17 April 2013
Portoroz 2013 Workshop

News in the astroparticle field

Marco Cirelli
(CNRS IPhT Saclay)

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Selected News in the astroparticle field:

DM and cosmic neutrinos

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- DM: the charged CRs anomaly

PAMELA, Fermi, HESS, **AMS**

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- DM: the charged CRs anomaly

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- DM: the 135 GeV γ-ray line

  Fermi

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DM and cosmic neutrinos

- DM: the charged CRs anomaly

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- DM: the 135 GeV γ-ray line

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- DM: the light DM DD hints

  DAMA/LIBRA, **CDMS**, CoGeNT, CRESST

Selected news in the astroparticle field:

DM and cosmic neutrinos

- DM: the charged CRs anomaly

  PAMELA, Fermi, HESS, **AMS**

- DM: the 135 GeV γ-ray line

  Fermi

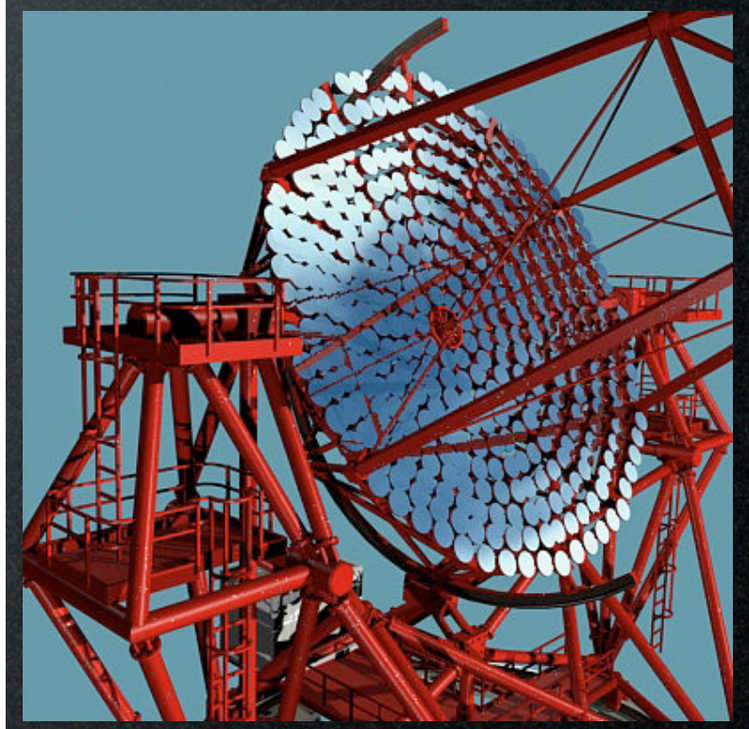
- DM: the light DM DD hints

  DAMA/LIBRA, **CDMS**, CoGeNT, CRESST

- Neutrinos: the N_{eff} puzzle

  WMAP, SPT, ACT, **Planck**

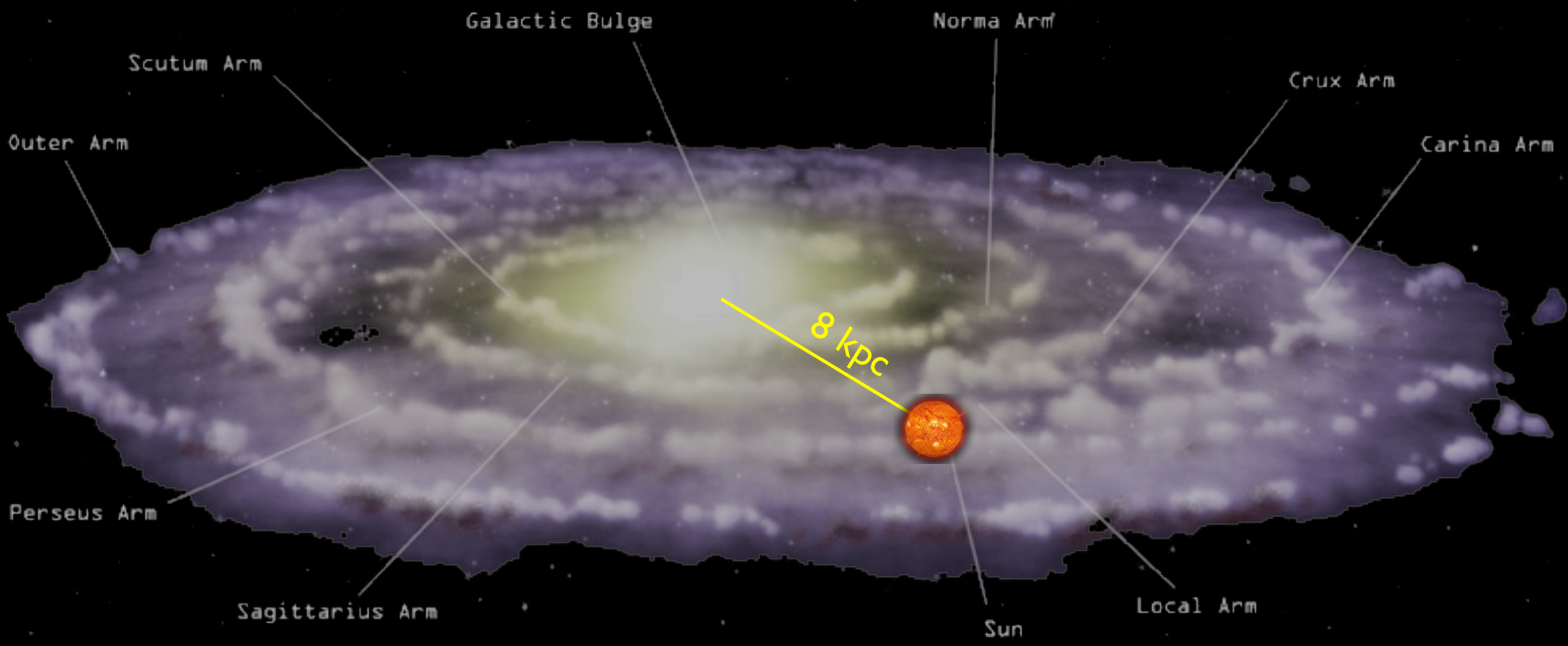
Charged CRs



1. the PAMELA/Fermi/HESS ‘excesses’

Indirect Detection: basics

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



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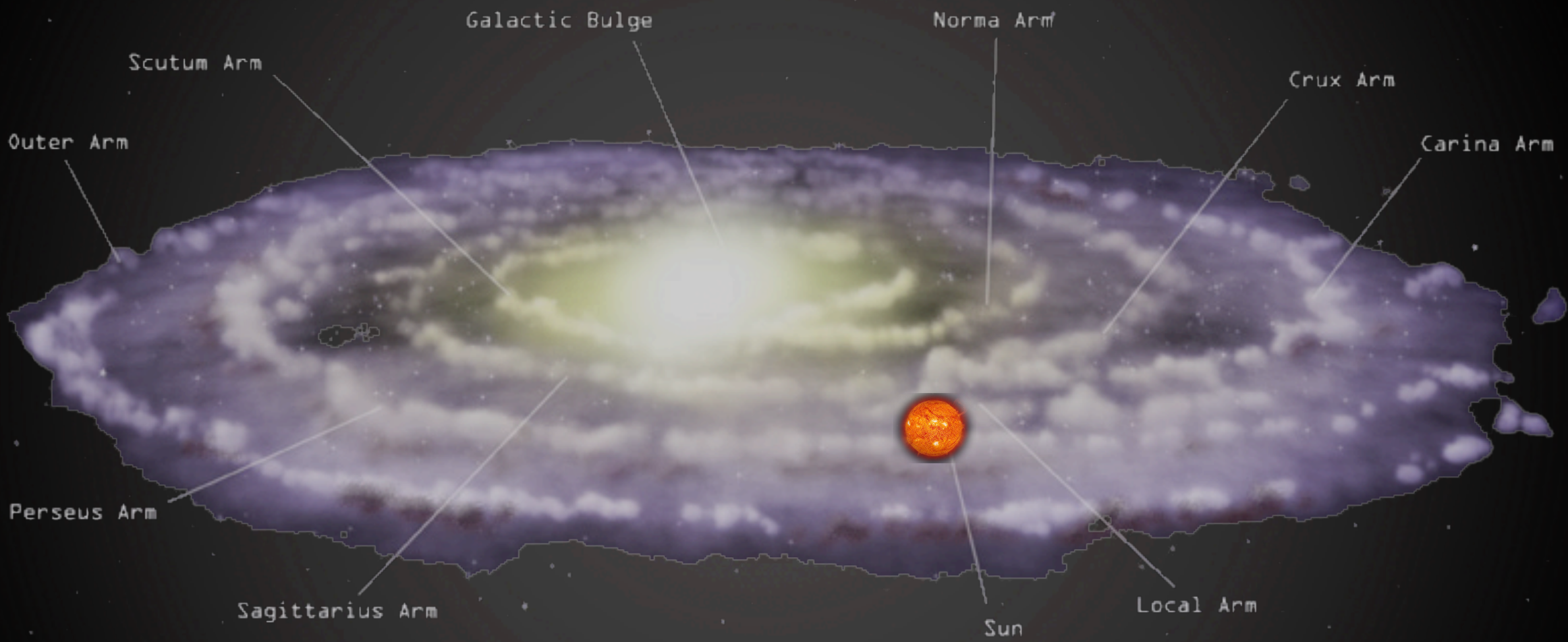

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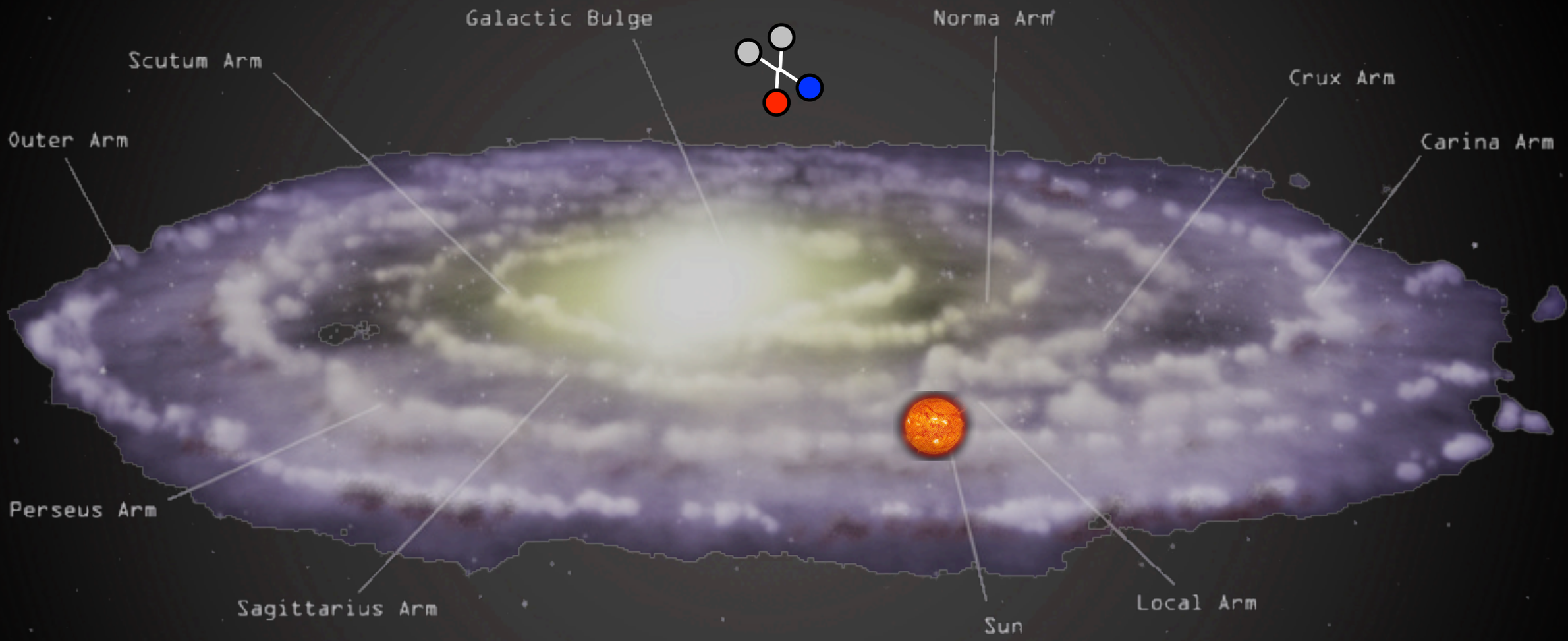

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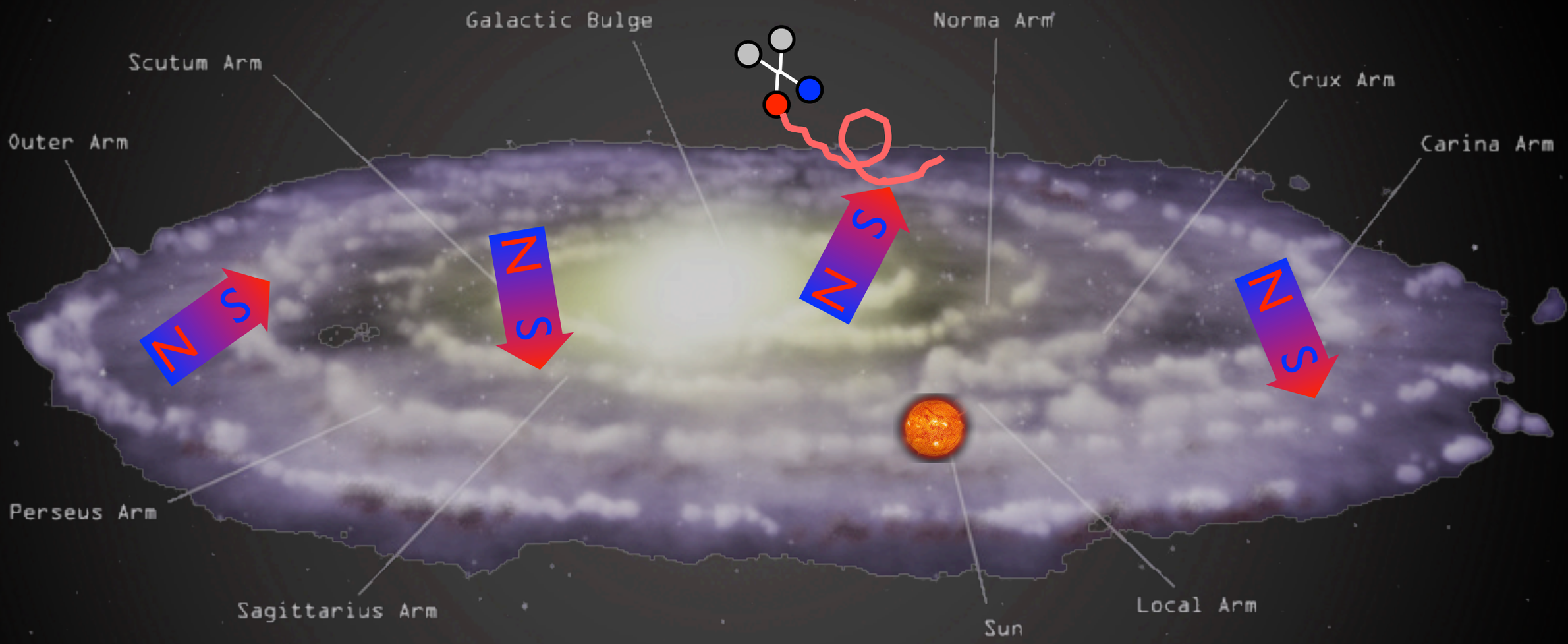

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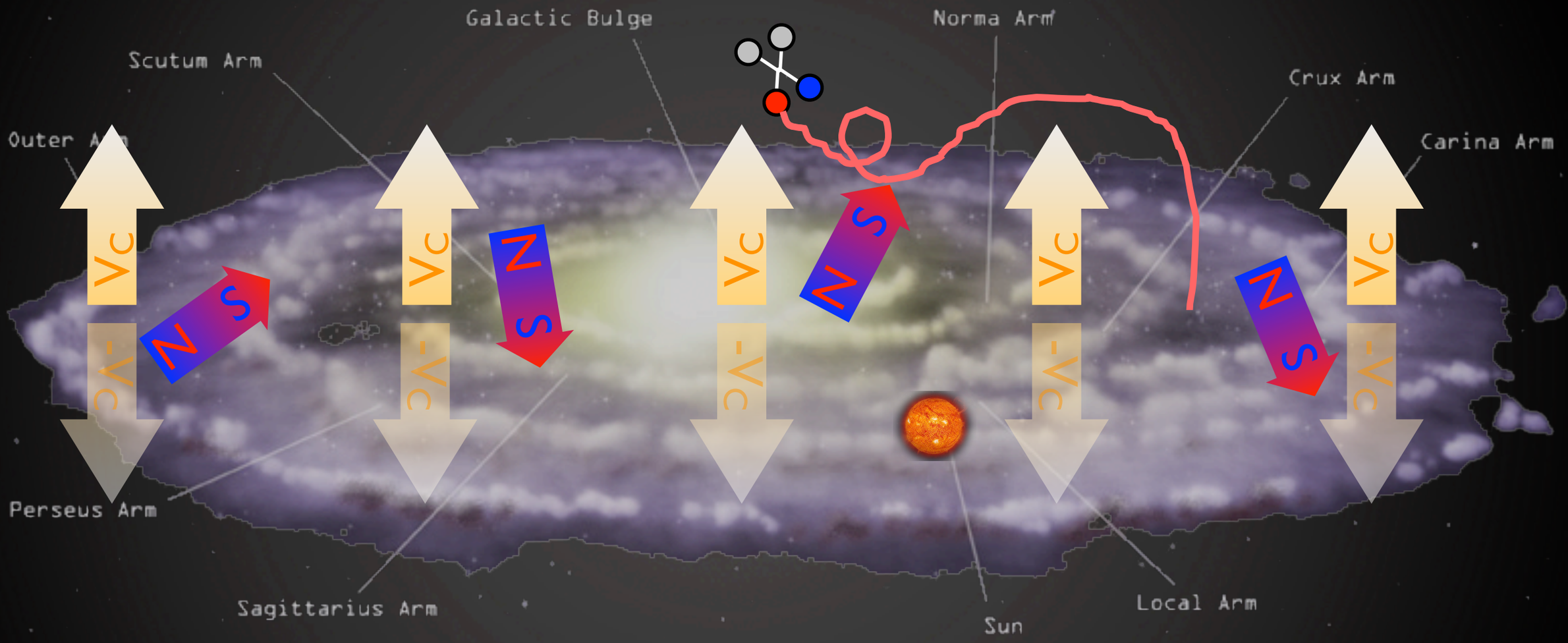

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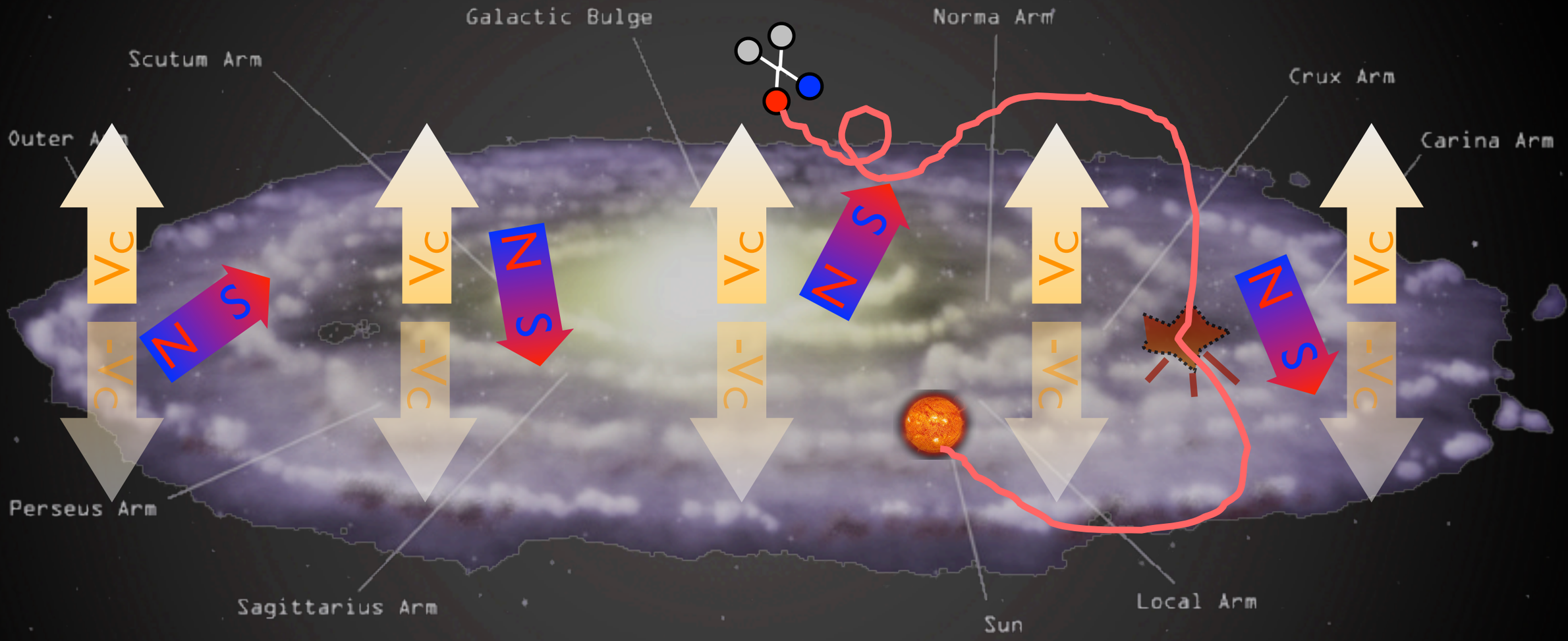

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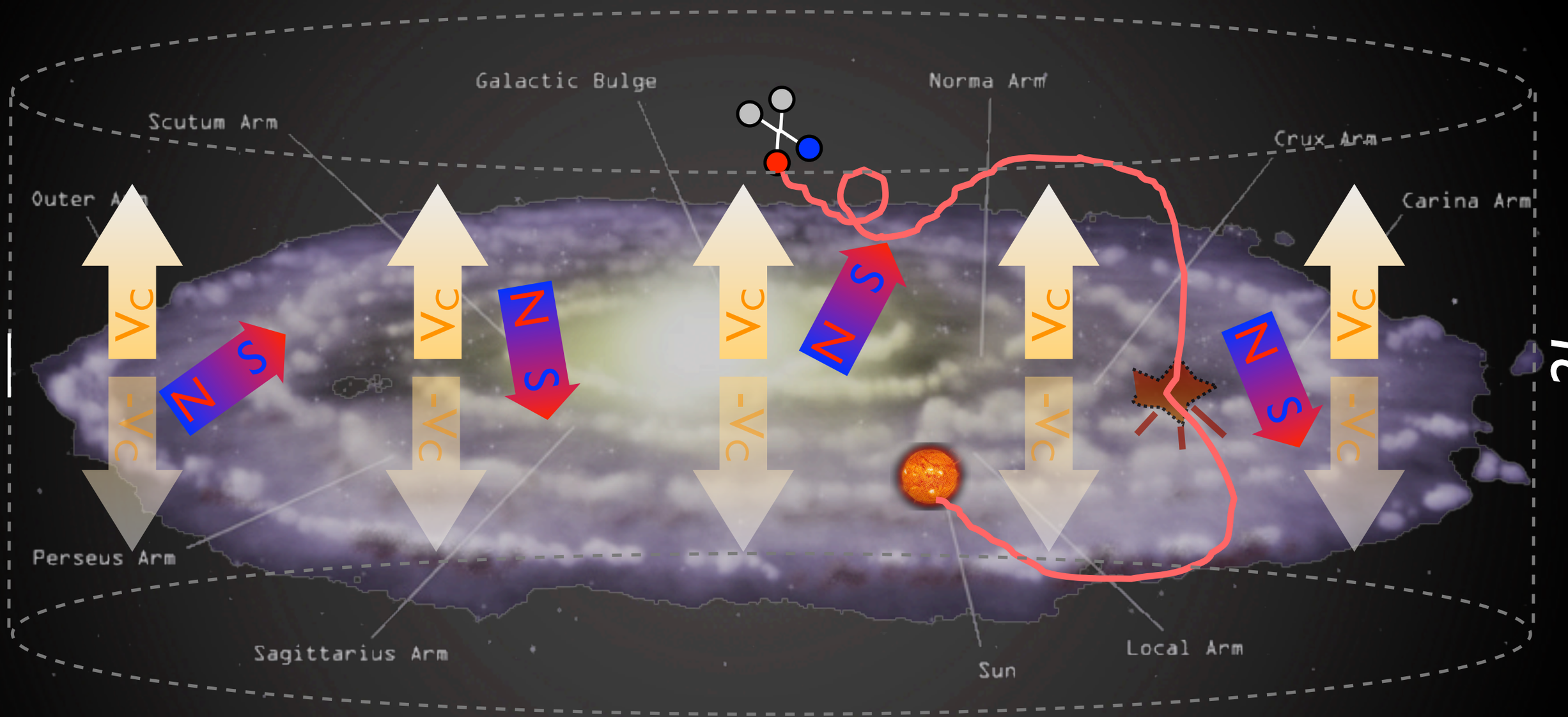


Salati, Chardonnay, Barrau, Donato, Taillet, Fornengo, Maurin, Brun... '90s, '00s

spectrum

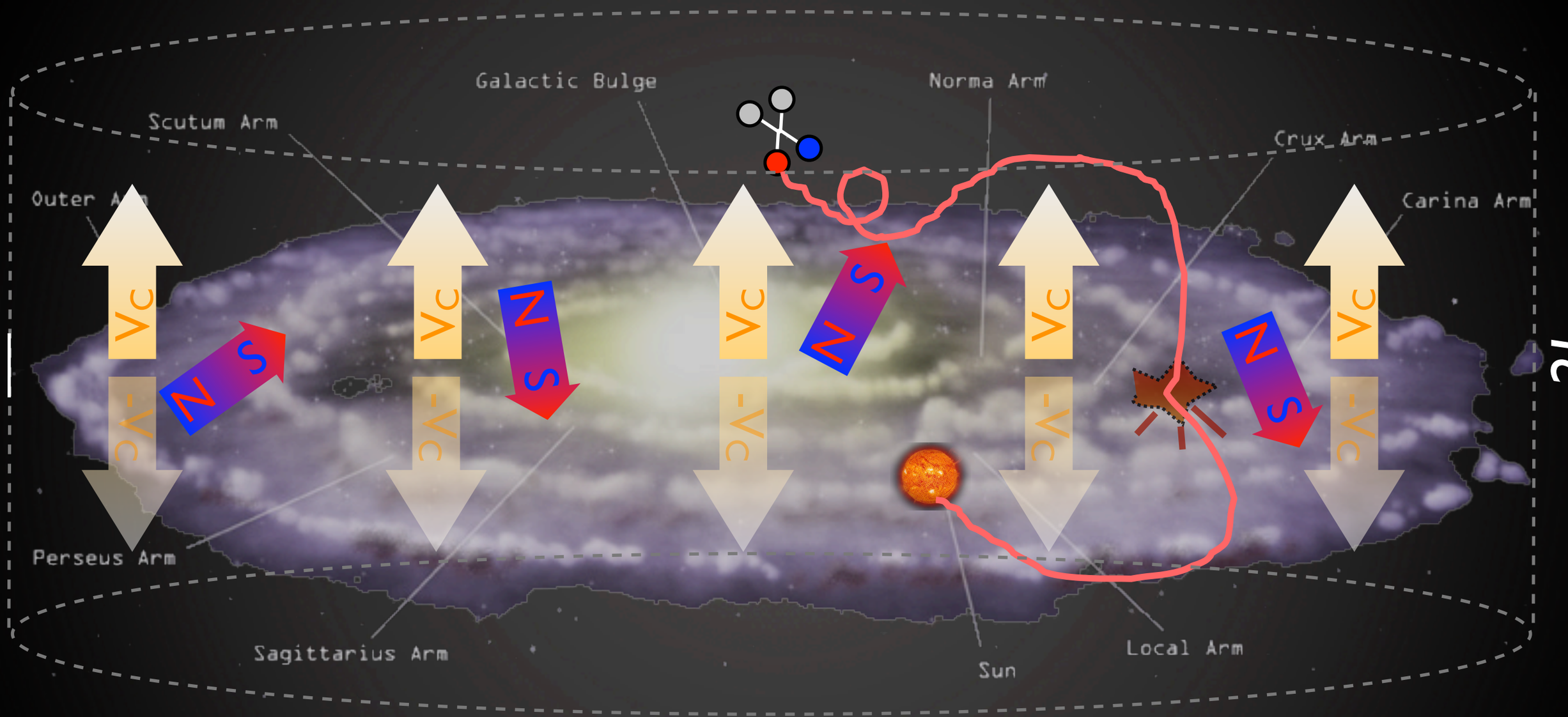
$$\frac{\partial f}{\partial t} - K(E)\cdot\nabla^2 f - \frac{\partial}{\partial E}\left(b(E) f\right) + \frac{\partial}{\partial z}(V_c f) = Q_{\rm inj} - 2h\delta(z)\Gamma_{\rm spall} f$$

diffusion | energy loss | convective wind | source | spallations

[uncert]

Indirect Detection: basics

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

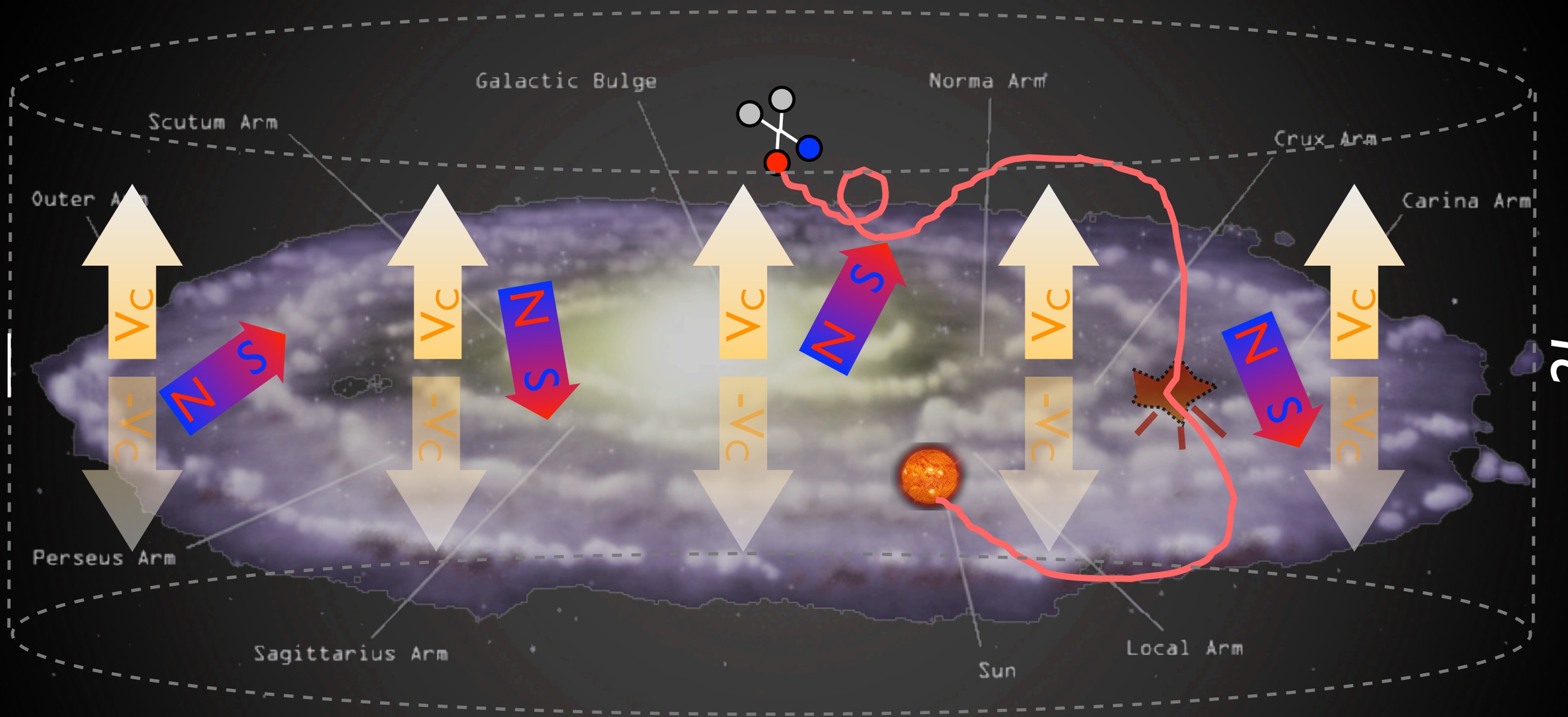


What sets the overall expected flux?

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

Indirect Detection: basics

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

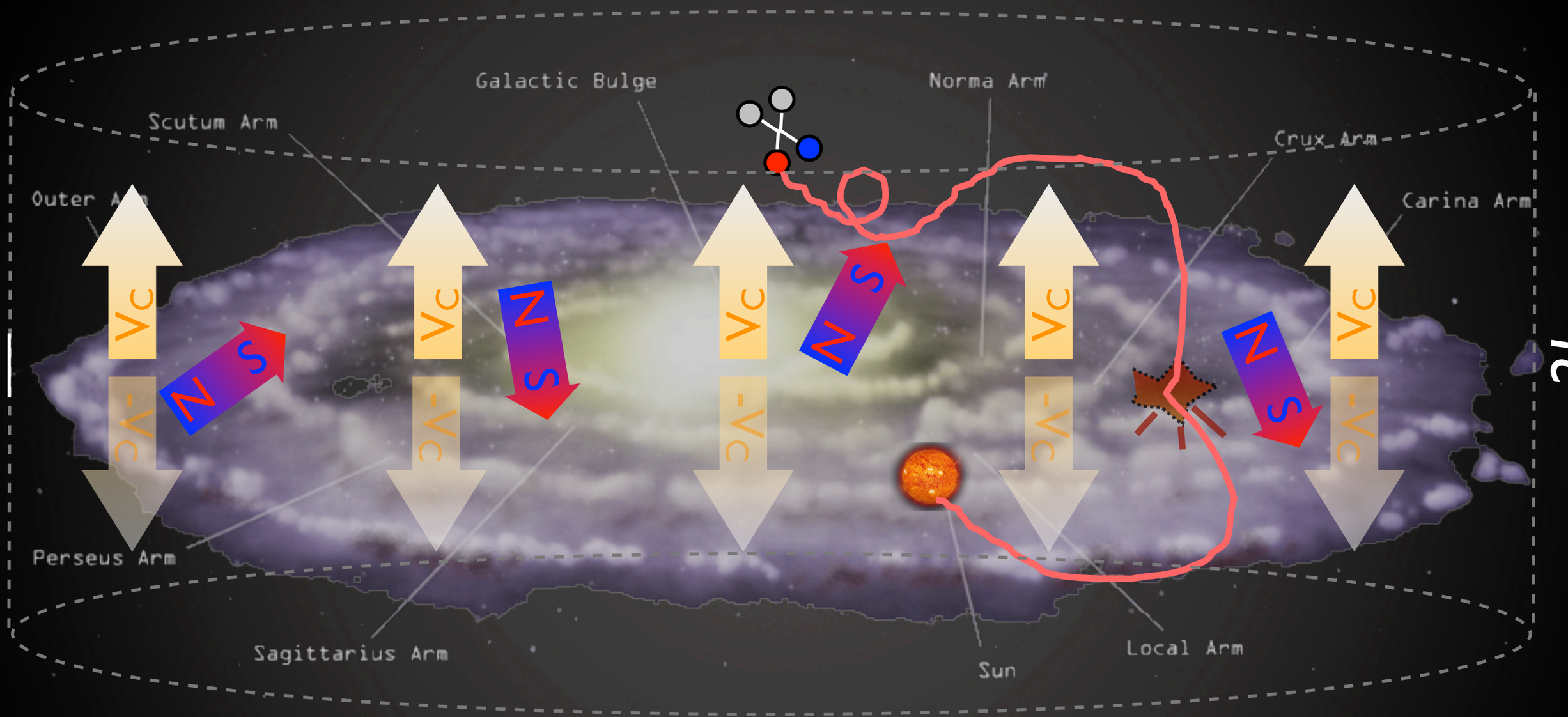


What sets the overall expected flux?

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

Indirect Detection: basics

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



What sets the overall expected flux?

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

reference cross section:

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

DM halo profiles

From N-body numerical simulations:

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

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

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

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

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

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:

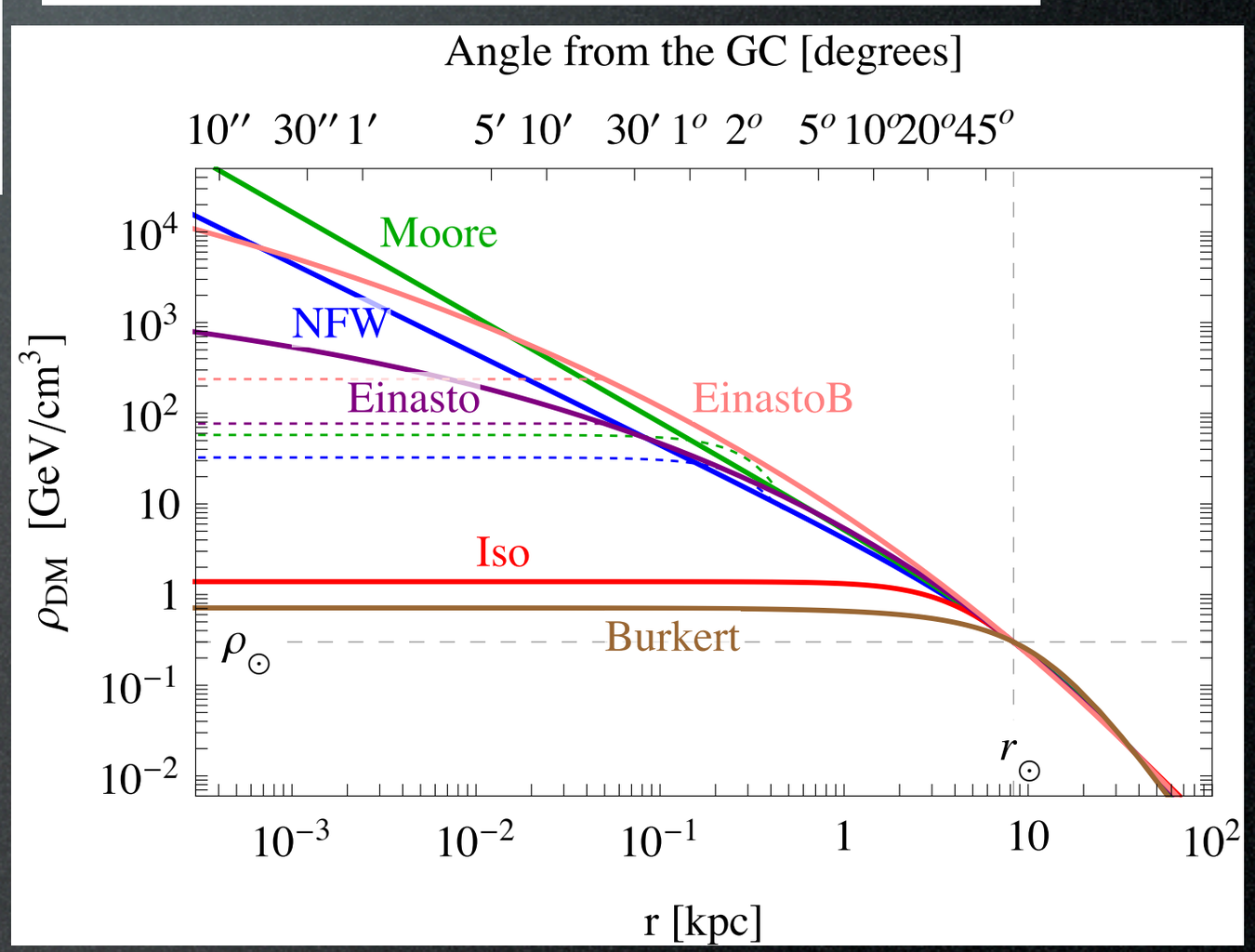
cuspy: NFW, Moore

mild: Einasto

smooth: isothermal, Burkert

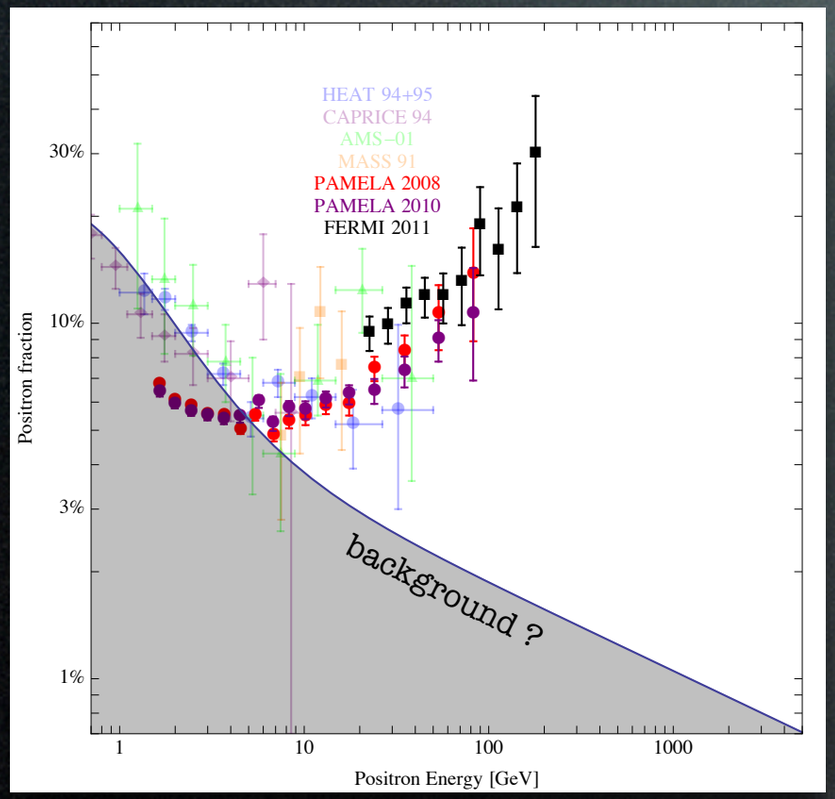
EinastoB = steepened Einasto

(effect of baryons?)

