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Minimal Dark Matter

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R.Franceschini (Pisa)

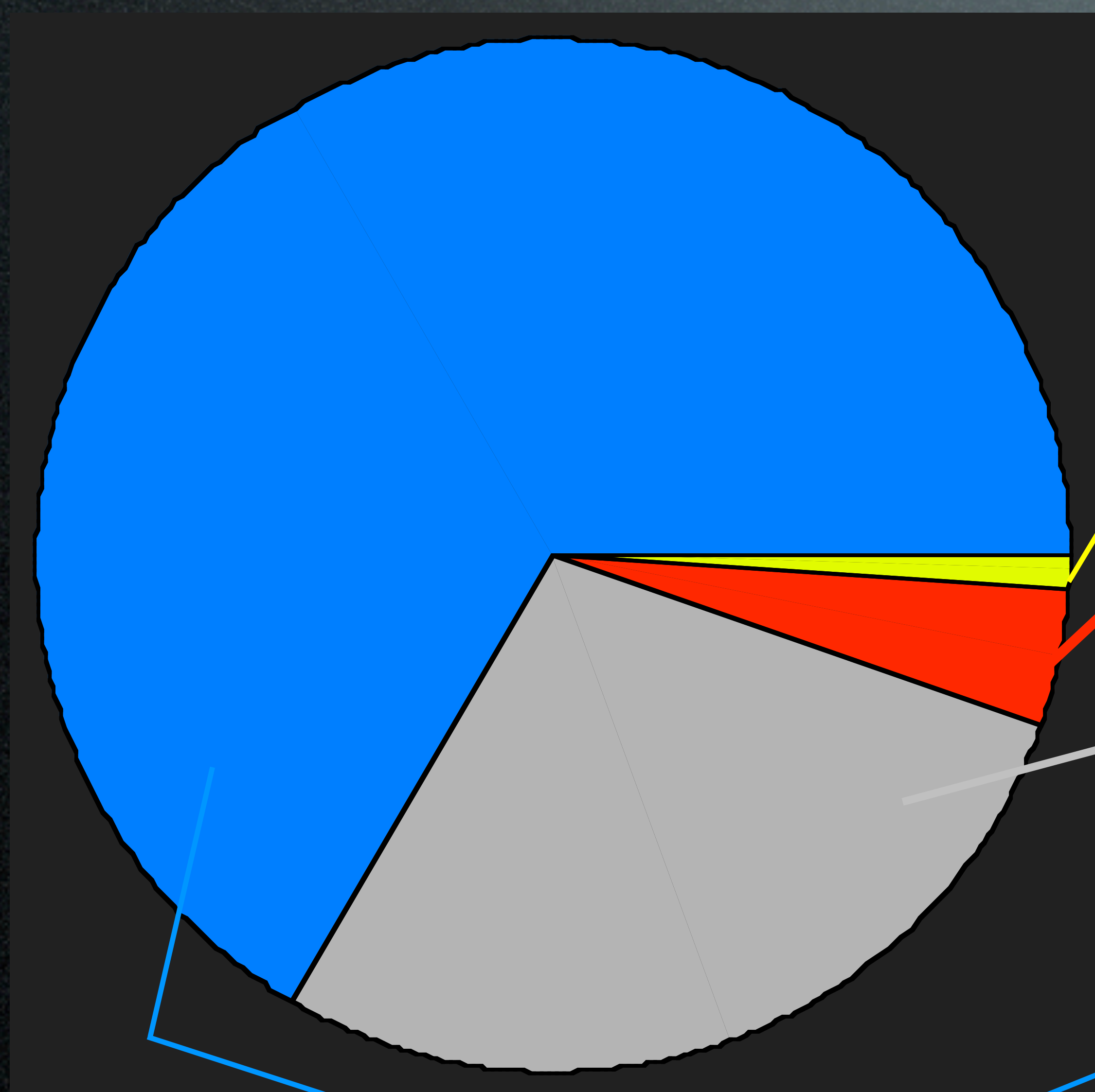
Nuclear Physics B 753 (2006)
and
Nuclear Physics B 787 (2007)
and
0802.3378 (2008)

Contents

- (my point of view on) the status of DM and of DM candidates
- change direction: Minimal DM!
  - MDM properties and viability
- MDM detection and phenomenology

The cosmic inventory

Most of the Universe is Dark



$\Omega_{\rm lum} \sim 0.01$

-mass to light ratio in typical systems

$\Omega_{\rm b} \simeq 0.040 \pm 0.005$

-BBN
-CMB

$\Omega_{\rm DM} \sim 0.24$

particle physics $\cap$ cosmology

$\Omega_{\rm de} \sim 0.7$

- CMB + SNIa
- CMB - DM
- acoustic peak in baryons

$\left(\Omega_x = \frac{\rho_x}{\rho_c}\text{; CMB first peak} \Rightarrow \Omega_{\rm tot} = 1 \text{ (flat);}\right.$

$\left.\text{HST } h = 0.71 \pm 0.07\right)$

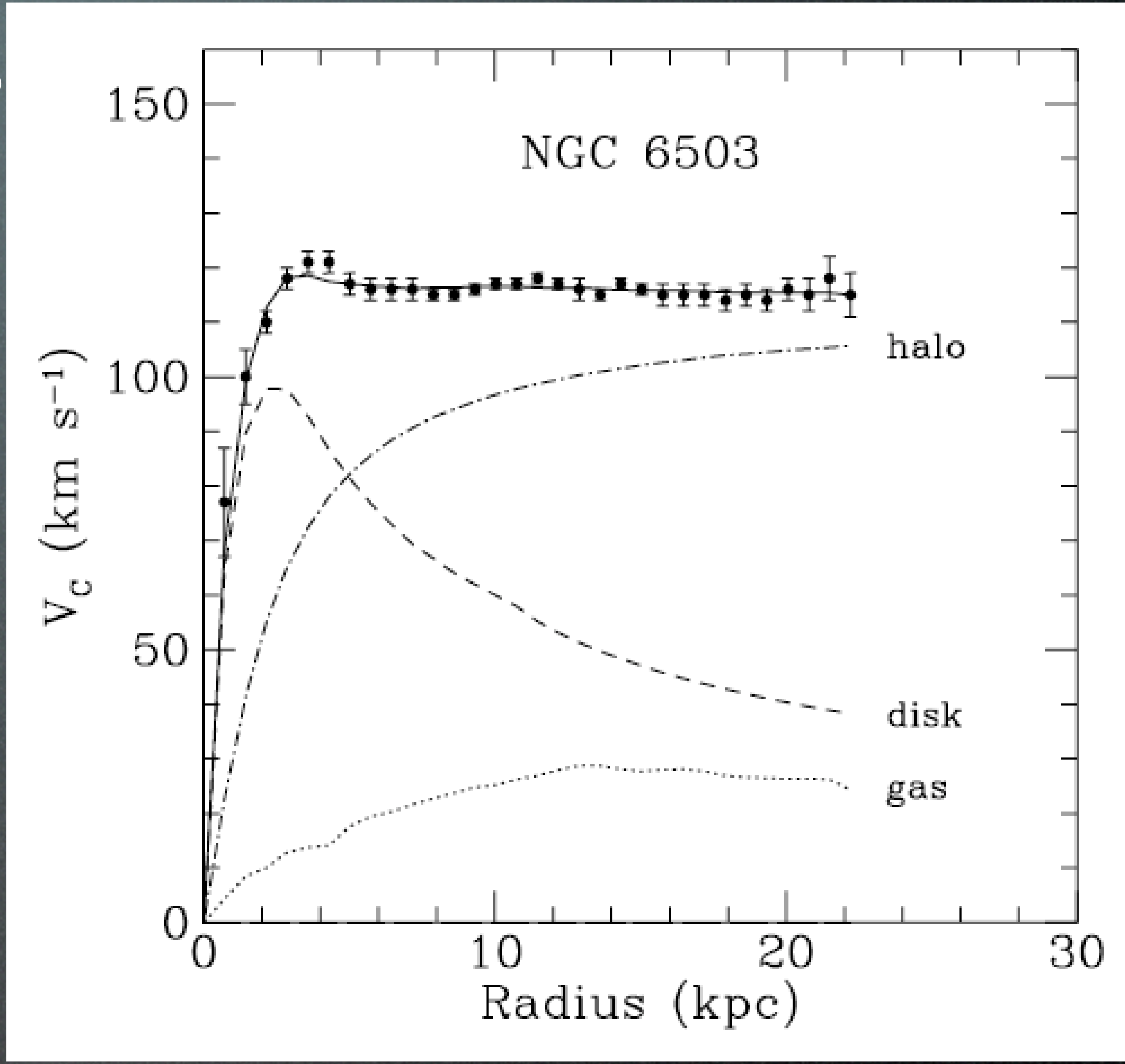
The Evidence for DM

1) galaxy rotation curves

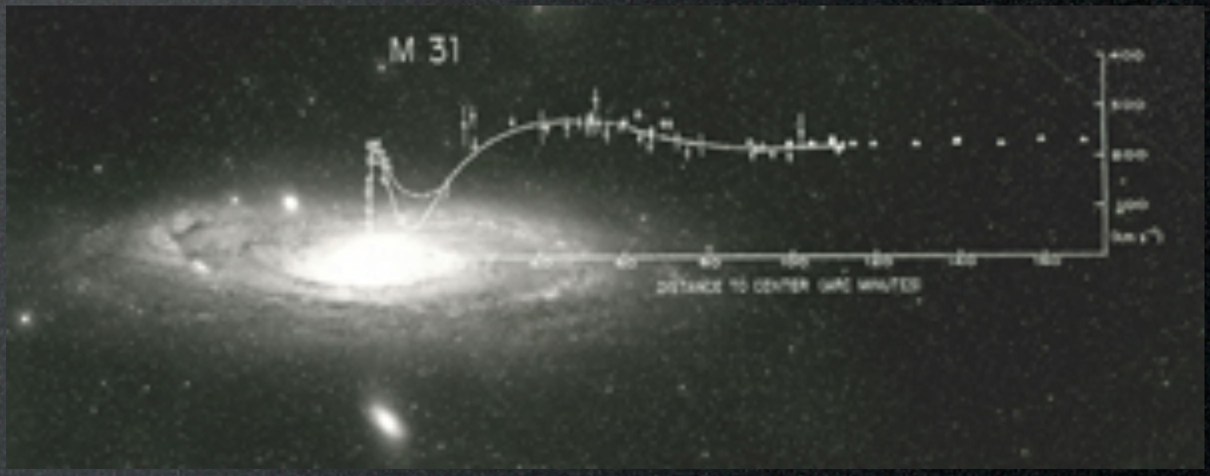
$$v_c(r) = \sqrt{\frac{2G_N M(r)}{r}}$$

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

$$\Omega_M \gtrsim 0.1$$



Begeman et al., MNRAS 249 (1991)



The Evidence for DM

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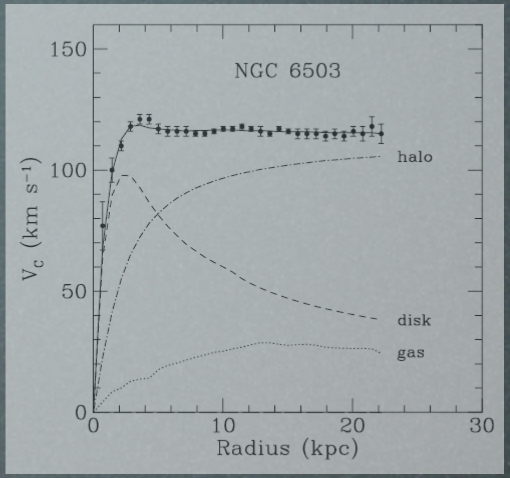


$$\Omega_M \gtrsim 0.1$$

2) clusters of galaxies

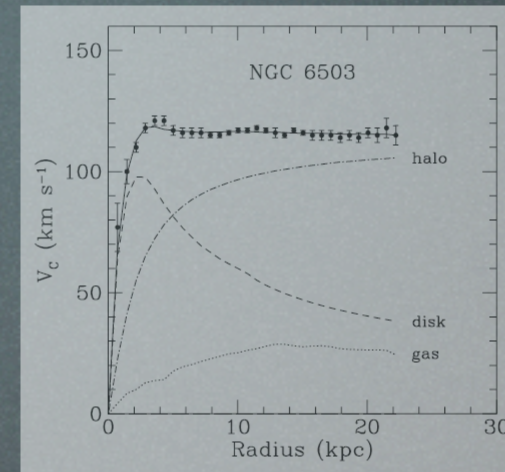
- "rotation curves"
- gravitation lensing
- X-ray gas temperature

$$\Omega_M \sim 0.2 \div 0.4$$

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

The Evidence for DM

1) galaxy rotation curves



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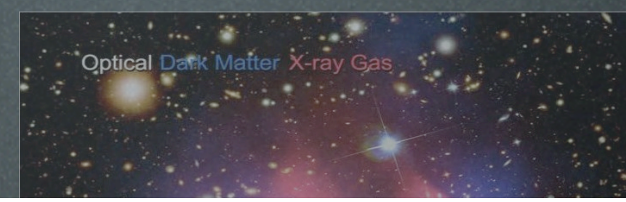
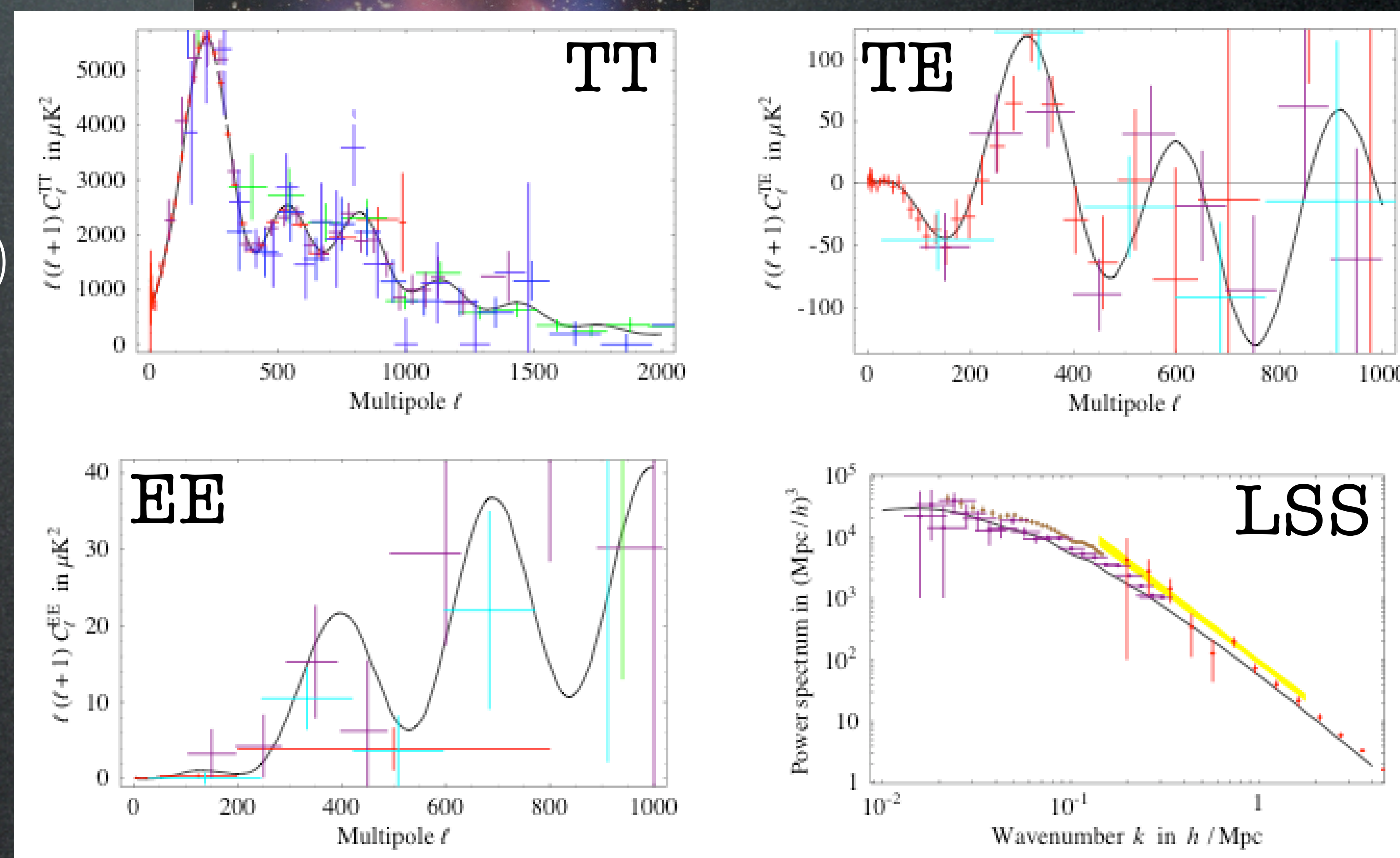


$\Omega_M \sim 0.2 \div 0.4$

3) CMB+LSS(+SNIa:)

WMAP-3yr
ACbar
CBI
Boomerang
DASI
VSA

SDSS, 2dFRGS
LyA Forest Croft
LyA Forest SDSS

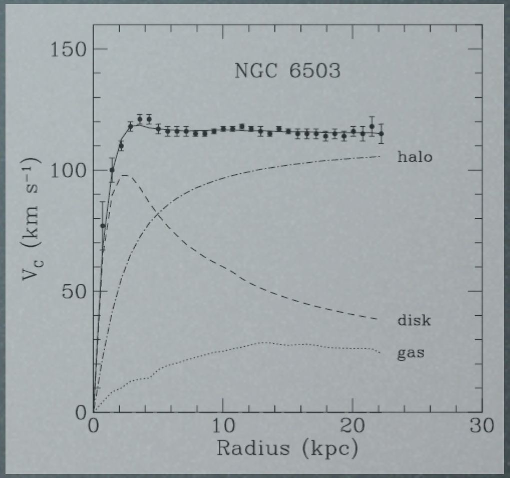


$\Omega_M \approx 0.26 \pm 0.05$

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

The Evidence for DM

1) galaxy rotation curves



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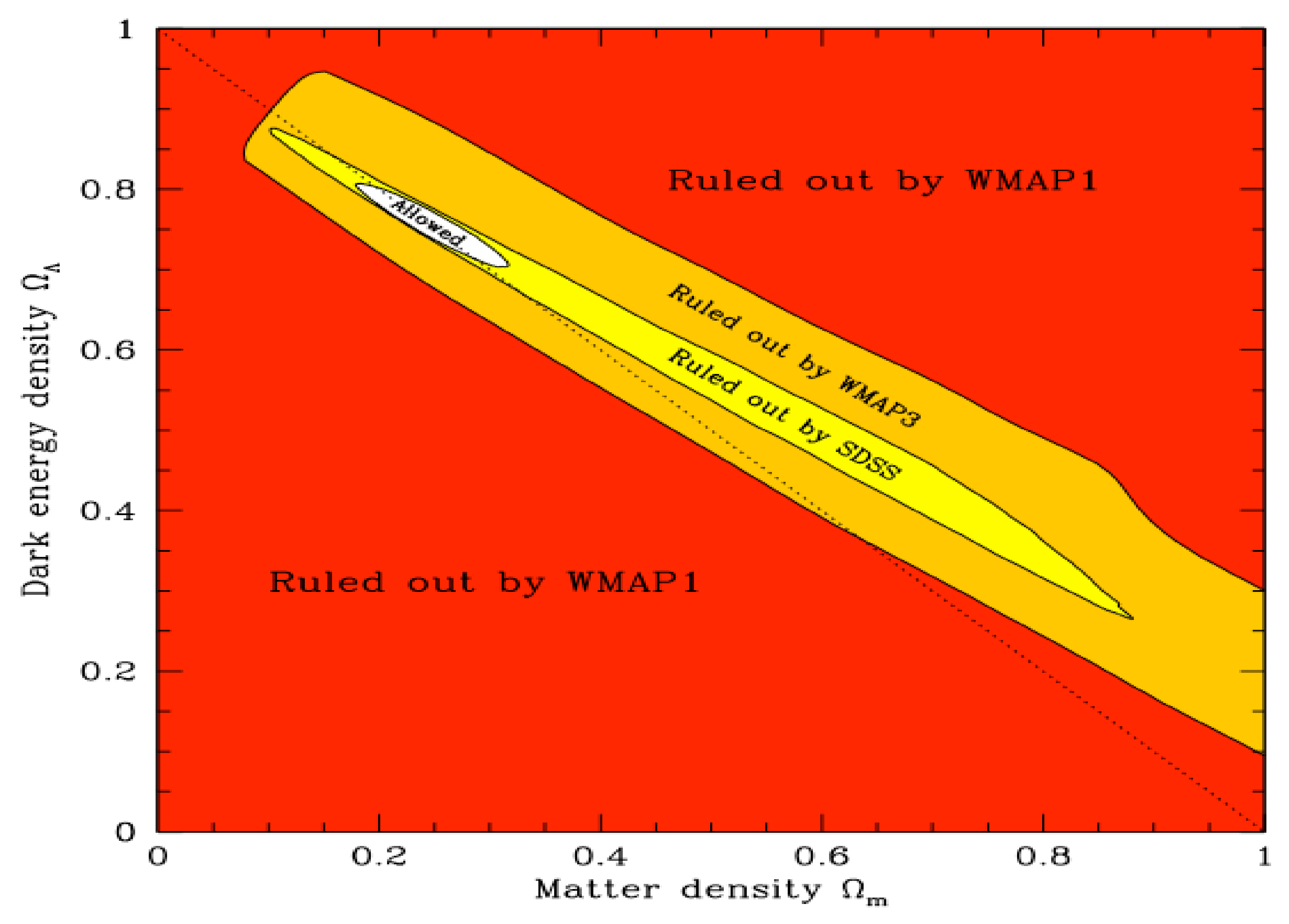

M.Tegmark et al., astro-ph/0608632

The Evidence for DM

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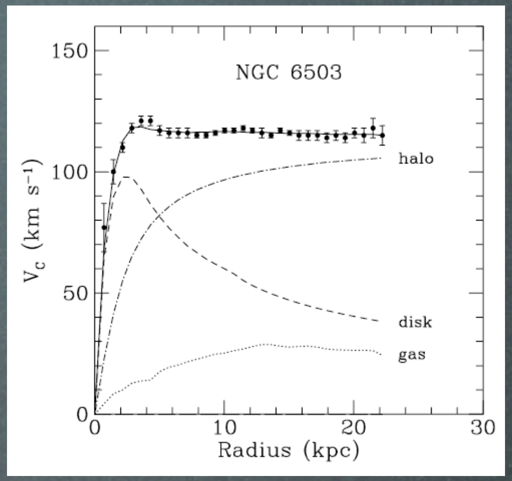

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details

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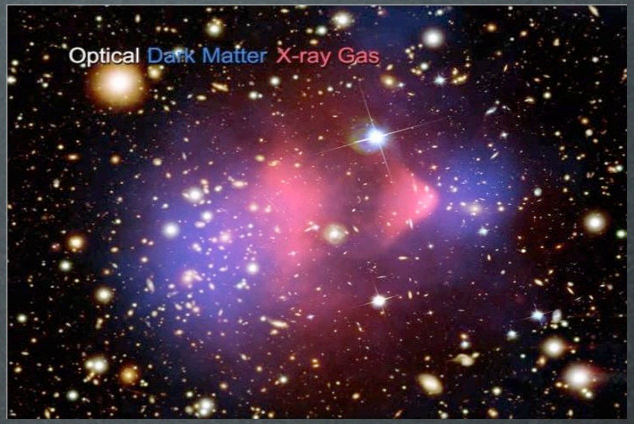

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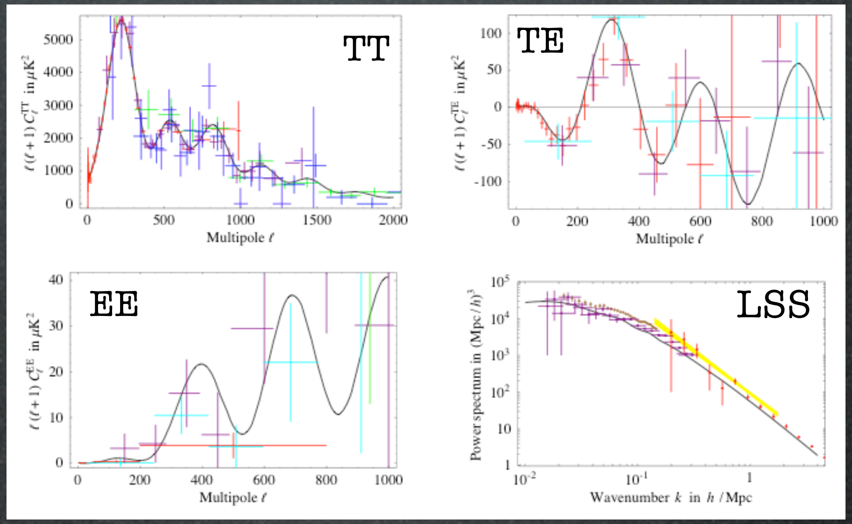


$\Omega_M \approx 0.26 \pm 0.05$

details

DM is there.

What is DM?

Most likely a

weakly int., massive, neutral, stable

relic particle.

