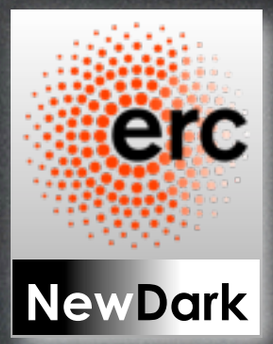
21 November 2014
LAPP Annecy

Dark Matter Indirect Detection:

some anomalies, many constraints, quite some hopes

Marco Cirelli

(CNRS IPhT Saclay)



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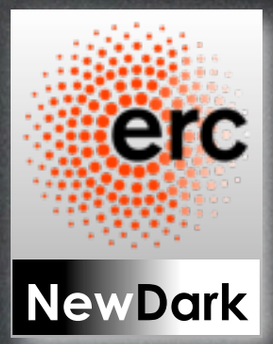

Introduction

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DM exists

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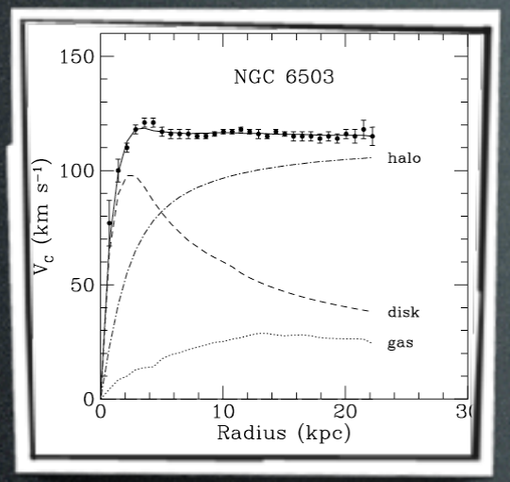
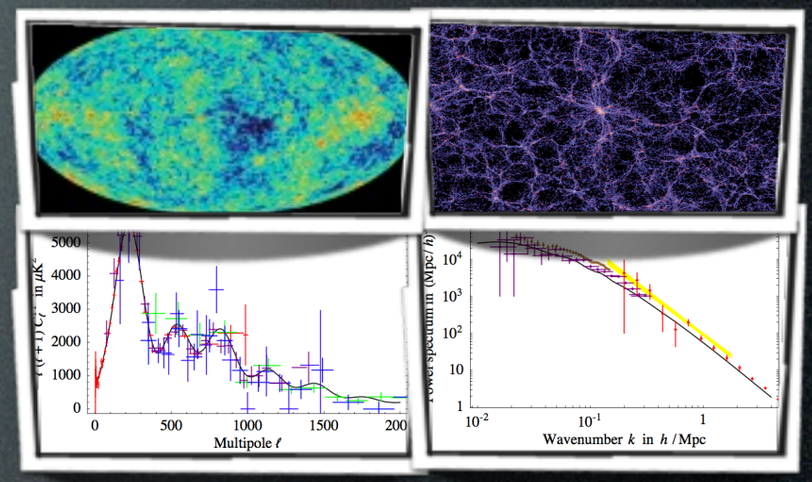


galactic rotation curves

weak lensing (e.g. in clusters)



'precision cosmology' (CMB, LSS)

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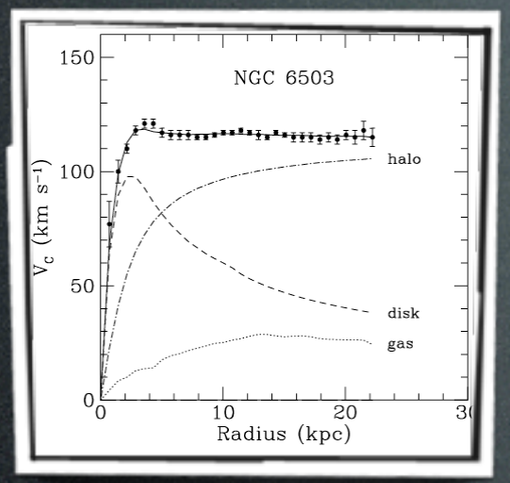

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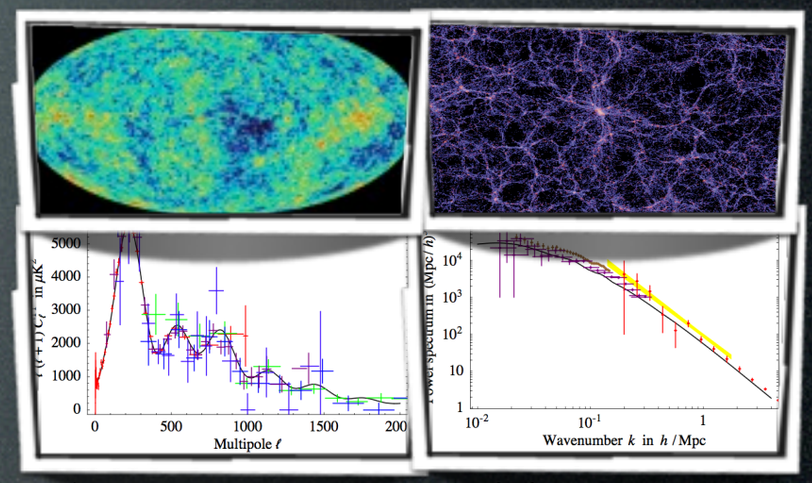

'precision cosmology' (CMB, LSS)

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

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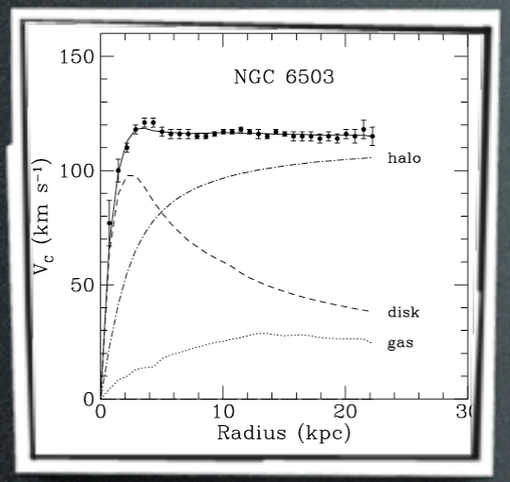

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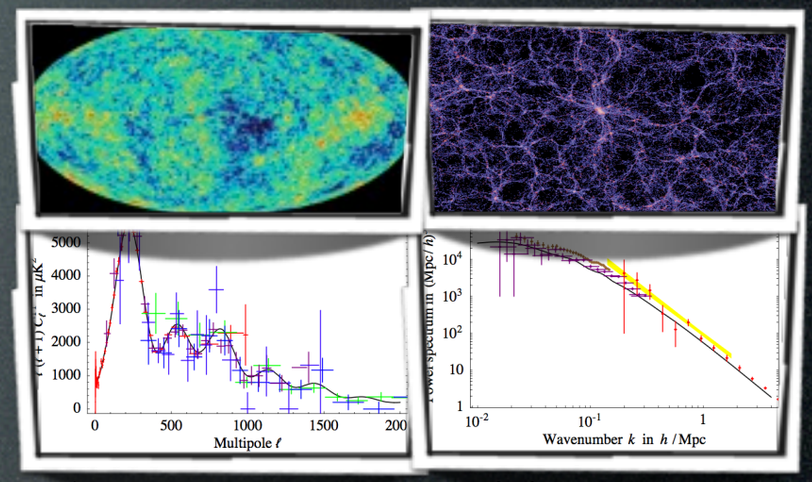
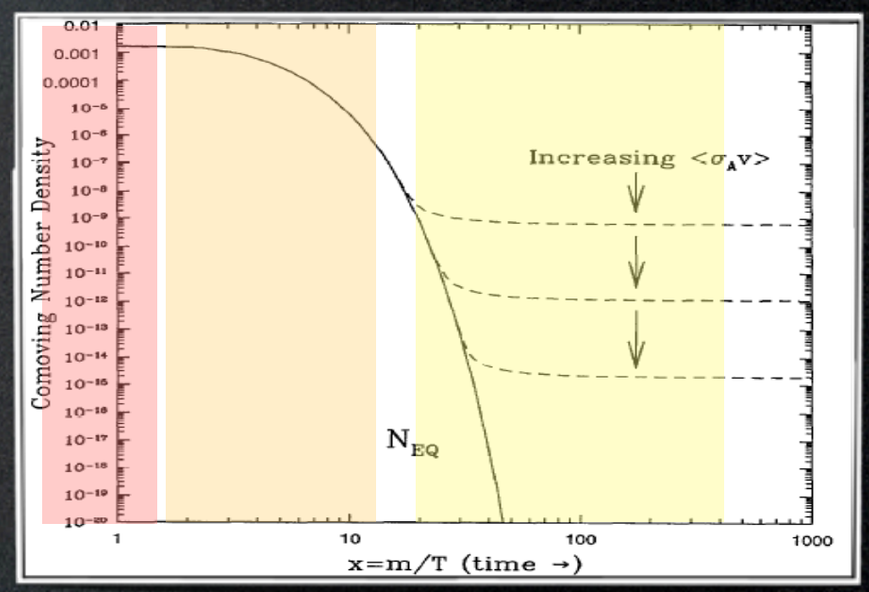


'precision cosmology' (CMB, LSS)

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

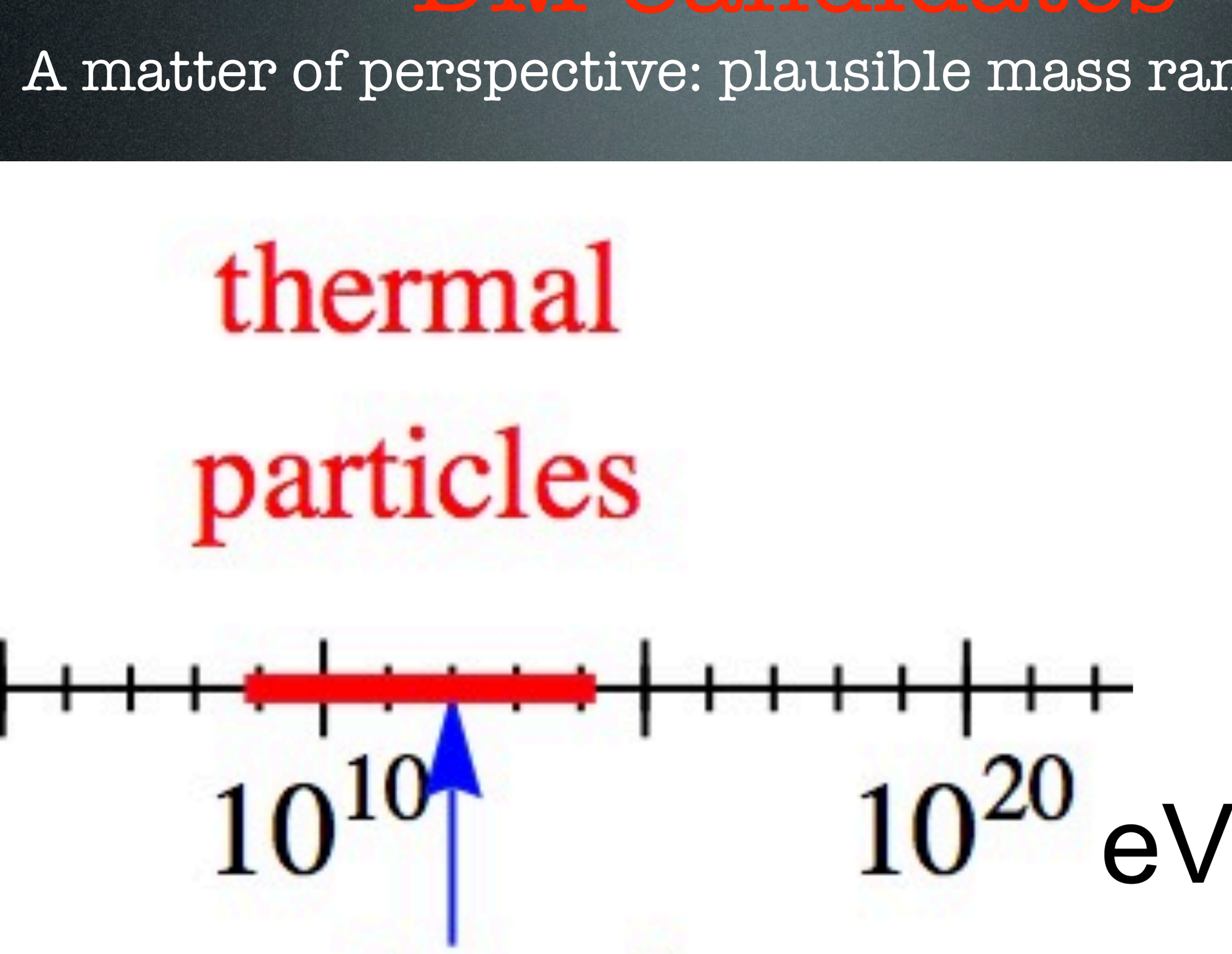


DM Candidates

A matter of perspective: plausible mass ranges

thermal

particles



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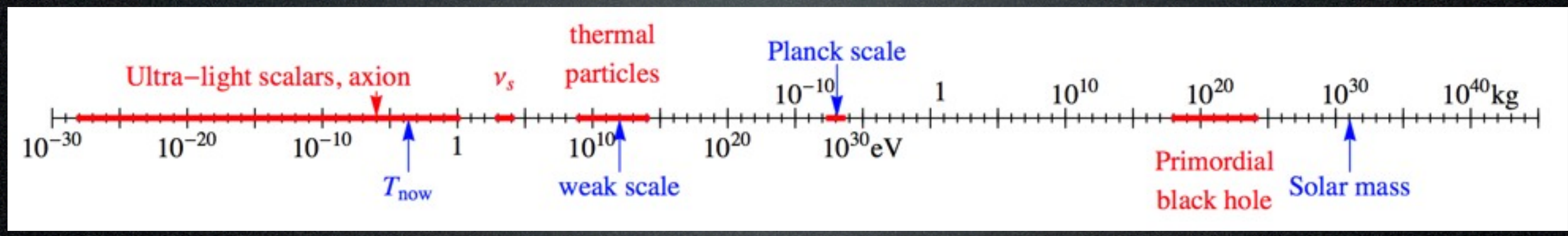


'only' 90 orders of magnitude!

DM Candidates

A matter of perspective: plausible mass ranges

Color code: ID, DD

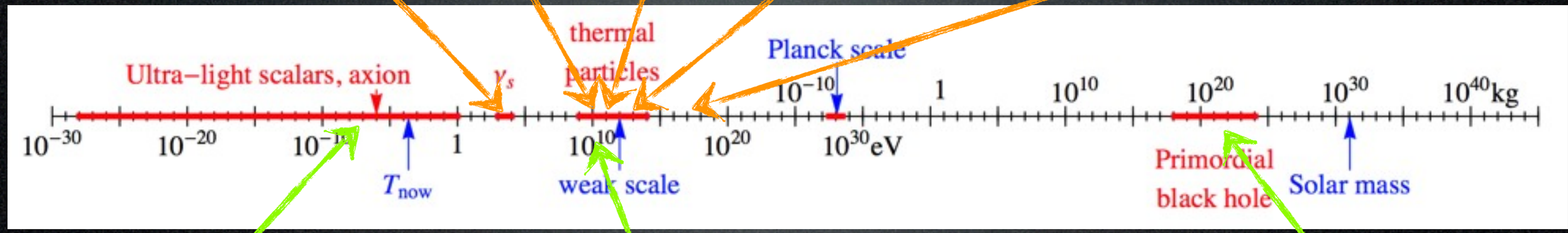
3.5 KeV line

GeV gamma excess at GC

Fermi 135 GeV line

PAMELA, Fermi, HESS excesses

PeV neutrinos Icecube



some activity recently

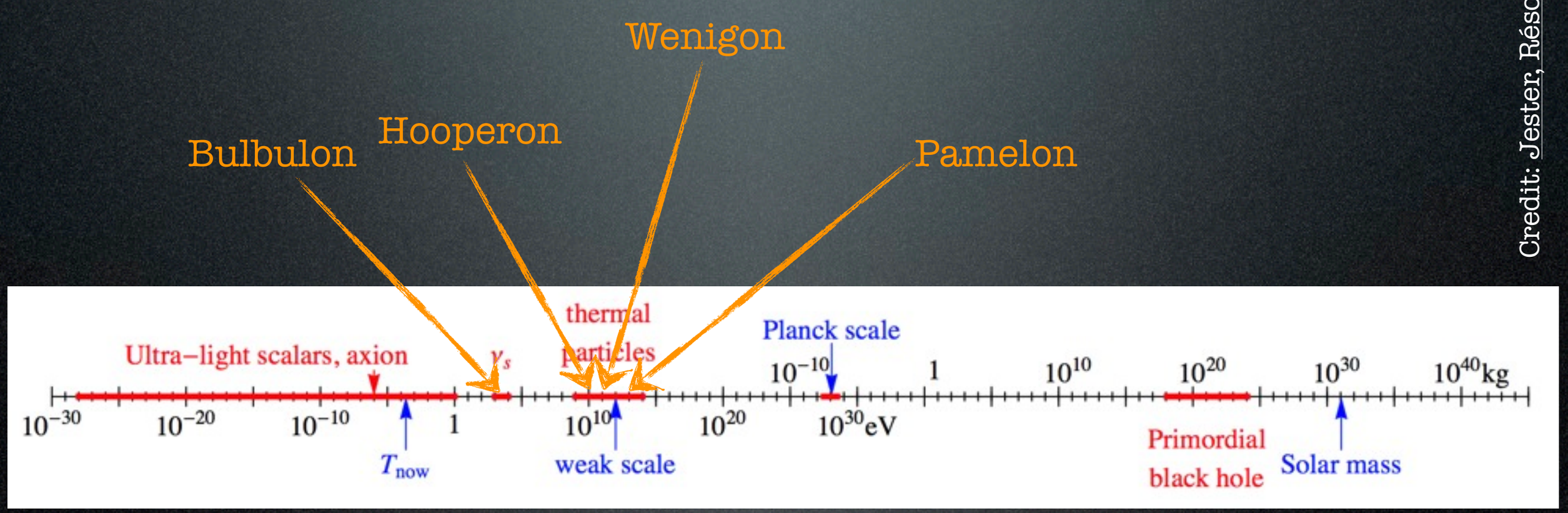
Light DM ('Dama') anomaly

lots of activity recently

'only' 90 orders of magnitude!

DM Candidates

A matter of perspective: plausible mass ranges



Credit: Jester, Résonaances

‘only’ 90 orders of magnitude!

DM detection

direct detection

Xenon, CDMS, Edelweiss... (CoGeNT, Dama/Libra...)

production at colliders

LHC

indirect

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

  Fermi, ICT, radio telescopes...
- e^+ from annihil in galactic halo or center

  PAMELA, Fermi, HESS, AMS, **balloons...**
- $\bar{p}$ 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

  SK, Icecube, Km3Net

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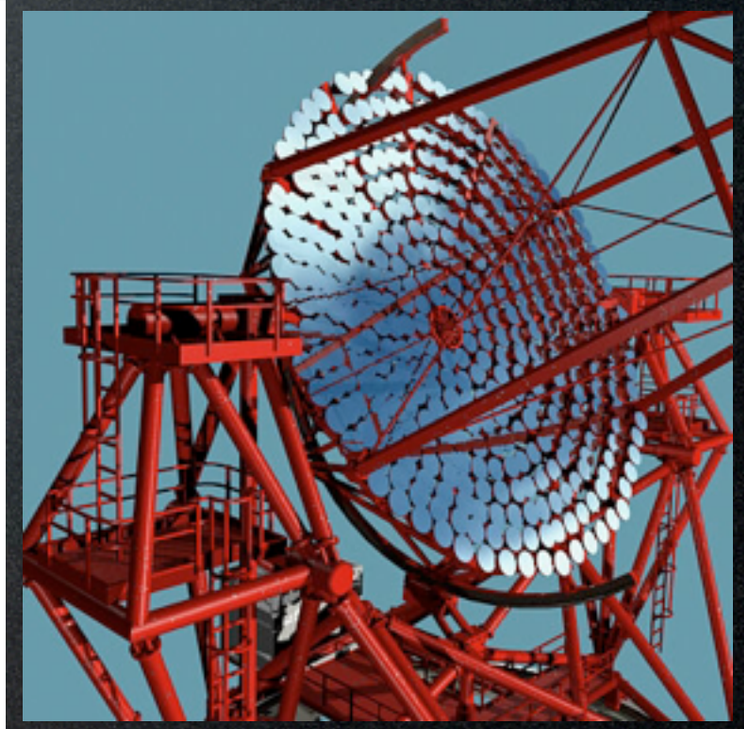
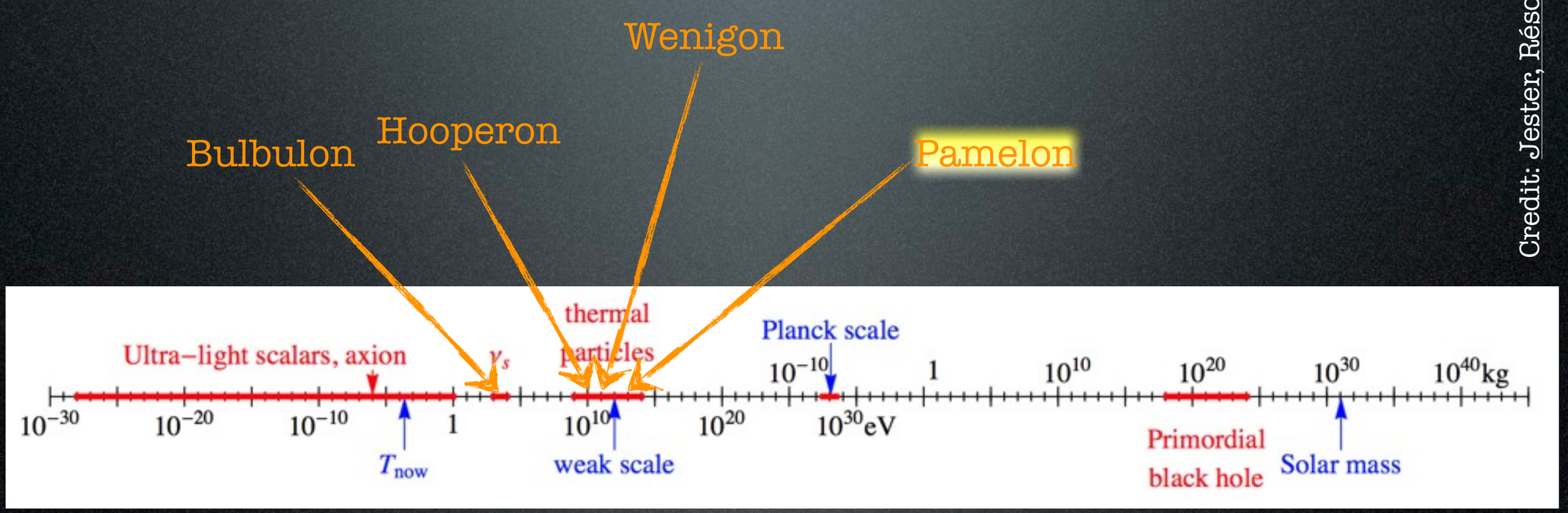
Charged CRs



1. the PAMELA/Fermi/HESS ‘excesses’

DM Candidates

A matter of perspective: plausible mass ranges



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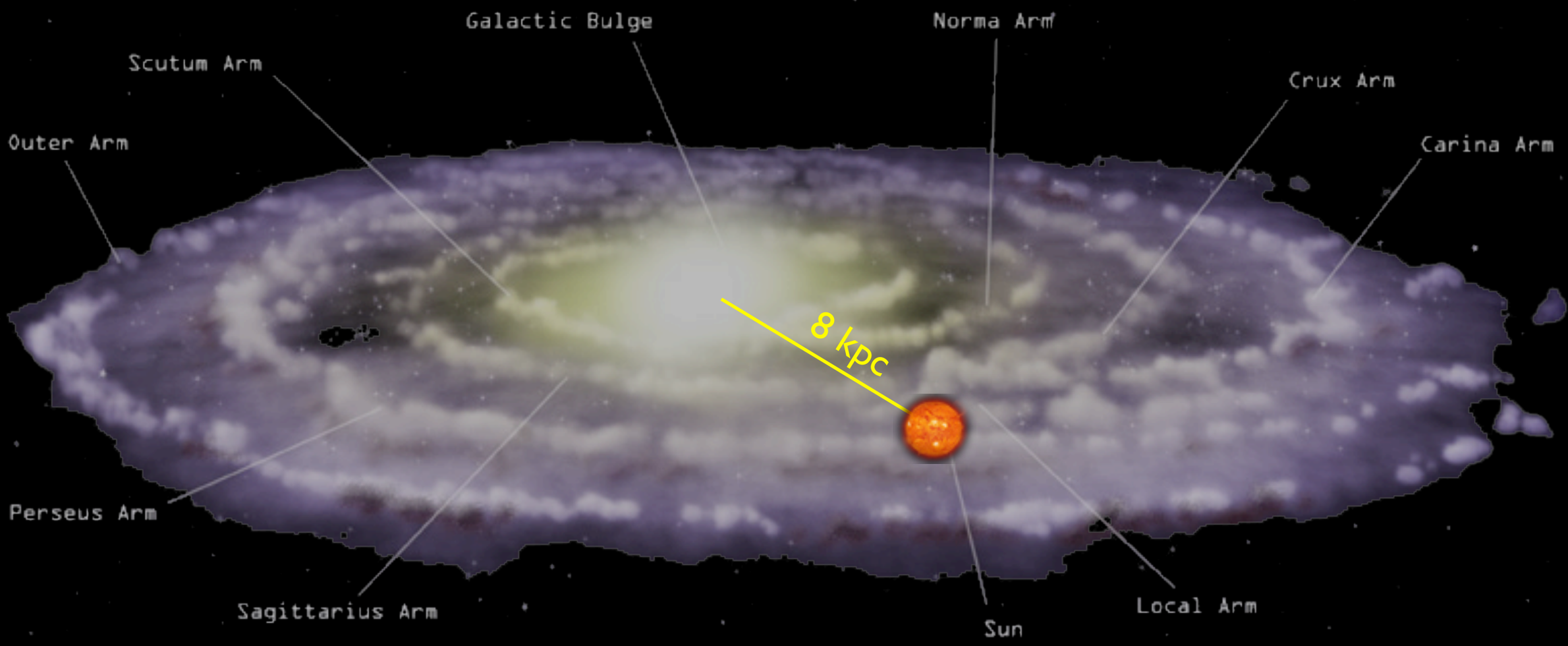
Indirect Detection: basics

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



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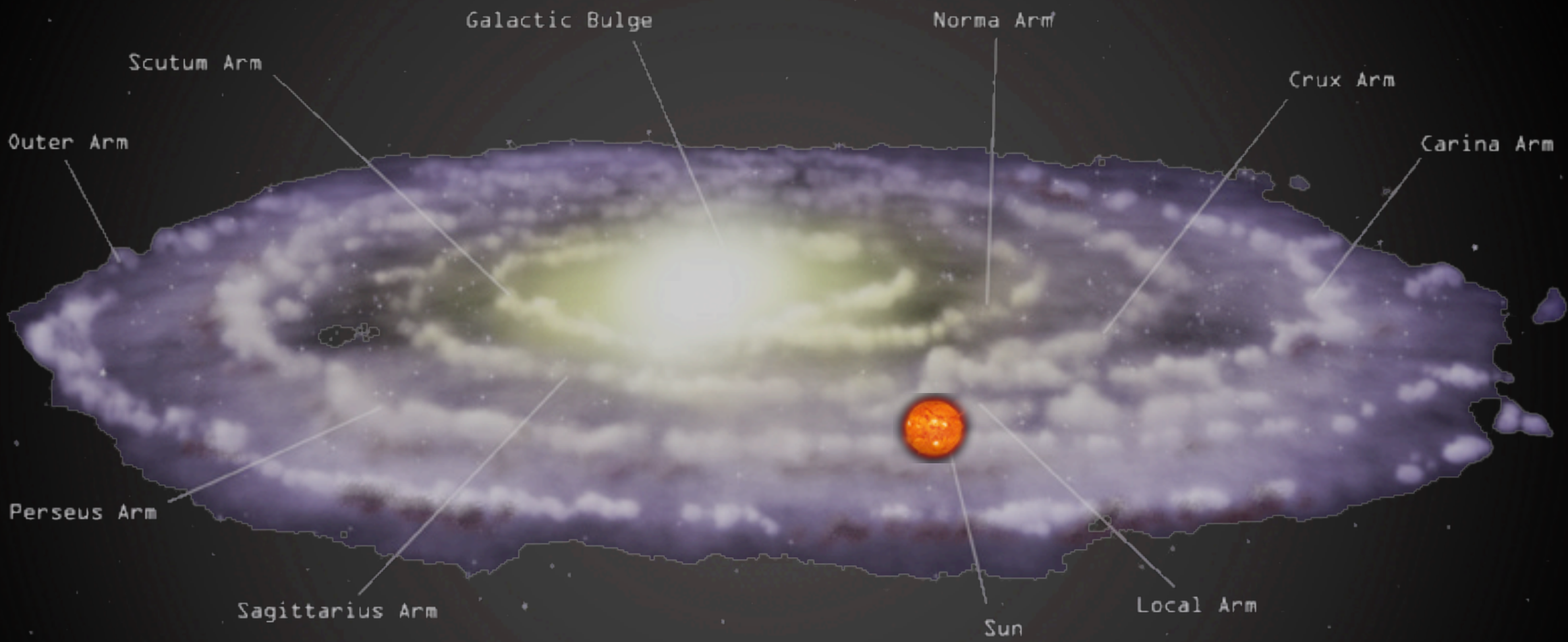

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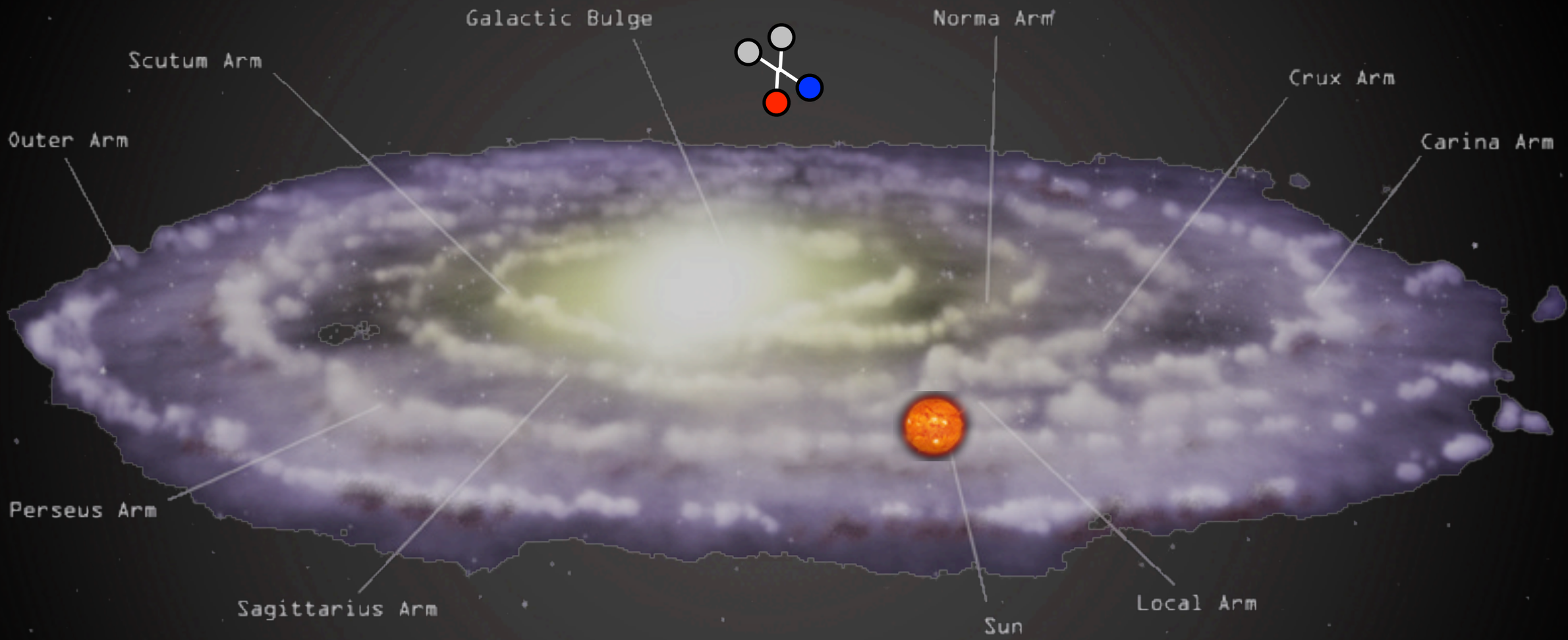

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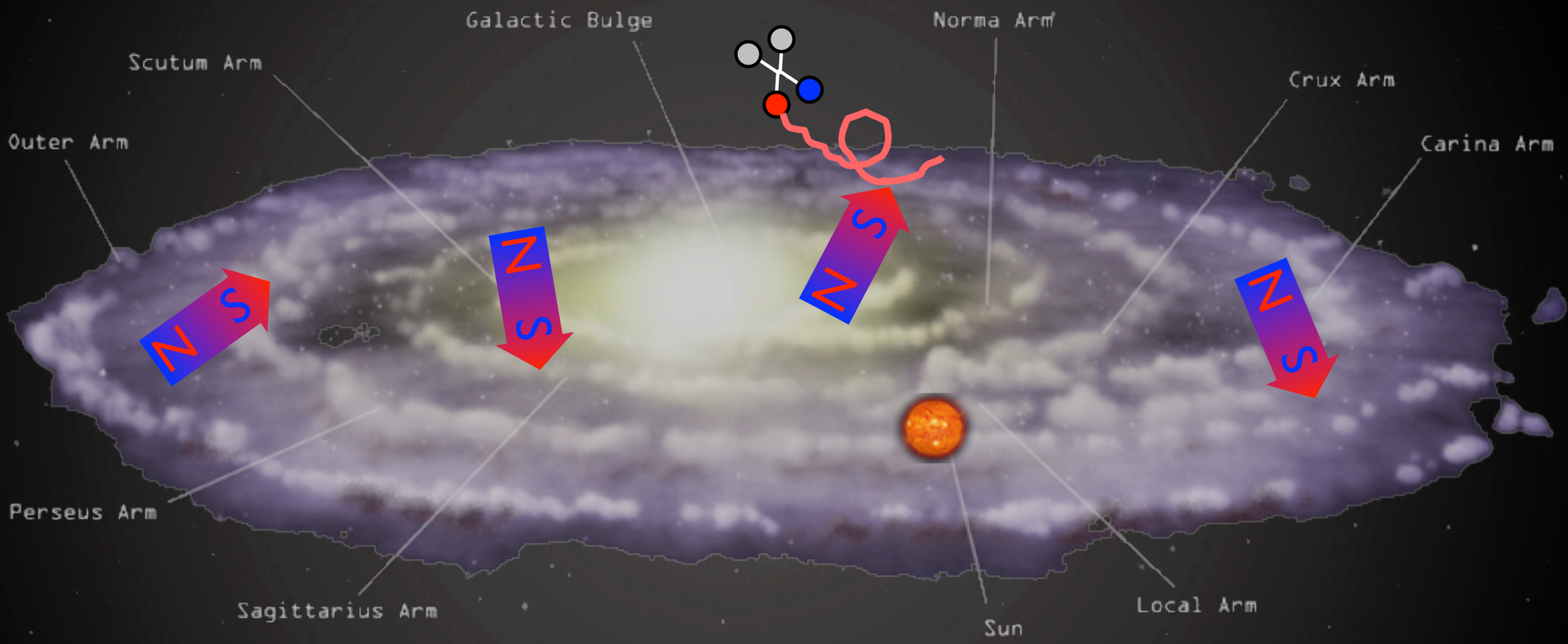

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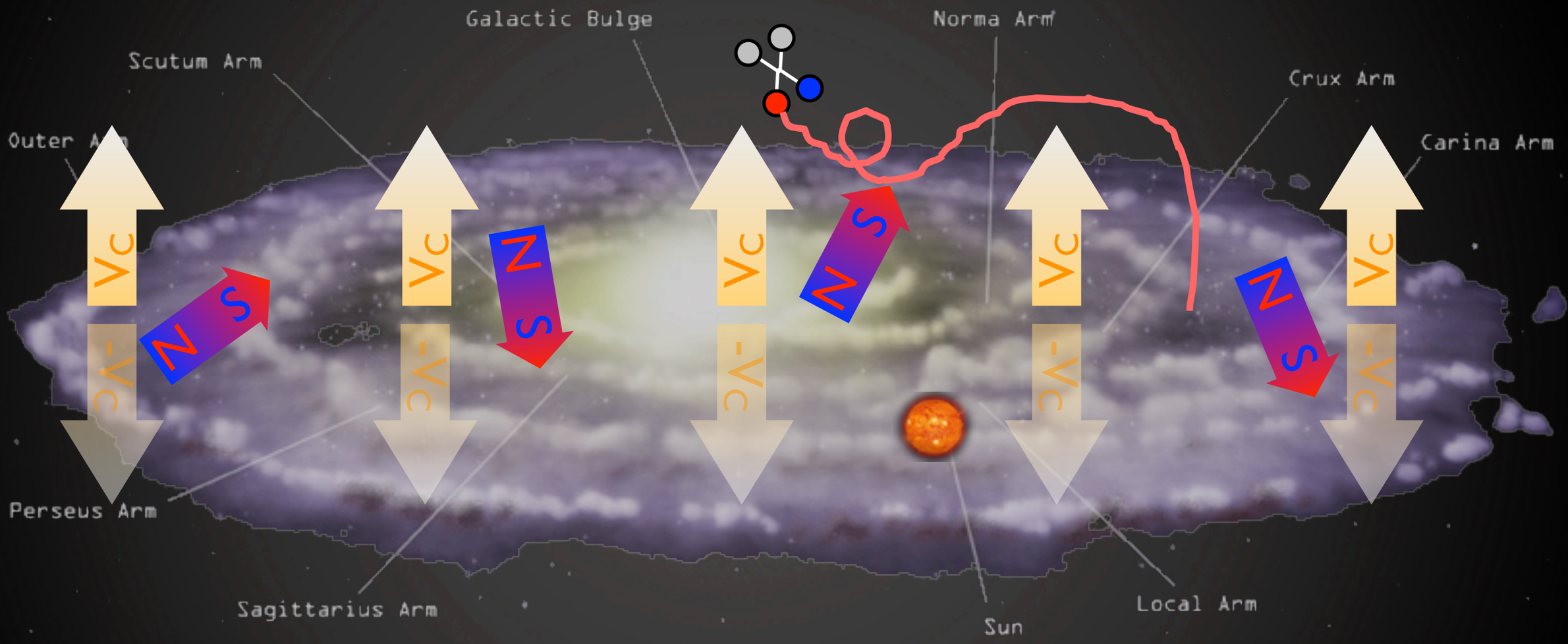

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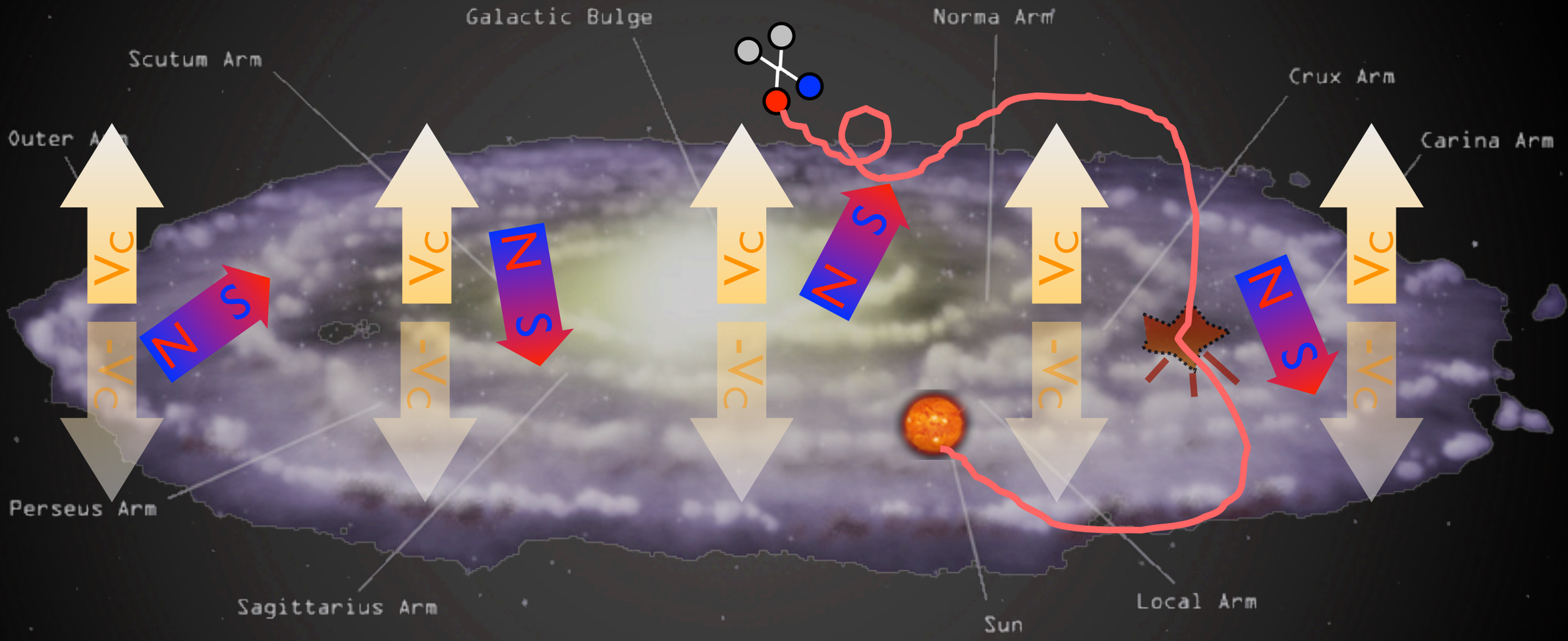

