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Minimal Dark Matter

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and
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Minimalistic approach

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

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

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

and systematically search for the ideal DM candidate...

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On top of the SM, add **only** one extra multiplet $\mathcal{X} = \begin{pmatrix} \chi_1 \\ \chi_2 \\ \vdots \end{pmatrix}$

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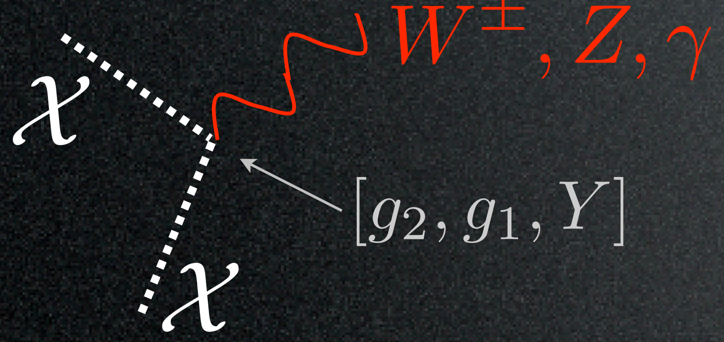
gauge interactions

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



(other terms in the

(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
$\underline{2}$		
$\underline{3}$		
$\underline{4}$		
$\underline{5}$		
$\underline{7}$		

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

$$\mathcal{X} = \begin{pmatrix} \mathcal{X}_1 \\ \mathcal{X}_2 \\ \vdots \\ \mathcal{X}_n \end{pmatrix}$$

these are all possible choices:

$n \leq 5$ for fermions

$n \leq 7$ for scalars

to avoid explosion in the running coupling

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

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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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etc.

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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:

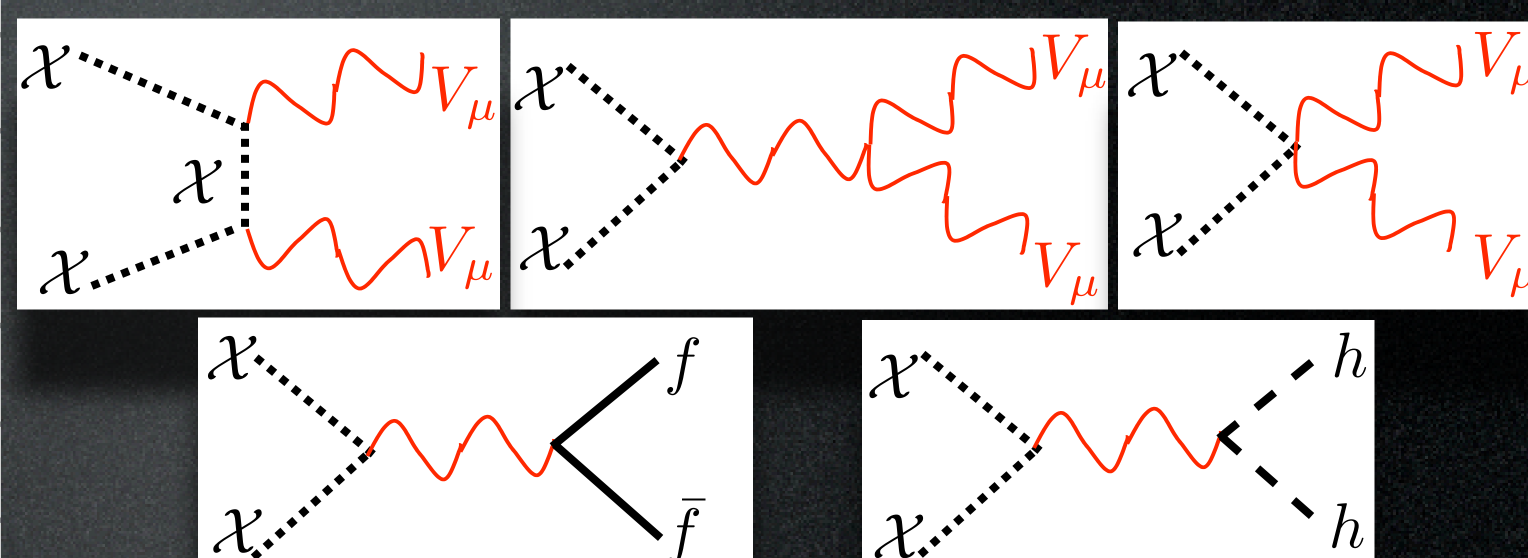
$$\Omega_{\rm DM} = \frac{6\ 10^{-27}{\rm cm}^3{\rm s}^{-1}}{\langle\sigma_{\rm ann} v\rangle} \simeq 0.24$$

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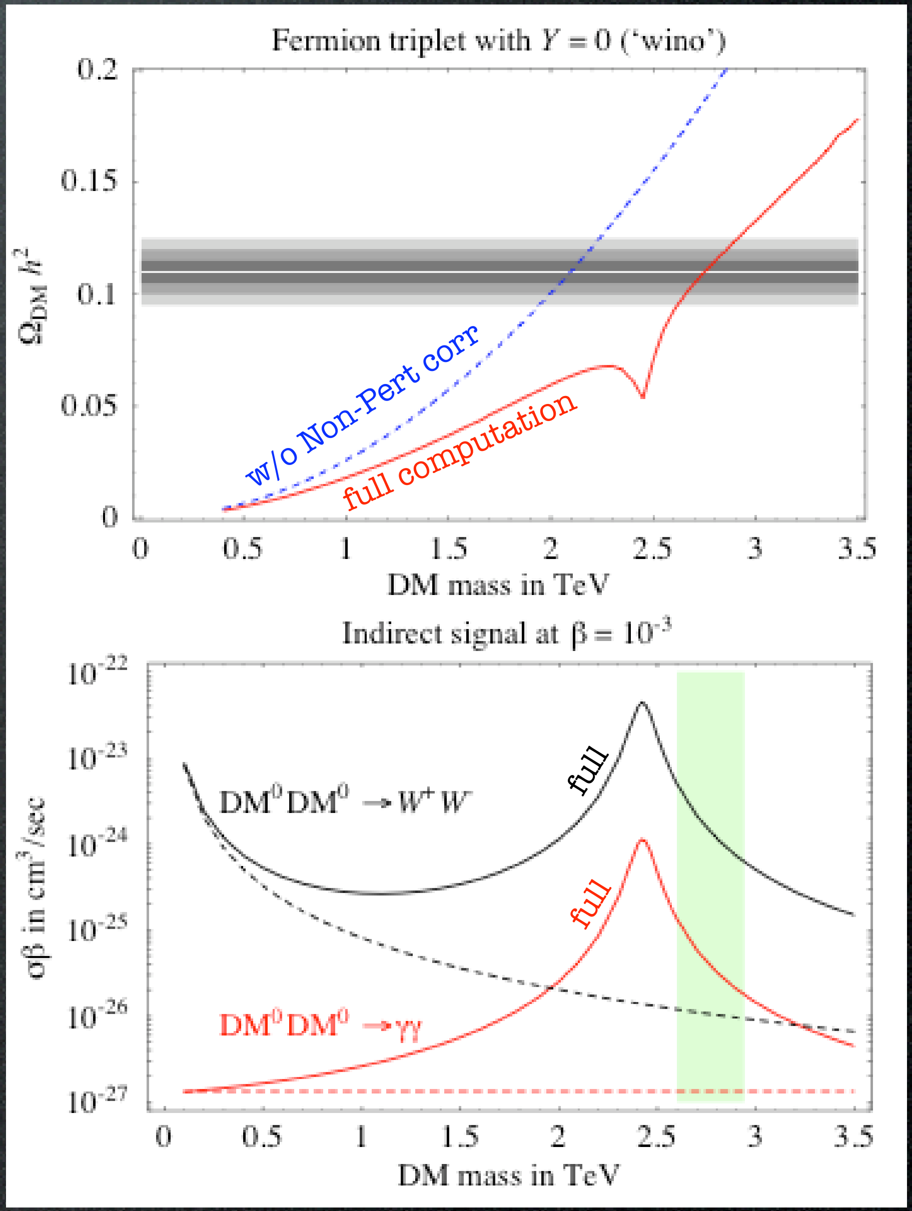
$SU(2)_L$	$U(1)_Y$	spin	M (TeV)
2	1/2	S	
		F	1.0
3	0	S	2.5
		F	2.7
	1	S	
		F	
4	1/2	S	
		F	
	3/2	S	
		F	
5	0	S	9.4
		F	10
	1	S	
		F	
	2	S	
		F	
7	0	S	25

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



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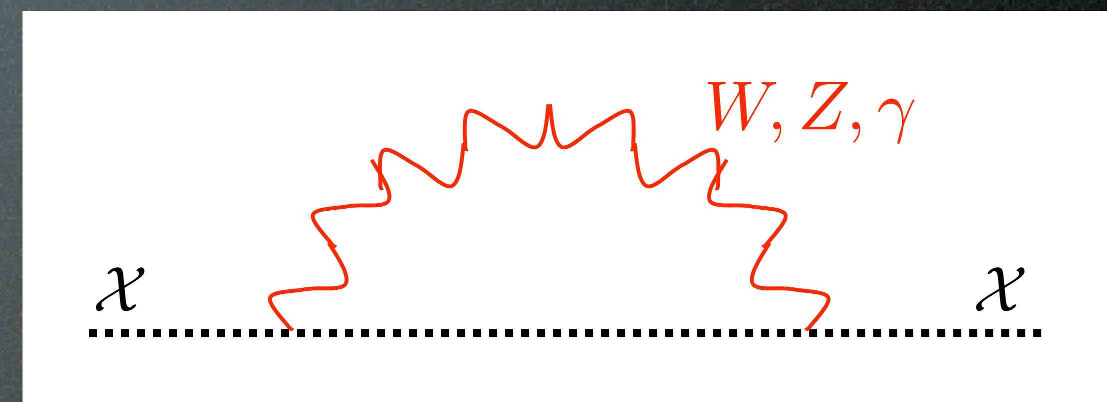
	3/2	S		729
		F		712
5	0	S	9.4	166
		F	10	166
	1	S		537
		F		534
	2	S		906
		F		900
7	0	S	25	166

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

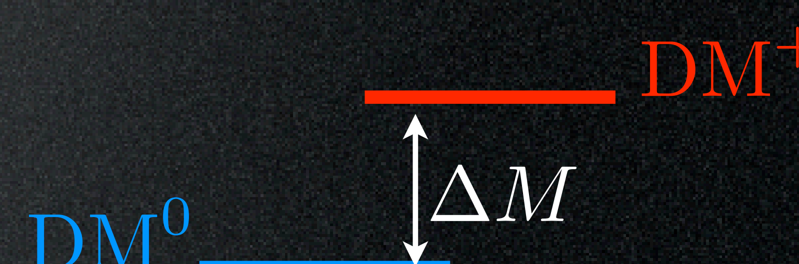
tree level



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

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

The neutral component is the lightest



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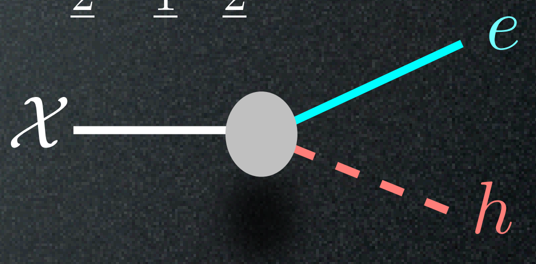
List all allowed SM couplings:

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



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

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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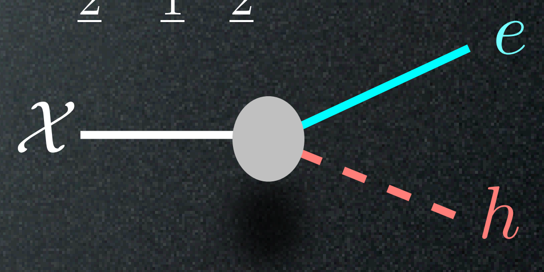

← e.g. $\overset{1/2\;\;-1/2\;\;1/2\;\;-1/2}{\chi L H H^*}$, with $\underline{4}\;\underline{2}\;\underline{2}\;\underline{2}$

dim=5 operator, induces

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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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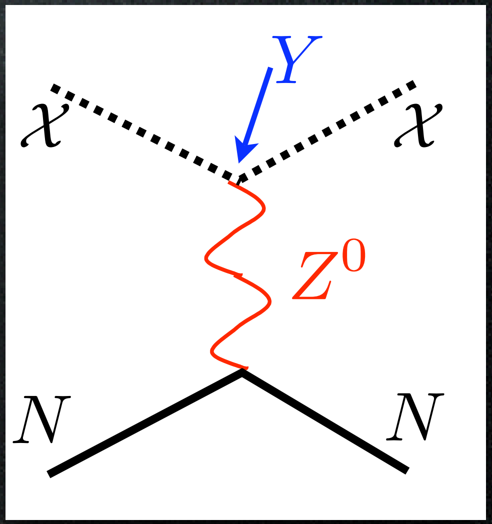
Candidates with $Y \neq 0$
interact as



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

$\gg$ present bounds
e.g. Xenon

need $Y = 0$

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We have a winner!