Most likely a

weakly int., massive, neutral, stable

has the correct

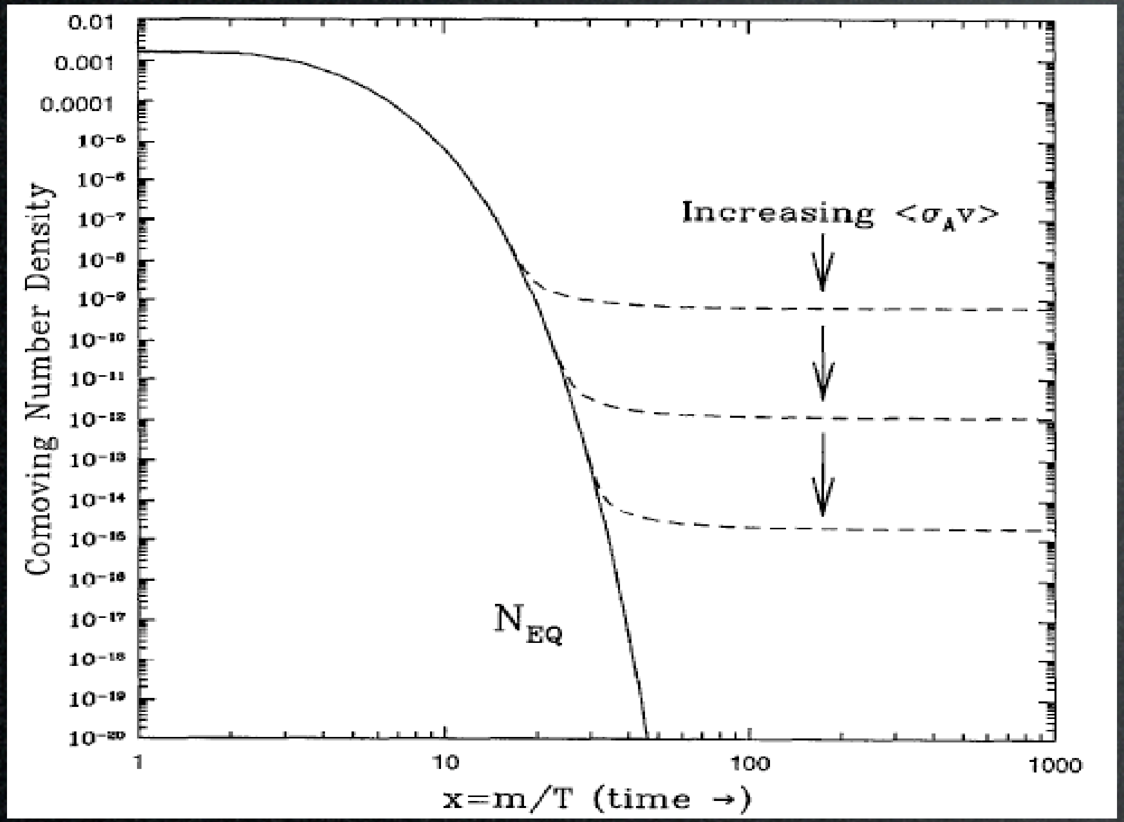
relic abundance today!

Boltzmann eq. in the Early Universe:

$$\Omega_X \approx \frac{6\ 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma_{\mathrm{ann}}v\rangle}$$

Weak cross section:

$$\langle\sigma_{\mathrm{ann}}v\rangle \approx \frac{\alpha_w^2}{M^2} \approx \frac{\alpha_w^2}{\mathbf{1\ TeV}^2} \Rightarrow \Omega_X \sim \mathcal{O}(\text{few } 0.1)$$



Kolb,Turner, The Early Universe, 1995

Most likely a

weakly int., massive, neutral, stable

has the correct **relic abundance** today!

(or we would have seen it...)

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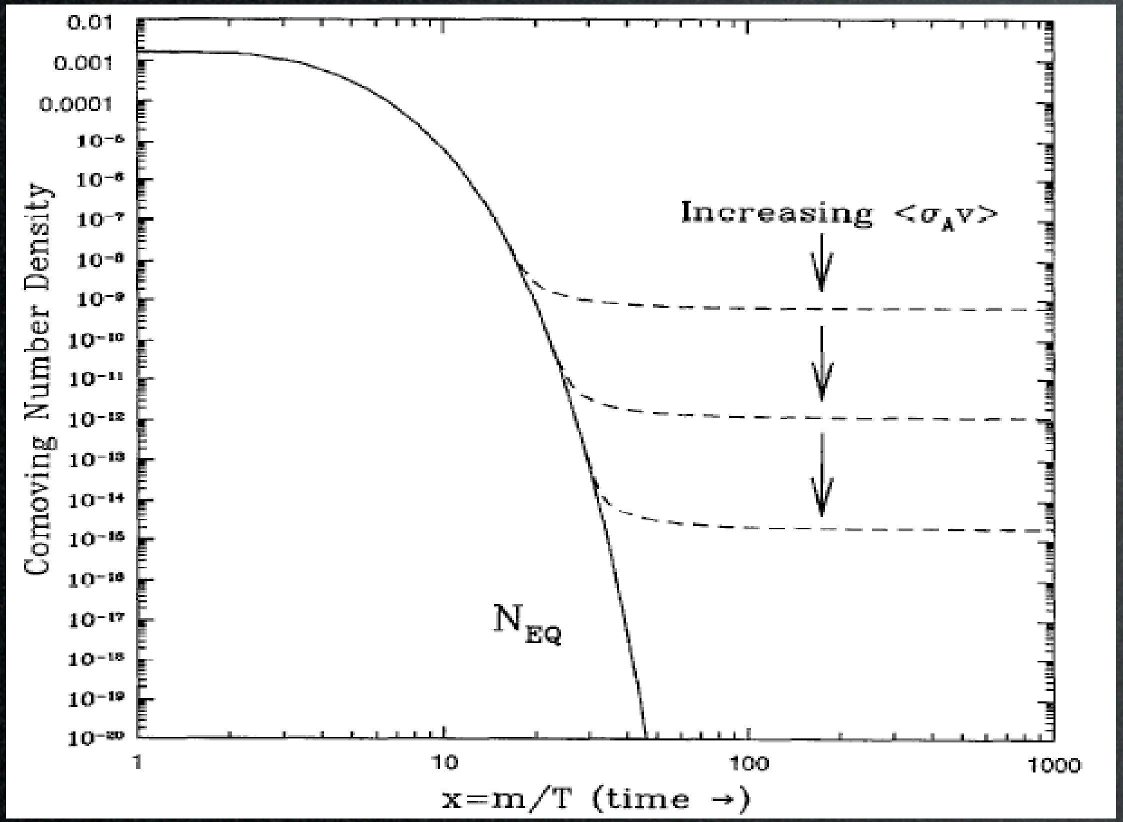

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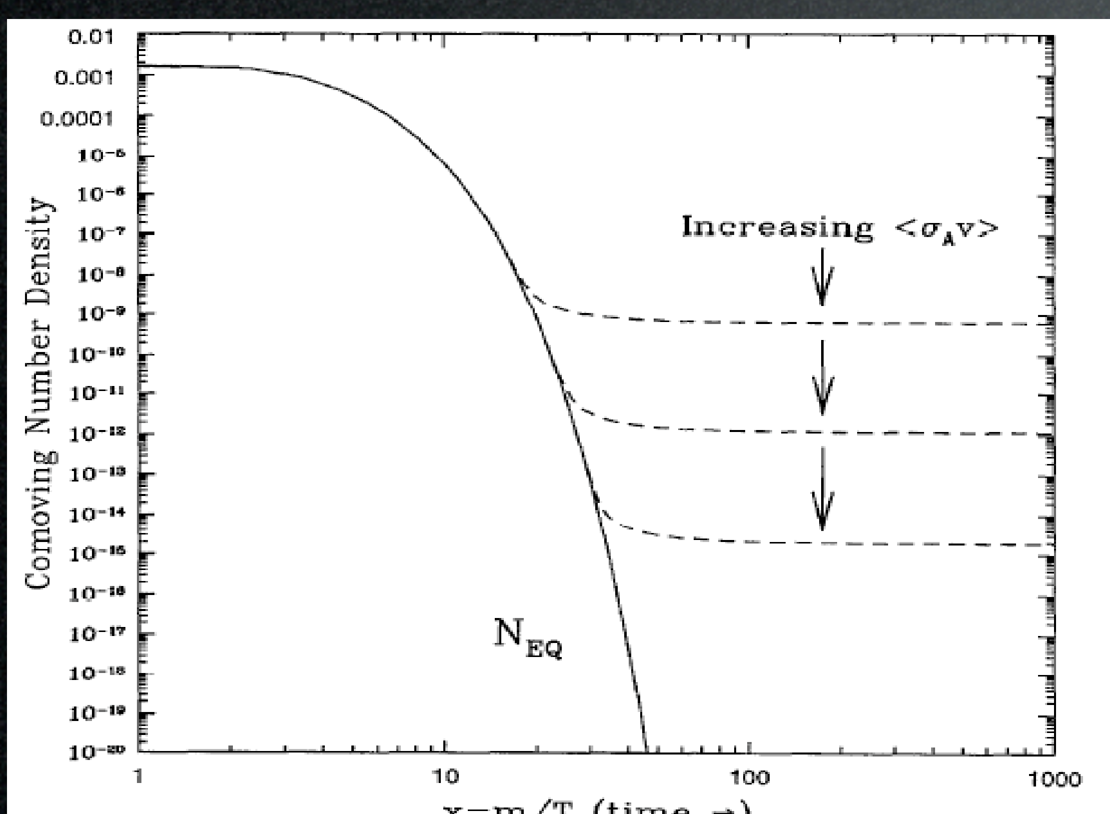

Kolb,Turner, The Early Universe, 1995

at least on cosmological
time scales, i.e.

$$\tau > t_{\rm universe}$$

Most likely a

weakly int., massive, neutral, stable

Theories beyond the SM have ambitious goals (hierarchy prob, EWSB, unification).
As a *byproduct*, they can provide DM candidates at the EW scale.

Popular candidates:

SuperSymmetric LSP,
Little Higgs' heavy photon,
Extra dimensional LKP...

...BUT:

Most likely a

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("little hierarchy problem", ft in LH etc)

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(ii) these theories have many parameters,
DM phenomenology is unclear (scatter plots)

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...BUT: (i) these theories already start to be uncomfortably fine tuned ("little hierarchy problem", ft in LH etc)

(ii) these theories have many parameters, DM phenomenology is unclear (scatter plots)

(iii) DM stability is imposed by hand (R-parity, T-parity, KK parity)

Minimalistic approach

Minimalistic approach

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

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

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

and systematically search for the ideal DM candidate...

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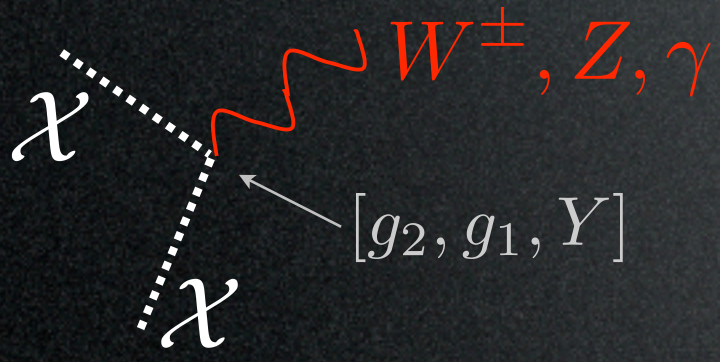
gauge interactions

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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weakly int., massive, neutral, stable

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

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

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

these are all possible choices:

$n \leq 5$ for fermions

$n \leq 7$ for scalars

to avoid explosion in the running coupling

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

The ideal DM candidate is

weakly int., massive, neutral, stable

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

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

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

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

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

etc.

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

$SU(2)_L$	$U(1)_Y$	spin
$\underline{2}$	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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etc.

The ideal DM candidate is

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

The mass M is determined by the relic abundance:

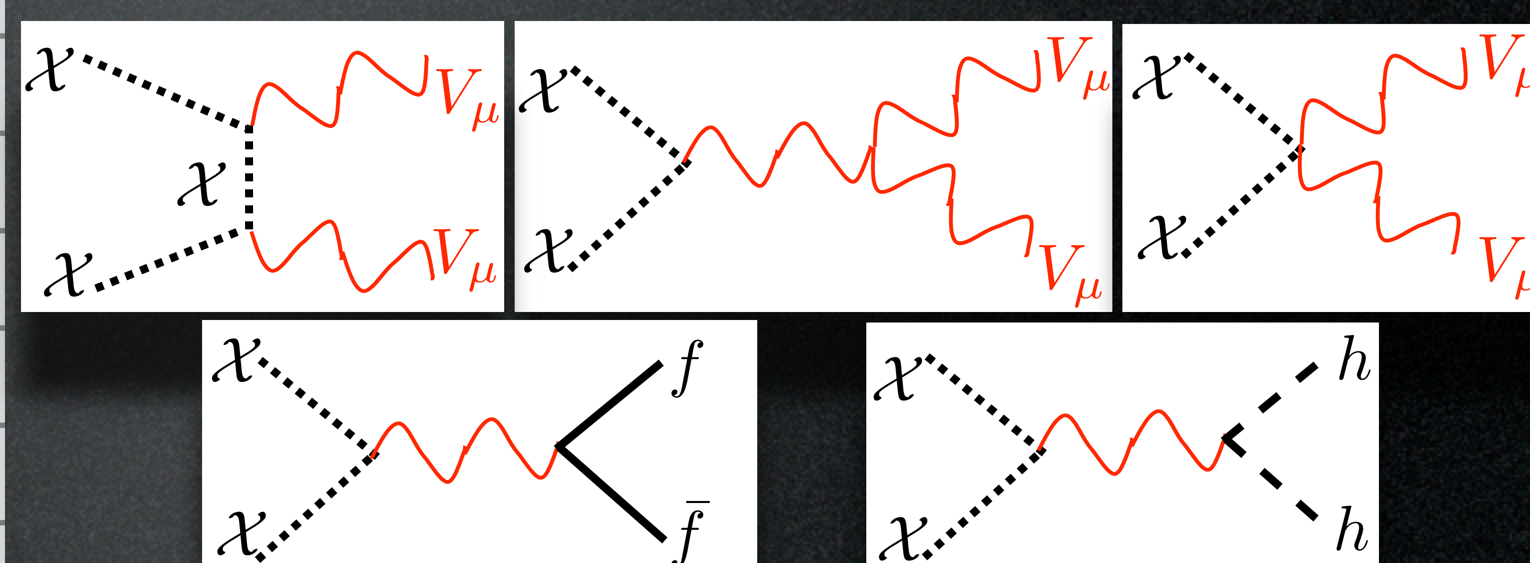
$$\Omega_{\rm DM} = \frac{6\ 10^{-27}{\rm cm}^3{\rm s}^{-1}}{\langle \sigma_{\rm ann} v\rangle} \simeq 0.24$$

for $\mathcal{X}$ scalar

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

for $\mathcal{X}$ fermion

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



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

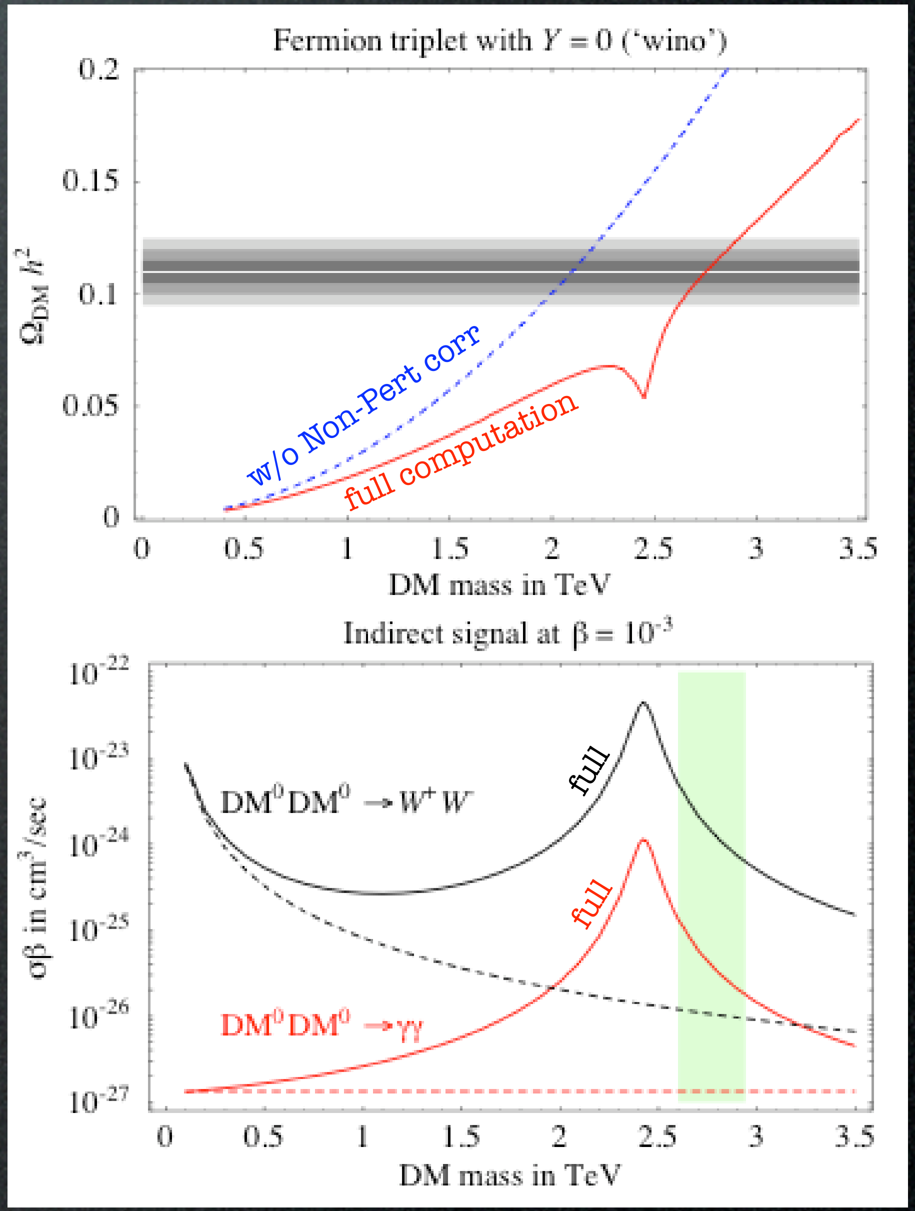
The ideal DM candidate is
weakly int., massive, neutral, stable

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

Non-perturbative corrections
(and other smaller corrections) ← (more later)
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 $R \sim \mathcal{O}({\rm few}) \to \mathcal{O}(10^2)$



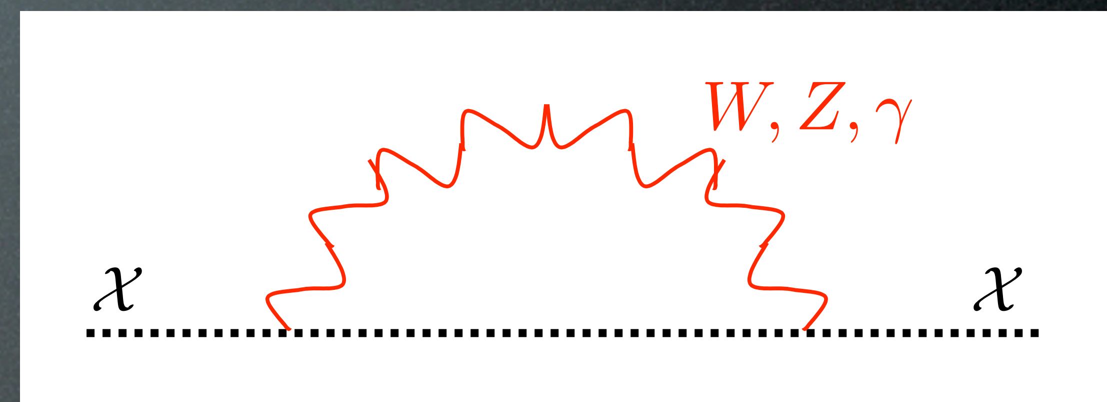
The ideal DM candidate is

weakly int., massive, neutral, stable

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

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

tree level



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

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

The neutral component is the lightest

The ideal DM candidate is

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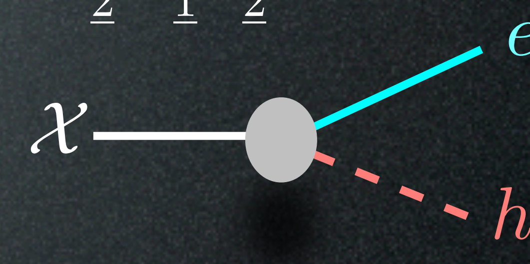
$SU(2)_L$	$U(1)_Y$	spin	M (TeV)	ΔM(MeV)	decay ch.
$\underline{2}$	1/2	S		348	EL
		F	1.0	342	EH
$\underline{3}$	0	S	2.5	166	HH^*
		F	2.7	166	LH
	1	S		540	HH, LH
		F		526	LH
$\underline{4}$	1/2	S		353	HHH^*
		F		347	(LHH^*)
	3/2	S		729	HHH
		F		712	(LHH)
$\underline{5}$	0	S	9.4	166	(HHH^*H^*)
		F	10	166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

List all allowed SM couplings:

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



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

dim=5 operator, induces

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

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

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$SU(2)_L$	$U(1)_Y$	spin	M (TeV)	ΔM(MeV)	decay ch.
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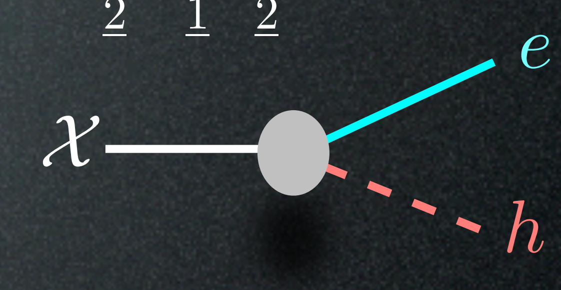

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dim=5 operator, induces

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

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

No allowed decay!

Automatically stable!

The ideal DM candidate is

weakly int., massive, neutral, stable

and

not excluded

by direct searches!

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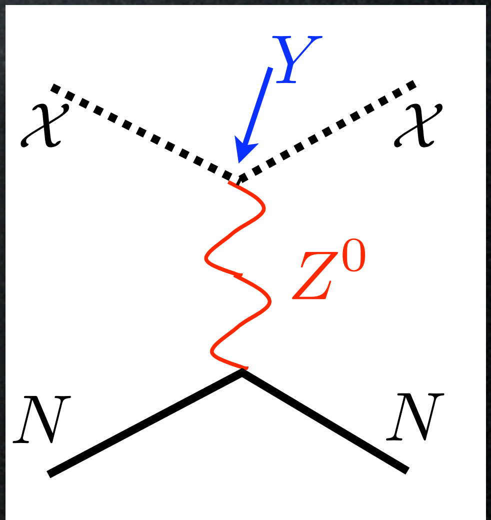
		F		534	—
	2	S		906	$(H^*H^*H^*H^*)$
		F		900	—
7	0	S	25	166	—

and

not excluded

by direct searches!

Candidates with $Y \neq 0$ interact as



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

$\gg$ present bounds

e.g. CDMS

need $Y = 0$

The ideal DM candidate is

weakly int., massive, neutral, stable

and

not excluded

by direct searches!

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

The ideal DM candidate is

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

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and

not excluded

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5	0	S	9.4	166	(HHH^*H^*)
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	1	S		537	$(HH^*H^*H^*)$
		F		534	—
	2	S		906	$(H^*H^*H^*H^*)$
		F		900	—
7	0	S	25	166	—

← We have a winner!

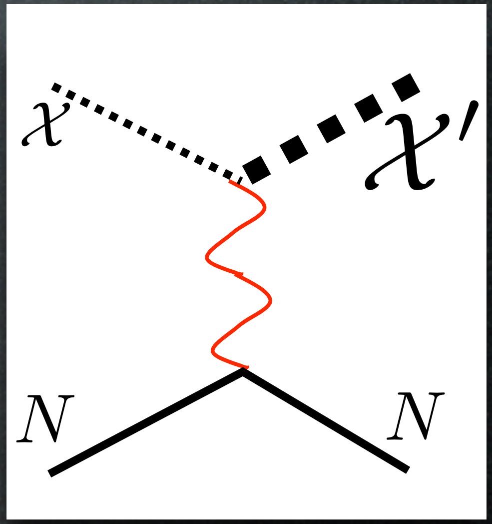
← and a 2° place

(other terms in the scalar potential)

If you want to cure ill candidates...

$Y \neq 0$: introduce some mechanism to forbid coupling with Z^0 anyway

e.g. mixing with an extra singlet splits the 2 components of $\mathcal{X}$; if splitting is large enough, NC scattering is kinematically forbidden...



stability: impose some symmetry to forbid decays (e.g. R-parity)...

...the case of SuSy higgsino

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

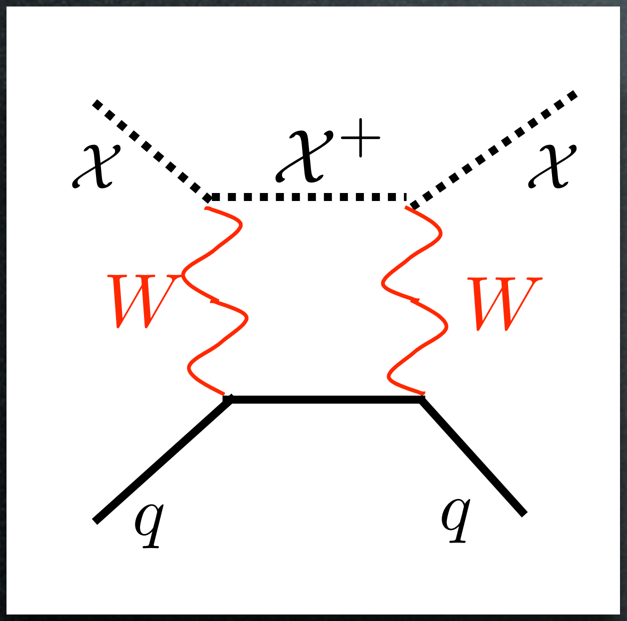
indirect

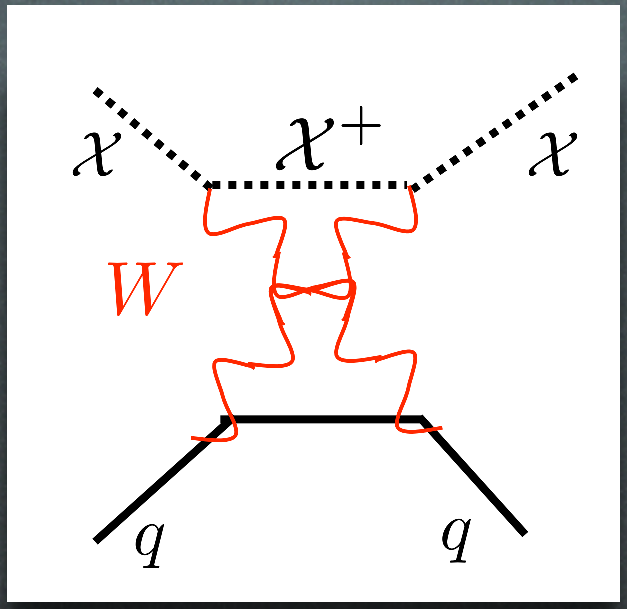
- γ from annihil in galactic halo or center (line + continuum)
- e^+ from annihil in galactic halo or center
- $\bar{p}$ from annihil in galactic halo or center
- $\bar{D}$ from annihil in galactic halo or center
- $\nu, \bar{\nu}$ from annihil in massive bodies

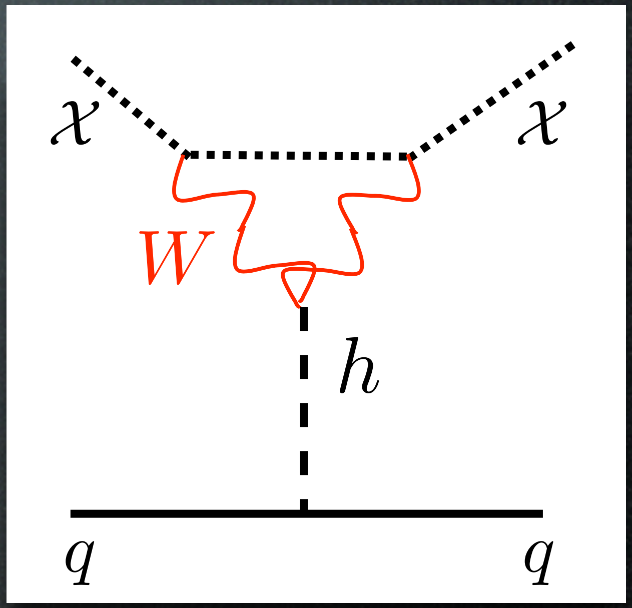
tracing in Cosmic Rays?

