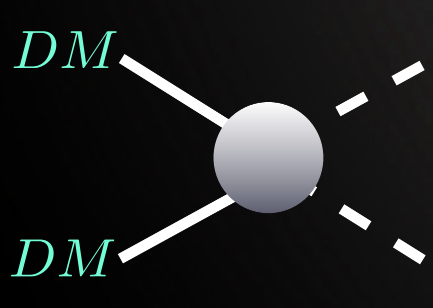
$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$ and γ

$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ \ldots$ and γ

Basic picture: targets

γ from DM annihilations in dwarf galaxies





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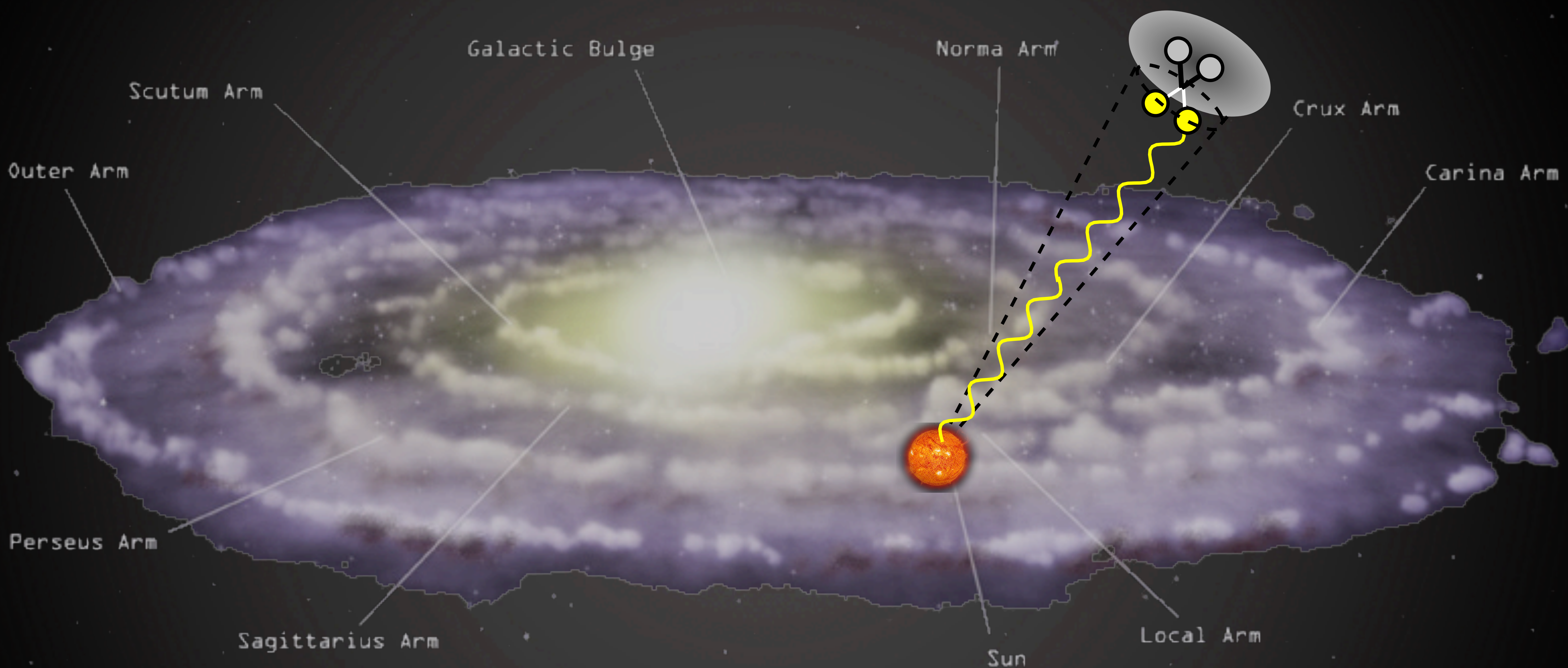
Basic picture: targets

γ from DM annihilations in subhaloes



DM, DM

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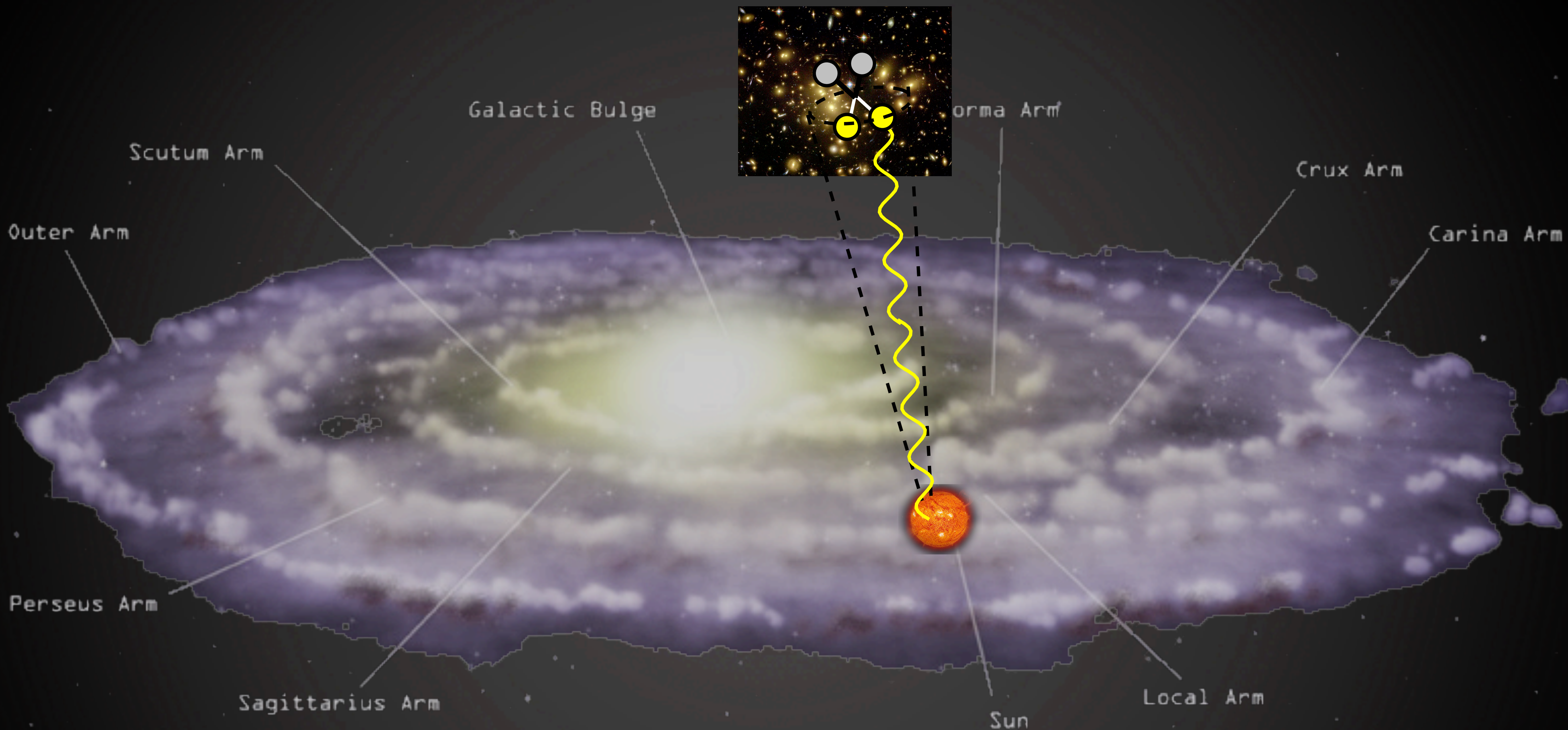
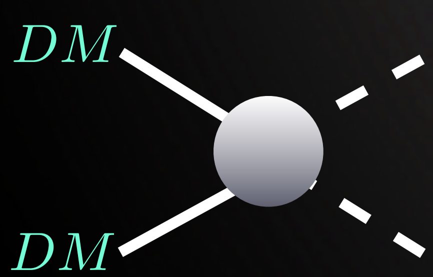
Basic picture: targets

γ from DM annihilations in galaxy clusters





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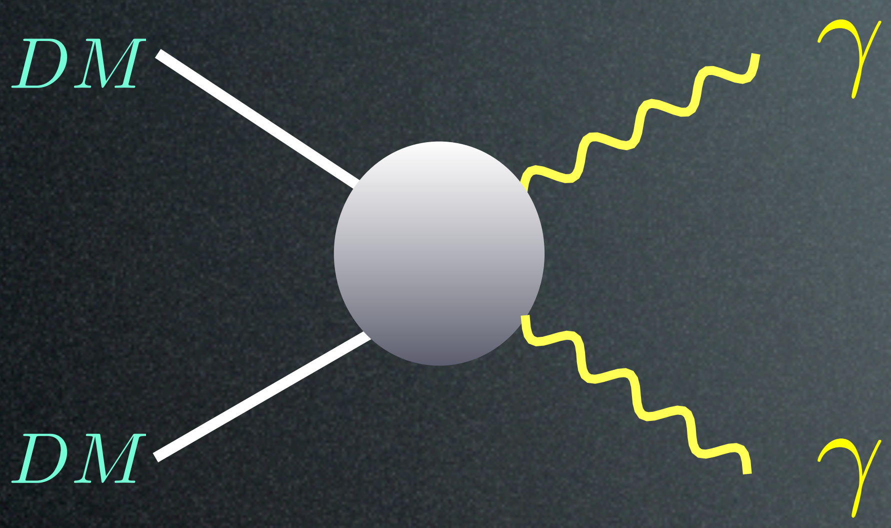
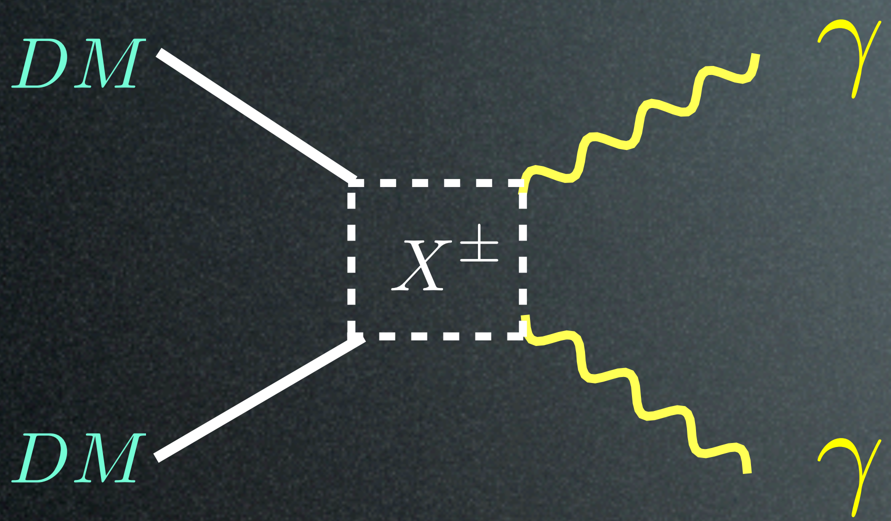
$$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ldots \text{ and } \gamma$$

Prompt emission: line(s)



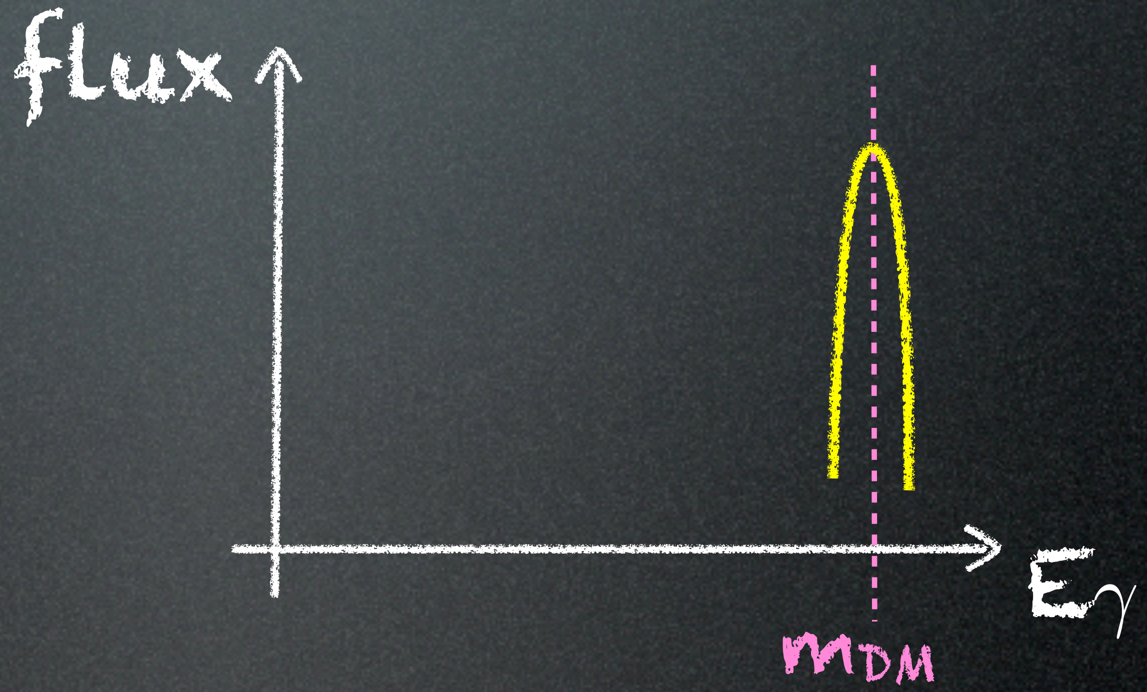
primary
channels

Prompt emission: line(s)

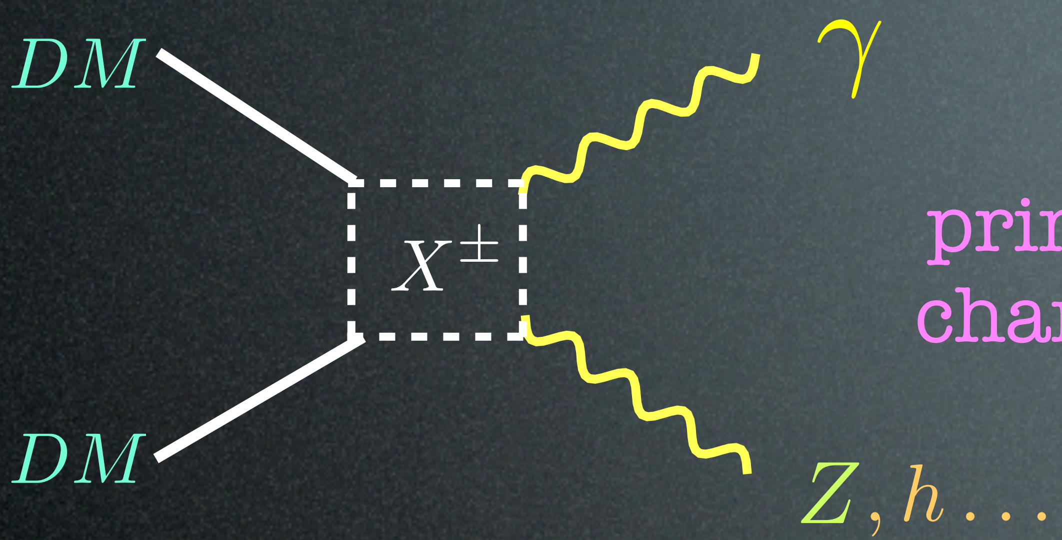


primary channels

$$E_\gamma = m_{\rm DM}$$



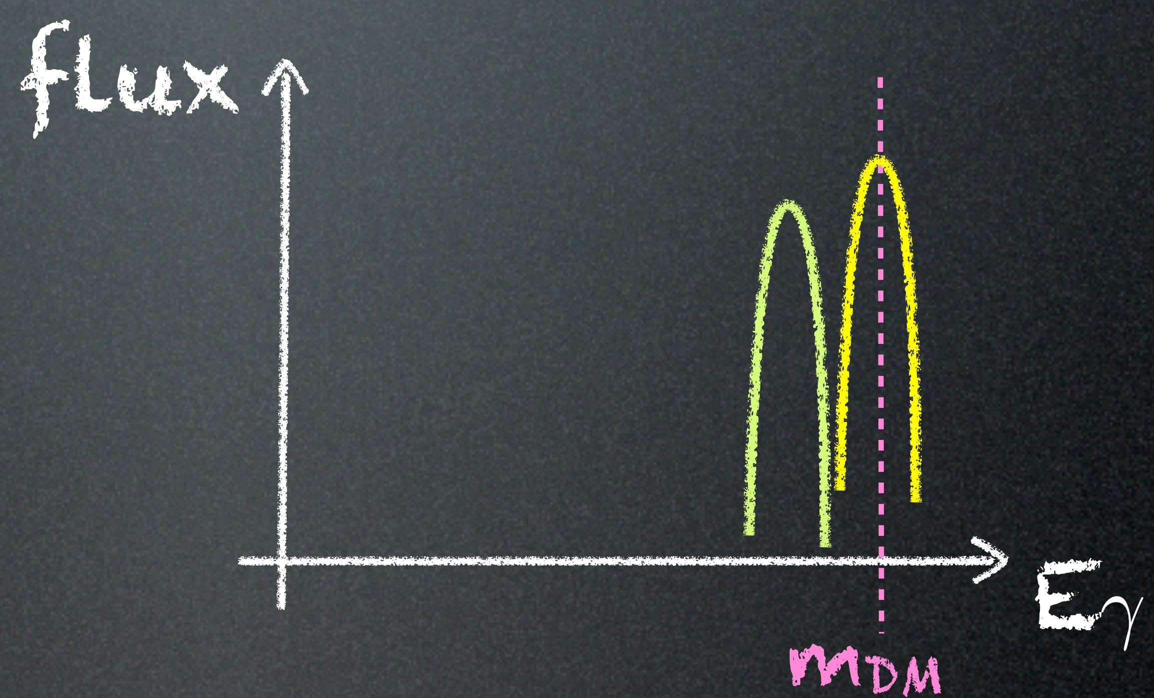
Prompt emission: line(s)



primary
channels

$$E_\gamma = m_{\rm DM}$$

$$E_\gamma = m_{\rm DM}\left(1 - \frac{m_Z^2}{4\, m_{\rm DM}^2}\right)$$



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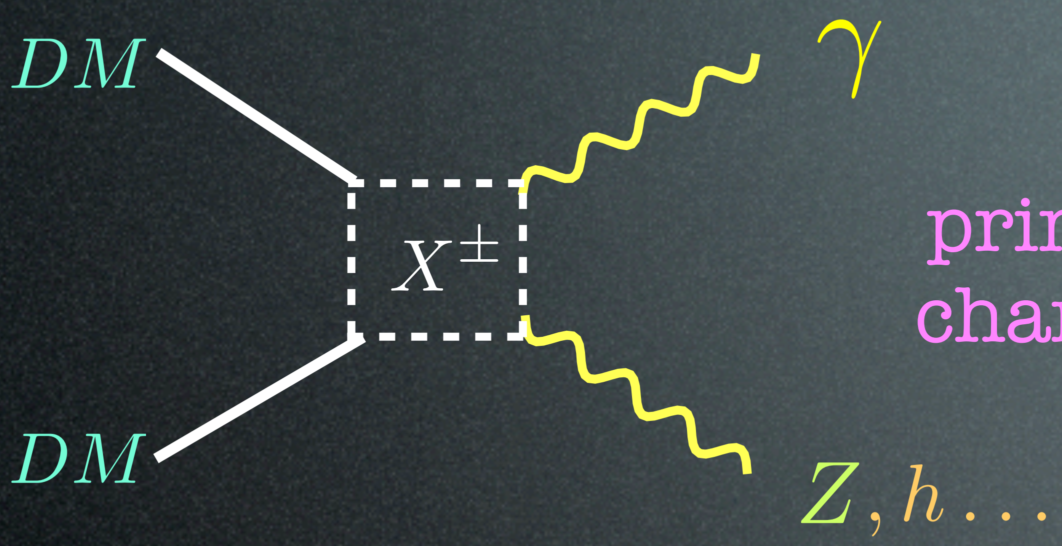

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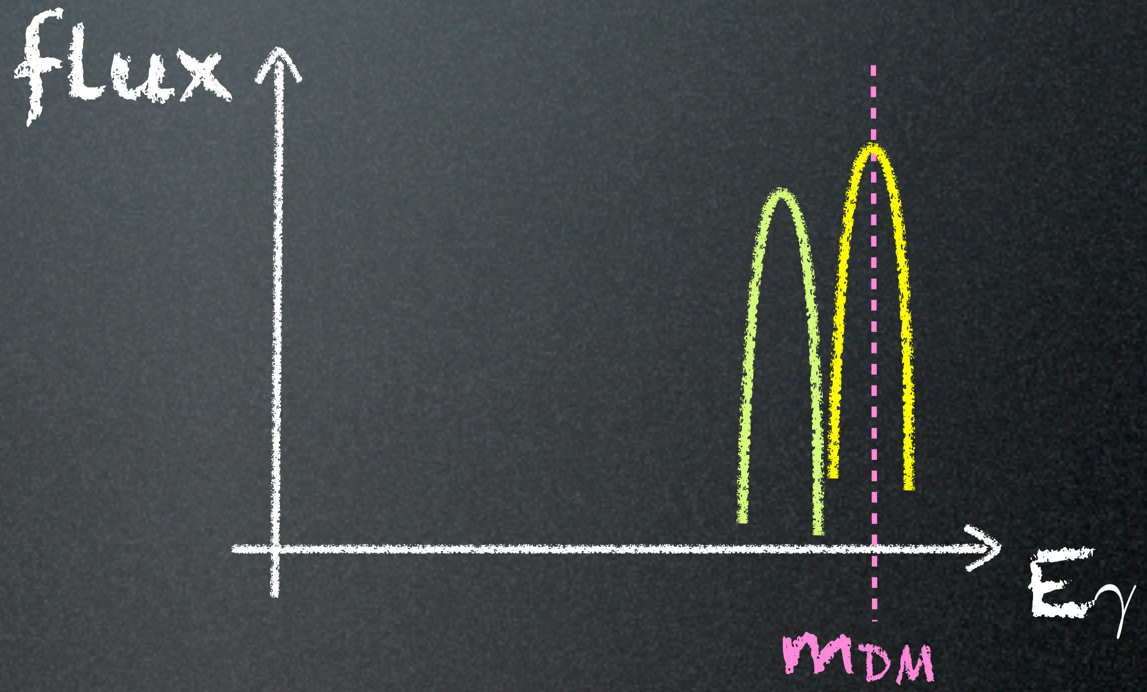
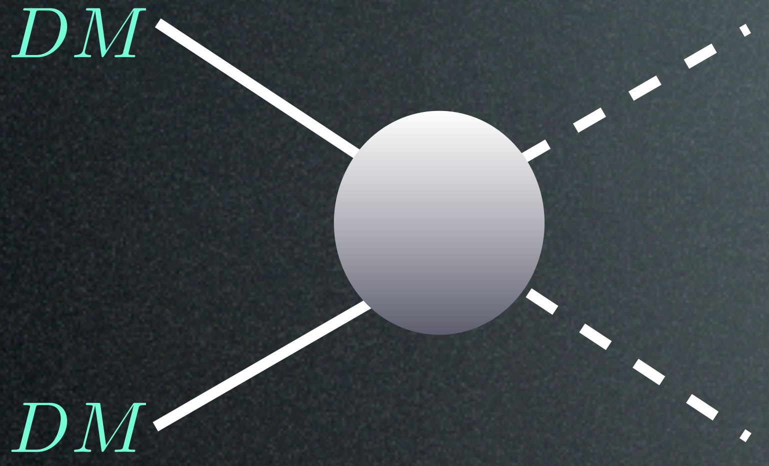


So what are the particle physics parameters?

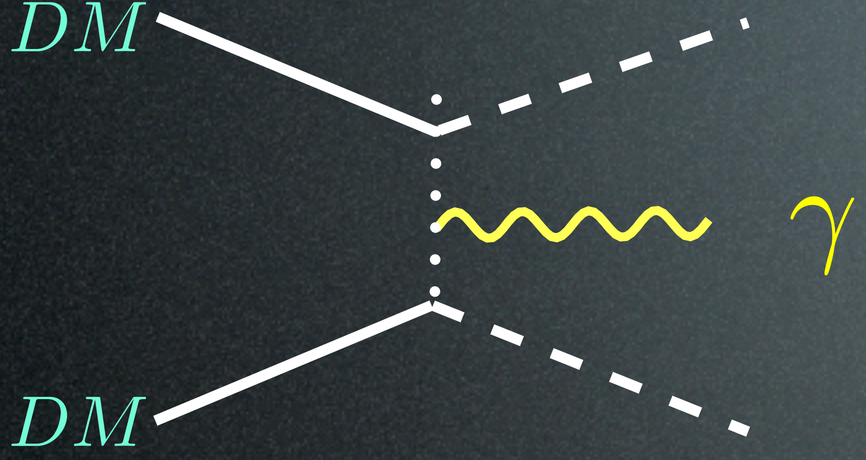
1. Dark Matter mass

2. annihilation cross section $\sigma_{\rm ann}$

Prompt emission: sharp features



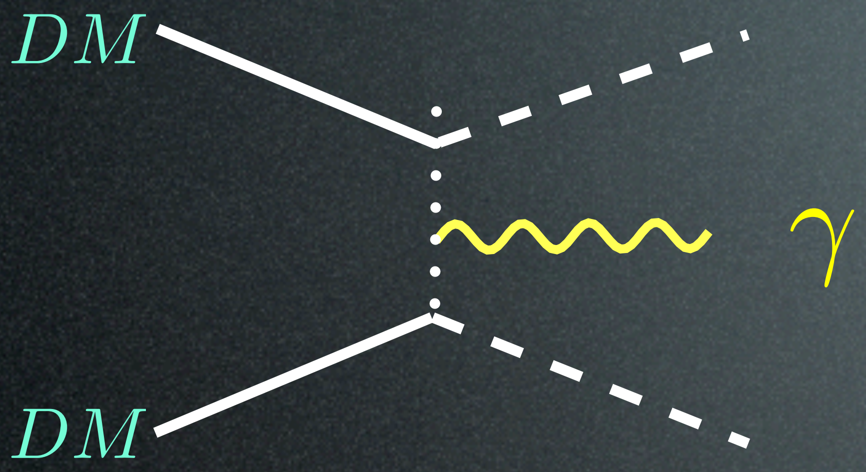
Prompt emission: sharp features



Internal Bremsstrahlung

Bergström 1989

Prompt emission: sharp features



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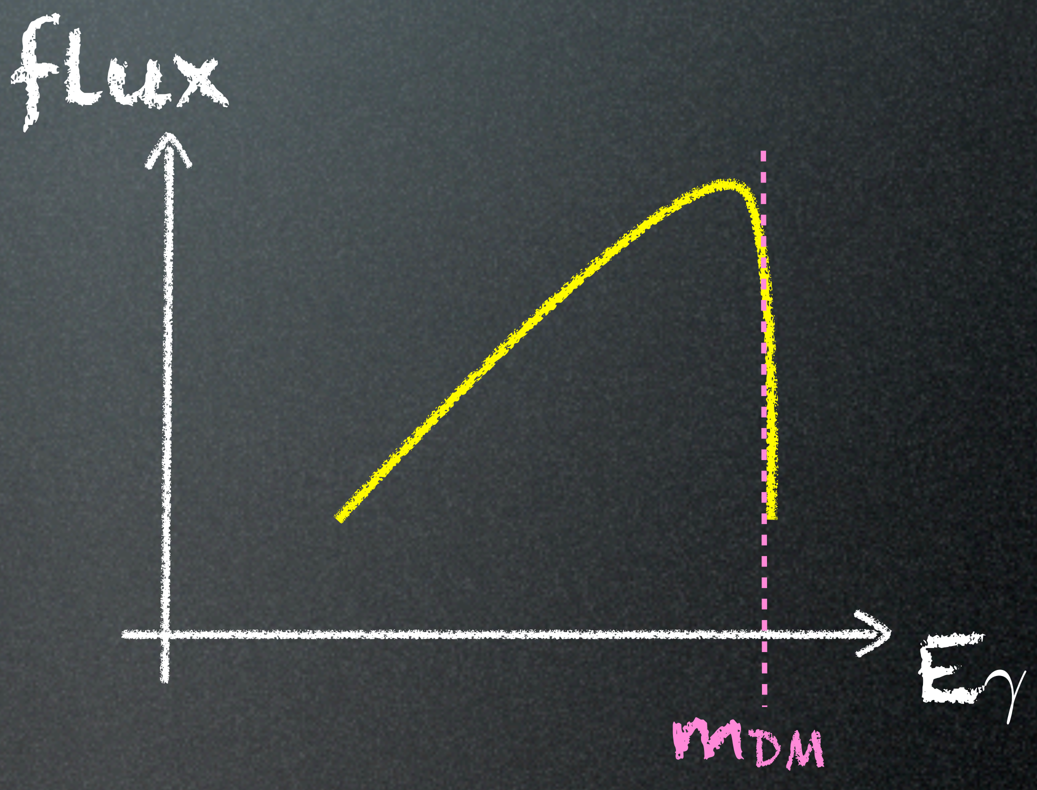
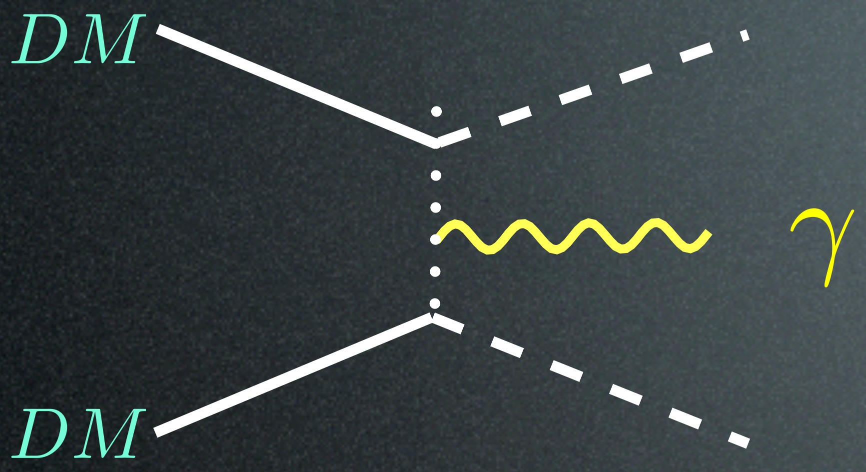
Bergström 1989



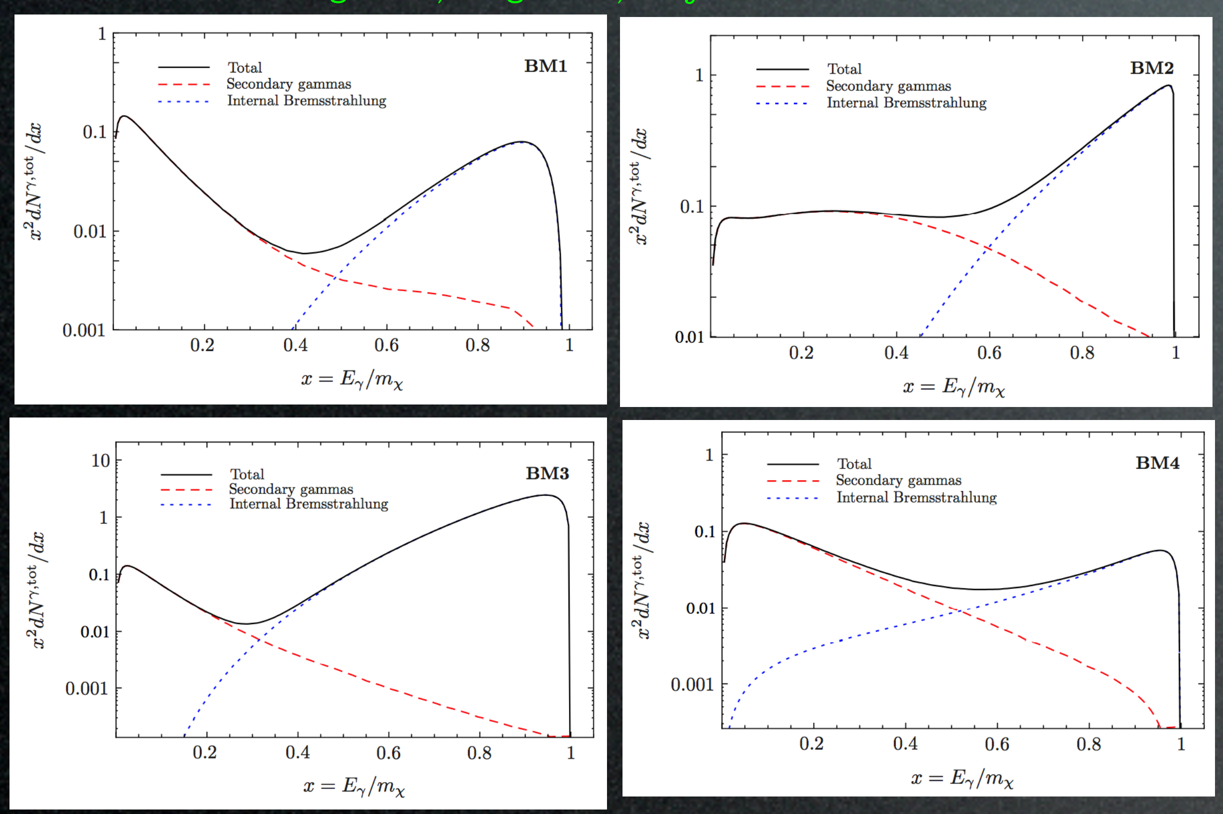
Prompt emission: sharp features

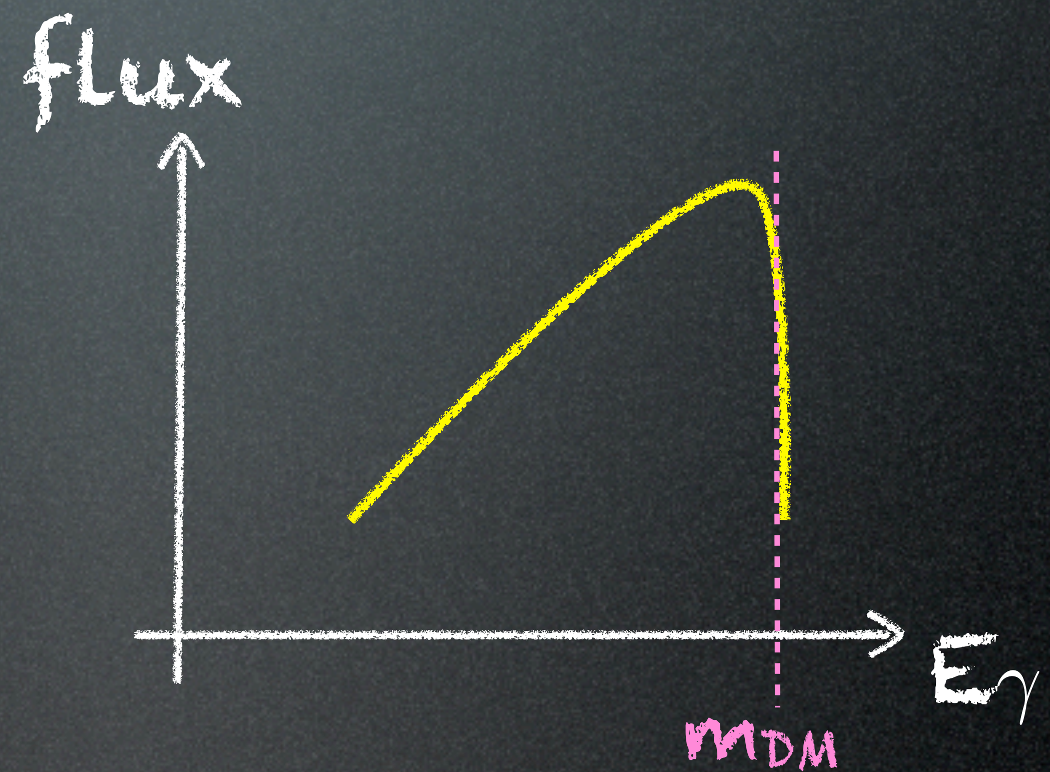


Internal Bremsstrahlung

Bergström 1989

Bringmann, Bergstrom, Edsjo 0710.3169



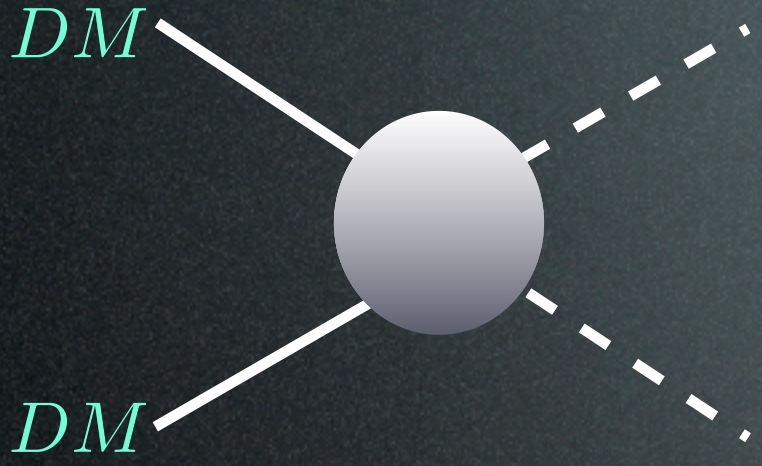


So what are the particle physics parameters?