(other terms in the scalar potential)

and a 2° place

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

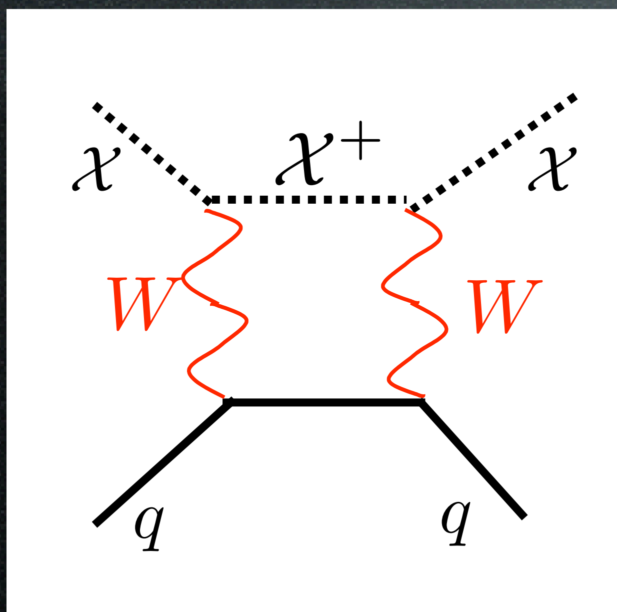
indirect

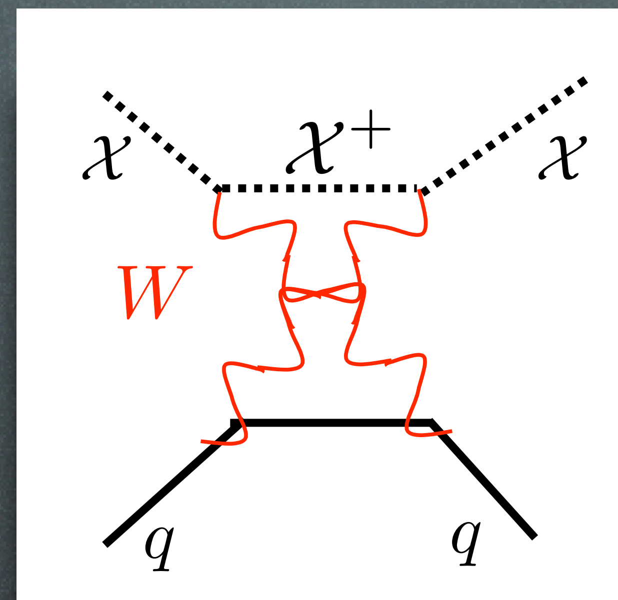
- γ from annihil in galactic halo or center
  (line + continuum)
- e^+ from annihil in galactic halo or center
- $\bar{p}$ from annihil in galactic halo or center
- $\bar{D}$ from annihil in galactic halo or center
- $\nu, \bar{\nu}$ from annihil in massive bodies

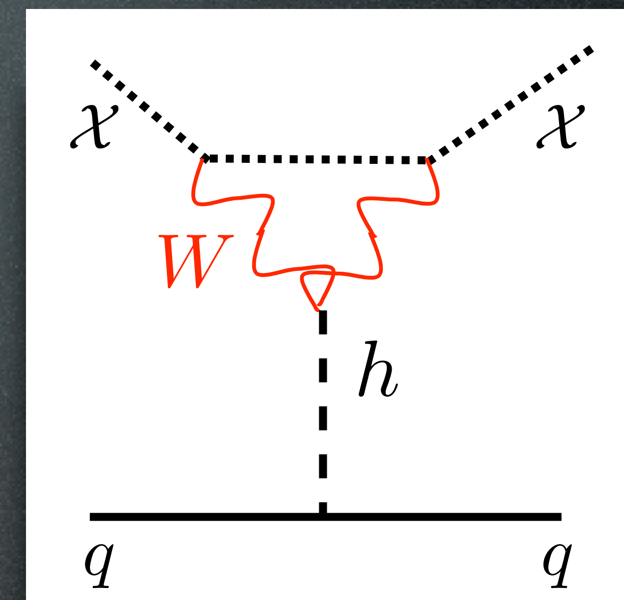
tracing in Cosmic Rays?