1. Direct Detection

one-loop interactions







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

larger for higher n

Spin-Independent

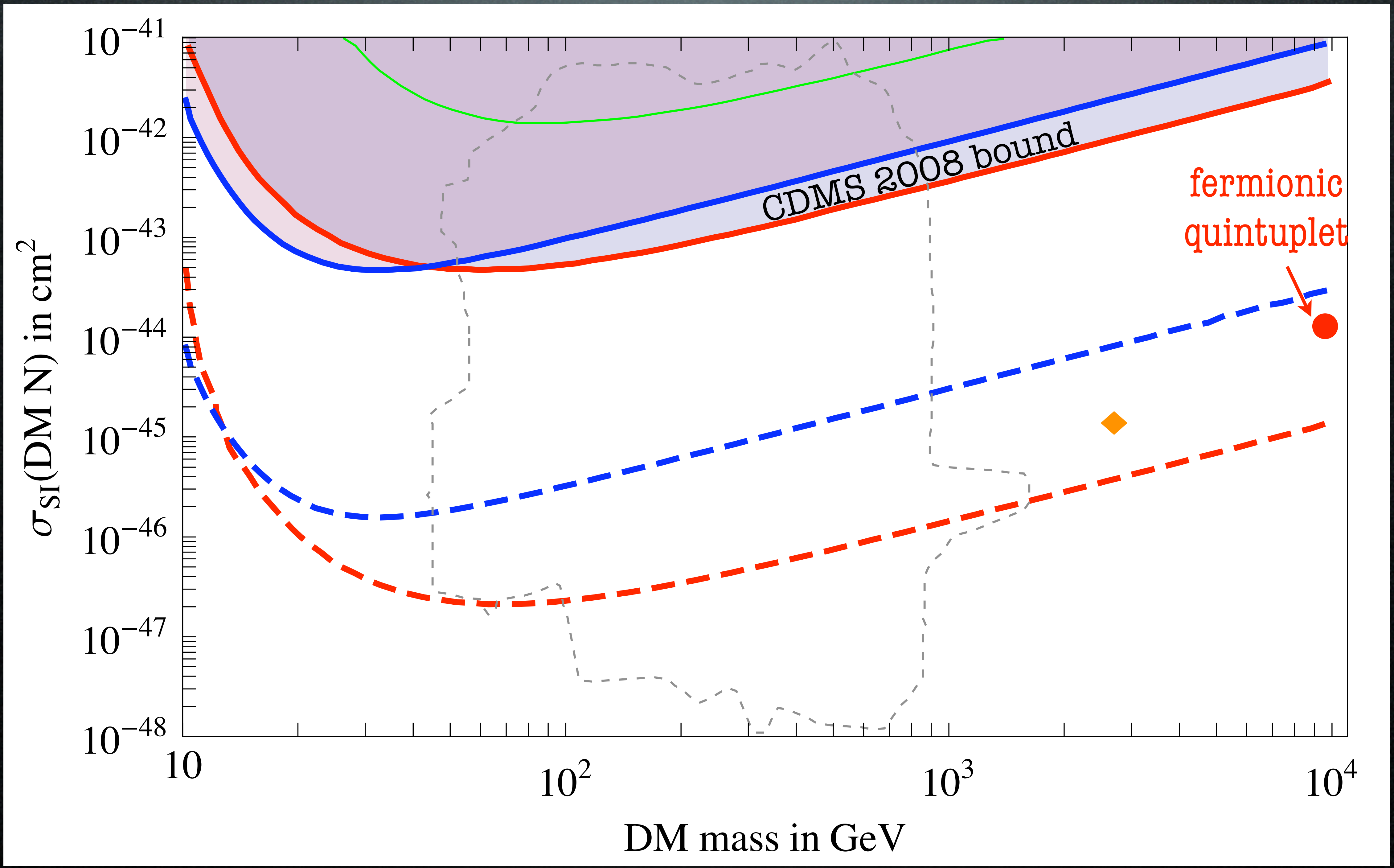
$$\propto \frac{m_q}{M_W^3}$$

Spin-Dependent

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

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

1. Direct Detection



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

[skip to conclusions]

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

Large production for small M.

$2\times$ LHC to produce heavy candidates.

A clean signature:

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

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

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

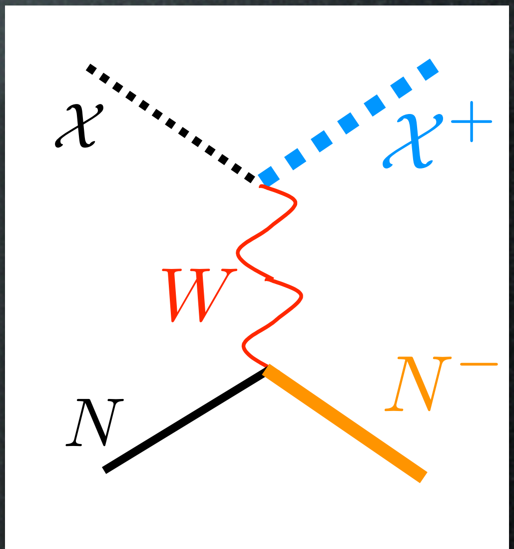
$$\tau \simeq 44\text{cm}/(n^2-1)$$

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

[skip to conclusions]

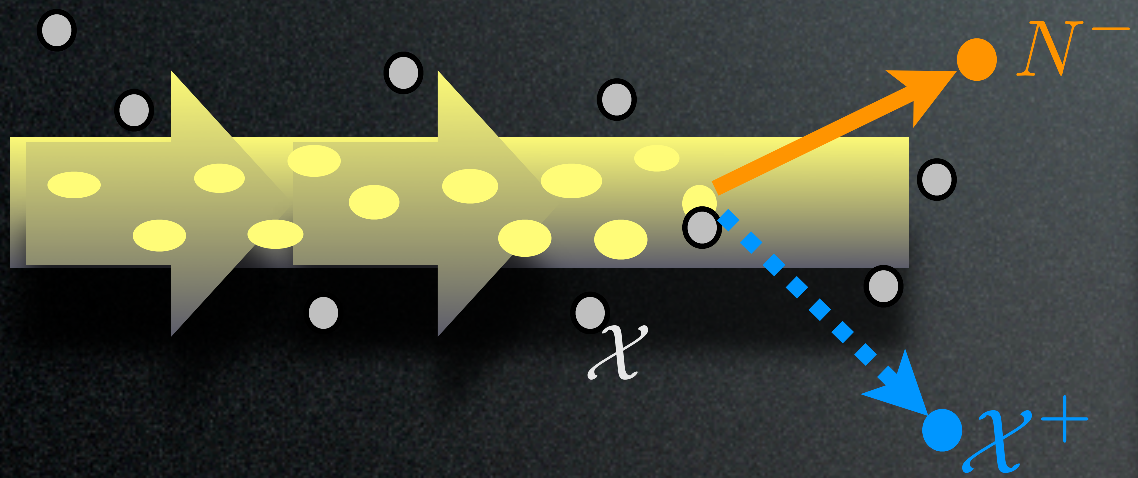
Interlude: the "DMtron"

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



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

Accelerate nuclei and
use DM as diffuse target.



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

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

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

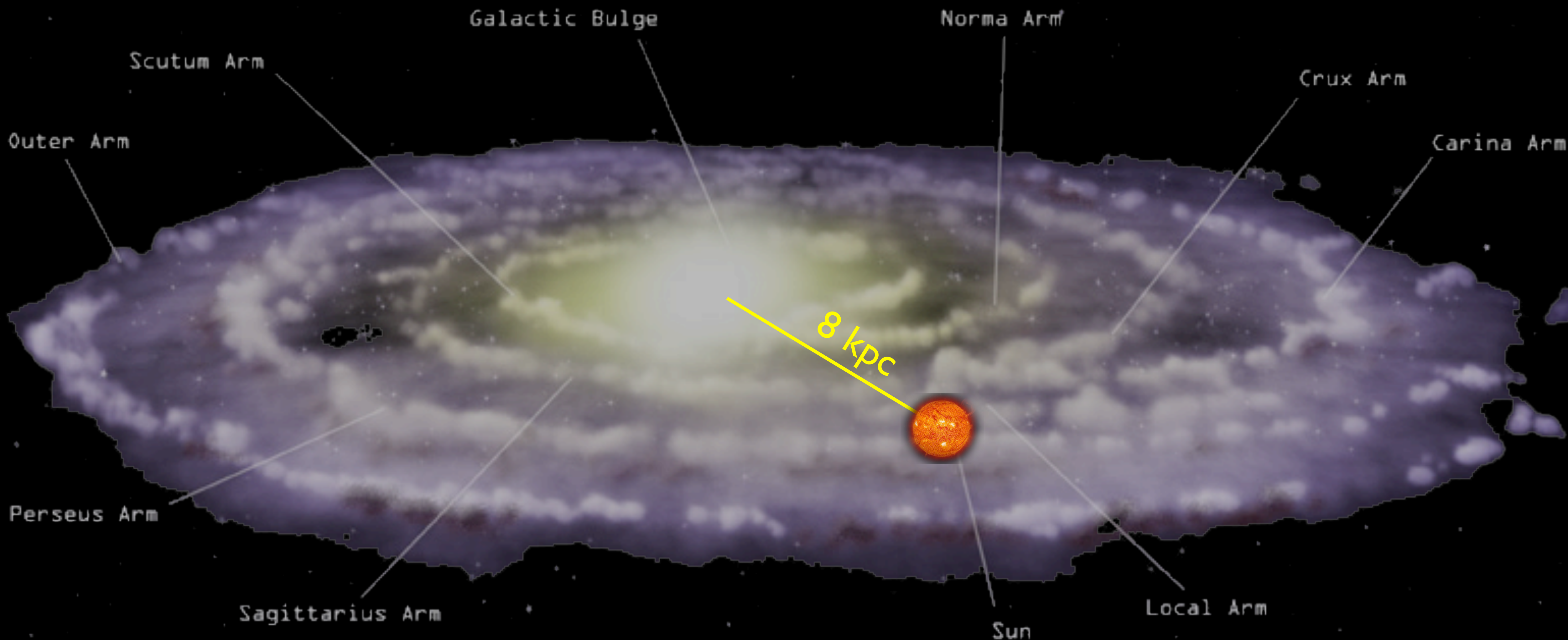
number of targets
number of bullets
"efficiency"

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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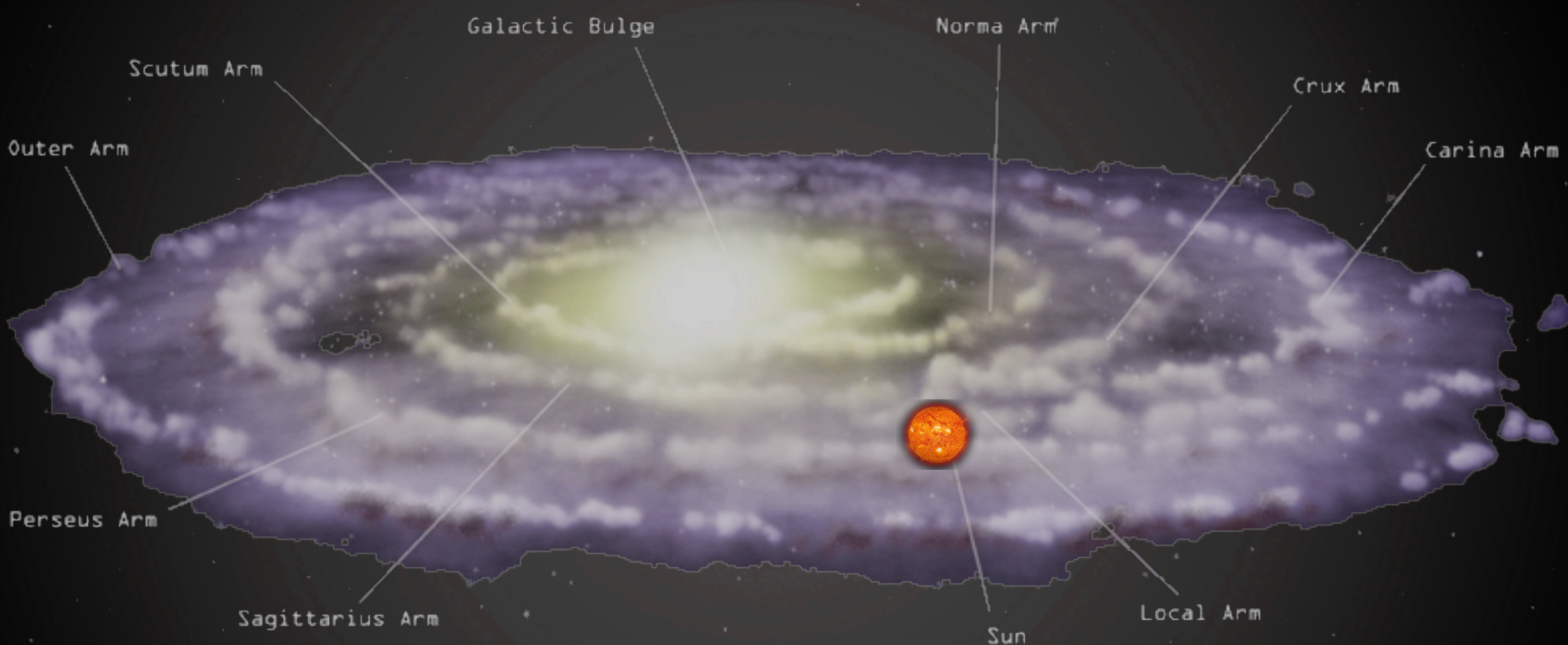

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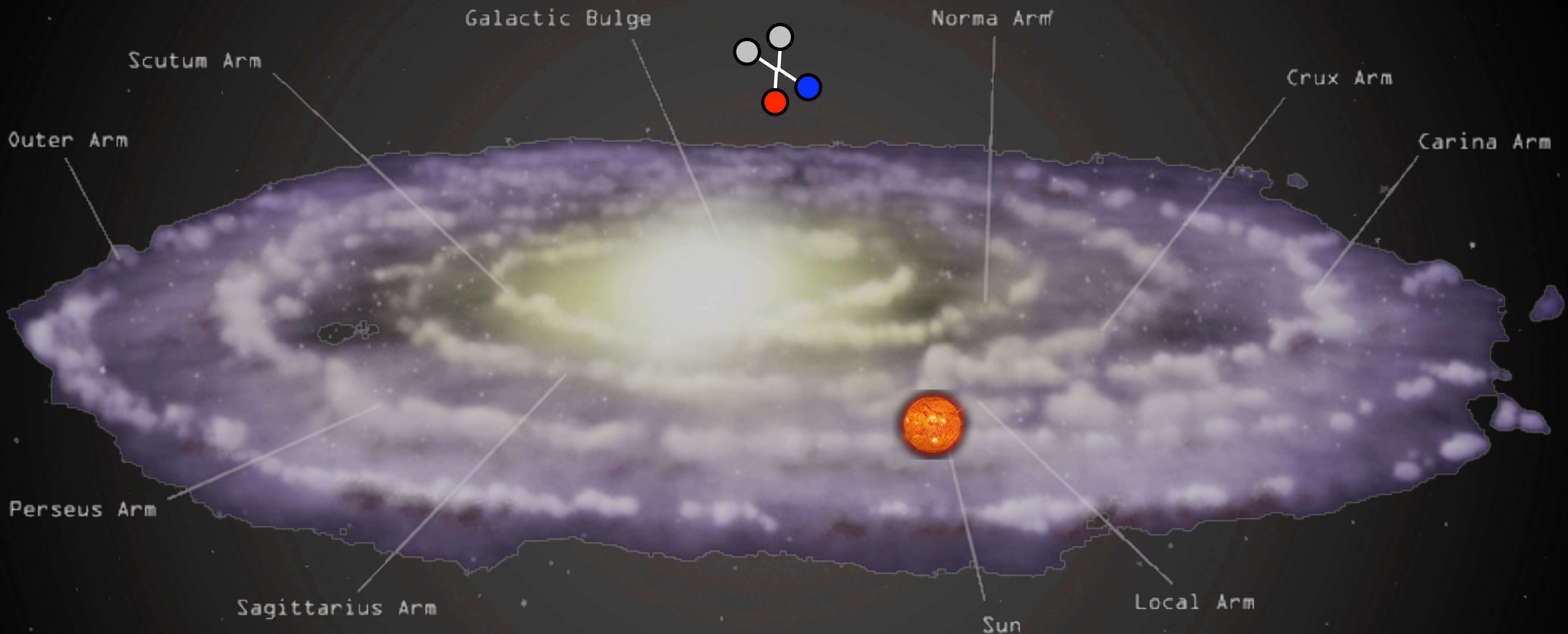

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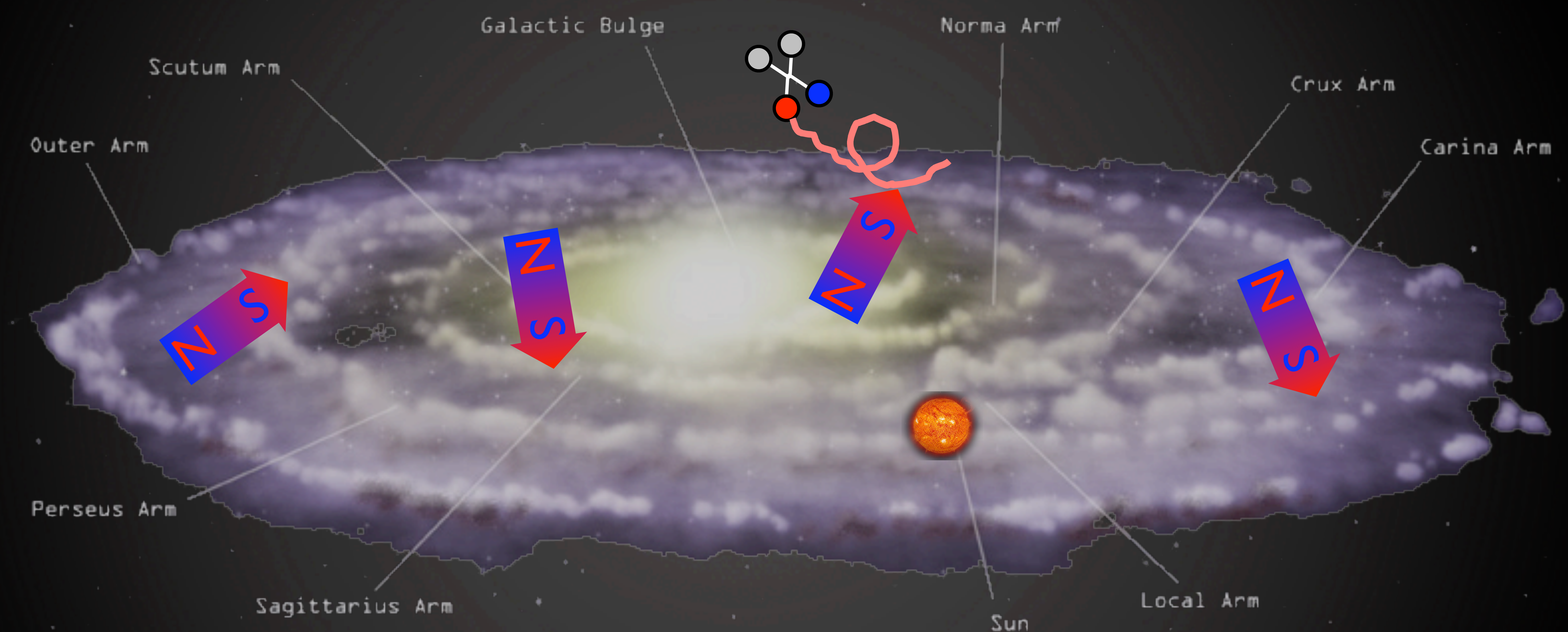

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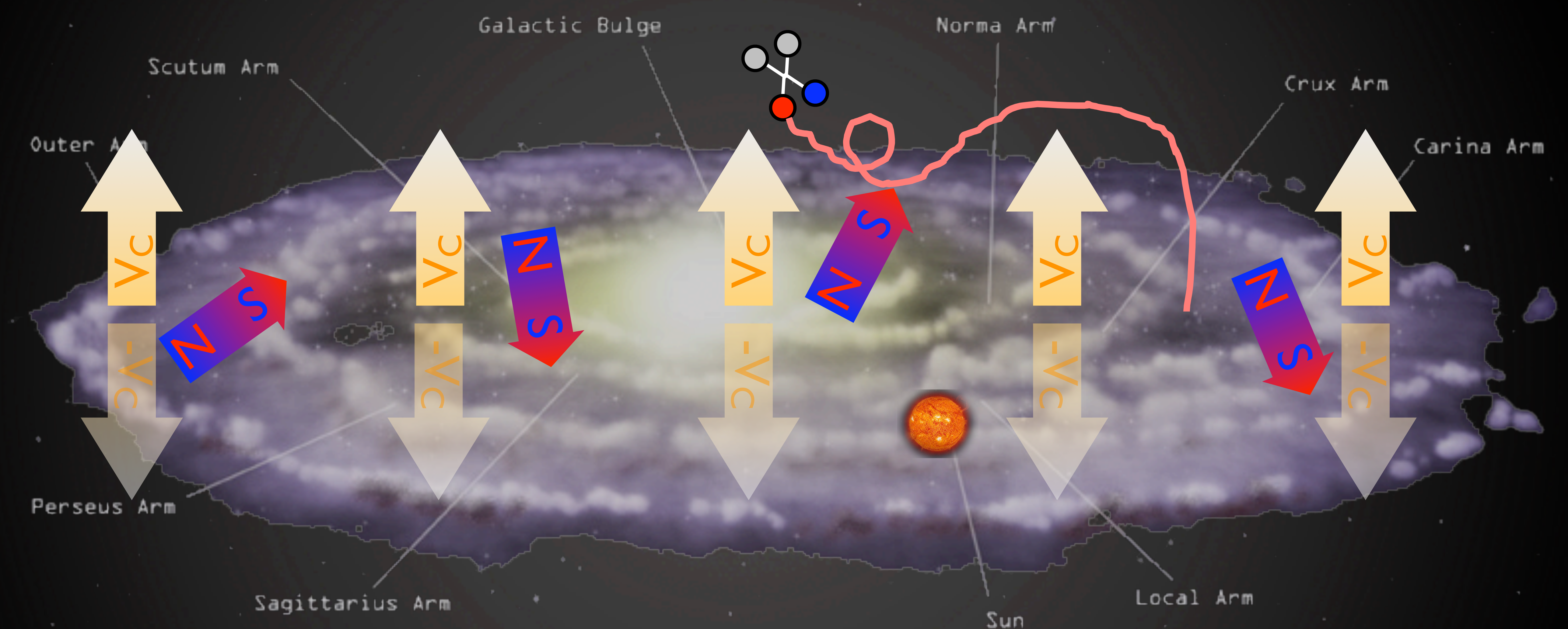

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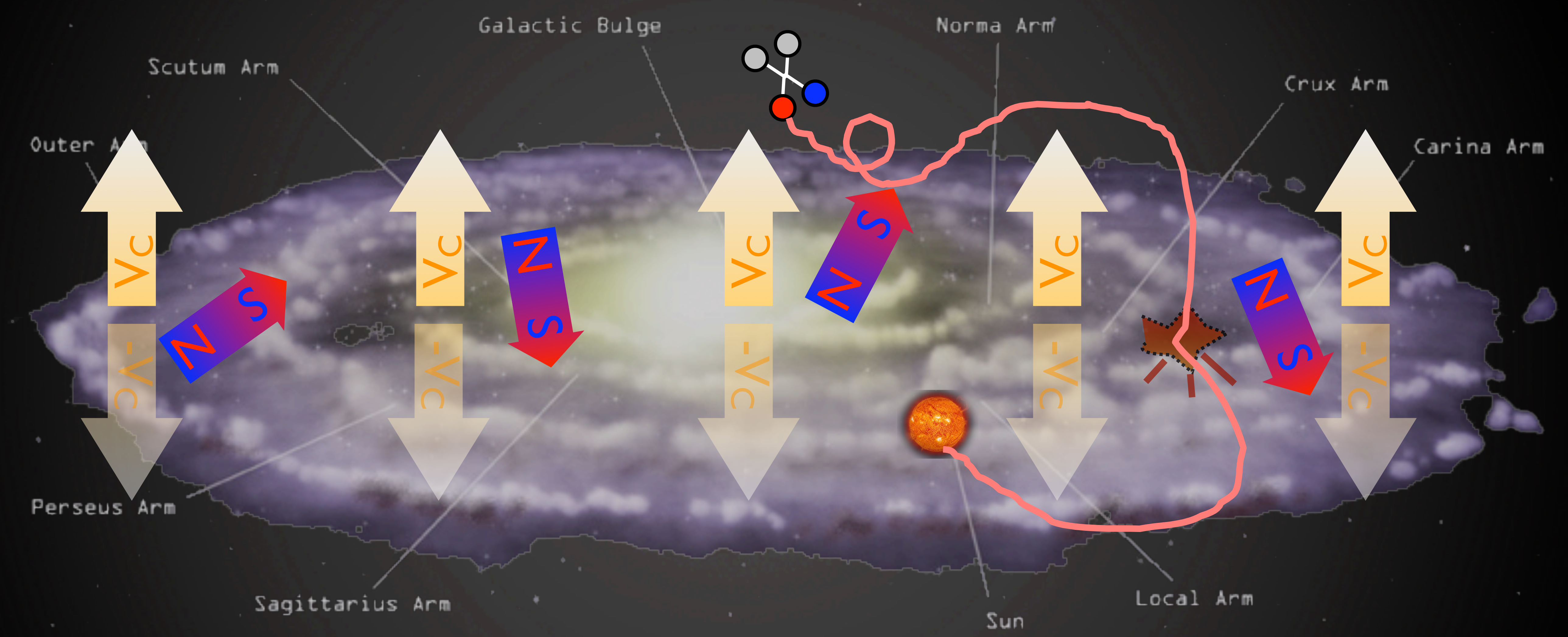

