UniverseNET School and Meeting
23 September 2008

New particles as Dark Matter

Marco Cirelli
(CNRS, IPhT-CEA/Saclay)

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Minimal Dark Matter

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(CNRS, IPhT-CEA/Saclay)

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Nuclear Physics B 753 (2006)
Nuclear Physics B 787 (2007)
Nuclear Physics B 800 (2008)
0808.3867 [astro-ph]
0809.2409 [hep-ph]
and work in progress

Statement

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Minimalistic approach

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

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

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

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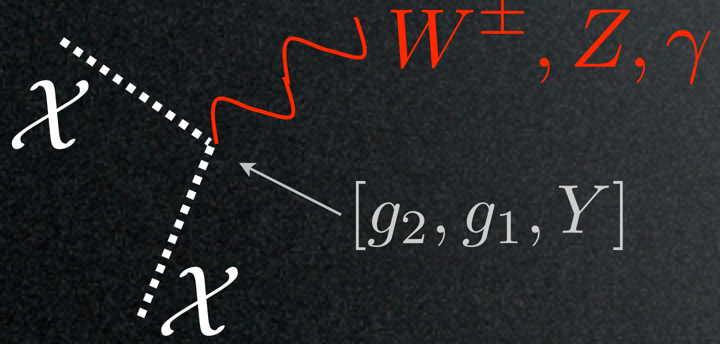
gauge interactions



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

(other terms in the scalar potential)

(one loop mass splitting)

and systematically search for the ideal DM candidate...

The ideal DM candidate is

weakly int., massive, neutral, stable

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

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

these are all possible choices:

$n \leq 5$ for fermions

$n \leq 7$ for scalars

to avoid explosion in the running coupling

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

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

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

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

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

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

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

etc.

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

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

The mass M is determined by the relic abundance:

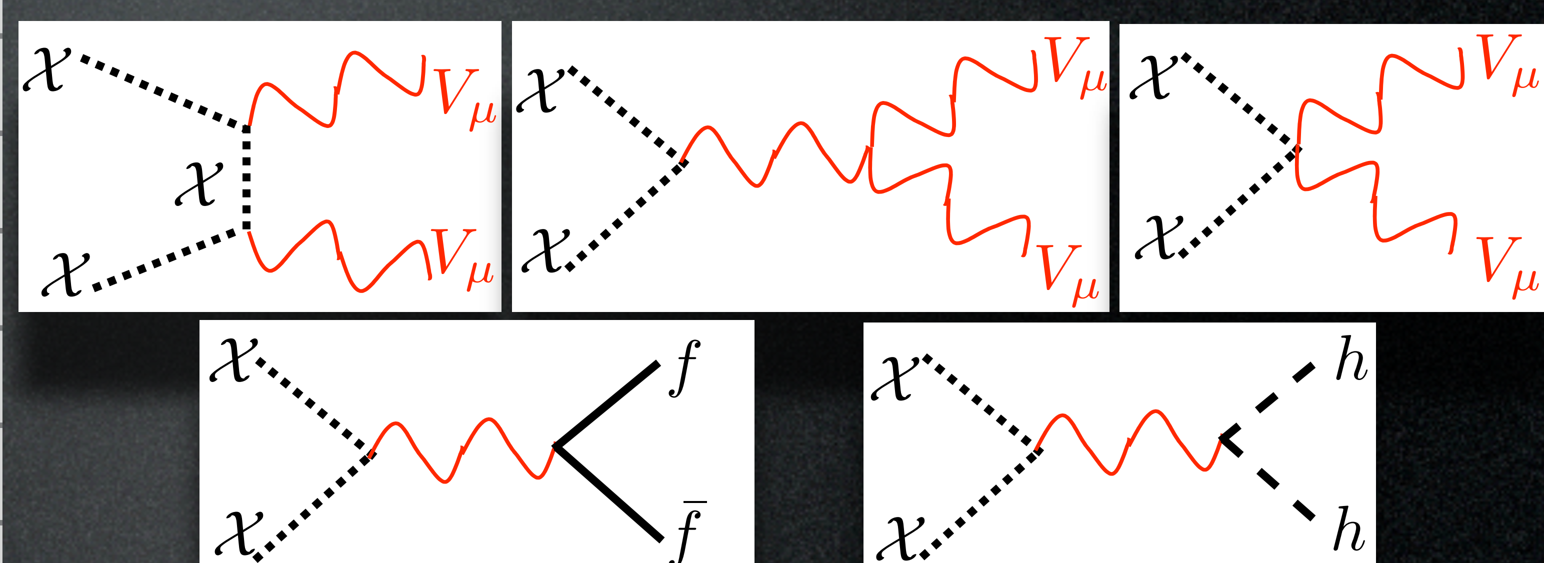
$$\Omega_{\rm DM} = \frac{6\ 10^{-27}{\rm cm}^3{\rm s}^{-1}}{\langle \sigma_{\rm ann} v\rangle} \simeq 0.24$$

for $\mathcal{X}$ scalar

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

for $\mathcal{X}$ fermion

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



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

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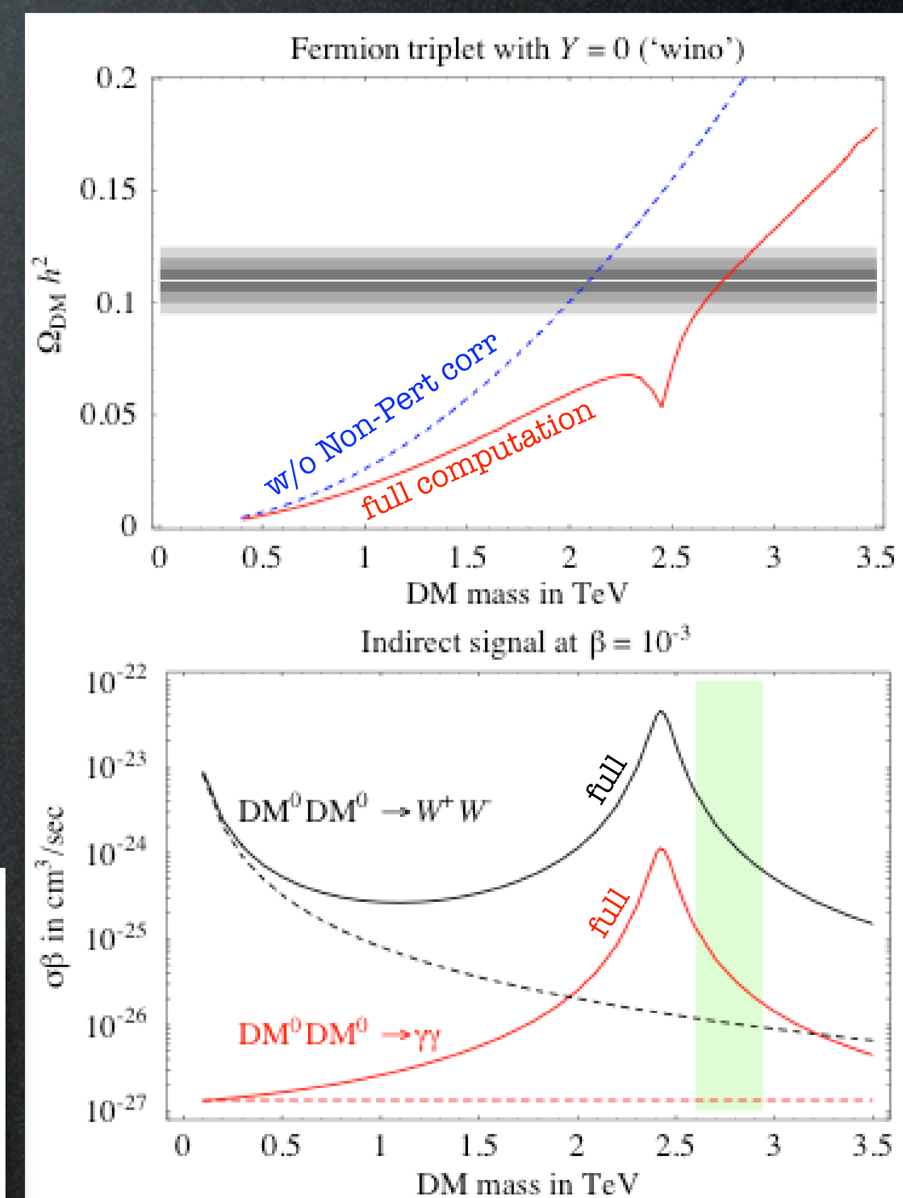
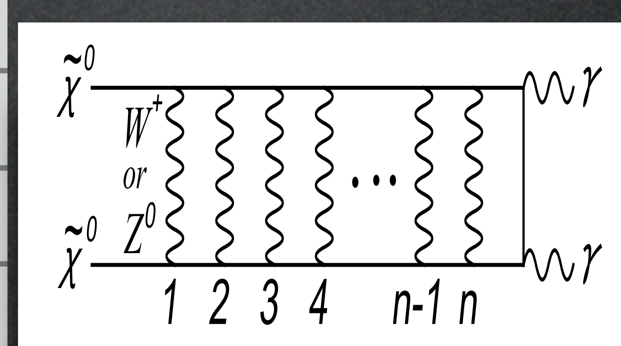
$SU(2)_L$	$U(1)_Y$	spin	M (TeV)
2	1/2	S	
		F	1.0
3	0	S	2.5
		F	2.7
	1	S	
		F	
4	1/2	S	
		F	
	3/2	S	
		F	
5	0	S	9.4
		F	10
	1	S	
		F	
	2	S	
		F	
7	0	S	25

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

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

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





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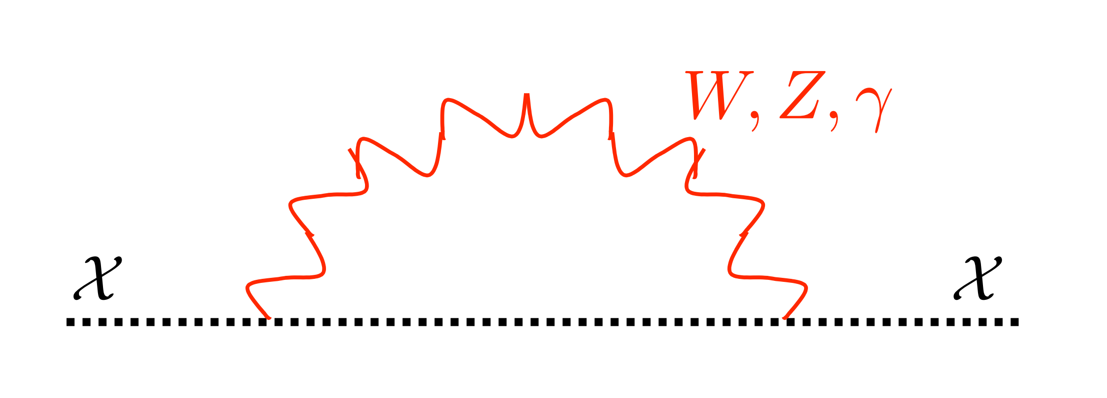
	1	S		537
		F		534
	2	S		906
		F		900
7	0	S	25	166

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

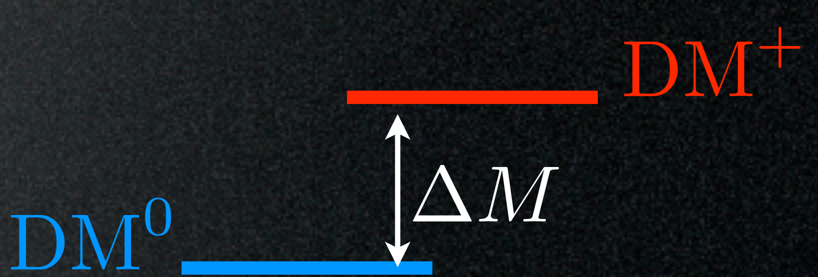
tree level



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

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

The neutral component is the lightest



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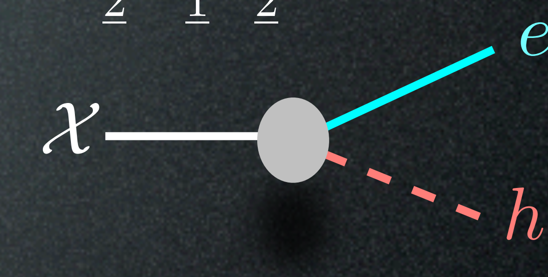
List all allowed SM couplings:

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



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dim=5 operator, induces

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

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

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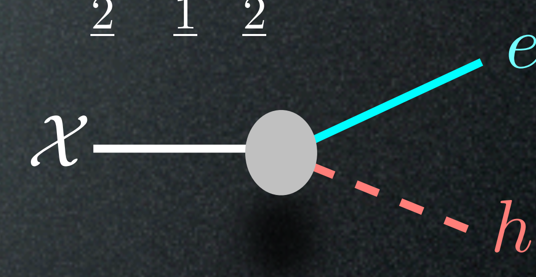

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for $\Lambda \sim M_{\text{Pl}}$

No allowed decay!

Automatically stable!

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and

not excluded

by direct searches!

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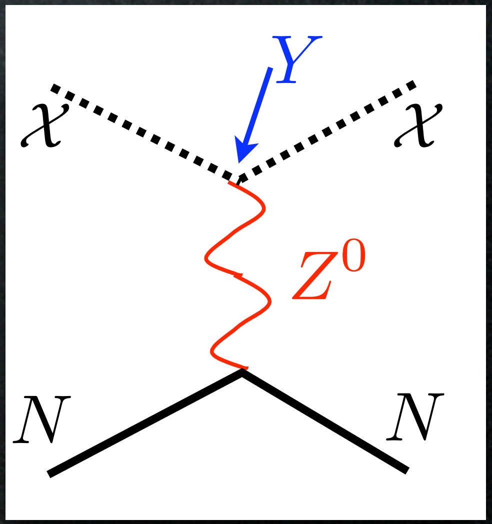
Candidates with $Y \neq 0$ interact as



$\sigma \simeq G_F^2 M_N^2 Y^2$

$\gg$ present bounds

e.g. Xenon, CDMS

need $Y = 0$

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We have a winner!

and a 2° place

(other terms in the scalar potential)

Recap:

A fermionic $SU(2)_L$ quintuplet with $Y = 0$
provides a DM candidate with $M = 10$ TeV,
which is fully successful:

- neutral
- ***automatically*** stable

like proton stability in SM!

and

not yet discovered by DM searches.

A scalar $SU(2)_L$ eptaplet with $Y = 0$ also does.

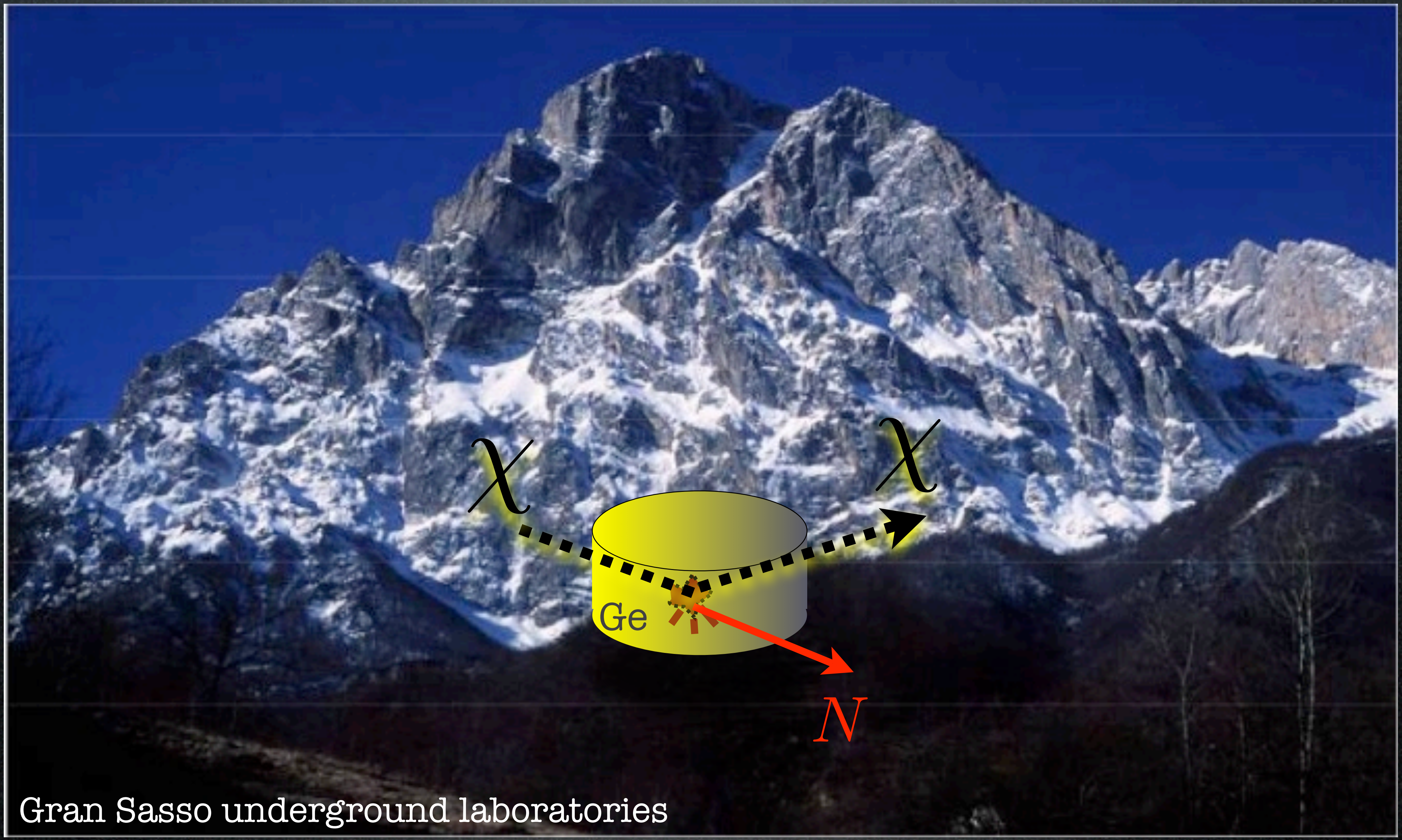
(Other candidates can be cured via non-minimalities.)

Detection and Phenomenology

DM detection

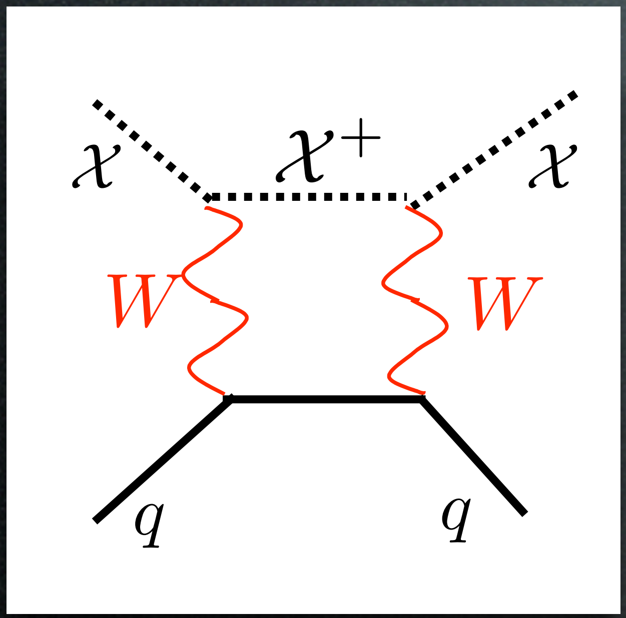
- direct detection
- production at colliders
- indirect
  - γ from annihil in galactic halo or center (line + continuum)
  - e^+ from annihil in galactic halo or center
  - $\bar{p}$ from annihil in galactic halo or center
  - $\bar{D}$ from annihil in galactic halo or center
  - $\nu, \bar{\nu}$ from annihil in massive bodies
- tracing in Cosmic Rays?

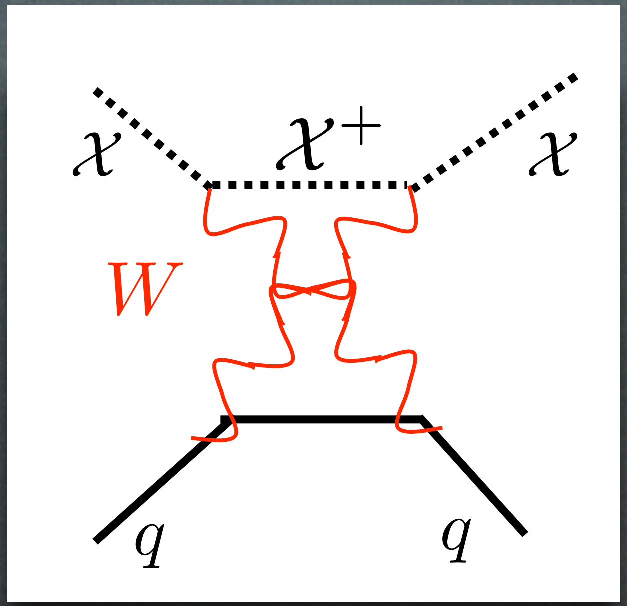
1. Direct Detection

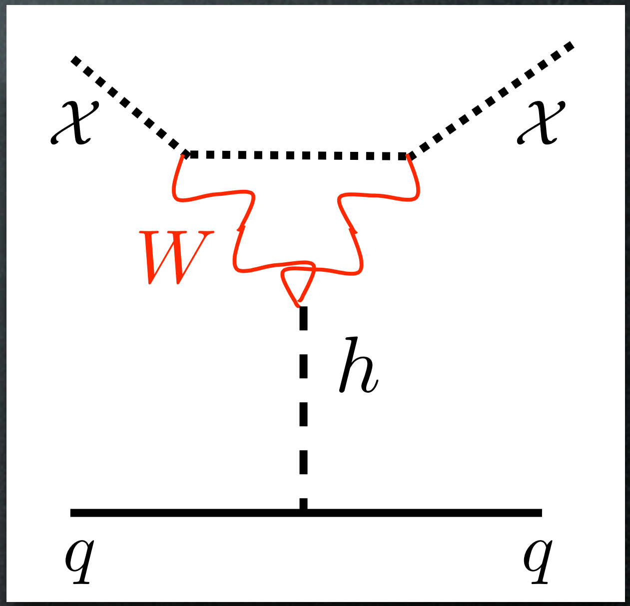


1. Direct Detection

one-loop processes







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

larger for higher n

Spin-Independent

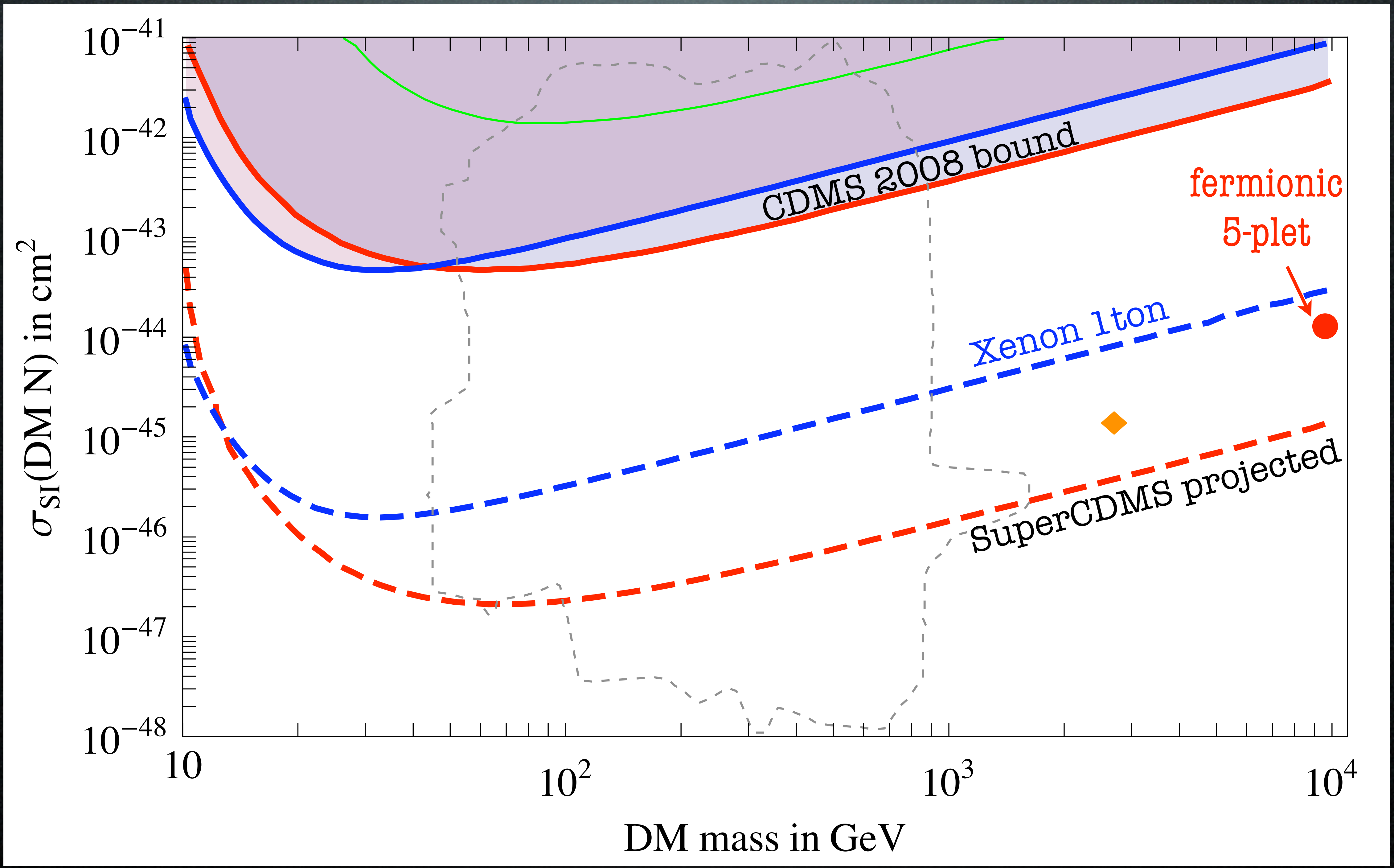
$$\propto \frac{m_q}{M_W^3}$$

Spin-Dependent

$$\propto \frac{1}{MM_W}$$

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

1. Direct Detection

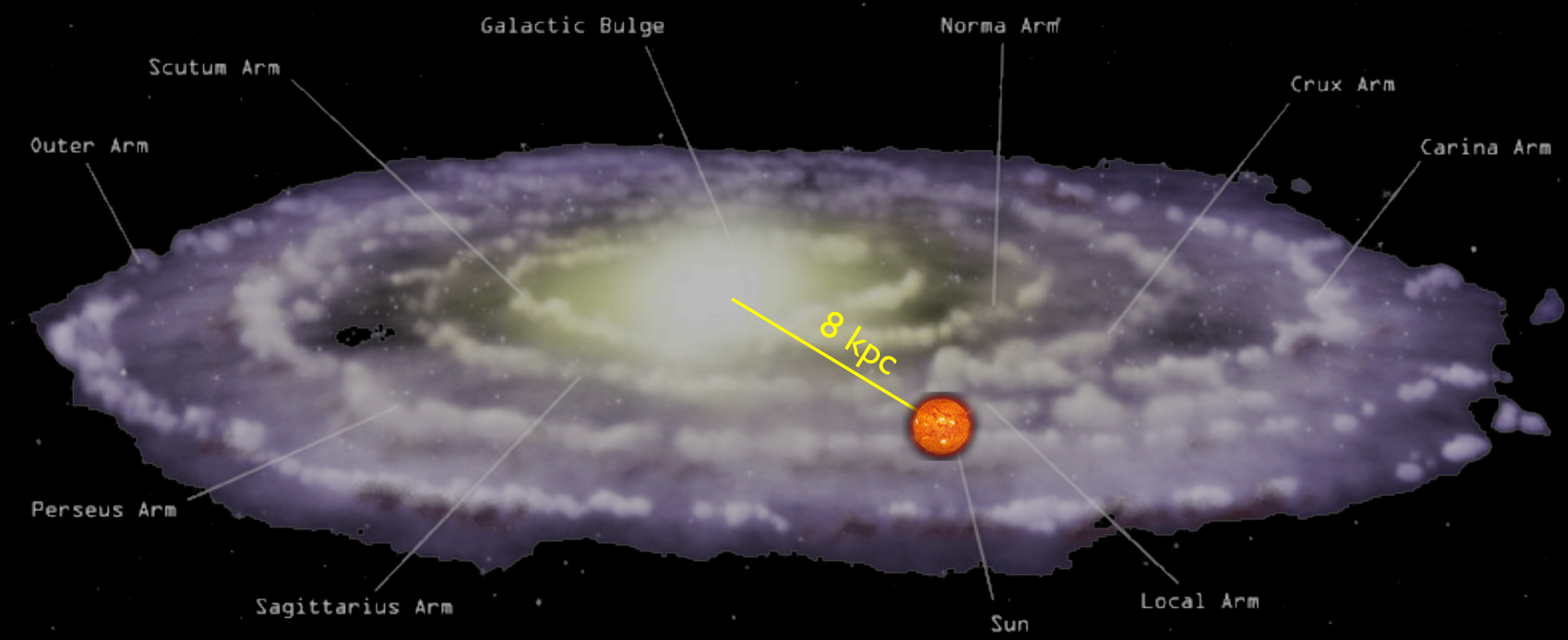


(NB: no free parameters => one predicted point per candidate)

[skip to conclusions]

3. Indirect Detection

i.e. $\nu, \bar{p}, e^{+}, \gamma, \bar{D}$ from MDM annihilations in halo or body.