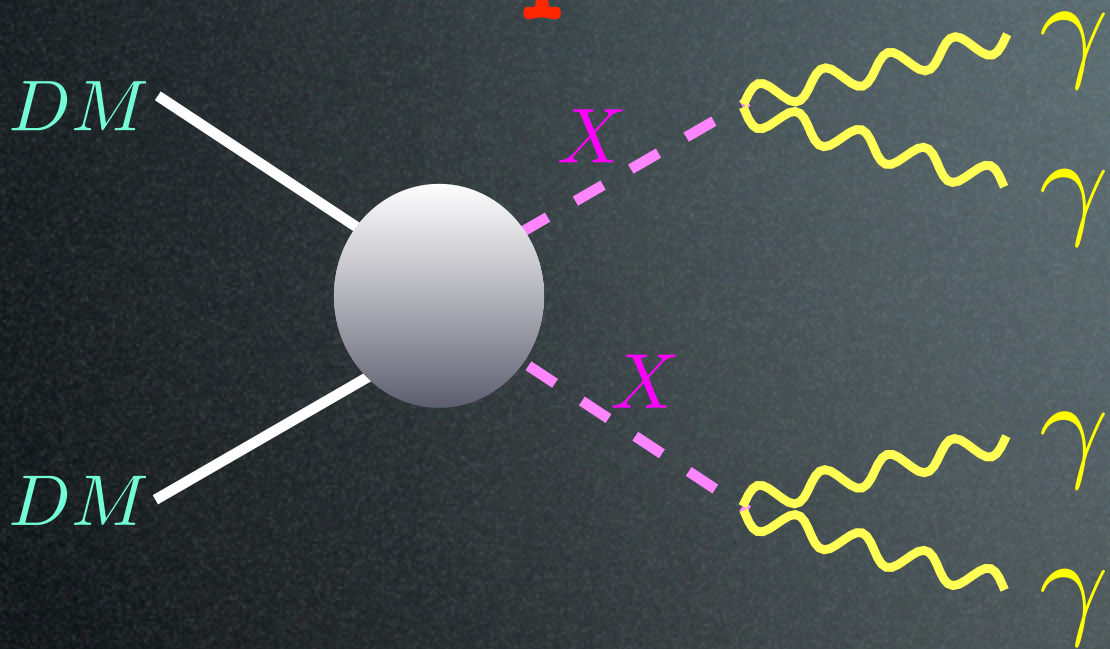
1. Dark Matter mass.

The rest depends on the model

Prompt emission: sharp features



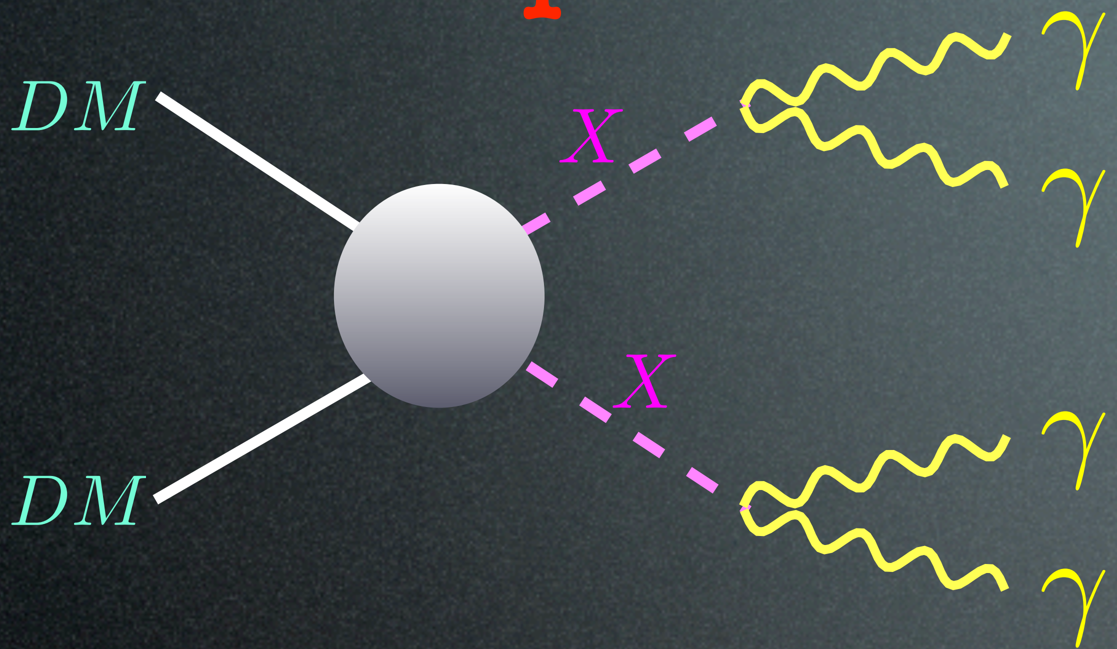
Prompt emission: sharp features



Ibarra, Lopez Gehler, Pato 1205.0007
Fan, Reece 1209.1097

Metastable intermediate states

Prompt emission: sharp features

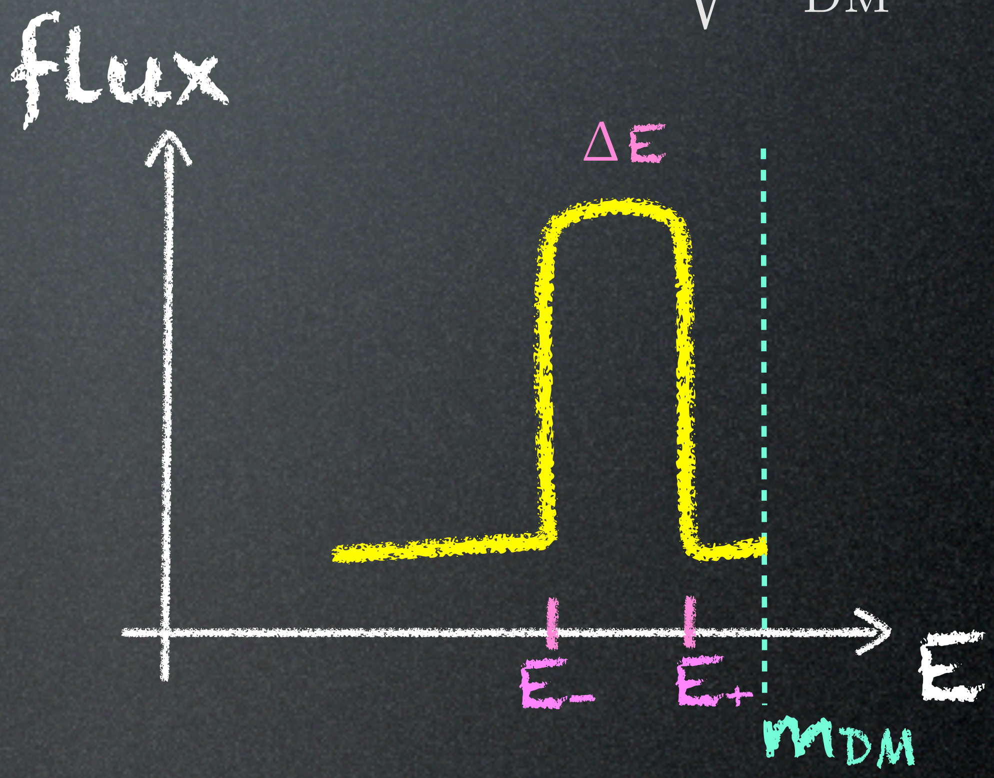


Ibarra, Lopez Gehler, Pato 1205.0007
Fan, Reece 1209.1097

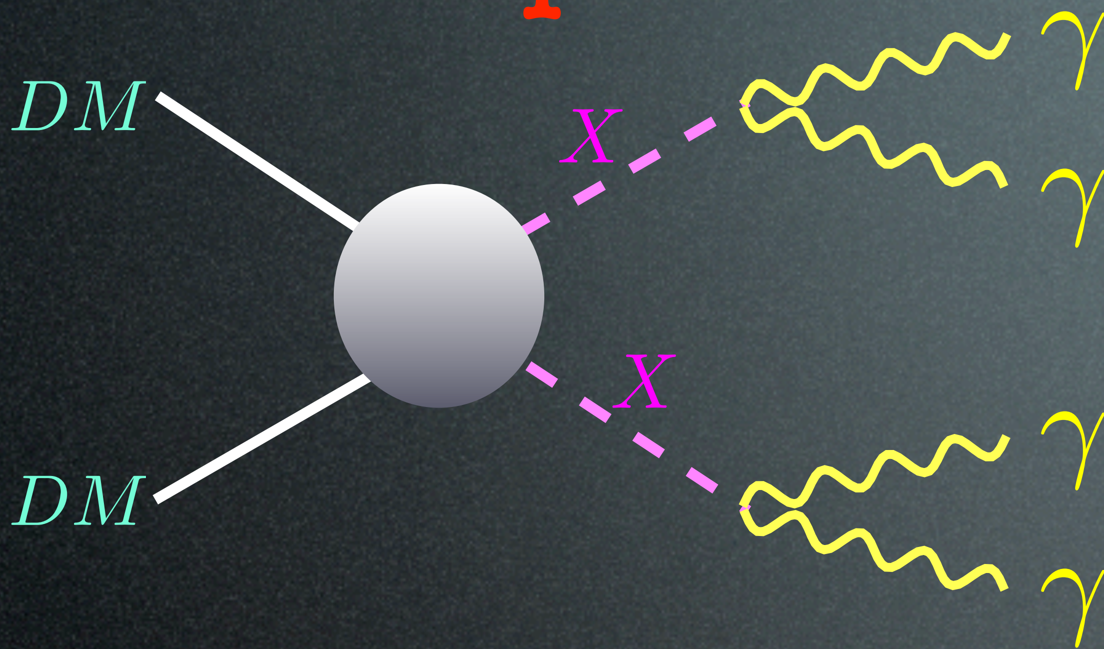
Metastable intermediate states

$$E_{\pm} = \frac{m_{\rm DM}}{2}\left(1 \pm \sqrt{1 - \frac{m_X^2}{m_{\rm DM}^2}}\right)$$

$$\Delta E = \sqrt{m_{\rm DM}^2 - m_X^2}$$



Prompt emission: sharp features



Ibarra, Lopez Gehler, Pato 1205.0007
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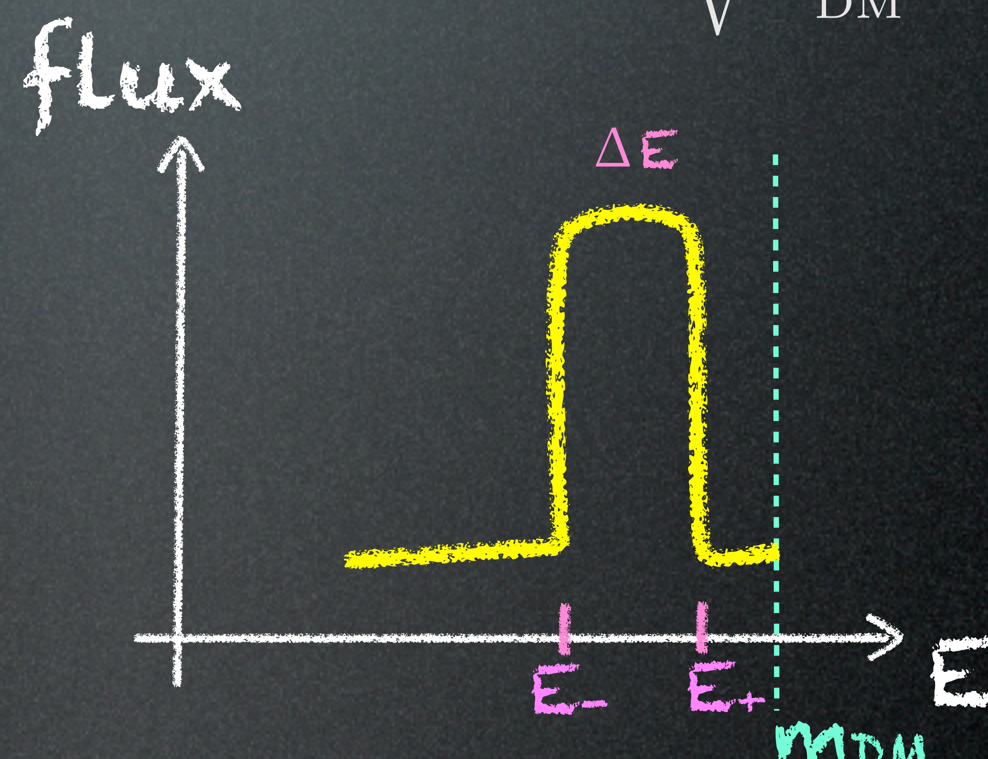
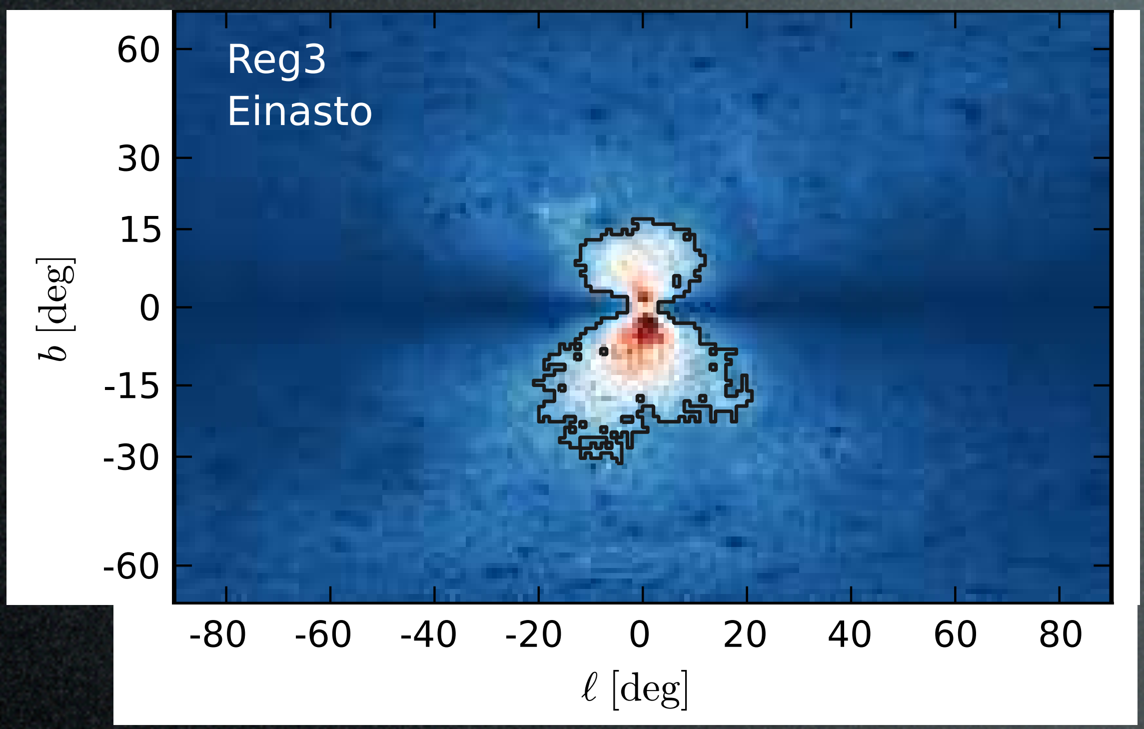


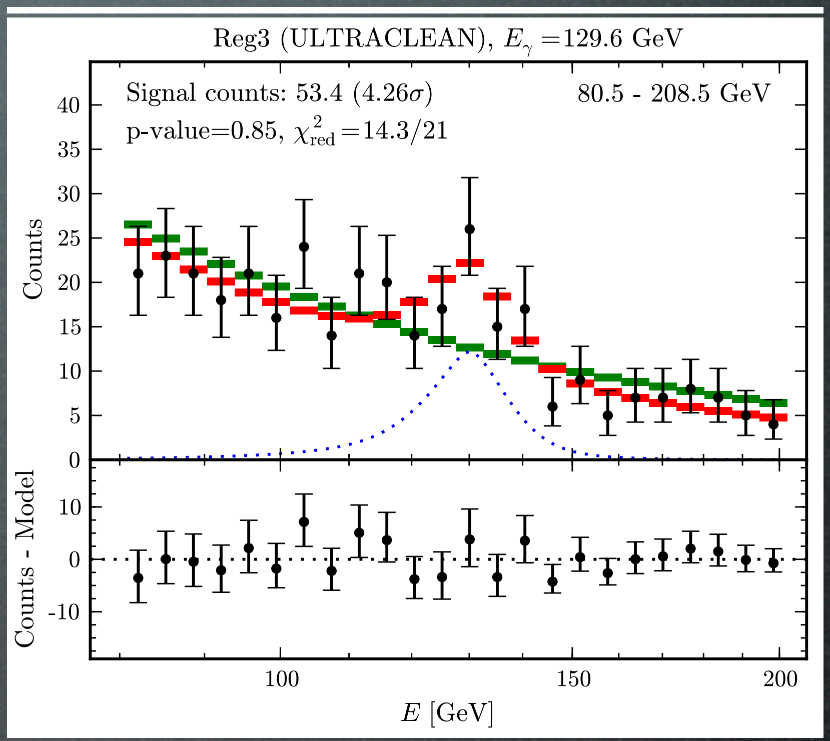
So what are the particle physics parameters?

1. Dark Matter mass
2. The mediator mass

Fermi 130 GeV line

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





Ch. Weniger, 1204.2797

4.6σ (3.3σ with LEE)

$\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma} \simeq 1.3\cdot 10^{-27}\text{cm}^3/\text{s}$ (large!)

Fermi 130 GeV line

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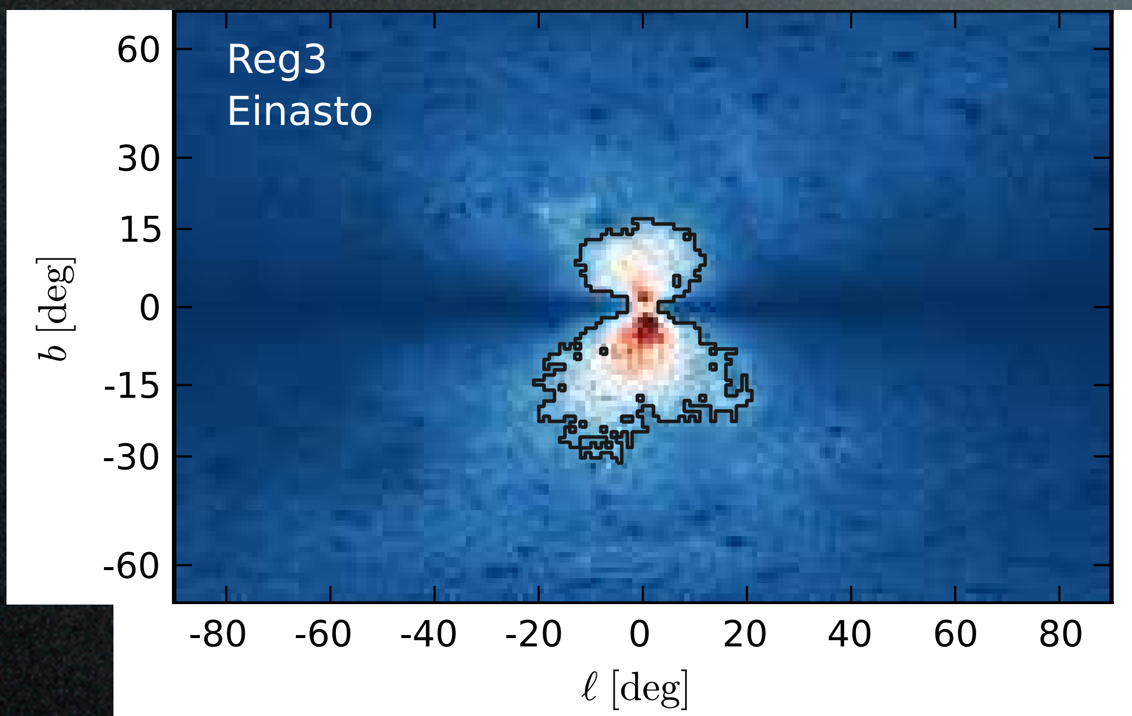

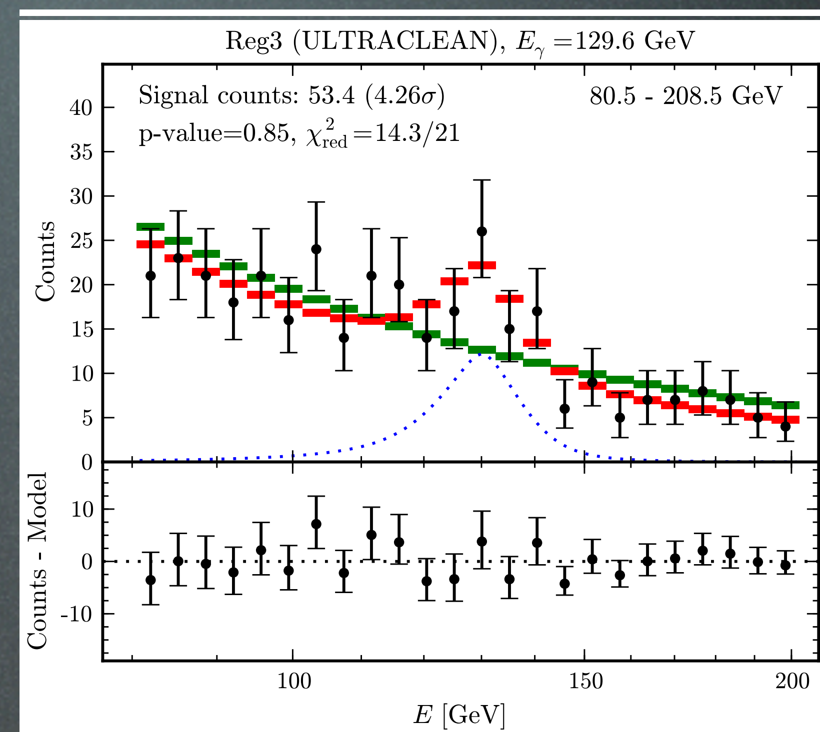

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4.6σ (3.3σ with LEE)

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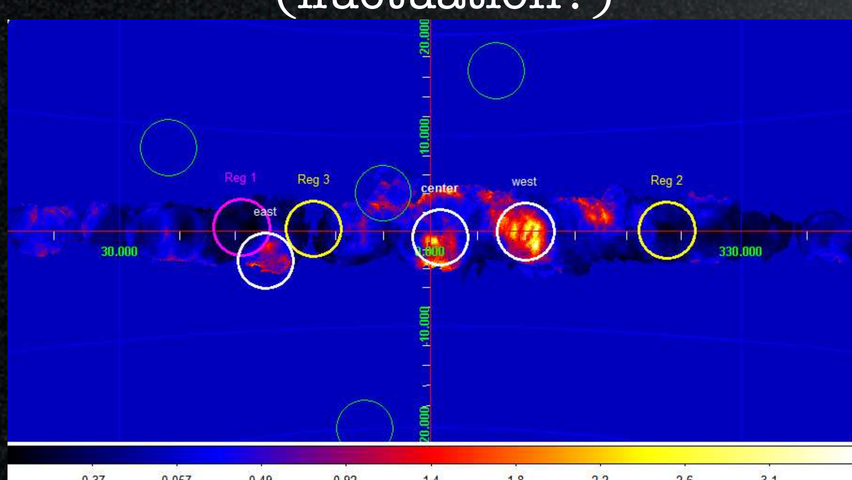
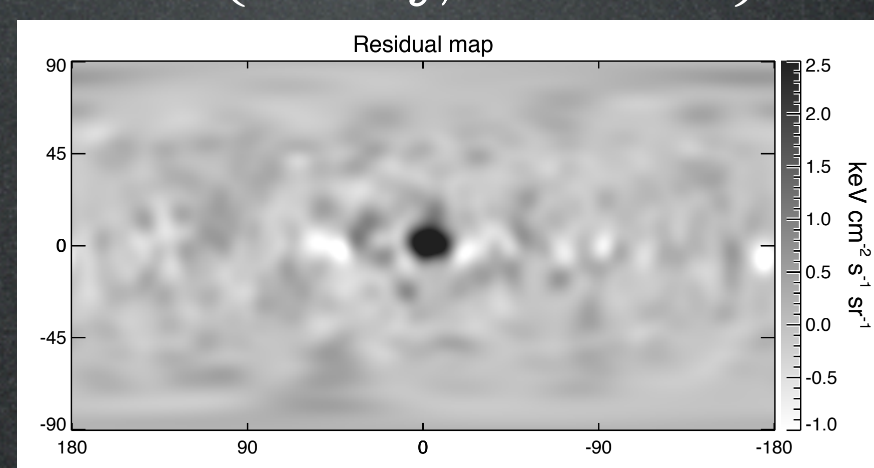
Similar excesses found elsewhere (fluctuation?)



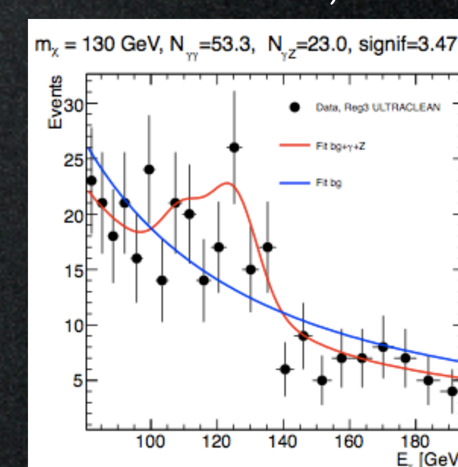
Boyarsky, Malyshev, Ruchayskyi, 1205.4700

The excess is only in the GC (actually, a bit off-set)



Su, Finkbeiner, 1206.1616

And there might be 2 lines: 111 GeV, 129 GeV



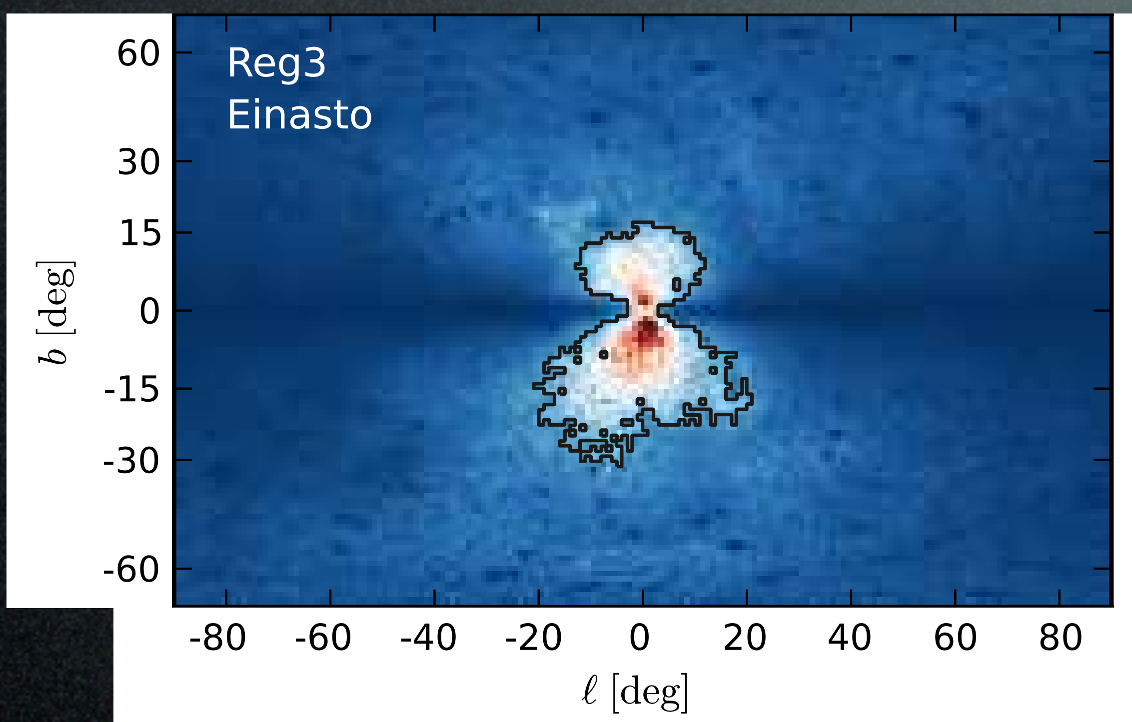
Rajaraman, Tait, Whiteson 1205.4723

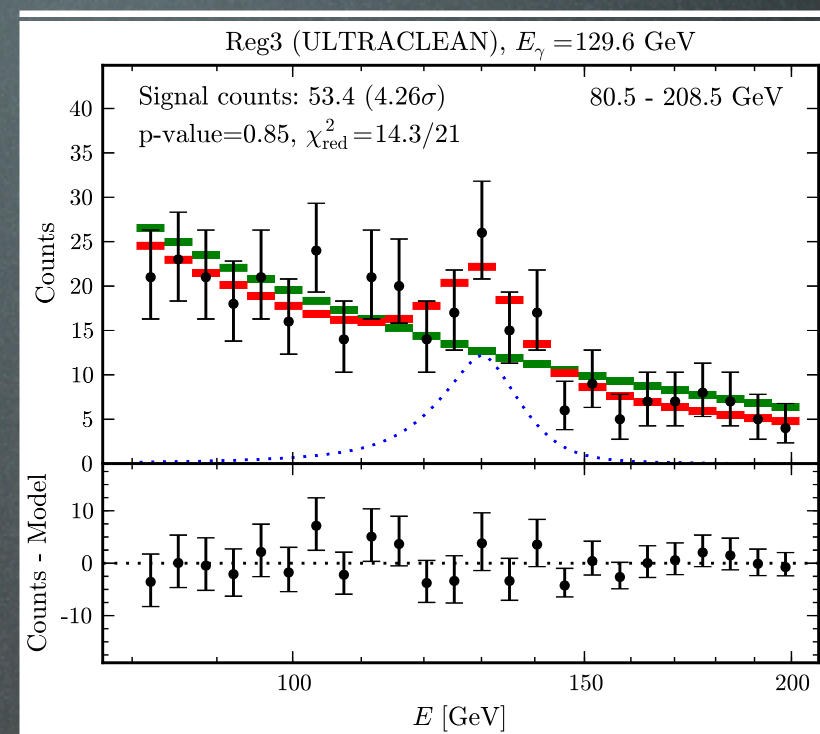
Su, Finkbeiner 1206.1616

Su Finkbeiner 1207.7060

Fermi 130 GeV line

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





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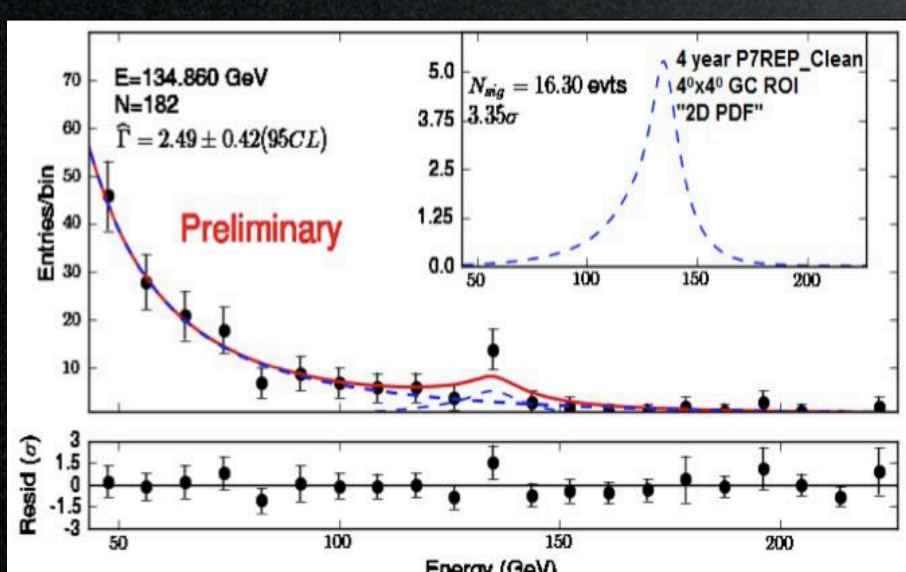
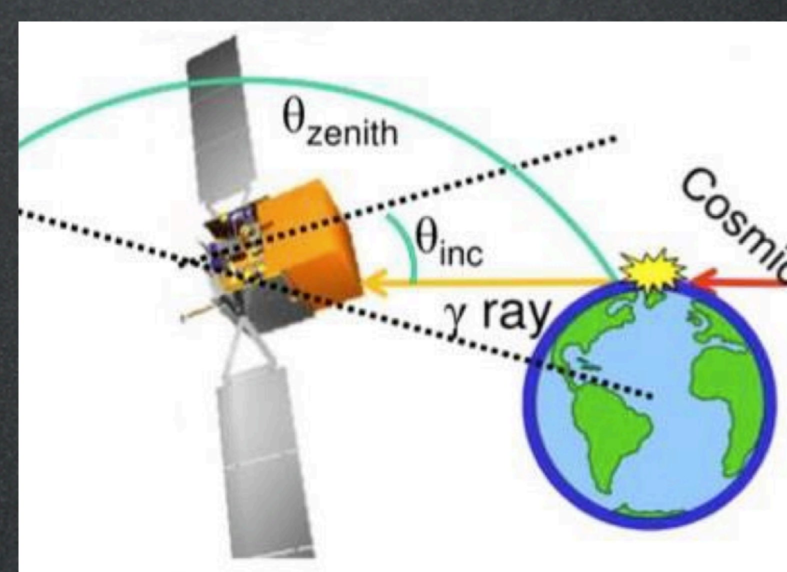
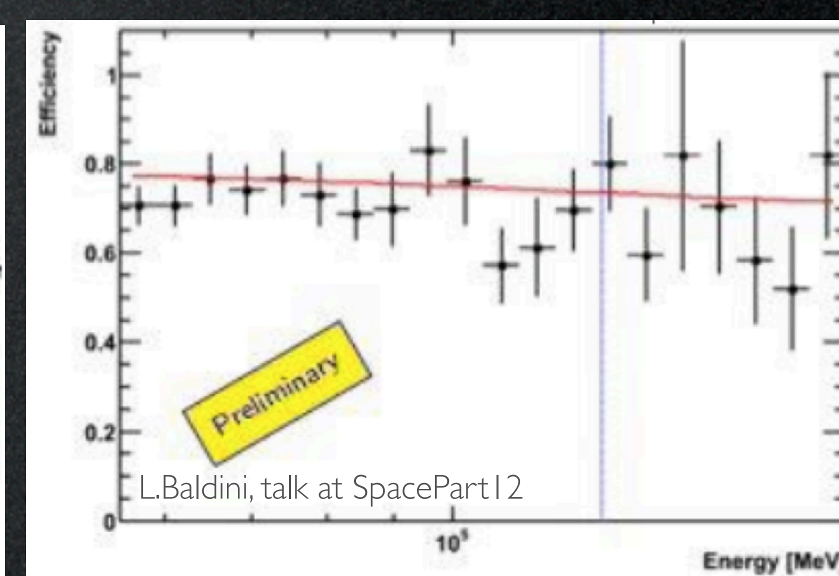
4.6σ (3.3σ with LEE)

$\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma} \simeq 1.3\cdot 10^{-27}{\rm cm}^3/{\rm s}$ (large!)

The Fermi coll's cold shower. An instrumental effect?