1. Direct Detection

one-loop processes







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

larger for higher n

Spin-Independent

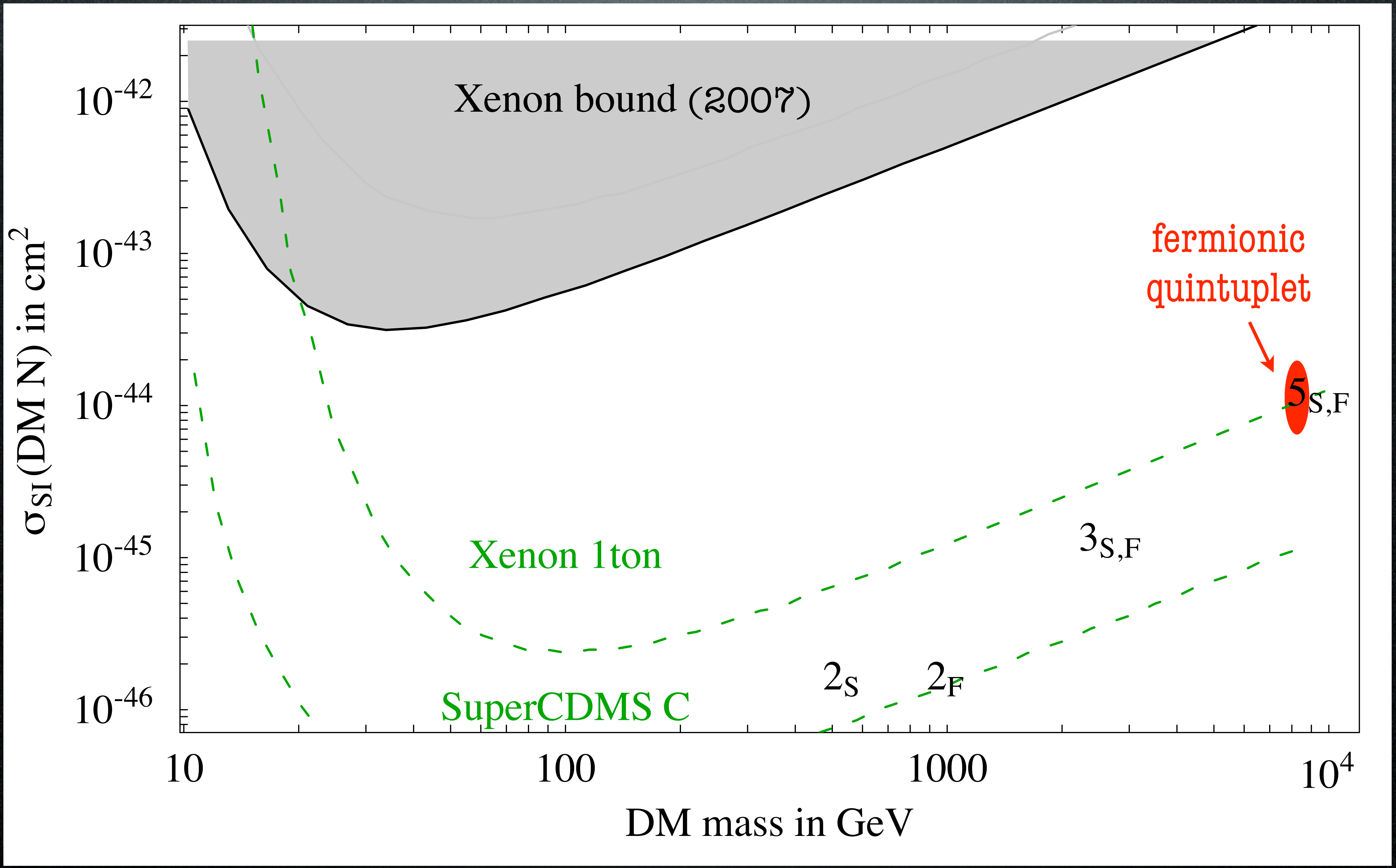
$$\propto \frac{m_q}{M_W^3}$$

Spin-Dependent

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

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

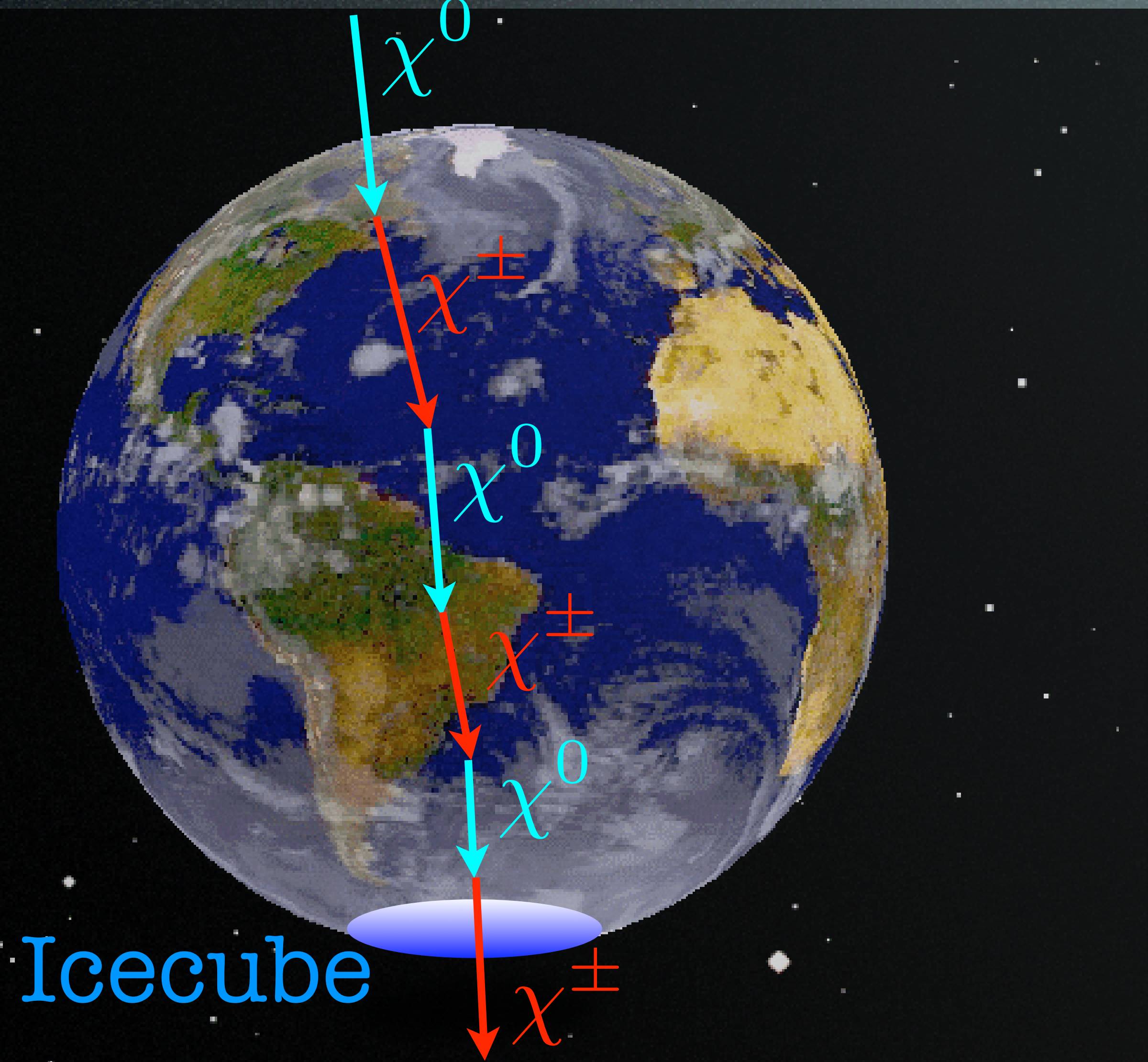
1. Direct Detection

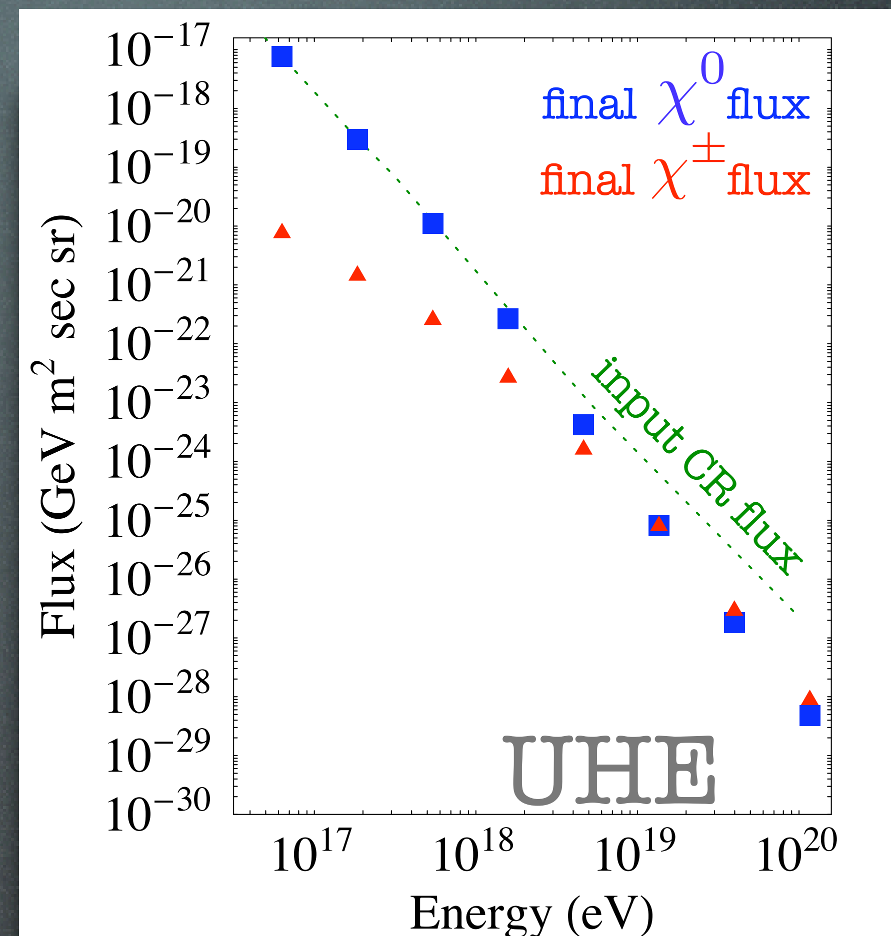


(NB: no free parameters => one predicted point per candidate)

[skip to conclusions]

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,
- could 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	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.

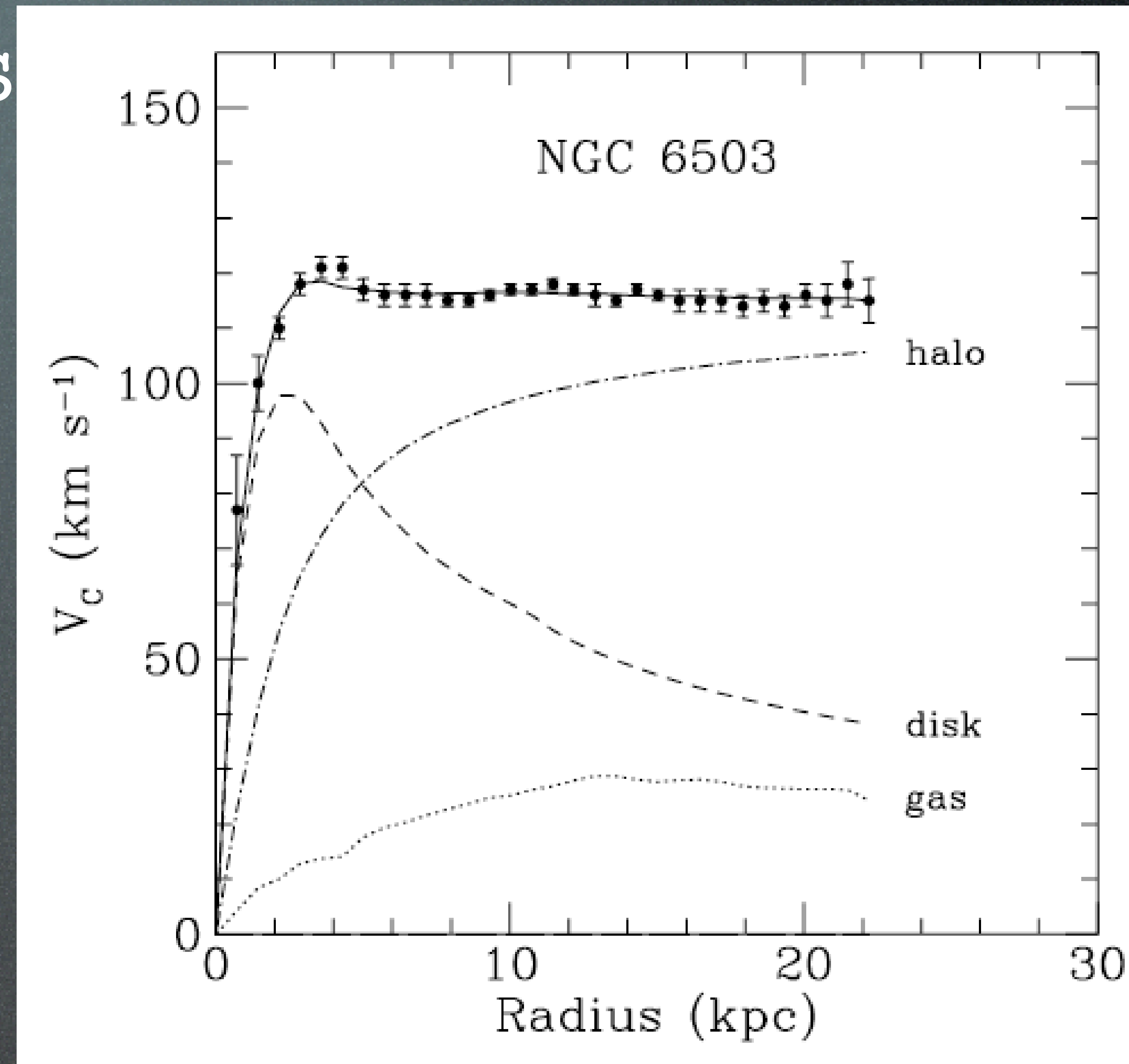
The Evidence for DM

1) galaxy rotation curves

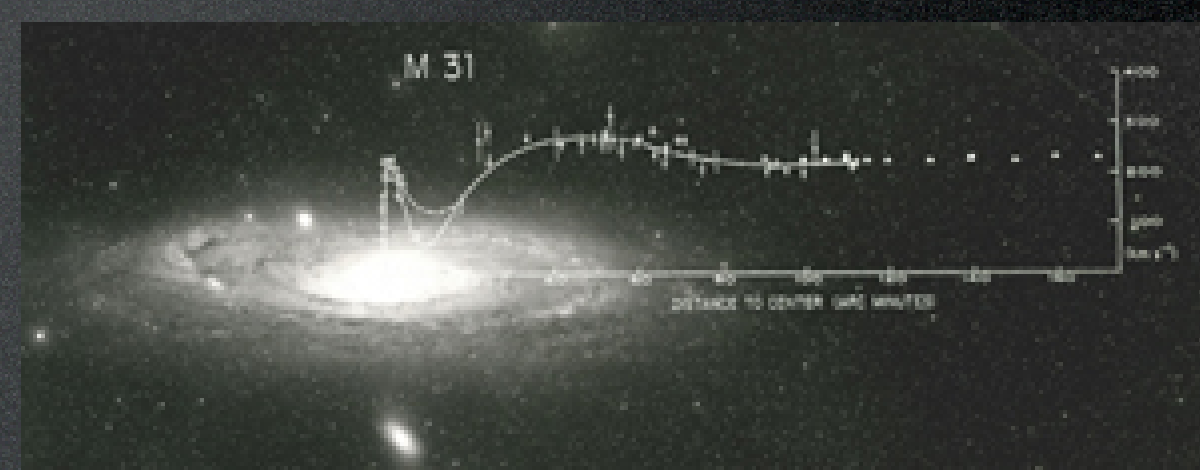
$$v_c(r) = \sqrt{\frac{2G_N M(r)}{r}}$$

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

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



Begeman et al., MNRAS 249 (1991)



The Evidence for DM

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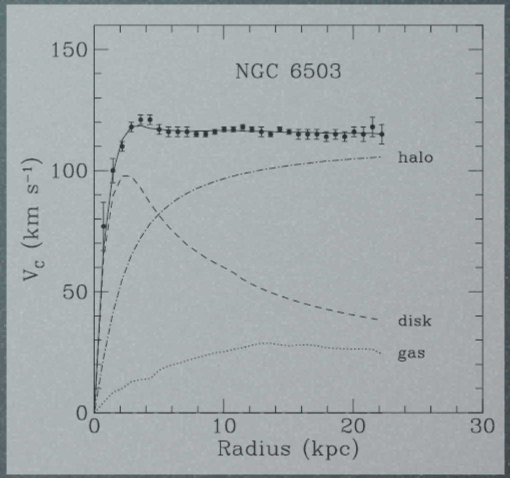


$$\Omega_M \gtrsim 0.1$$

2) clusters of galaxies

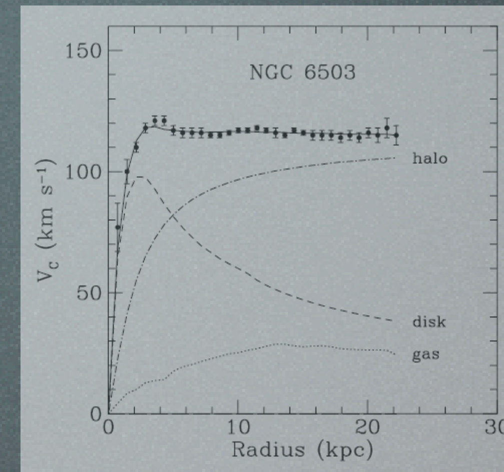
- "rotation curves"
- gravitation lensing
- X-ray gas temperature

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

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

The Evidence for DM

1) galaxy rotation curves



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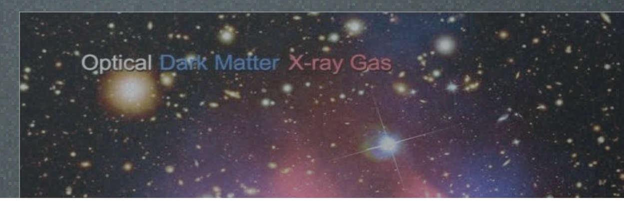
2) clusters of galaxies