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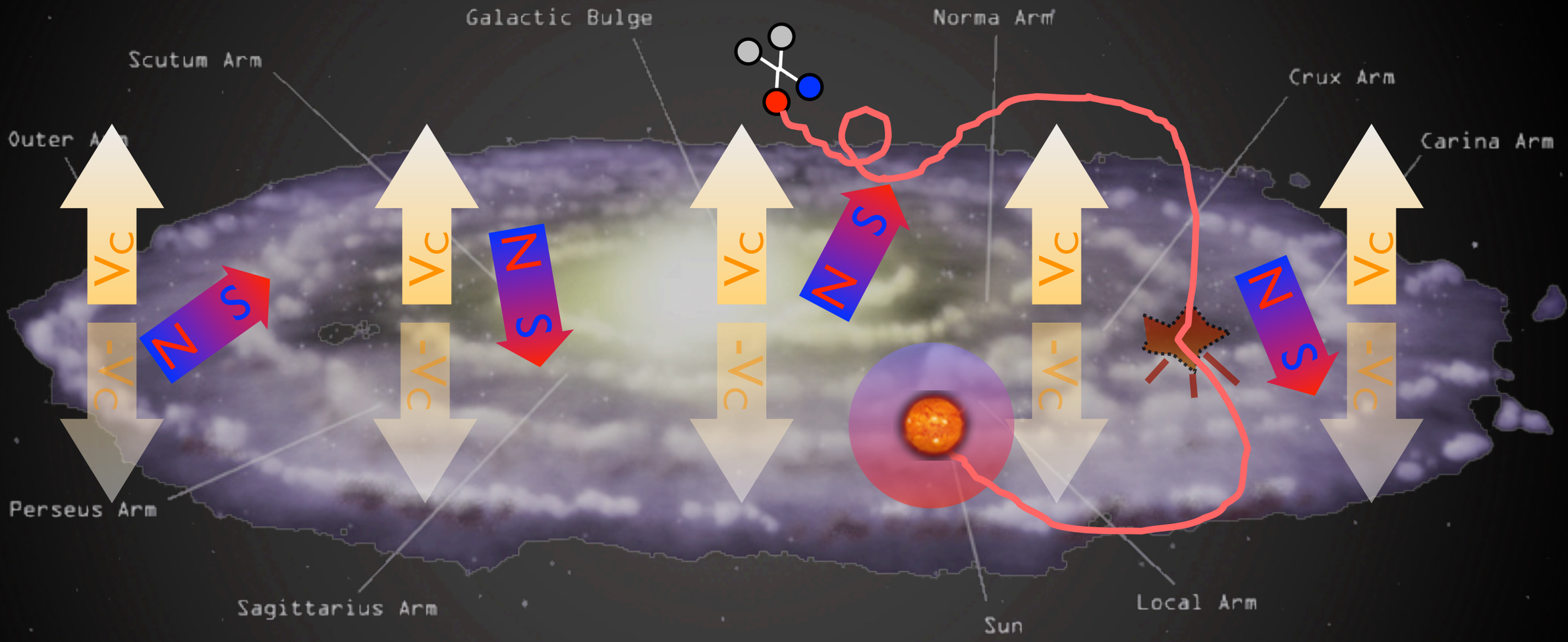

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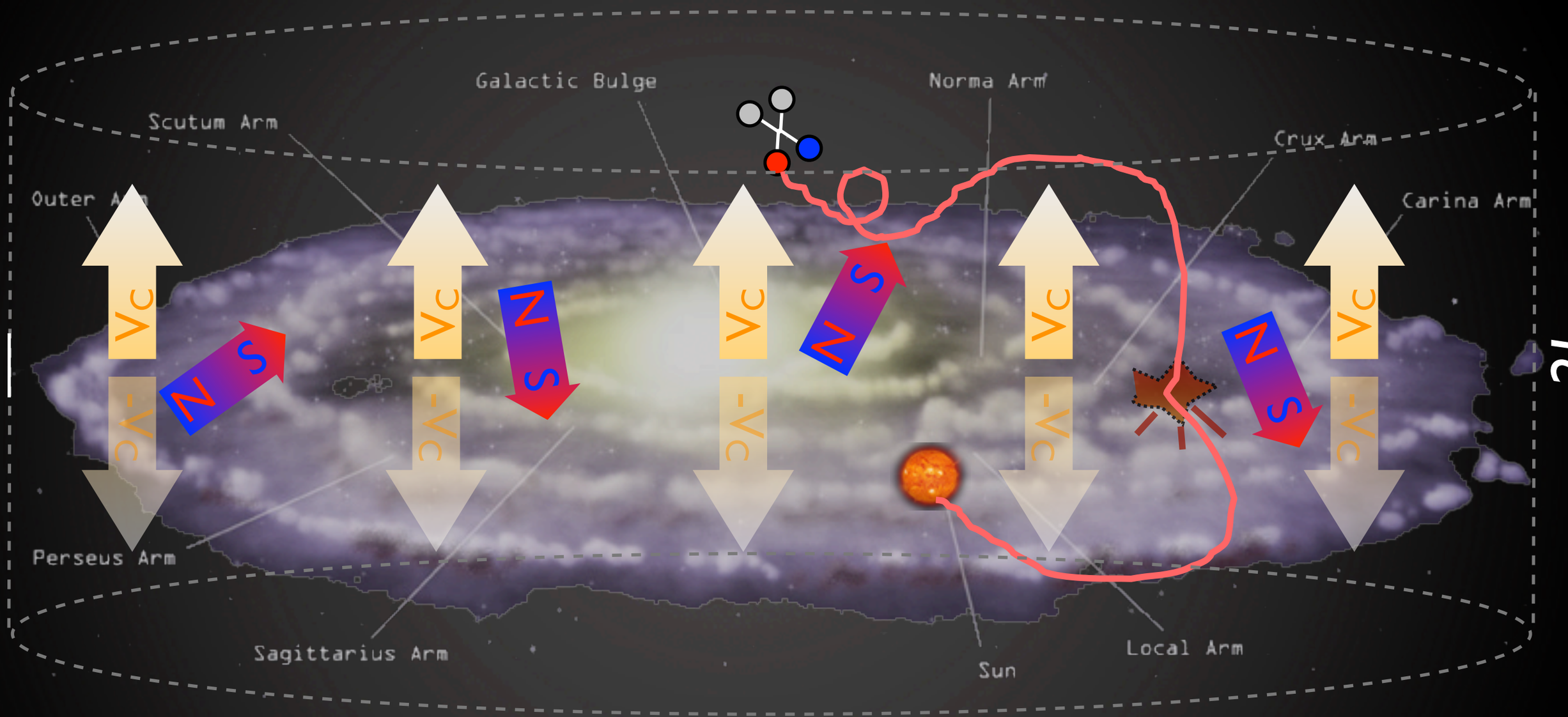


Salati, Chardonnay, Barrau, Donato, Taillet, Fornengo, Maurin, Brun... '90s, '00s

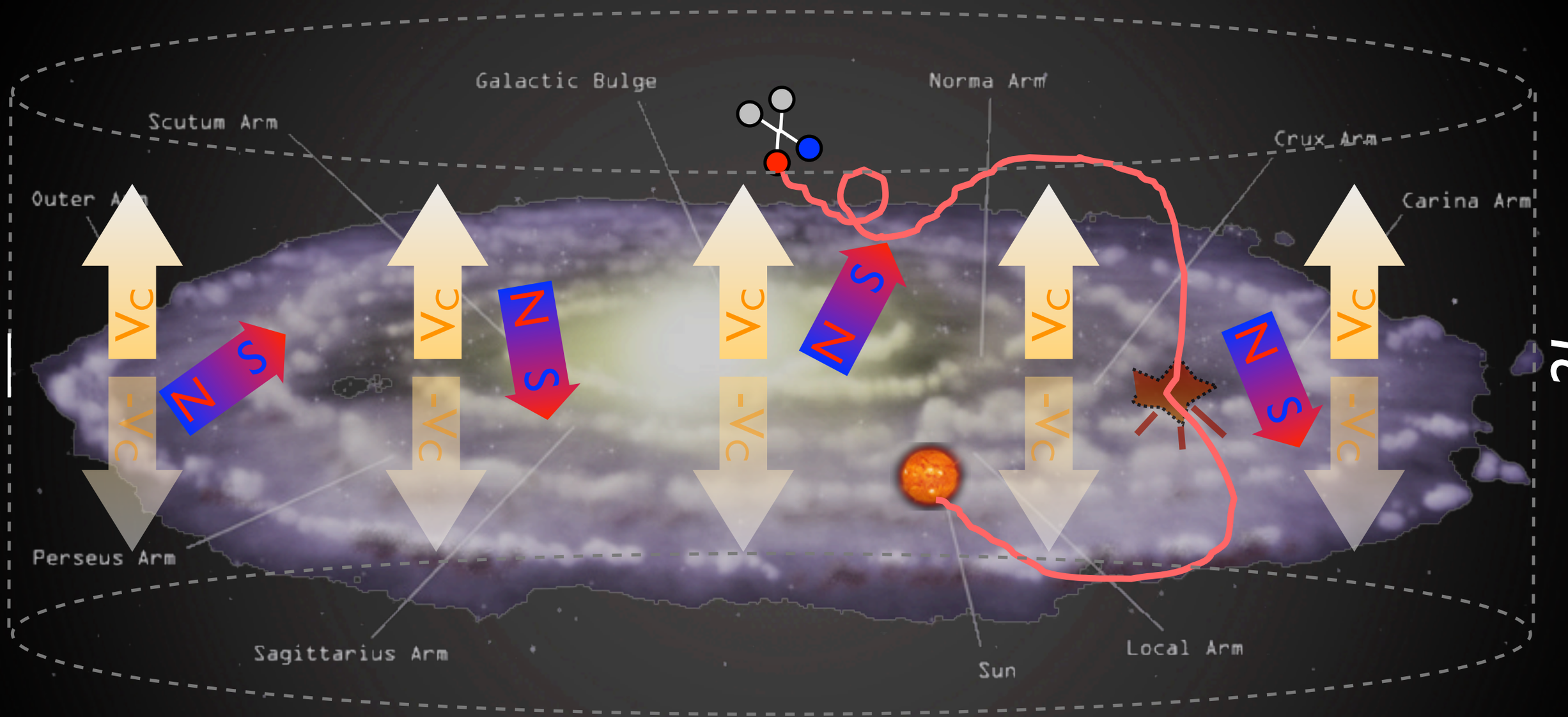
spectrum

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

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?

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

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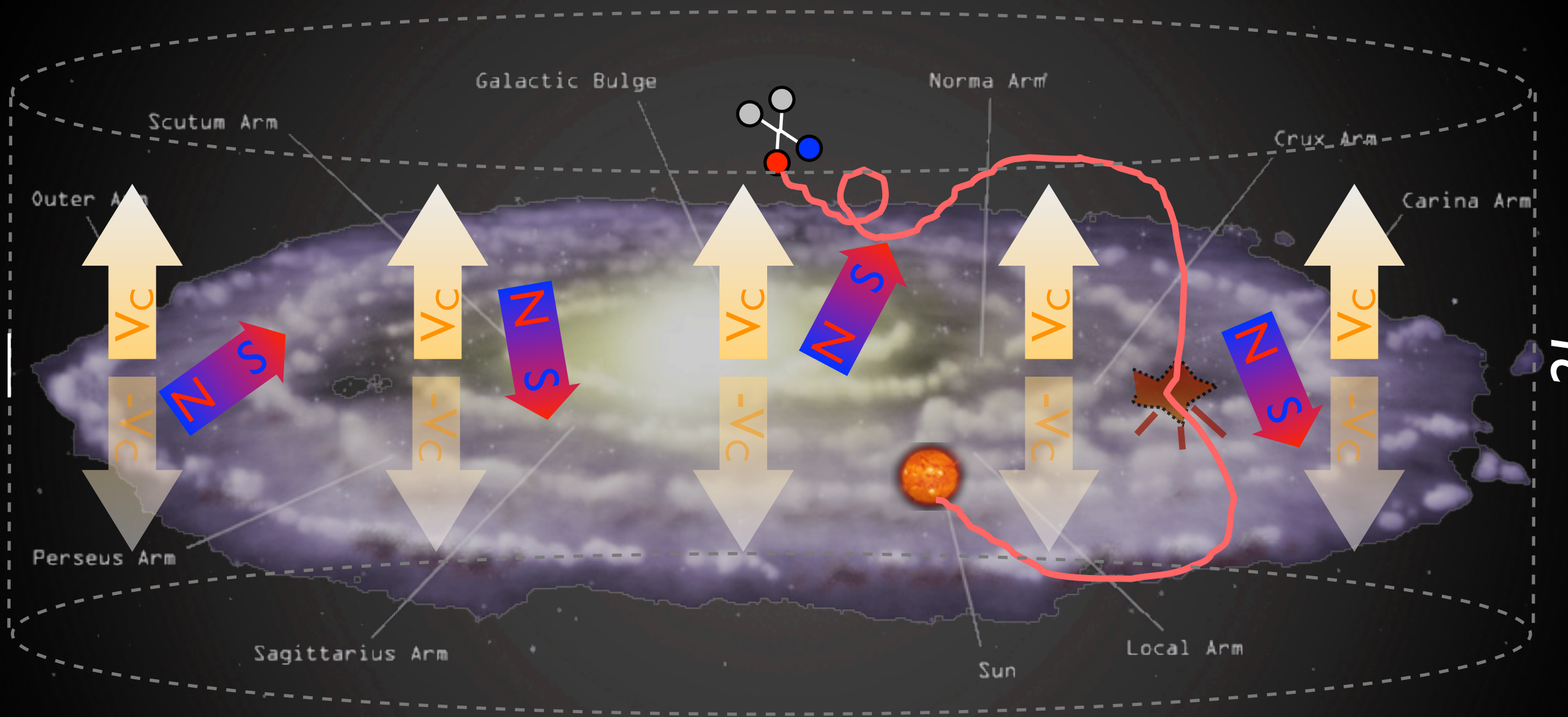

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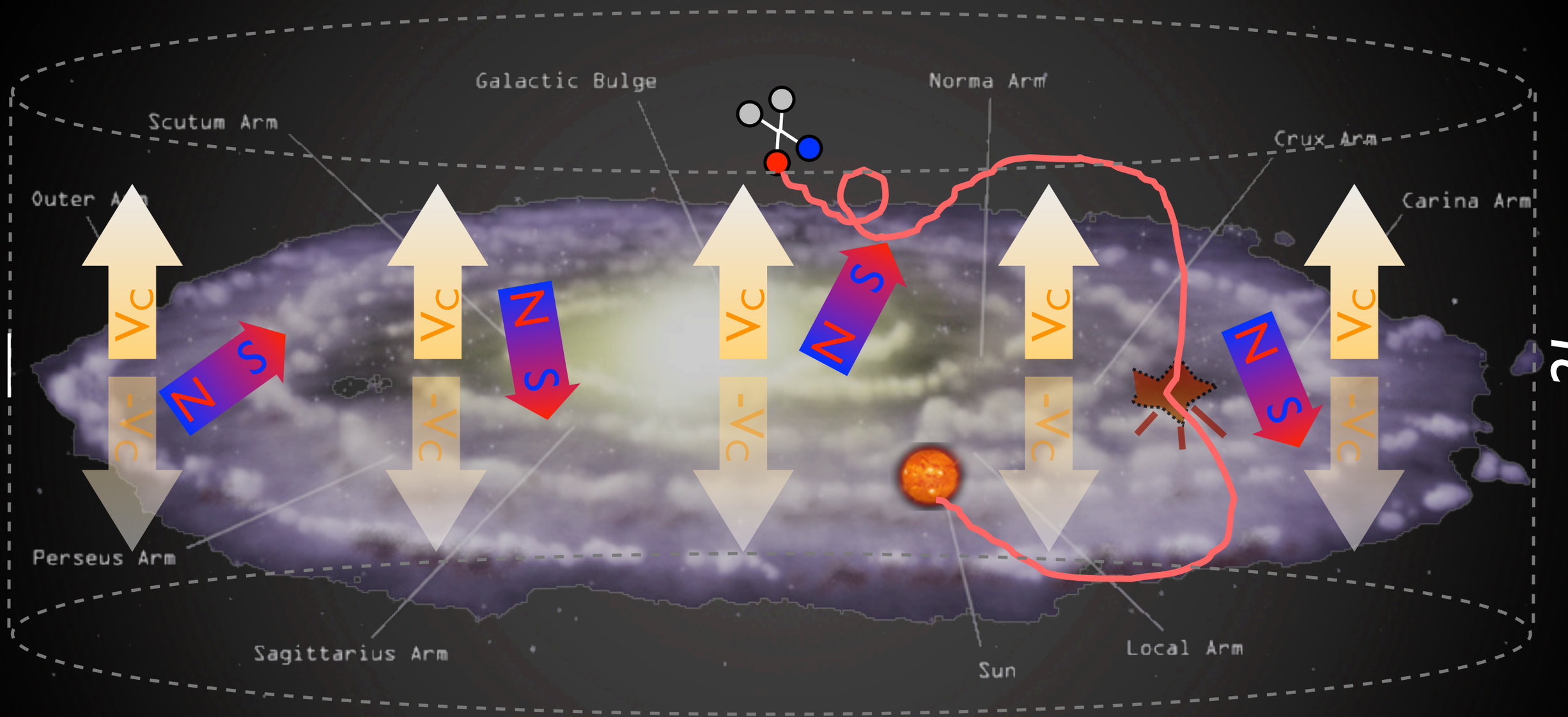

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$$\text{flux} \propto \underbrace{n^2}_{\text{astro\& cosmo}} \underbrace{\sigma_{\text{annihilation}}}_{\text{particle}}$$

reference cross section:

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

DM halo profiles

From N-body numerical simulations:

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

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

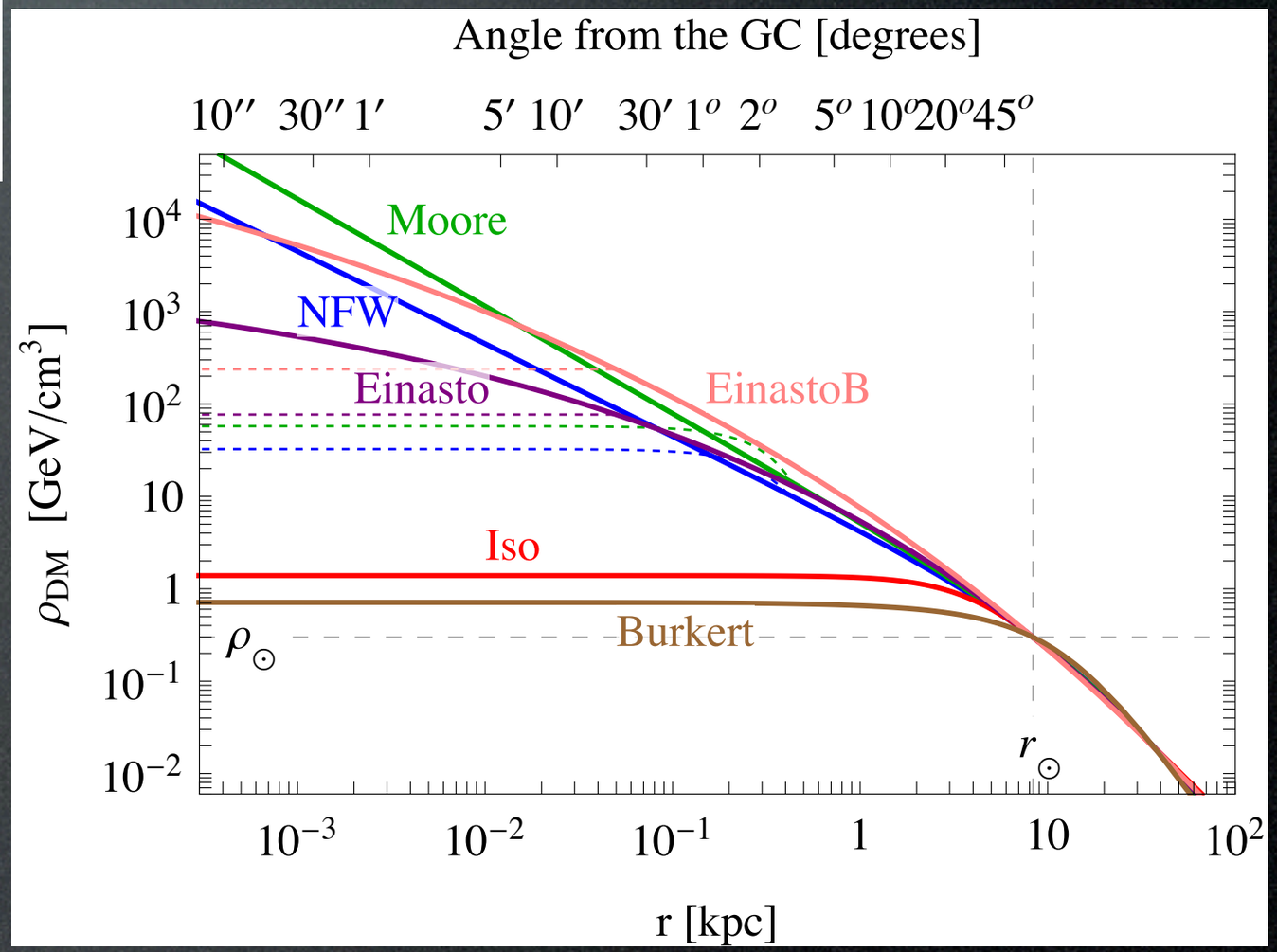
$$\text{Isothermal}: \quad \rho_{\rm Iso}(r) = \frac{\rho_s}{1+(r/r_s)^2}$$

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

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

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

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



6 profiles:

cuspy: NFW, Moore

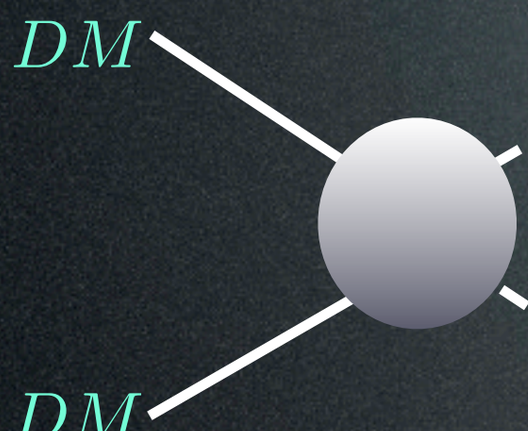
mild: Einasto

smooth: isothermal, Burkert

EinastoB = steepened Einasto

(effect of baryons?)

Indirect Detection: basics



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

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

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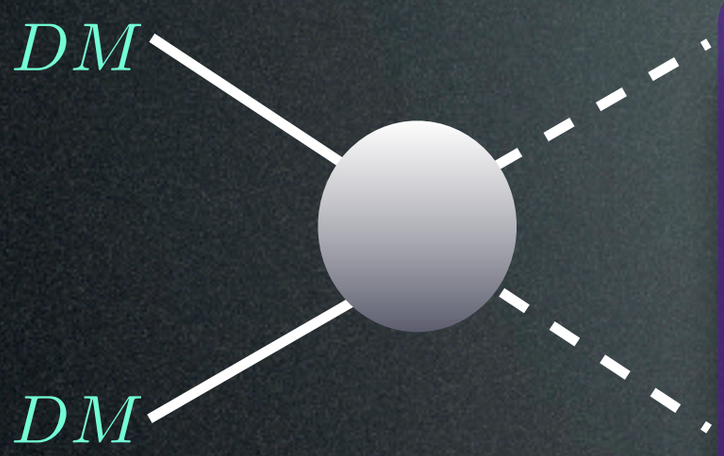

$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^{\mp}, \overset{(-)}{p}, \overset{(-)}{D} \ldots$

primary channels

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

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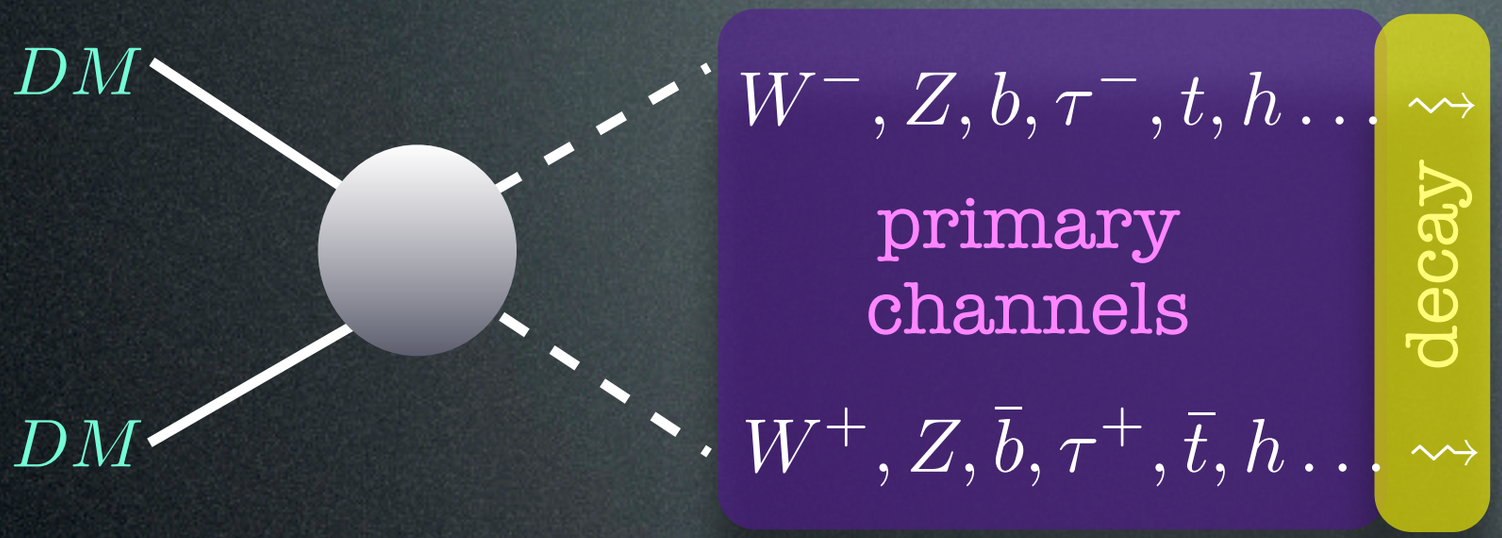

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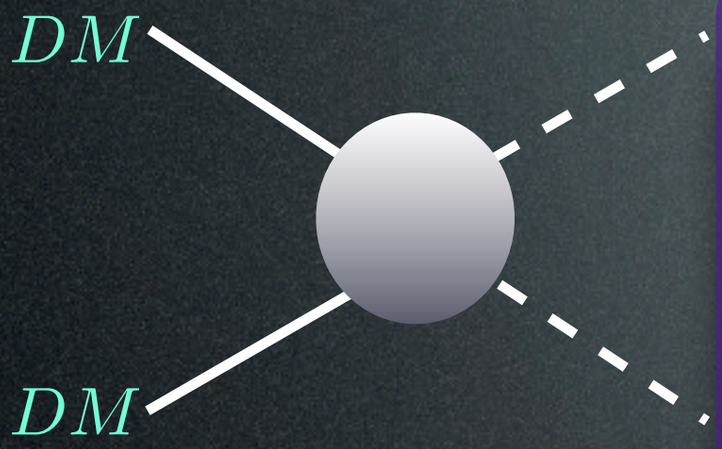


$W^-, Z, b, \tau^-, t, h \ldots$

primary channels

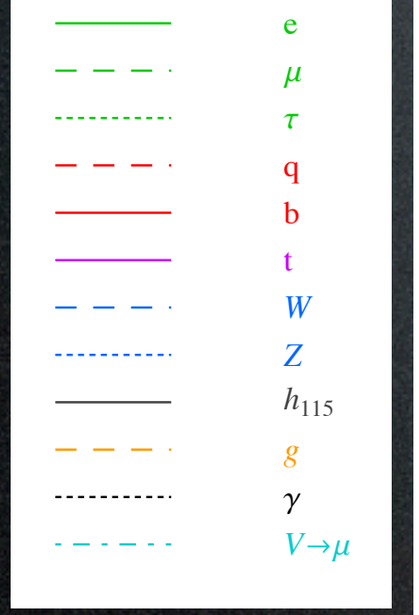
$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots$

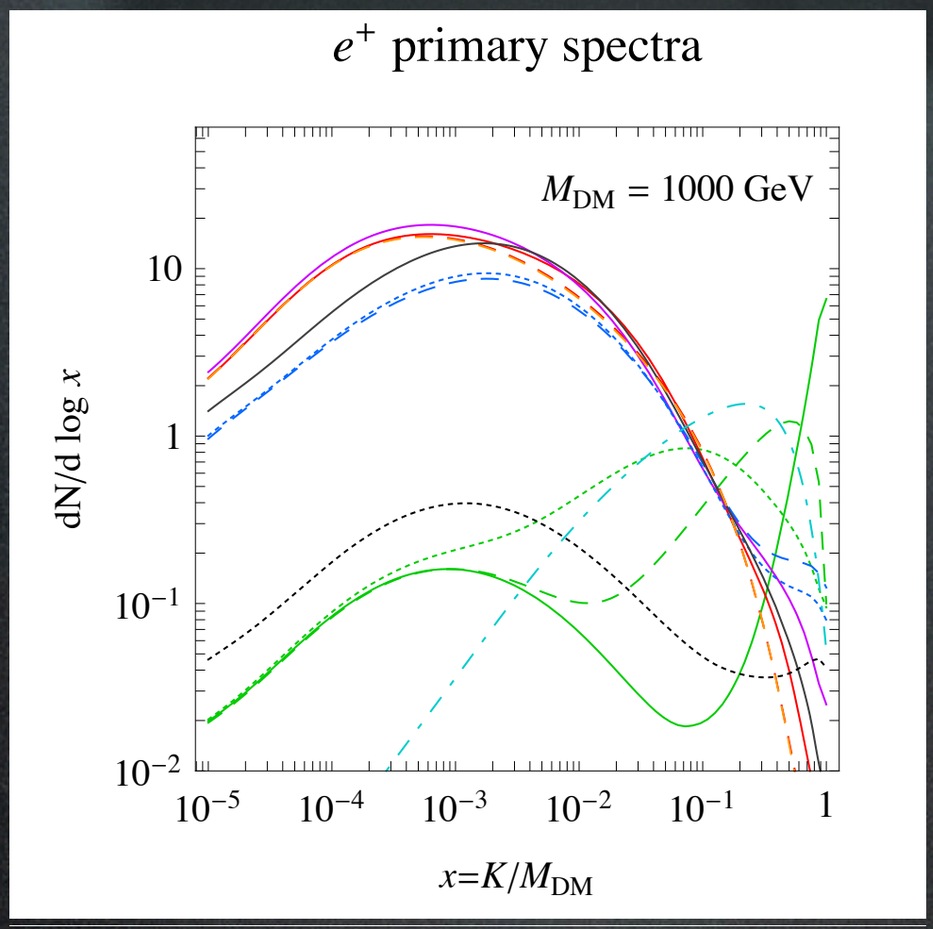
decay

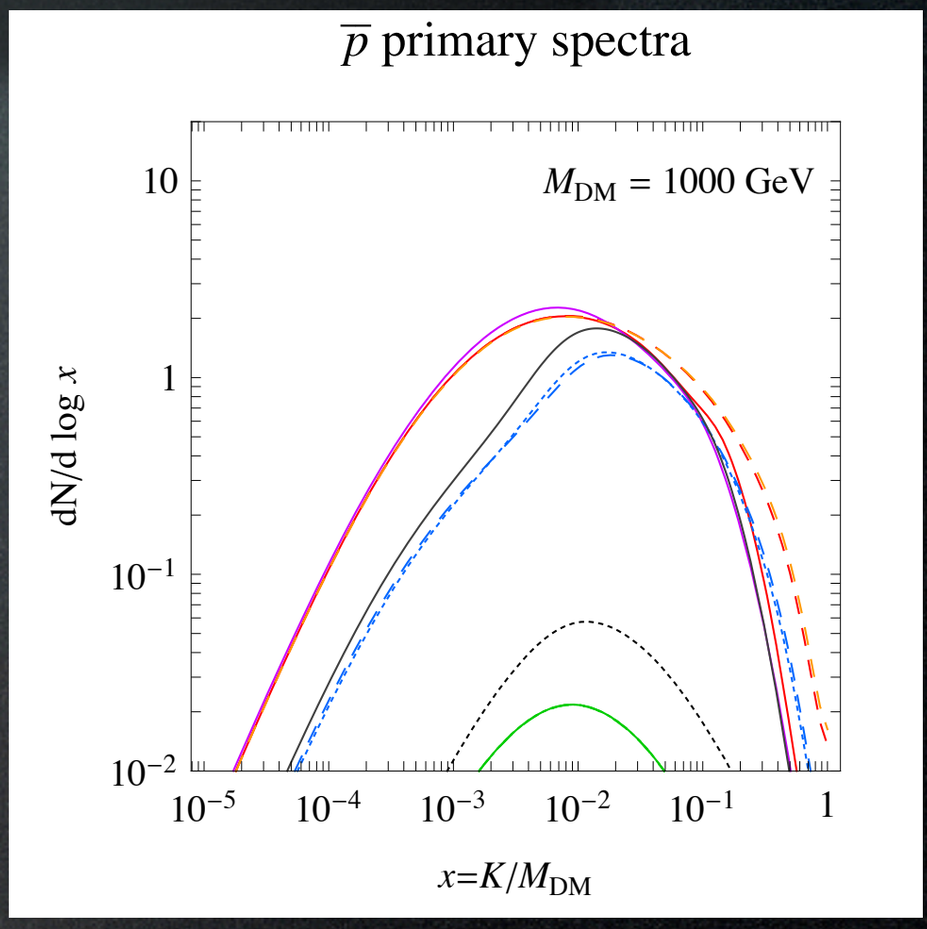
$e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots$

final products

$e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ldots$







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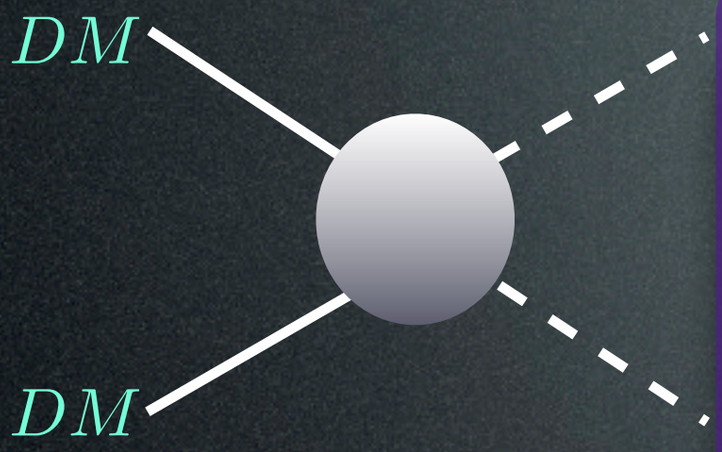
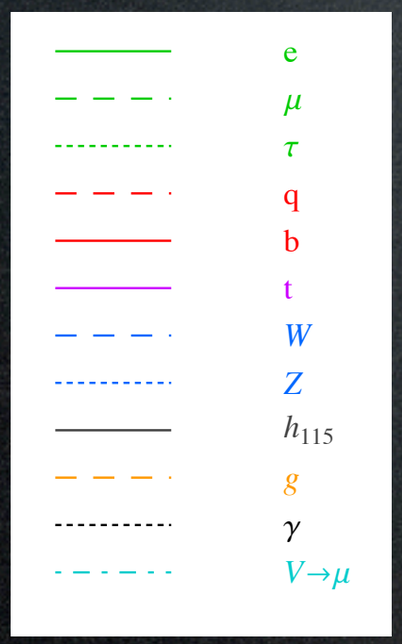
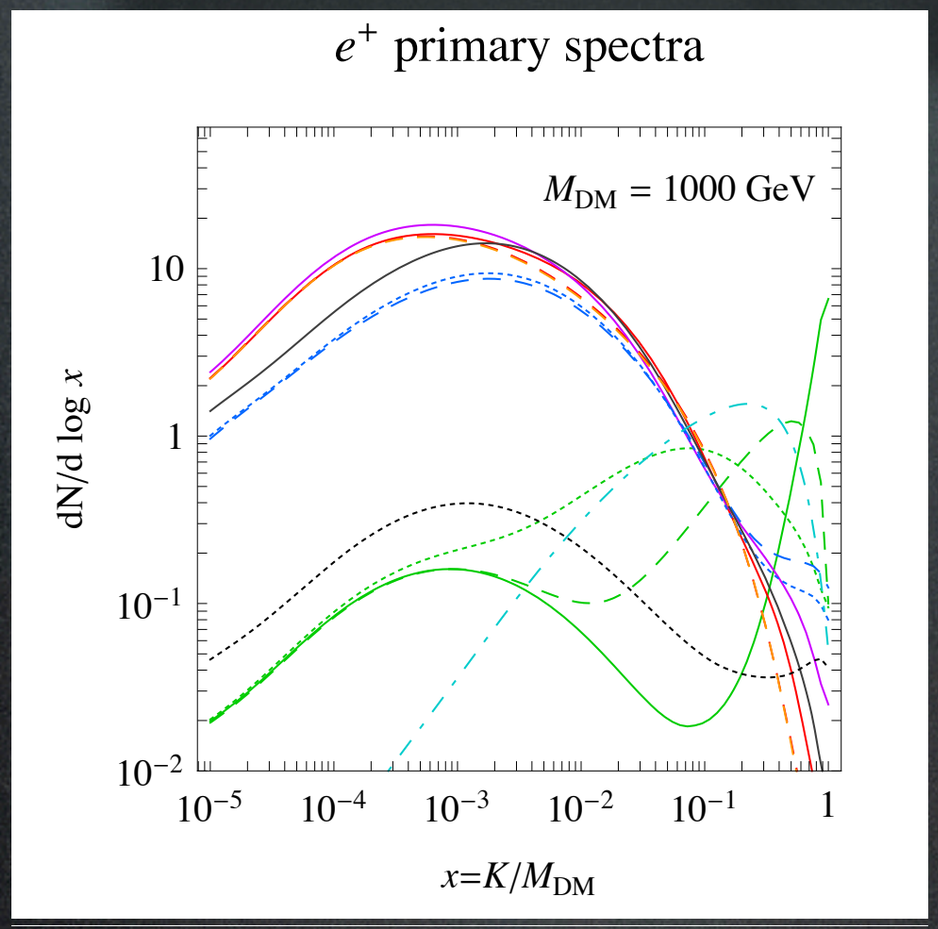


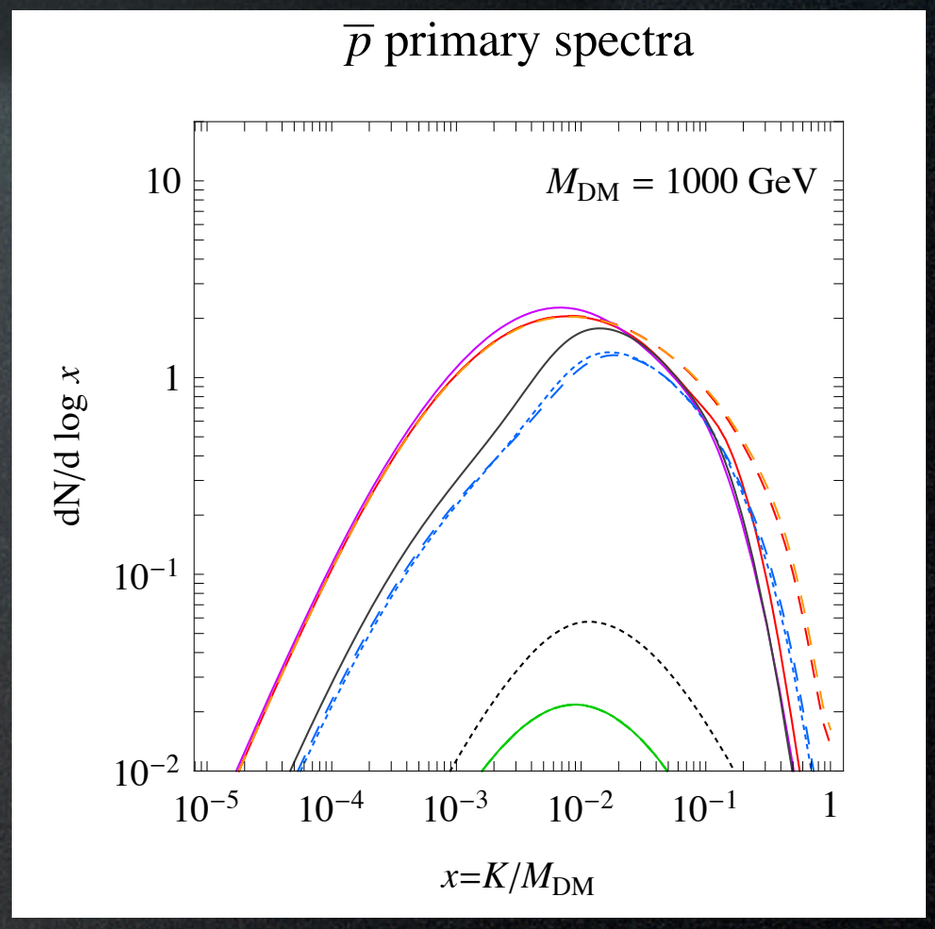
$W^-, Z, b, \tau^-, t, h \ldots$ — primary channels — $W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots$

decay

$e^{\mp}, \overset{(-)}{p}, \overset{(-)}{D} \ldots$ — final products — $e^{\pm}, \overset{(-)}{p}, \overset{(-)}{D} \ldots$





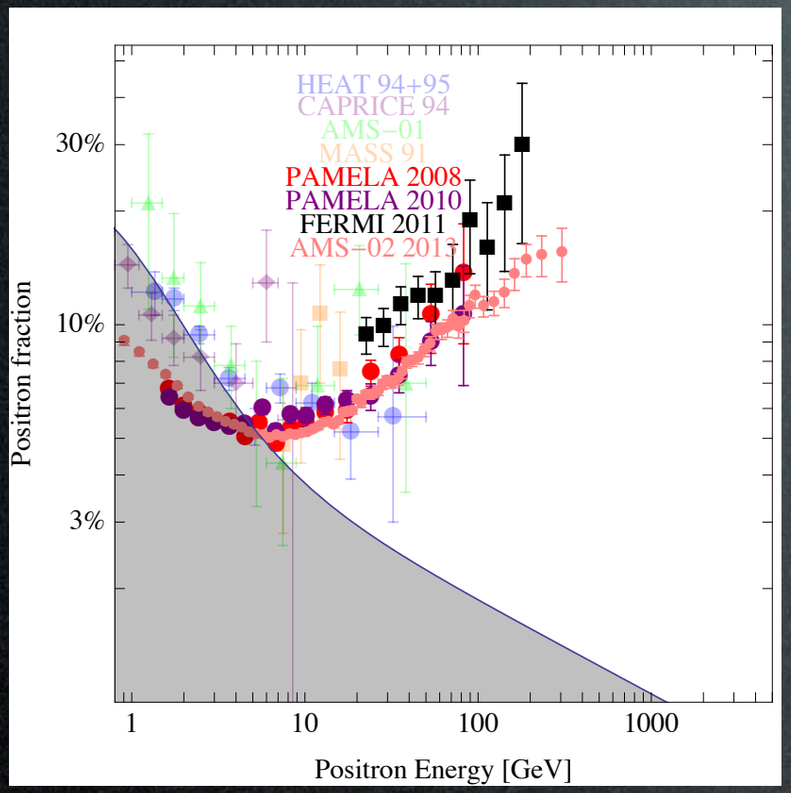


So what are the particle physics parameters?