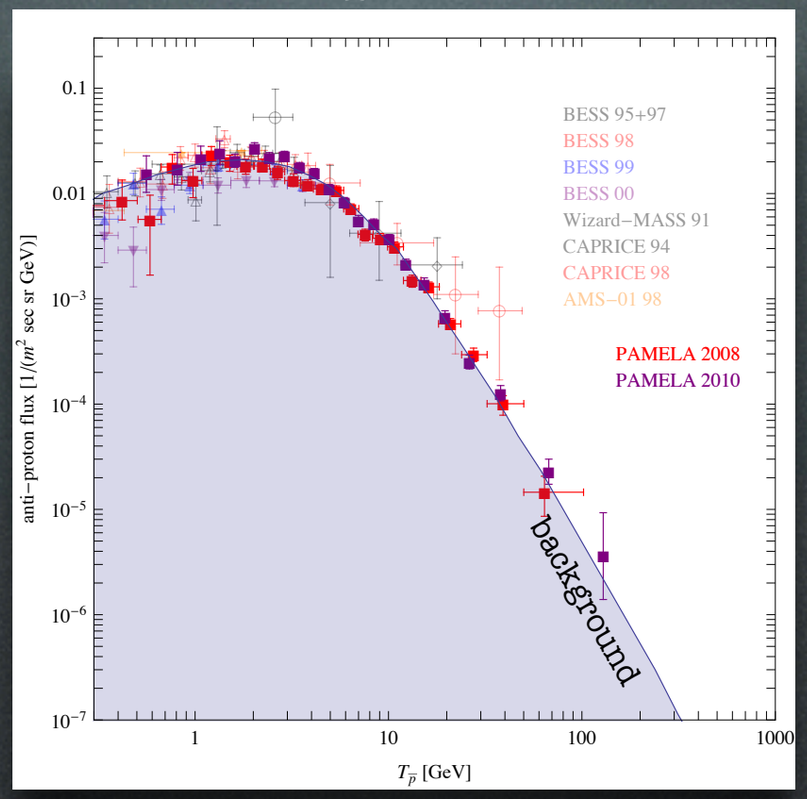


Positrons & Electrons

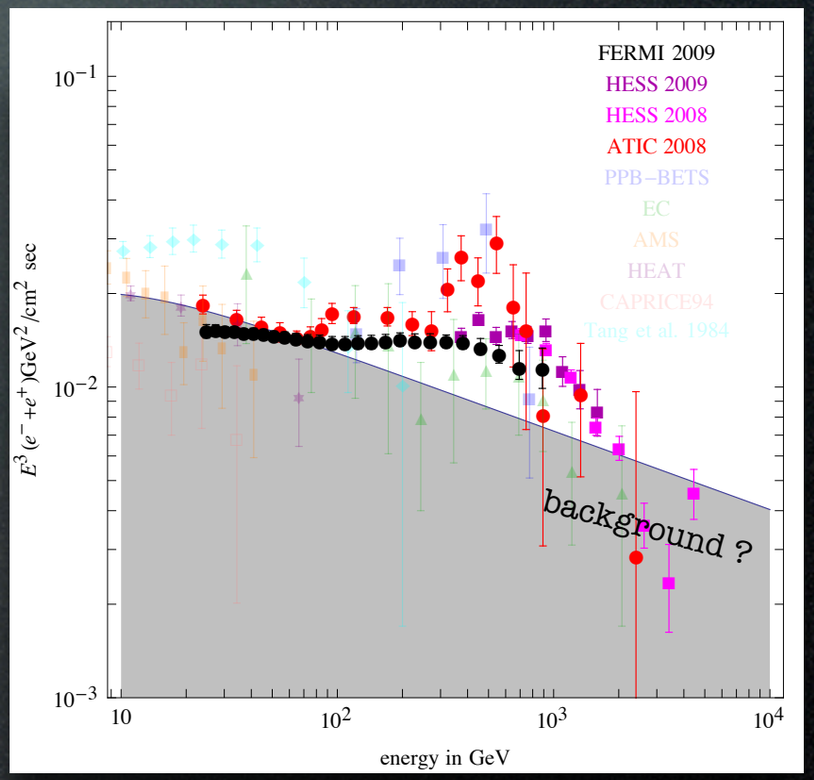
positron fraction



antiprotons



electrons + positrons



Positrons & Electrons

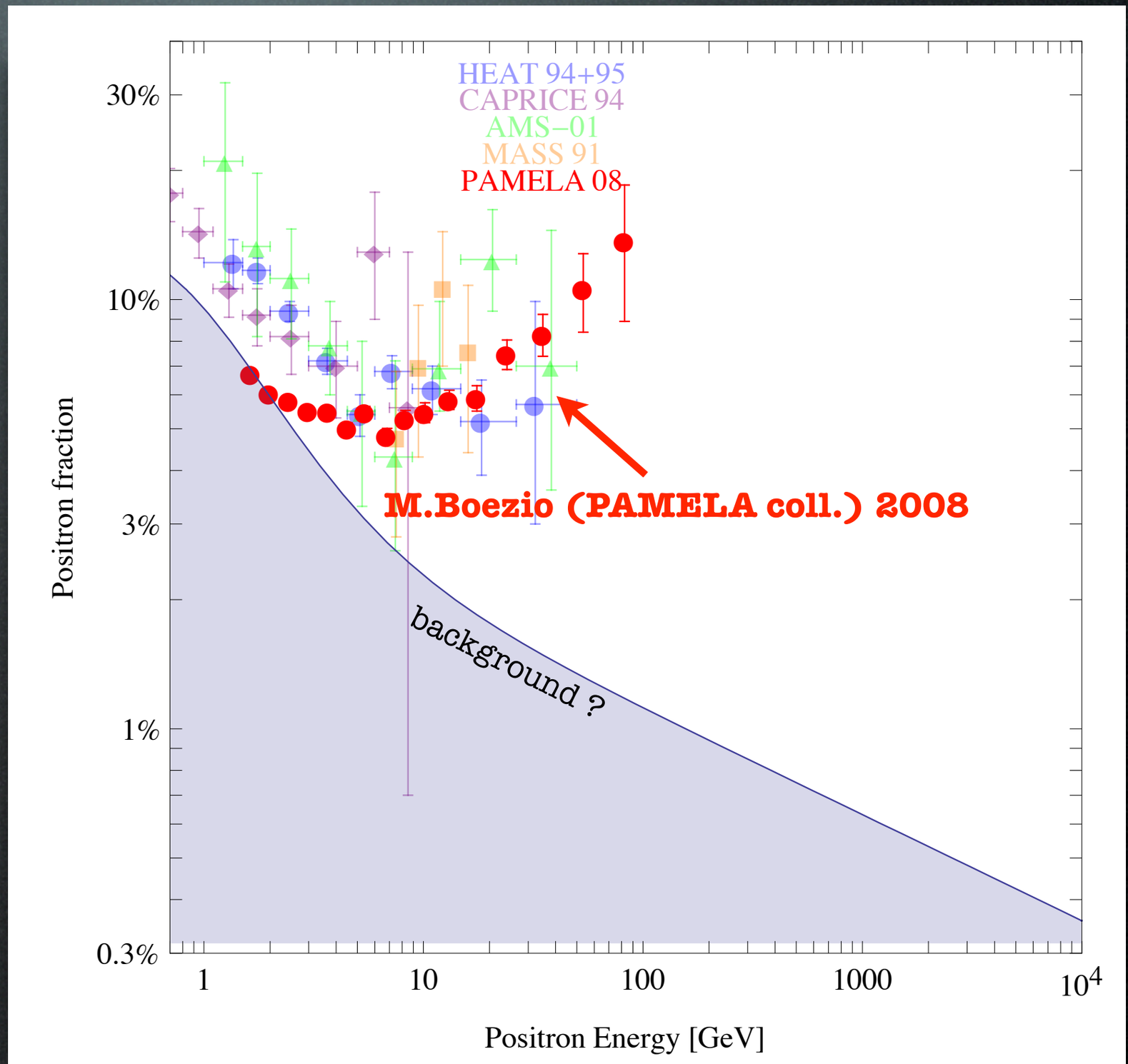
Positrons from PAMELA:

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

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

(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!
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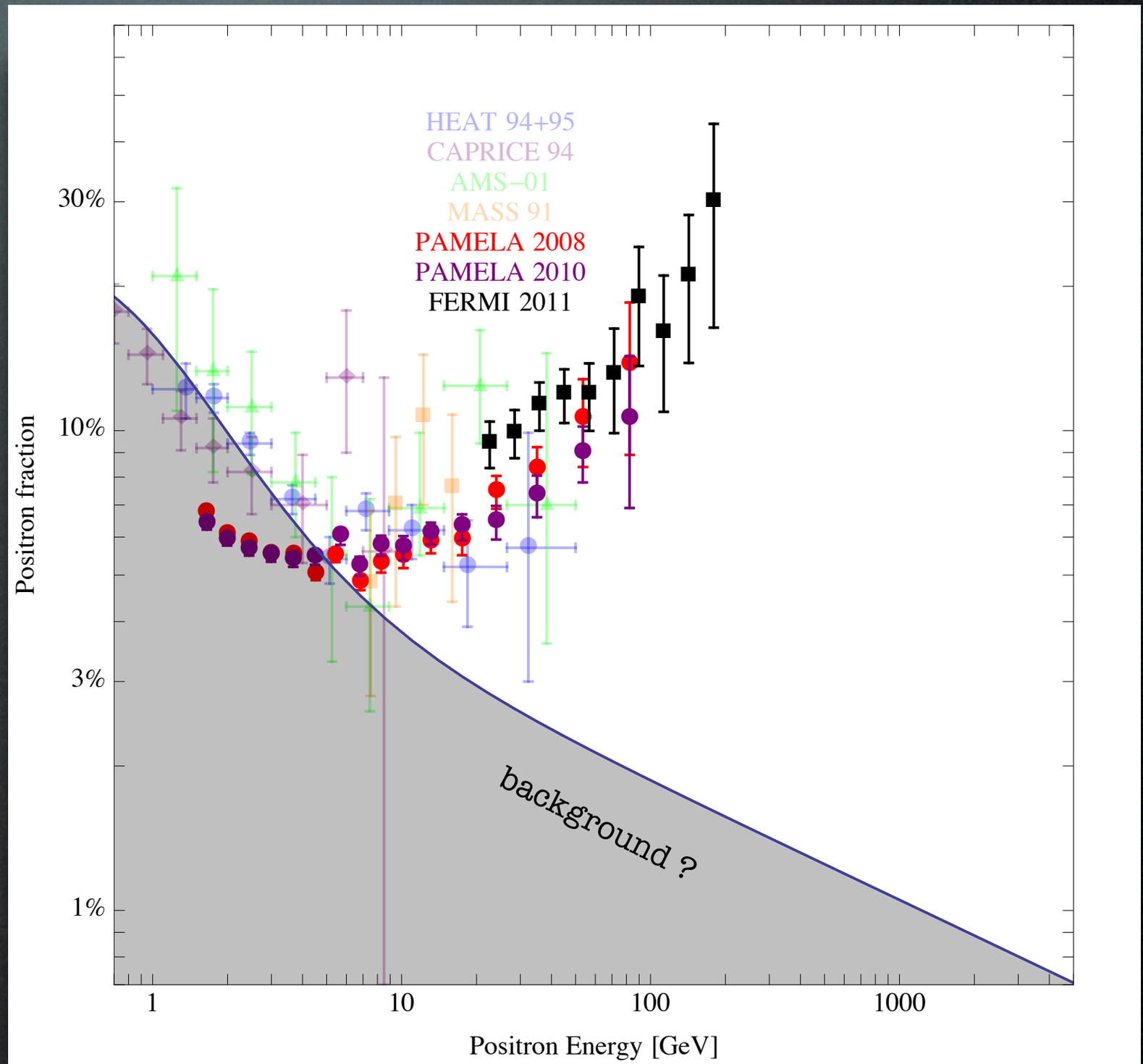


Adriani et al., Nature 458 (2009) 607; ApP 34 (2010) 1

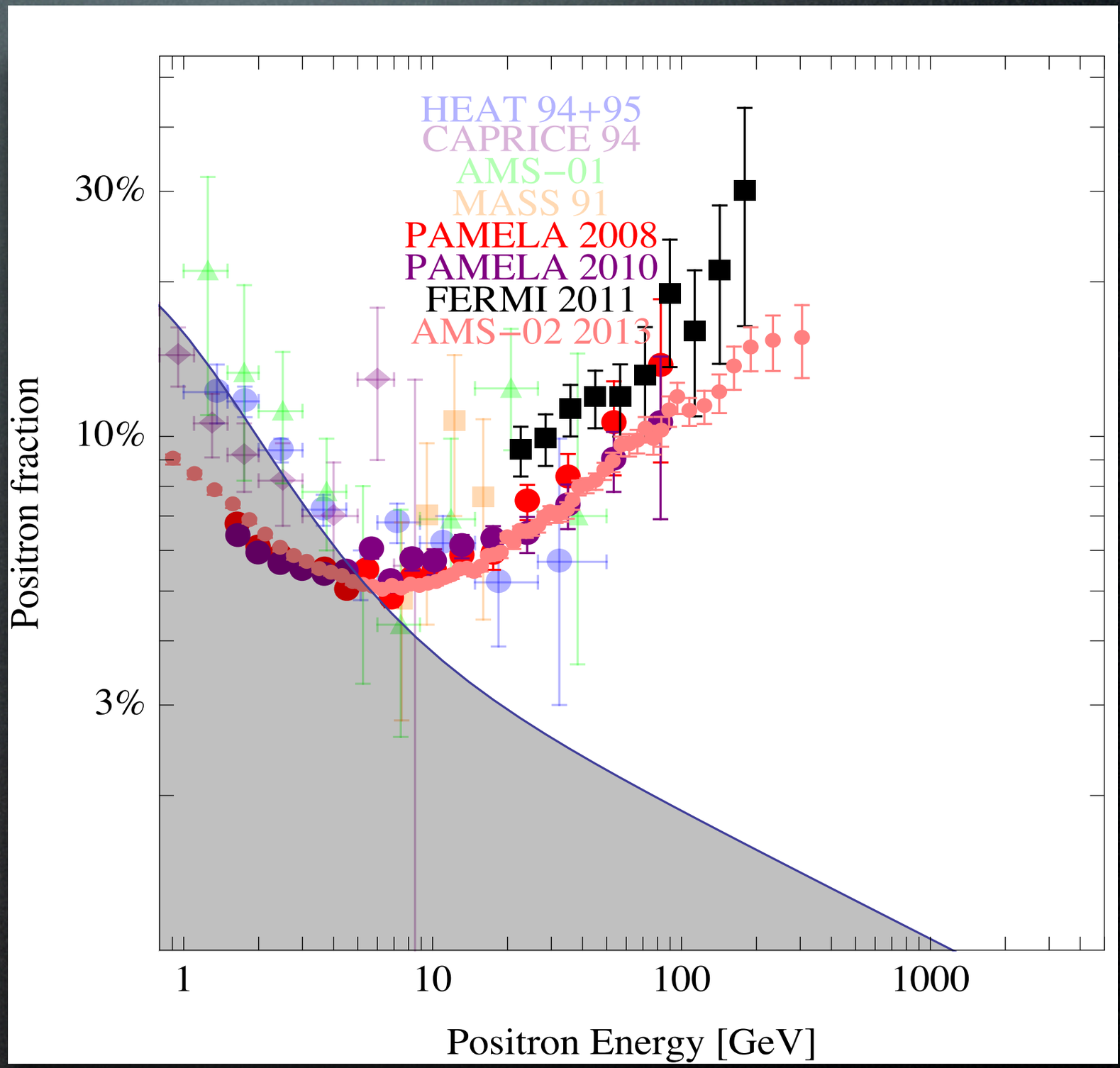
Fermi coll., 1109.0521

Positrons & Electrons

Positrons from PAMELA and FERMI and AMS-02:

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

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

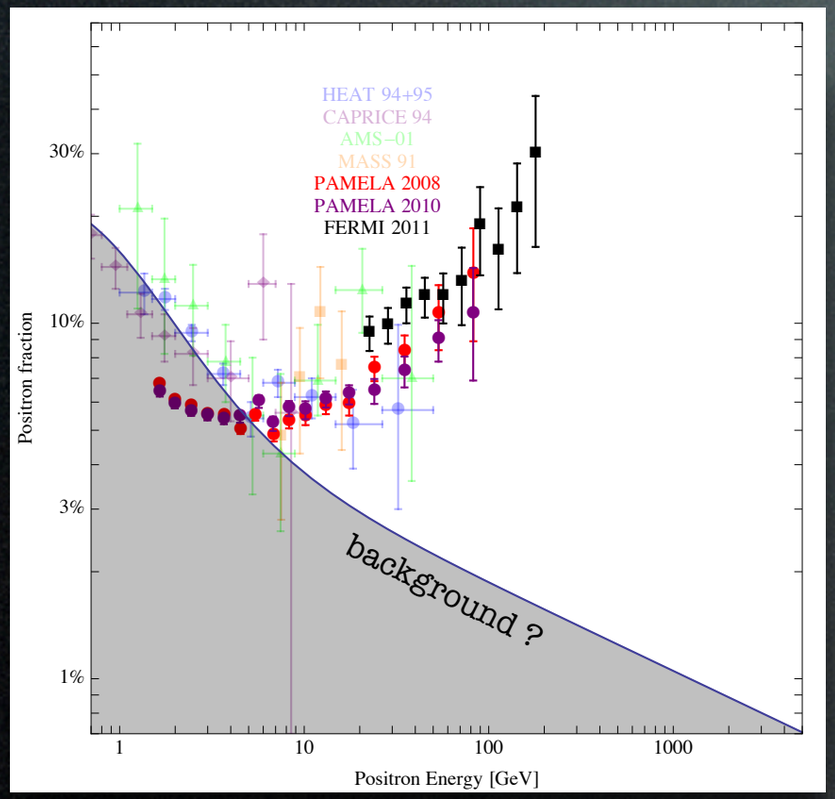


Adriani et al., Nature 458 (2009) 607; ApP 34 (2010) 1

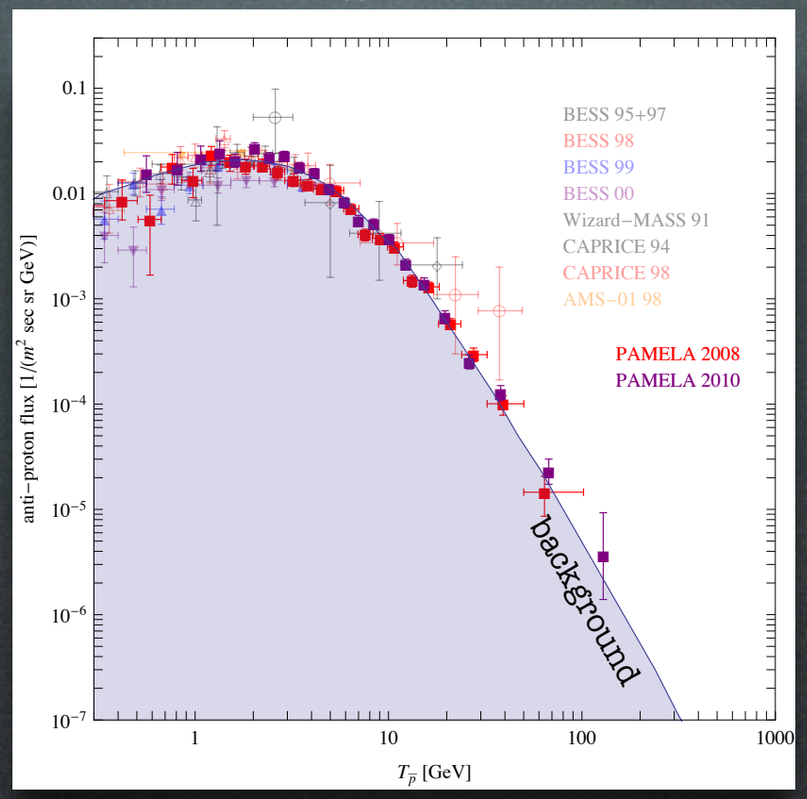
Fermi coll., 1109.0521 **AMS-02 coll., PRL 110, 141102 (2013)**

Positrons & Electrons

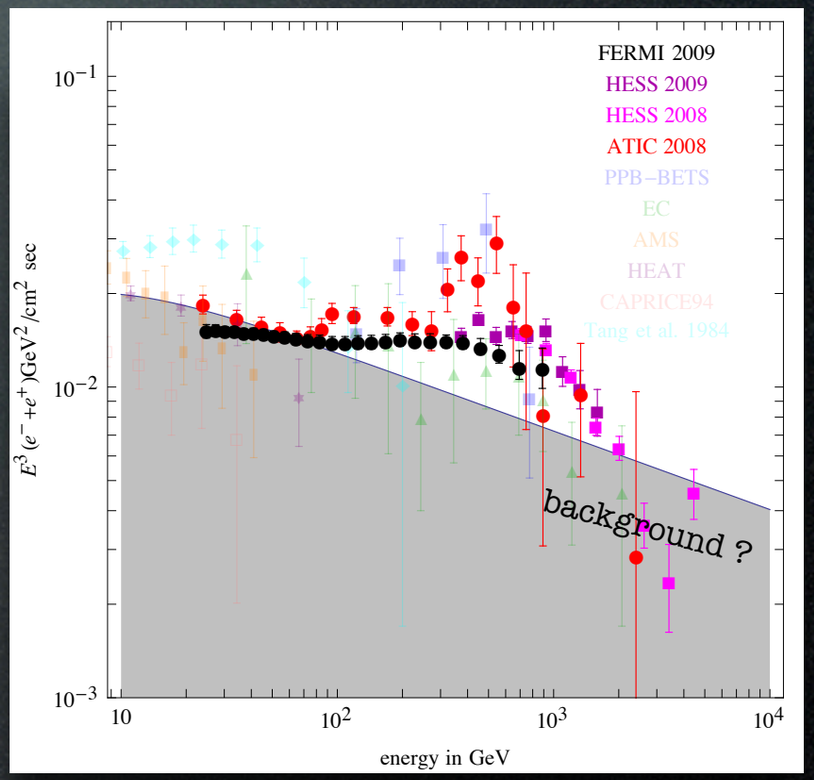
positron fraction



antiprotons



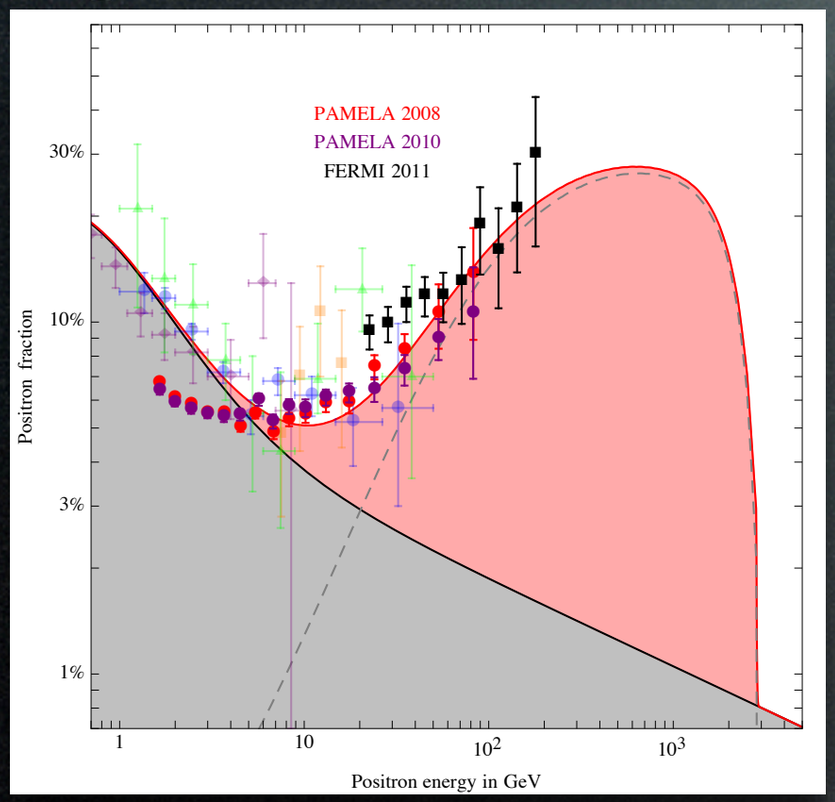
electrons + positrons



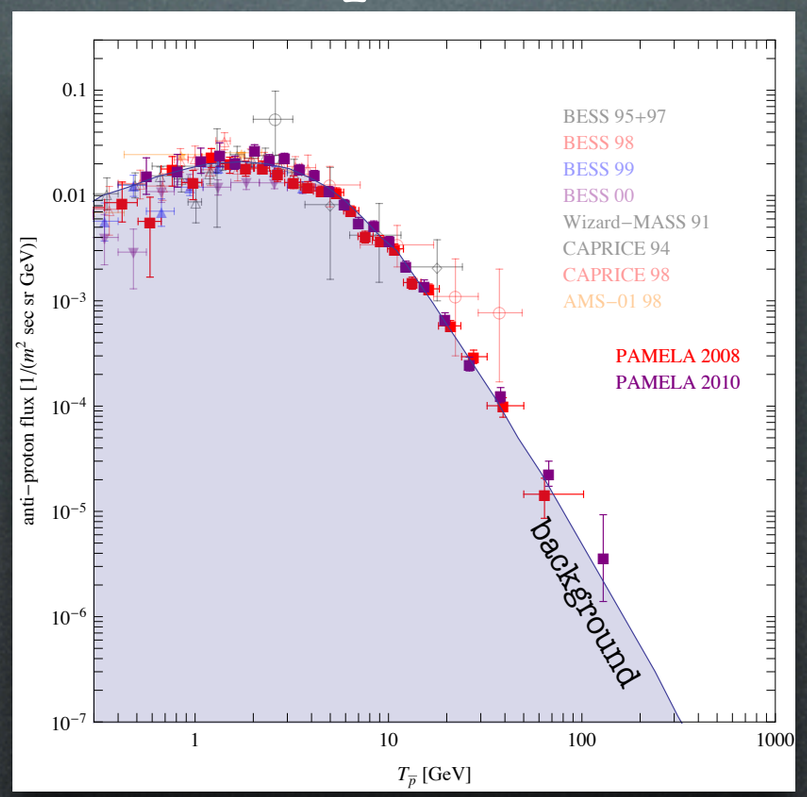
Are these signals of Dark Matter?

Positrons & Electrons

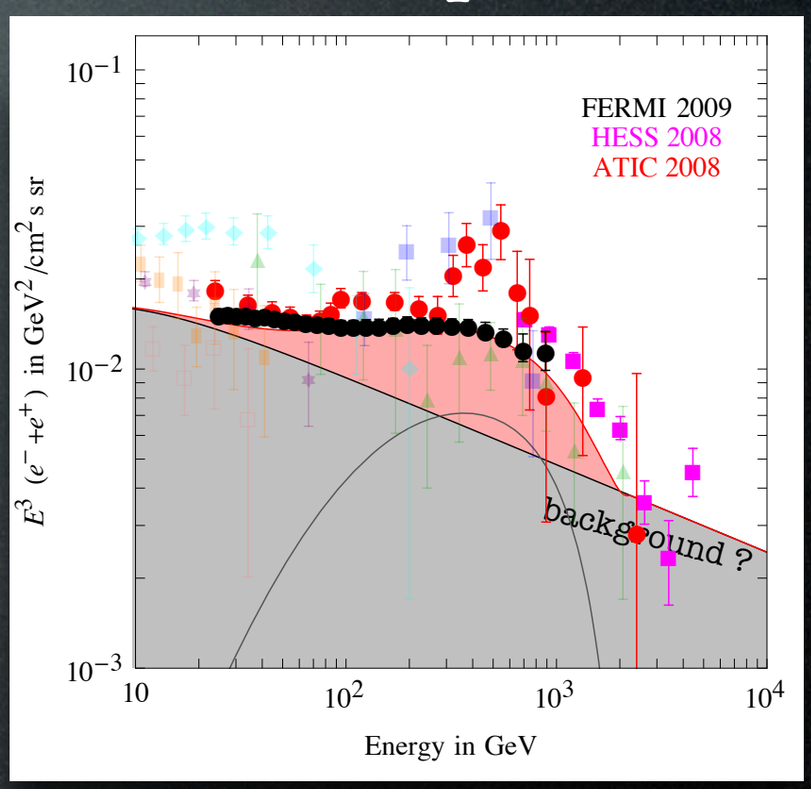
positron fraction



antiprotons



electrons + positrons

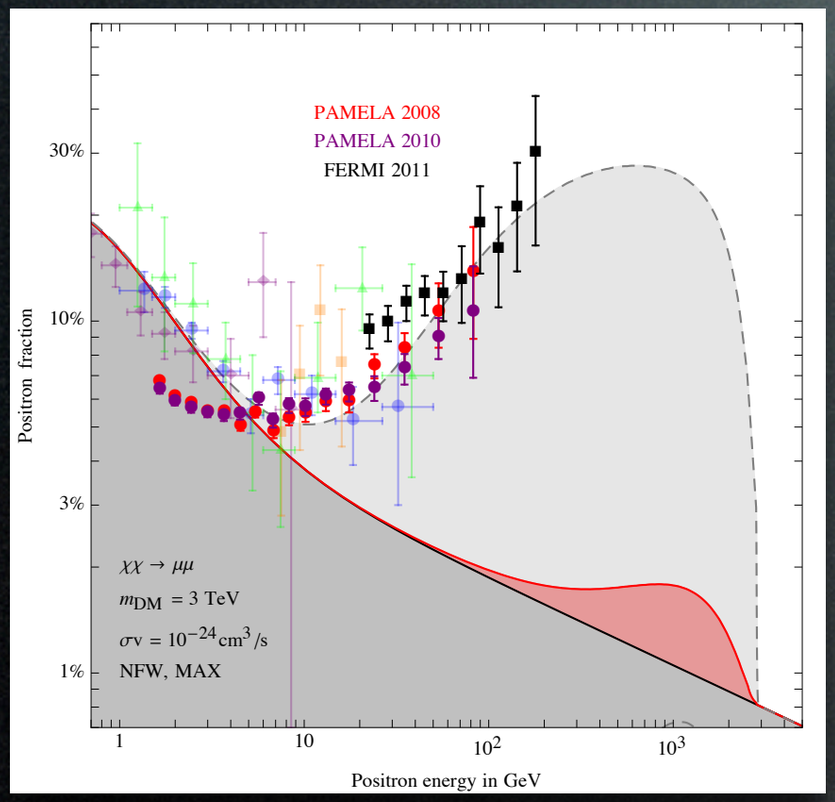


Are these signals of Dark Matter?

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

Positrons & Electrons

positron fraction



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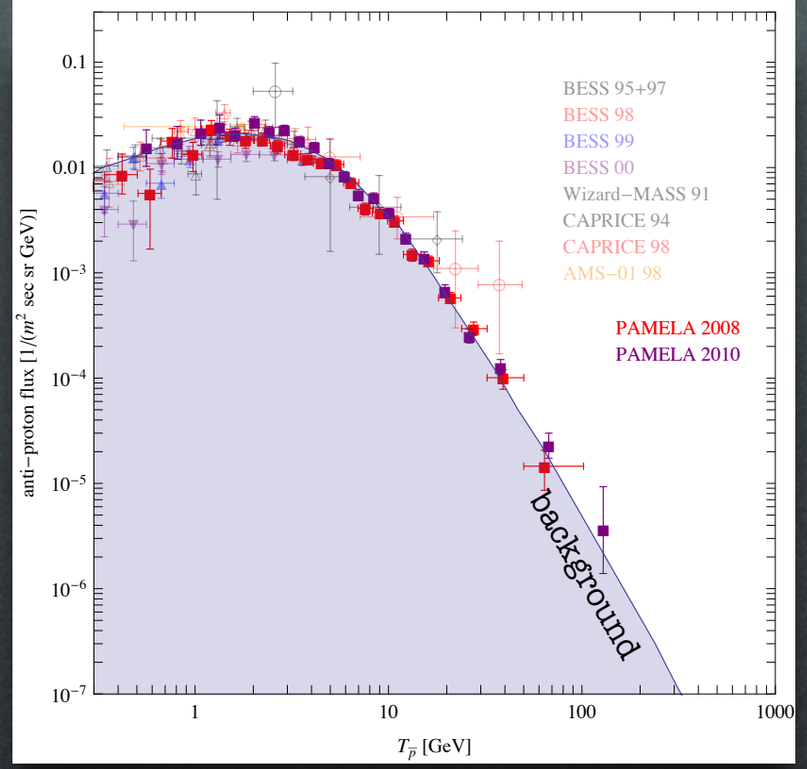

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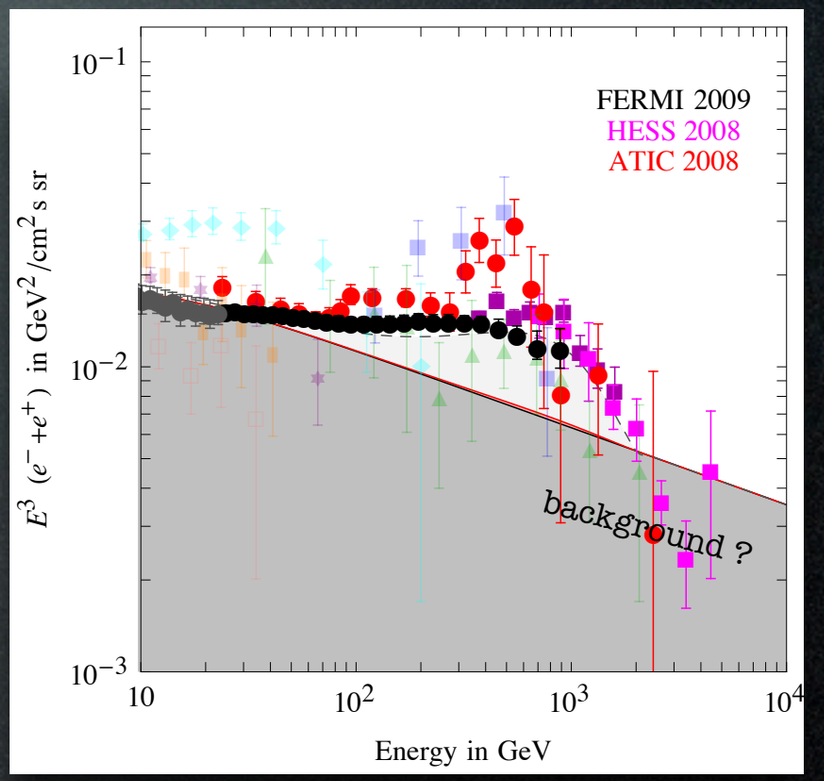


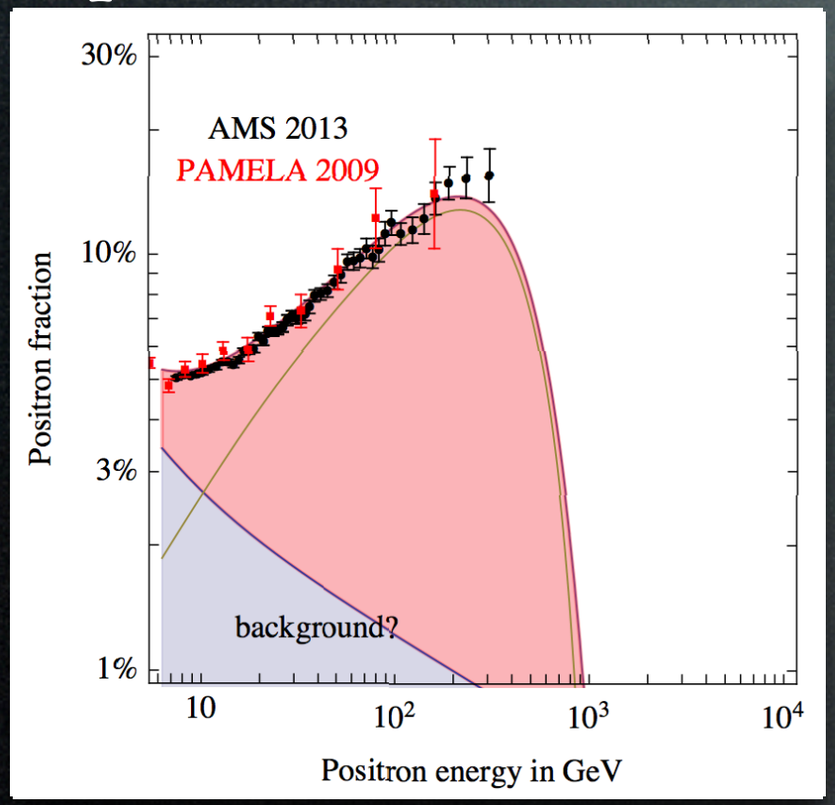
Are these signals of Dark Matter?

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 2013

positron fraction



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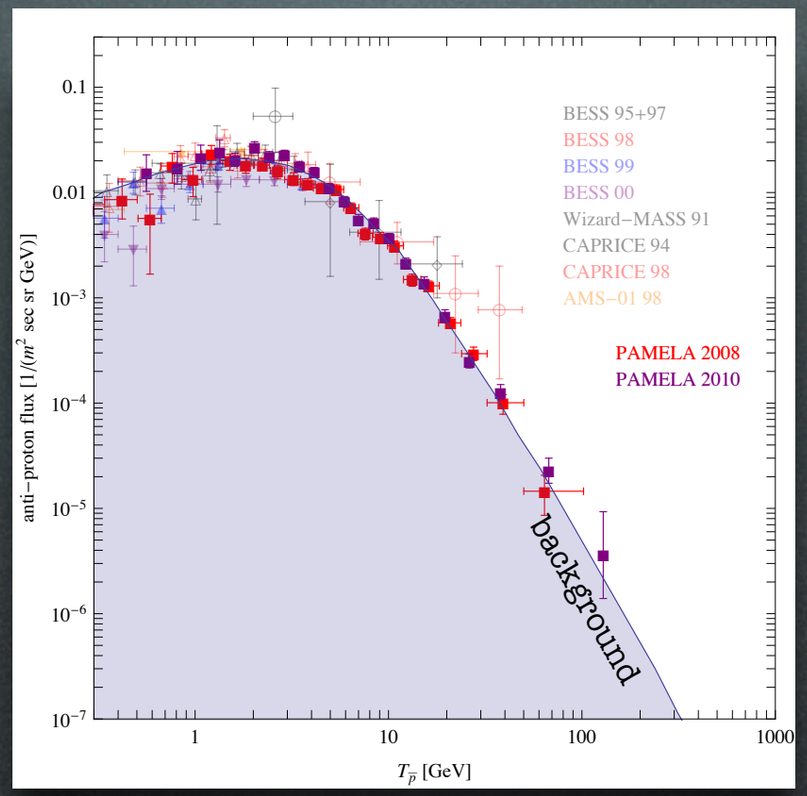

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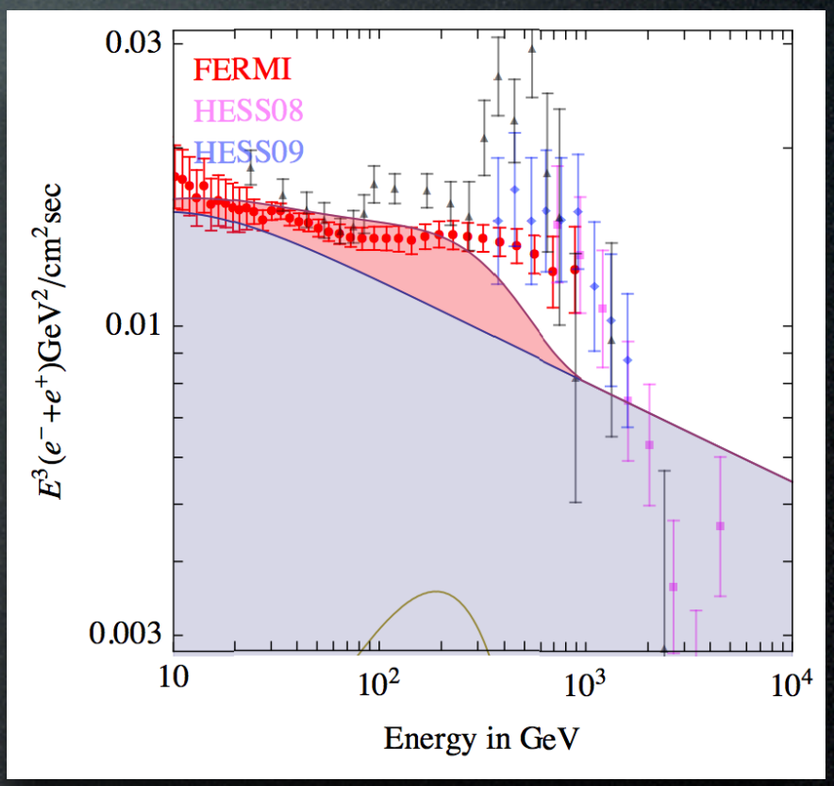
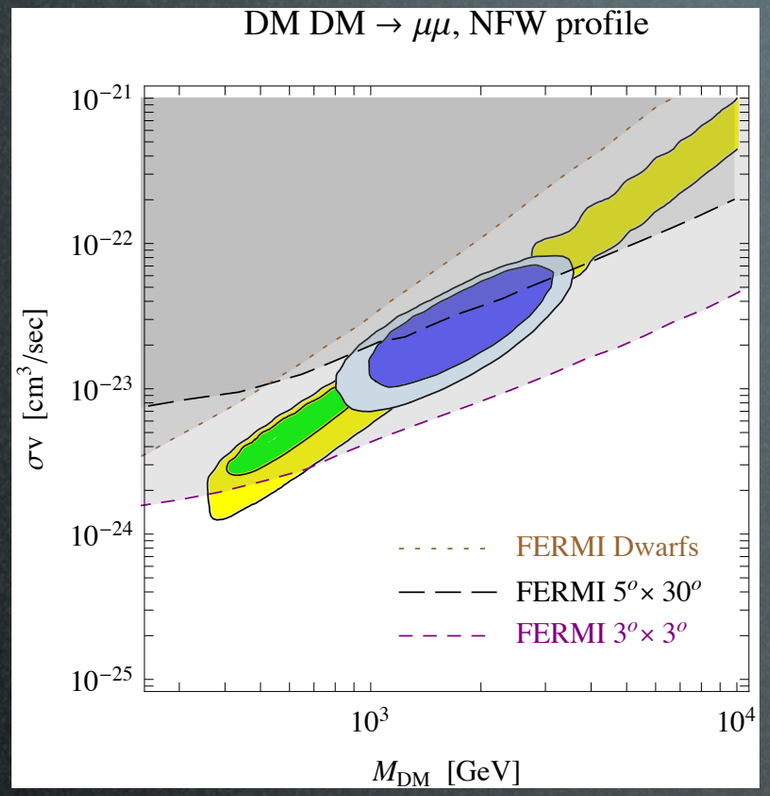


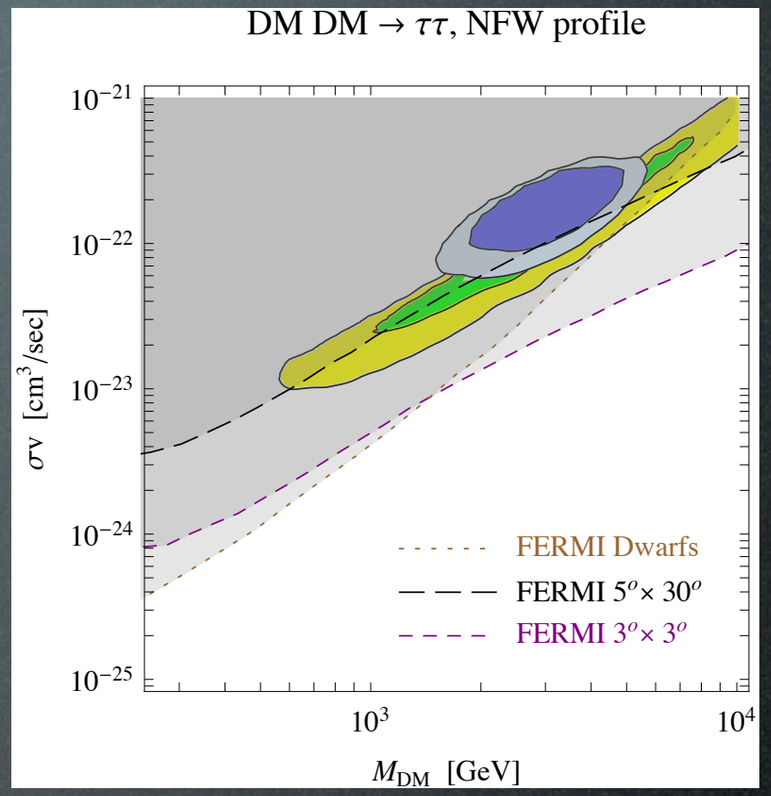
Are these signals of Dark Matter?

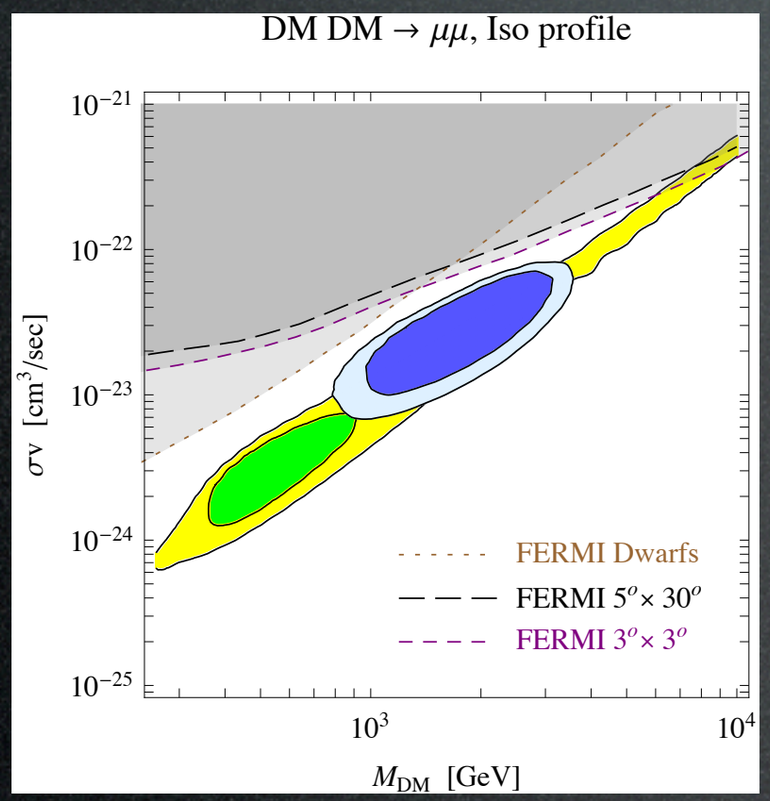
YES: one TeV, leptophilic DM
with huge $\langle \sigma v \rangle \approx 10^{-23}\,\mathrm{cm}^3/\mathrm{sec}$
'tension' between positron frac and $e^+ + e^-$

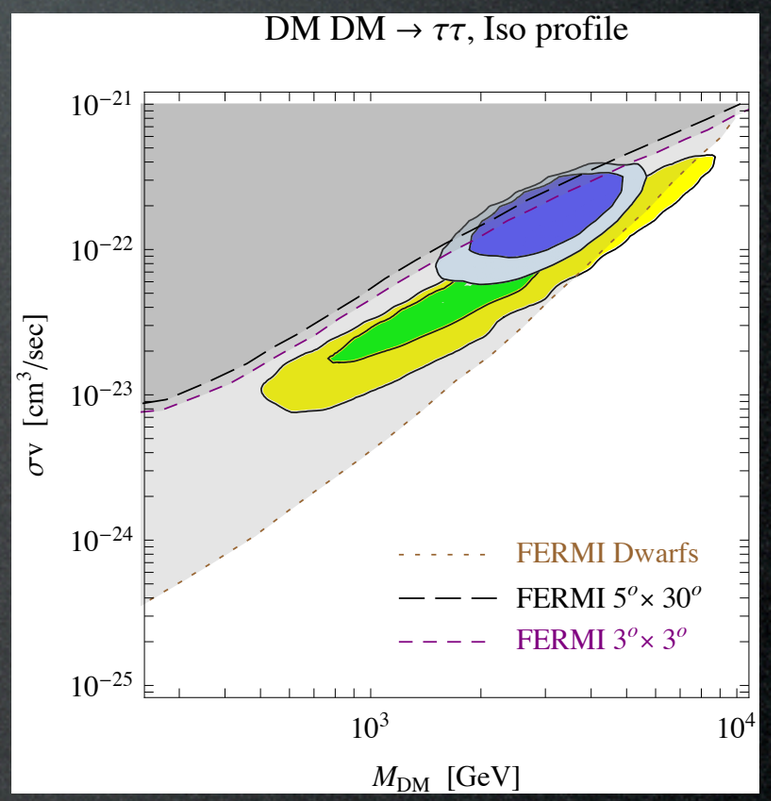
Addendum (2013) to Cirelli, Kadastik, Raidal, Strumia 0809.2409 (2008)

PS: post AMS 2013









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

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)		

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.

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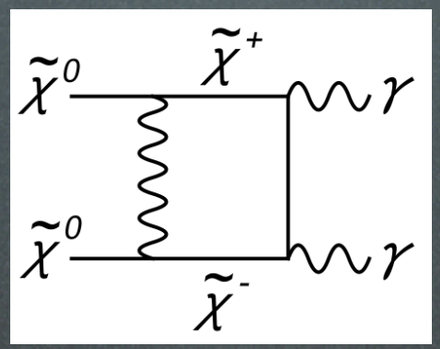
NP QM effect that can enhance the annihilation cross section by orders of magnitude in the regime of small velocity and relatively long range force.

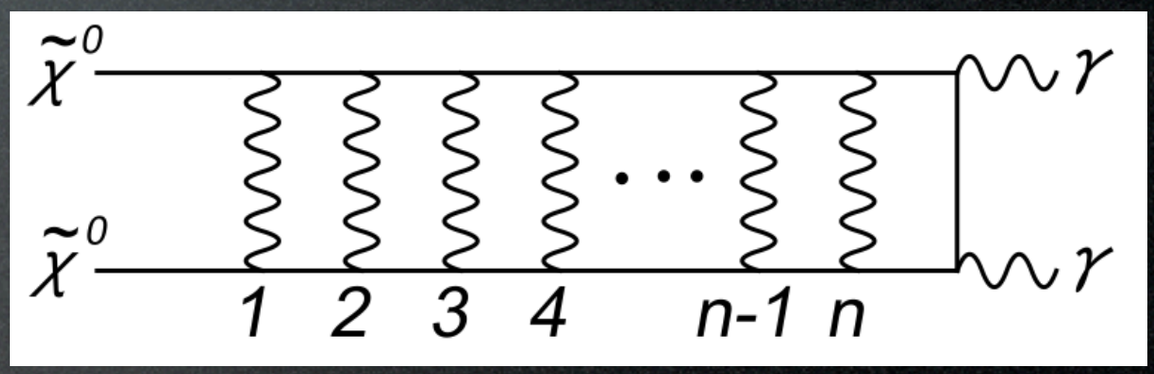
In terms of Feynman diagrams:

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?