Theorist's reaction

2. the '130 GeV line' frenzy

It's 'easy' to make a line:
any 2-body final state
with at least one γ. But:

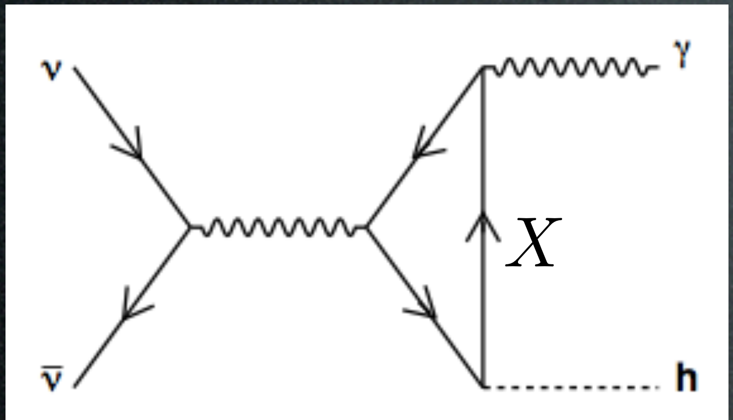
Challenges

DM is neutral: need '*something*' to couple to γ

Challenges

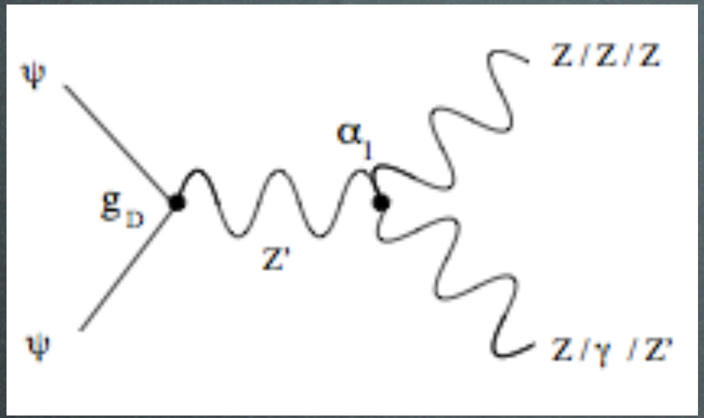
DM is <u>neutral</u>: need ‘something’ to couple to γ

a loop



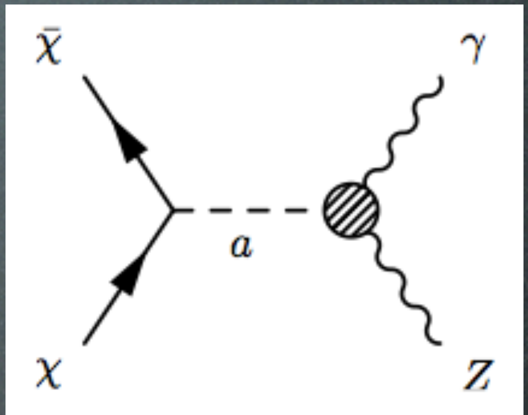
‘Higgs in space!’ 0912.0004
Kyae, Park 1205.4151
Cline 1205.2688

Chern-Simons



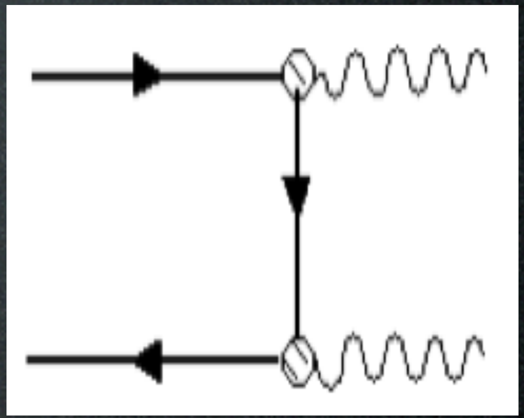
Dudas et al., 1205.1520

axions



Lee & Park[2] 1205.4675

magn dipole



Heo, Kim 1207.1341

...

$X \in$ SM
MSSM
dark sector...

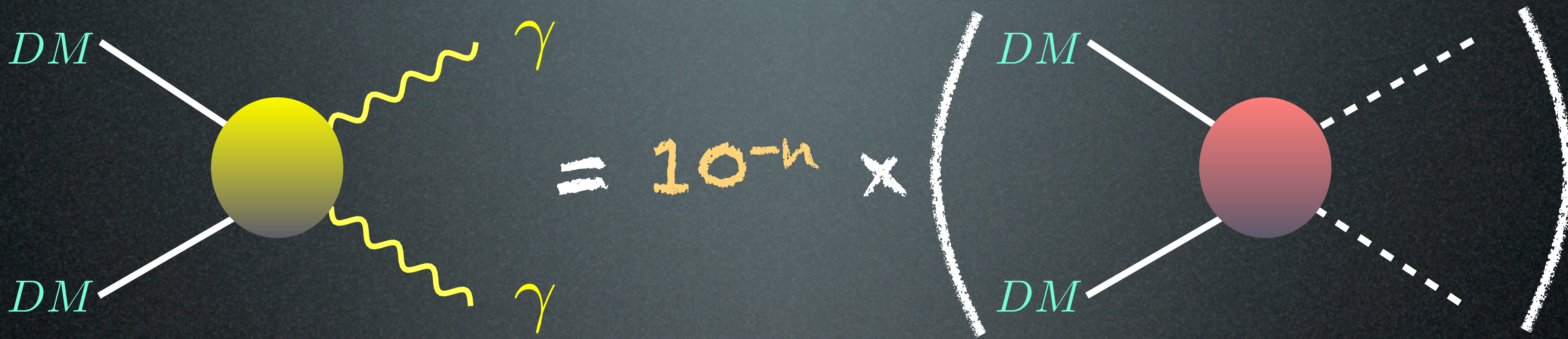
Challenges

DM is neutral: need ‘something’ to couple to γ

The ‘something’ implies usually a suppression,

Challenges

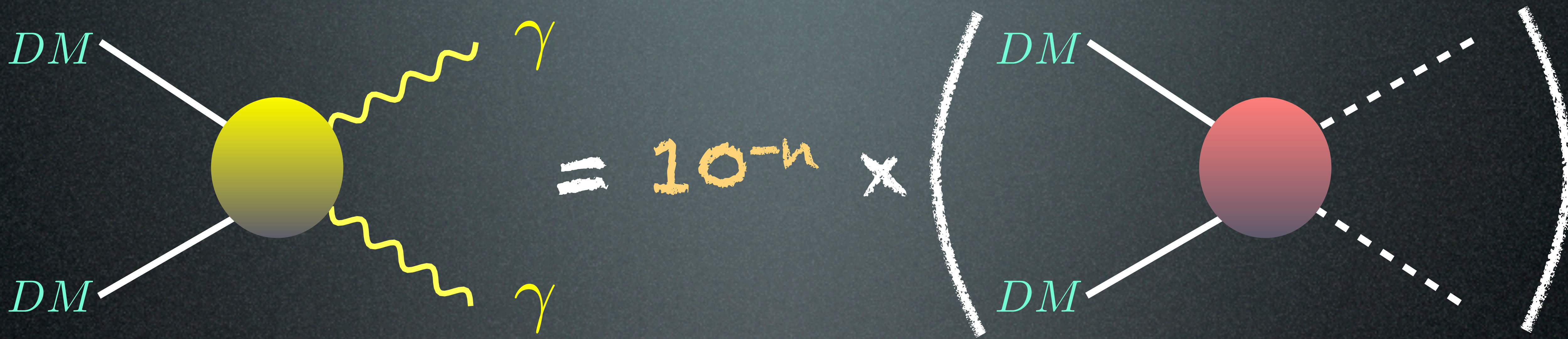
DM is neutral: need '**something**' to couple to γ



The '**something**' implies usually a suppression,
but one needs a large $\gamma\gamma$ cross section (o(10^{27} cm^3/s))

Challenges

DM is neutral: need '*something*' to couple to γ



The '*something*' implies usually a suppression,
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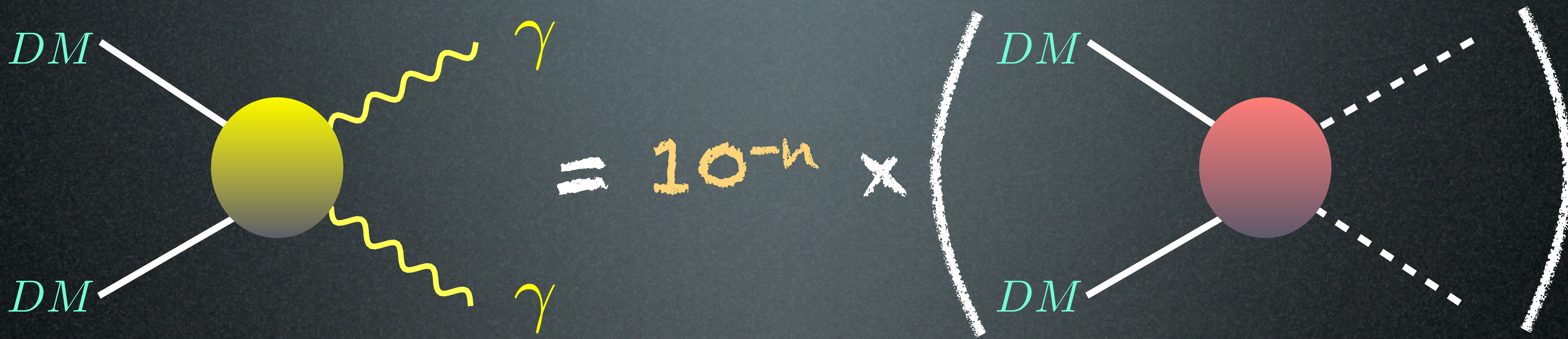
so the corresponding unsuppressed processes
are **too** large:

- may overshoot other observations
- too large annihilation in the EU

Buchmuller, Garny 1206.7056
Cohen et al. 1207.0800
Cholis, Tavakoli, Ullio 1207.1468
Huang et al. 1208.0267

Challenges

DM is neutral: need '*something*' to couple to γ



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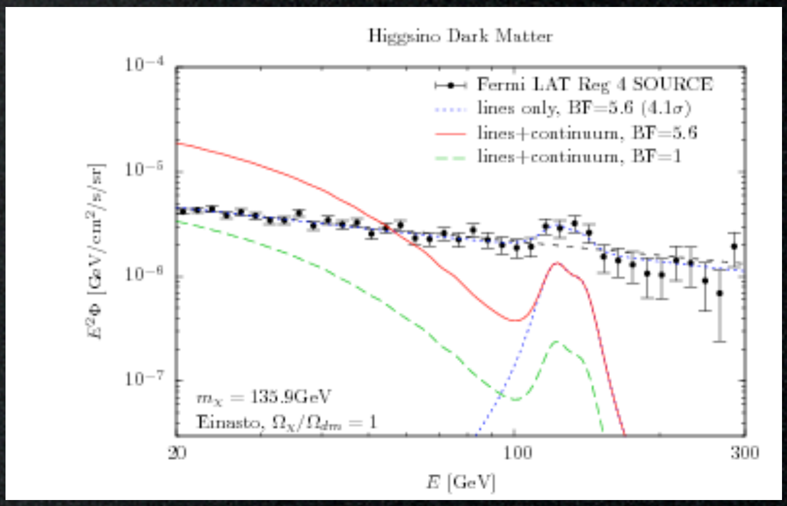

Challenges

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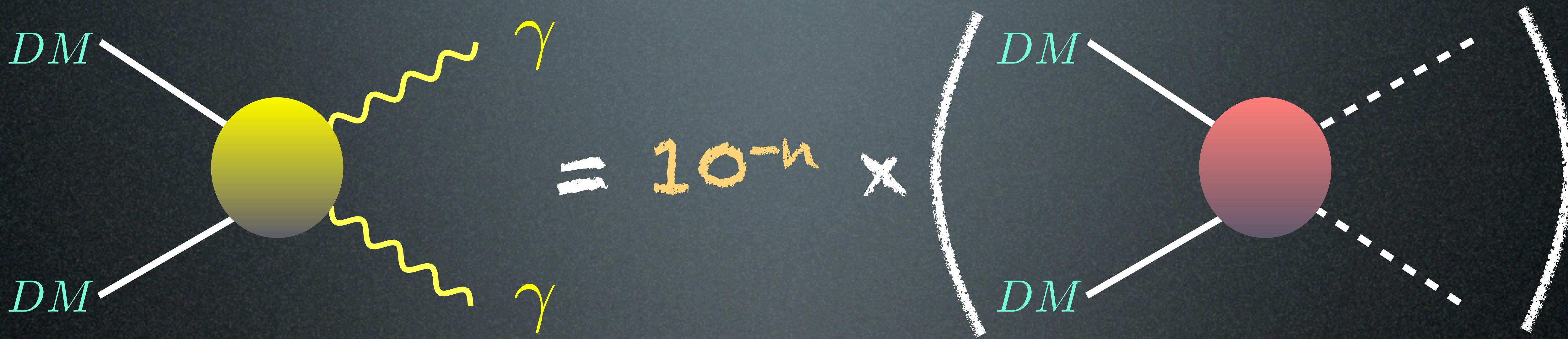

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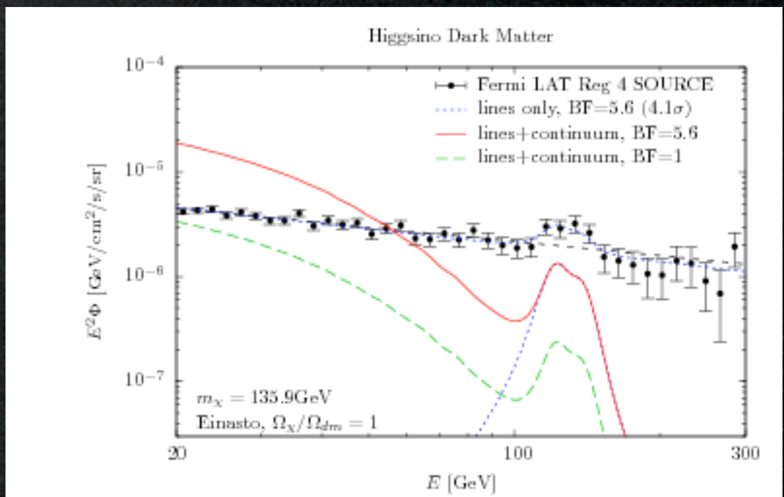


But solutions exist

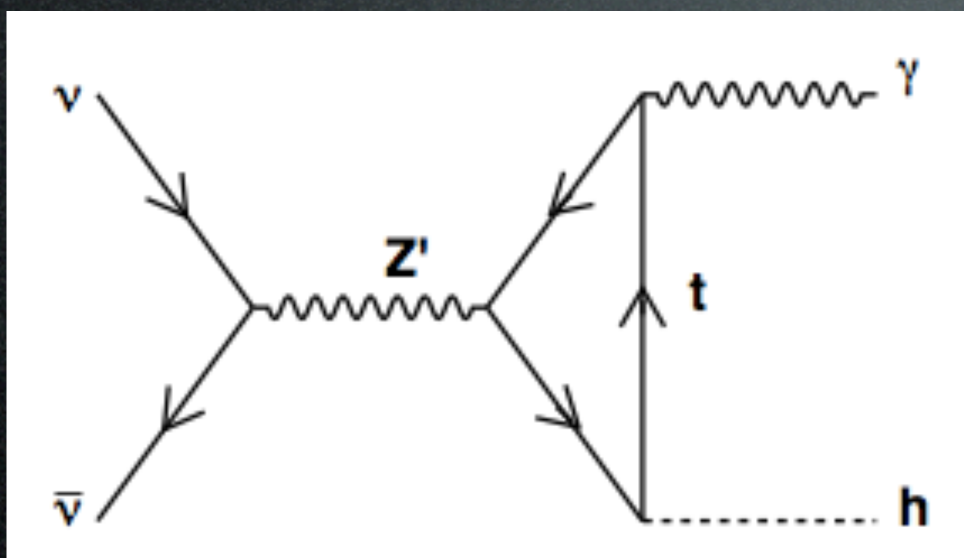
Model building

not exhaustive!

Ex. 1: ‘resonance, loop and forbidden channel’

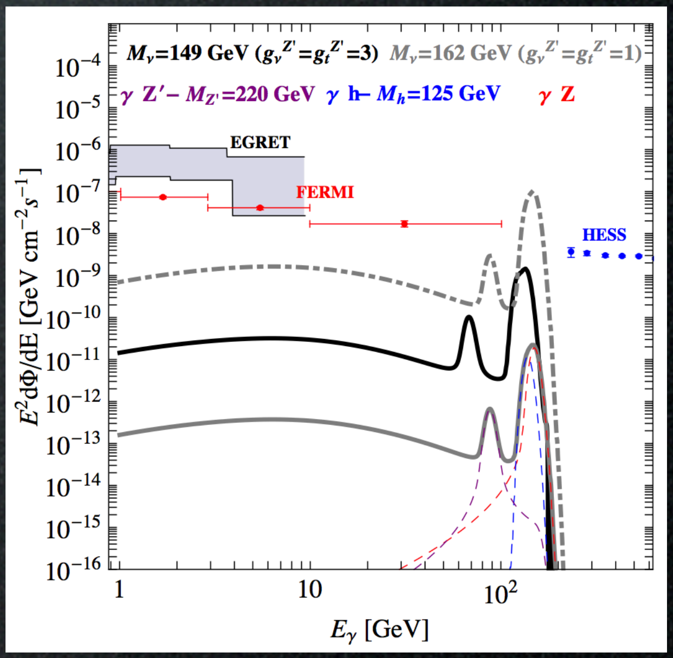
(a) DM charged under U’(1)
(b) Z’ is t_R-philic
(c) $m_{DM} \lesssim m_{top}$

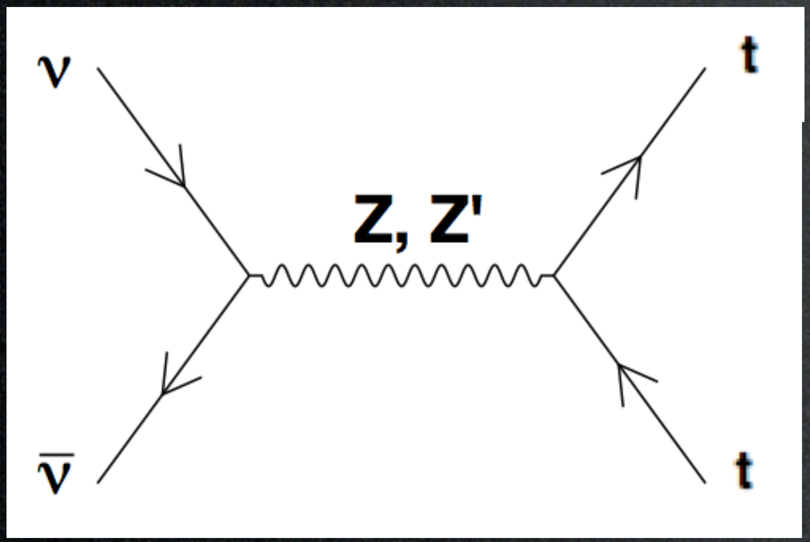
Jackson, Servant, Shaughnessy, Tait, Taoso, ‘Higgs in space’, 0912.0004



⇨ line(s)

with large rate
if on resonance (a)
(masses & couplings)





today:
kinematically forbidden (c)
little in other channels (b) (only via Z-Z’ mixing)
⇨ small continuum

Early Universe:
⇨ relic abundance

However:
- anomalies, need to UV complete (b)

Model building

not exhaustive!

Ex. 2: 'resonance, tri-boson vertices, Chern-Simons'

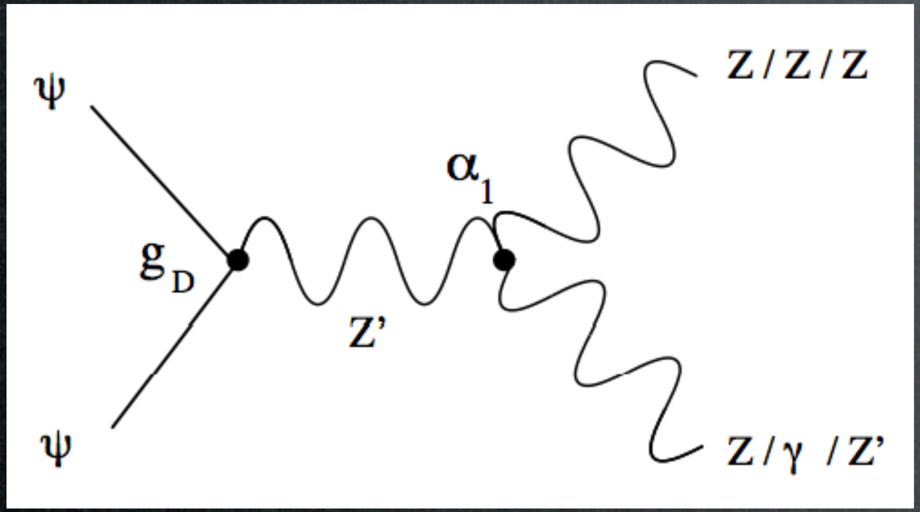
(a) DM charged under U'(1)

(b) anomaly cancellation → tri-boson CS terms

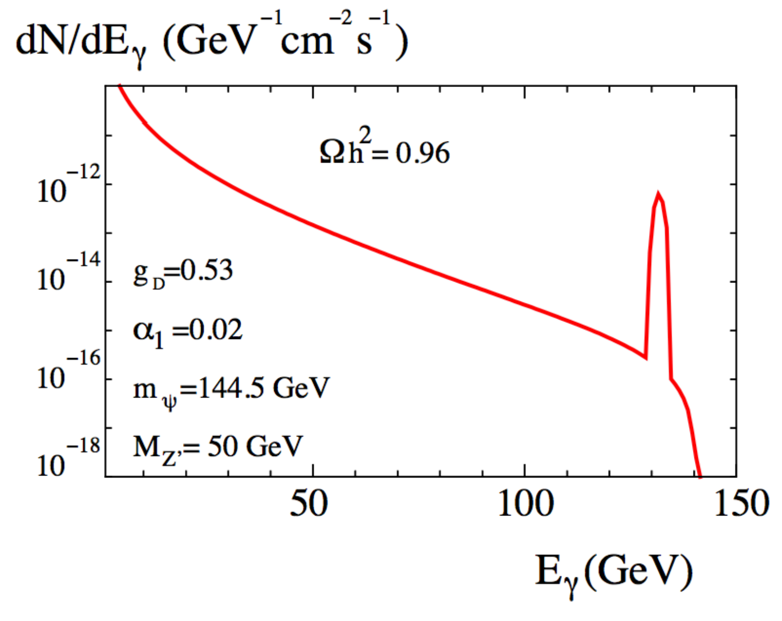
$$\mathcal{L}_{\rm CS} = \alpha\, \varepsilon^{\mu\nu\rho\sigma}\, Z'_\mu Z_\nu F^Y_{\rho\sigma}$$

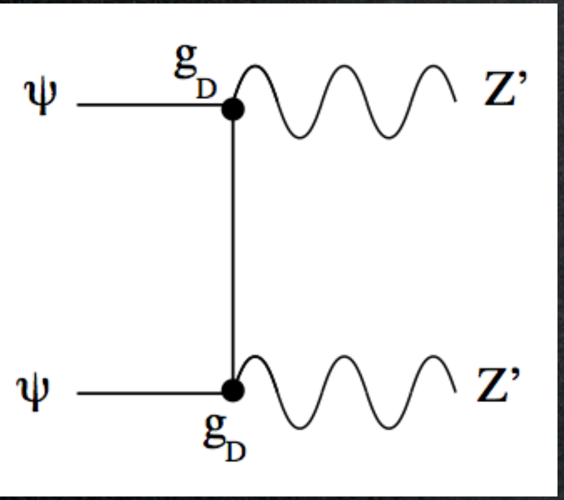
Dudas, Mambrini, Pokorski, Romagnoni 2009-2012, 1205.1520

(c) $m_{Z'} < m_{DM}$



→ line (b)

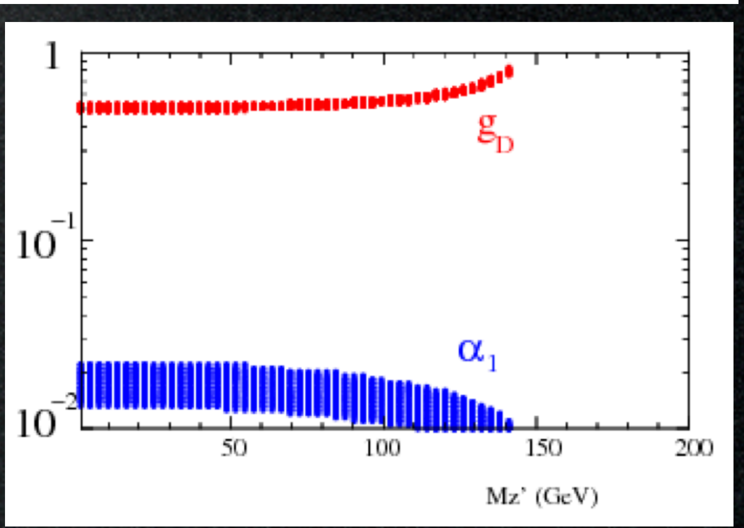




→ relic abundance

a different diagram wrt to line, open thanks to (c), works for large gauge coupling and small (loop?) CS coeff

→ Continuum? Under control



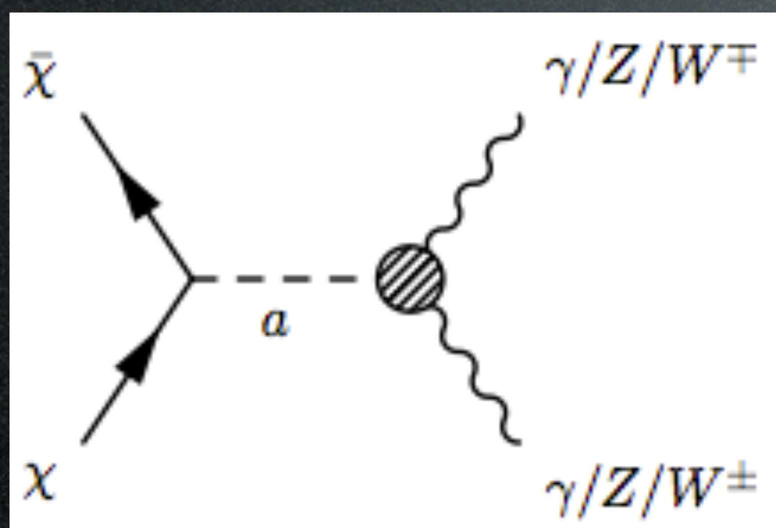
Model building

not exhaustive!

Ex. 3: ‘pseudo-scalar mediation, p- and s-waves’

(a) DM charged under $U(1)_{PQ}$
(b) anomalies → tri-boson terms

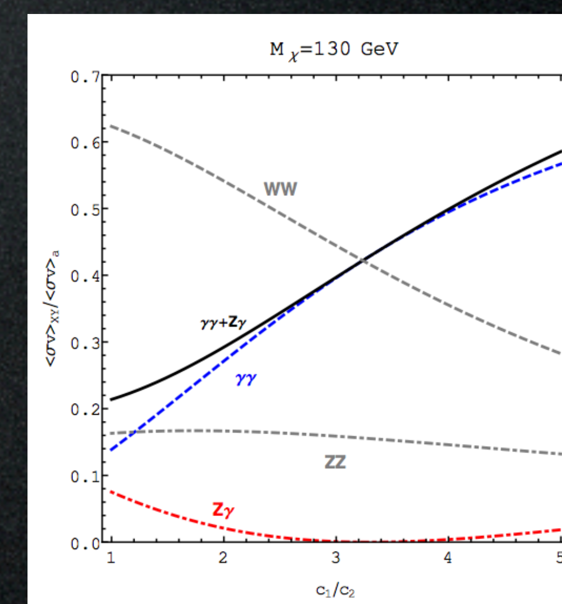
Lee, Park[2], 1205.4675

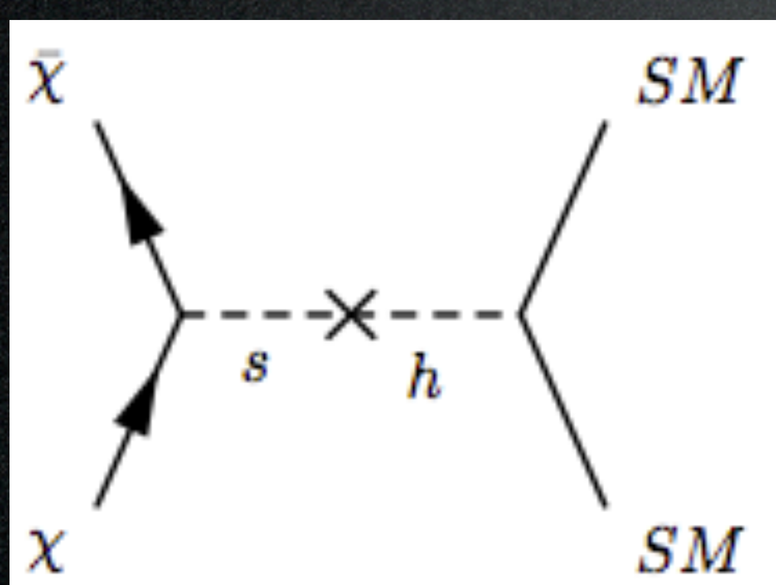


line (b)

with large rate
if on resonance (a)

Continuum? Assume couplings
to W and Z are suppressed





Exchange of s/h is p-wave,
i.e. v dependent.

Suppressed today, large in EU.

relic abundance

Model building

not exhaustive!

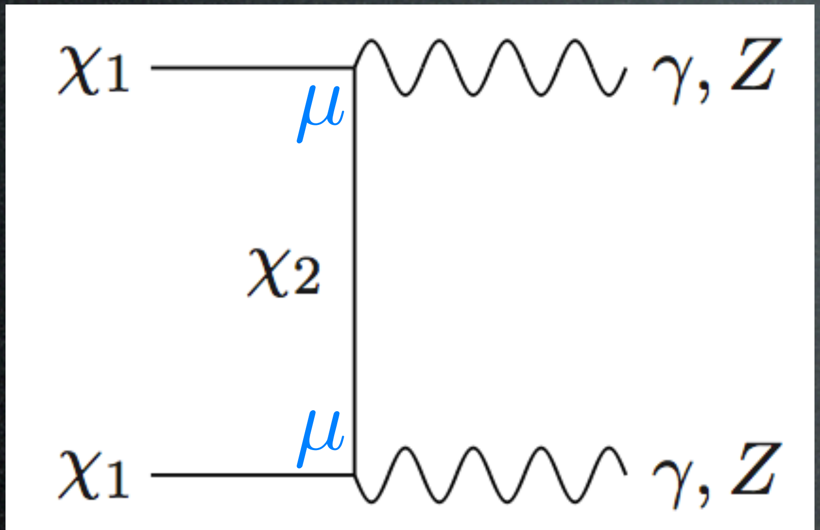
Ex. 4: 'magnetic moments and coannihilations'

Tulin, Yu, Zurek 1208.0009
Cline, Moore, Frey 1208.2685

(a) DM has a magnetic moment

$$\mu\,\bar{\chi}_1\sigma_{\mu\nu}\chi_2\,F^{\mu\nu}$$

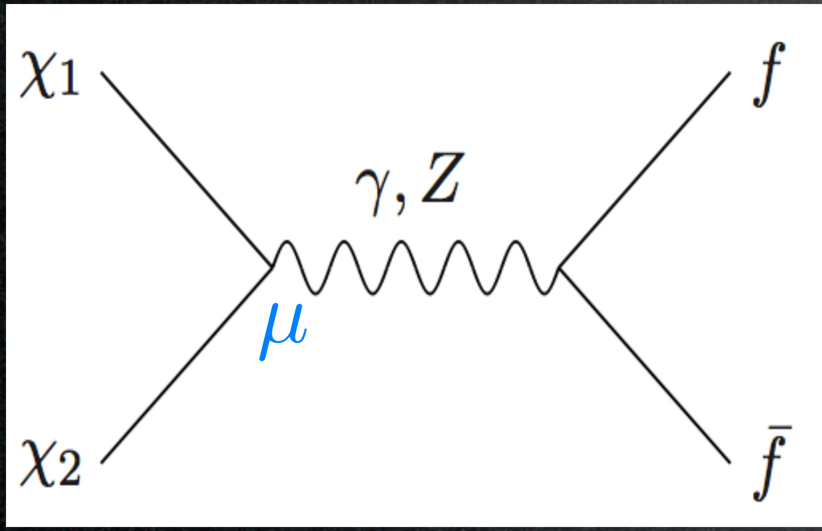
(b) DM sits in a multiplet with ~10 GeV splitting



→ line (a)

with large rate
if μ is large

→ Continuum? Under control (it's same order as γγ)



→ relic abundance

is set by coannihilations,
they would be too effective for large μ,
but the splitting (b) suppresses.

→ Continuum? Ultra suppressed by the splitting (b)

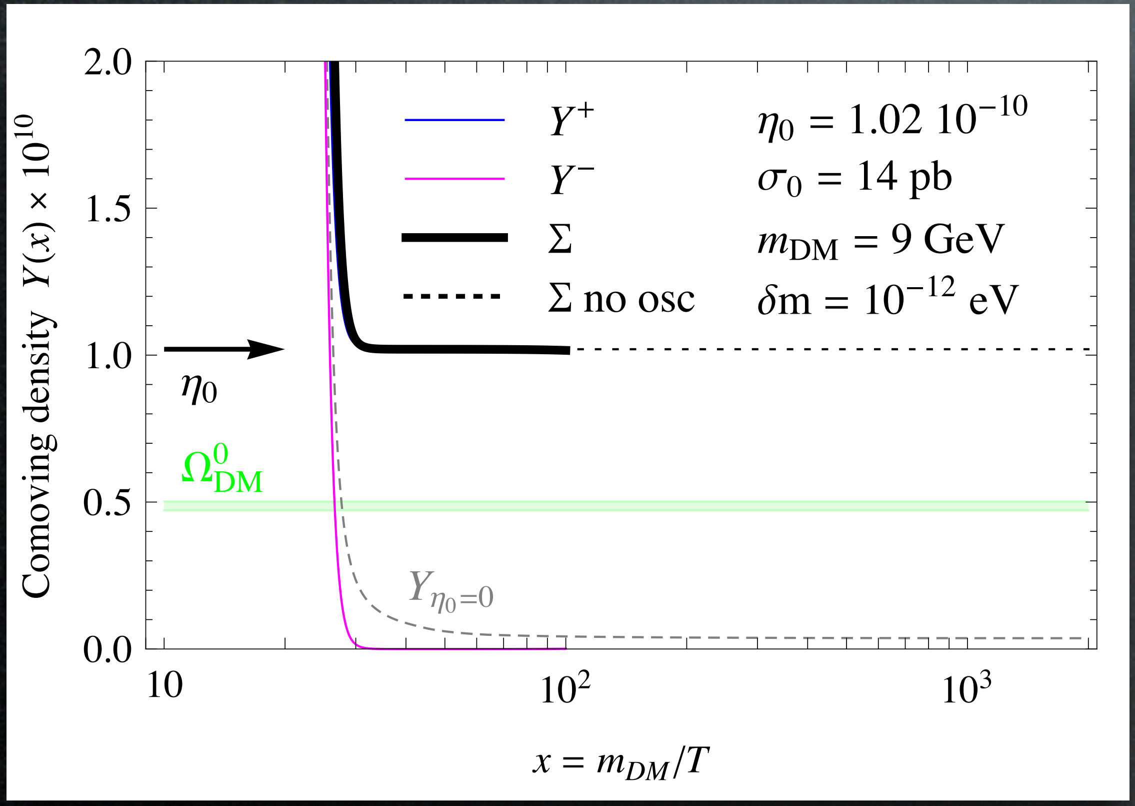
Model building

not exhaustive!

Nussinov 1985
Kaplan, Luty, Zurek 2009
Cirelli, Panci, Servant, Zaharijas 2011
Tulin, Yu, Zurek 1208.0009

Ex. 5: ‘asymmetric DM’

(a) DM-$\overline{\text{DM}}$ initial asymmetry
(b) DM-$\overline{\text{DM}}$ mixing → late time oscillations, re-balance



relic abundance (a)

is produced via the asymmetry
is decoupled from the annihilation

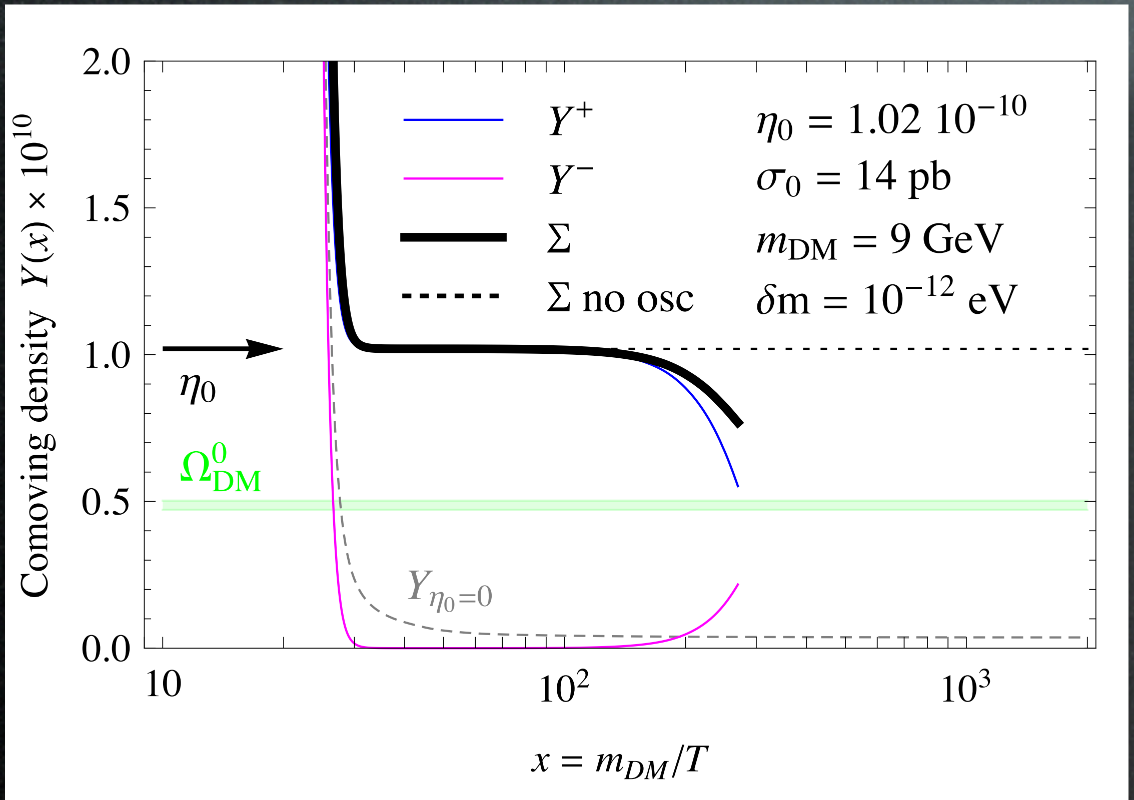
Model building

not exhaustive!