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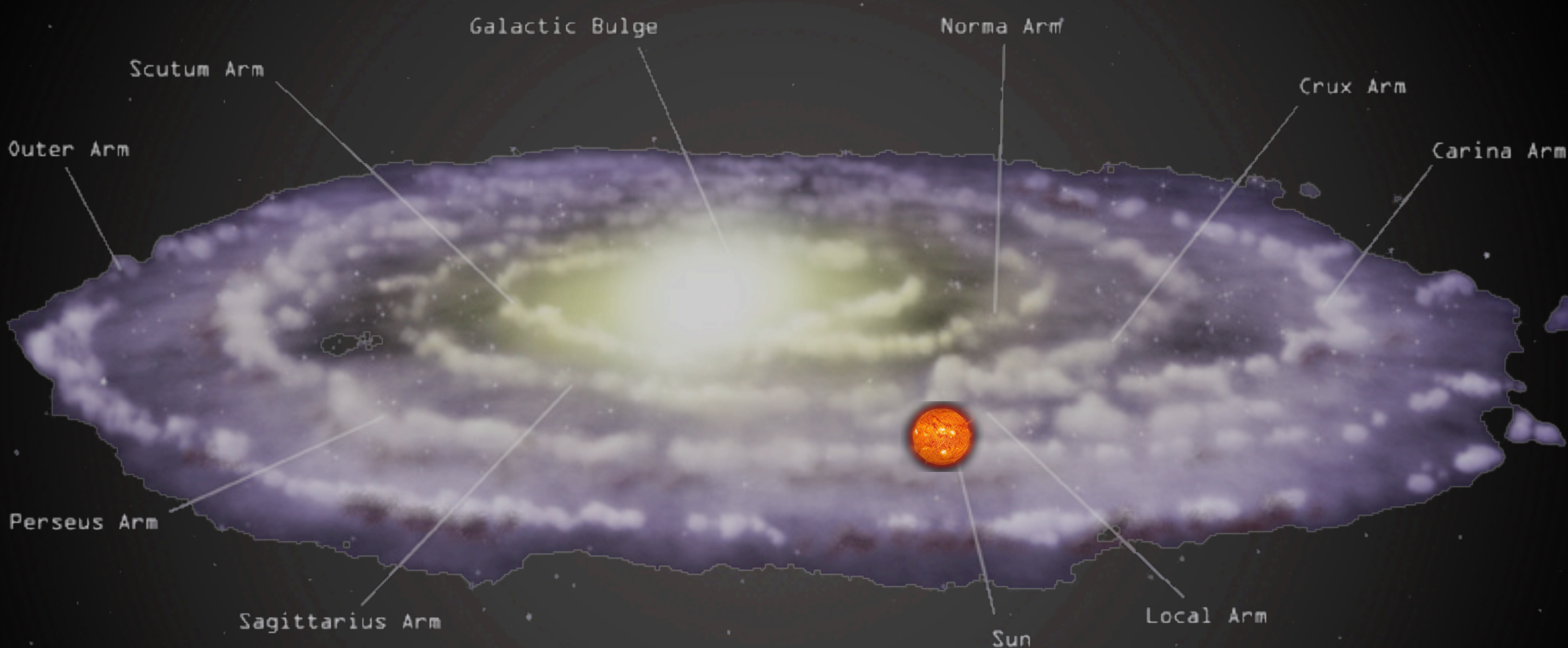

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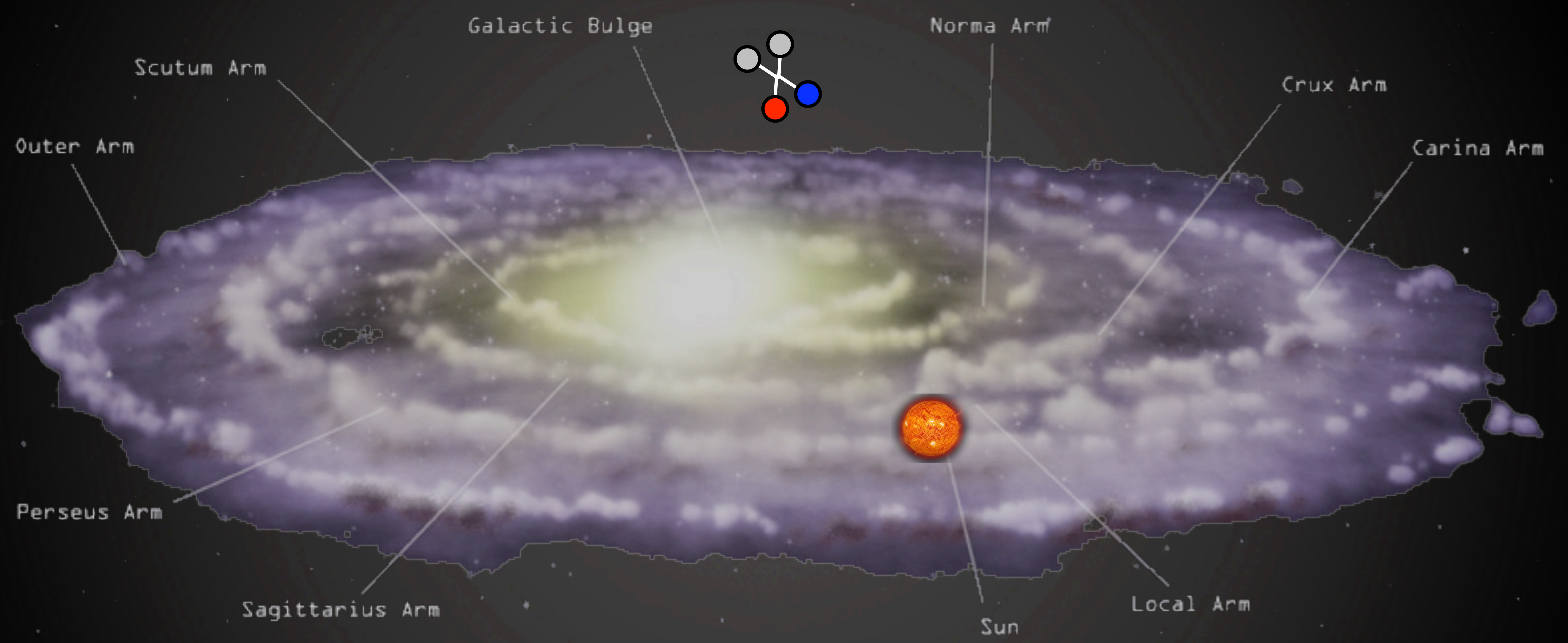

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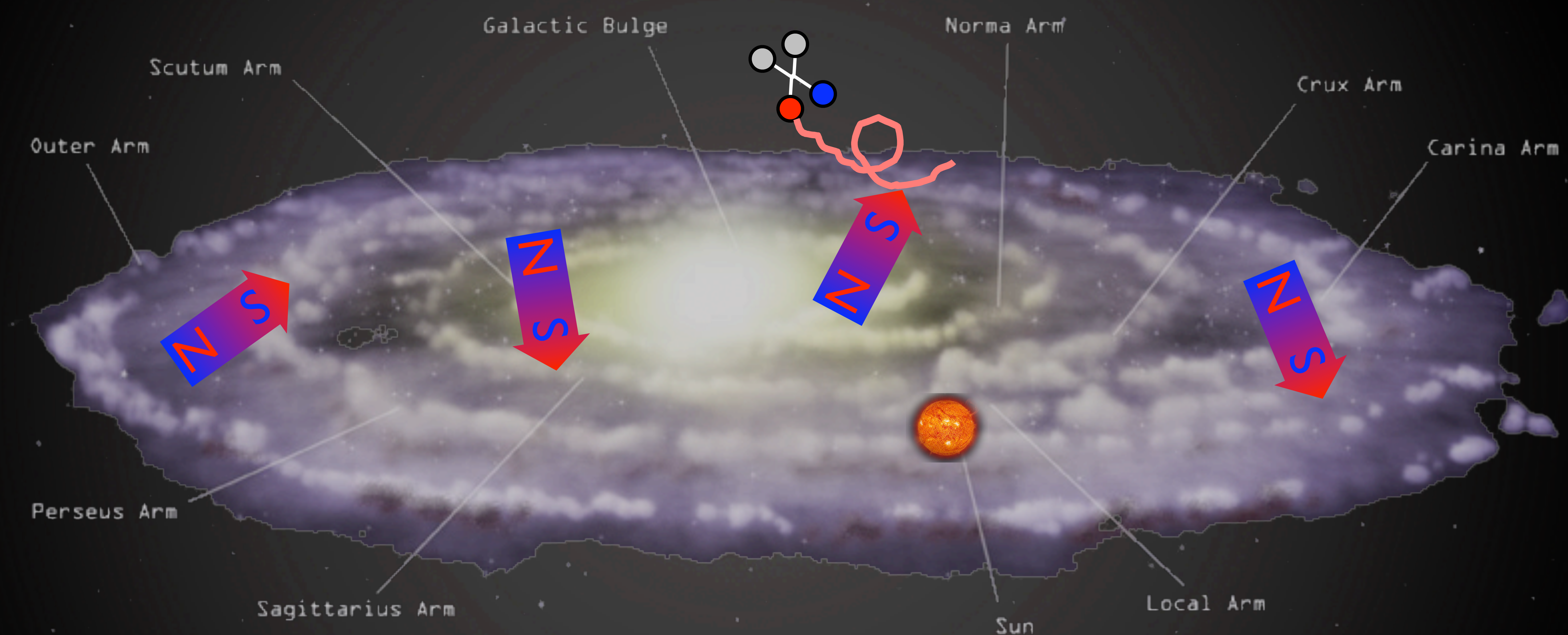

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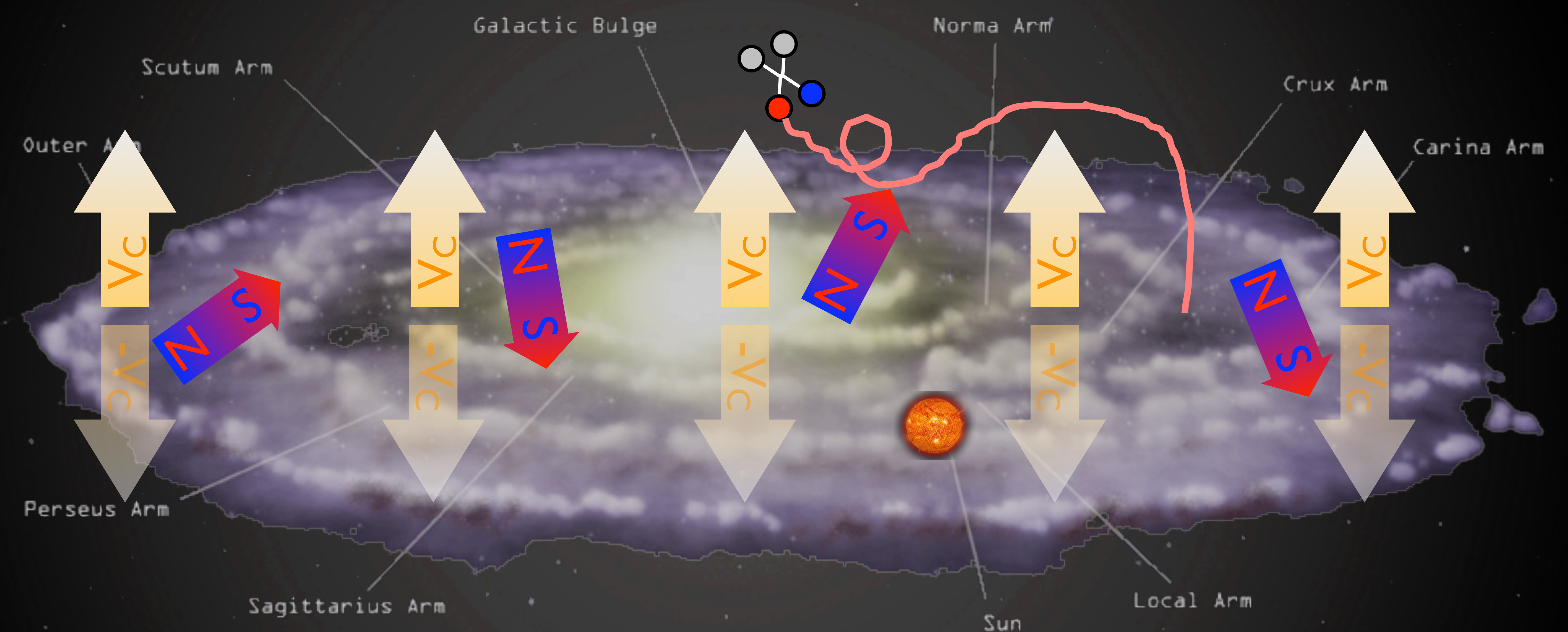

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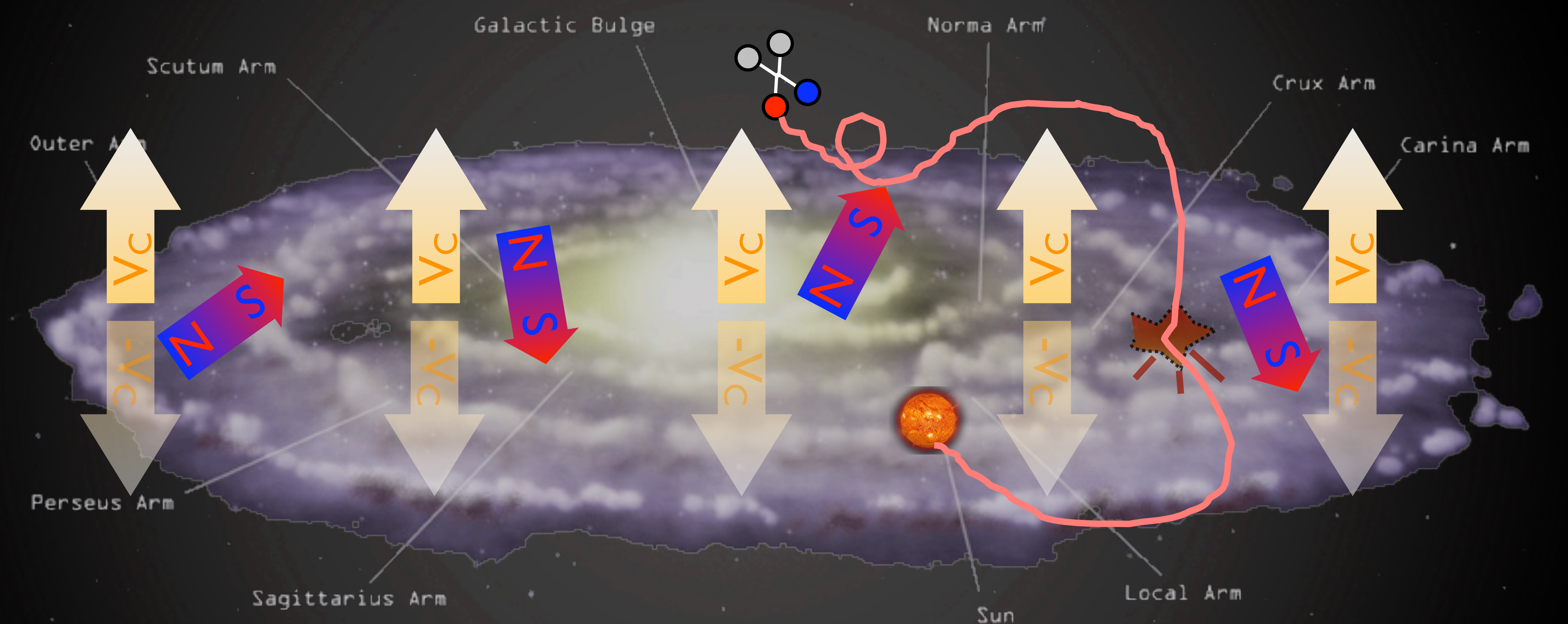

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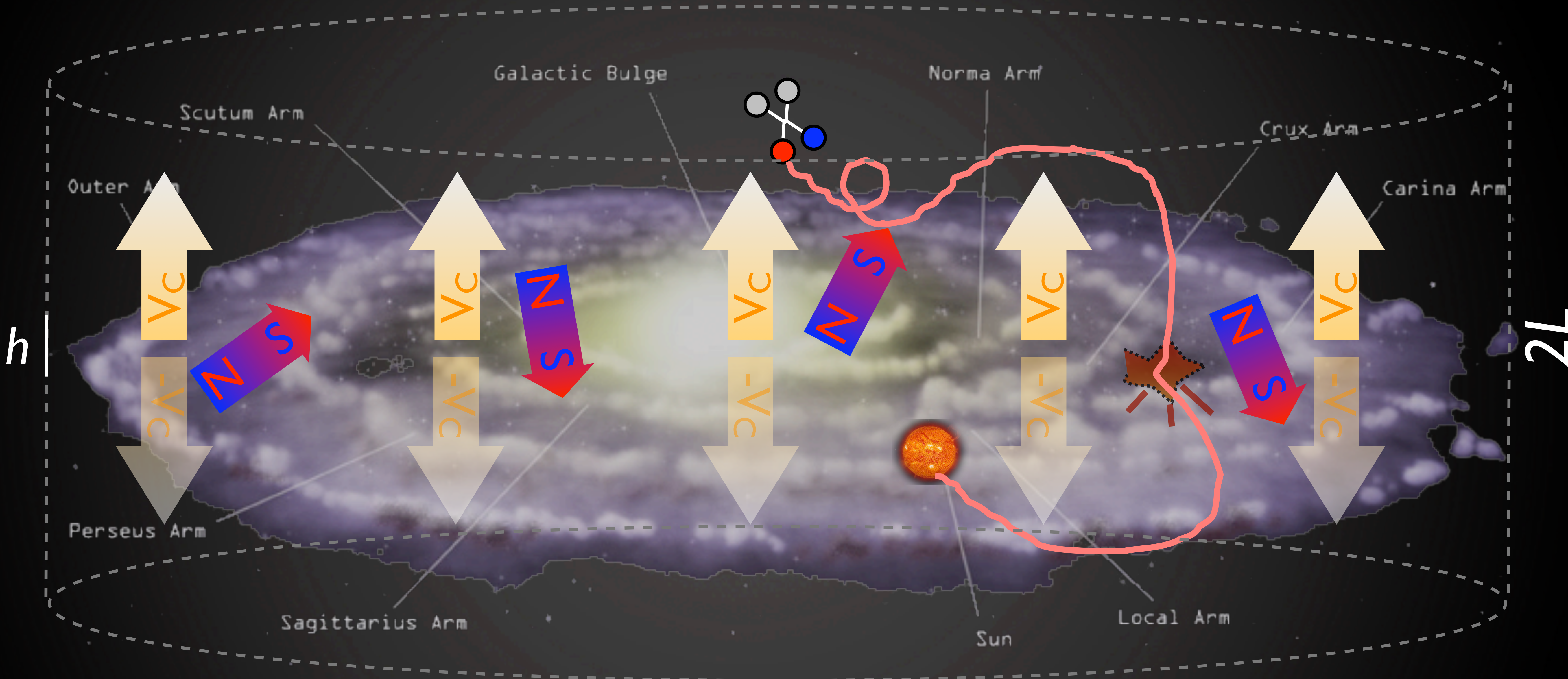


spectrum

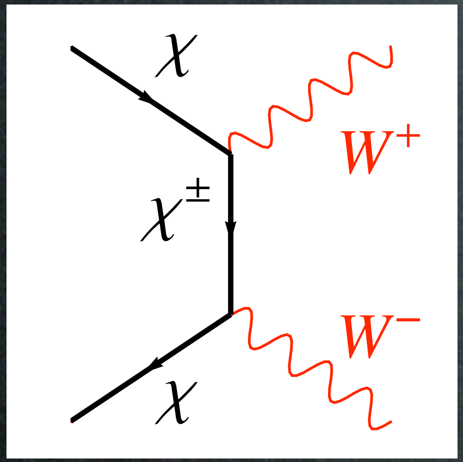
$$\frac{\partial f}{\partial t} - K(E) \cdot \nabla^2 f - \frac{\partial}{\partial E}(b(E) f) + \frac{\partial}{\partial z}(V_c f) = Q_{\rm inj} - 2h\delta(z)\Gamma_{\rm spall} f$$

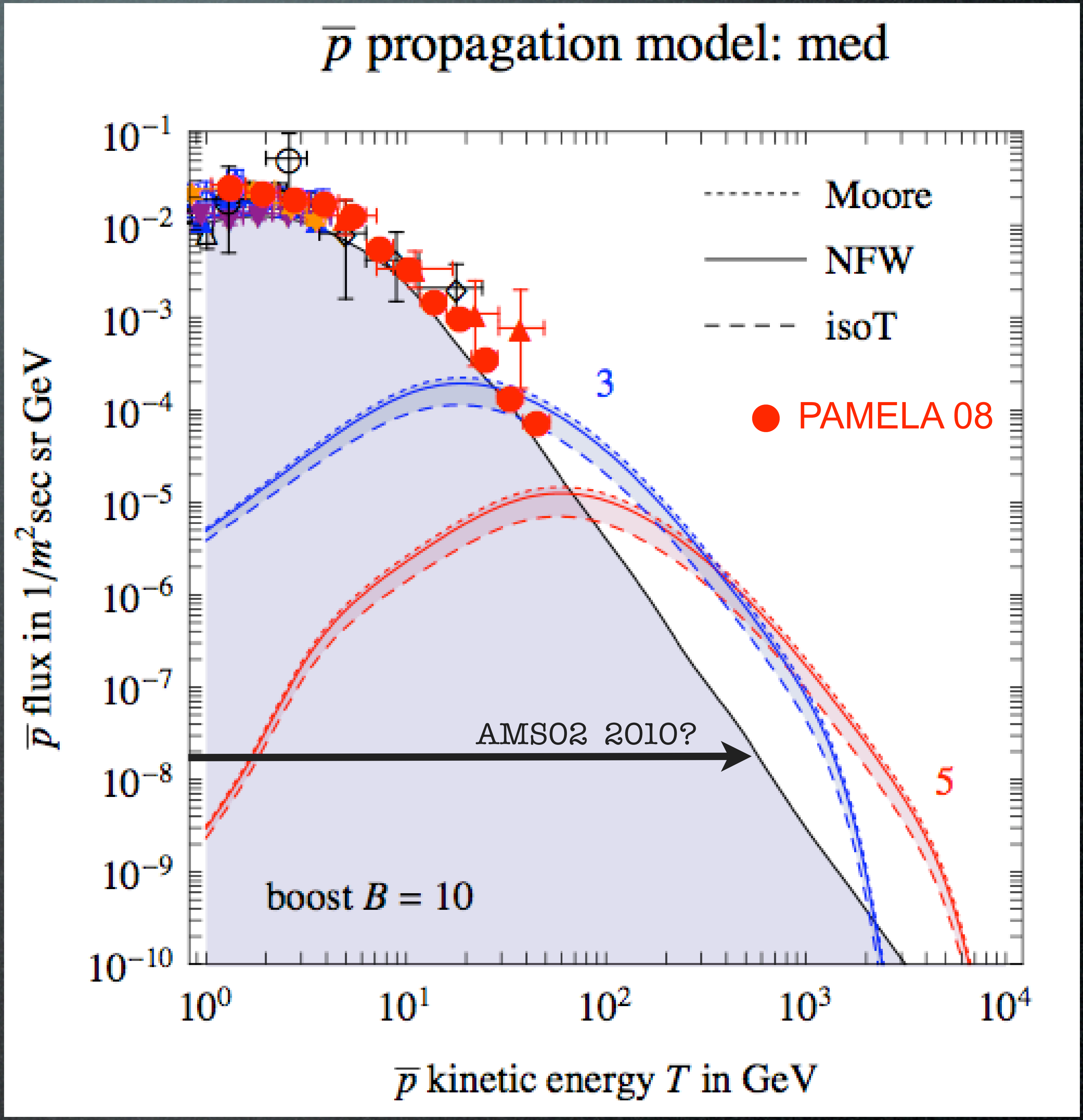
diffusion — energy loss — convective wind — source — spallations

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

3. Indirect Detection

Results for anti-protons:





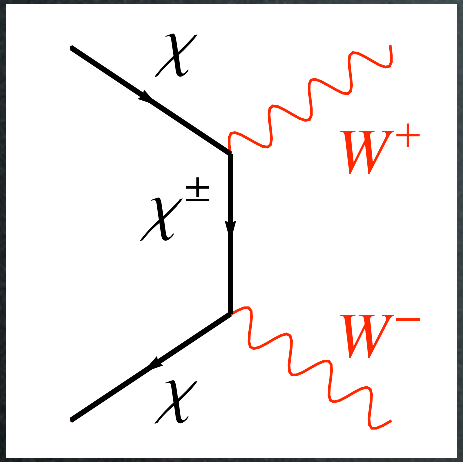
Astro uncertainties:

- propagation model
- DM halo profile
- boost factor B

Distinctive signal,
PAMELA prelim., AMS02.

3. Indirect Detection

Results for positrons:



Astro uncertainties:

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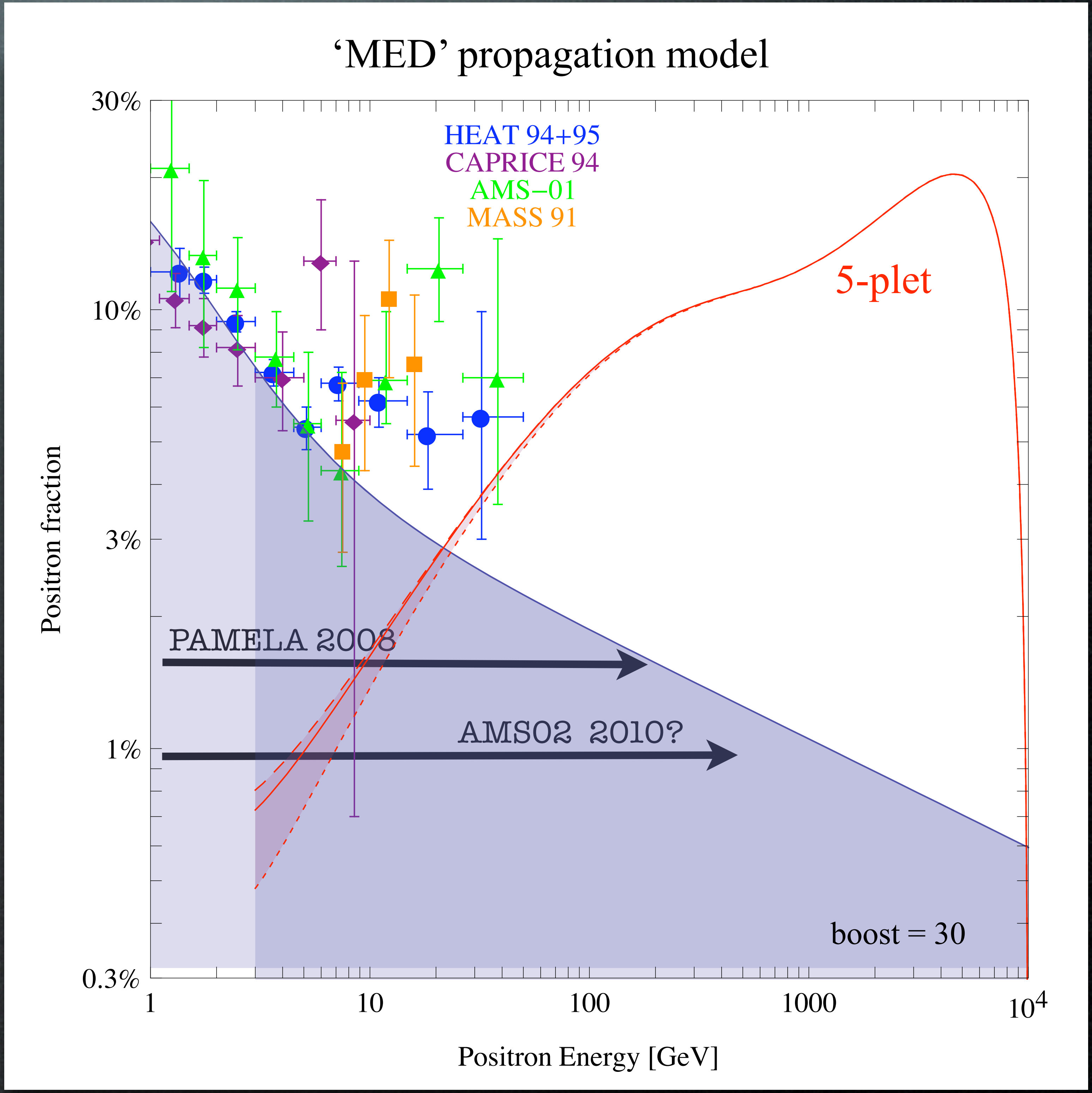
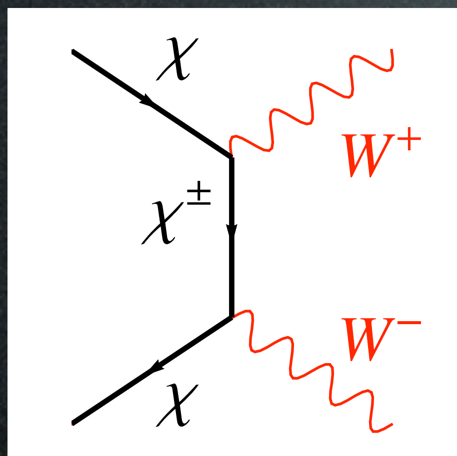
- boost factor B



Distinctive signal,
quite robust vs astro,
awaiting PAMELA, AMS02.