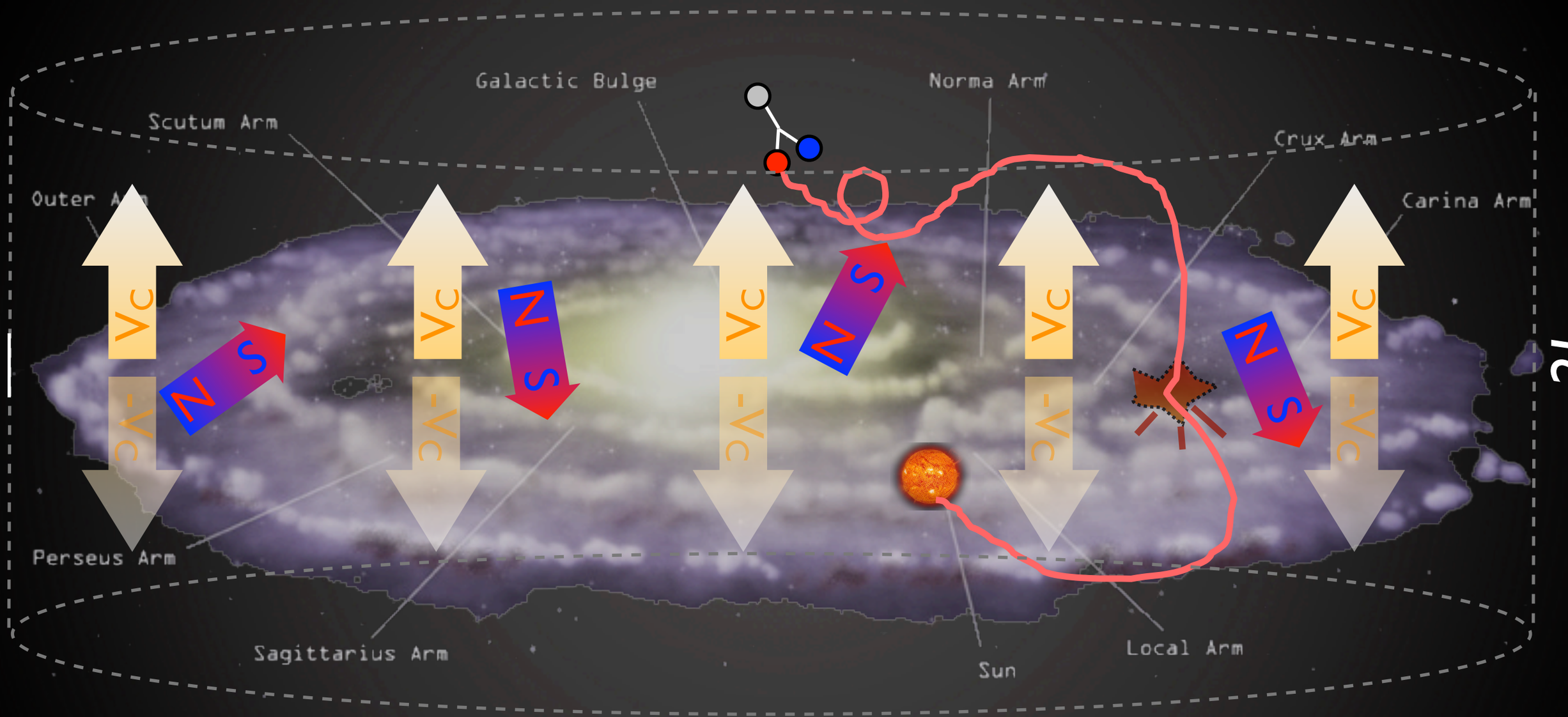
- dim 6 suppressed operator in GUT Arvanitaki, Dimopoulos et al., 2008+09

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

- 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?

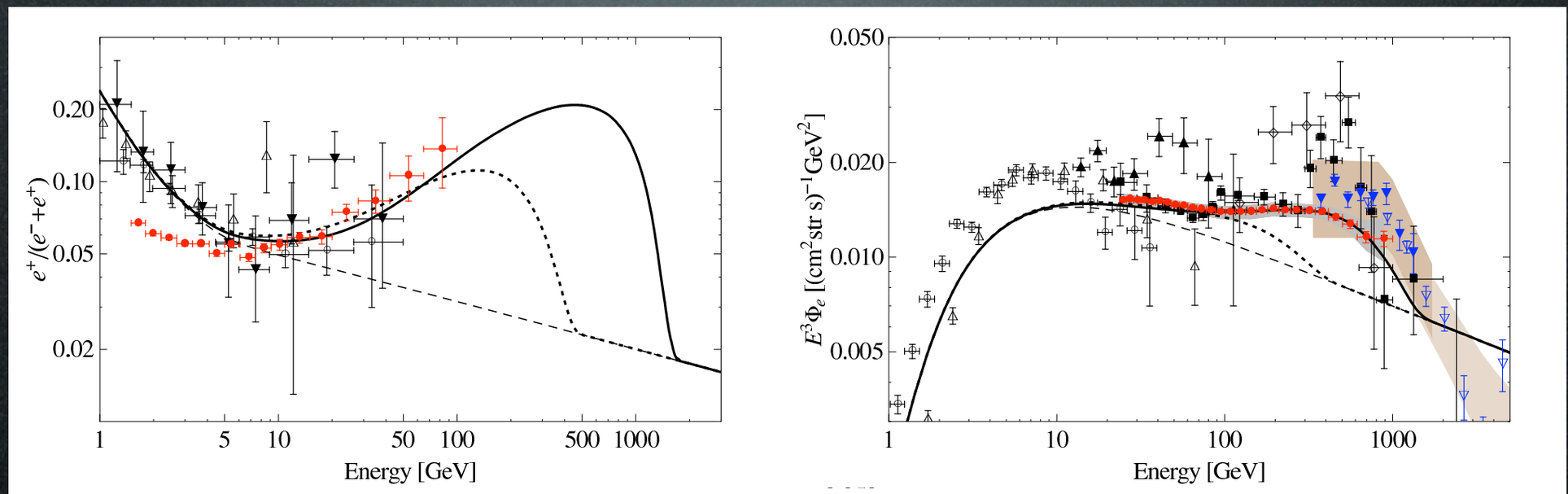
$$\text{flux} \propto n\ \Gamma_{\text{decay}}$$

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

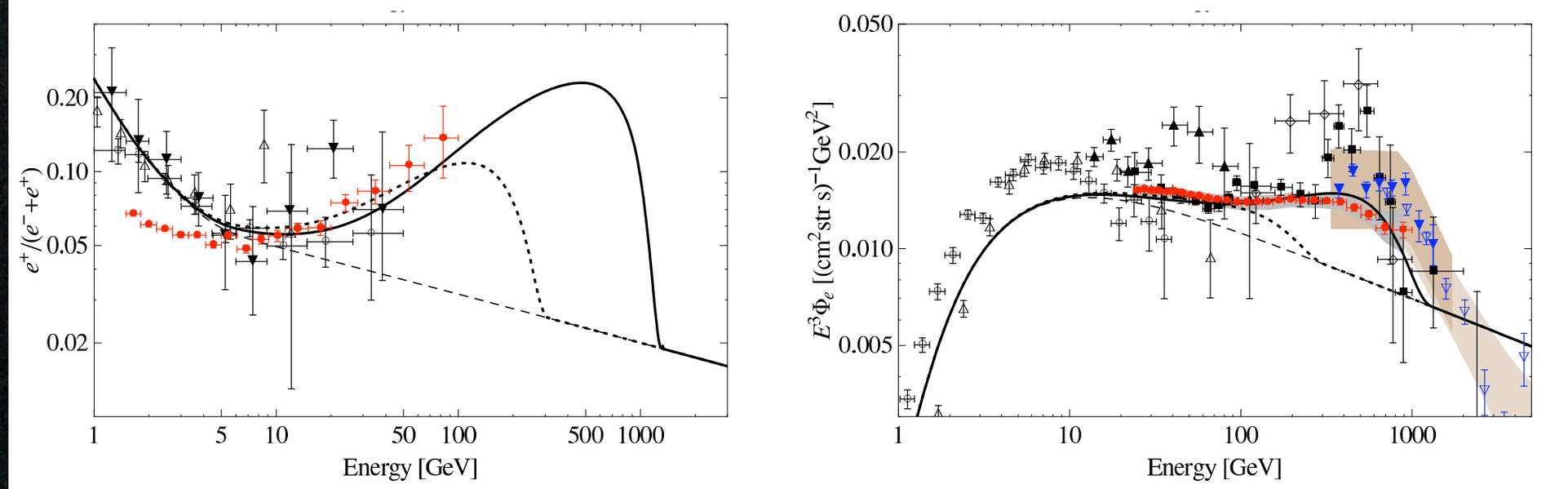
Decaying DM

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

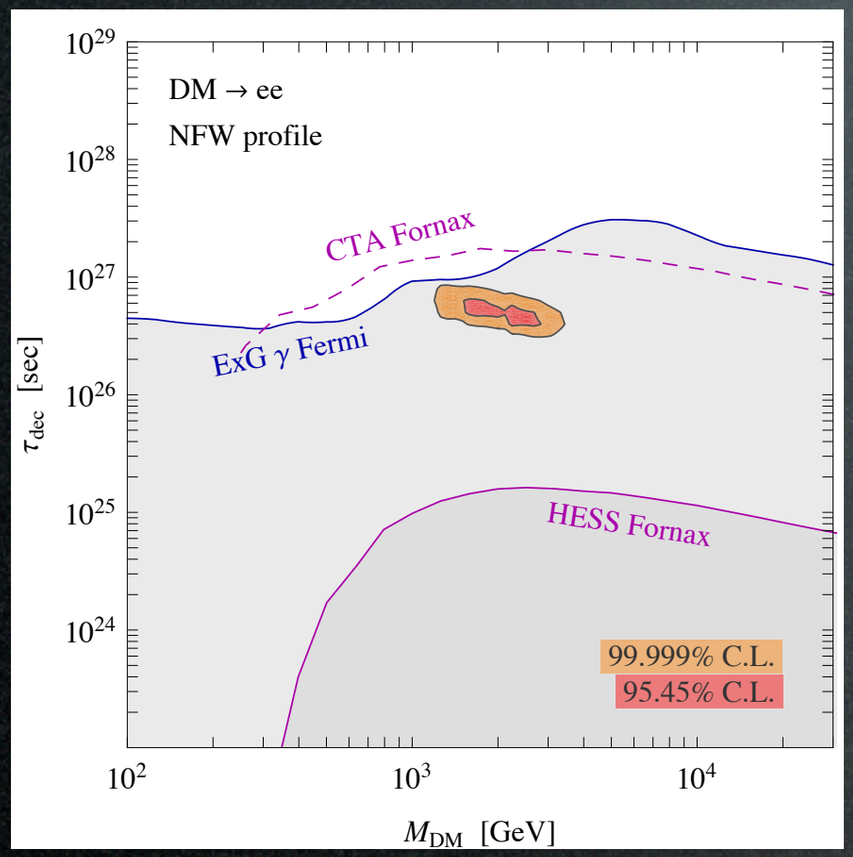


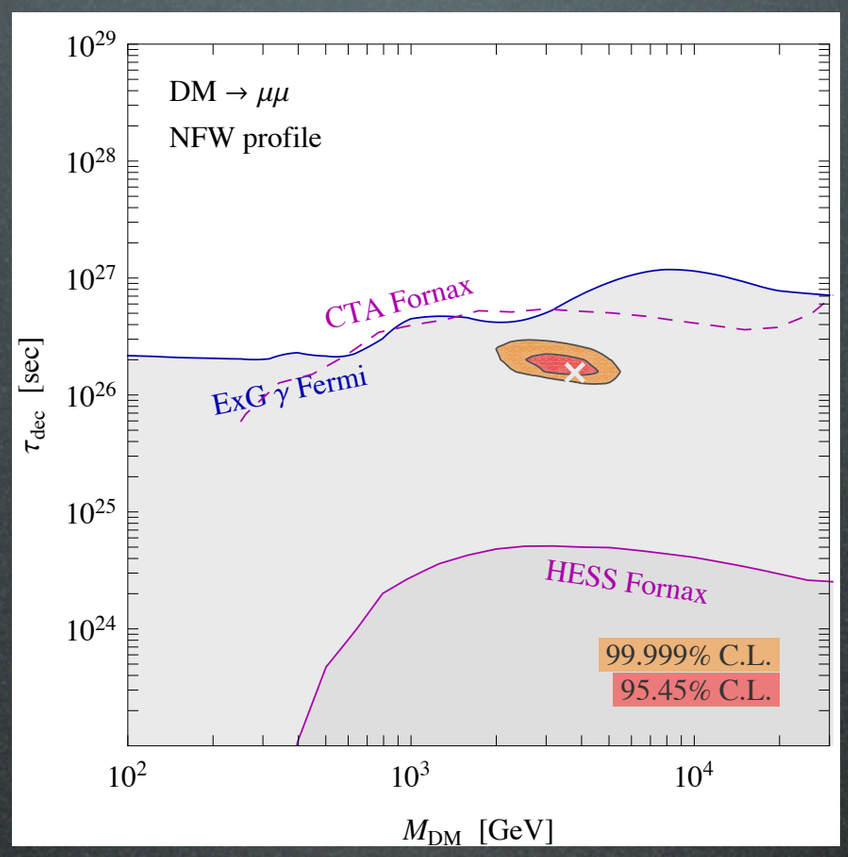
Ibarra, Tran, Weniger 2009

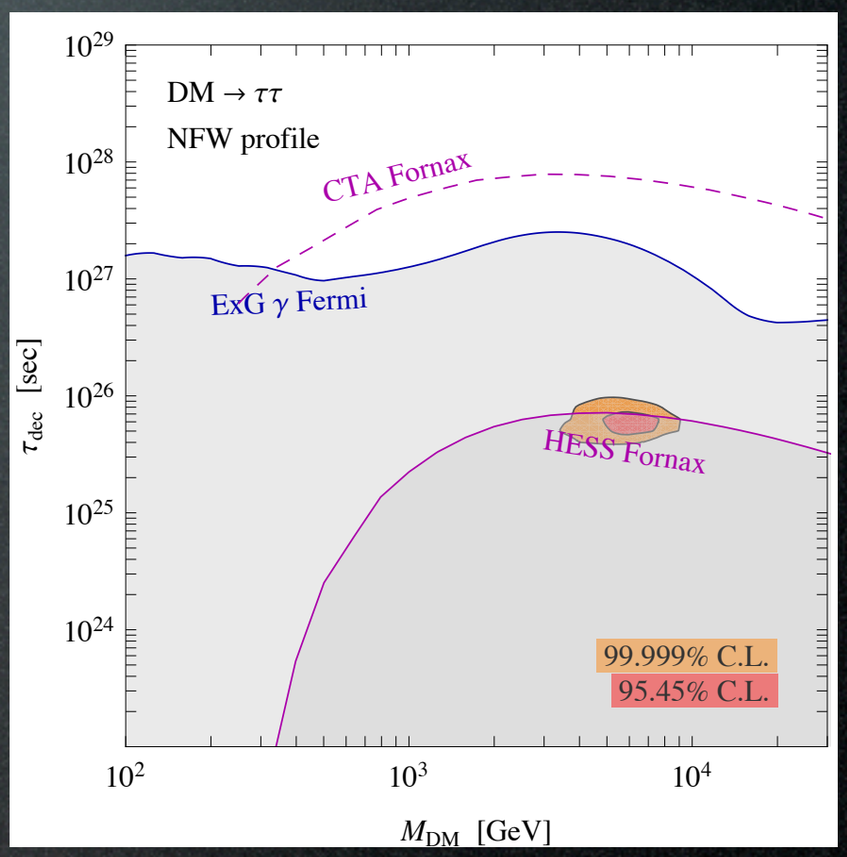
Decaying DM

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

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

The "Theory of DM"

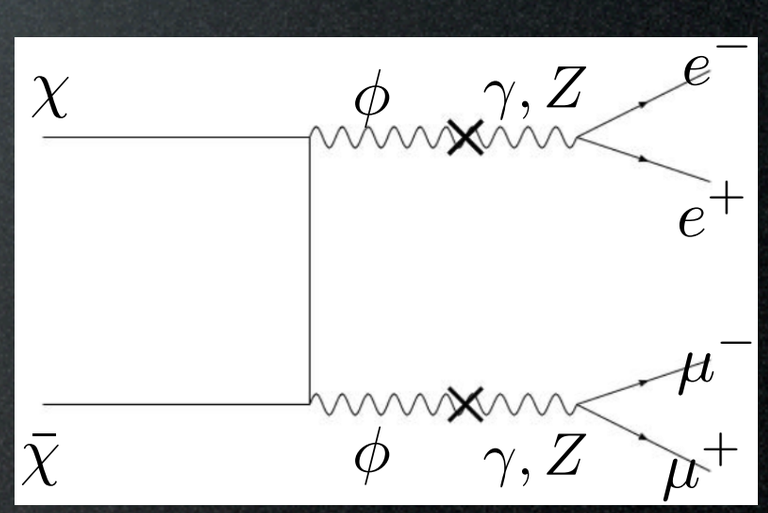
Arkani-Hamed, Weiner, Finkbeiner et al. 0810.0713
0811.3641

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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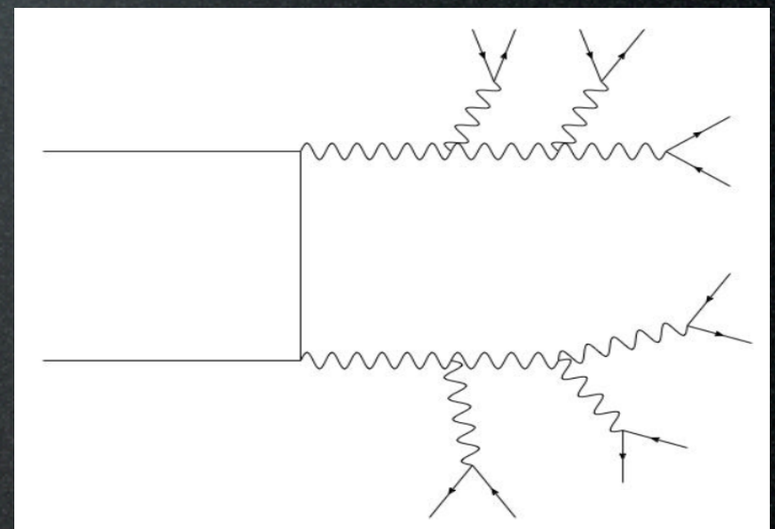


Extras:

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
$\hookrightarrow e^+e^-$

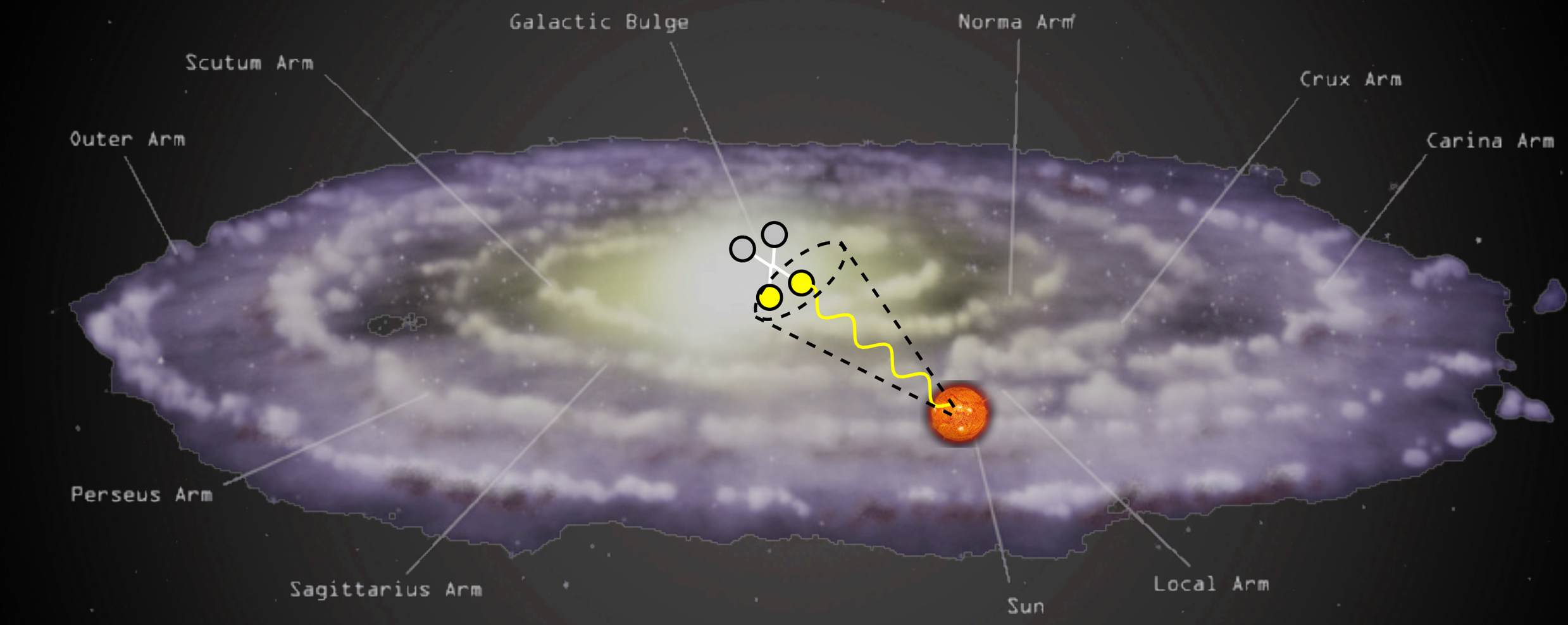
Gamma rays

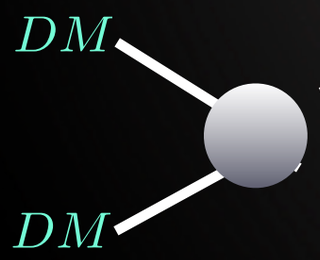
2. the ‘135 GeV line’

[skip to next]

Basic picture: targets

γ from DM annihilations in galactic center

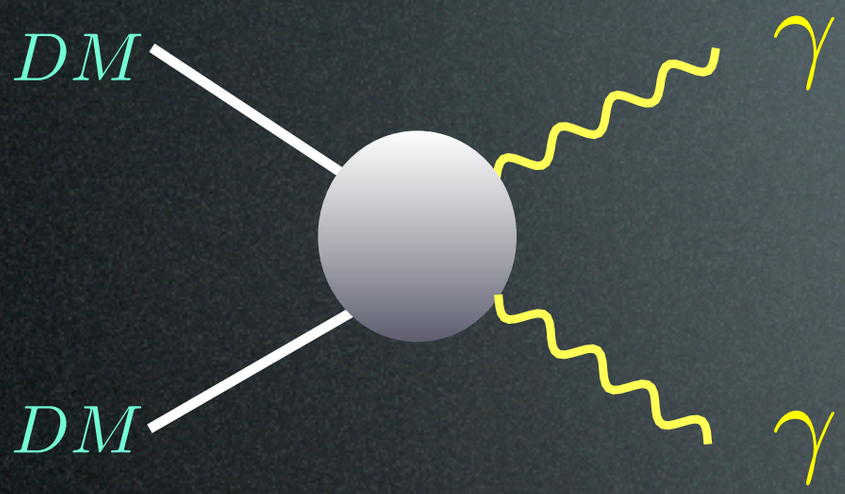




$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^{\mp},\ \overset{(-)}{p},\ \overset{(-)}{D}\ \ldots \text{ and } \gamma$$

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

Prompt emission: line(s)



primary
channels

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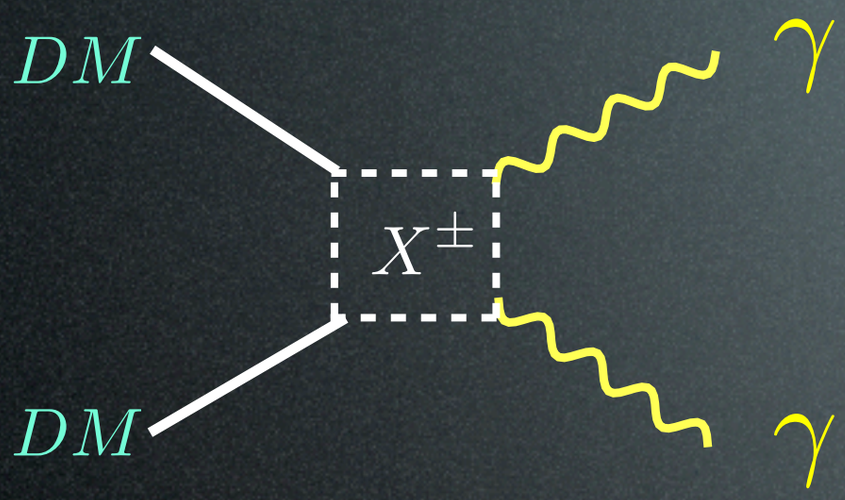
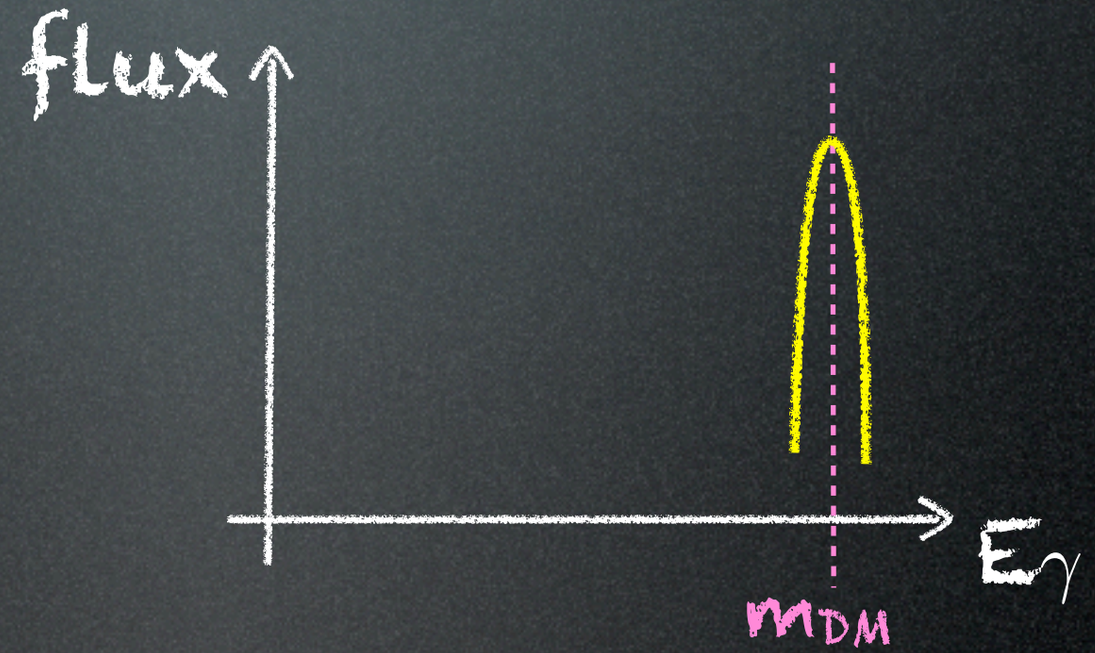


primary channels

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



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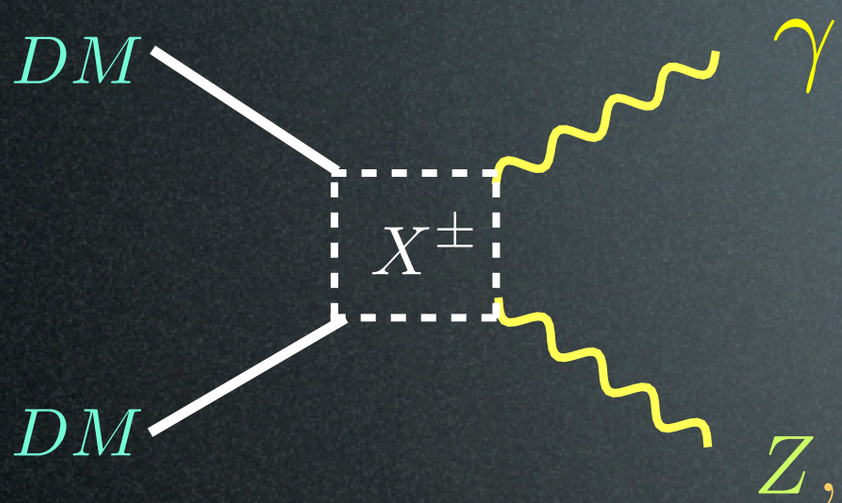

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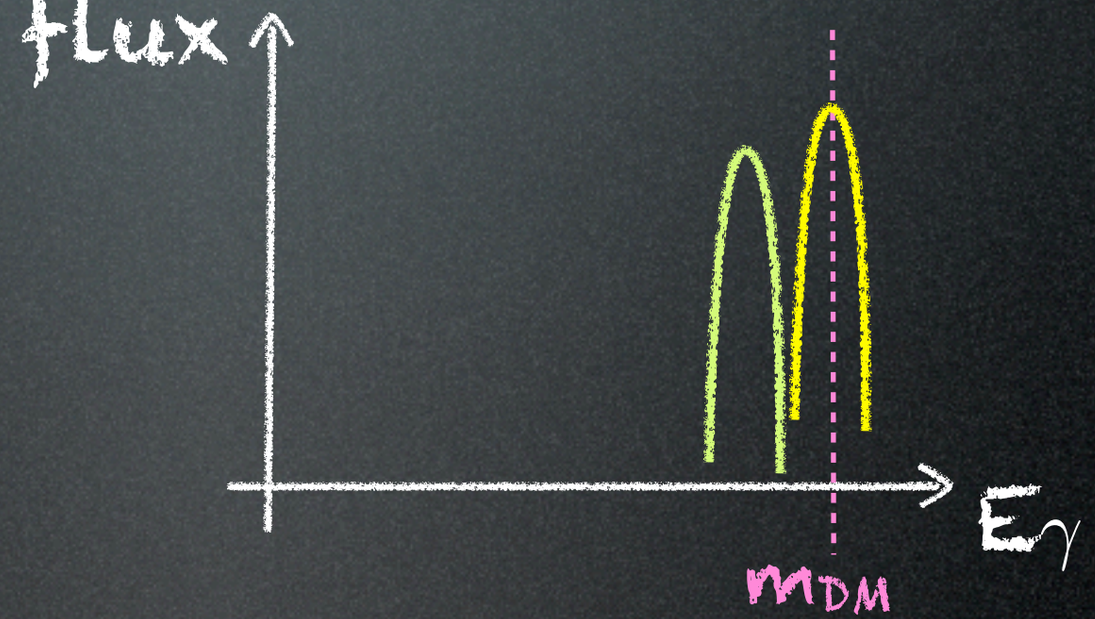

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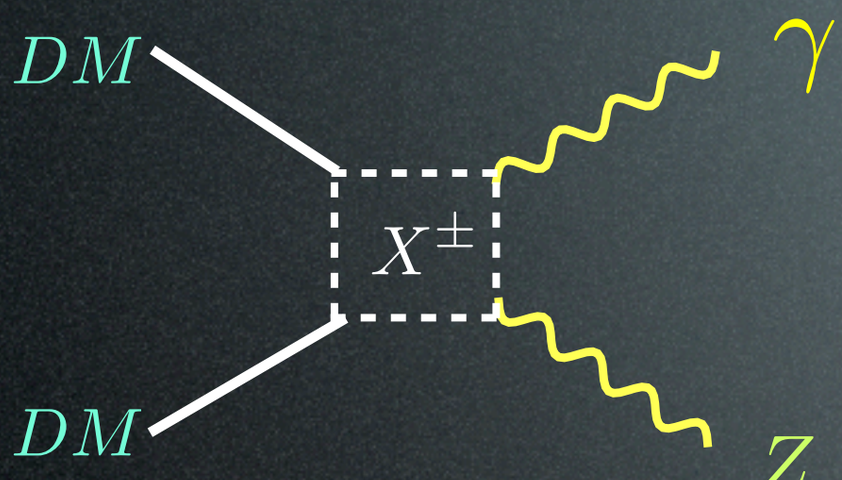

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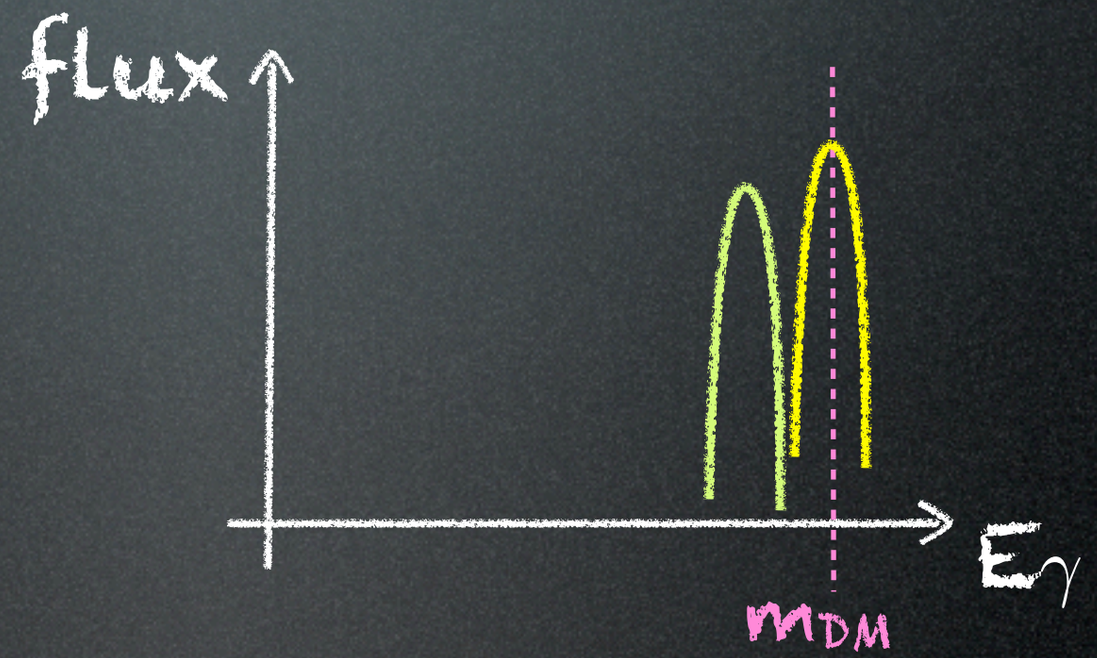


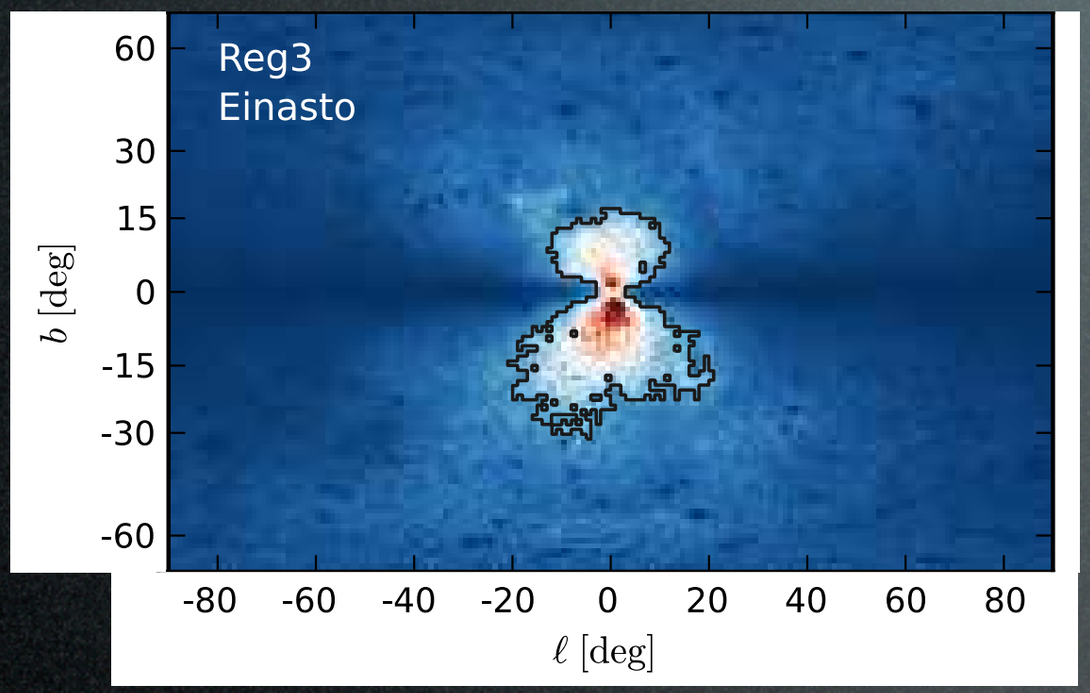
So what are the particle physics parameters?

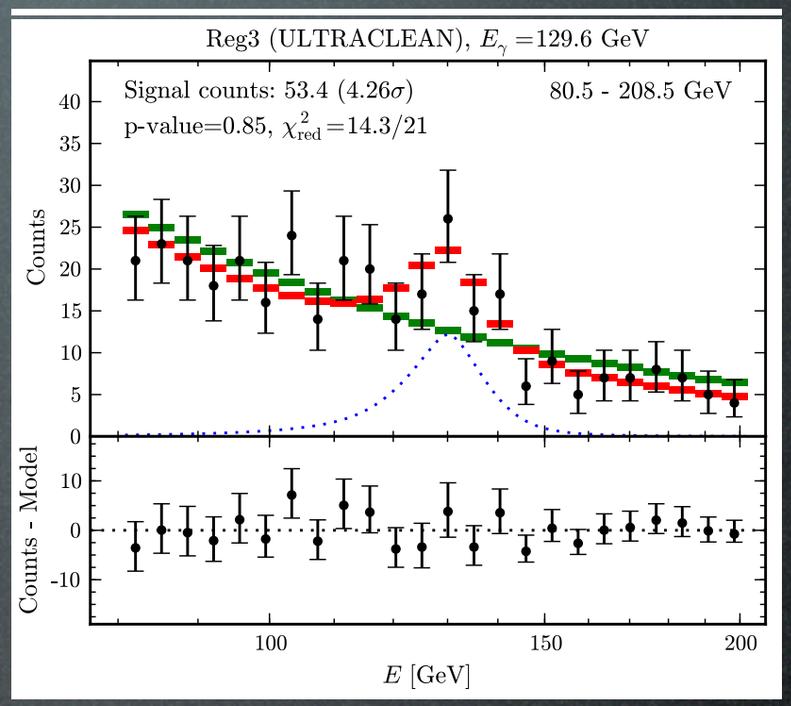
1. Dark Matter mass

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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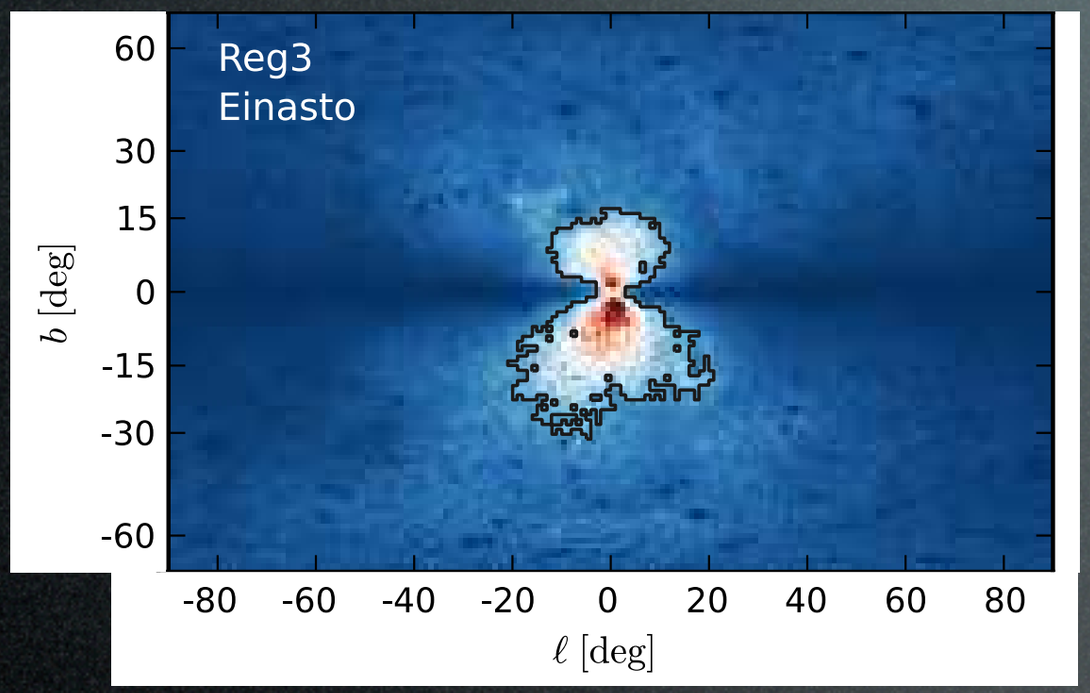

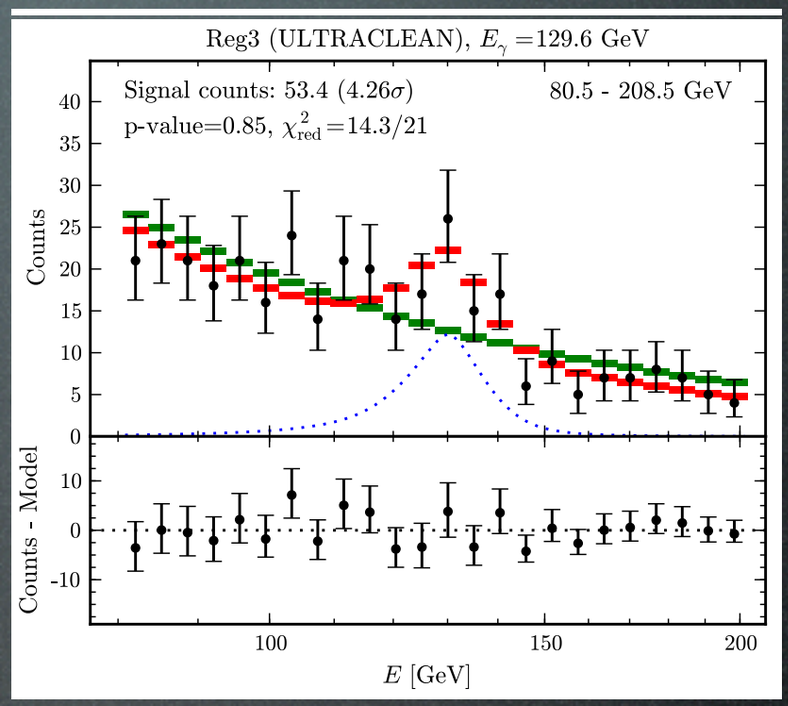

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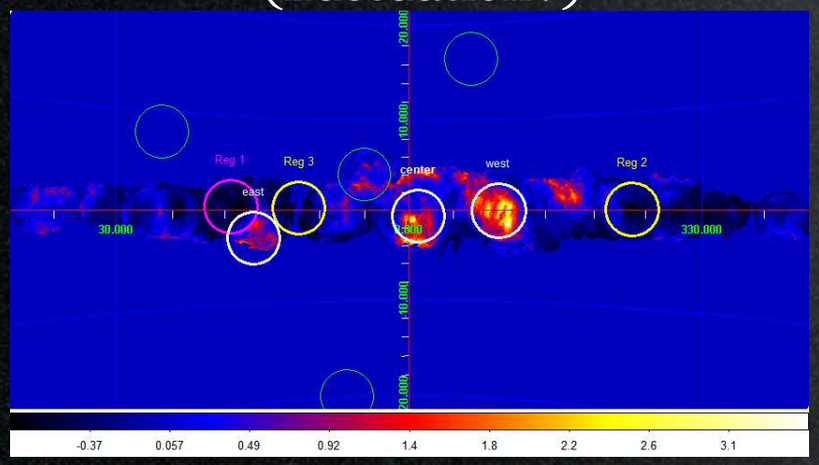
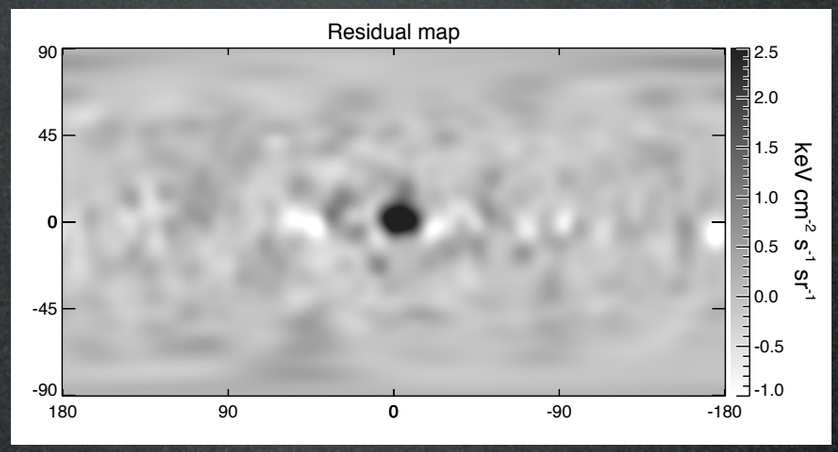
Similar excesses found elsewhere (fluctuation?)