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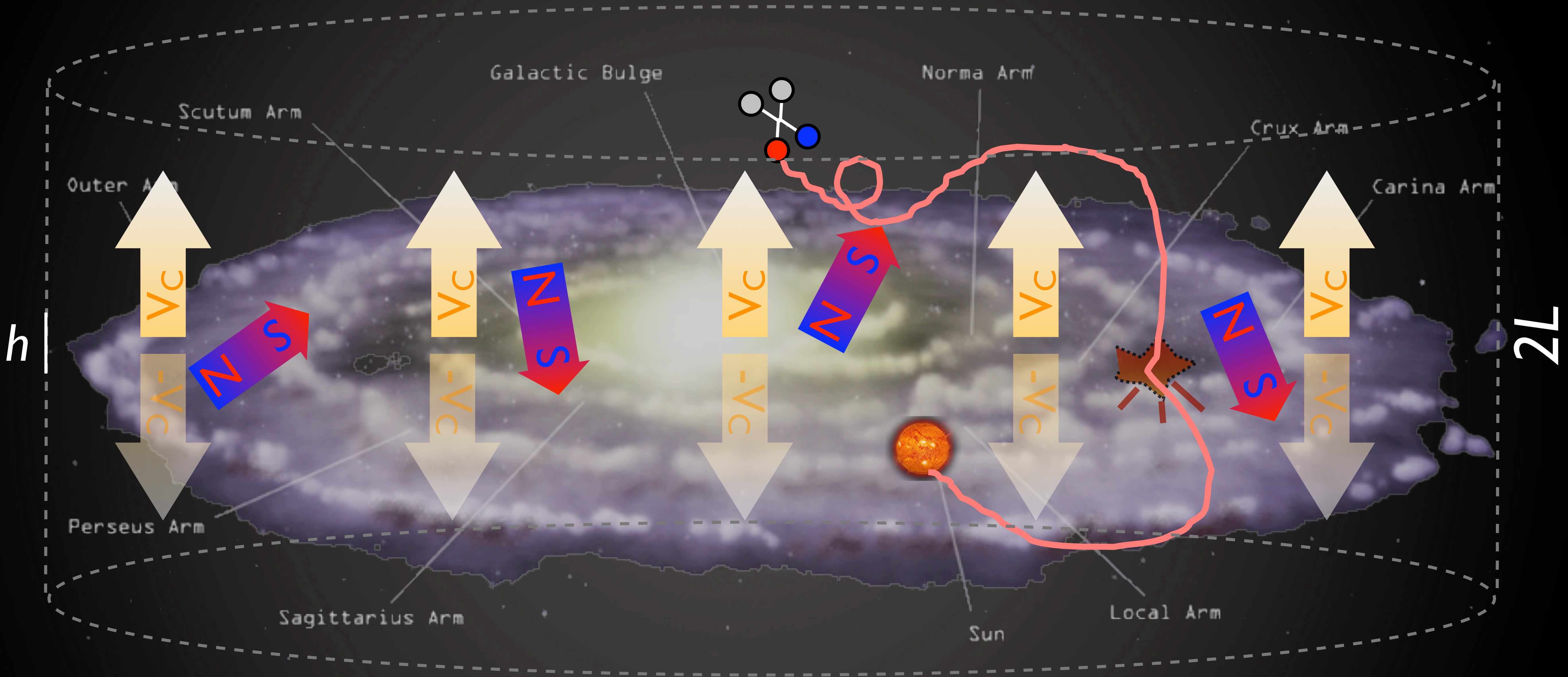

Salati, Chardonnay, Barrau, Donato, Taillet, Fornengo, Maurin, Brun... '90s, '00s

spectrum

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

diffusion energy loss convective wind source spallations

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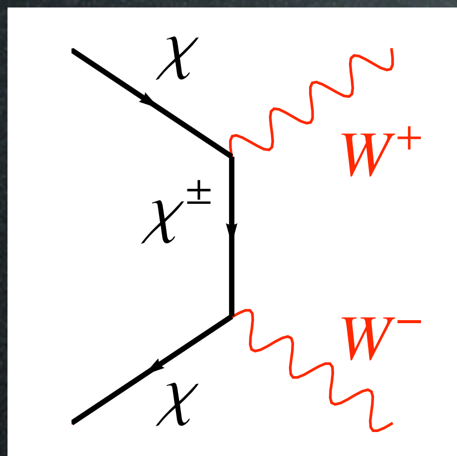
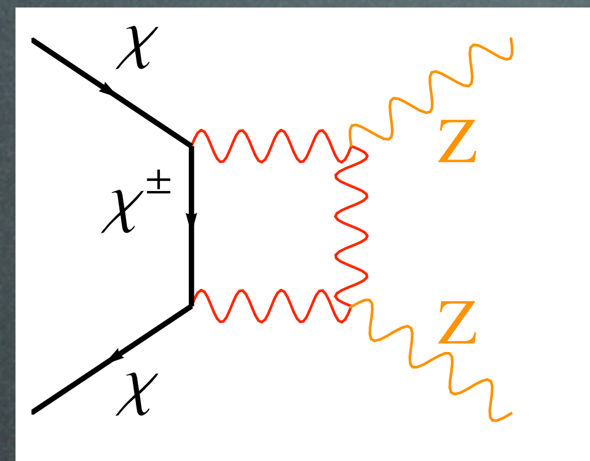


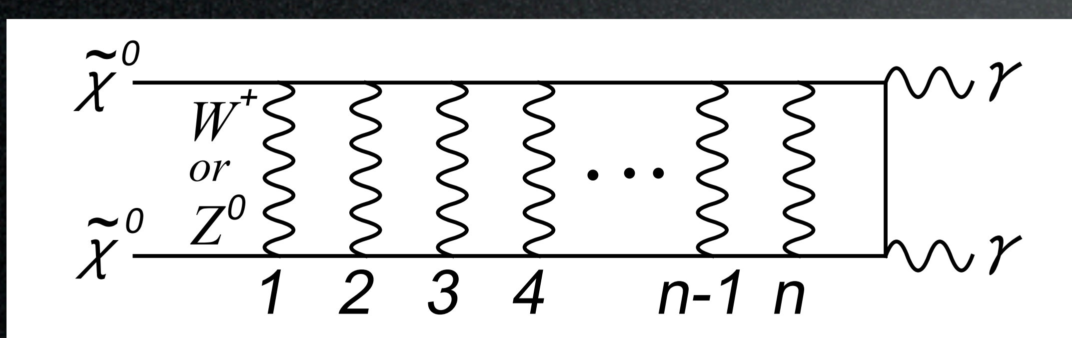


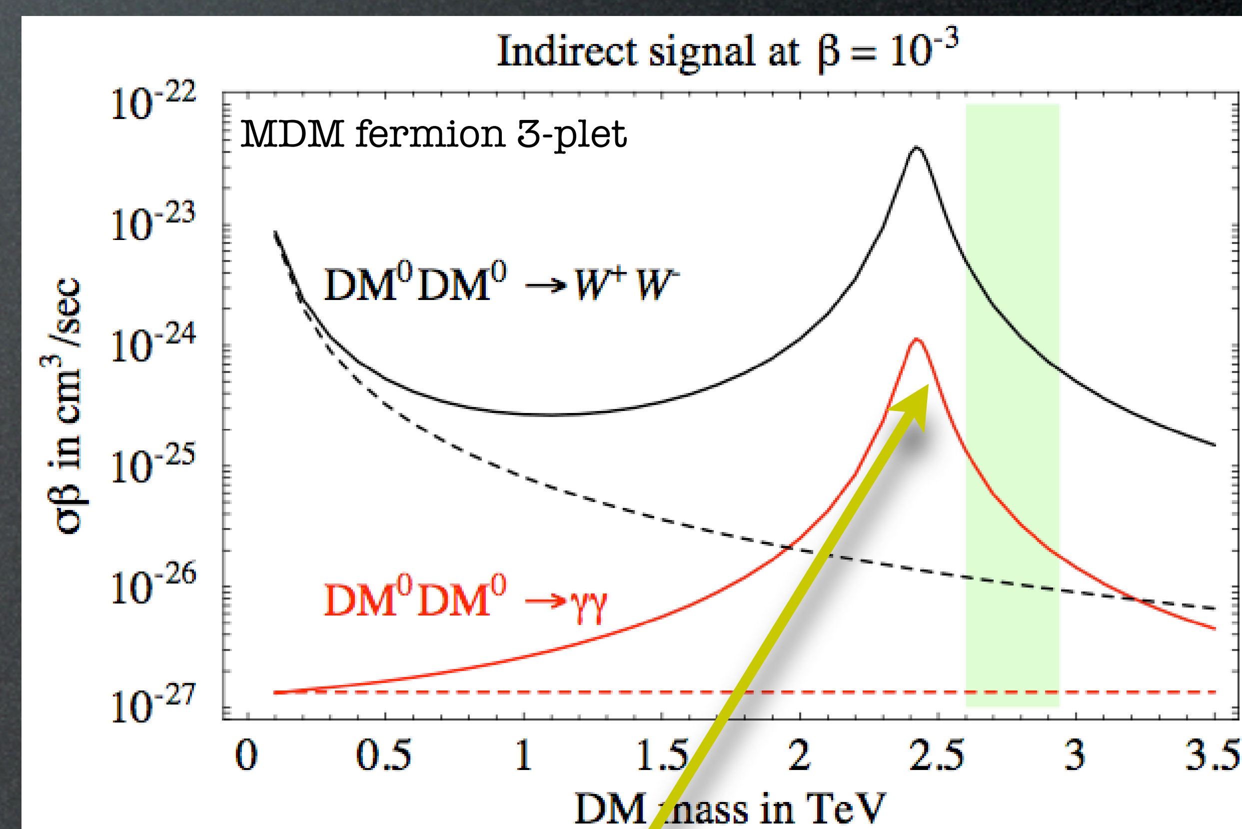
$+ \quad W^{\pm}, Z \to \bar{p}, e^+, \gamma \ldots$

(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

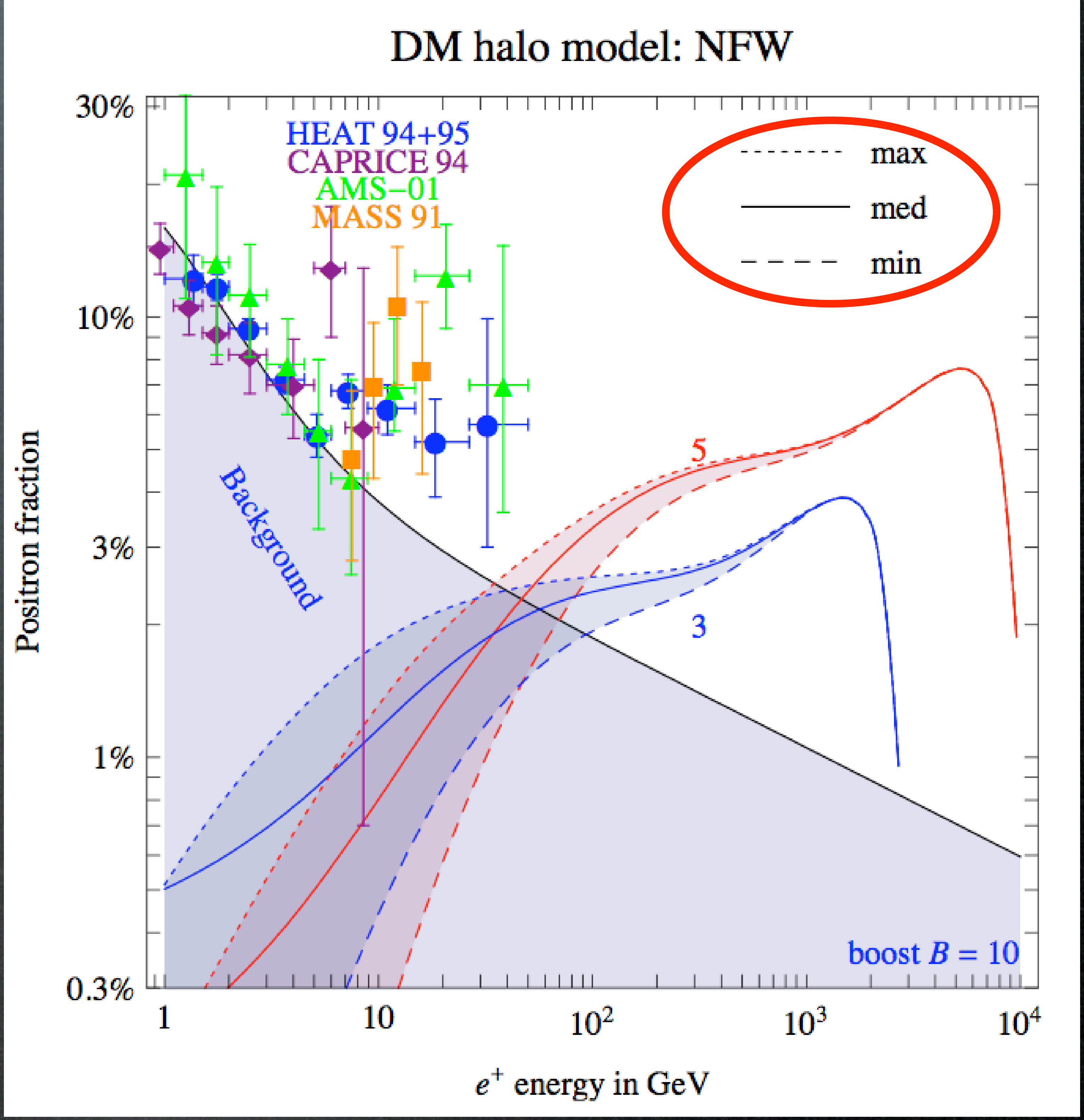
Hisano et al., 2004, 2005
Cirelli, Strumia, Tamburini, 2007

3. Indirect Detection

Results for positrons:

Astro uncertainties:

- propagation model
- DM halo profile
- boost factor B



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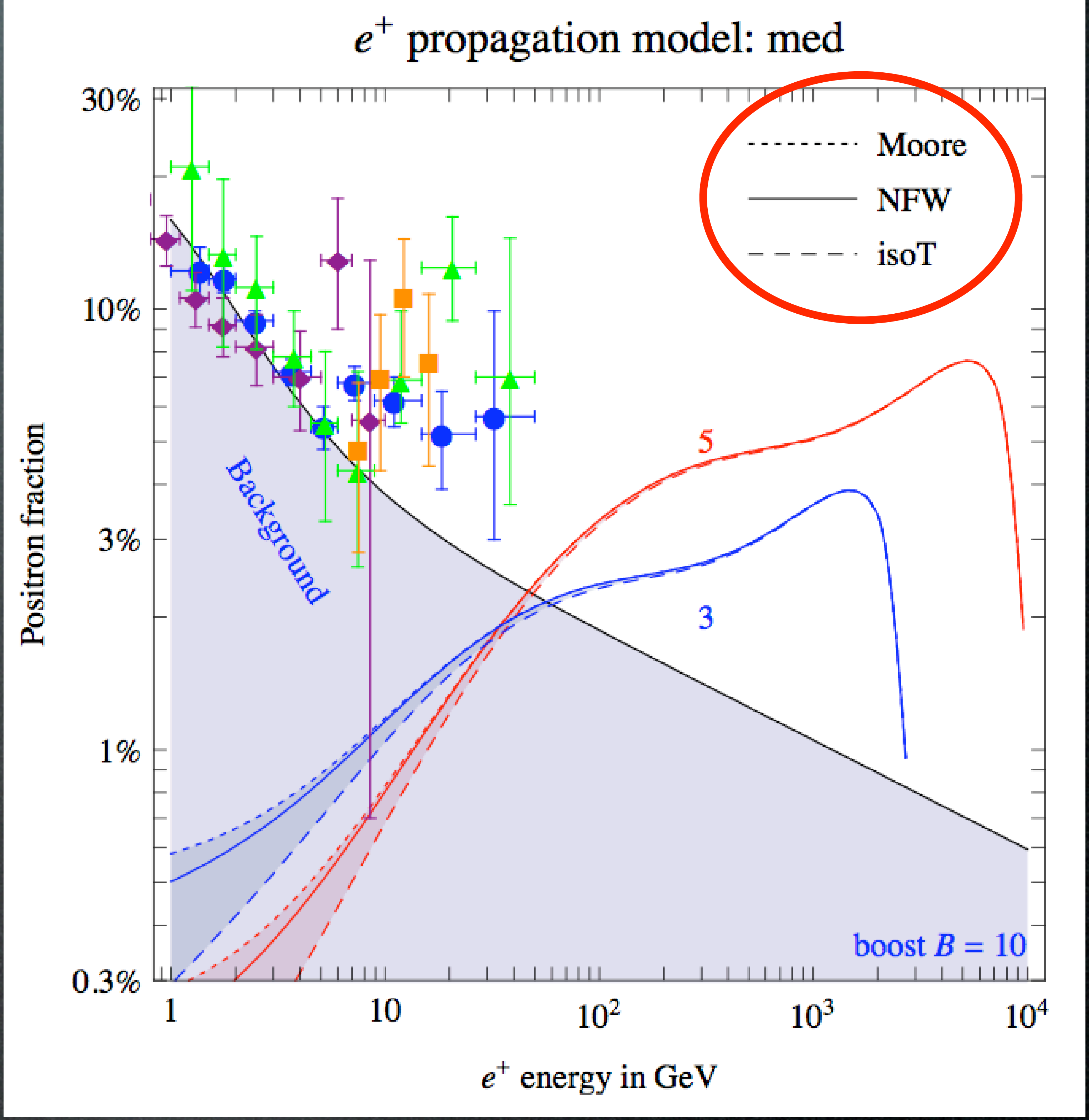

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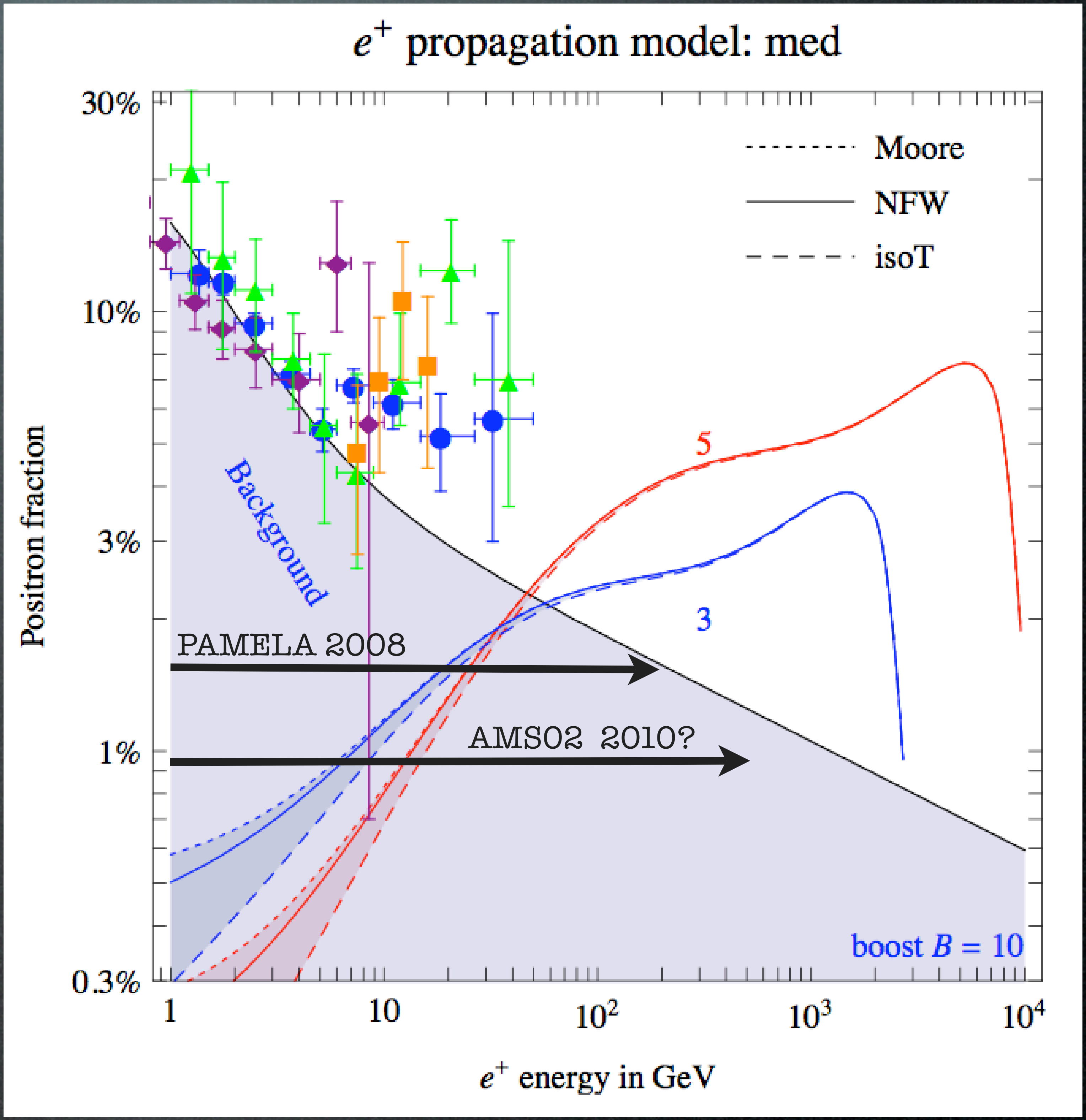


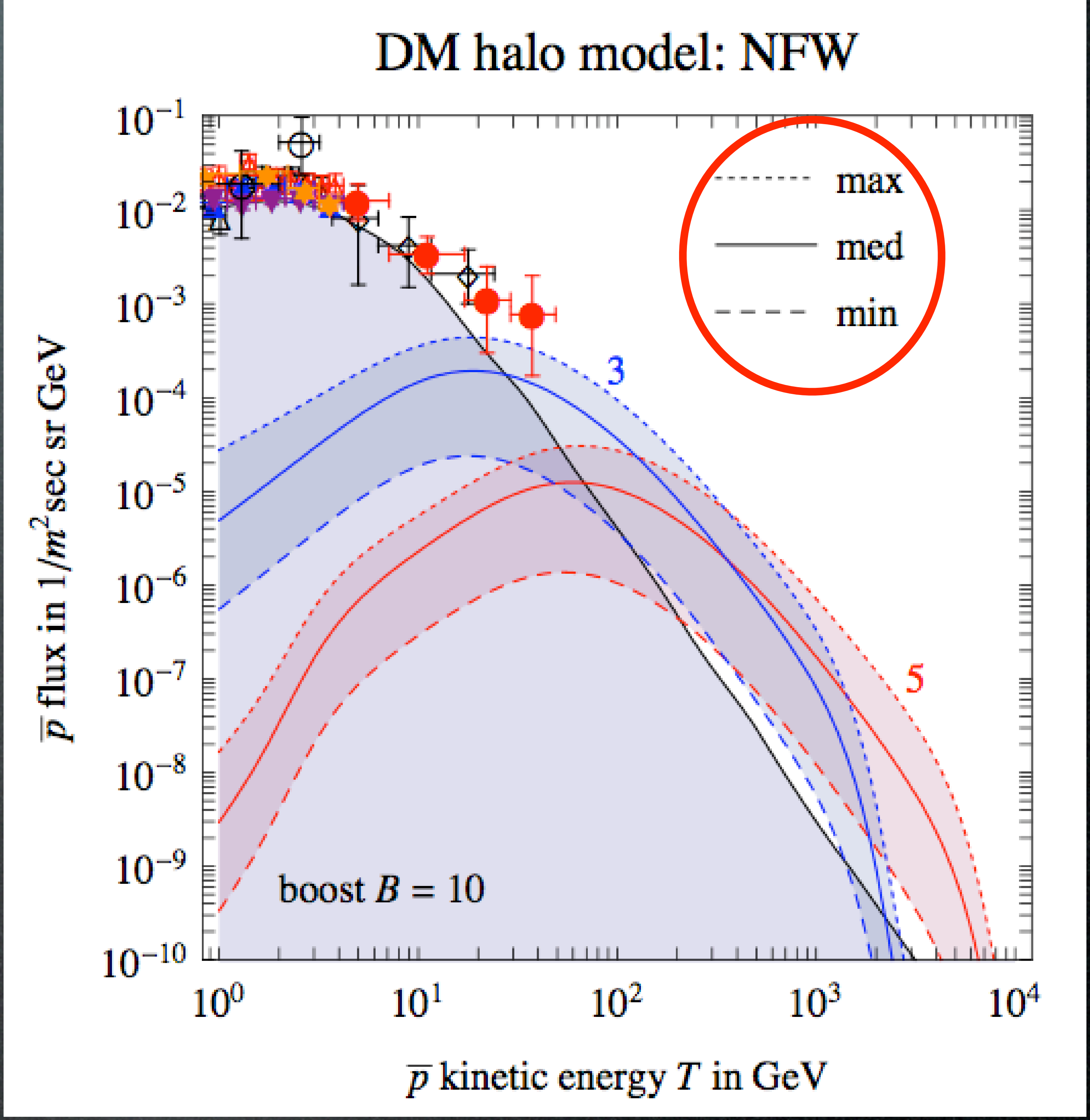
Distinctive signal,
quite robust vs astro,
awaiting PAMELA, AMS02.