3. Indirect Detection

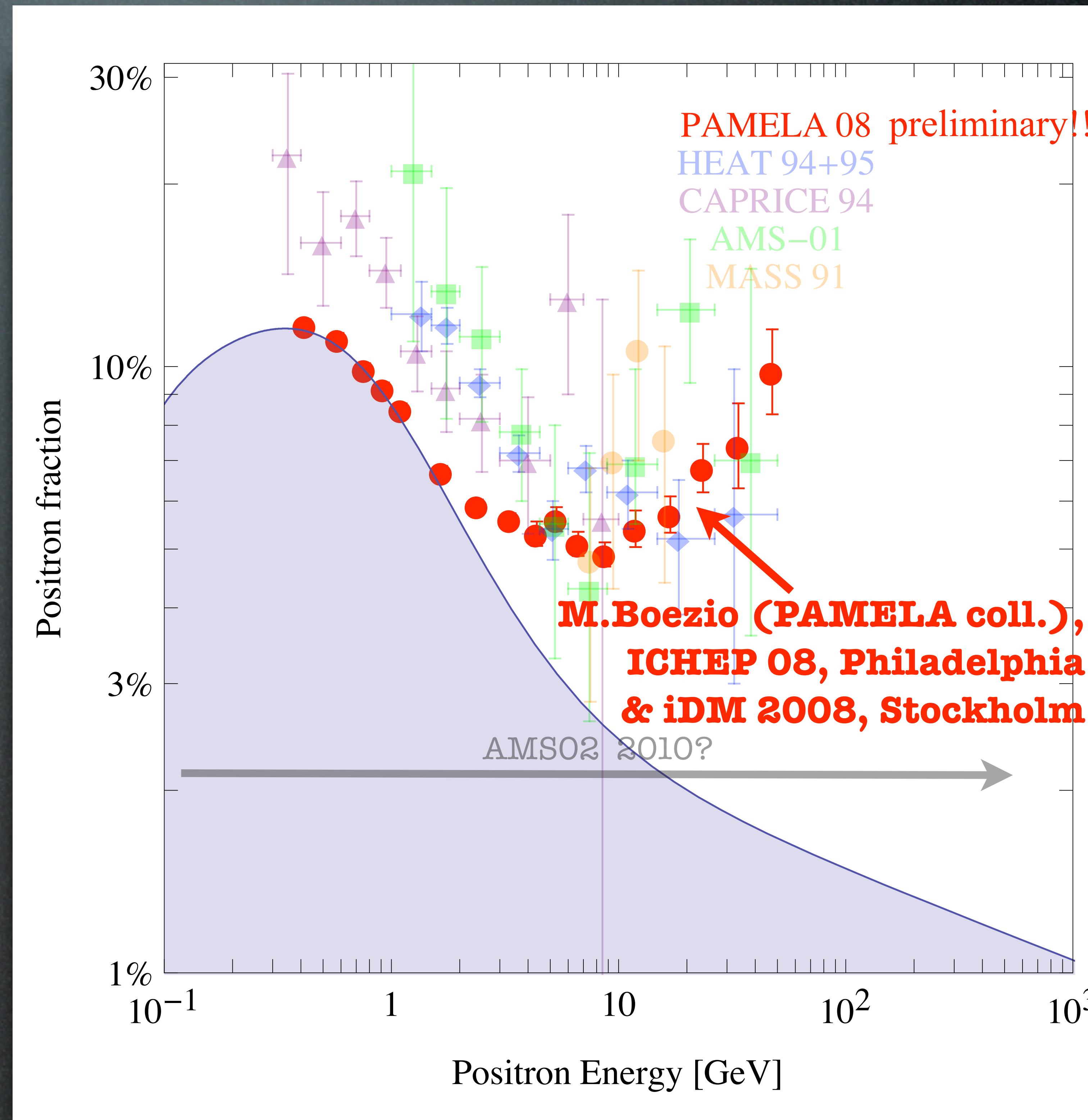
Results for positrons:



Astro uncertainties:

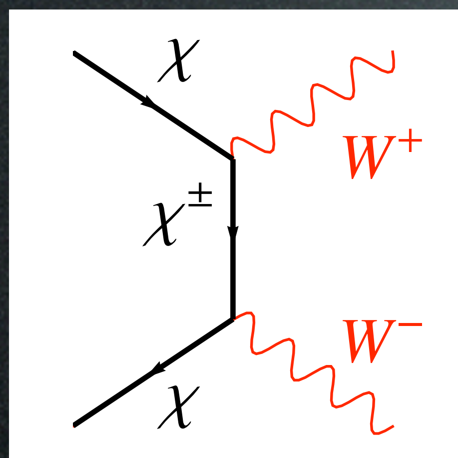
- propagation model
- DM halo profile
- boost factor B

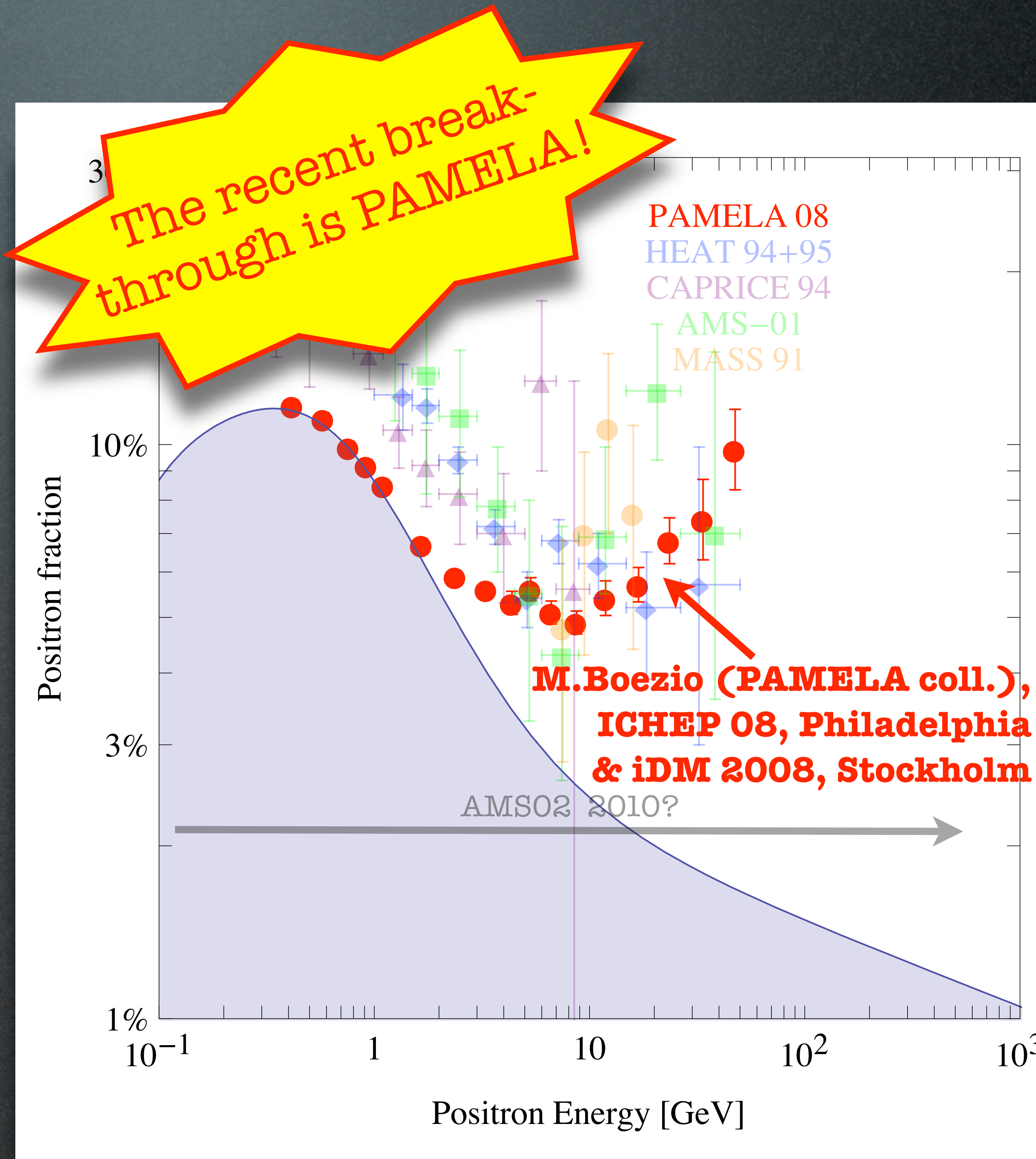
Distinctive signal,
quite robust vs astro,
here is PAMELA!



3. Indirect Detection

Results for positrons:





Astro uncertainties:

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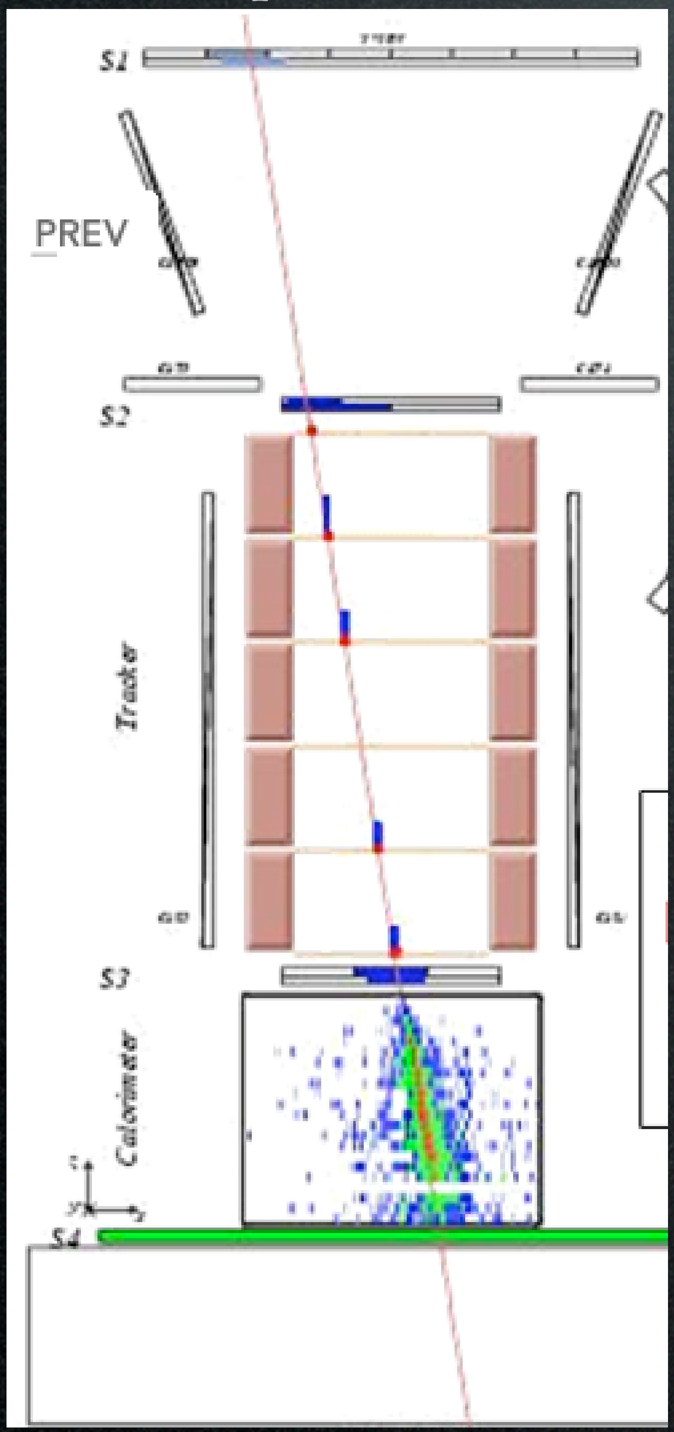
- boost factor B

Distinctive signal,
quite robust vs astro,
here is PAMELA!

3. Indirect Detection

PAMELA

92 GeV positron event

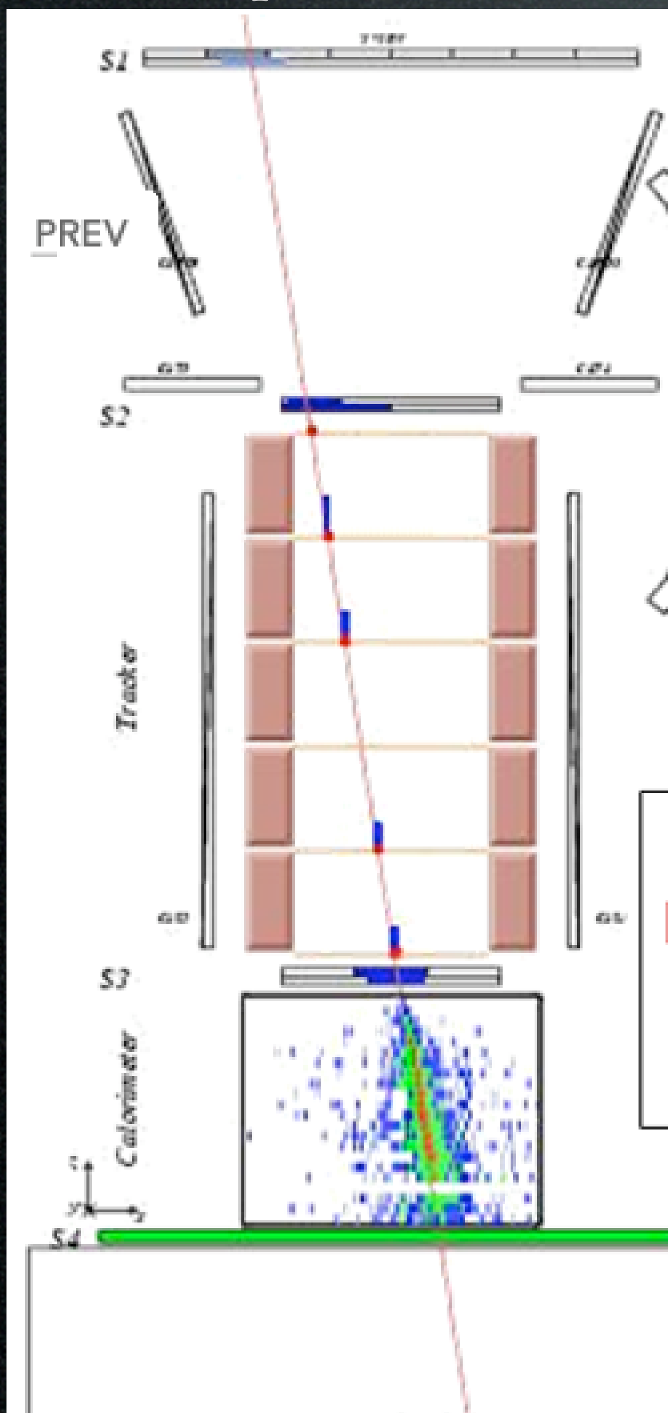


Payload for
Anti-
Matter
Exploration and
Light-nuclei
Astrophysics

http://pamela.roma2.infn.it

3. Indirect Detection

92 GeV positron event



PAMELA

Payload for
Anti-
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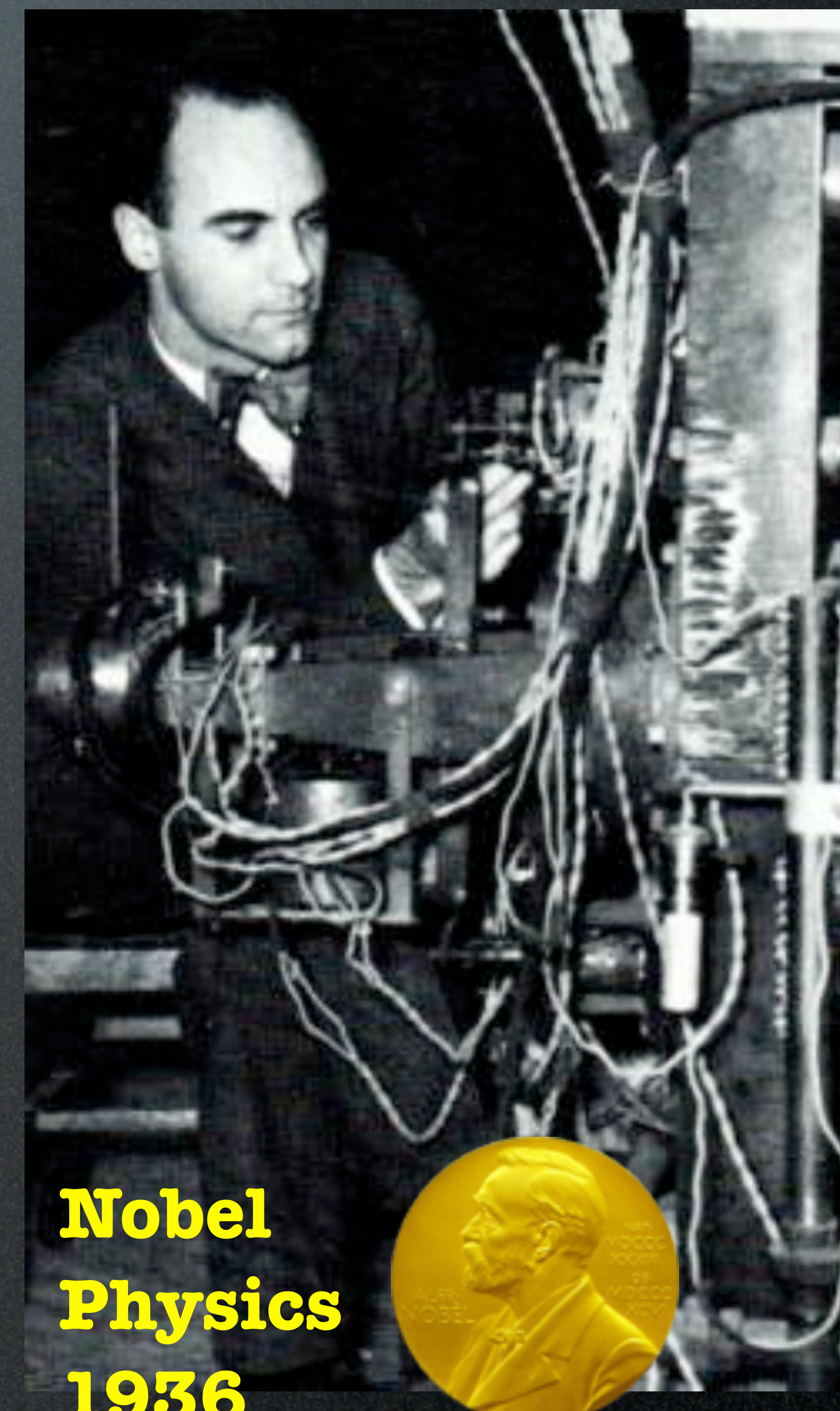
http://pamela.roma2.infn.it

Carl D. Anderson



Nobel Physics 1936

"for his discovery of the positron"

3. Indirect Detection

PAMELA

Payload for
Anti-
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Exploration and
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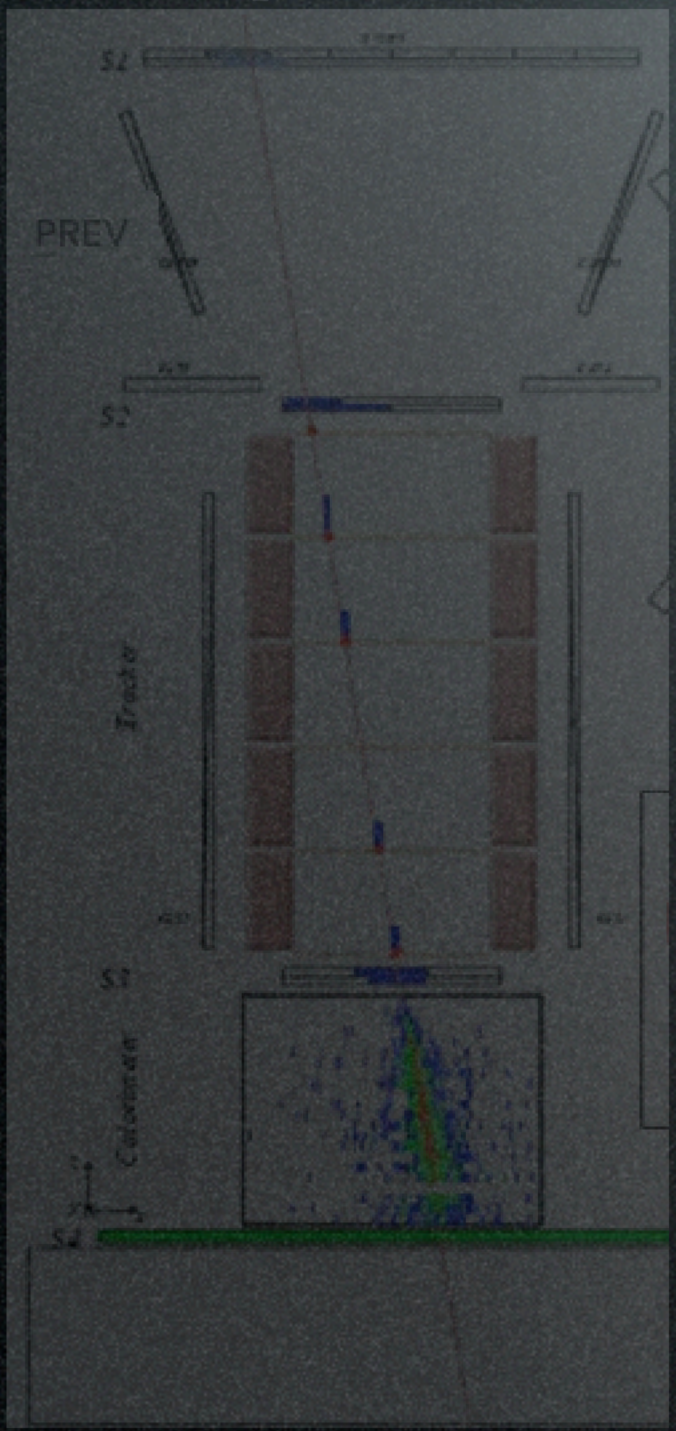
Astrophysics

92 GeV positron event



http://pamela.roma2.infn.it

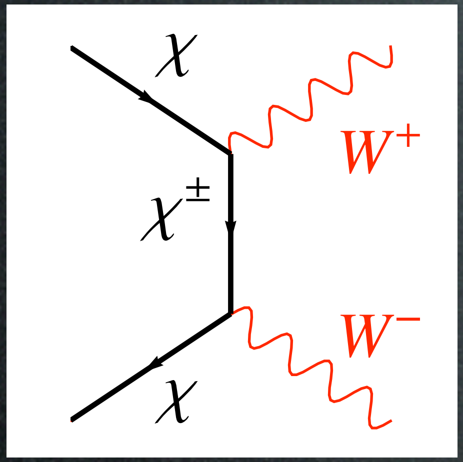
Carl D. Anderson

Nobel
Physics
1936

"for his discovery of the positron"

3. Indirect Detection

Results for positrons:



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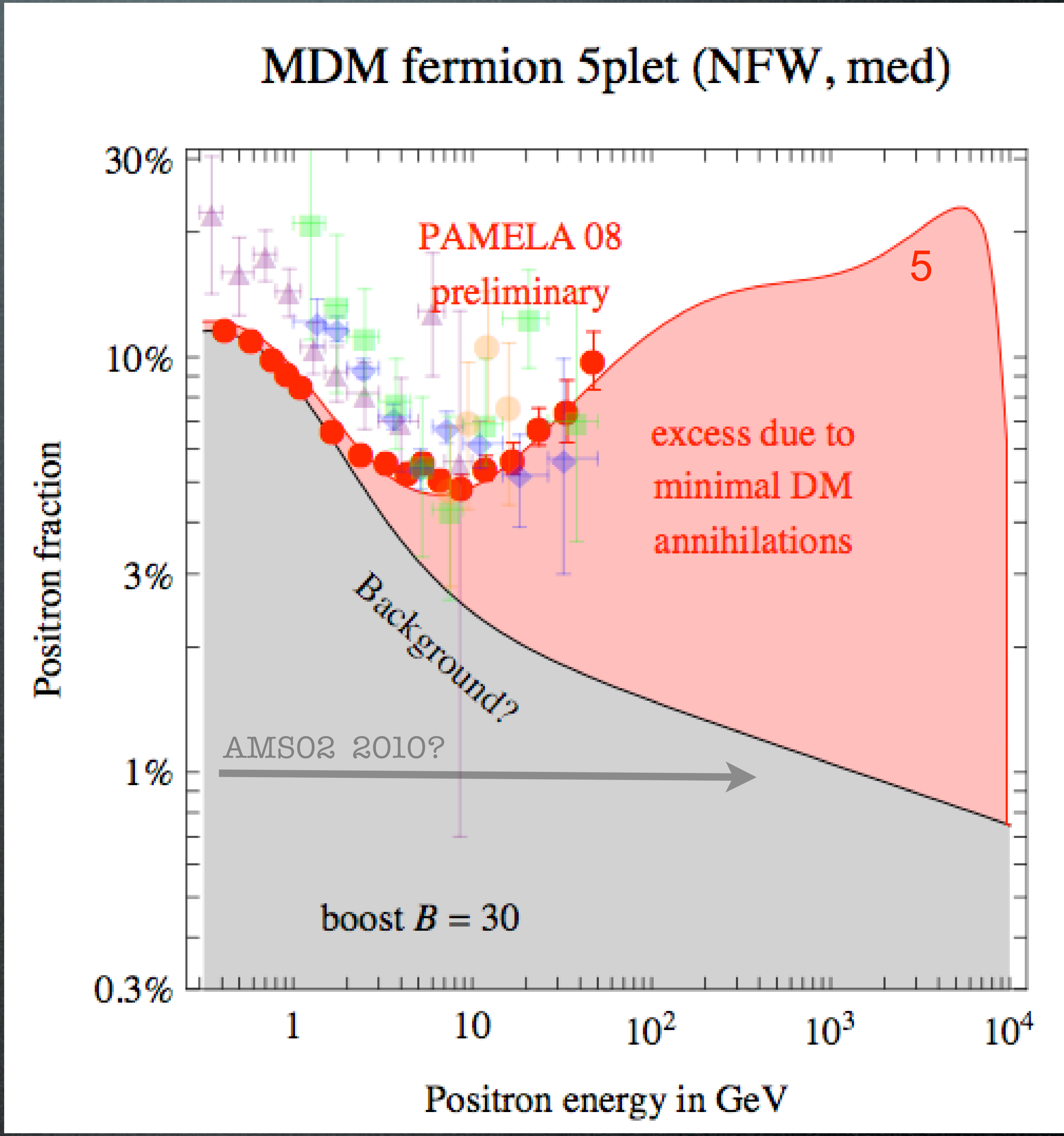
Distinctive signal, quite robust vs astro, here is PAMELA!



Conclusions

The DM problem requires physics beyond the SM.

Introducing the minimal amount of it,
we find some fully successful DM candidates:
massive, neutral, *automatically* stable.

The “best” is the
fermionic $SU(2)_L$ quintuplet with $Y = 0$.
$(M = 10\ \mathrm{TeV})$

Its phenomenology is precisely computable:

- can be found in next gen direct detection exp’s,
- too heavy to be produced at LHC,
- gives signals in indirect detection exp’s,
- can be searched for in UHE CR.