Nussinov 1985
Kaplan, Luty, Zurek 2009
Cirelli, Panci, Servant, Zaharijas 2011
Tulin, Yu, Zurek 1208.0009

Ex. 5: 'asymmetric DM'

(a) DM-$\overline{\text{DM}}$ initial asymmetry
(b) DM-$\overline{\text{DM}}$ mixing → late time oscillations, re-balance



➡ relic abundance (a)

is produced via the asymmetry
is decoupled from the annihilation

Annihilations resume (b)

Model building

not exhaustive!

Nussinov 1985
Kaplan, Luty, Zurek 2009
Cirelli, Panci, Servant, Zaharijas 2011
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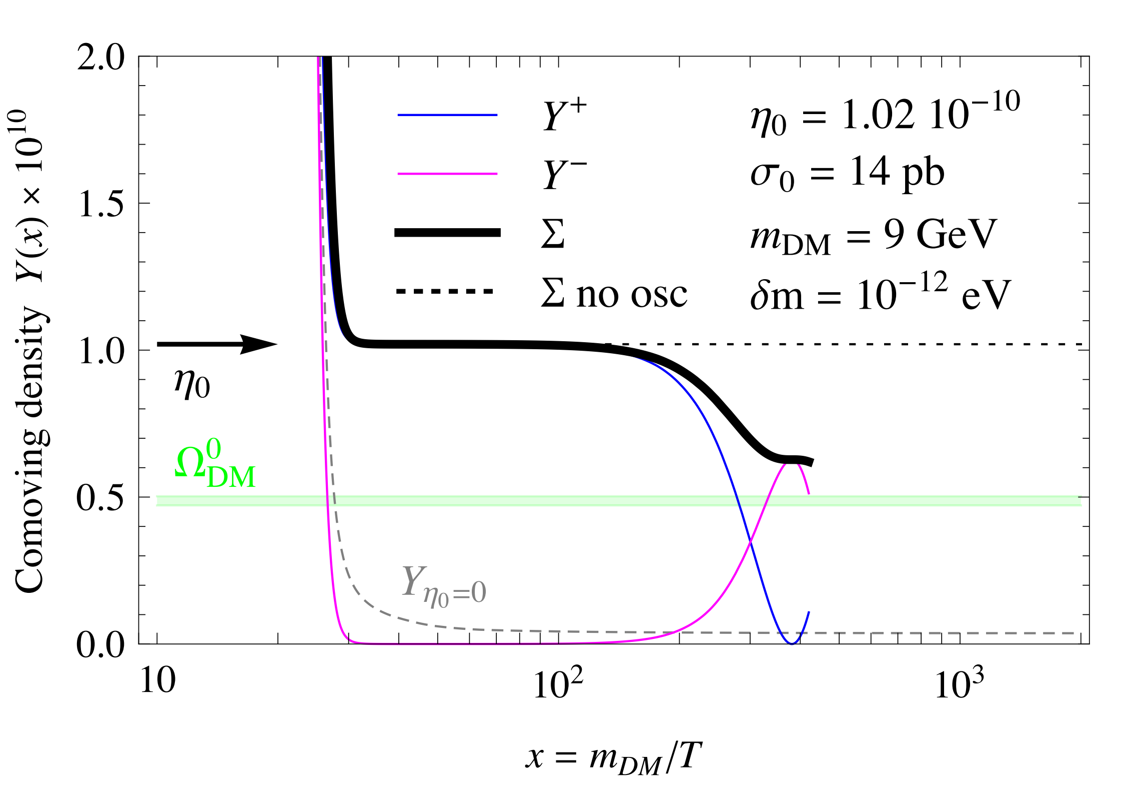

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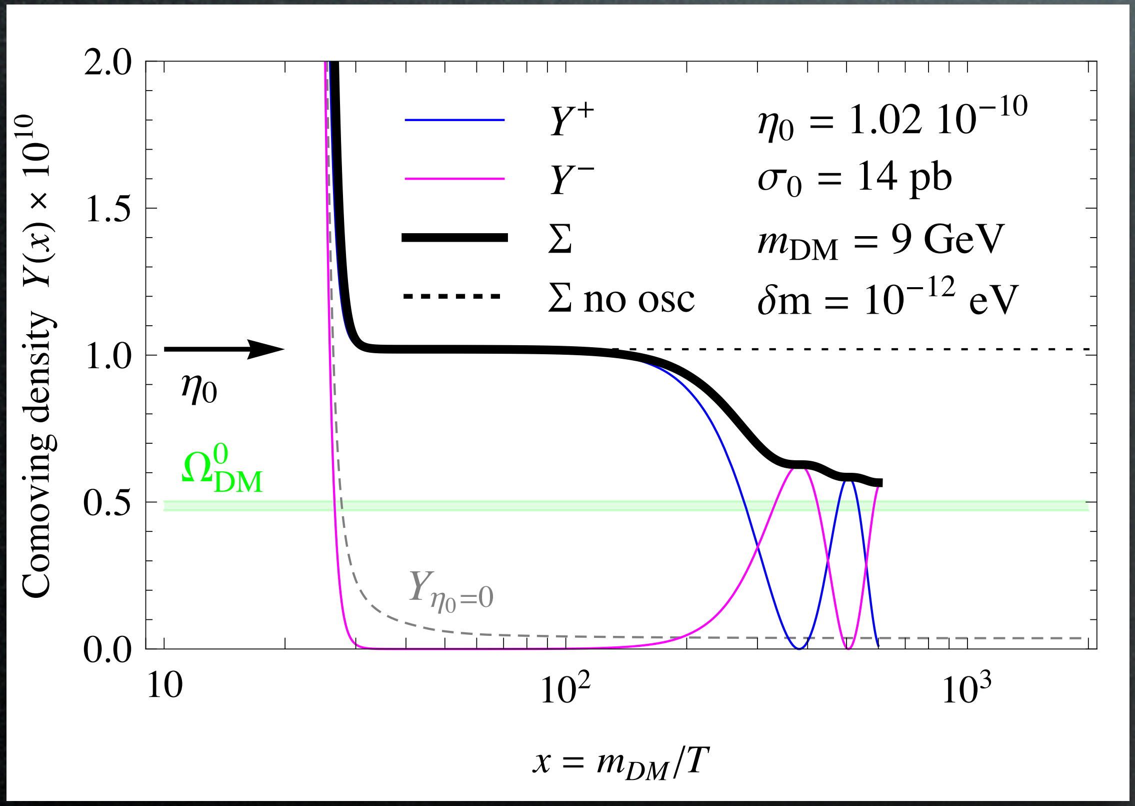

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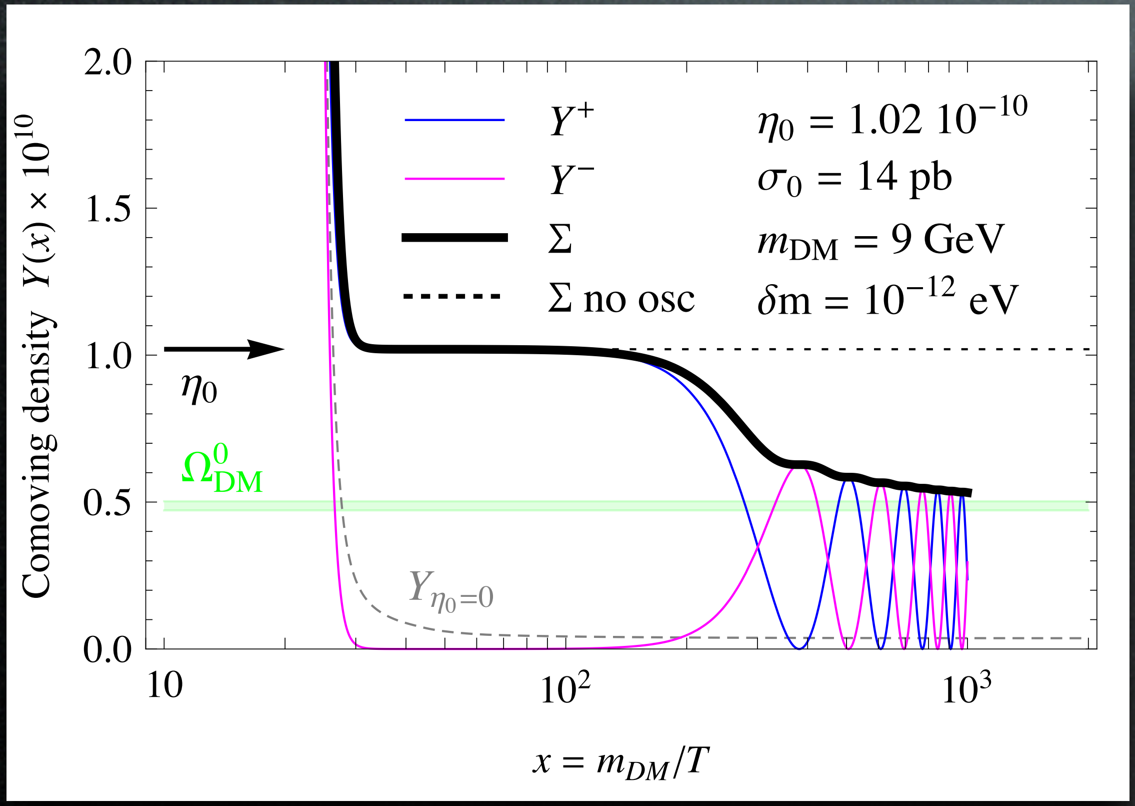

relic abundance (a)

is produced via the asymmetry
is decoupled from the annihilation

Annihilations resume (b)

(and the cross section needs to be large)

Model building

not exhaustive!

Nussinov 1985
Kaplan, Luty, Zurek 2009
Cirelli, Panci, Servant, Zaharijas 2011
Tulin, Yu, Zurek 1208.0009

Ex. 5: 'asymmetric DM'

(a) DM-$\overline{\text{DM}}$ initial asymmetry
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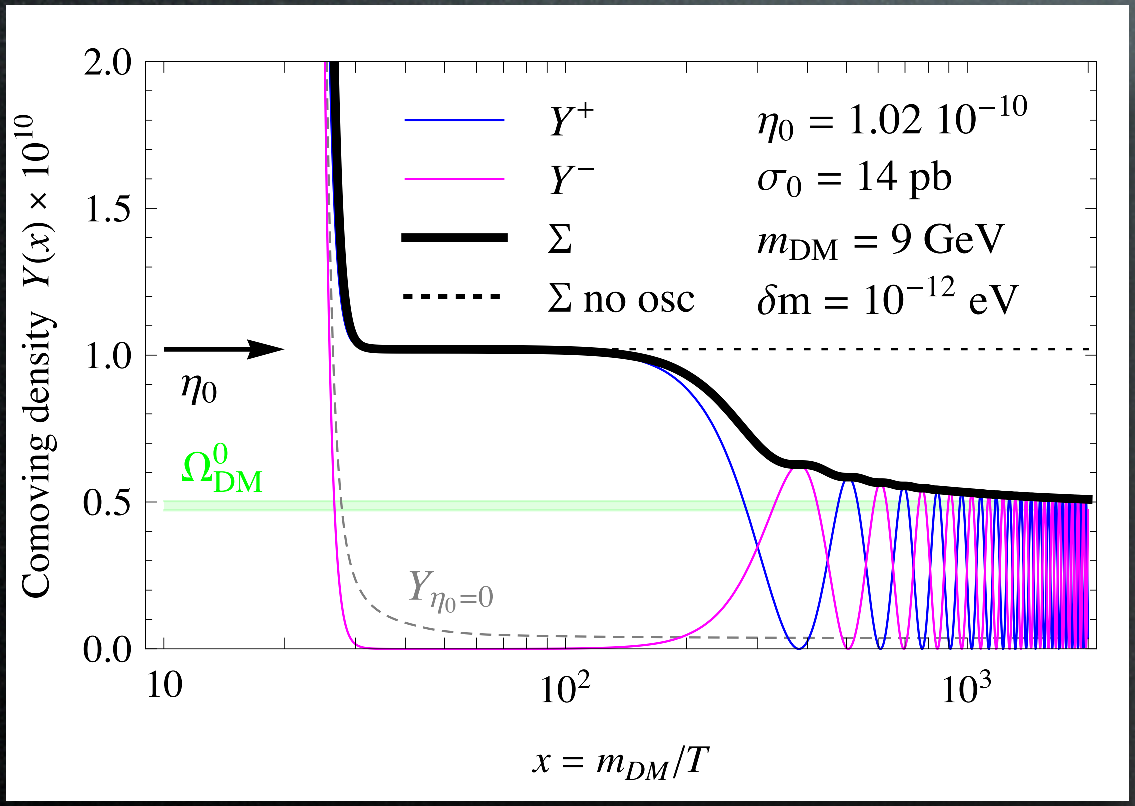

relic abundance (a)

is produced via the asymmetry
is decoupled from the annihilation

Annihilations resume (b) → line

(and the cross section needs to be large)

Model building

not exhaustive!

Nussinov 1985
Kaplan, Luty, Zurek 2009
Cirelli, Panci, Servant, Zaharijas 2011
Tulin, Yu, Zurek 1208.0009

Ex. 5: 'asymmetric DM'

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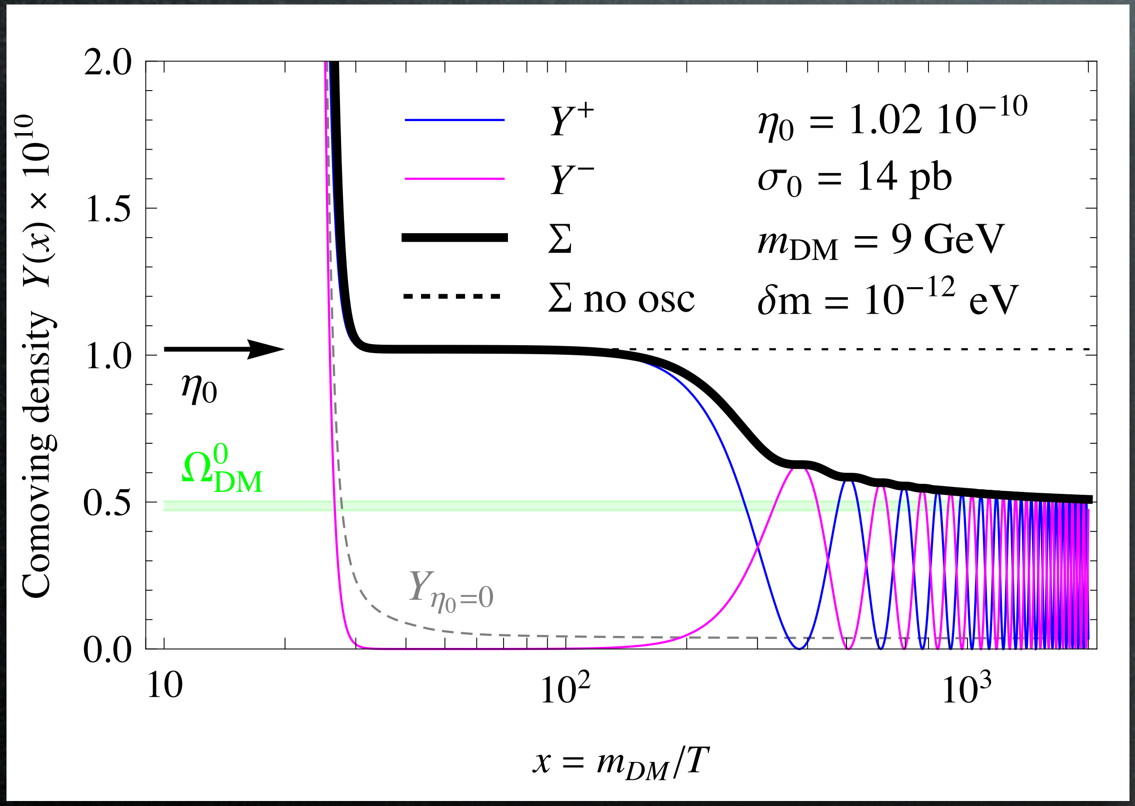


→ relic abundance (a)

is produced via the asymmetry
is decoupled from the annihilation

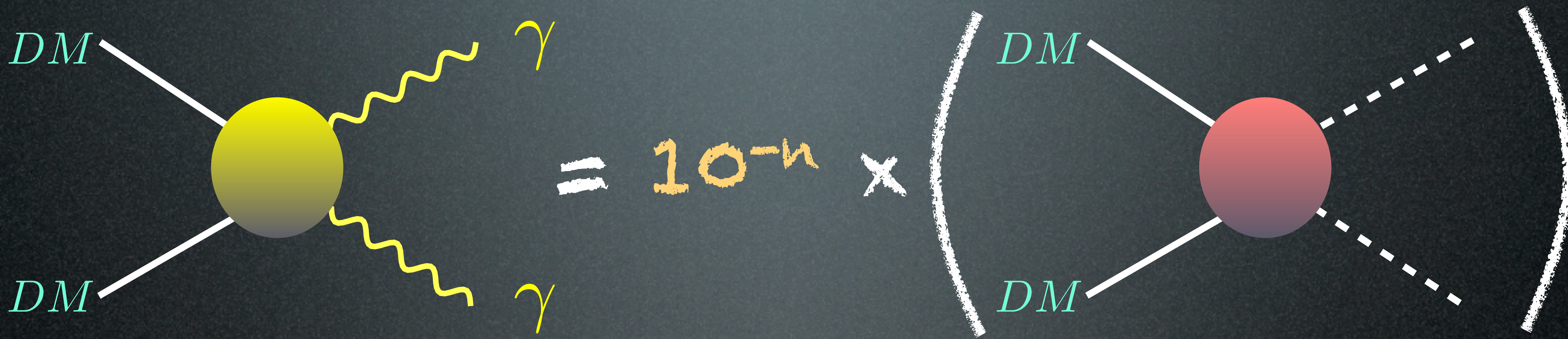
Annihilations resume (b) → line

(and the cross section needs to be large)

→ Continuum? Needs to be suppressed in some way today.

Challenges

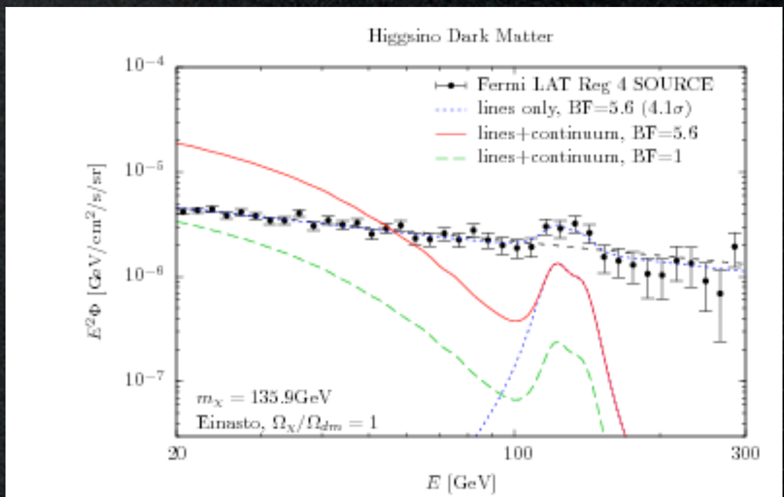
DM is neutral: need 'something' to couple to γ



The 'something' implies usually a suppression,
but one needs a large $\gamma\gamma$ cross section (o(10^{27} cm^3/s))

so the corresponding unsuppressed processes
are **too** large:

- may overshoot other observations
- too large annihilation in the EU



But solutions exist

Model building

- may overshoot other observations
- too large annihilation in the EU

But solutions exist

Model building

- may overshoot other observations
- too large annihilation in the EU

But solutions exist

In summary:

- kinematically forbidden channel
- different diagrams
- s-wave vs p-wave
- coannihilations and splitting
- DM production is decoupled from annihilations
- ...

Direct Detection

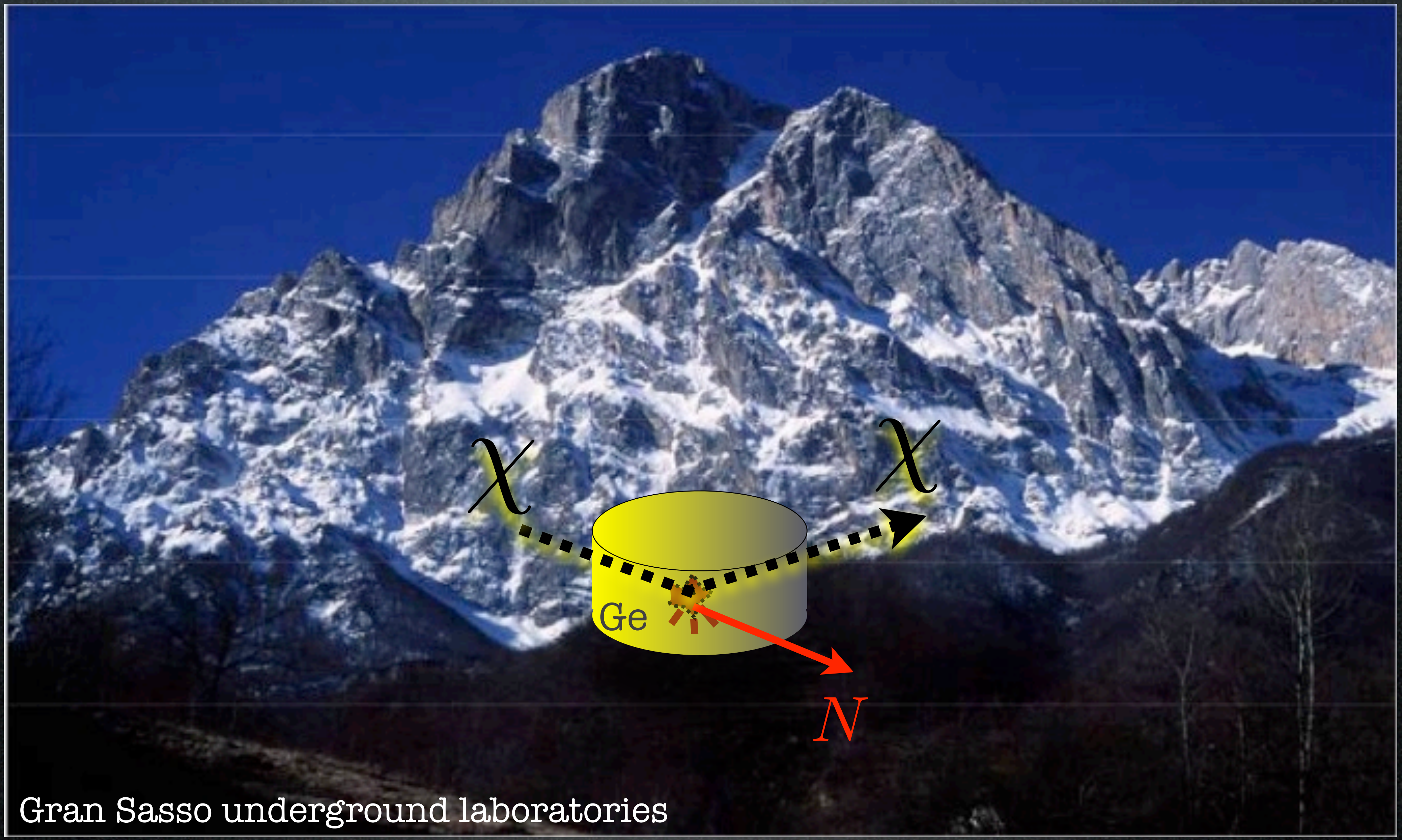
3. the ‘DAMA/CoGeNT/CRESST anomaly’

Direct Detection: **basics**

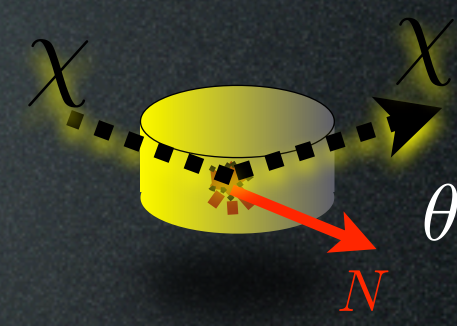
Gran Sasso underground laboratories

Direct Detection: basics

Direct Detection: basics



Direct Detection: basics



recoil energy

$$E_R = \frac{\mu_\chi^2 v^2}{m_N}(1-\cos\theta)$$

$$\mu_\chi = \frac{m_\chi m_N}{m_\chi + m_N} \longrightarrow \begin{cases} m_\chi \text{ for small } m_\chi \\ m_N \text{ for large } m_\chi \end{cases}$$

recoil energy spectrum

$$\frac{dR}{dE_R} = \frac{1}{2}\frac{\rho_\odot}{m_\chi}\frac{\sigma}{\mu^2}\int_{v_{\rm min}(E_R)}^{v_{\rm esc}} \frac{1}{v} f(\vec{v})\, {\rm d}\vec{v}$$

with $f(\vec{v}) \propto e^{-v^2/V_c^2}$ + motion of Earth in (static?)halo

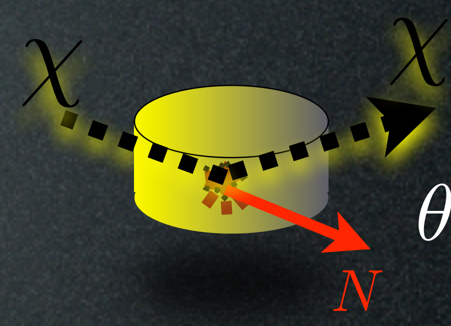
$\sigma \approx \sigma_n^{\rm SI} A^4$ $\times$ nuclear form factors

number of events

$$N = \mathcal{E}\,\mathcal{T}\int_{E_{\rm thres}}^{E_{\rm max}} \frac{dR}{dE_R}\, dE_R$$

Direct Detection: basics

recoil energy $$E_R = \frac{\mu_\chi^2 v^2}{m_N}(1-\cos\theta)$$



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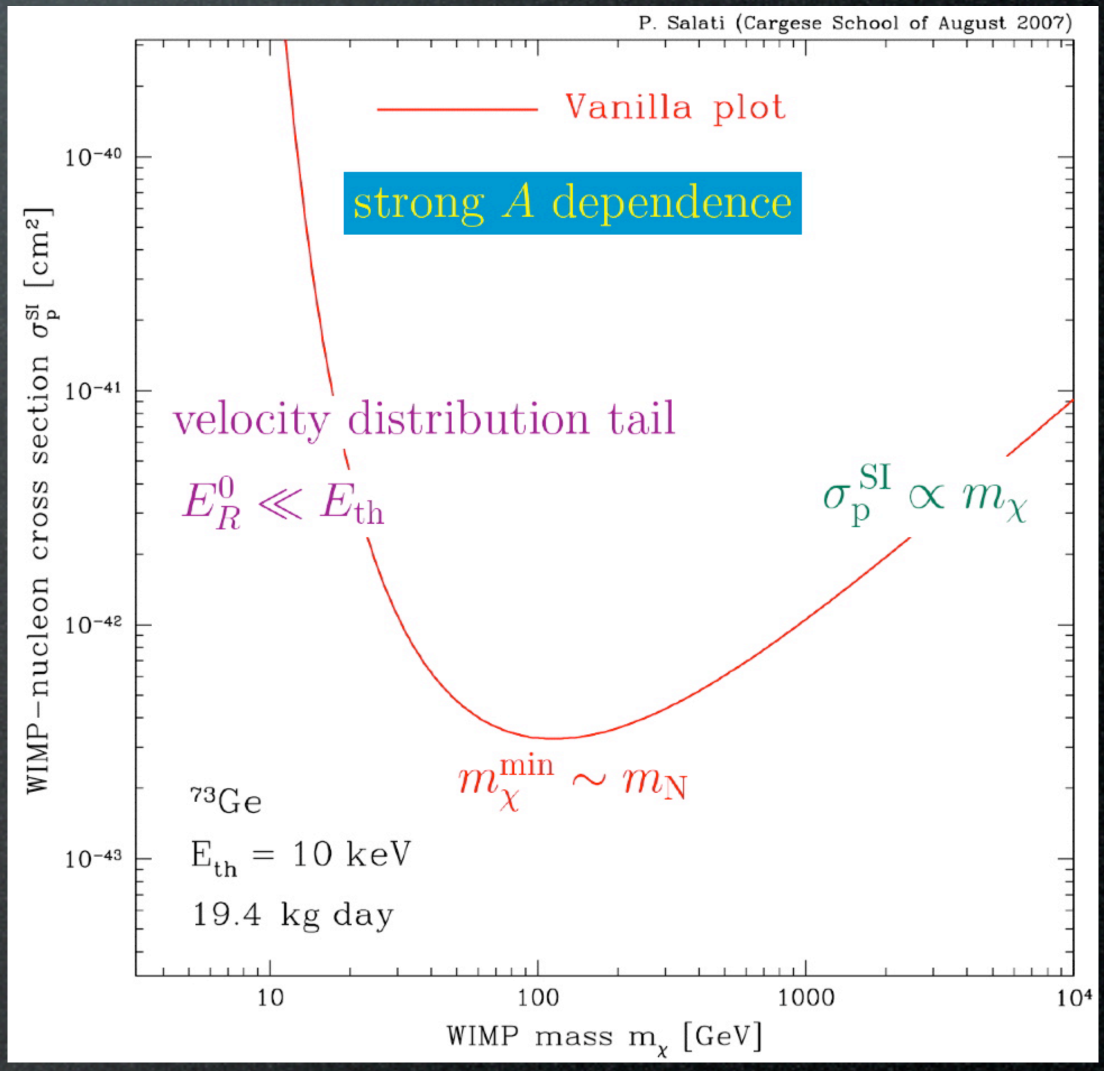
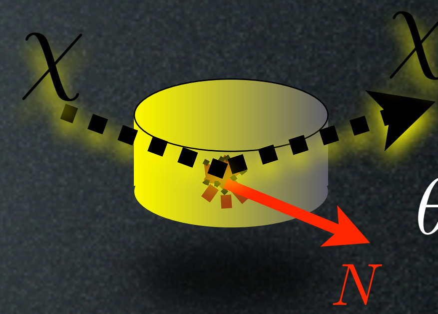


P.Salati, proceedings of Cargèse 2007

Direct Detection: basics

recoil energy $$E_R = \frac{\mu_\chi^2 v^2}{m_N}(1-\cos\theta)$$



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number of events

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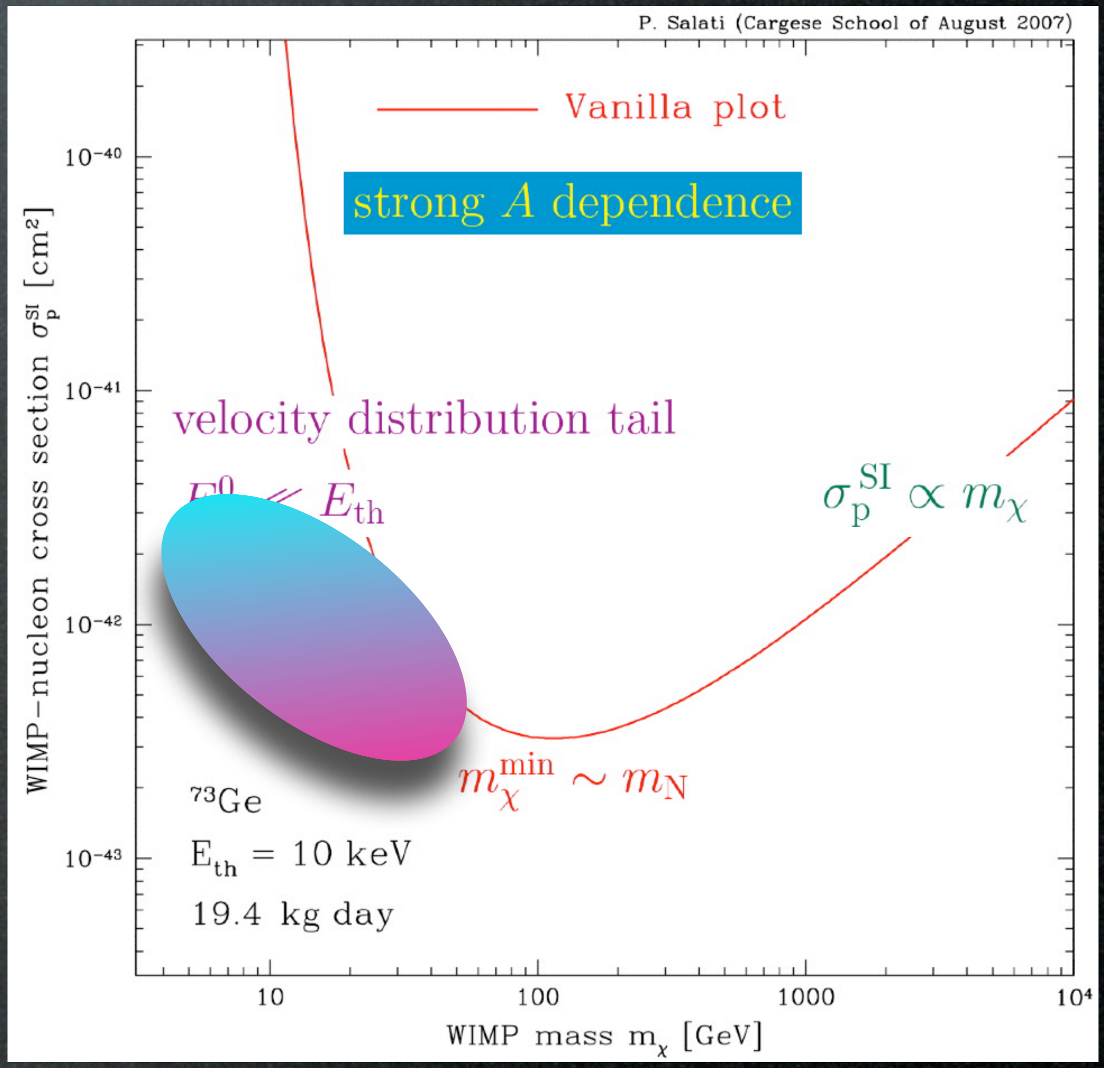
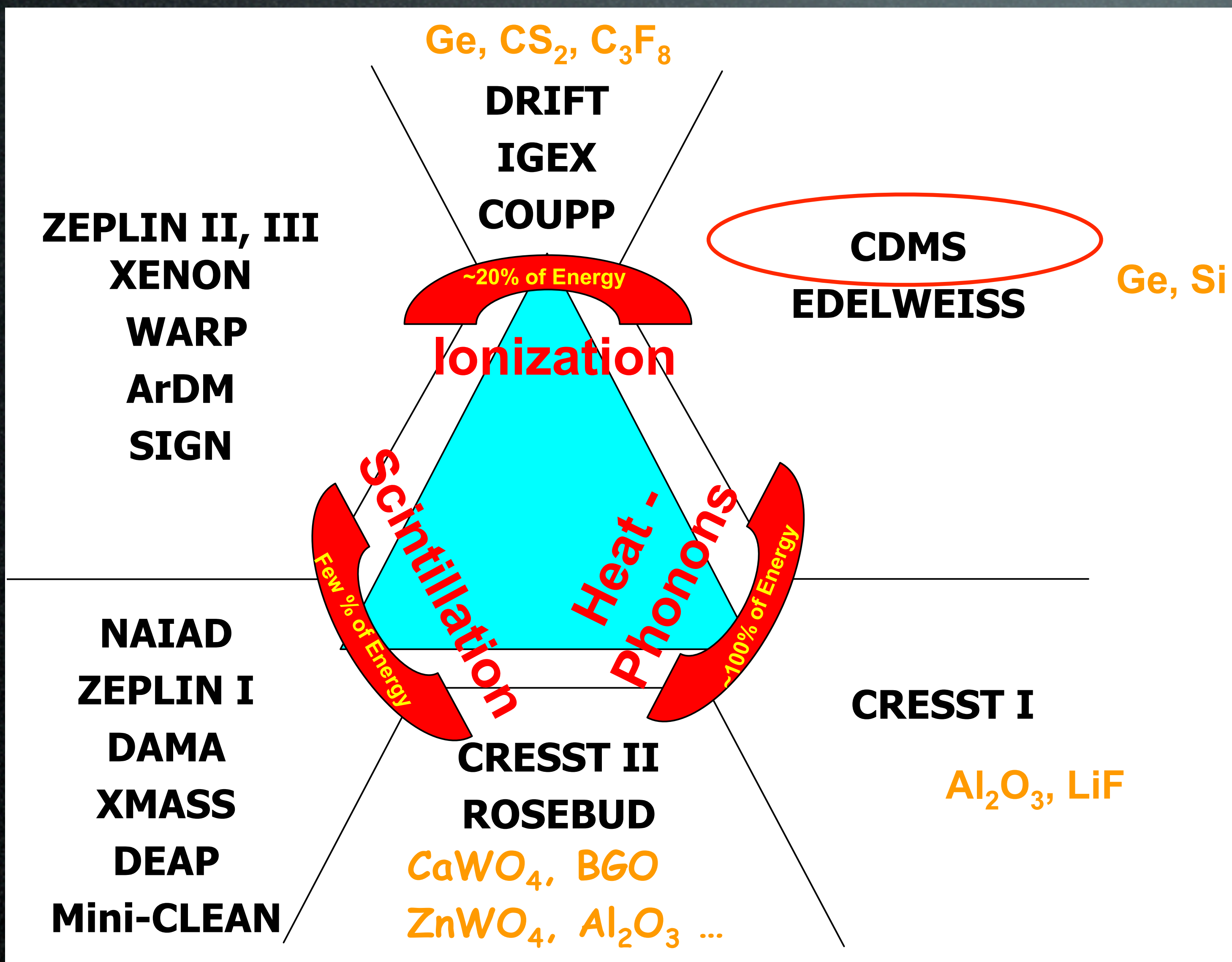