3. Indirect Detection

Results for anti-protons:

Astro uncertainties:

- propagation model
- DM halo profile
- boost factor B

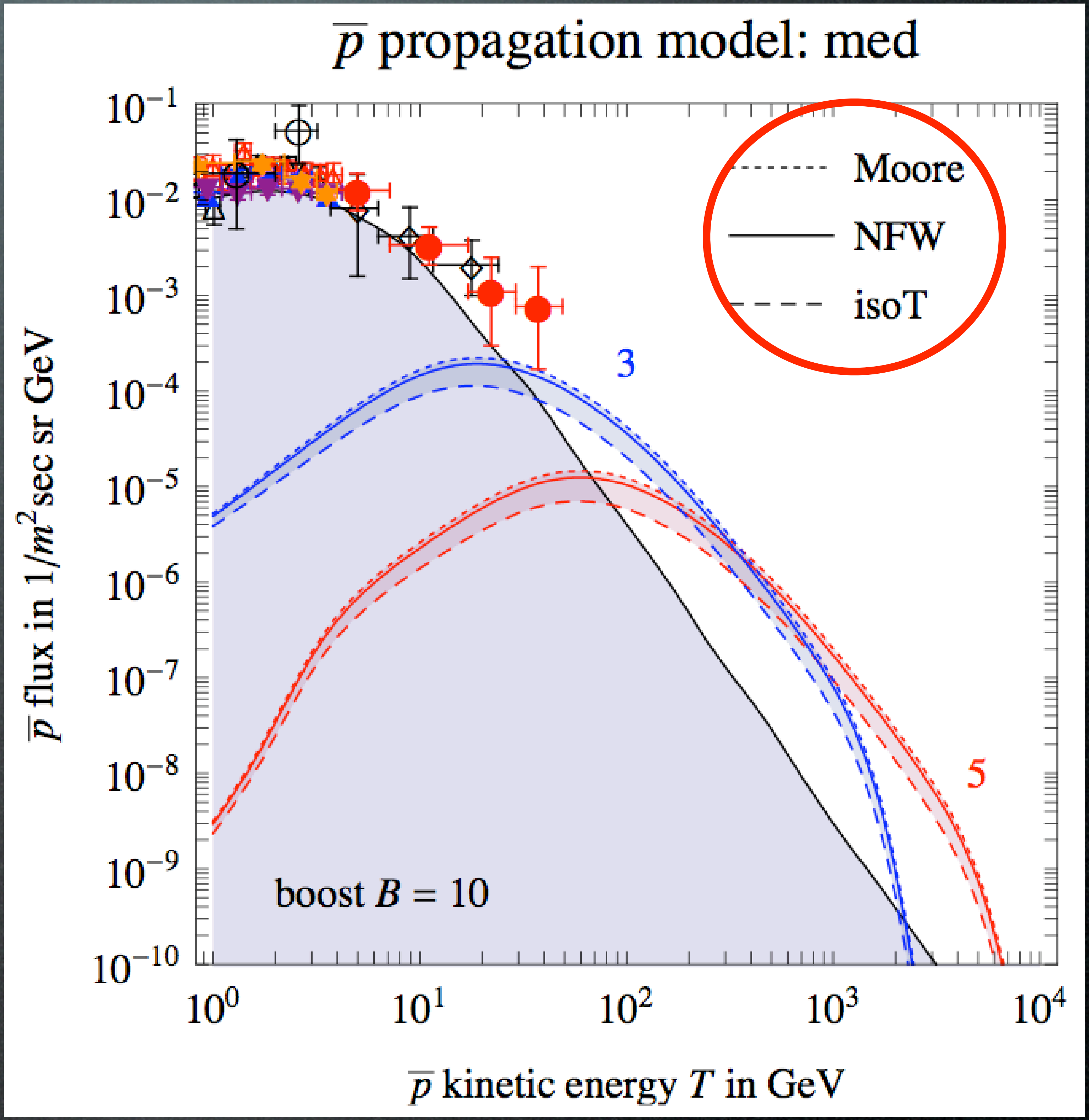


3. Indirect Detection

Results for anti-protons:

Astro uncertainties:

- propagation model
- DM halo profile
- boost factor B



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Results for anti-protons:

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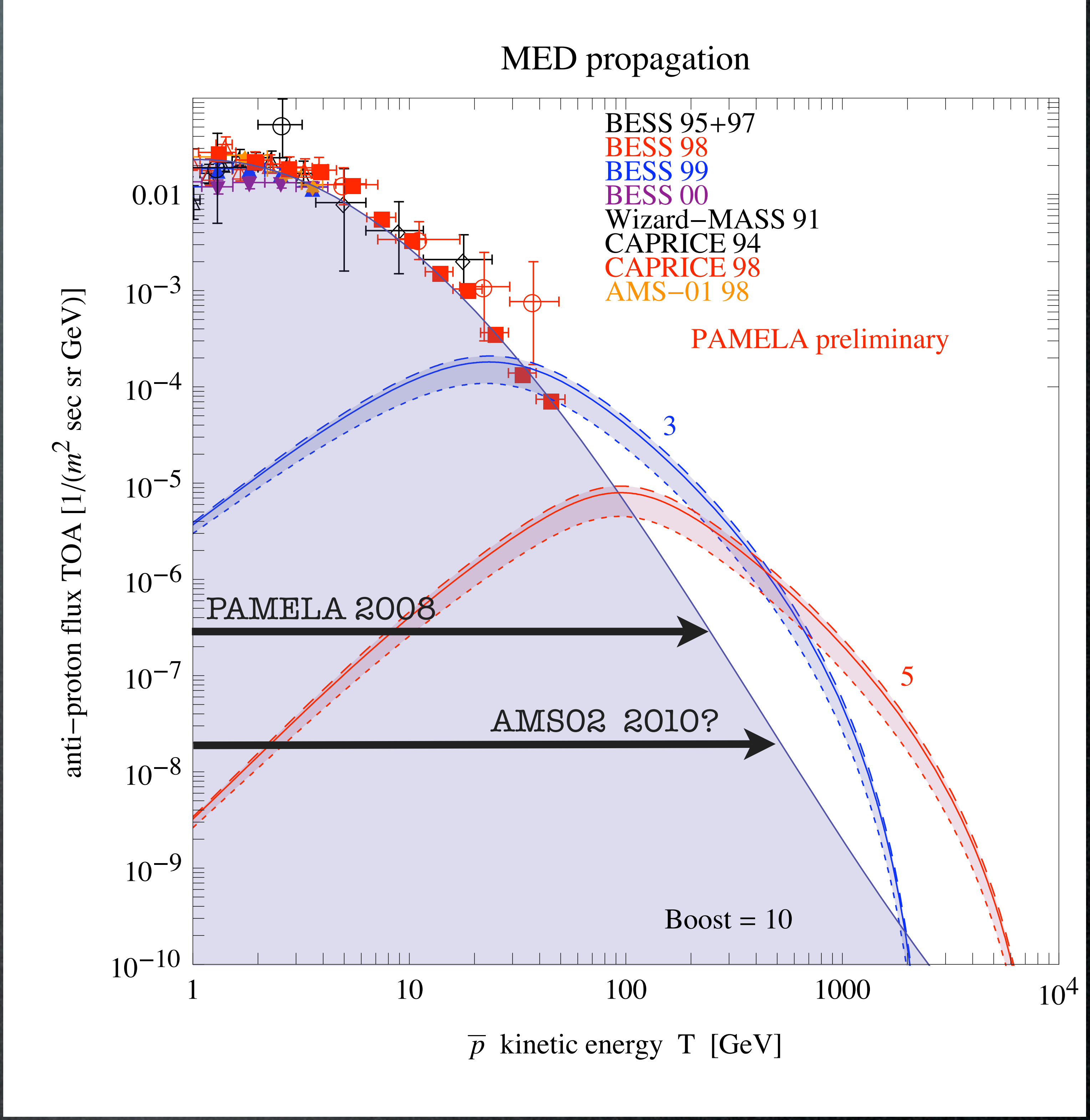
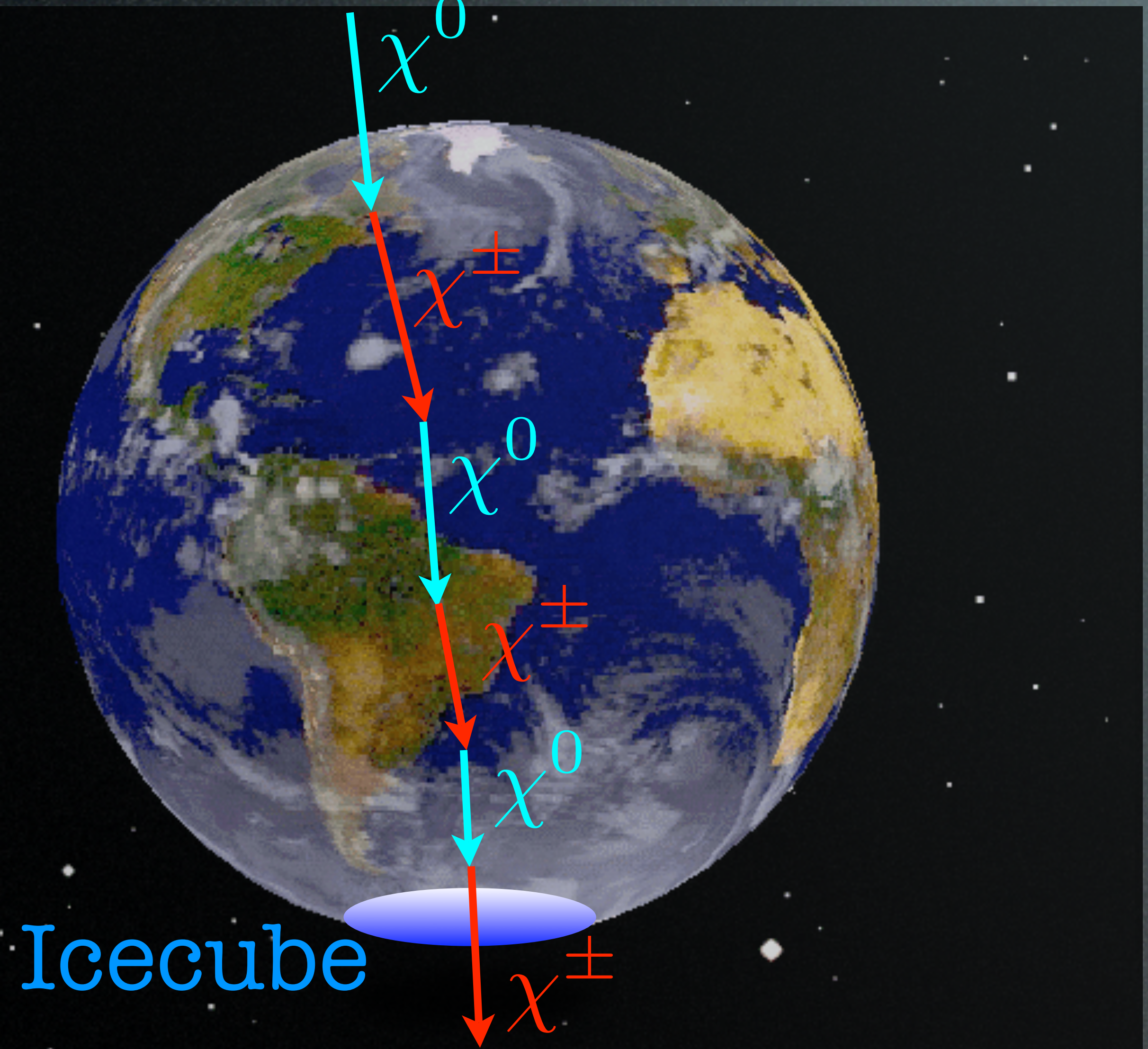
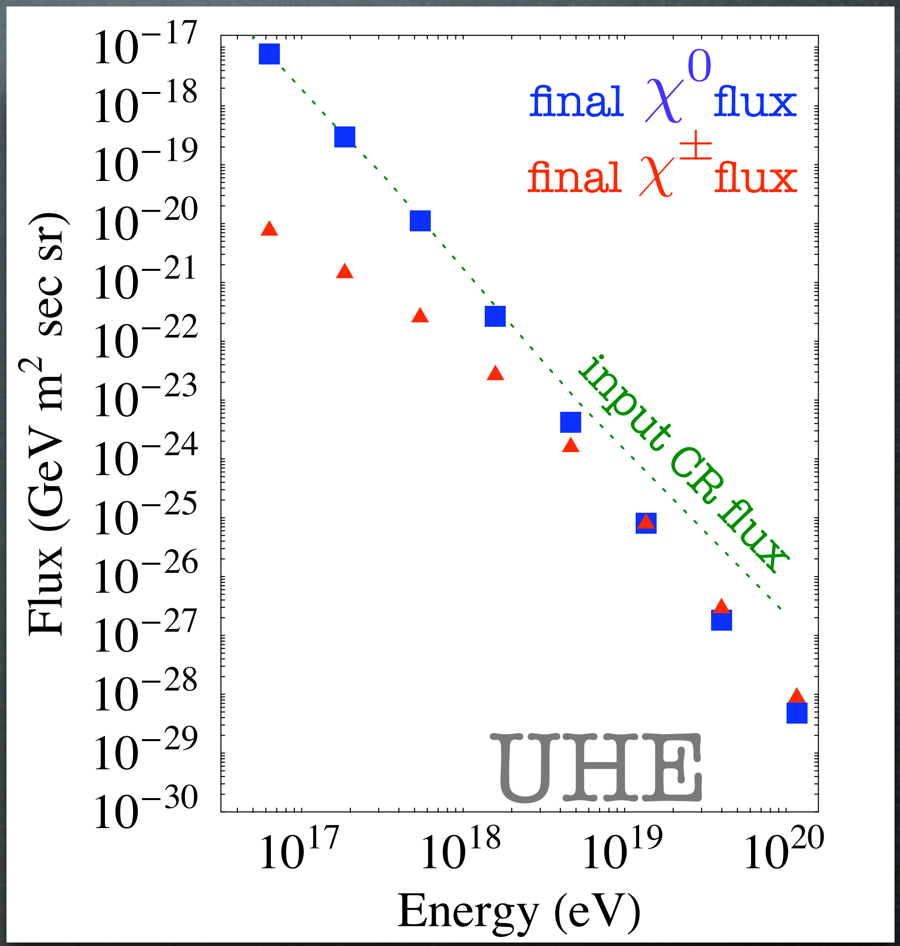


Distinctive signal,
more dependent on astro,
PAMELA prelim., AMS02.

4. Tracing in Cosmic Rays?





at U high Energy:
- high production
- $\chi^\pm$ lives long

MDM can cross the Earth with chain regeneration (like ν_τ).

Small ΔM makes $\chi^\pm$ long-living.

A clear track! DM is no more dark!

But: - production?

requires non-standard acceleration mechanism

- flux?

few events/km² yr above 10^{17} eV

- particle ID?

it's fat and fast, but looks like a light slow muon

$$\frac{dE}{dx} \propto \frac{1}{M} E$$

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 $Y=0$.
$(M = 10\ \text{TeV})$

Its phenomenology is precisely computable:
- can be found in next gen direct detection exp's,
- too heavy to be produced at LHC,
- can give signals in indirect detection exp's.

(Other candidates have different properties.)

Back-up
slides

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

- Higgsino (a fermion doublet)
- + something else (a singlet)
- stabilization by R-parity
- want unification also
- unification scale is low, need to embed in 5D to avoid proton decay

Mahbubani, Senatore 2005

MDM

- arbitrary multiplet, scalar or fermion
- nothing else (with Y=0)
- automatically stable
- forget unification, it's SM
- nothing

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

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 5^{th} 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.

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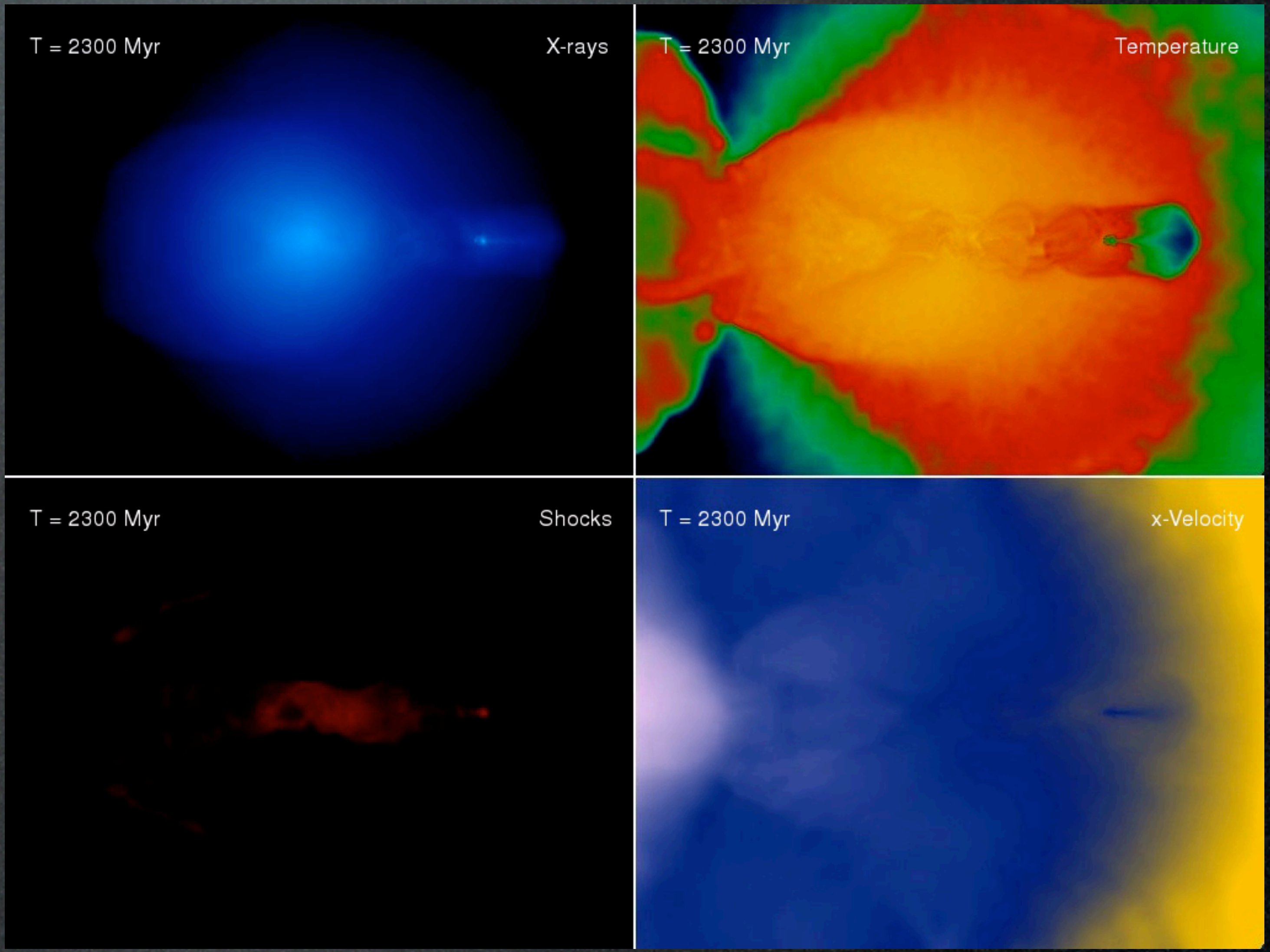


The Max Planck Studios in Hollywood seize the opportunity and make a 2.3-billion-years long blockbuster movie.

[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** $|\lambda'_H| \ll g^2_Y, g^2_2$ 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

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

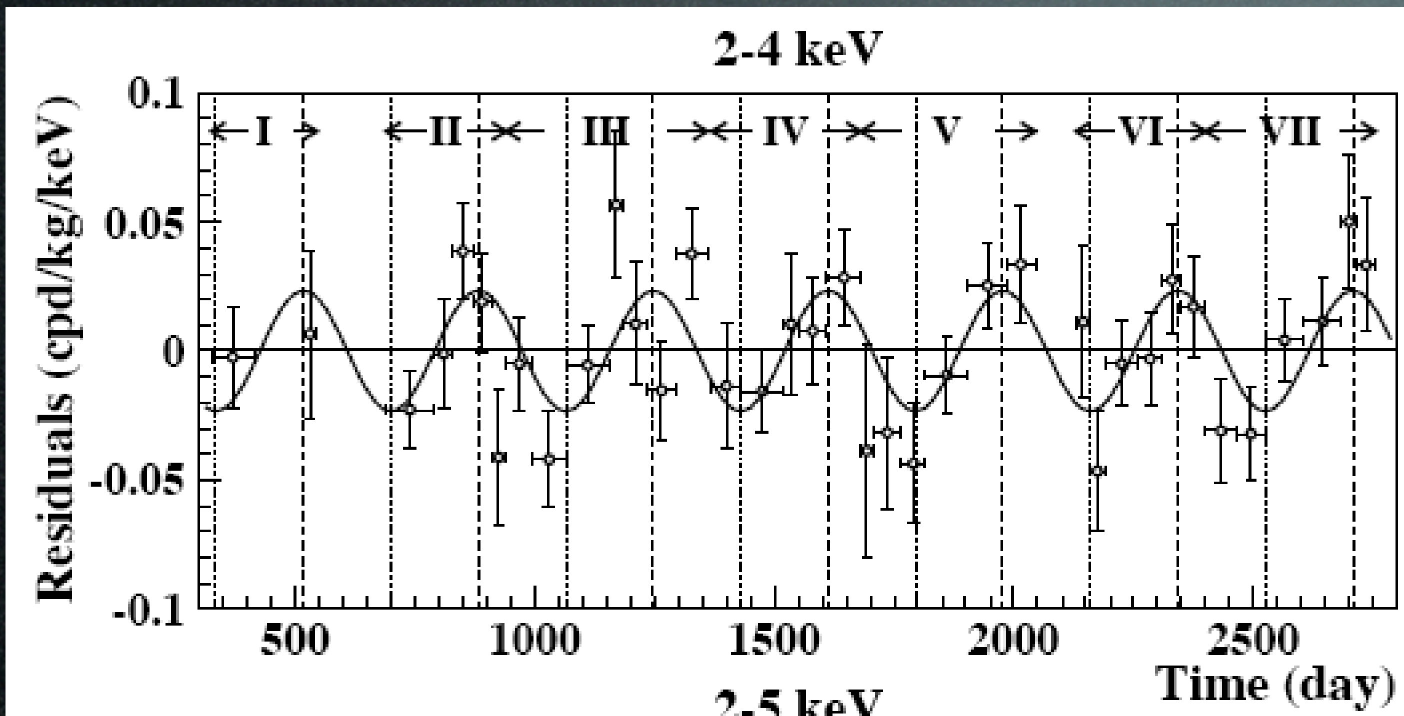
soft SUSYB terms

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

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

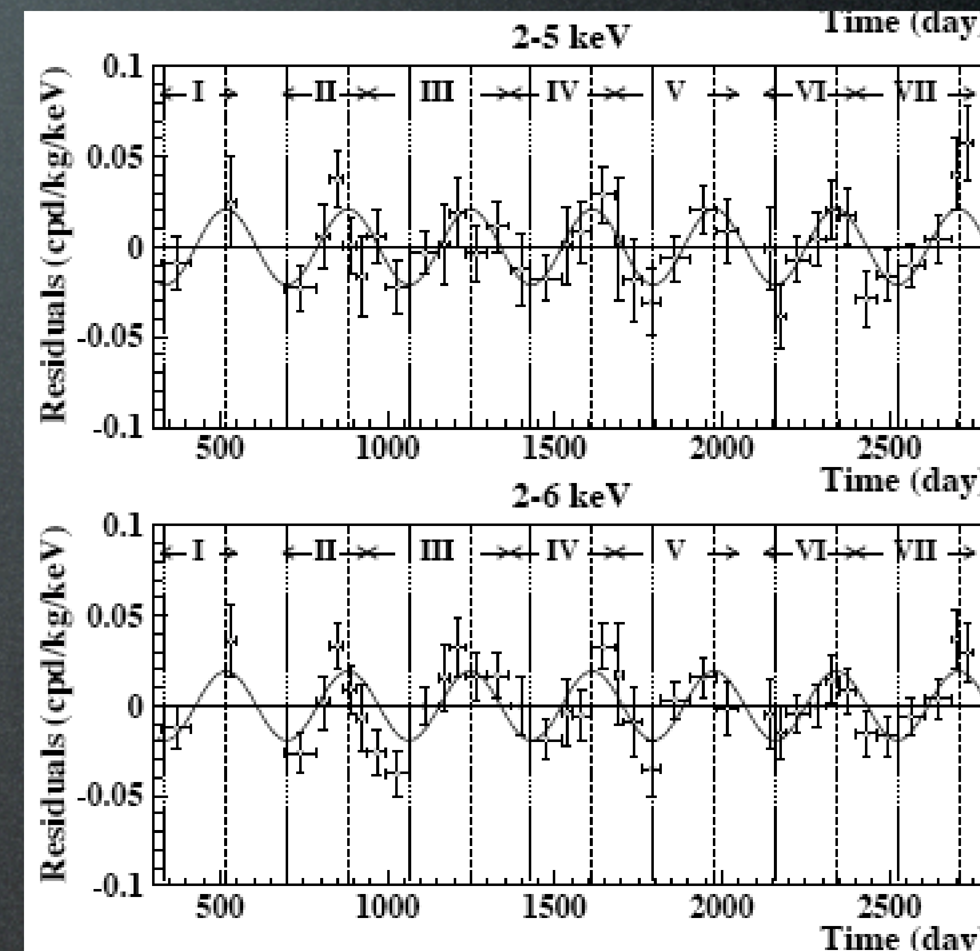
Direct detected *already*?