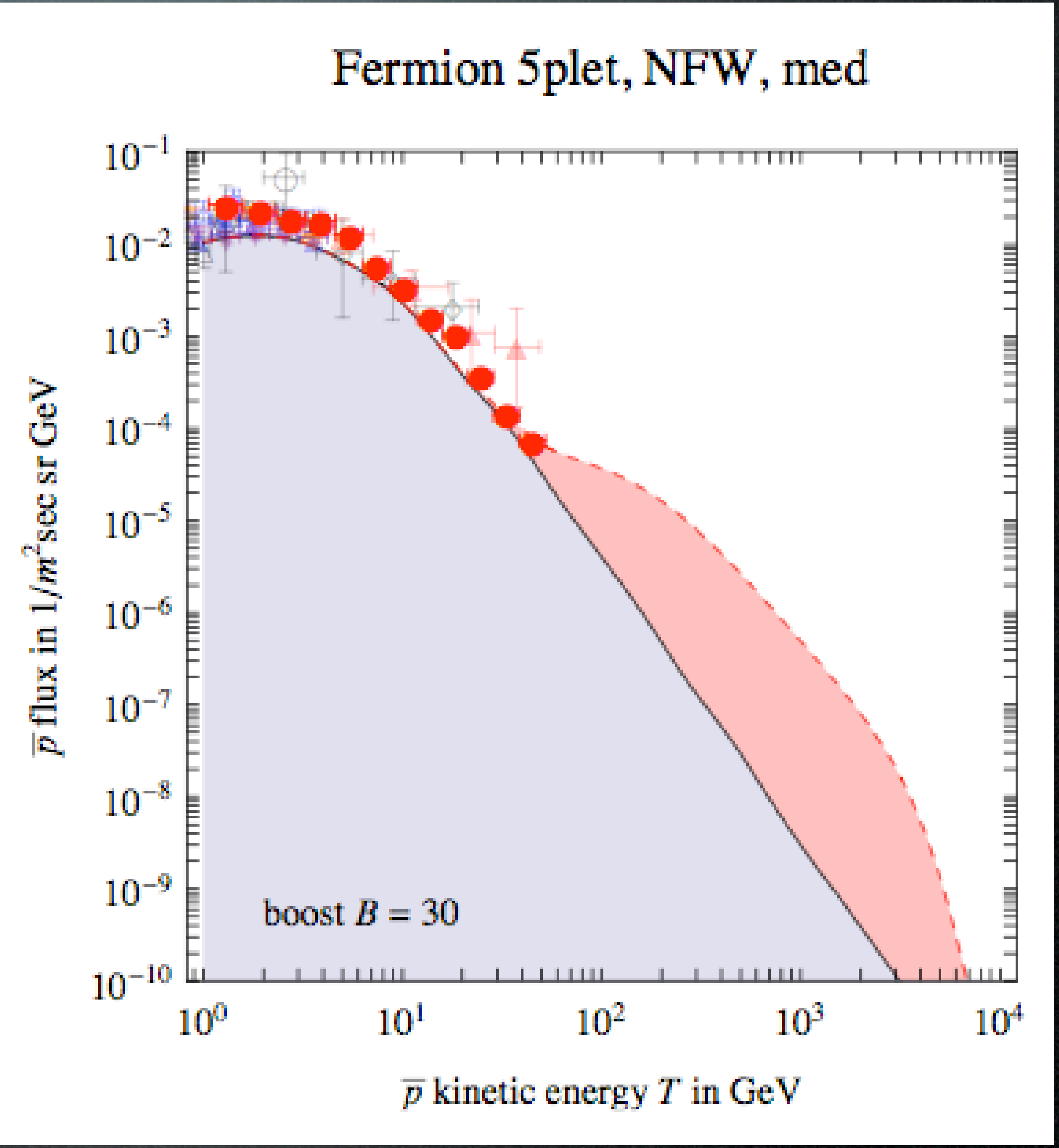
Back-up
slides

3. Indirect Detection

Results for anti-protons:

Astro uncertainties:

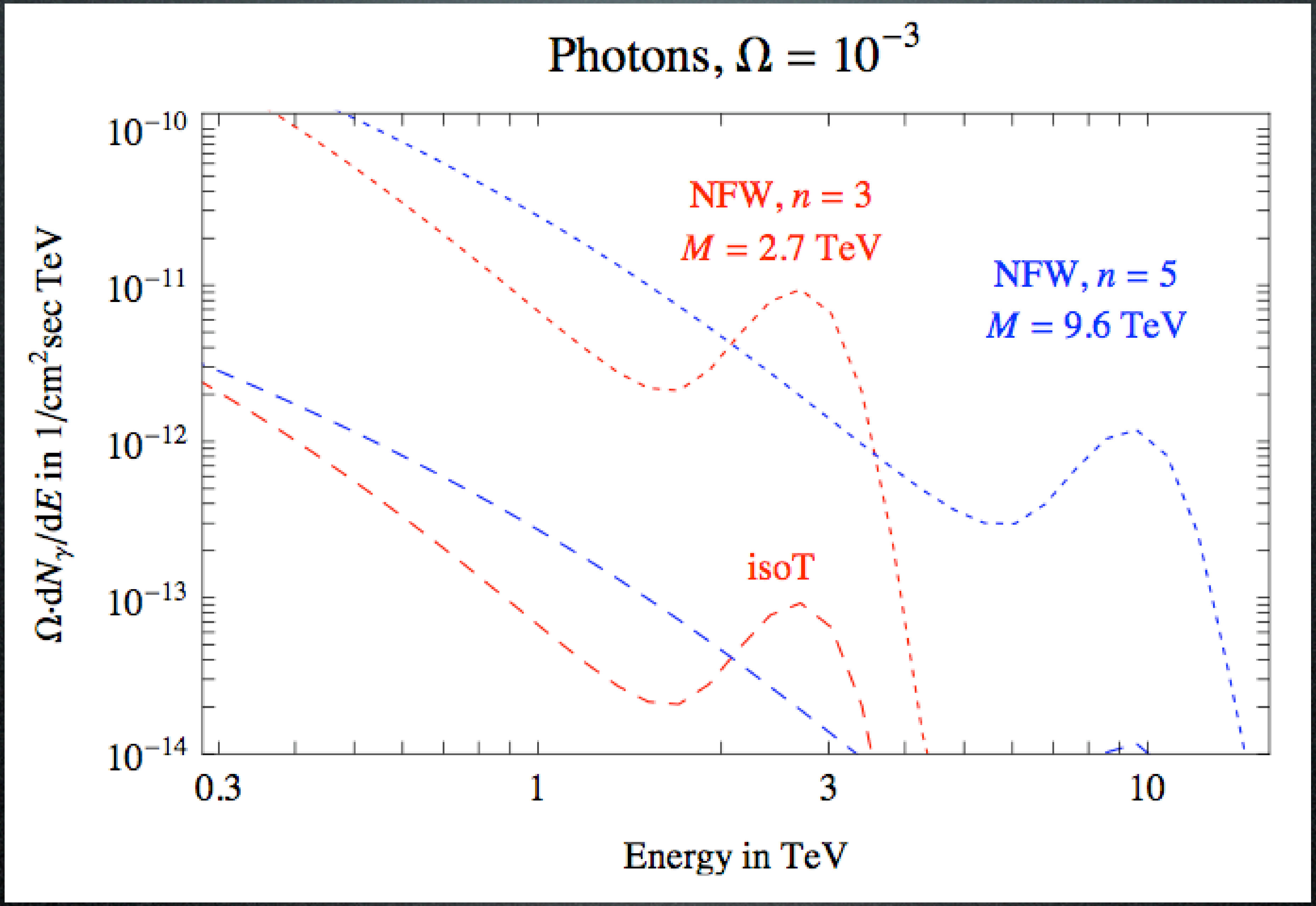
- propagation model
- DM halo profile
- boost factor B



Distinctive signal,
more dependent on astro,
PAMELA prelim., AMS02.

3. Indirect Detection

For instance, predicted signal in γ rays:



Comparison with SplitSuSy-like models

A-H, Dimopoulos and/or Giudice, Romanino 2004
Pierce 2004; Arkani-Hamed, Dimopoulos, Kachru 2005
Mahbubani, Senatore 2005

SplitSuSy-like	MDM
- Higgsino (a fermion doublet)	- arbitrary multiplet, scalar or fermion
- + something else (a singlet)	- nothing else (with Y=0)
- stabilization by R-parity	- automatically stable
- want unification also	- forget unification, it's SM
- unification scale is low, need to embed in 5D to avoid proton decay (Mahbubani, Senatore 2005)	- nothing

Common feature: the focus is on DM, not on SM hierarchy problem.

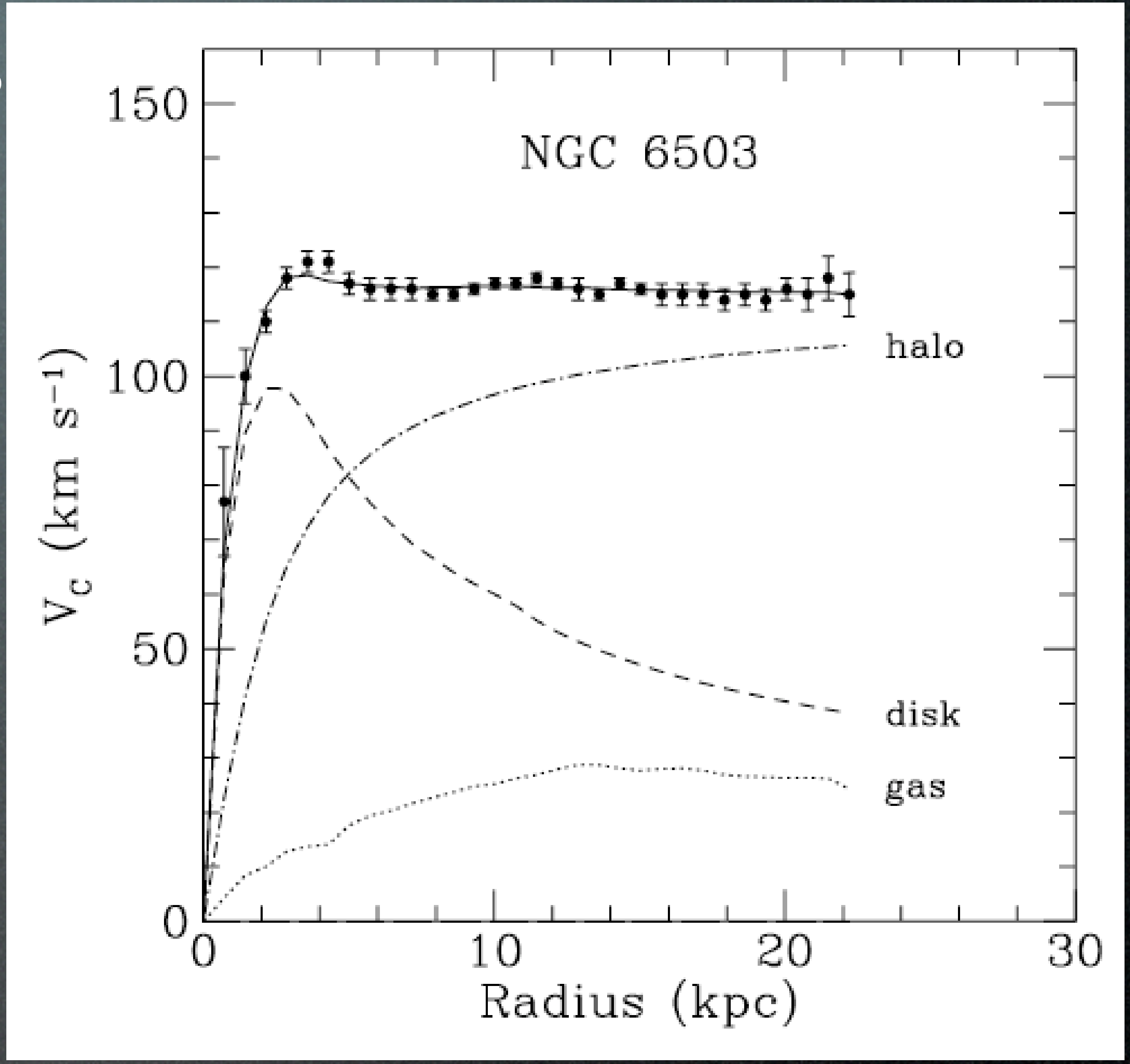
The Evidence for DM

1) galaxy rotation curves

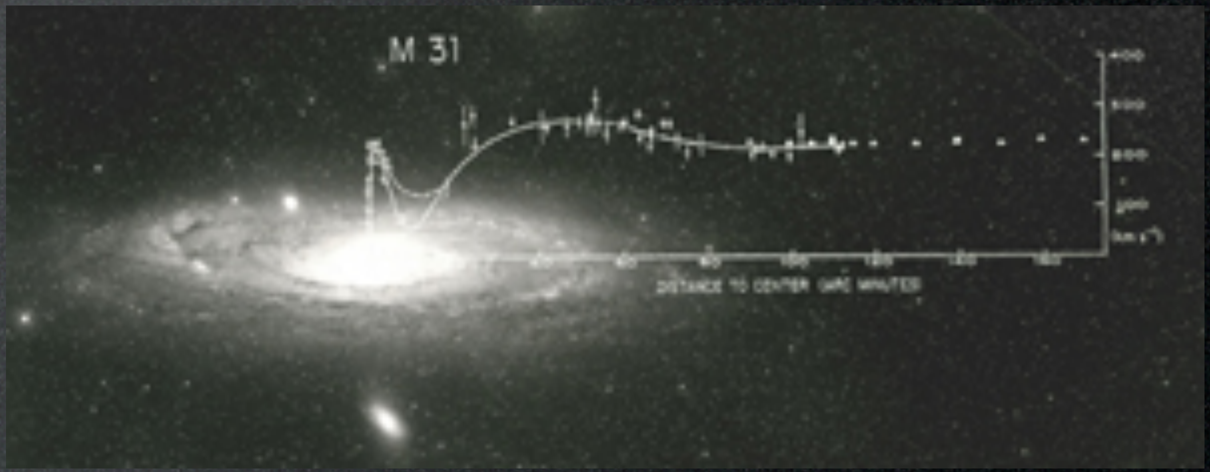
$$v_c(r) = \sqrt{\frac{2G_N M(r)}{r}}$$

$$v_c(r) \sim \text{const} \Rightarrow \rho_M(r) \sim \frac{1}{r^2}$$

$$\Omega_\mathrm{M} \gtrsim 0.1$$



Begeman et al., MNRAS 249 (1991)



The Evidence for DM

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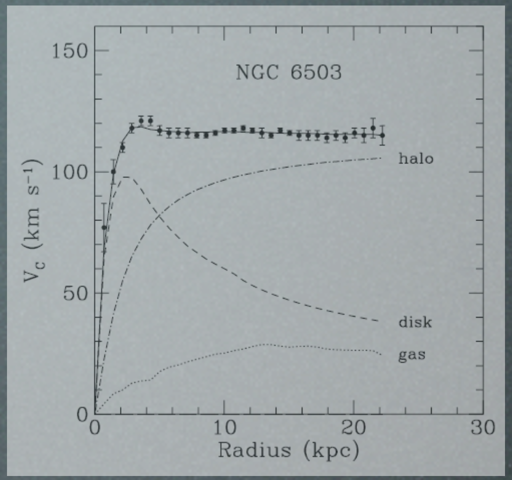


$\Omega_M \gtrsim 0.1$

2) clusters of galaxies

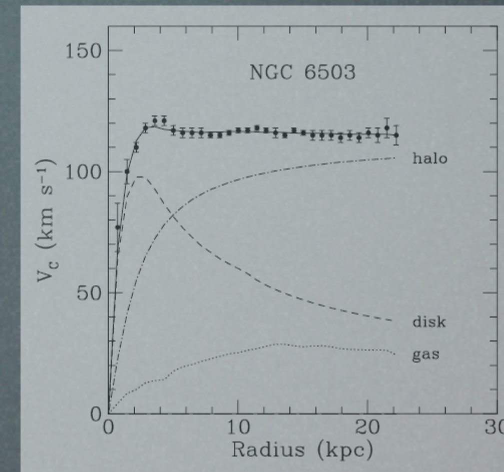
- "rotation curves"
- gravitation lensing
- X-ray gas temperature

$\Omega_M \sim 0.2 \div 0.4$

"bullet cluster" - NASA
astro-ph/0608247
[further developments]

The Evidence for DM

1) galaxy rotation curves



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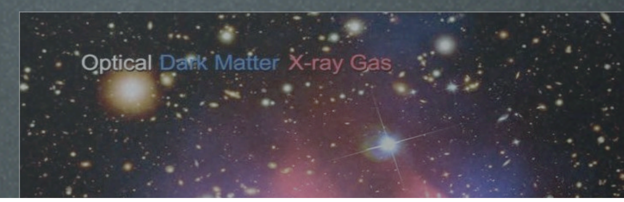
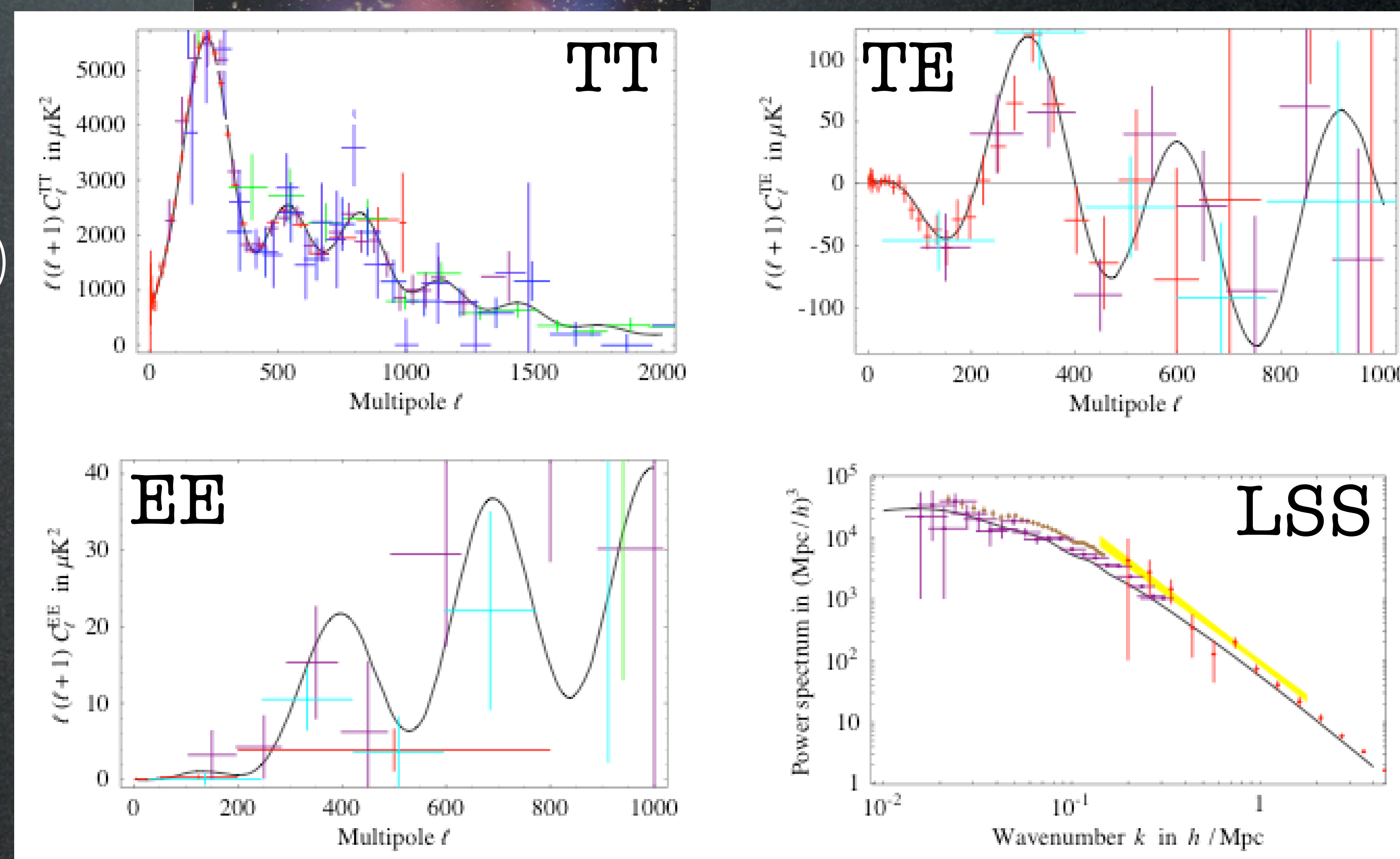


$\Omega_M \sim 0.2 \div 0.4$

3) CMB+LSS(+SNIa:)

WMAP-3yr
ACbar
CBI
Boomerang
DASI
VSA

SDSS, 2dFRGS
LyA Forest Croft
LyA Forest SDSS

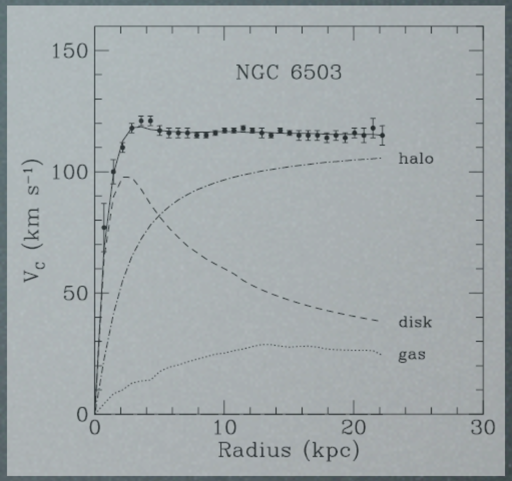


$\Omega_M \approx 0.26 \pm 0.05$

M.Cirelli and A.Strumia, astro-ph/0607086

The Evidence for DM

1) galaxy rotation curves



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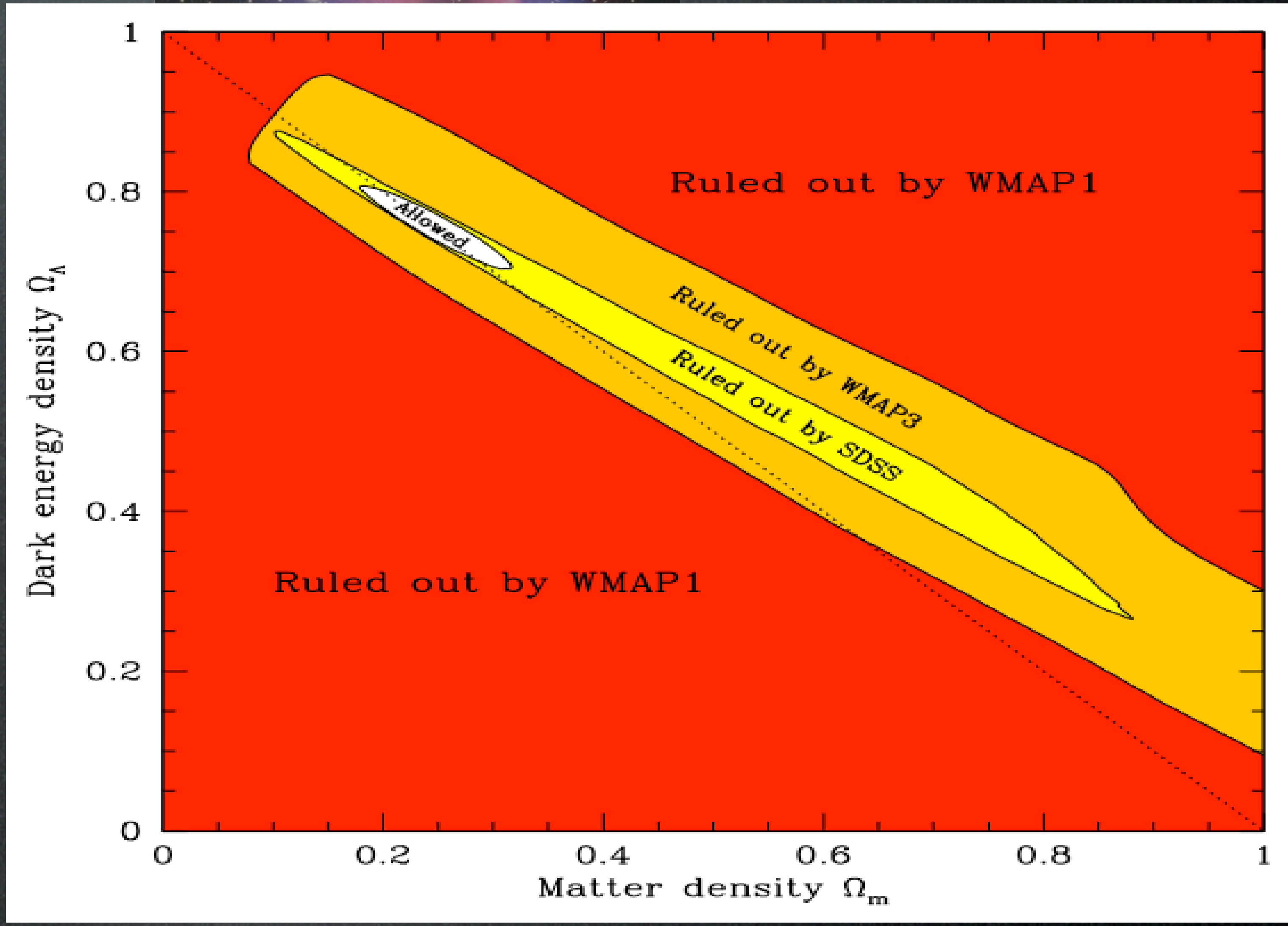
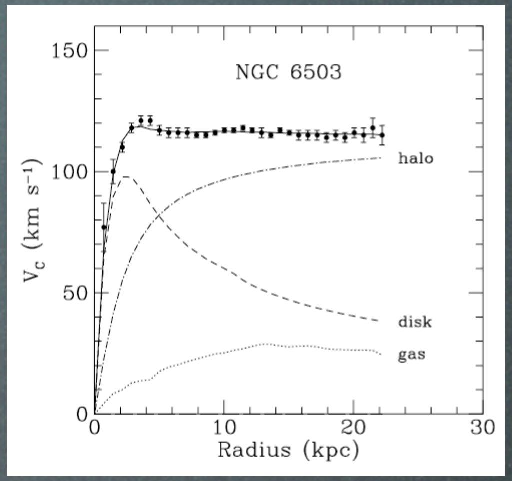


M.Tegmark et al., astro-ph/0608632

The Evidence for DM

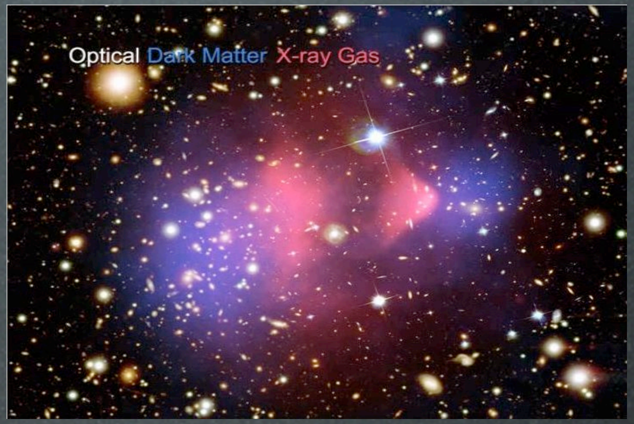
1) galaxy rotation curves



$\Omega_M \gtrsim 0.1$

details

2) clusters of galaxies



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details

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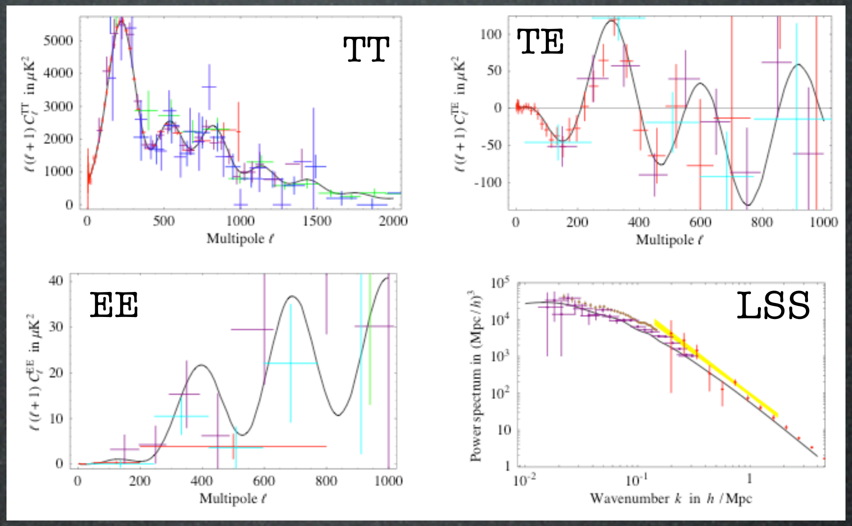


$\Omega_M \approx 0.26 \pm 0.05$

details

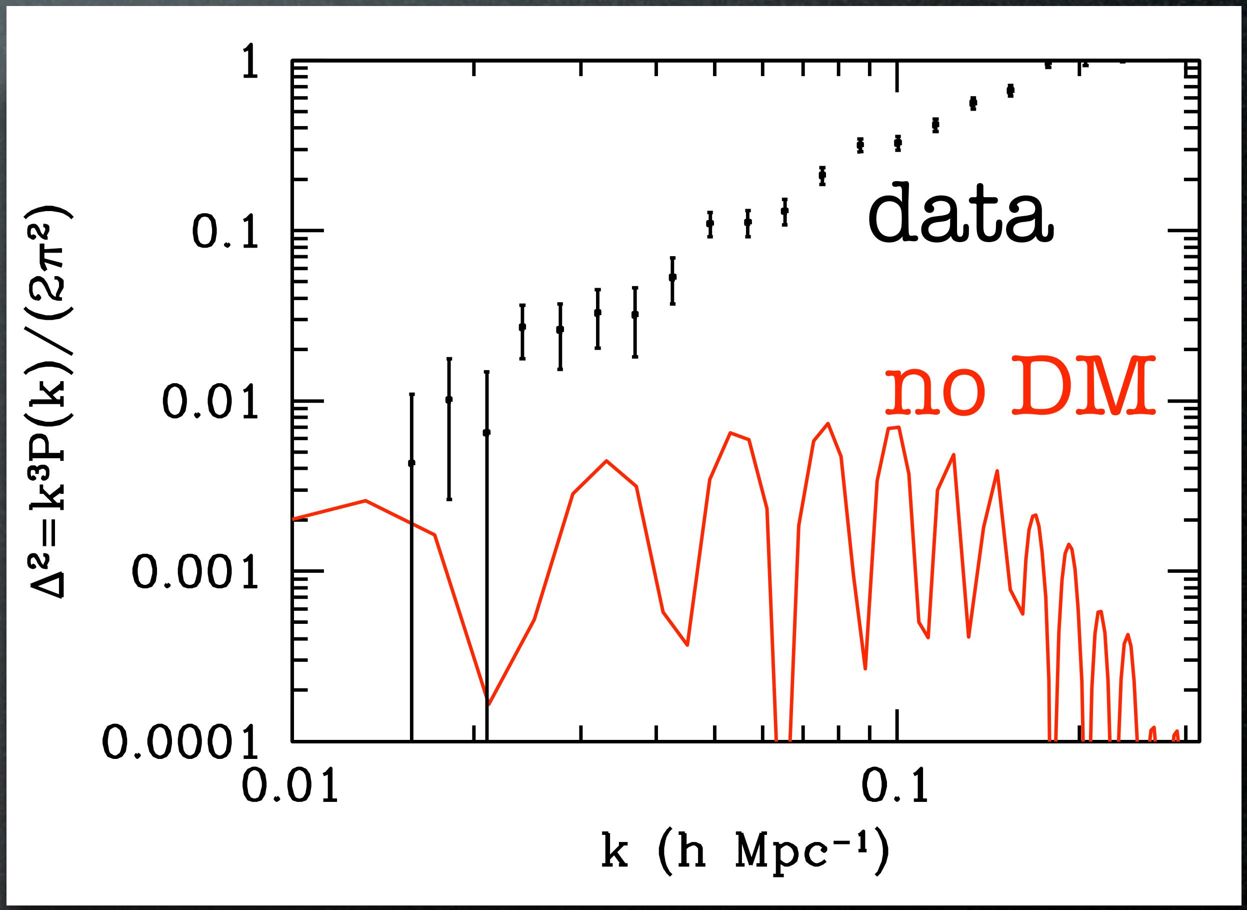
DM is there.