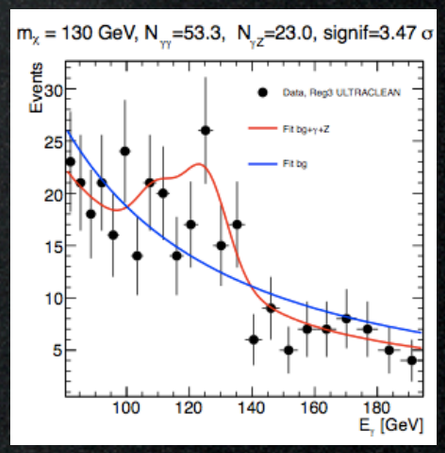
Boyarsky, Malyshev, Ruchayskyi, 1205.4700

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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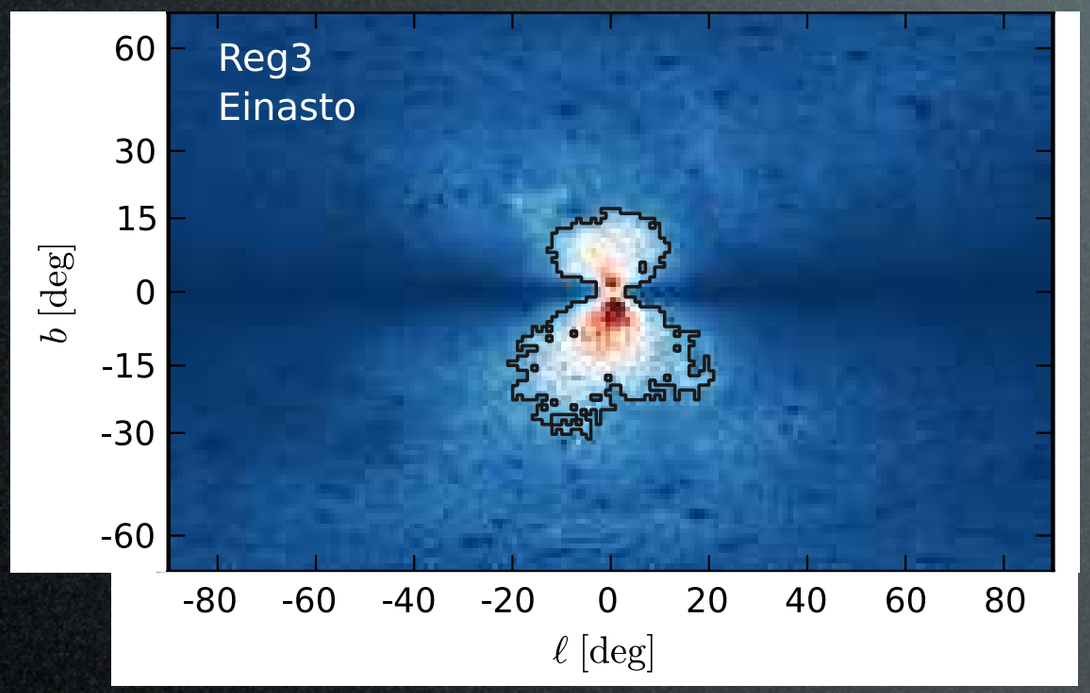

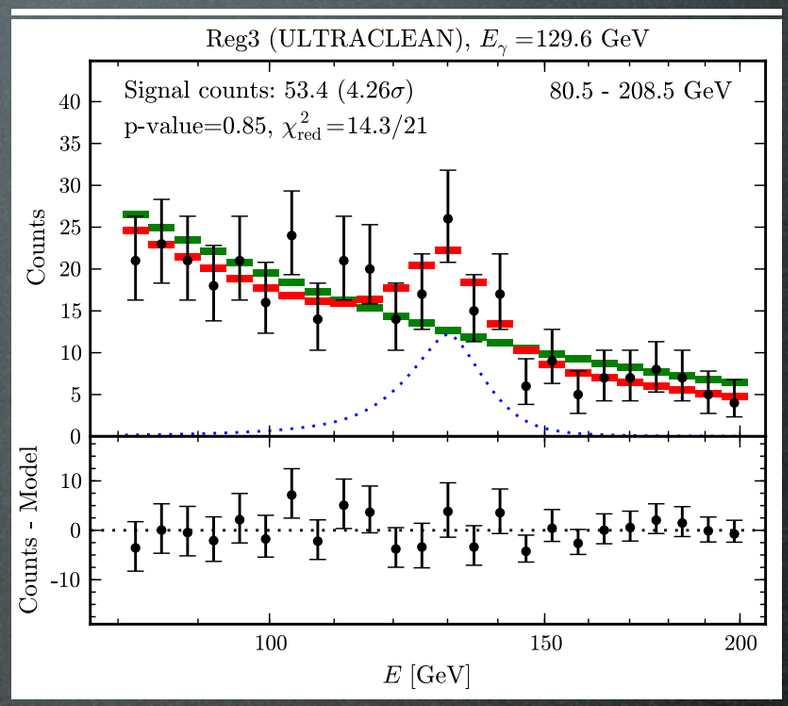

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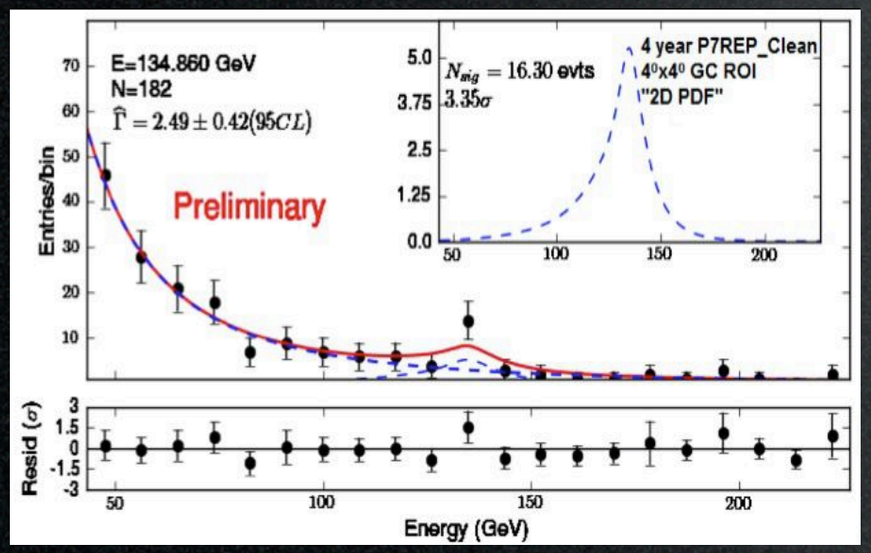
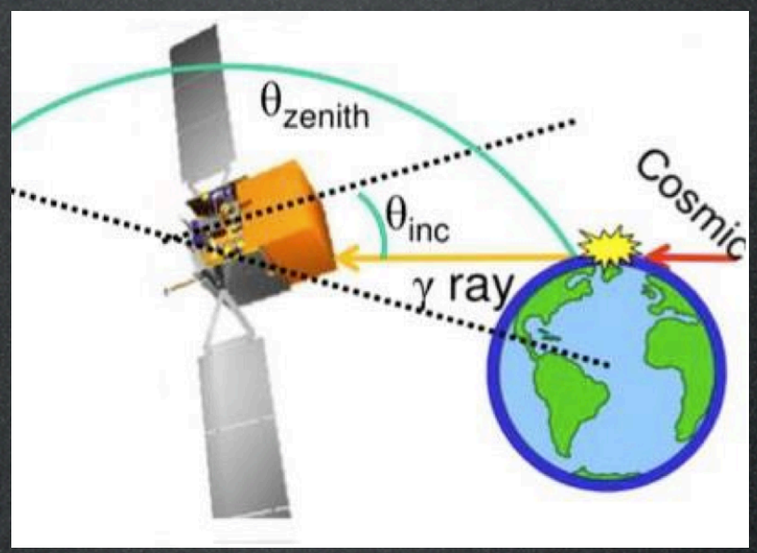
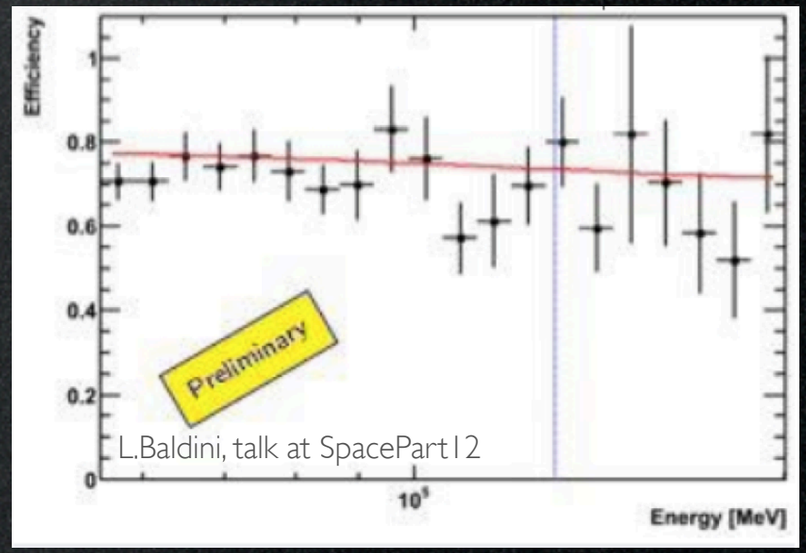
The Fermi coll's cold shower. An instrumental effect?







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:

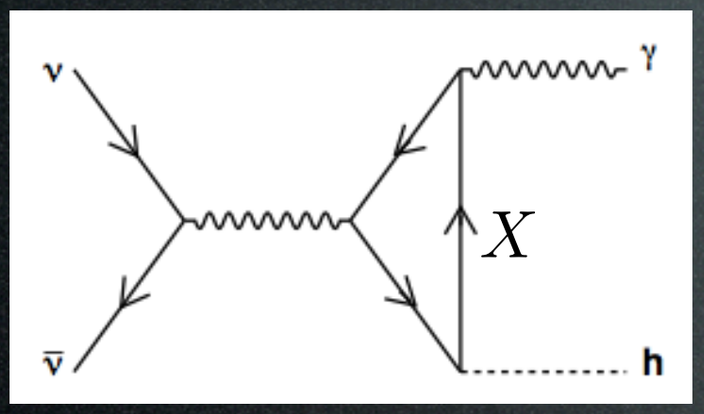
Challenges

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

Challenges

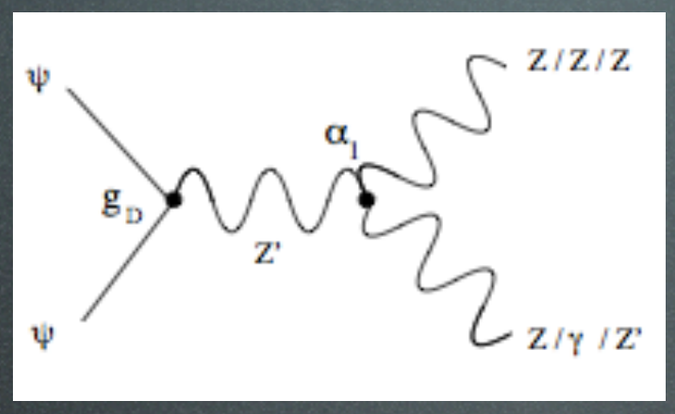
DM is <u>neutral</u>: need '**something**' to couple to γ

a loop



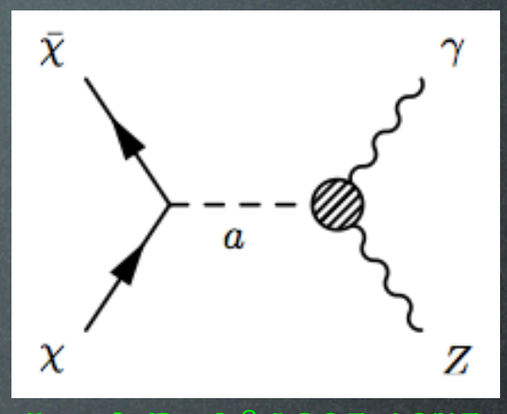
'Higgs in space!' 0912.0004
Kyae, Park 1205.4151
Cline 1205.2688

Chern-Simons



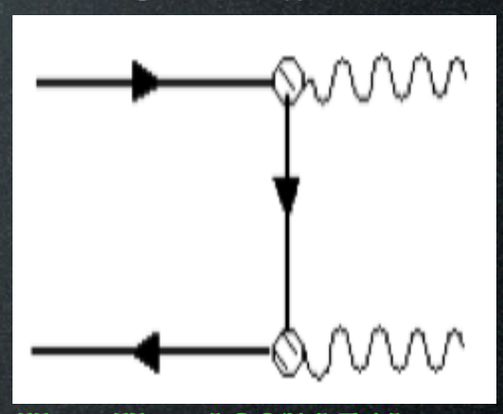
Dudas et al., 1205.1520

axions



Lee & Park[2] 1205.4675

magn dipole



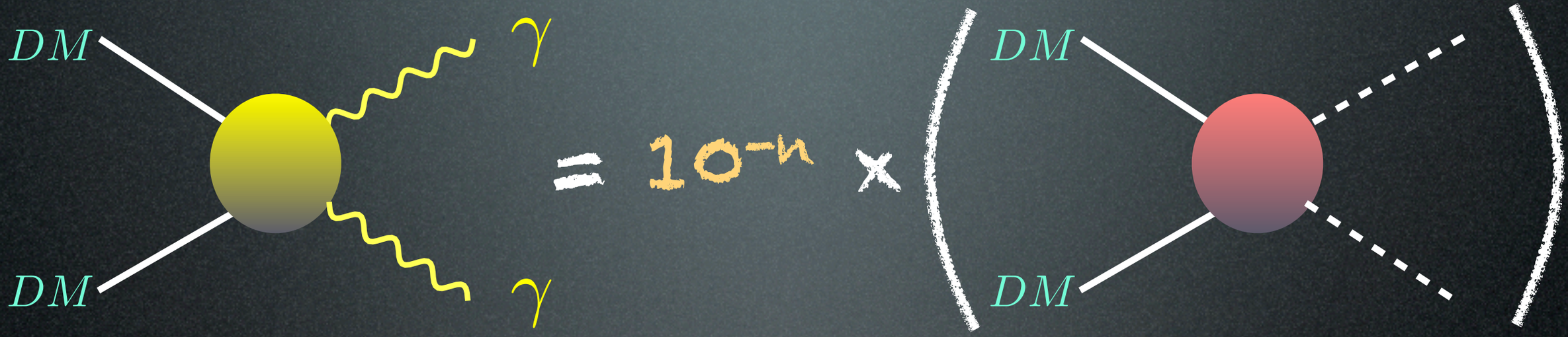
Heo, Kim 1207.1341

...

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

Challenges

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



The '*something*' implies usually a suppression,

Challenges

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

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

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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

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

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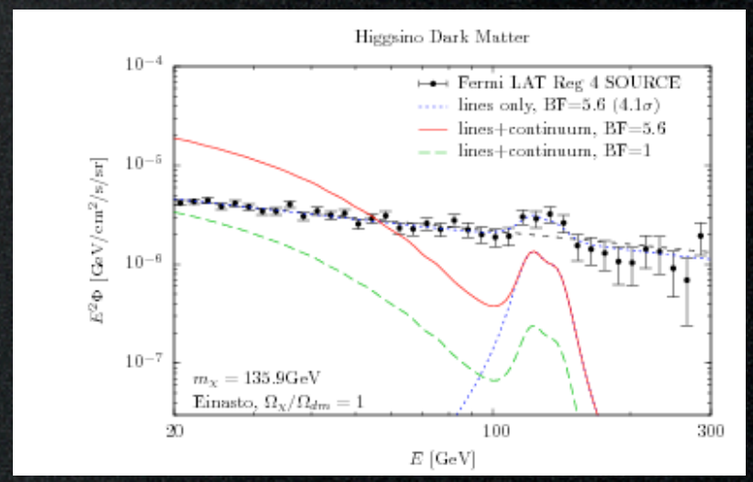

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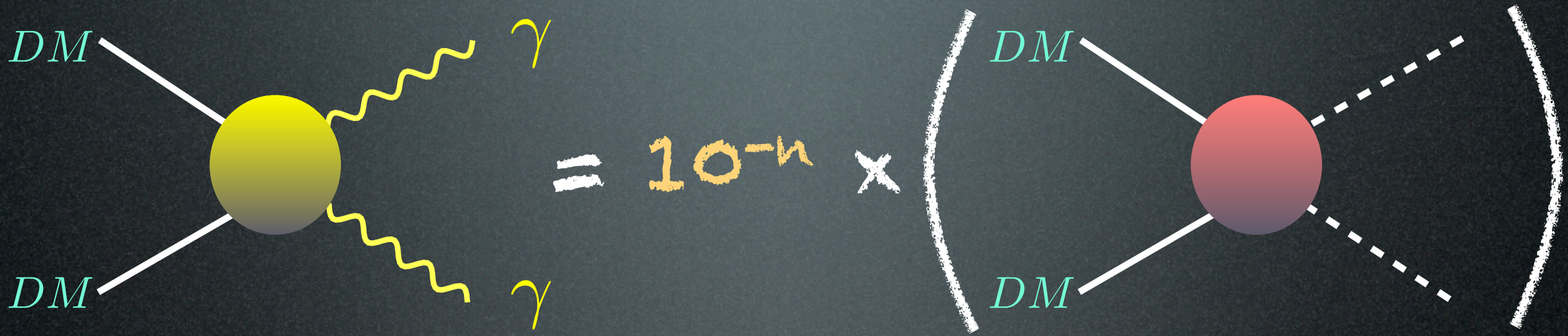

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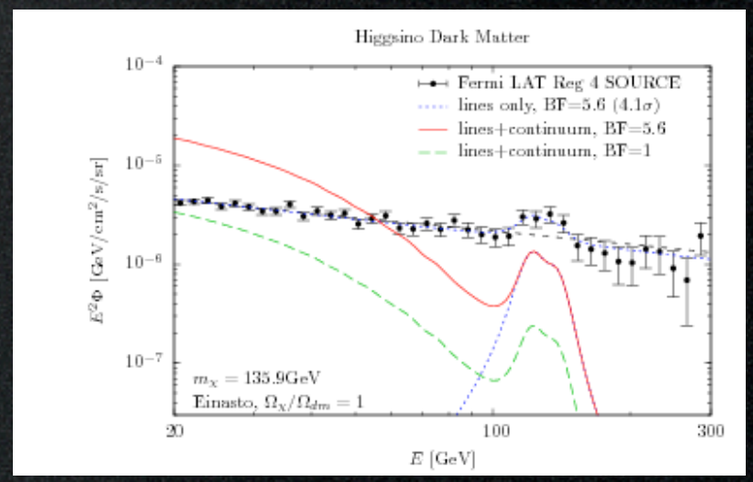


But solutions exist

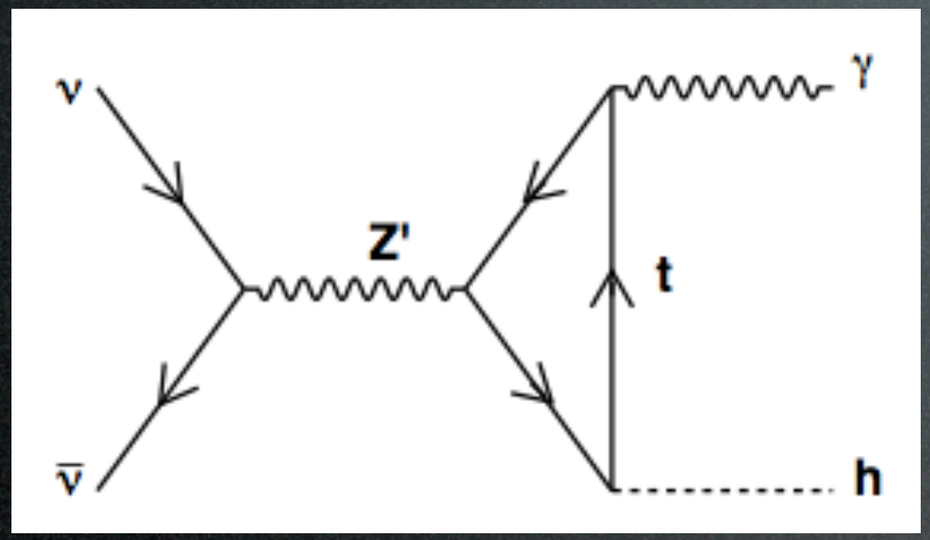
Model building

not exhaustive!

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

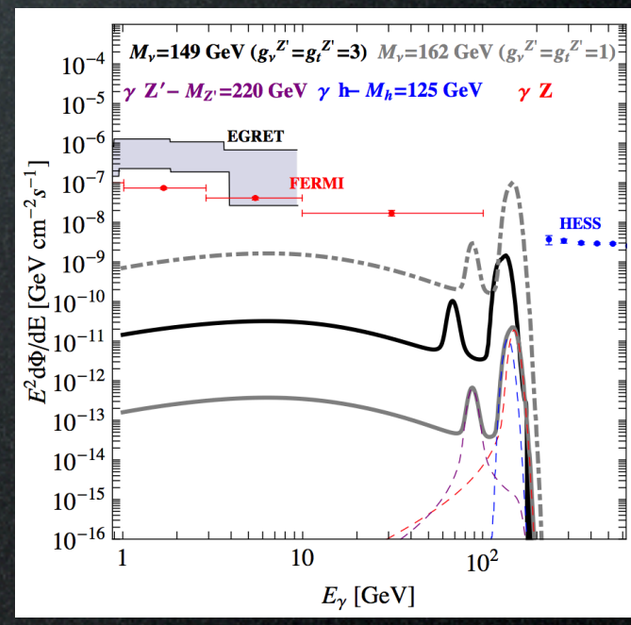
(a) DM charged under U'(1)
(b) Z' is t_R-philic
(c) $m_{DM} \lesssim m_{top}$

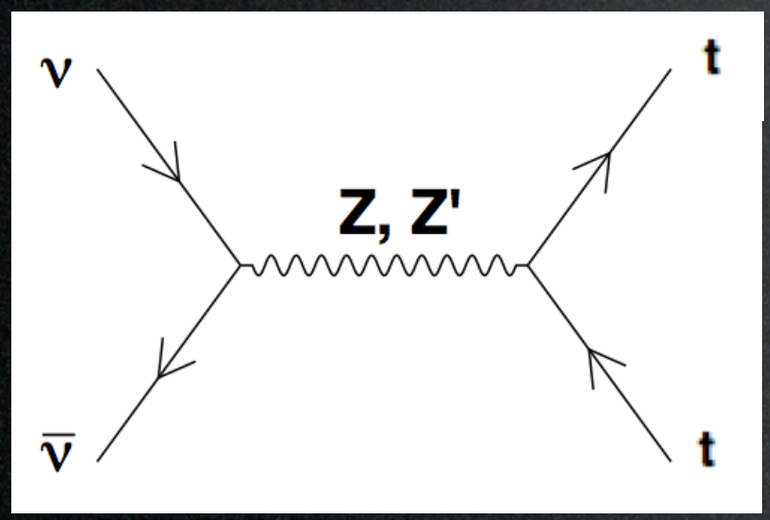
Jackson, Servant, Shaughnessy, Tait, Taoso, 'Higgs in space', 0912.0004



➡ 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)

Model building

not exhaustive!

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

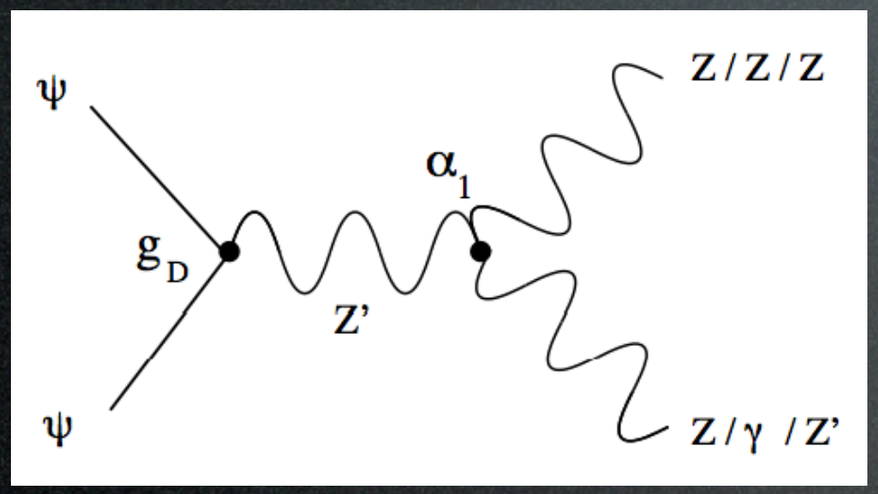
(a) DM charged under U'(1)

(b) anomaly cancellation → tri-boson CS terms

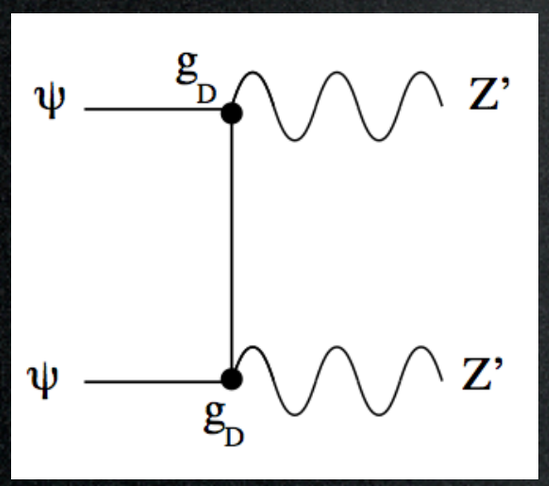
$$\mathcal{L}_{\rm CS} = \alpha\, \varepsilon^{\mu\nu\rho\sigma}\, Z'_\mu Z_\nu F^Y_{\rho\sigma}$$

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

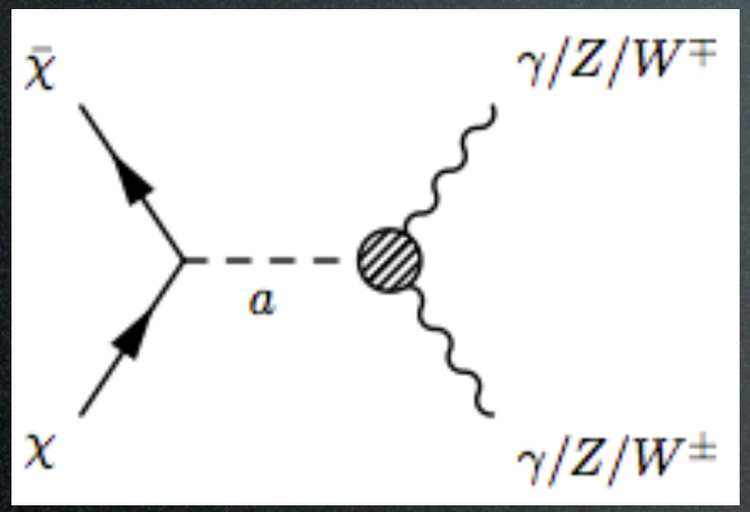
Model building

not exhaustive!

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

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

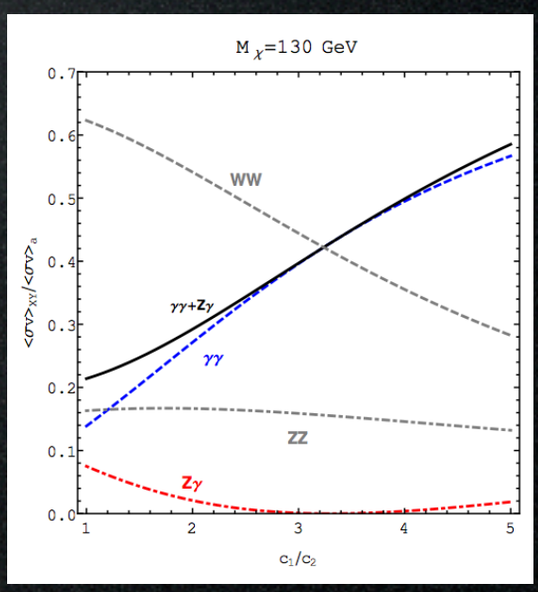
Lee, Park[2], 1205.4675

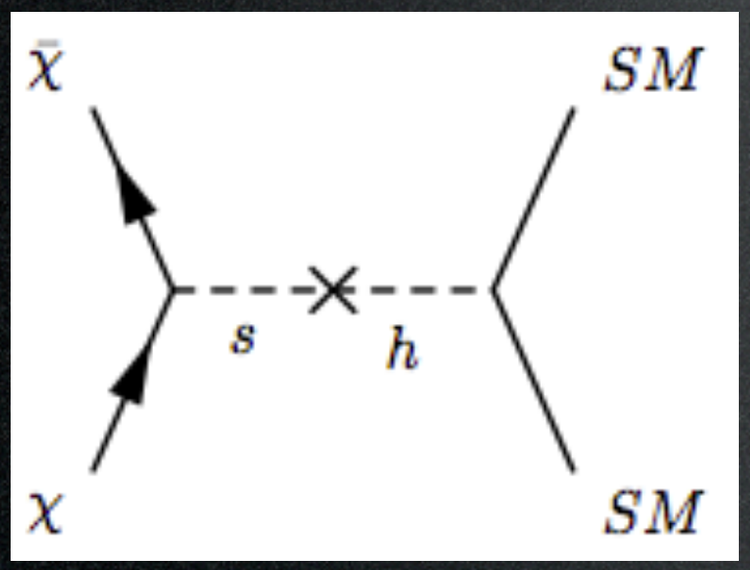


➡ line (b)

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!

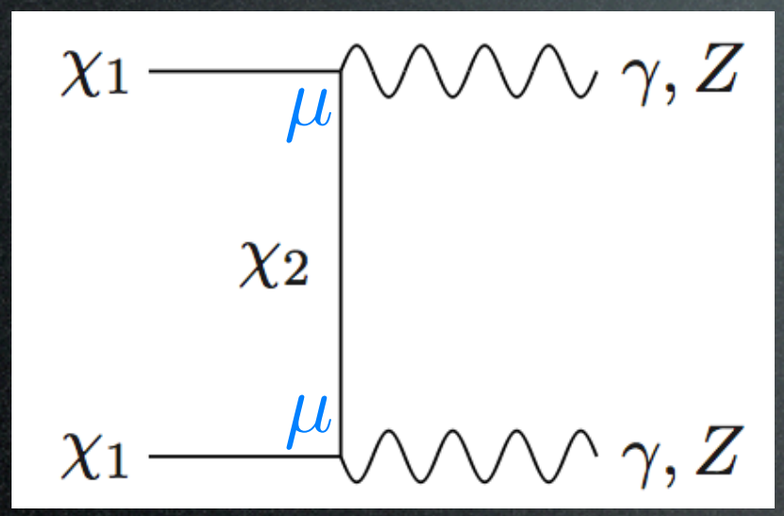
Ex. 4: 'magnetic moments and coannihilations'

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

(a) DM has a magnetic moment

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

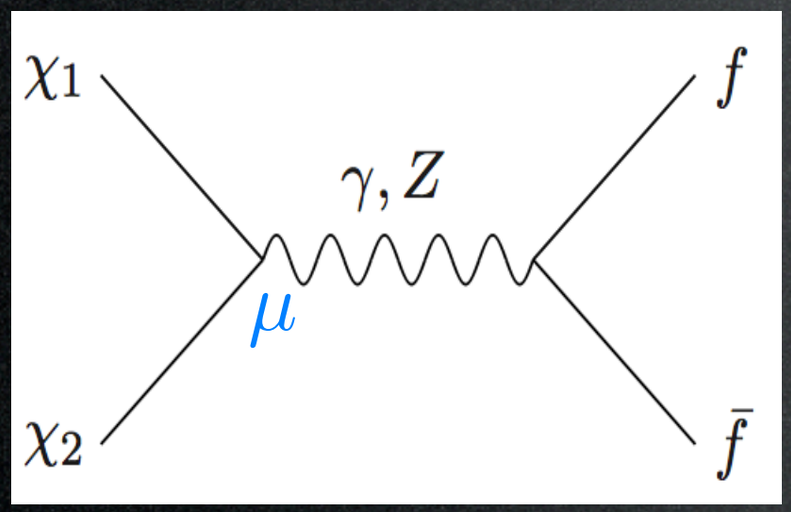
(b) DM sits in a multiplet with ~10 GeV splitting



➡ line (a)

with large rate
if μ is large

➡ Continuum? Under control (it's same order as $\gamma\gamma$)



➡ 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)

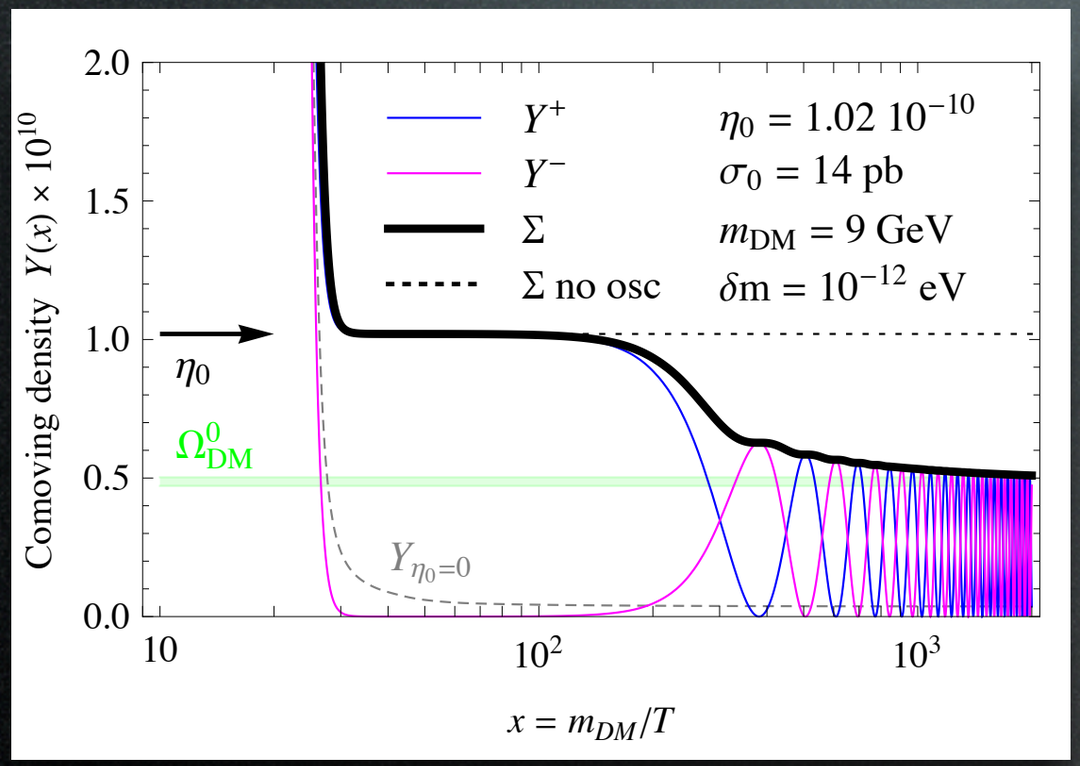
Model building

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)

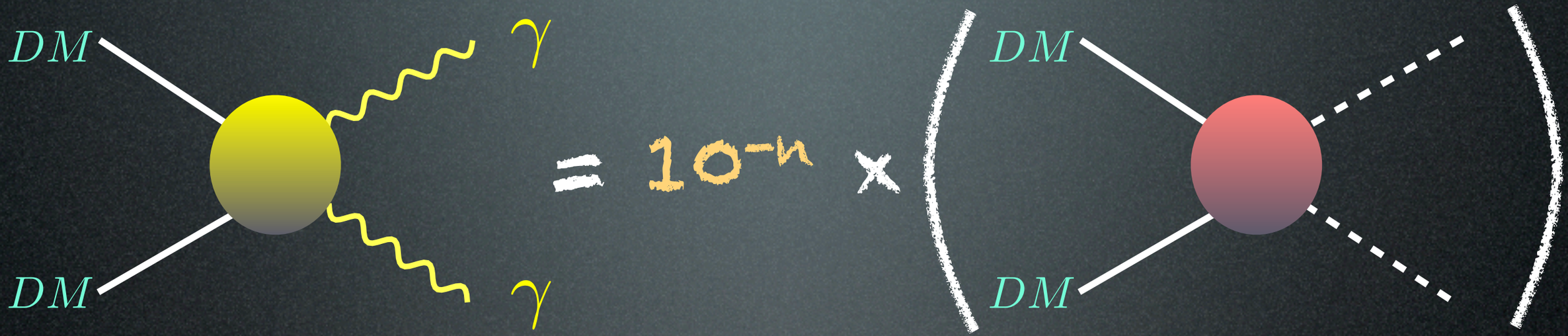
is produced via the asymmetry
is decoupled from the annihilation

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
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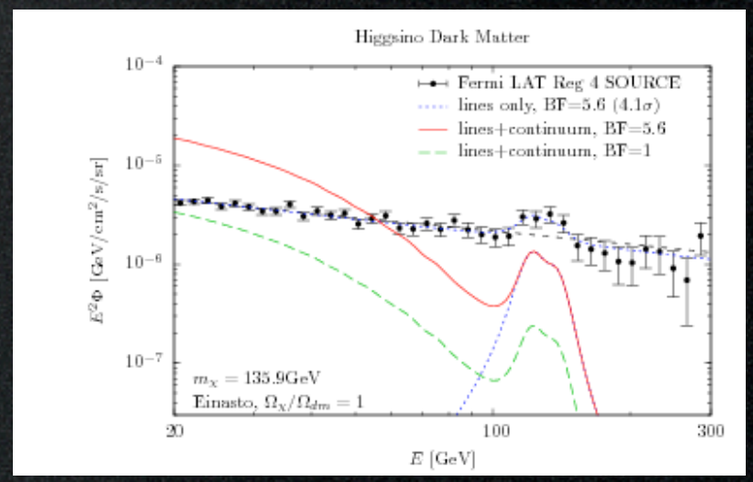


But solutions exist

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'

[skip to next]

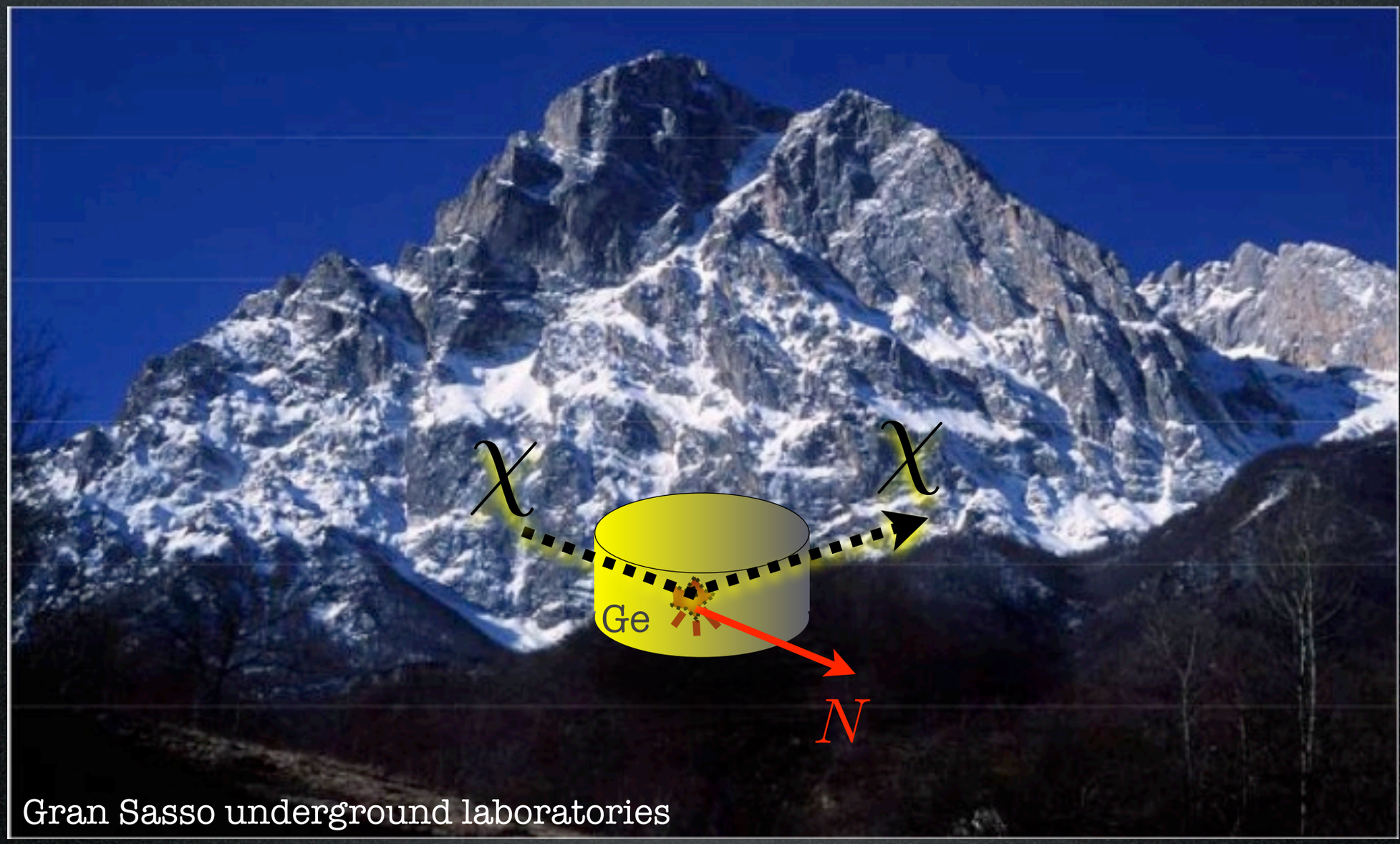
Direct Detection: **basics**

Gran Sasso underground laboratories

Direct Detection: basics

Gran Sasso underground laboratories

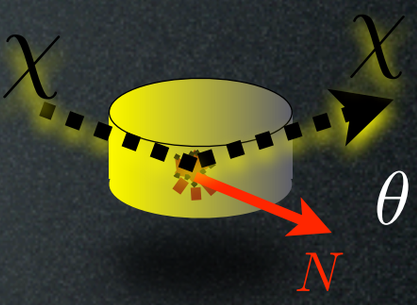
Direct Detection: basics



Gran Sasso underground laboratories

Direct Detection: basics

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



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

recoil energy spectrum

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

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

$\sigma \approx \sigma_n^{\rm SI}\, A^4$ × 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

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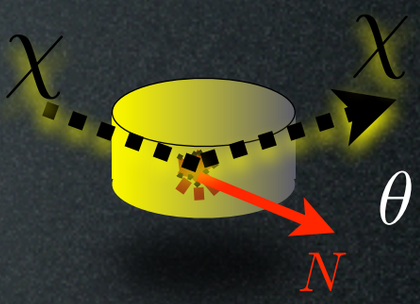

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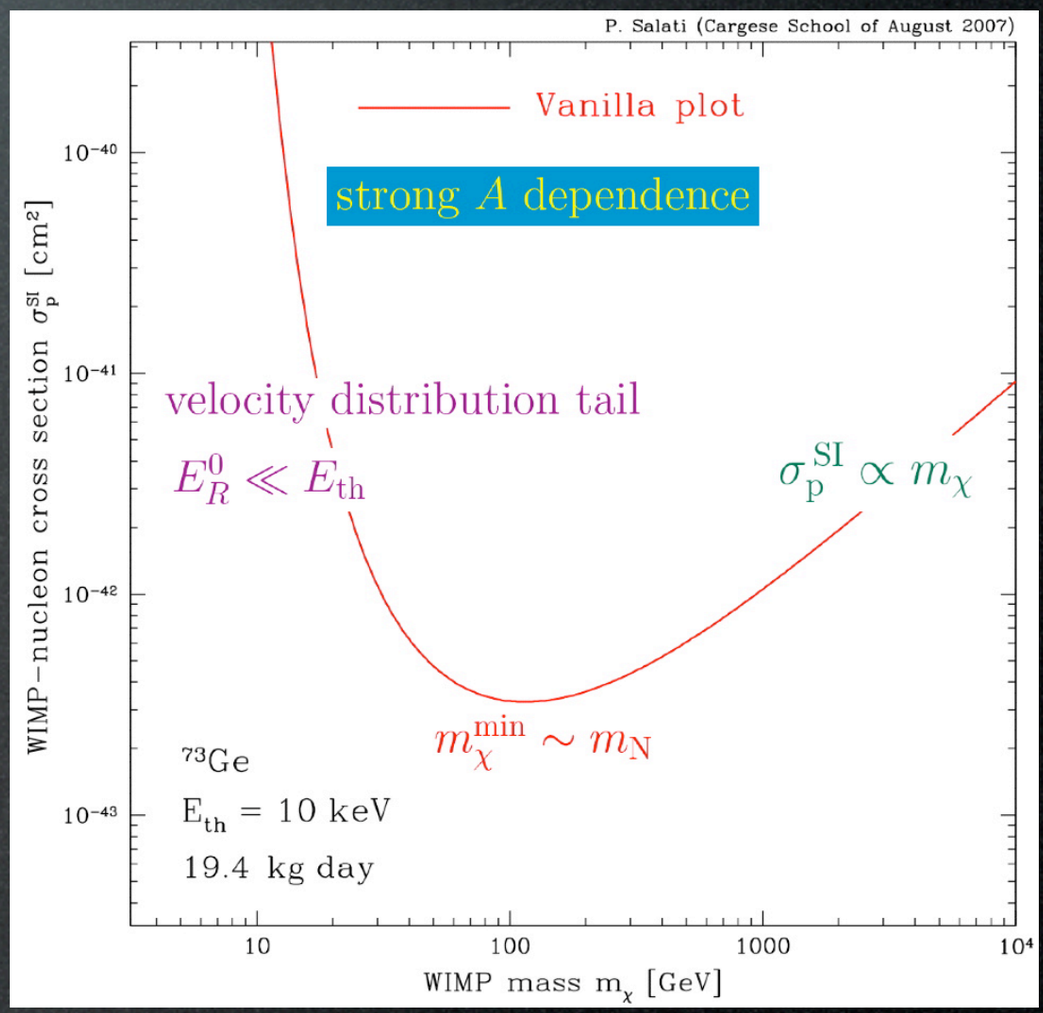

P.Salati, proceedings of Cargèse 2007

Direct Detection: basics

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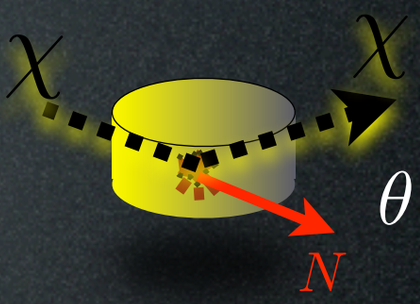