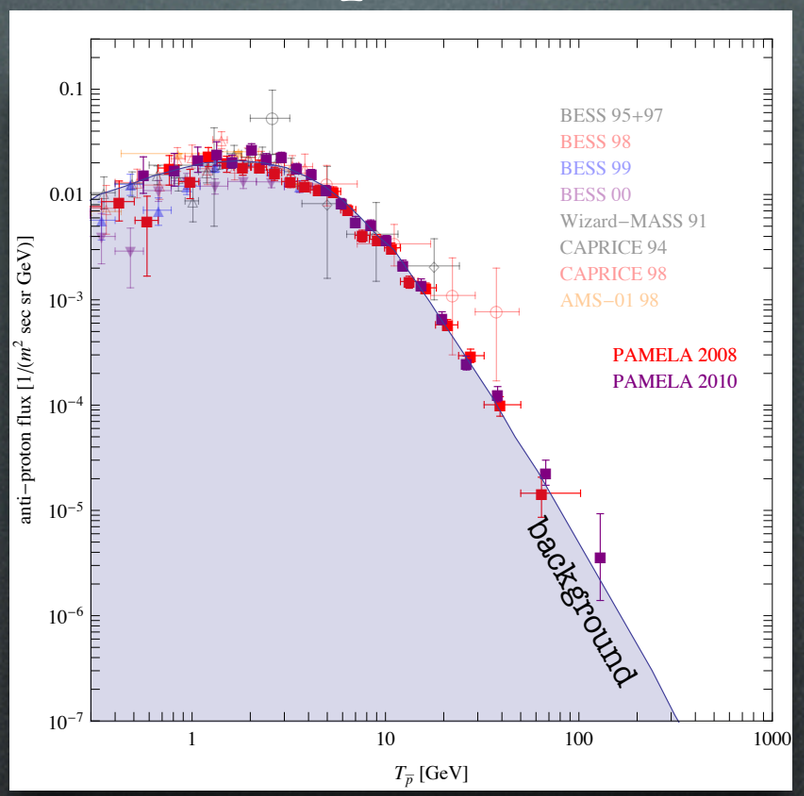
1. Dark Matter mass
2. primary channel(s)

Positrons & Electrons

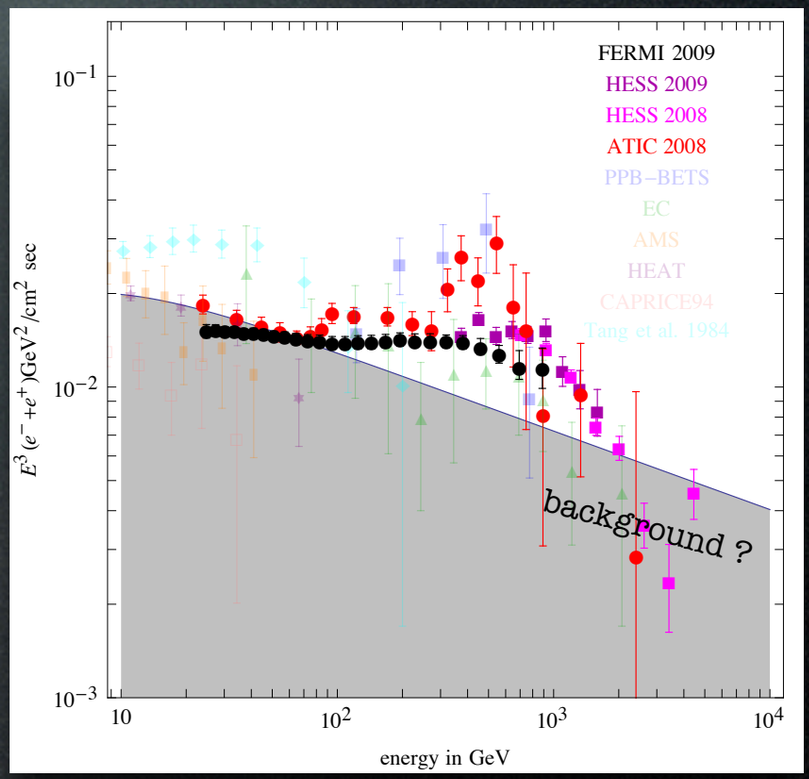
positron fraction



antiprotons

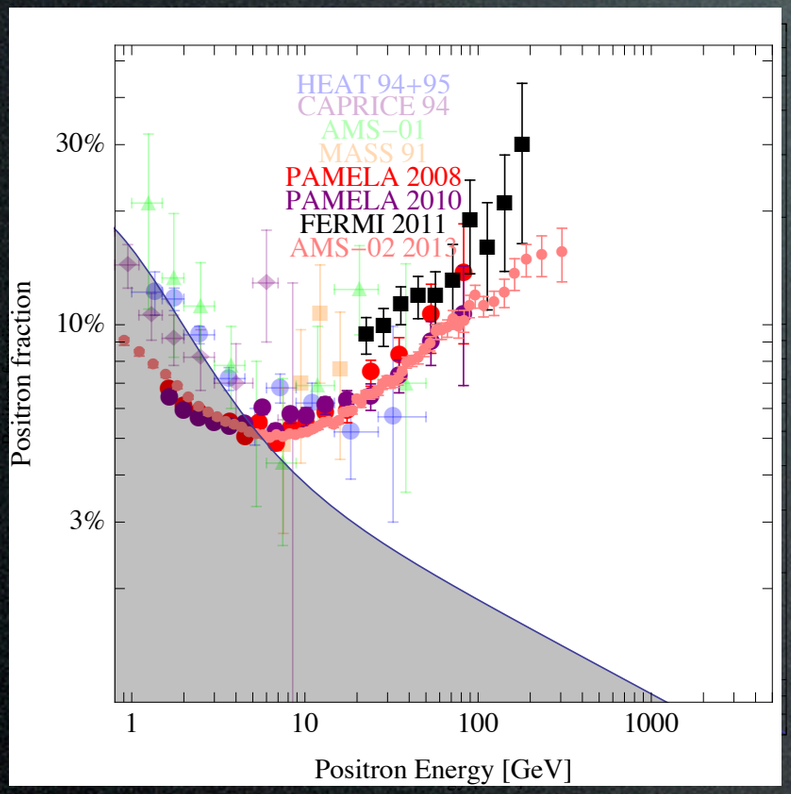


electrons + positrons

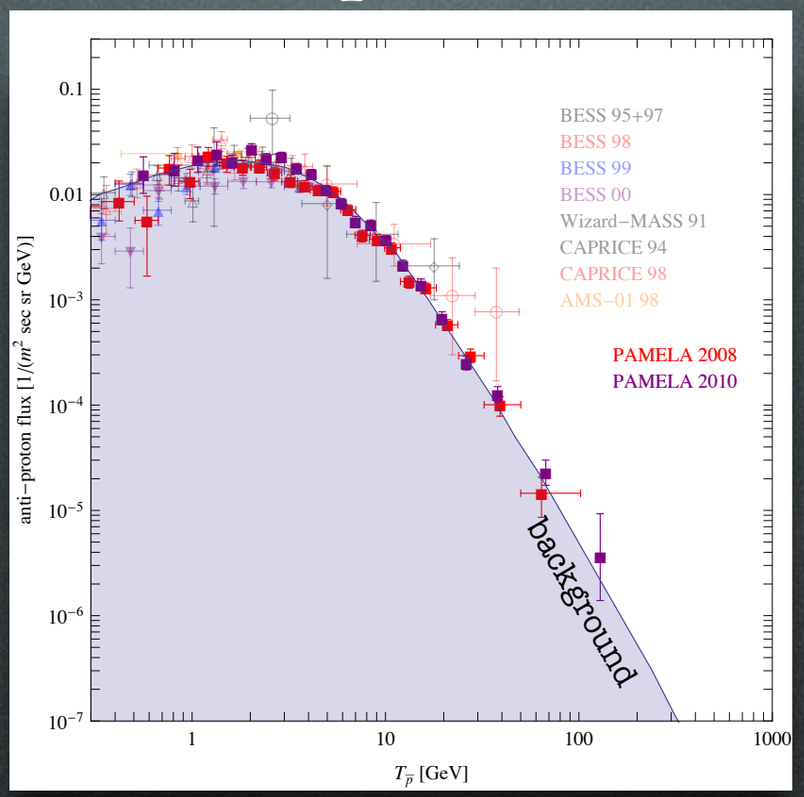


Positrons & Electrons

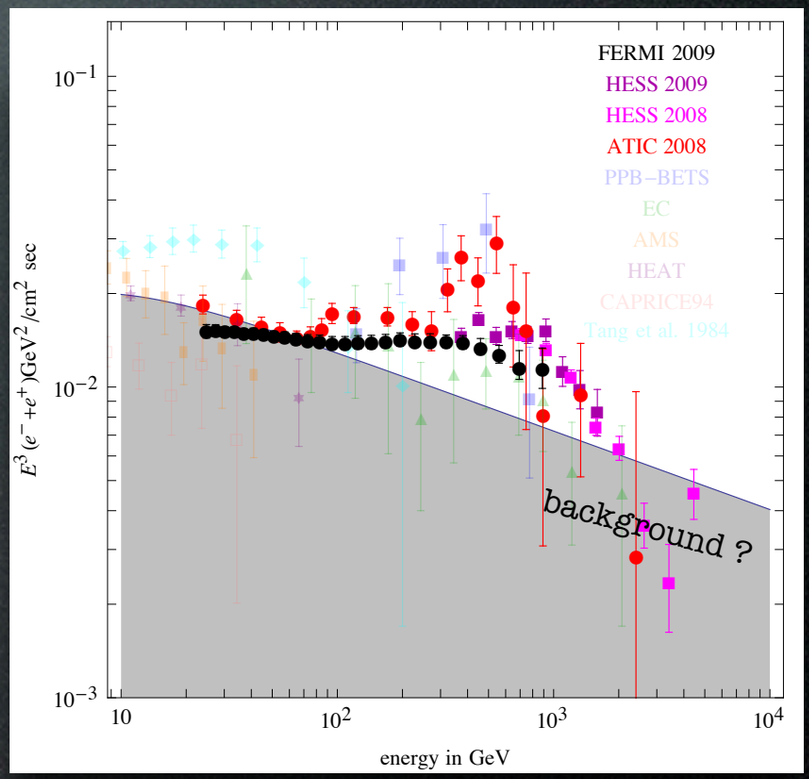
positron fraction



antiprotons



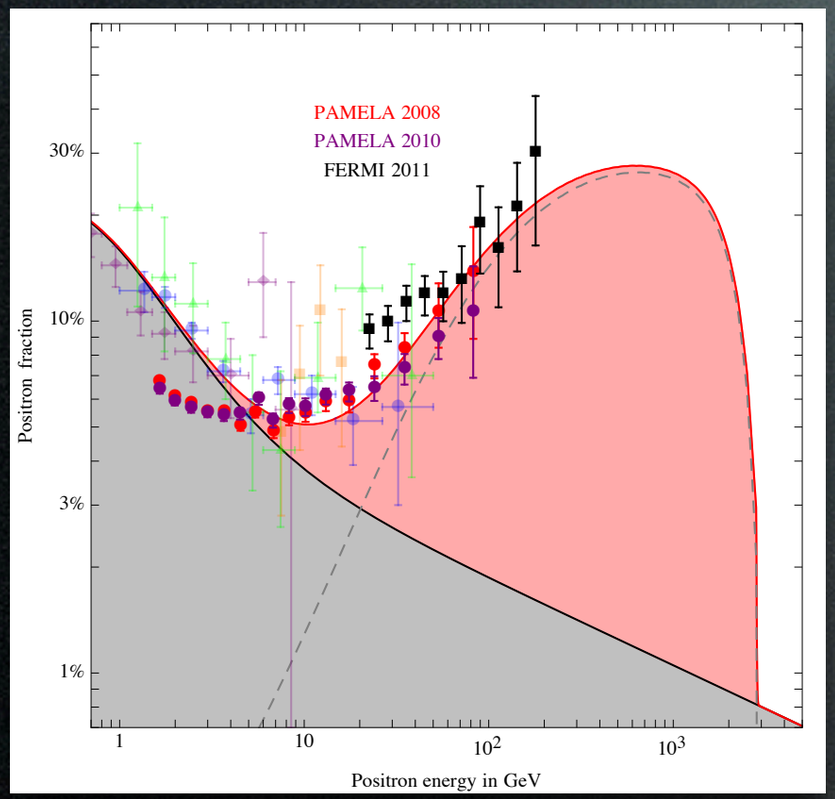
electrons + positrons



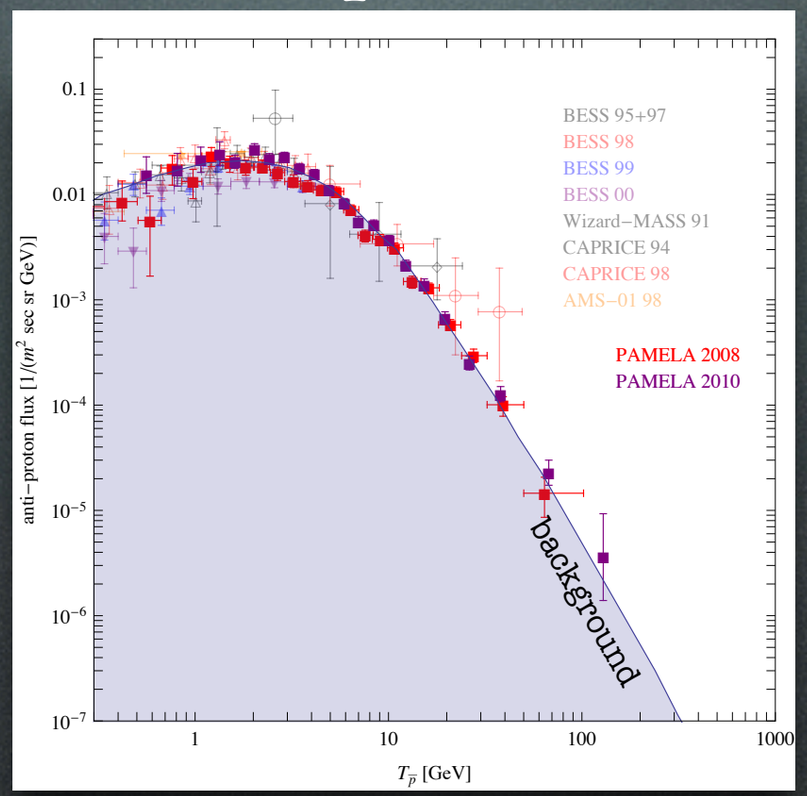
Are these signals of Dark Matter?

Positrons & Electrons

positron fraction



antiprotons



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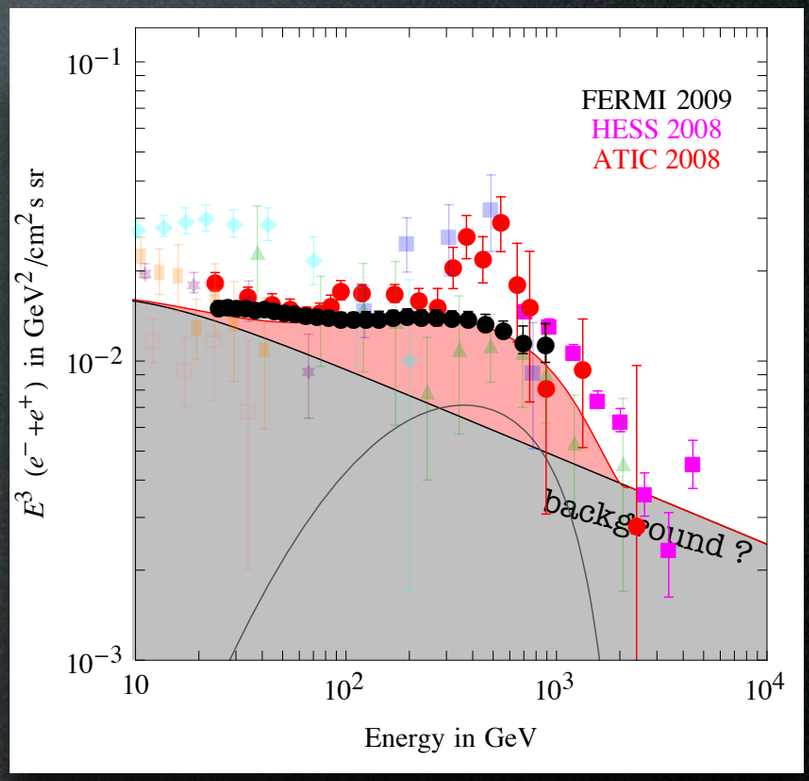
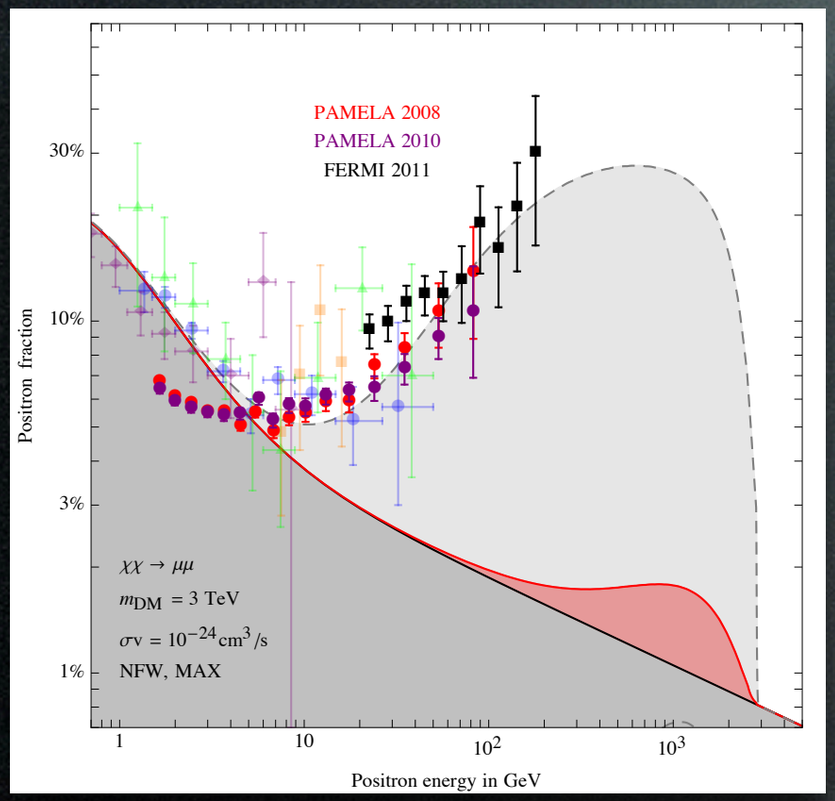


Are these signals of Dark Matter?

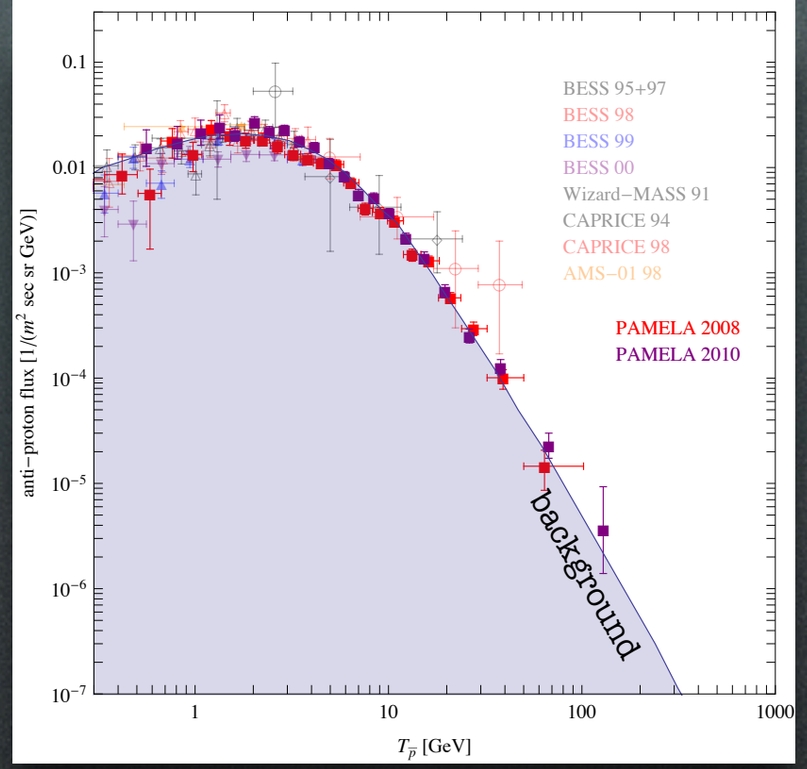
YES: few TeV, leptophilic DM
with huge $\langle \sigma v \rangle \approx 10^{-23}\,\mathrm{cm}^3/\mathrm{sec}$

Positrons & Electrons

positron fraction



antiprotons



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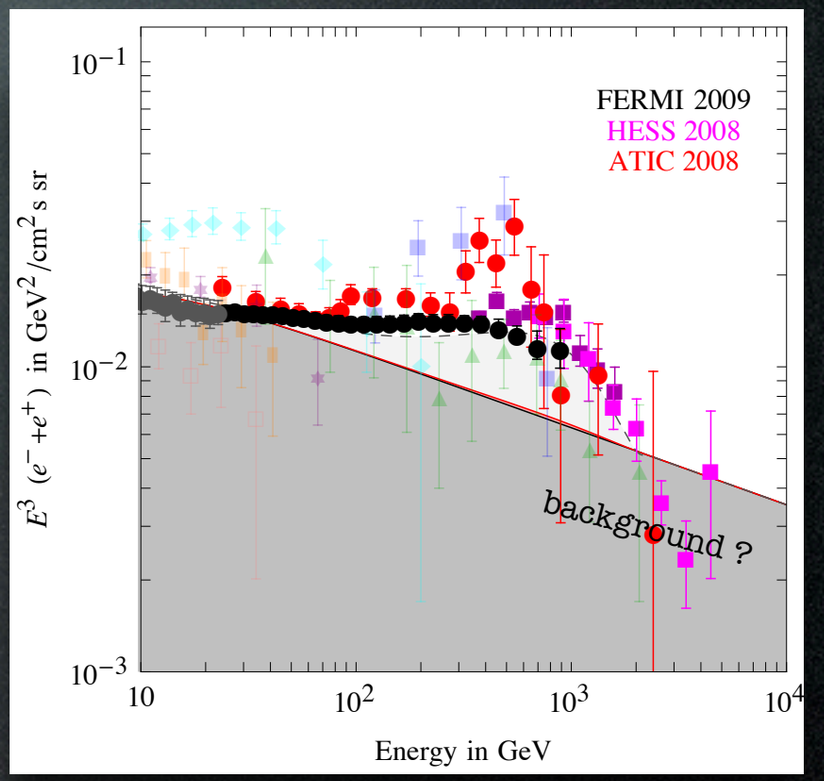


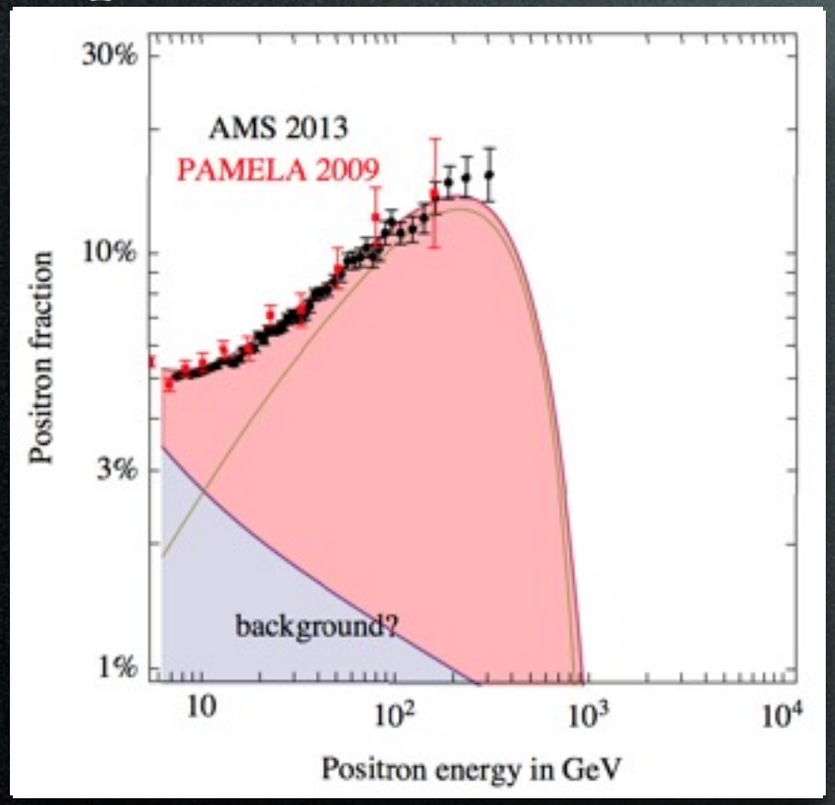
Are these signals of Dark Matter?

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

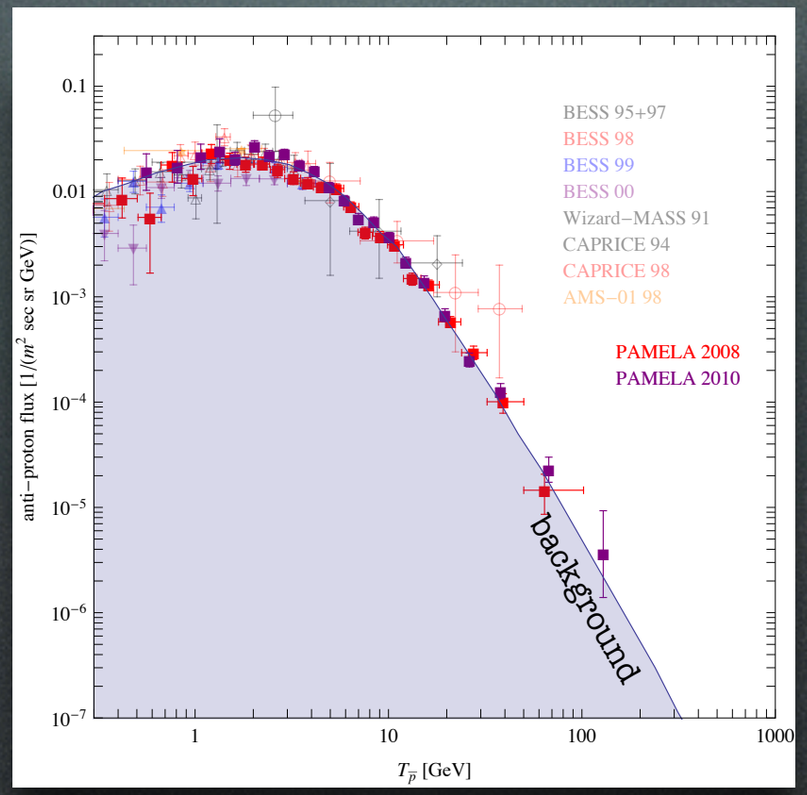
NO: a formidable 'background' for future searches

PS: post AMS 2014

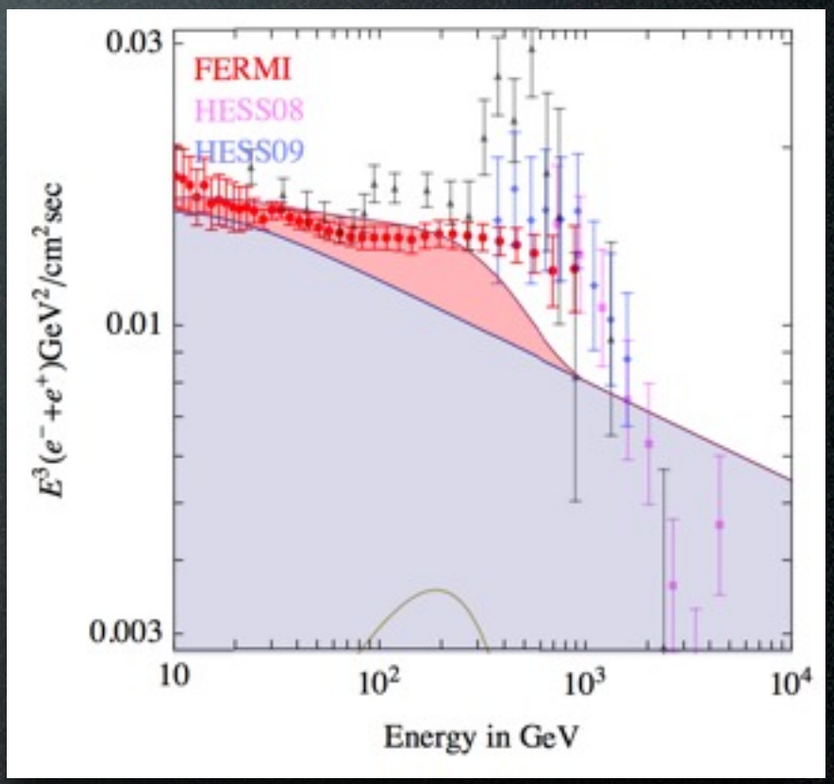
positron fraction



antiprotons



electrons + positrons

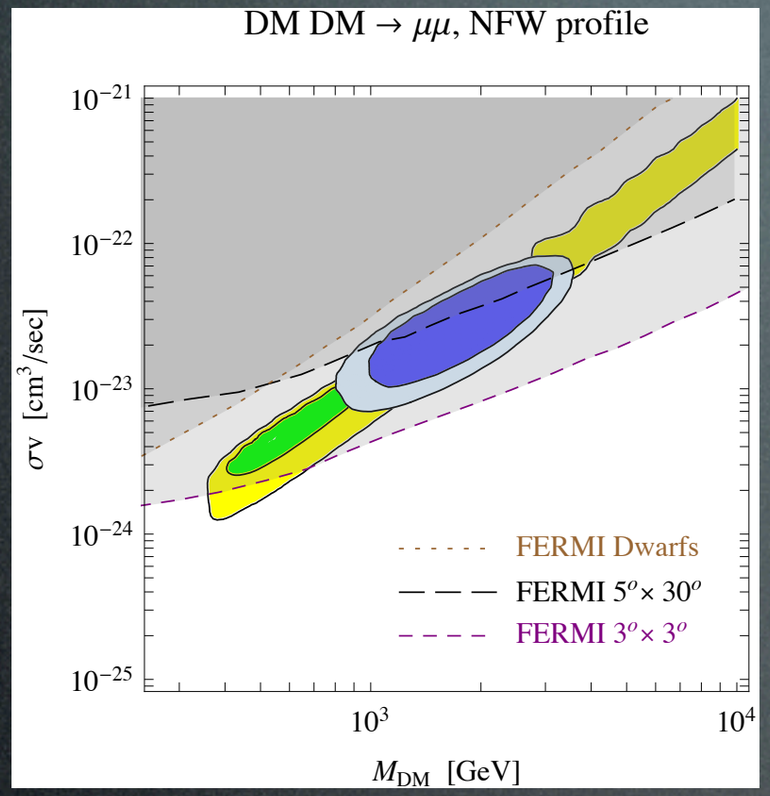


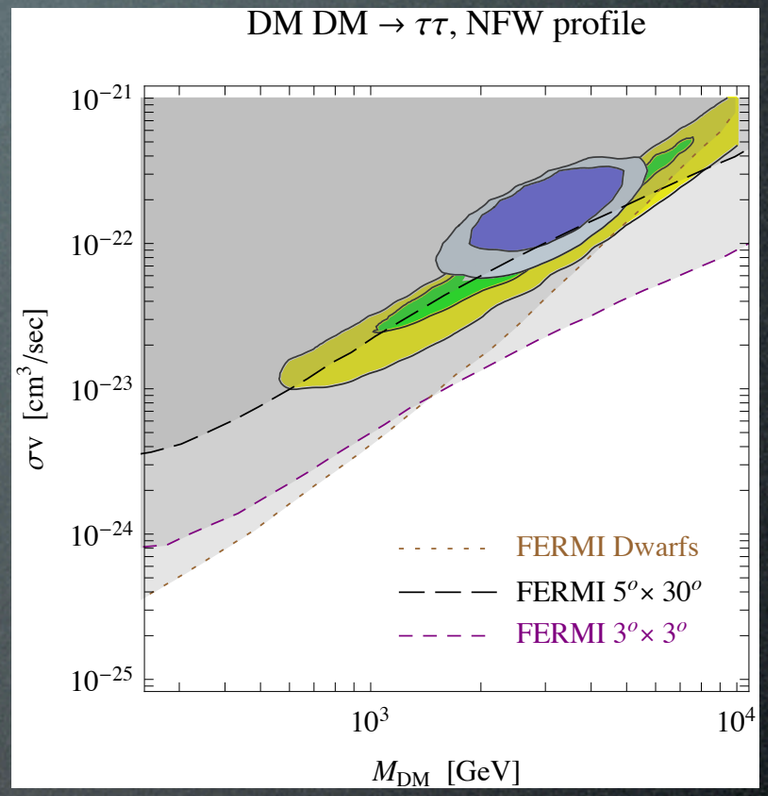
Are these signals of Dark Matter?

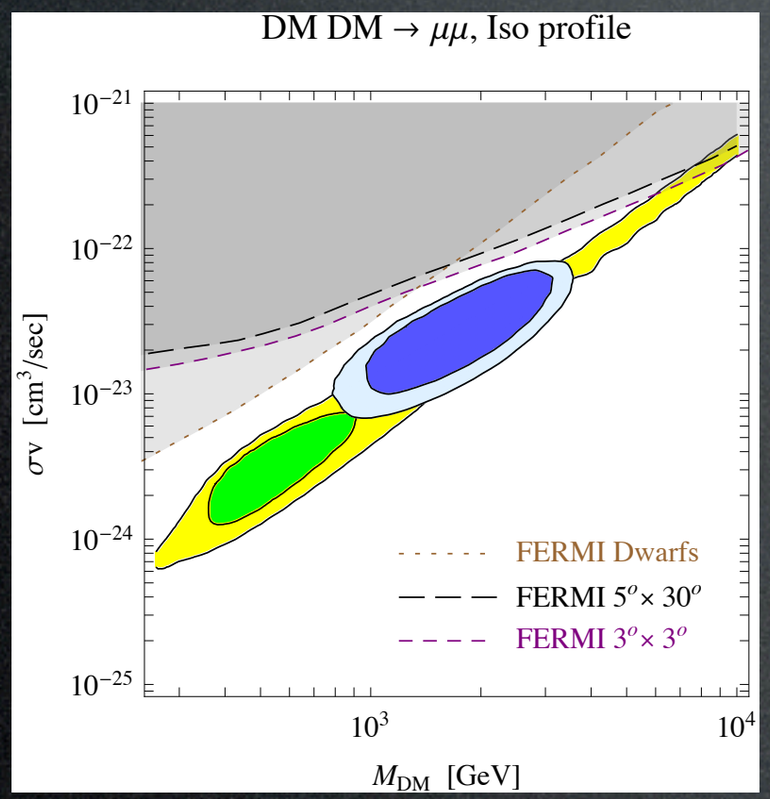
YES: one TeV, leptophilic DM
with huge $\langle \sigma v \rangle \approx 10^{-23}\,\mathrm{cm}^3/\mathrm{sec}$
'tension' between positron frac and $e^+ + e^-$

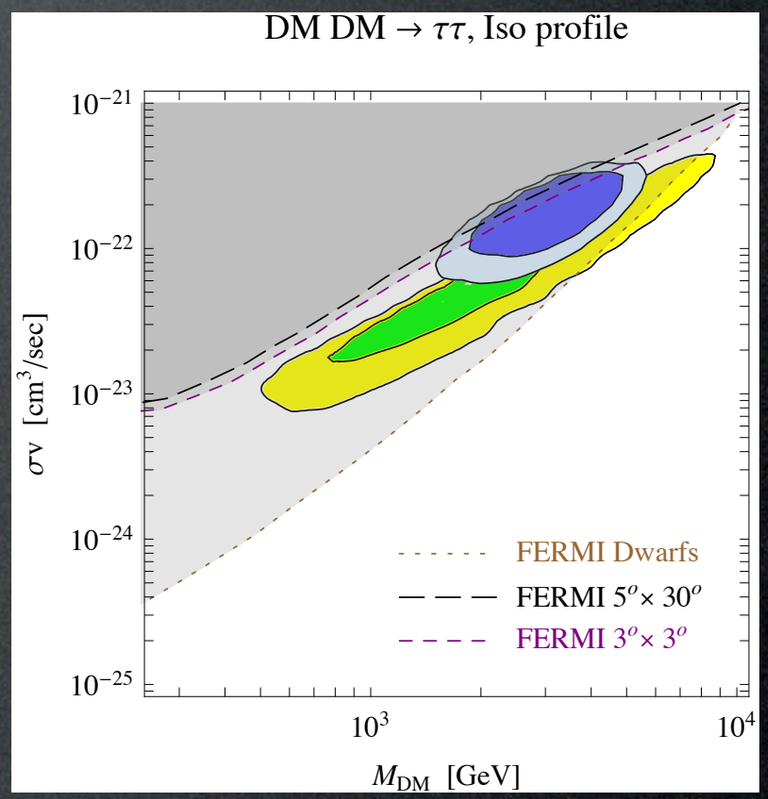
Addendum (2013) to Cirelli, Kadastik, Raidal, Strumia 0809.2409 (2008)

PS: post AMS 2014









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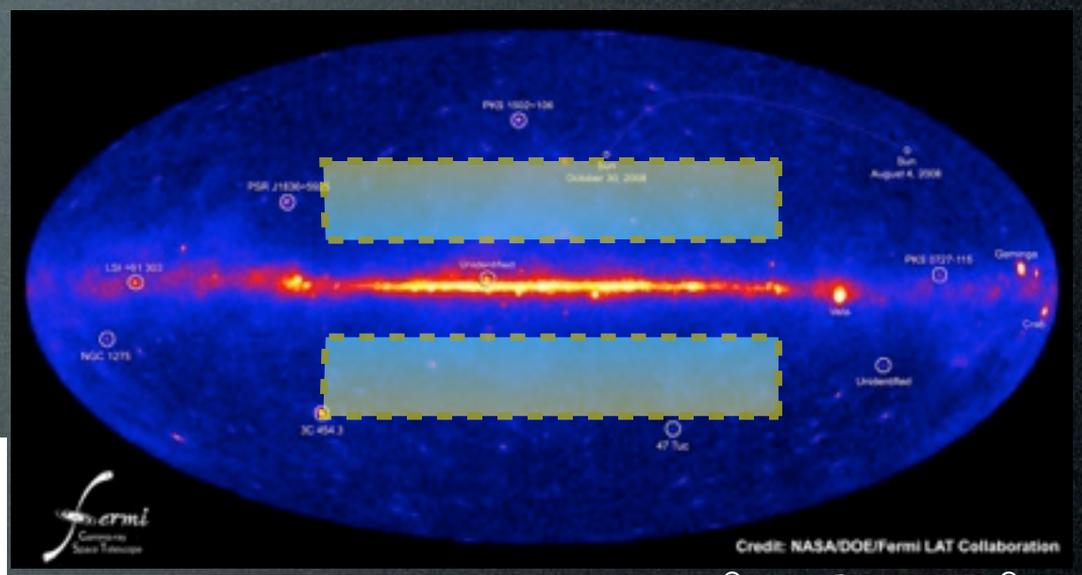
Gamma constraints

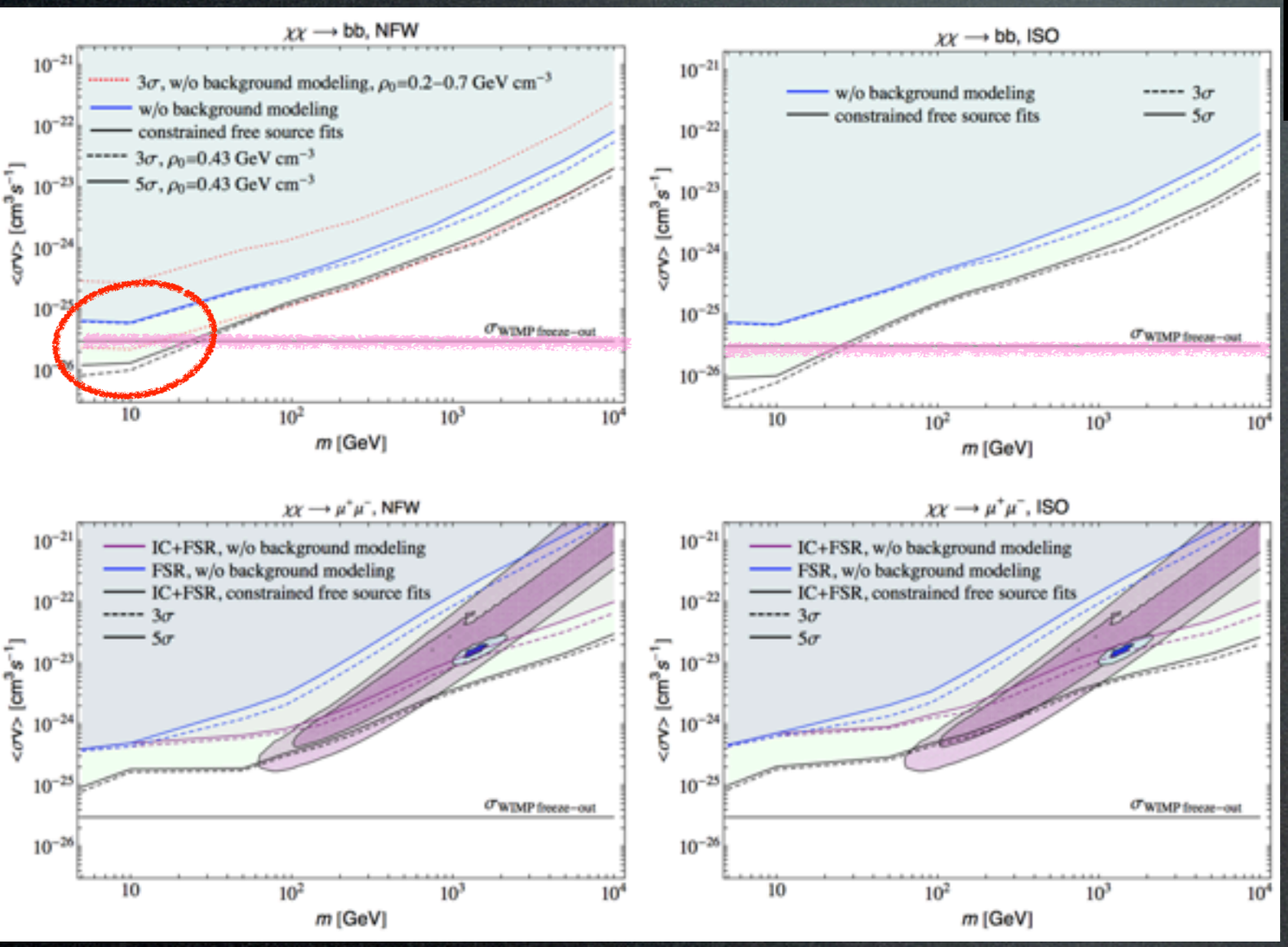
γ from Inverse Compton on $e^{\pm}$ in halo

Updated results from the **FERMI** coll. itself



$5^\circ < b < 15^\circ$

$-80^\circ < \ell < +80^\circ$



FERMI coll., Cuoco - Zaharijas, 1205.6474

See also:
Papucci, Strumia, 0912.0742

Gamma constraints

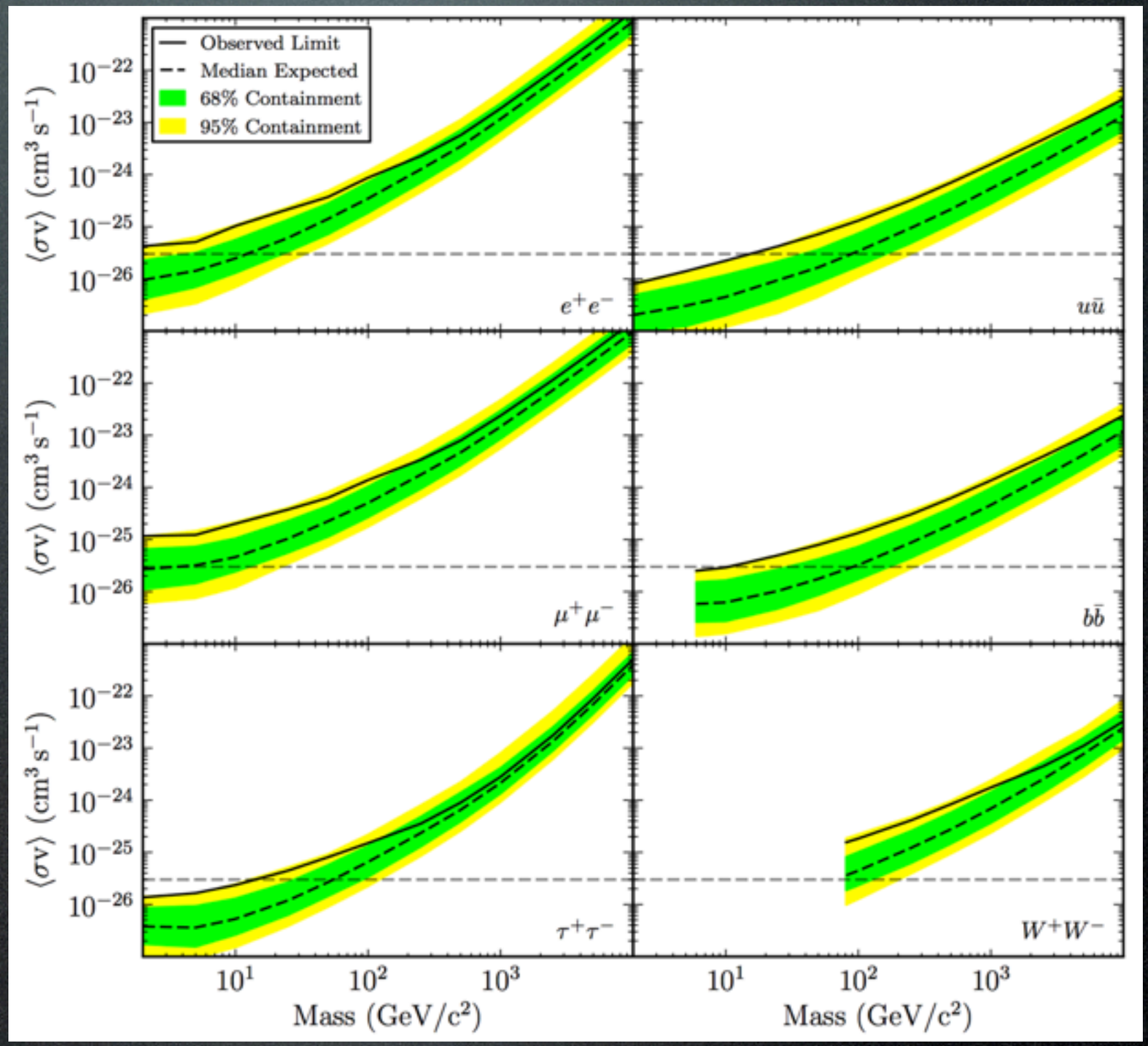
γ from DM annihilations in Satellite Galaxies

FERMI

1310.0828 Fermi coll.,
Alex Drlica-Wagner

4 years data:
weaker bound

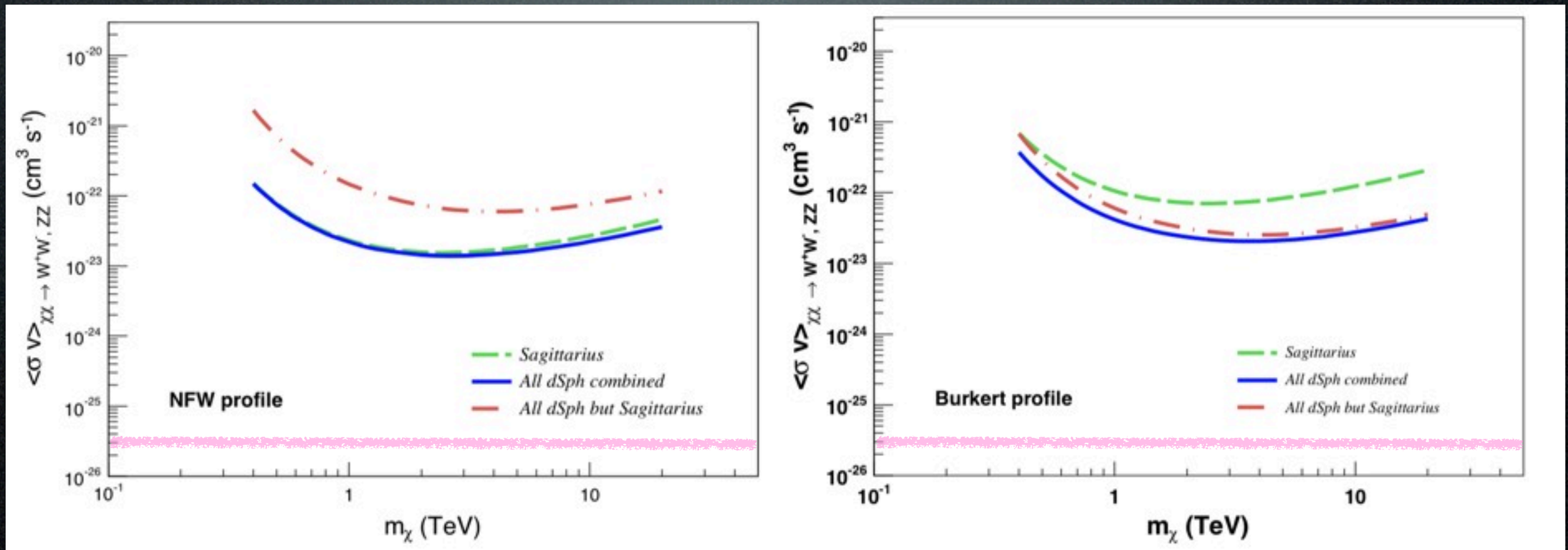
(or 10 GeV DM
peeping out?)

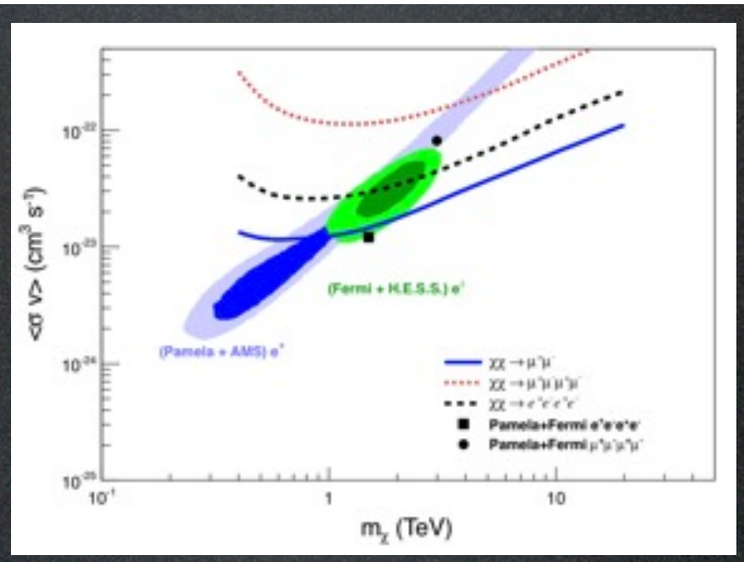


Gamma constraints

γ from DM annihilations in Satellite Galaxies

HESS 1410.2589 HESS coll.





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

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

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)		

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?

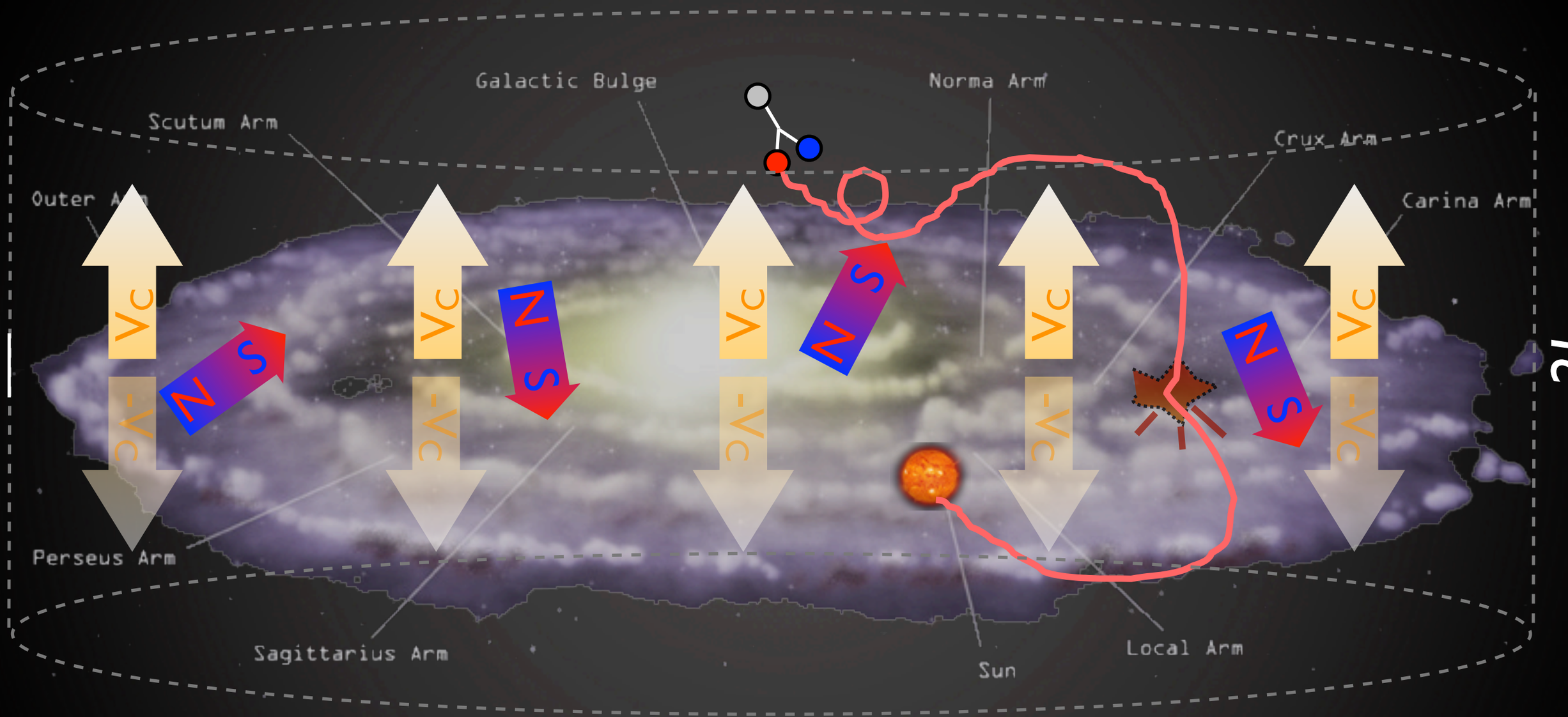
- dim 6 suppressed operator in GUT — Arvanitaki, Dimopoulos et al., 2008+09

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

- 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?

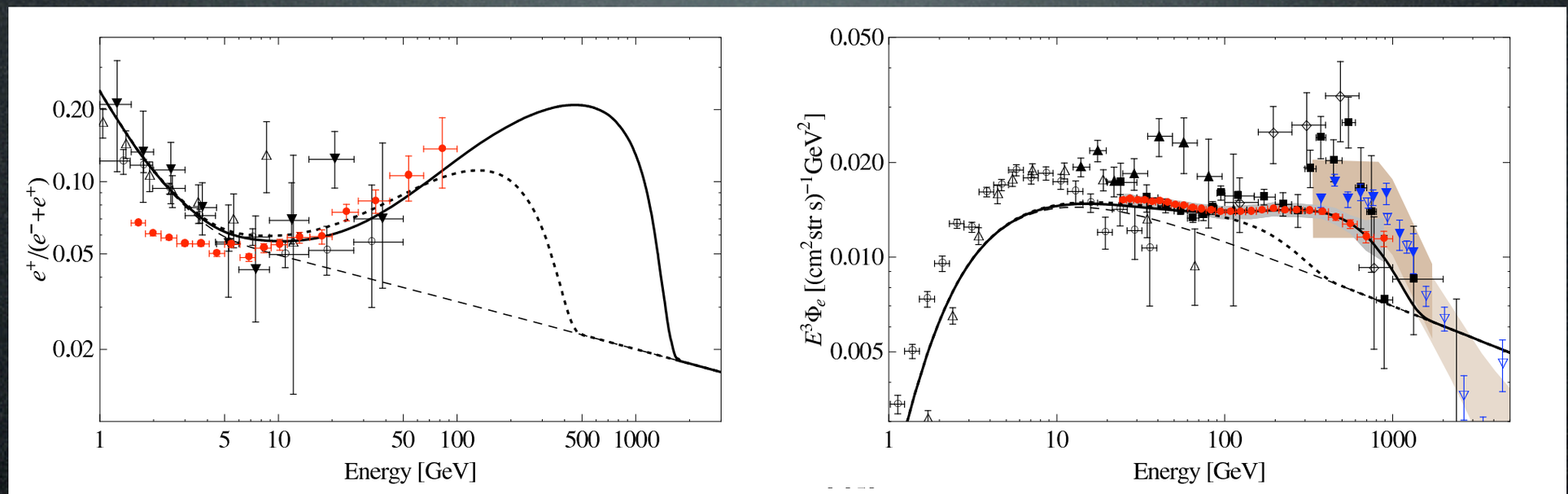
$$\text{flux} \propto n\ \Gamma_{\text{decay}}$$

$$\Gamma^{-1}_{\text{decay}} = \tau_{\text{decay}} \approx 10^{26}\text{sec}$$

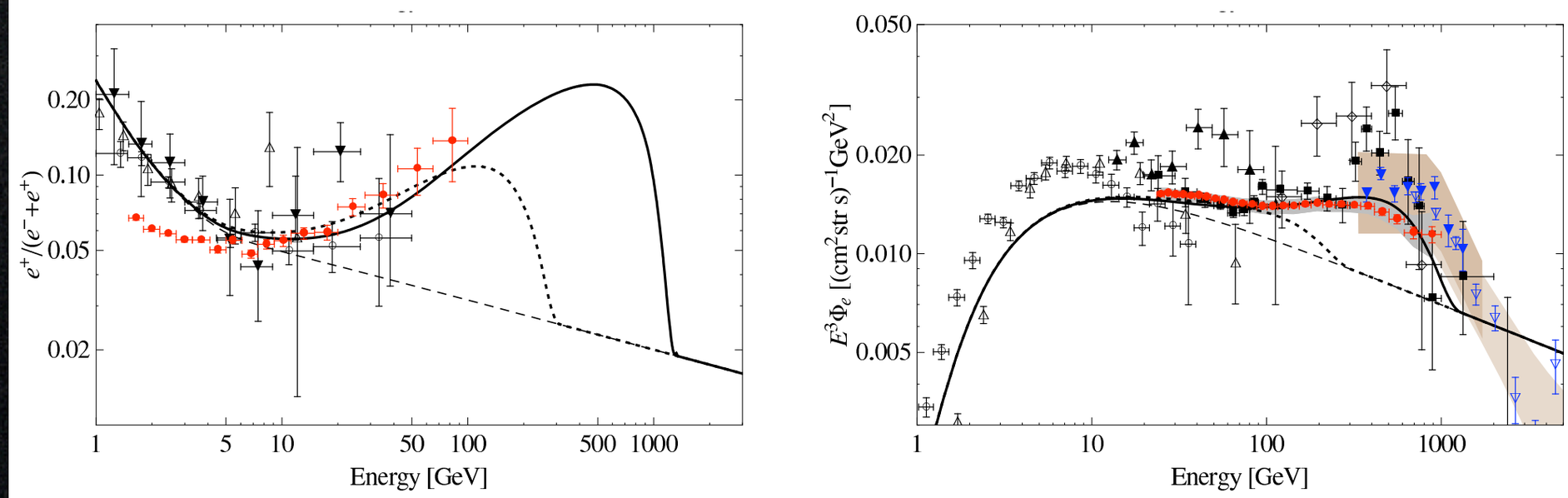
Decaying DM

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 $M_{\mathrm{DM}} = 2.5\,\mathrm{TeV}$:

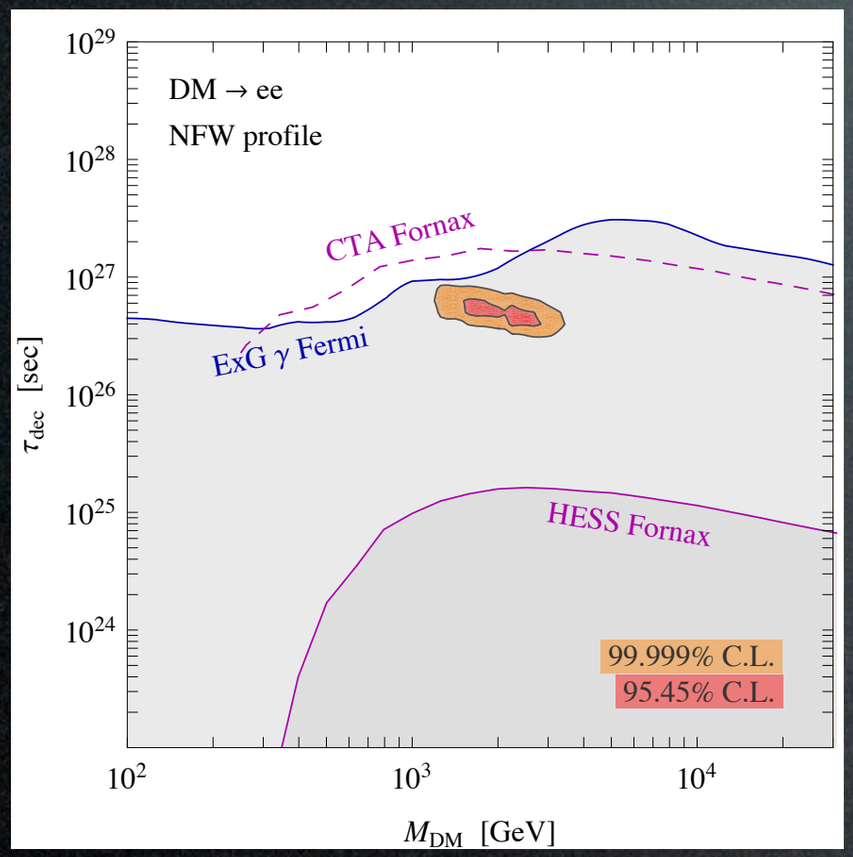


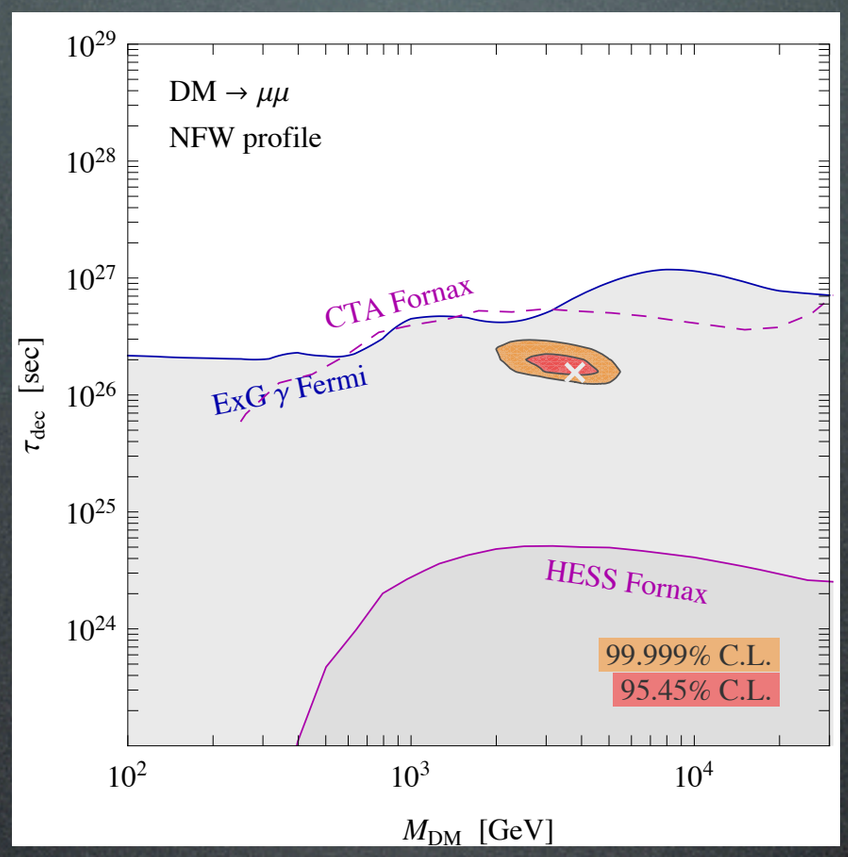
Ibarra, Tran, Weniger 2009

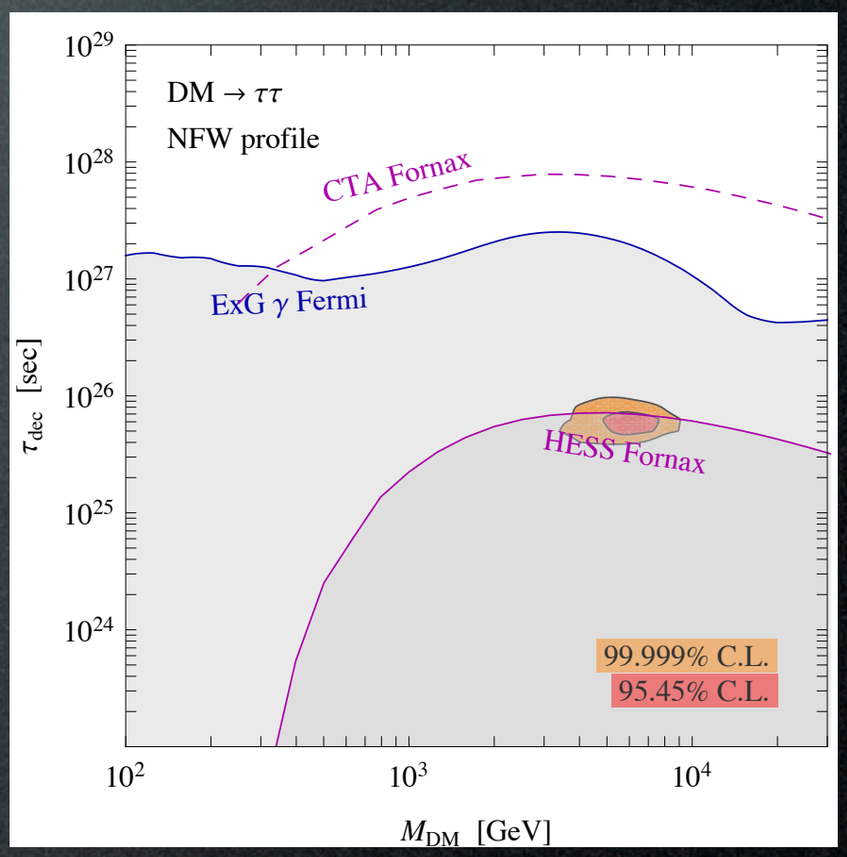
Decaying DM

But, again: gamma ray constraints

(although: no radio, neutrino constraints)







Cirelli, Moulin, Panci, Serpico, Viana 1205.5283

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

Model building

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

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

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

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

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

- 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 #

- Decaying DM

Ibarra et al., 2007-2009 Nardi, Sannino, Strumia 0811.4153
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The "Theory of DM"

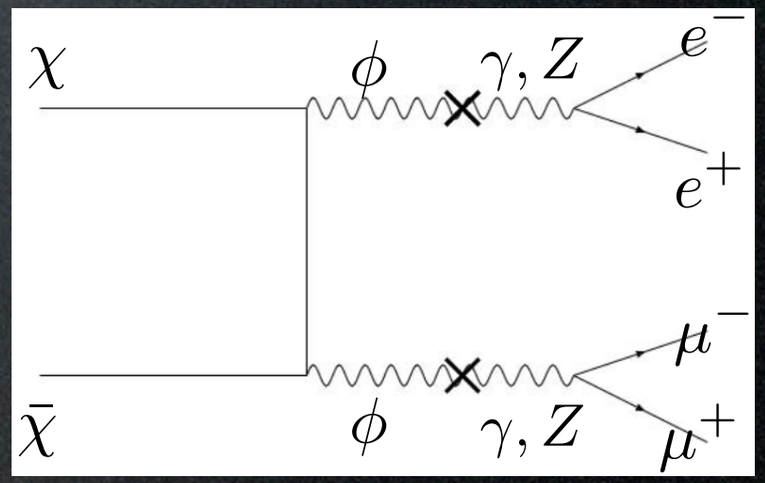
Arkani-Hamed, Weiner, Finkbeiner et al. 0810.0713
0811.3641

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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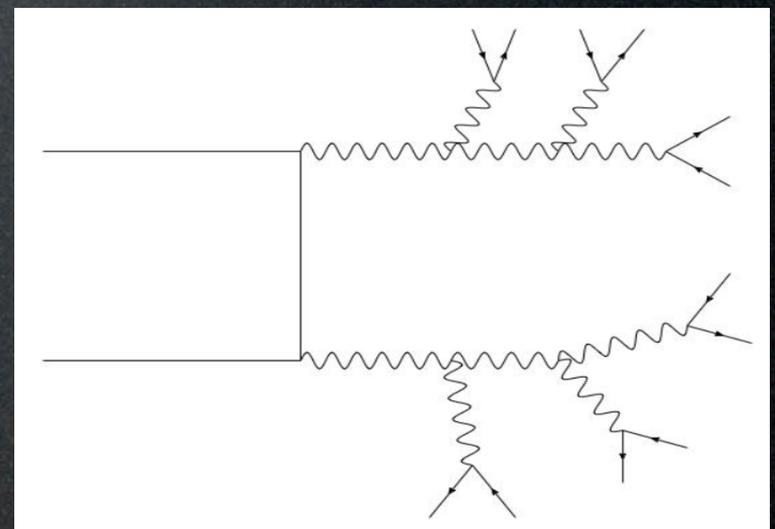


Extras:

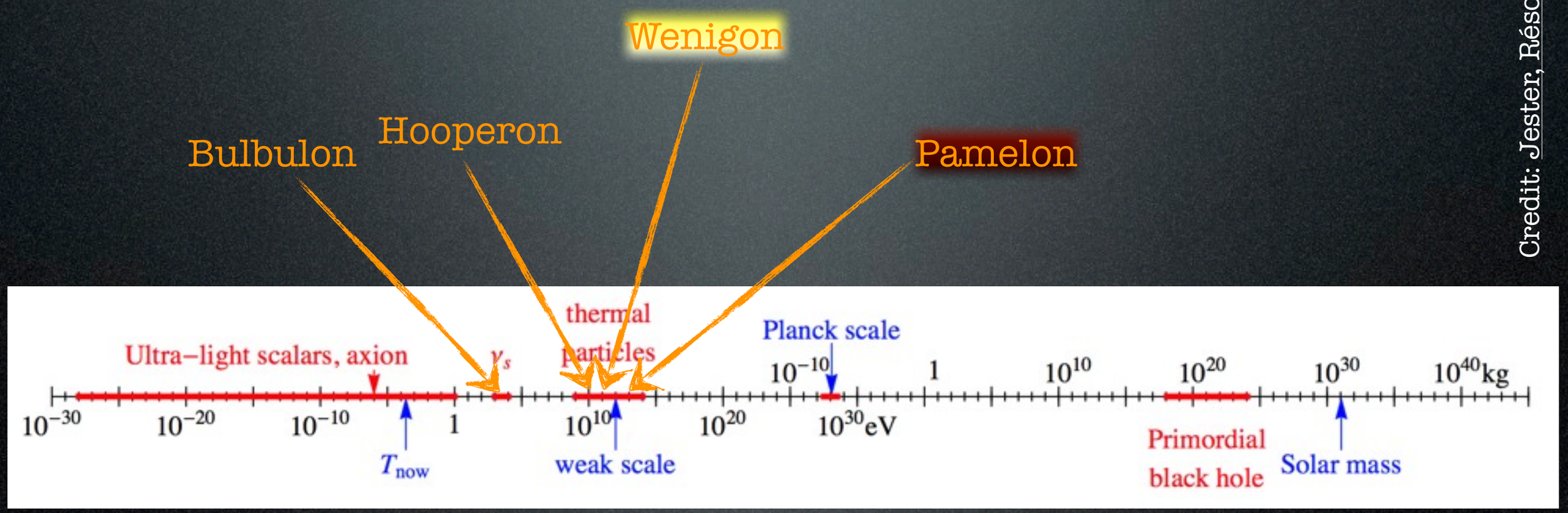
χ is a multiplet of states and ϕ is non-abelian gauge boson:
splitting $\delta M \sim 200$ KeV (via loops of non-abelian bosons)
- inelastic scattering explains DAMA
- eXcited state decay $\chi\chi \to \chi\chi^*$ explains INTEGRAL
$\hookrightarrow e^+e^-$

Gamma rays

2. the ‘130 GeV line’

DM Candidates

A matter of perspective: plausible mass ranges

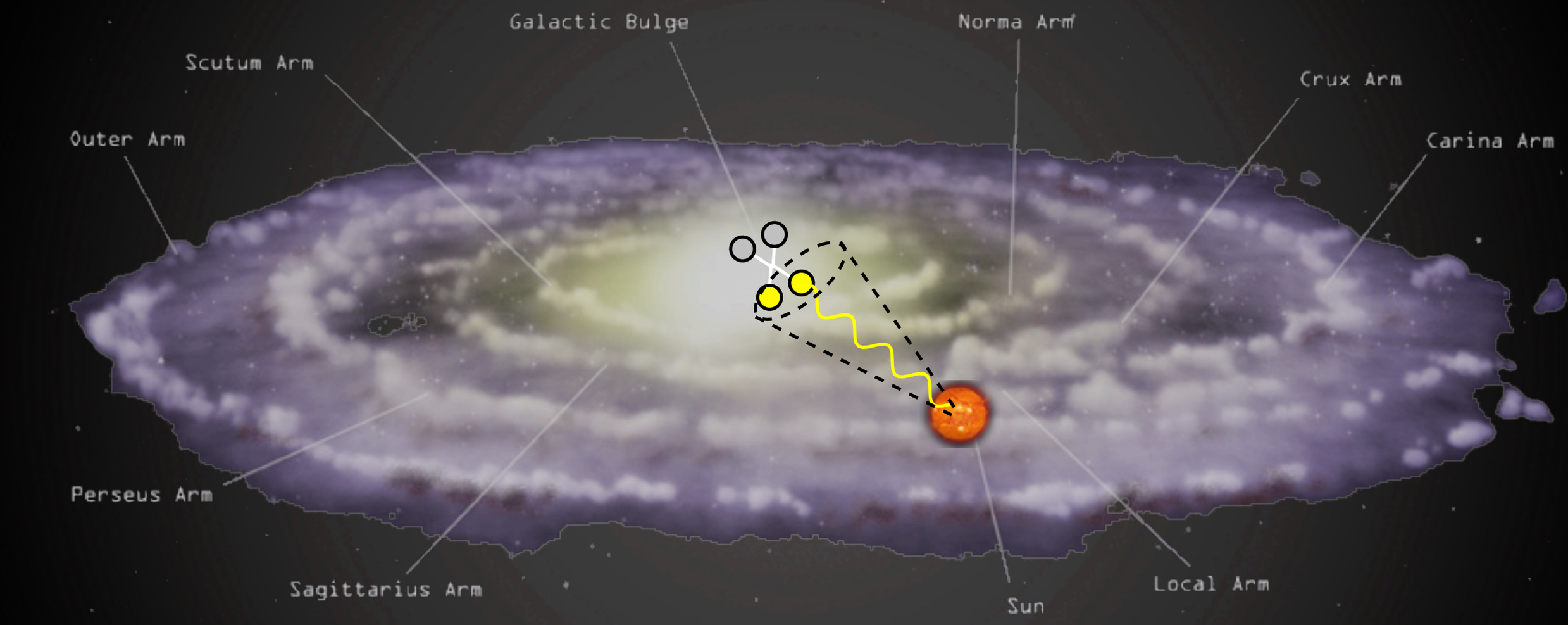


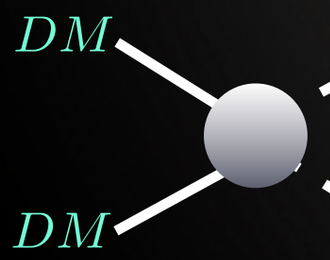
Credit: Jester, Résonaances

‘only’ 90 orders of magnitude!

Basic picture: targets

γ from DM annihilations in galactic center

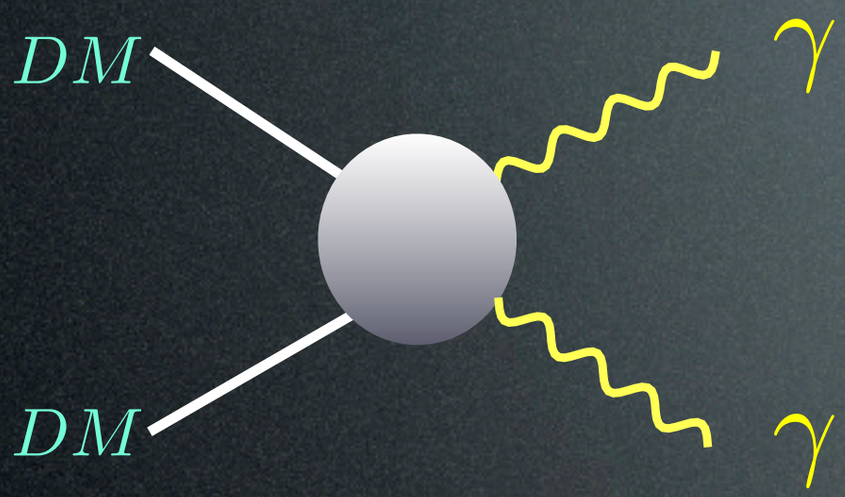




$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^{\mp},\ \overset{(-)}{p},\ \overset{(-)}{D}\ \ldots \text{ and } \gamma$$

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

Prompt emission: line(s)



primary
channels

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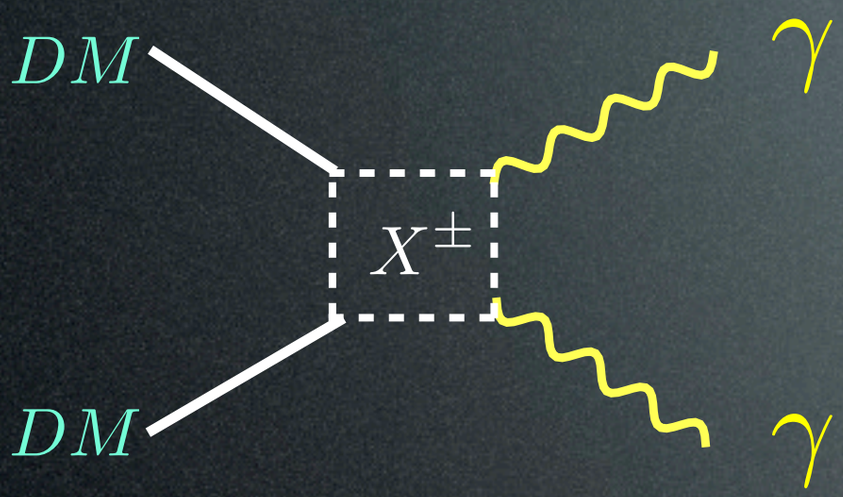

primary channels

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

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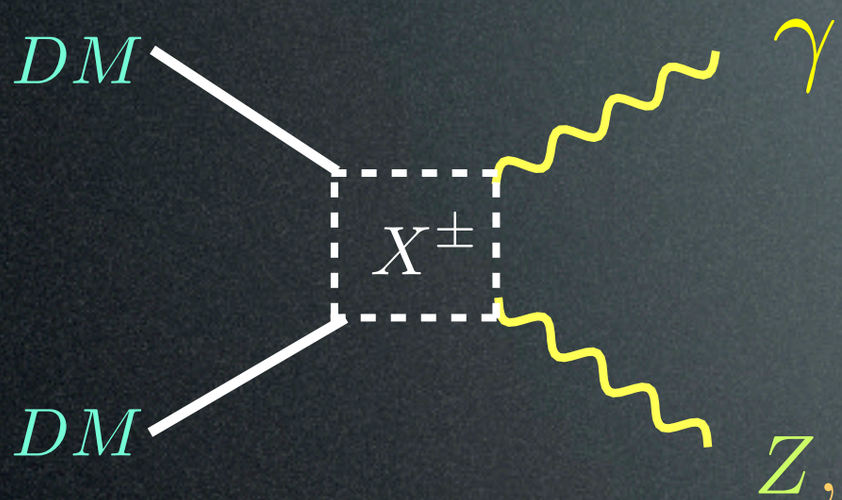

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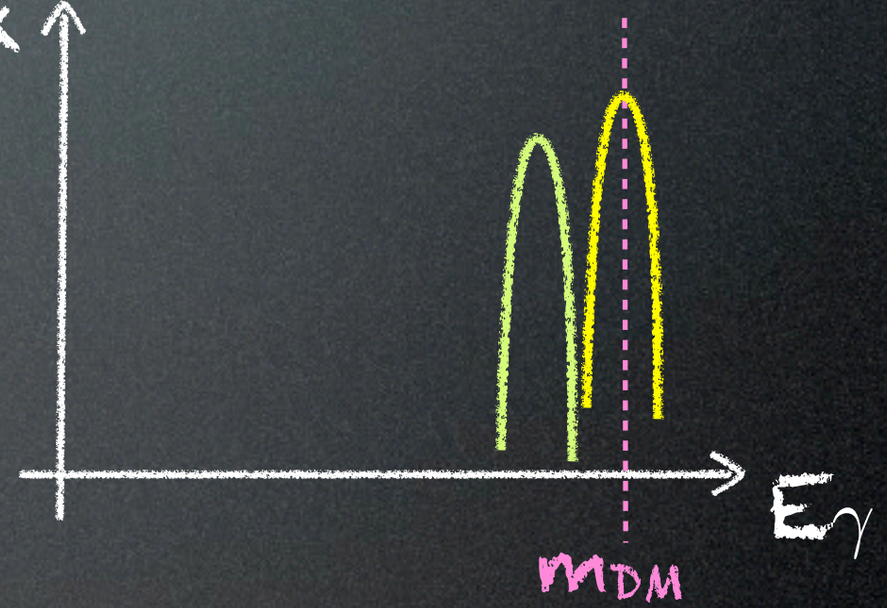

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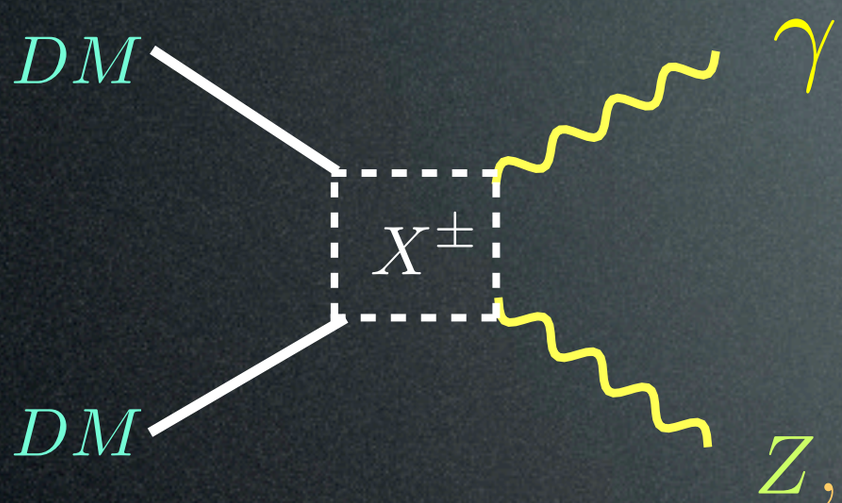

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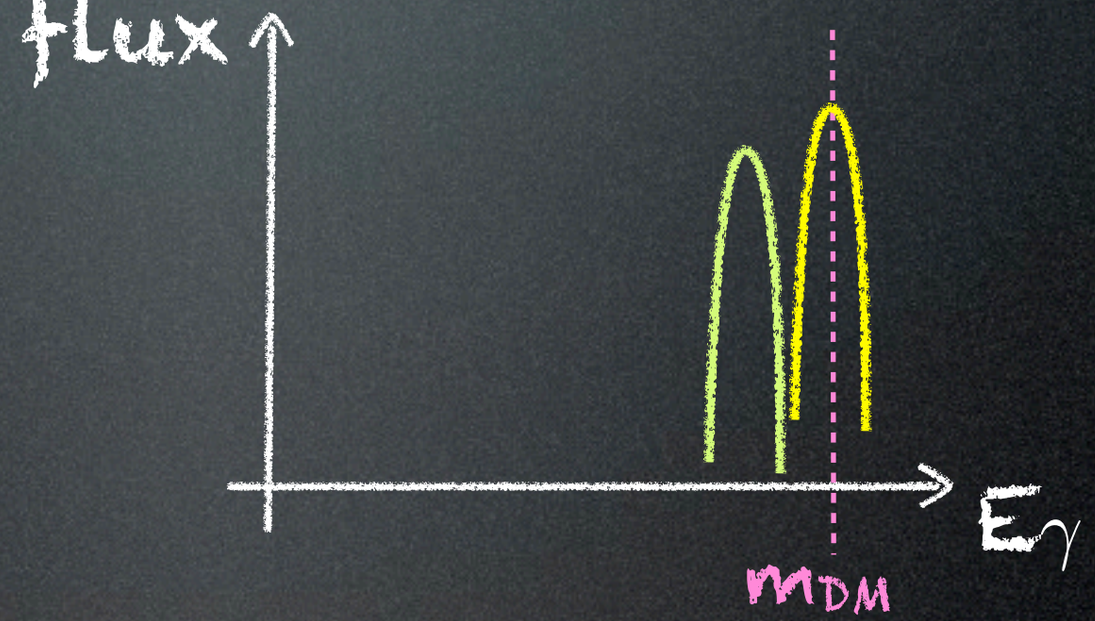


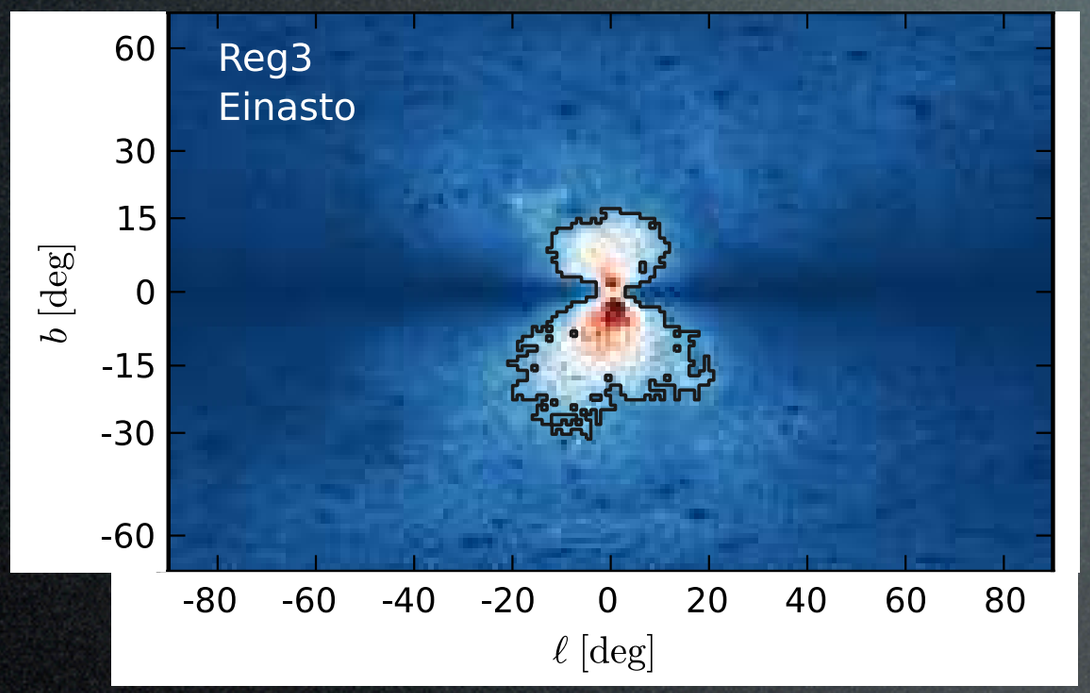
So what are the particle physics parameters?

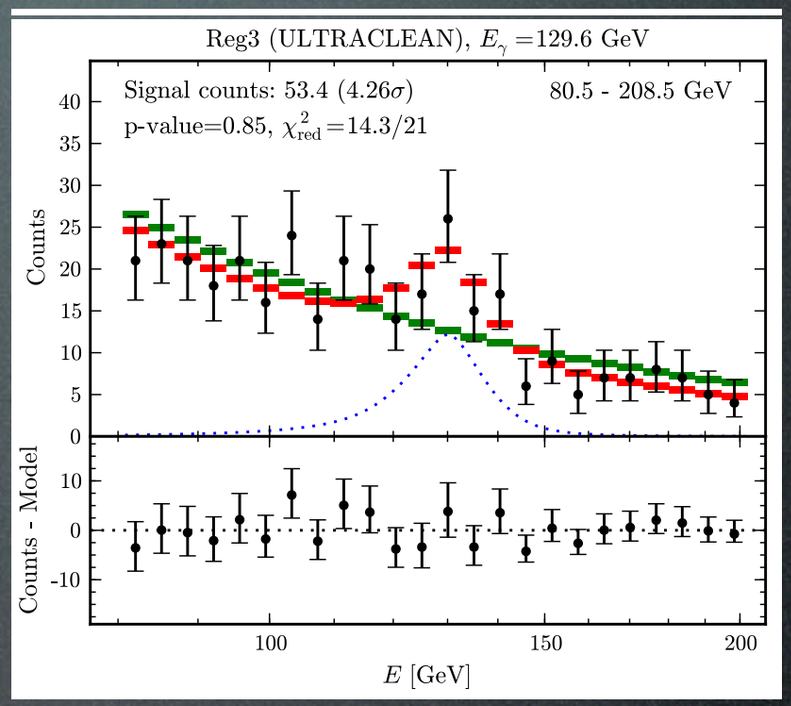
1. Dark Matter mass

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

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)

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

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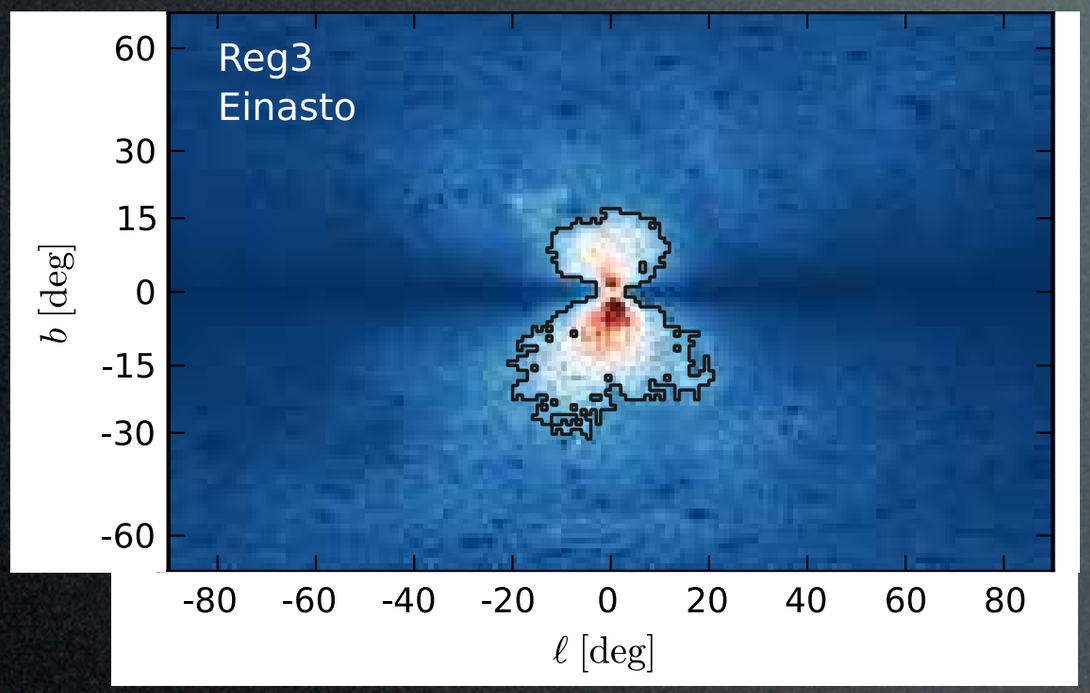

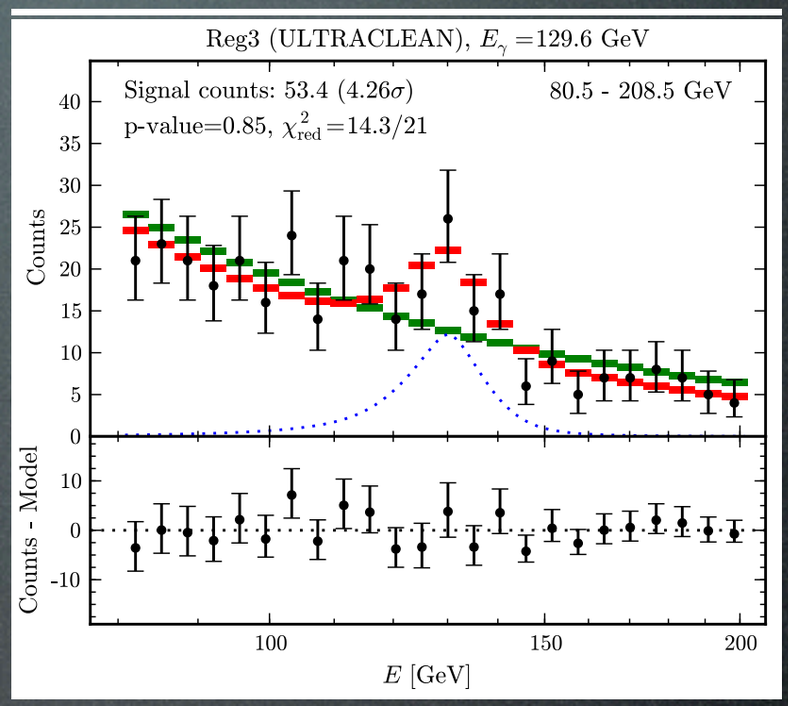

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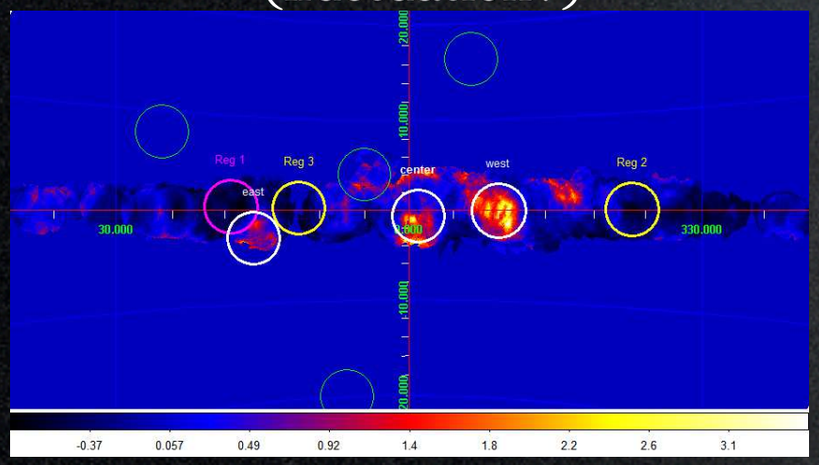
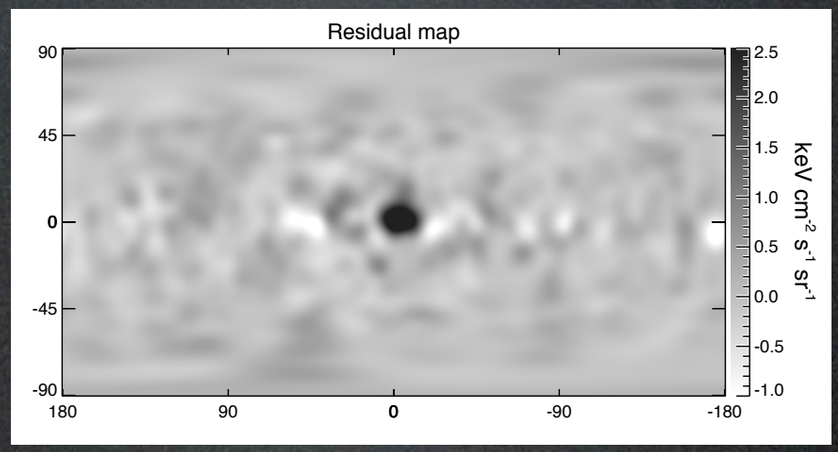
Similar excesses found elsewhere (fluctuation?)



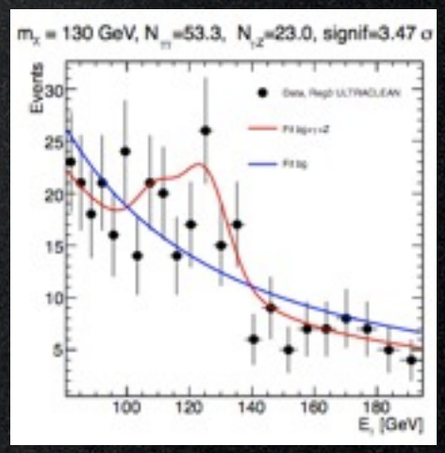
Boyarsky, Malyshev, Ruchayskyi, 1205.4700

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

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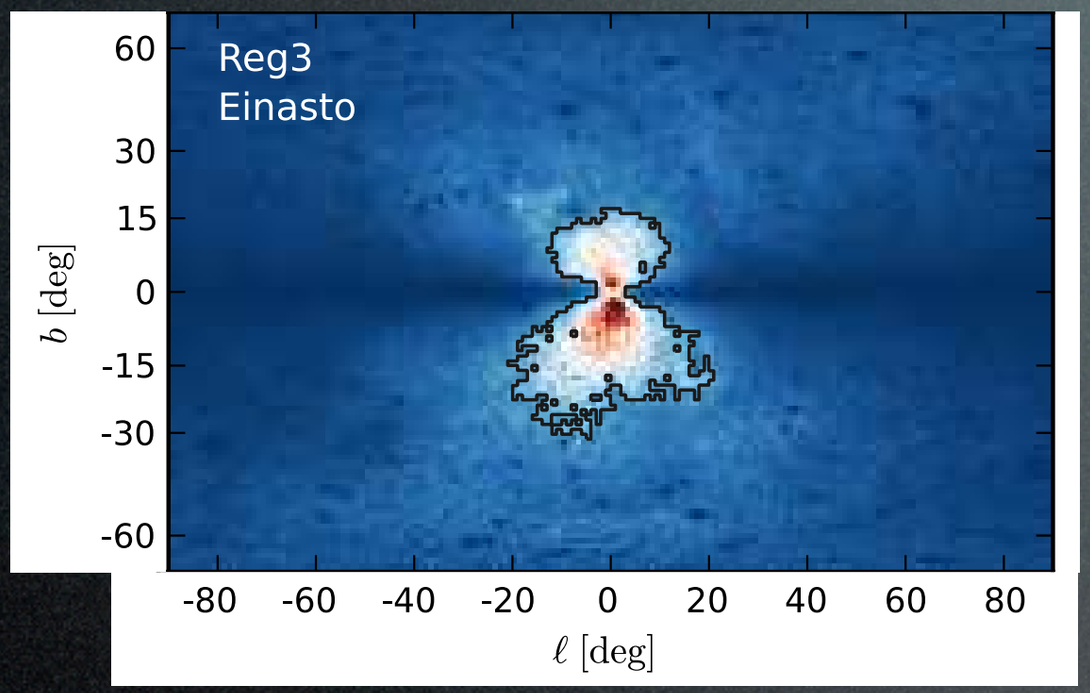

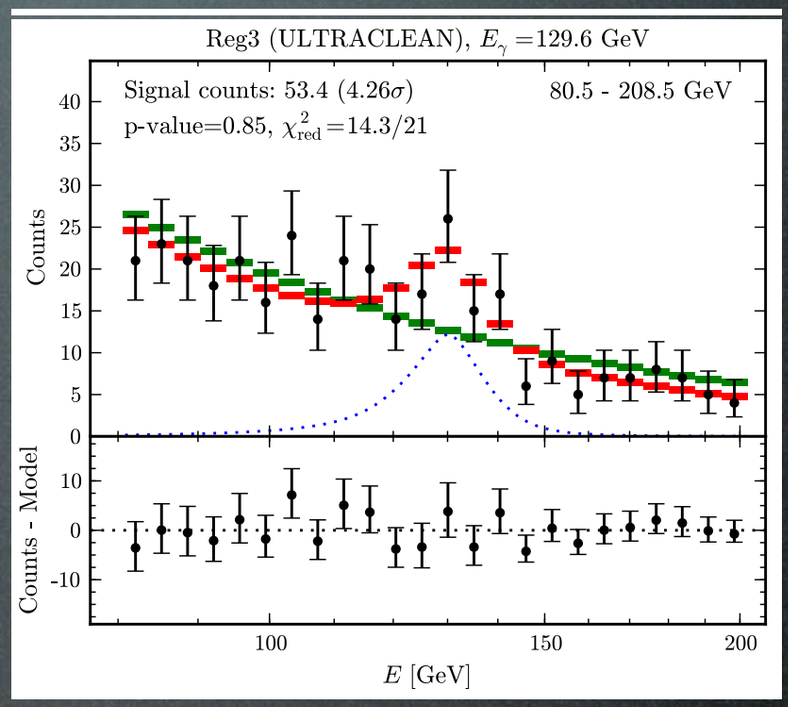

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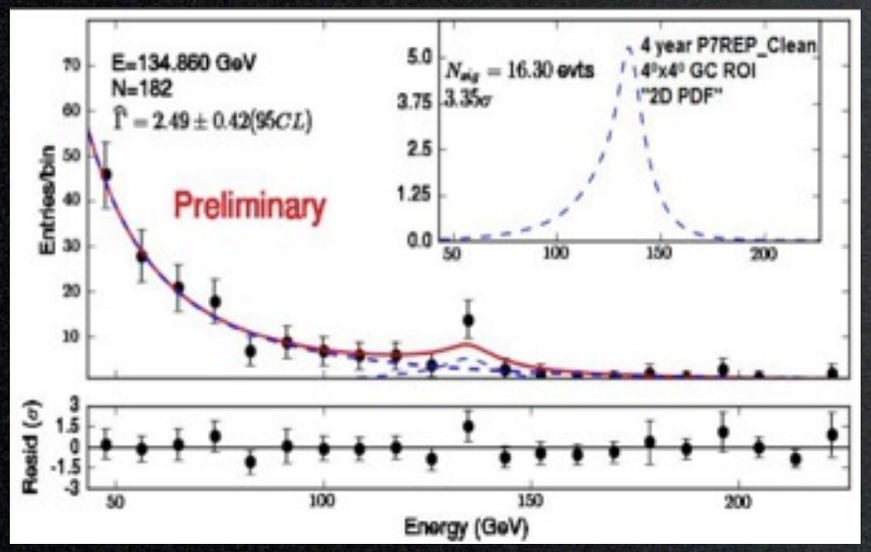
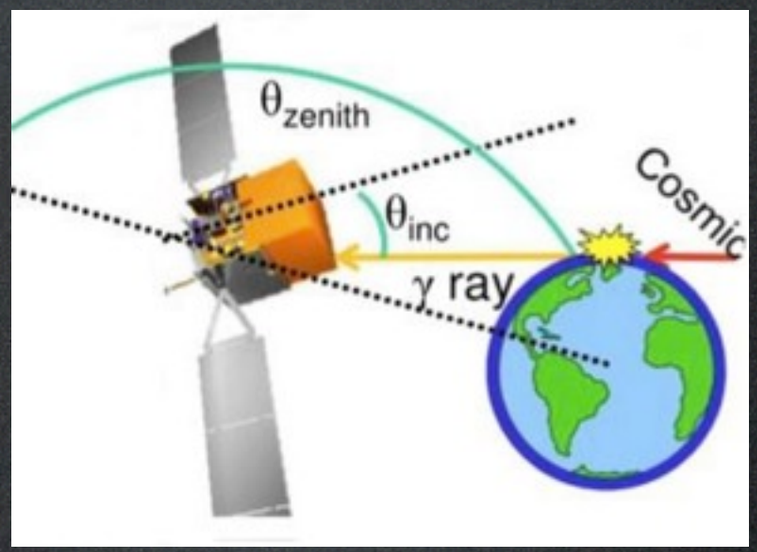
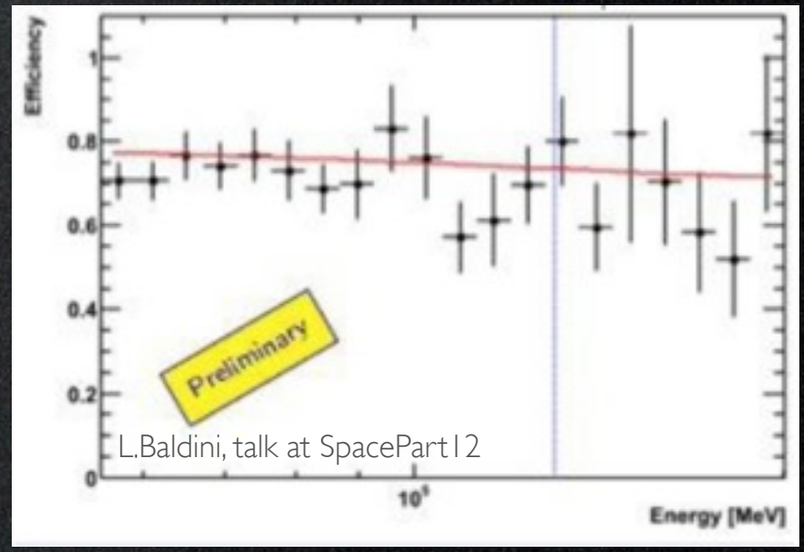
The Fermi coll's cold shower. An instrumental effect?







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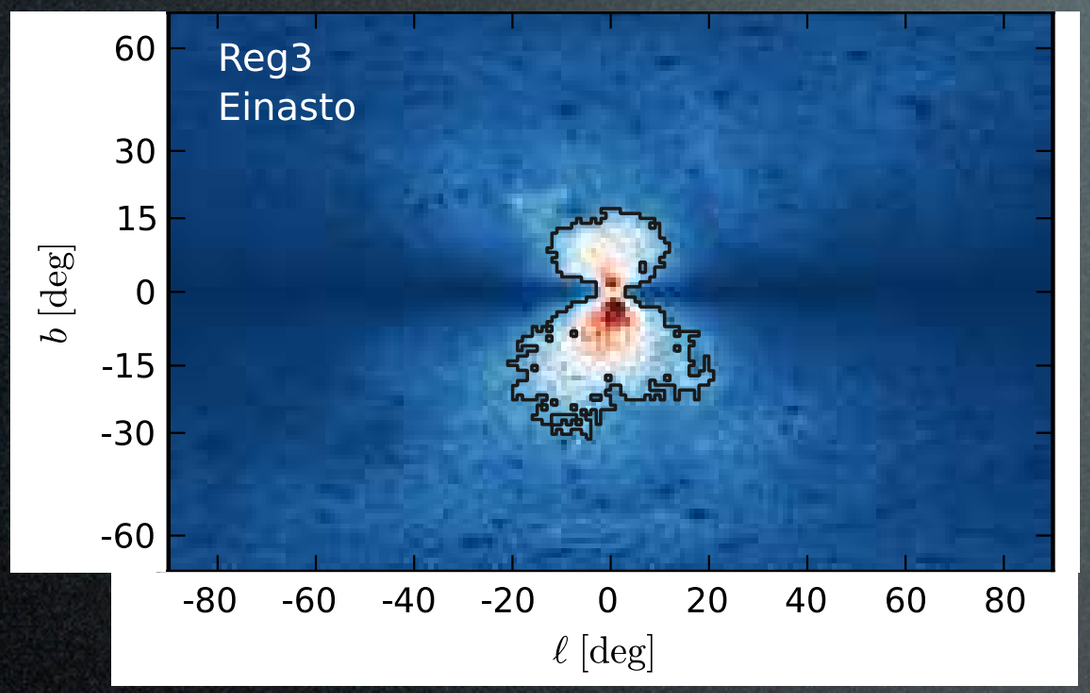

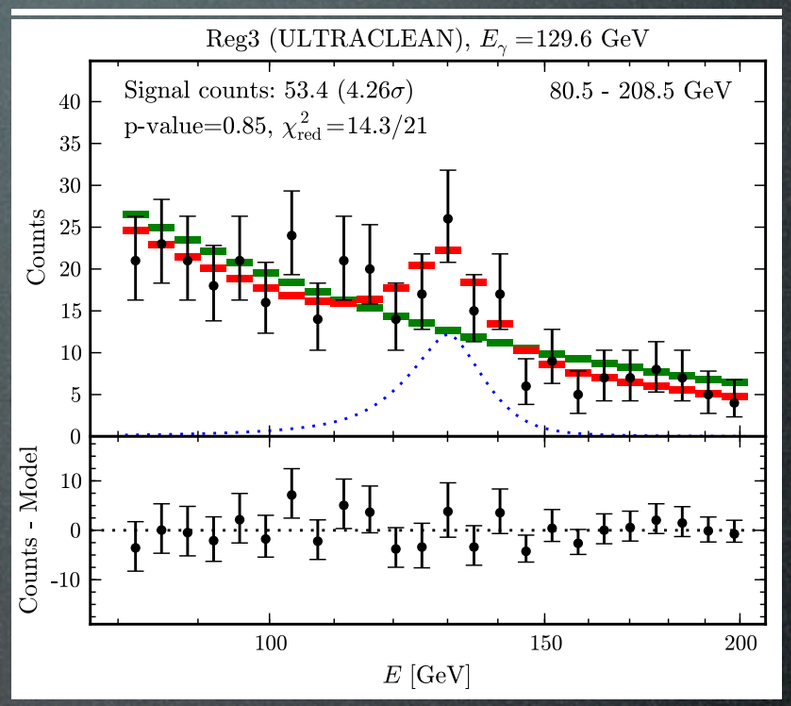

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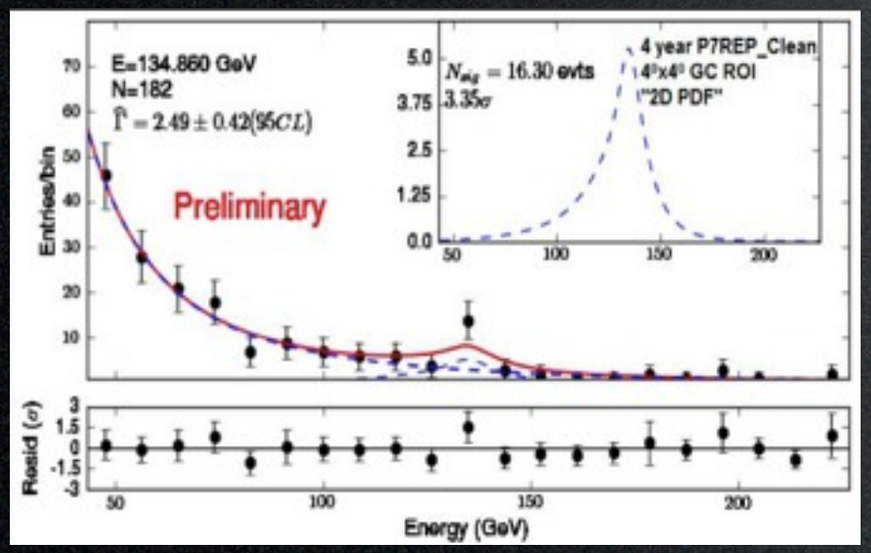
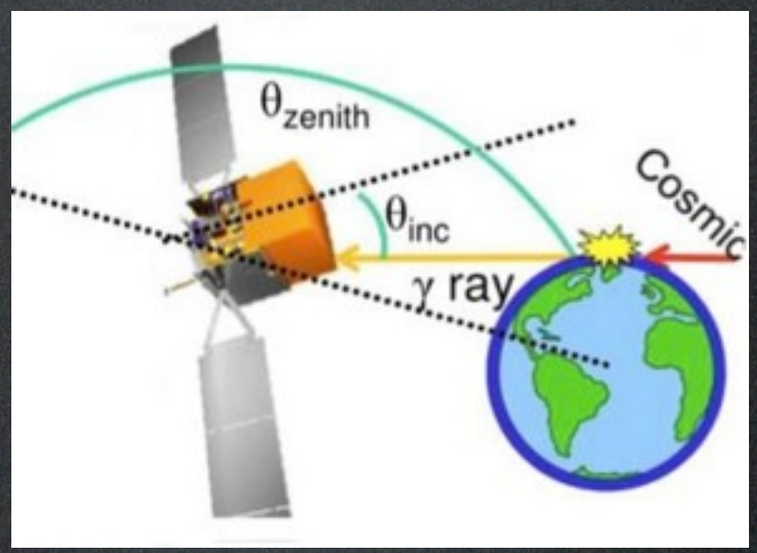
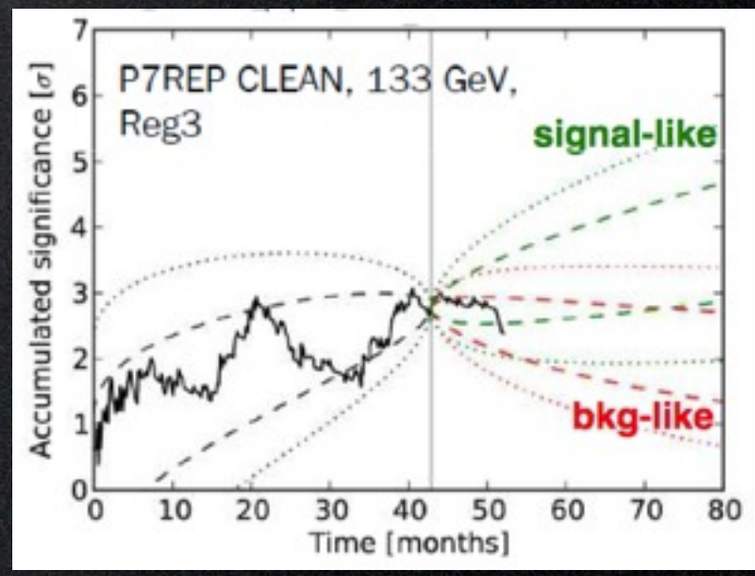






Theorist's reaction

2. the '130 GeV line' frenzy

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

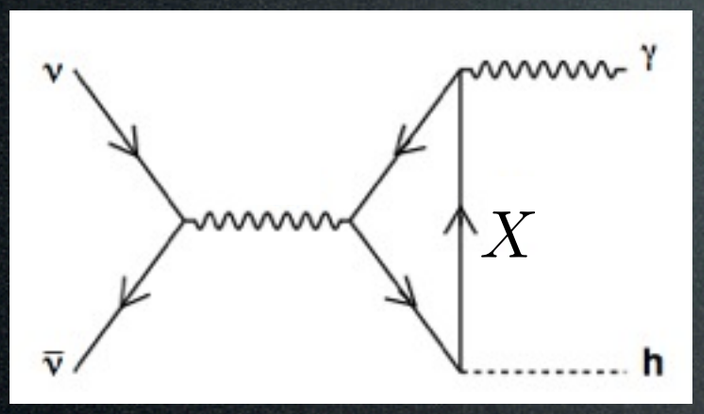
Challenges

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

Challenges

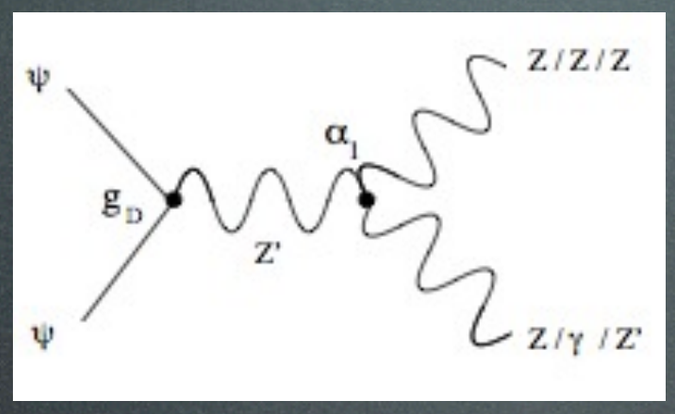
DM is <u>neutral</u>: need '*something*' to couple to γ

a loop



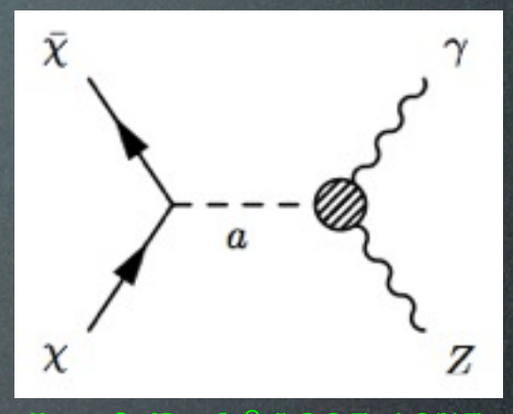
'Higgs in space!' 0912.0004
Kyae, Park 1205.4151
Cline 1205.2688

Chern-Simons



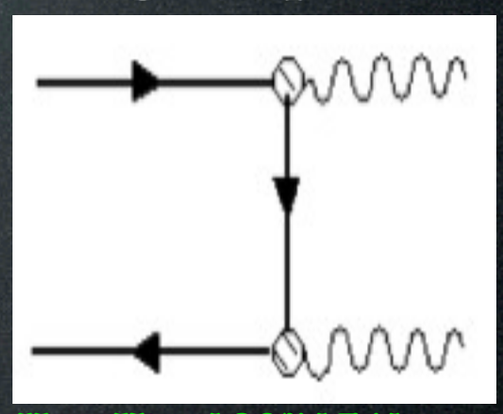
Dudas et al., 1205.1520

axions



Lee & Park[2] 1205.4675

magn dipole



Heo, Kim 1207.1341

...

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

Challenges

DM is <u>neutral</u>: need '*something*' to couple to γ

The '*something*' implies usually a suppression,

Challenges

DM is <u>neutral</u>: need '**something**' to couple to γ

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

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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

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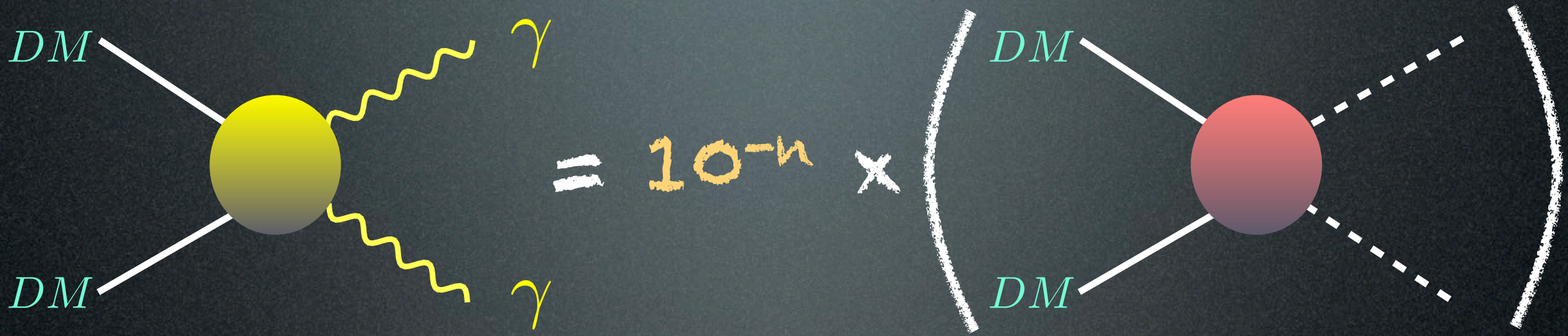

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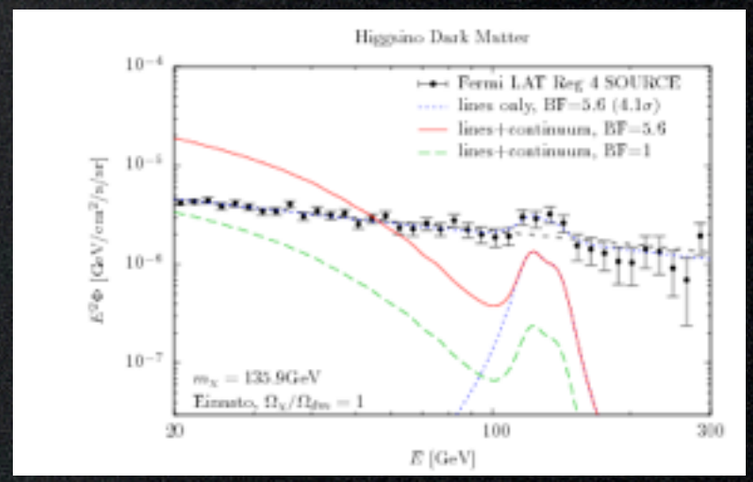

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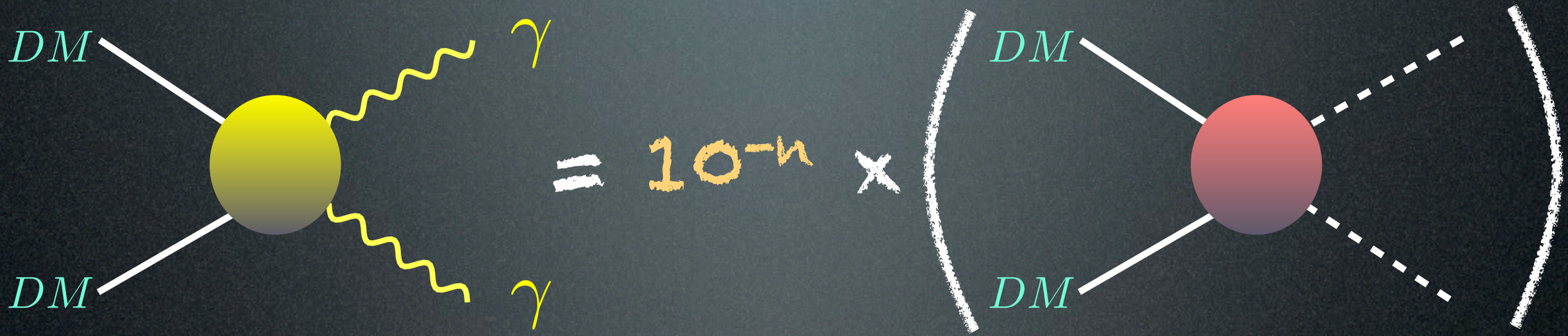

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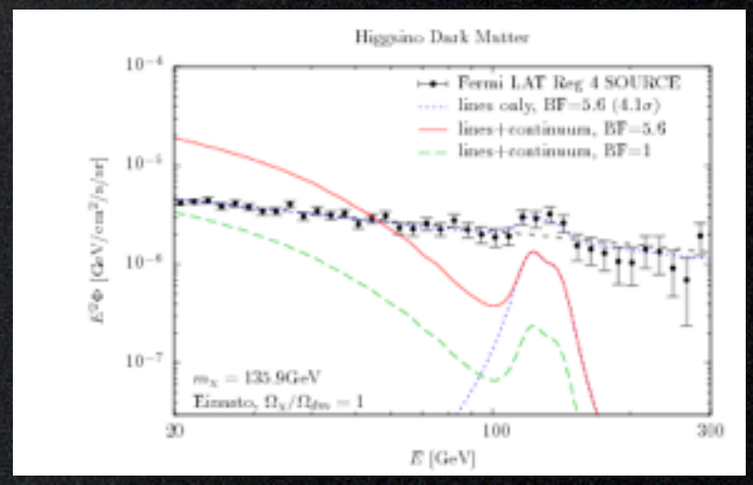
But solutions exist



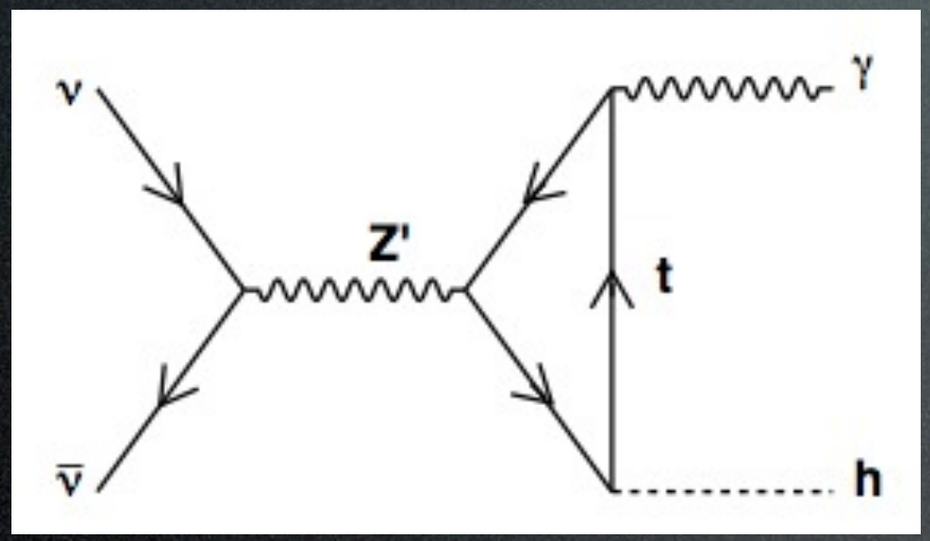
Model building

not exhaustive!

Ex. 1: 'resonance, loop and forbidden channel'

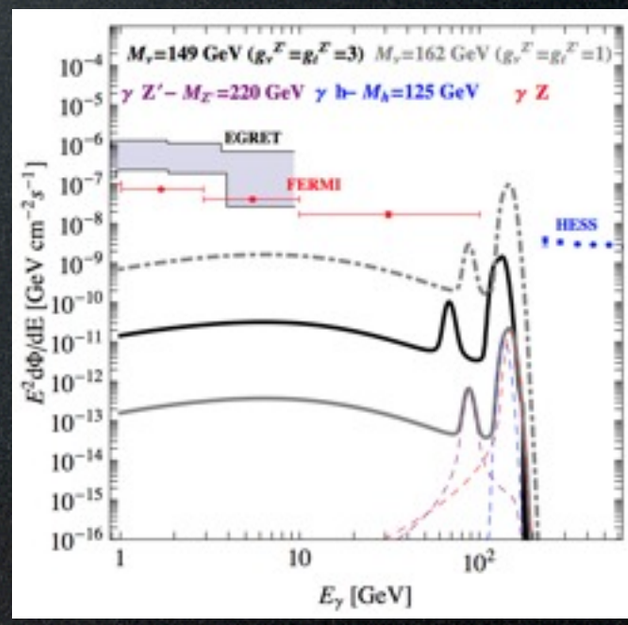
(a) DM charged under U'(1)
(b) Z' is t_R-philic
(c) $m_{DM} \lesssim m_{top}$

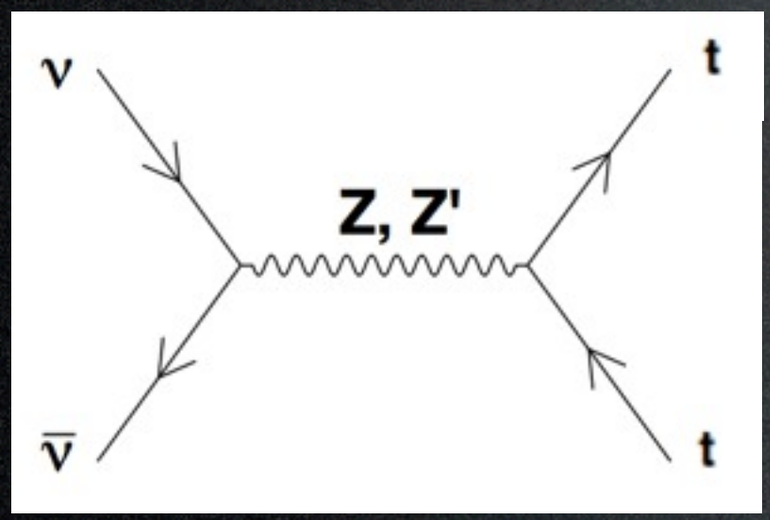
Jackson, Servant, Shaughnessy, Tait, Taoso, 'Higgs in space', 0912.0004



➡ line(s)

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





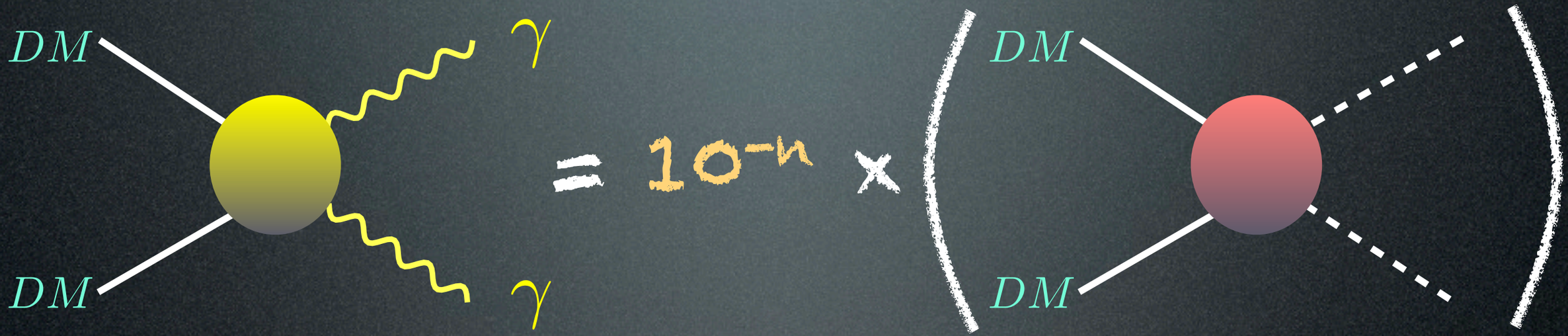
today:
kinematically forbidden (c)
little in other channels (b) (only via Z-Z' mixing)
➡ small continuum

Early Universe:
➡ relic abundance

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

Challenges

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



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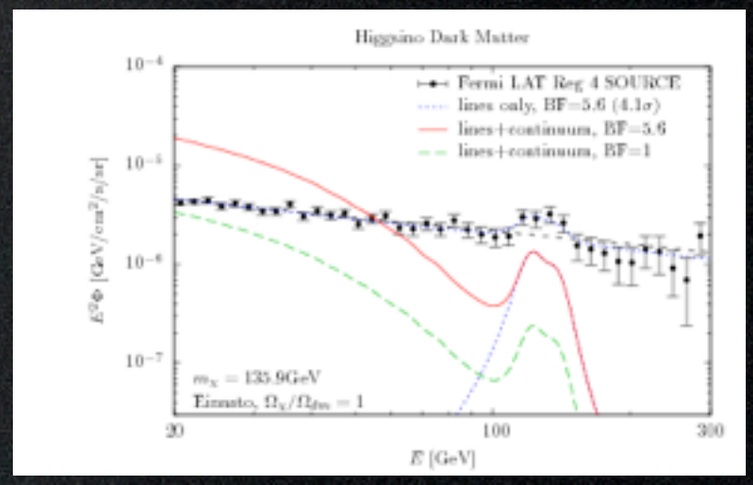


Model building

- 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:

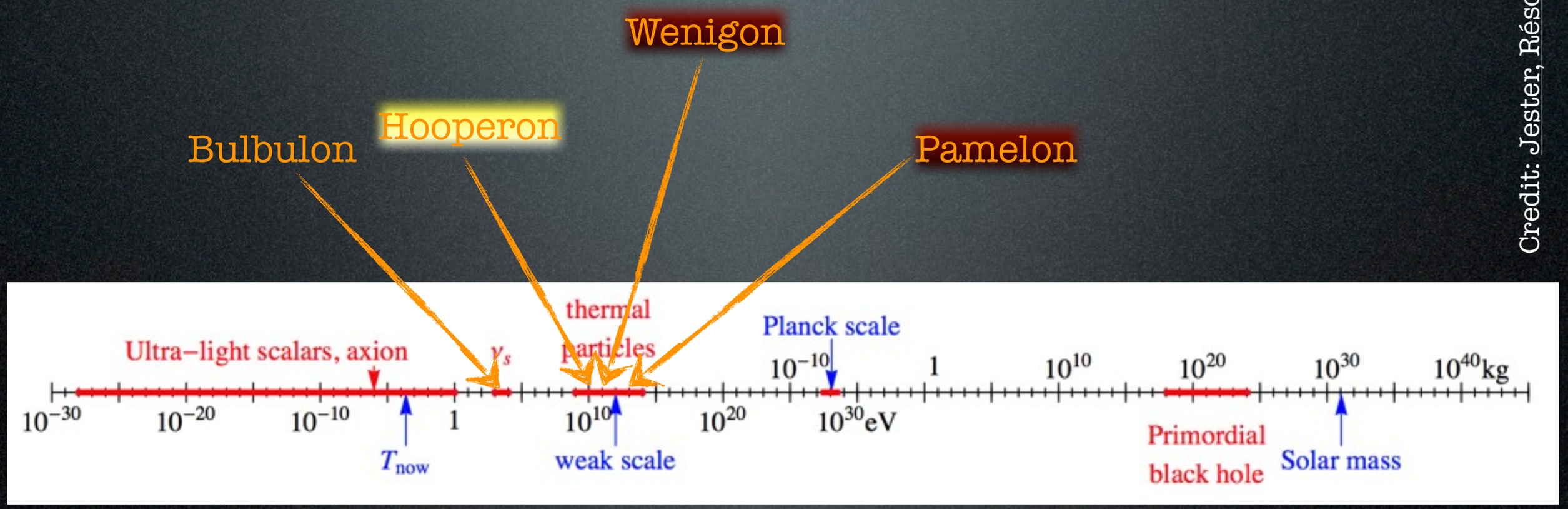
- kinematically forbidden channel
- different diagrams
- s-wave vs p-wave
- coannihilations and splitting
- DM production is decoupled from annihilations
- ...

Gamma rays

3. the ‘Hooperon’

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?

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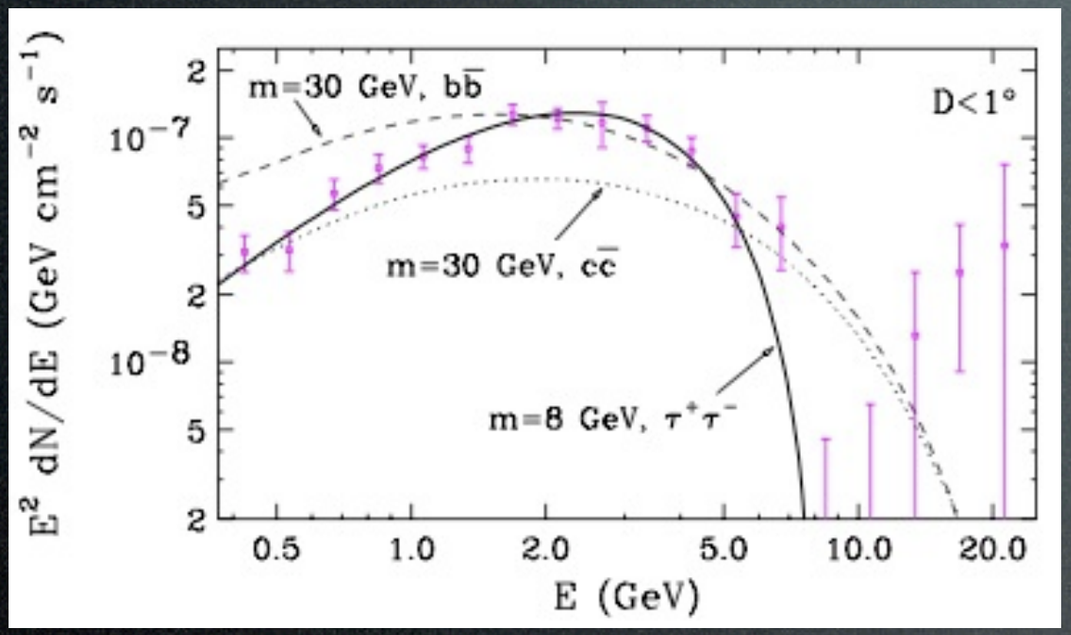

Hooper, Goodenough 1010.2752

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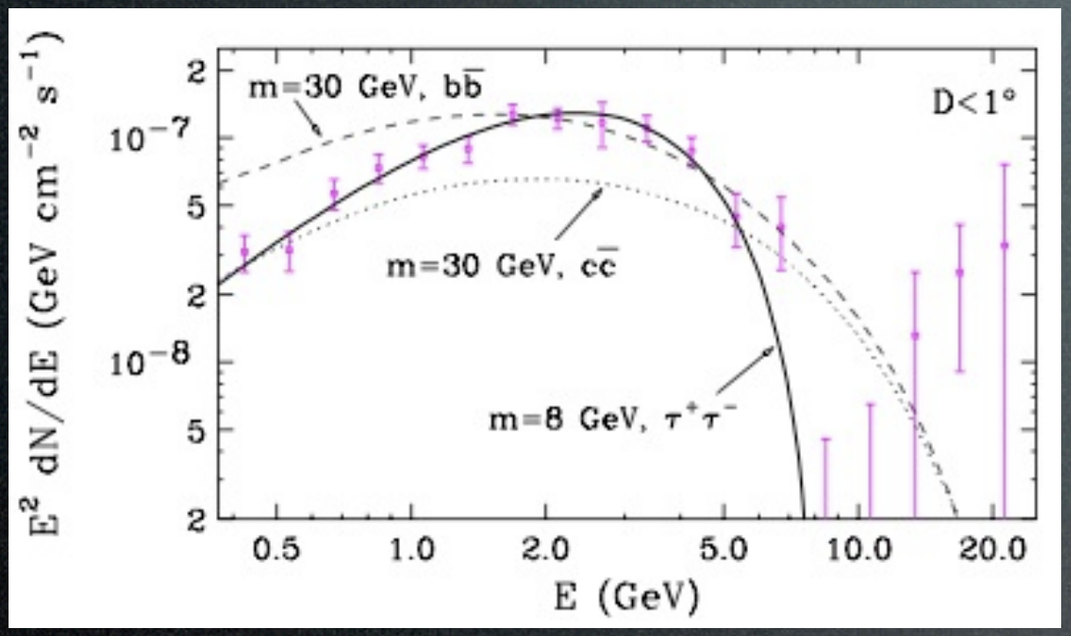
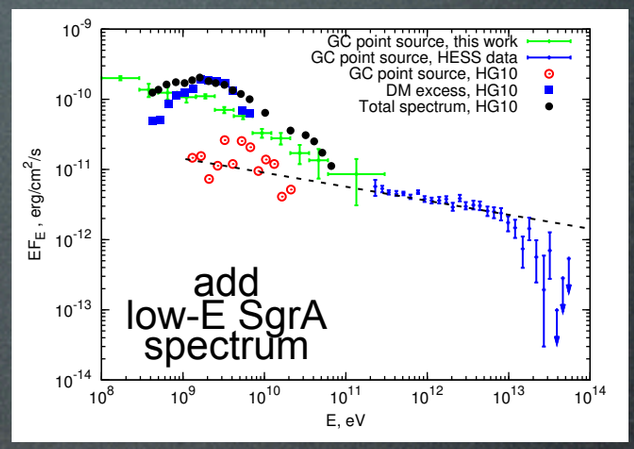
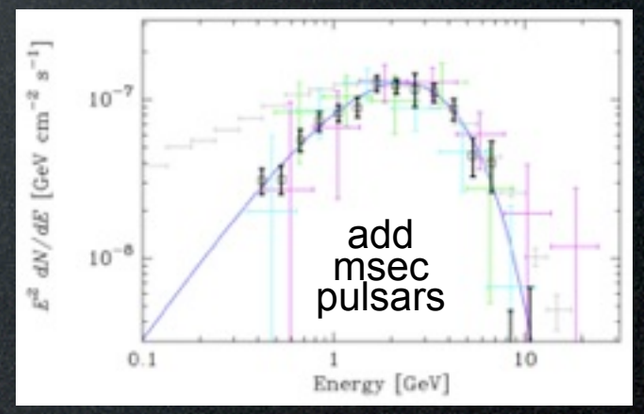


Hooper, Goodenough 1010.2752

Objection: know your backgrounds!



Boyarsky et al., 1012.5839



Abazajian 1011.4275

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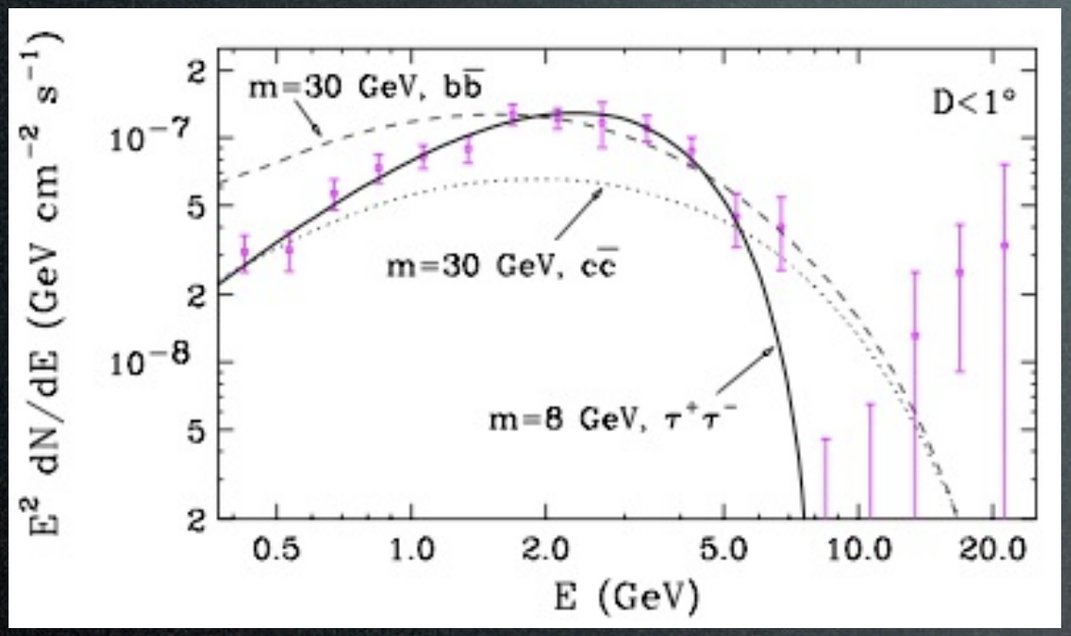

Hooper, Goodenough 1010.2752

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

A diffuse GeV excess from around the GC

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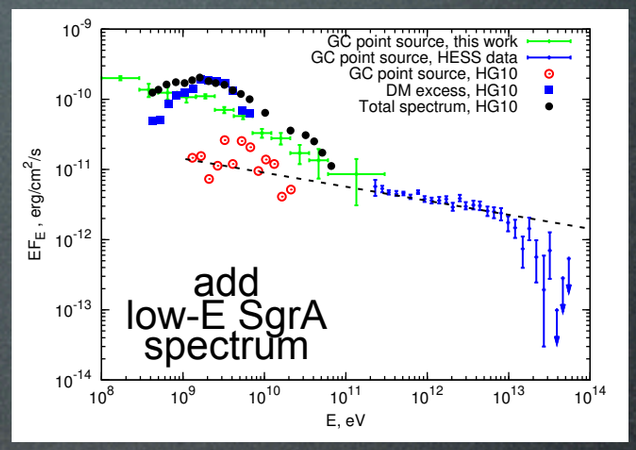
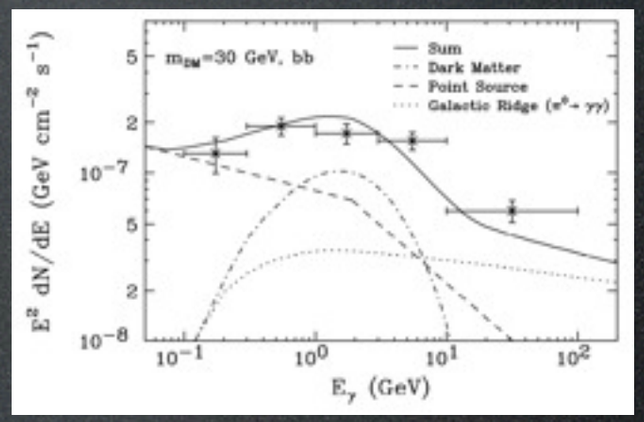
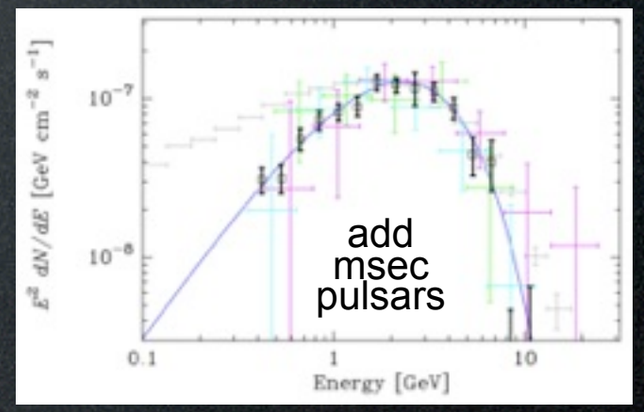


Boyarsky et al., 1012.5839

Still works...



Hooper, Linden 1110.0006



Abazajian 1011.4275

No, too few

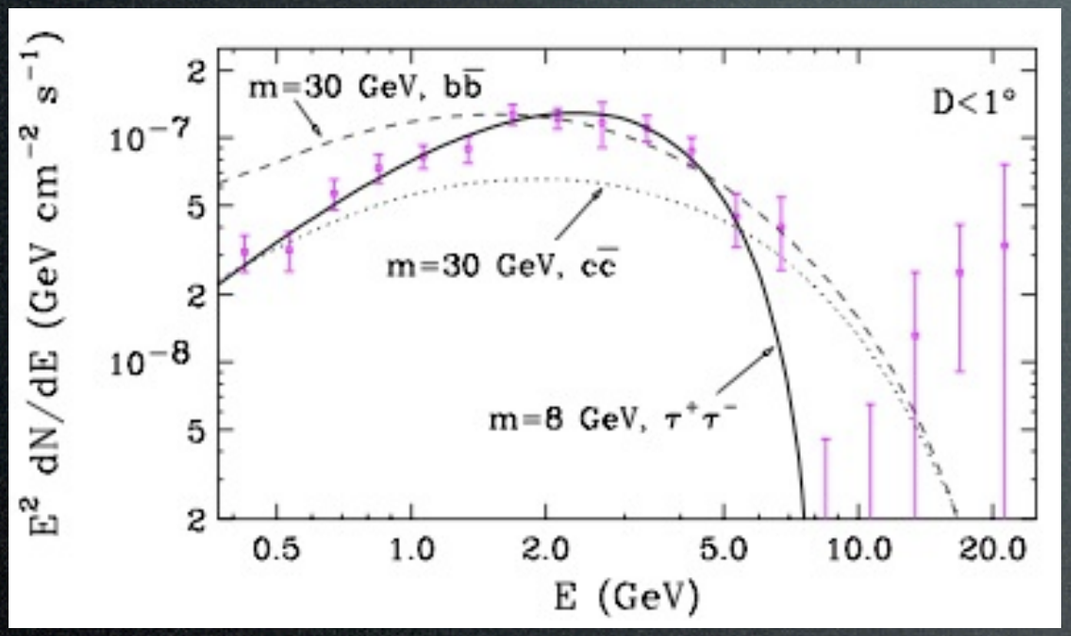
(and we should have seen them elsewhere)

and wrong spectra

Hooper et al. 1305.0830

GeV gamma excess?

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



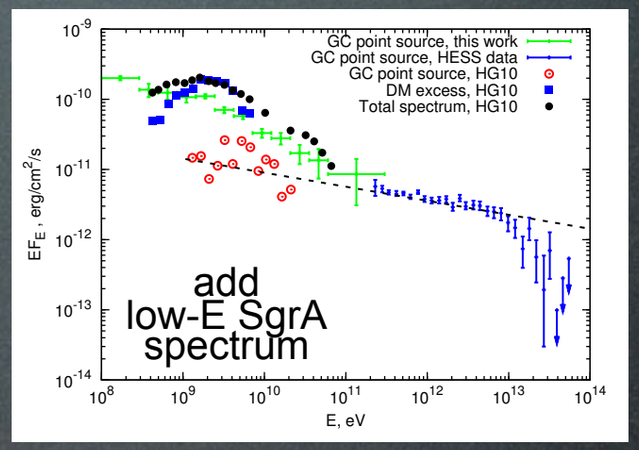
Hooper, Goodenough 1010.2752

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

A diffuse GeV excess from around the GC

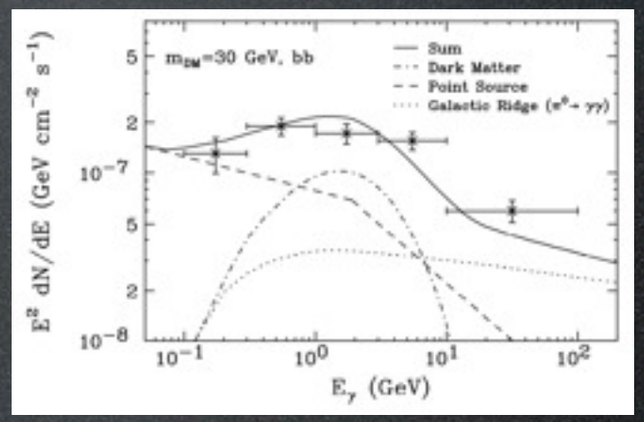
Dan Hooper

Objection: know your backgrounds!

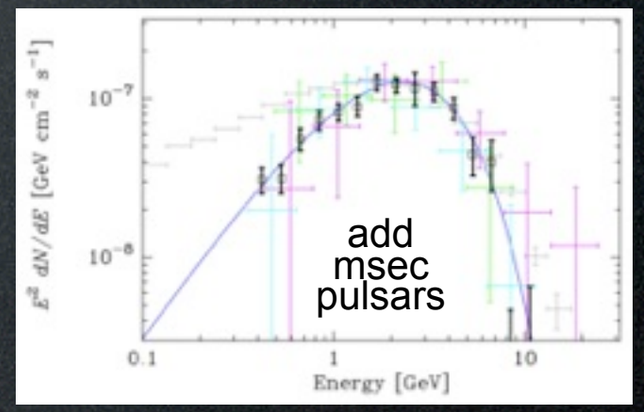


Boyarsky et al., 1012.5839

Still works...



Hooper, Linden 1110.0006



Abazajian 1011.4275

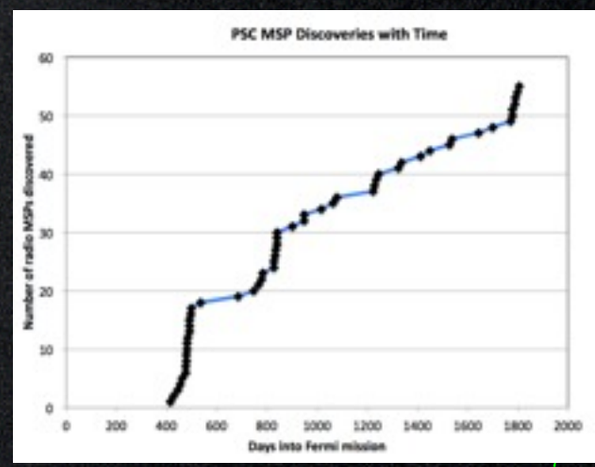
No, too few

(and we should have seen them elsewhere)

and wrong spectra

Hooper et al. 1305.0830

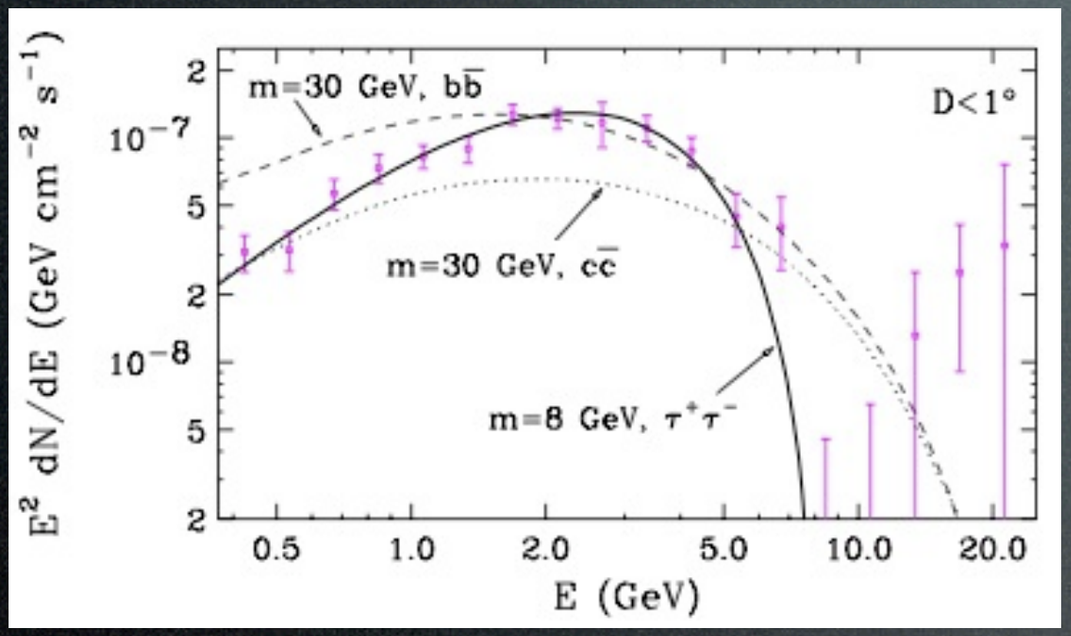
MSPs exist.



Caraveo 1312.2913

GeV gamma excess?

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



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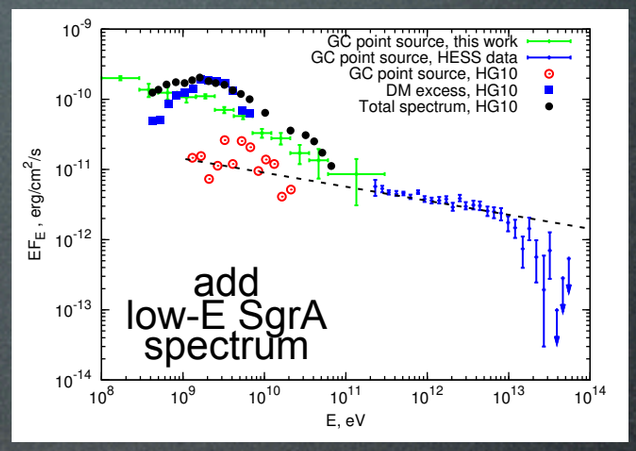
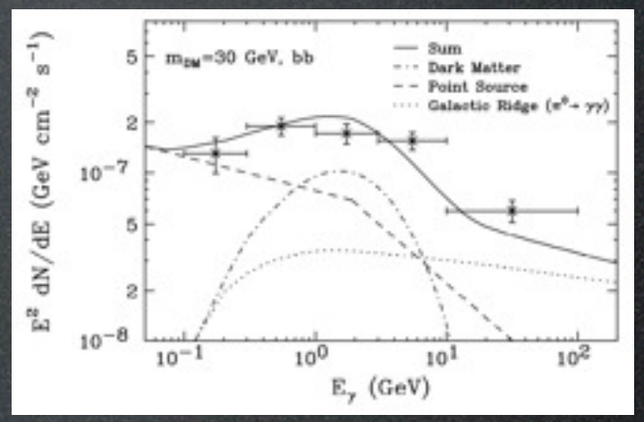
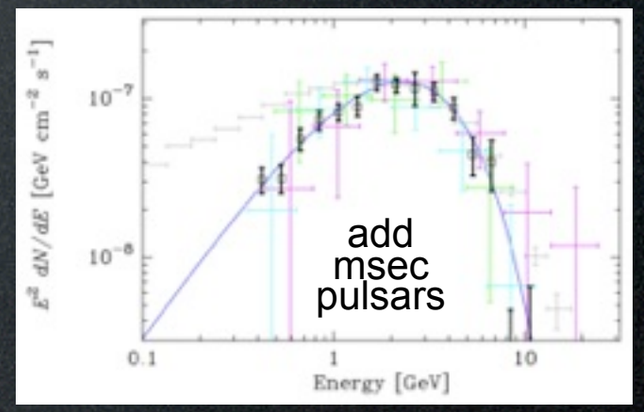


Boyarsky et al., 1012.5839

Still works...



Hooper, Linden 1110.0006



Abazajian 1011.4275

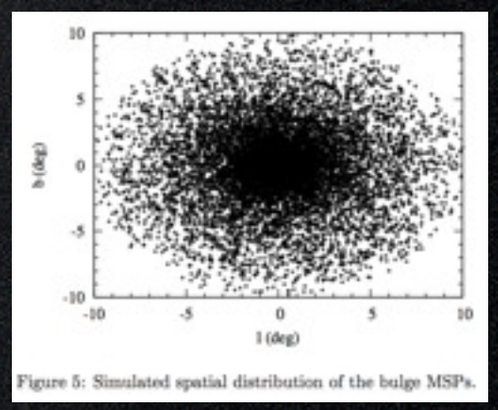
No, too few

(and we should have seen them elsewhere)

and wrong spectra

Hooper et al. 1305.0830

No no, MSPs can do.

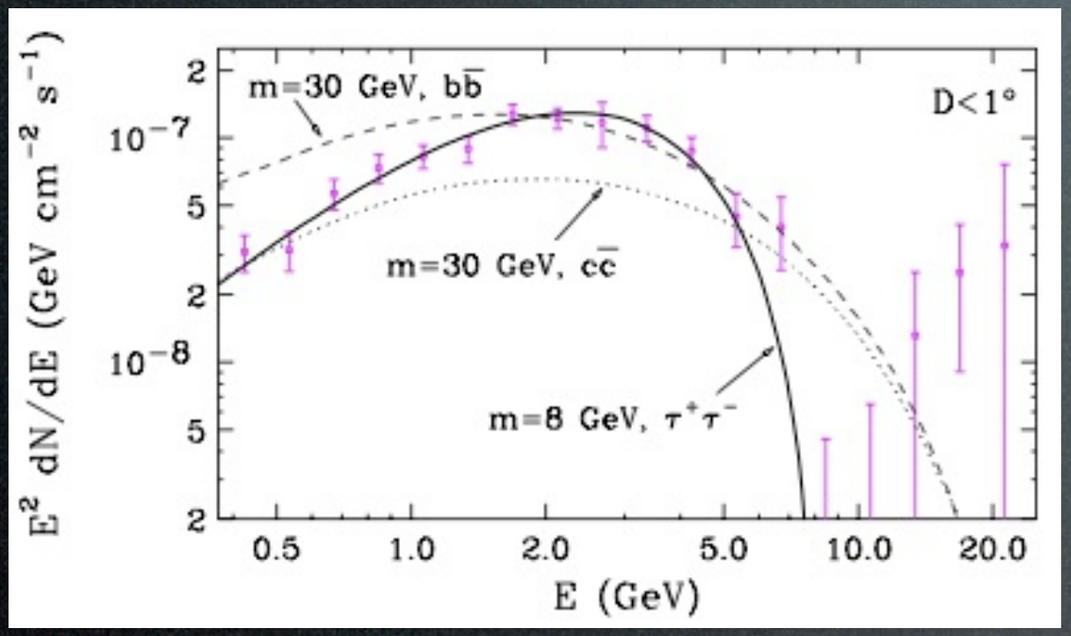


Yuan, Zhang 1404.2318

(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?