What is DM?

The Evidence for DM

How would the power spectra be without DM?
(and no other extra ingredient)

LSS



Dodelson, Liguori 2006

The thrilling story of the bullet cluster

Farrar, Rosen (2006) astro-ph/0610298

"The bullet goes too fast!"

With a surprising twist, the bullet cluster that just killed MOND repents and reverts into an advocate of a 5th force in the DM sector, that pulled in the merger.

[back]

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"Not too fast for the law."

In a breath-taking finale, Newton and hydro dynamical laws regain control: the bullet is a uncommon guy (7%), but he is not too fast for them.

[back]

The thrilling story of the bullet cluster

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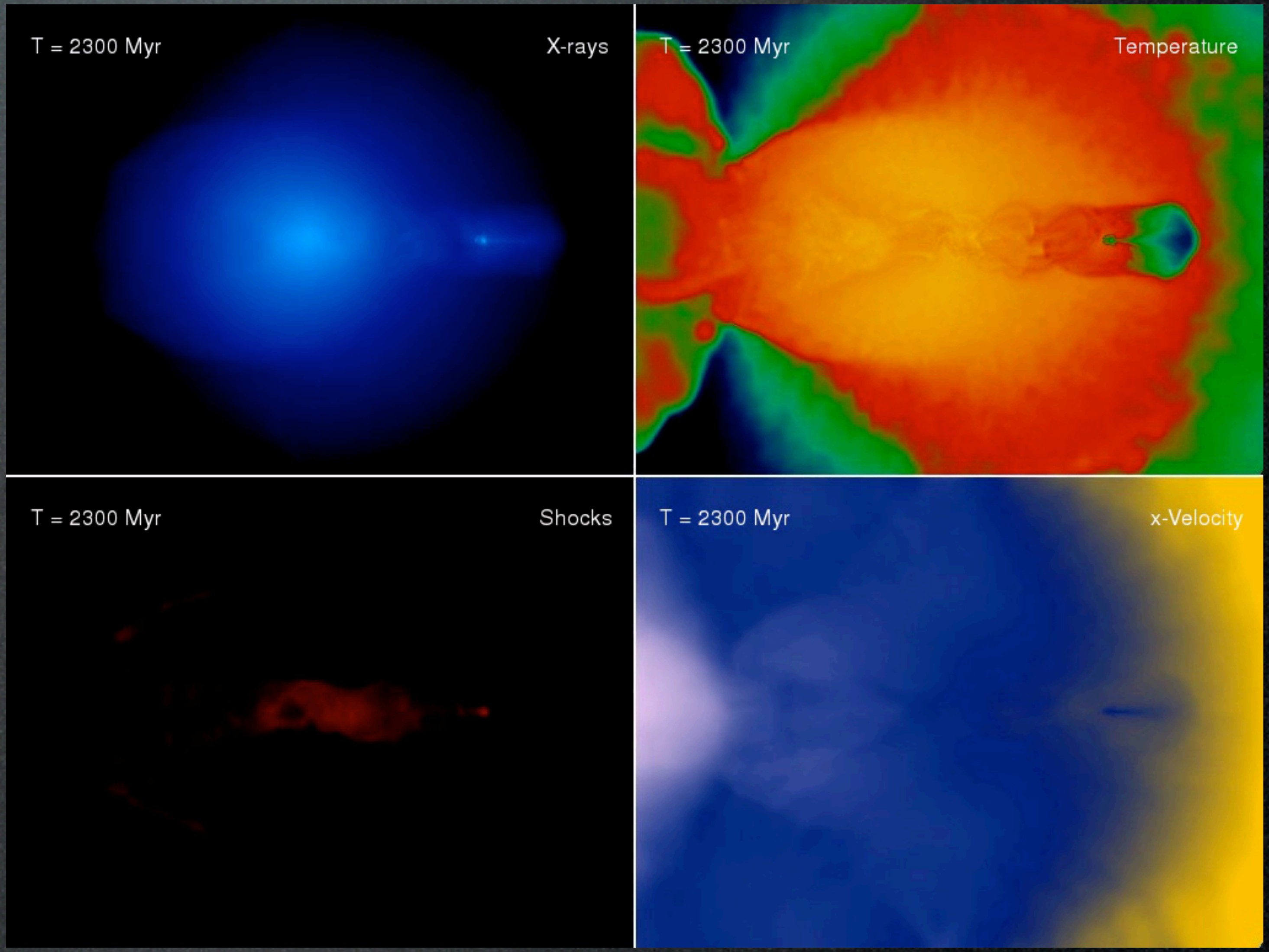


The Max Planck Studios in Hollywood seize the opportunity and make a 2.3-billion-years long blockbuster movie.

[back]

Non-Minimal terms in the scalar case

Quadratic and quartic terms in $\mathcal{X}$ and H :

$$\lambda_H(\mathcal{X}^* T^a_{\mathcal{X}} \mathcal{X})\,(H^* T^a_H H) + \lambda'_H |\mathcal{X}|^2 |H|^2 + \frac{\lambda_{\mathcal{X}}}{2}(\mathcal{X}^* T^a_{\mathcal{X}} \mathcal{X})^2 + \frac{\lambda'_{\mathcal{X}}}{2}|\mathcal{X}|^4$$

[1] [2] [3] [4]

- do not induce decays (even number of $\mathcal{X}$, and $\langle \mathcal{X} \rangle = 0$)
- [3] and [4] do not give mass terms
- after EWSB, [2] gives a common mass $\sqrt{\lambda'_H} v \approx \mathcal{O}(\lesssim 100 \text{ GeV})$ to all $\mathcal{X}_i$ components; negligible for $M = \mathcal{O}(\text{TeV})$
- after EWSB, [1] gives mass splitting $\Delta M_{\text{tree}} = \frac{\lambda_H v^2 |\Delta T^3_{\mathcal{X}}|}{4M} = \lambda_H \cdot 7.6 \text{ GeV} \frac{\text{TeV}}{M}$ between $\mathcal{X}_i$ components; assume $\lambda_H \lesssim 0.01$ so that $\Delta M_{\text{tree}} \ll \Delta M$
- [1] (and [2]) gives annihilations $\bar{\mathcal{X}}\mathcal{X} \to \bar{H} H$ assume $|\lambda'_H| \ll g_Y^2, g_2^2$ so that these are subdominant

(Anyway, scalar MDM is less interesting.)

[back to Lagrangian]
[back to table]

Neutralino "properties"

neutralino mass matrix in MSSM ($\tilde{B} - \tilde{W}^3 - \tilde{H}_1^0 - \tilde{H}_2^0$ basis)

$$M_\chi = \begin{pmatrix} M_1 & 0 & -m_Z c_\beta s_W & m_Z s_\beta s_W \\ 0 & M_2 & m_Z c_\beta c_W & -m_Z s_\beta c_W \\ -m_Z c_\beta s_W & m_Z c_\beta c_W & 0 & -\mu \\ m_Z s_\beta s_W & -m_Z s_\beta c_W & -\mu & 0 \end{pmatrix}$$

superpotential

$$\mathcal{W} = -\mu \mathcal{H}_1 \mathcal{H}_2 + \mathcal{H}_1 h_e^{ij} \mathcal{L}_{Li} \mathcal{E}_{Rj} + \mathcal{H}_1 h_d^{ij} \mathcal{Q}_{Li} \mathcal{D}_{Rj} - \mathcal{H}_2 h_u^{ij} \mathcal{Q}_{Li} \mathcal{U}_{Rj}$$

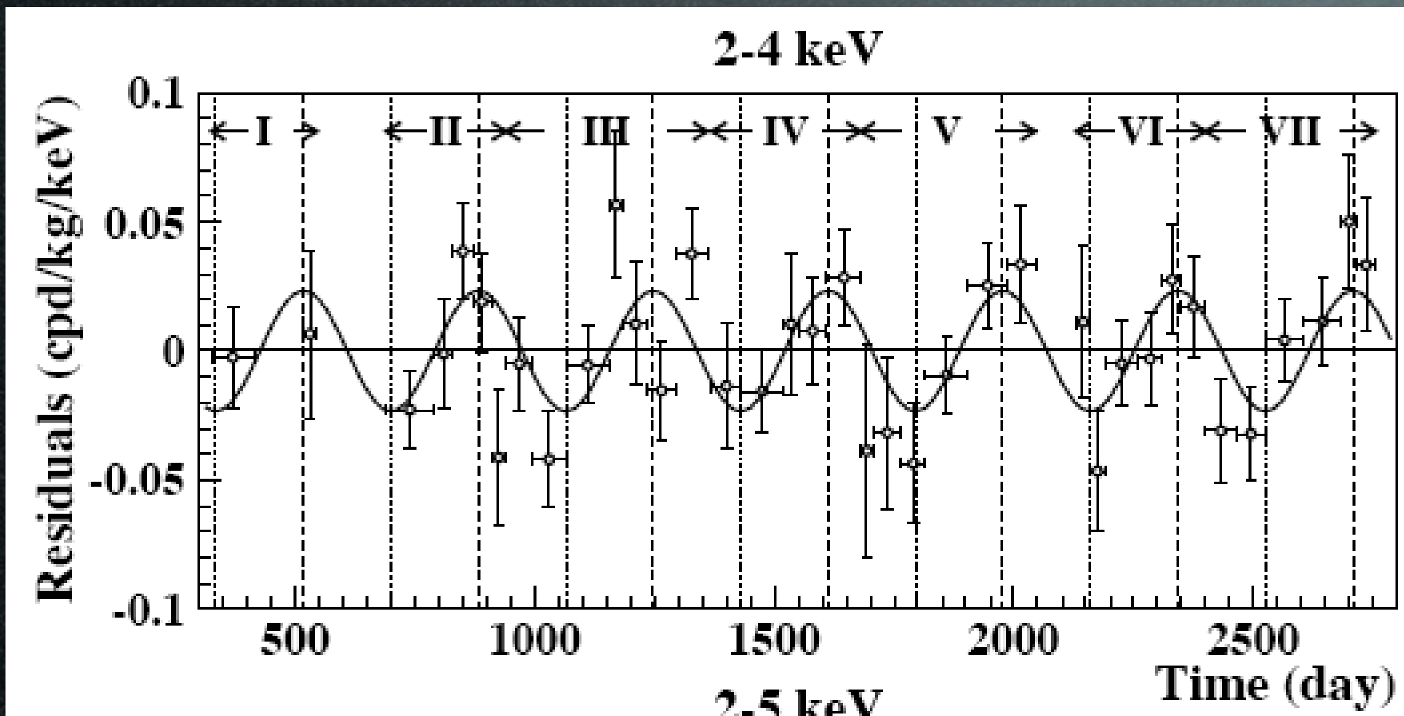
soft SUSYB terms

$$\mathcal{L}_{\rm soft} = -\frac{1}{2}\left(M_1 \bar{\tilde{B}} \tilde{B} + M_2 \bar{\tilde{W}}^a \tilde{W}^a + M_3 \bar{\tilde{G}}^a \tilde{G}^a\right) + \ldots$$

$$\tan\beta = \frac{\langle v_1 \rangle}{\langle v_2 \rangle}$$

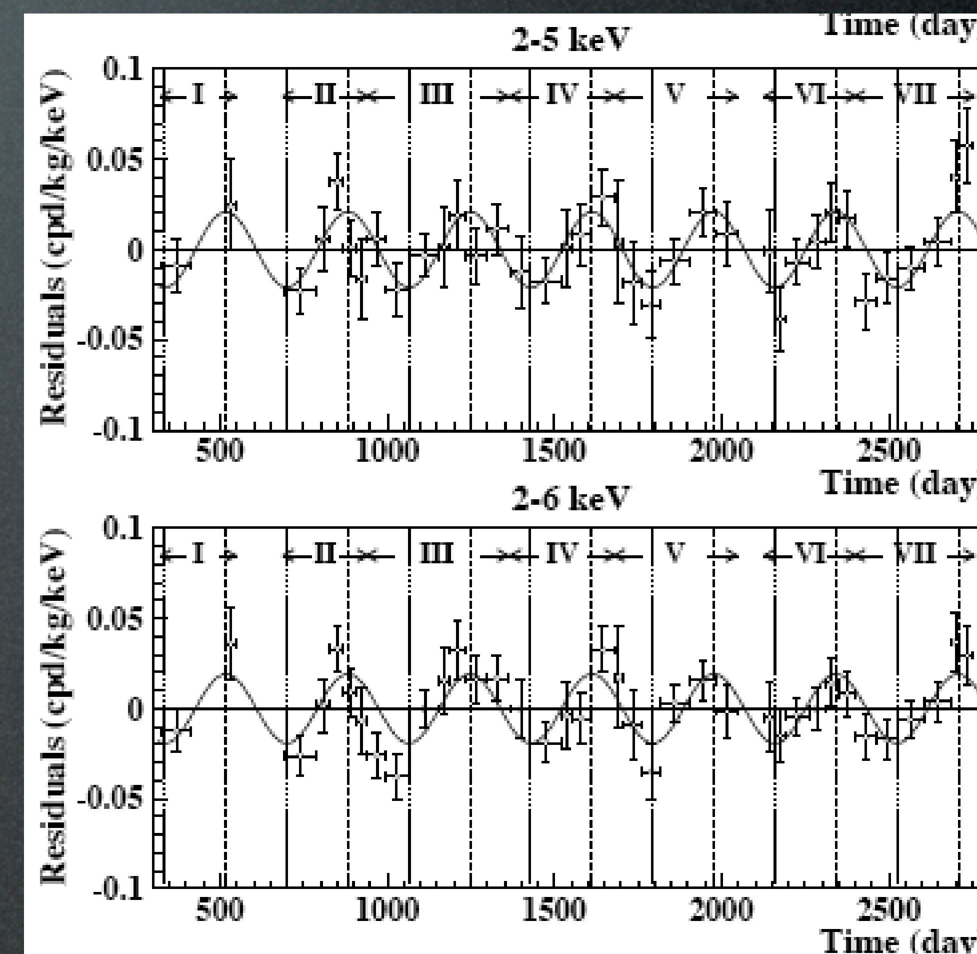
Direct detected *already*?

DAMA annual modulation:



DAMA Coll.

however:
-raw data??
-bkgd (Rn emission)
-higher bins not expon suppressed



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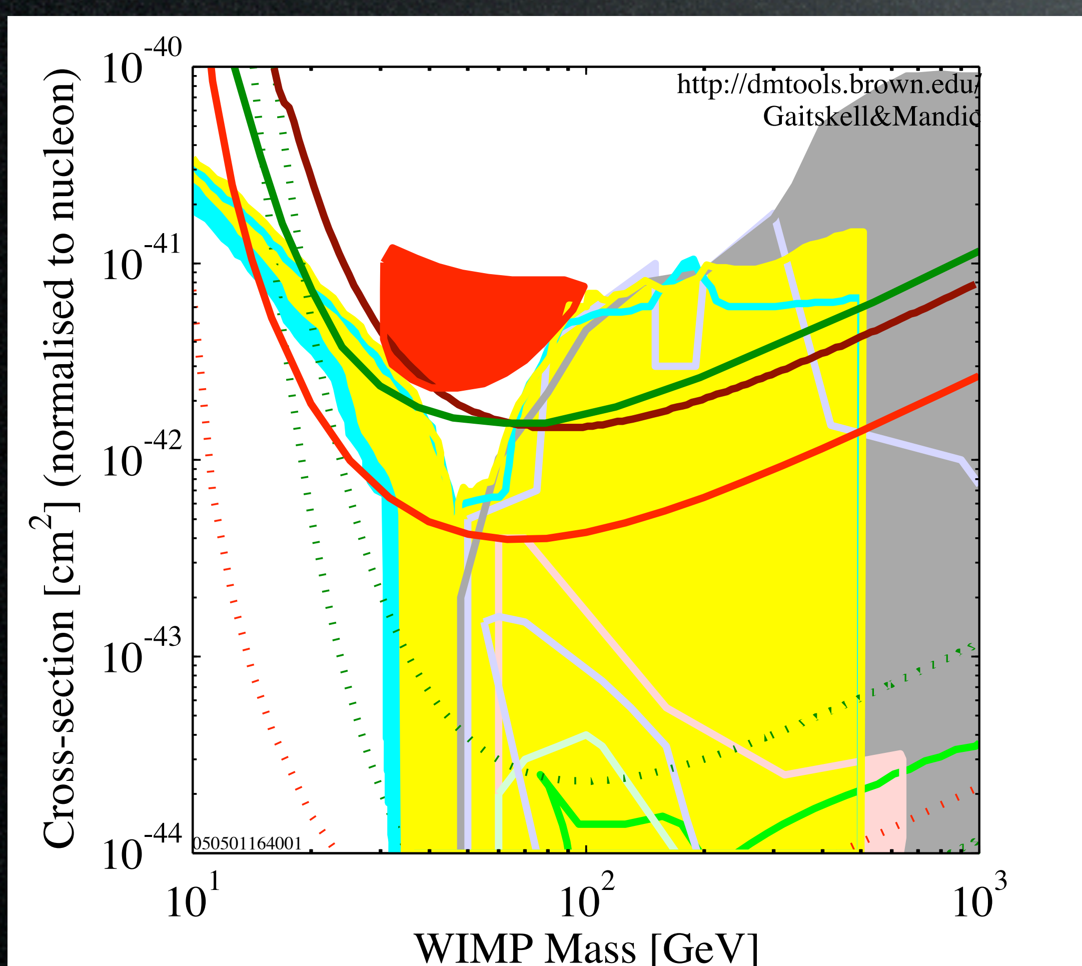
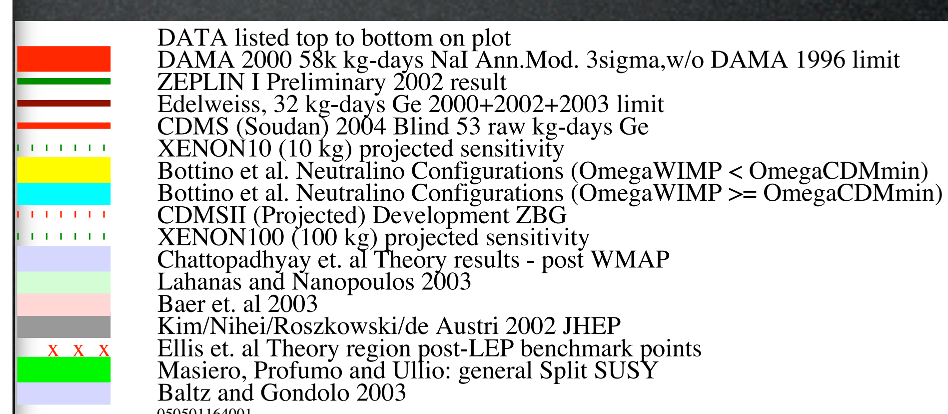
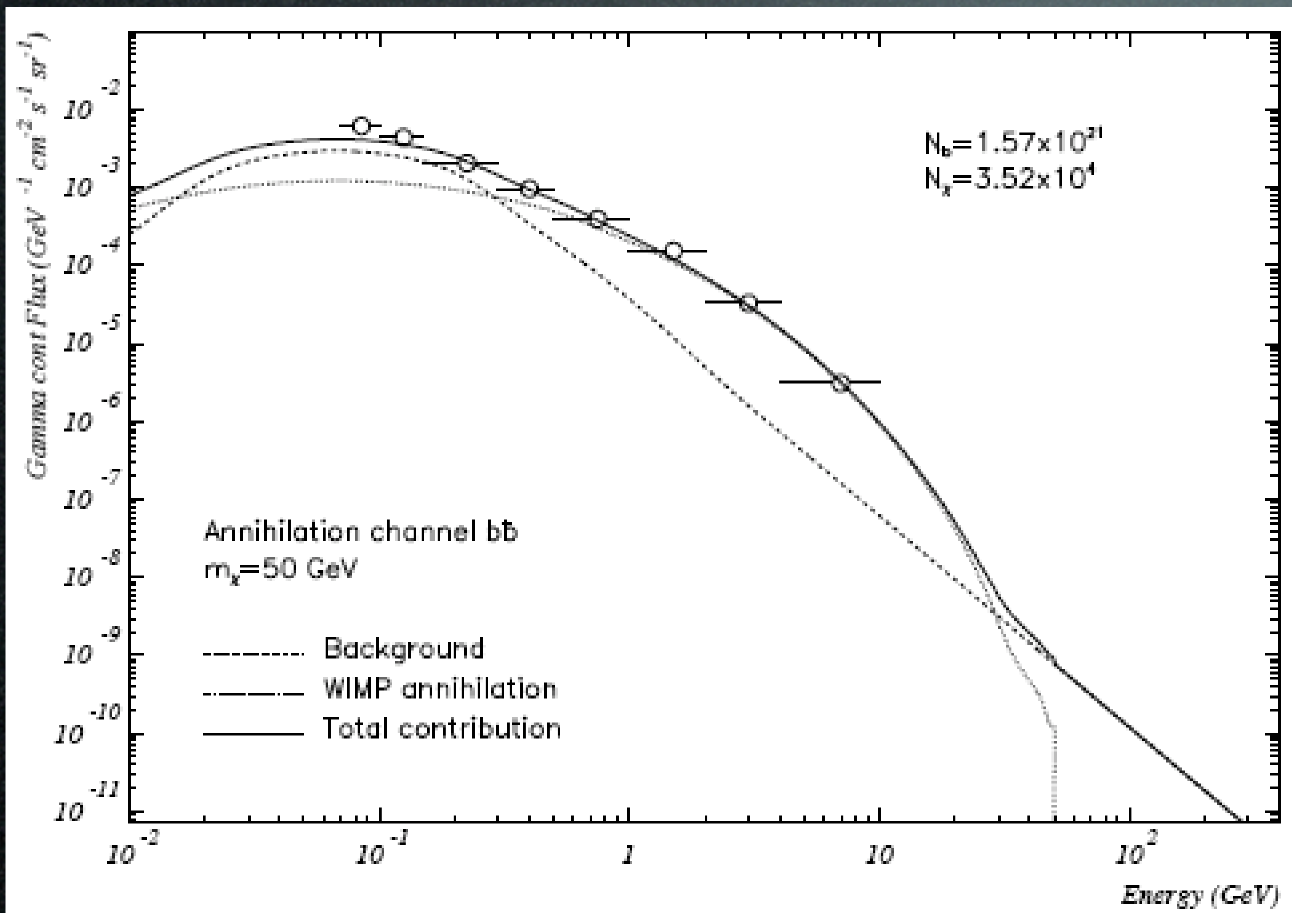




[back to DM detection]

Hints from photons?

EGRET excess

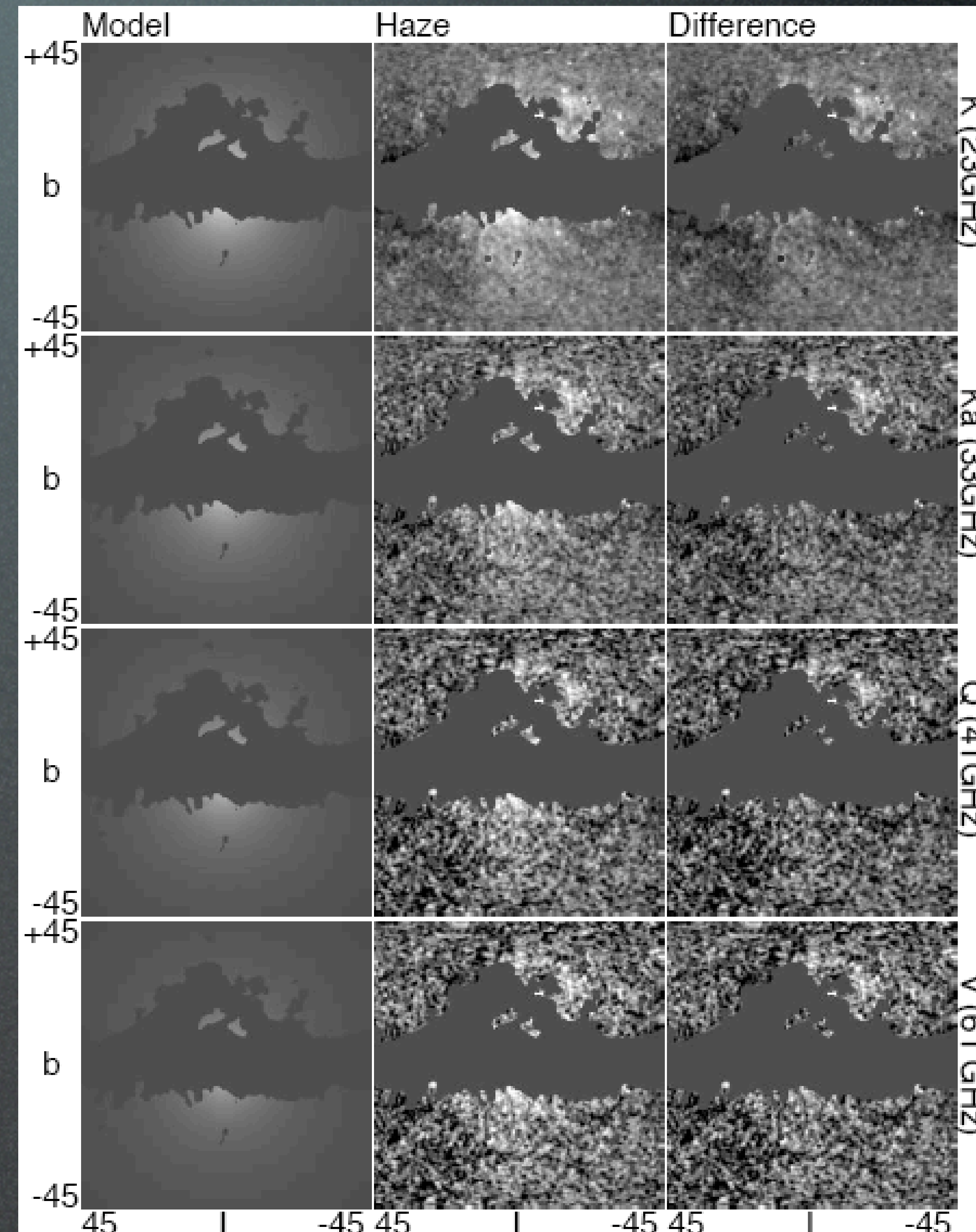


Ullio et al., ApP 21 (2004), astro-ph/0305075

however:
- source not centered
- variability...