DAMA annual modulation:

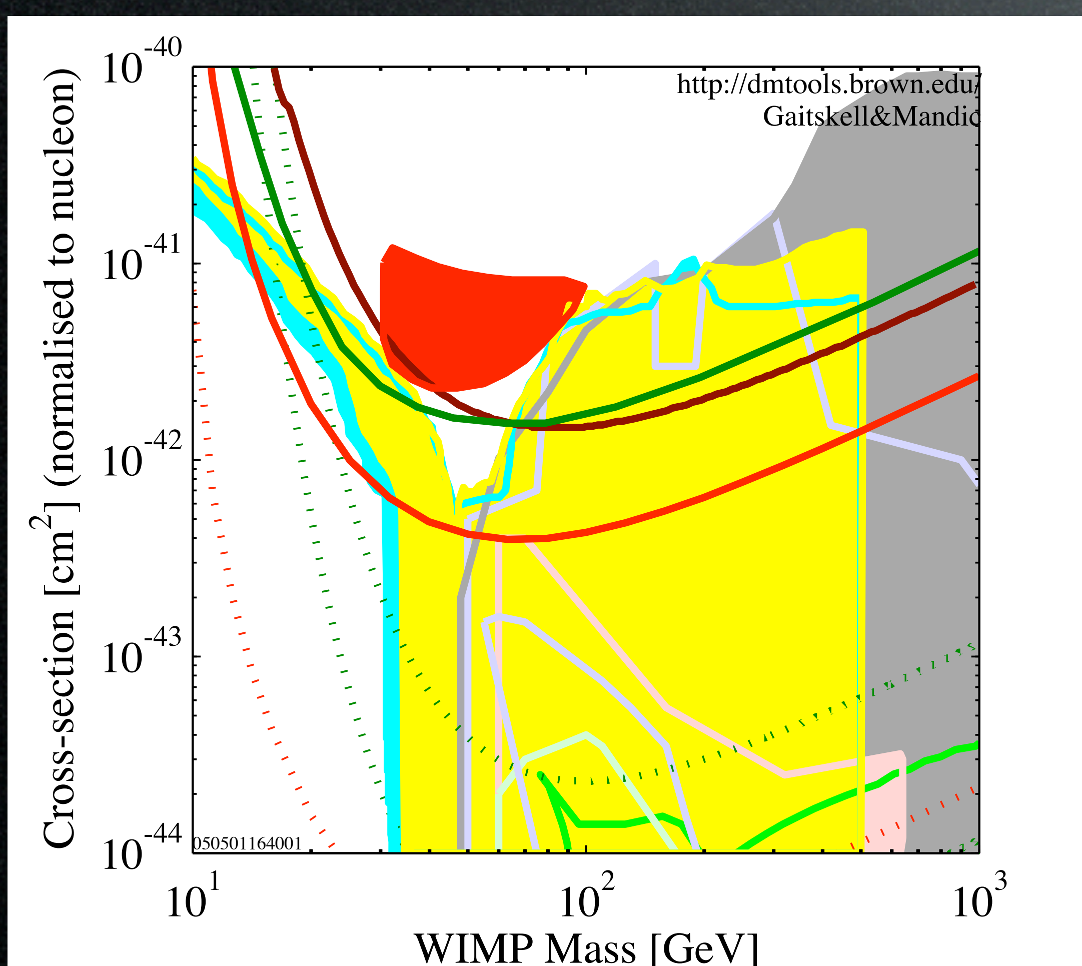


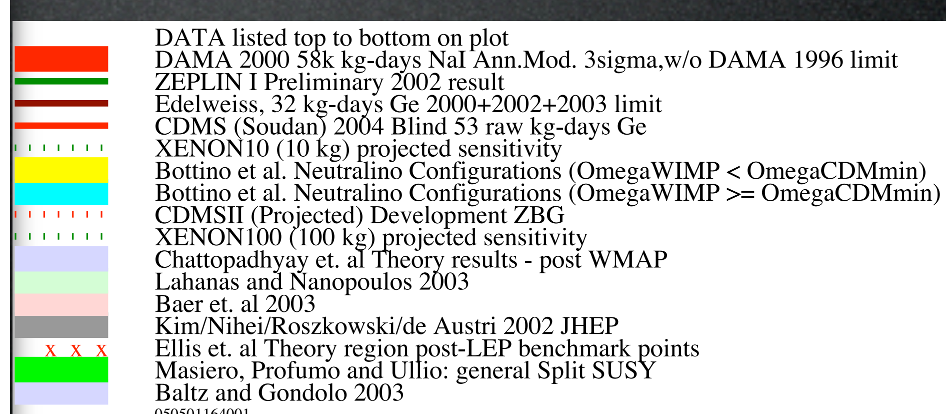
DAMA Coll.

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



DAMA Coll.

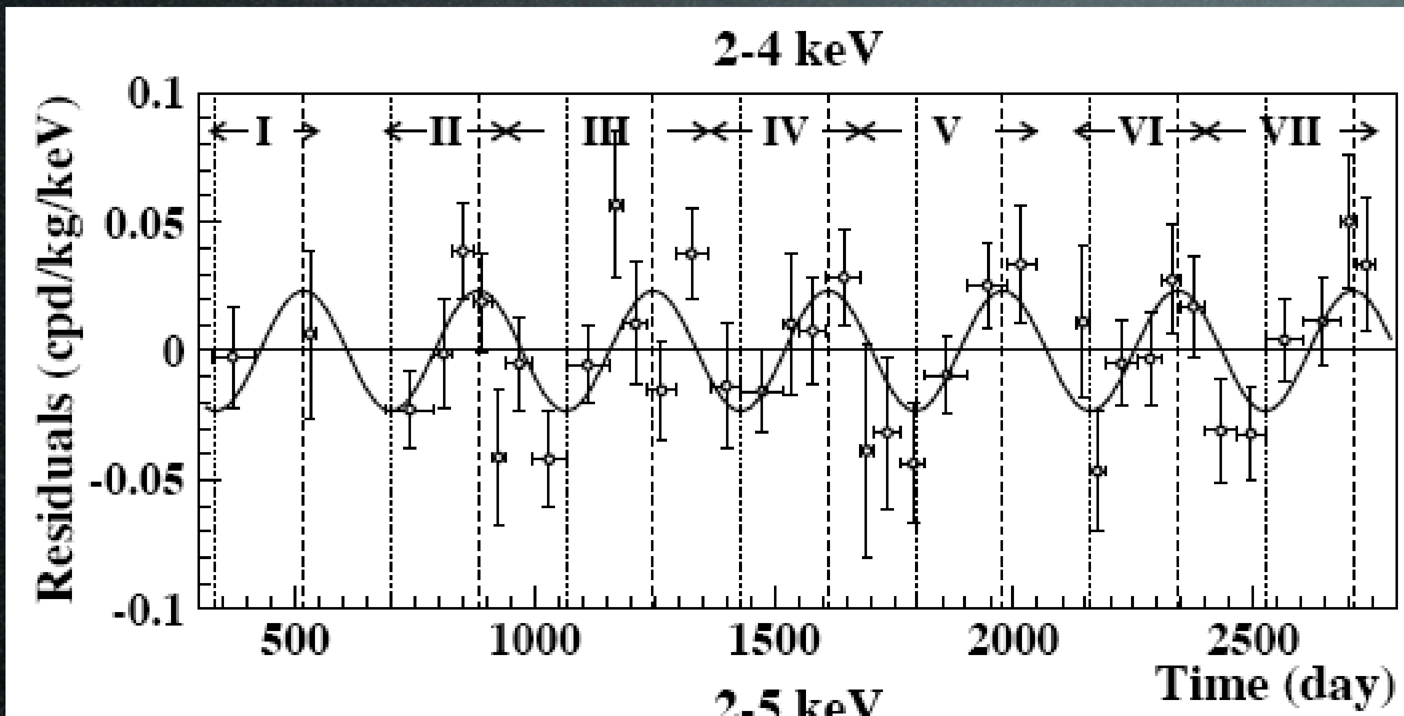




[back to DM detection]

Direct detected *already*?

DAMA annual modulation:



DAMA Coll.

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-raw data??
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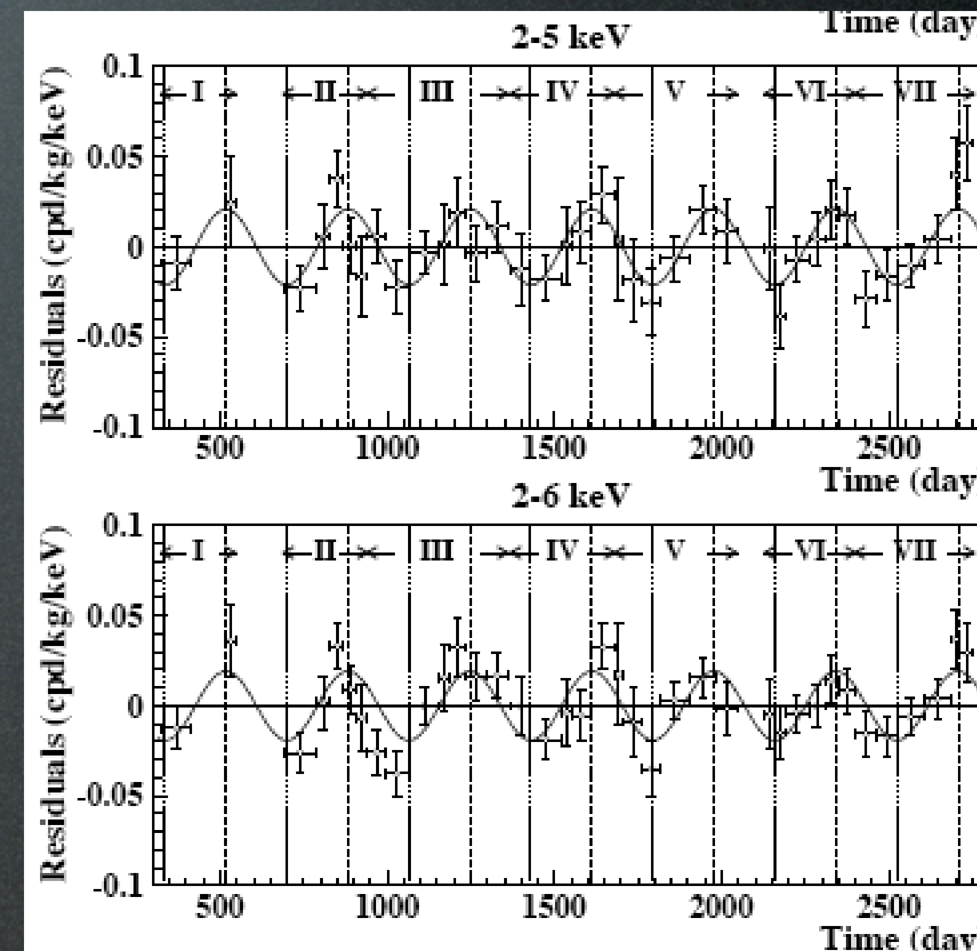
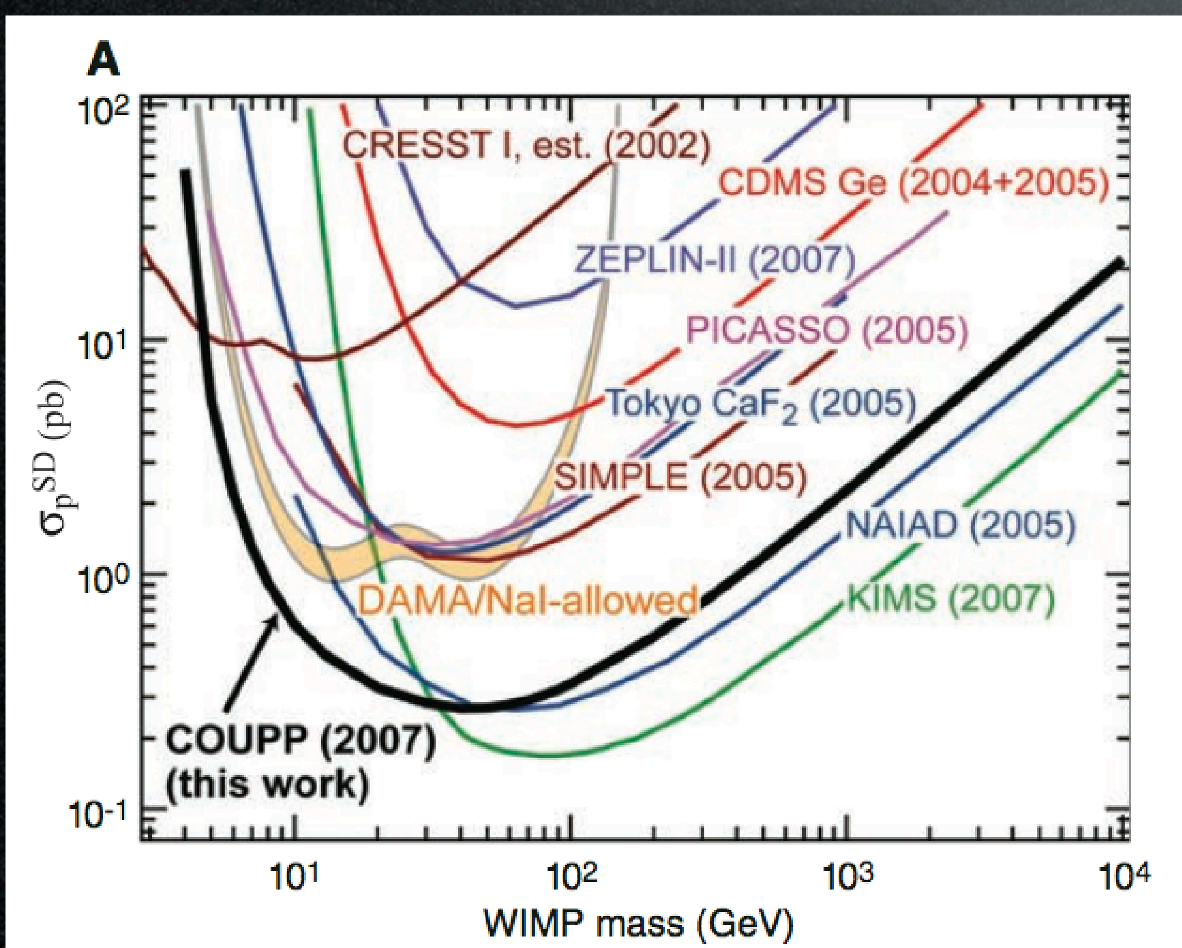


DAMA Coll.

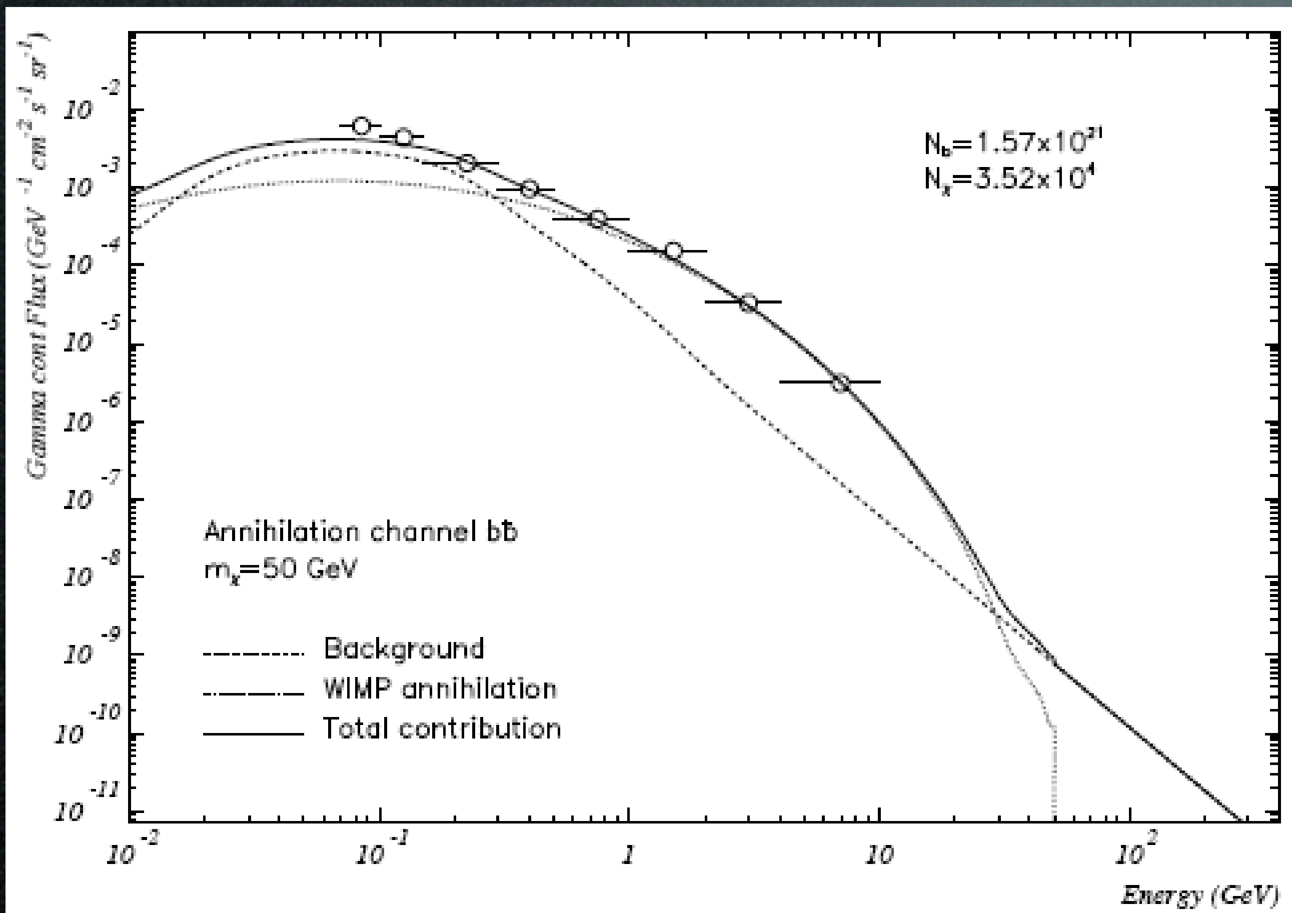


COUPP Coll. 2008

[back to DM detection]

Indirect Detection: photons

EGRET excess

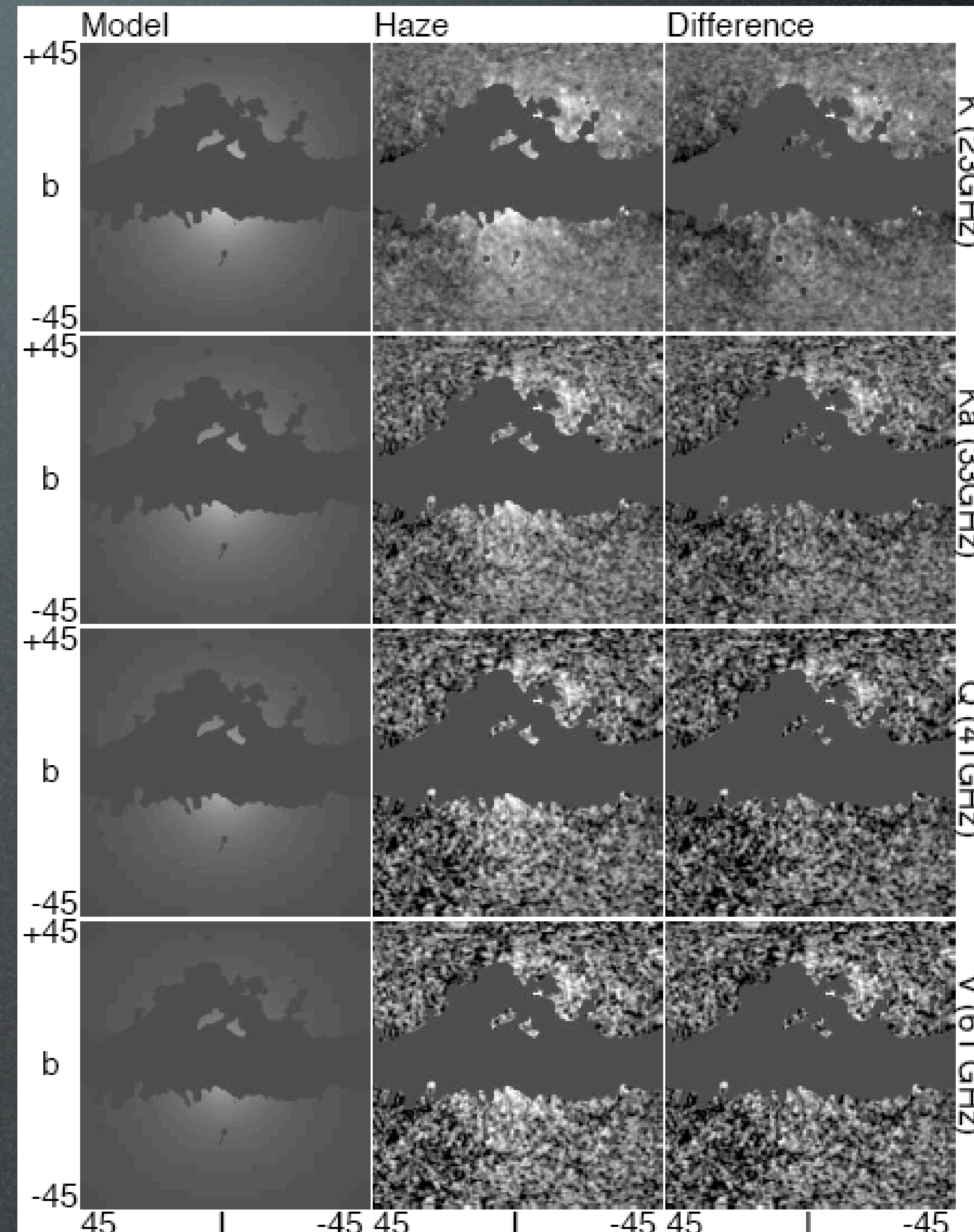


Ullio et al., ApP 21 (2004), astro-ph/0305075

however:
- source not centered
- variability...

+ CANGAROO (2004)
+ HESS (2004)

WMAP "haze"



Finkbeiner, ApJ 614 (2004)

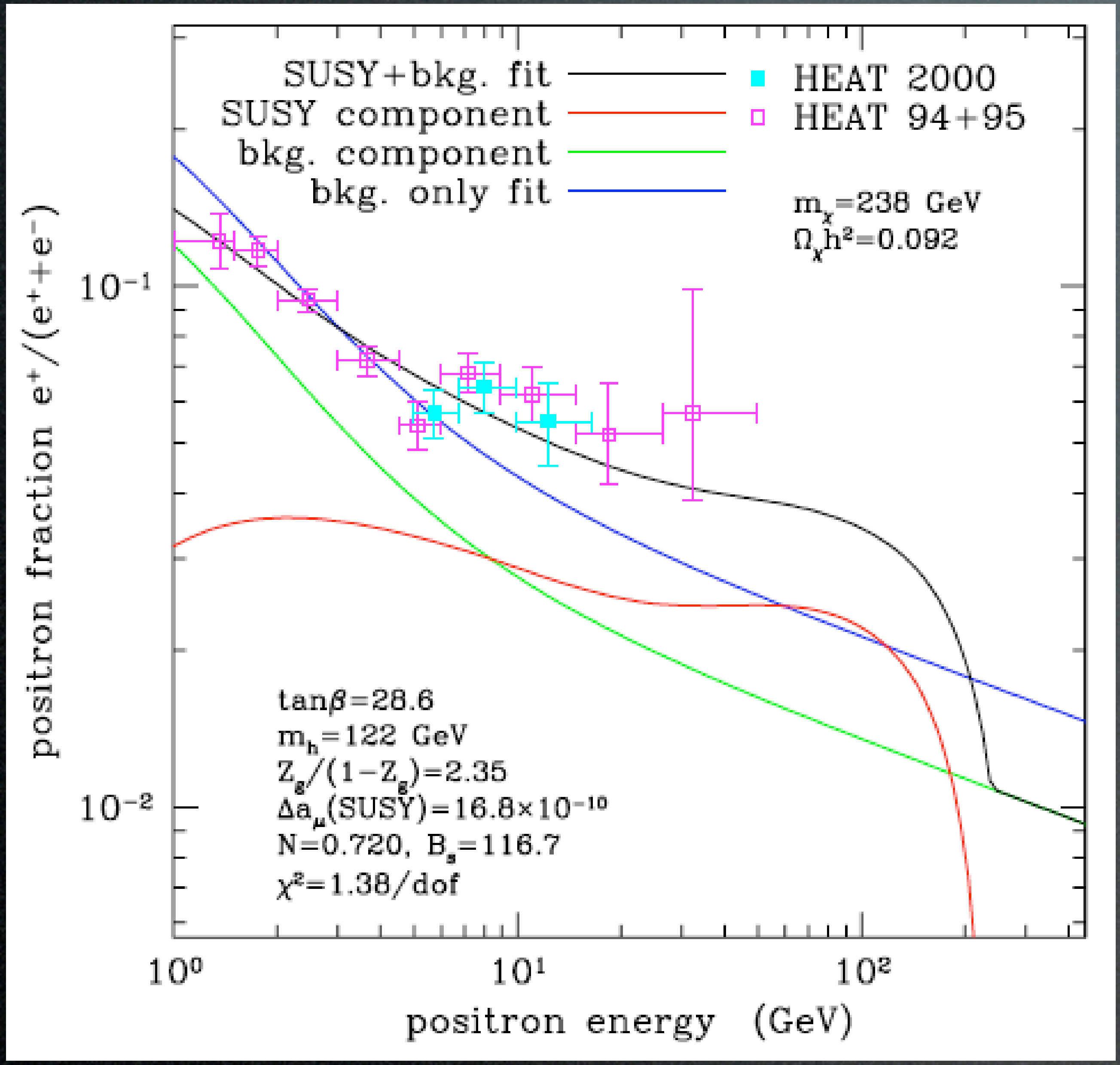
(Synchrotron rad from e^+e^- from DM annihilations)

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]

Indirect Detection: positrons

HEAT excess (1994+95 & 2000)



Baltz, Edsjo, Gondolo, Freese PRD65 (2002)

however:
- the proper HEAT excess is that in cyan, “impossible” to fit with DM
- the plateau can be instrumental
- flux requires too much DM...

[back to DM detection]

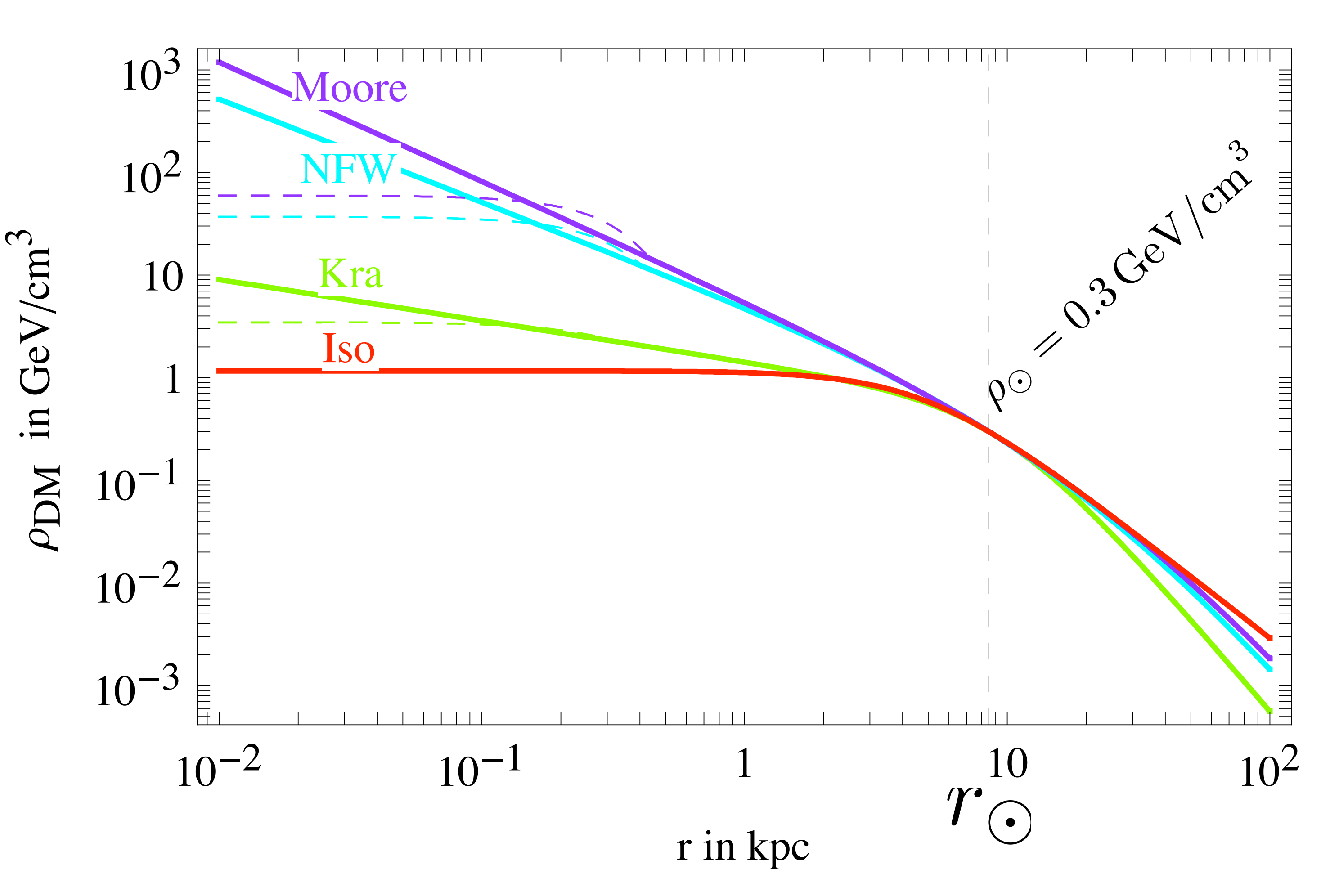
DM halo profiles

From N-body numerical simulations:

$$\rho(r) = \rho_\odot \left[\frac{r_\odot}{r}\right]^\gamma \left[\frac{1 + (r_\odot/r_s)^\alpha}{1 + (r/r_s)^\alpha}\right]^{(\beta-\gamma)/\alpha}$$

Halo model	α	β	γ	r_s in kpc
Cored isothermal	2	2	0	5
Navarro, Frenk, White	1	3	1	20
Moore	1	3	1.16	30

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



cuspy: NFW, Moore
smooth: isothermal

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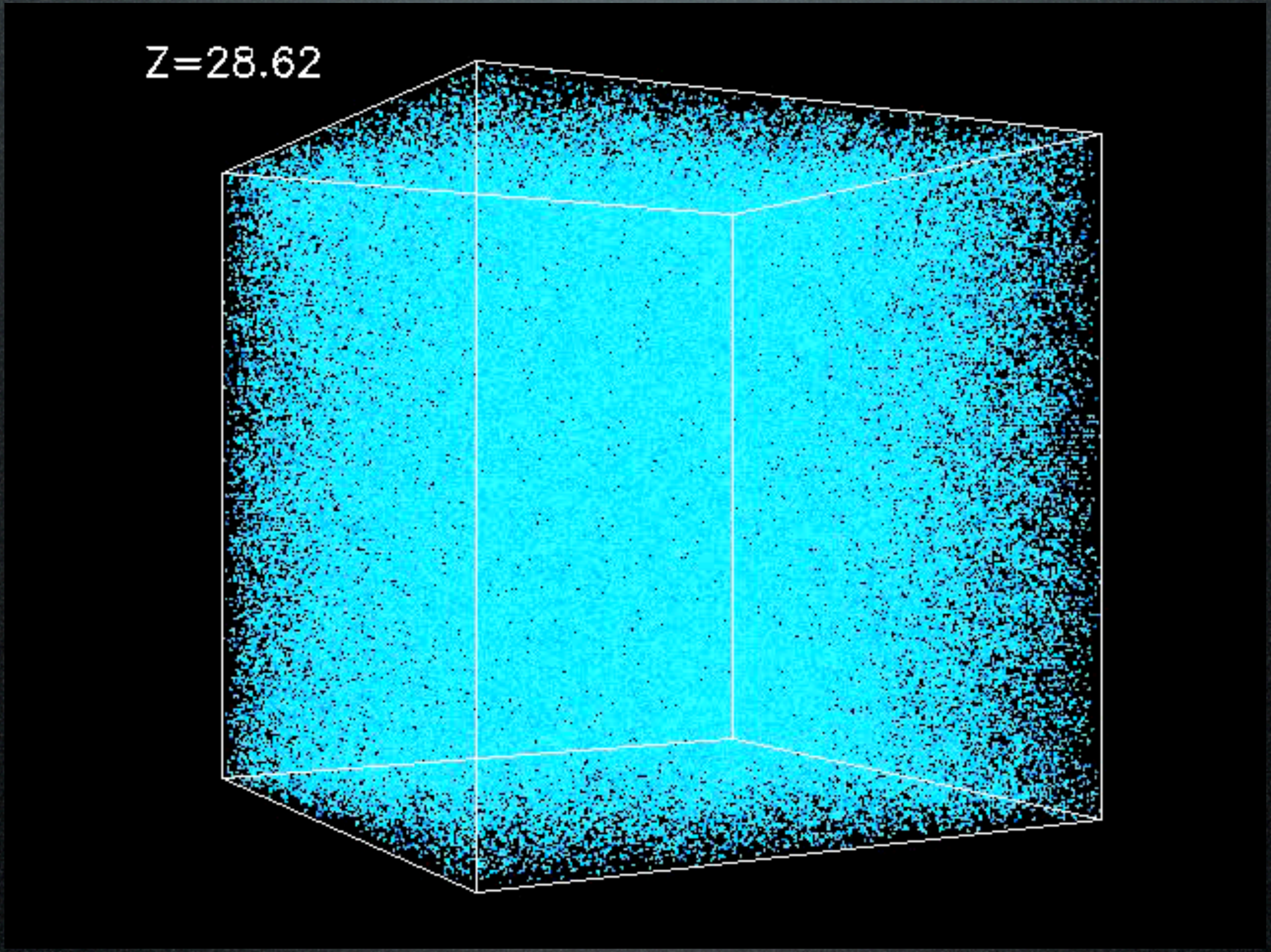
DM N-body simulations

$2\ 10^6$ CDM particles, 43 Mpc cubic box

DM N-body simulations

2 10^6 CDM particles, 43 Mpc cubic box

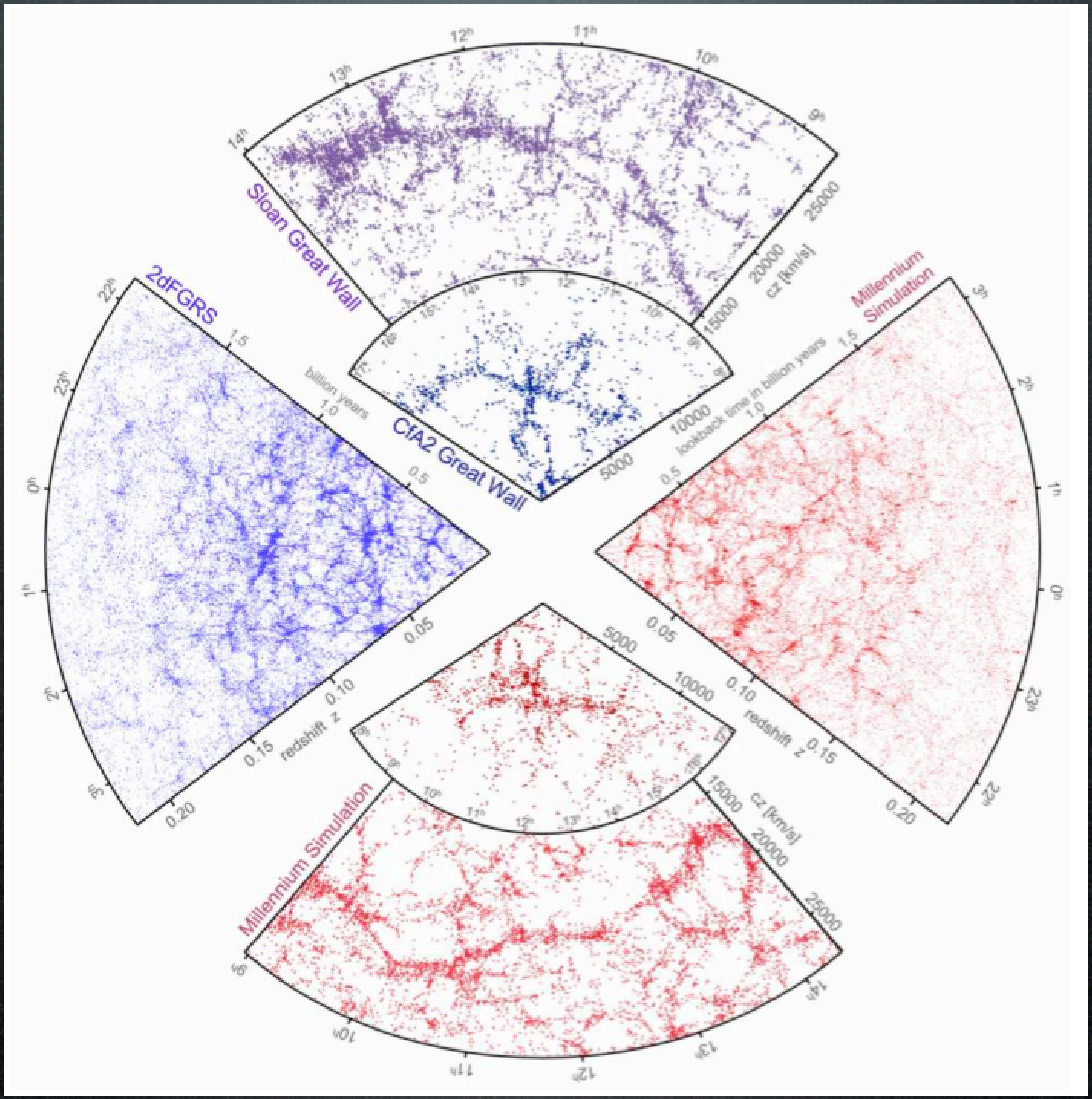


Andrey Kravtsov, cosmicweb.uchicago.edu

DM N-body simulations

2dF: 2.2 10^5 galaxies

SDSS: 10^6 galaxies,
2 billion lyr

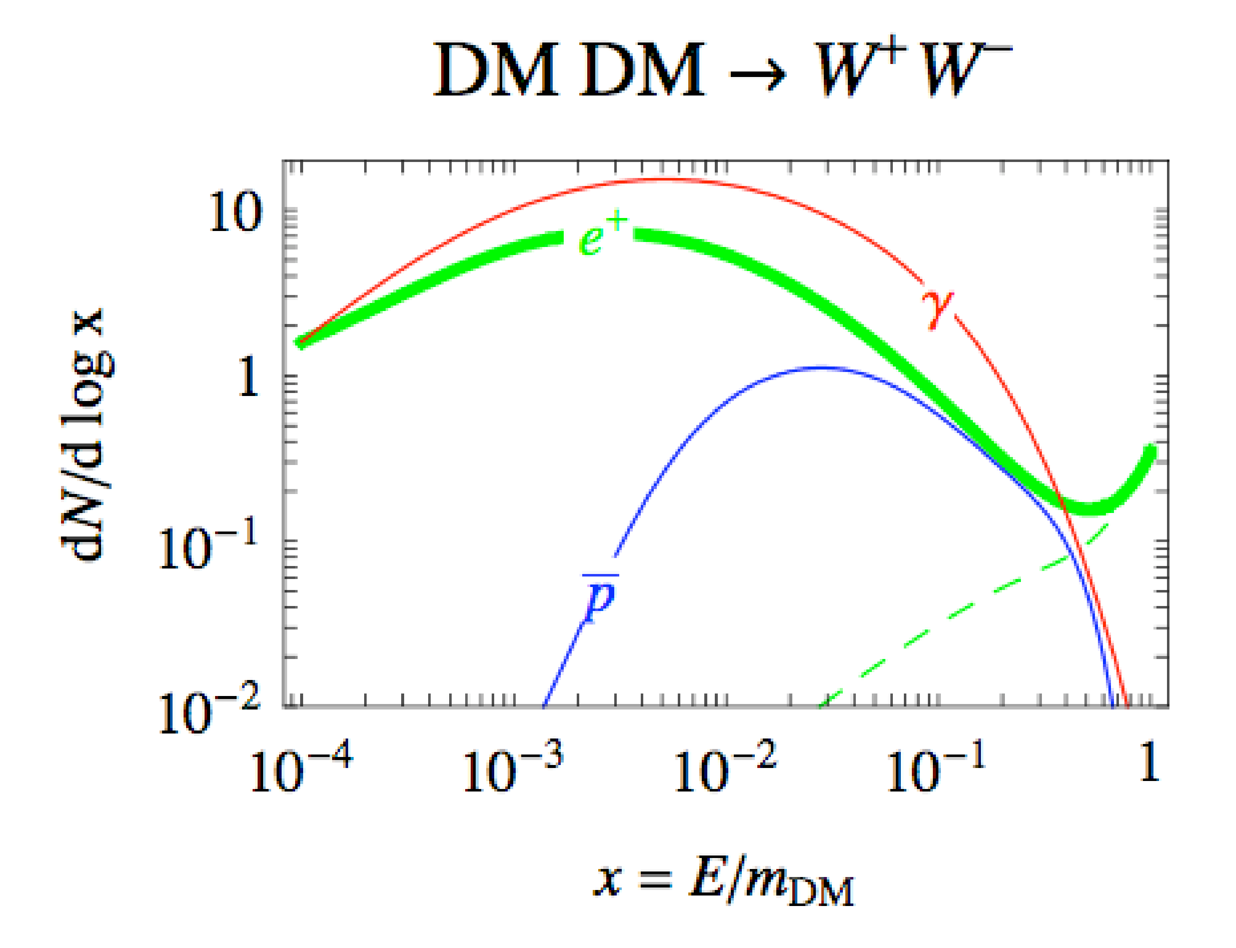


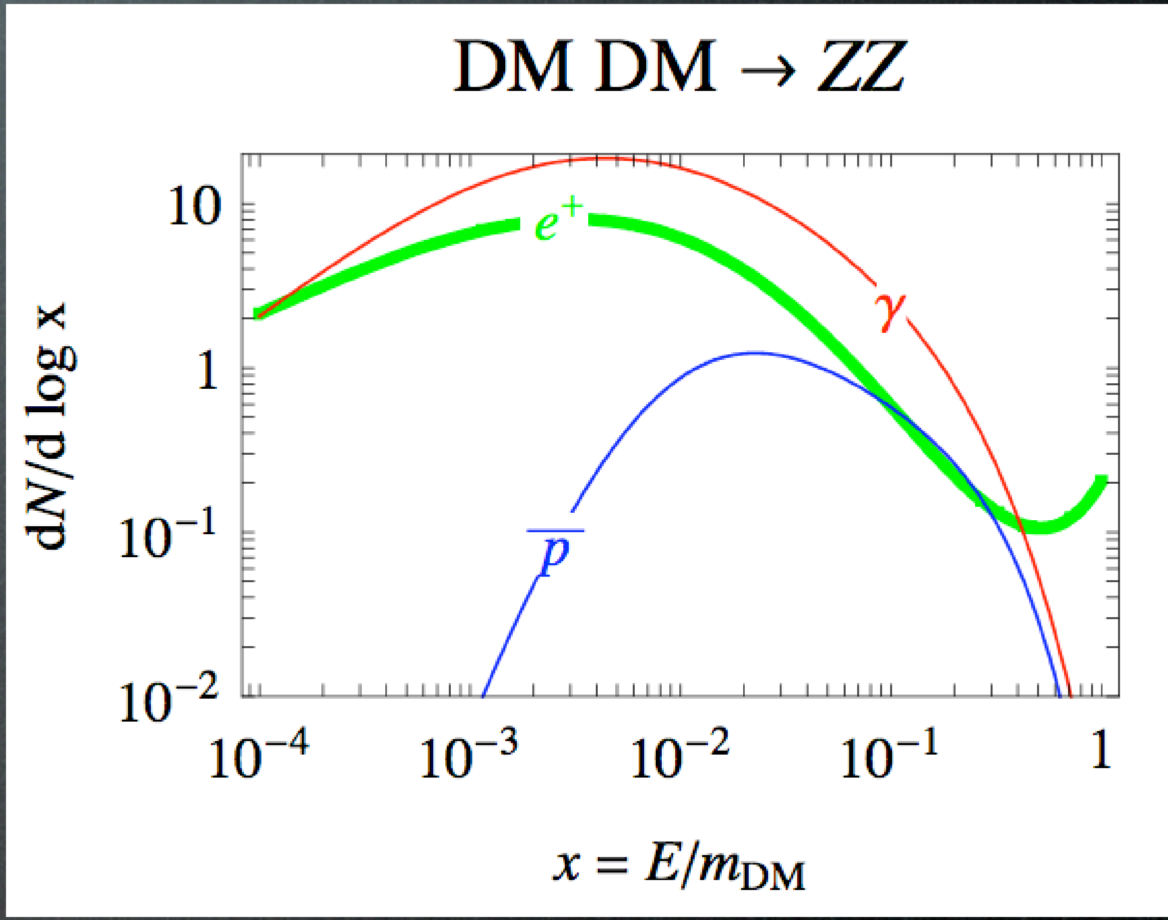
Millennium:
10^{10} particles,
500 h^{-1} Mpc

Springel, Frenk, White, Nature 440 (2006)

3. Indirect Detection

Primary spectra:





3. Indirect Detection

Propagation for positrons:

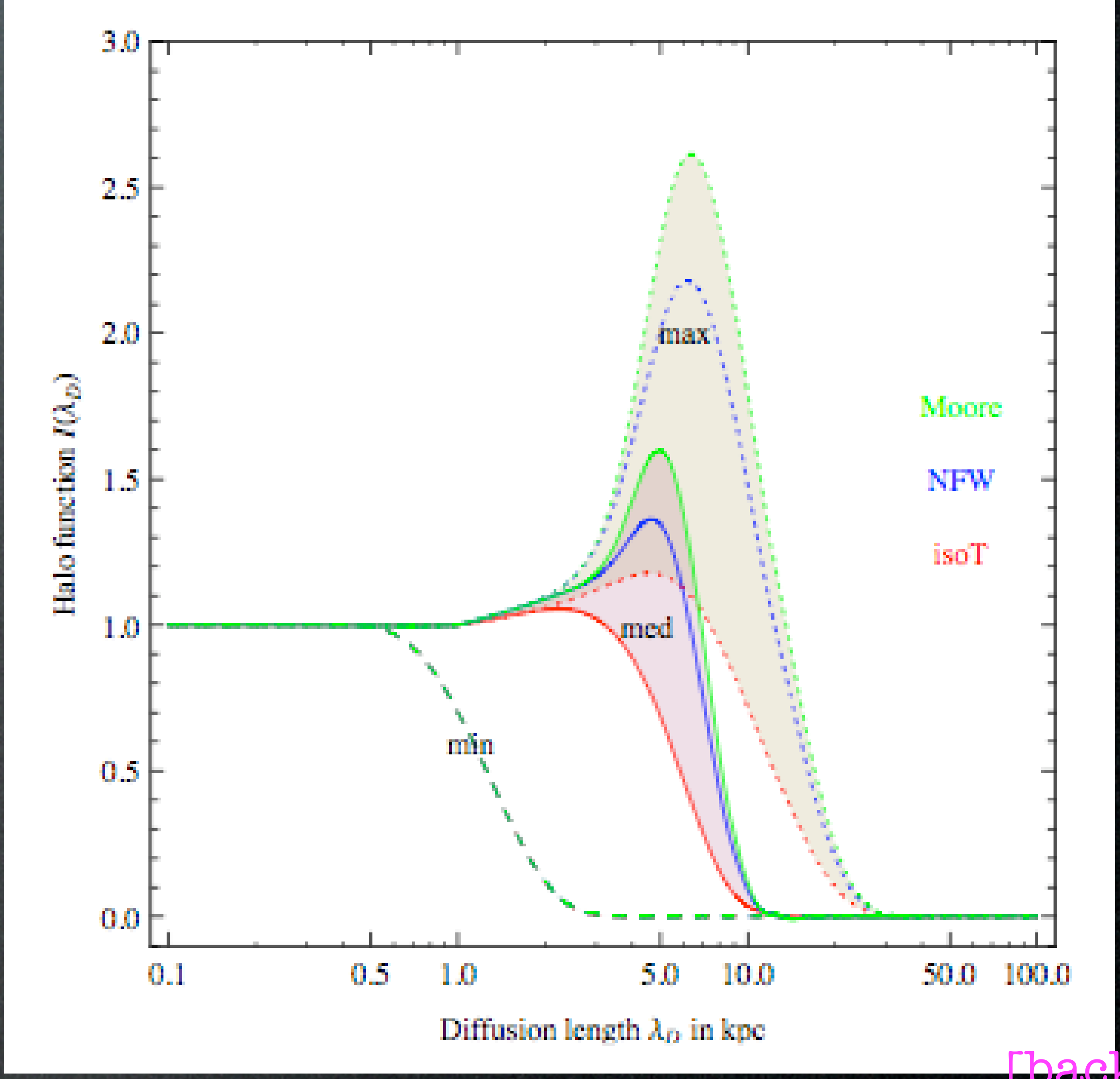
$$\frac{\partial f}{\partial t} - K(E)\cdot\nabla^2 f - \frac{\partial}{\partial E}\left(b(E) f\right) = Q$$

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

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

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

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

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3. Indirect Detection

Propagation for antiprotons:

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

diffusion — convective wind — spallations

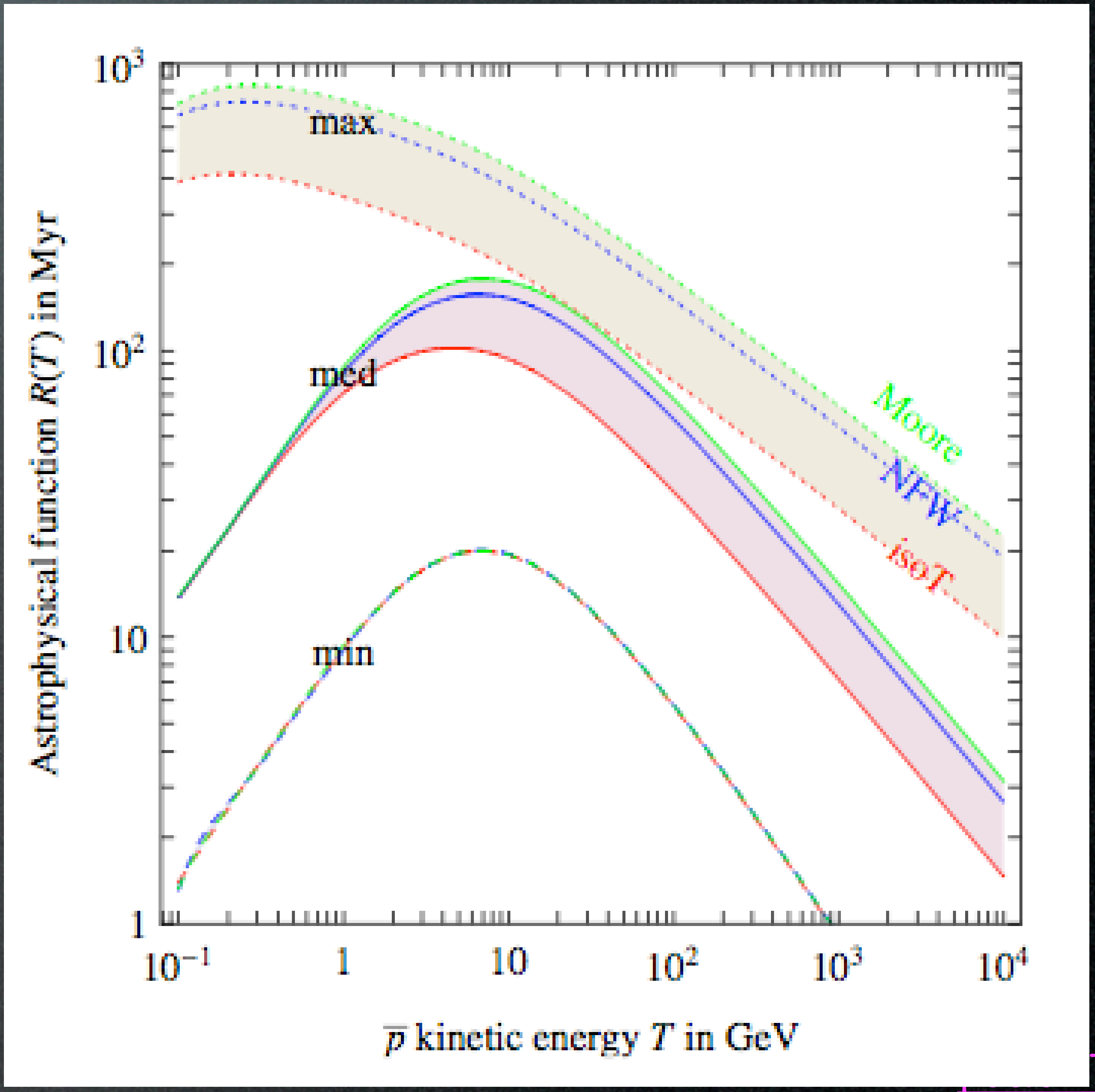
$K(T) = K_0 \beta\, (p/\text{GeV})^\delta$

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:

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



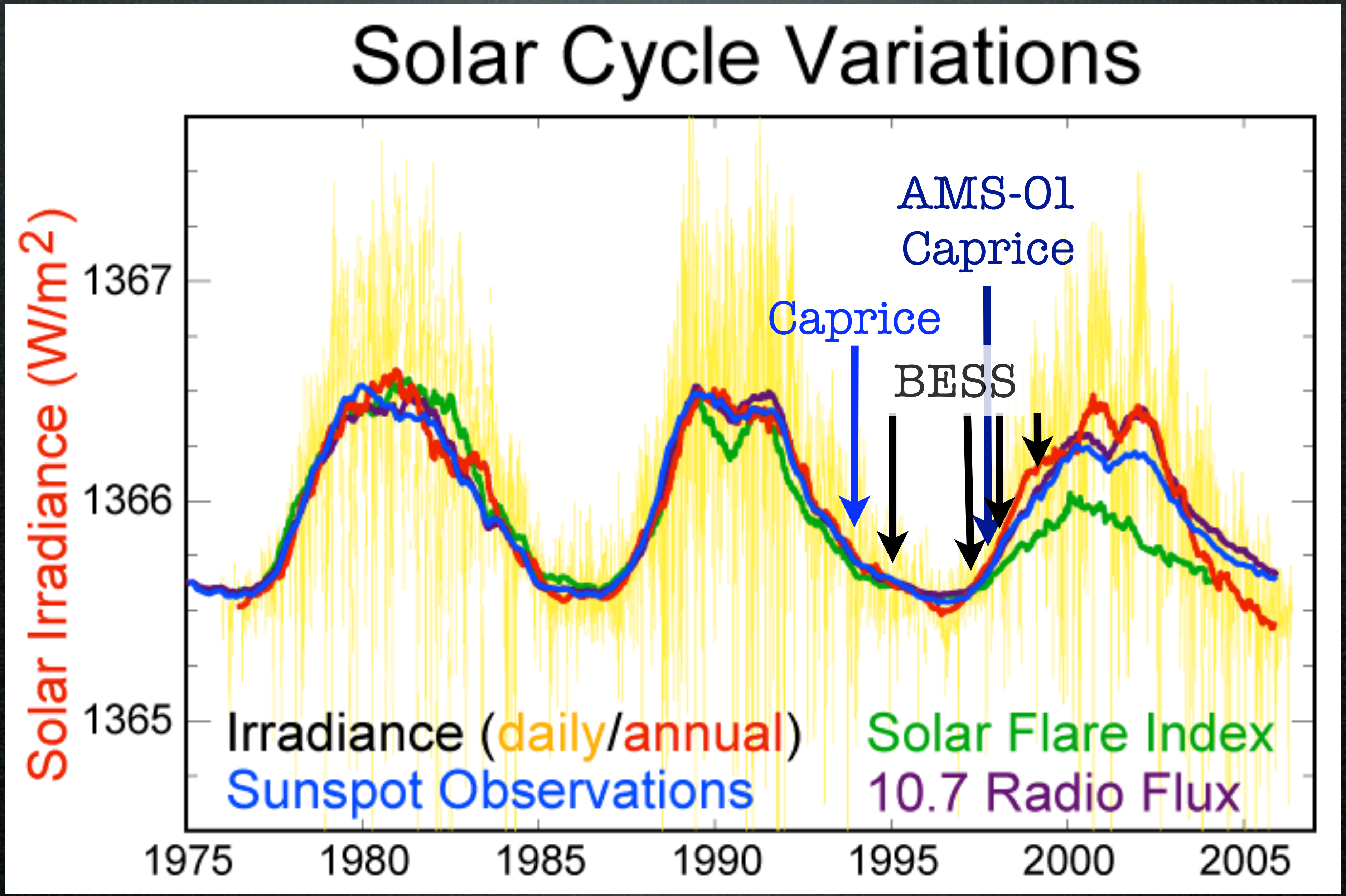
Indirect Detection

Solar wind Modulation of cosmic rays:

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

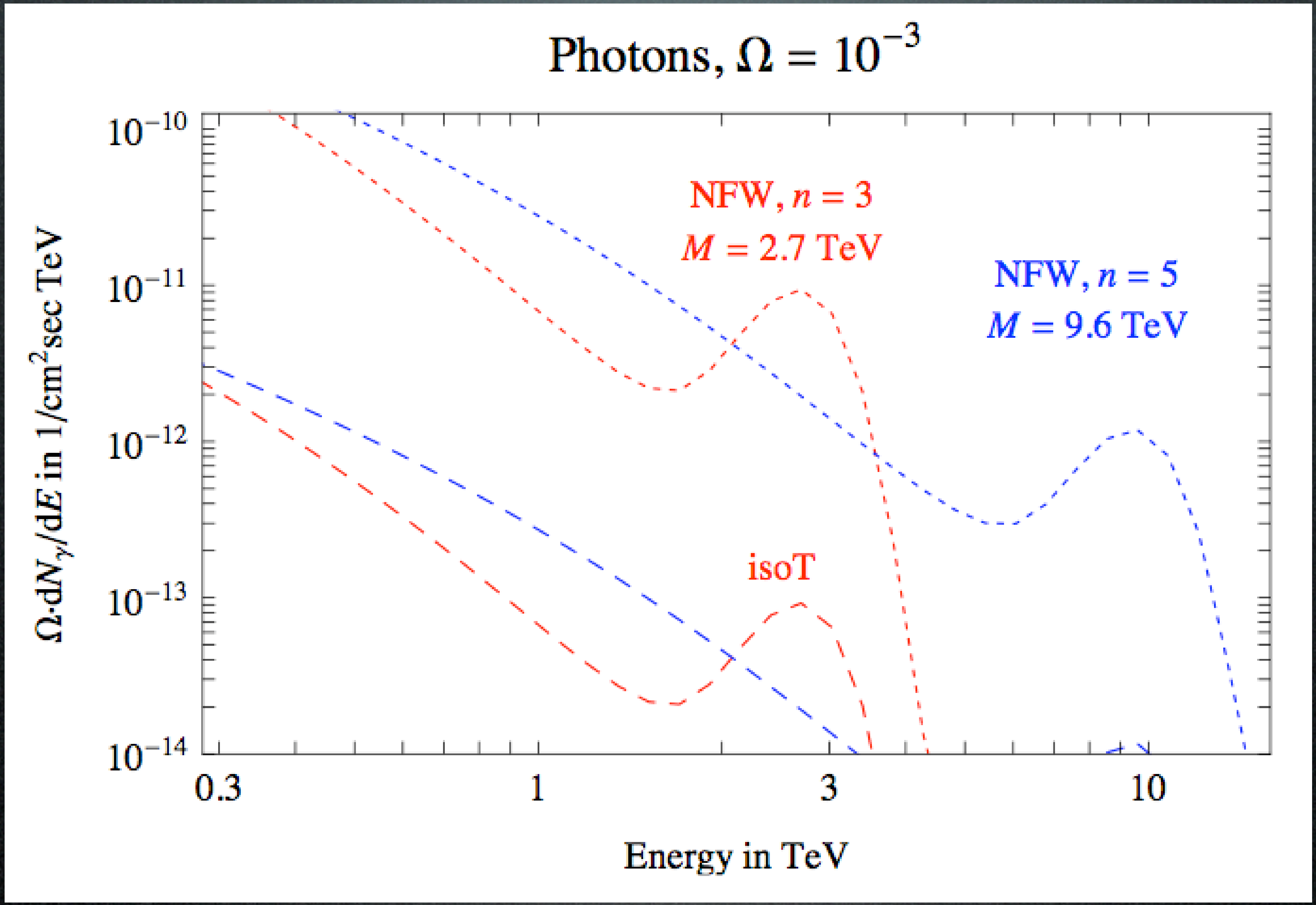
spectrum at Earth — spectrum far from Earth

Fisk potential $\phi_F \simeq 500$ MV



Indirect Detection

For instance, predicted signal in γ rays:

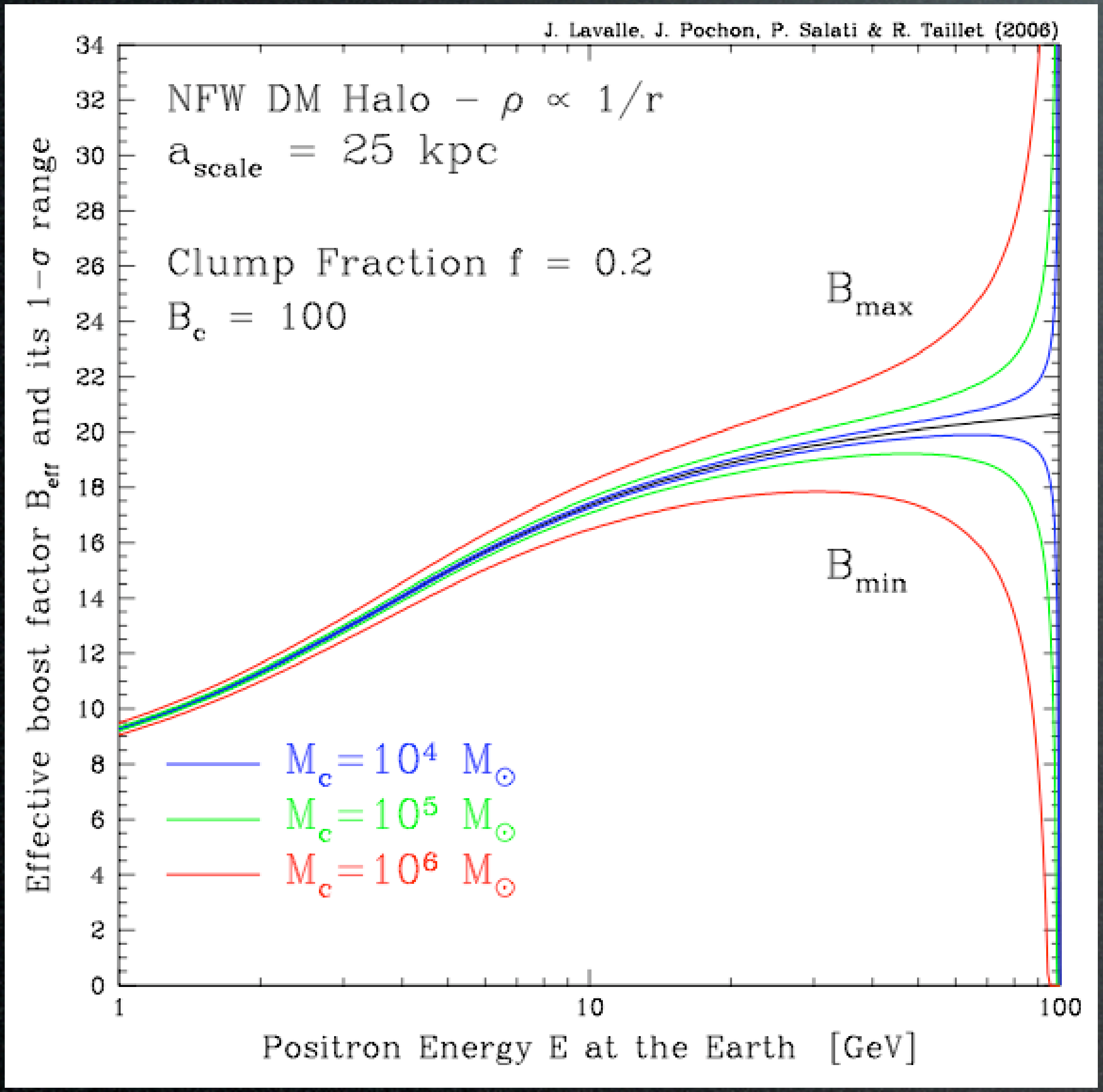


Indirect Detection

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

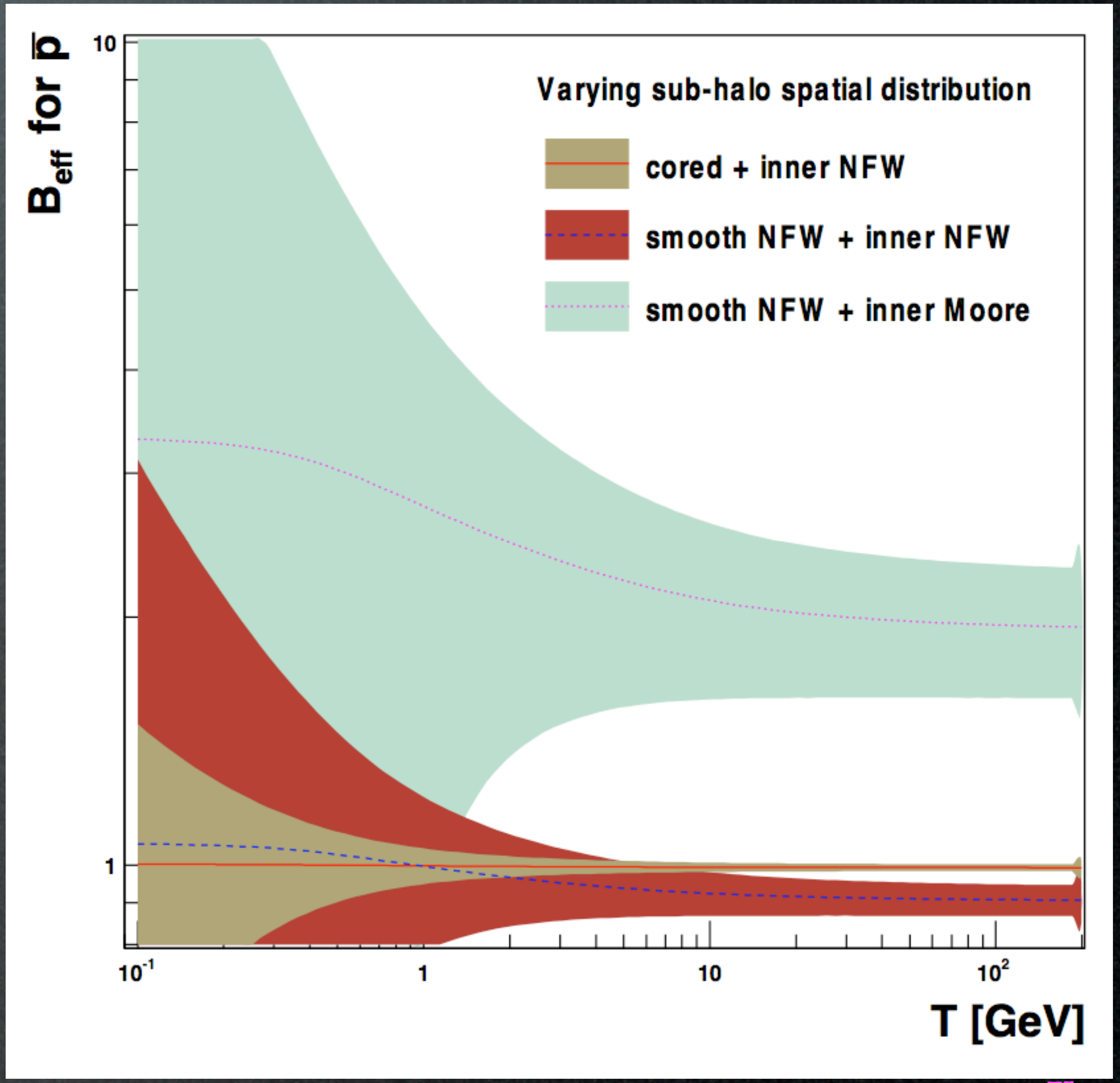
In principle, B is different for e^+, anti-p and gammas,
energy dependent,
dependent on many astro assumptions,
with an energy dependent variance, at high energy for e^+, at low energy for anti-p.

positrons



Lavalle et al. 2006

antiprotons



Lavalle et al. 2007

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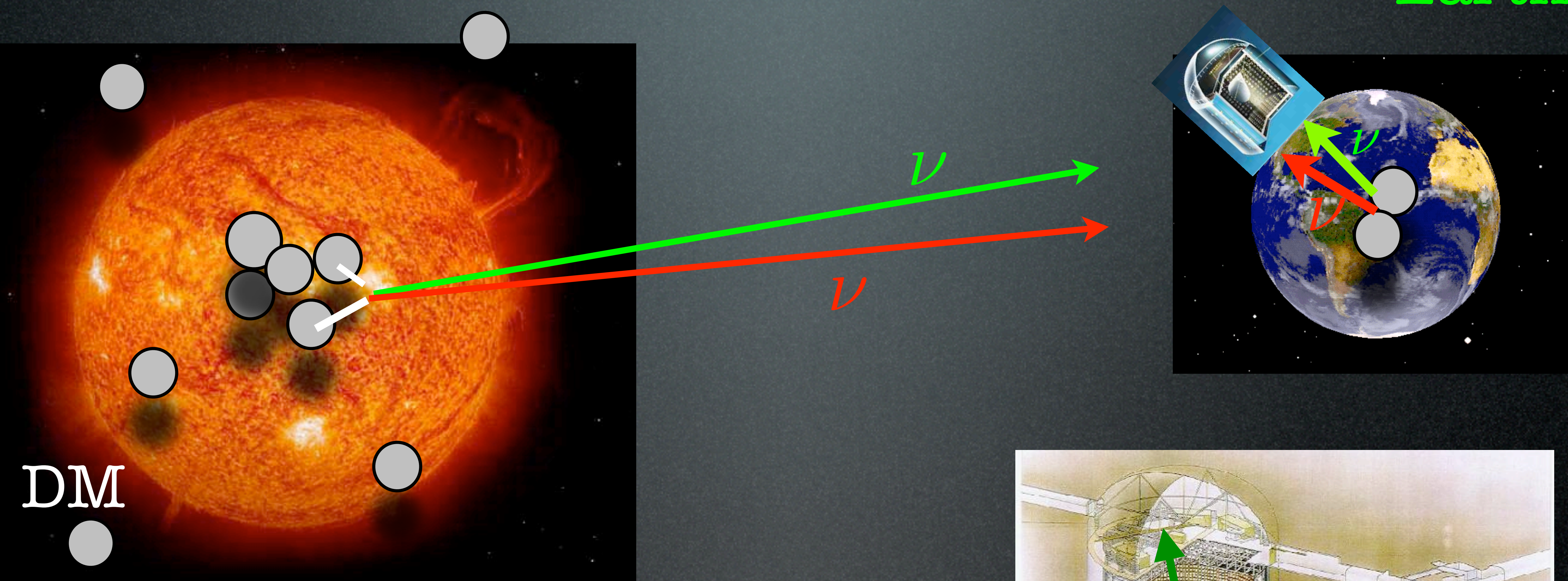
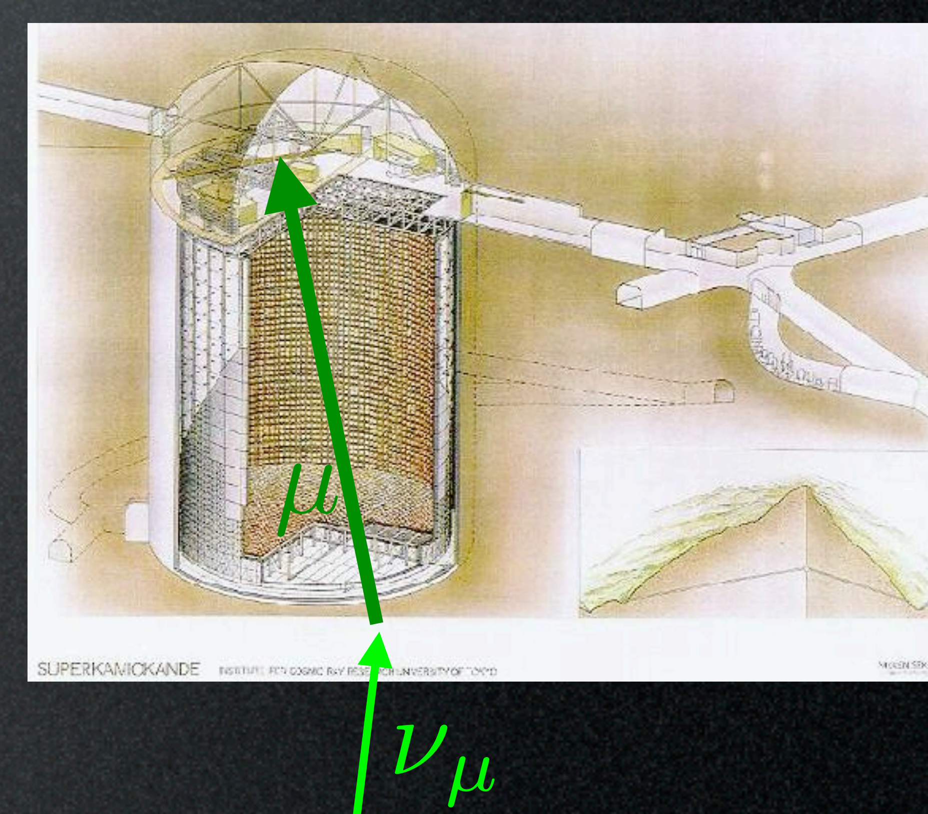
Neutrinos from DM



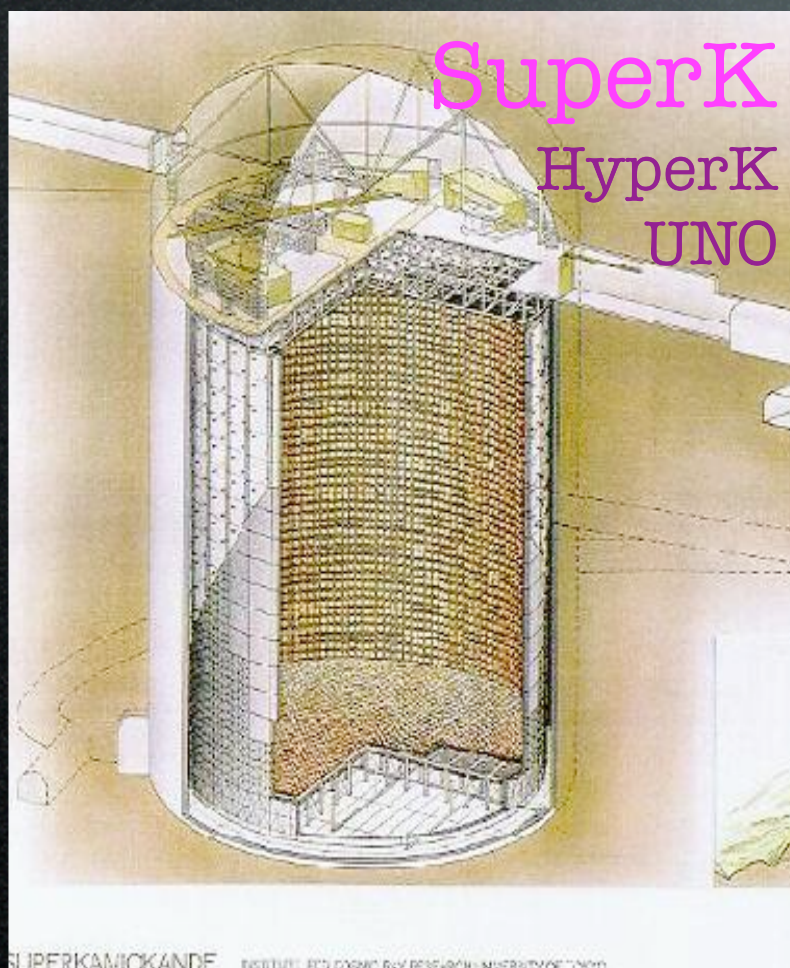
up-going muons:

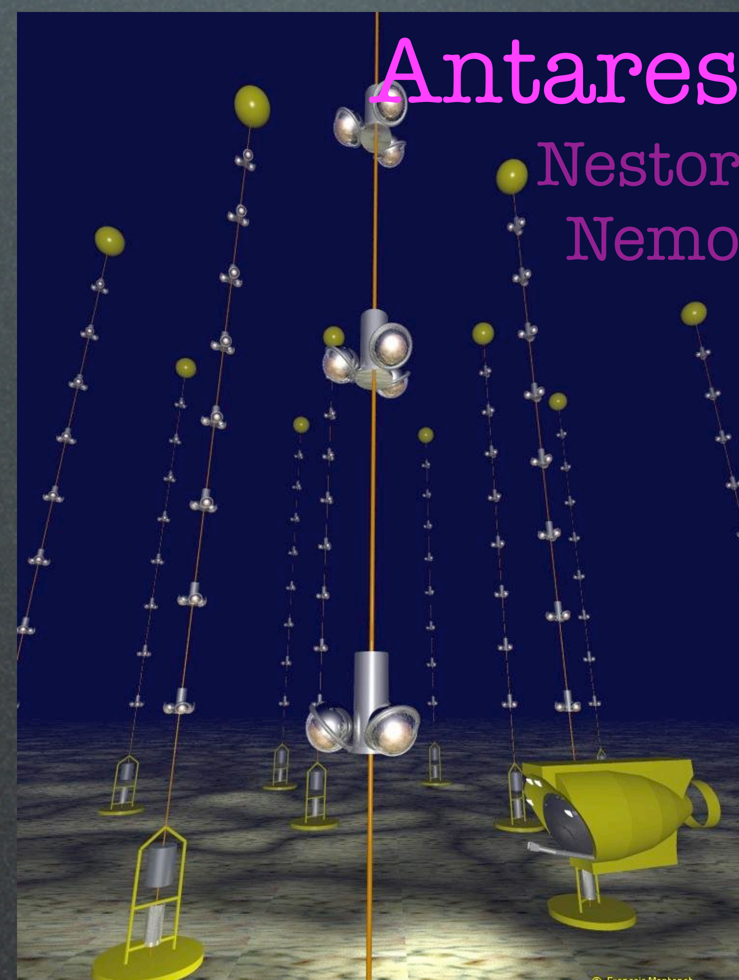


[back to DM detection]

"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]