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A diffuse GeV excess from around the GC

Dan Hooper

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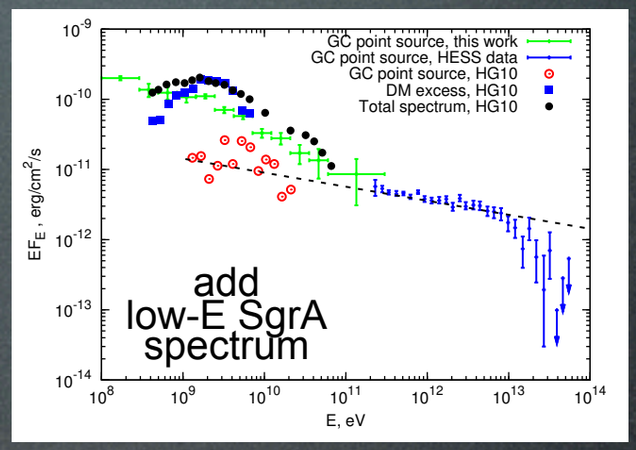

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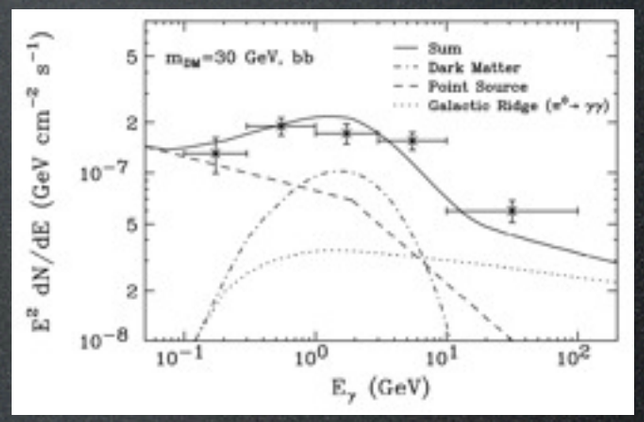
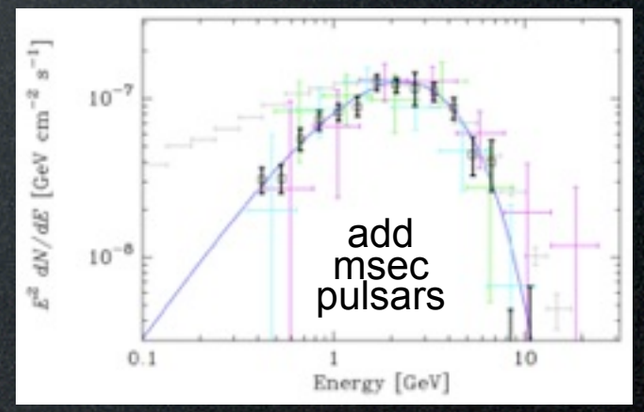


Hooper, Linden 1110.0006



Abazajian 1011.4275

No, too few

(and we should have seen them elsewhere)

and wrong spectra

Hooper et al. 1305.0830

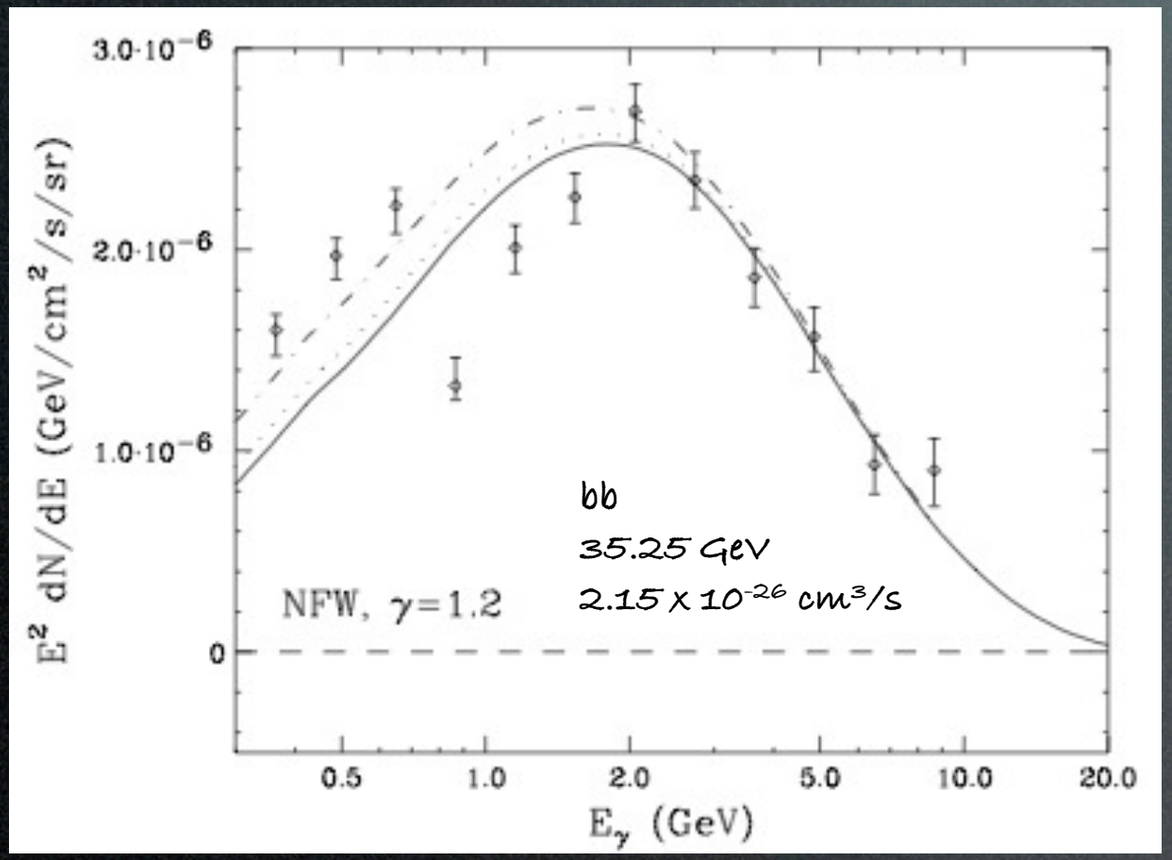
No no, MSPs can do:

they can give a large if not dominant contribution to the excess.

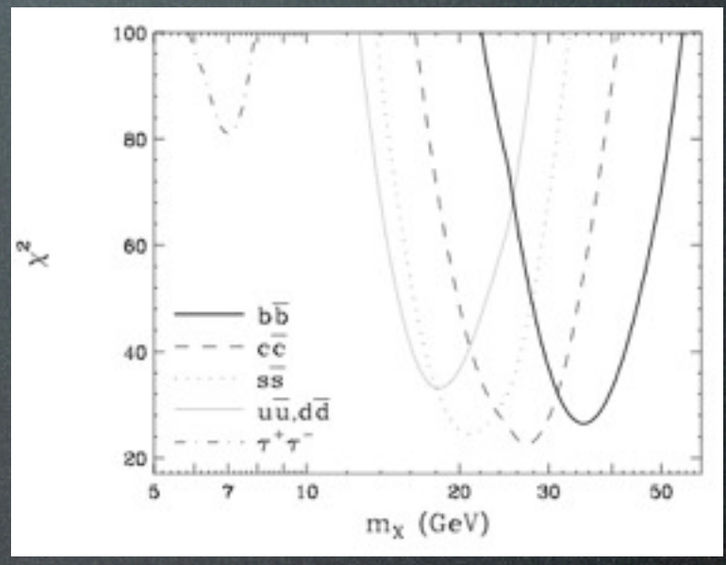
Petrović, Serpico, Zaharijas 1411.2980

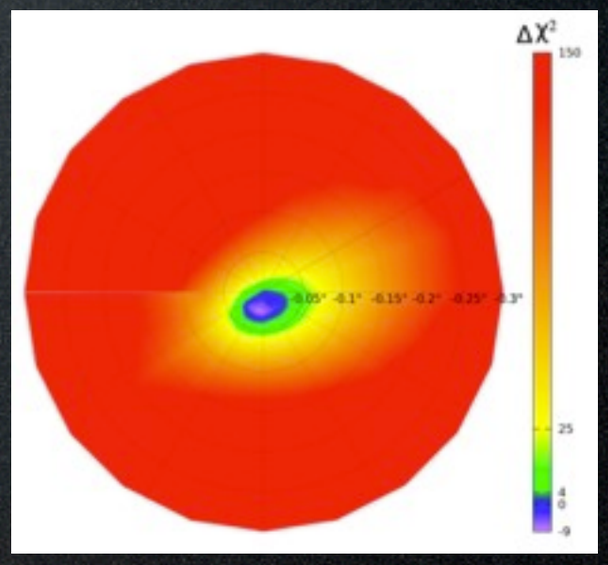
GeV gamma excess?

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

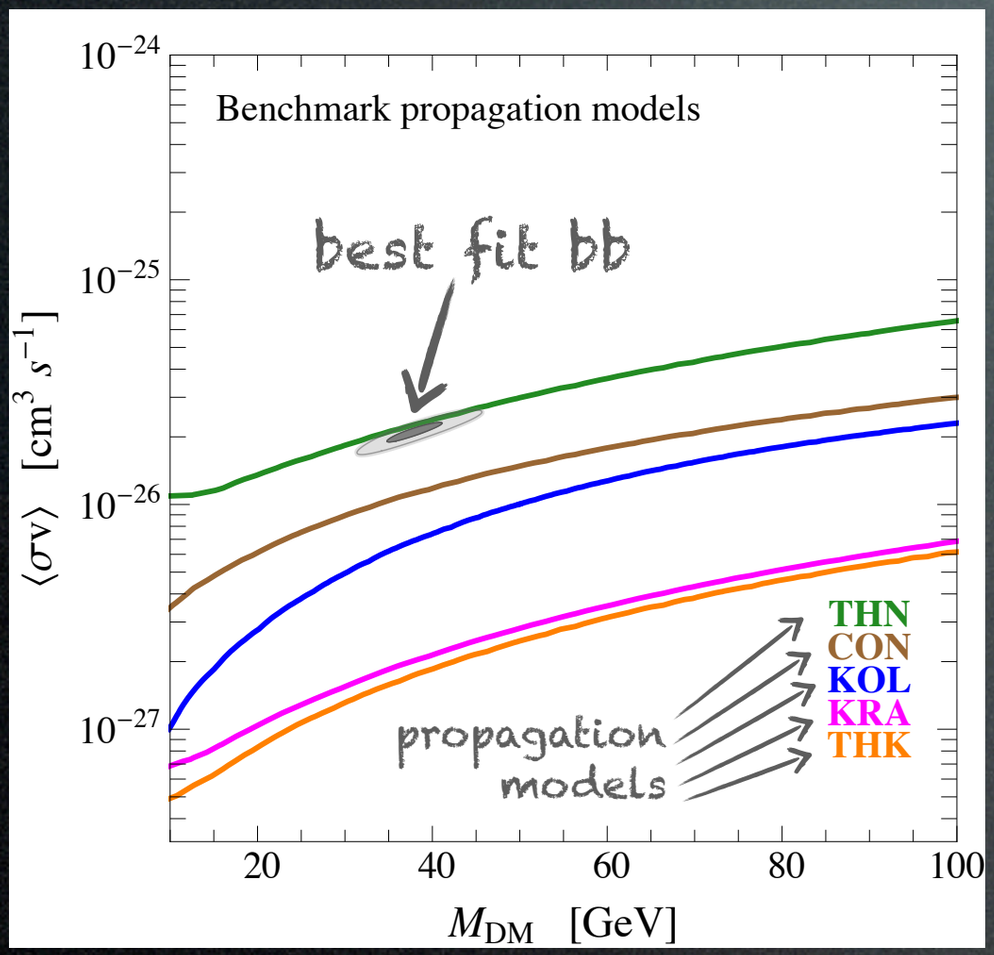
A compelling case for annihilating DM

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?



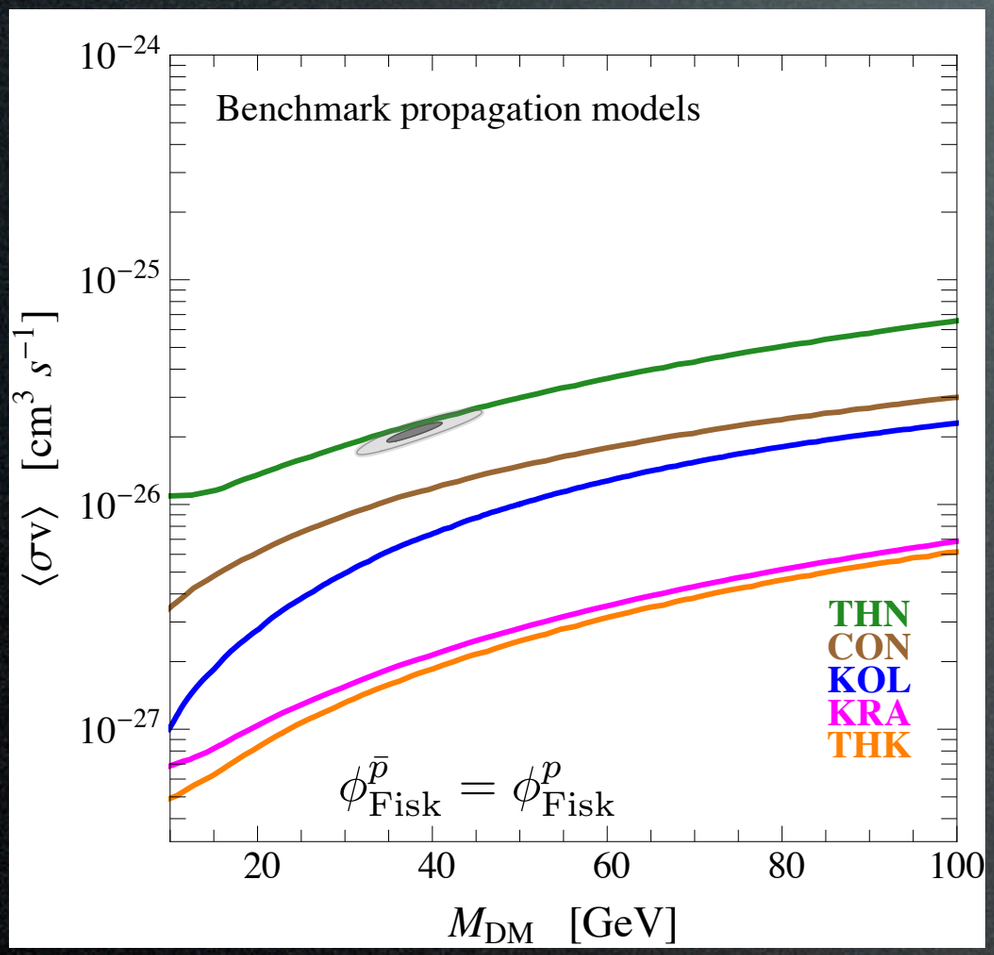
Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173

Antiproton constraints may be very relevant! But not robust.

Fermi-LAT excess

GeV gamma excess?

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



Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173

Antiproton constraints may be very relevant! But <u>not</u> robust.

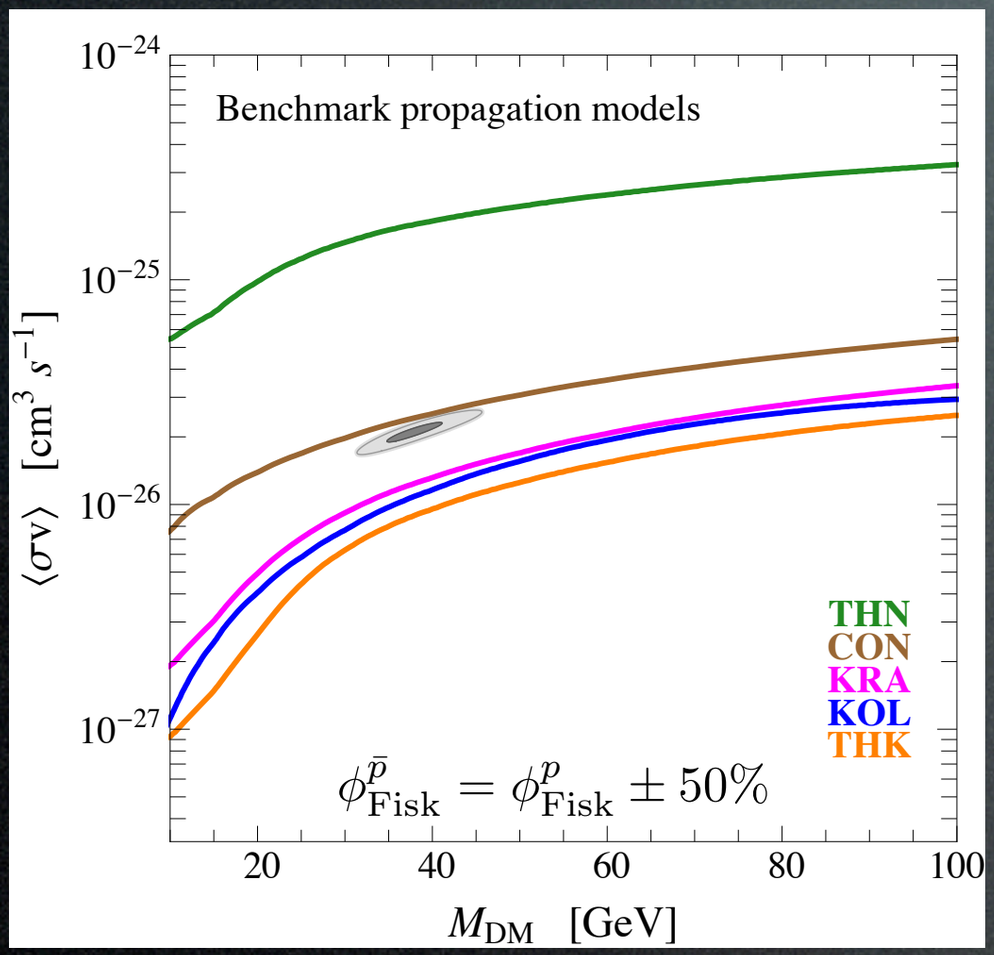
<u>Assumption</u>: fixed solar modulation

<u>Result</u>: hooperon excluded
(except unrealistic THN)

Fermi-LAT excess

GeV gamma excess?

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



Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173

Antiproton constraints may be very relevant! But <u>not</u> robust.

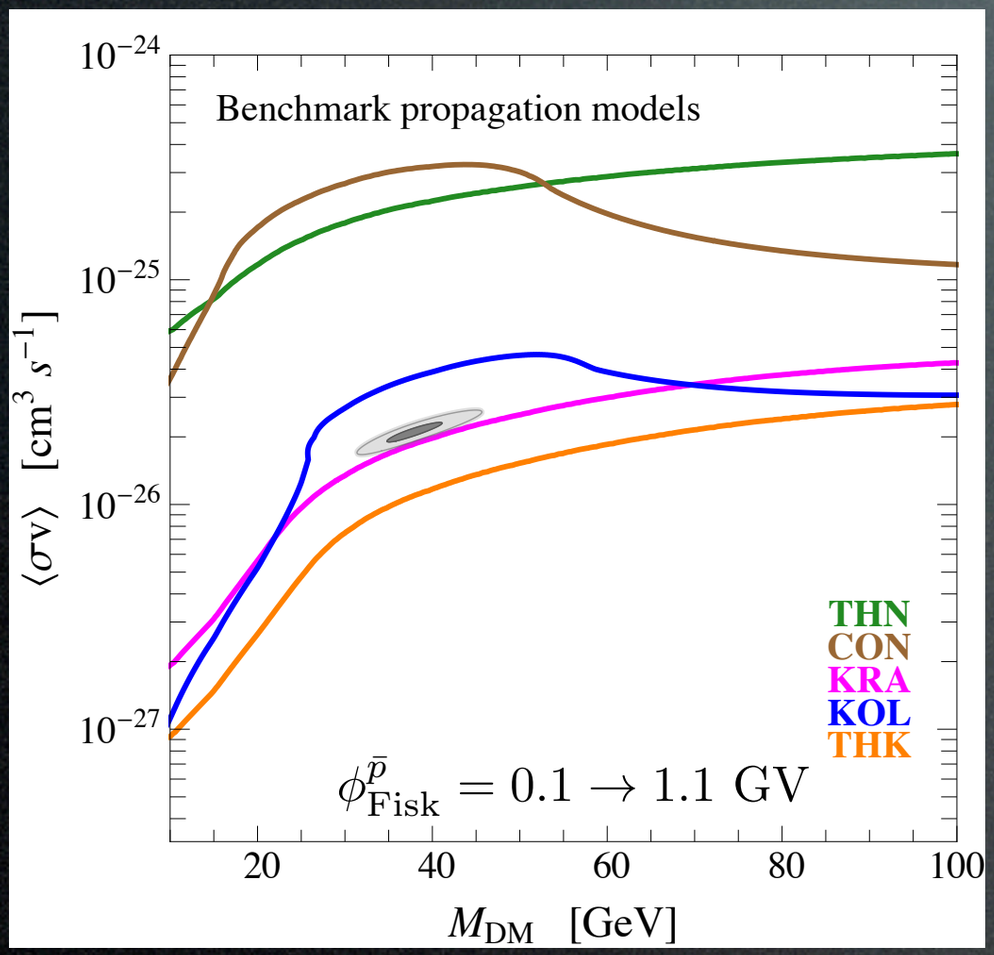
<u>Assumption</u>: flexible solar modulation

<u>Result</u>: hooperon may be excluded or not

Fermi-LAT excess

GeV gamma excess?

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



Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173

Antiproton constraints may be very relevant! But not robust.

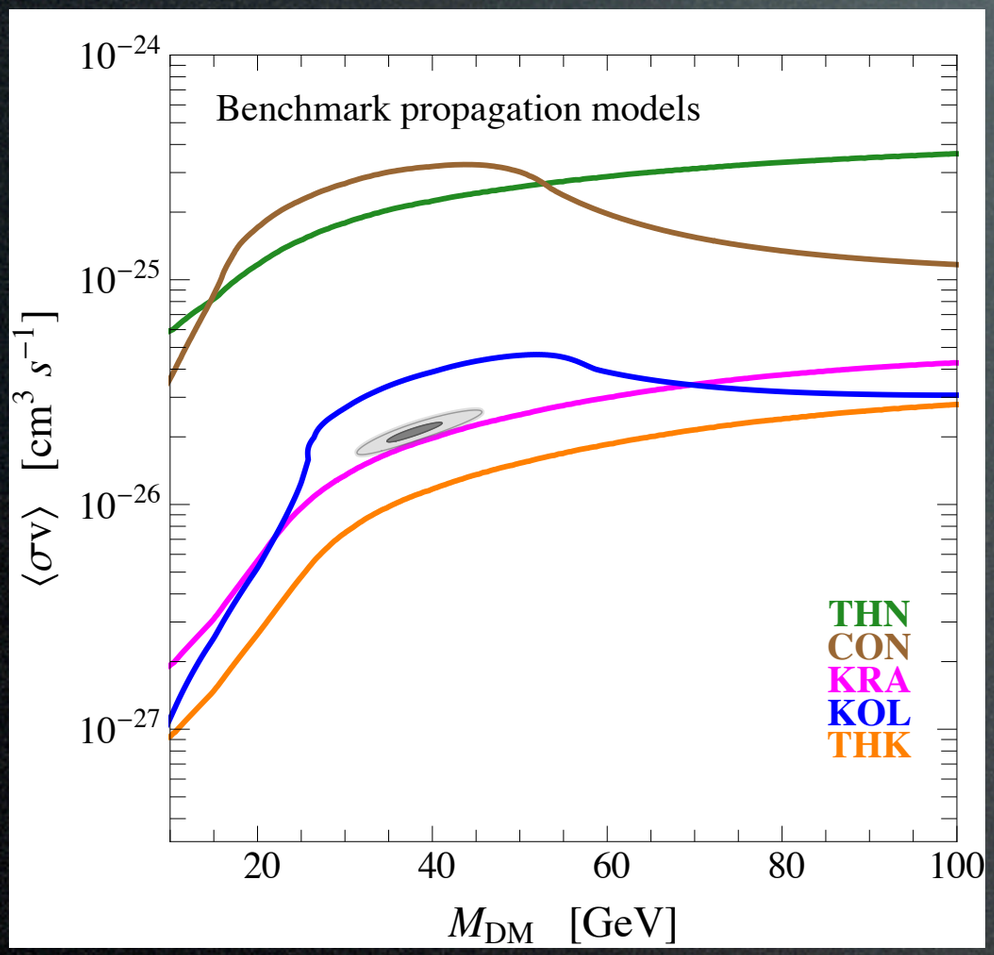
Assumption: conservative solar modulation

Result: hooperon probably reallowed (except THK models)

Fermi-LAT excess

GeV gamma excess?

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



Fermi-LAT excess

Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173

Antiproton constraints may be very relevant! But not robust.

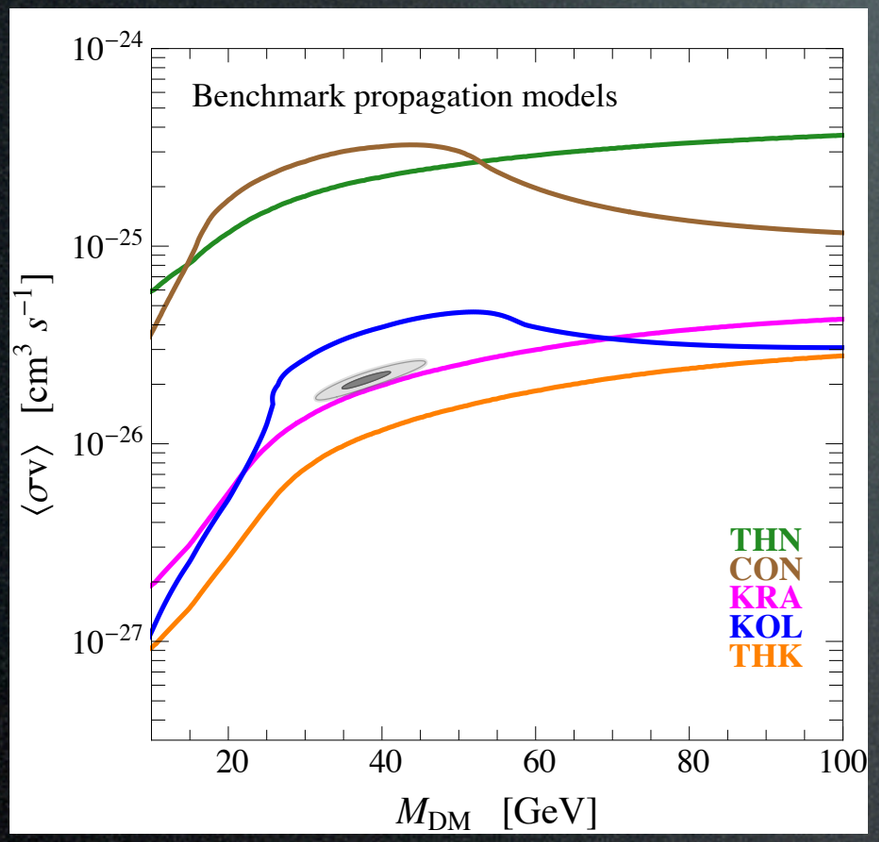
Assumption: conservative solar modulation

Result: hooperon probably reallowed (except THK models)

NB Conclusion differs from Bringmann, Vollmann, Weniger 1406.6027 which finds exclusion / strong tension

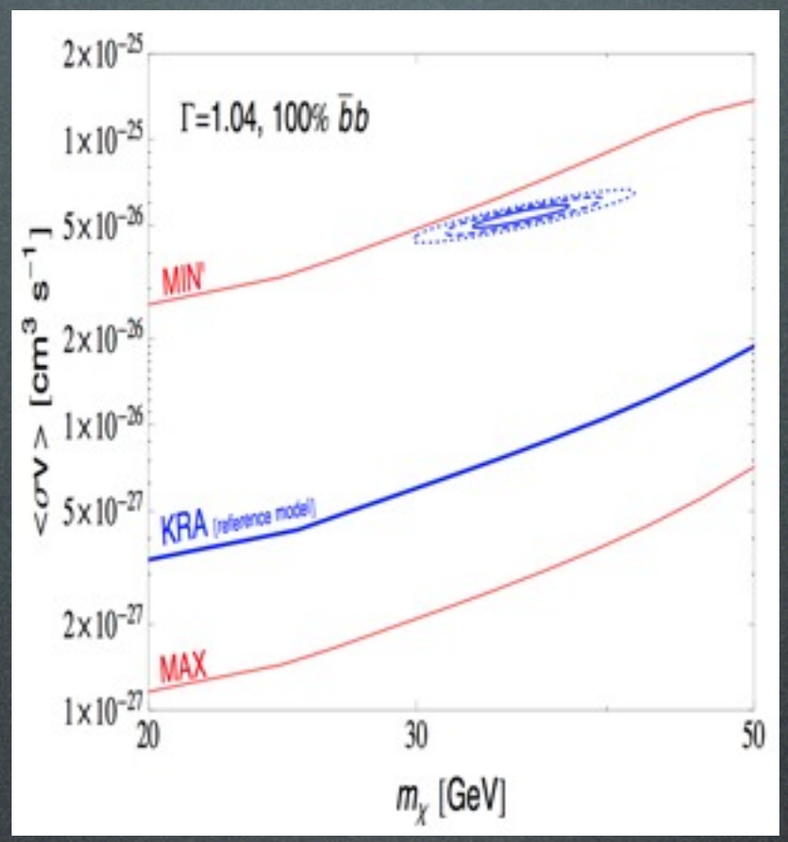
GeV gamma excess?

Antiproton constraints compared:



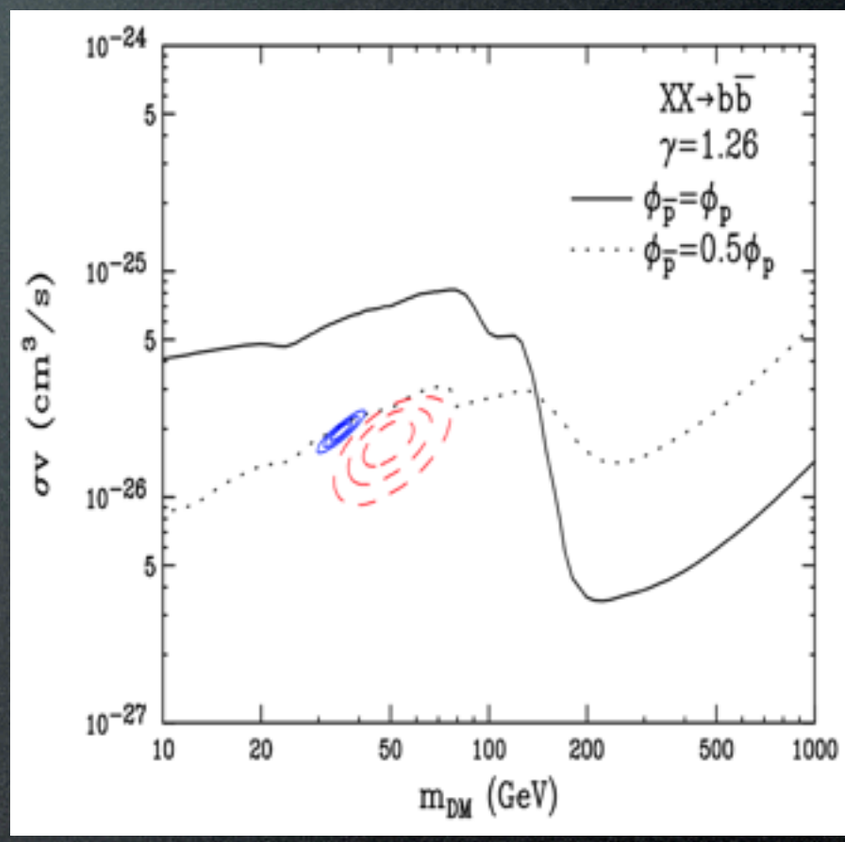
Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173

May be very relevant!
But not robust.



Bringmann, Vollmann, Weniger 1406.6027

'Rule out' or
'considerable tension'.



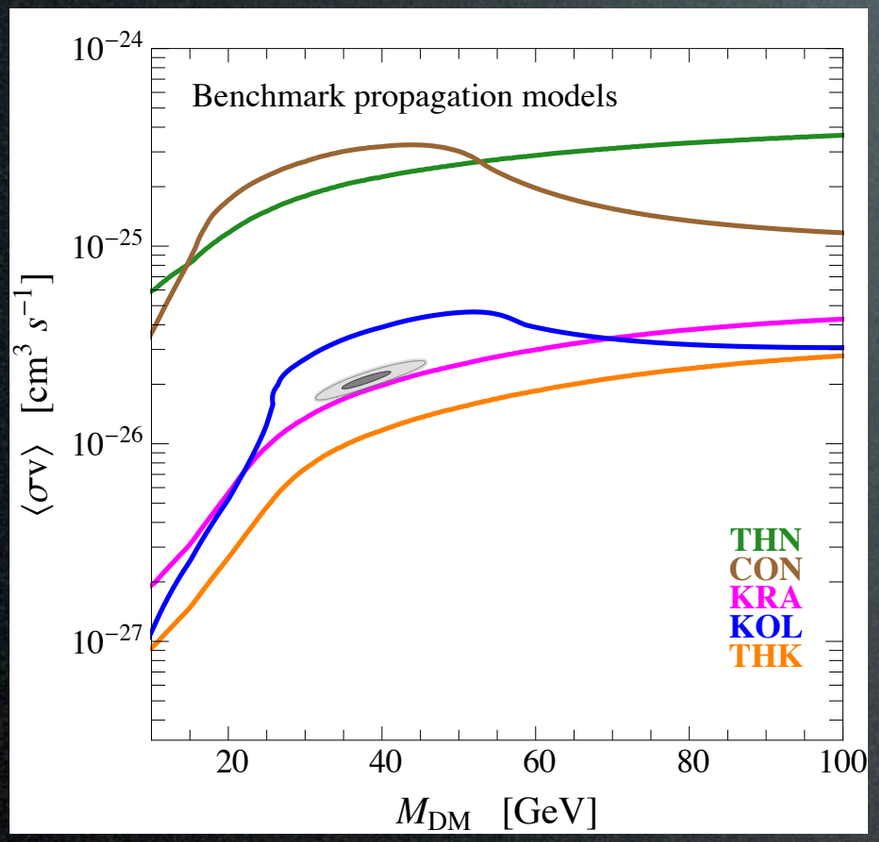
Hooper, Linden, Mertsch 1410.1527

'Significantly less stringent'.

How come?!?

GeV gamma excess?

Antiproton constraints compared:



Cirelli, Gaggero, Giesen, Taoso, Urbano 1407.2173

May be very relevant!
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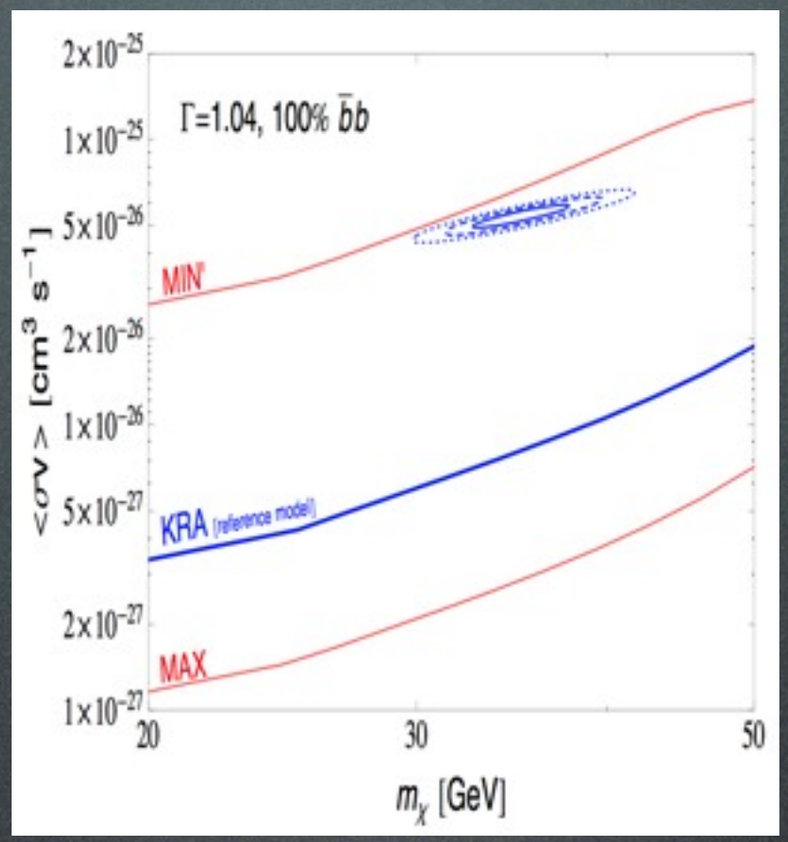

Bringmann, Vollmann, Weniger 1406.6027

'Rule out' or
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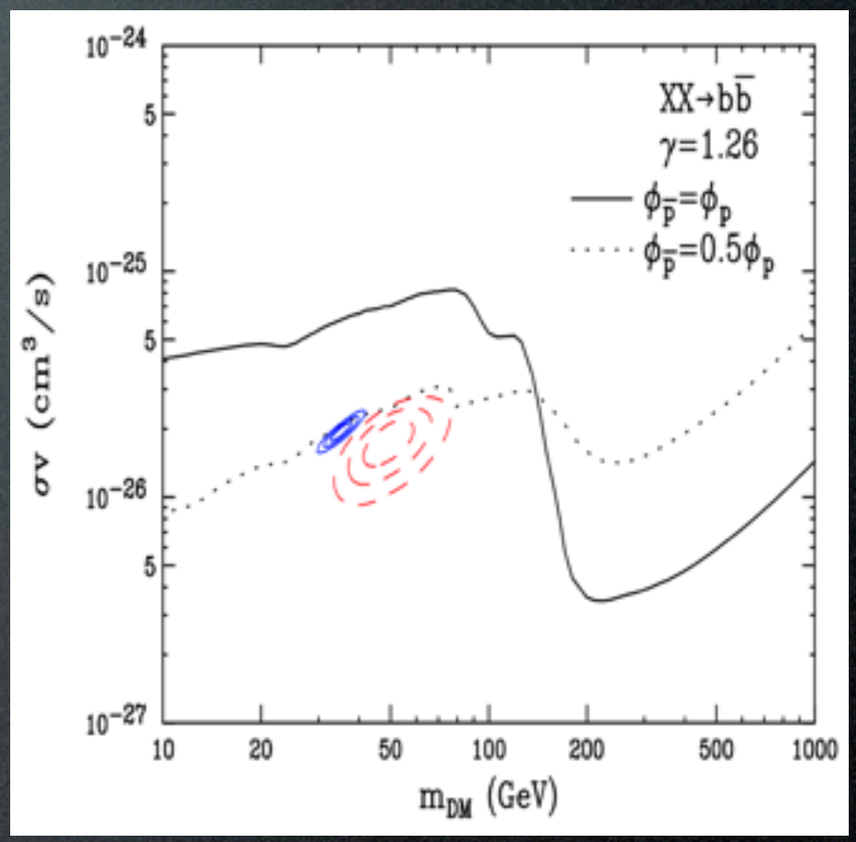


Hooper, Linden, Mertsch 1410.1527

'Significantly less stringent'.

How come?!? The devil is in the (CR propagation) details:
solar modulation, convection, primary injection spectrum, tertiaries...

GeV gamma excess?