+ CANGAROO (2004)
+ HESS (2004)

WMAP "haze"



Finkbeiner, ApJ 614 (2004)

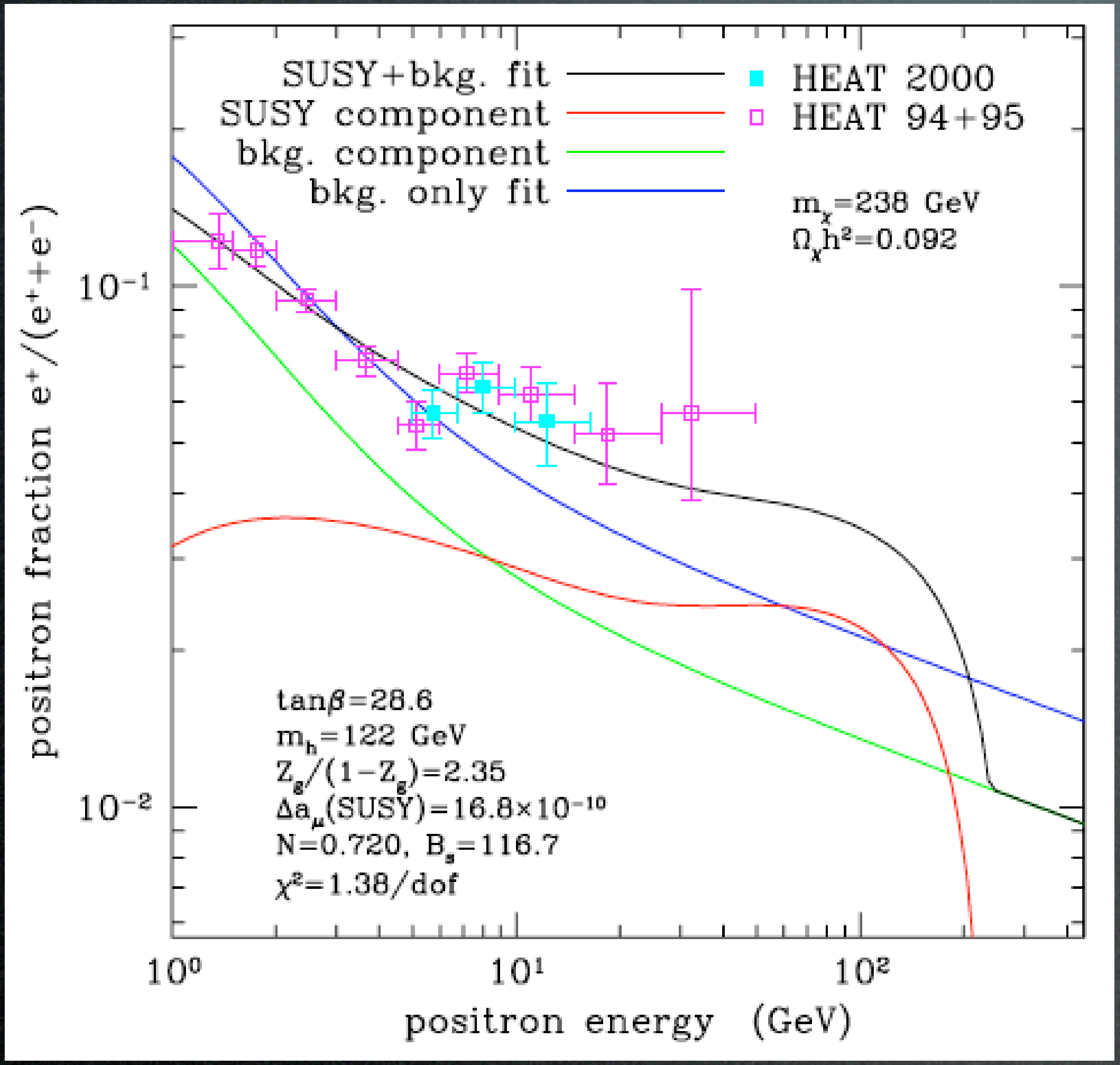
(Synchrotron rad from e^+e^- from DM annihilations)

The Galactic emission found by Finkbeiner (2004) in the *WMAP* data in excess of the expected foreground Galactic ISM signal may be a signature of such dark matter annihilation.

[back to DM detection]

Hints from positrons?

HEAT excess (1994+95 & 2000)



Baltz, Edsjo, Gondolo, Freese PRD65 (2002)

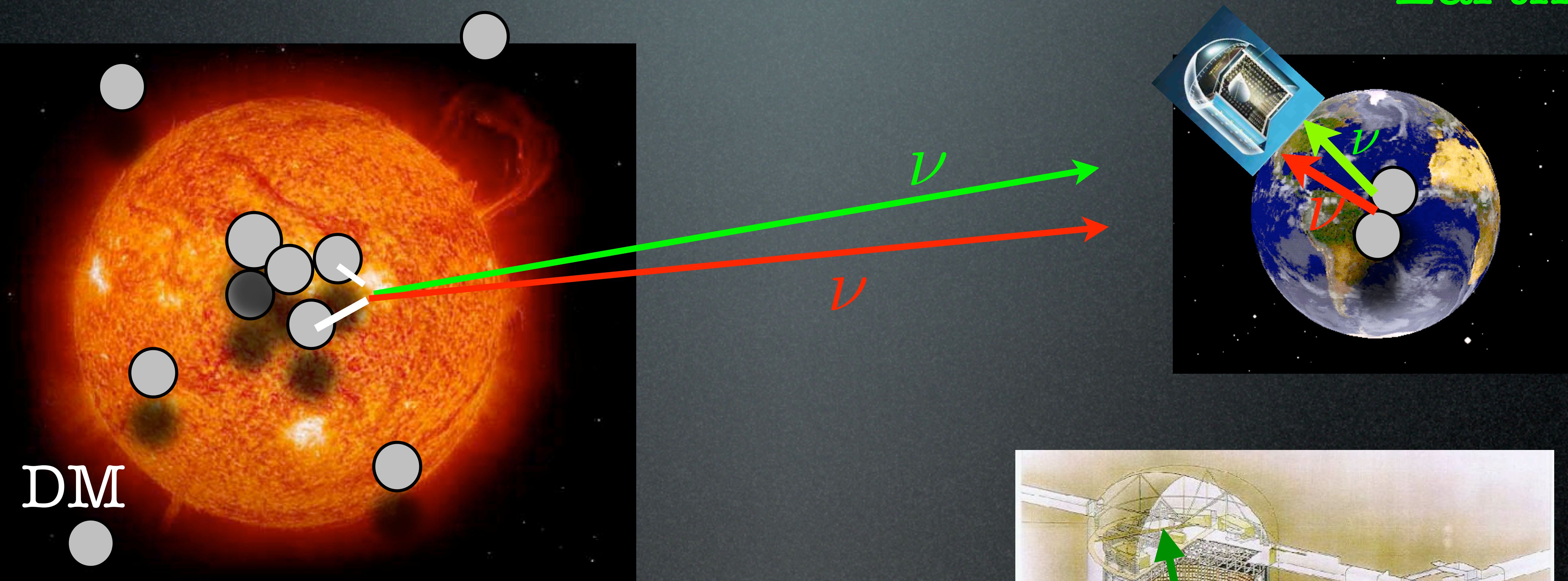
however:
-random trajectories in magnetic field
-flux requires too much DM...

[back to DM detection]

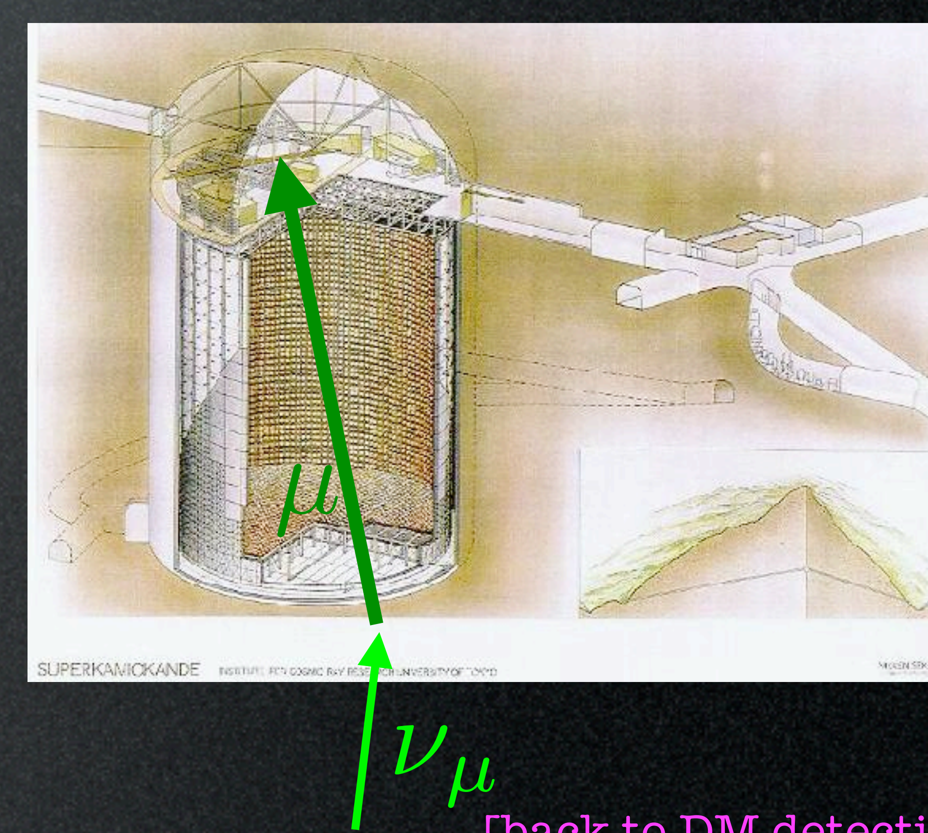
Neutrinos from DM

Sun

Earth



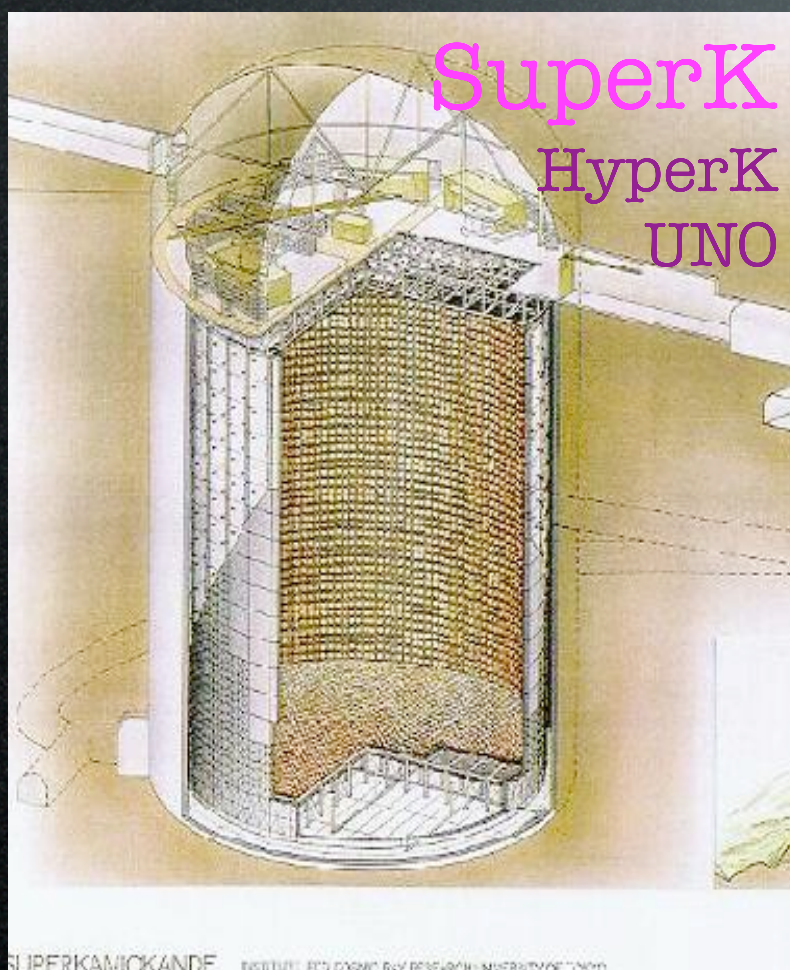
up-going muons:

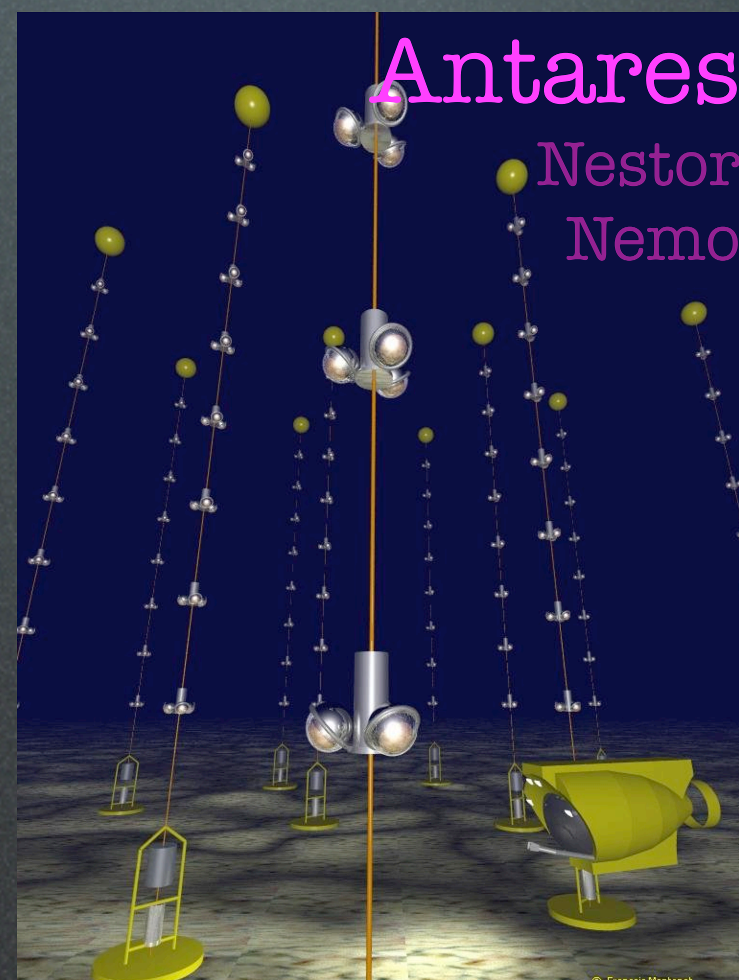


[back to DM detection]

"Neutrino Telescopes"

UnderGround	UnderWater	UnderIce





	UnderGround	UnderWater	UnderIce
Size:	``small"	large	large/huge
Energy thres:	GeV	tens GeV	100 GeV
Energy resol:	GeV	10 GeV	tens GeV
Angle resol:	degree	few degrees	tens degrees

[back to DM detection]

2. Production at colliders

$$\hat\sigma_{u\bar d} = \frac{g_{\mathcal{X}} g_2^4 (n^2-1)}{13824\ \pi \hat s}\beta \cdot \begin{cases} \beta^2 & \text{if } \mathcal{X} \text{ is a fermion} \\ 3-\beta^2 & \text{if } \mathcal{X} \text{ is a scalar} \end{cases}$$

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

Large production for small M.

$2\times$ LHC to produce heavy candidates.

A clean signature:

$\mathcal{X}^\pm \to \mathcal{X}^0 \pi^\pm$	:	$\Gamma_\pi = (n^2-1)\frac{G_F^2 V_{ud}^2 \Delta M^3 f_\pi^2}{4\pi}\sqrt{1-\frac{m_\pi^2}{\Delta M^2}}$,	$\mathrm{BR}_\pi = 97.7\%$
$\mathcal{X}^\pm \to \mathcal{X}^0 e^\pm \overset{(-)}{\nu}_e$	:	$\Gamma_e = (n^2-1)\frac{G_F^2 \Delta M^5}{60\pi^3}$	$\mathrm{BR}_e = 2.05\%$
$\mathcal{X}^\pm \to \mathcal{X}^0 \mu^\pm \overset{(-)}{\nu}_\mu$	:	$\Gamma_\mu = 0.12\ \Gamma_e$	$\mathrm{BR}_\mu = 0.25\%$

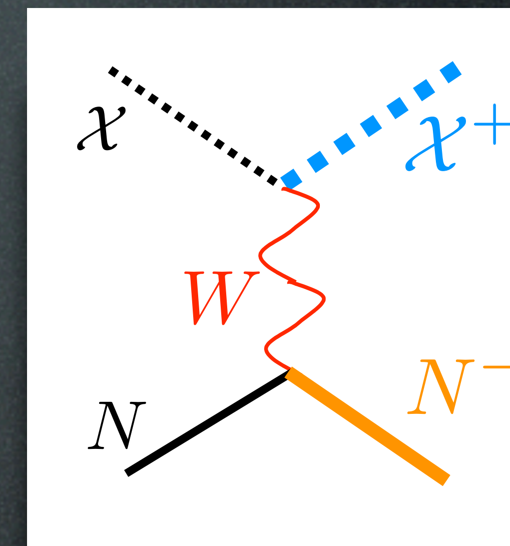
$$\tau \simeq 44\mathrm{cm}/(n^2-1)$$

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

[skip to conclusions]

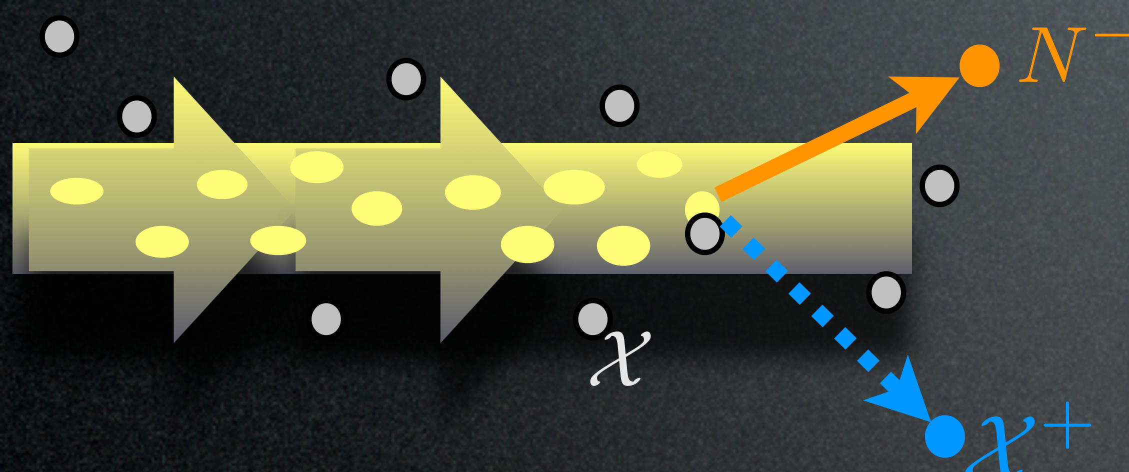
Interlude: the “DMtron”

Can one have CC DM interactions?
(tree level!)



Need to provide $\Delta M = M_{\mathcal{X}^+} - M_{\mathcal{X}} = 166\ \mathrm{MeV}$

Accelerate nuclei and
use DM as diffuse target.



$$\hat\sigma(a\,\mathcal{X} \to a'\,\mathcal{X}^\pm) = \sigma_0 \frac{n^2-1}{4}\left[1 - \frac{\ln(1+4E^2/M_W^2)}{4E^2/M_W^2}\right]$$

$$\sigma_0 = \frac{G_F^2 M_W^2}{\pi} = 1.1\,10^{-34}\ \mathrm{cm}^2$$

$$\frac{dN}{dt} = \varepsilon N_p \sigma \frac{\rho_{\rm DM}}{M} = \varepsilon \frac{10}{\rm year} \frac{N_p}{10^{20}} \frac{\rho_{\rm DM}}{0.3\mathrm{GeV/cm^3}} \frac{\rm TeV}{M} \frac{\sigma}{3\sigma_0}$$

number of targets
number of bullets
“efficiency”

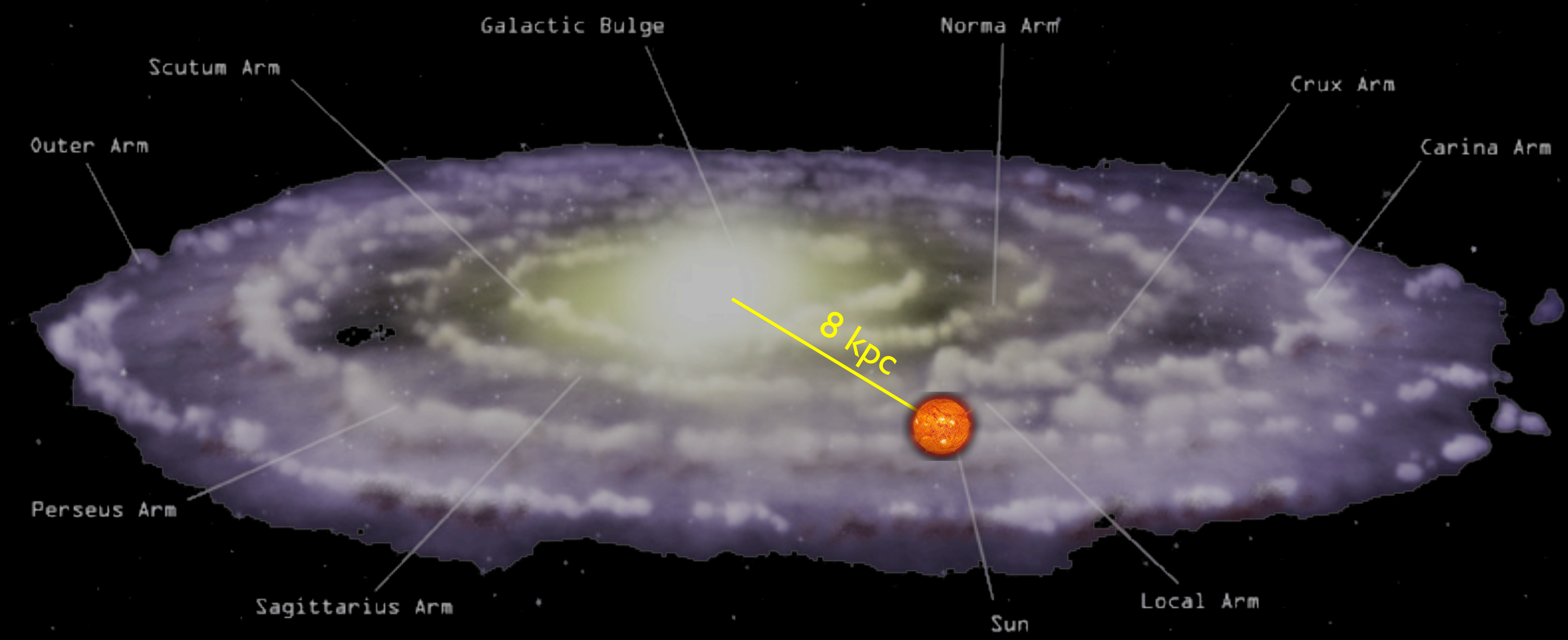
not
unreasonable?

tagging $\mathcal{X}^+$....

[skip to conclusions]

3. Indirect Detection

i.e. $\nu, \bar{p}, e^+, \gamma, \bar{D}$ from MDM annihilations in halo or body.



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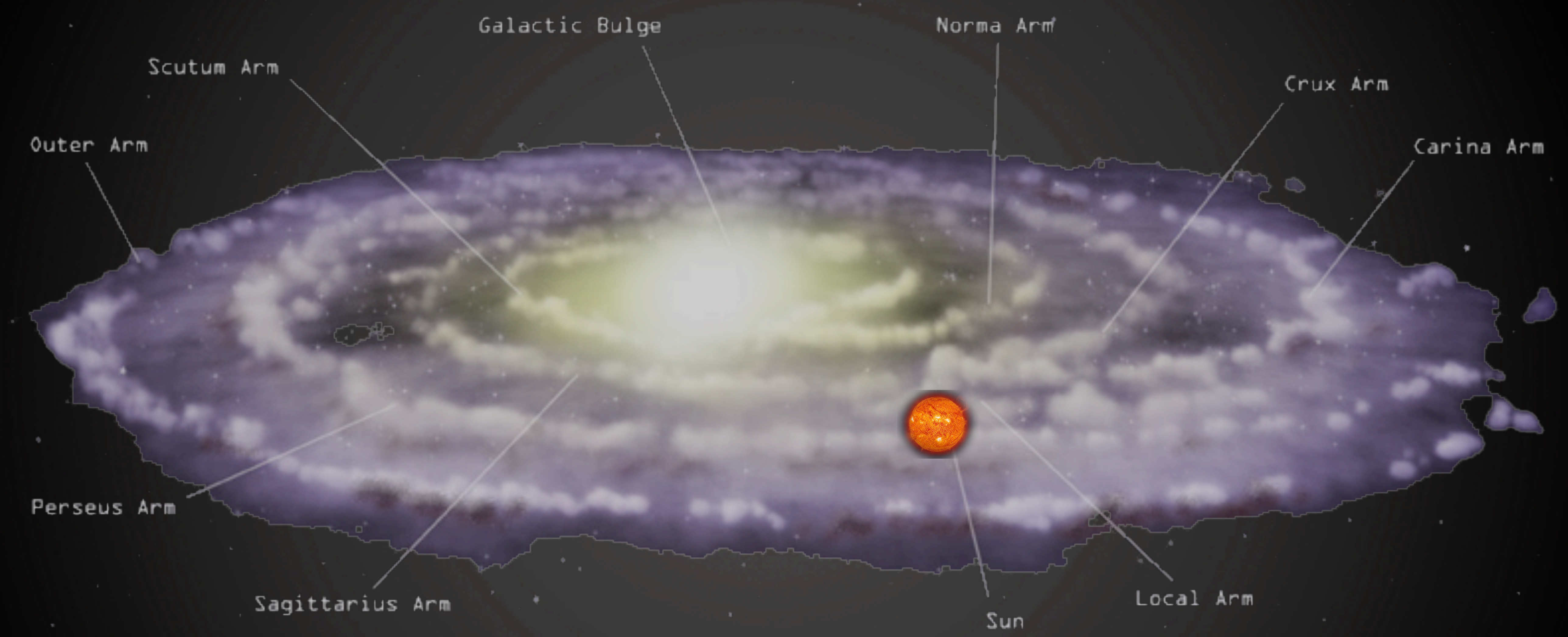

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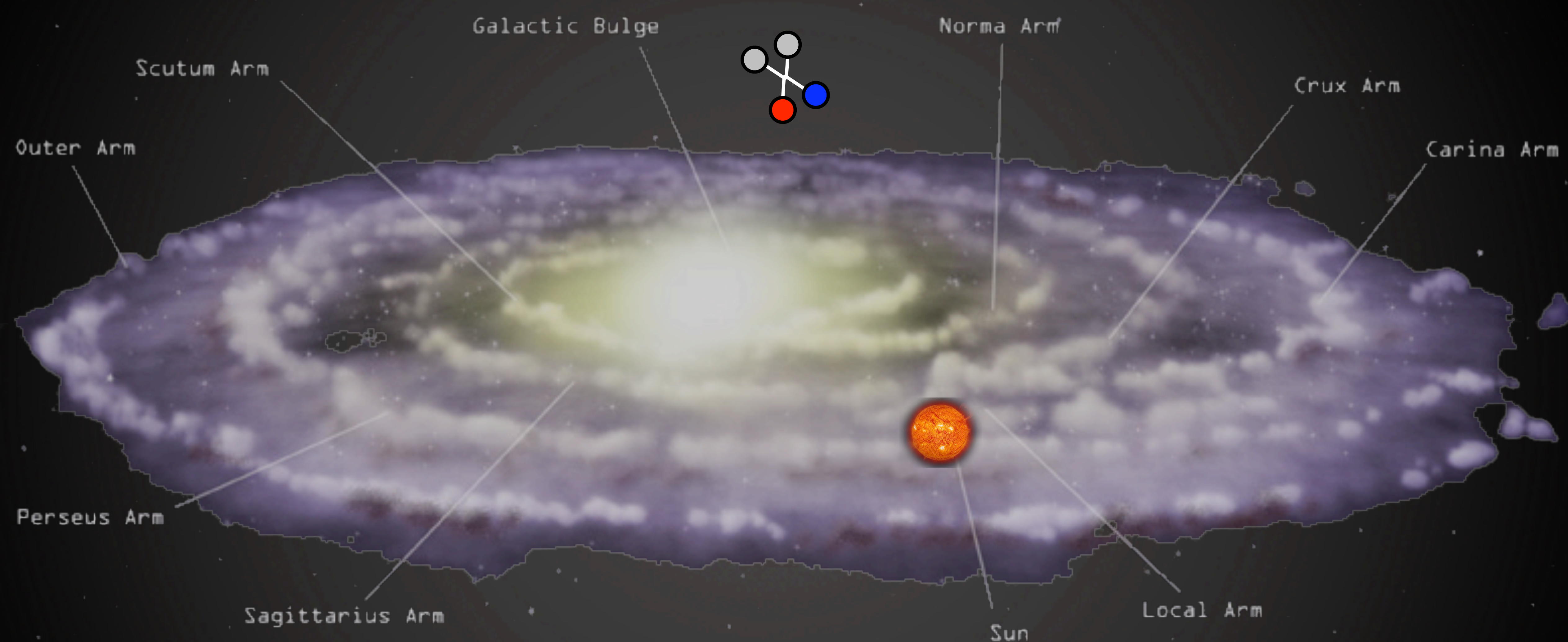