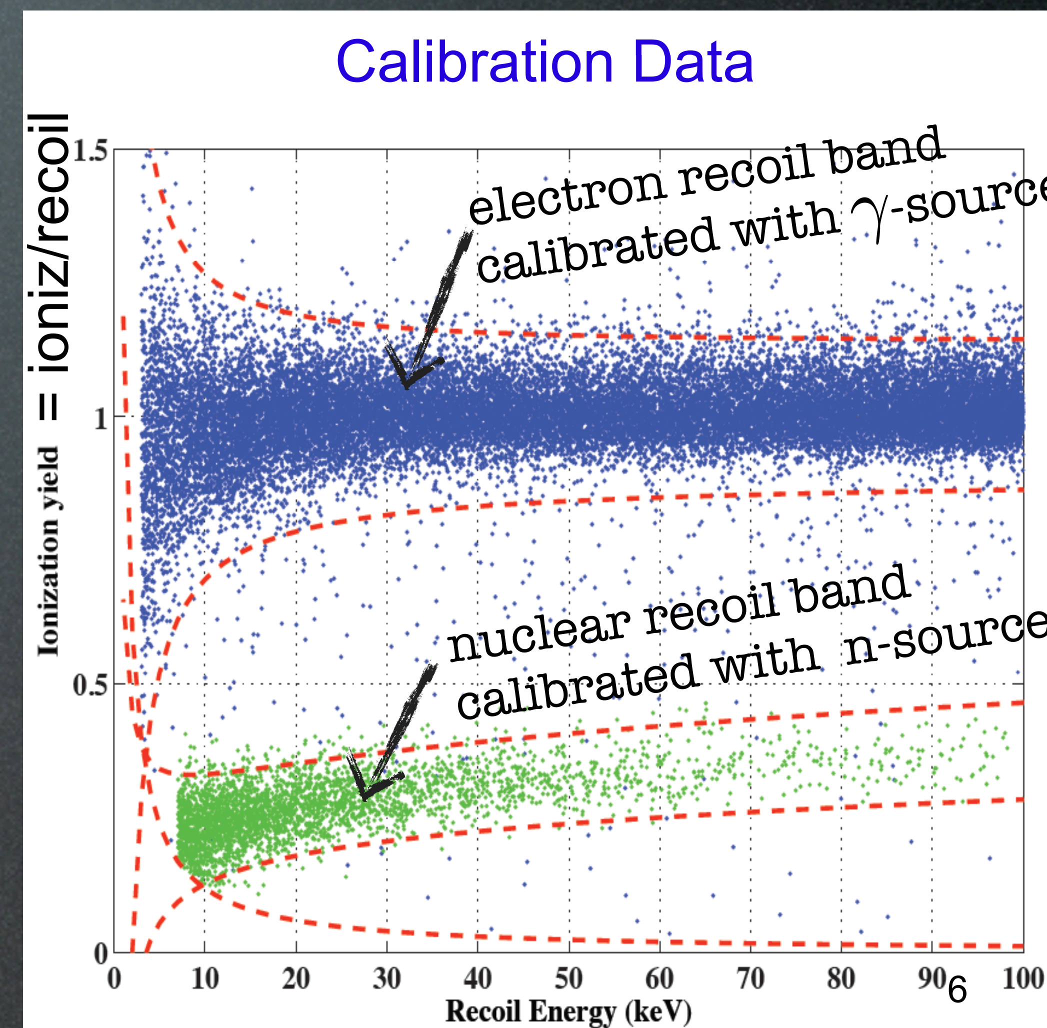
P.Salati, proceedings of Cargèse 2007

Direct Detection: basics

Background rejection



[credit: B.Sadoulet]

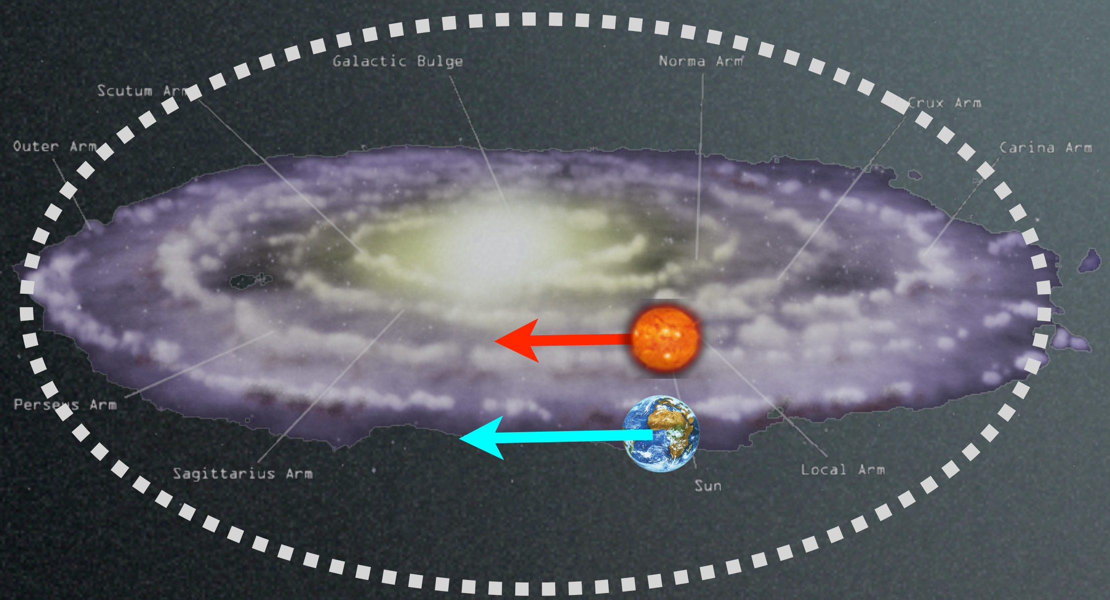


CDMS coll.

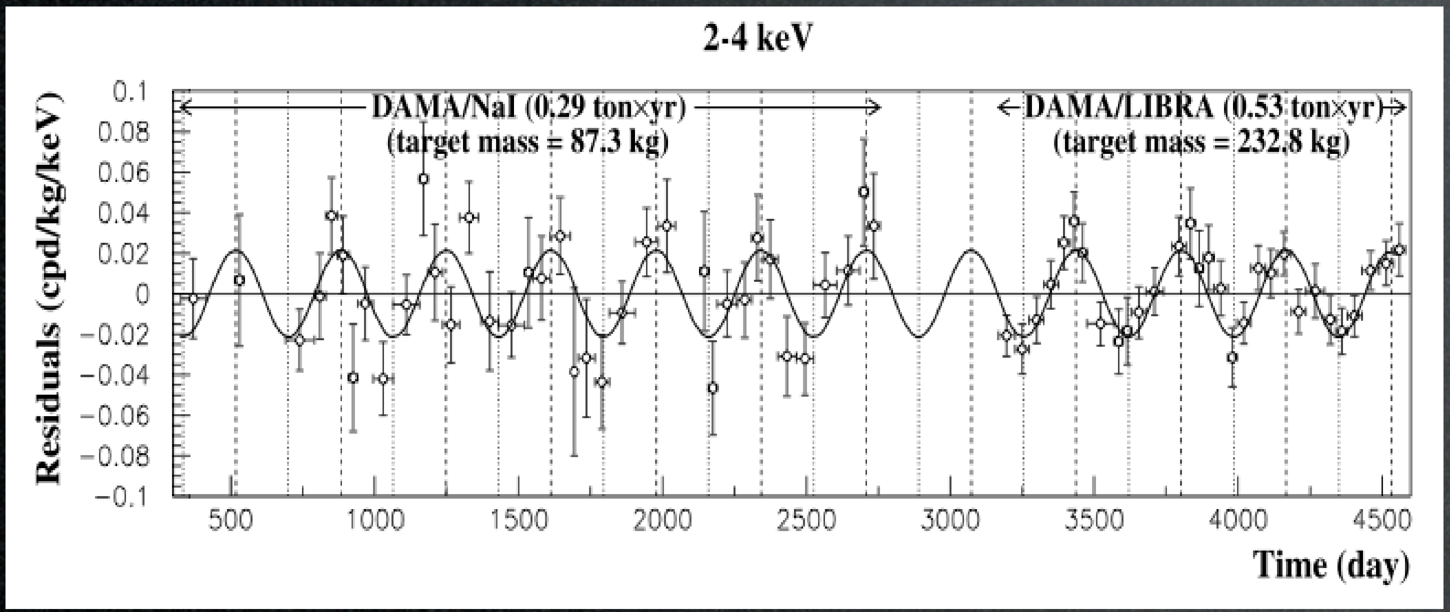
measure two quantities to discriminate Sign & Bkgd, on event-by-event basis

Direct Detection: hints

DAMA/Libra NaI(Tl)



Annual modulation seen (8σ):

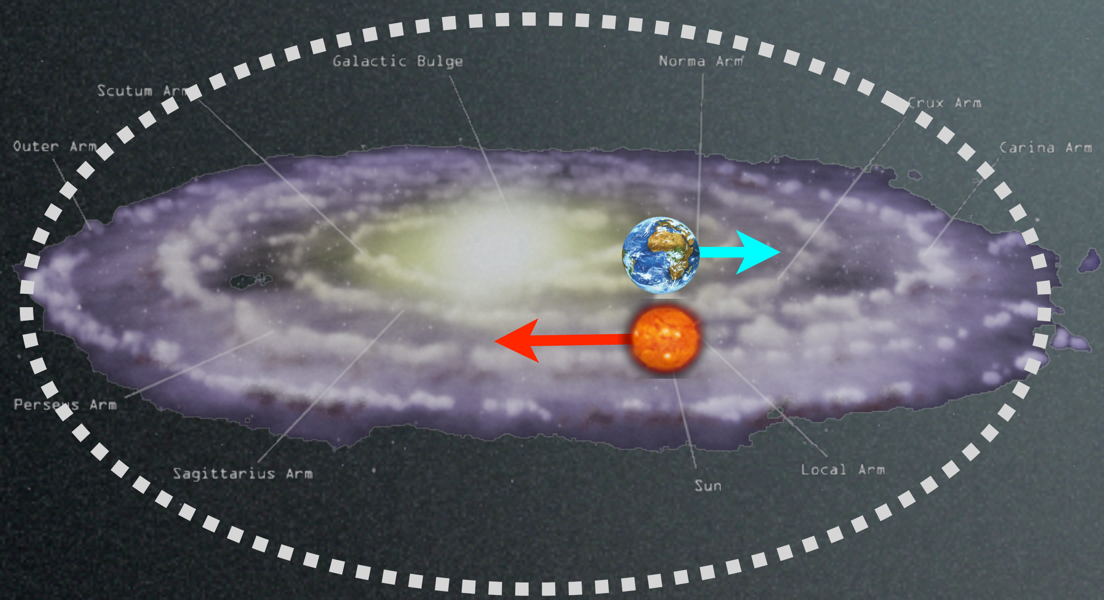


DAMA Coll., 0804.2741, 2008

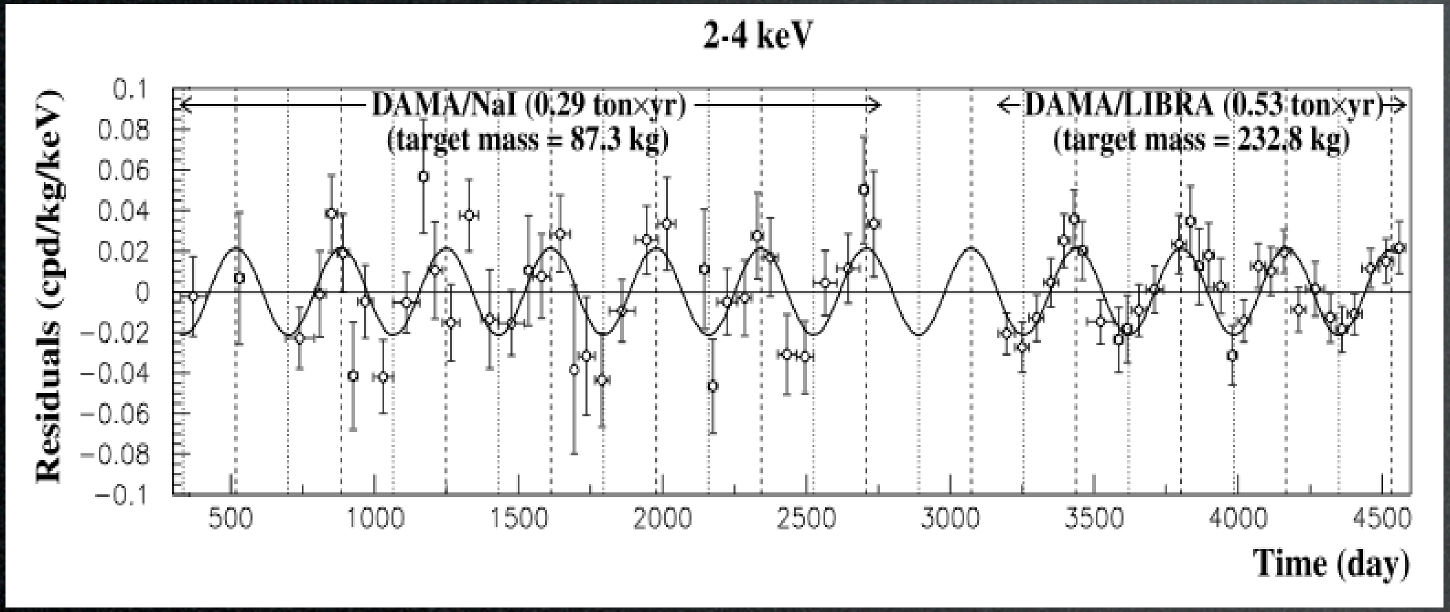
Direct Detection: hints

DAMA/Libra

NaI(Tl)



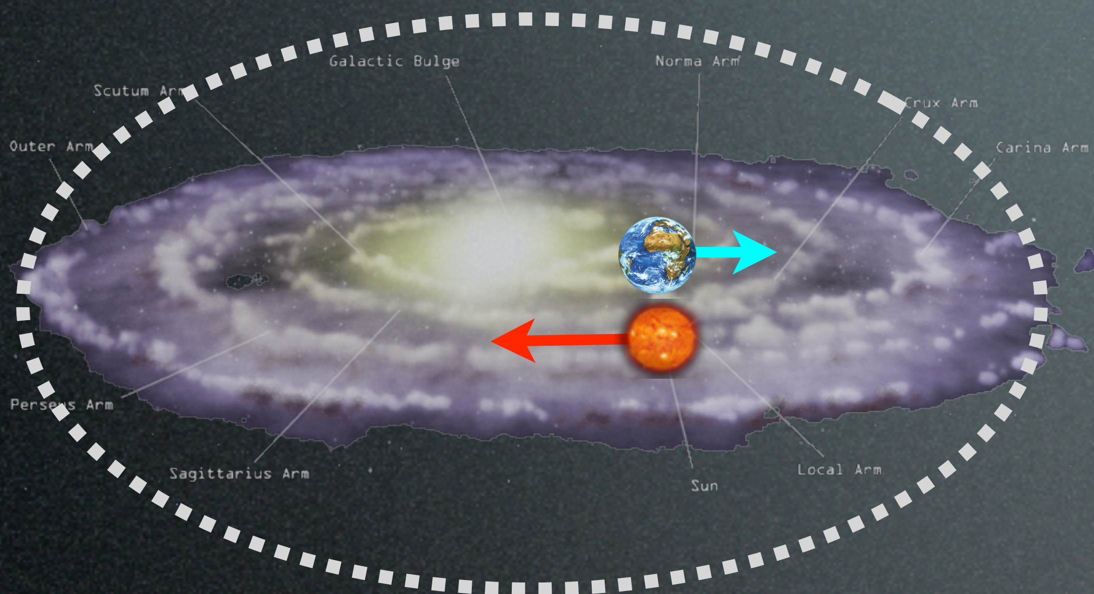
Annual modulation seen (8σ):



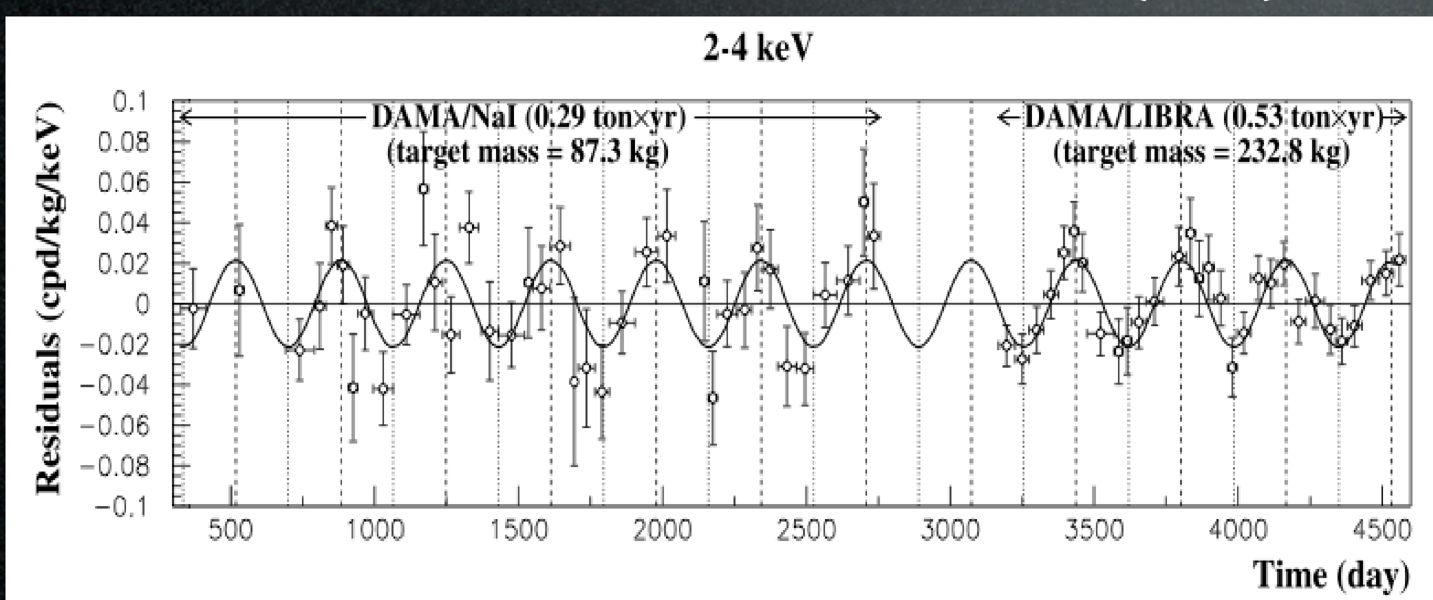
DAMA Coll., 0804.2741, 2008

Direct Detection: hints

DAMA/Libra



Annual modulation seen (8σ):



DAMA Coll., 0804.2741, 2008

An instrumental effect?

Summary of the results obtained in the additional investigations of possible systematics or side reactions
(DAMA/LIBRA – NIMA592(2008)297, EPJC56(2008)333)

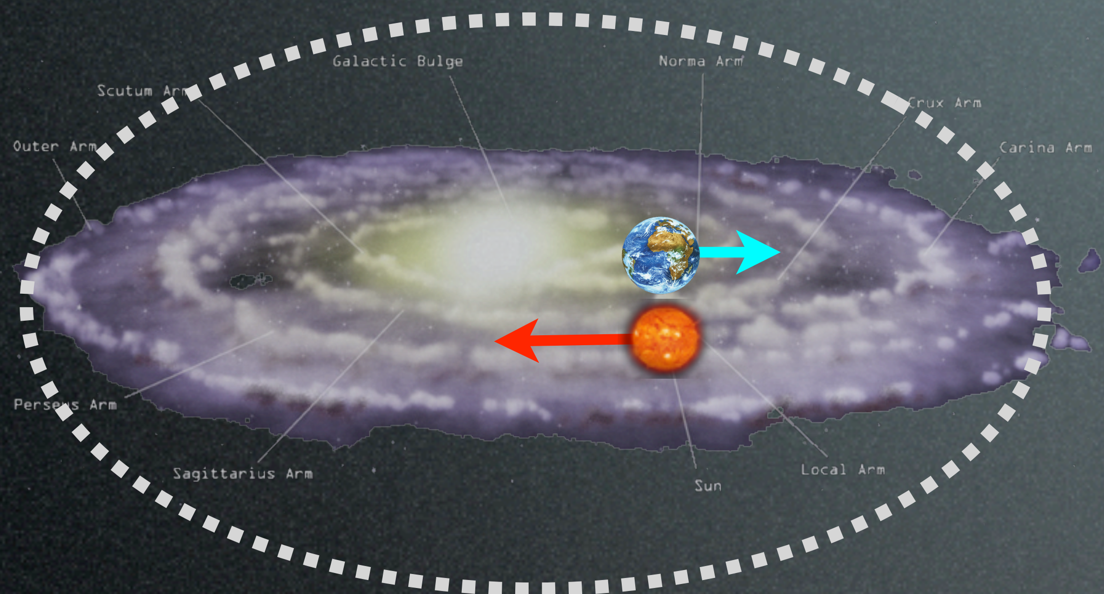
Source	*Main comment*	*Cautious upper limit (90%C.L.)*
RADON	Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.	$<2.5\times10^{-6}$ cpd/kg/keV
TEMPERATURE	Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield→ huge heat capacity + T continuously recorded	$<10^{-4}$ cpd/kg/keV
NOISE	Effective full noise rejection near threshold	$<10^{-4}$ cpd/kg/keV
ENERGY SCALE	Routine + instrinsic calibrations	$<1\text{-}2\times10^{-4}$ cpd/kg/keV
EFFICIENCIES	Regularly measured by dedicated calibrations	$<10^{-4}$ cpd/kg/keV
BACKGROUND	No modulation above 6 keV; no modulation in the (2-6) keV *multiple-hits* events; this limit includes all possible sources of background	$<10^{-4}$ cpd/kg/keV
SIDE REACTIONS	Muon flux variation measured by MACRO	$<3\times10^{-5}$ cpd/kg/keV

+ even if larger they cannot satisfy all the requirements of annual modulation signature → **Thus, they can not mimic the observed annual modulation effect**

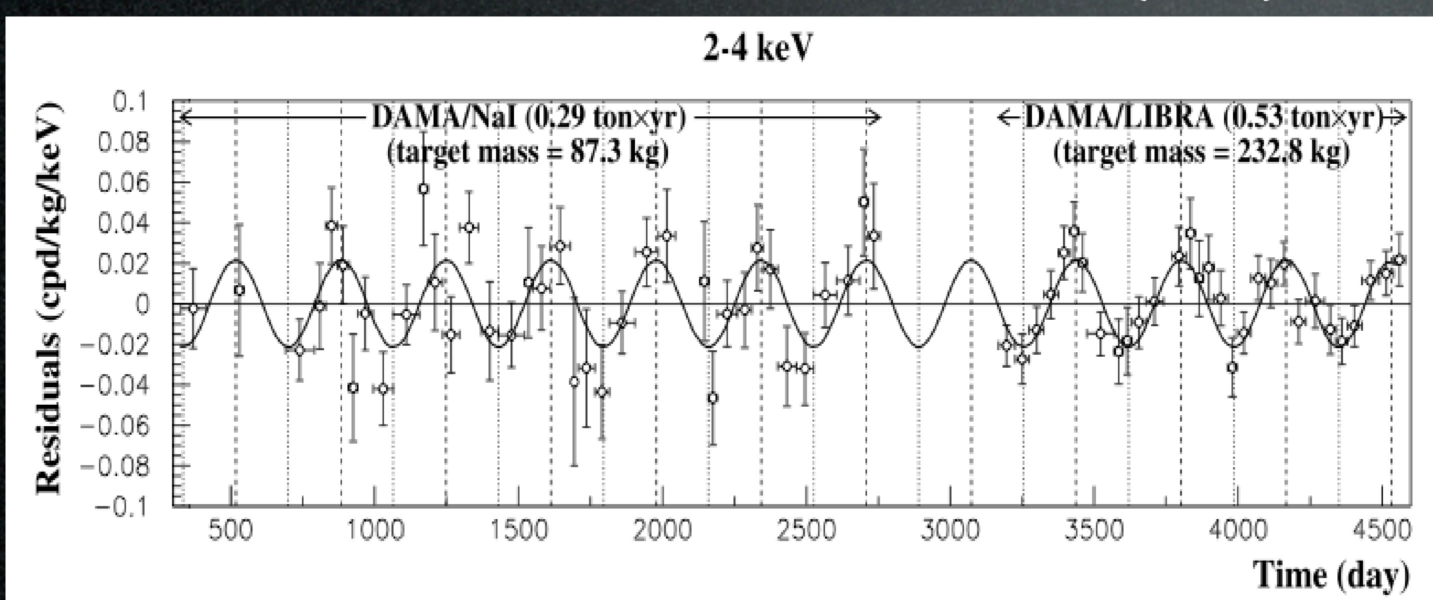
'NO!' e.g. P.Belli, KITP workshop 12.2009

Direct Detection: hints

DAMA/Libra



Annual modulation seen (8σ):

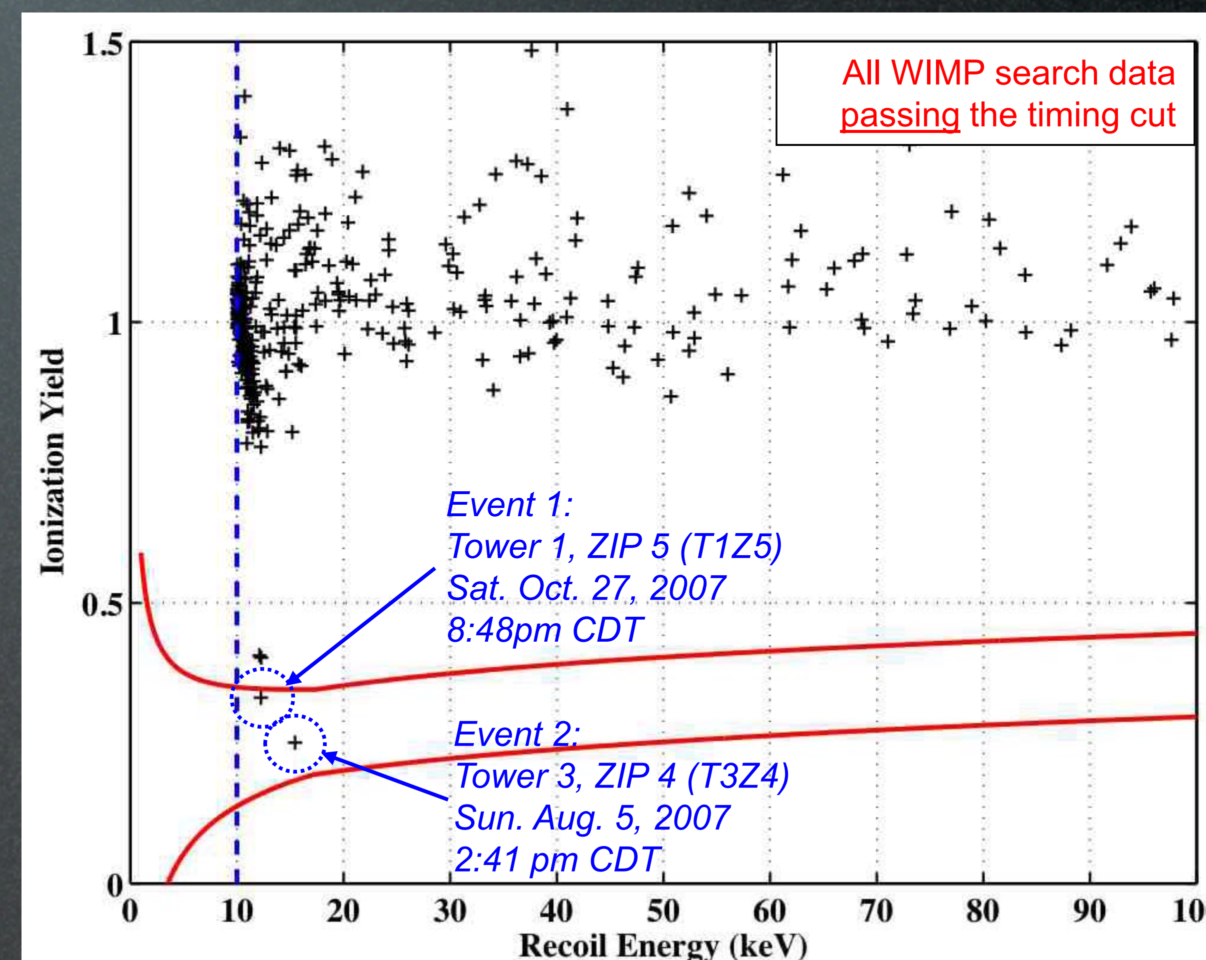


DAMA Coll., 0804.2741, 2008

CDMS

Ge+Si

2 events seen,
with 0.6 exp'd background

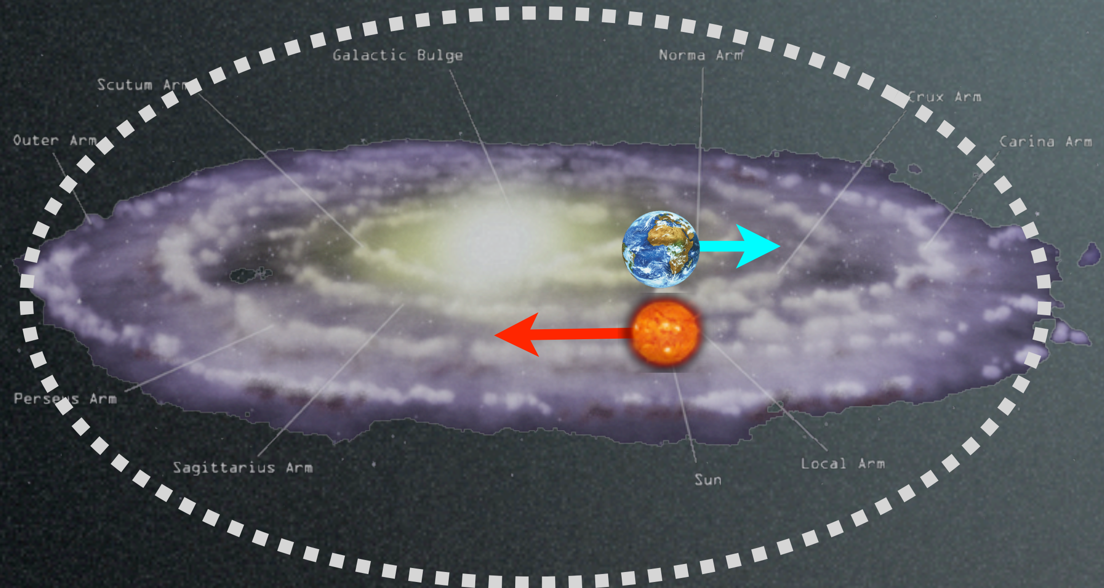


CDMS coll., Science 327 (2010), 0912.3592

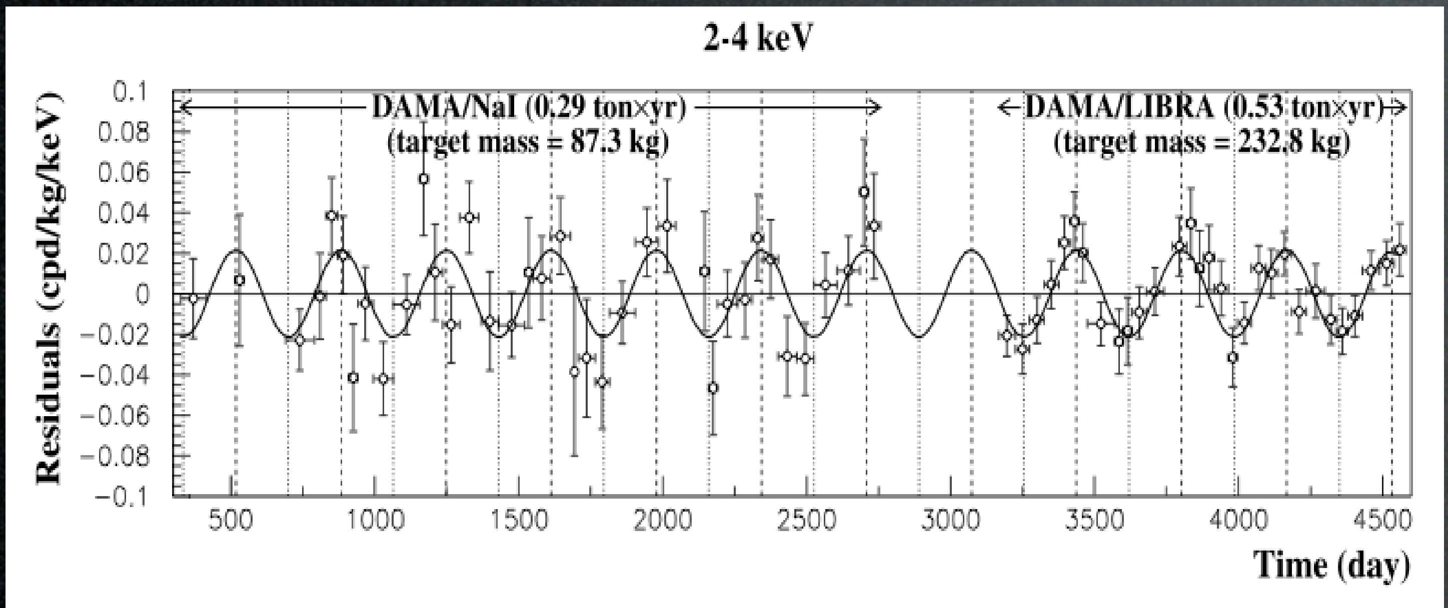
cited 500 times

Direct Detection: hints

DAMA/Libra



Annual modulation seen (8σ):



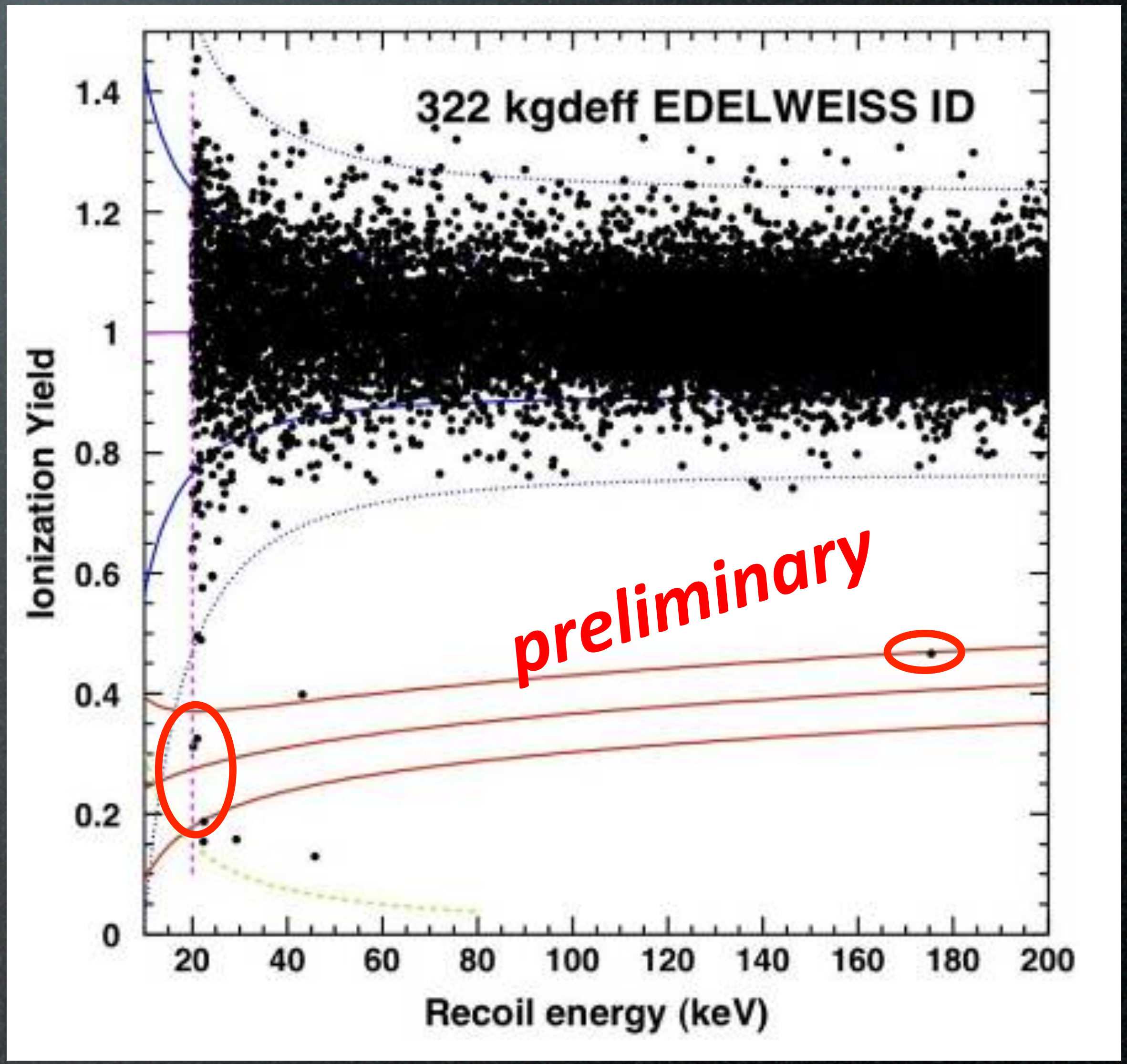
DAMA Coll., 0804.2741, 2008

Edelweiss

Ge

3 events seen

'background starts to appear'

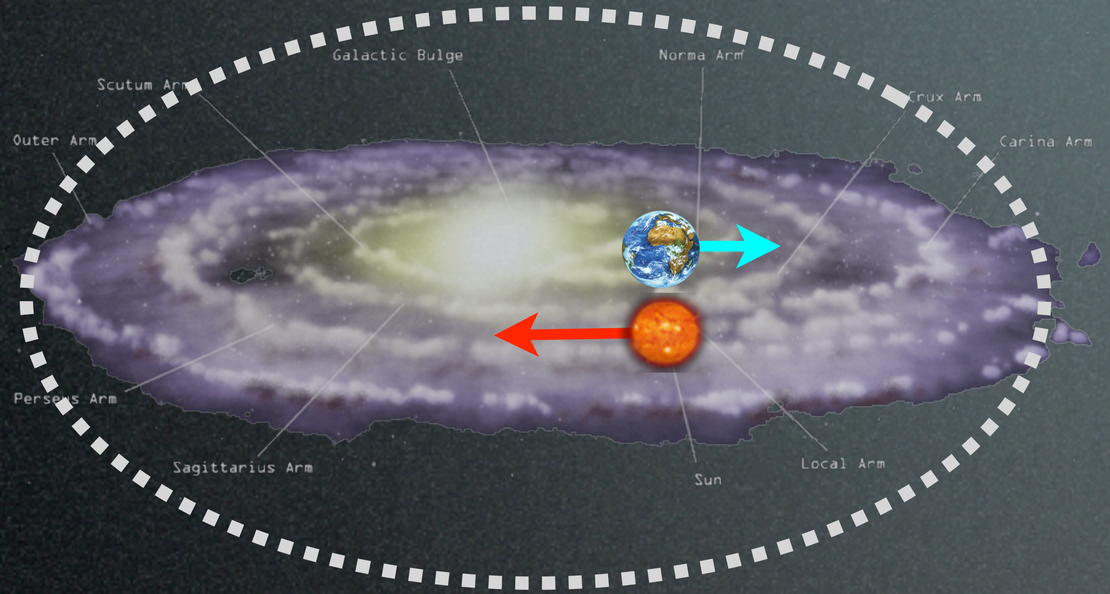


Edelweiss coll, TeVPA 2010
and 1011.2319

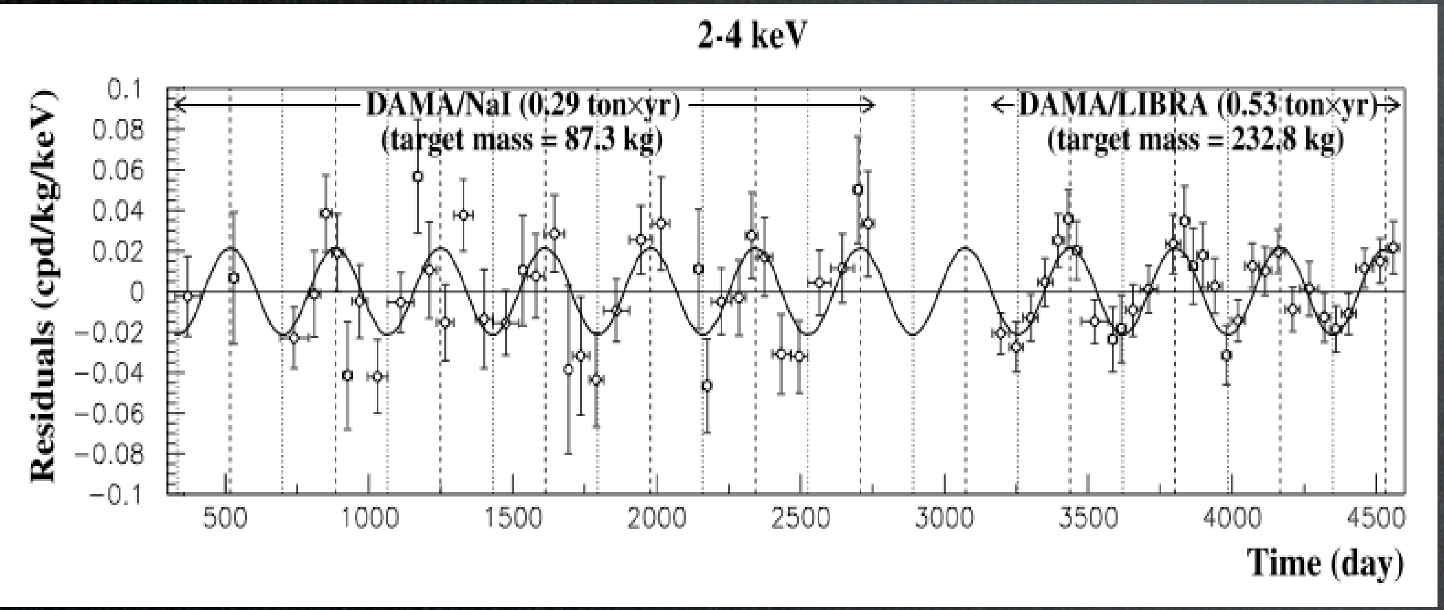
cited 500/10 = 50 times

Direct Detection: hints

DAMA/Libra



Annual modulation seen (8σ):

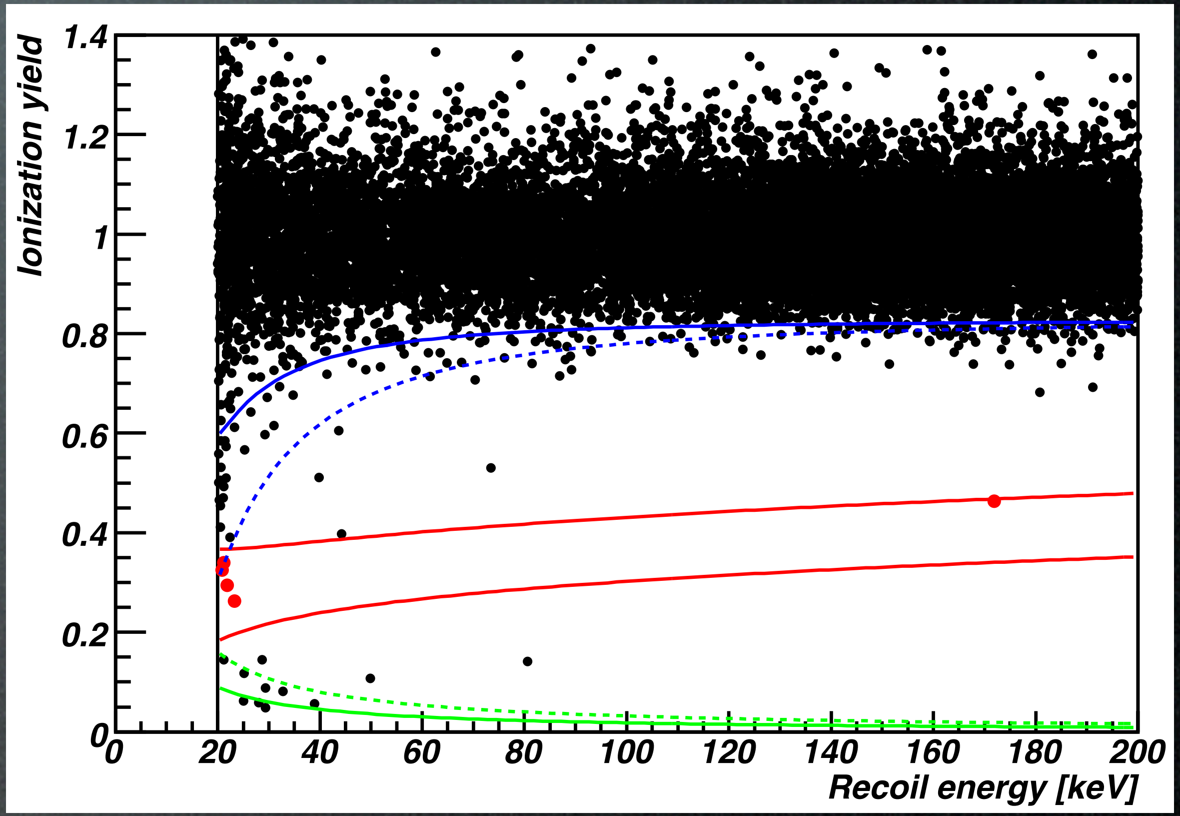


DAMA Coll., 0804.2741, 2008

Edelweiss

Ge

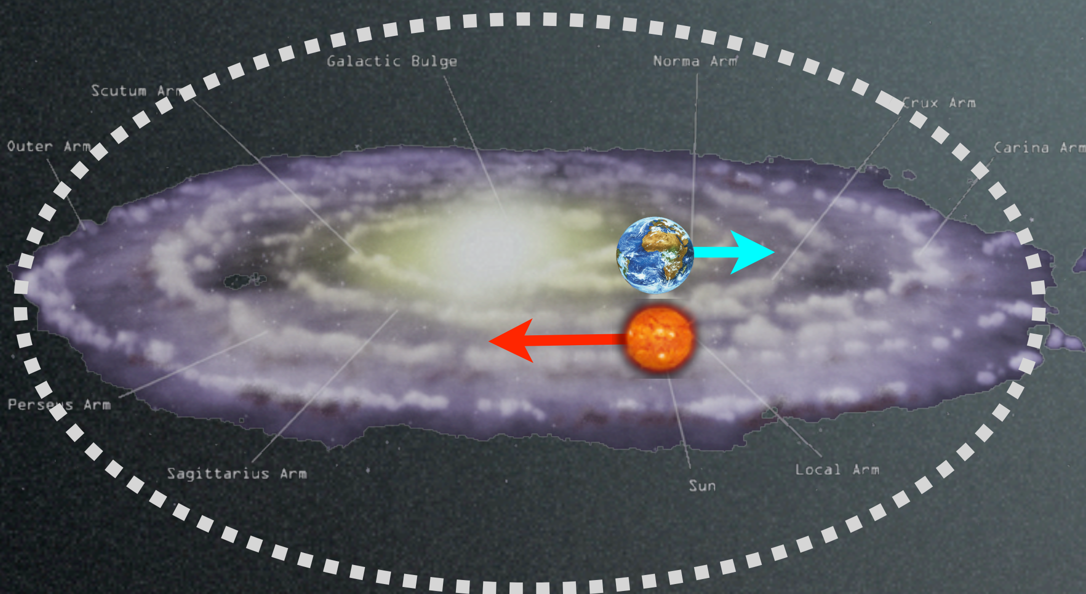
5 events seen,
with 3 exp'd background



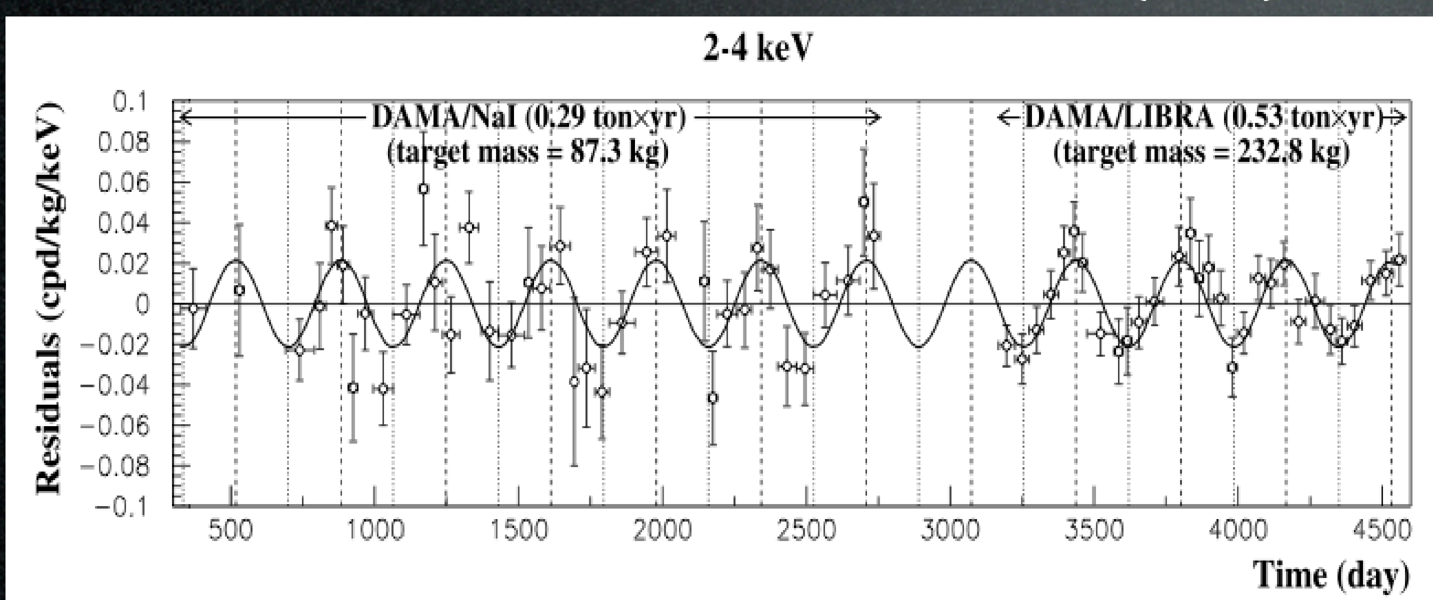
Edelweiss coll, 1103.4070

Direct Detection: hints

DAMA/Libra



Annual modulation seen (8σ):

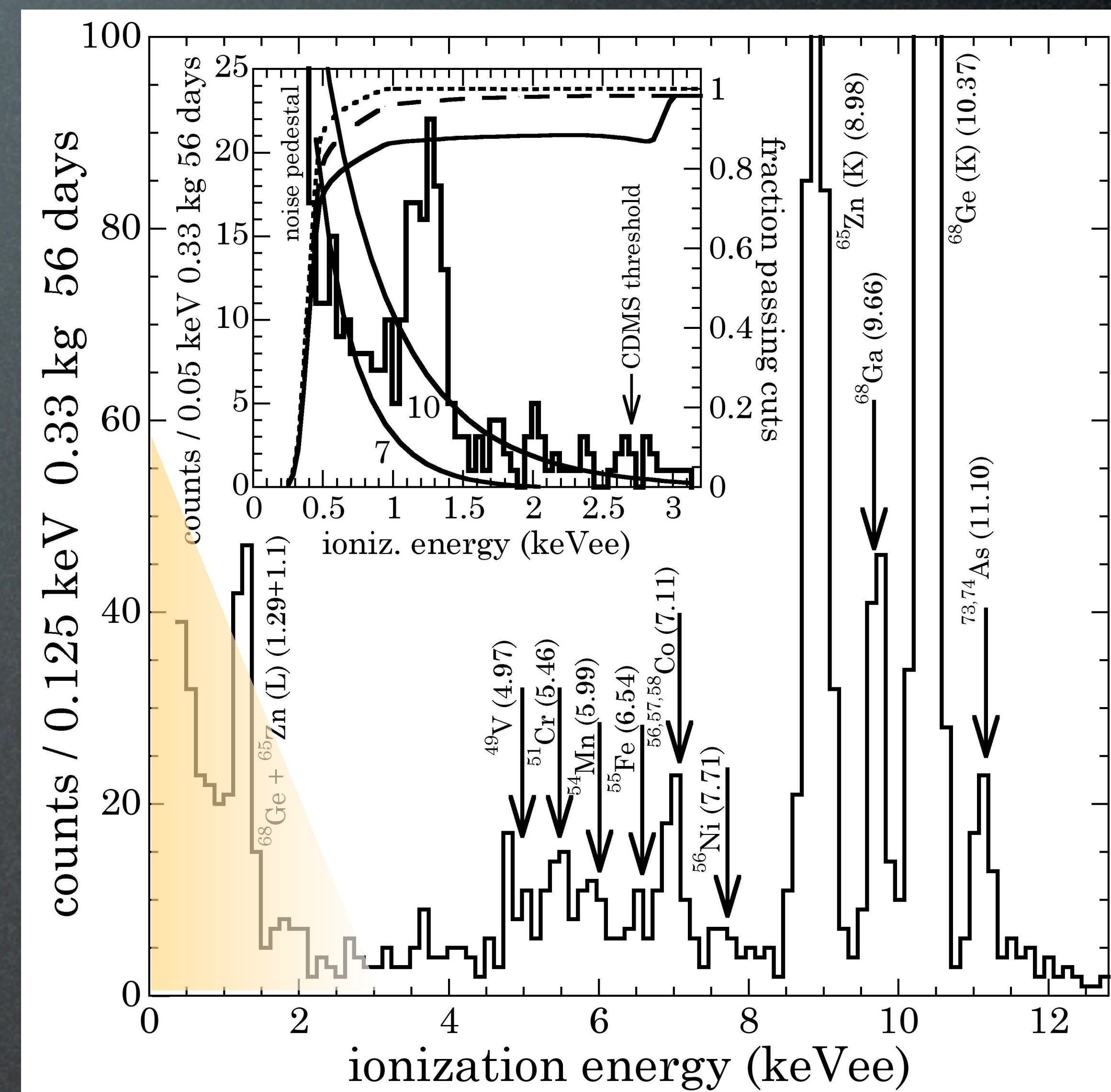


DAMA Coll., 0804.2741, 2008

CoGeNT

Ge

'irreducible excess of bulk events below 3 KeVee'

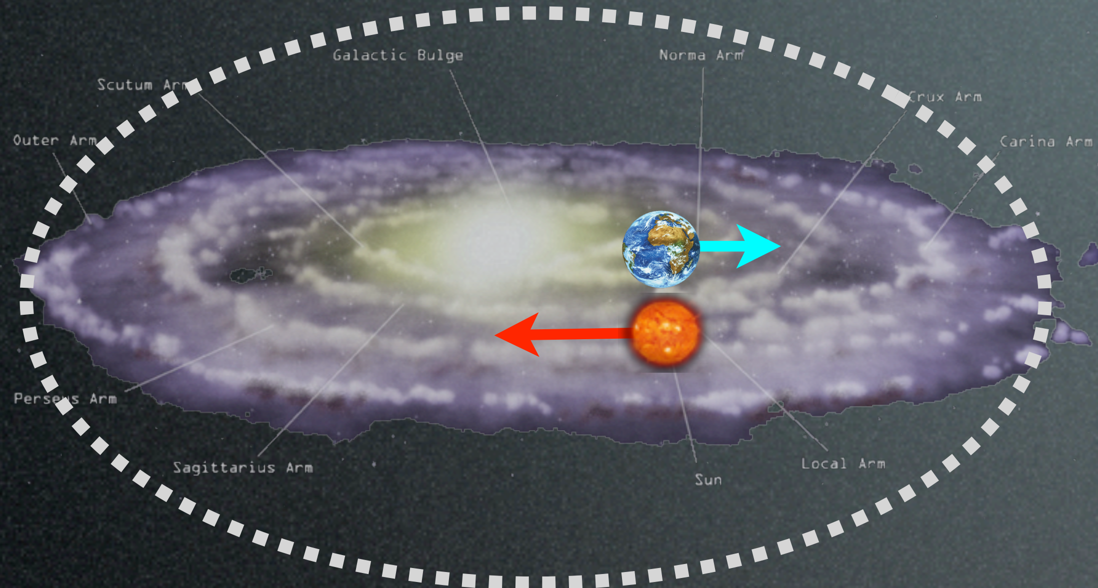


CoGeNT Coll., 1002.4703

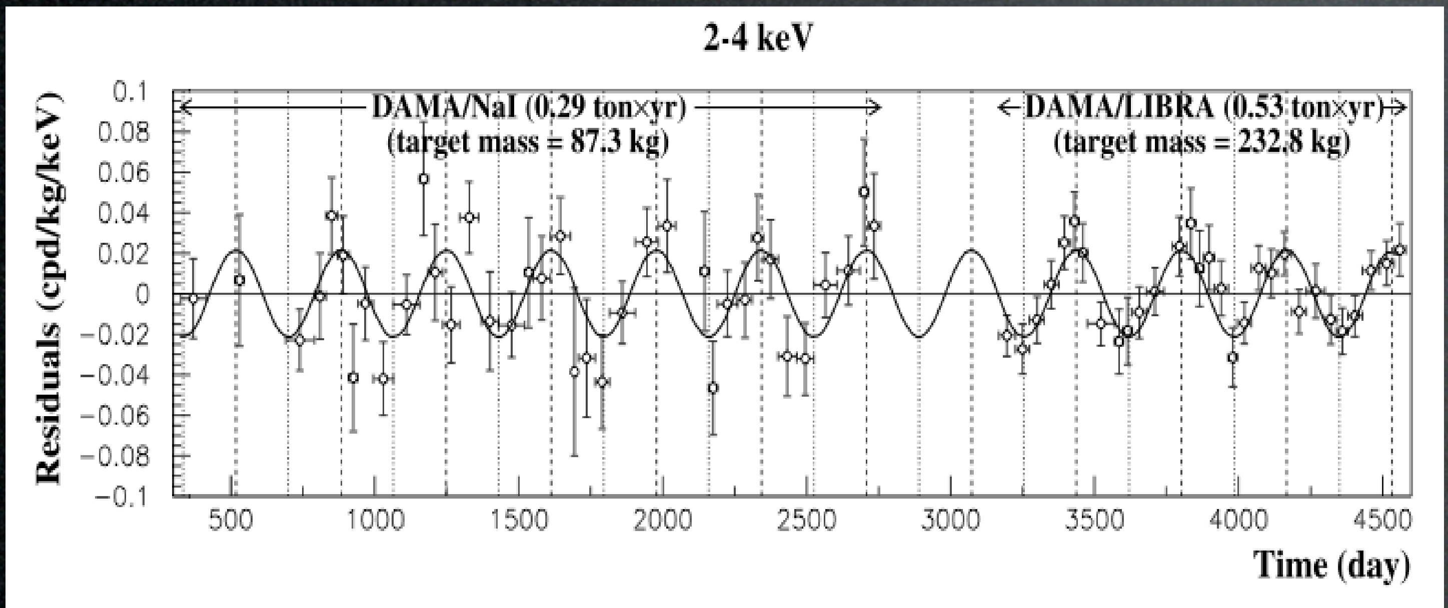
We lack a satisfactorily explanation [...]. It is tempting to consider a cosmological origin [...]. Prudence and past experience prompt us to continue work to exhaust less exotic possibilities.

Direct Detection: hints

DAMA/Libra



Annual modulation seen (8σ):

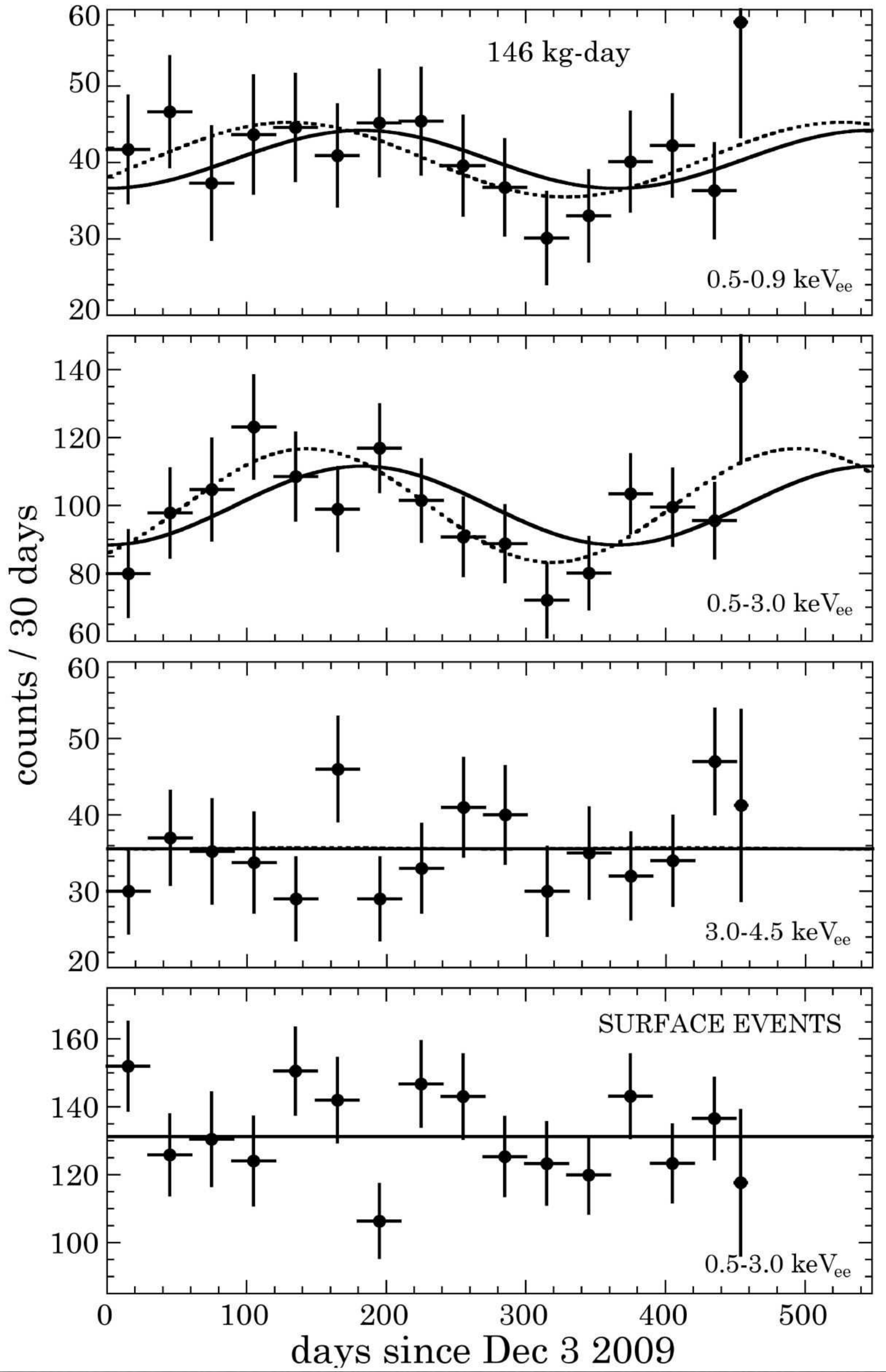


DAMA Coll., 0804.2741, 2008

CoGeNT

Ge

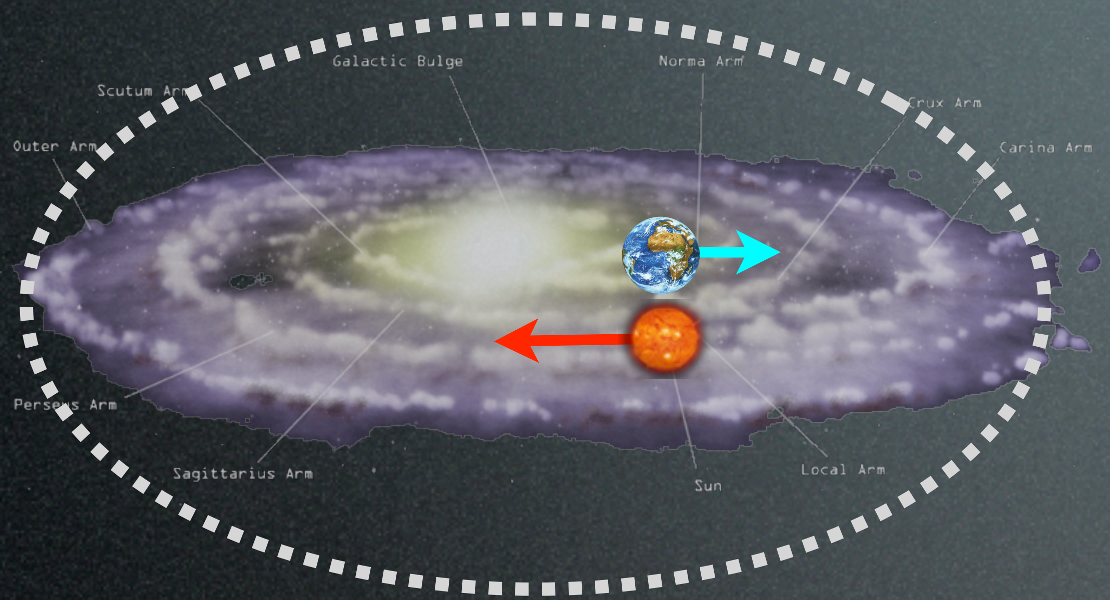
'irreducible excess of bulk events below 3 KeVee'



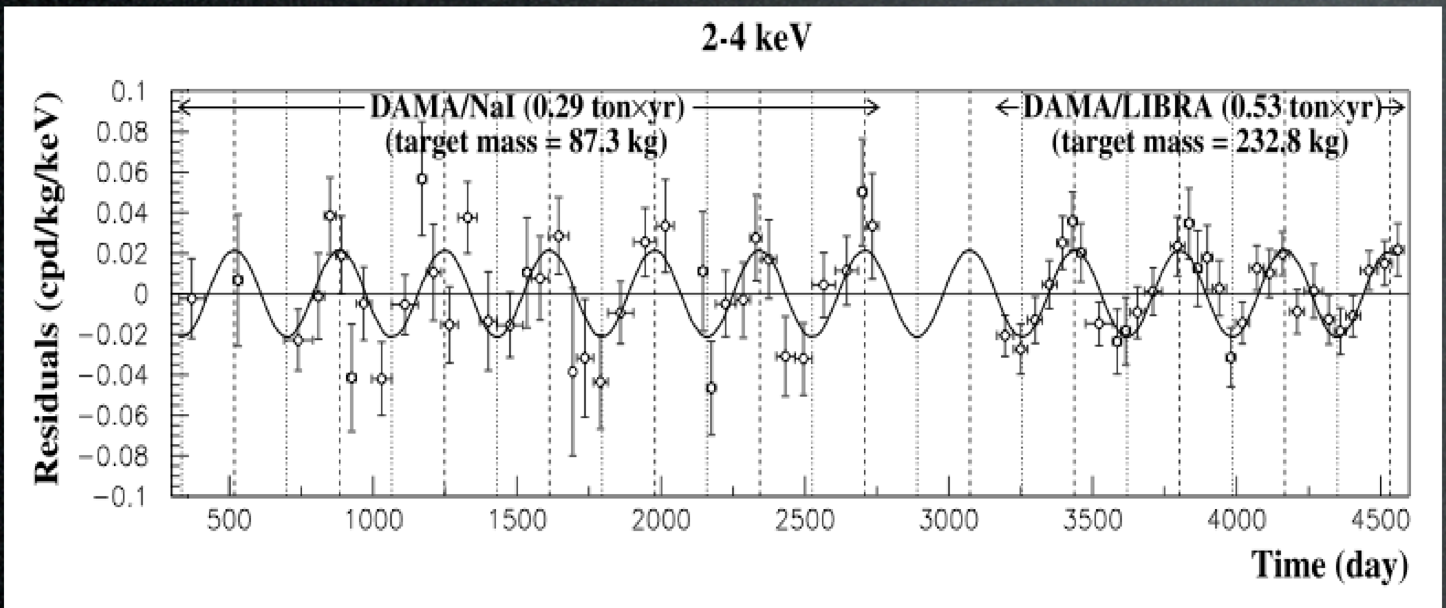
CoGeNT coll., 1106.0650

Direct Detection: hints

DAMA/Libra



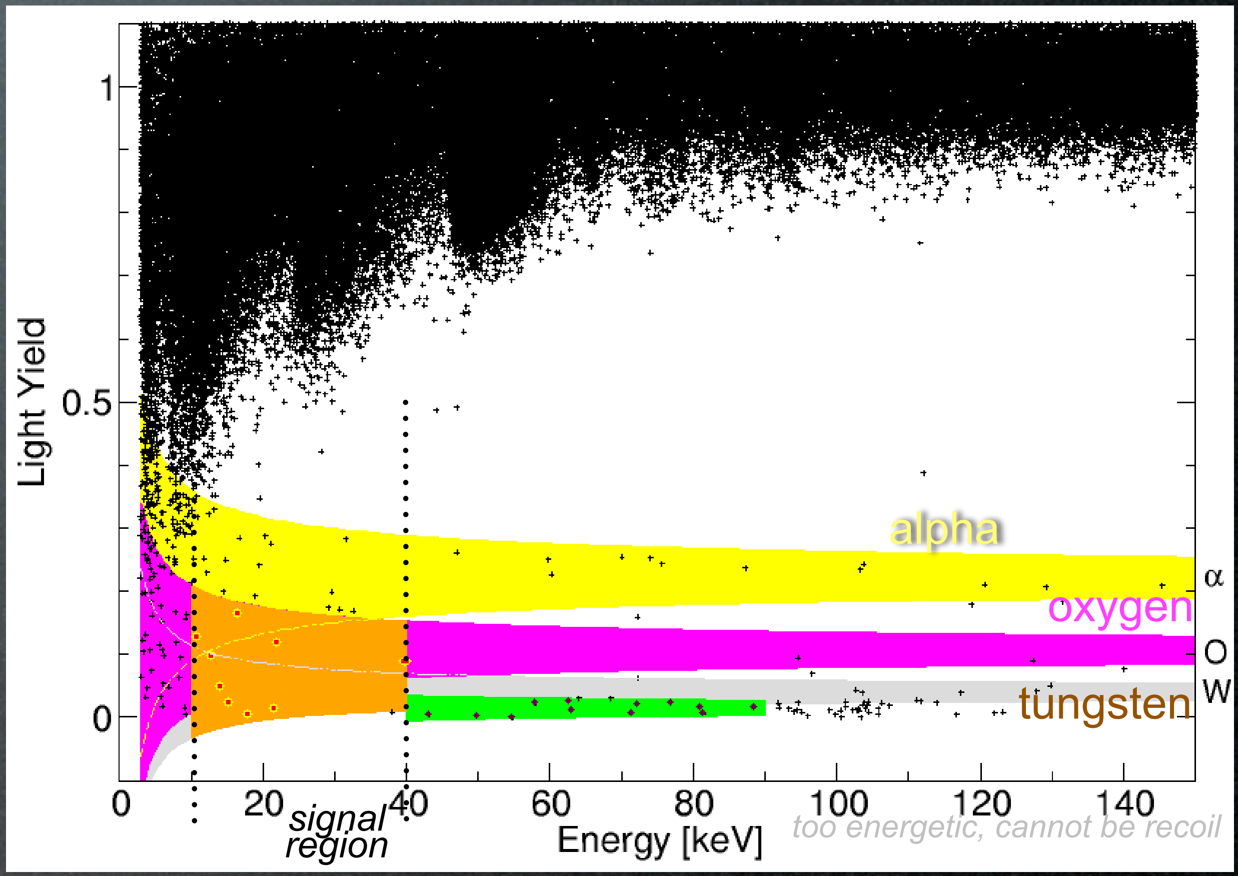
Annual modulation seen (8σ):



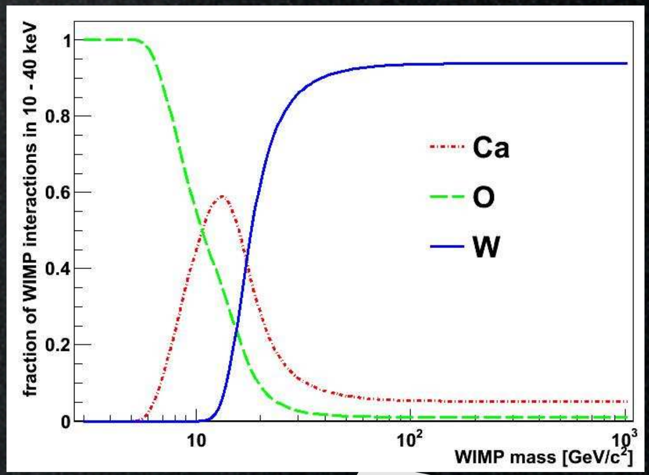
DAMA Coll., 0804.2741, 2008

CRESST-II $CaWO_4$

67 events seen on Oxygen, twice the exp'd background



CRESST-II Coll., 1109.0702



Theorist's reaction

3. the 'light DM' fit-olympics

Direct Detection: hints

Plotolympics 2011: fits performed by different groups

Belli+Fornengo+al., 1106.4667

Farina+Pappadopulo+Strumia+ Volansky, 1107.0715

Arina+Hamann+Wong, 1105.5121

(Kopp+)Schwetz+Zupan, 1106.6241 & 1110.2721

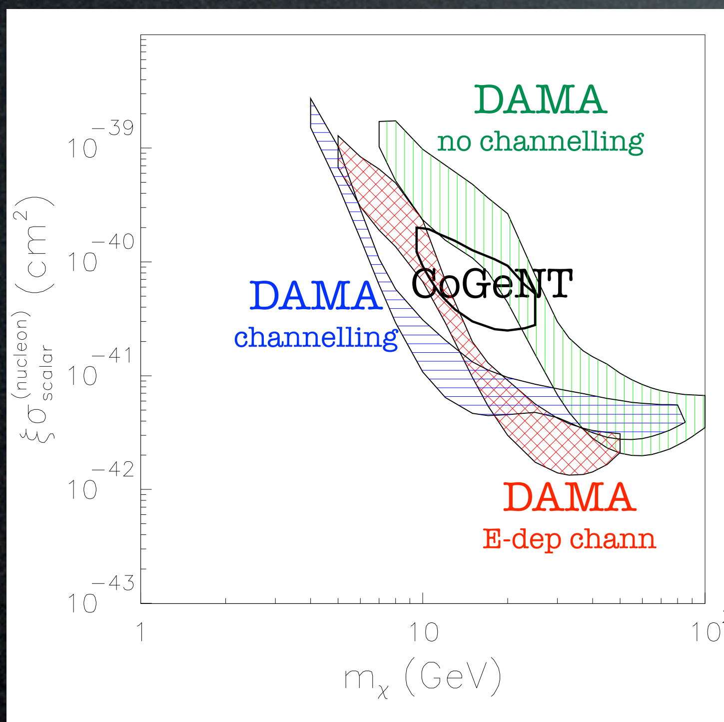
Hooper+Kelso, 1106.1066

Space available
Call 911-drk-mttr
now!

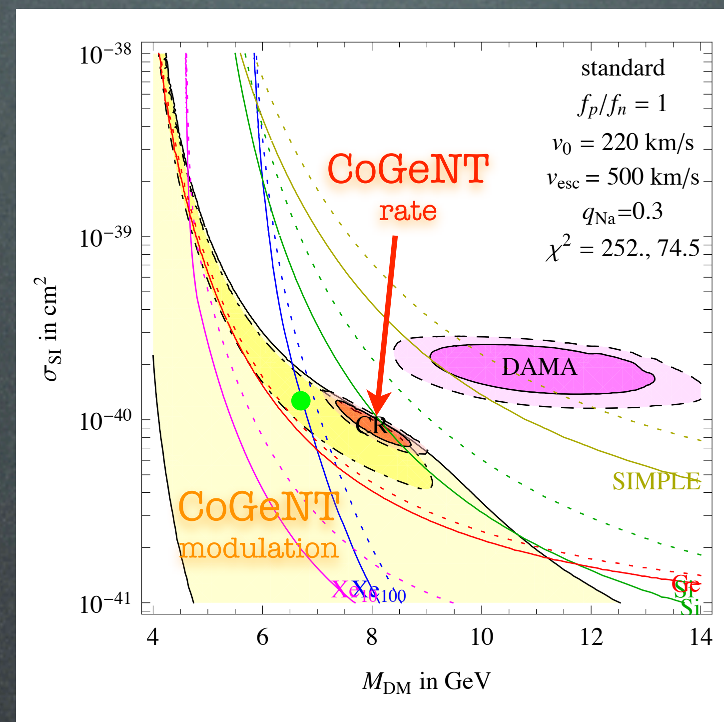
Direct Detection: hints

Plotolympics 2011: fits performed by different groups

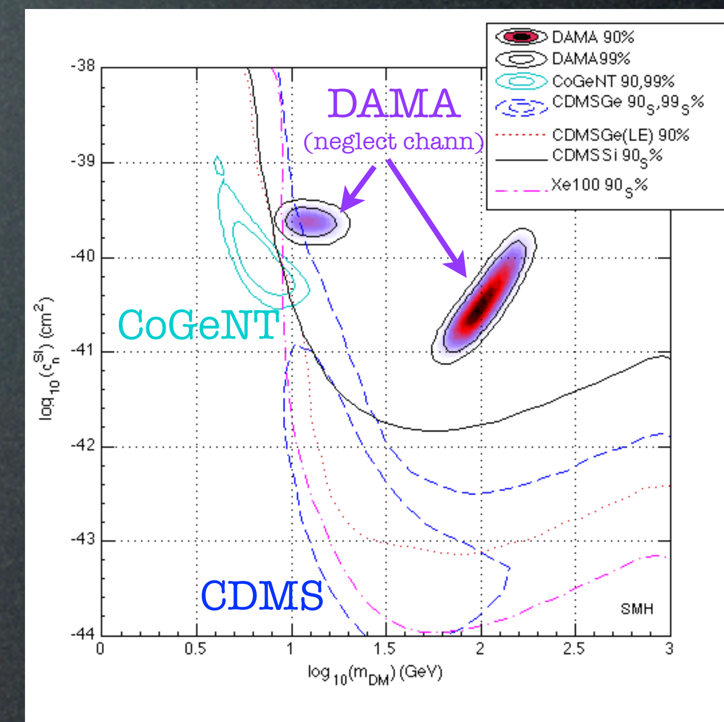
Discipline: Standard Fit: SI, standard halo



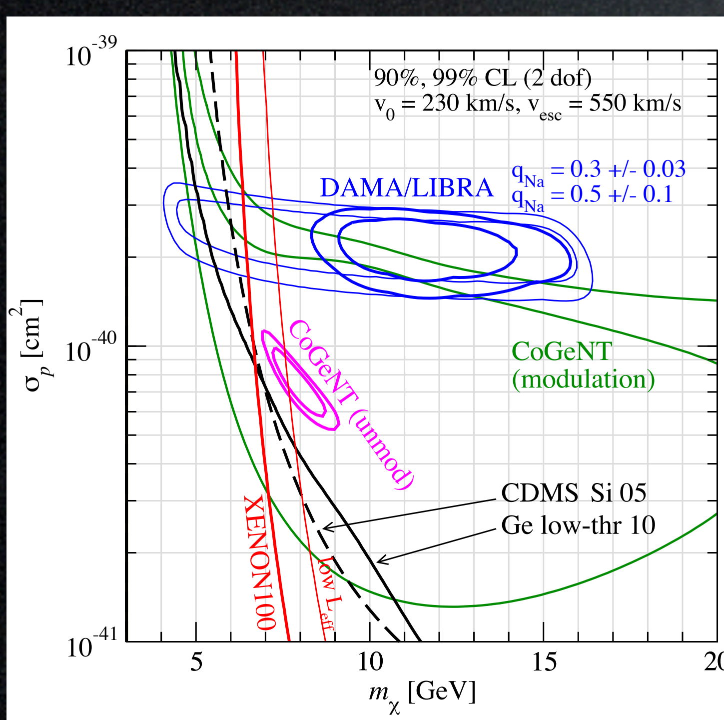
Belli+Fornengo+al., 1106.4667



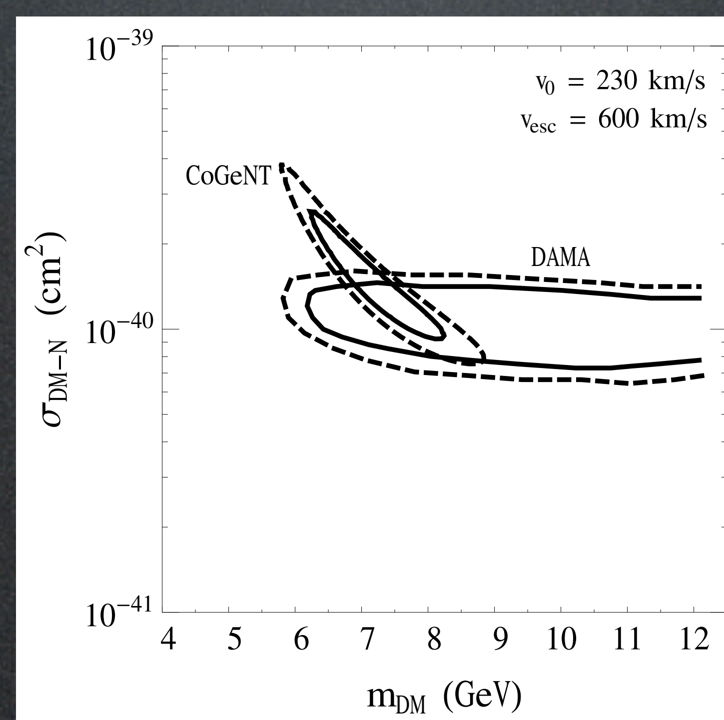
Farina+Pappadopulo+Strumia+ Volansky, 1107.0715



Arina+Hamann+Wong, 1105.5121



(Kopp+)Schwetz+Zupan, 1106.6241 & 1110.



Hooper+Kelso, 1106.1066

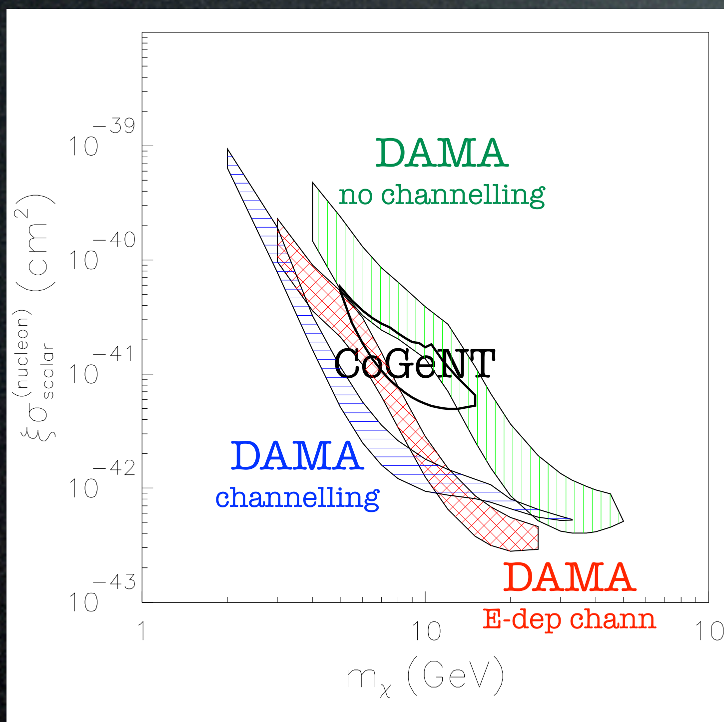
Comments:

- the ballparks agree, but the individual regions differ
  [do not ask me why]
- DAMA and CoGeNT overlap or not???

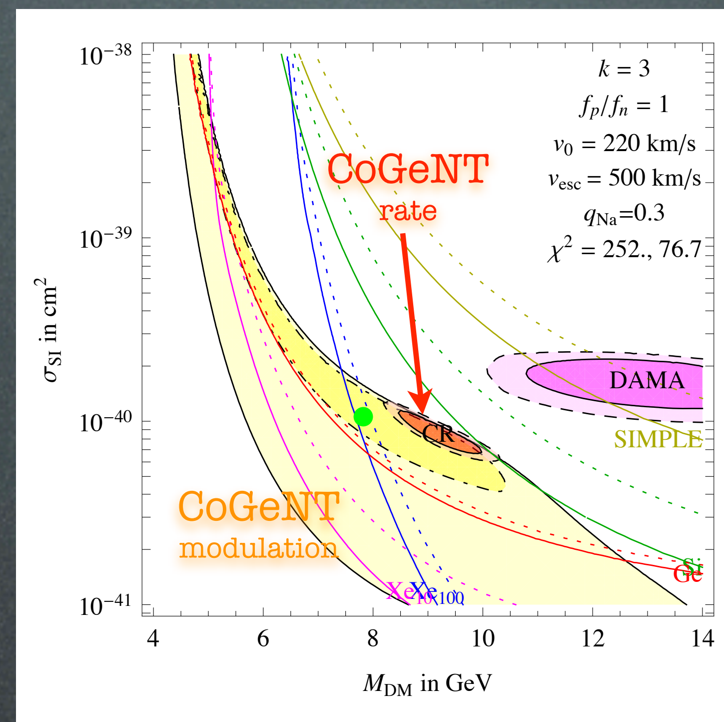
Direct Detection: hints

Plotolympics 2011: fits performed by different groups

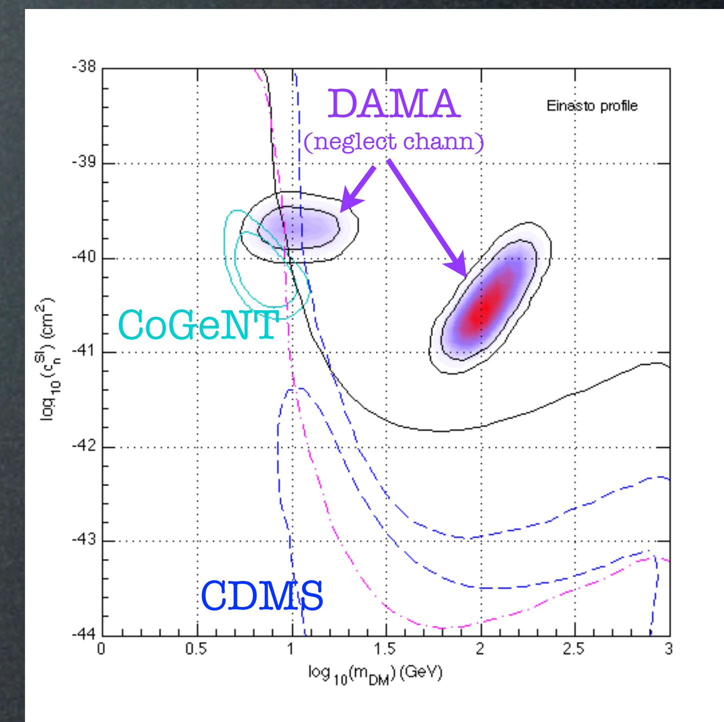
Discipline: Astro Fit: modifying velocity distrib, local density, profile...



Belli+Fornengo+al., 1106.4667



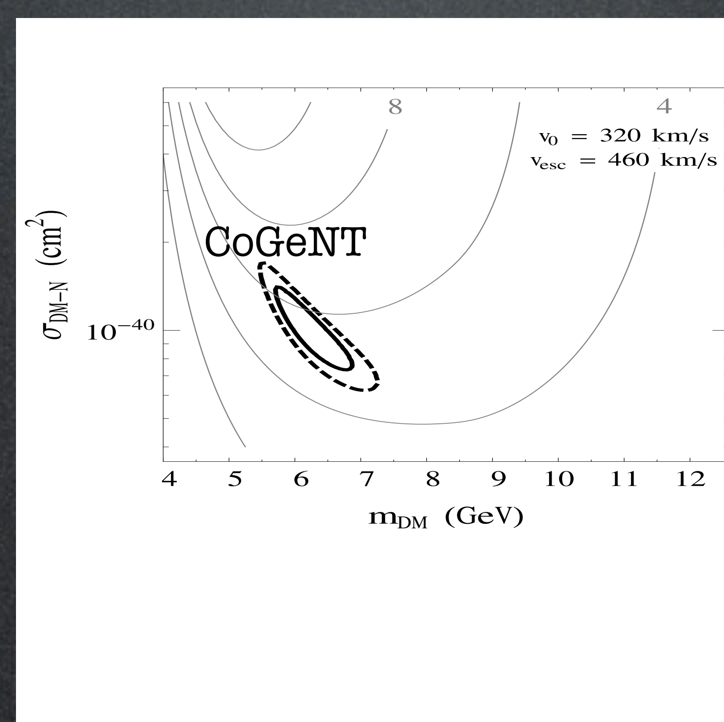
Farina+Pappadopulo+Strumia+ Volansky, 1107.0715



Arina+Hamann+Wong, 1105.5121

Boycott

(Kopp+)Schwetz+Zupan, 1106.6241 & 1110.



Hooper+Kelso, 1106.1066

Comments:

- not big quantitative change

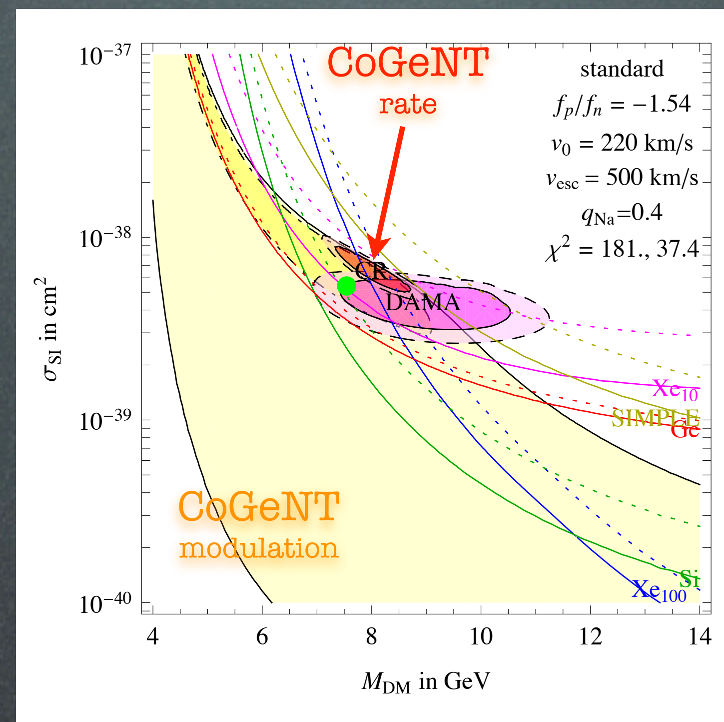
Direct Detection: hints

Plotolympics 2011: fits performed by different groups

Discipline: Isospin Fit: assuming different coupling to **p** and **n**...

Boycott

Belli+Fornengo+al., 1106.4667



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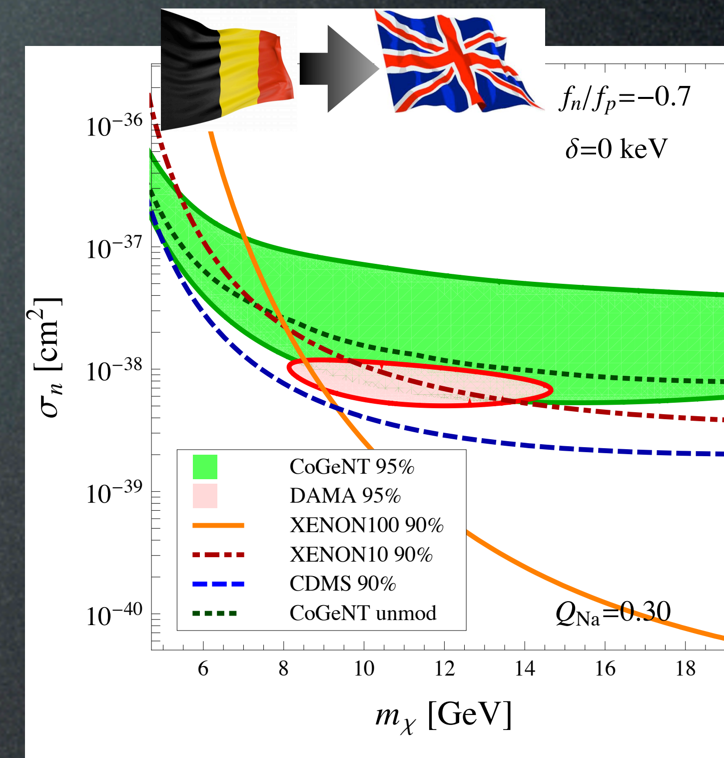
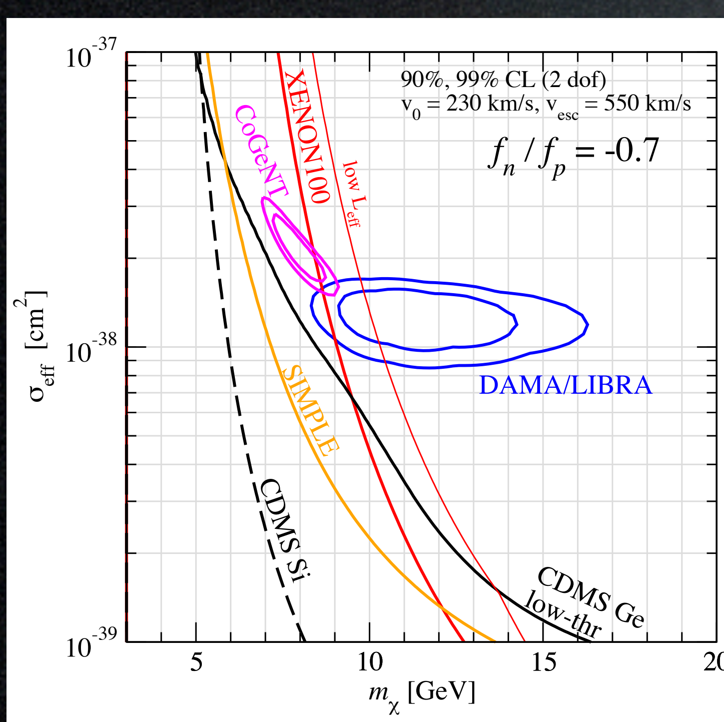


Frandsen+Kahlhoefer+al., 1105.3734



(Kopp+)Schwetz+Zupan, 1106.6241 & 1110.

Not qualified

Hooper+Kelso, 1106.1066

Comments:

- those who dared to try find some improvement

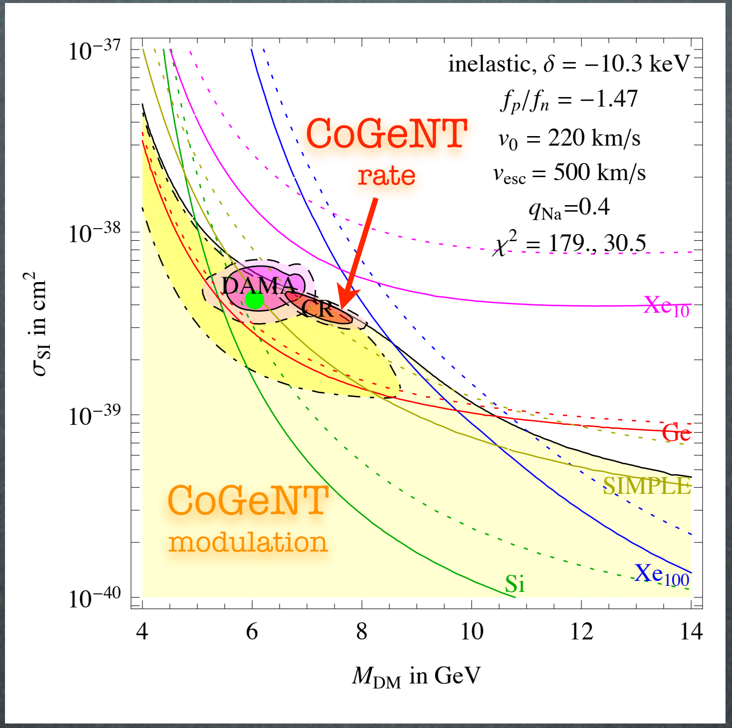
Direct Detection: hints

Plotolympics 2011: fits performed by different groups

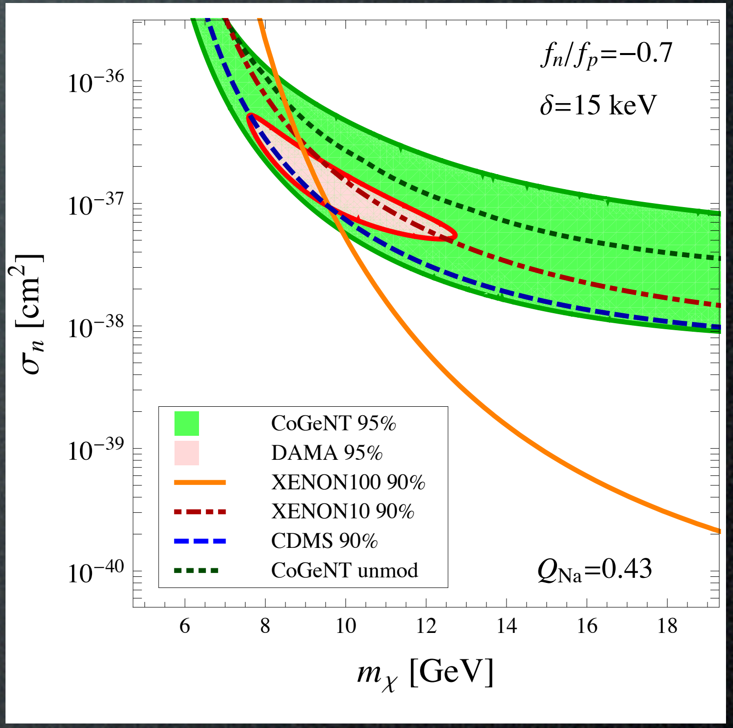
Discipline: Isospin & Inelastic Fit: different coupling + inelastic scatt

Boycott

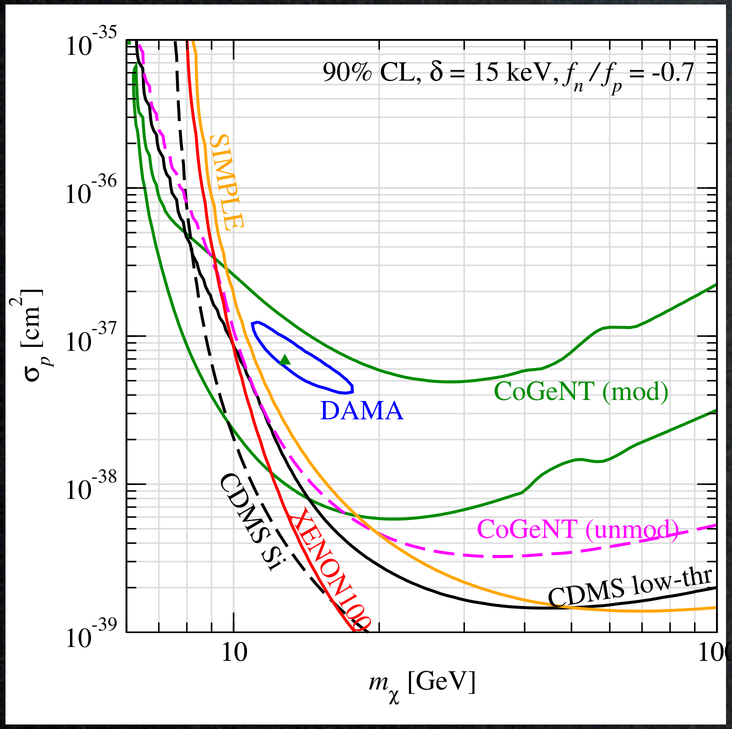
Belli+Fornengo+al., 1106.4667



Farina+Pappadopulo+Strumia+Volansky, 1107.0715



Frandsen+Kahlhoefer+al., 1105.3734



(Kopp+)Schwetz+Zupan, 1106.6241 & 1110.

Not qualified

Hooper+Kelso, 1106.1066

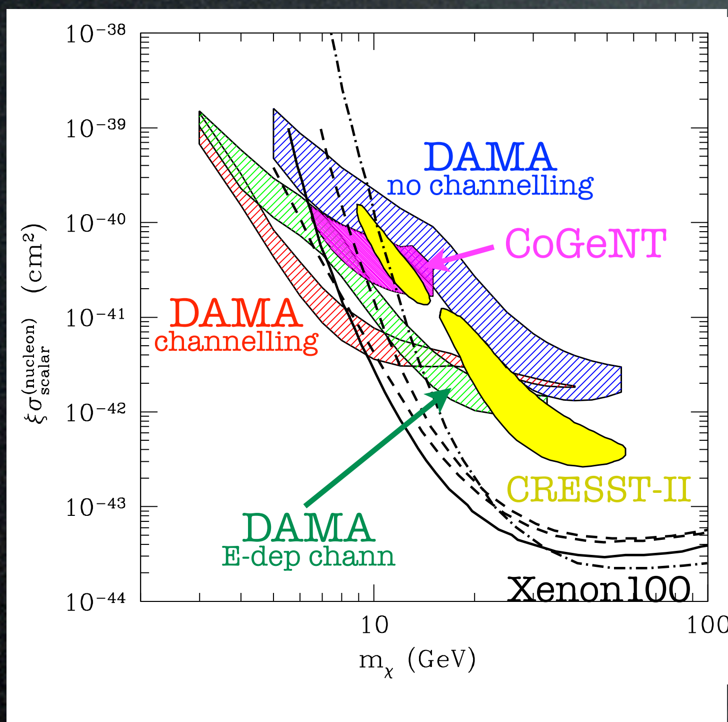
Comments:

- those who dared to try find some **more** improvement

Direct Detection: hints

Plotolympics 2011: fits performed by different groups

Discipline: CRESST-II overtime: add 1109.0702



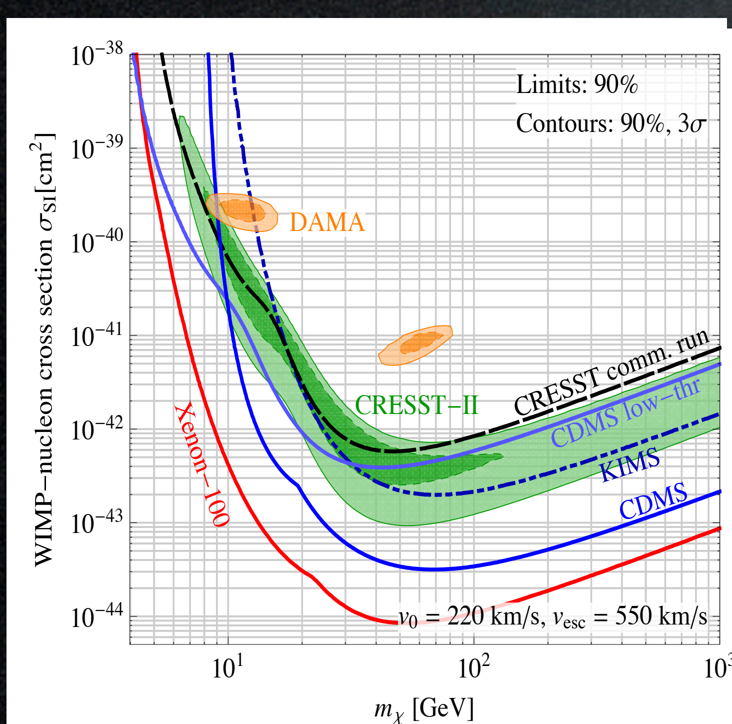
Belli+Fornengo+al., 1106.4667

No show

Farina+Pappadopulo+Strumia+ Volansky, 1107.0715

No show

Frandsen+Kahlhoefer+al., 1105.3734



(Kopp+)Schwetz+Zupan, 1106.6241 & 1110.

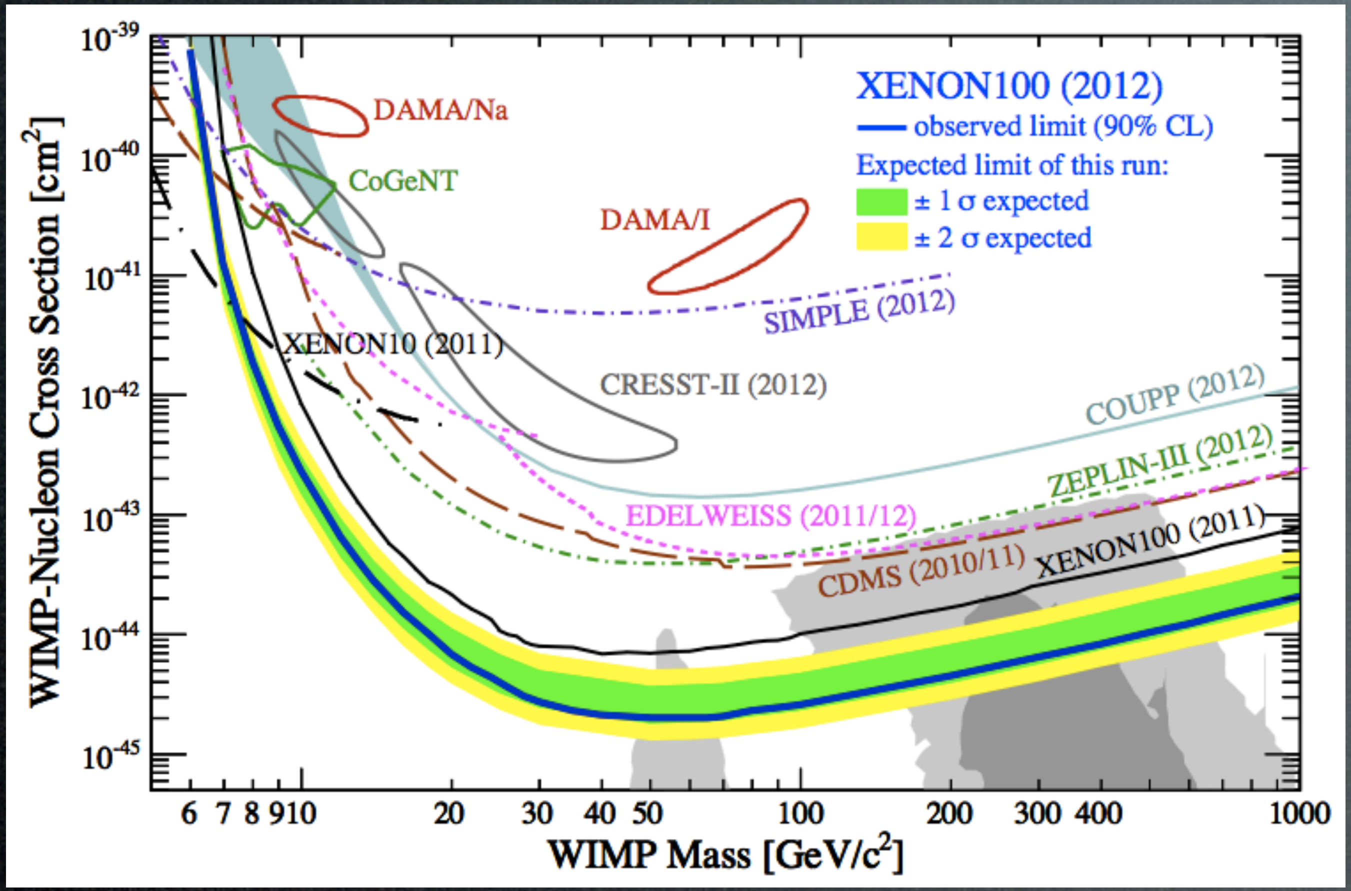
No show

Hooper+Kelso, 1106.1066

Comments:

- does CRESST-II agree or not?