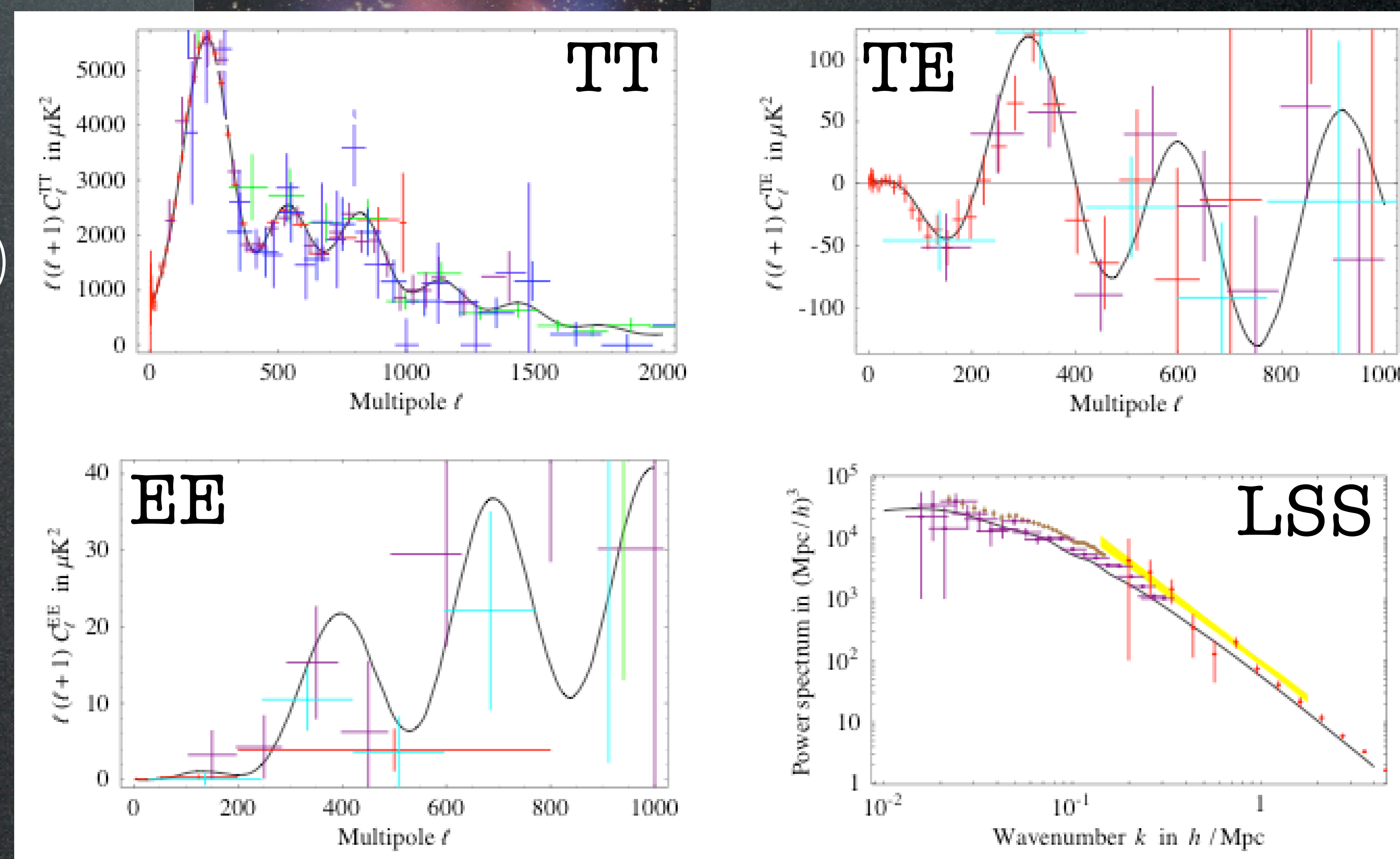


$\Omega_M \sim 0.2 \div 0.4$

3) CMB+LSS(+SNIa:)

WMAP-3yr
ACbar
CBI
Boomerang
DASI
VSA

SDSS, 2dFRGS
LyA Forest Croft
LyA Forest SDSS

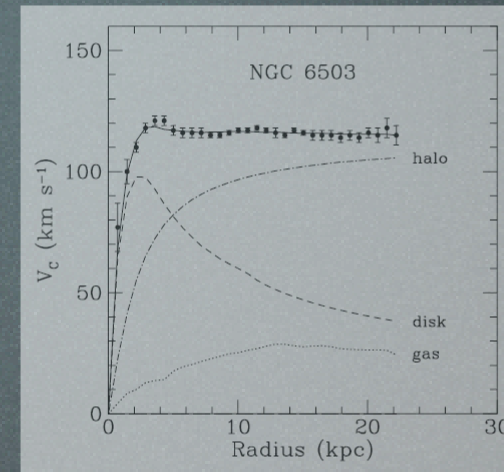


$\Omega_M \approx 0.26 \pm 0.05$

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

The Evidence for DM

1) galaxy rotation curves



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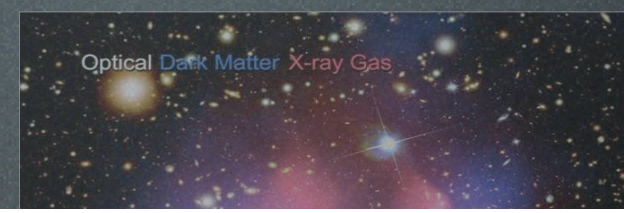
2) clusters of galaxies



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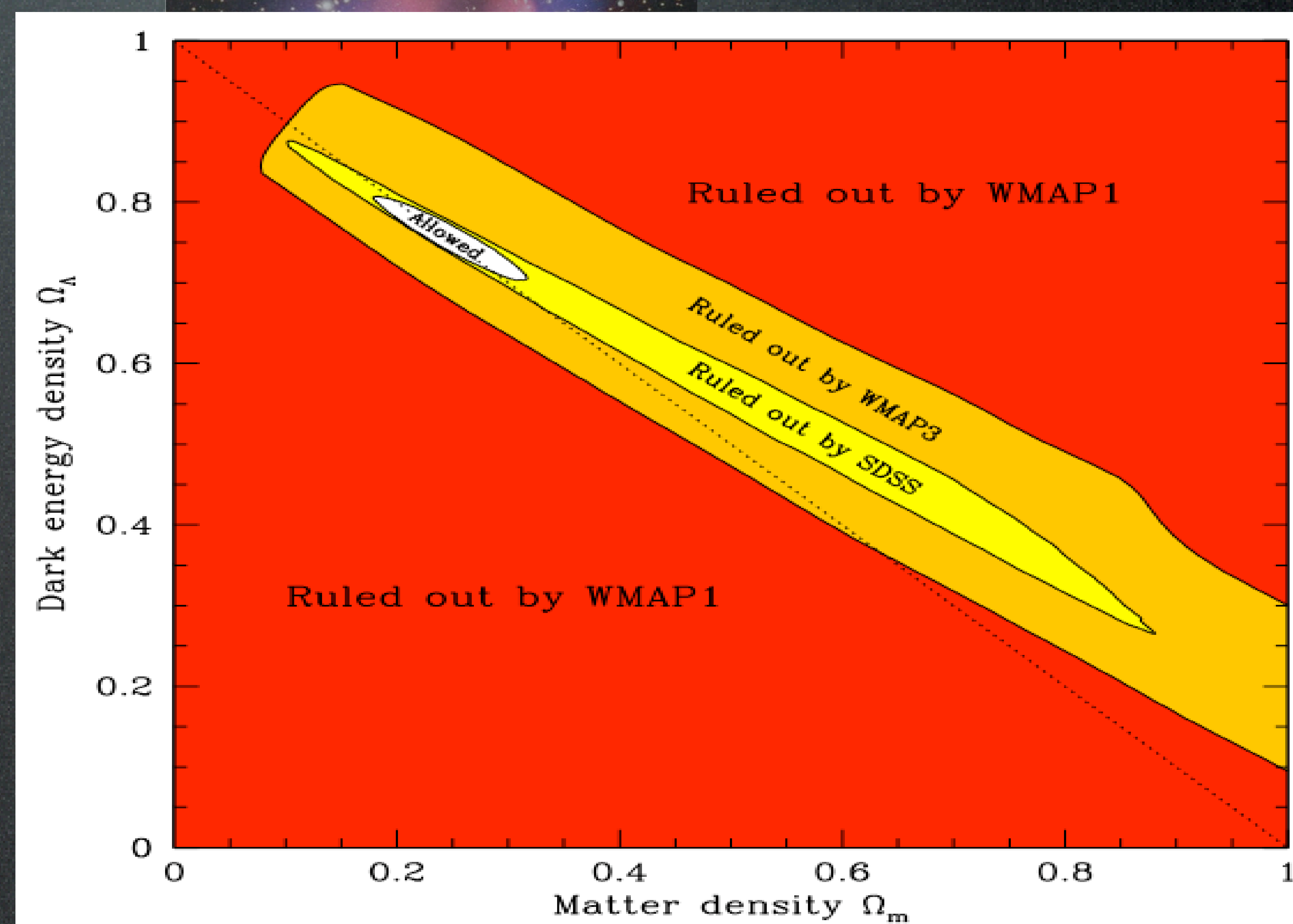
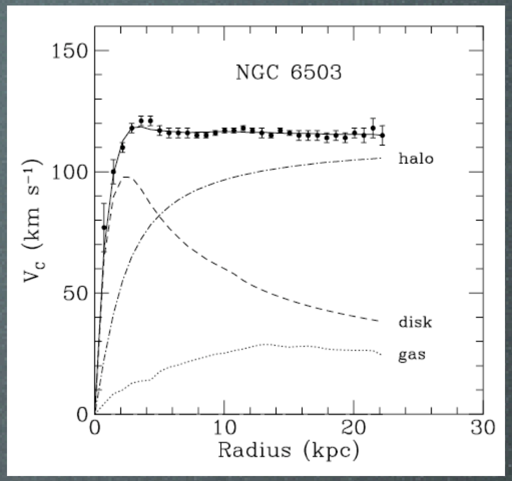


M.Tegmark et al., astro-ph/0608632

The Evidence for DM

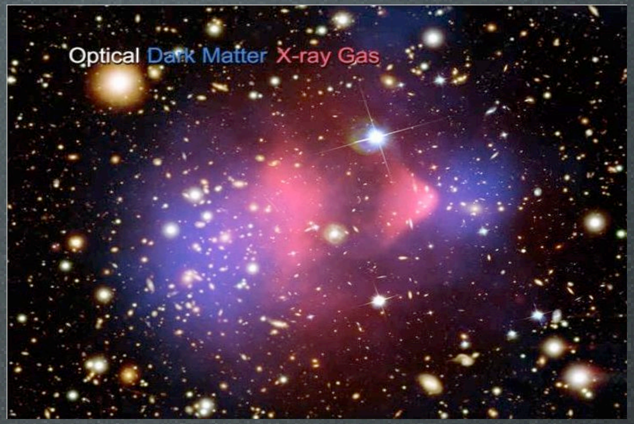
1) galaxy rotation curves



$\Omega_M \gtrsim 0.1$

details

2) clusters of galaxies



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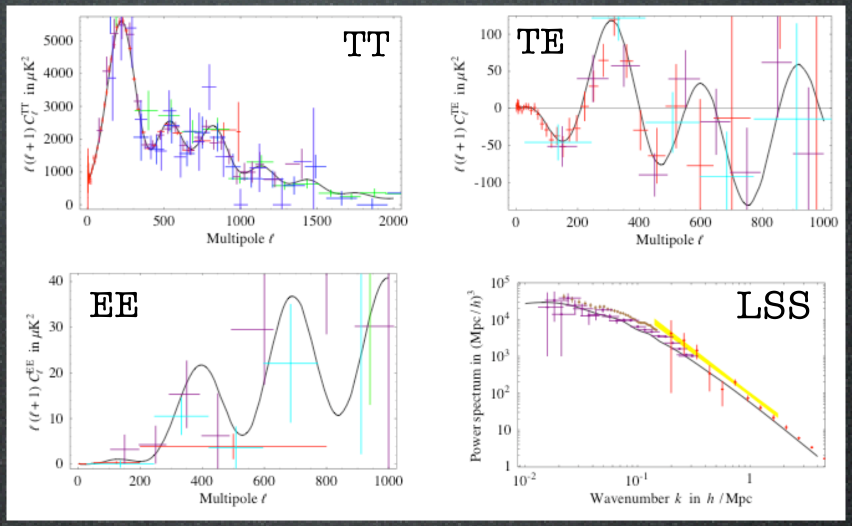
details