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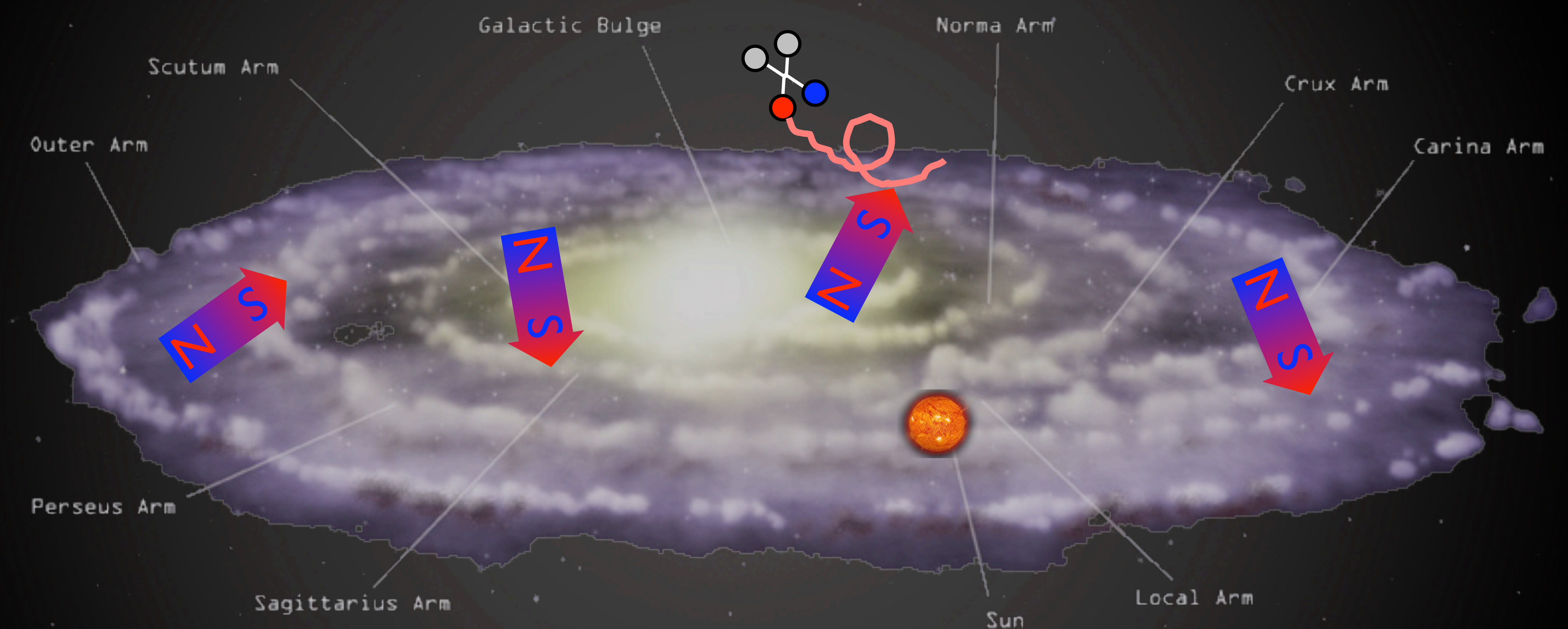

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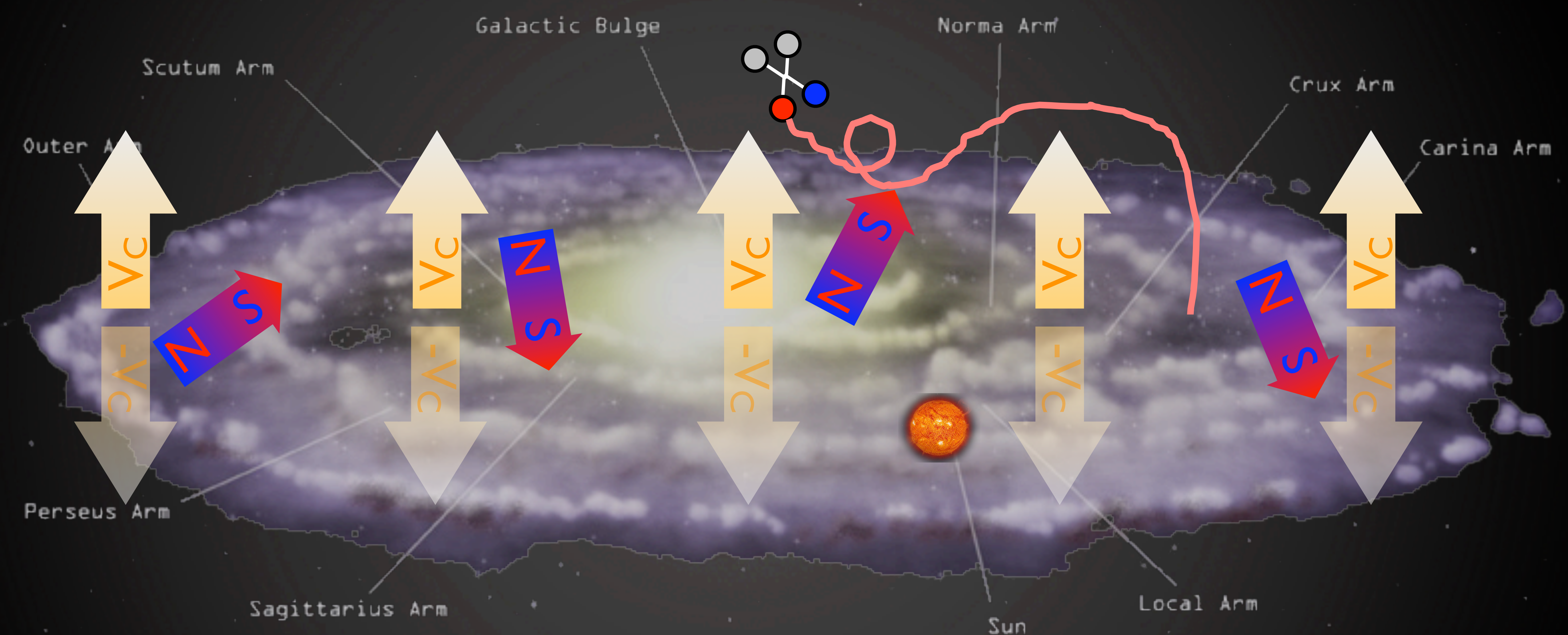

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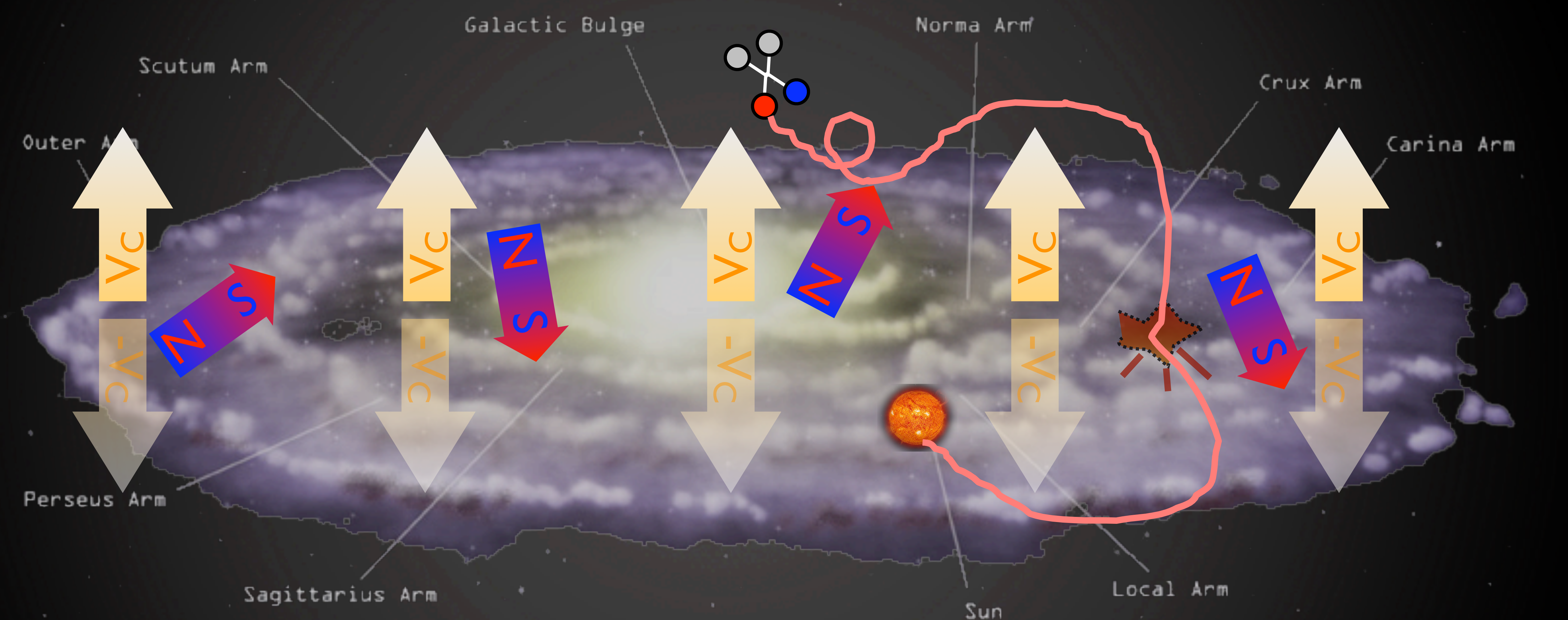

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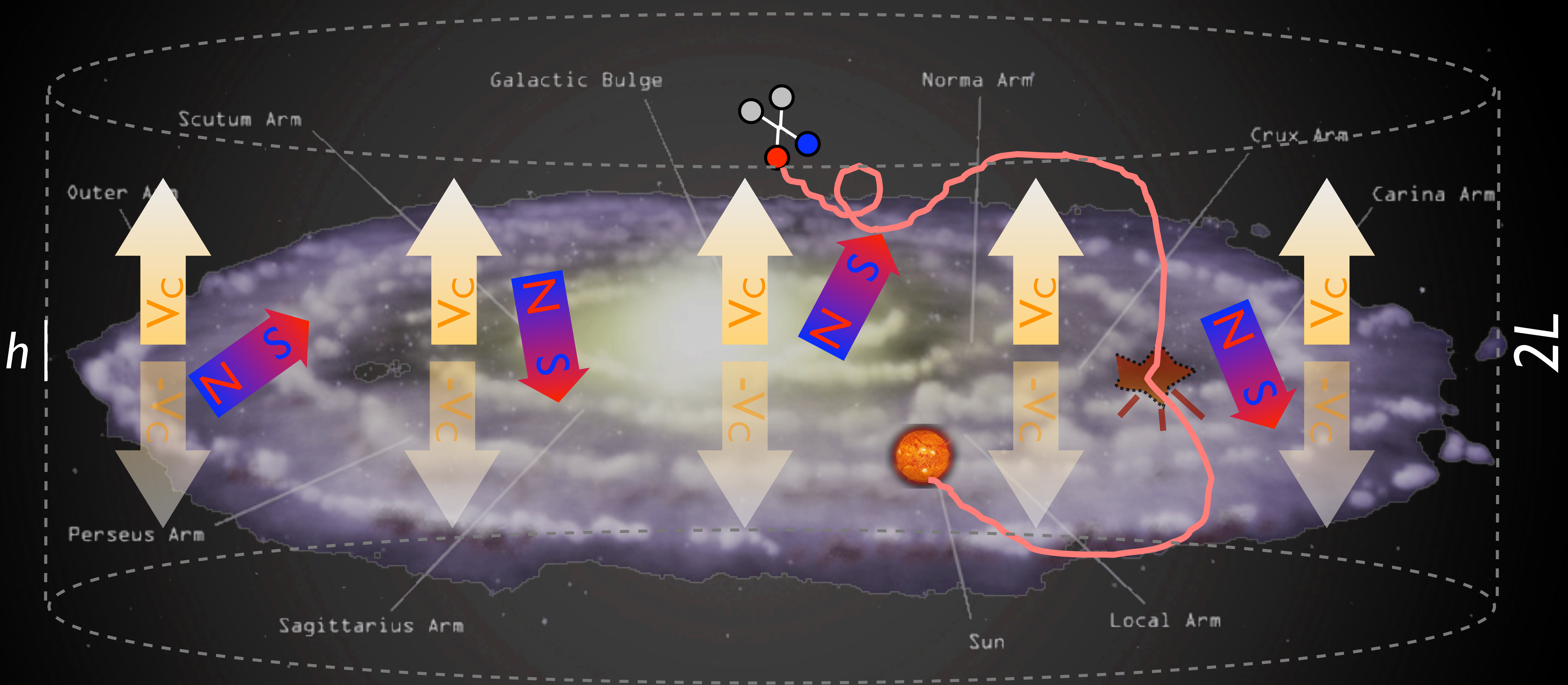


Salati, Chardonnay, Barrau, Donato, Taillet, Fornengo, Maurin, Brun... '90s, '00s

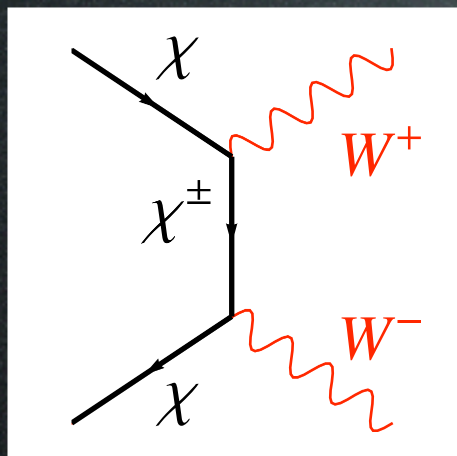
spectrum

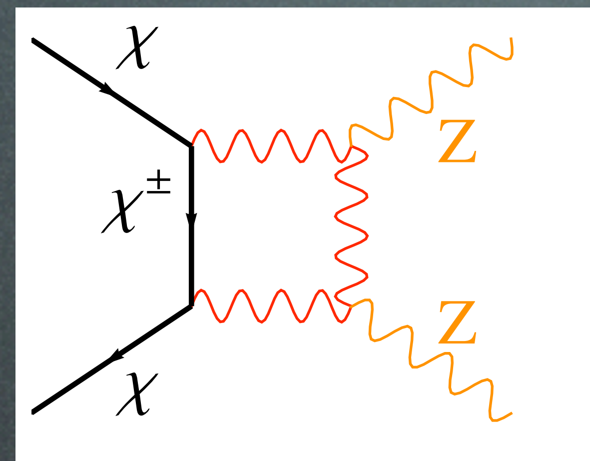
$$\frac{\partial f}{\partial t} - K(E)\cdot\nabla^2 f - \frac{\partial}{\partial E}\left(b(E) f\right) + \frac{\partial}{\partial z}(V_c f) = Q_{\rm inj} - 2h\delta(z)\Gamma_{\rm spall} f$$

diffusion energy loss convective wind source spallations

3. Indirect Detection

i.e. $\nu, \bar{p}, e^+, \gamma, \bar{D}$ from MDM annihilations in halo or body.



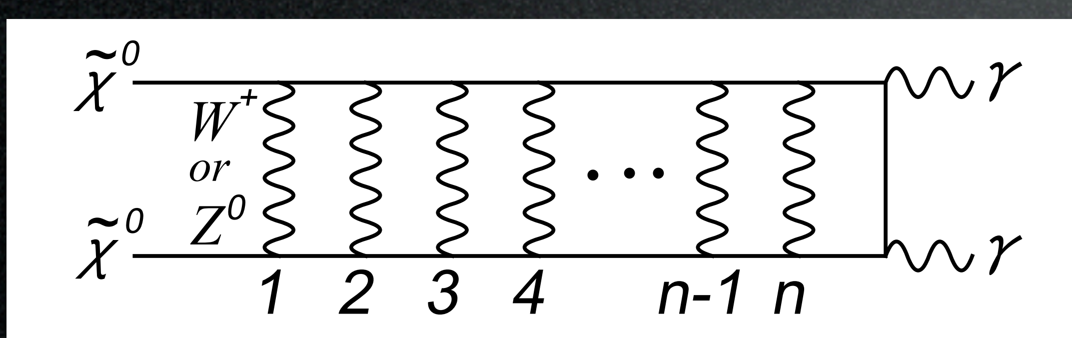


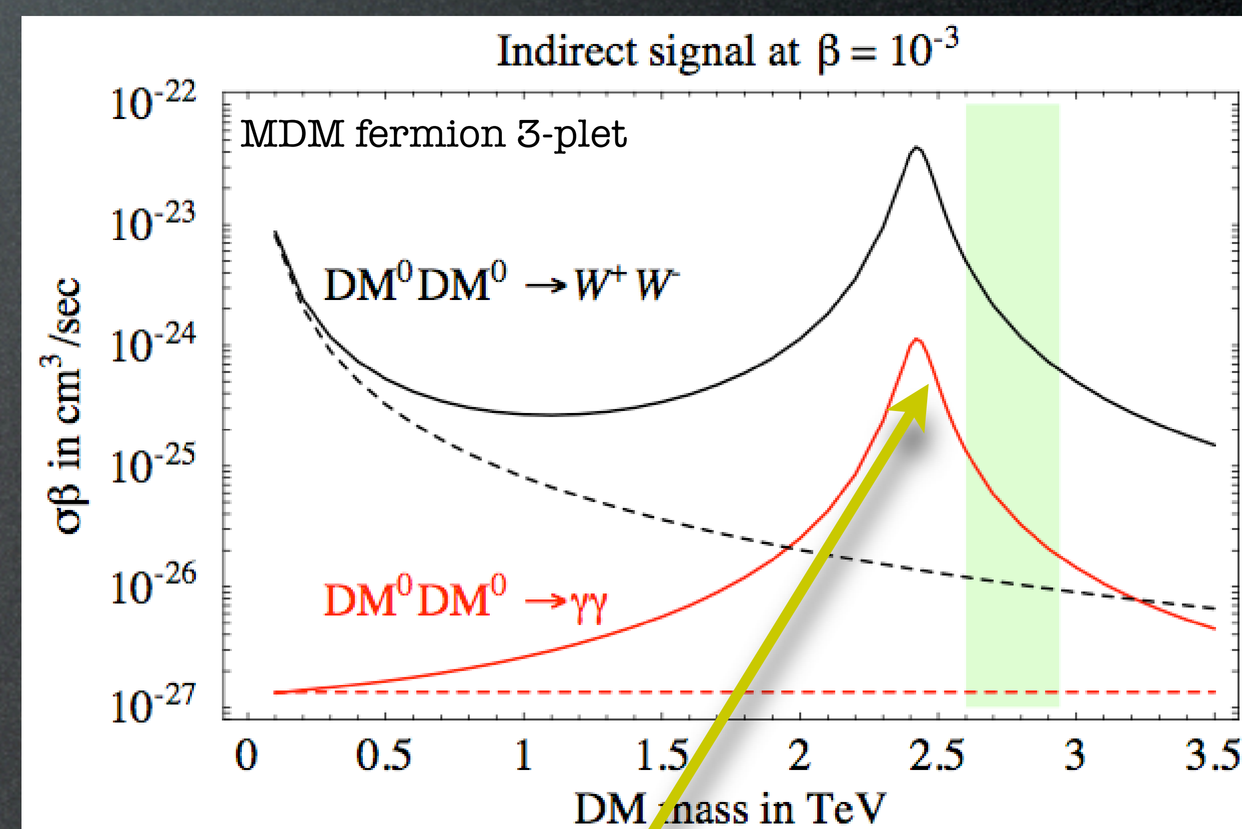
$+ \quad W^\pm, Z \to \bar{p}, e^+, \gamma \ldots$

(channels for MDM with Y=0)

Enhanced cross section in vector bosons due to resummed diagrams when Non-Relativistic $\bar{\mathcal{X}}\mathcal{X}$ are a "bound state":

$$\alpha_2 M_W \sim \Delta M \approx E_B \sim \alpha_2^2 M$$



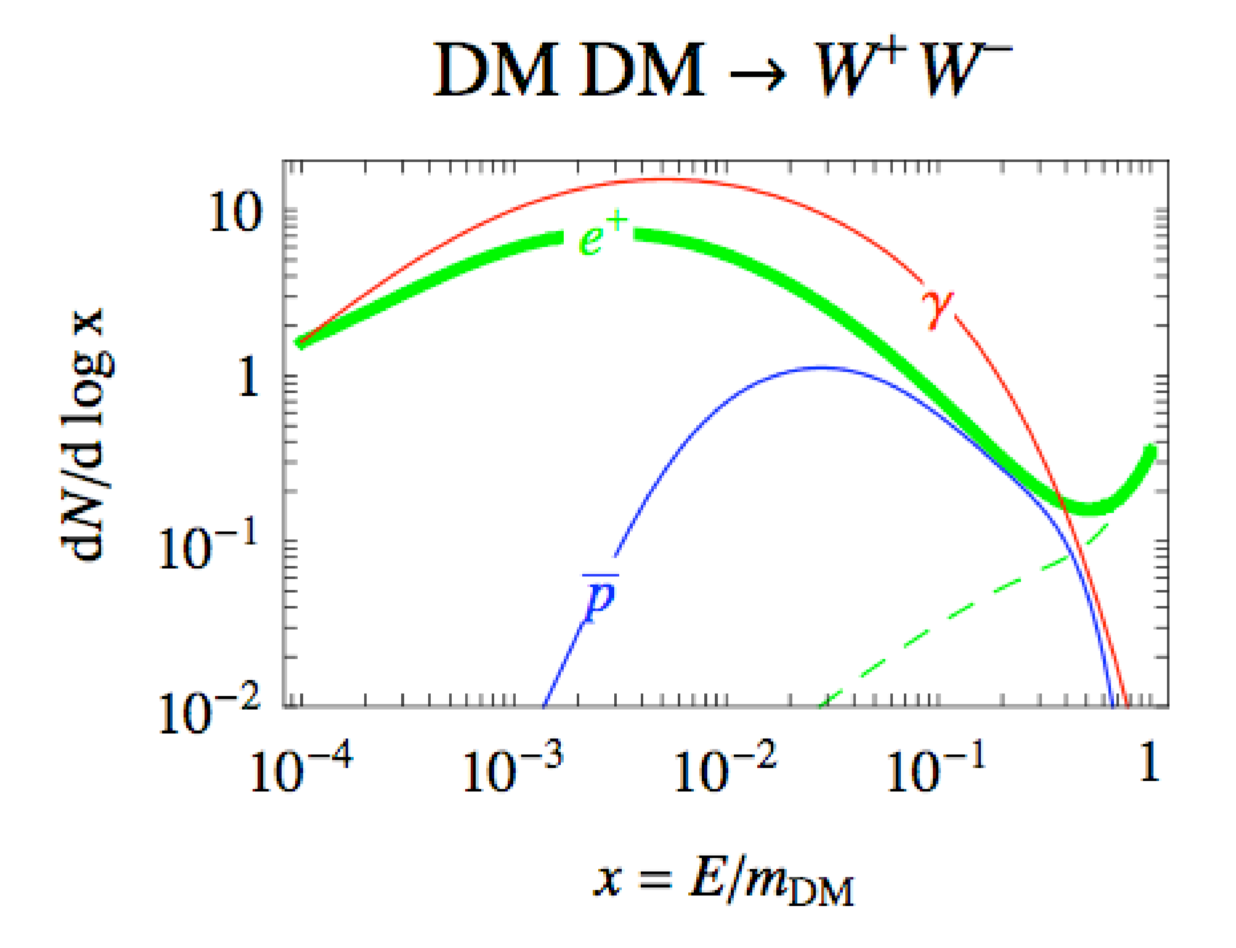


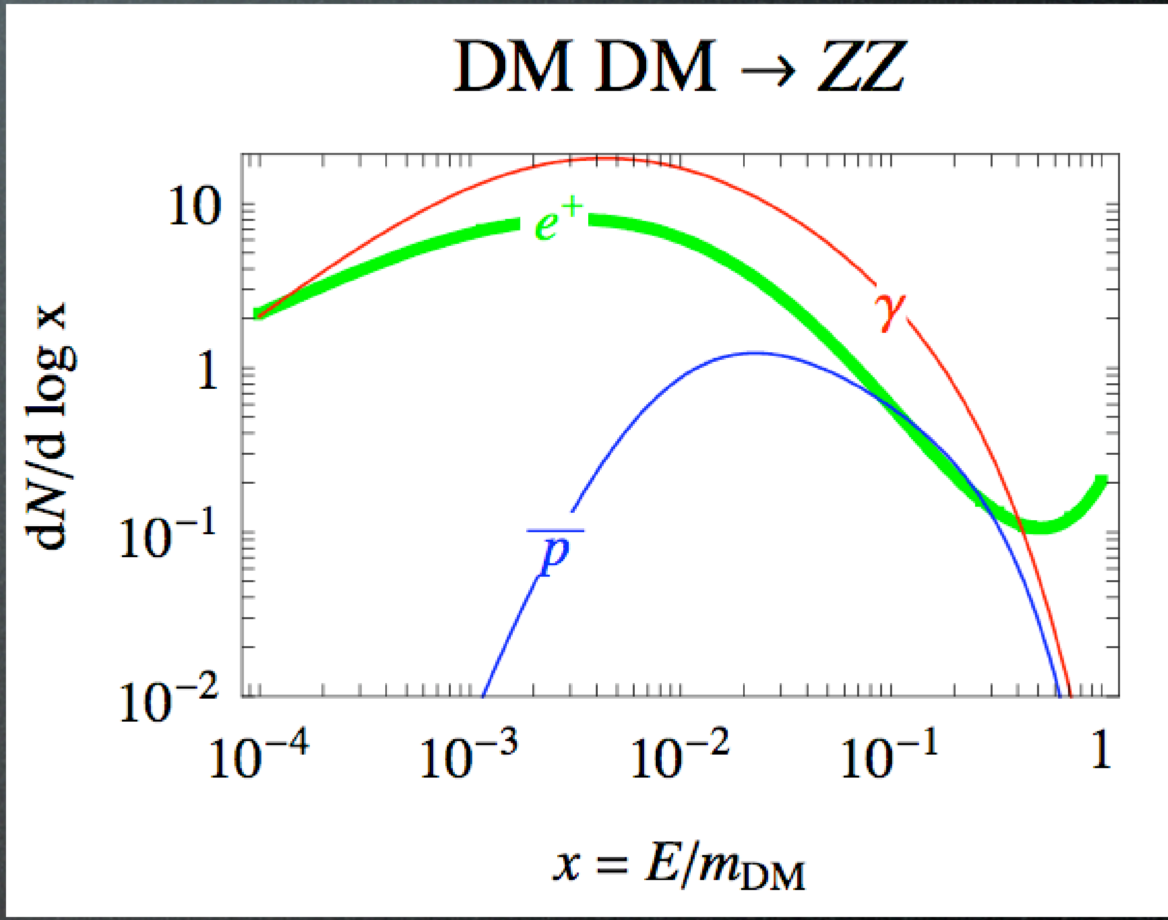
resonances

Hisano et al., 2004, 2005
Cirelli, Strumia, Tamburini, 2007

3. Indirect Detection

Primary spectra:





3. Indirect Detection

Propagation for positrons:

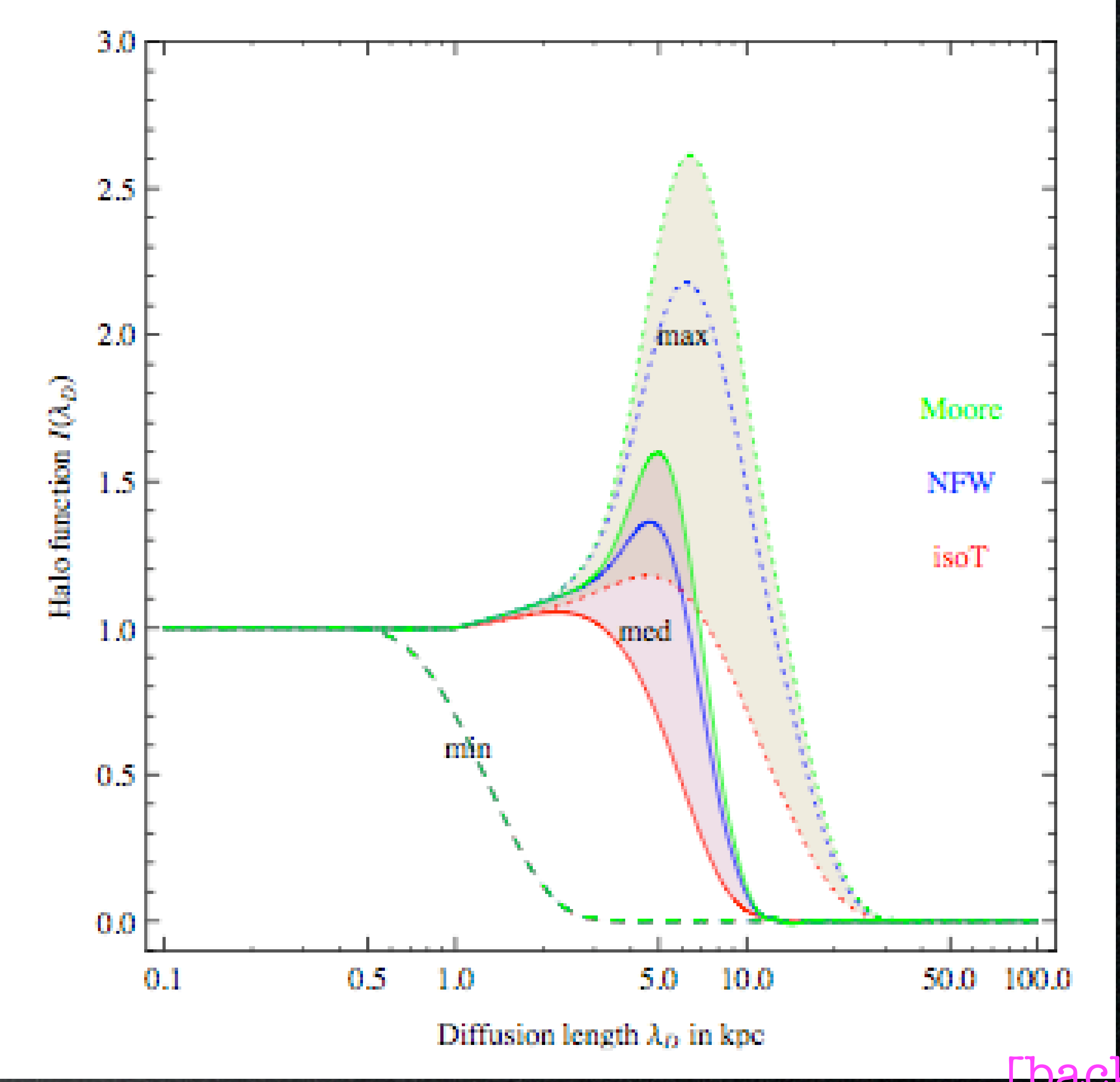
$$\frac{\partial f}{\partial t} - K(E) \cdot \nabla^2 f - \frac{\partial}{\partial E}\left(b(E) f\right) = Q$$

diffusion
$K(E) = K_0 (E/\mathrm{GeV})^\delta$

energy loss
$b(E) = (E/\mathrm{GeV})^2/\tau_E$
$\tau_E = 10^{16}\,\mathrm{s}$

$$Q = \frac{1}{2}\left(\frac{\rho}{M_{\mathrm{DM}}}\right)^2 f_{\mathrm{inj}}, \qquad f_{\mathrm{inj}} = \sum_k \langle \sigma v \rangle_k \frac{dN^k_{e^+}}{dE}$$

Model	δ	K_0 in kpc^2/Myr	L in kpc
min (M2)	0.55	0.00595	1
med	0.70	0.0112	4
max (M1)	0.46	0.0765	15



Solution:

$$\Phi_{e^+}(E, \vec{r}_\odot) = B \frac{v_{e^+}}{4\pi} \frac{\tau_E}{E^2} \int_E^{M_{\mathrm{DM}}} dE' \, Q(E') \cdot I\left(\lambda_D(E, E')\right)$$

$$\lambda_D^2 = 4 K_0 \tau_E \left[\frac{(E/\mathrm{GeV})^{\delta-1} - (E'/\mathrm{GeV})^{\delta-1}}{\delta - 1}\right]$$

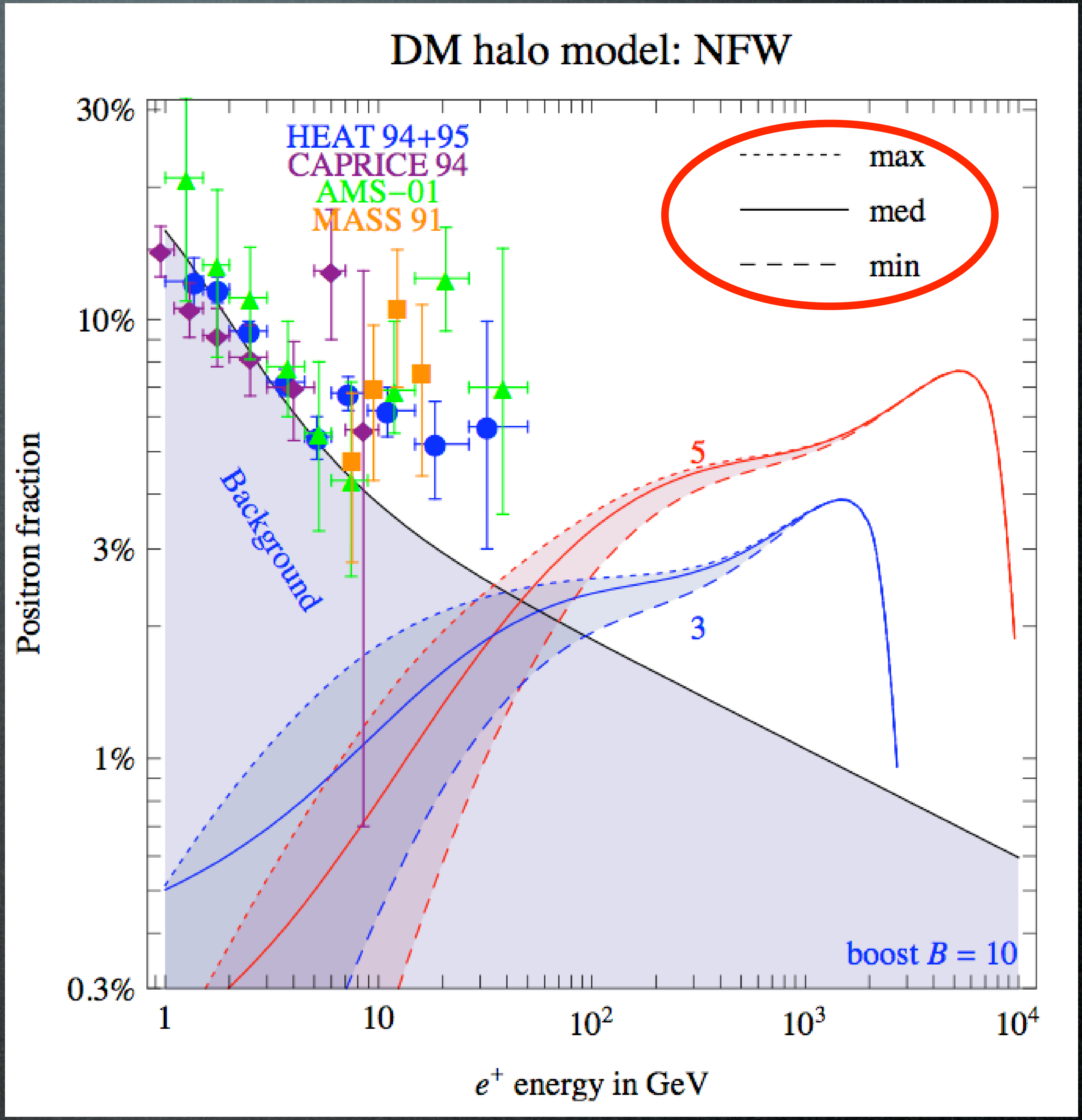
[back]

3. Indirect Detection

Results for positrons:

Astro uncertainties:

- propagation model
- DM halo profile
- boost factor B



3. Indirect Detection

Propagation for antiprotons:

$$\frac{\partial f}{\partial t} - K(T)\cdot\nabla^2 f + \frac{\partial}{\partial z}\left(\mathrm{sign}(z)\, f\, V_{\mathrm{conv}}\right) = Q - 2h\,\delta(z)\,\Gamma_{\mathrm{ann}} f$$

diffusion | convective wind | spallations

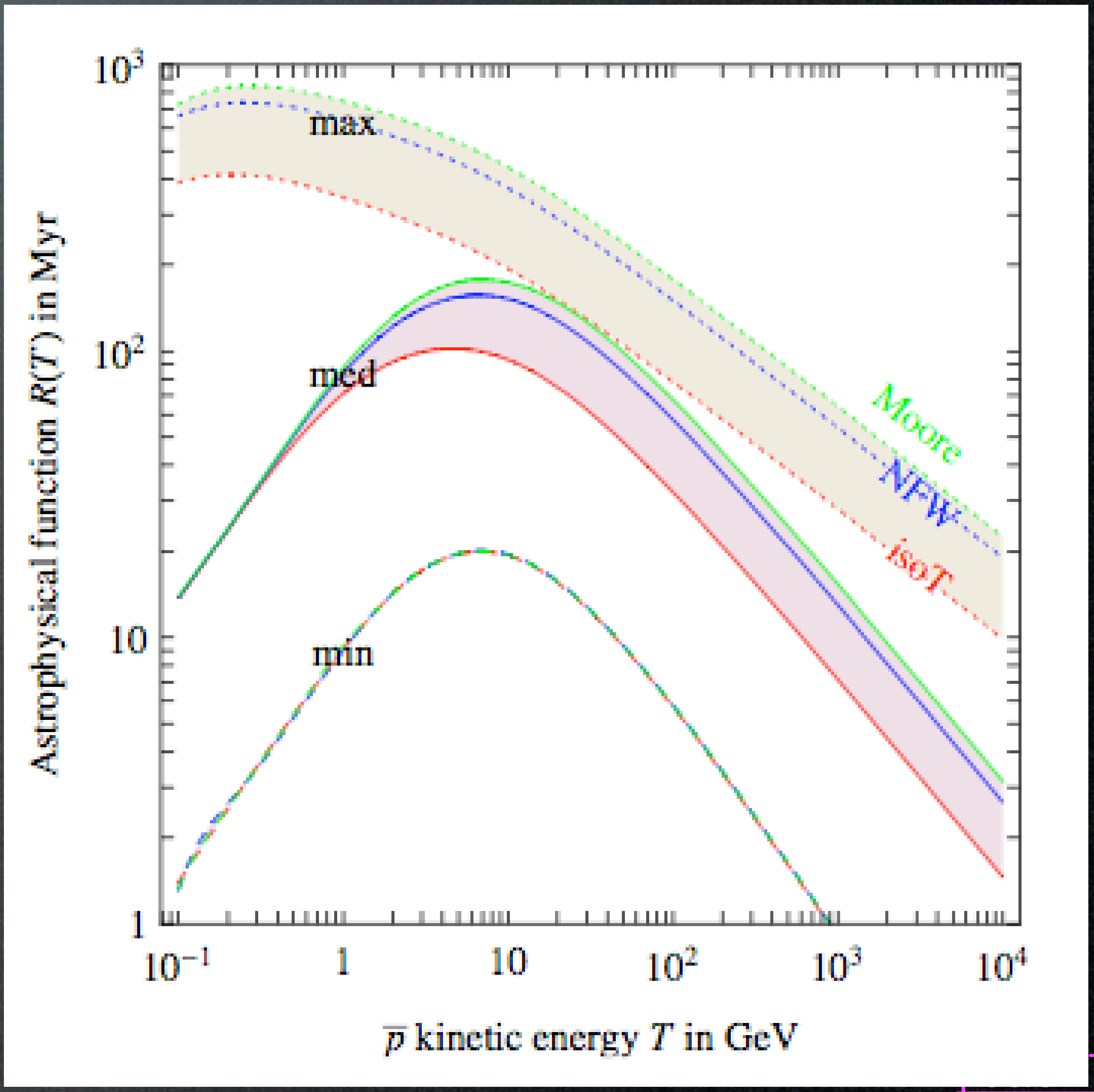
$K(T) = K_0 \beta\, (p/\mathrm{GeV})^{\delta}$

T kinetic energy

Model	δ	K_0 in kpc^2/Myr	L in kpc	V_{conv} in km/s
min	0.85	0.0016	1	13.5
med	0.70	0.0112	4	12
max	0.46	0.0765	15	5

Solution:

$$\Phi_{\bar p}(T, \vec r_\odot) = B\,\frac{v_{\bar p}}{4\pi}\left(\frac{\rho_\odot}{M_{\mathrm{DM}}}\right)^2 R(T) \sum_k \frac{1}{2}\langle\sigma v\rangle_k \frac{dN^k_{\bar p}}{dT}$$



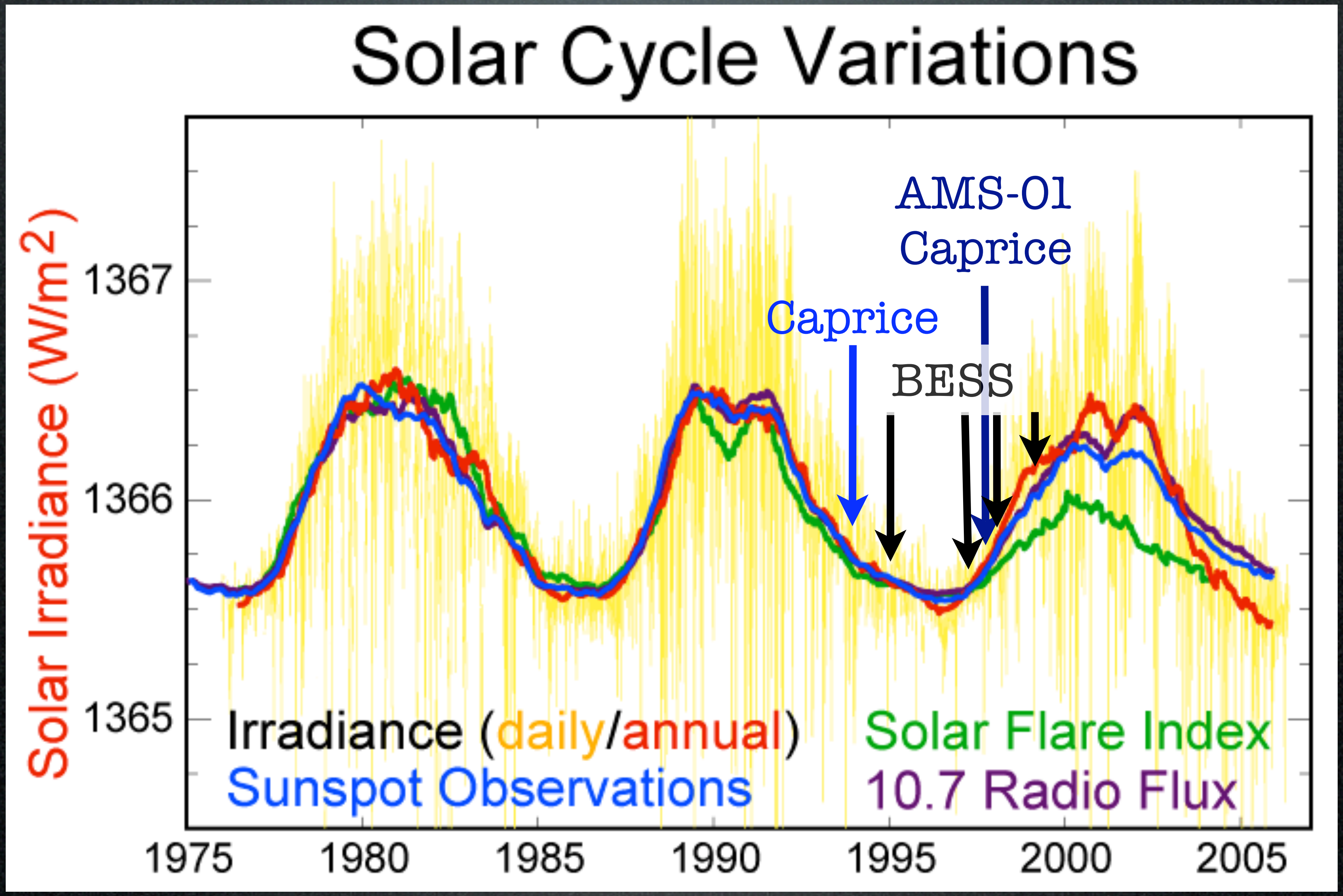
Indirect Detection

Solar wind Modulation of cosmic rays:

$$\frac{d\Phi_{\bar{p}\oplus}}{dT_\oplus} = \frac{p_\oplus^2}{p^2}\frac{d\Phi_{\bar{p}}}{dT}, \qquad T = T_\oplus + |Ze|\phi_F$$

spectrum at Earth — spectrum far from Earth

Fisk potential $\phi_F \simeq 500$ MV

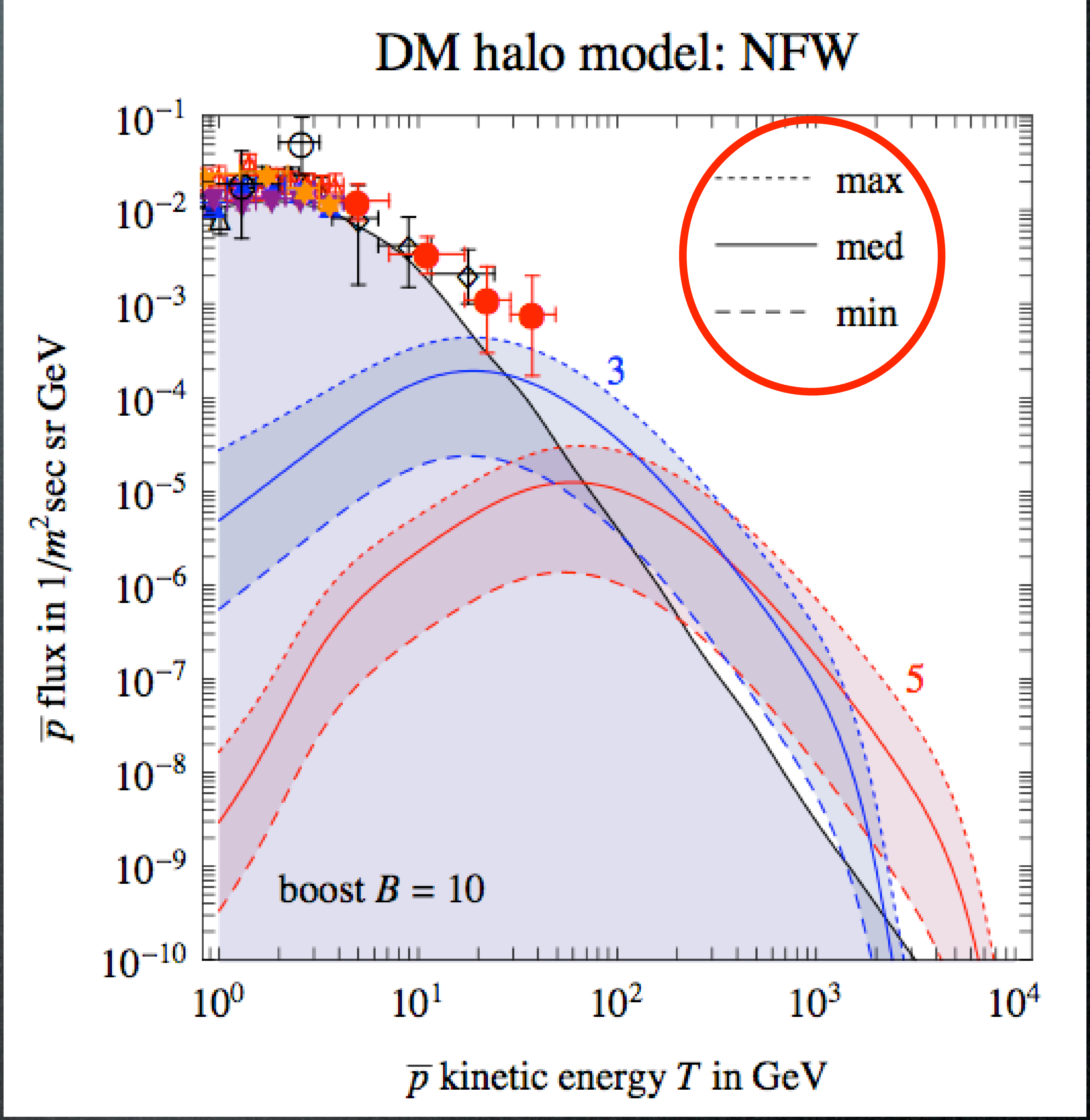


3. Indirect Detection

Results for anti-protons:

Astro uncertainties:

- propagation model
- DM halo profile
- boost factor B

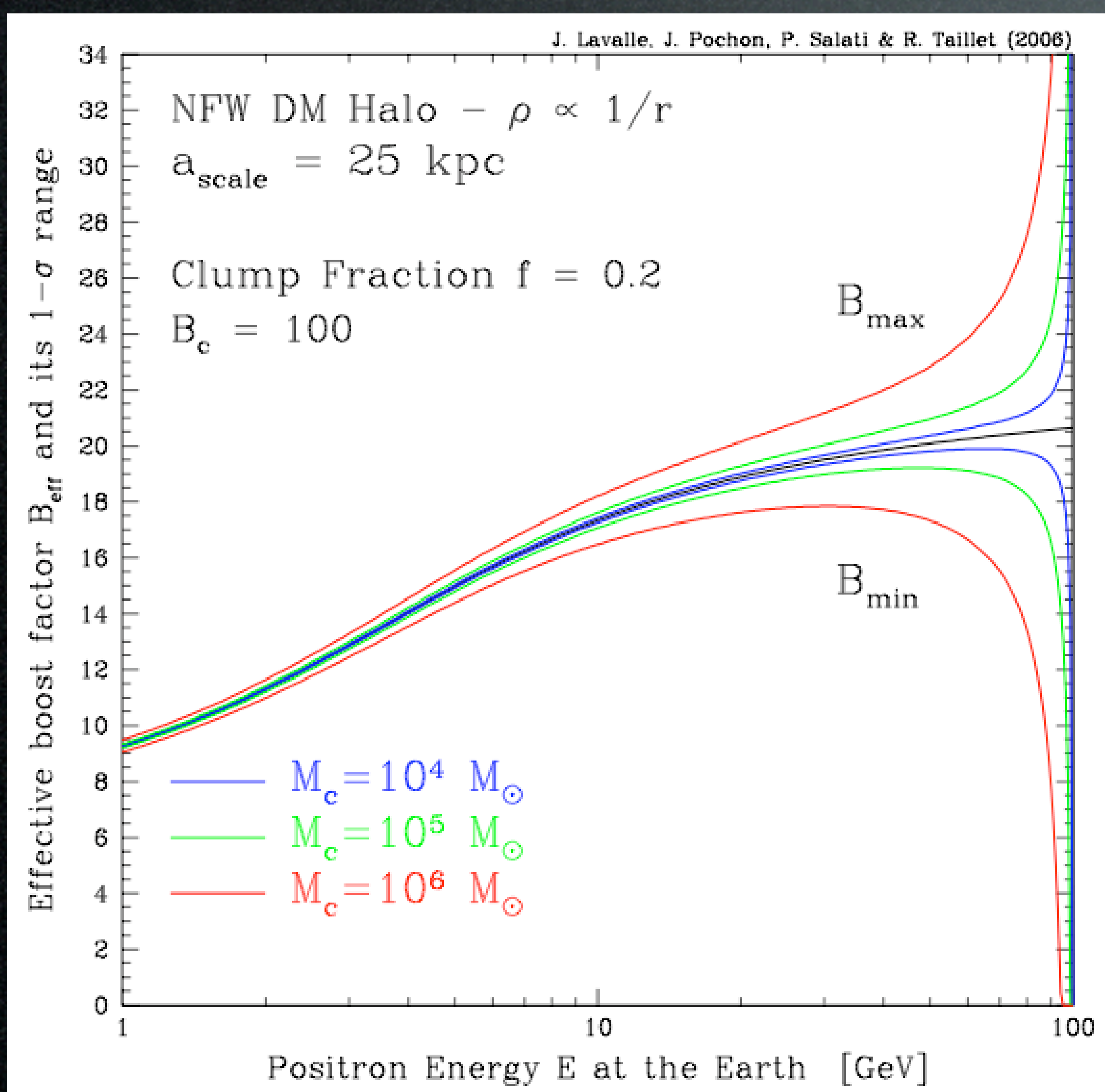


Indirect Detection

Boost Factor: local clumps in the DM halo enhance the density, boost the flux from annihilations. Typically: $B \simeq 1 \rightarrow 20 \quad (10^4)$

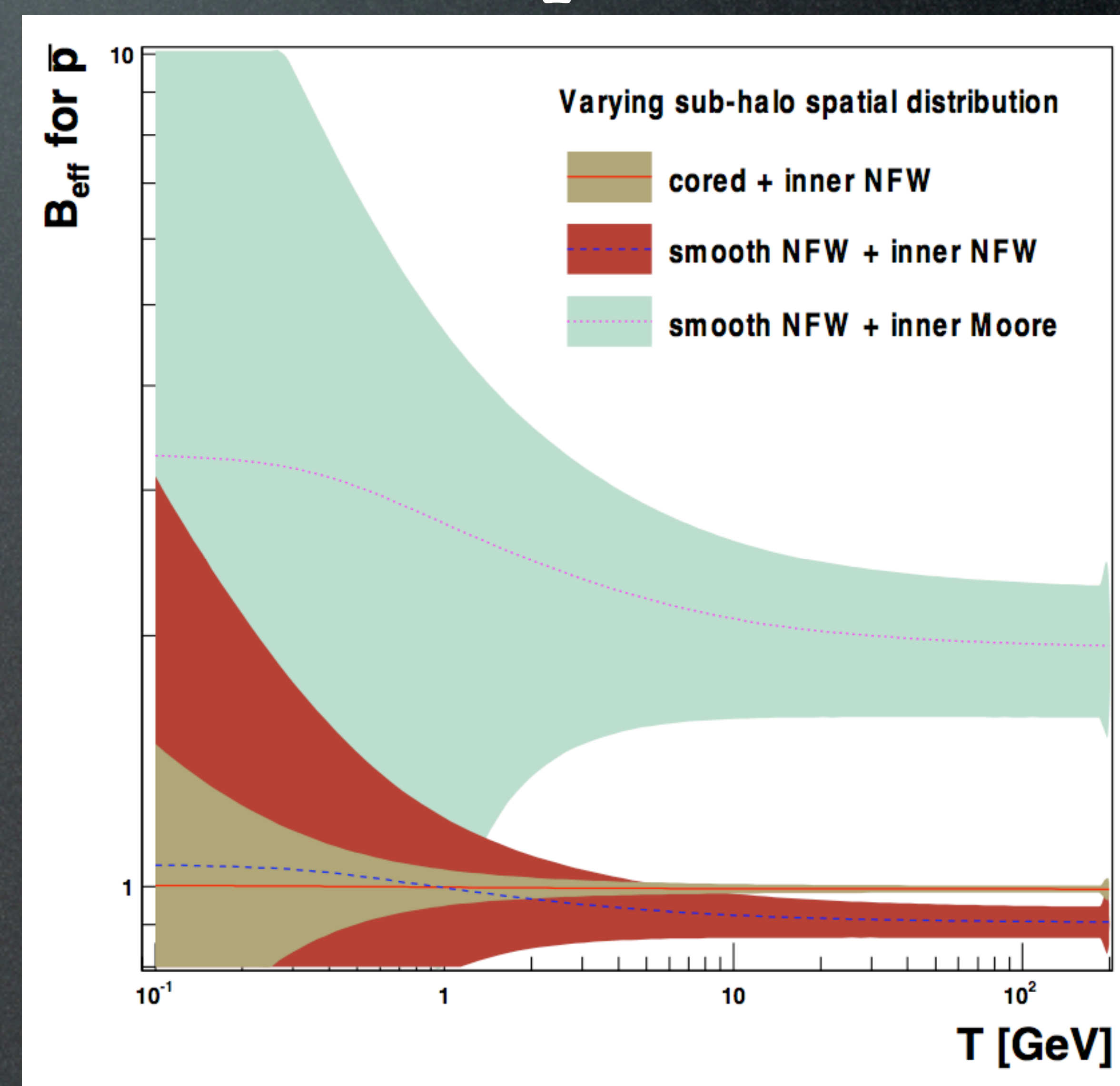
In principle, B is different for e^+, anti-p and gammas,
energy dependent,
dependent on many astro assumptions,
with an energy dependent variance, at high energy for e^+, at low energy for anti-p.

positrons



Lavalle et al. 2006

antiprotons



Lavalle et al. 2007

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