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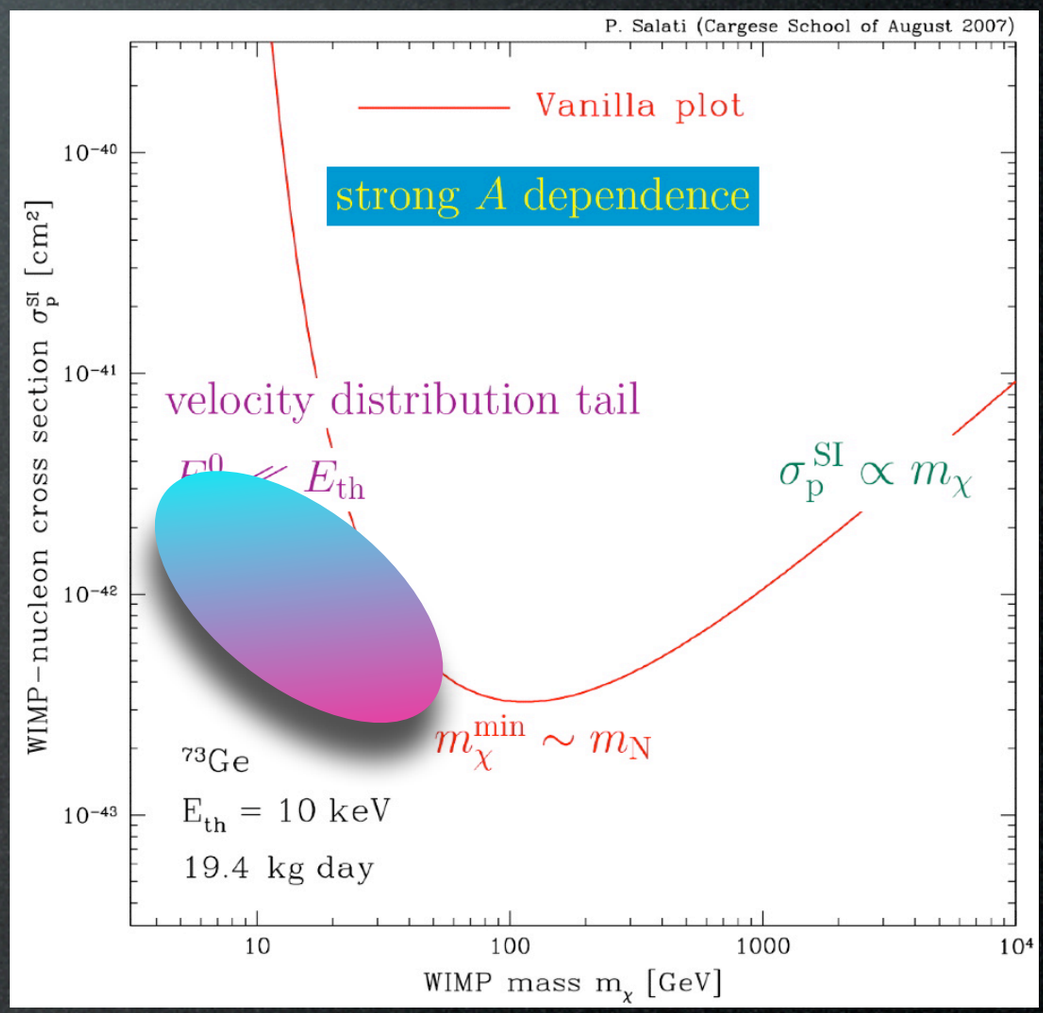
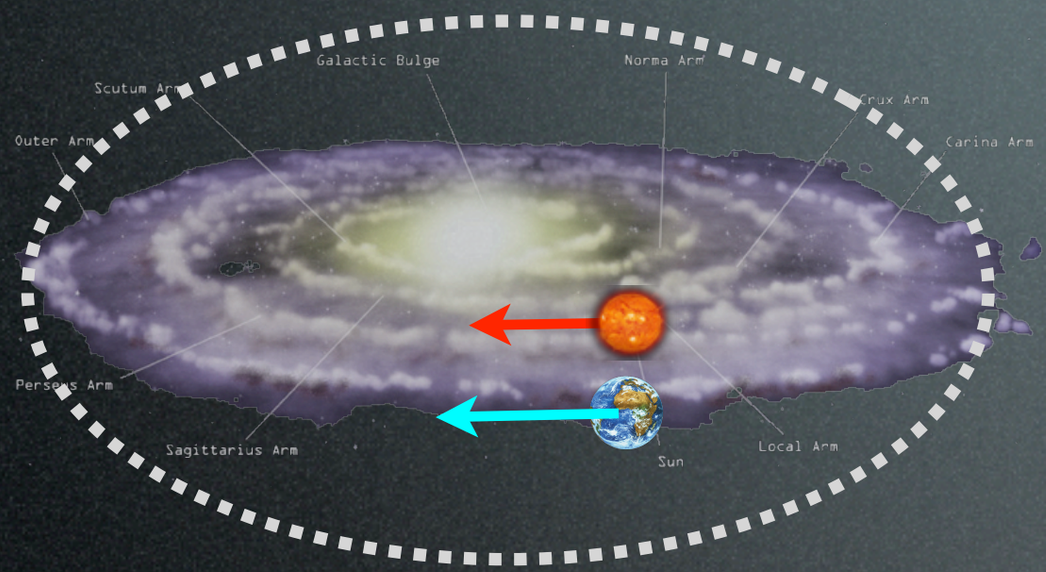


P.Salati, proceedings of Cargèse 2007

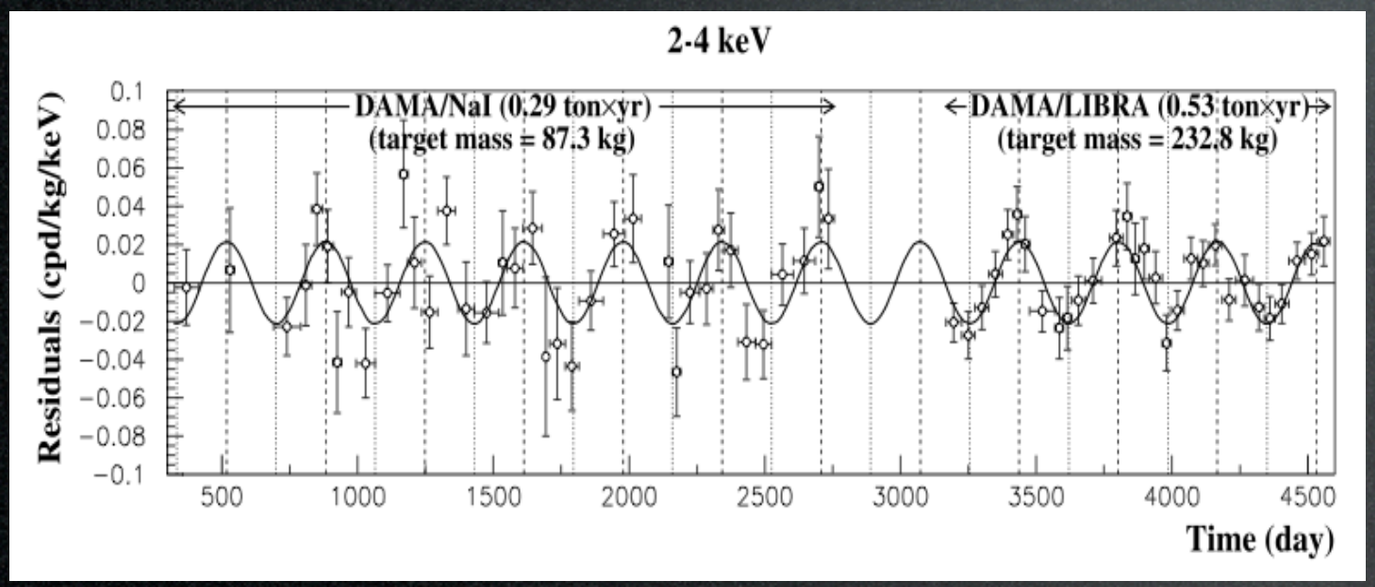
Direct Detection: hints

DAMA/Libra

NaI(Tl)



Annual modulation seen (8σ):

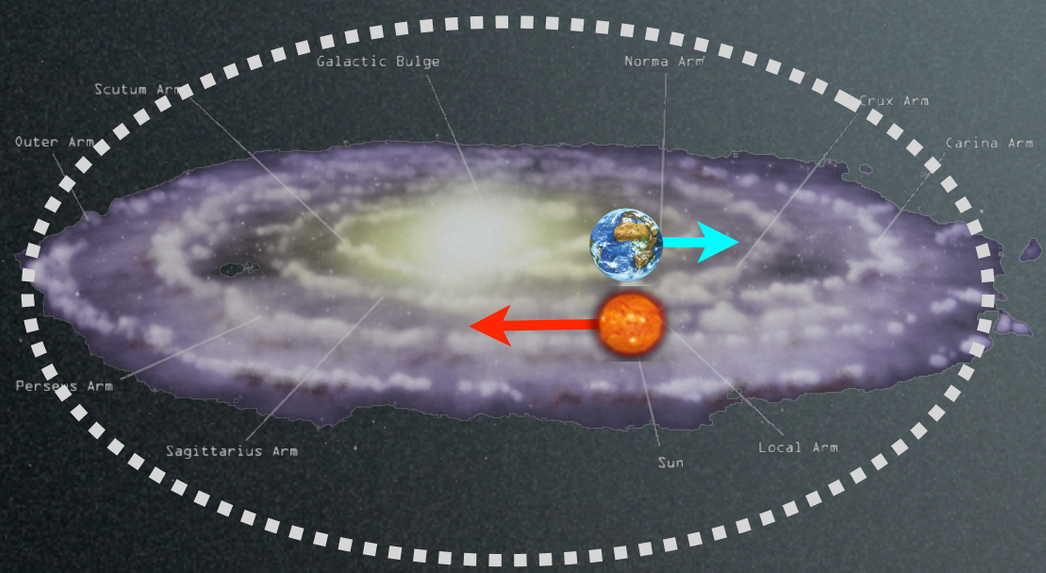


DAMA Coll., 0804.2741, 2008

Direct Detection: hints

DAMA/Libra

NaI(Tl)



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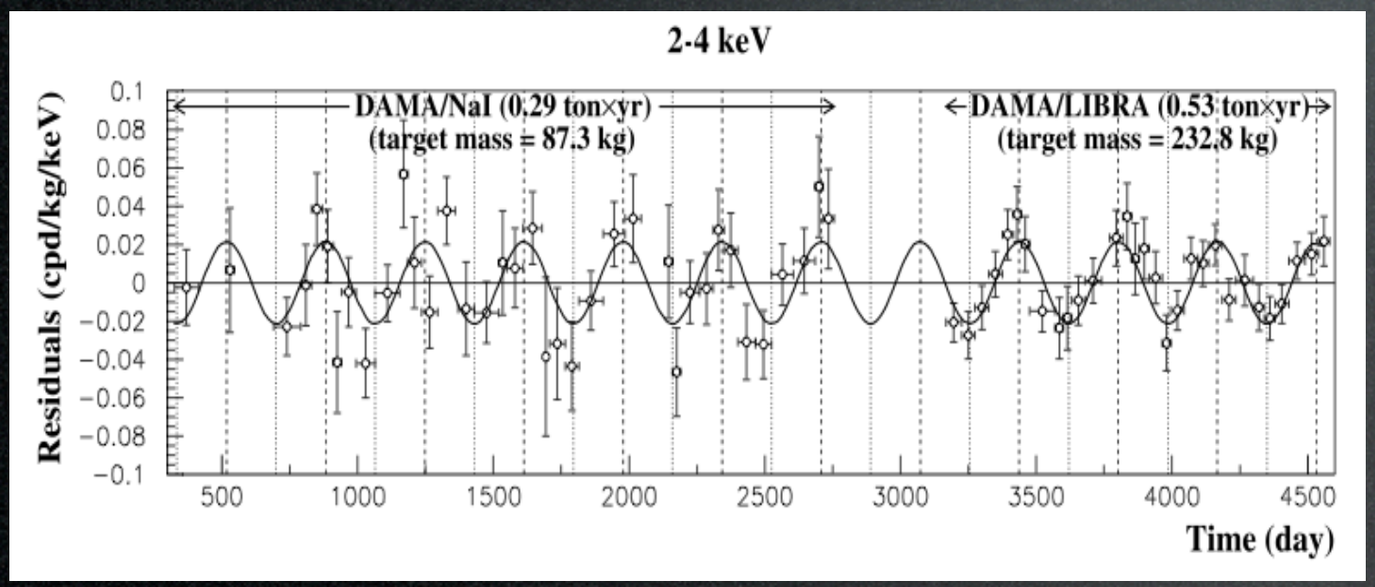
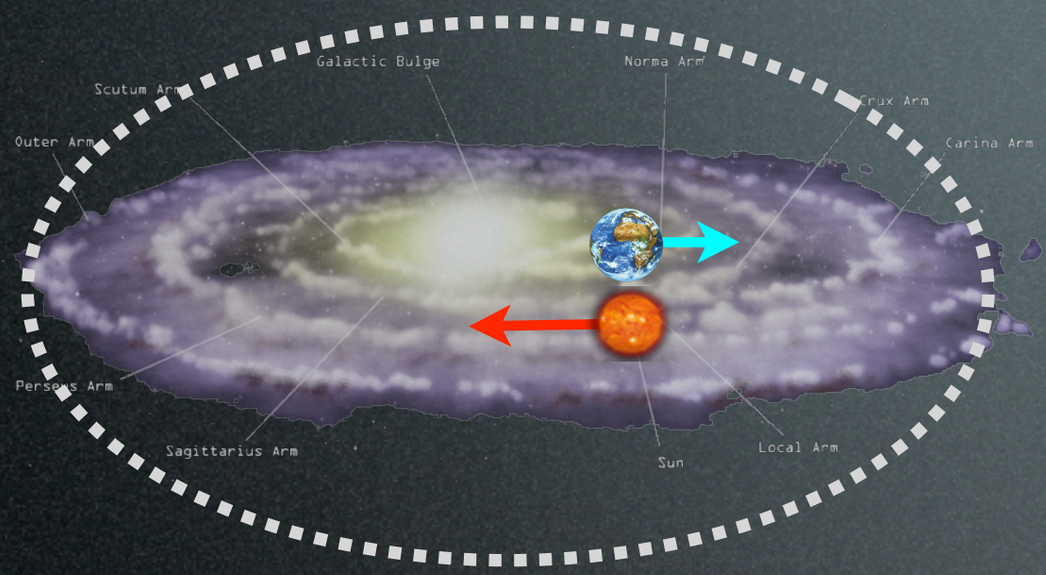


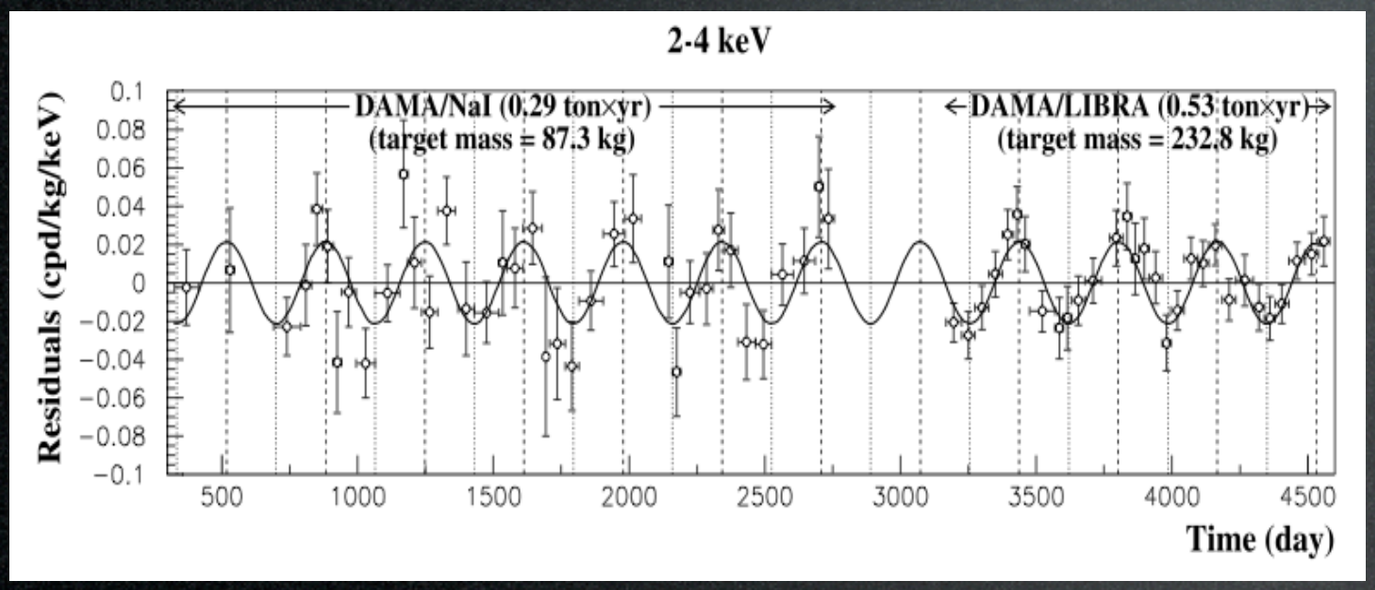
DAMA Coll., 0804.2741, 2008

Direct Detection: hints

DAMA/Libra



Annual modulation seen (8σ):

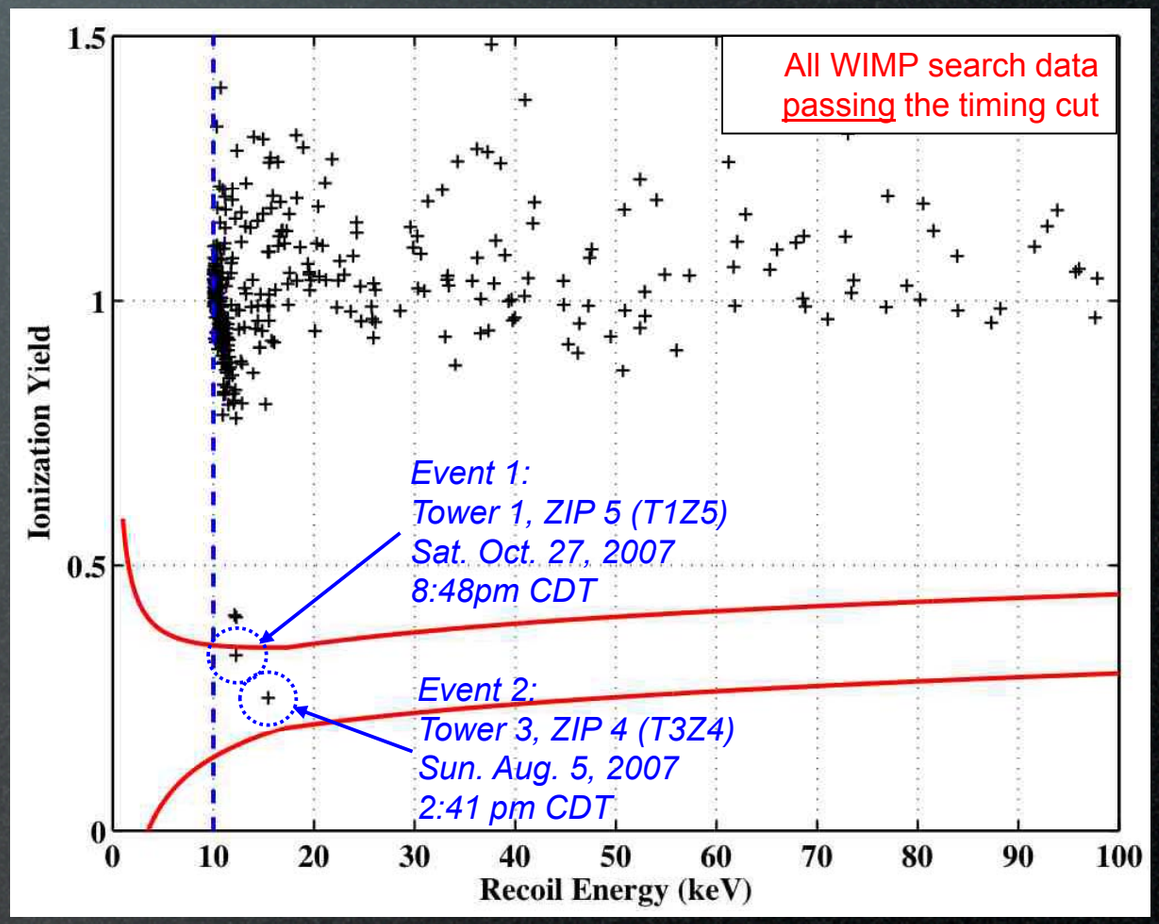


DAMA Coll., 0804.2741, 2008

CDMS

Ge

2 events seen,
with 0.6 exp'd background

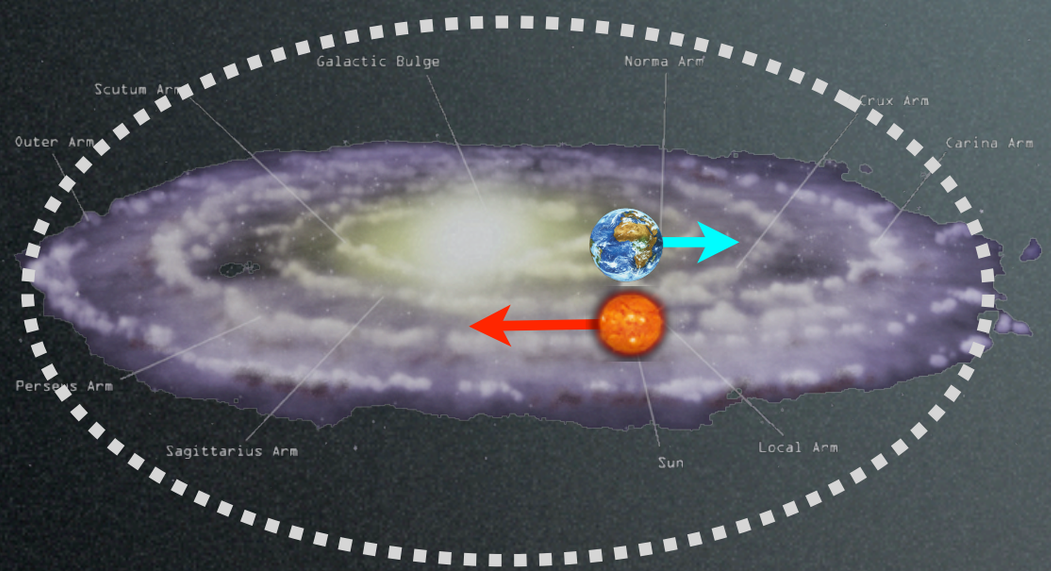


CDMS coll., Science 327 (2010), 0912.3592

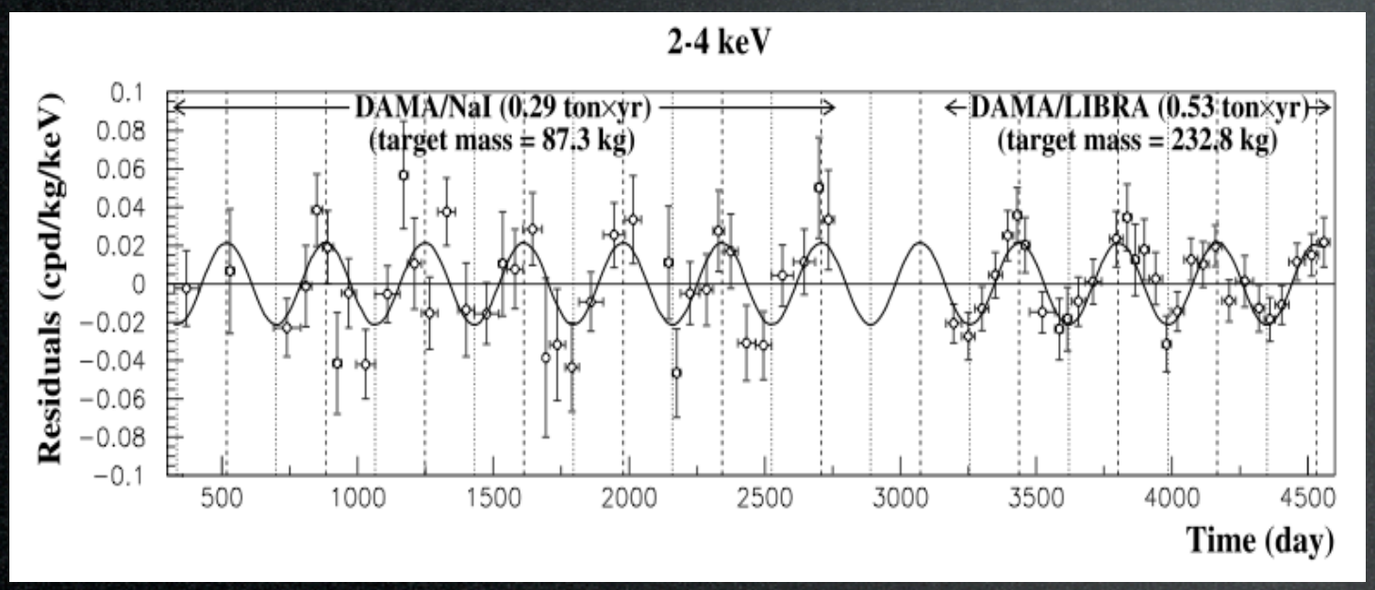
cited 500 times

Direct Detection: hints

DAMA/Libra



Annual modulation seen (8σ):



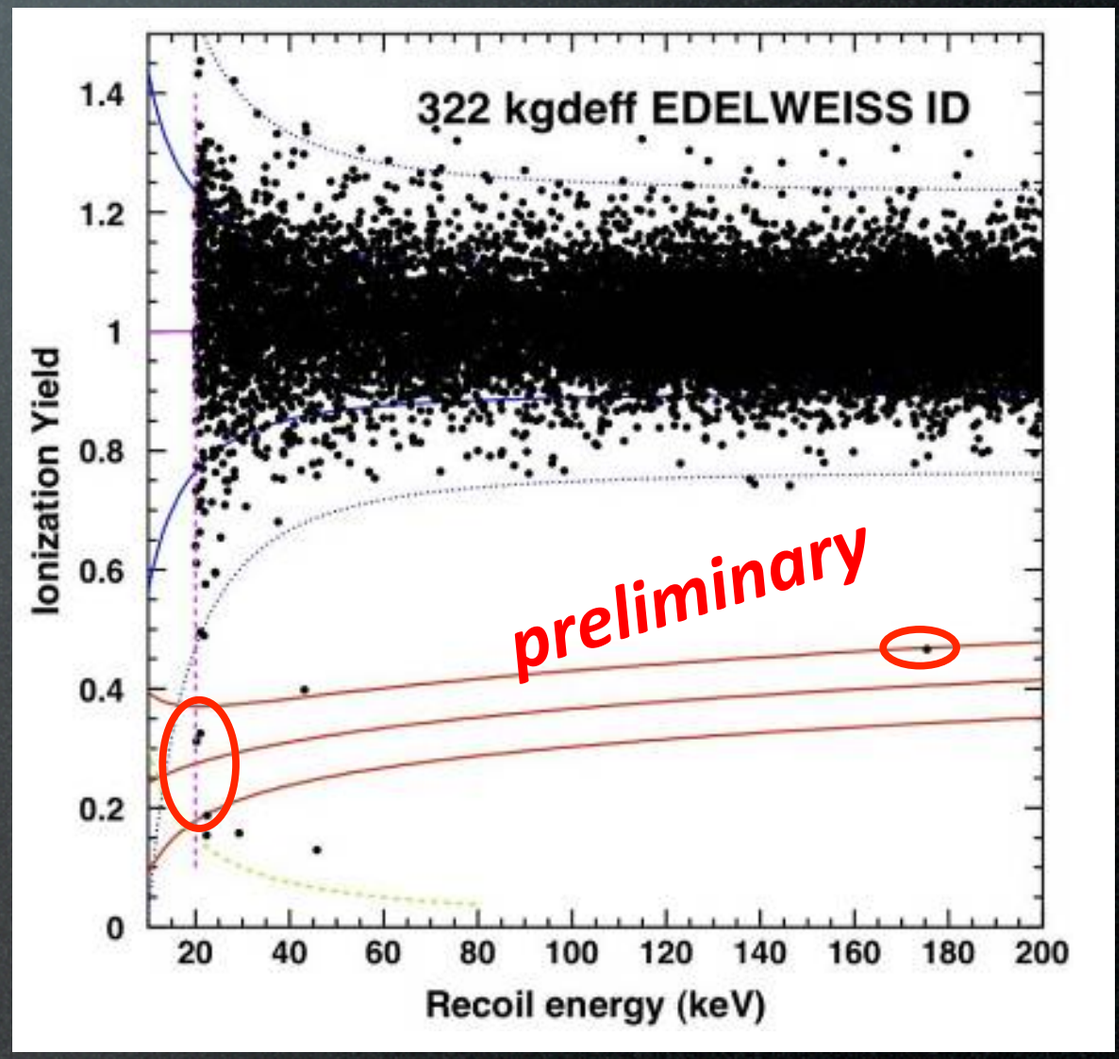
DAMA Coll., 0804.2741, 2008

Edelweiss

Ge

3 events seen

'background starts to appear'

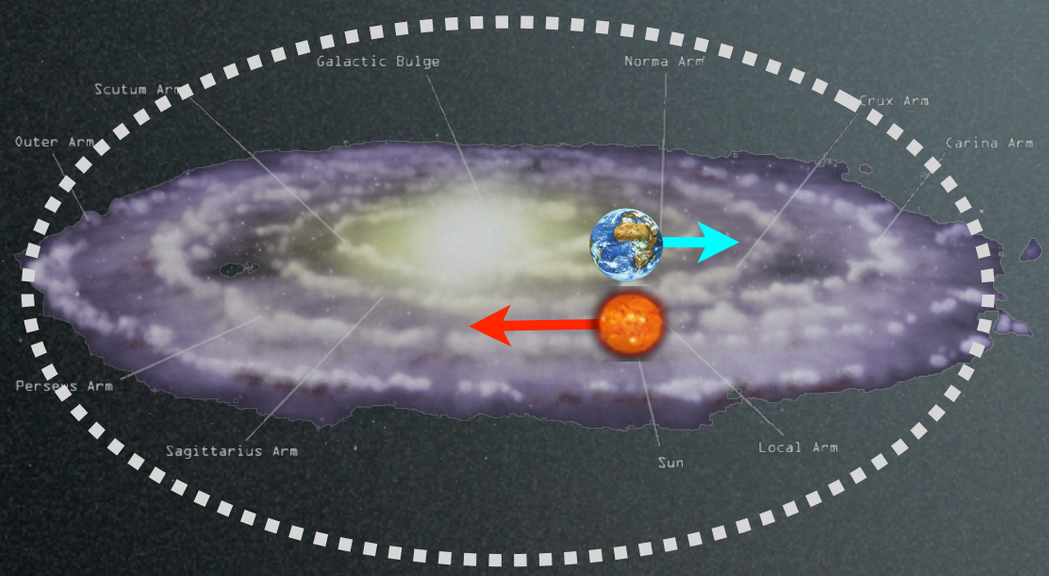


Edelweiss coll, TeVPA 2010
and 1011.2319

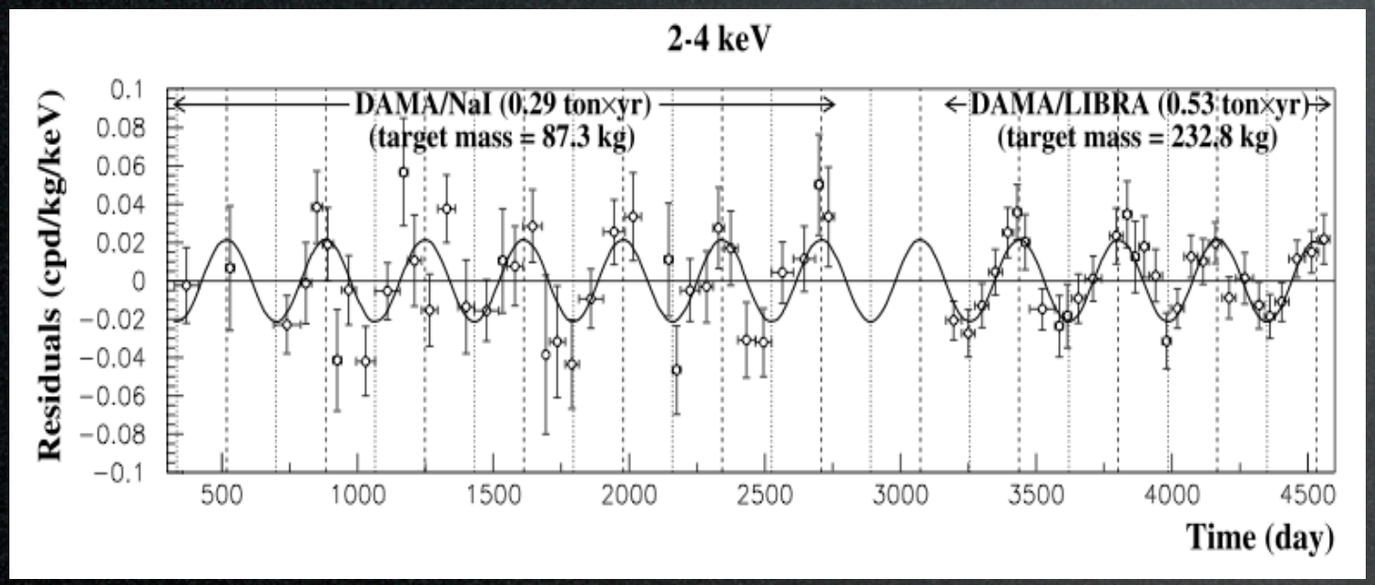
cited 500/10 = 50 times

Direct Detection: hints

DAMA/Libra



Annual modulation seen (8σ):

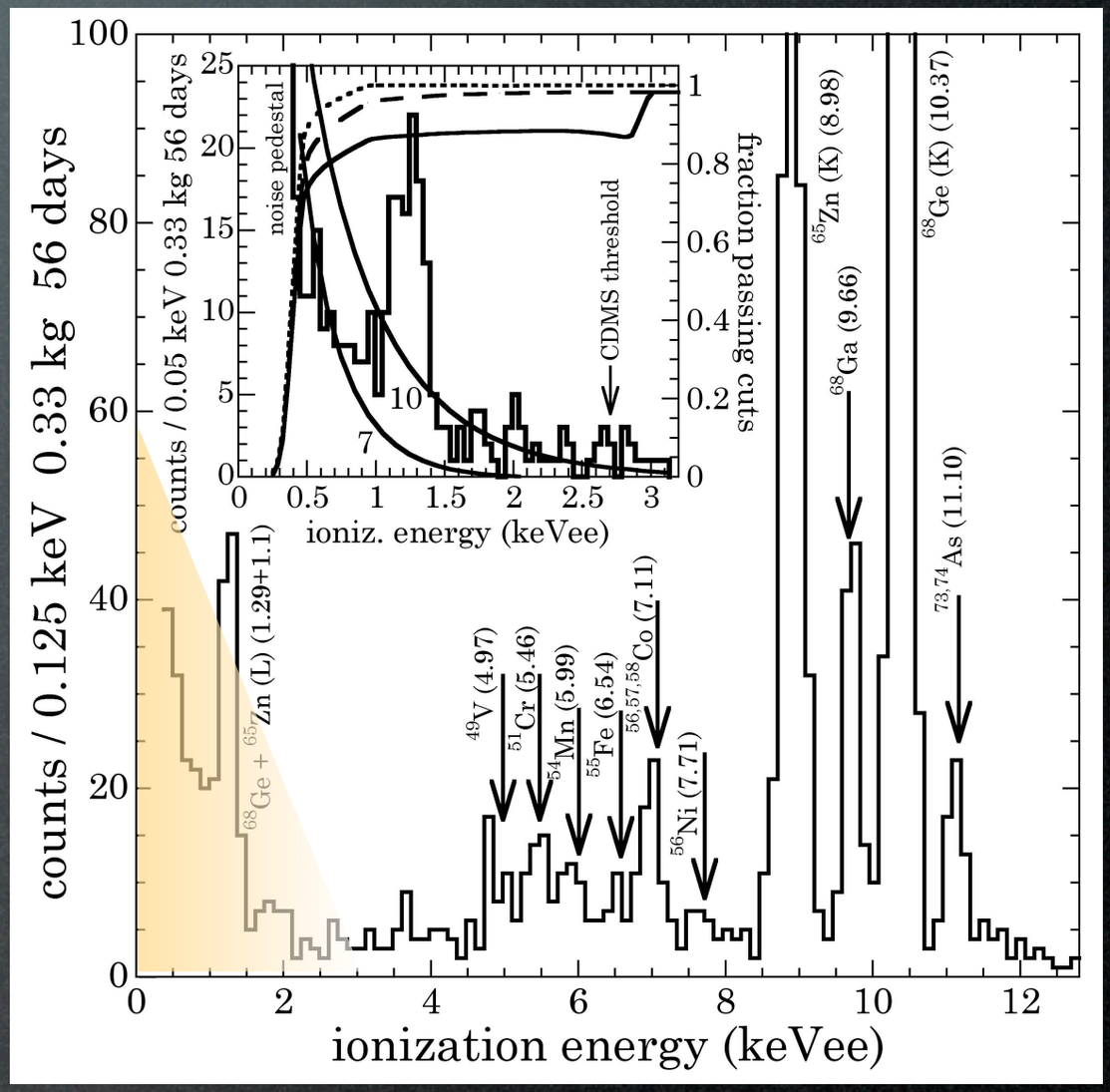


DAMA Coll., 0804.2741, 2008

CoGeNT

Ge

'irreducible excess of bulk events below 3 KeVee'

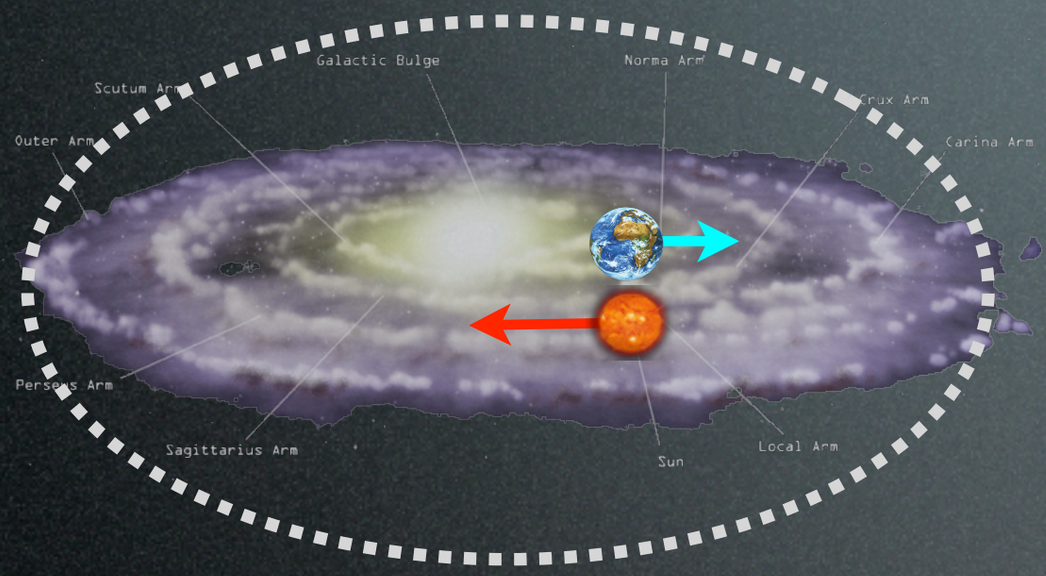


CoGeNT Coll., 1002.4703

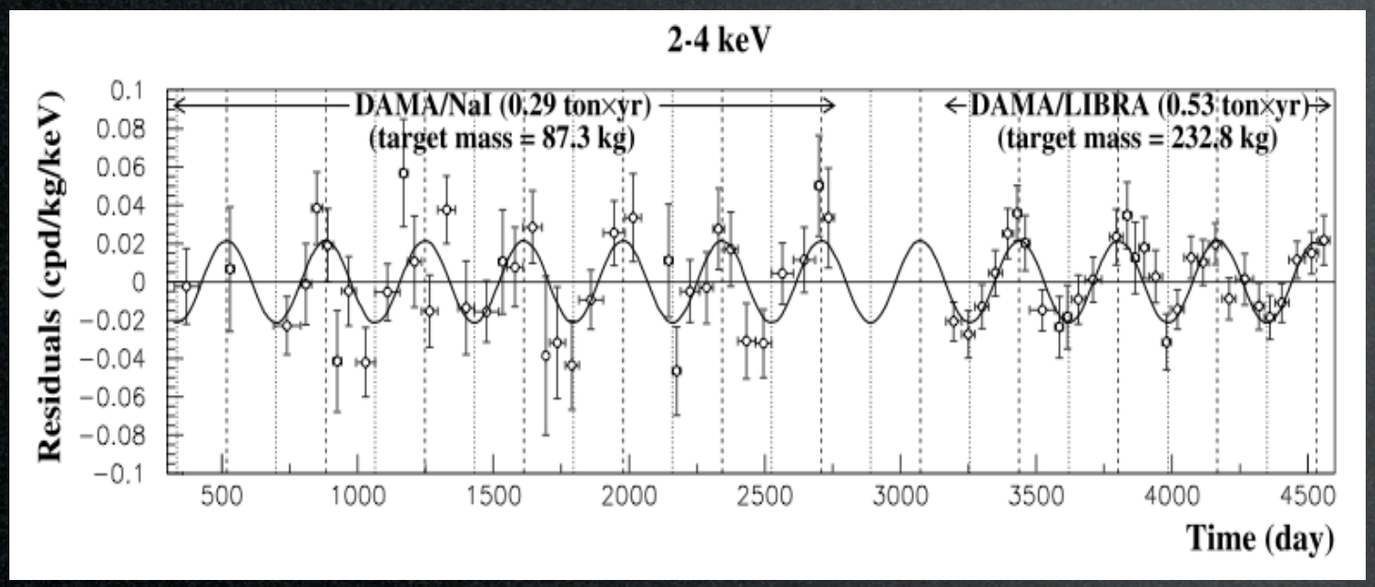
We lack a satisfactorily explanation [...]. It is tempting to consider a cosmological origin [...]. Prudence and past experience prompt us to continue work to exhaust less exotic possibilities.

Direct Detection: hints

DAMA/Libra



Annual modulation seen (8σ):

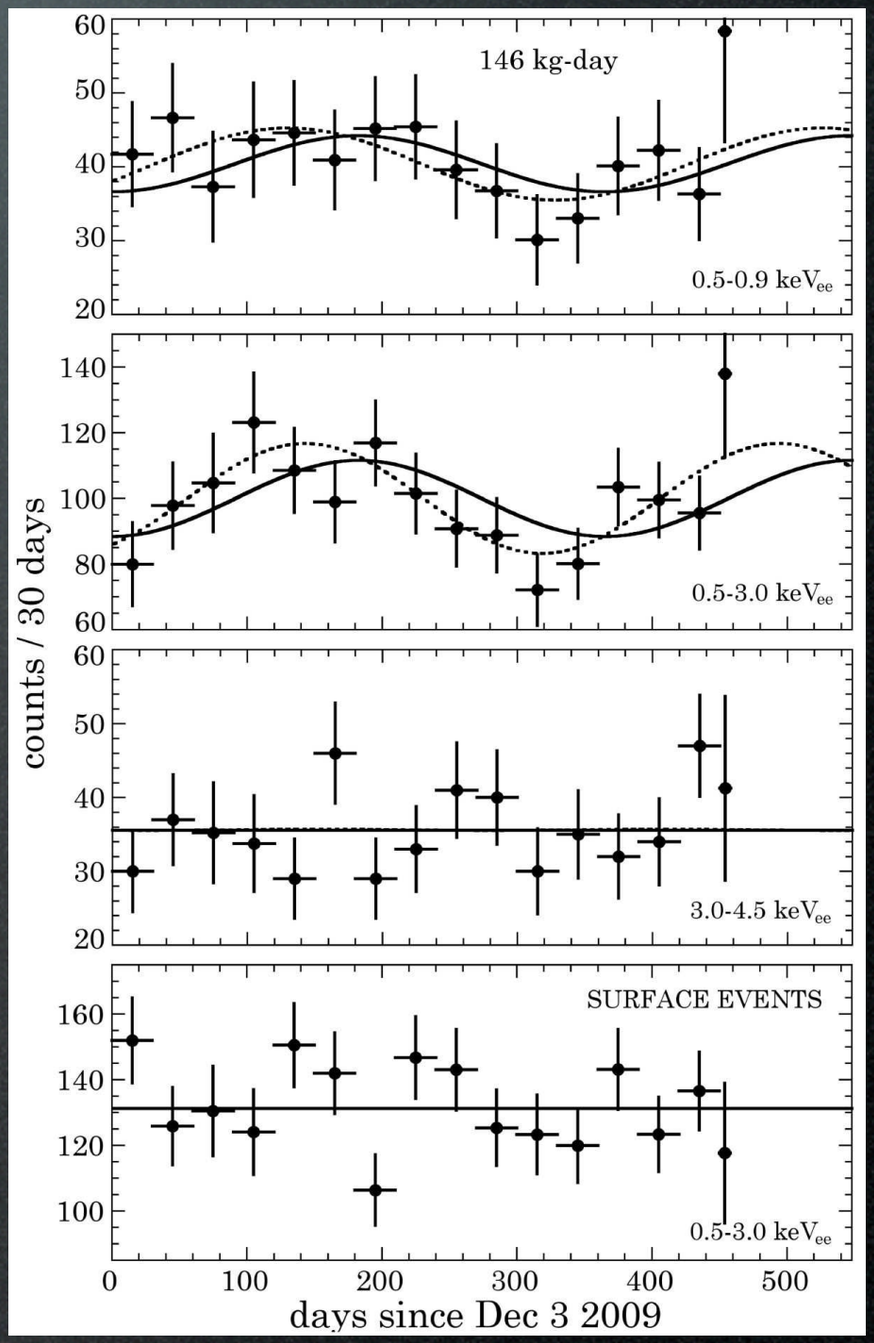


DAMA Coll., 0804.2741, 2008

CoGeNT

Ge

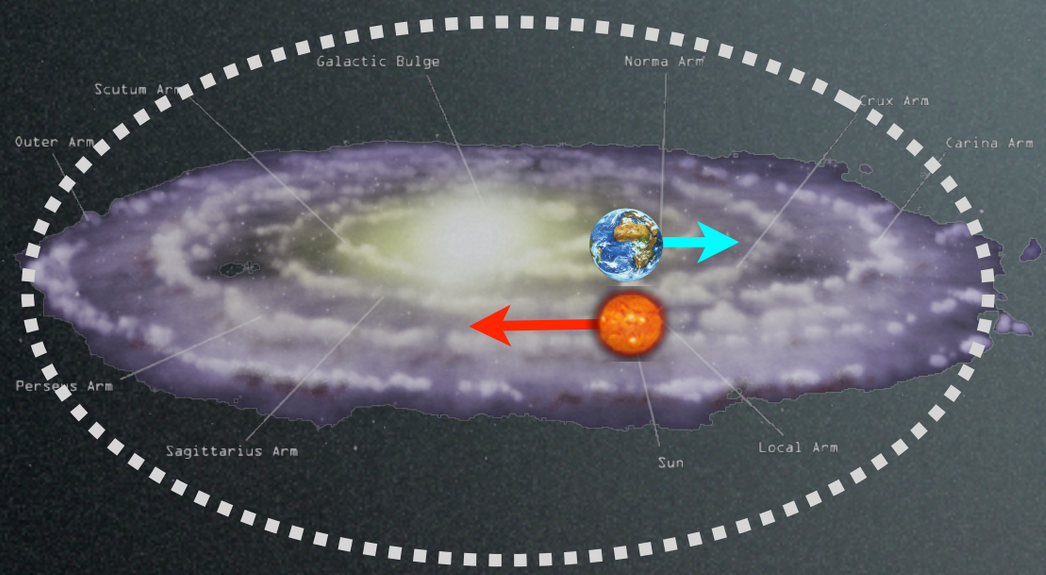
'irreducible excess of bulk events below 3 KeVee'



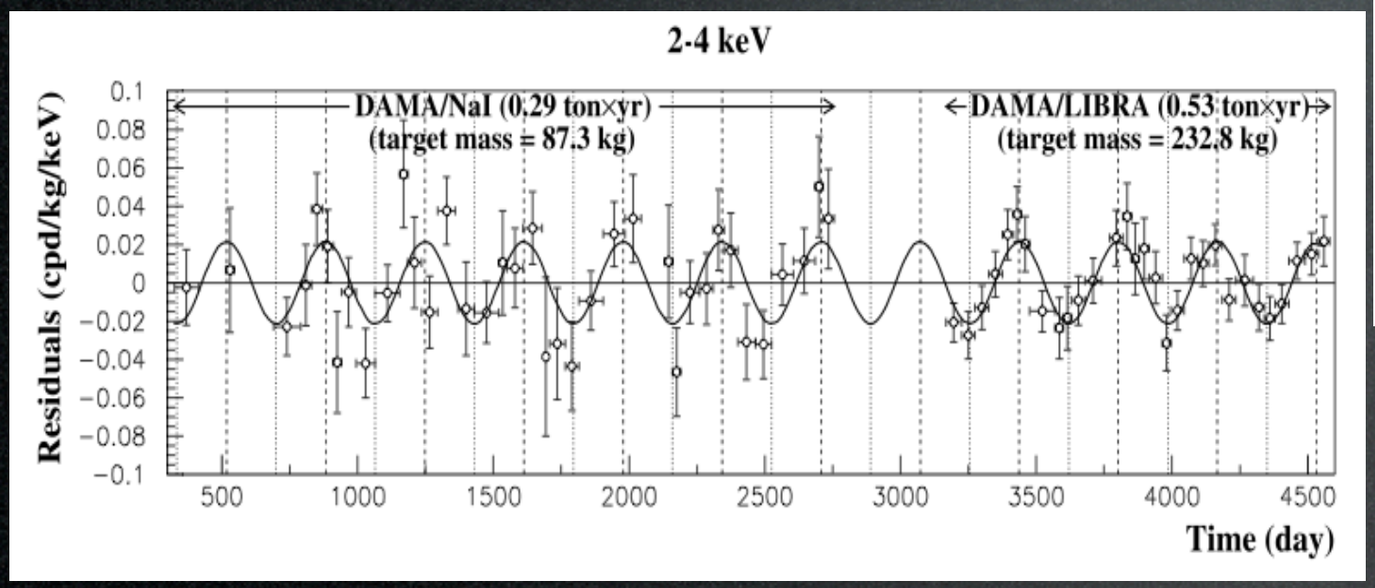
CoGeNT coll., 1106.0650

Direct Detection: hints

DAMA/Libra



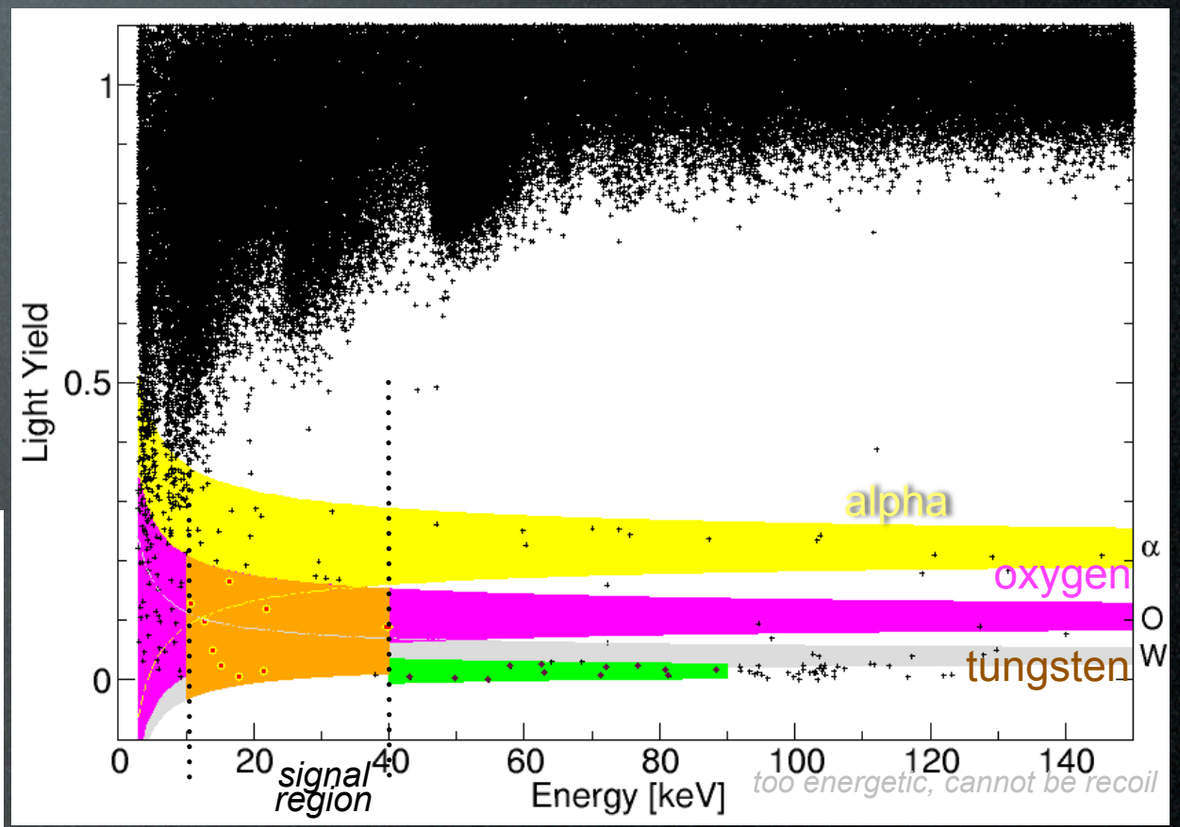
Annual modulation seen (8σ):



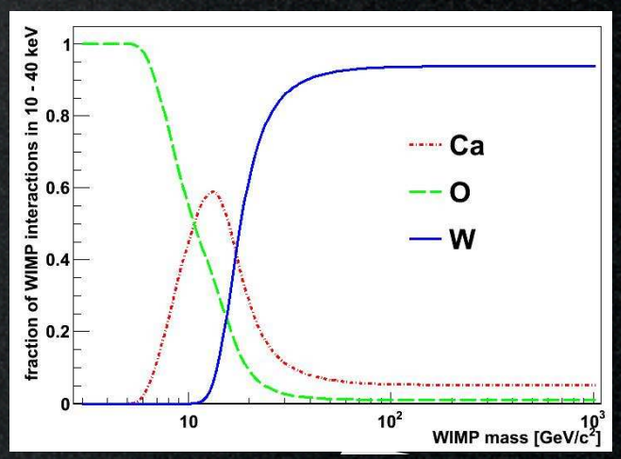
DAMA Coll., 0804.2741, 2008

CRESST-II $CaWO_4$

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



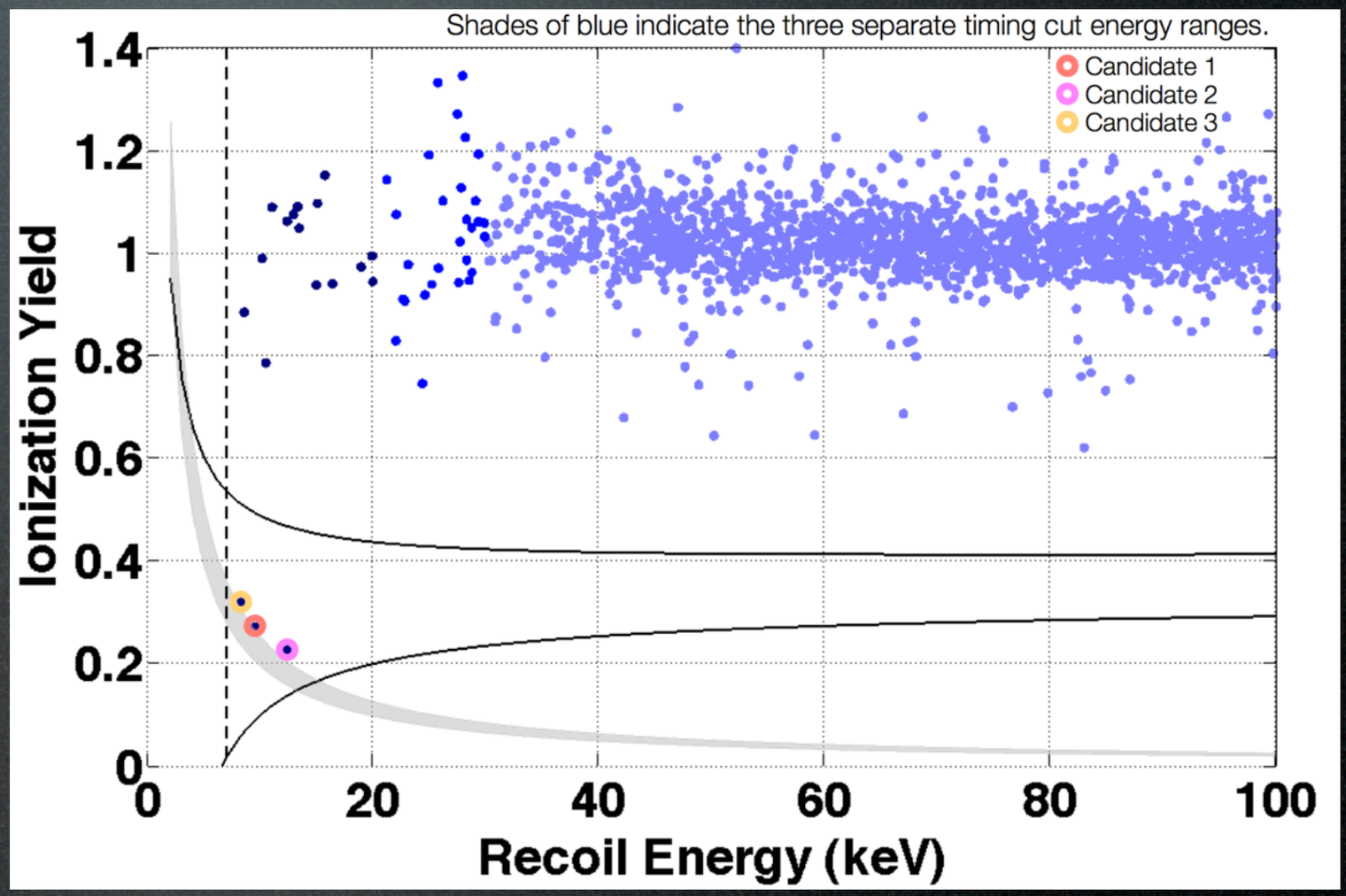
CRESST-II Coll., 1109.0702



PS: CDMS-Si 2013

CDMS Si

3 events seen on Si,
with 0.41 exp'd background
(a bit less than 3σ)



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

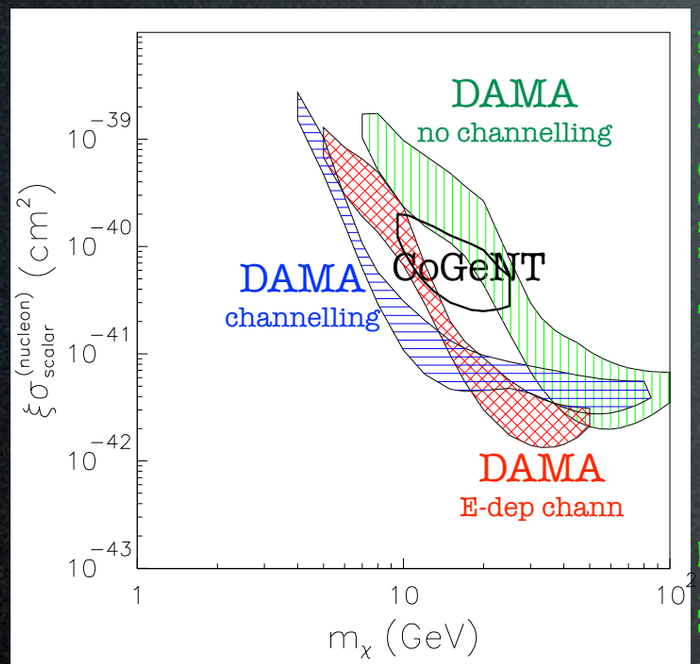
Hooper+Kelso, 1106.1066

Space available
Call 911-drk-mttr now!

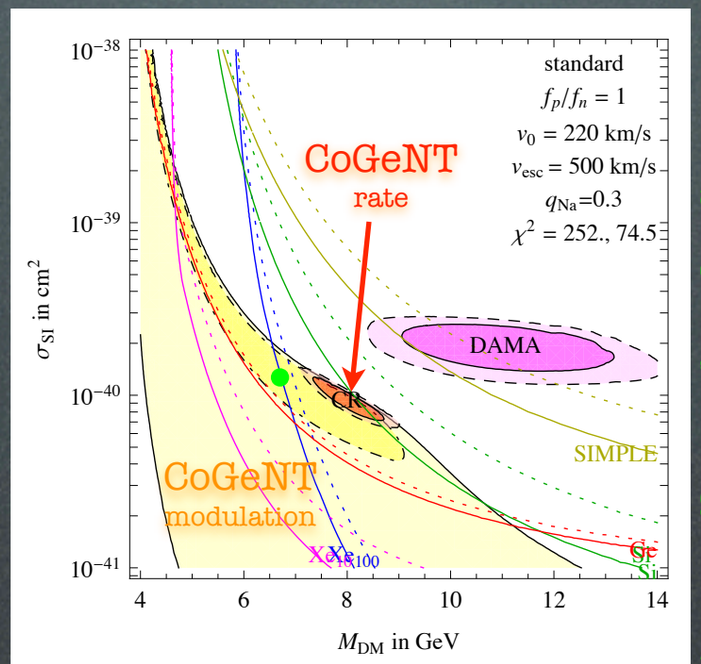
Direct Detection: hints

Plotolympics 2011: fits performed by different groups

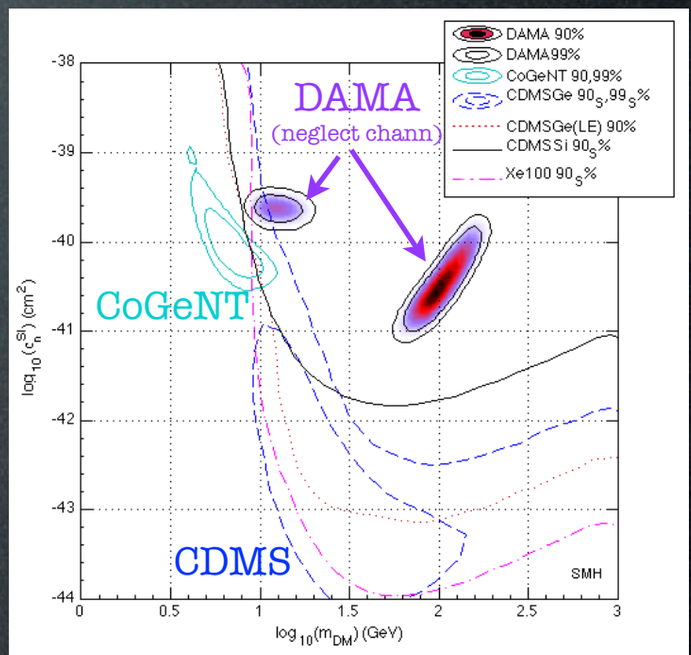
Discipline: Standard Fit: SI, standard halo



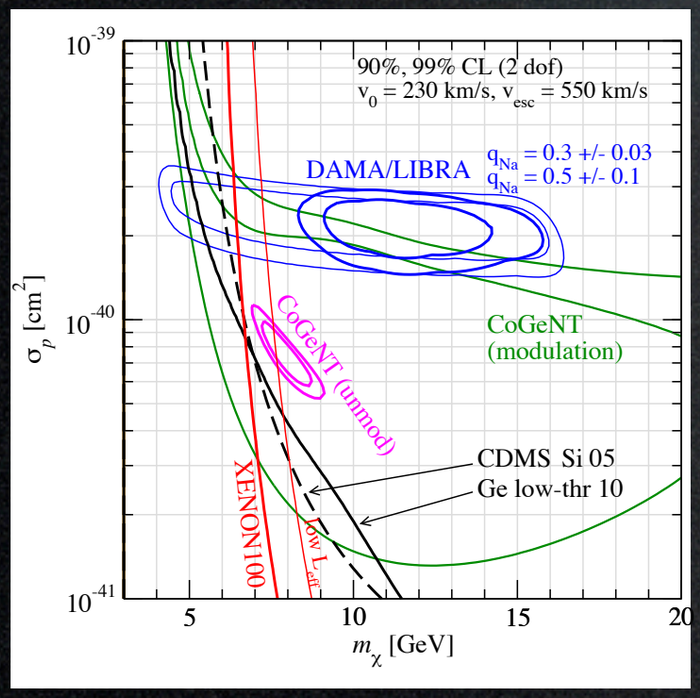
Belli+Fornengo+al., 1106.4667



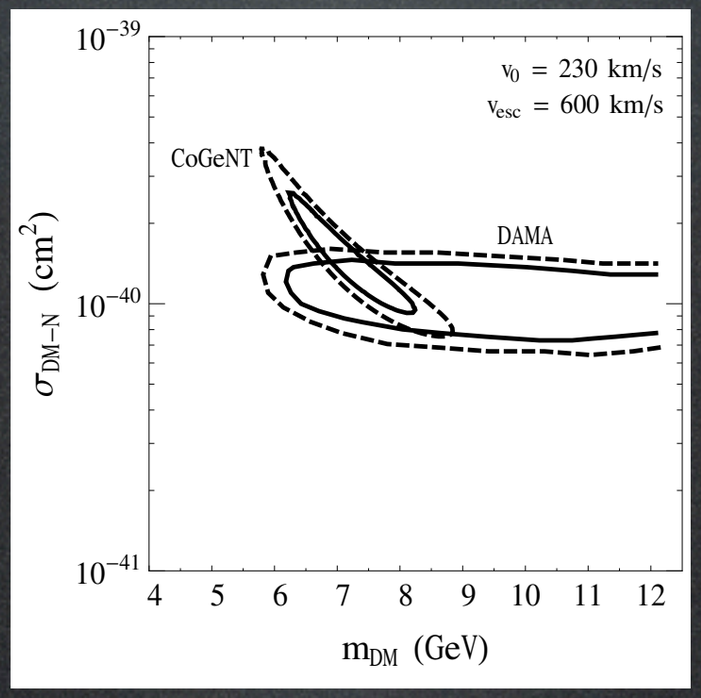
Farina+Pappadopulo+Strumia+Volansky, 1107.0715



Arina+Hamann+Wong, 1105.5121



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



Hooper+Kelso, 1106.1066

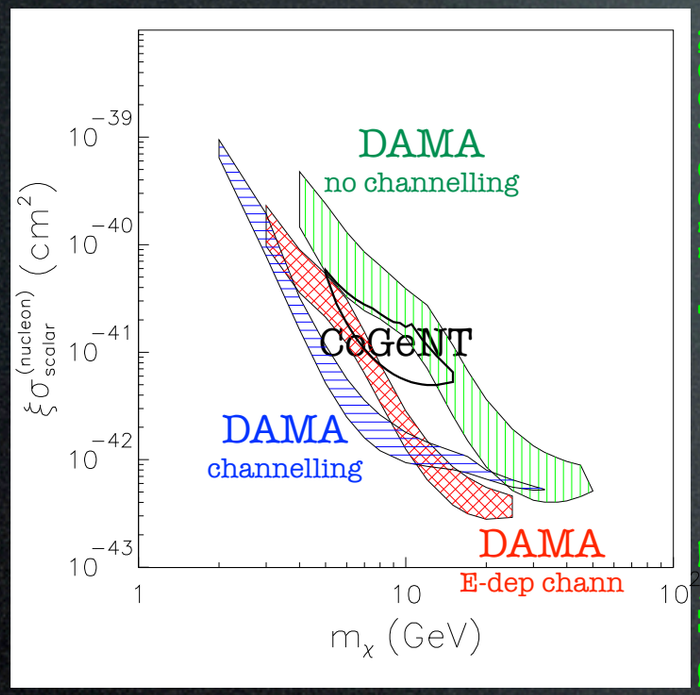
Comments:

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

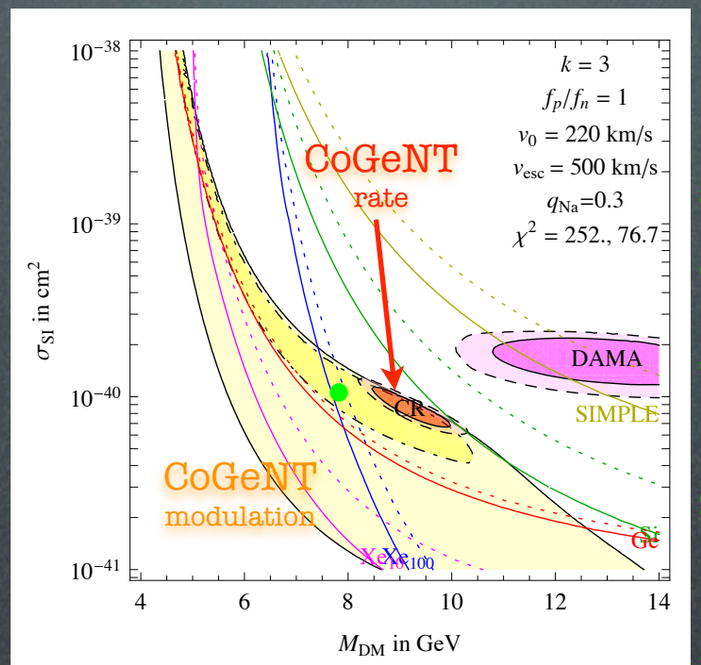
Direct Detection: hints

Plotolympics 2011: fits performed by different groups

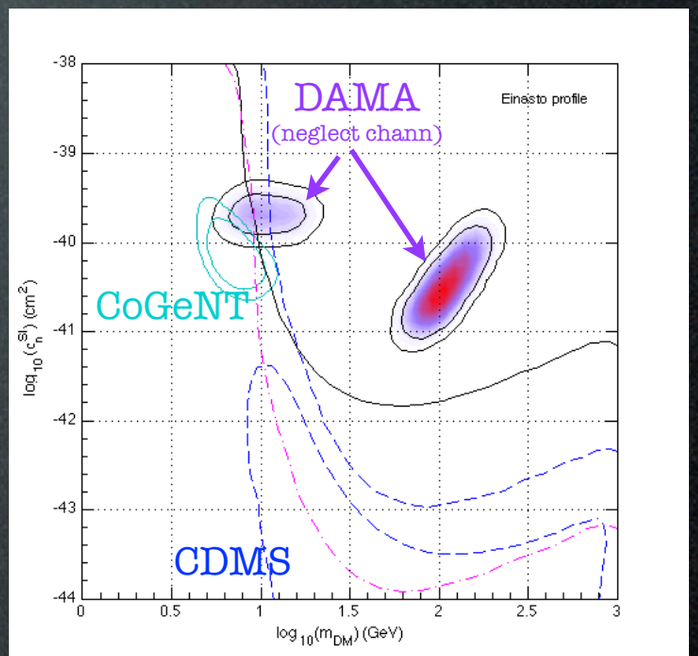
Discipline: Astro Fit: modifying velocity distrib, local density, profile...



Belli+Formengo+al., 1106.4667



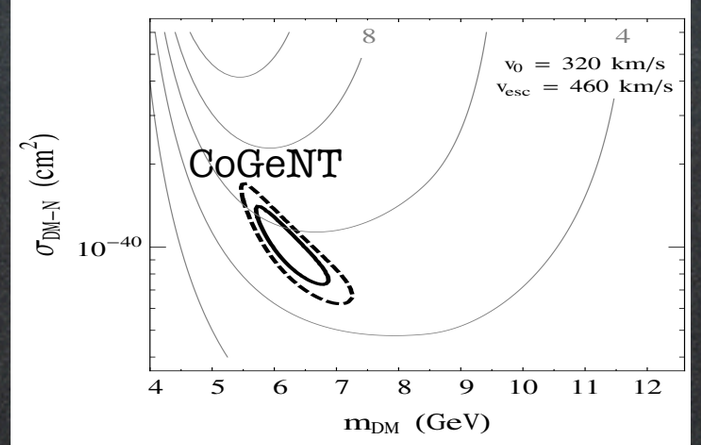
Farina+Pappadopulo+Strumia+ Volansky, 1107.0715



Arina+Hamann+Wong, 1105.5121

Boycott

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



Hooper+Kelso, 1106.1066

Comments:

- not big quantitative change

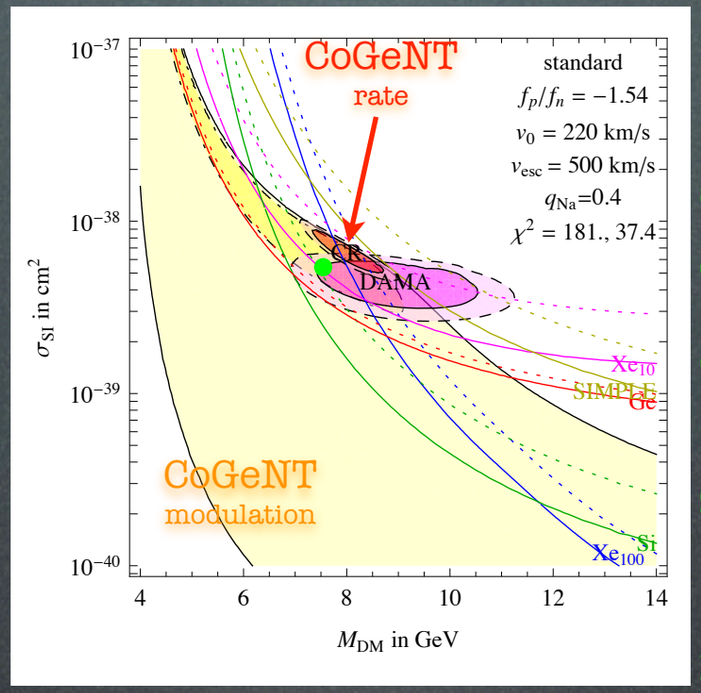
Direct Detection: hints

Plotolympics 2011: fits performed by different groups

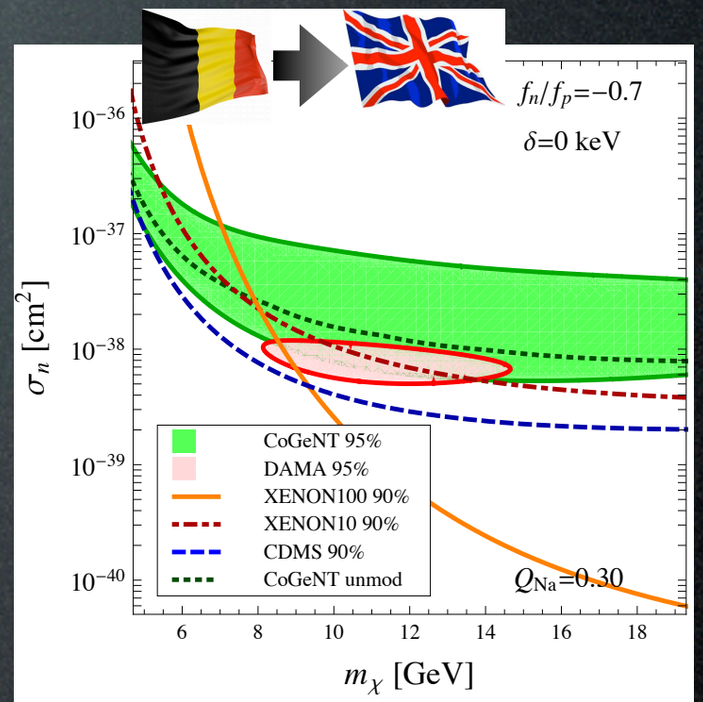
Discipline: Isospin Fit: assuming different coupling to **p** and **n**...

Boycott

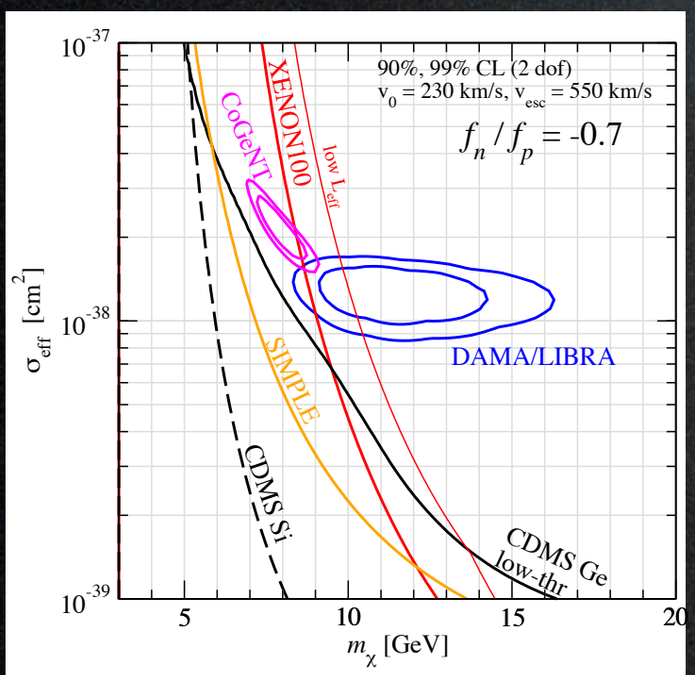
Belli+Bernabei+Cerulli+Fornengo+al., 1106.4667



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 improvement

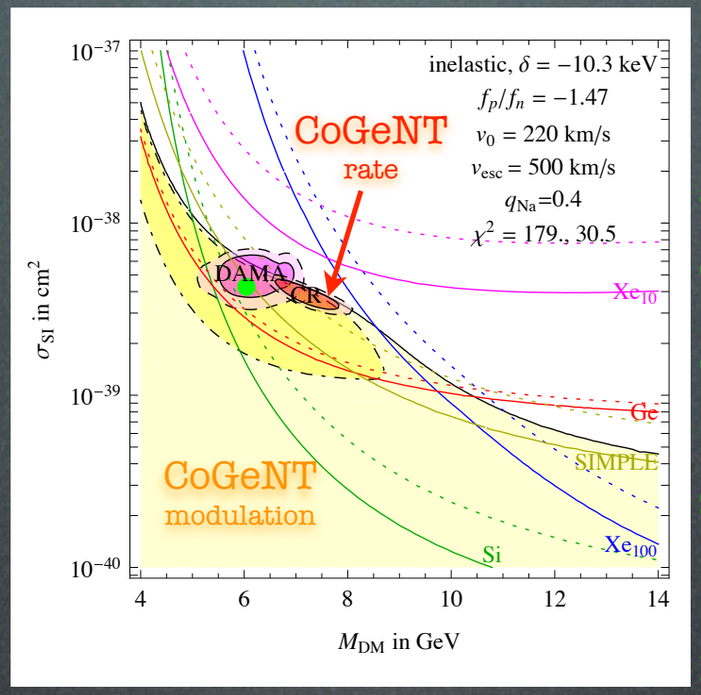
Direct Detection: hints

Plotolympics 2011: fits performed by different groups

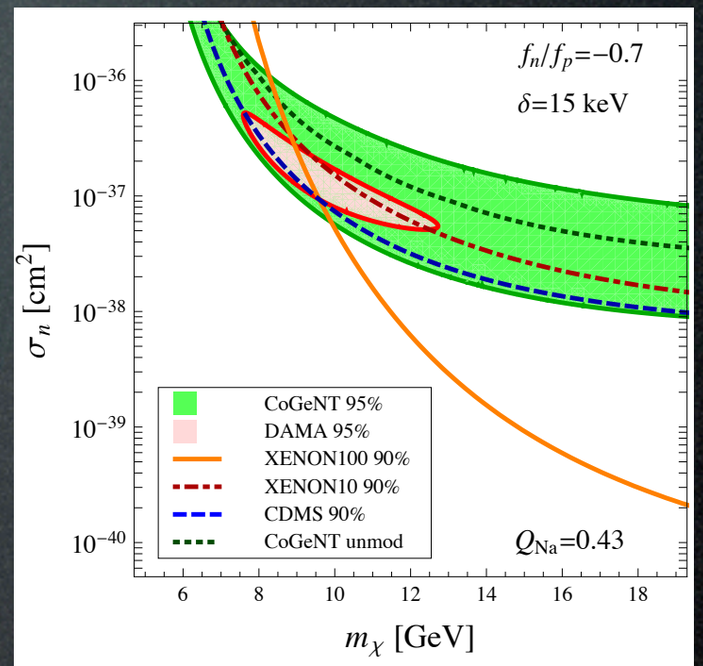
Discipline: Isospin & Inelastic Fit: different coupling + inelastic scatt

Boycott

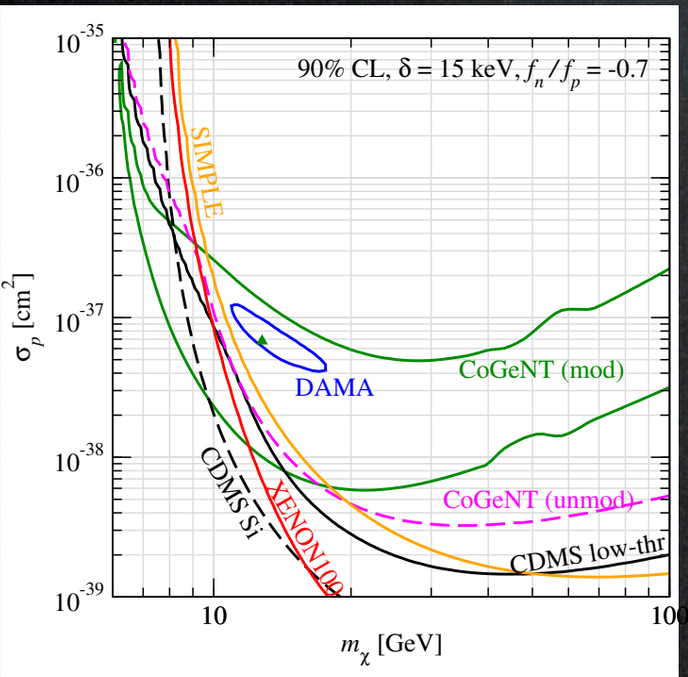
Belli+Fornengo+al., 1106.4667



Farina+Pappadopulo+Strumia+ Volansky, 1107.0715



Frandsen+Kahlhoefer+al., 1105.3734



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

Not qualified

Hooper+Kelso, 1106.1066

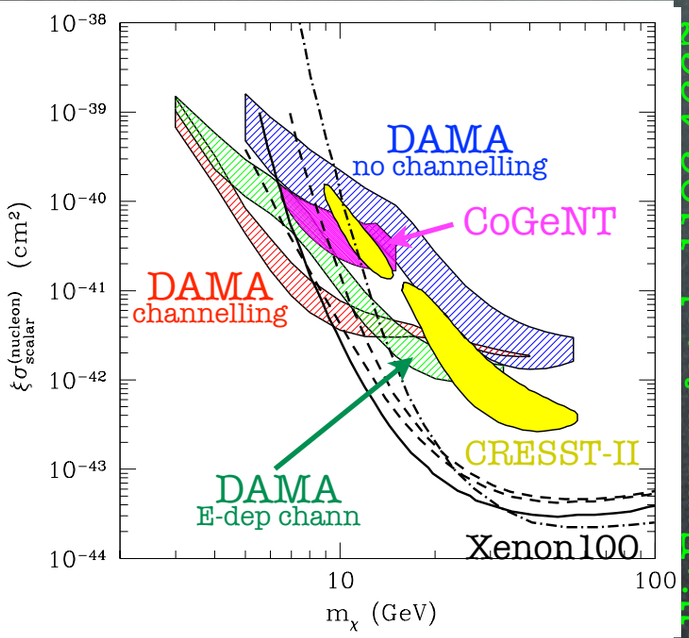
Comments:

- 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



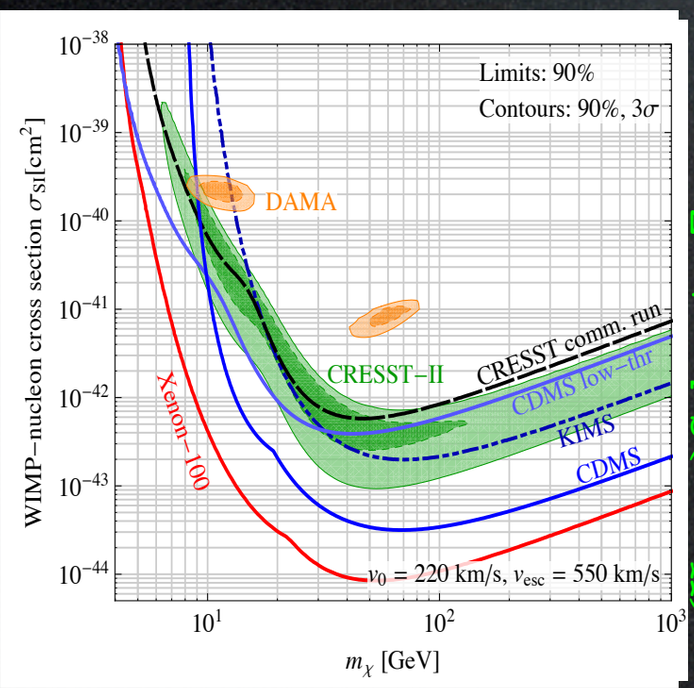
Belli+Fornengo+al., 1106.4667

No show

Farina+Pappadopulo+Strumia+Volansky, 1107.0715

No show

Frandsen+Kahlhoefer+al., 1105.3734



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

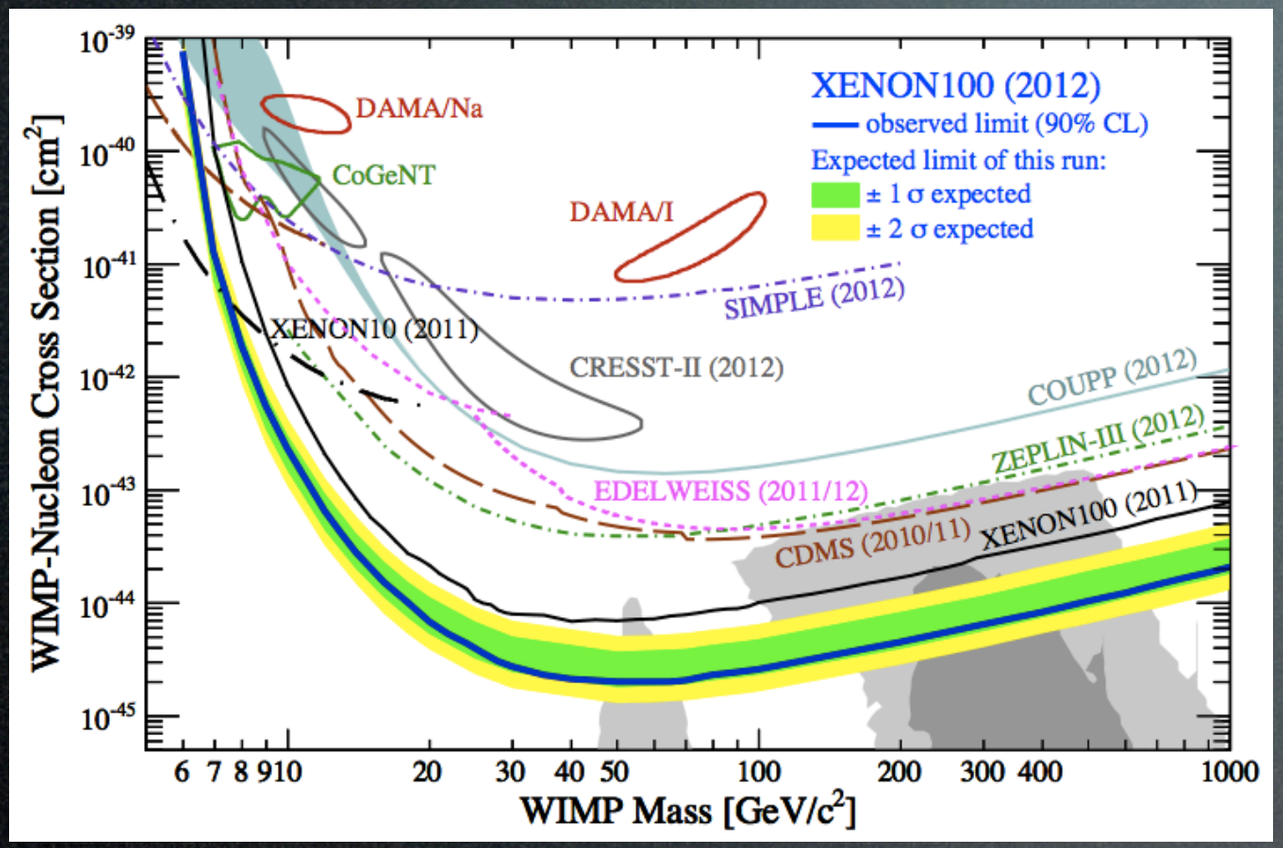
No show

Hooper+Kelso, 1106.1066

Comments:

- does CRESST-II agree or not?

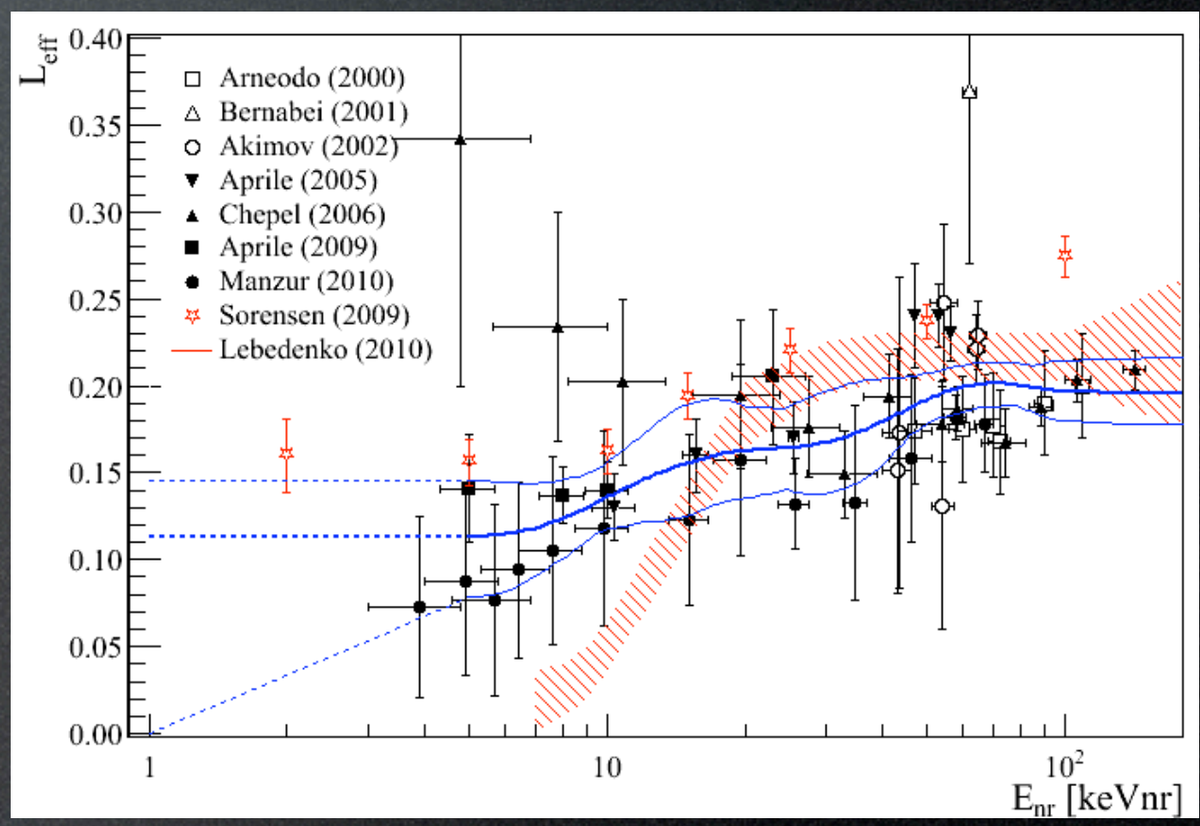
Direct Detection: constraints



Xenon 100 XENON 100 Coll., 1207.5988

225 live days
2 events seen
(1.0 exp'd bkgd)