3) CMB+LSS(+SNIa:)



$\Omega_M \approx 0.26 \pm 0.05$

details

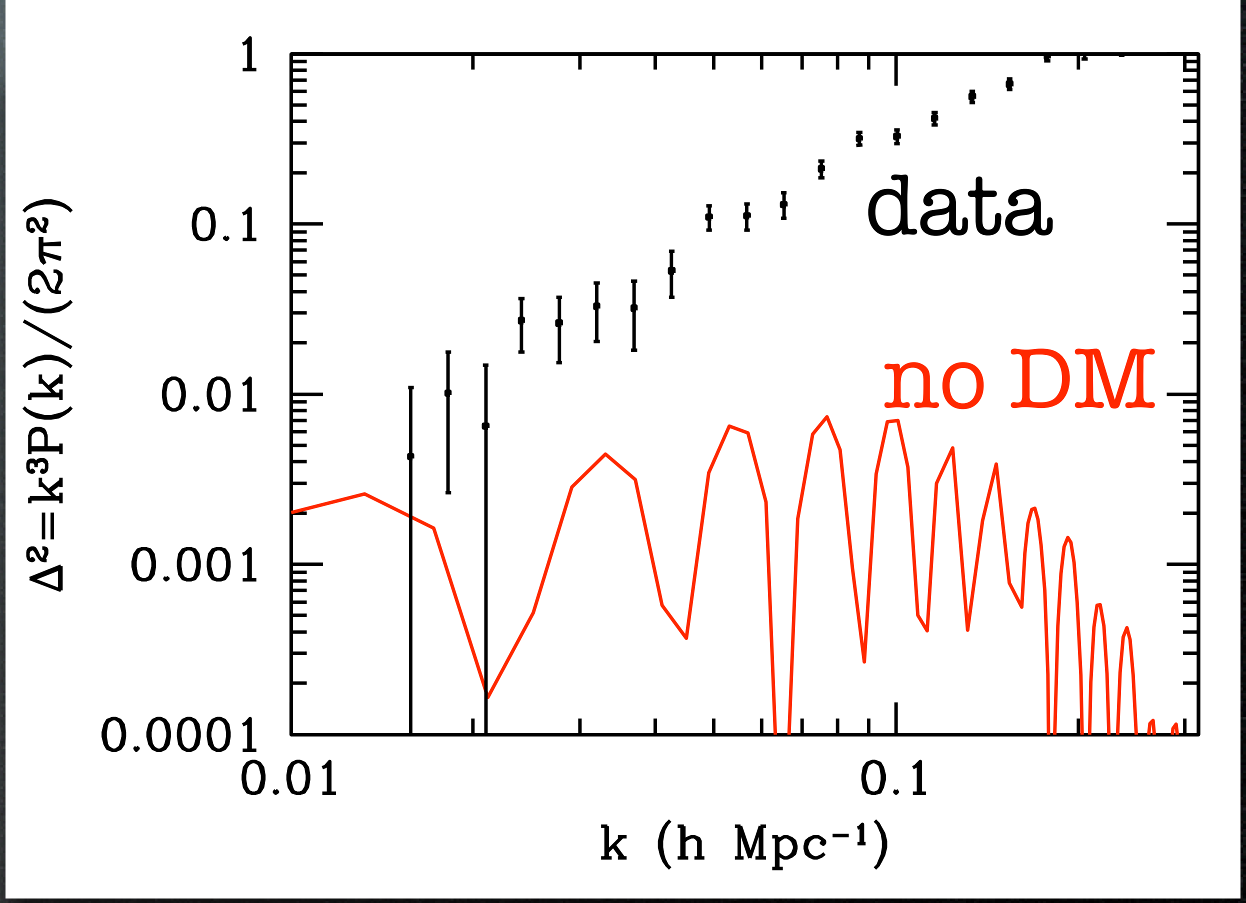
DM is there.

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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Springel, Farrar (2007) astro-ph/0703232

"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]

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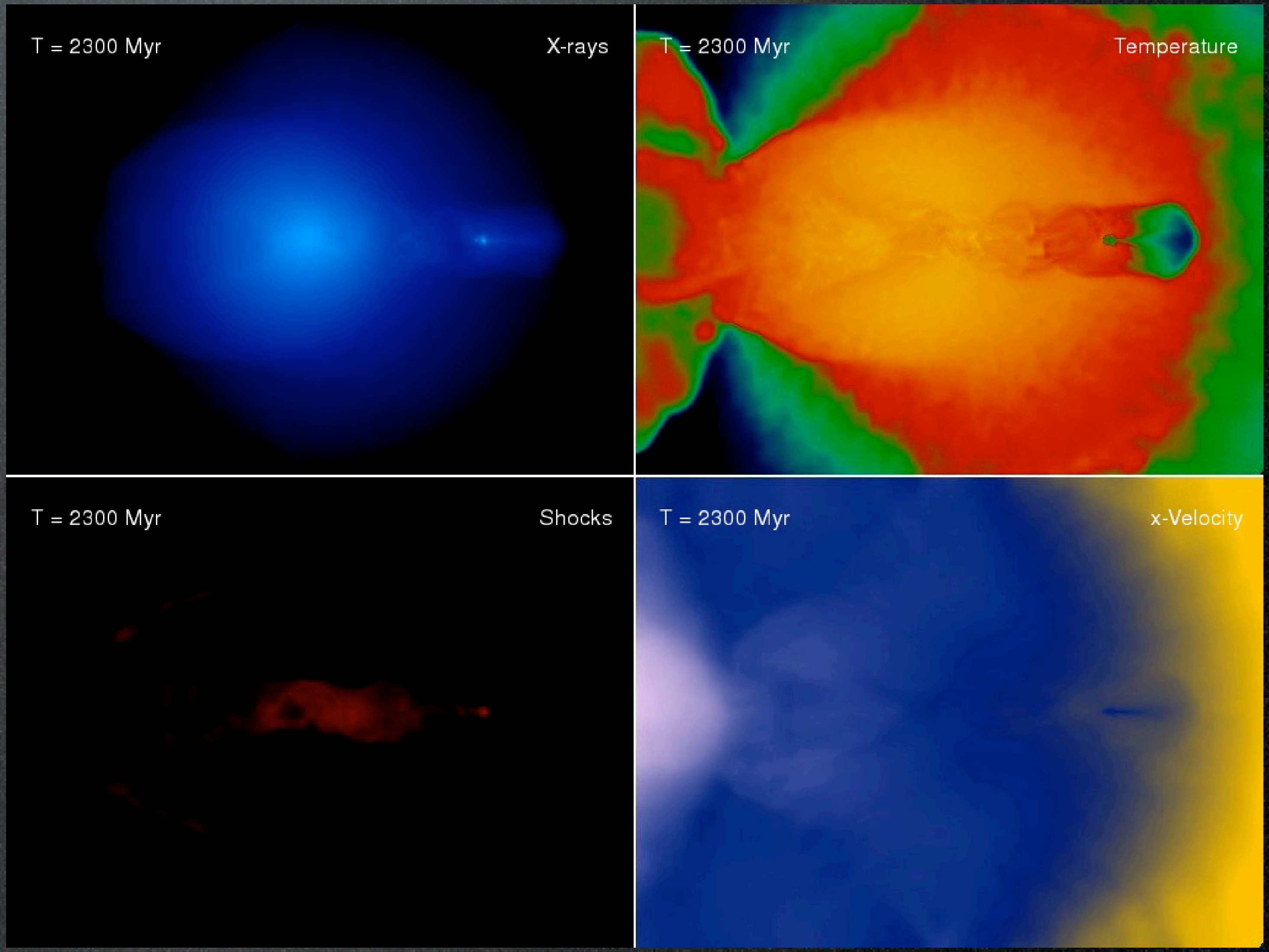


The Max Planck Studios in Hollywood seize the opportunity and make a 2.3-billion-years long blockbuster movie.

[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 $\Delta M_{\text{tree}} = \dfrac{\lambda_H v^2 |\Delta T^3_{\mathcal{X}}|}{4M} = \lambda_H \cdot 7.6\ \text{GeV} \dfrac{\text{TeV}}{M}$ 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