Direct Detection: constraints



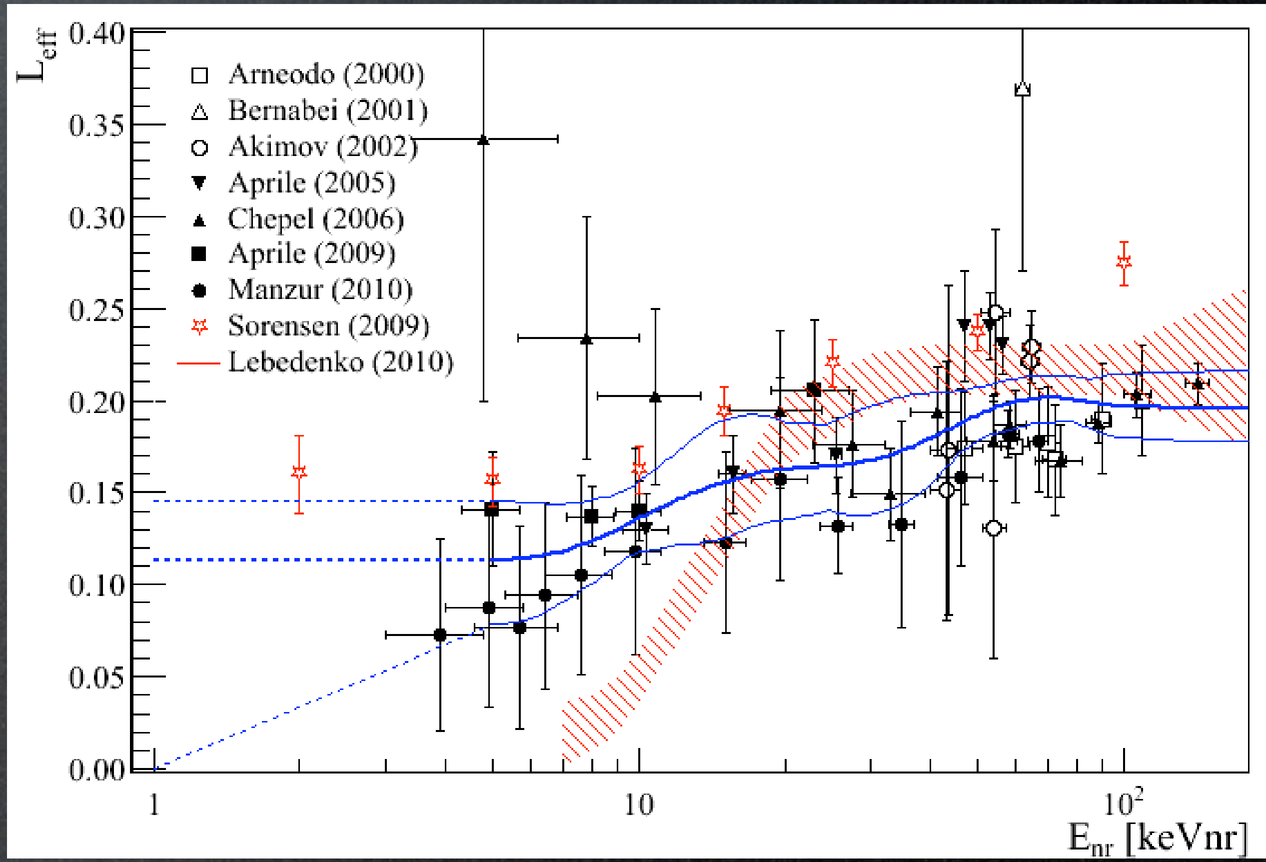
Xenon 100 XENON 100 Coll., 1207.5988

225 live days

2 events seen

(1.0 exp'd bkgd)

scintillation efficiency in LXe

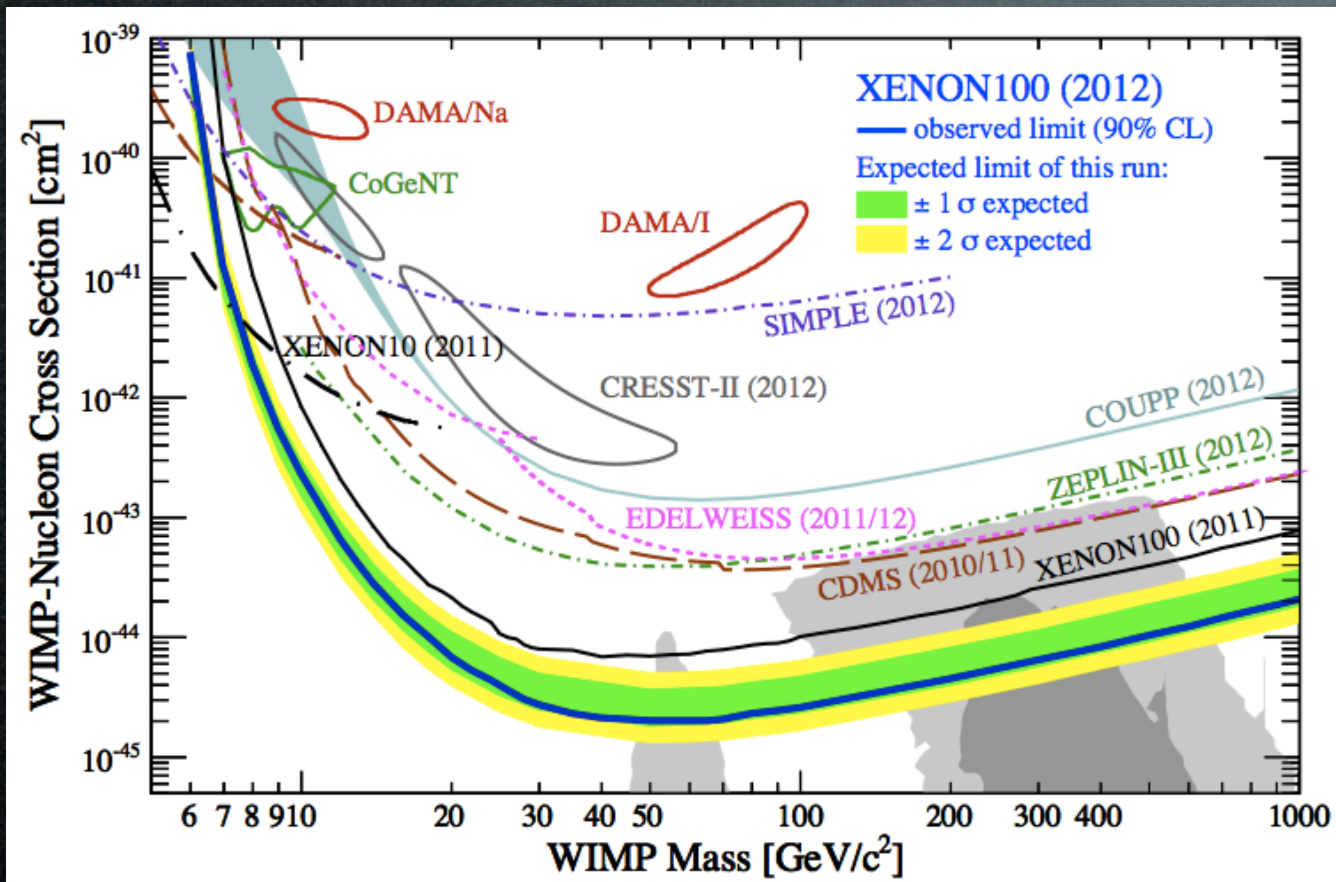


XENON 100 Coll., 1005.2615

ferocious criticism in

Collar & McKinsey, 1005.0838v1, v2, v3

Direct Detection: constraints



Xenon 100 XENON 100 Coll., 1207.5988

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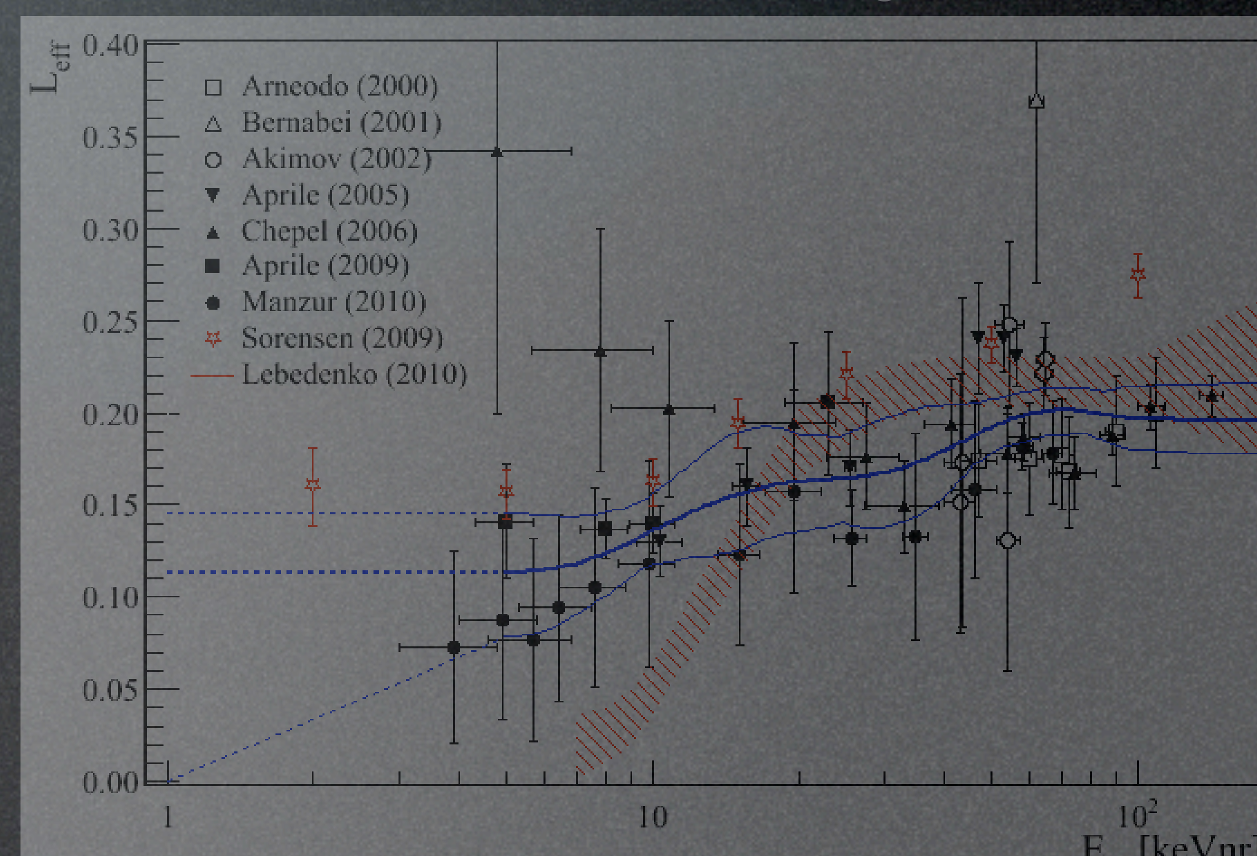
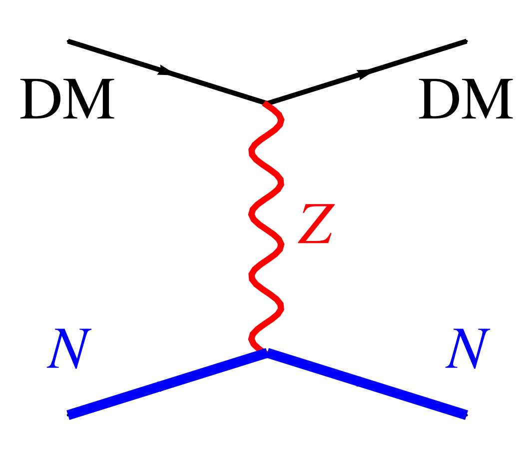


XENON 100 Coll., 1005.2615

ferocious criticism in
Collar & McKinsey, 1005.0838v1, v2, v3

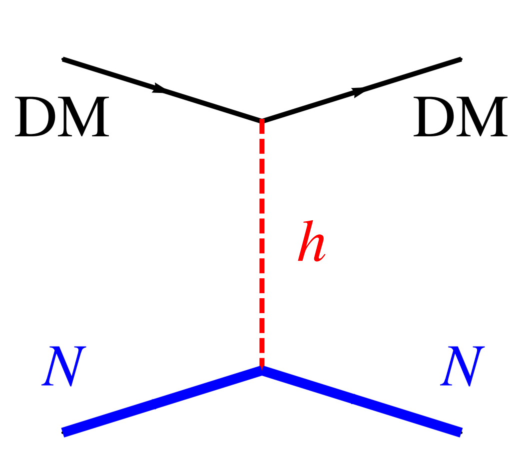
Direct Detection: ‘**theory**’

SM weak scale SI interactions



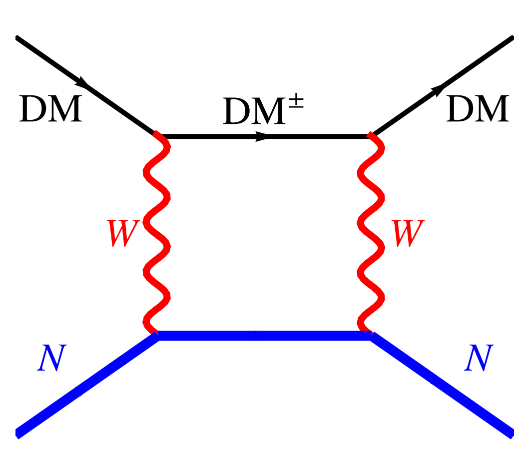
tree level, vector

$$\sigma_{\rm SI} \sim \frac{\alpha^2\ m_N^2}{M_Z^4}$$



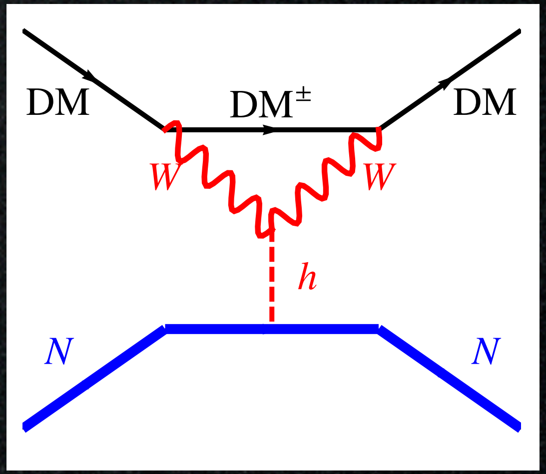
tree level, scalar

$$\sigma_{\rm SI} \sim \frac{\alpha^2\ m_N^4}{M_h^6}$$



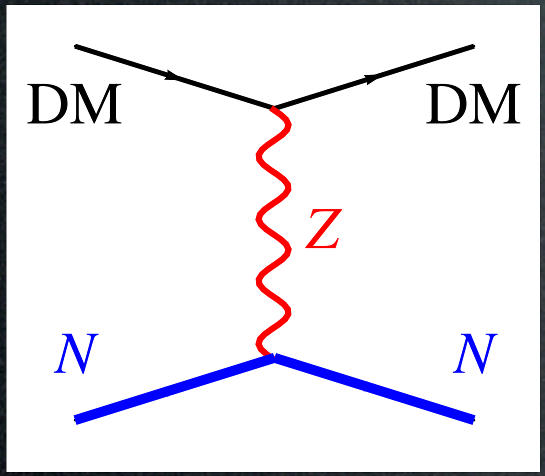
one loop

$$\sigma_{\rm SI} \sim \frac{\alpha^4\ m_N^4}{M_W^6}$$

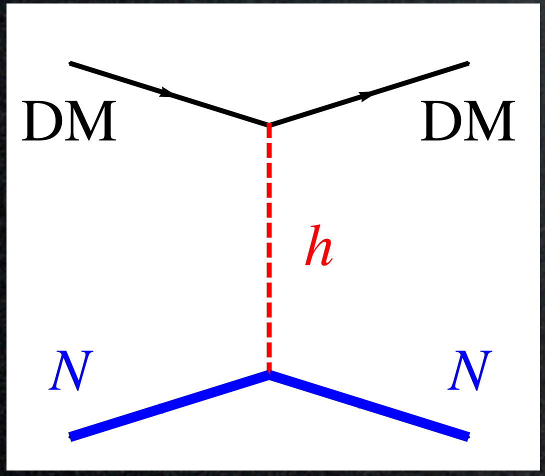


Direct Detection: ‘theory’

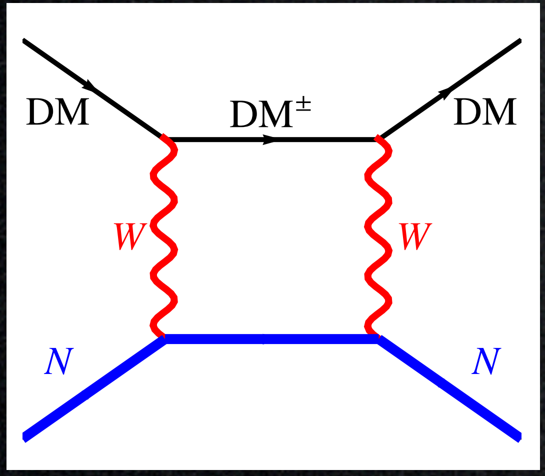
SM weak scale SI interactions



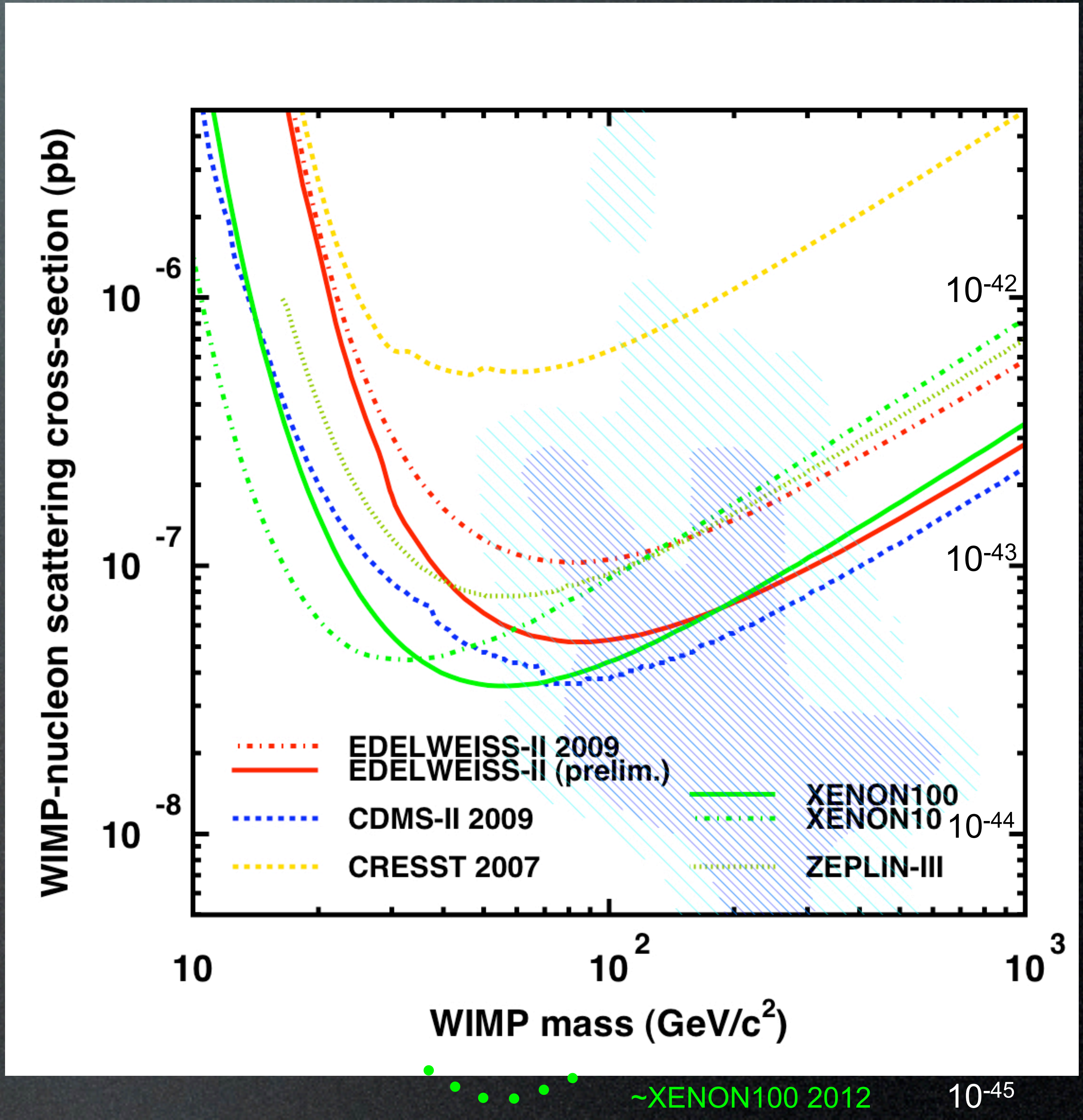
tree level, vector



tree level, scalar



one loop



Edelweiss Collaboration (at TeVPA 2010)

Direct Detection: ‘theory’

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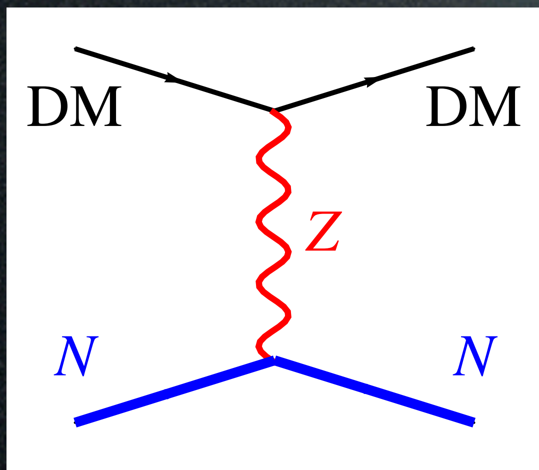
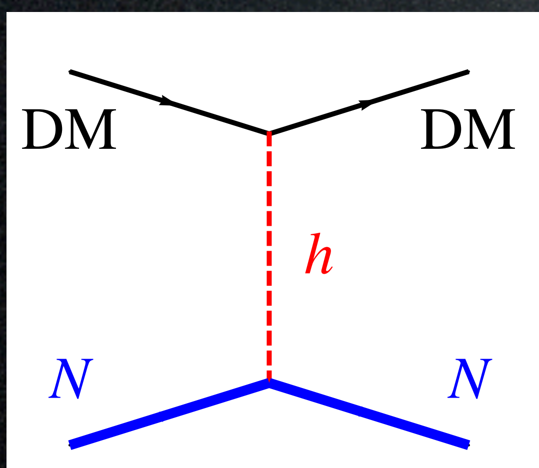
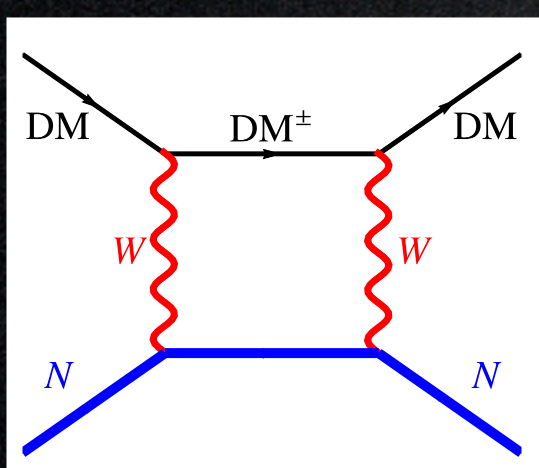


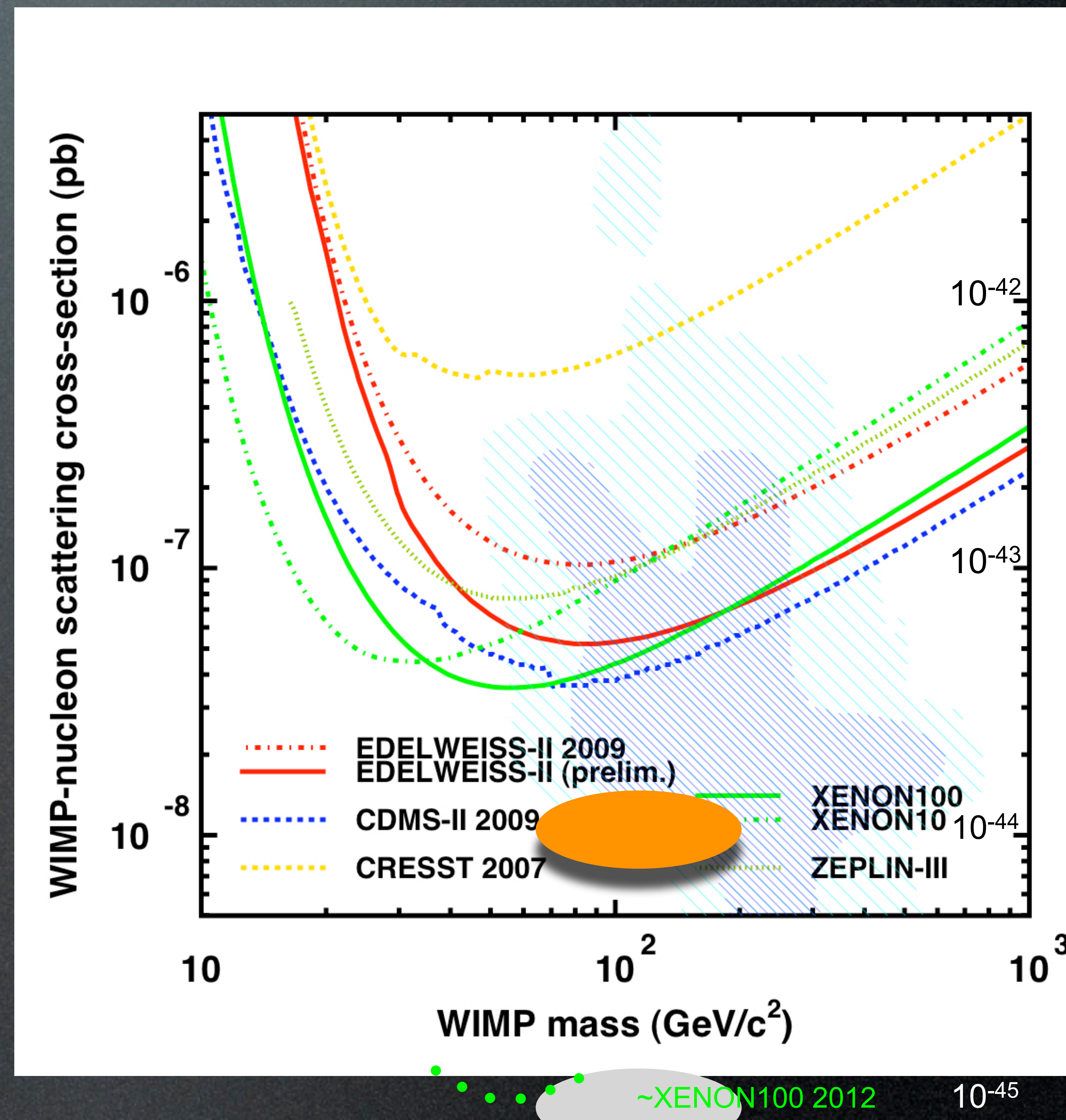
tree level, vector



tree level, scalar



one loop

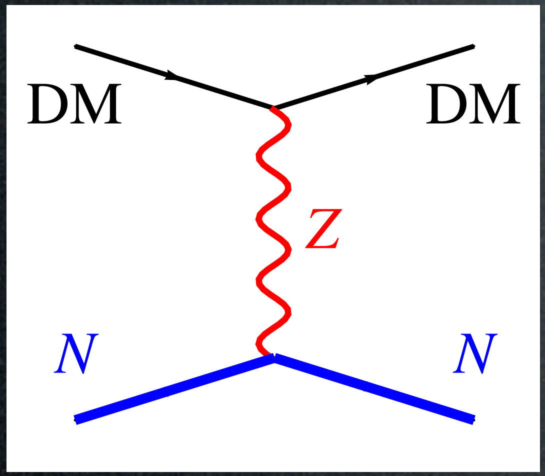


Edelweiss Collaboration (at TeVPA 2010)

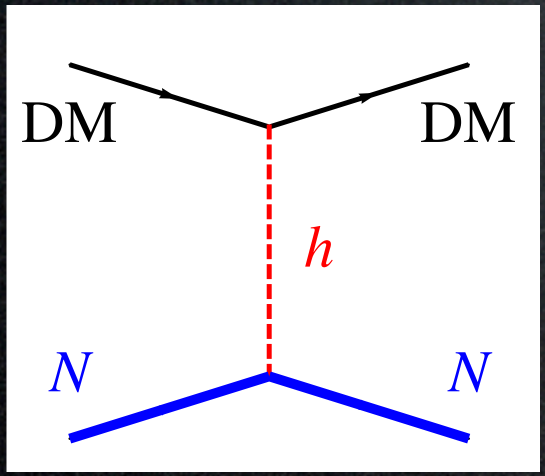
Direct Detection: ‘theory’

SM weak scale SI interactions

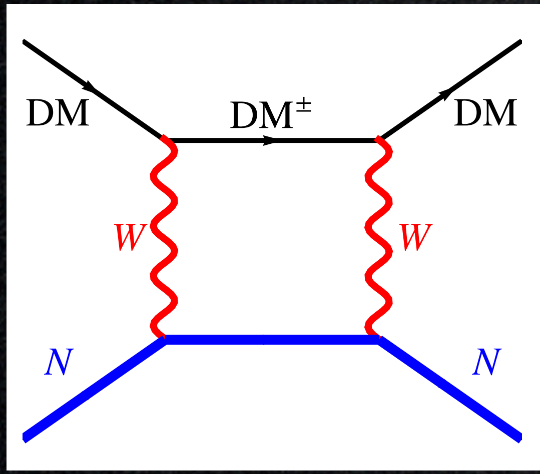
Still viable under which conditions?



tree level, vector



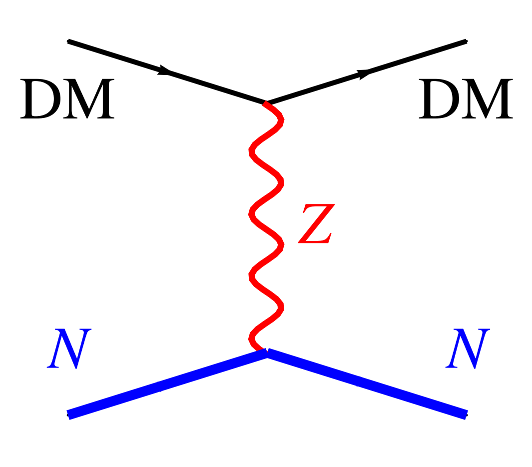
tree level, scalar



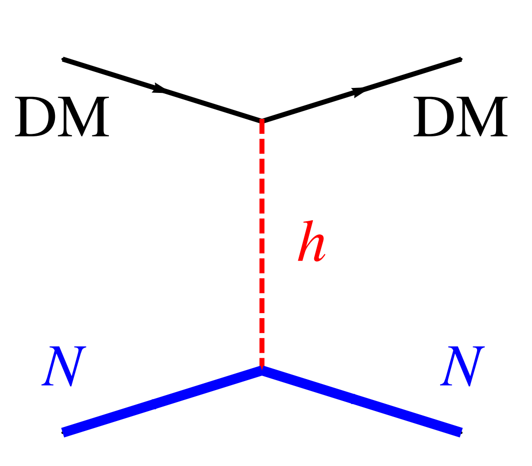
one loop

Direct Detection: ‘theory’

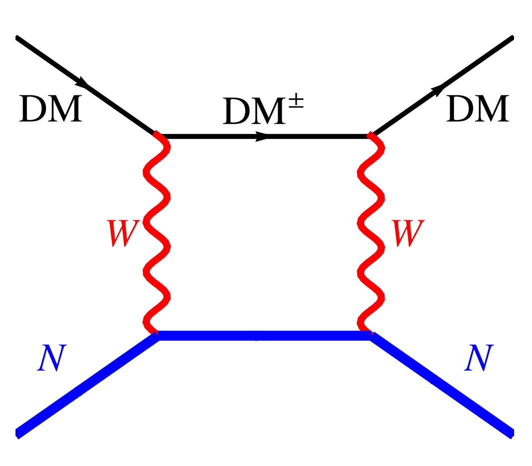
SM weak scale SI interactions



~~tree level, vector~~



tree level, scalar



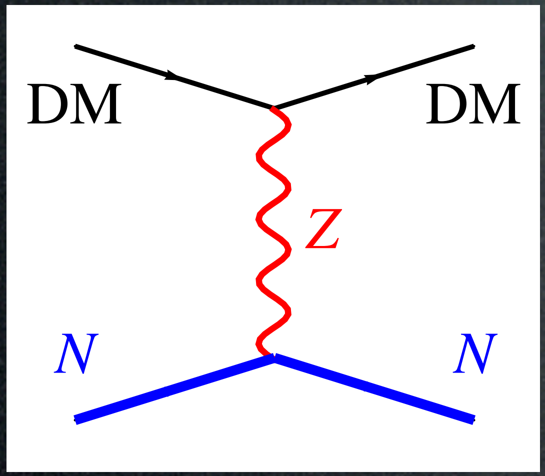
one loop

Still viable under which conditions?

- real particle
  (Majorana fermion, real scalar)

Direct Detection: ‘theory’

SM weak scale SI interactions



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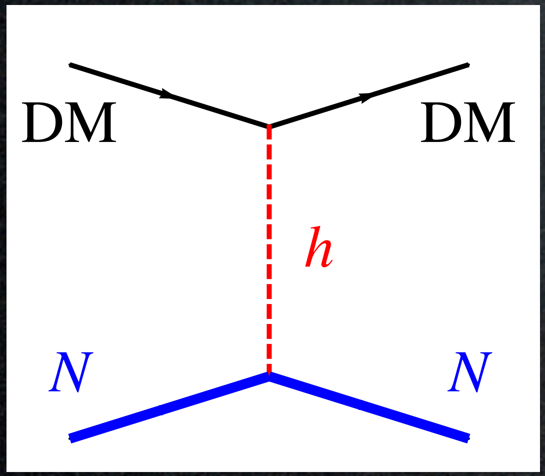

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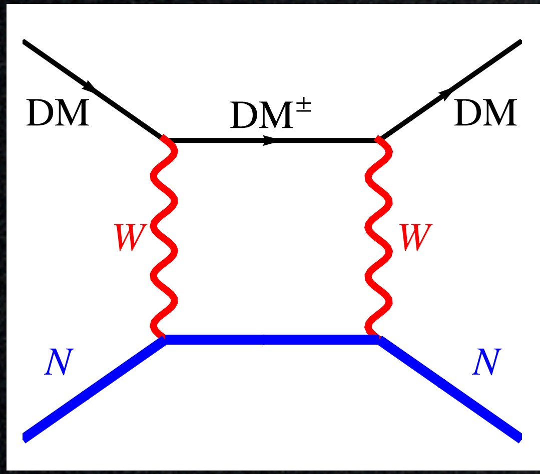


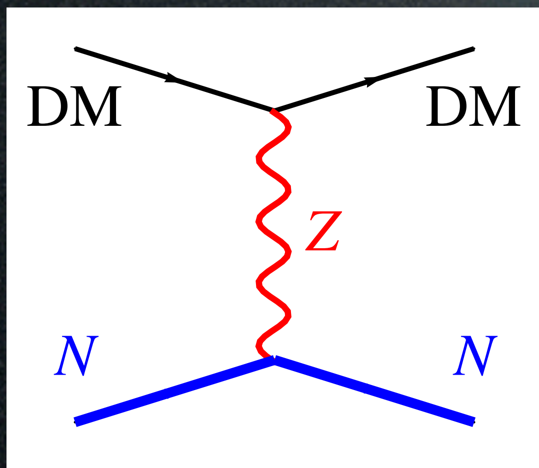
one loop

Still viable under which conditions?

- real particle
  (Majorana fermion, real scalar)
- hypercharge $Y = 0$

Direct Detection: 'theory'

SM weak scale SI interactions



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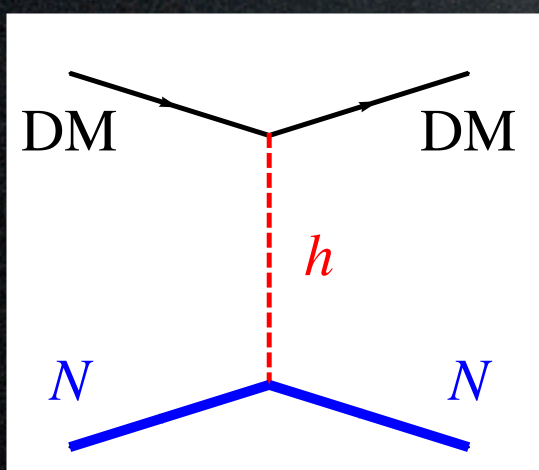
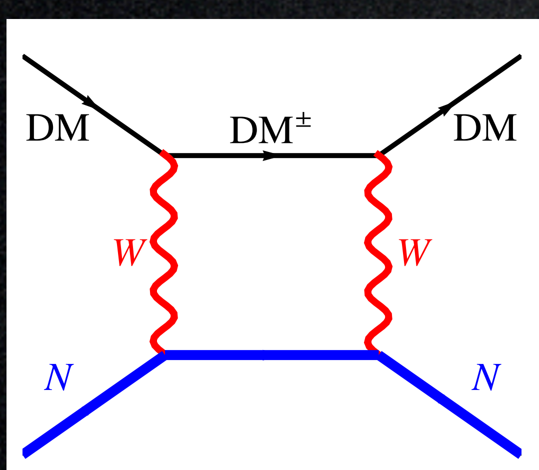


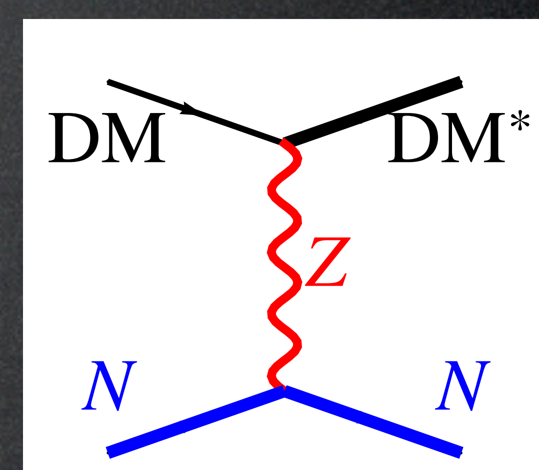
~~tree level, scalar~~



one loop

Still viable under which conditions?

- real particle
  (Majorana fermion, real scalar)
- hypercharge $Y = 0$
- SD interactions only
- inelastic scattering



Conclusions

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The field of Dark Matter searches is thriving (mainly data driven).

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'Anomalies' pop up in many places
(but they also often fade away)

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- DAMA anomaly

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