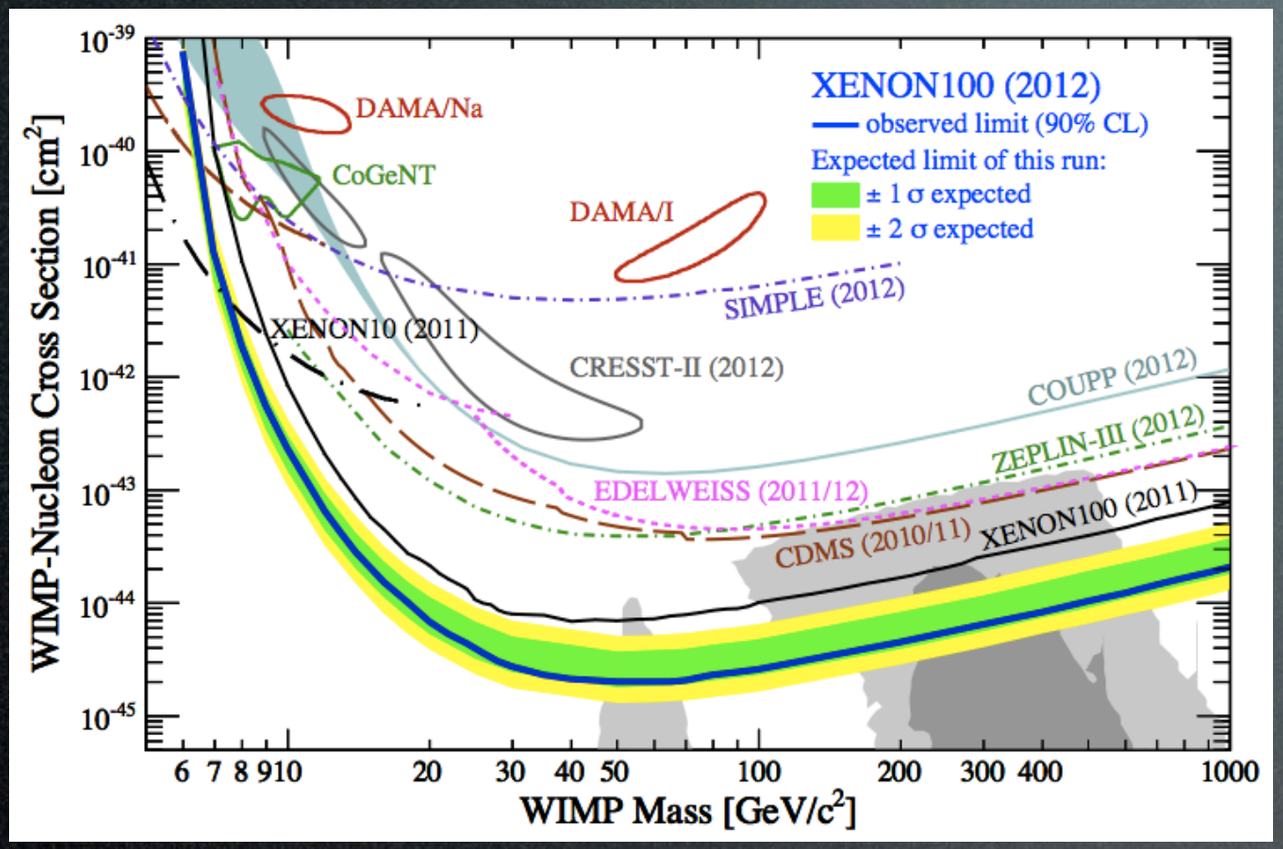
scintillation efficiency in LXe



XENON 100 Coll., 1005.2615

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

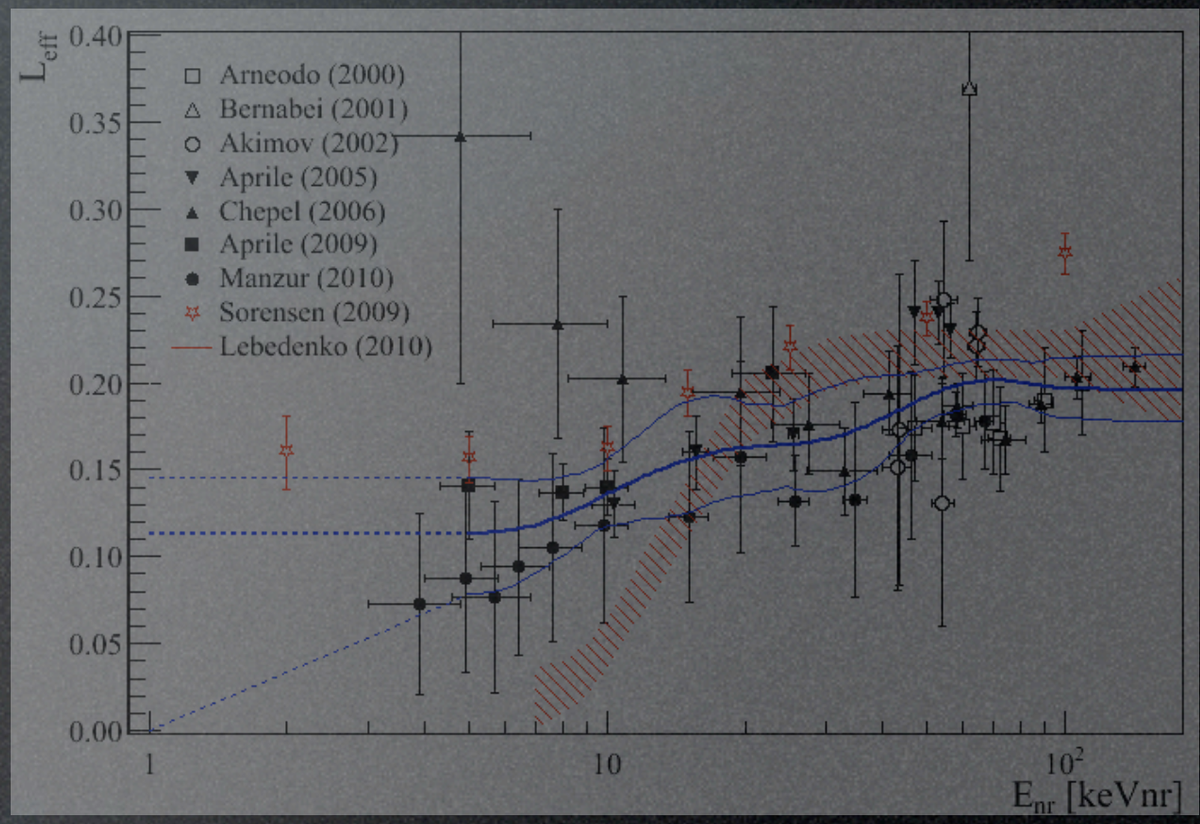
Direct Detection: constraints



Xenon 100 XENON 100 Coll., 1207.5988

225 live days
2 events seen
(1.0 exp'd bkgd)

scintillation efficiency in LXe

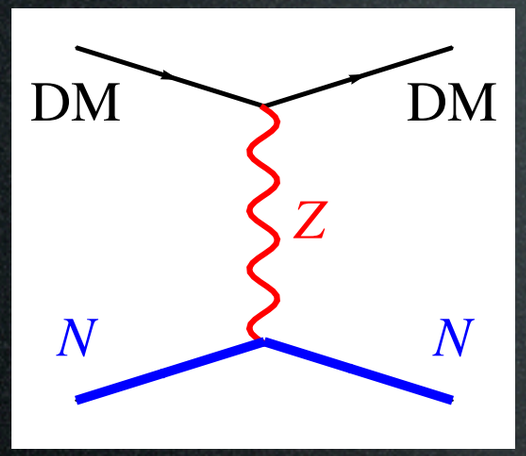


XENON 100 Coll., 1005.2615

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

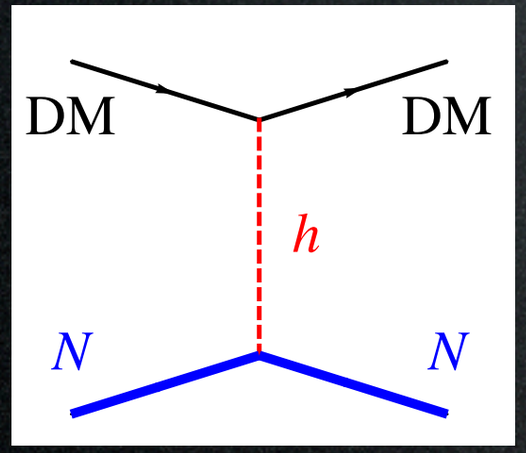
Direct Detection: '**theory**'

SM weak scale SI interactions



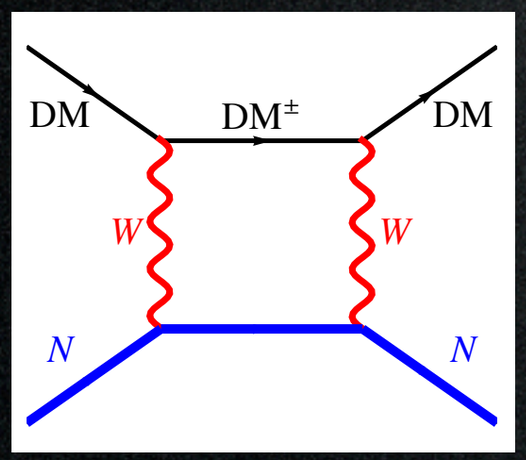
tree level, vector

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



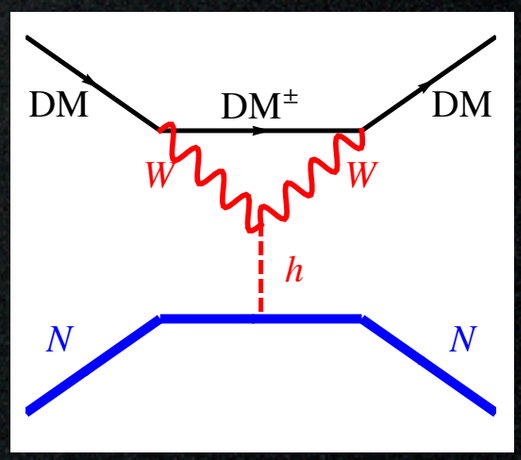
tree level, scalar

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



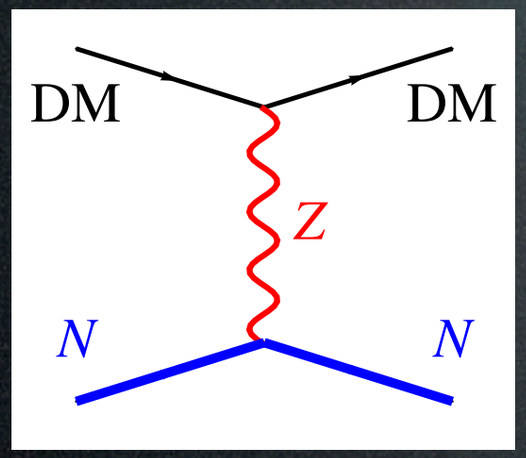
one loop

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

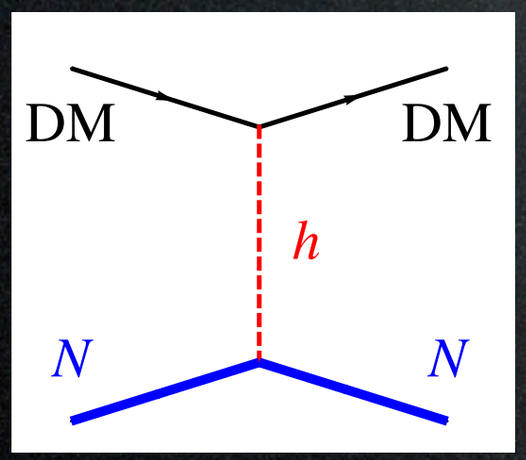


Direct Detection: 'theory'

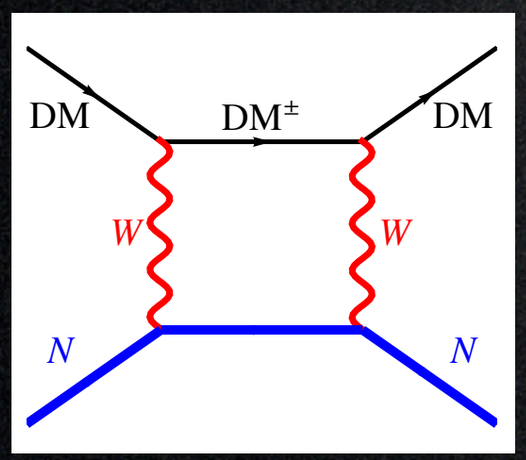
SM weak scale SI interactions



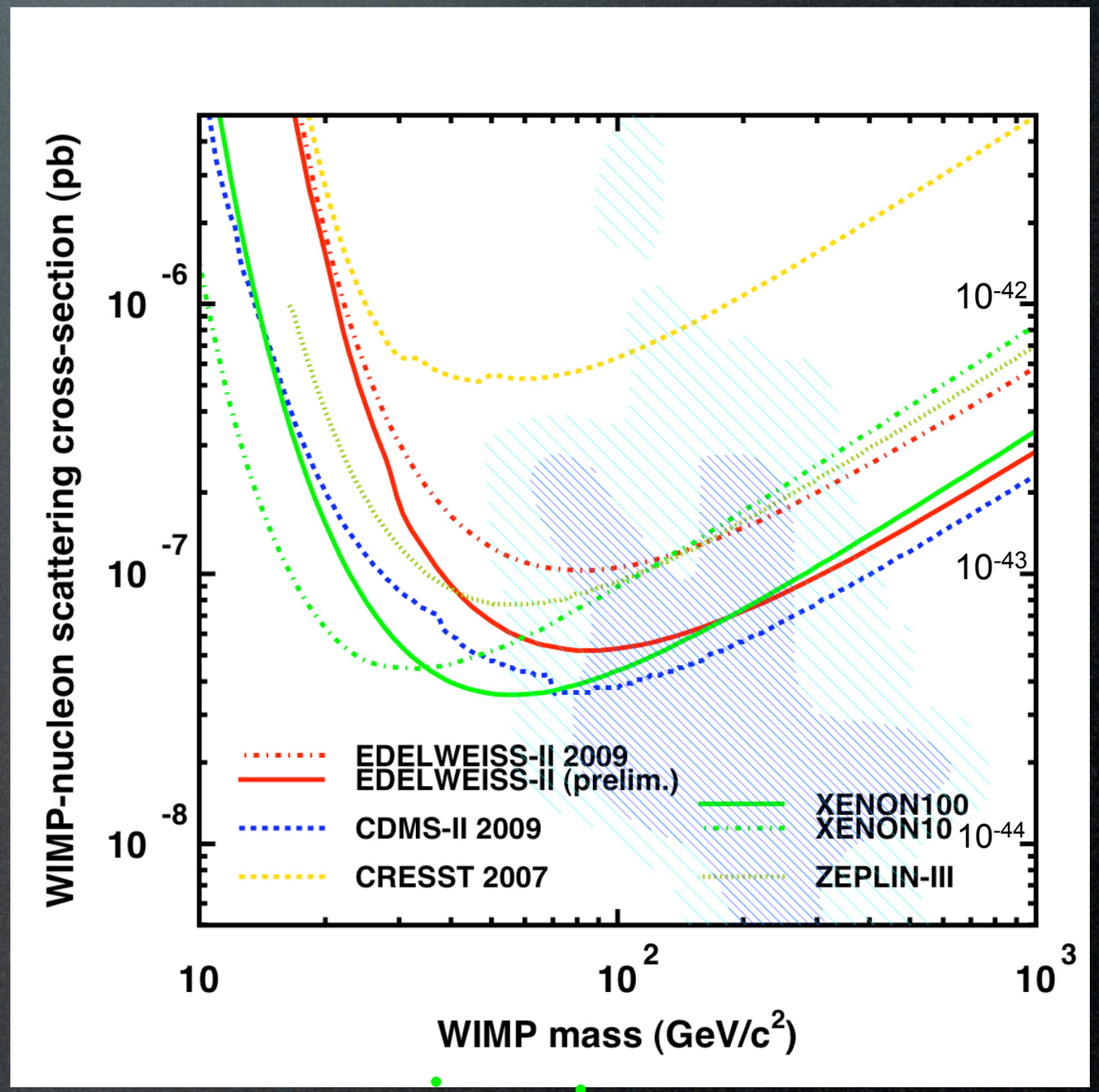
tree level, vector



tree level, scalar

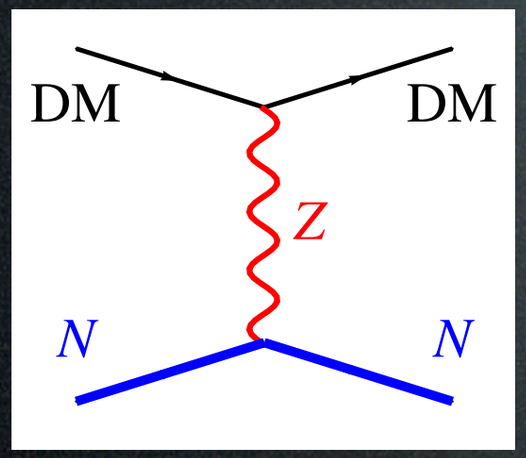


one loop

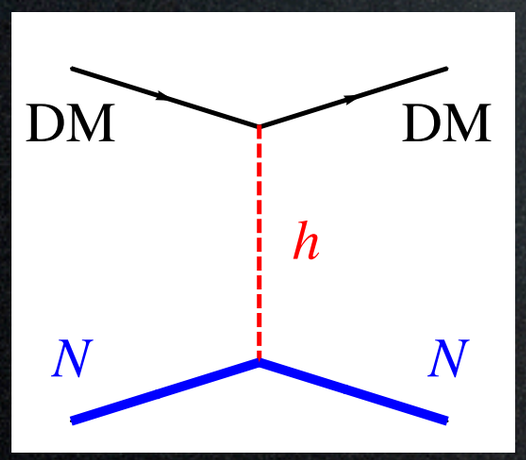


Direct Detection: 'theory'

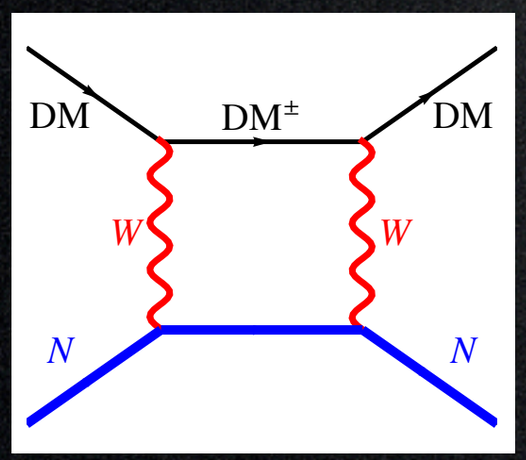
SM weak scale SI interactions



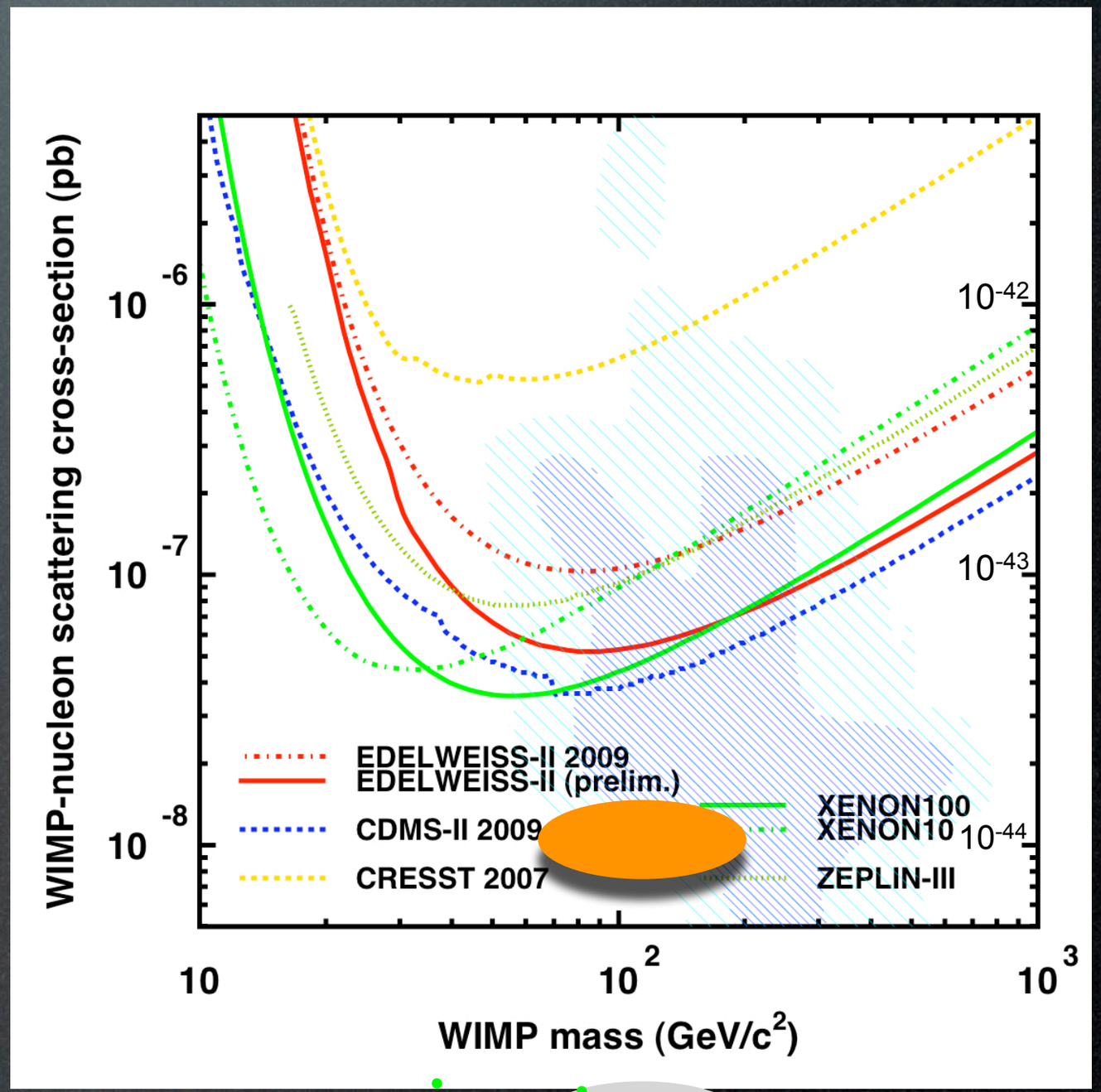
tree level, vector



tree level, scalar

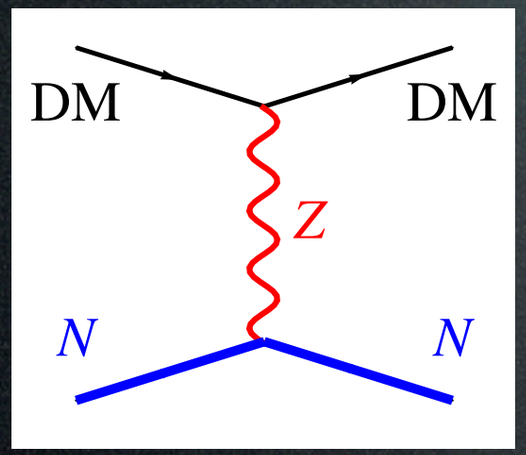


one loop



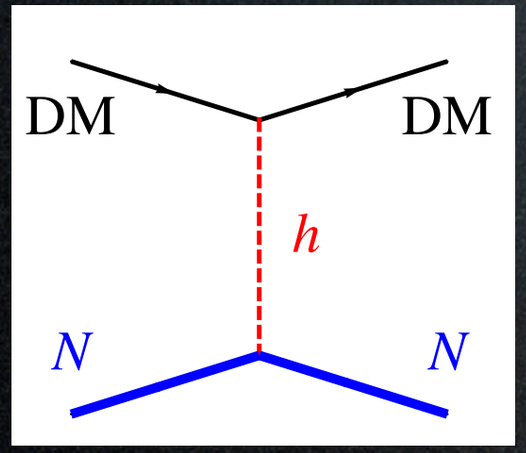
Direct Detection: 'theory'

SM weak scale SI interactions

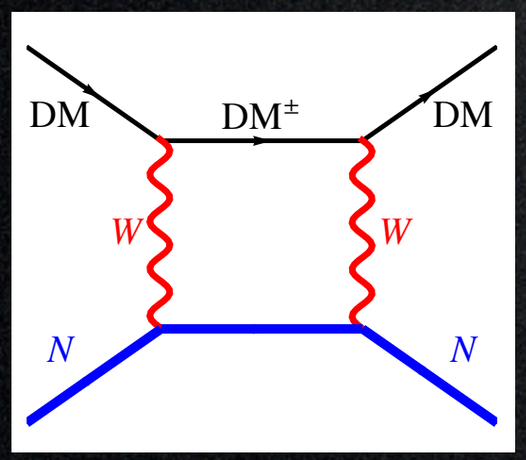


tree level, vector

Still viable under which conditions?



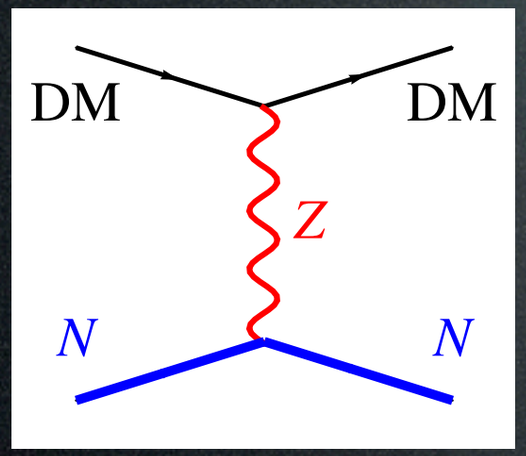
tree level, scalar



one loop

Direct Detection: 'theory'

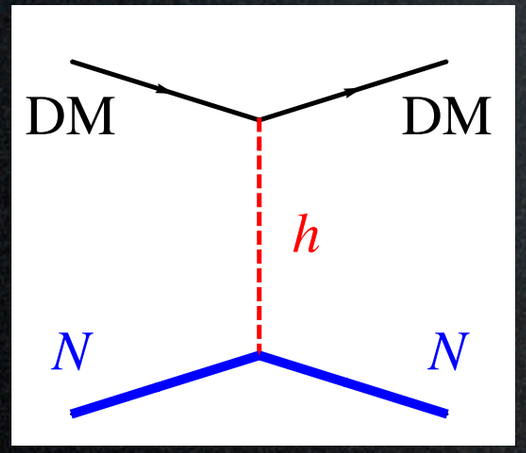
SM weak scale SI interactions



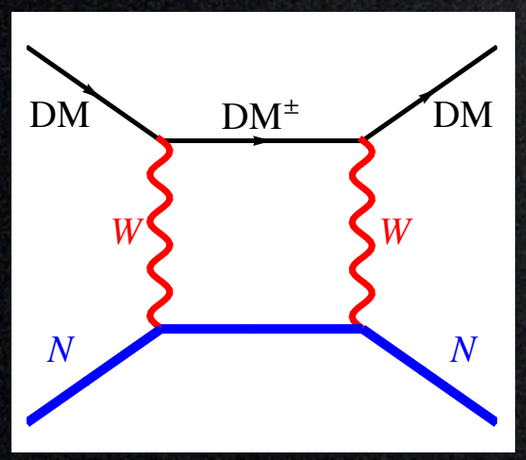
tree level, vector

Still viable under which conditions?

- real particle
  (Majorana fermion, real scalar)



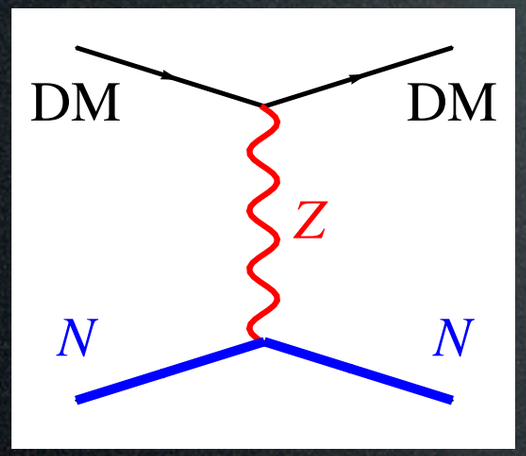
tree level, scalar



one loop

Direct Detection: 'theory'

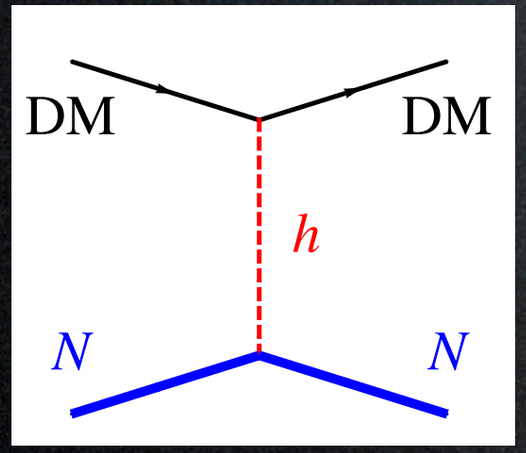
SM weak scale SI interactions



~~tree level, vector~~

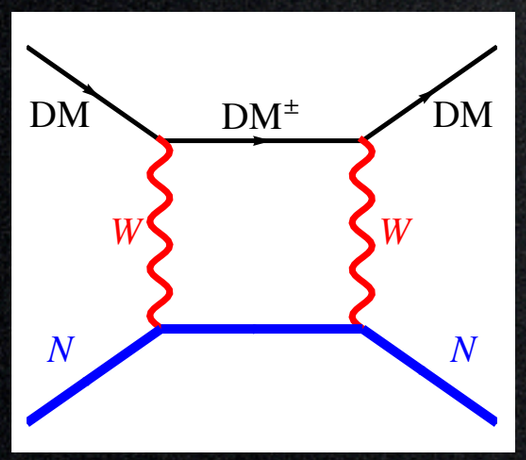
Still viable under which conditions?

- real particle
  (Majorana fermion, real scalar)



~~tree level, scalar~~

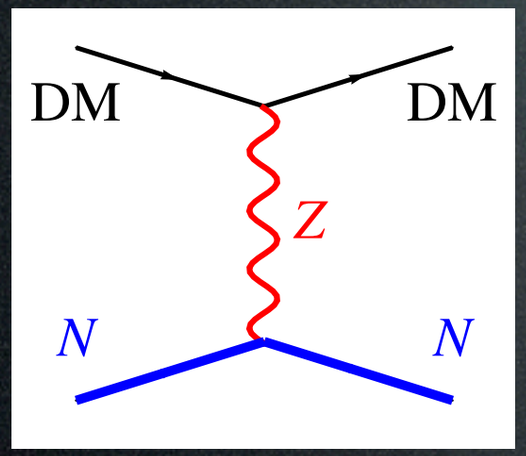
- hypercharge $Y = 0$



one loop

Direct Detection: 'theory'

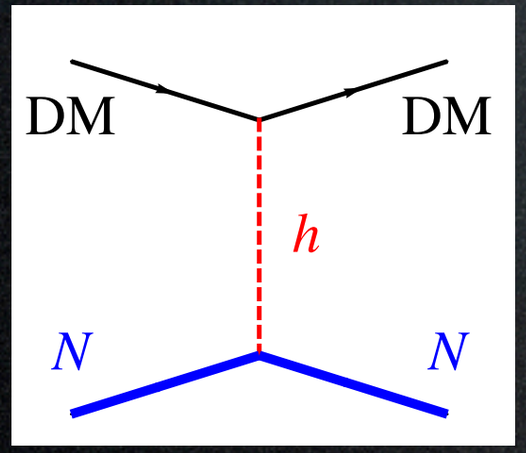
SM weak scale SI interactions



tree level, vector

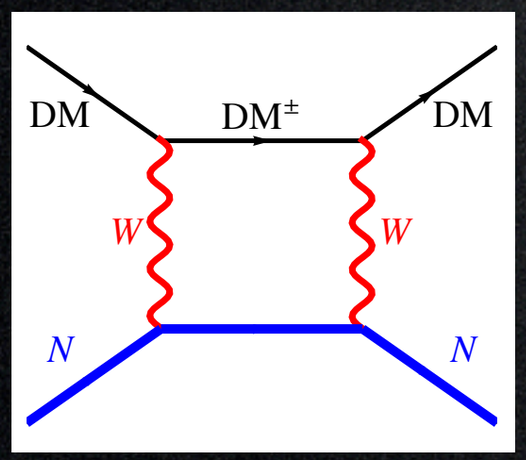
Still viable under which conditions?

- real particle
  (Majorana fermion, real scalar)

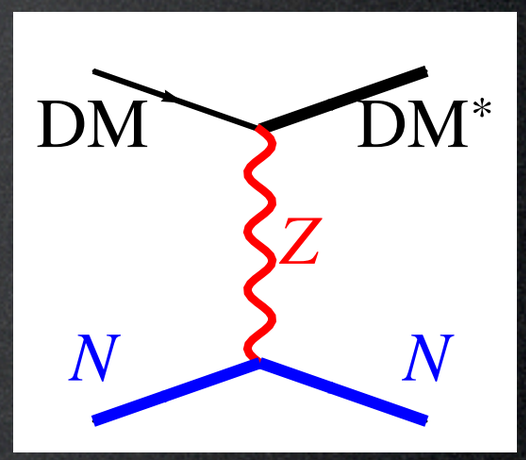


tree level, scalar

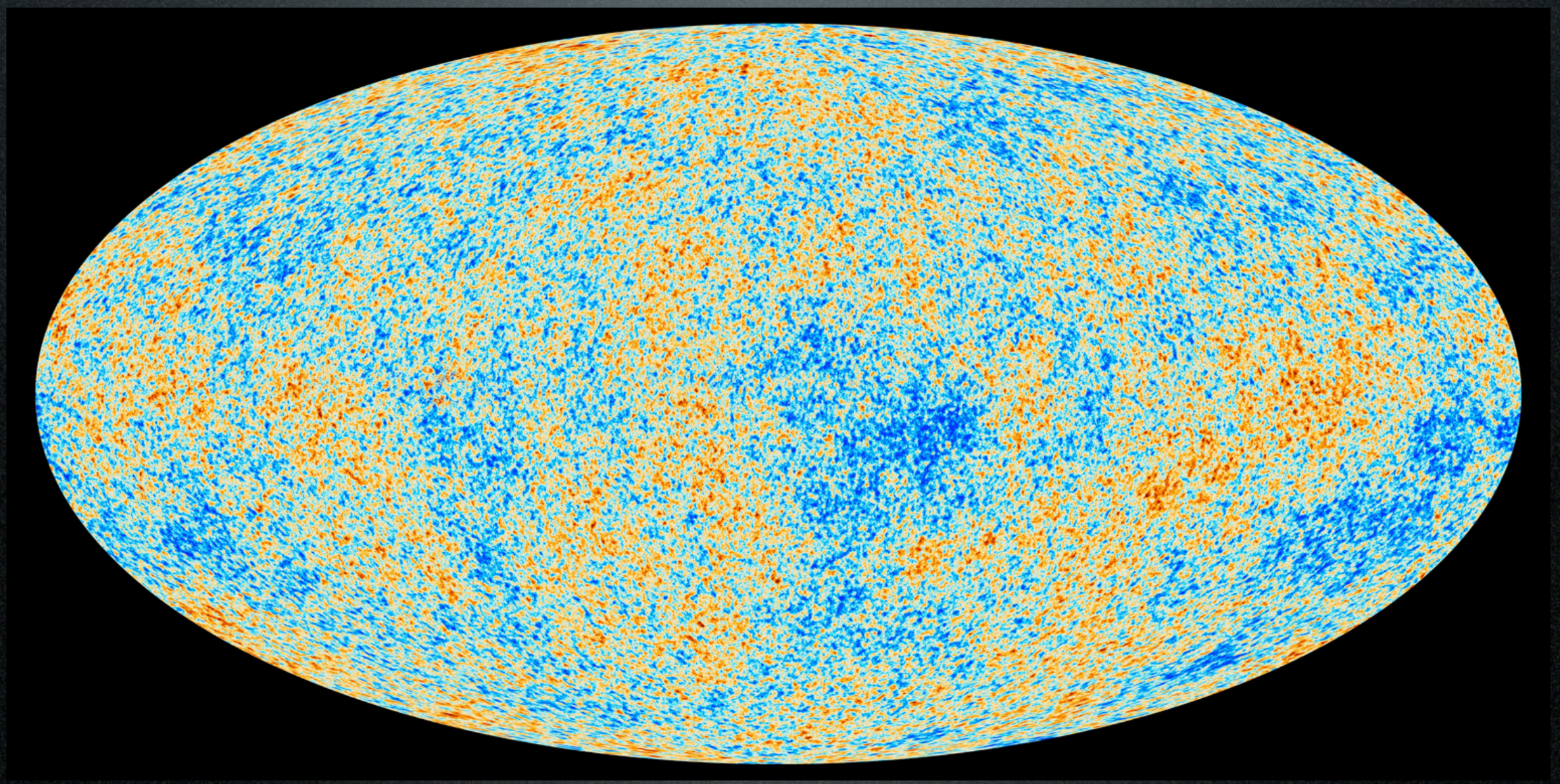
- hypercharge $Y = 0$
- SD interactions only
- inelastic scattering



one loop



Cosmic Neutrinos

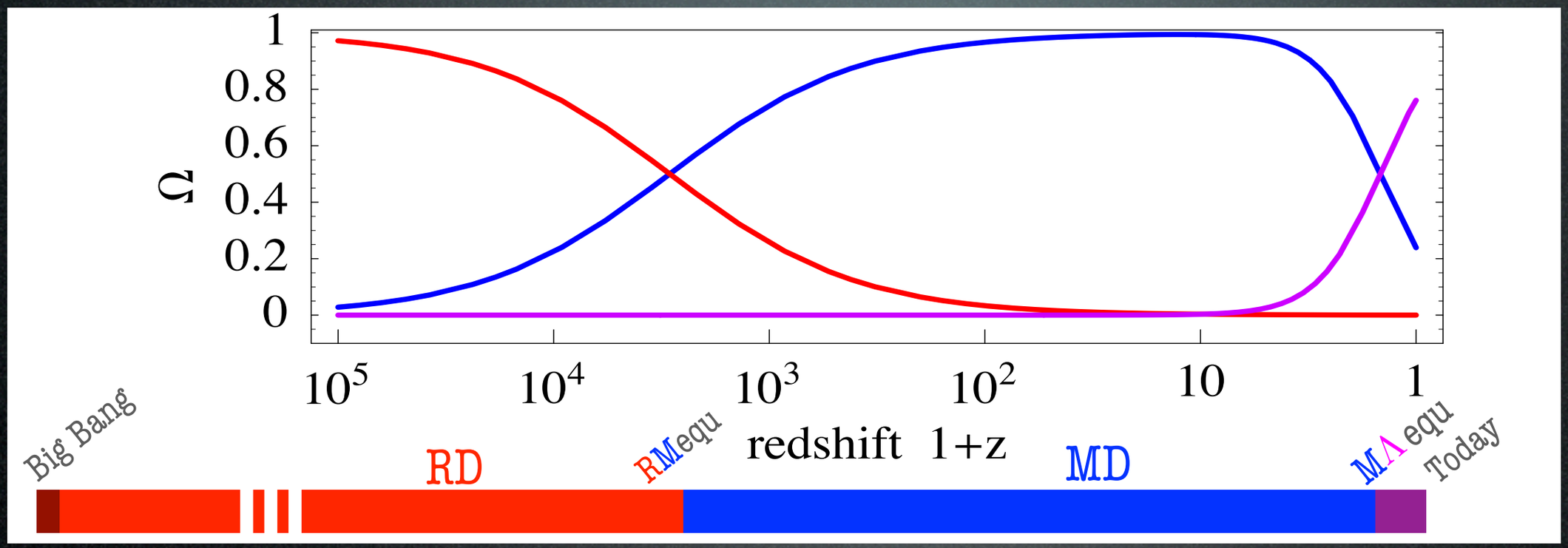


4. the 'N_{eff} puzzle'

[skip to conclusions]

Neutrinos in the Cosmo

The Universe is made of: radiation, matter (DM+b+e), dark energy



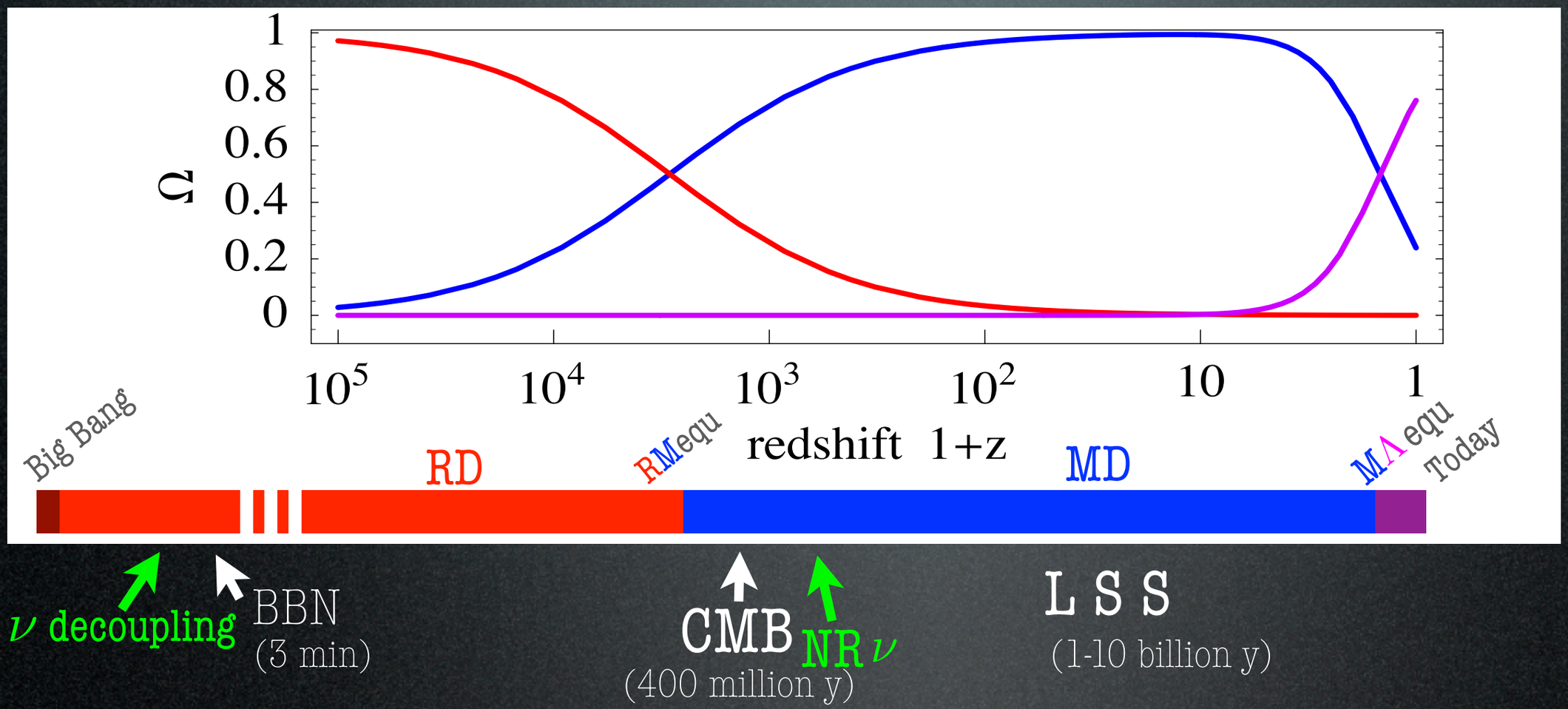
BBN
(3 min)

CMB
(400 million y)

LSS
(1-10 billion y)

Neutrinos in the Cosmo

The Universe is made of: radiation, matter (DM+b+e), dark energy and neutrinos



Neutrinos are significant because:

- main component of the rel energy density that sets expansion rate of the Universe
- (ordinary neutrinos have a mass, so) turn from Rel to NRel at a crucial time
- may free-stream or interact among themselves, or with new light particles

[thanks to M.Frigerio]

Neutrinos in BBN

Equation for neutron/proton ratio:

$$\dot{r} \equiv \frac{dT}{dt}\frac{dr}{dT} = \Gamma_{p\to n}(1-r) - r\Gamma_{n\to p} \qquad r = \frac{n_n}{n_n + n_p}$$

$$\dot{T} \sim -H(T,\rho)T$$

Hubble parameter
depends on
total energy density

(A)

$$H = \sqrt{\frac{8\pi}{3} G_{\rm N}\, \rho_{\rm rel}}$$

$$\rho_{\rm rel} = \rho_\gamma \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_\nu\right]$$

weak interactions

$$n \longleftrightarrow p + e^- + \bar{\nu}_e$$

$$n + \nu_e \longleftrightarrow p + e^-$$

$$n + e^+ \longleftrightarrow p + \bar{\nu}_e.$$

depend on ν_e and $\bar{\nu}_e$ densities

(B)

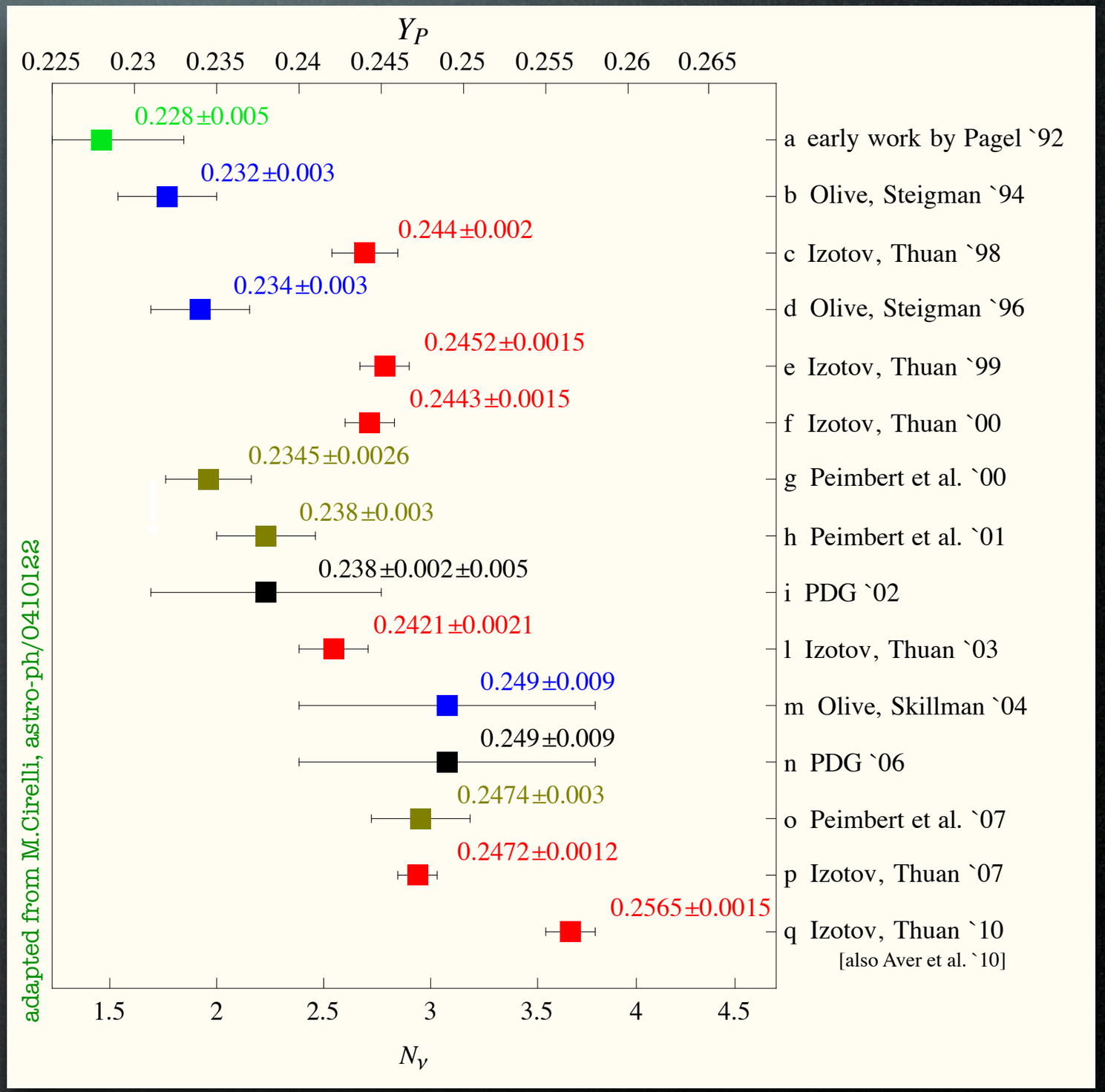
(A) more neutrinos $\Rightarrow$ faster expansion

(B) depletion of ν_e density $\Rightarrow$ modified weak rates

Neutrinos in BBN

Compare BBN output with observations:

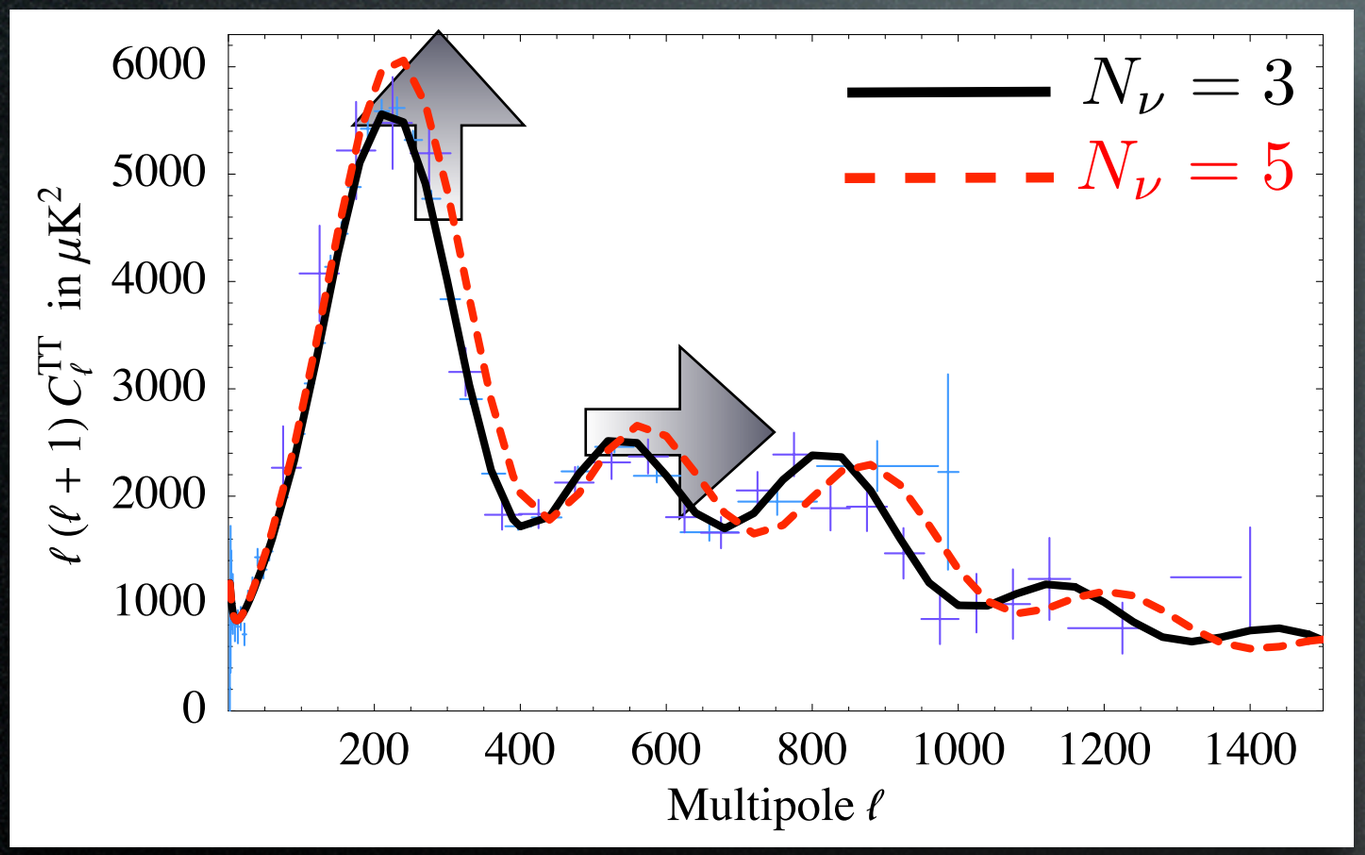
Determinations of primordial ^{4}He are somehow controversial.



$$N_\nu \simeq 3.8 \pm 0.35 \quad (1\sigma)$$

Neutrinos in CMB+LSS

N_ν sets the total relativistic energy content and affects the peaks of CMB (and LSS) spectra:



Caveat: plot for illustration only, all parameters fixed except N_ν

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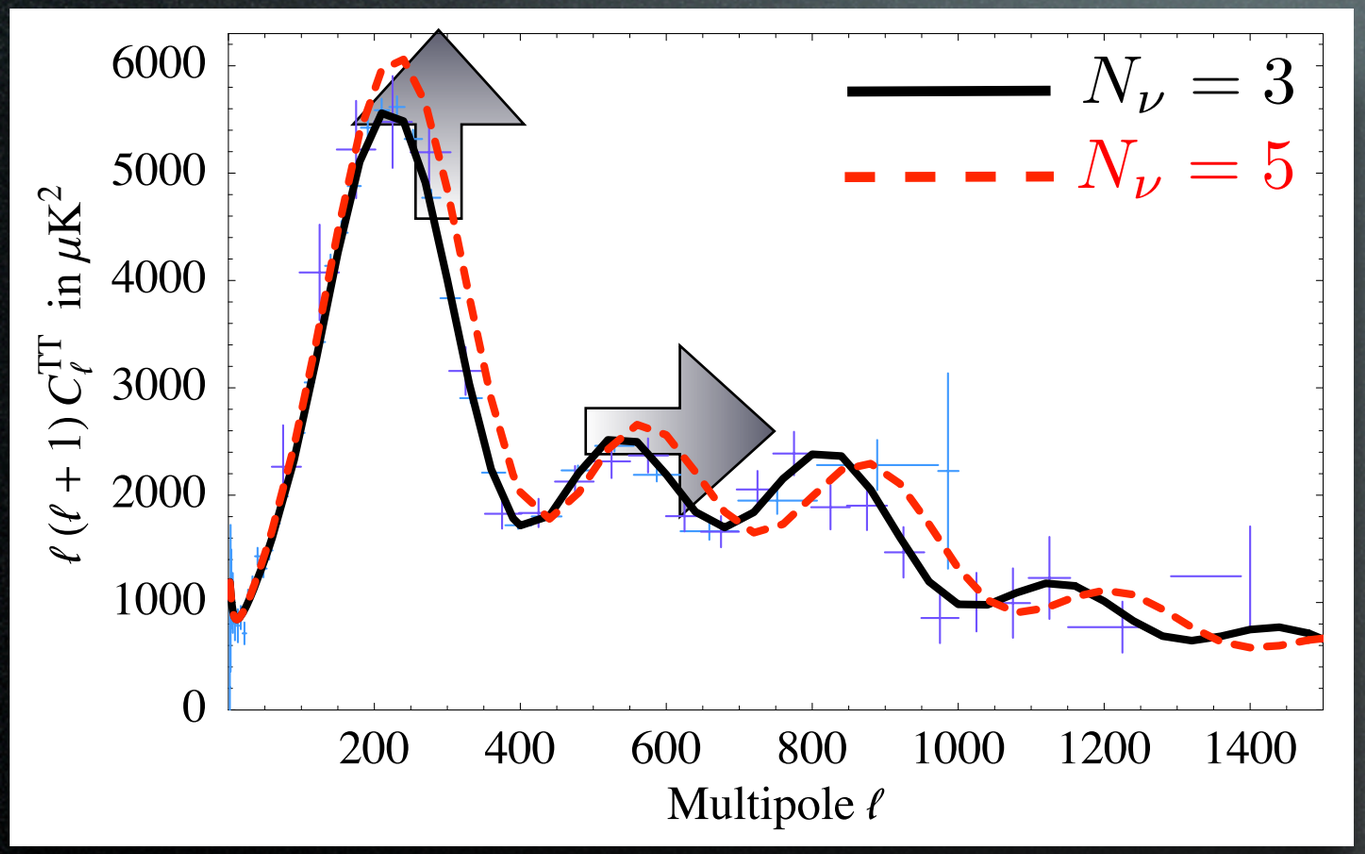


Caveat: plot for illustration only, all parameters fixed except N_ν

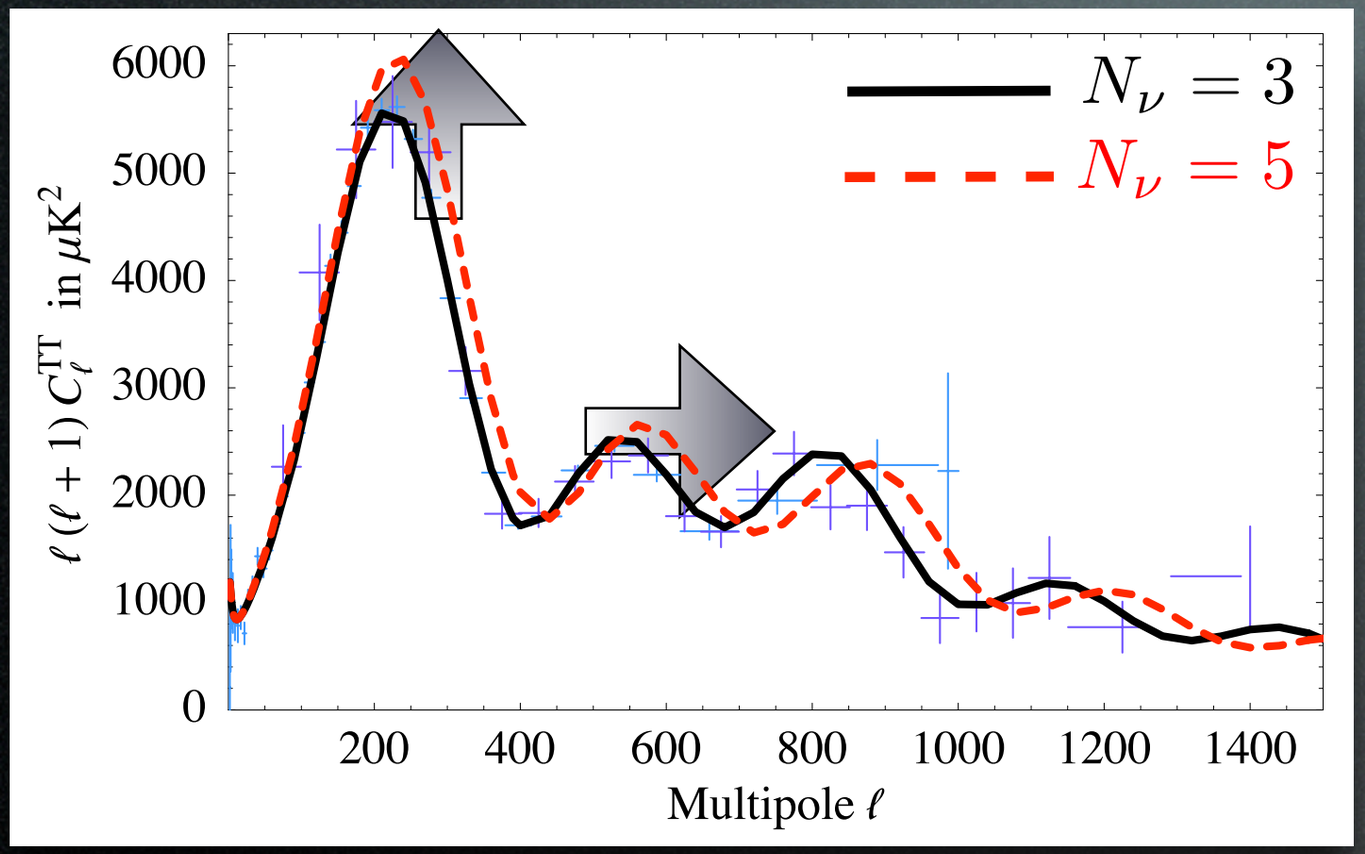
a determination of N_ν :

$$N_\nu \simeq 5 \pm 1$$

(global fit)
Seljak 2006,
Mangano 2007,
Cirelli, Strumia 2006,
Hamann et al. 2010...

Neutrinos in CMB+LSS

N_ν sets the total relativistic energy content and affects the peaks of CMB (and LSS) spectra:



Caveat: plot for illustration only, all parameters fixed except N_ν

a determination of N_ν :

$$N_\nu = 3.26 \pm 0.35$$

(1σ)

(global fit)
WMAP 9yr

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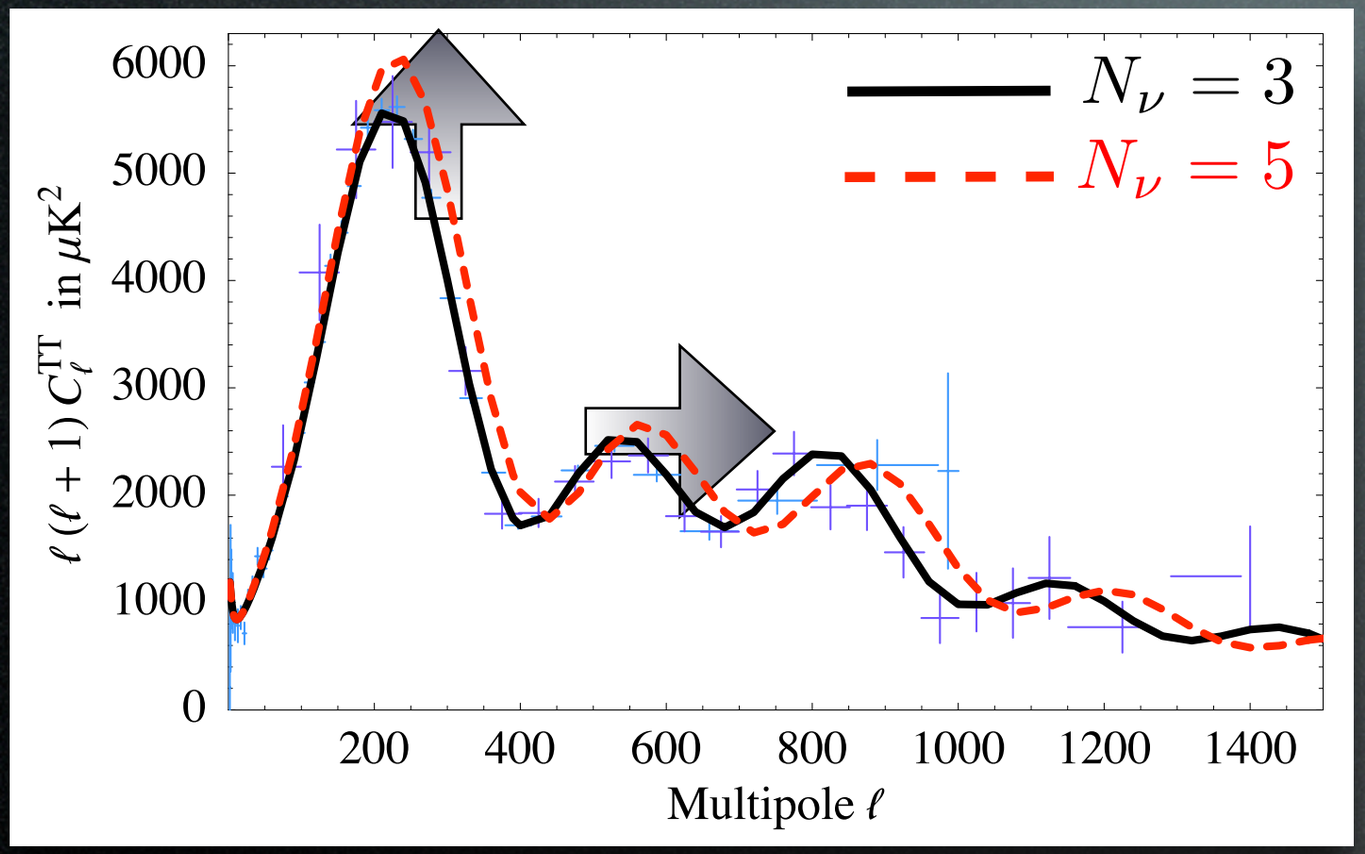


Caveat: plot for illustration only, all parameters fixed except N_ν

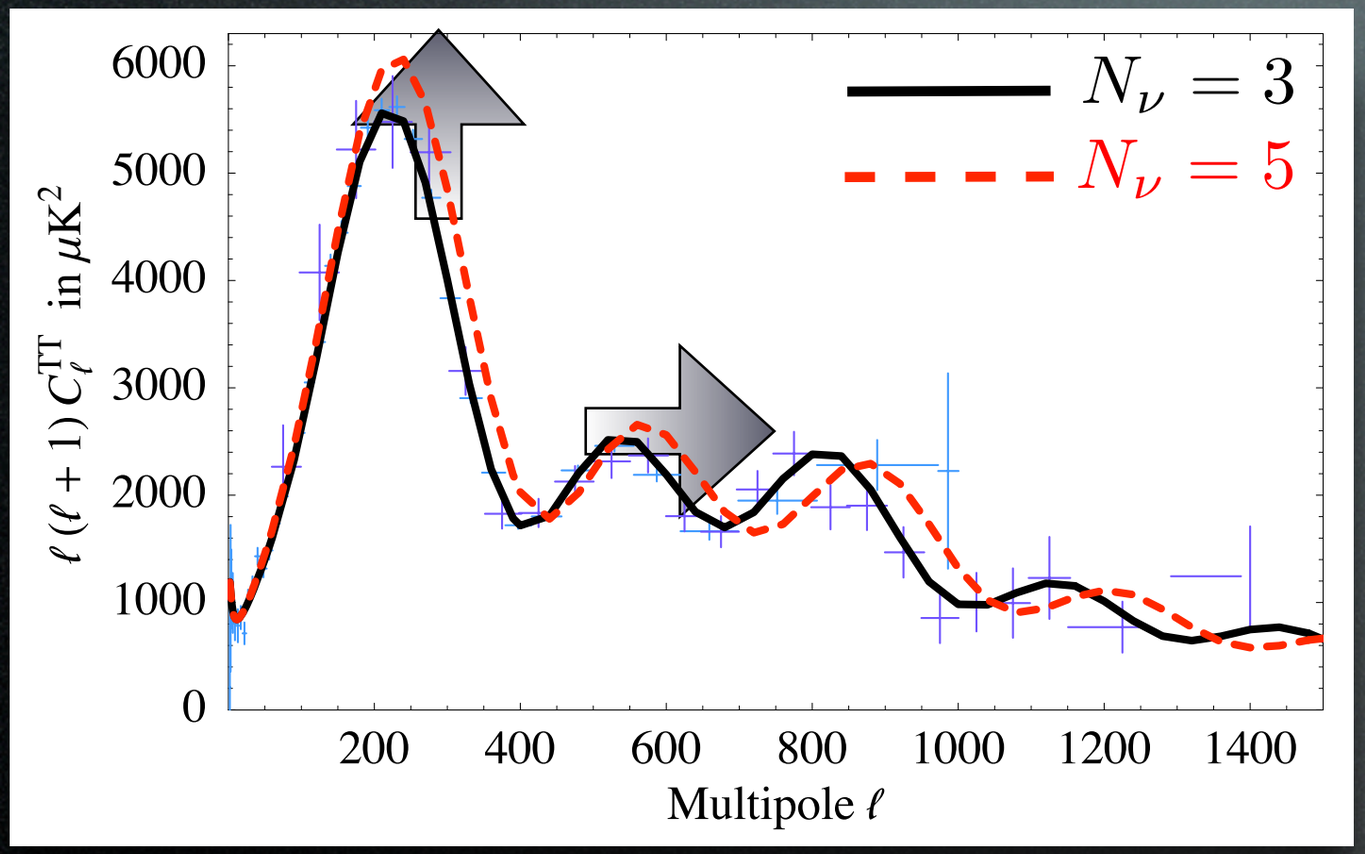
a determination of N_ν :

$$N_\nu = 4.34 \pm 0.40 \quad (1\sigma)$$

(global fit)
WMAP 9yr **v2**

Neutrinos in CMB+LSS

N_ν sets the total relativistic energy content and affects the peaks of CMB (and LSS) spectra:



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$$N_\nu = 4.34 \pm 0.40 \quad (1\sigma)$$

(global fit)
WMAP 9yr **v2**

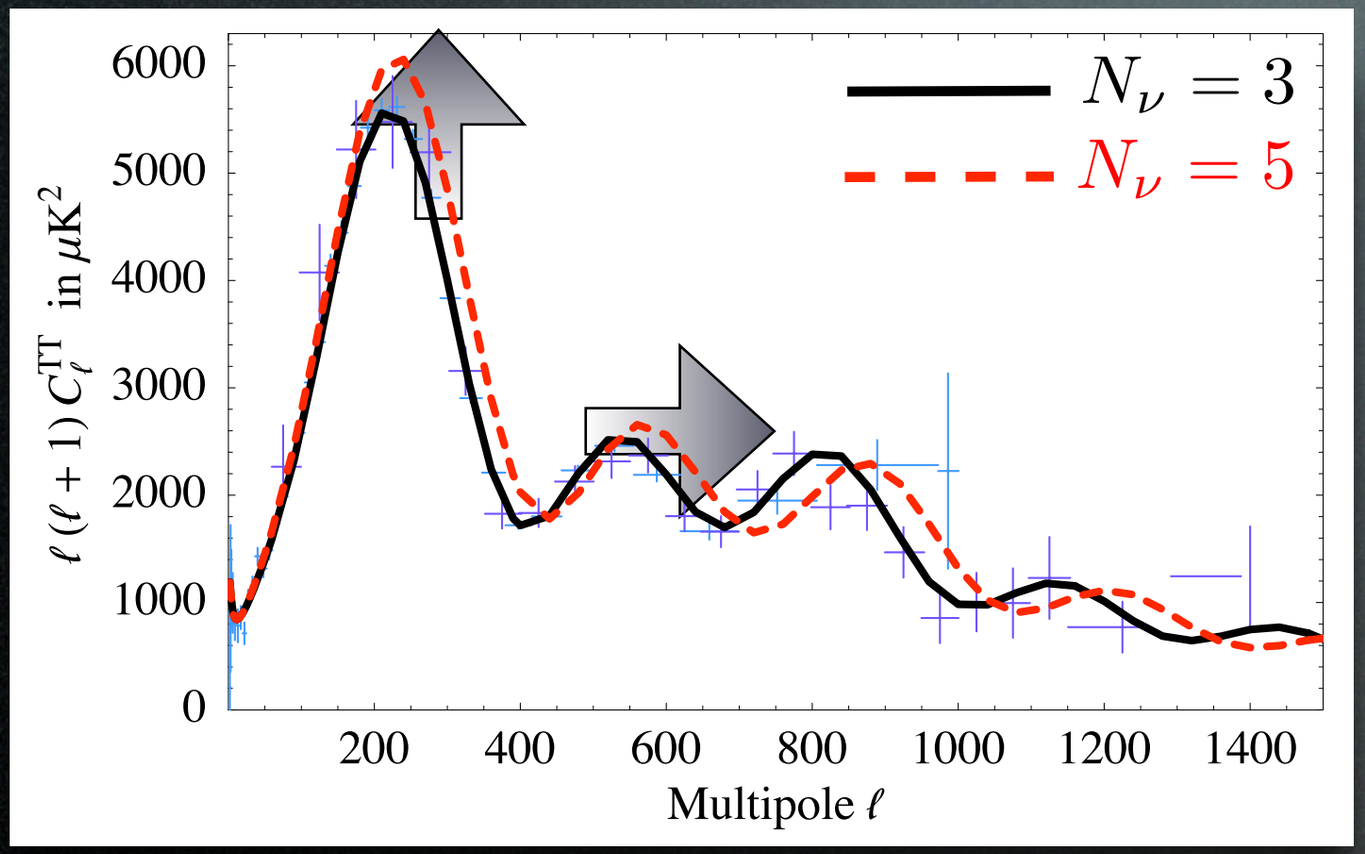
$N_\nu = 3.23 \pm 0.47$ adding ACT

$N_\nu = 3.76 \pm 0.34$ adding SPT

Di Valentino, Galli et al, 1303.7343

Neutrinos in CMB+LSS

N_ν sets the total relativistic energy content and affects the peaks of CMB (and LSS) spectra:



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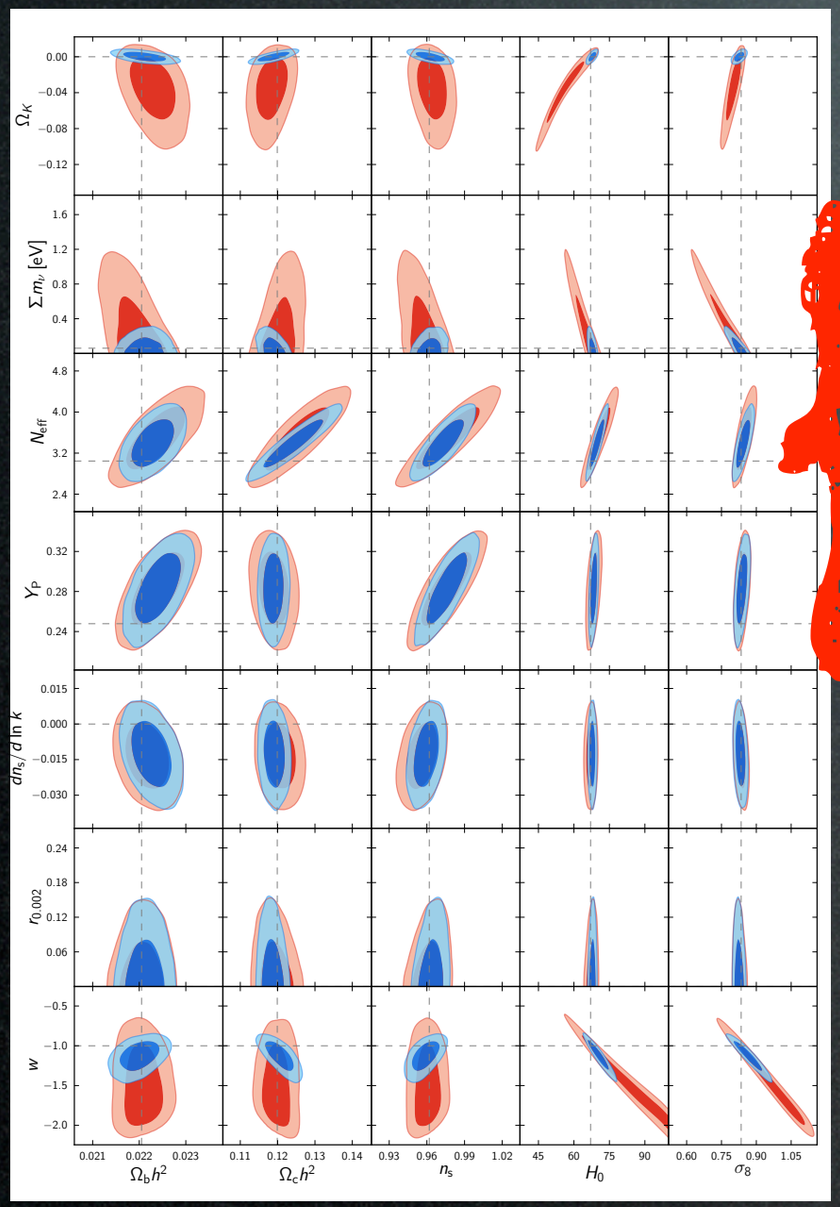
Di Valentino, Galli et al, 1303.7343

$$N_\nu = 3.30 \pm 0.27$$

Planck 2013

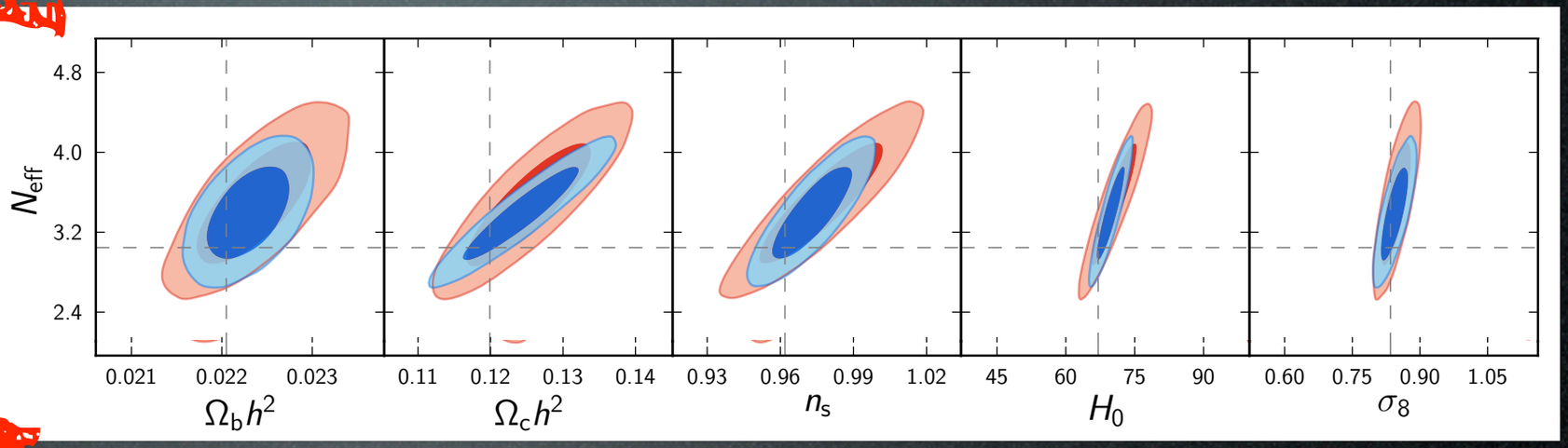
Neutrinos in CMB+LSS

Degeneracies:



Planck + WMAPpol

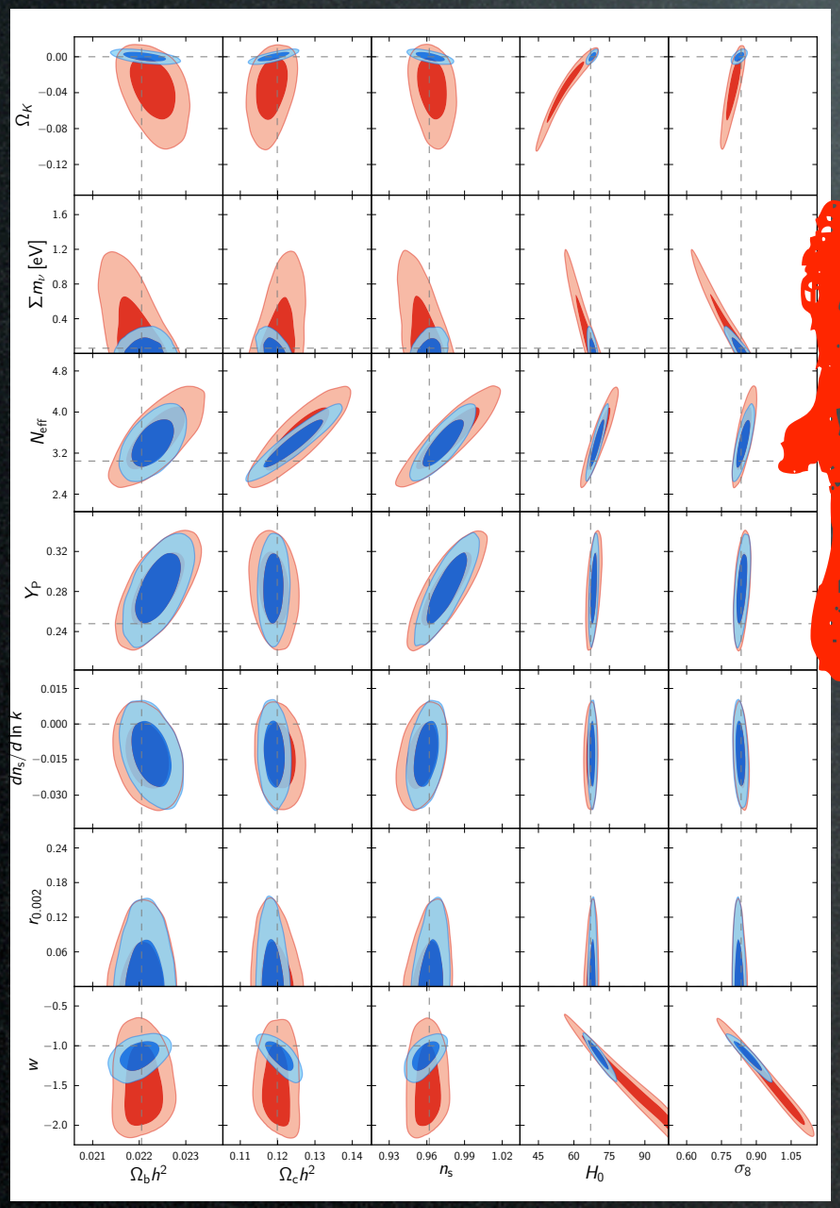
Planck + WMAPpol + BAO



E.g. a large H_0 re-allows a large N_{eff}

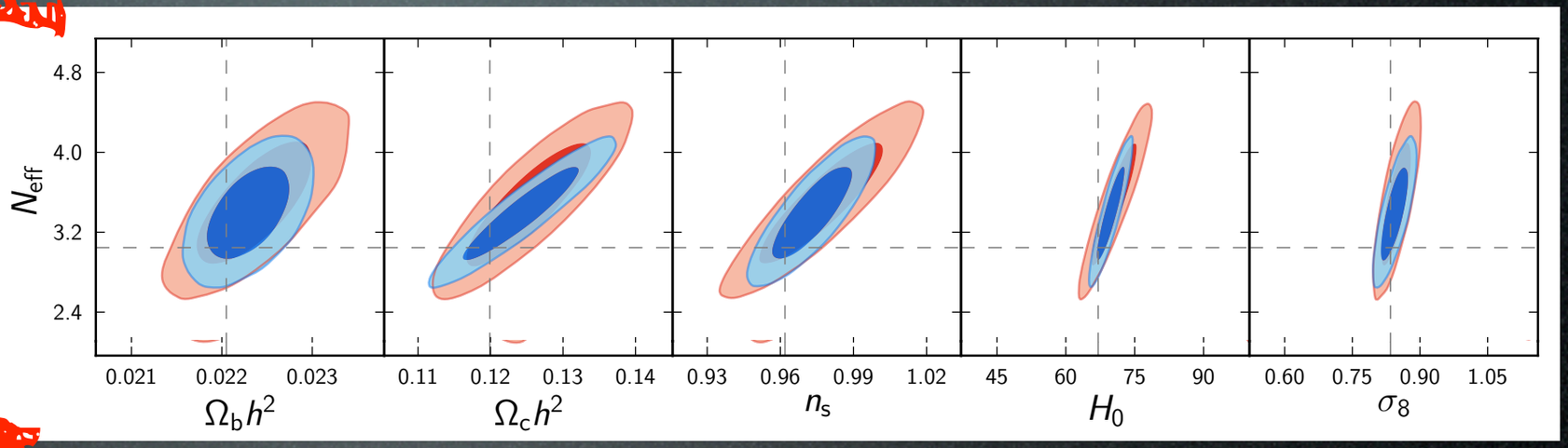
Neutrinos in CMB+LSS

Degeneracies:



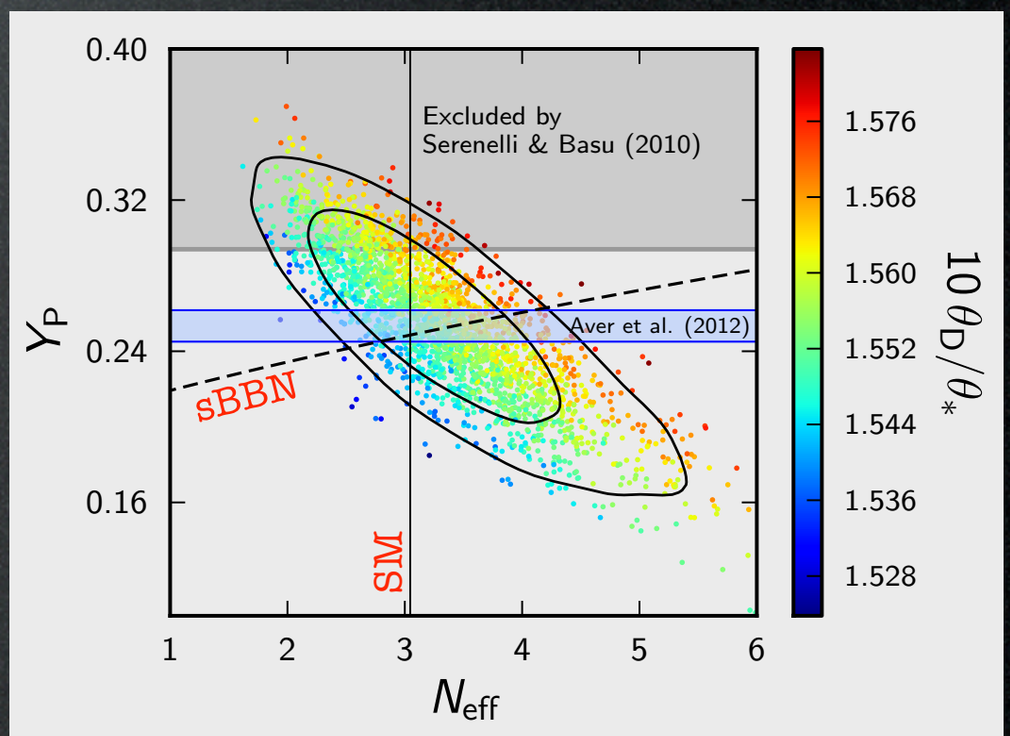
Planck + WMAPpol

Planck + WMAPpol + BAO



E.g. a large H_0 re-allows a large N_{eff}

PS ^{4}He and N_{eff} both from CMB: everything converges to standard



Conclusions

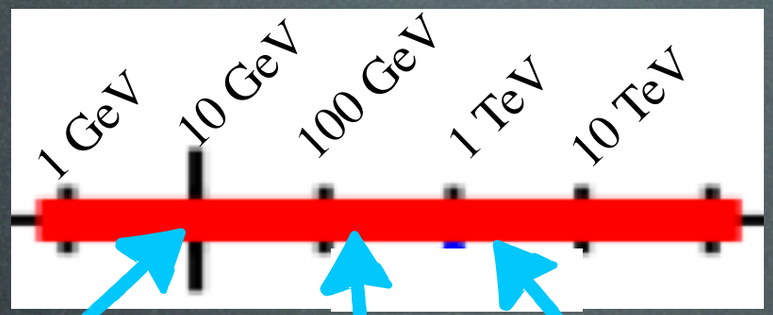
Dark Matter:

Conclusions

Dark Matter: confusion is maximal

Conclusions

Dark Matter: confusion is maximal



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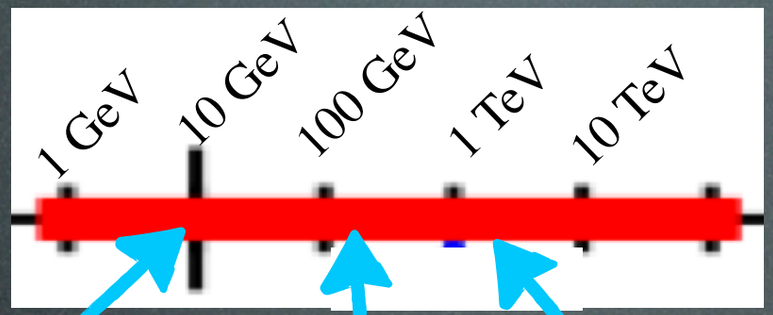
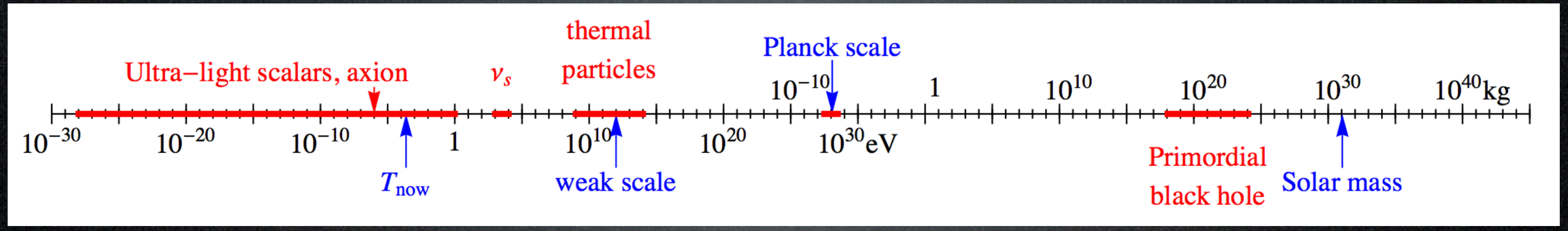
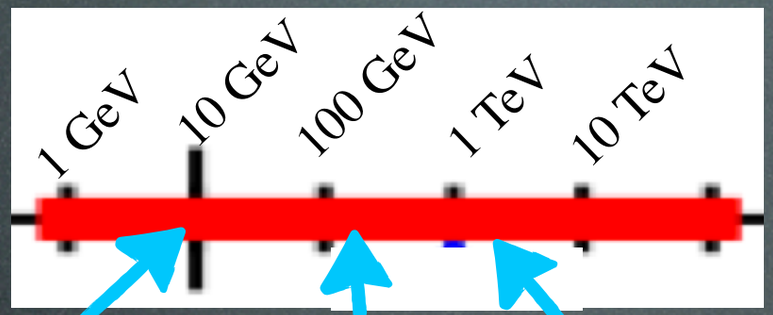
Dark Matter: confusion is maximal

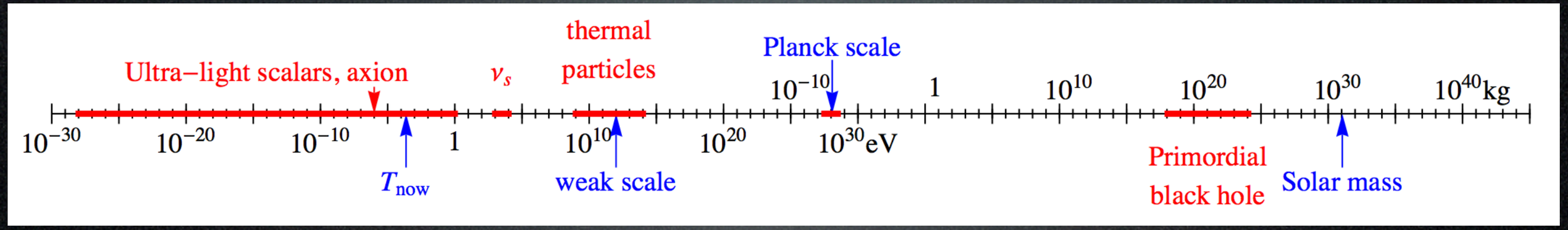




Conclusions

Dark Matter: confusion is maximal

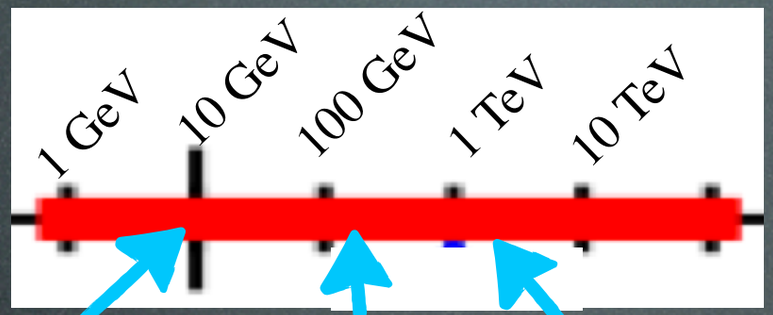


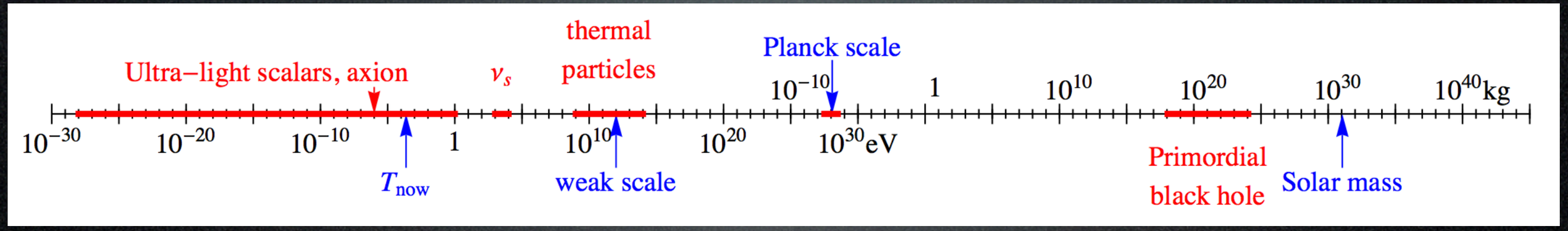


Cosmic Neutrinos:

Conclusions

Dark Matter: confusion is maximal

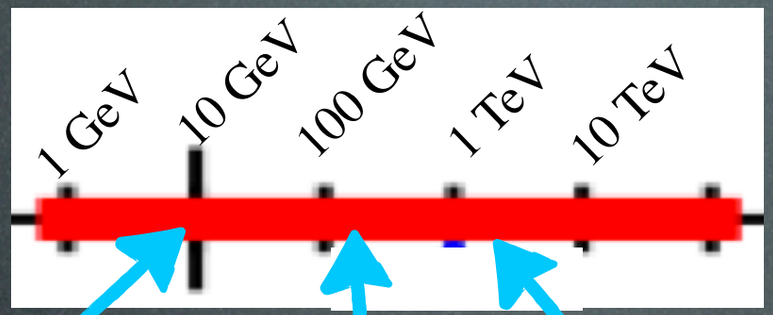


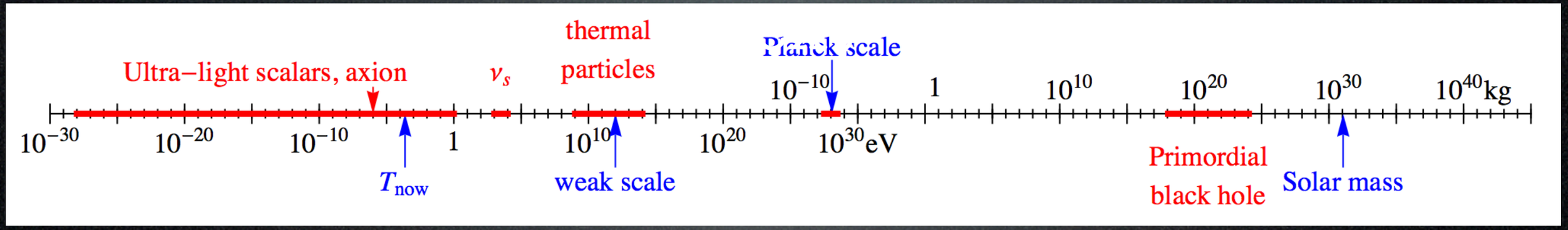


Cosmic Neutrinos: confusion is nearly maximal

Conclusions

Dark Matter: confusion is maximal



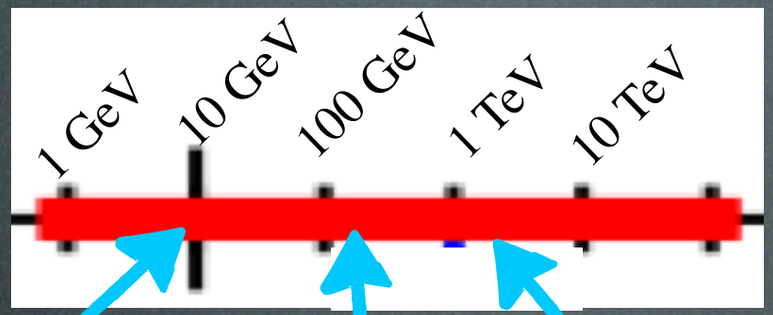


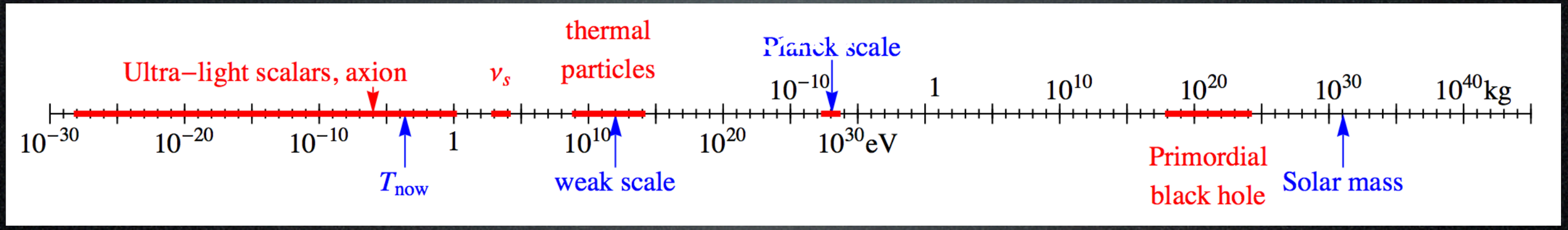
Cosmic Neutrinos: confusion is nearly maximal

state of the art is $N_\nu = 3.30 \pm 0.27$

Conclusions

Dark Matter: confusion is maximal





Cosmic Neutrinos: confusion is nearly maximal

state of the art is $N_\nu = 3.30 \pm 0.27$

Disappointed? Is it a cover-up?