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

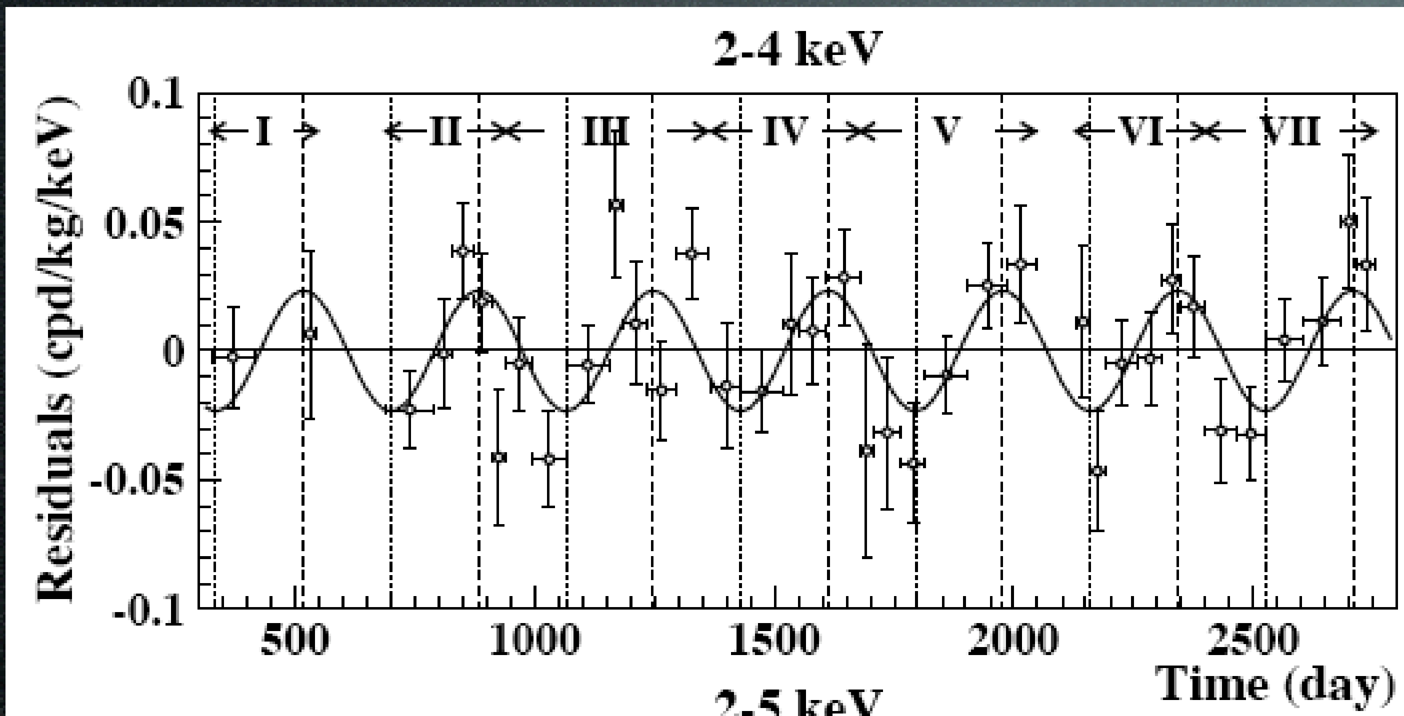
soft SUSYB terms

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

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

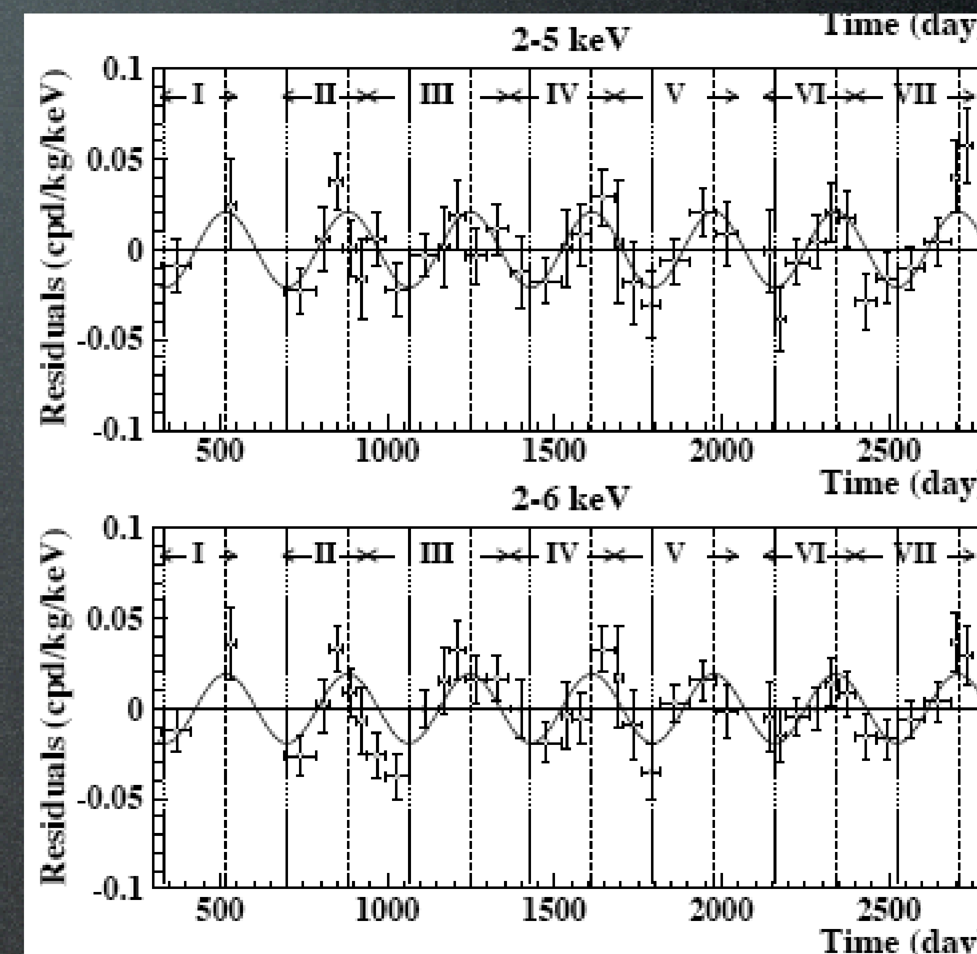
Direct detected *already*?

DAMA annual modulation:

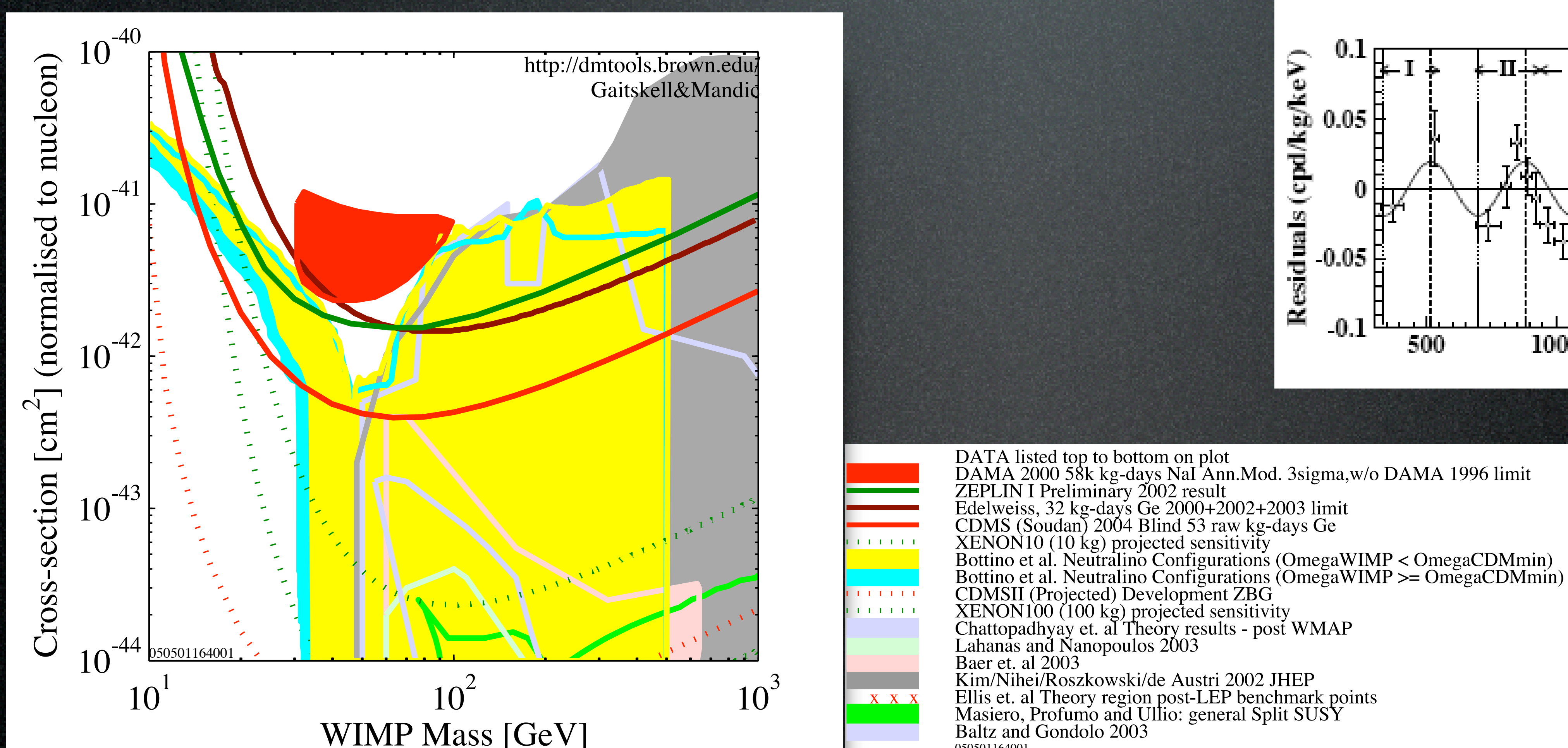


DAMA Coll.

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



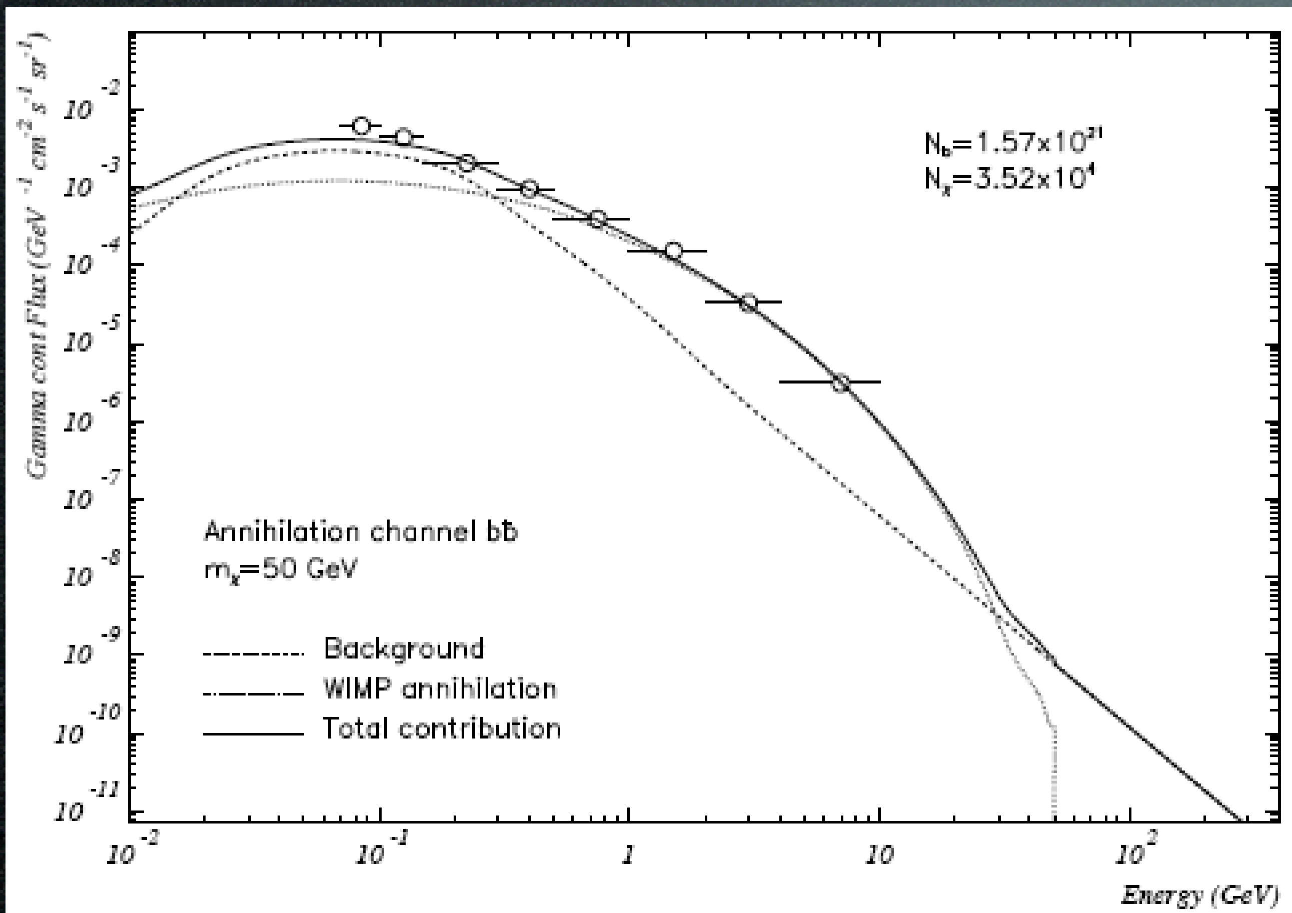
DAMA Coll.



[back to DM detection]

Hints from photons?