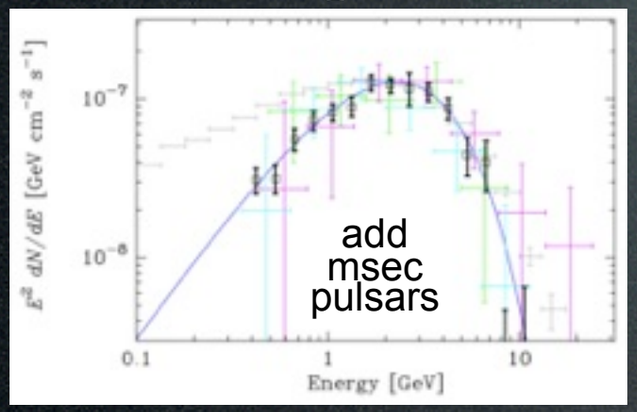
An excess with respect to **what**?
Extracting 'data points' is not trivial:

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

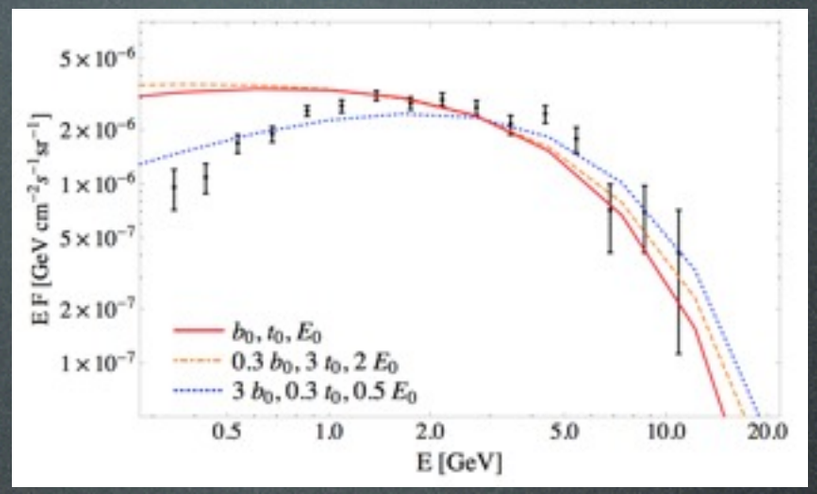


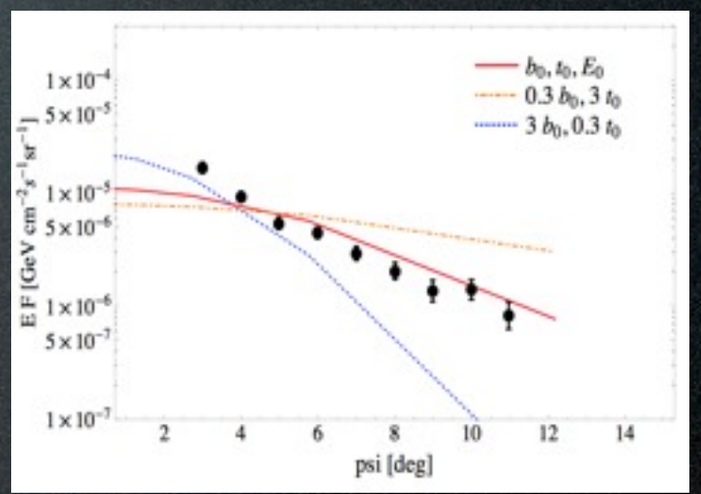
Abazajian 1011.4275
Hooper et al. 1305.0830
Yuan, Zhang 1404.2318

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

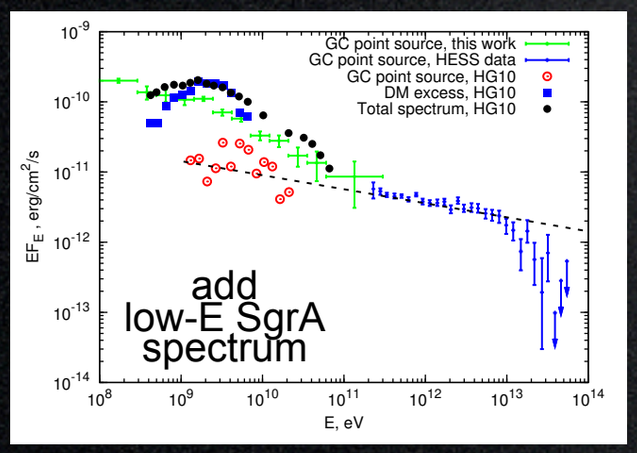
Petrović, Serpico, Zaharijas 1405.7928





but: can one really get everything right?

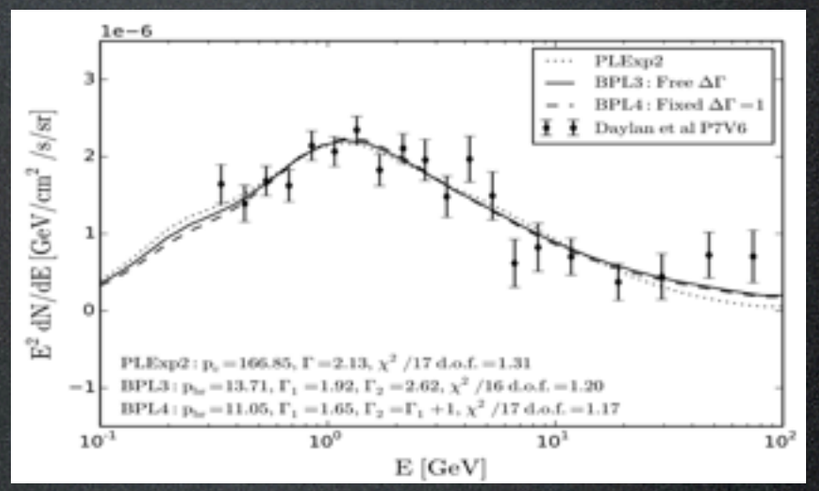
Non-trivial SgrA spectrum

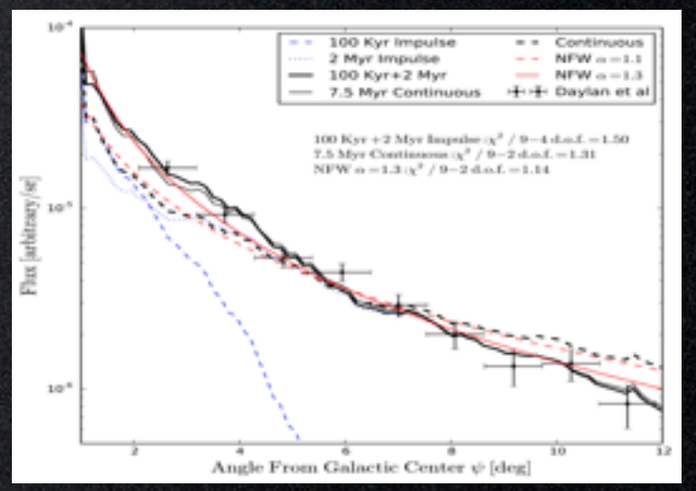


Boyarsky et al., 1012.5839

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



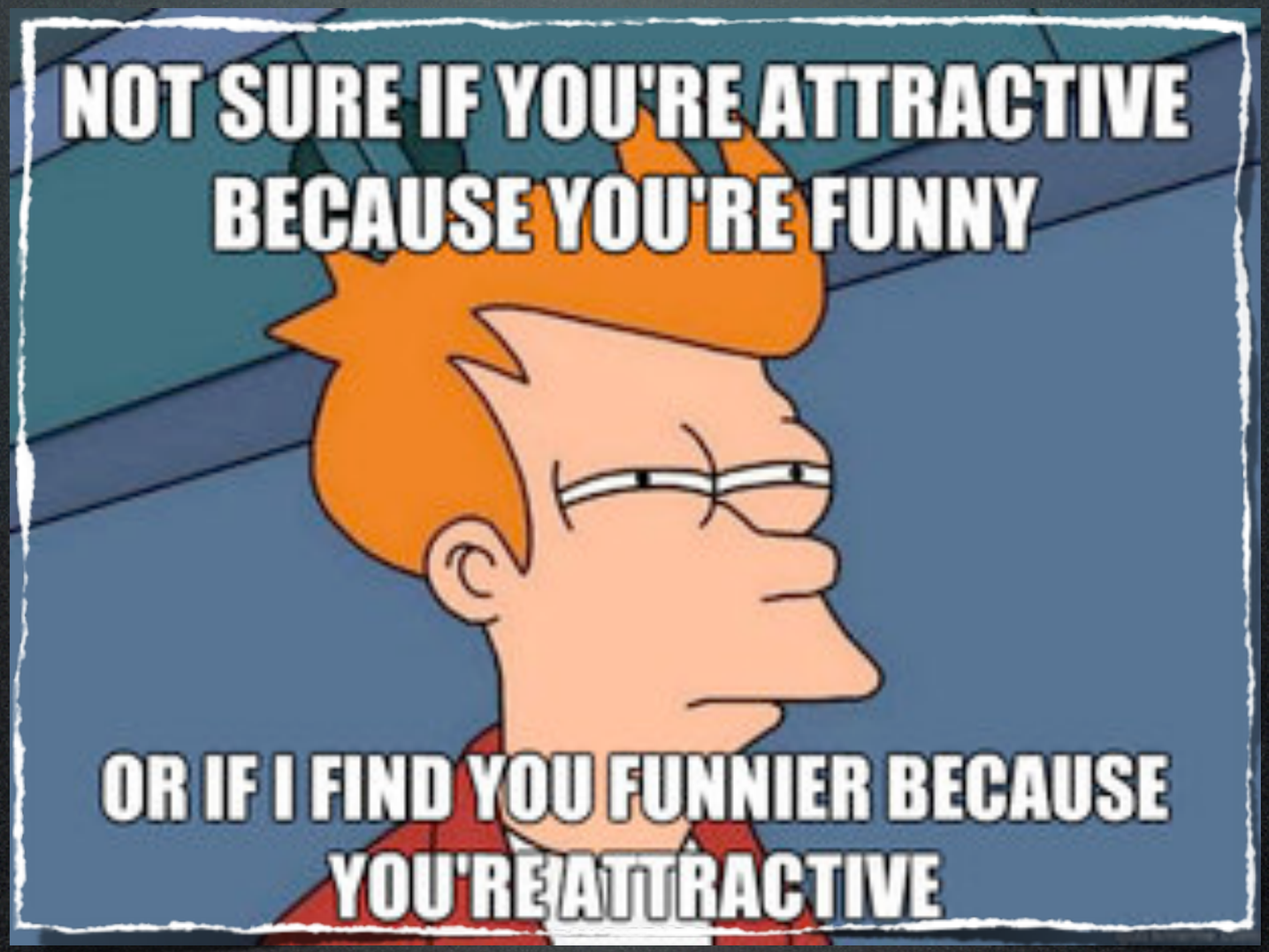


but: why correlation with gas density not seen?

Theorist's reaction

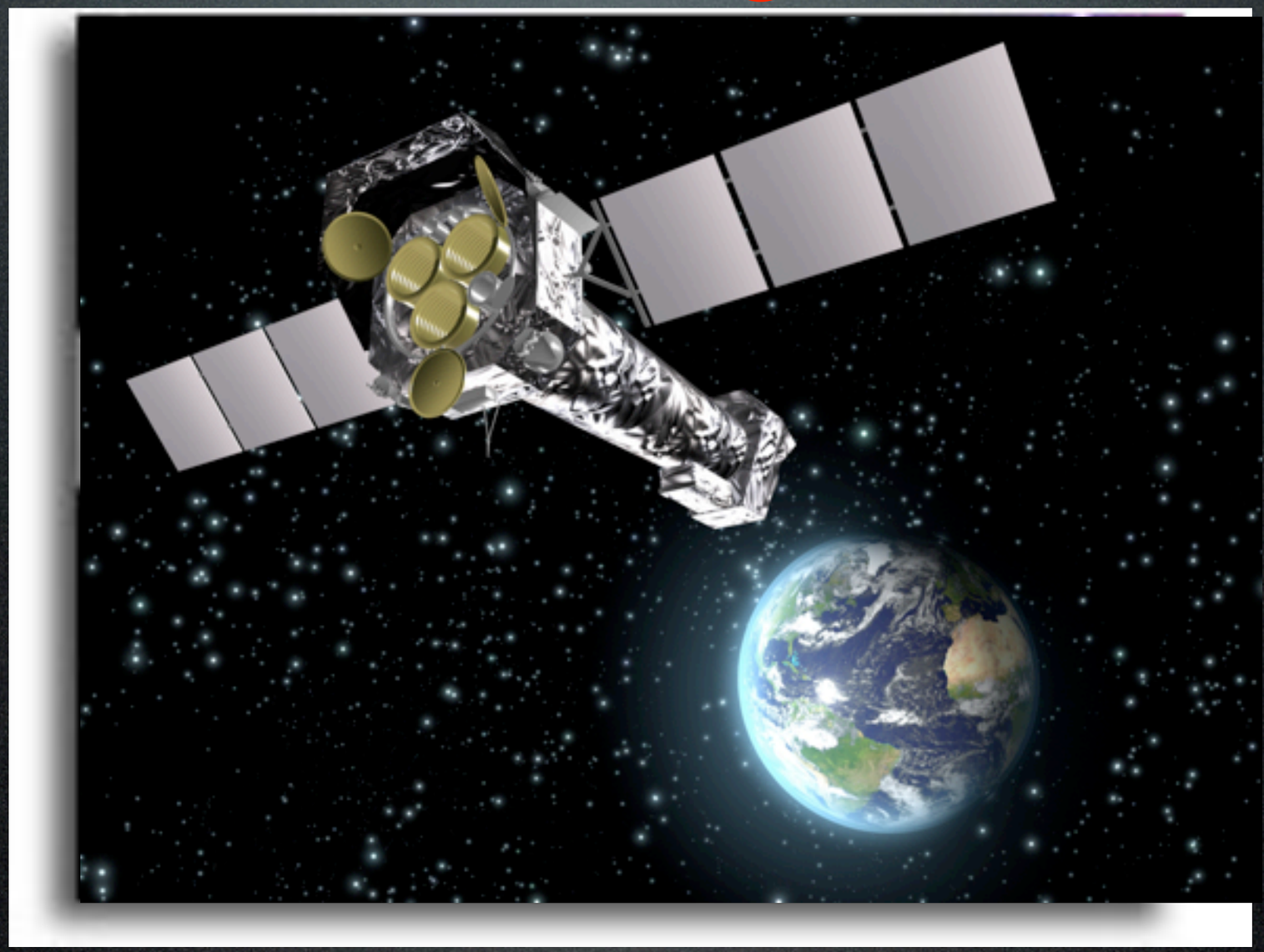
3. the 'Hooperon'

Theorist's reaction



3. the 'Hooperon'

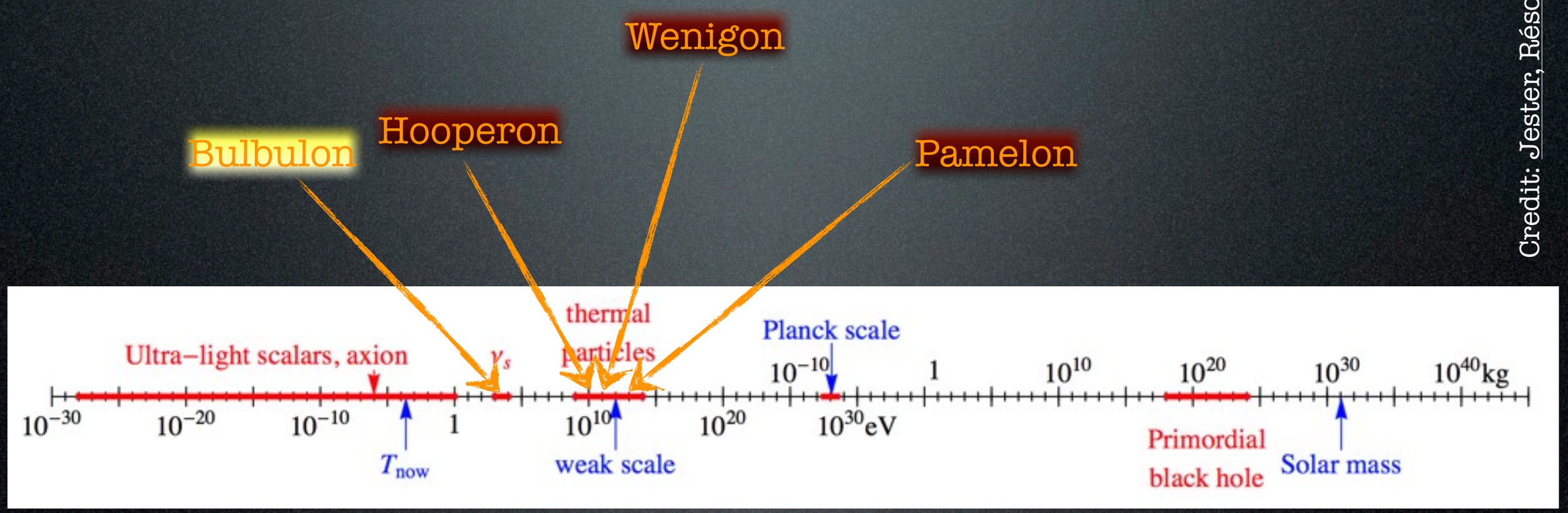
X-rays



4. the ‘3.5 KeV line’

DM Candidates

A matter of perspective: plausible mass ranges



Credit: Jester, Résonaances

‘only’ 90 orders of magnitude!

X-ray line

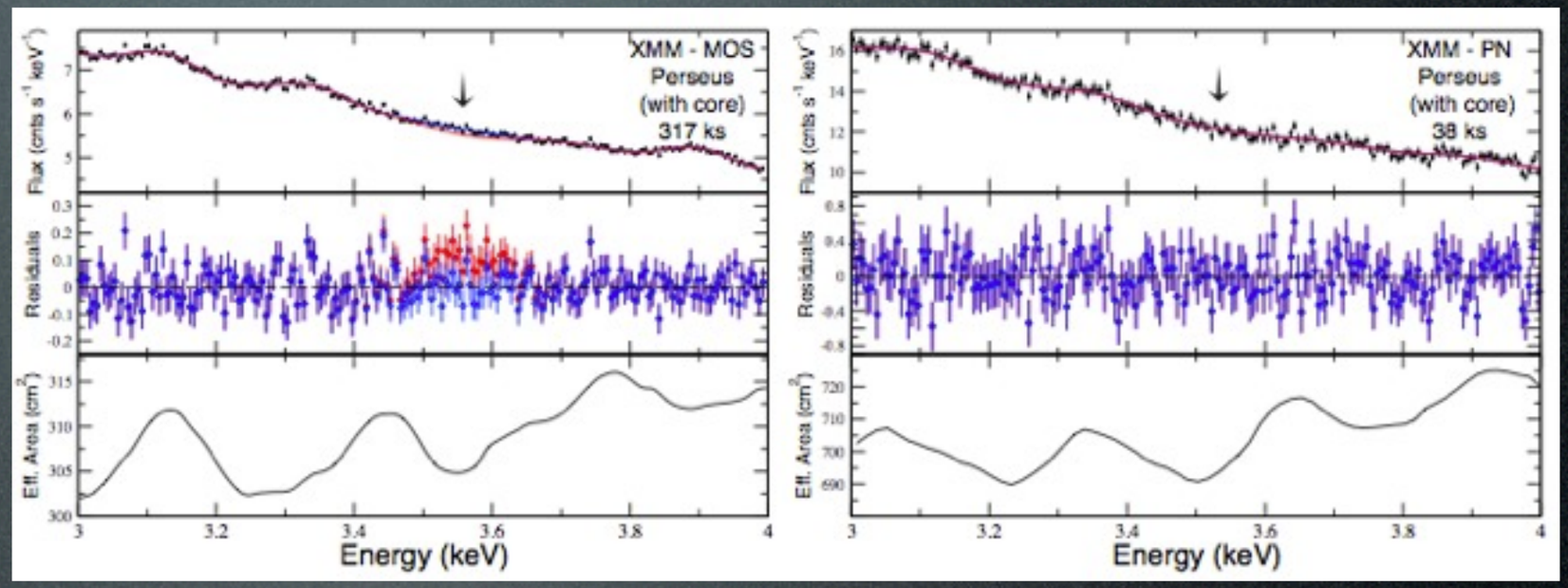
Bulbul et al., 1402.2301

3.55 - 3.57 ± 0.03 KeV

73 clusters

z = 0.01 - 0.35

$\gtrsim 4\sigma$



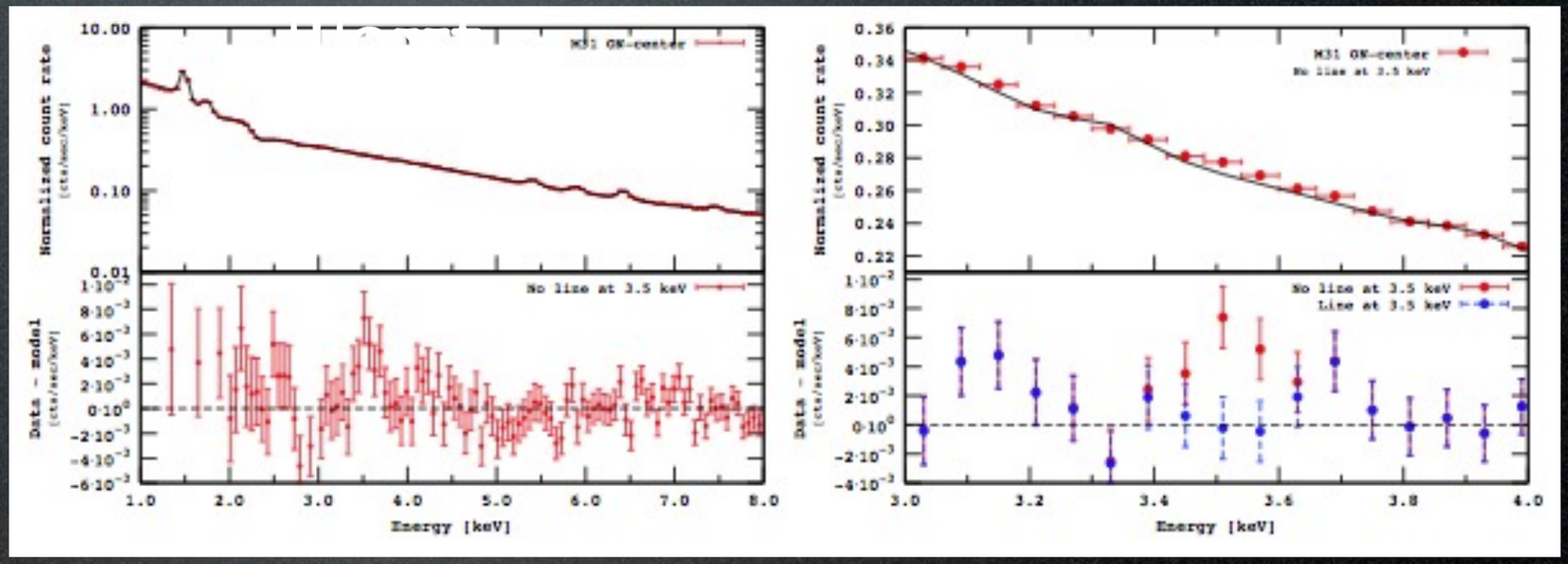
Boyarsky, Ruchayskiy, 1402.4119

3.5 KeV

Andromeda galaxy
+ Perseus cluster

z = 0 and 0.0179

4.4σ



Theorist's reaction

4. the '3.5 KeV' line

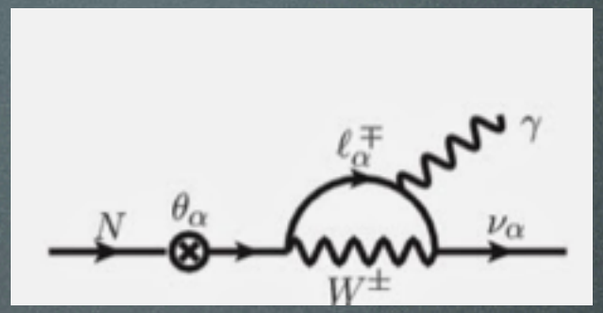
X-ray line

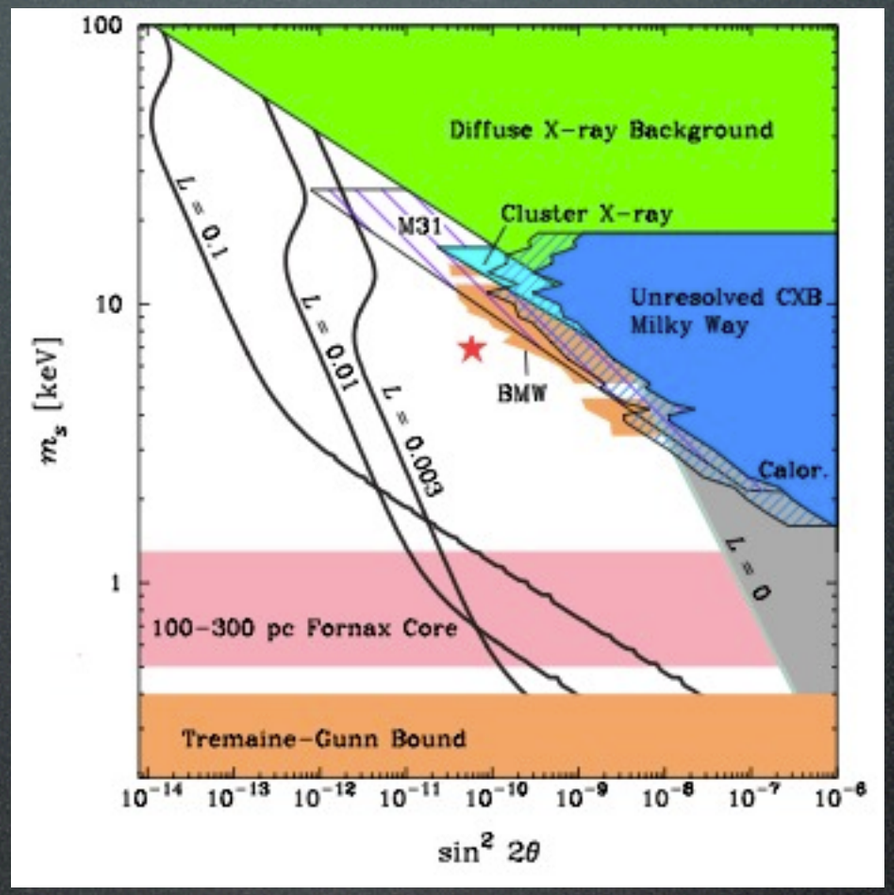
Sterile neutrino decay

$m_\nu = 7.1$ KeV

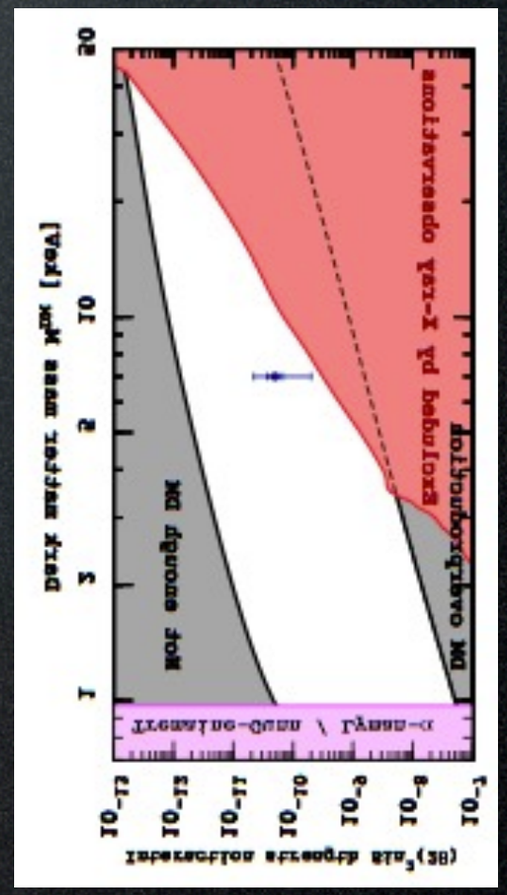
$\tau \simeq 10^{29}$ sec

$\sin^2 2\theta \sim$ few 10^{-11}





Bulbul et al., 1402.2301

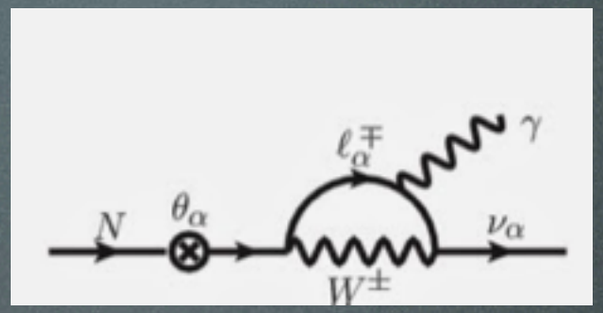


Boyarsky, Ruchayskiy et al., 1402.4119

X-ray line

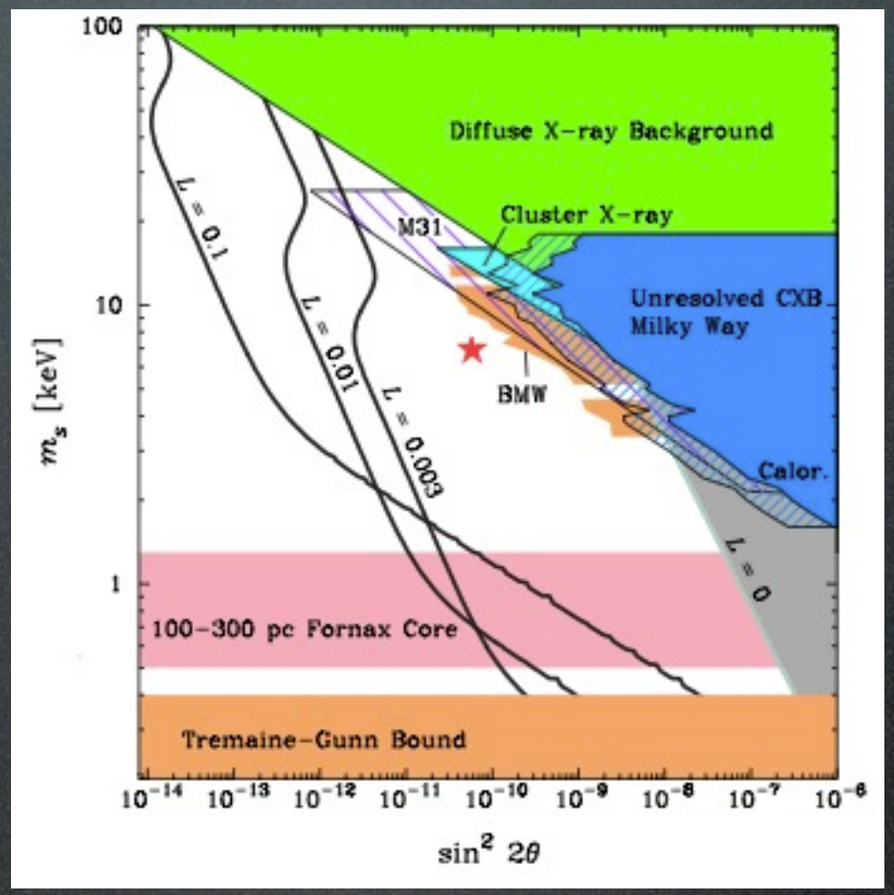
Sterile neutrino decay

$$m_\nu = 7.1 \text{ KeV}$$
$$\tau \simeq 10^{29} \text{ sec}$$
$$\sin^2 2\theta \sim \text{few } 10^{-11}$$

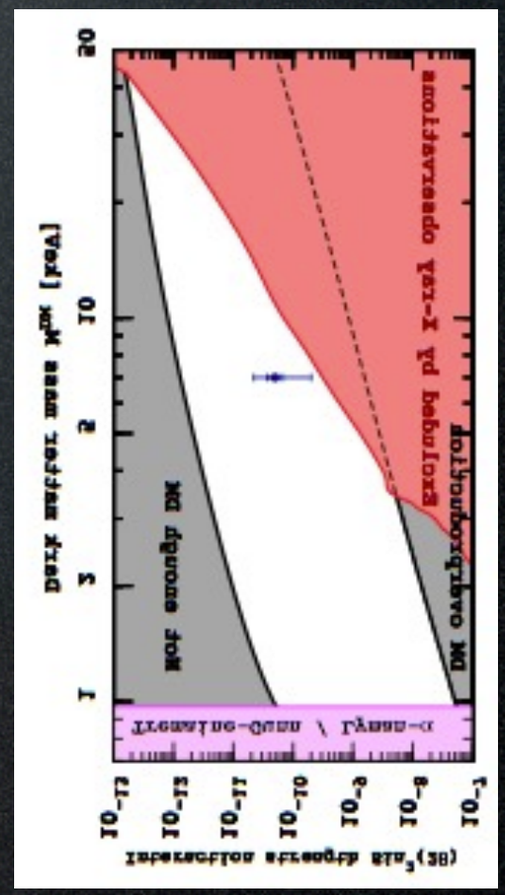


Possible challenges:

- EU production?
- Perseus flux too large?



Bulbul et al., 1402.2301



Boyarsky, Ruchayskiy et al., 1402.4119

X-ray line

Sterile neutrino decay

$$m_\nu = 7.1 \text{ KeV}$$
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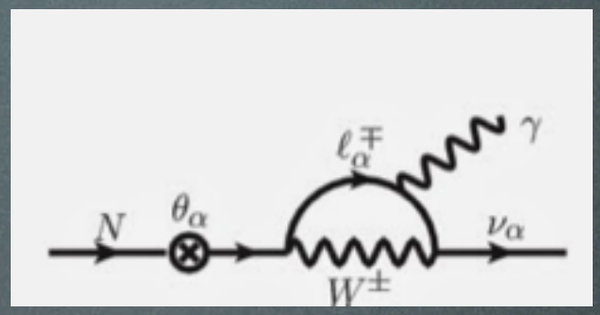

Possible challenges:

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Caveat:

Riemer-Sørensen, 1405.7943

- no line seen with Chandra in the Galactic Center (but conclusion depends on how one models the local background)
- no line seen in dSphs (but results are not conclusive) Malyshev et al., 1408.3531
- no line seen in other galaxies (but errors might be underestimated? says Boyarski's group) Anderson et al., 1408.4115
- no line seen in other clusters (but seen in Perseus with Suzaku! maybe it's proper of Perseus?) Urban, Strigari et al., 1411.0050
- morphology incompatible with DM Carlson, Profumo^2, 1411.1758

Perhaps reconciled if it is excited DM?
Cline & Frey, 1410.7766

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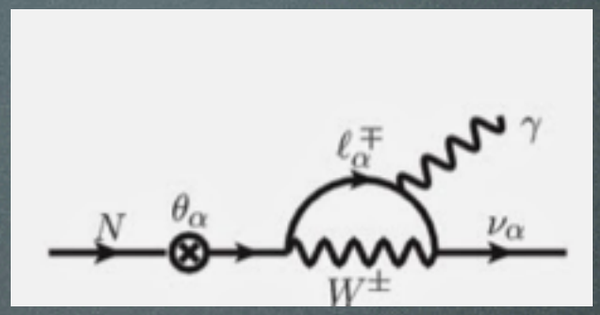

Possible challenges:

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Caveat 2:

- Jeltema & Profumo, 1408.1699: it's just Potassium/Clorine lines
- Bulbul et al. 1409.4143, Boyarsky at al. 1409.4388: bulls#!t
- Jeltema & Profumo, 1411.1759: insist

X-ray line

Sterile neutrino decay

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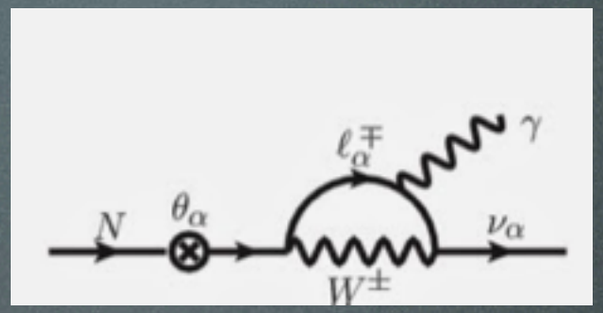

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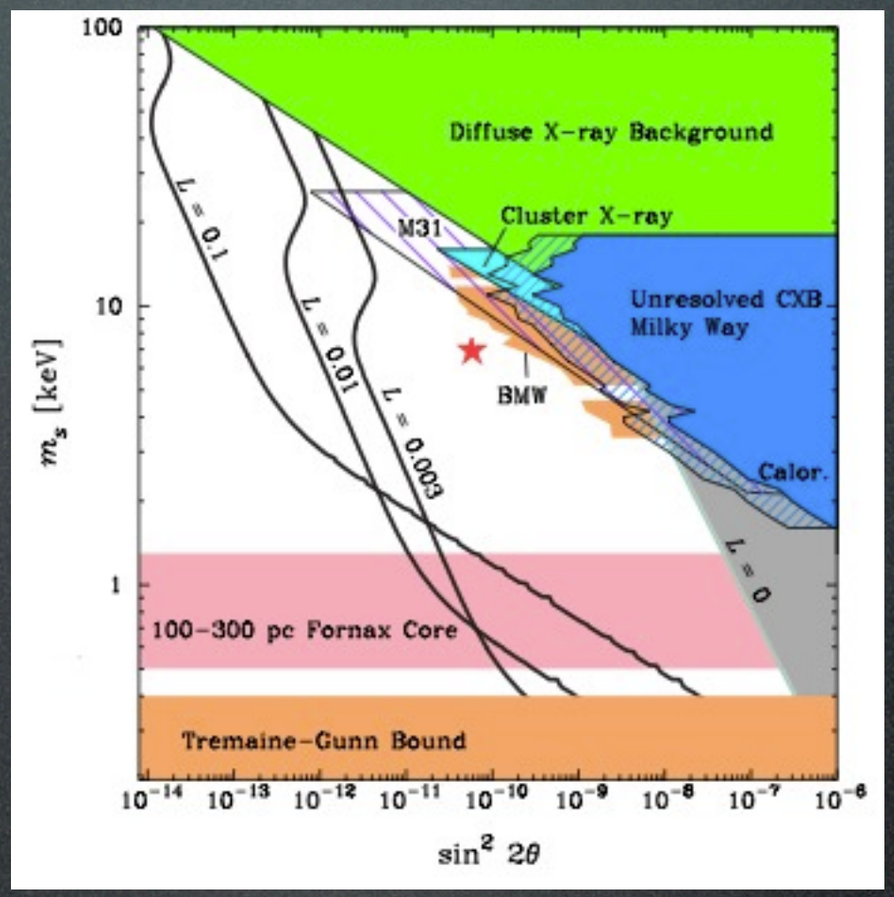
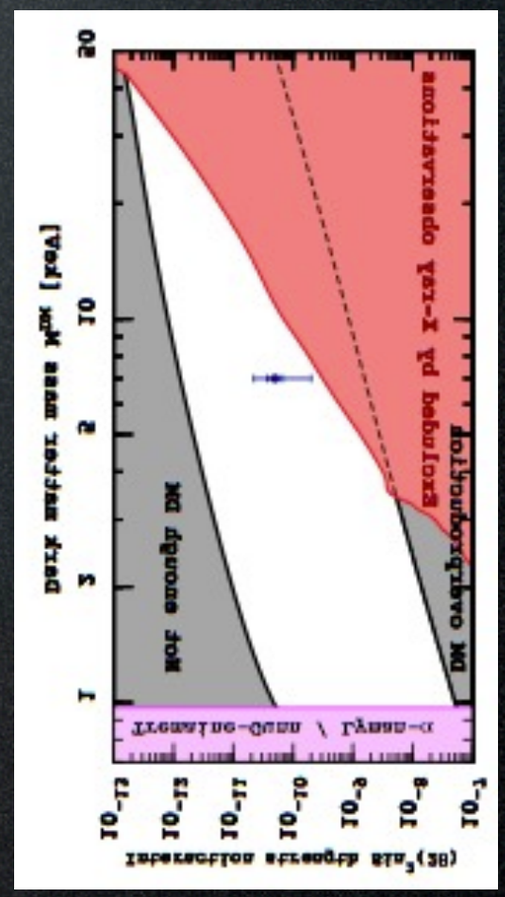


Bulbul et al., 1402.2301



Boyarsky, Ruchayskiy et al., 1402.4119

Other possibilities:

axion (1402.7335), axino (1403.1536, 1403.1782, 1403.6621), modulus (1403.1733), ALP (1403.2370), gravitino (1403.6503), excited DM (1404.4795), the good the bad and the unlikely (1403.1570), sgoldstino (1404.1339), magnetic DM (1404.5446), majoron (1404.1400), annihilating effective DM (1404.1927), 7KeV scalar DM (1404.2220)...

Conclusions & Outlook

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Constraints

Hopes

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γ FERMI

X XMM-Newton

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Old wise remarks:

- any convincing result must be multimessenger

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Old wise remarks:

- any convincing result must be multimessenger
- beware of uncertainties, beware of astrophysics