EGRET excess

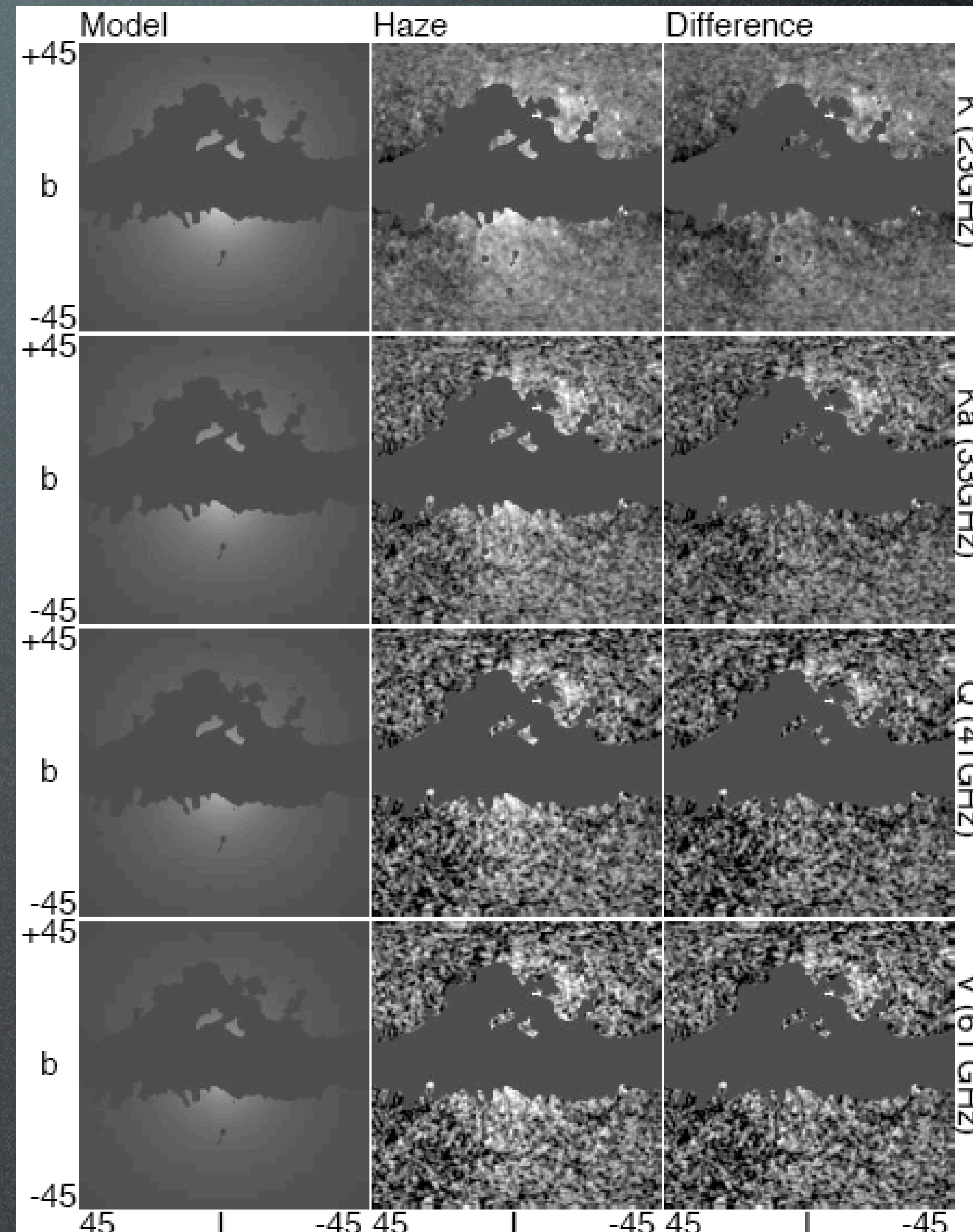


Ullio et al., ApP 21 (2004), astro-ph/0305075

however:
- source not centered
- variability...

+ CANGAROO (2004)
+ HESS (2004)

WMAP "haze"



Finkbeiner, ApJ 614 (2004)

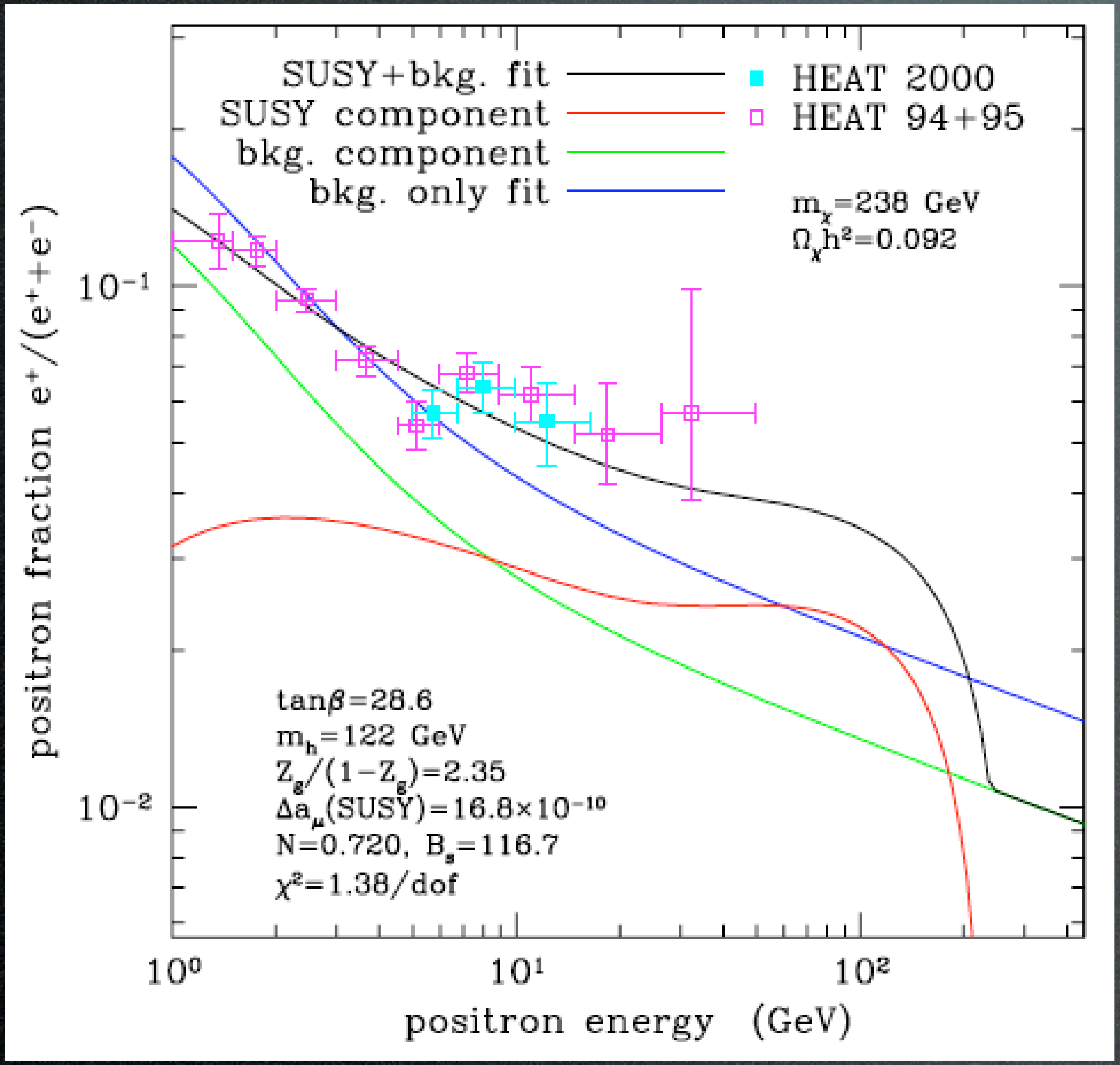
(Synchrotron rad from e^+e^- from DM annihilations)

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)

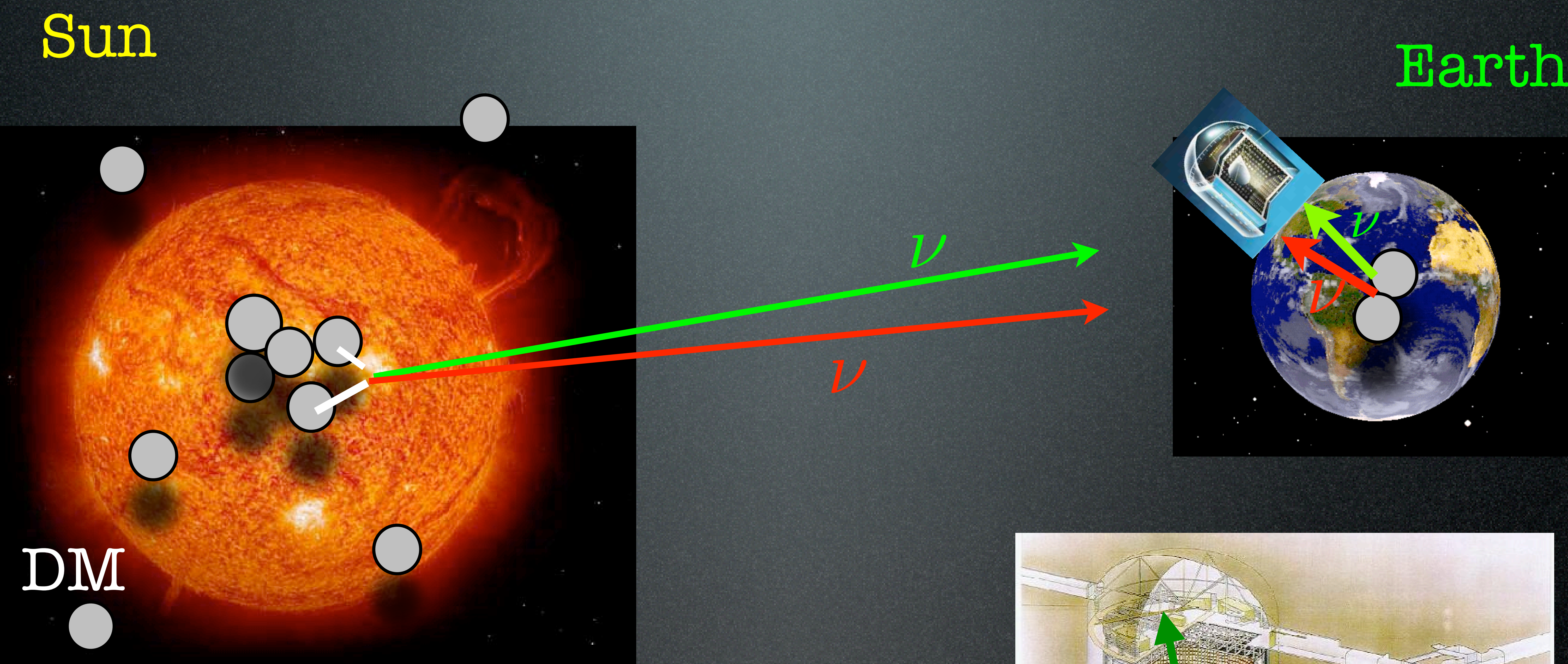


Baltz, Edsjo, Gondolo, Freese PRD65 (2002)

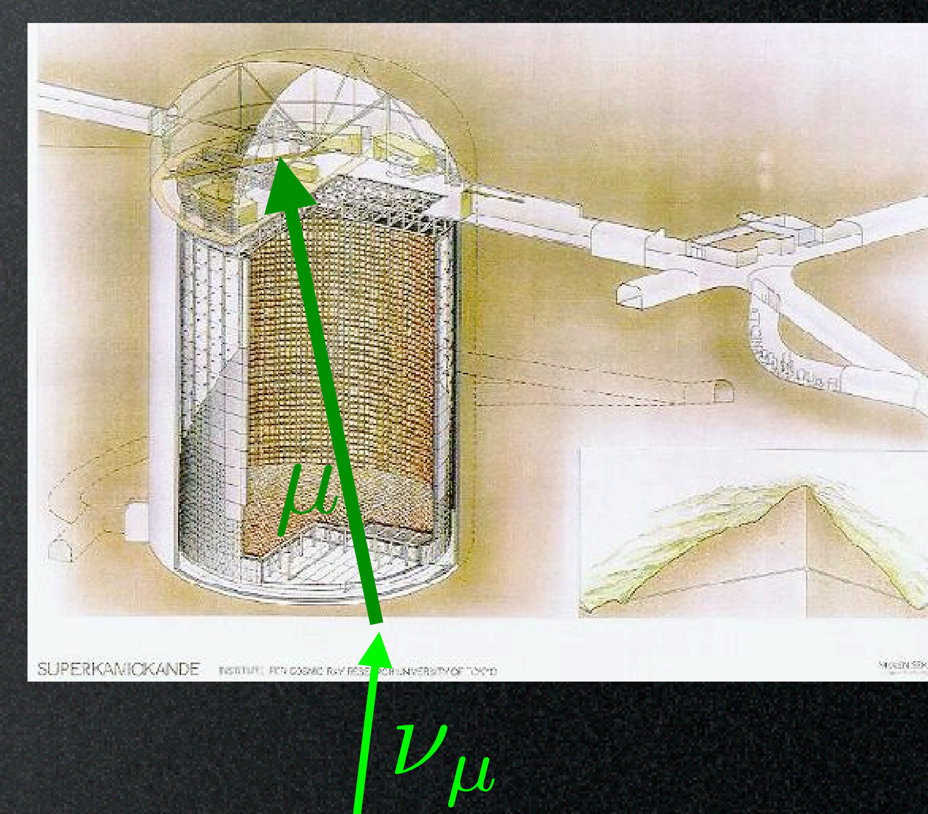
however:
-random trajectories in magnetic field
-flux requires too much DM...

[back to DM detection]

Neutrinos from DM



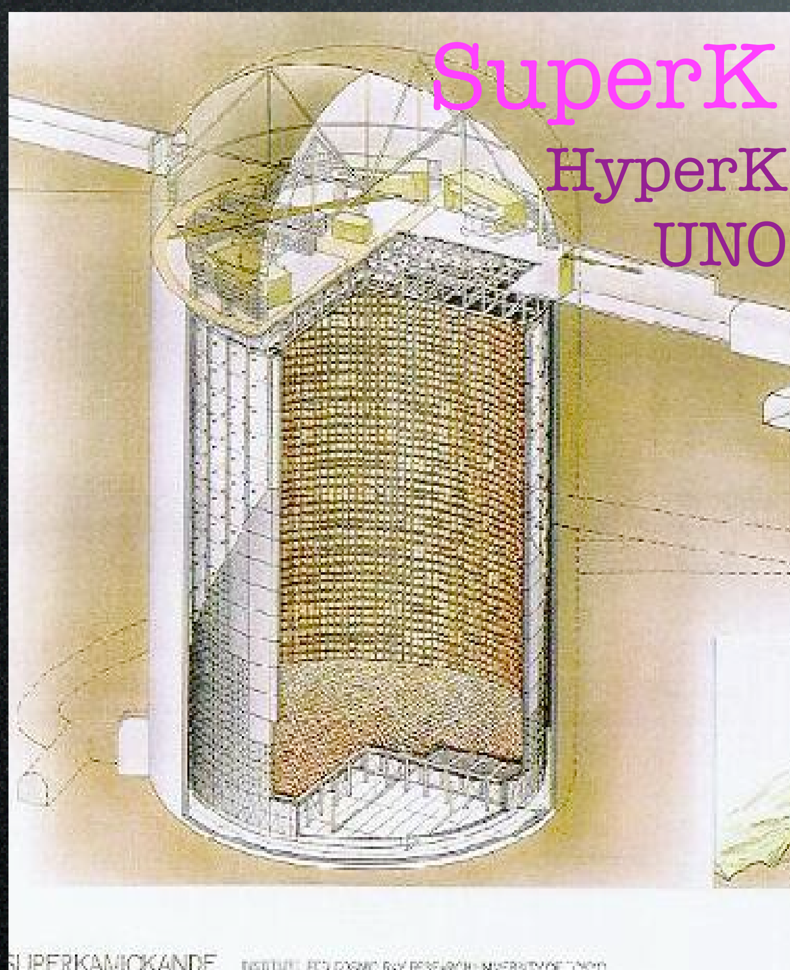
up-going muons:



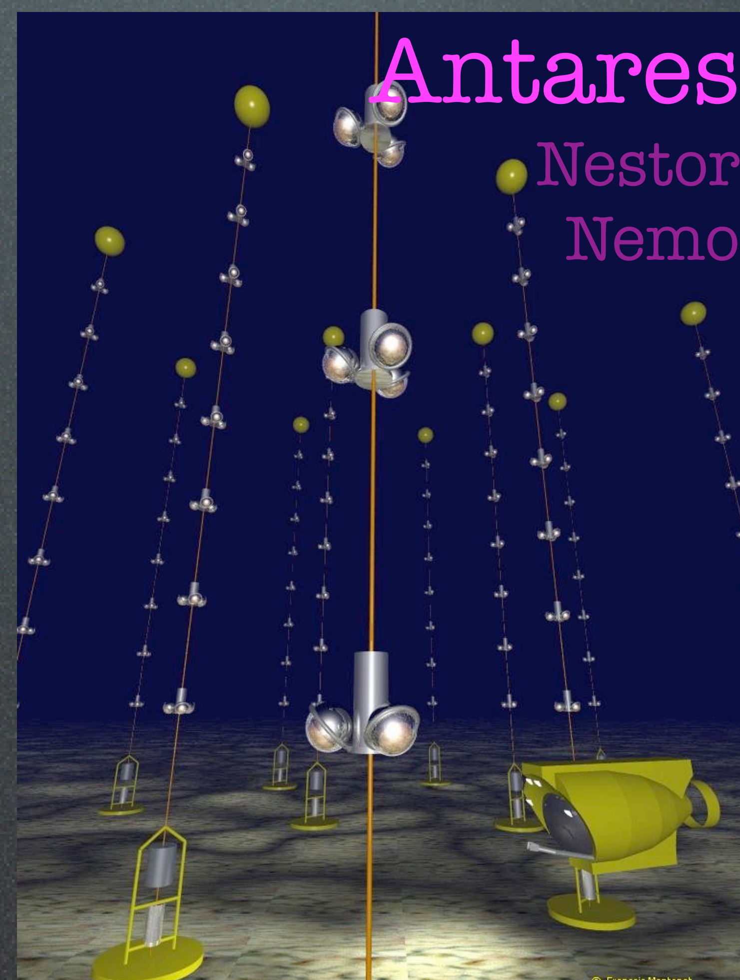
[back to DM detection]

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

Large production for small M.

$2\times$ LHC to produce heavy candidates.

A clean signature:

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

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

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

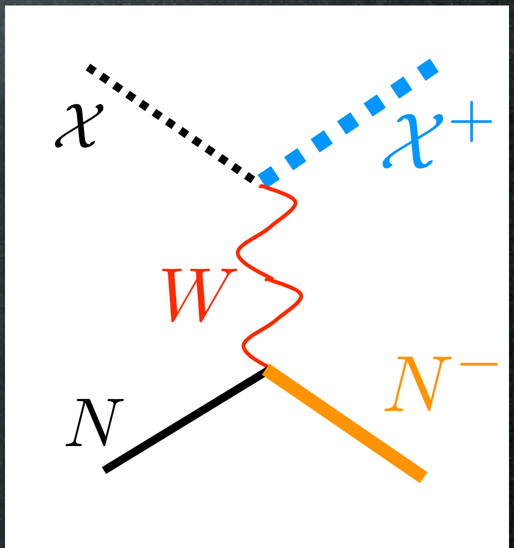
$$\tau \simeq 44\text{cm}/(n^2-1)$$

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]

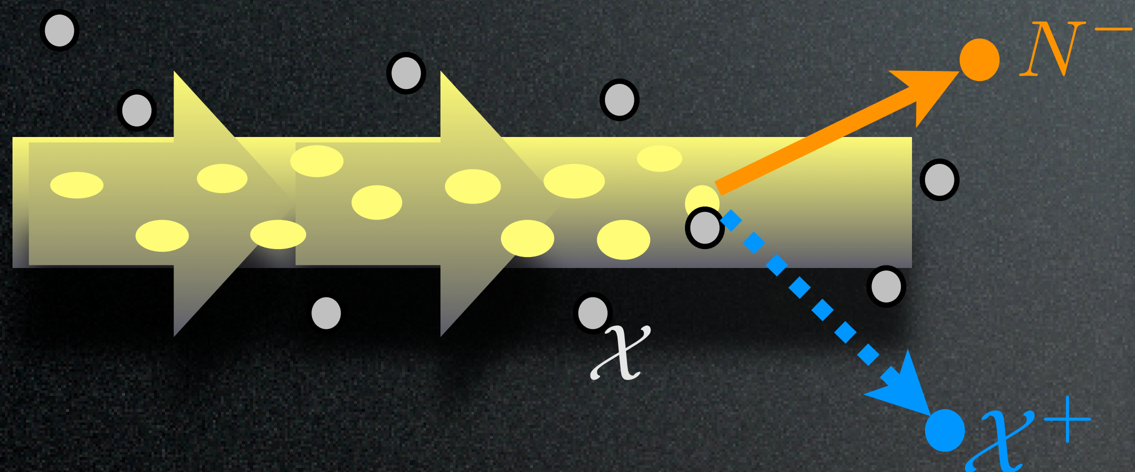
Interlude: the “DMtron”

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]

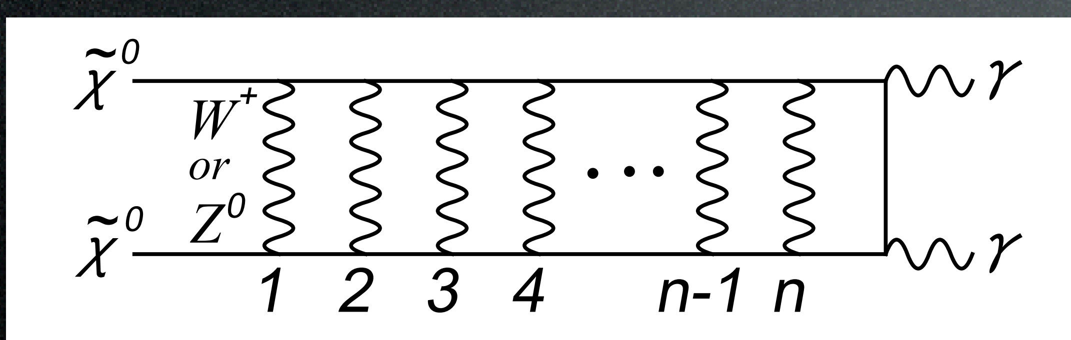
3. Indirect Detection

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

Signal in ν: promising at neutrino telescopes

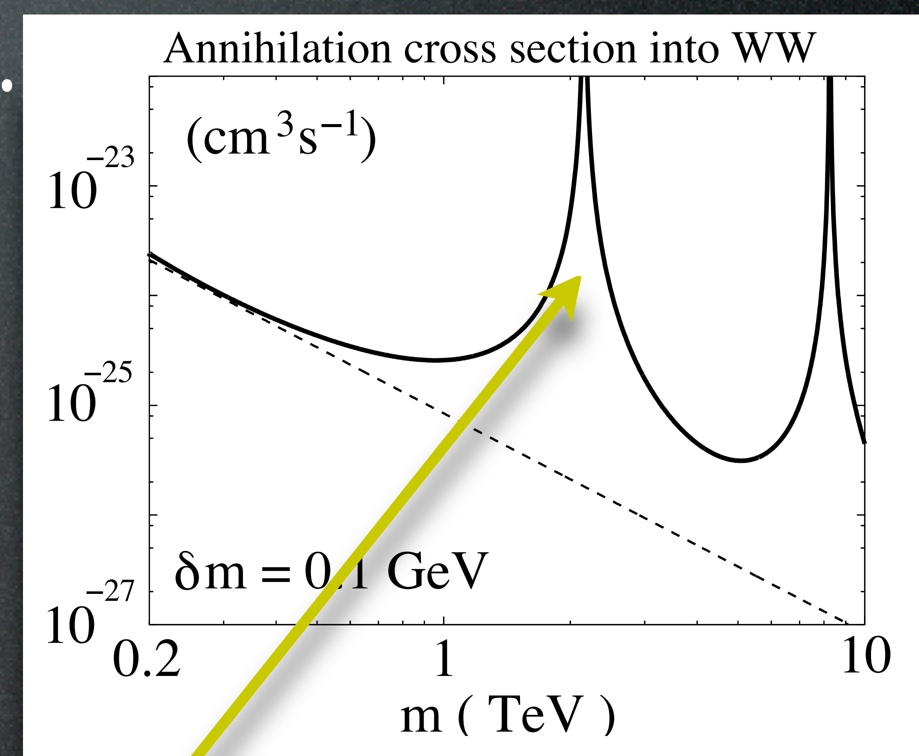
Enhanced cross section in vector bosons due to resummed diagrams when Non-Relativistic $\bar{\mathcal{X}}\mathcal{X}$ are a "bound state":

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



Hisano et al., 2004,
Hisano et al., 2005

e.g.



resonances match M for $n = \underline{3}$

Signal in $\bar{p}, e^+, \gamma$: promising if enhanced

3. Indirect Detection

For instance, predicted signal in γ rays: