

L'ENIGME DE LA MATIÈRE NOIRE

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24 AVRIL 2012

« Never underestimate the joy people
derive from hearing something they
already know »



Enrico Fermi

I. Why Dark Matter ?

II. Which Dark Matter ?

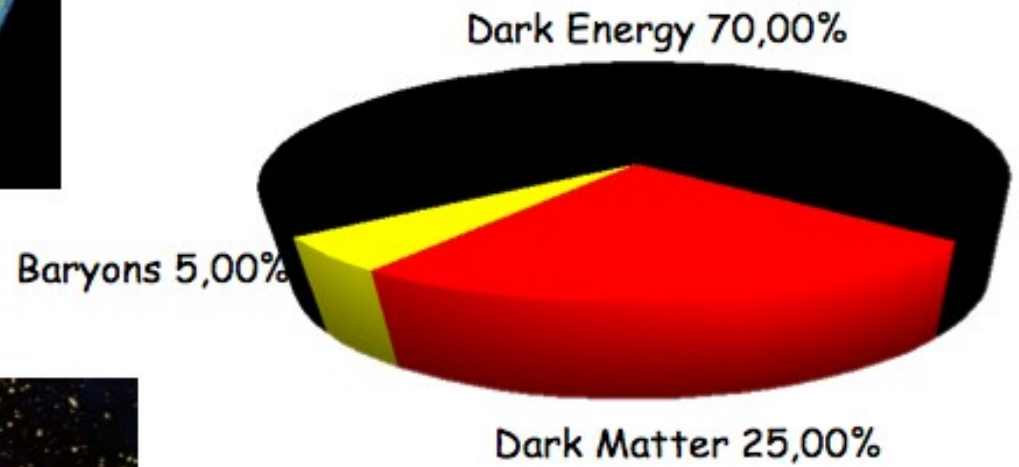
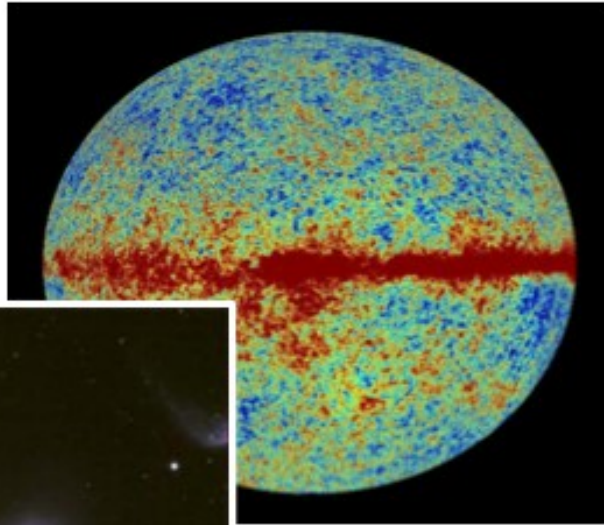
III. Dark Matter on Earth & in the Sky

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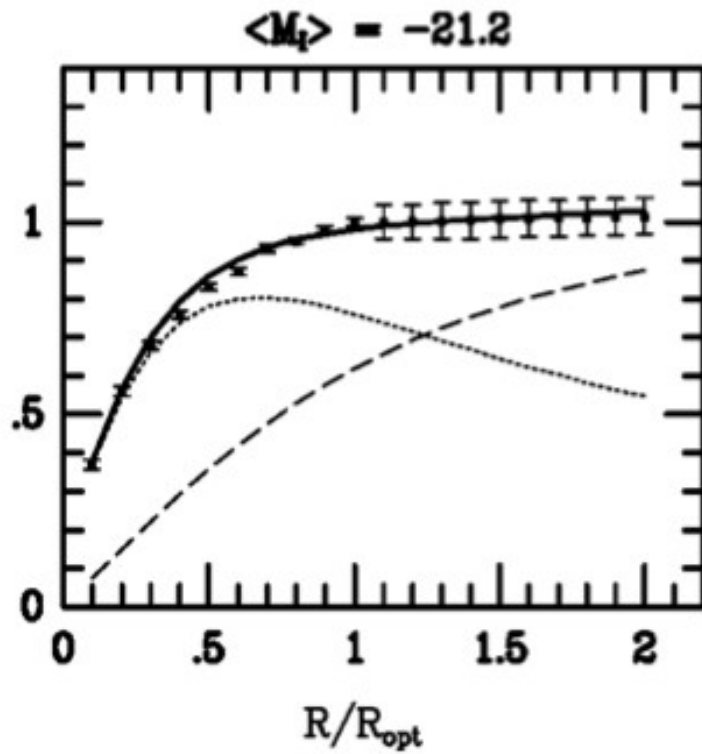
III. Dark Matter on Earth & in the Sky

The Concordance Model





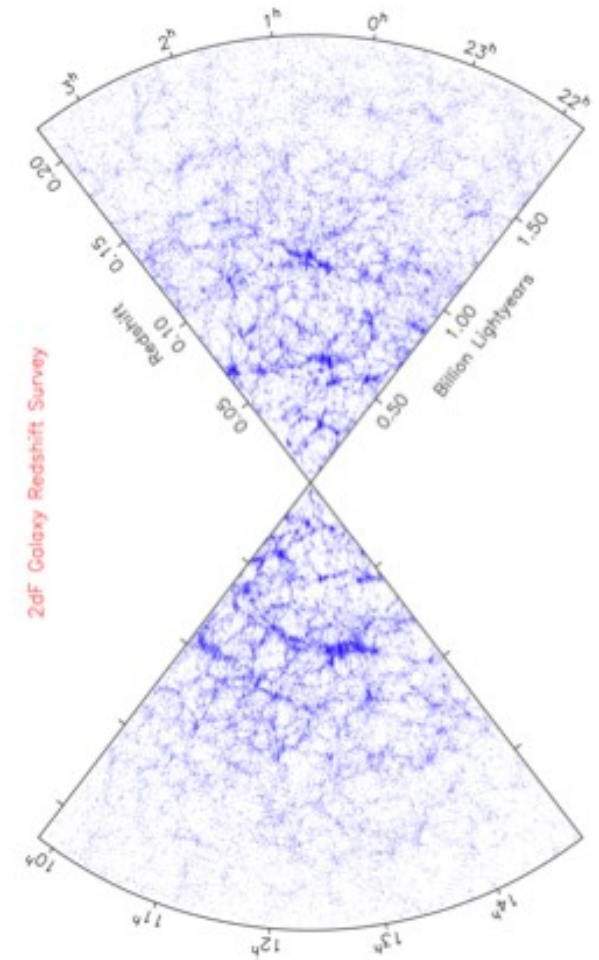
Gravitational evidences for Dark Matter



Galaxy rotation

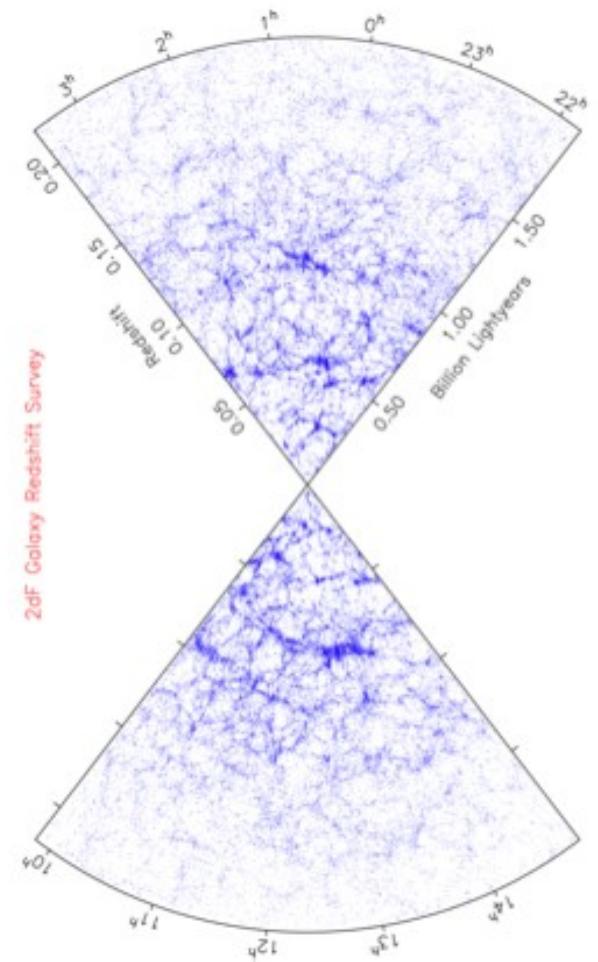
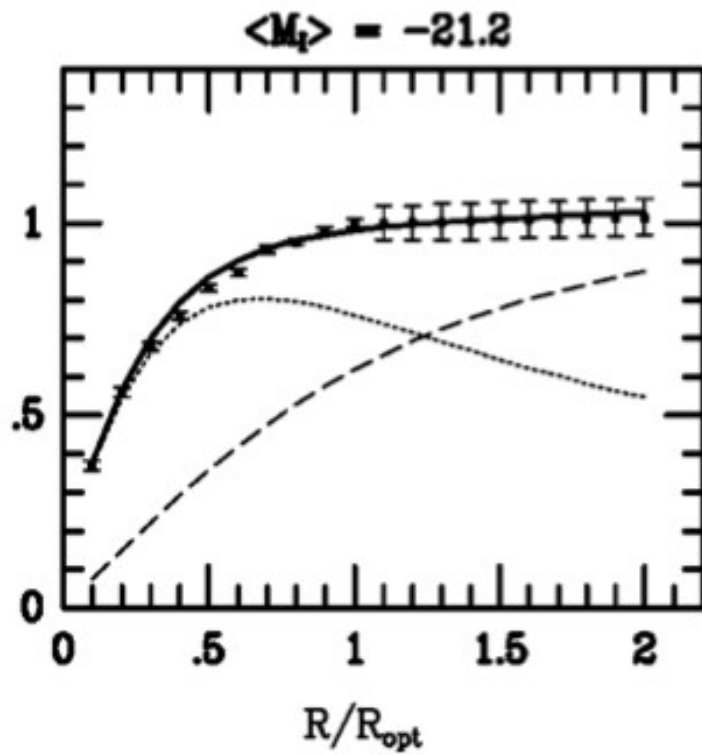


Galaxy clusters



Structures formation

Confidence

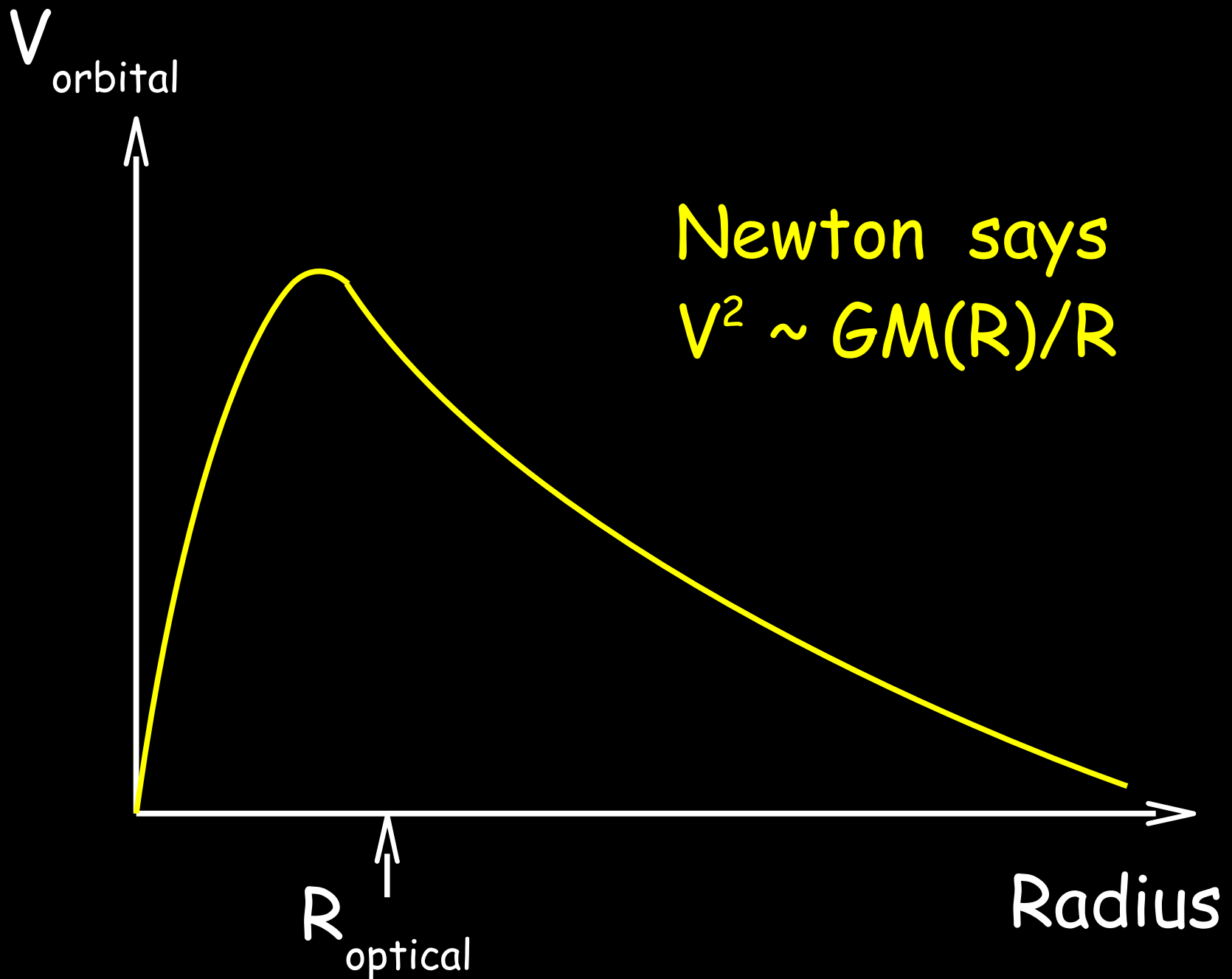


Complexity

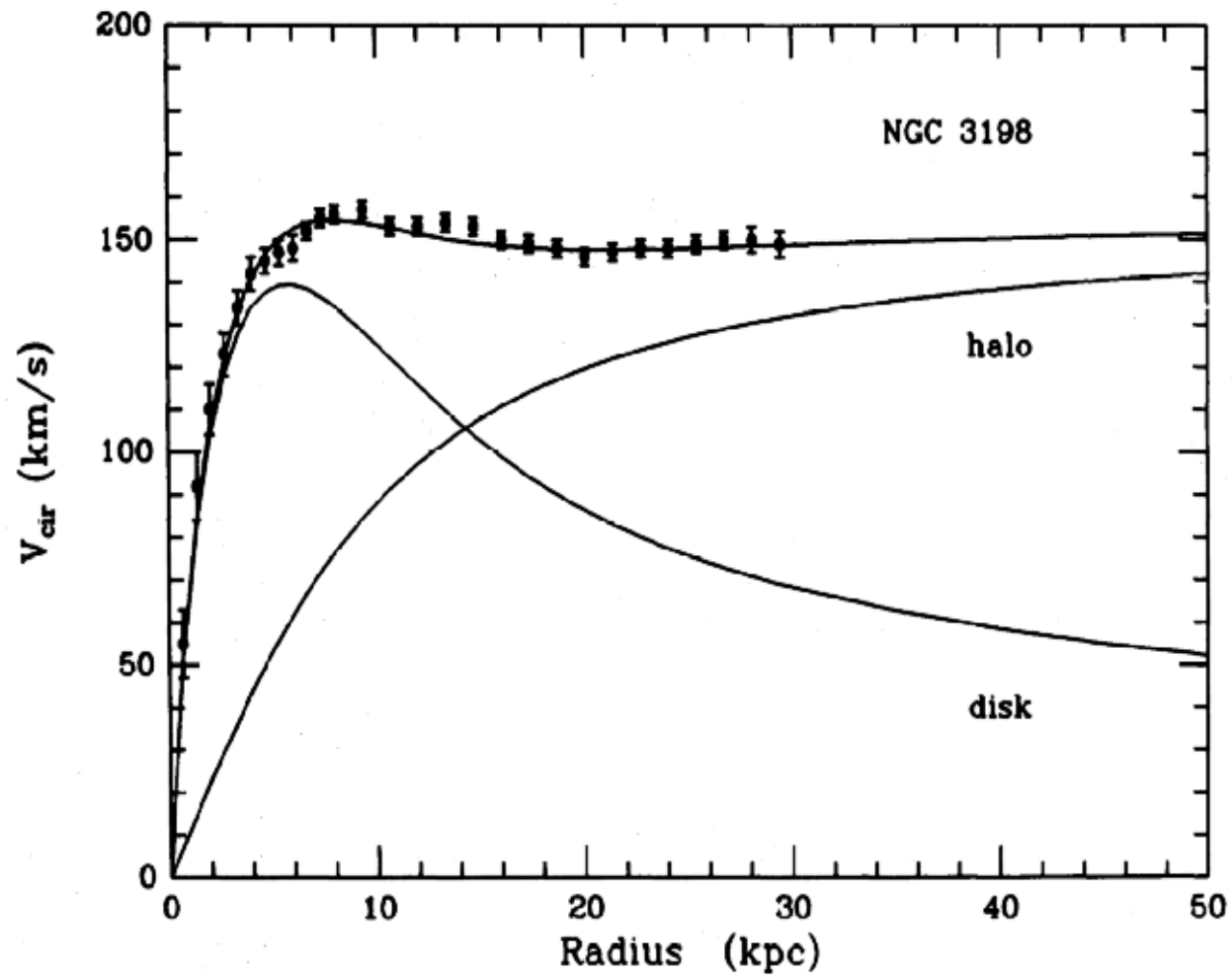
1. Rotation Curve of Spiral Galaxies

A photograph of a spiral galaxy, likely M33 (the Triangulum Galaxy), showing its central bulge and spiral arms. A yellow arrow originates from the center of the galaxy and points towards the right edge of the visible disk, indicating the optical radius.

$R_{\text{optical}} \sim 20 \text{ kpc}$



DISTRIBUTION OF DARK MATTER IN NGC 3198

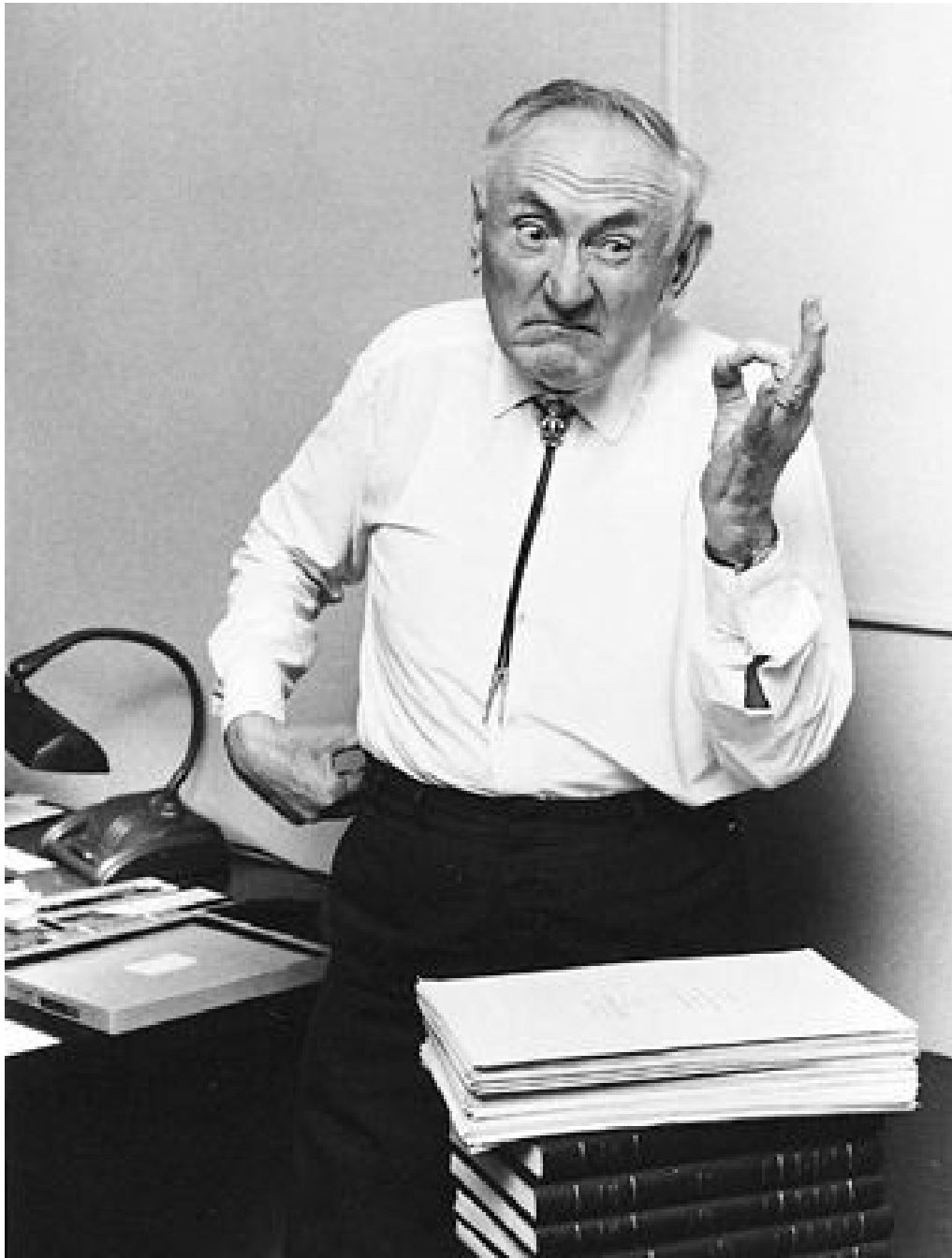


$$V \sim \text{const} \longrightarrow M(R) \sim R$$

Invisible
(Dark) Halo

2. Clusters of galaxies





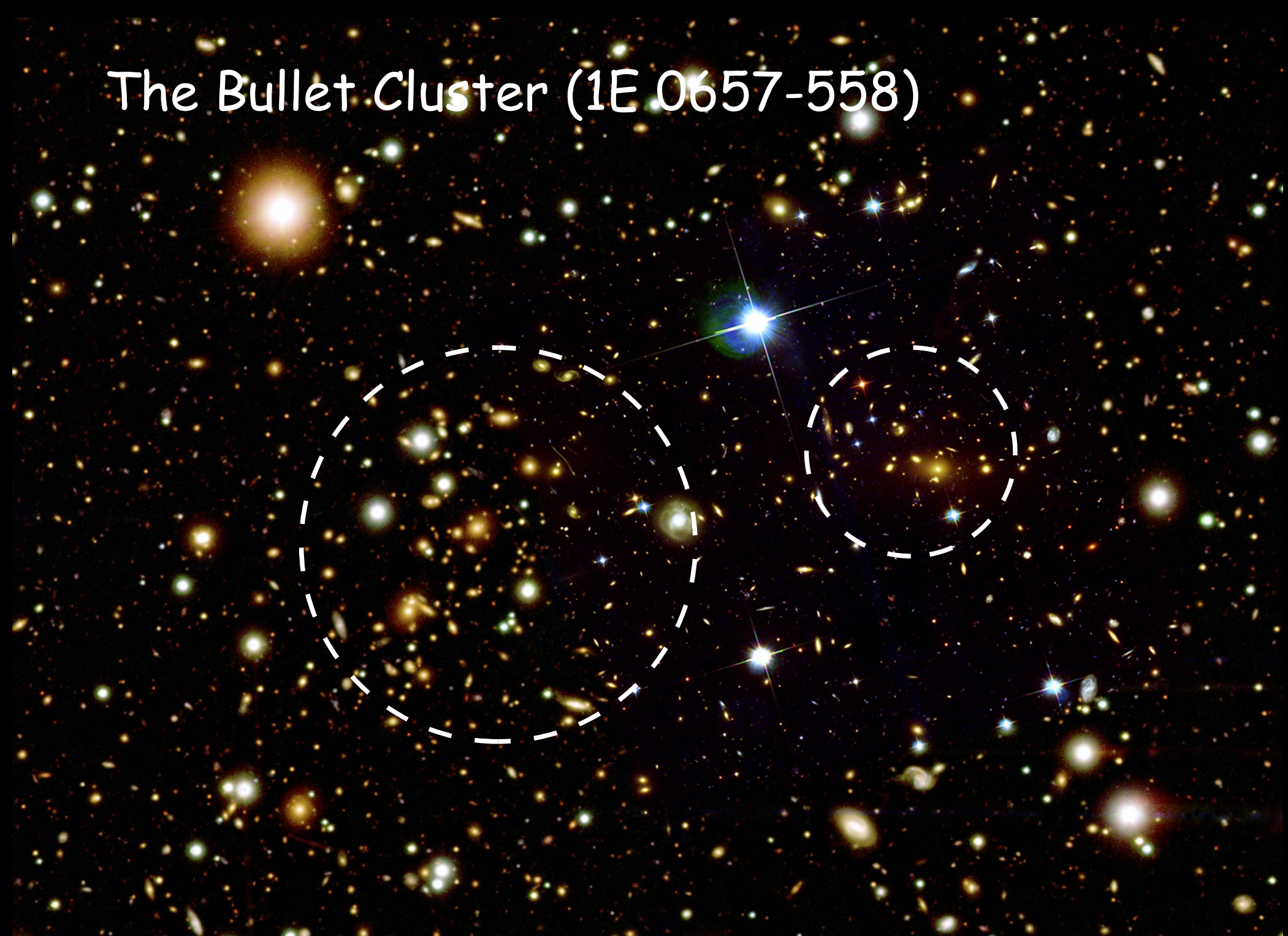
Fritz Zwicky

Invisible Matter
in Coma Cluster
(1933)

$$M/L \sim 100 M_{\odot}/L_{\odot}$$

(mass-to-light ratio)

The Bullet Cluster (1E 0657-558)

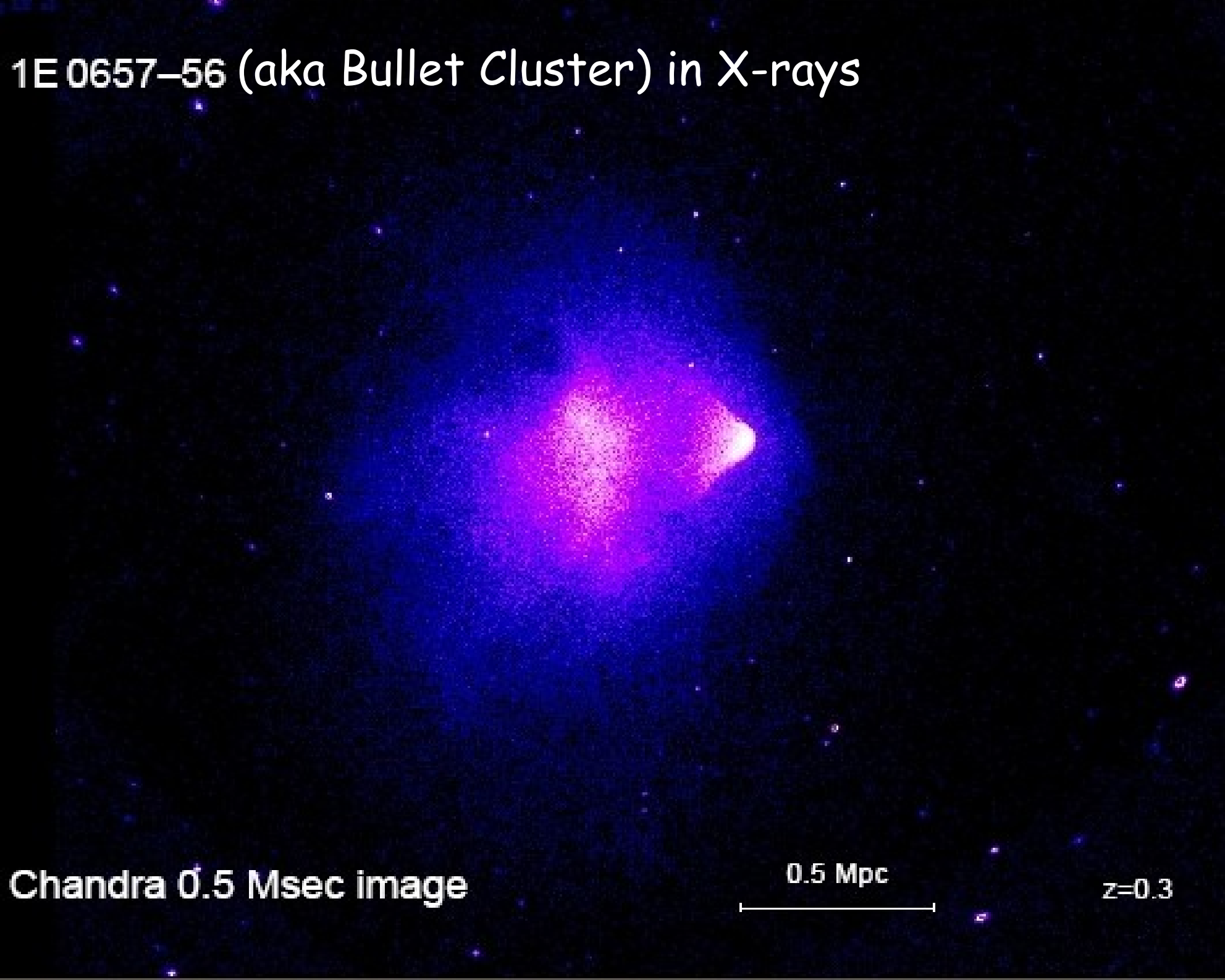


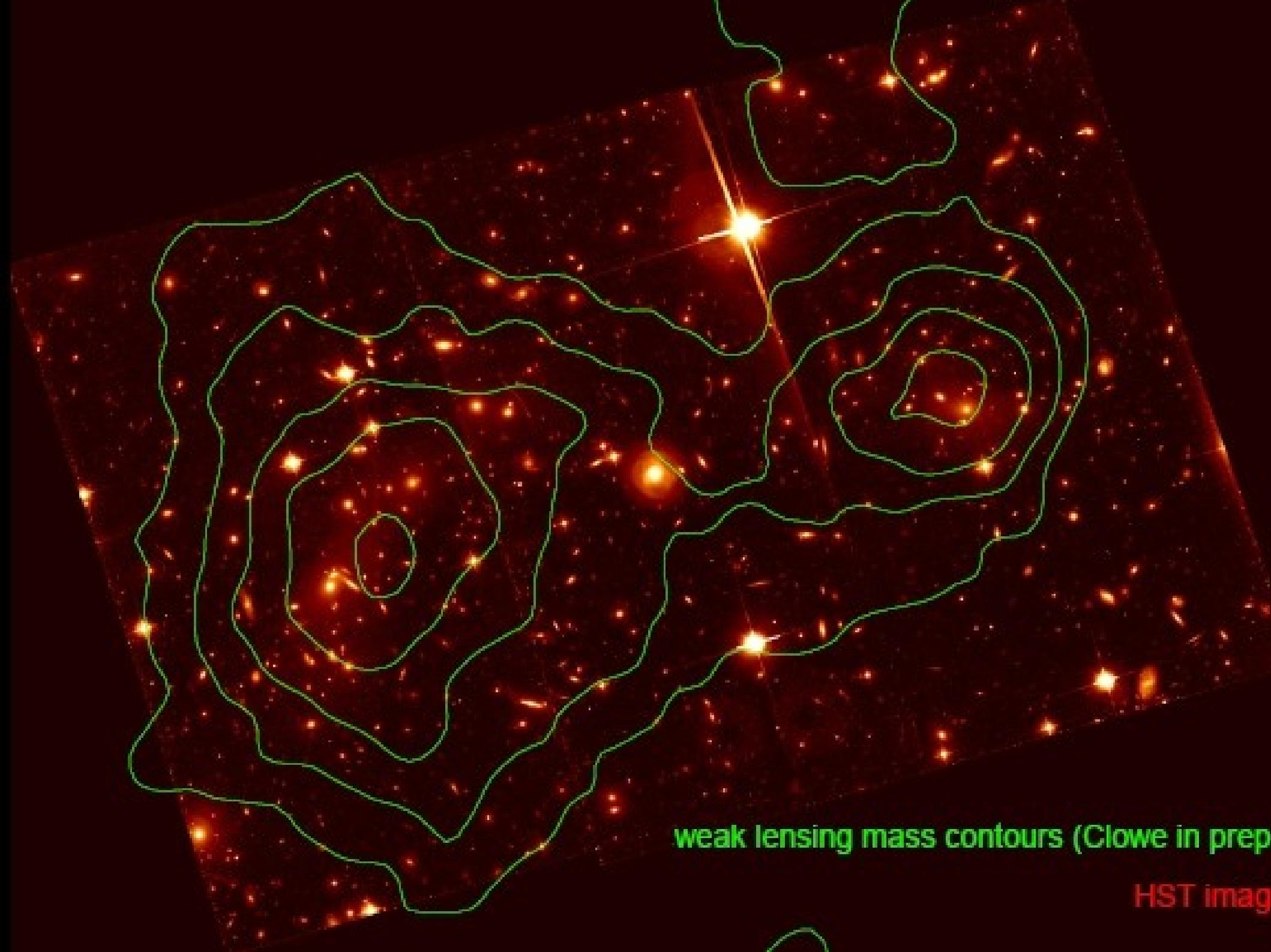
1E 0657-56 (aka Bullet Cluster) in X-rays

Chandra 0.5 Msec image

0.5 Mpc

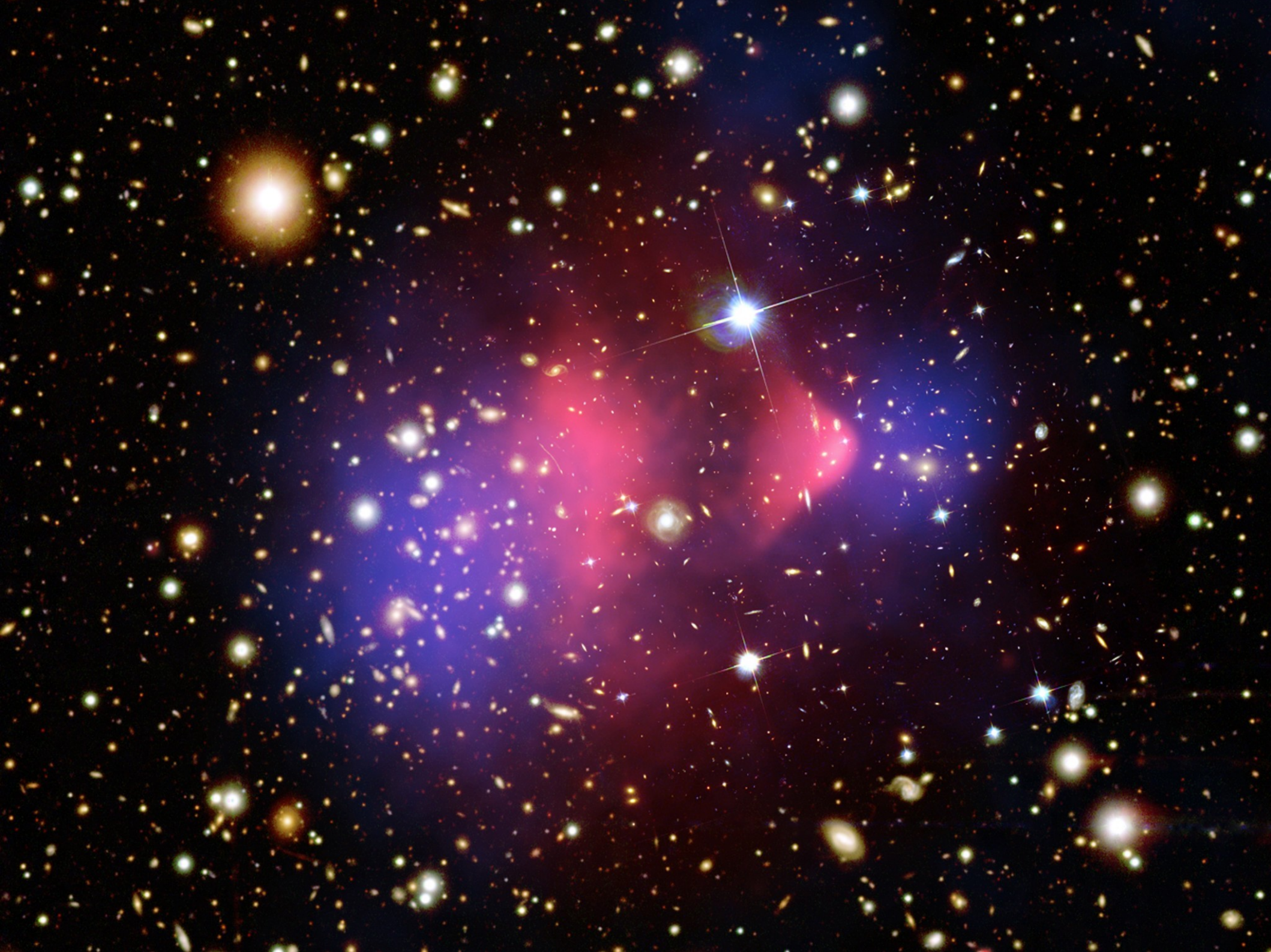
$z=0.3$



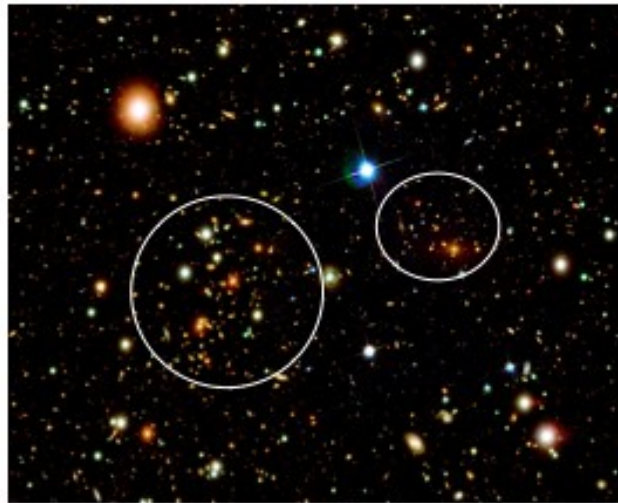


weak lensing mass contours (Clowe in prep)

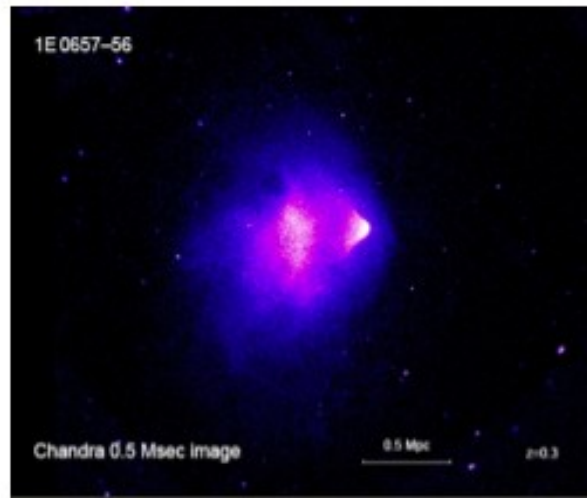
HST image



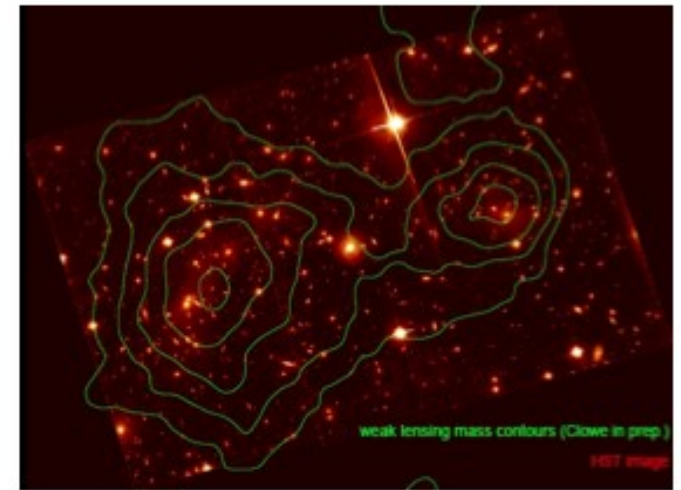
Visible



X-ray



Gravitational lensing



Galaxies

Intergalactic Hot Gas

Total Mass

$$M_{\text{visible}} \sim 10^{14} M_{\odot}$$

$$M_{\text{hot gas}} \sim 10^{15} M_{\odot}$$

$$M_{\text{tot}} \sim 10^{16} M_{\odot}$$

Visible Baryons

Missing Baryons

All Baryons *

Baryons

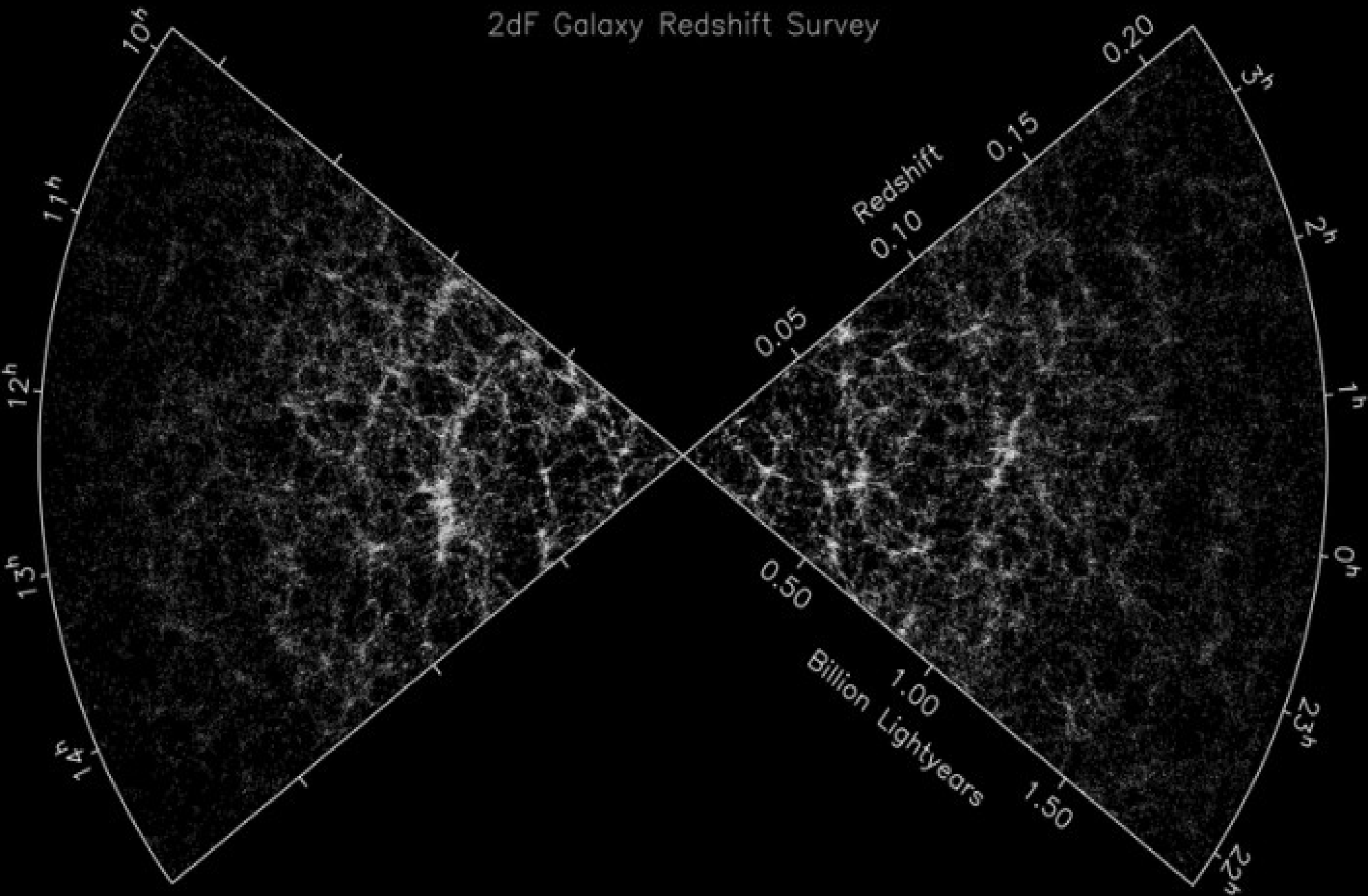
+

Dark Matter

* consistent with primordial nucleosynthesis

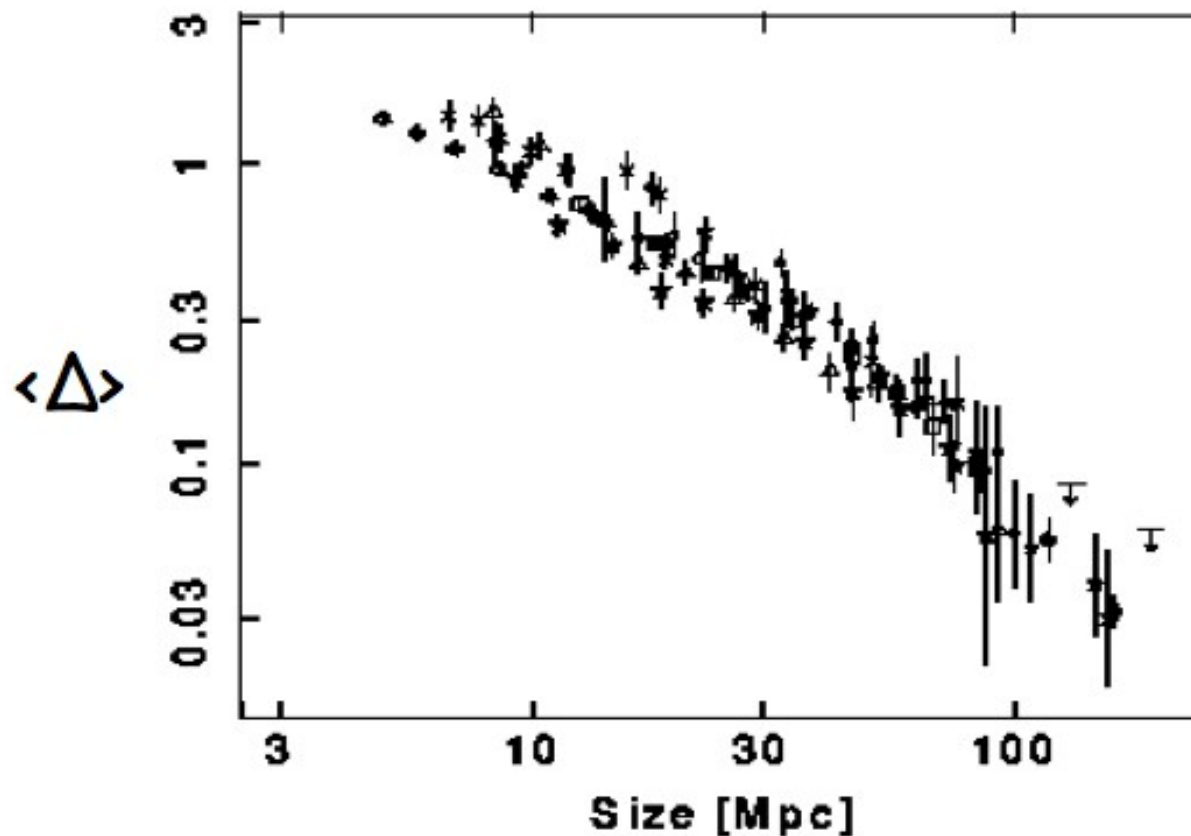


3. Large scale structure



Matter inhomogeneities are small on large scales

$$\Delta = |\delta\rho/\rho| \ll 1$$

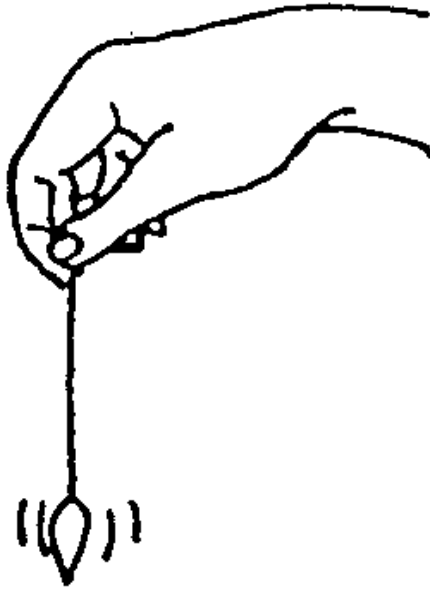


Evolution of inhomogeneities

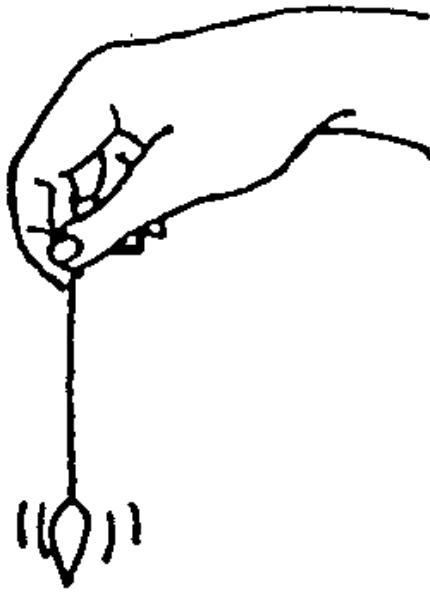
$$\ddot{\Delta} + (v_s^2 k^2 - 4\pi G \rho) \Delta = 0$$



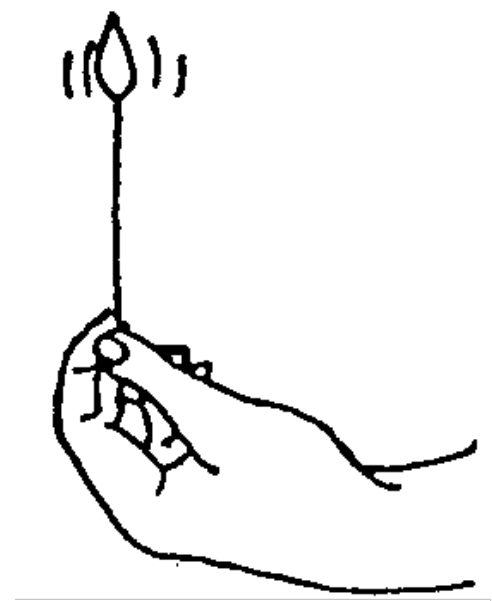
pressure vs gravity



PRESSURE > GRAVITY



PRESSURE > GRAVITY



GRAVITY > PRESSURE

$$\Delta \sim e^{\pm \omega t}$$

Jeans Instability

Evolution of inhomogeneities

$$\ddot{\Delta} + 2\frac{\dot{a}}{a}\dot{\Delta} + (v_s^2 k^2 - 4\pi G\rho)\Delta = 0$$

EXPANSION



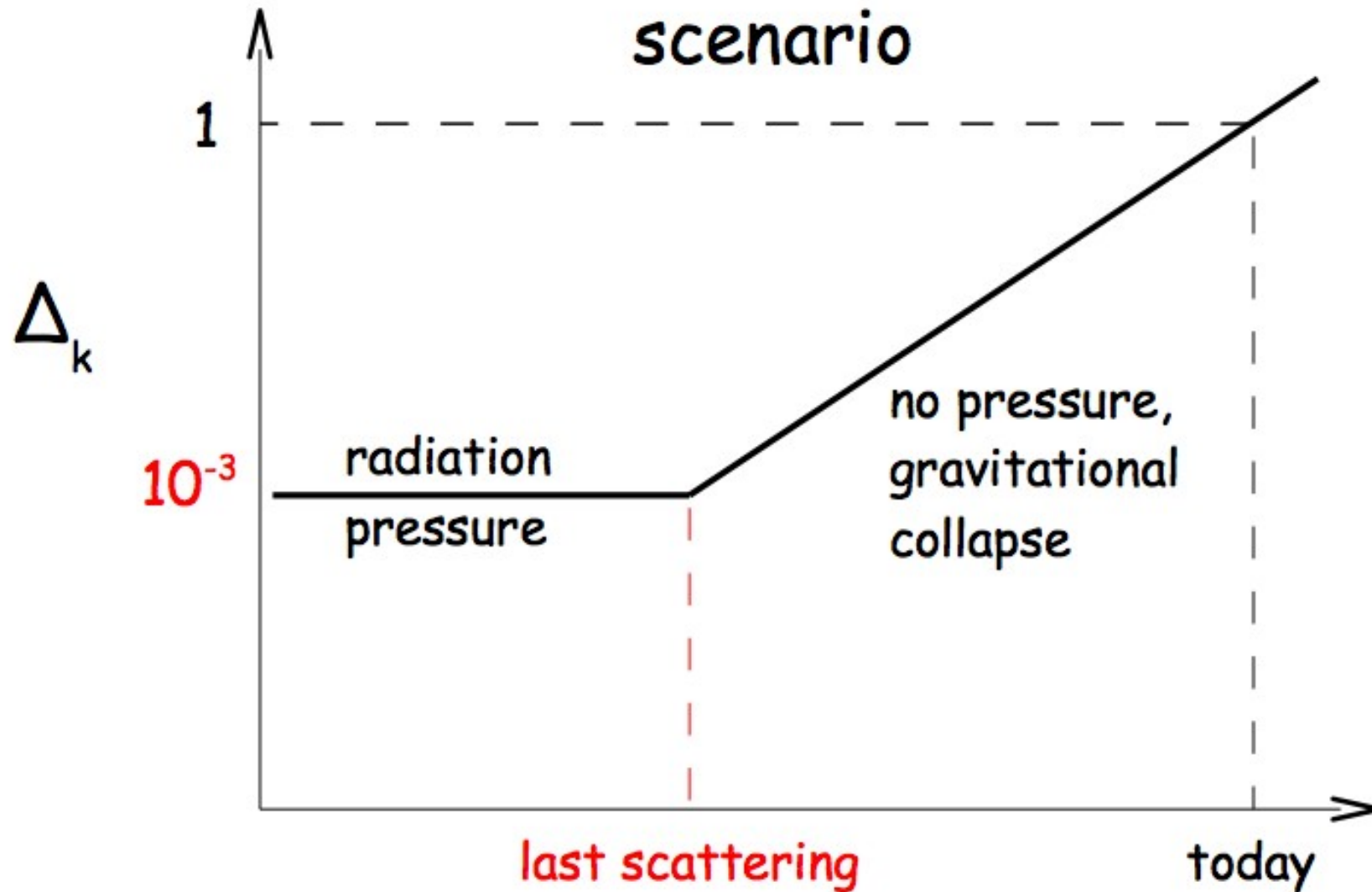
EXPANSION



$$\Delta \sim t^{2/3} \sim a(t)$$

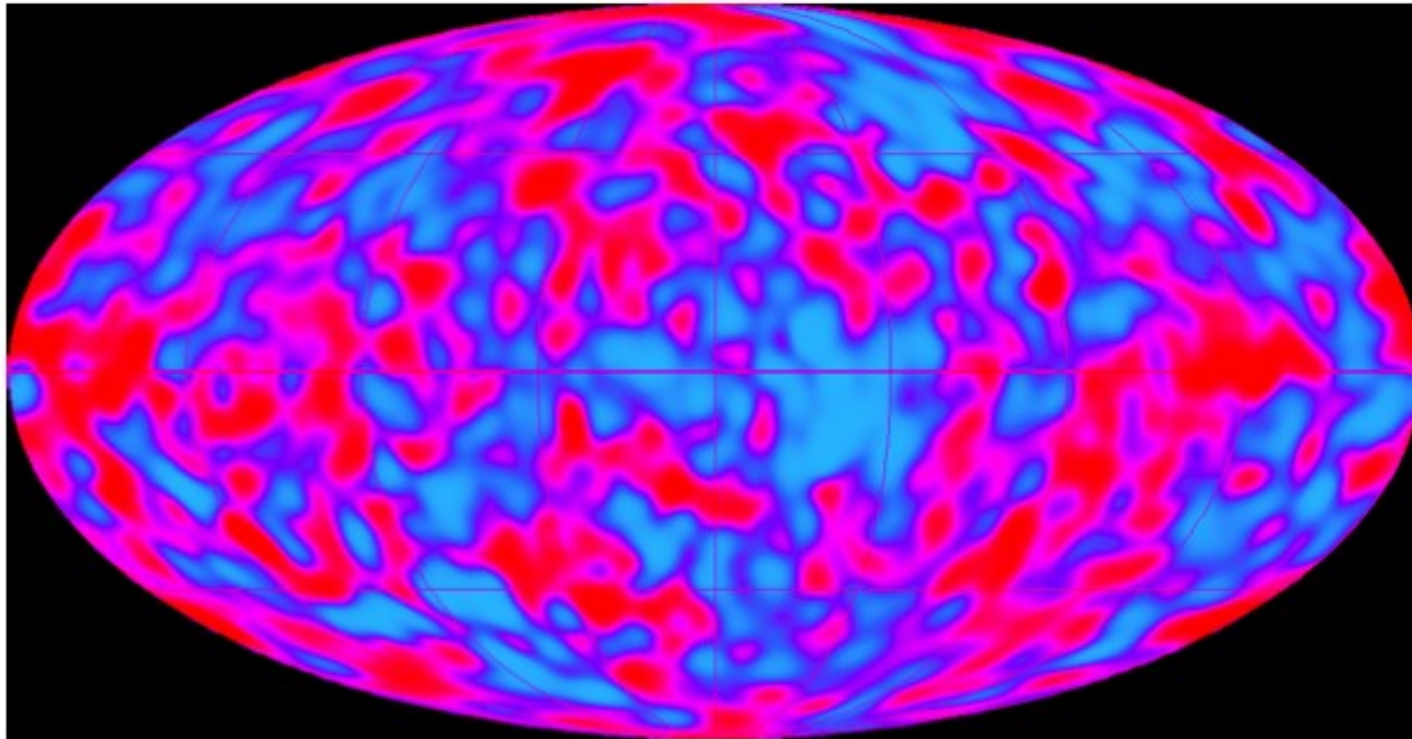
Jeans Instability
(matter dominated universe)

Only baryonic matter scenario



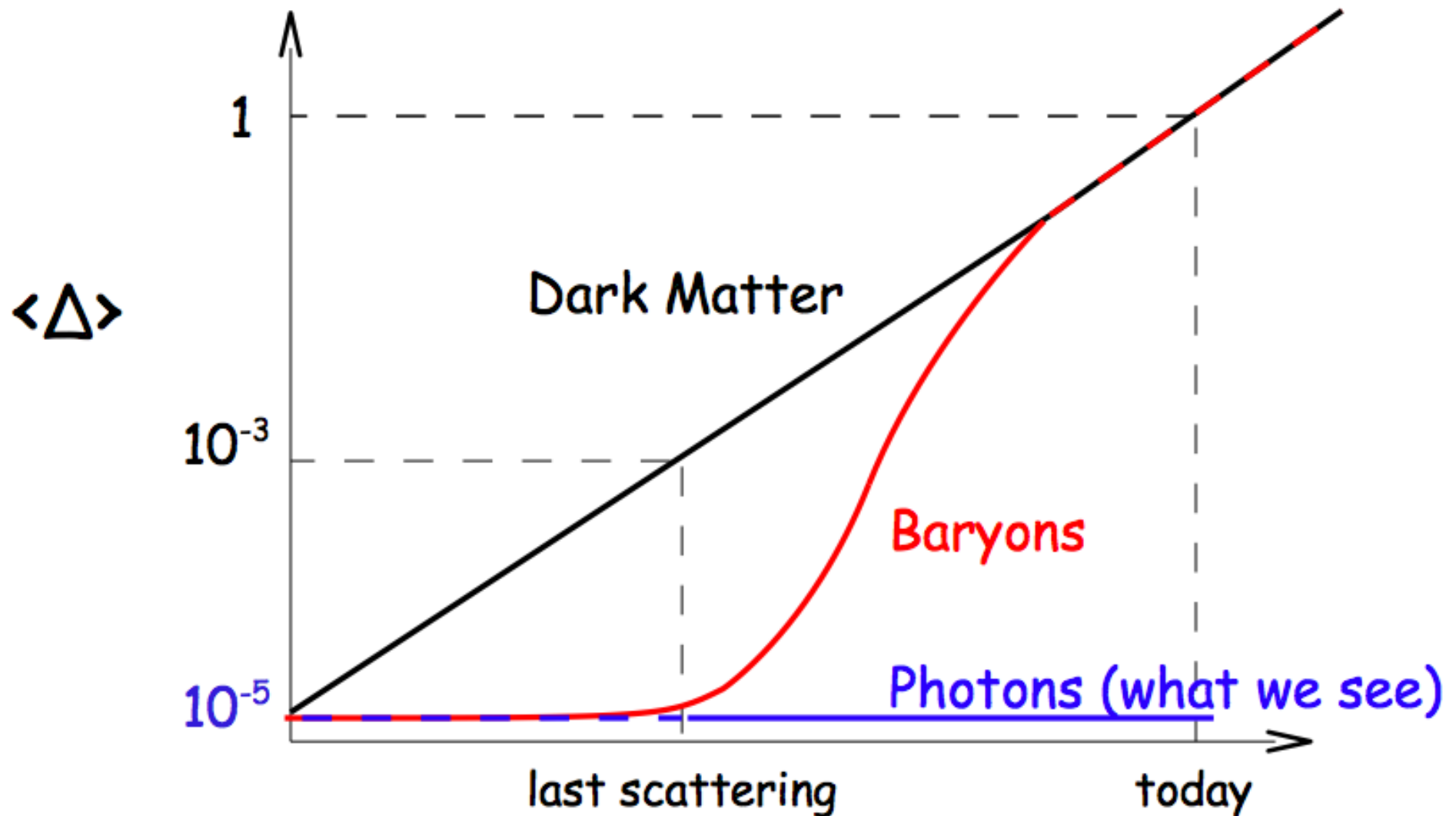
Scale factor $a(t)$

CMBR temperature anisotropies



$$\Delta \approx \delta T/T = O(10^{-5})$$

The (cold) dark matter scenario



Scale factor

Peebles, 1982

In Summary, good **gravitational** evidences for the existence of Dark Matter in the Universe

This Dark Matter **cannot be made of baryons** (ie protons)

Alternative scenarios (like a modification of the laws of gravity) seem to be contrived

I. Why Dark Matter ?

II. Which Dark Matter ?

III. Dark Matter on Earth & in the Sky

1. Cosmic neutrinos, a missed opportunity?

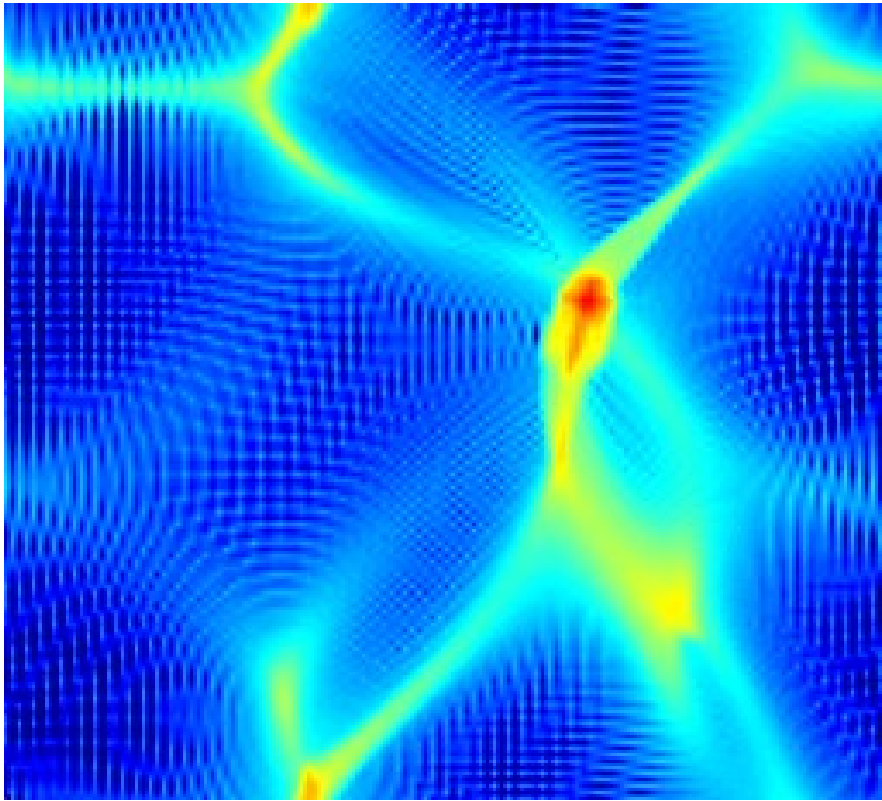
There are about **300 Neutrinos/cm³** in our Universe and neutrinos are **Massive**

Neutrino oscillations $\Delta m_{23}^2 \sim 10^{-3} \text{ eV}^2$

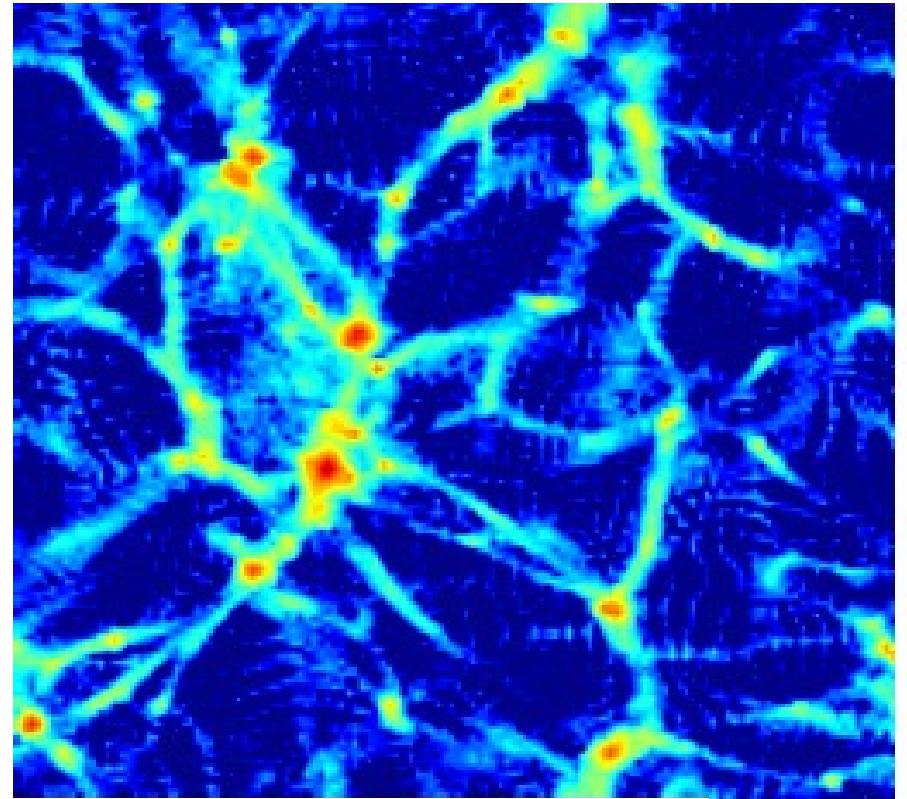
Tritium β -decay $m_\nu < 2 \text{ eV}$

→ $0.1 \% < \Omega_\nu < 12 \% \quad (\ll 25\%)$

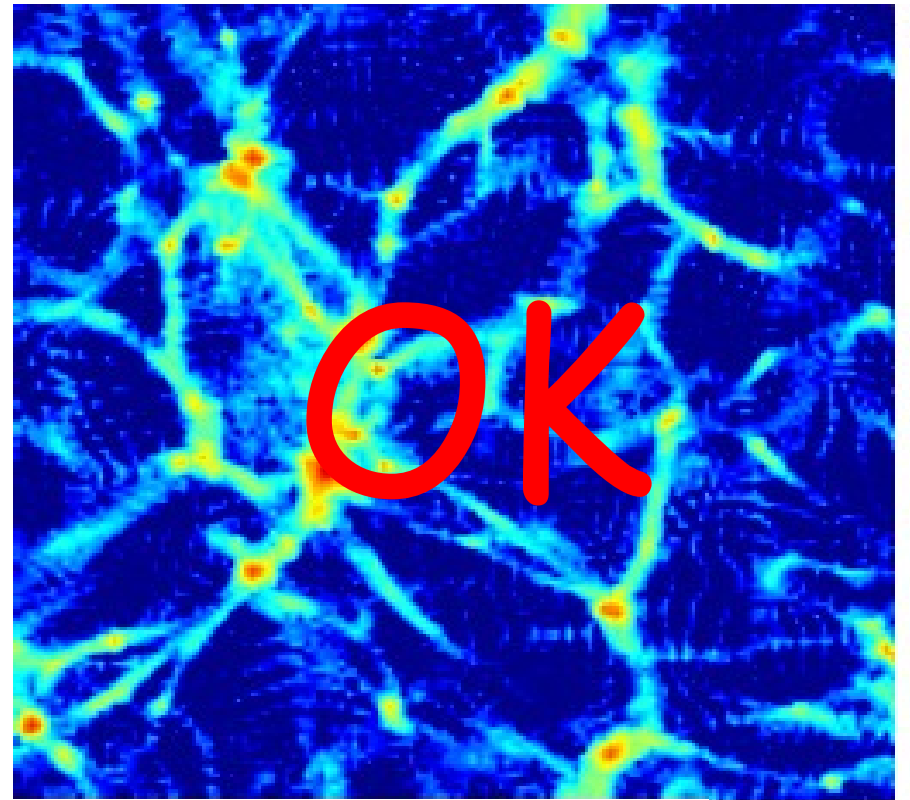
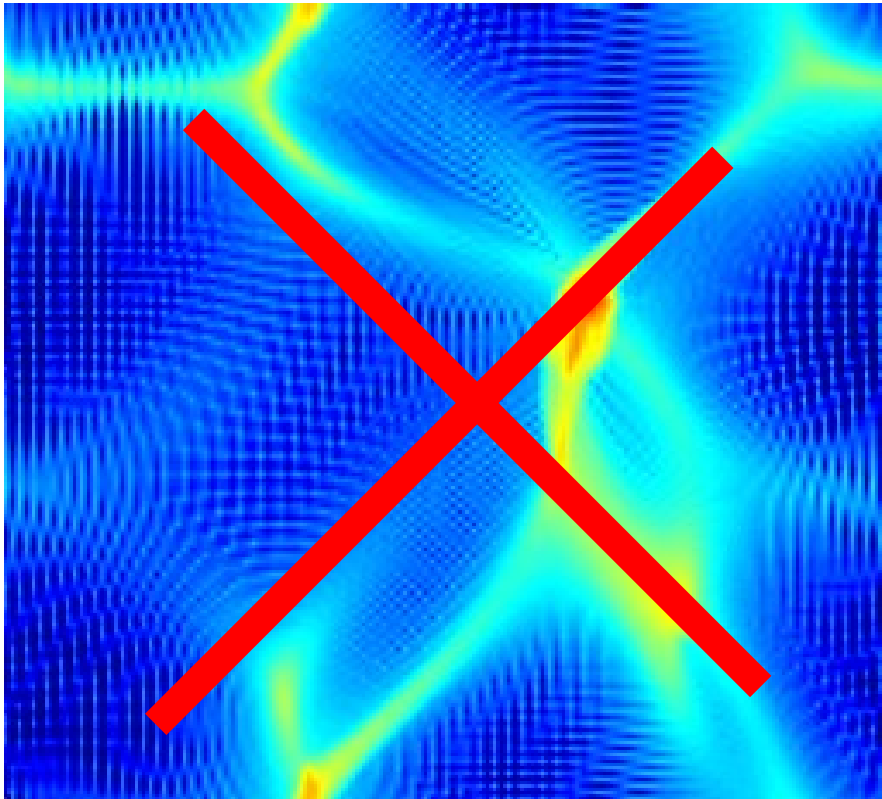
nb: Dark matter exists!



Hot Dark Matter
(like light neutrinos)



or Cold Dark Matter?
(typically more massive
particles)



Cold Dark Matter!
(perhaps a bit warm, but definitively not hot)

2. If there is a problem, invent a new particle!

e.g. **Neutron**

(Rutherford, 1920 -> Chadwick 1932)

Neutrino

(Pauli, 1930 -> Reines et al, 1956)

Z (Weinberg, 1967 -> 1983)

H (Symmetry breaking, 60's -> 2012?)

A Good Dark Matter Candidate is:

Neutral (little interaction with light)

Stable (or very long lived
 $T_{1/2} > \sim 10^{26} \text{ sec}$)

Possibly **Massive** ($M > \sim 100 \text{ eV} = \text{COLD}$)
particle

Stability from Symmetry

U(1) symmetry: $\Psi \rightarrow e^{i\beta} \Psi$

e.g. Proton stability = baryon number
conservation

Z_2 symmetry: $\Psi \rightarrow -\Psi$

e.g. R-parity in Supersymmetric
extensions of the Standard Model

Others: Topology

e.g. Monopoles

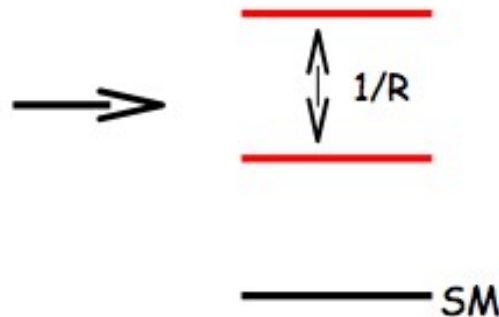
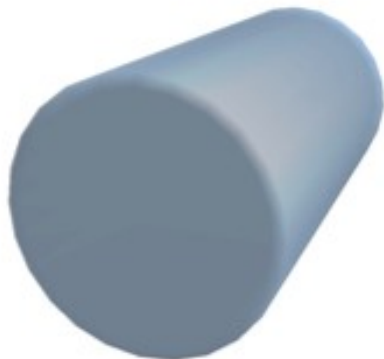
An Electroweak Connection ?

SUSY

$$\delta M_{\text{Higgs}}^2 = \text{[Self-energy loop]} + \text{[Dashed loop]} \sim M_{\text{Higgs}}^2 \ll M_{\text{Planck}}^2$$

R-parity: $\Psi_{\text{SM}} \rightarrow \Psi_{\text{SM}}$ $\Psi_{\text{susy}} \rightarrow -\Psi_{\text{susy}}$

Extra Dimensions



KK-parity: $\Psi_{\text{SM}} \rightarrow \Psi_{\text{SM}}$
 $\Psi_{\text{KK}} \rightarrow -\Psi_{\text{KK}}$

The Brout-Englert-Higgs portal



e.g. The Inert Doublet Model

$$\Psi_{\text{Higgs}} \rightarrow \Psi_{\text{Higgs}}$$

$$\Psi_{\text{Inert Higgs}} \rightarrow -\Psi_{\text{Inert Higgs}}$$

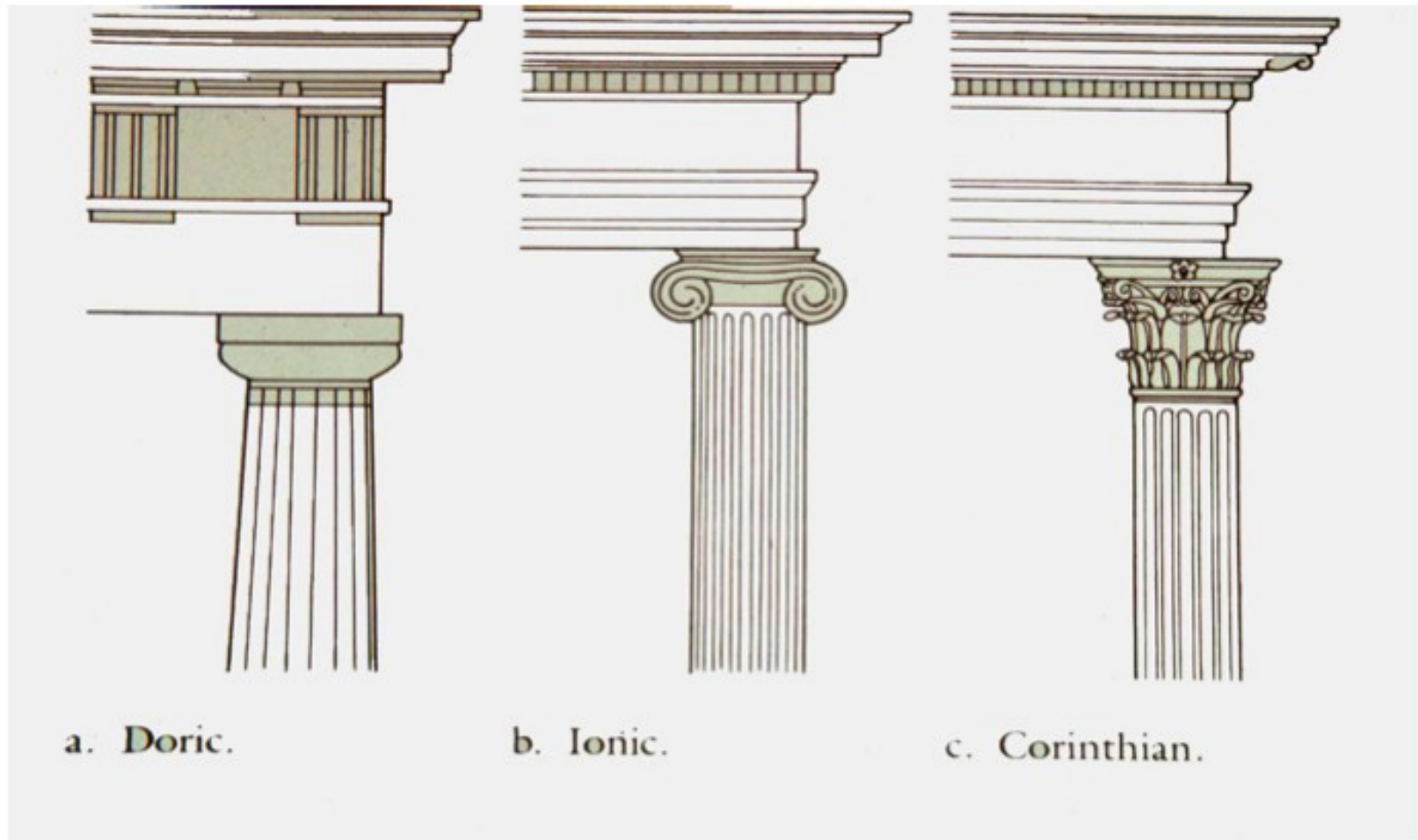
Easy way to prevent FCNC

WIMP Dark Matter Archetypes

Spin 0
The Inert Doublet

Spin $\frac{1}{2}$
The Neutralino

Spin 1
The Kaluza Klein photon

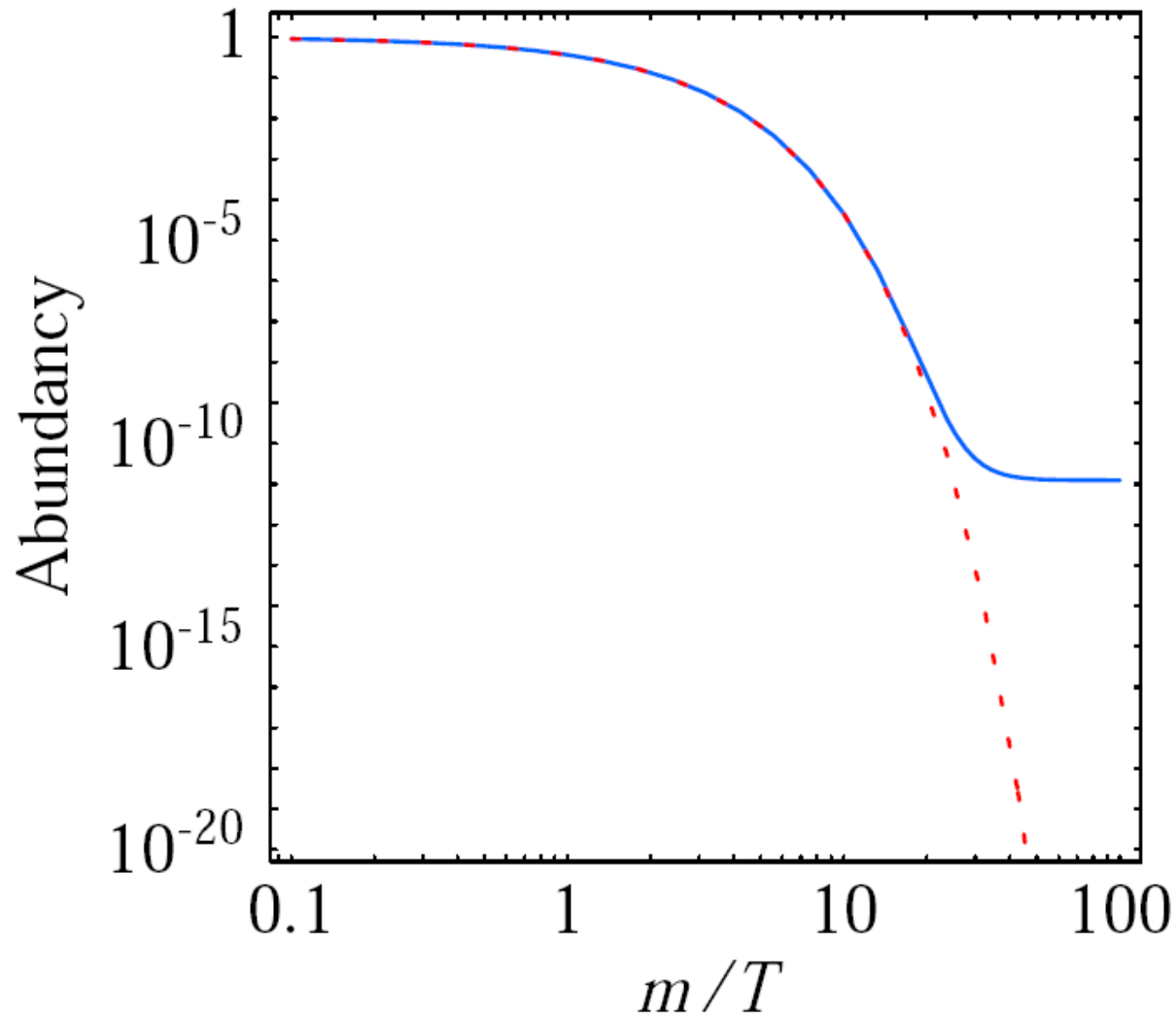


2. The WIMP* Miracle



* Weakly Interacting Massive Particle

Another view of the (so-called) WIMP Miracle



1. Let X be stable, neutral, massive
and $X + X \leftrightarrow SM + SM$ (annihilation)

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2. Initially ($T \sim M$) X in thermal
equilibrium

--> density $n = n_{Eq} \sim e^{-M/T}$

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2. Initially ($T \sim M$) X in thermal
equilibrium

$$\rightarrow \text{density } n = n_{Eq} \sim e^{-M/T}$$

3. **Evolution** (ie Boltzmann equation)

$$dn/dt + 3 H n \approx \langle \sigma v \rangle n_{Eq} (n_{Eq} - n)$$

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Expansion Rate

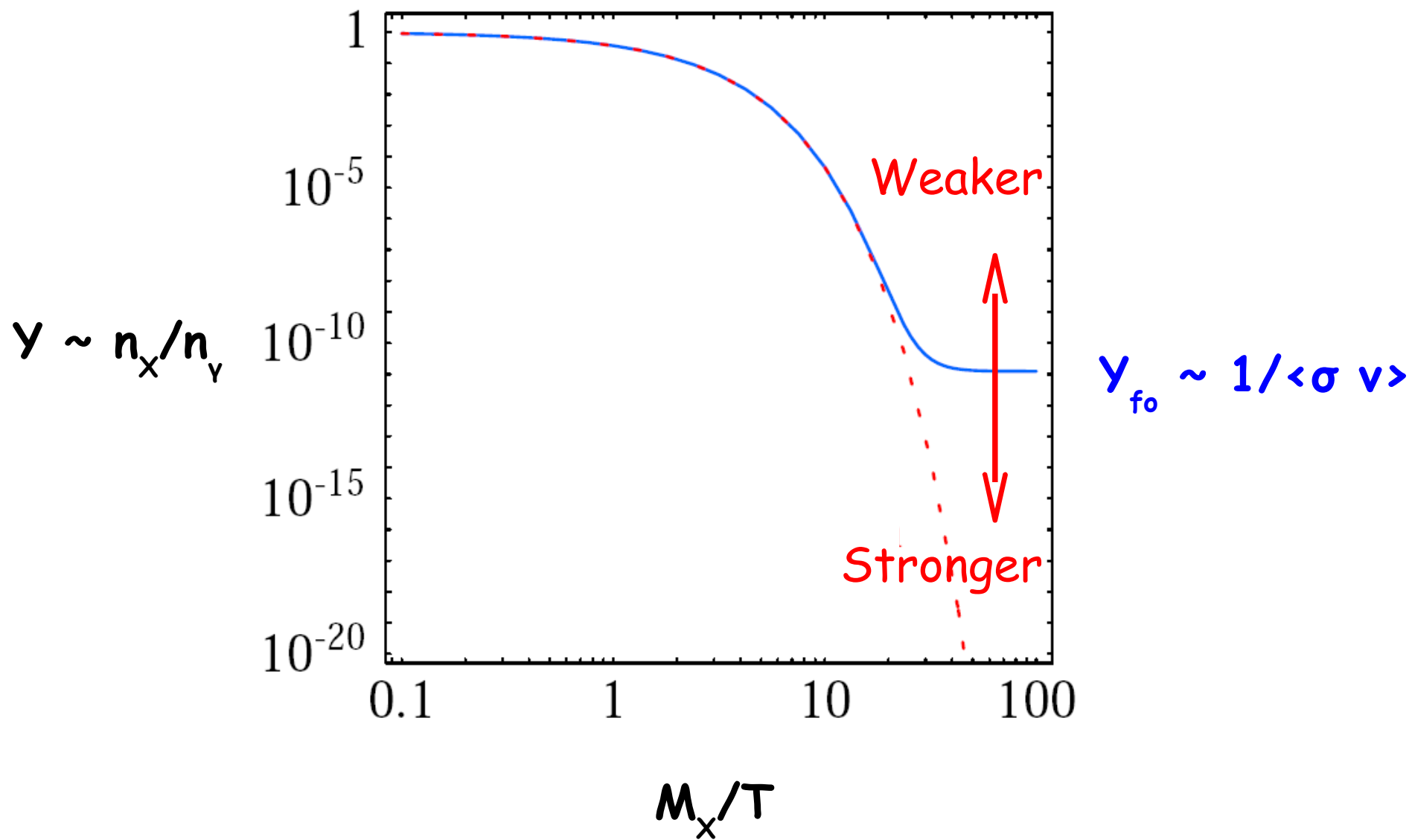
vs

Annihilation Rate

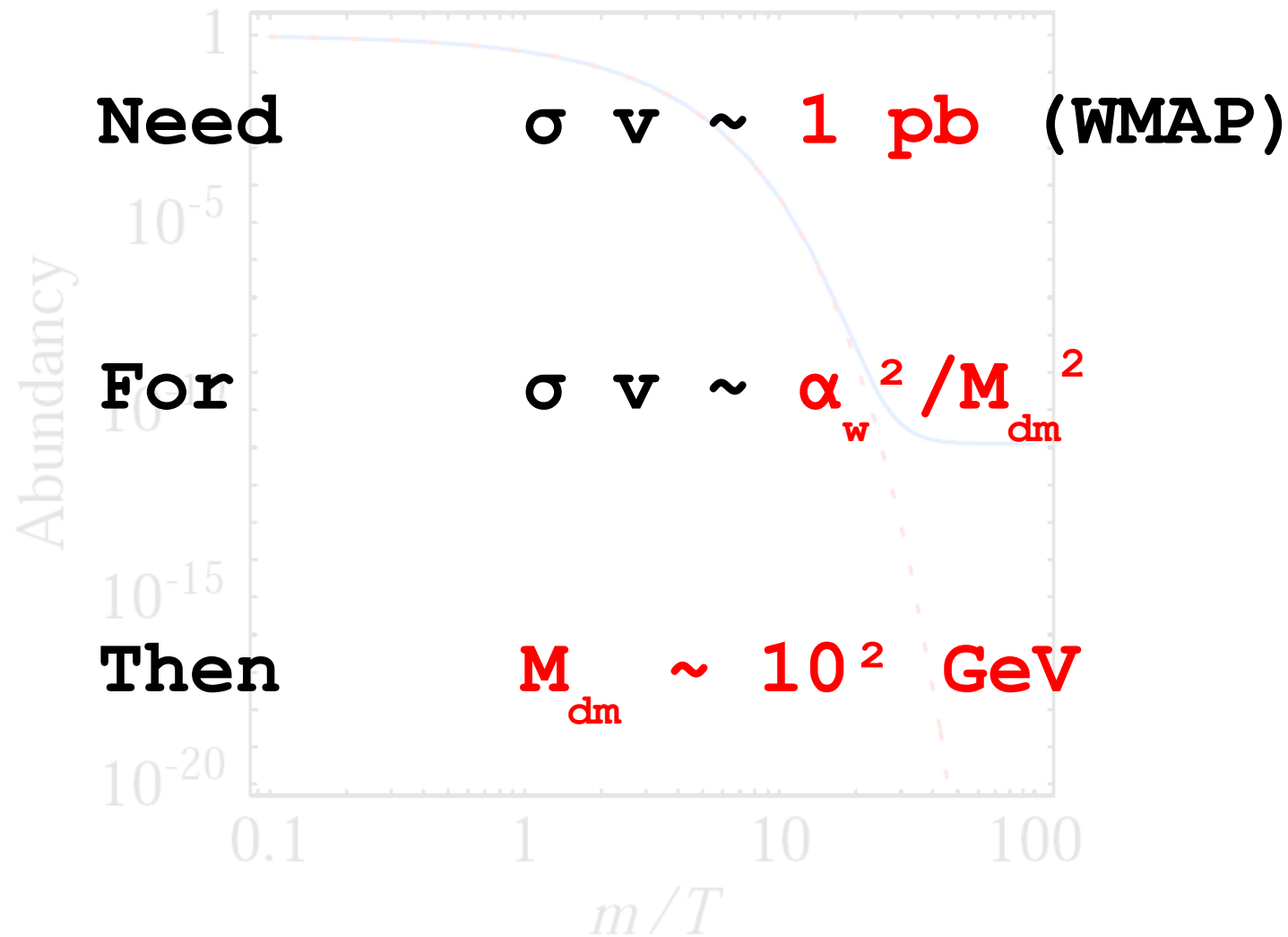
4. Freeze-Out of annihilations

$$n_{\text{FO}} \sim H / \langle \sigma v \rangle$$

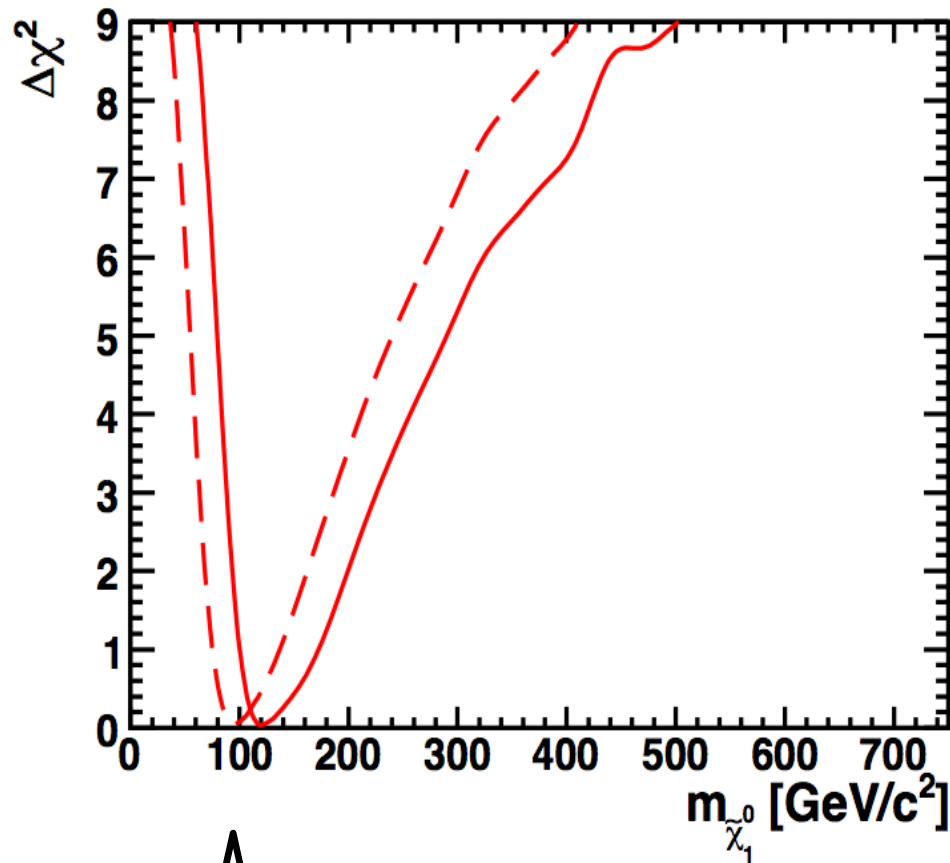
If annihilation  then n_{FO} 



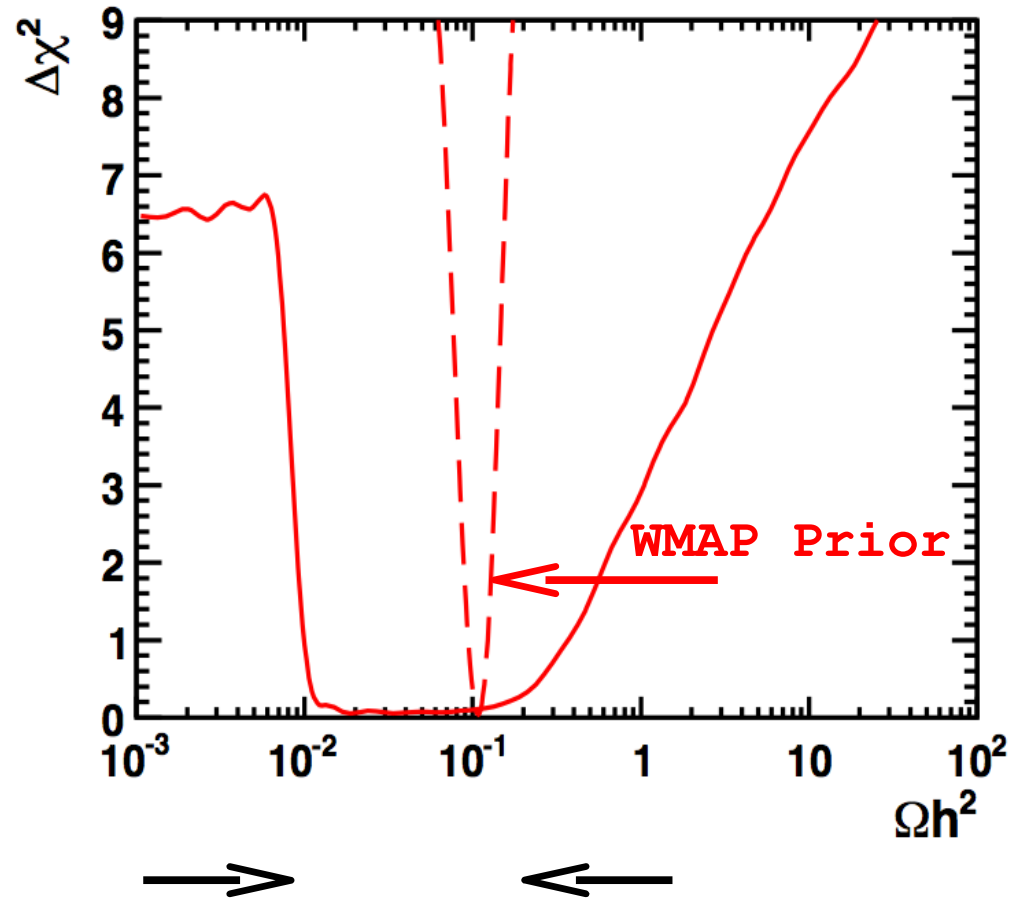
The WIMP Miracle ?



Neutralino Mass & Relic Density



↑
 $M_{\tilde{\chi}} \sim 100 \text{ GeV}$



Courtesy of Keith Olive
See also arXiv:0907.5568

e.g. Dirac Neutrino + EW Interactions

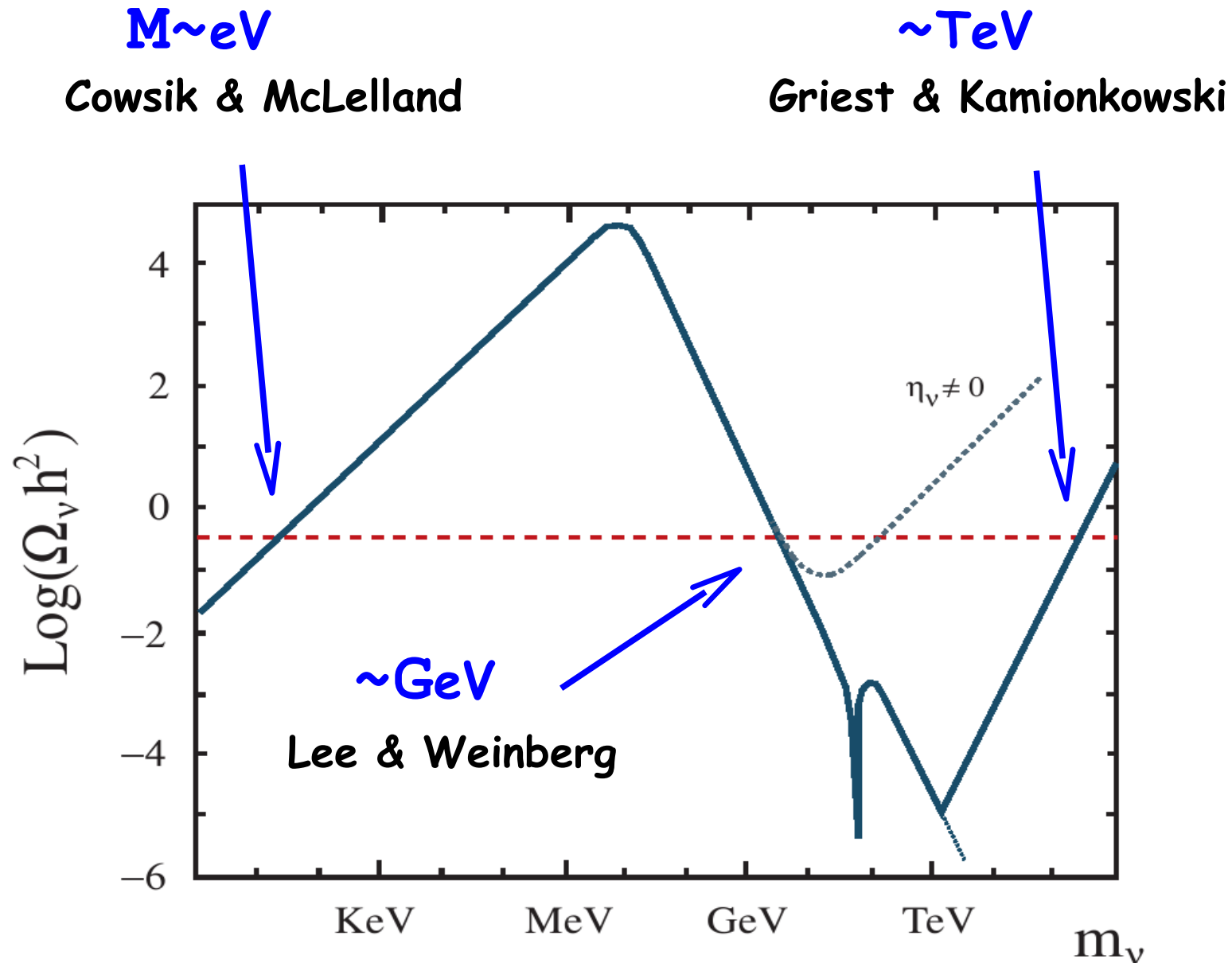
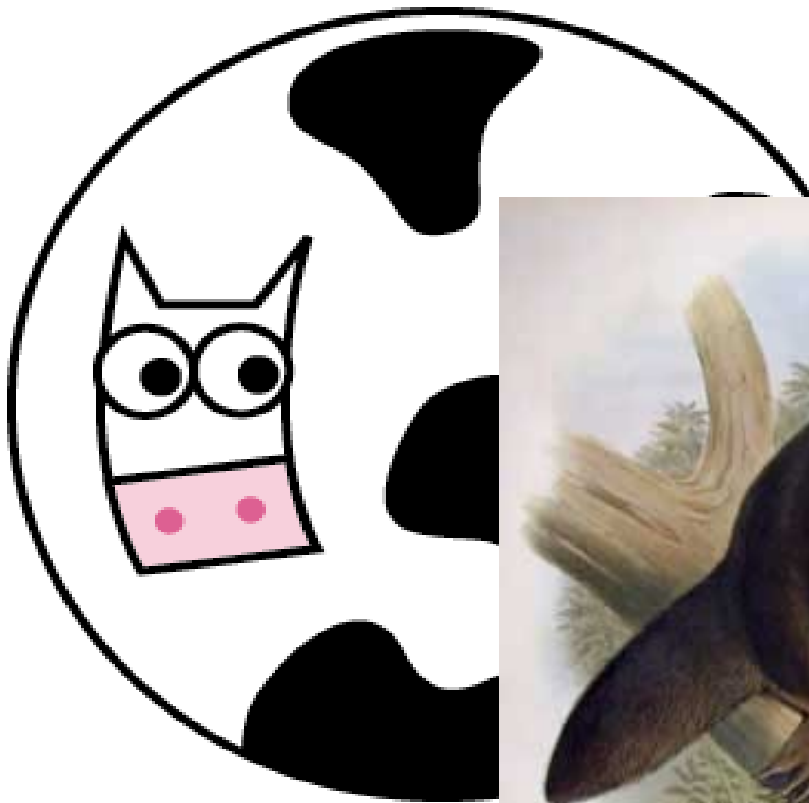


Figure © K. Kainulainen

So, which Dark Matter ?



So, which Dark Matter ?



Why I ❤️ Light ($\sim \text{GeV}$) Dark Matter

$$\Omega_{\text{dm}} / \Omega_{\text{b}} \approx 5$$

Why I ♥ Light ($\sim \text{GeV}$) Dark Matter

$$\Omega_{\text{dm}} / \Omega_{\text{b}} \approx 5$$

EW, SUSY, ... ?

Freeze-out, ... ?

$$\frac{\text{Mass}_{\text{dm}} \times \text{Density}_{\text{dm}}}{\text{Mass}_{\text{b}} \times \text{Density}_{\text{b}}} = O(1)$$

QCD Dynamics

Baryogenesis (?)

Why I ♥ Light ($\sim \text{GeV}$) Dark Matter

$$\Omega_{\text{dm}} / \Omega_{\text{b}} \approx 5$$

EW, SUSY, ... ?

Freeze-out, ... ?

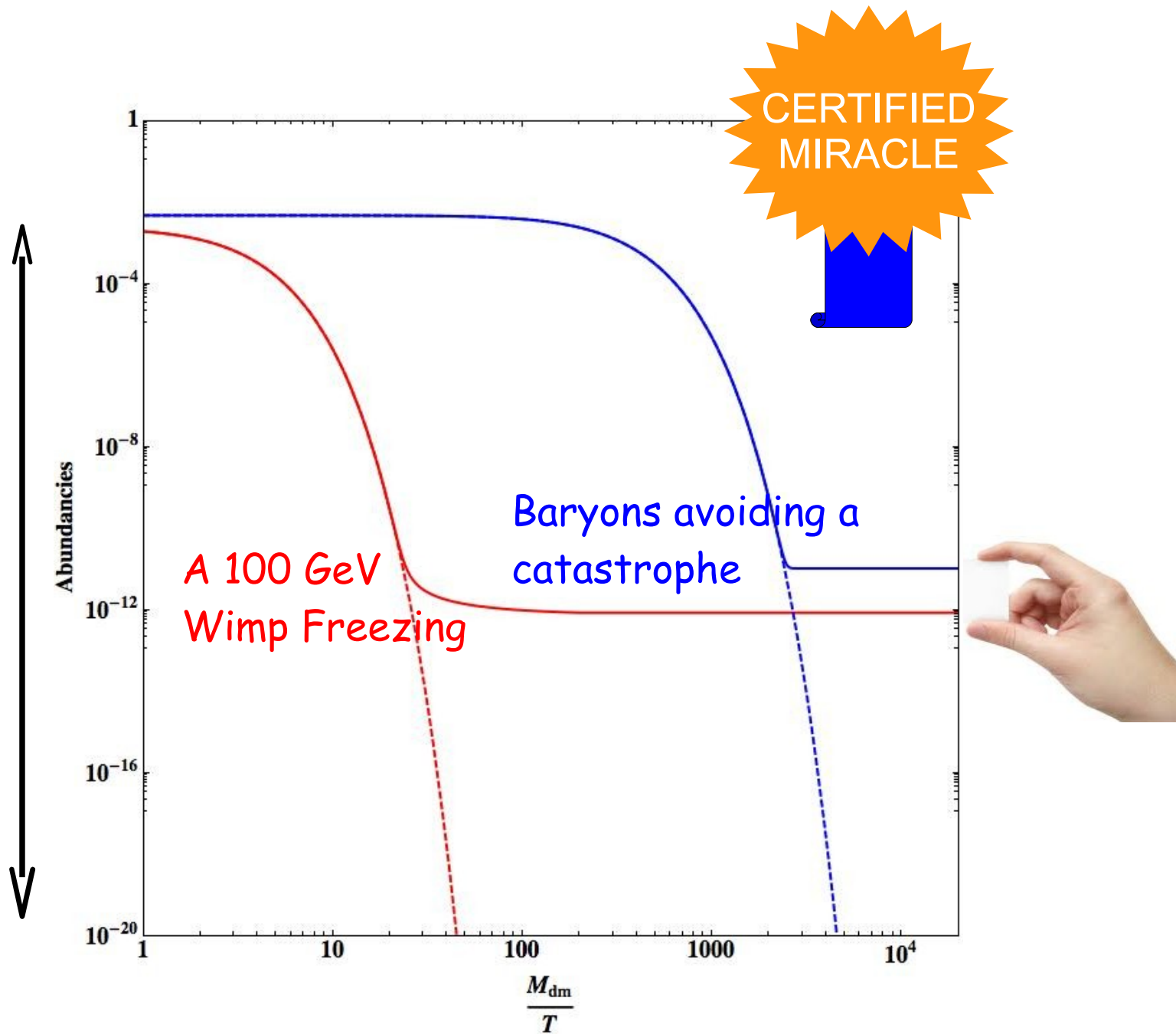
Is this a Coincidence ?

$$\frac{\text{Mass}_{\text{dm}} \times \text{Density}_{\text{dm}}}{\text{Mass}_{\text{b}} \times \text{Density}_{\text{b}}} = O(1)$$

QCD Dynamics

Baryogenesis (?)

Nussinov; Barr; Kaplan; Gudnasson et al; Dodelson et al; Kitano et al; Farrar et al; Lopez Honorez, Cosme & M.T.; Zurek et al; ... and some new scenarios recently



Asymmetric Dark & Baryonic Matters ?

« Vanilla » scenarios imply Light $\sim \text{GeV}$ DM

$$\frac{\text{Mass}_{\text{dm}} \times \cancel{\text{Density}_{\text{dm}}}}{\text{Mass}_{\text{b}} \times \cancel{\text{Density}_{\text{b}}}} = O(1)$$

Nussinov; Barr; Kaplan; Dodelson et al; Gudnasson et al; Dodelson et al; Kitano et al; Farrar et al; Lopez Honorez, Cosme & M.T.; Zurek et al; ...

And quite some variations on this idea more recently (Aidogenesis, Cogenesis, Xogenesis, Baryomorphosis, Darkogenesis,...)

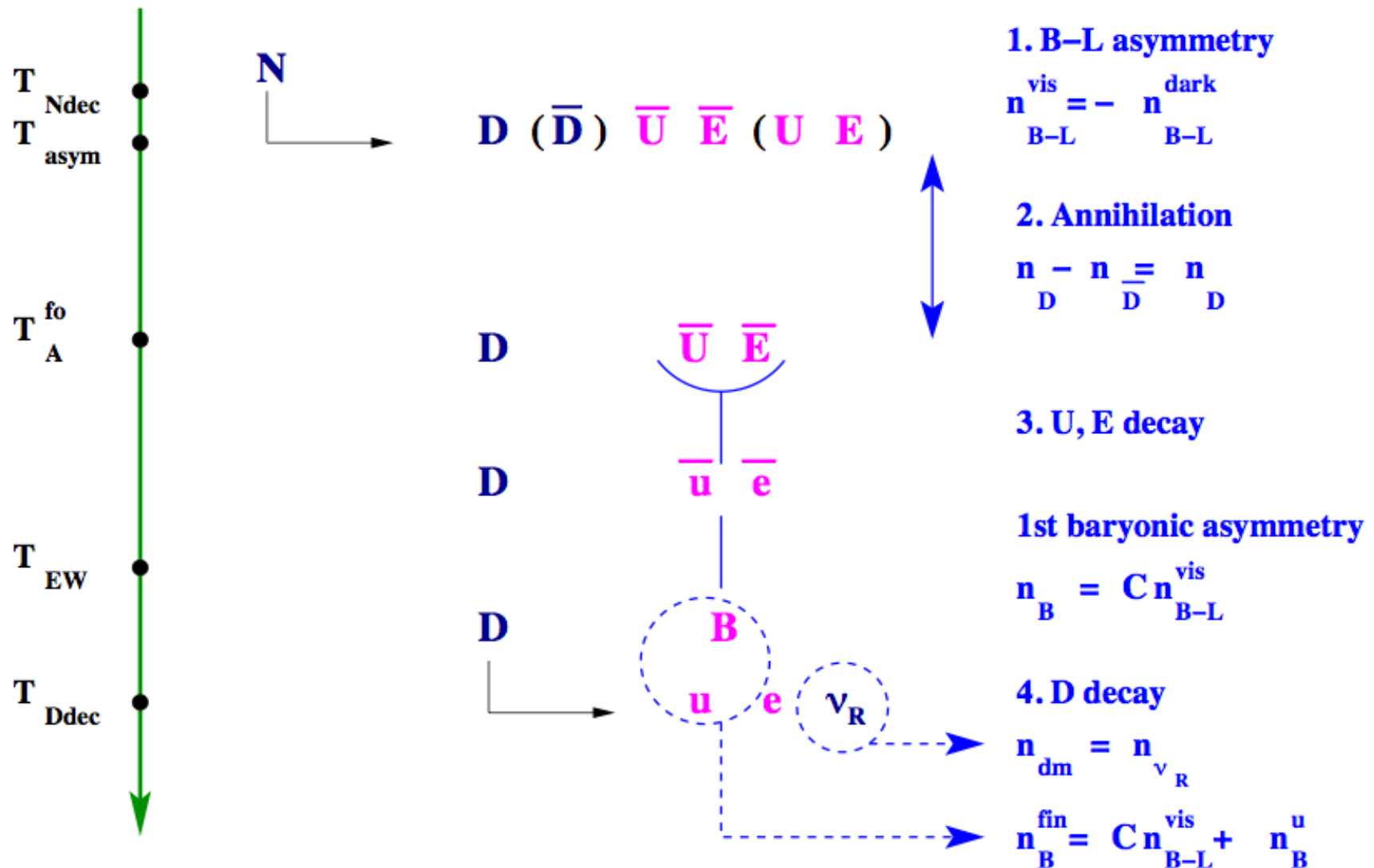


Figure 1: Steps of Matter Genesis

Just an example, taken from Lopez Honorez, Cosme & M.T. (2005)

Nice, if one likes complications....



Figure 1: Steps of Matter Genesis

We don't know what Dark Matter is made of, but we know it is not made of (light) neutrinos.

Particle physics propose simple scenario, the **WIMP paradigm**, that points to **new physics** @ the Electroweak energy scale.

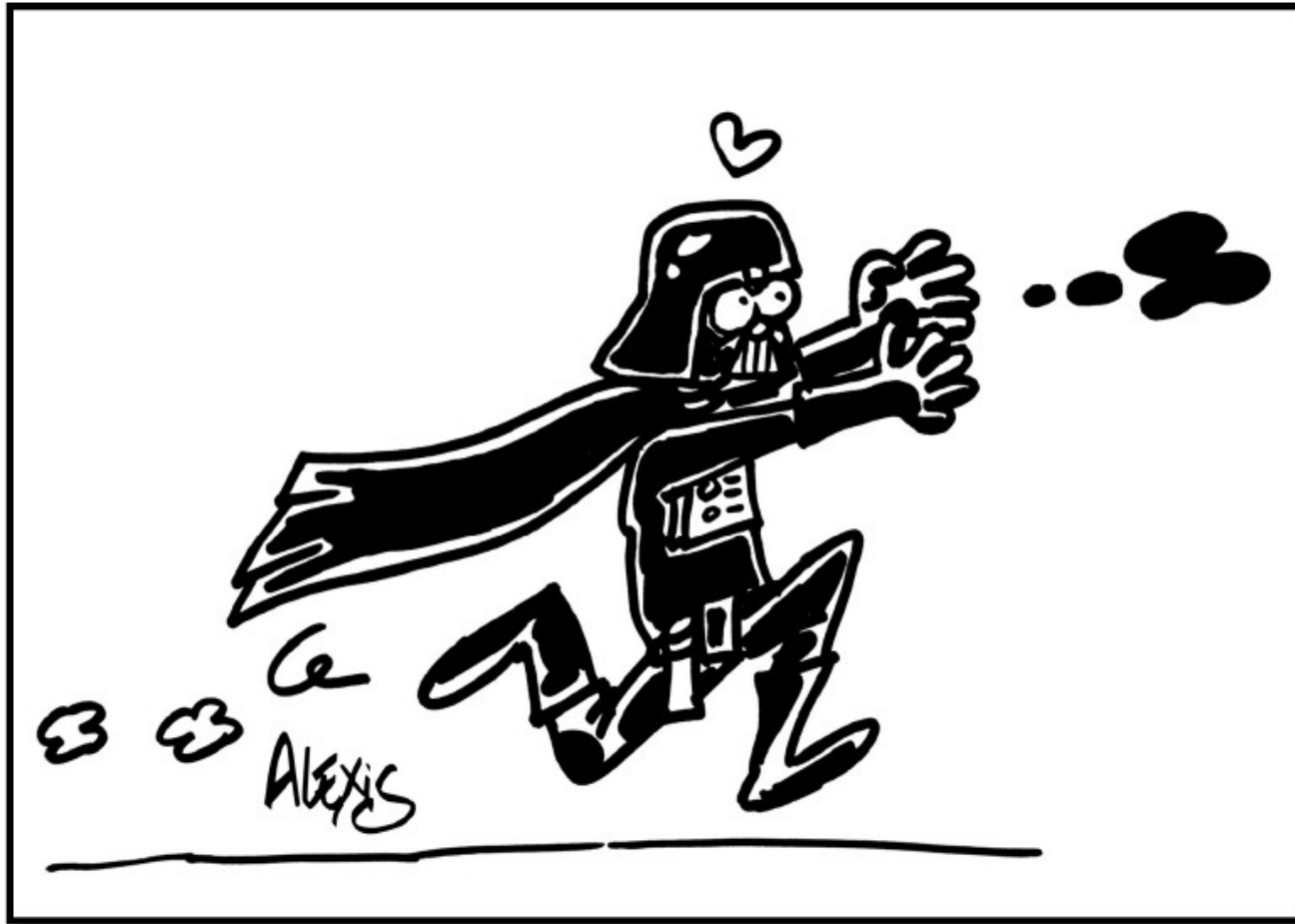
Of course, there are many other scenarios... But this opens the hope to probe DM with other interactions than gravity.

I. Why Dark Matter ?

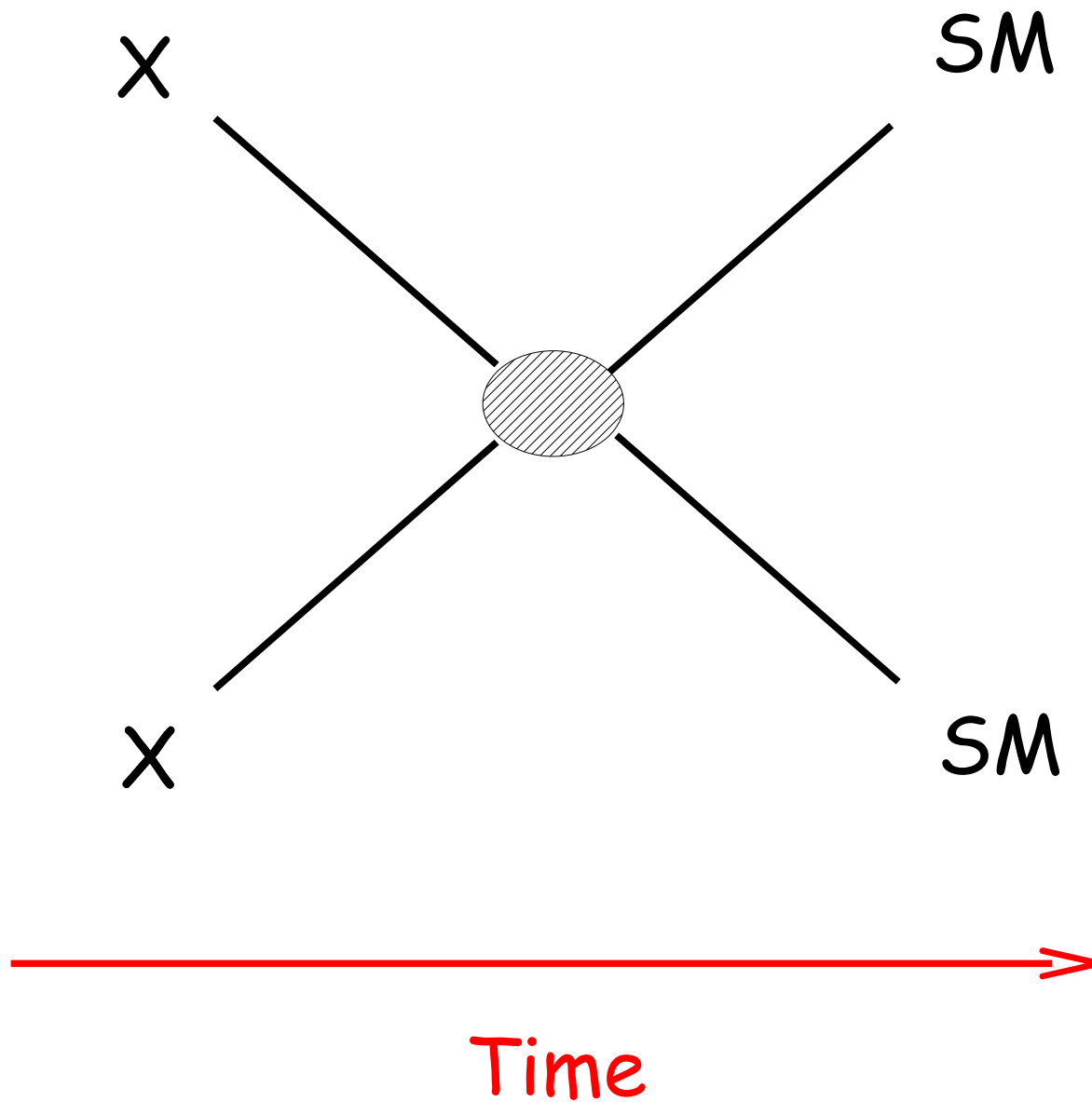
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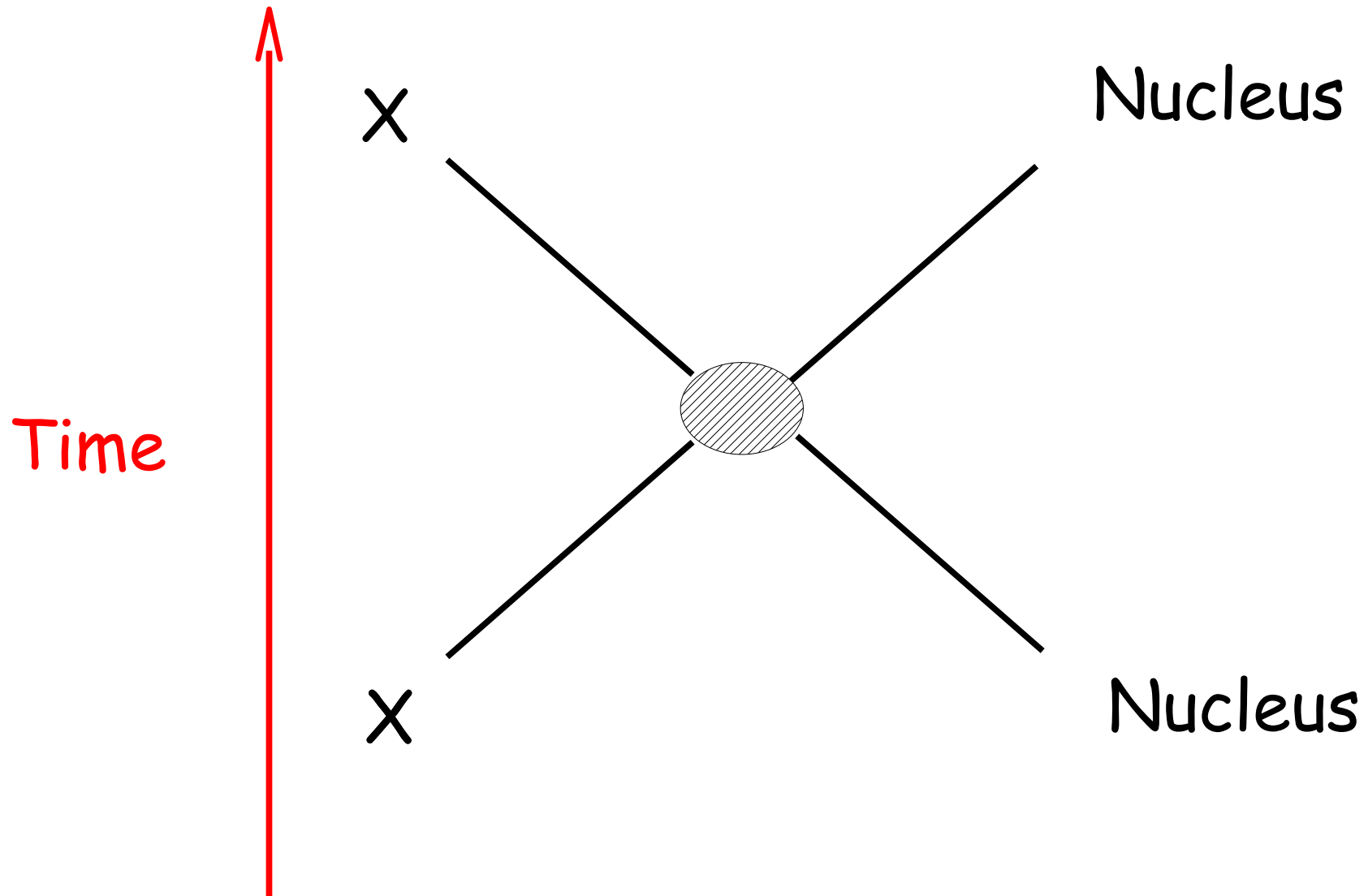
How to search for Dark Matter? Part 1



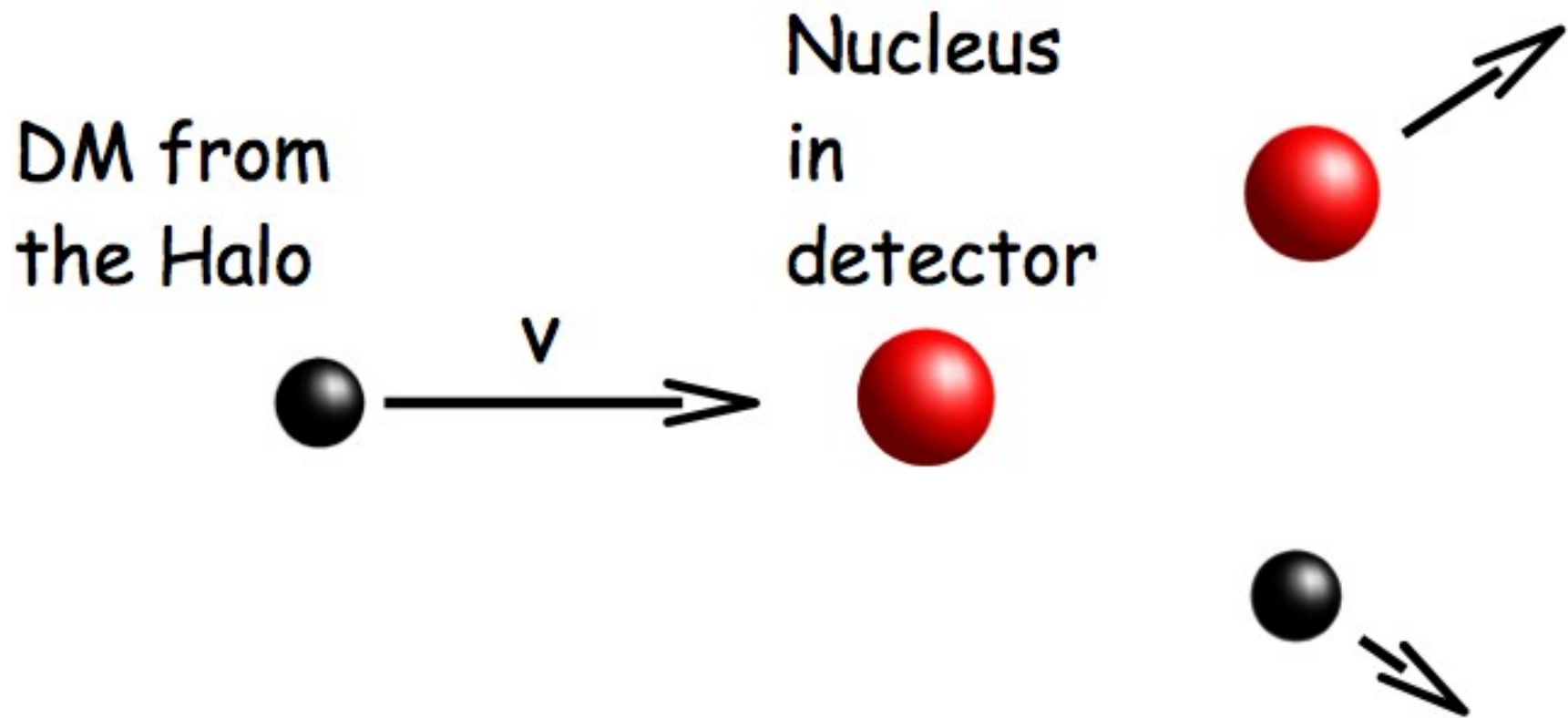
Dark Matter Abundance (Early Universe)



1. Dark Matter Direct Detection

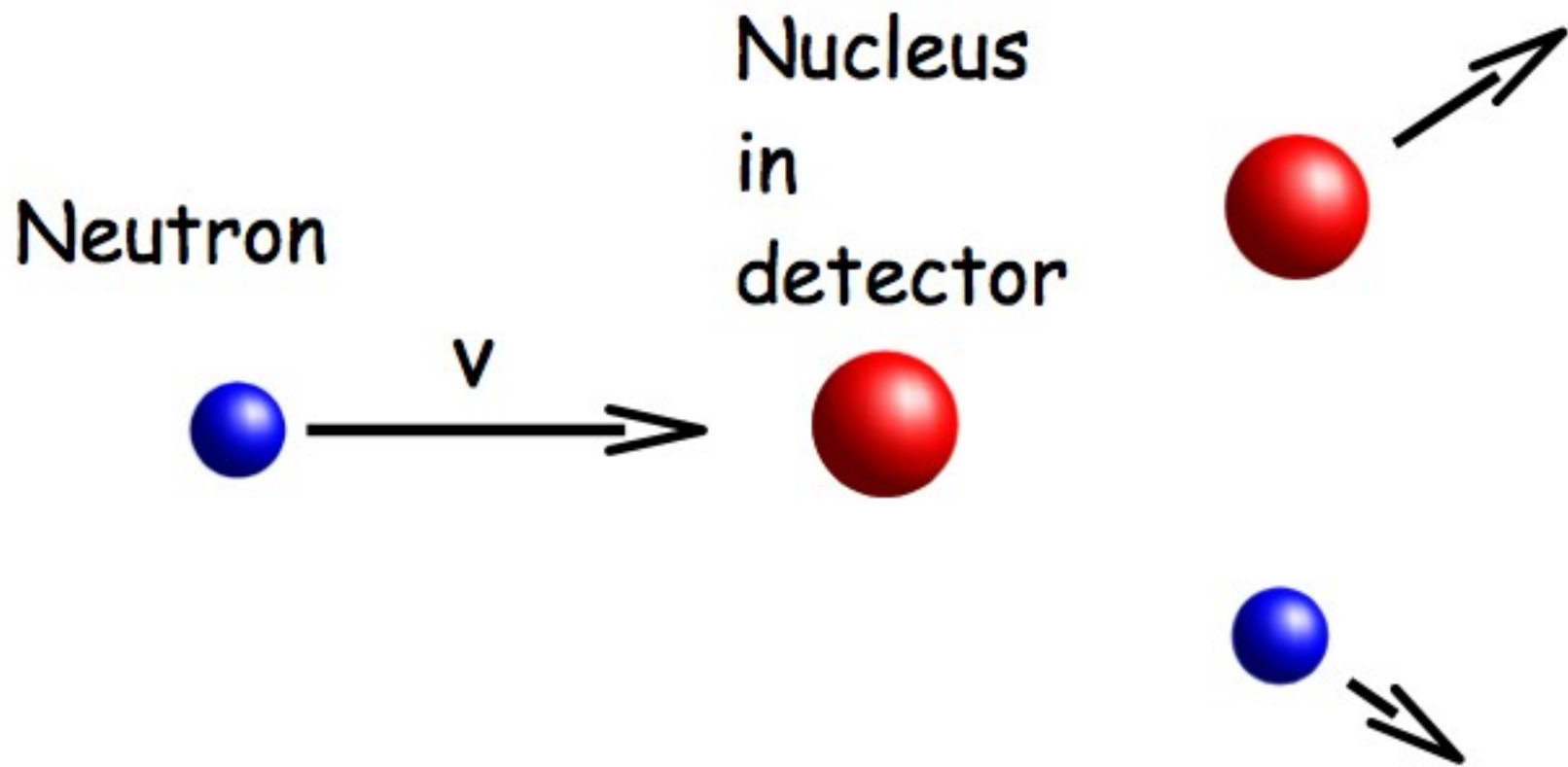


WIMP Direct Detection Searches In Brief



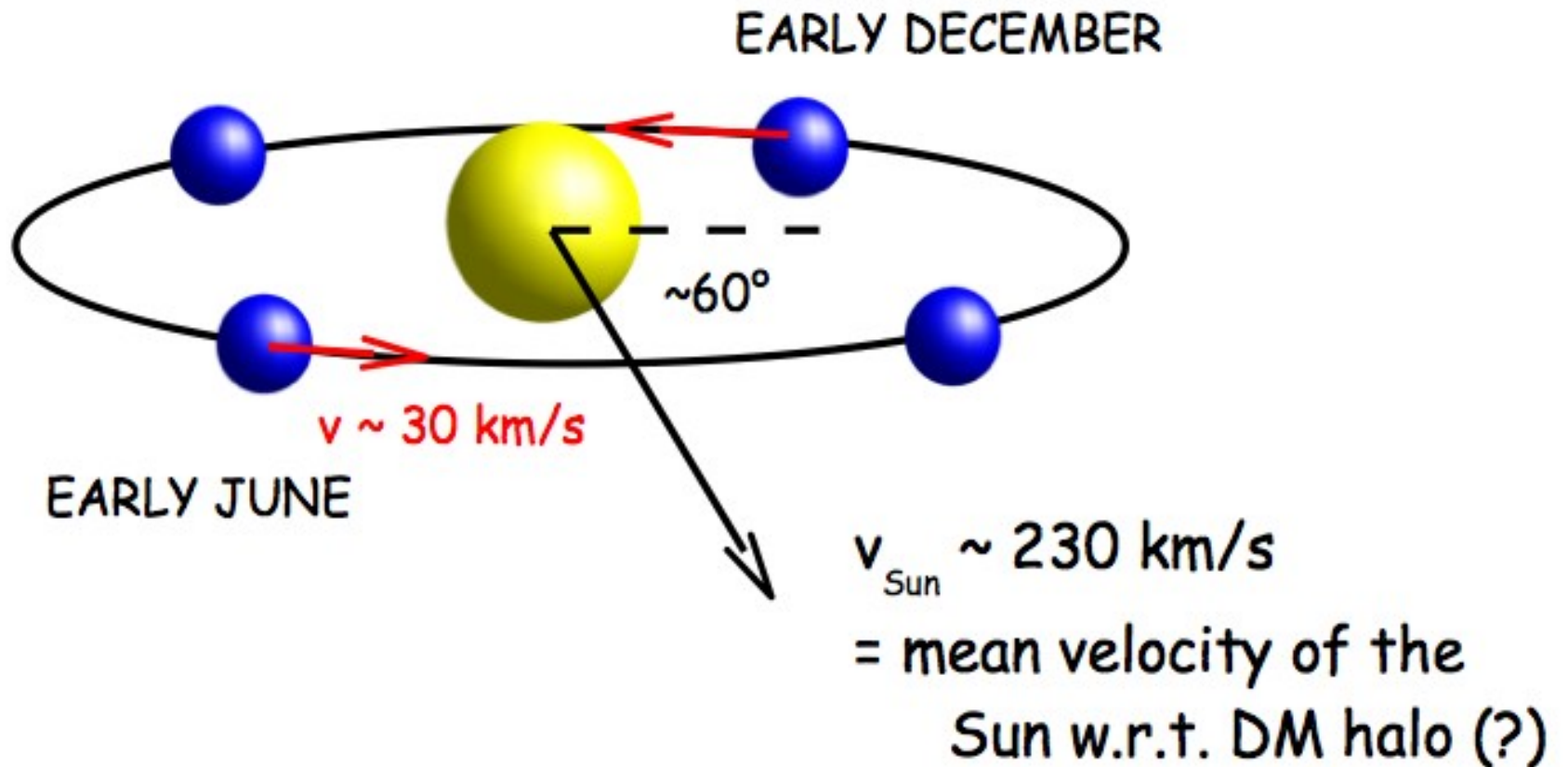
$E_{\text{recoil}} \sim \text{typically few keV}$

BACKGROUND!



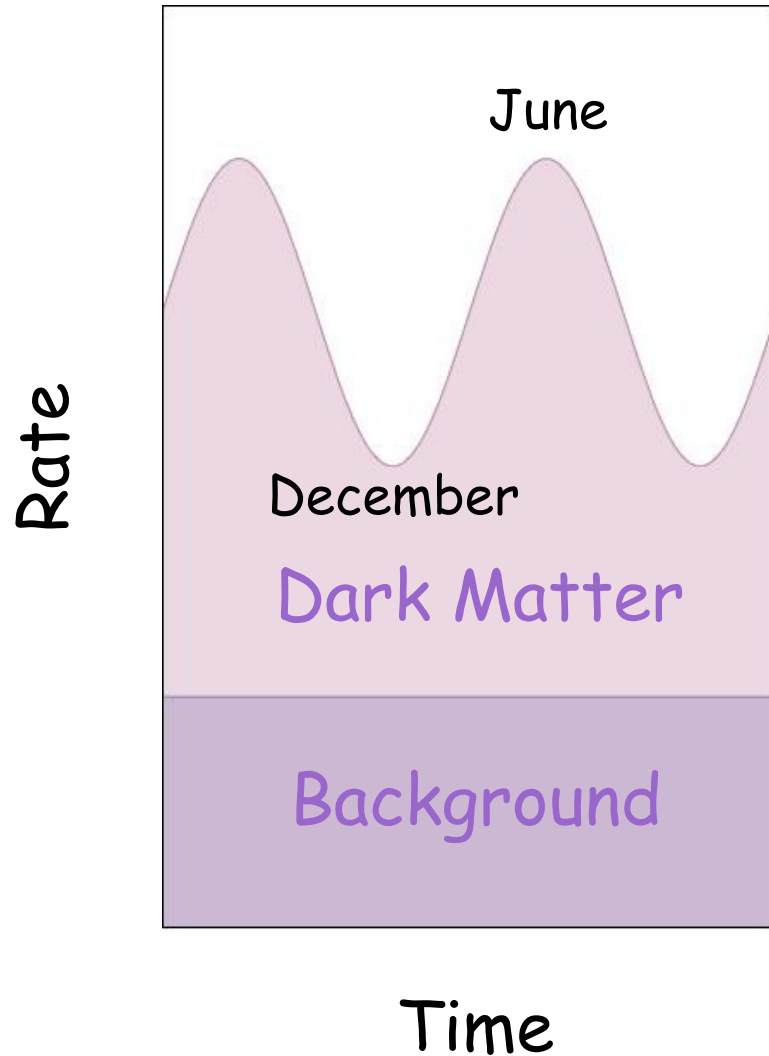
→ Go deep underground!
(and work hard on your background)

Seasonal modulation: a possible background free (?) signature of WIMPs?



Drukier, Freese & Spergel (1986)

First indices: DAMA/NaI & DAMA/Libra



Rem: not to scale!

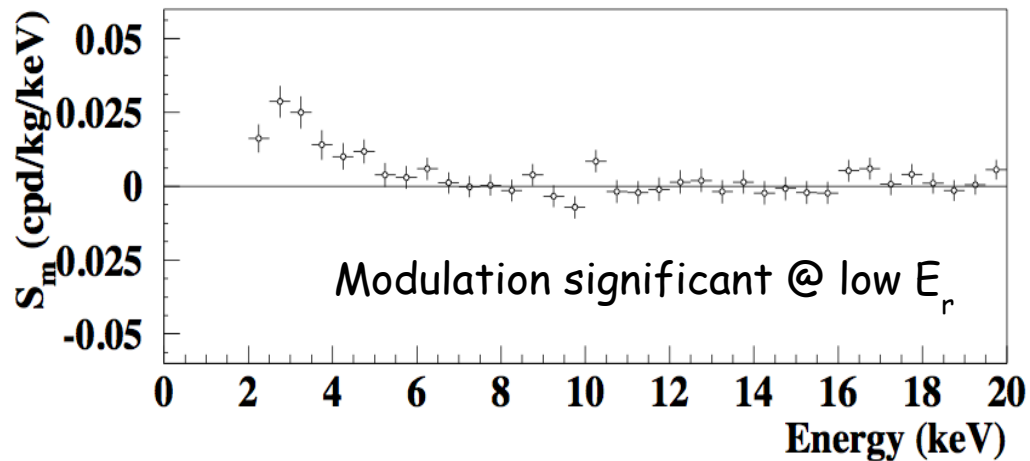
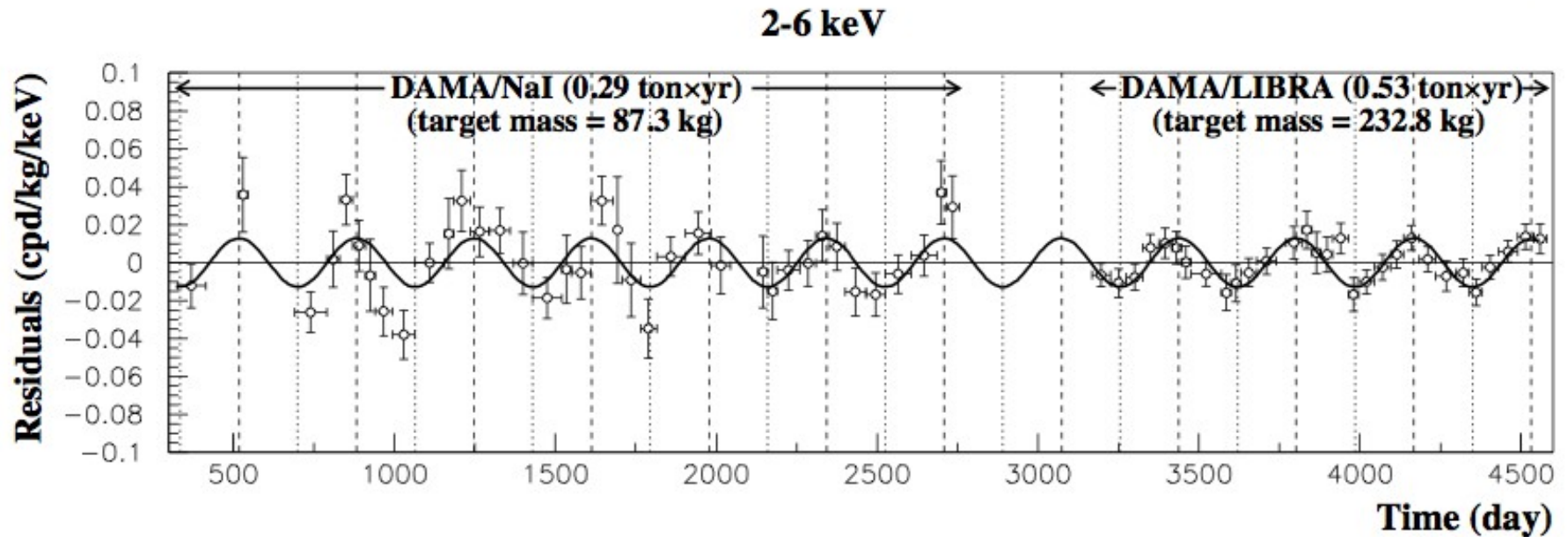
1. Modulation \sim few % level

2. Large Bckgrd

---> Single-hit events

Goes back to 1996!

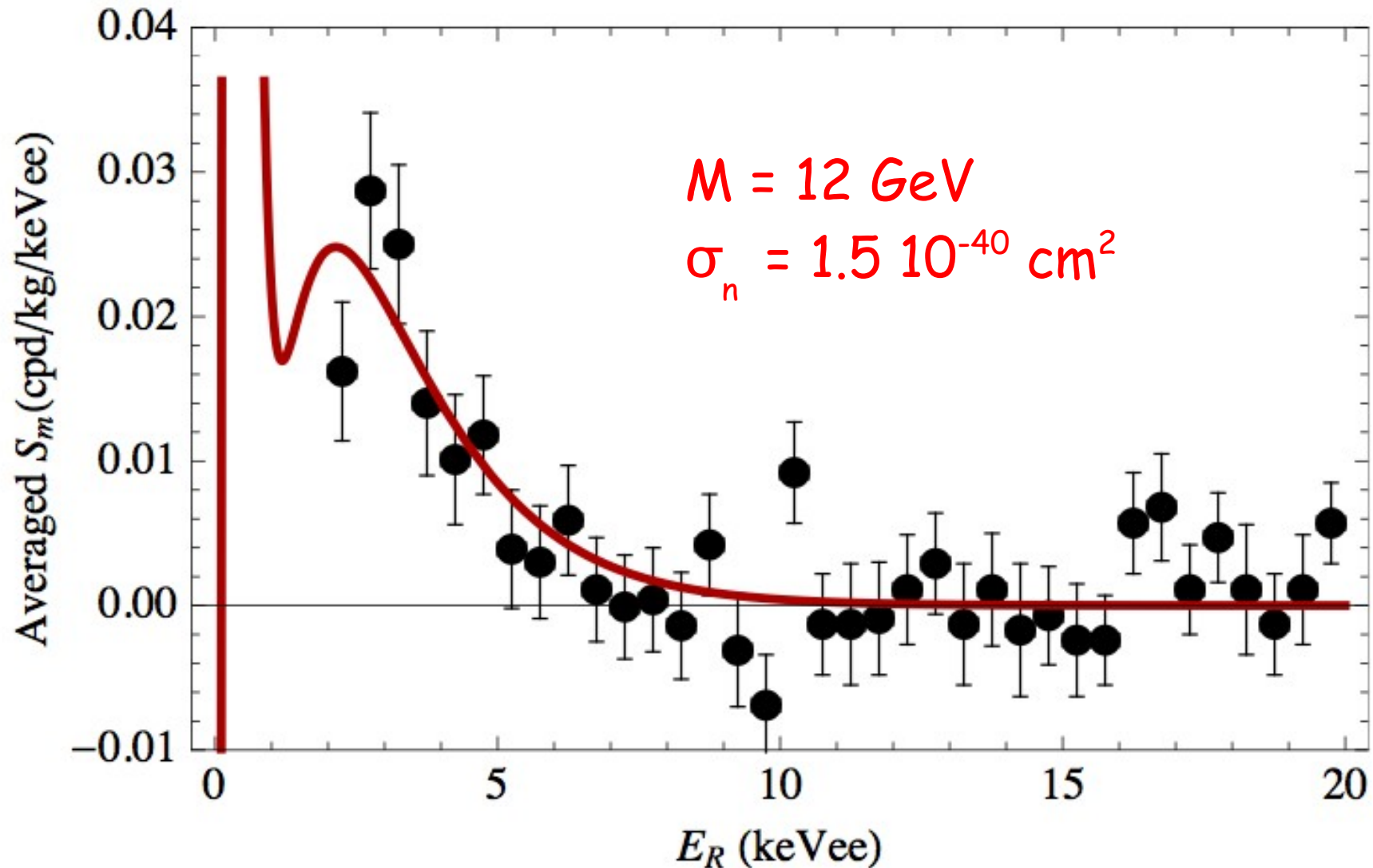
Combined DAMA/NaI & DAMA/Libra arXiv:0804.2741



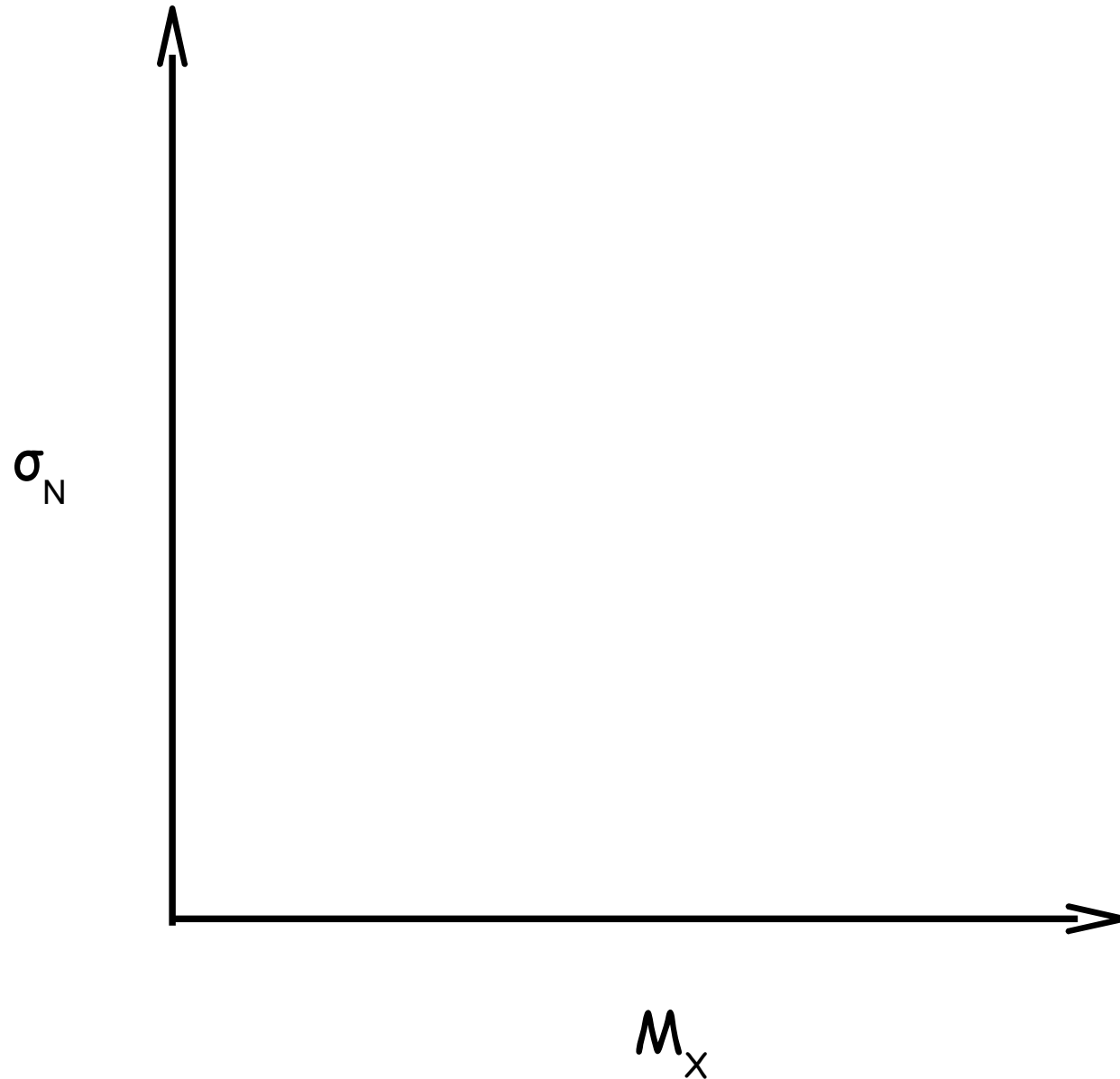
Max consistent with
early June

Significance C.L. = 8.2σ

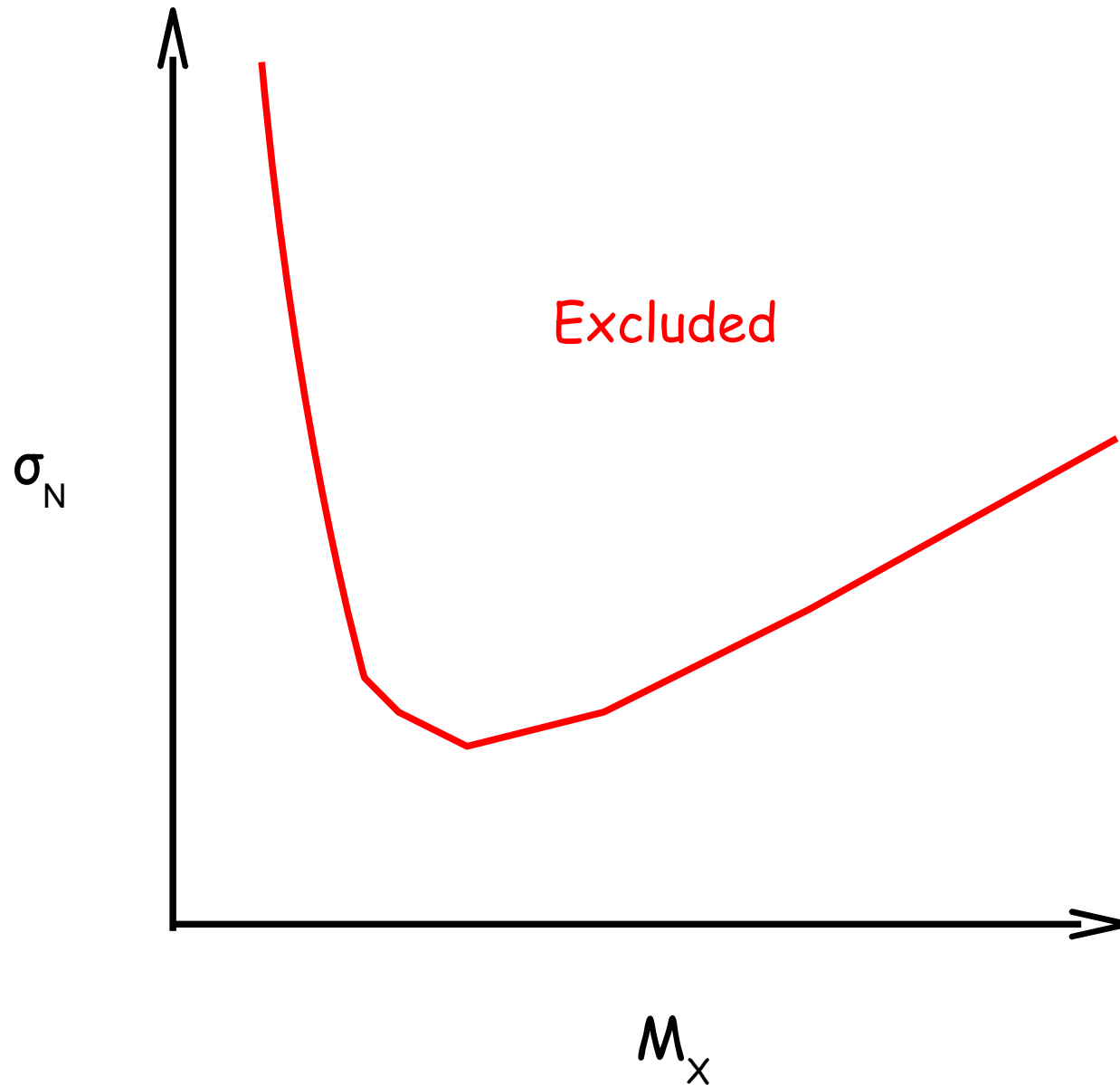
Elastic, spin-independent scattering, essentially with Na



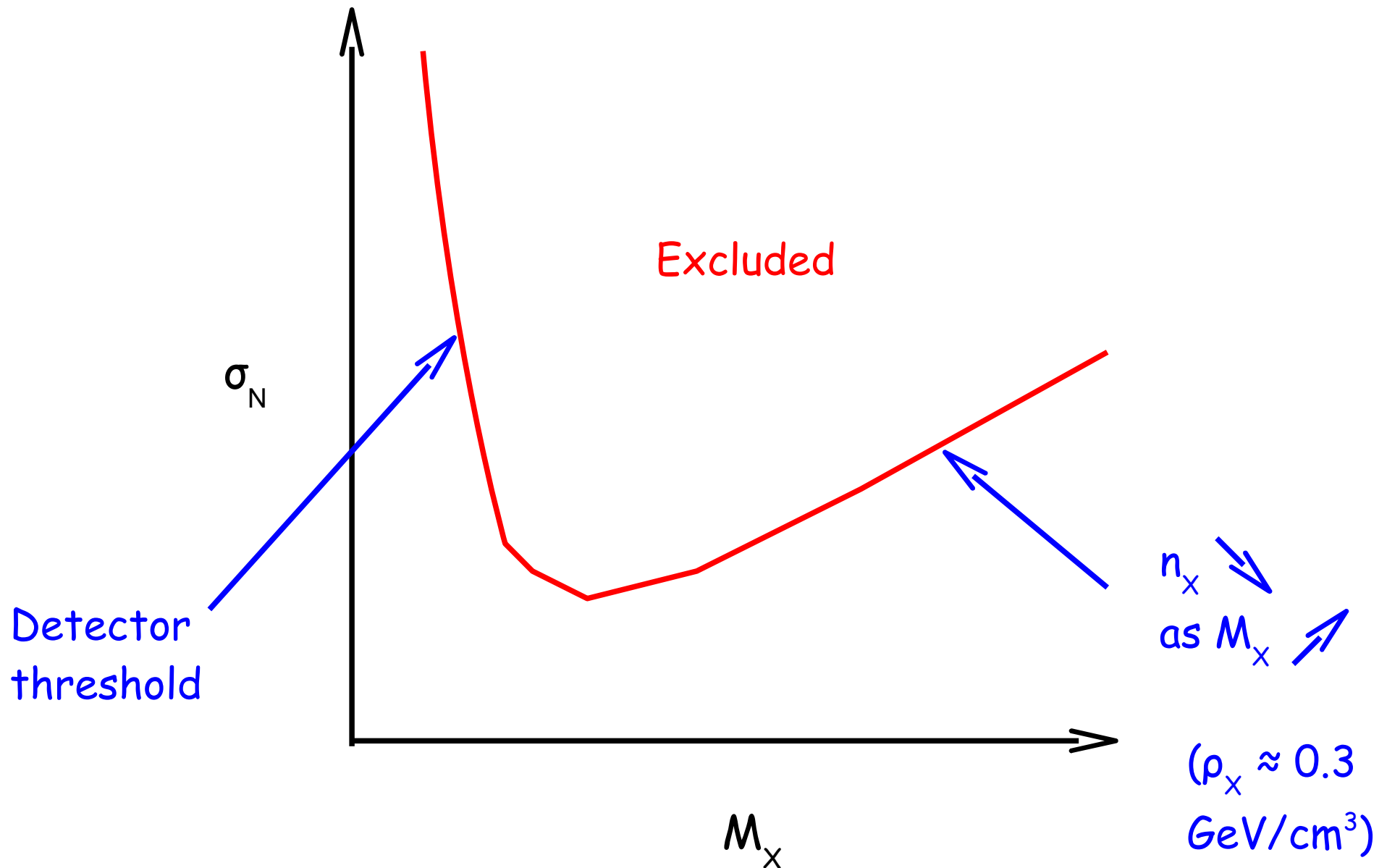
How Direct Search results are presented



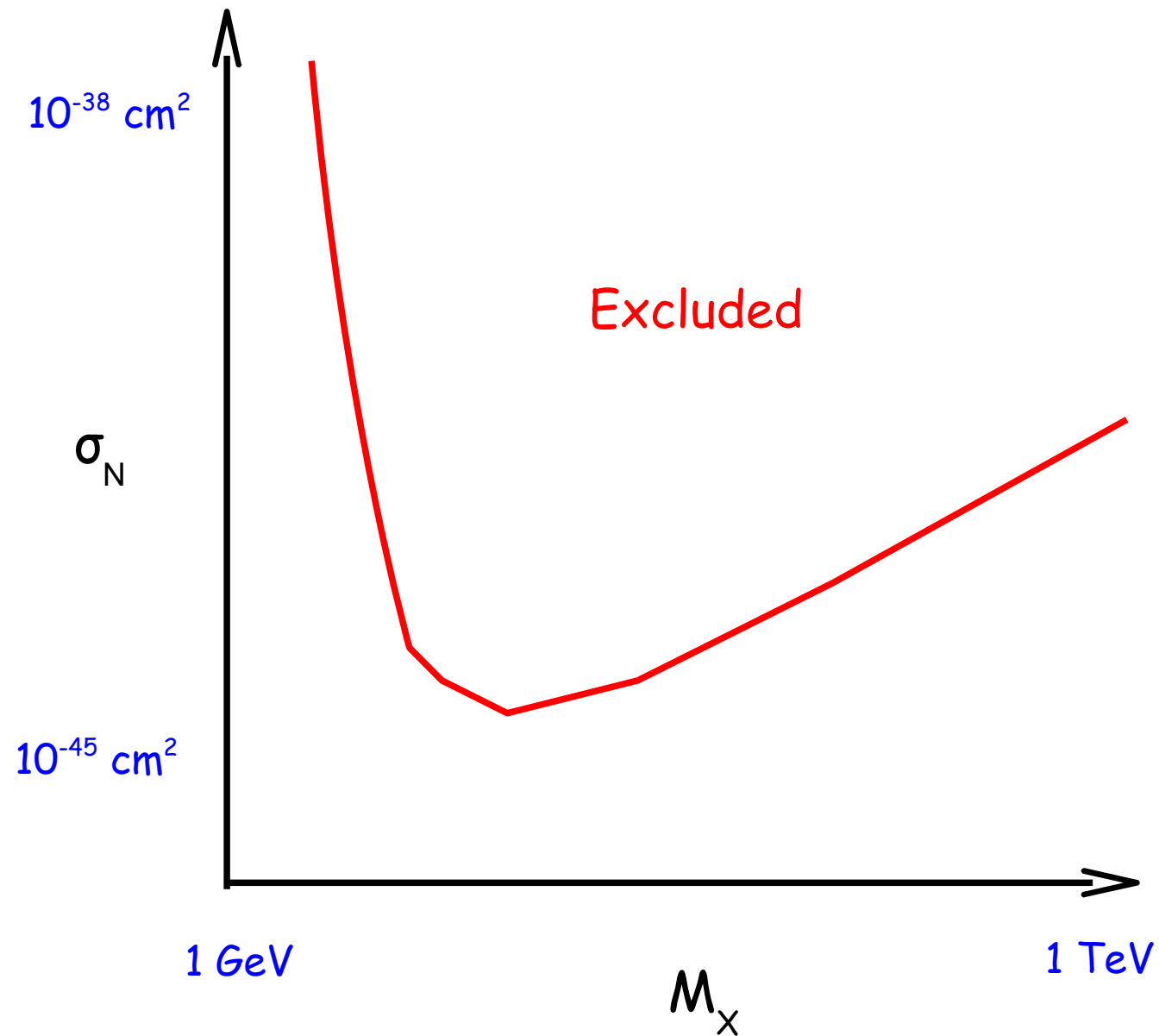
How Direct Search results are presented



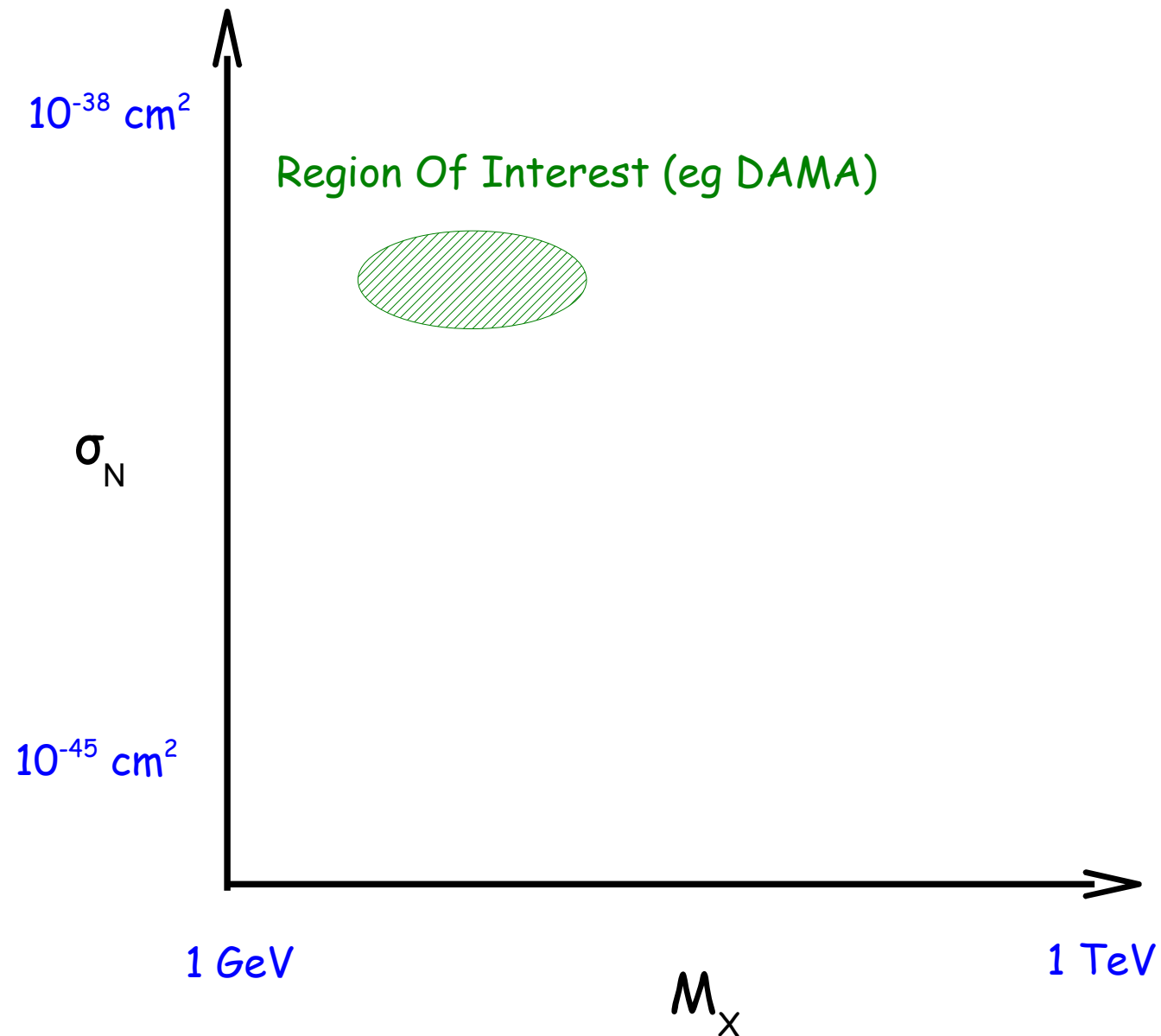
How Direct Search results are presented



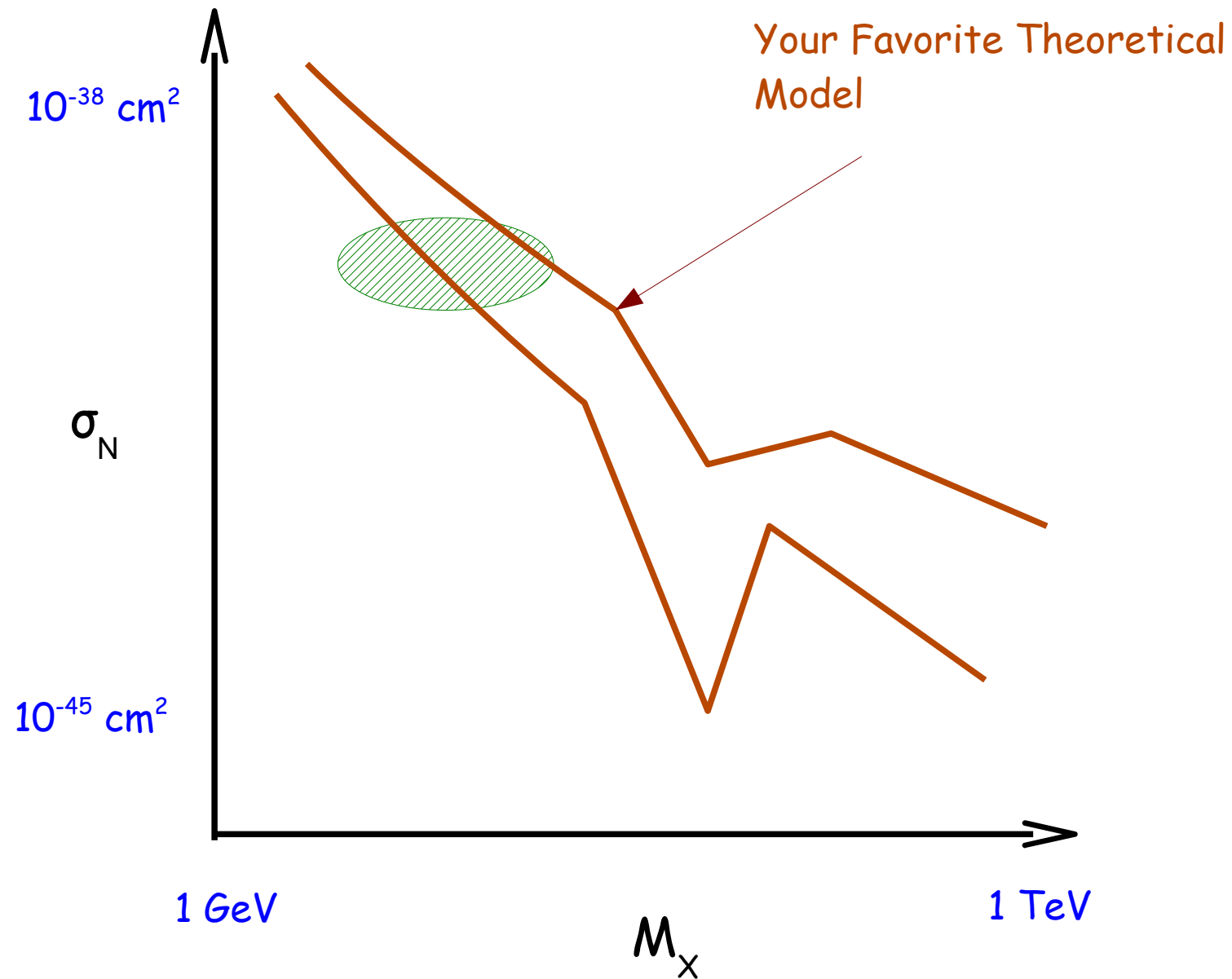
How Direct Search results are presented



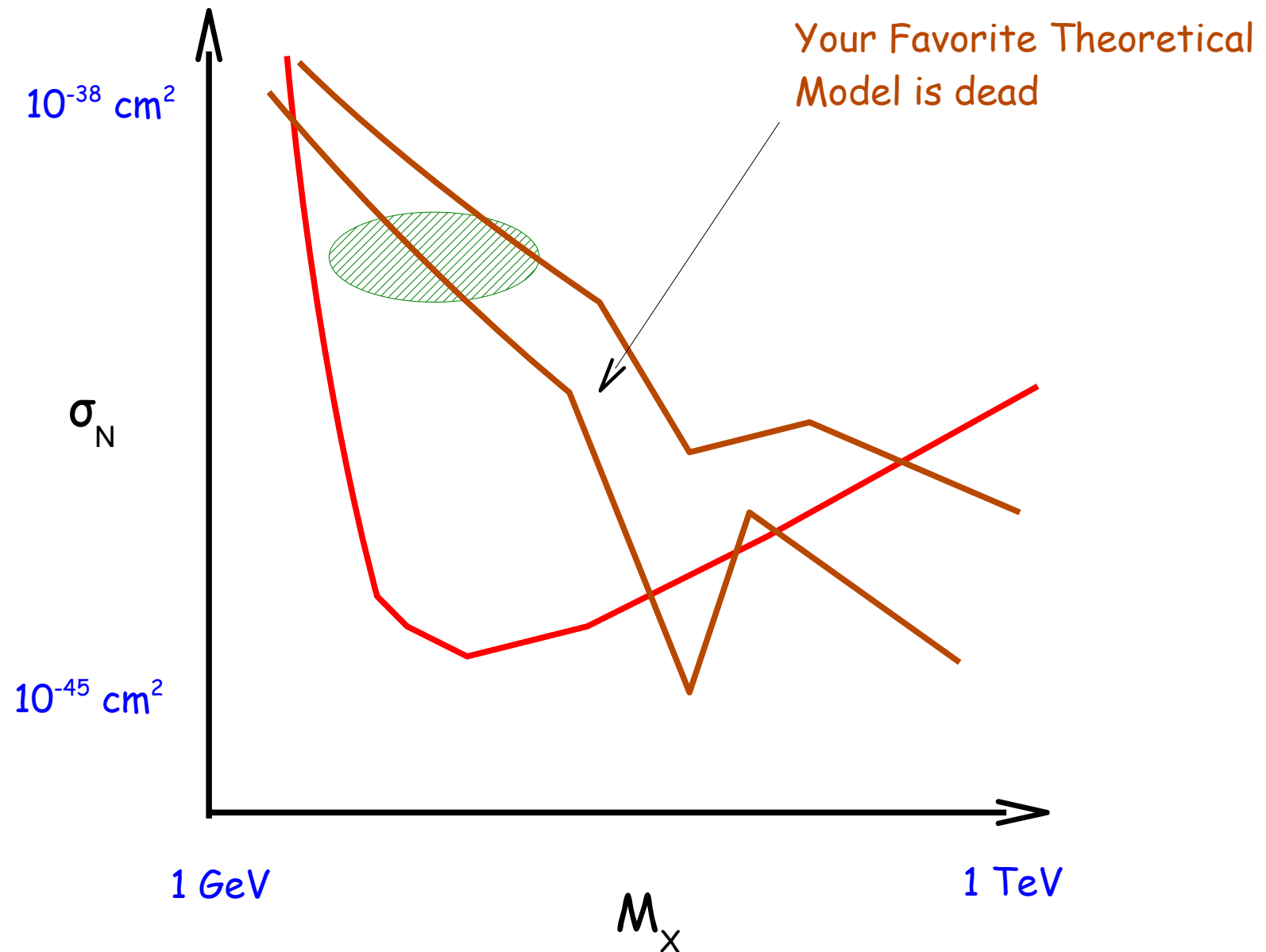
How Direct Search results are presented



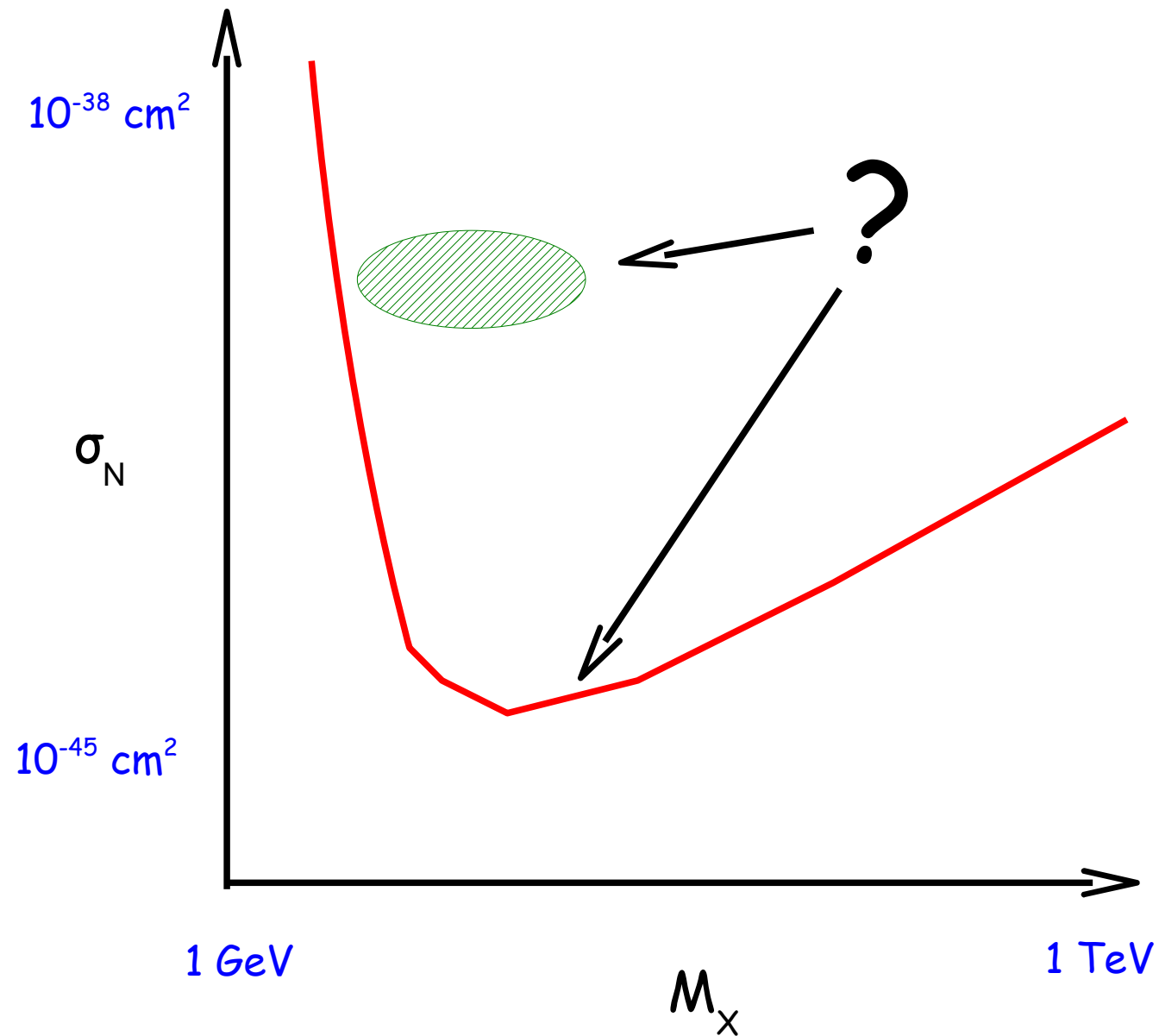
How Direct Search results are presented



How Direct Search results are presented



How Direct Search results are presented



CDMS-II	2 events...	November 2009	→
CoGeNT	Excess	March 2010	↗
Xenon100	(first results)	May 2010	↘
CDMS-II	(low recoil analysis)	December 2010	↓
Xenon100	(100 days exp.)	May 2011	→
Xenon10	Low recoil analysis	July 2010	→
CoGeNT	Modulation	May 2011	→
CRESST	Excess	September 2011	↗
CoGeNT	Contamination?	September 2011	→
CDMS-II	Modulation?	Winter 2012	↘

State of the Art

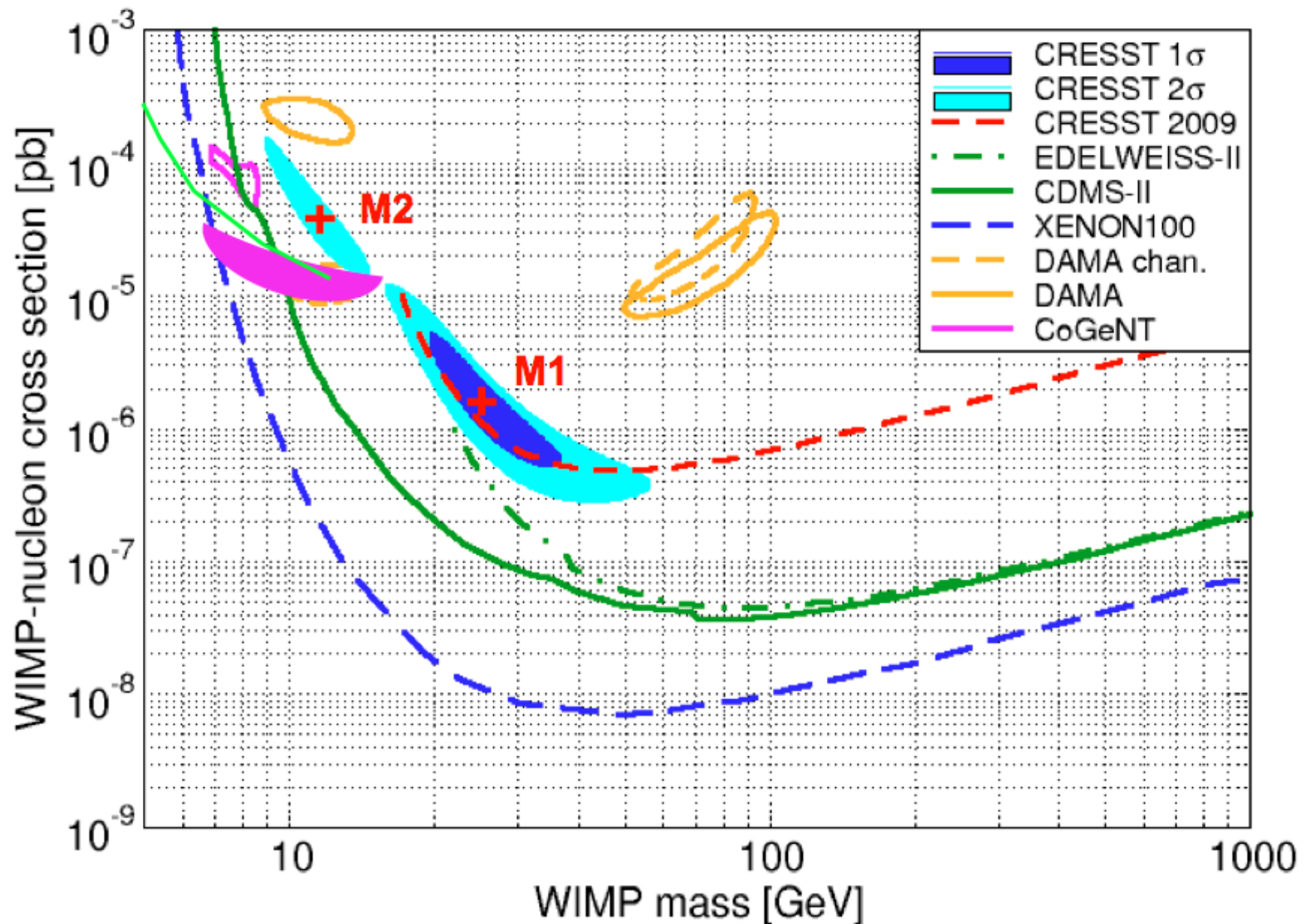
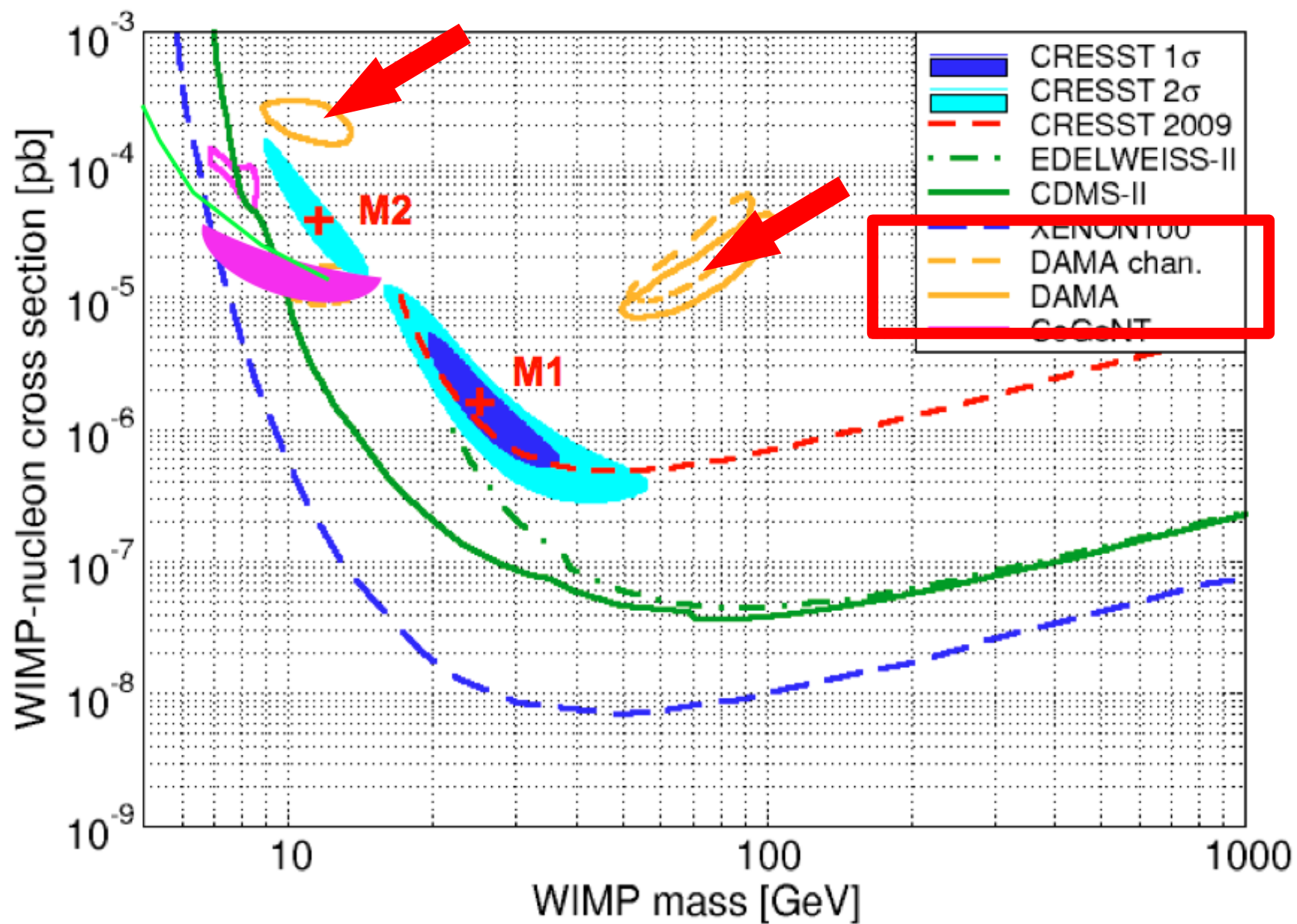
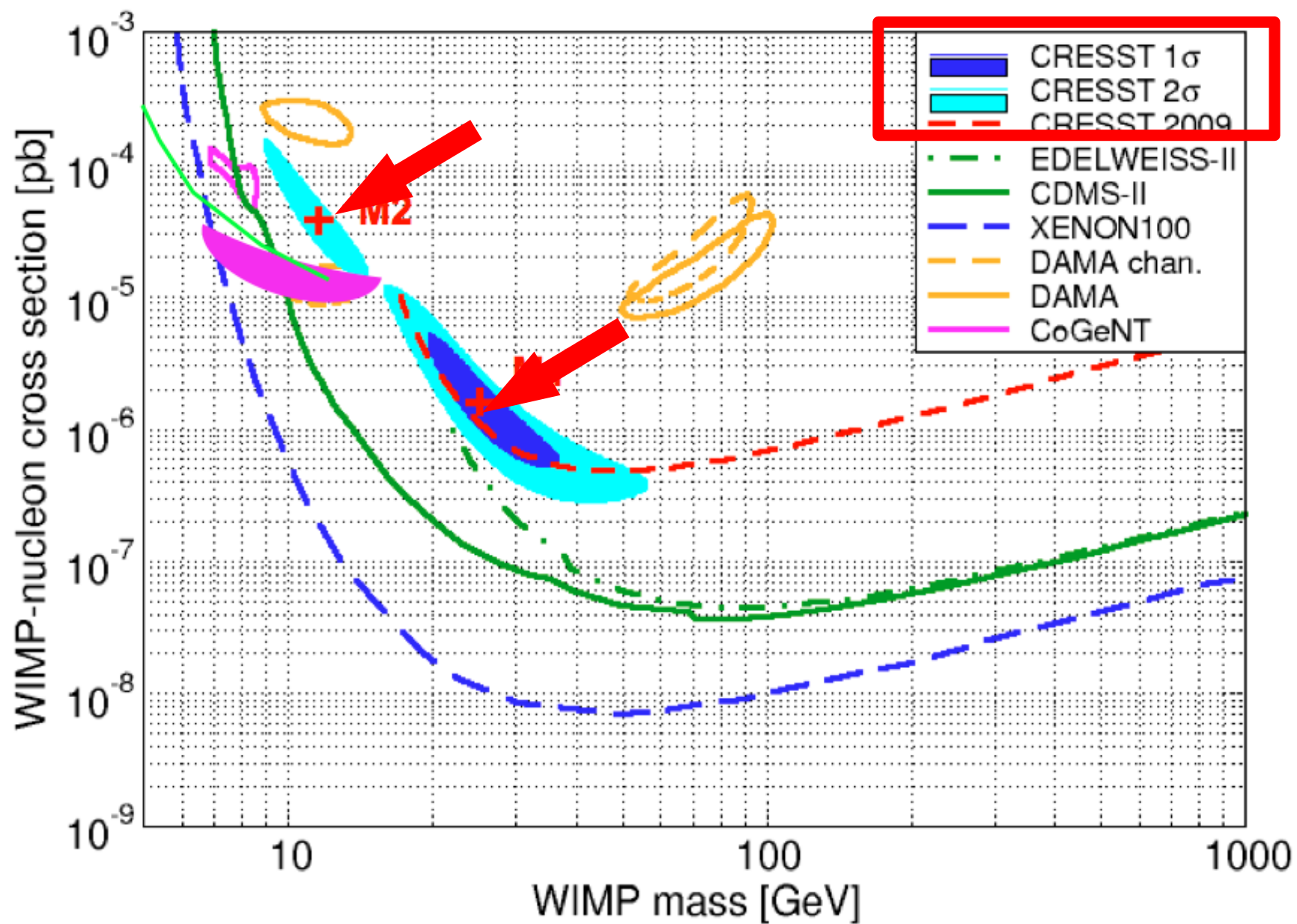
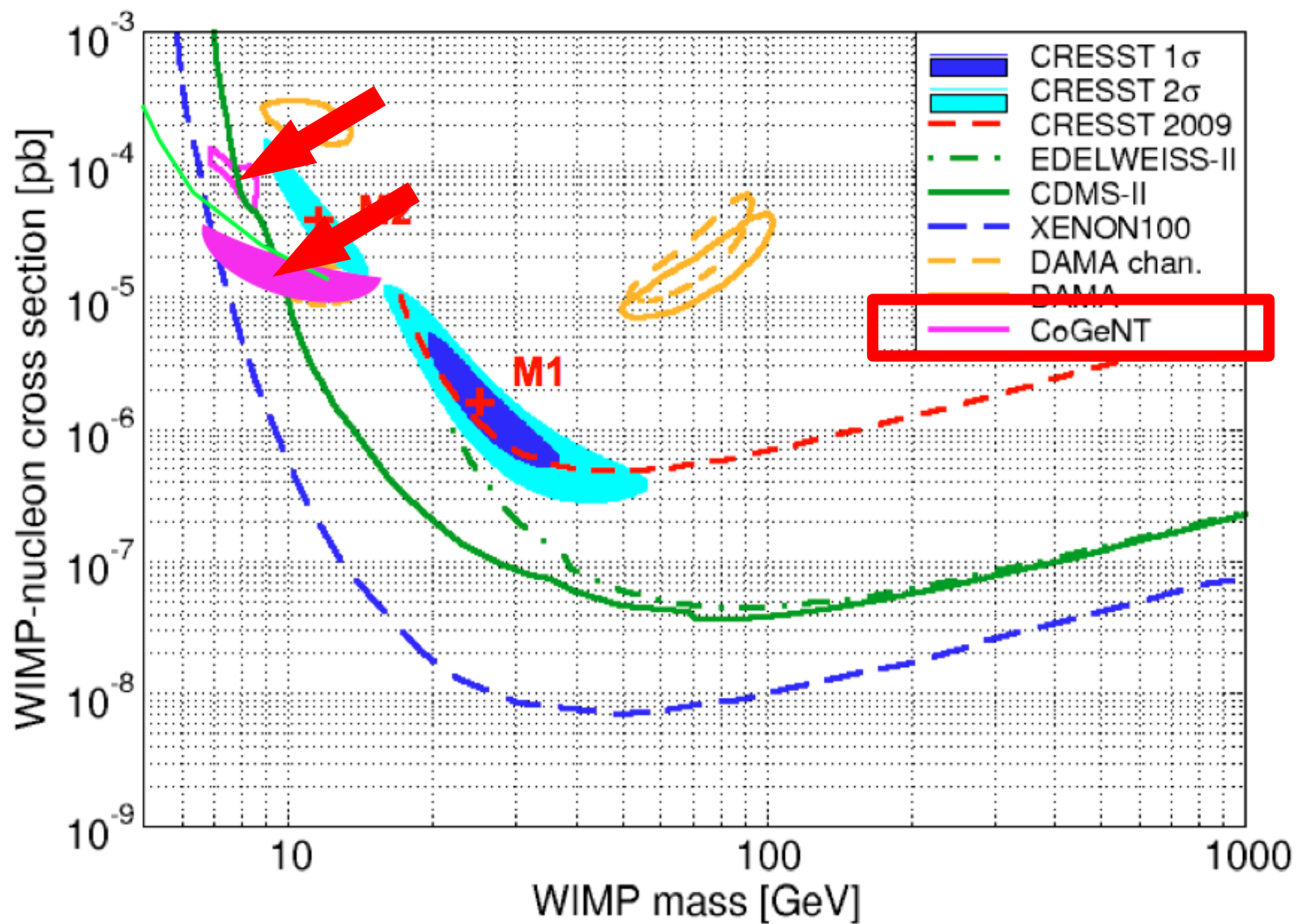


Fig. From CRESST (2011)







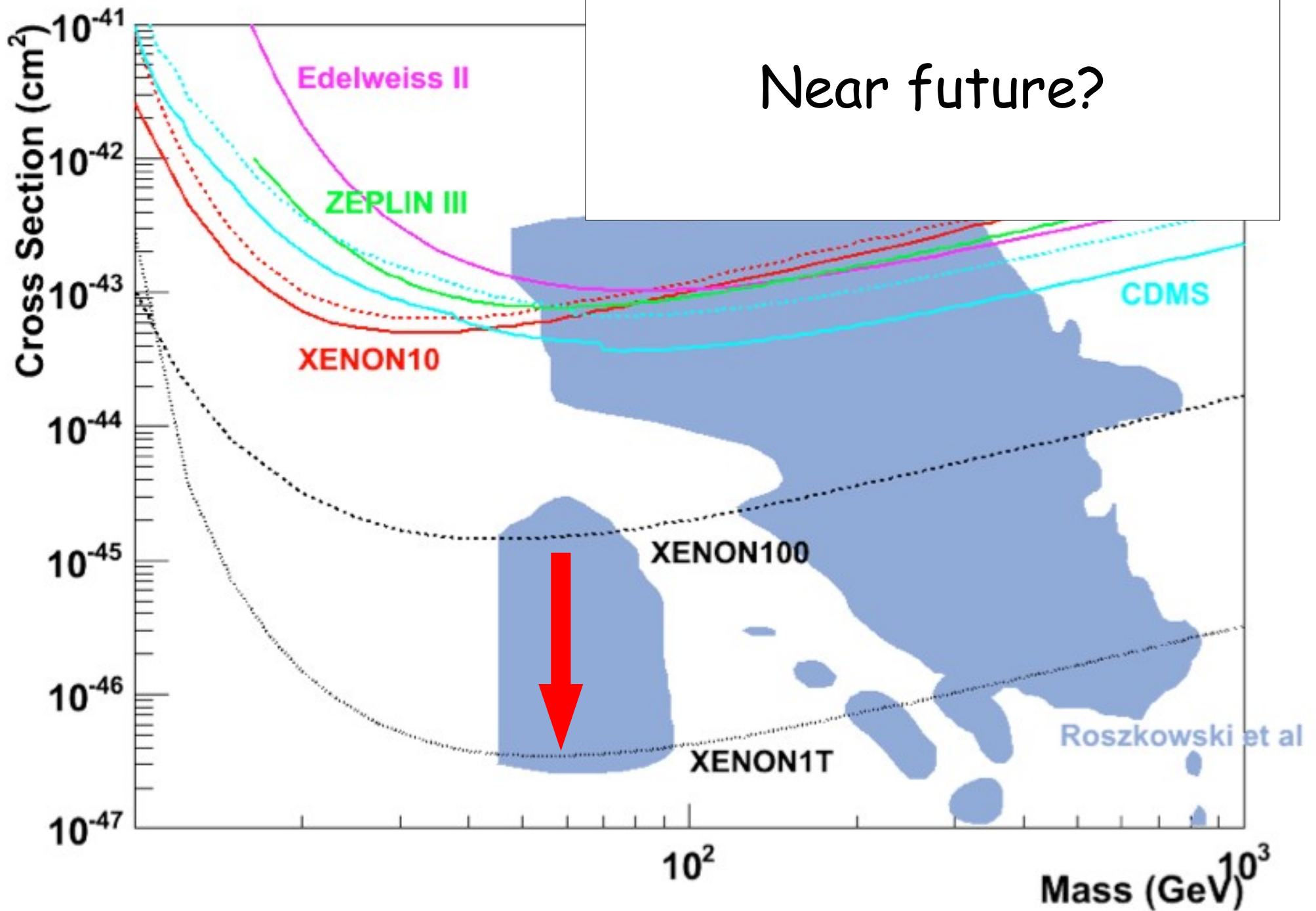
Direct search is an **heroic** effort to actually see dark matter.

The signal is expected to be very tiny, so background is the enemy.

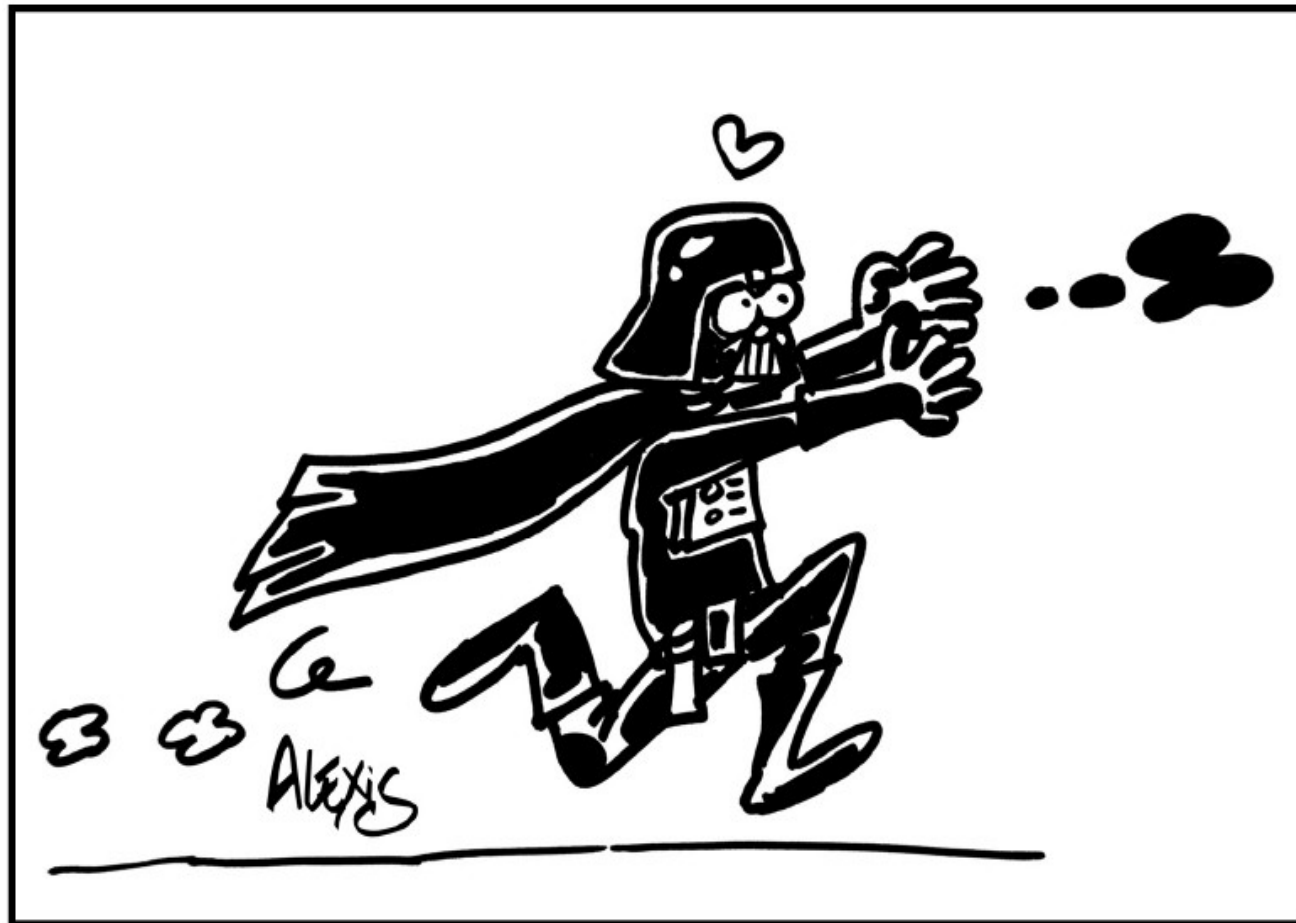
There are some positive signals, but there are excluded by other DM experiments.

Most likely the problem is background. Or perhaps it is DM, but of a kind we have not anticipated.

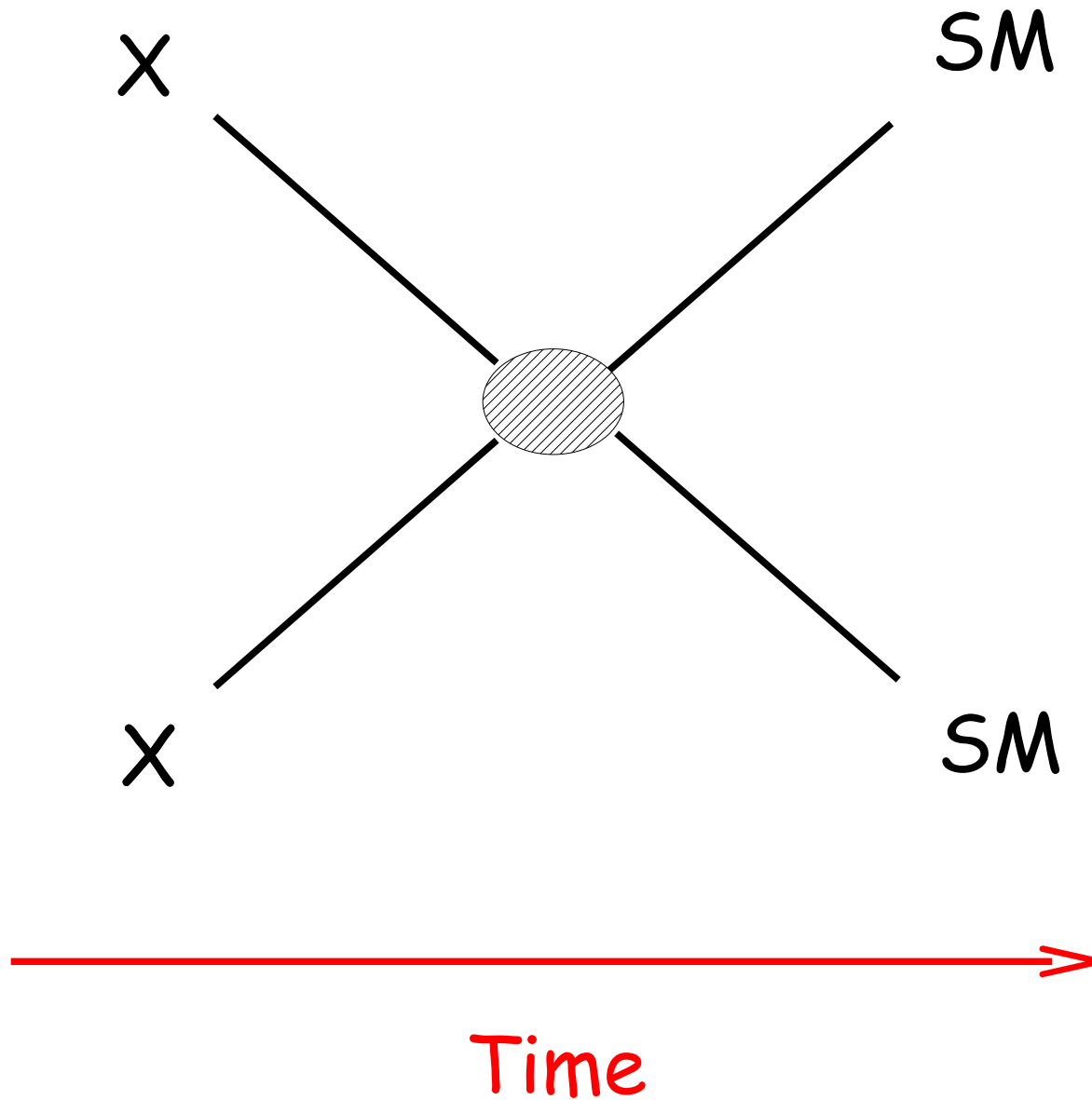
Near future?



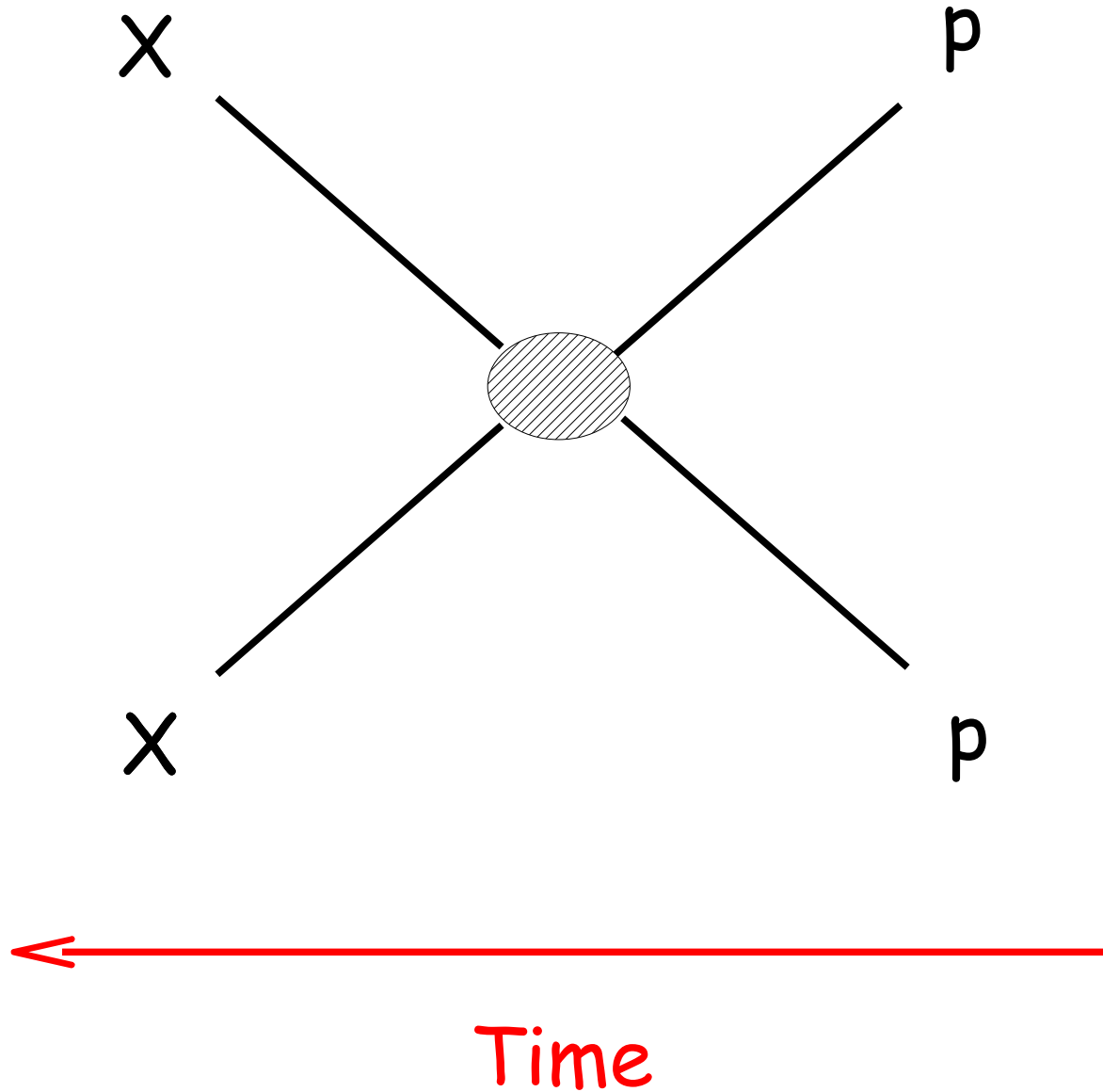
How to search for Dark Matter? Part 2



Dark Matter Abundance (Early Universe)

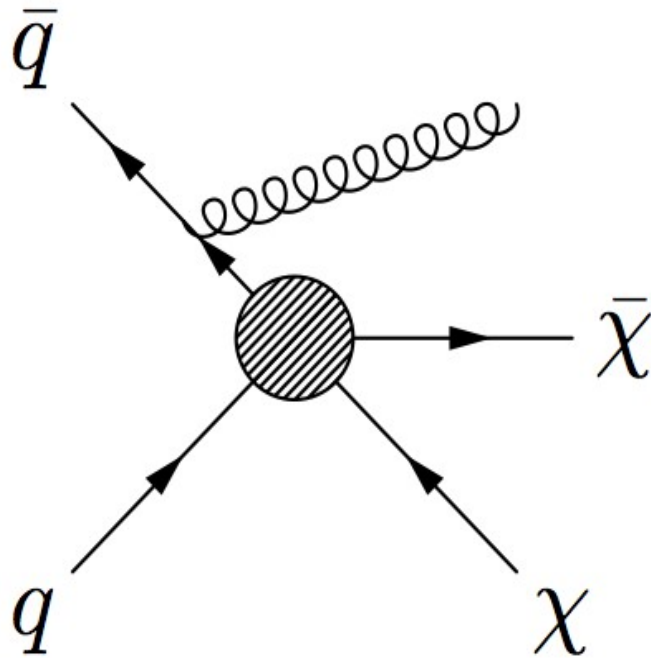


Dark Matter Production @ Colliders



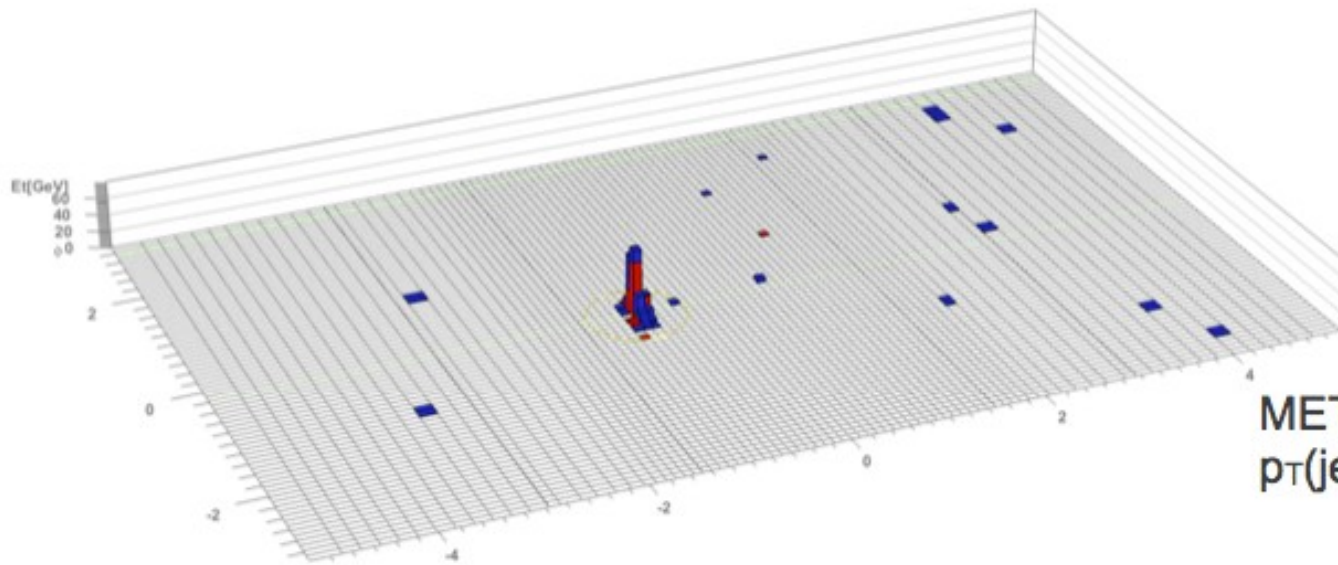
Eg LHC

$P + P \rightarrow \text{jets} + \text{Missing Energy}$

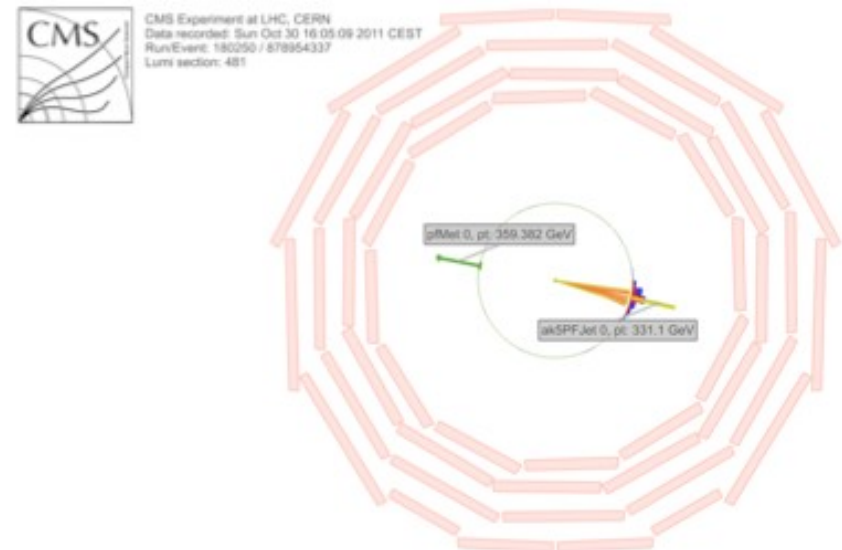


Possibly Dark Matter

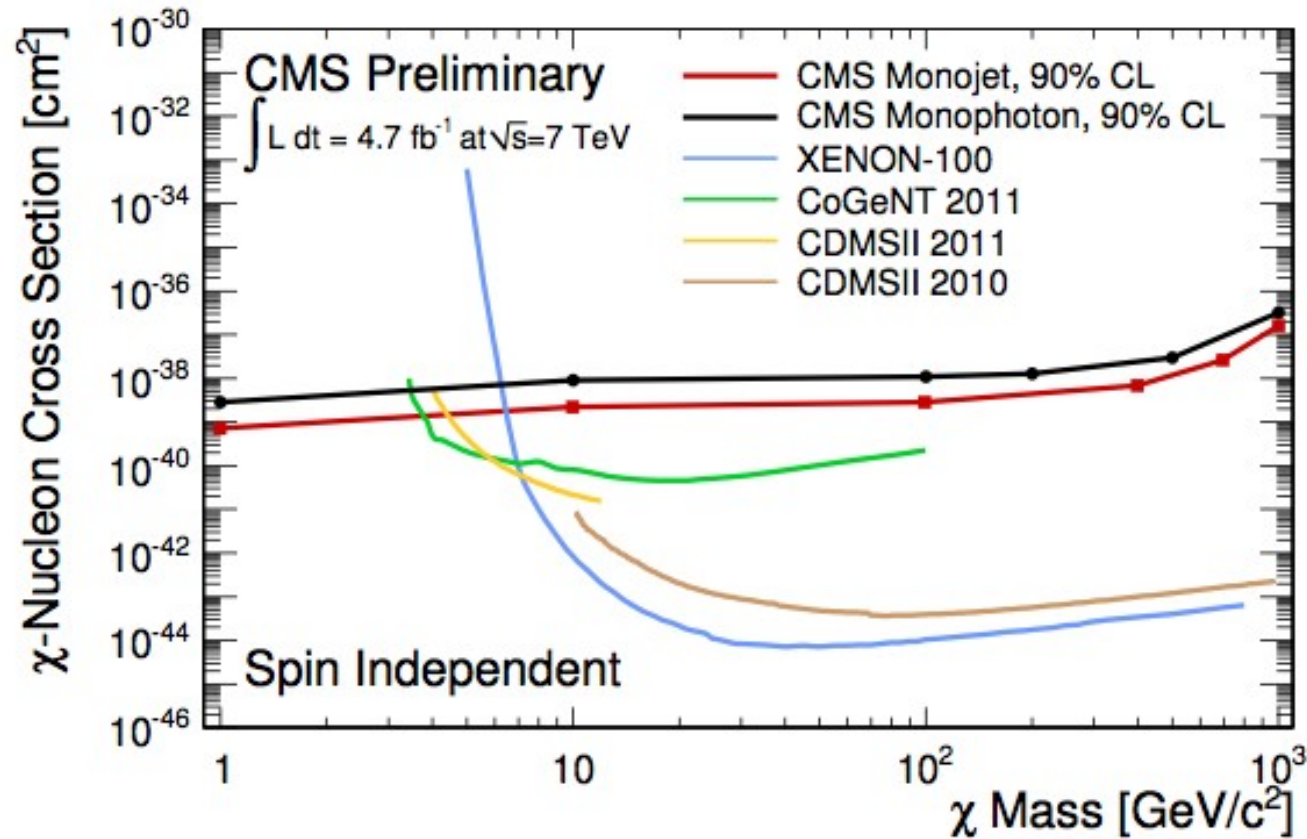
A MONOJET EVENT



$MET = 359$ GeV
 $p_T(\text{jet1}) = 331$ GeV

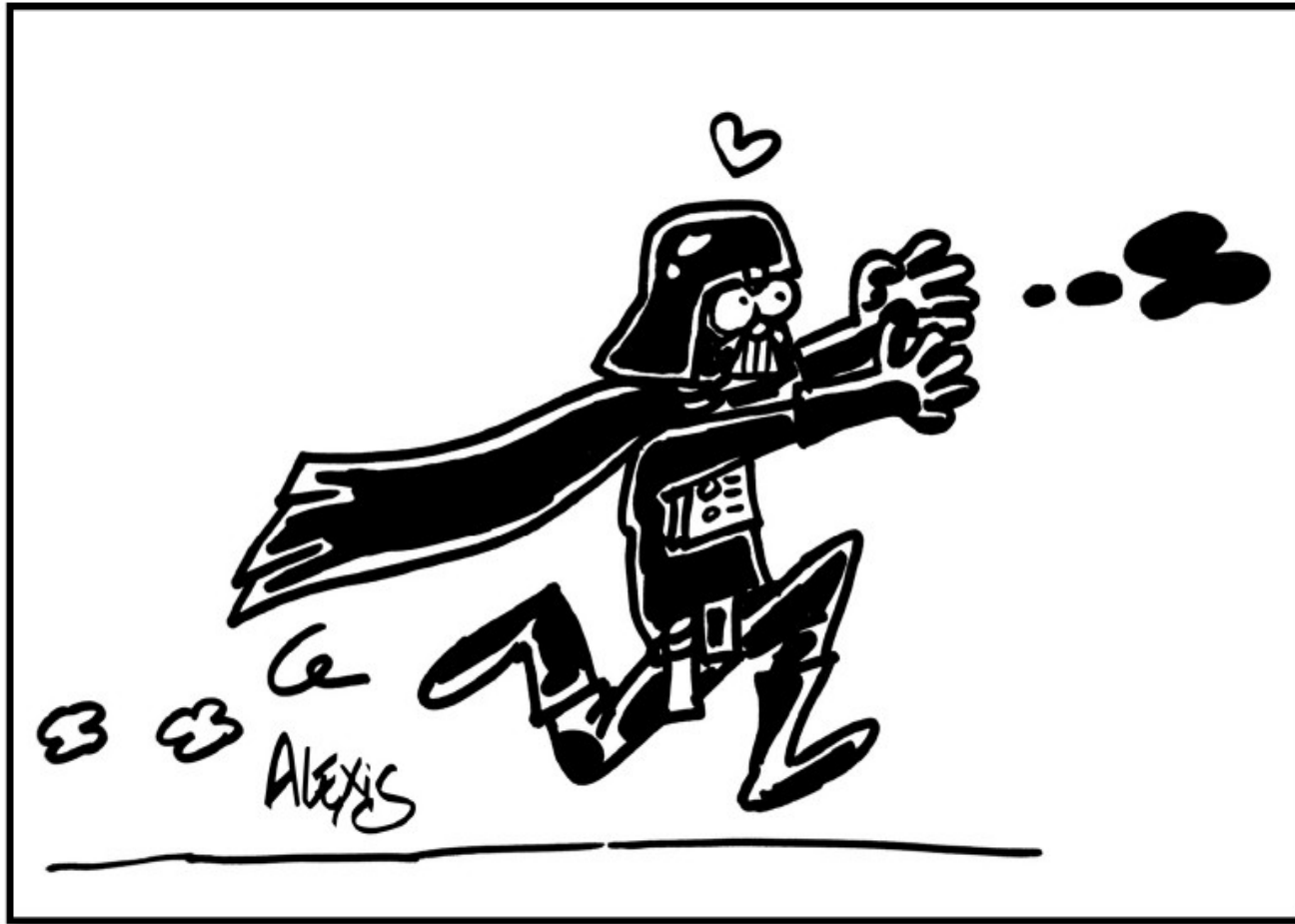


DARK MATTER SPIN-INDEPENDENT LIMITS

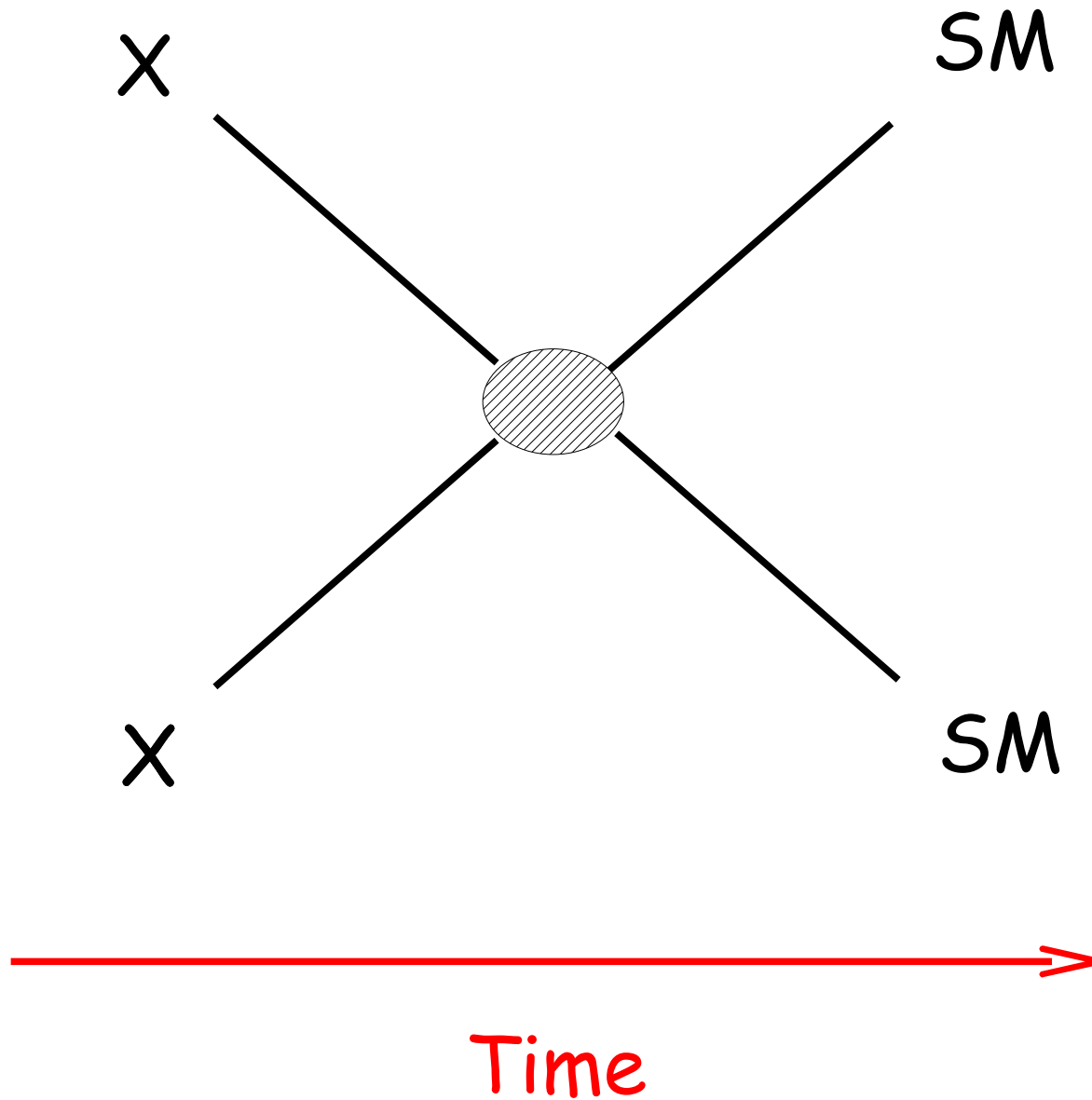


- *Best limits for low mass DM, below 3.5 GeV, a region as yet unexplored by direct detection experiments*

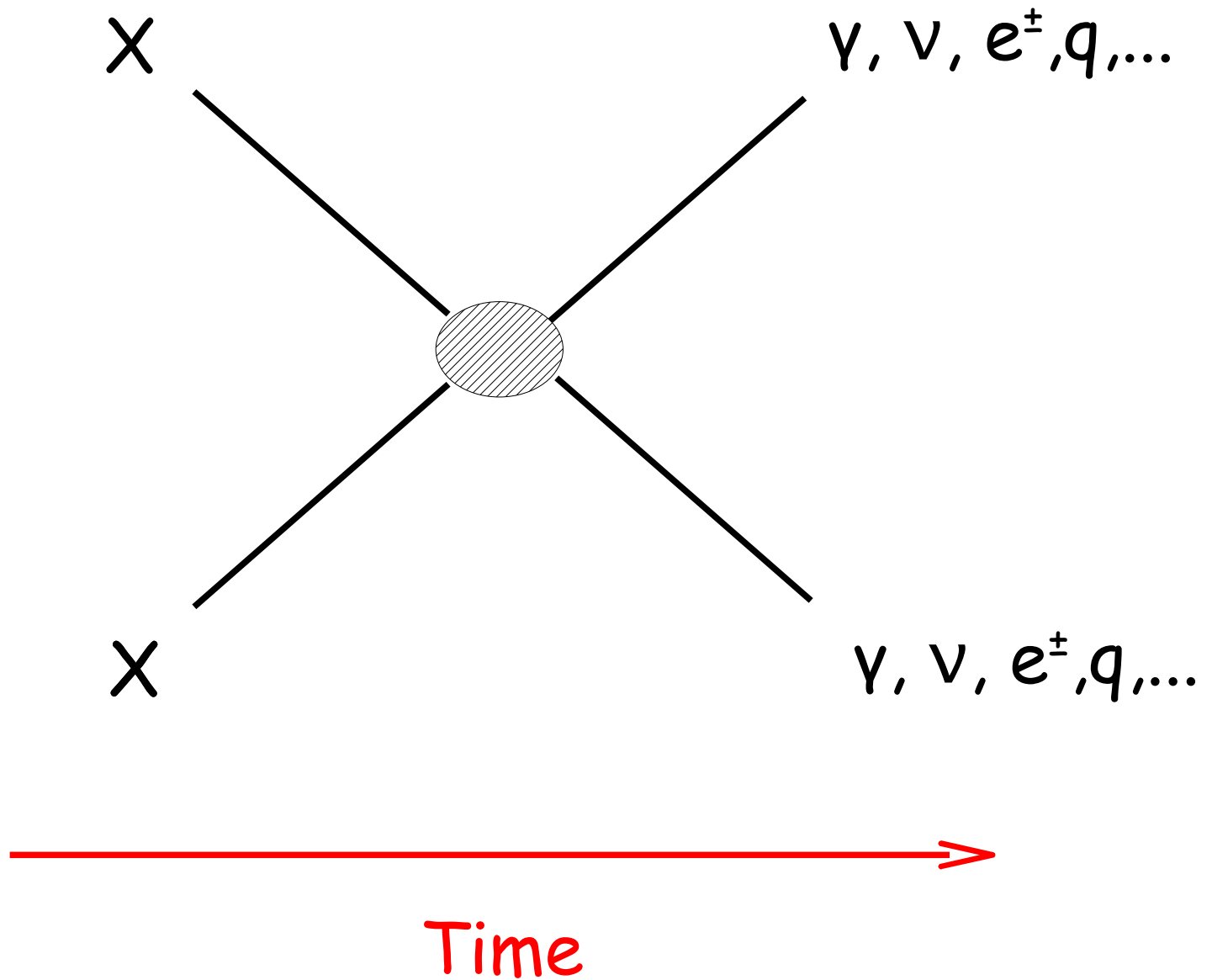
How to search for Dark Matter? Part 3



Dark Matter Abundance (Early Universe)



Indirect Searches



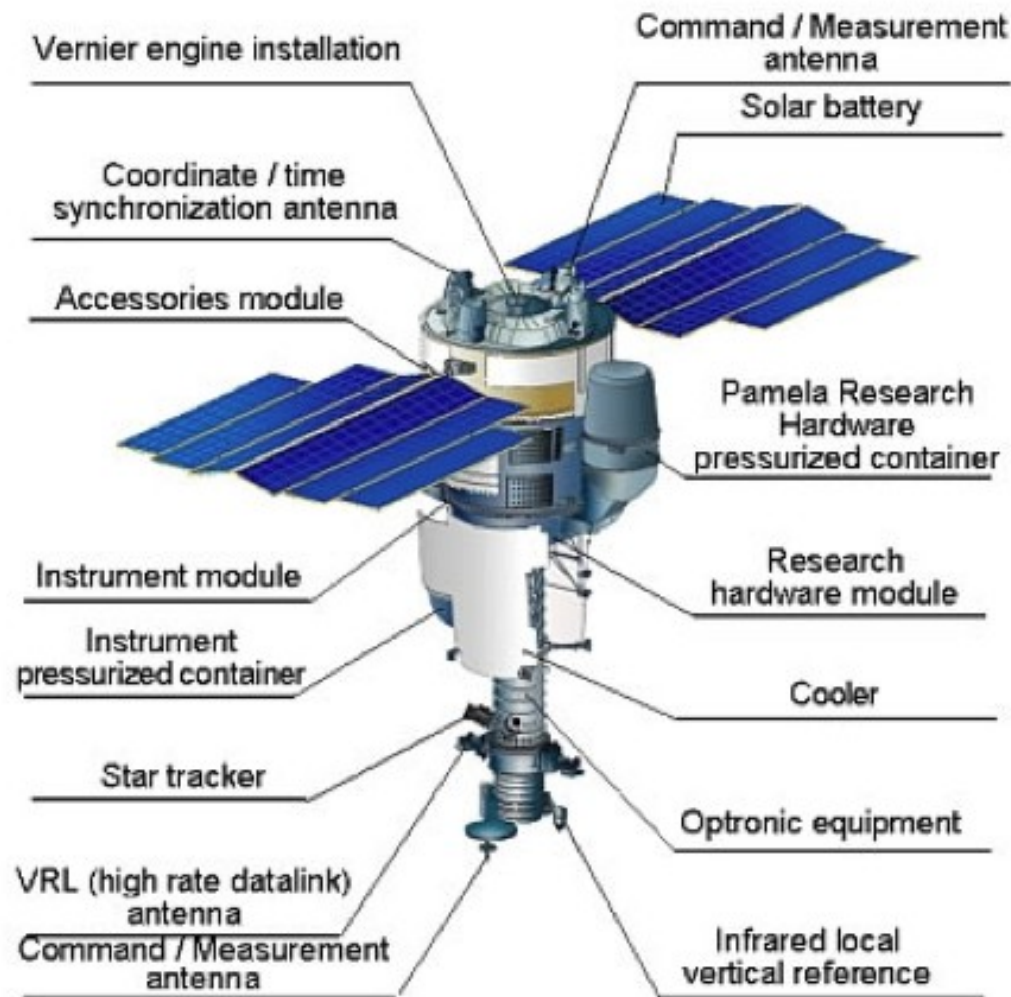
Dark Matter (ie WIMPs) may annihilate in

1. Antimatter (e^+ , anti-protons,...)

2. Neutrinos

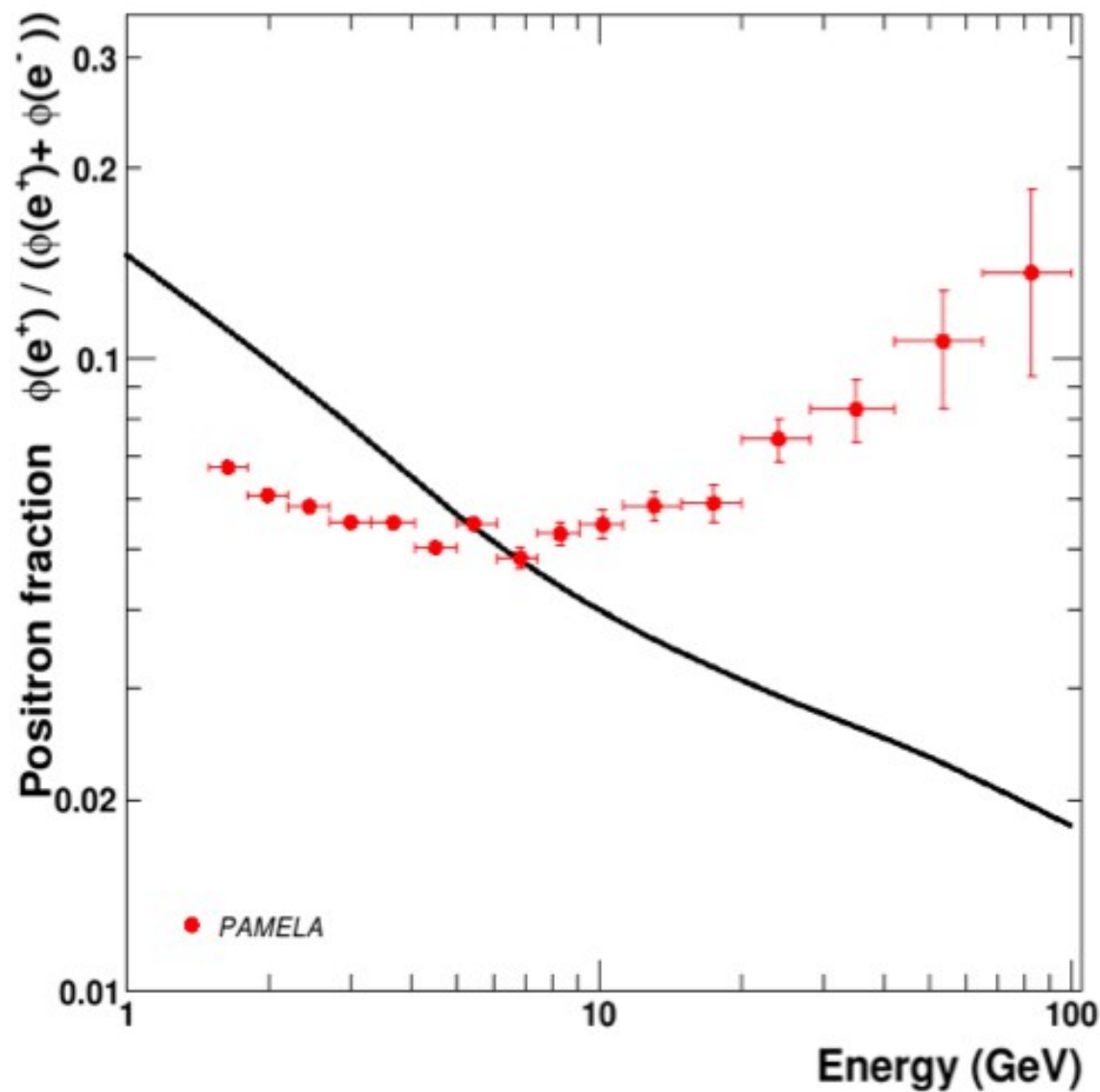
3. Gamma rays

PAMELA, a Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics

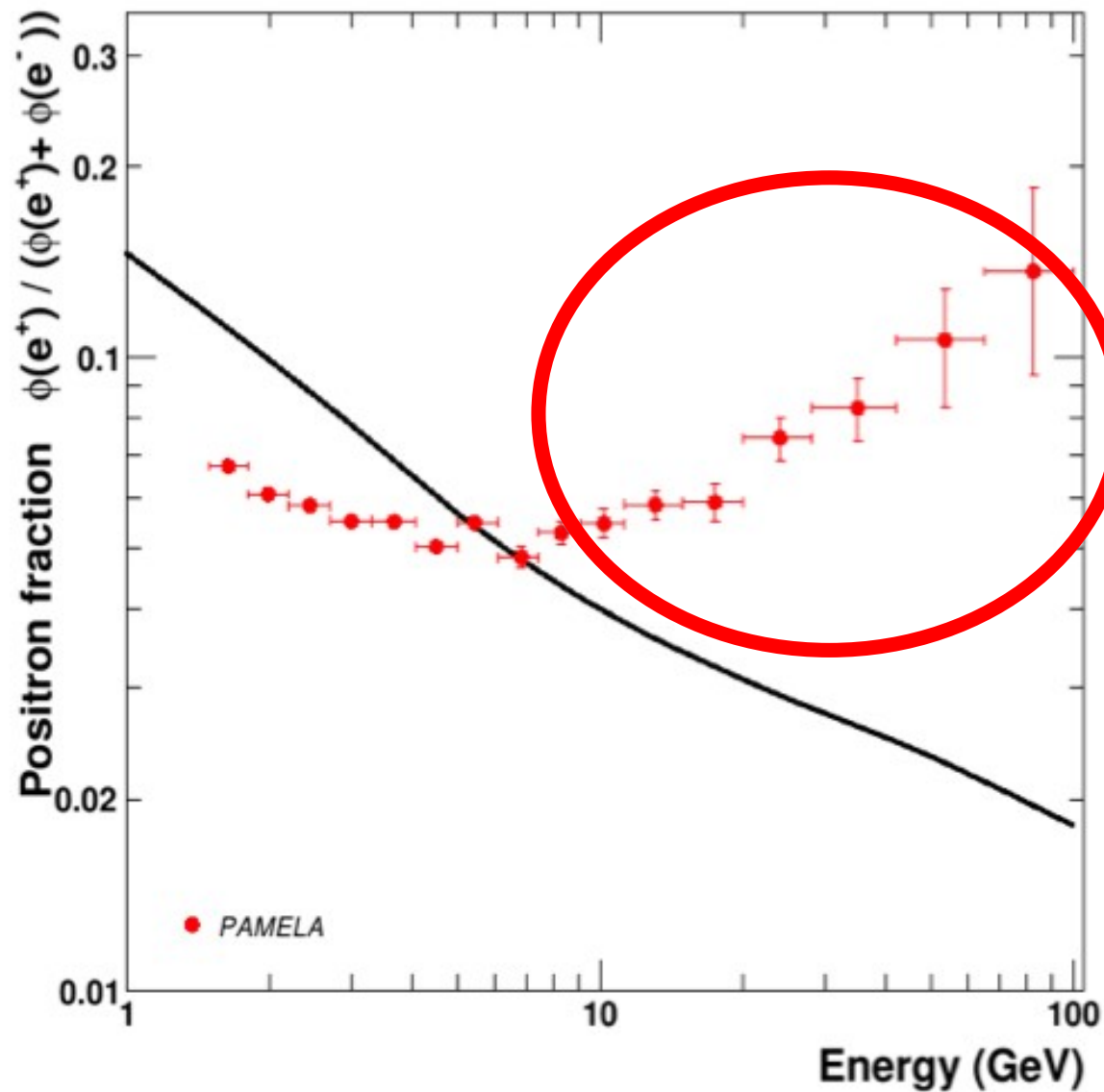


A picture of Pamela

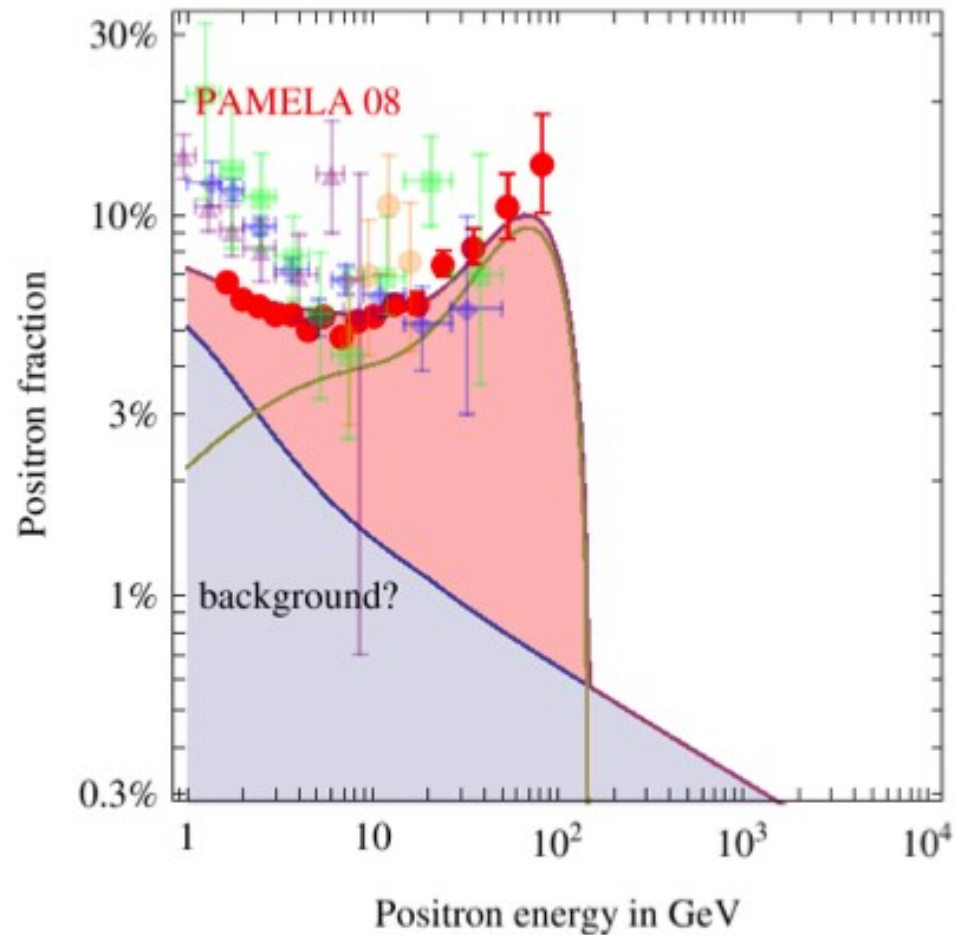
Pamela results (released October 28 2008)



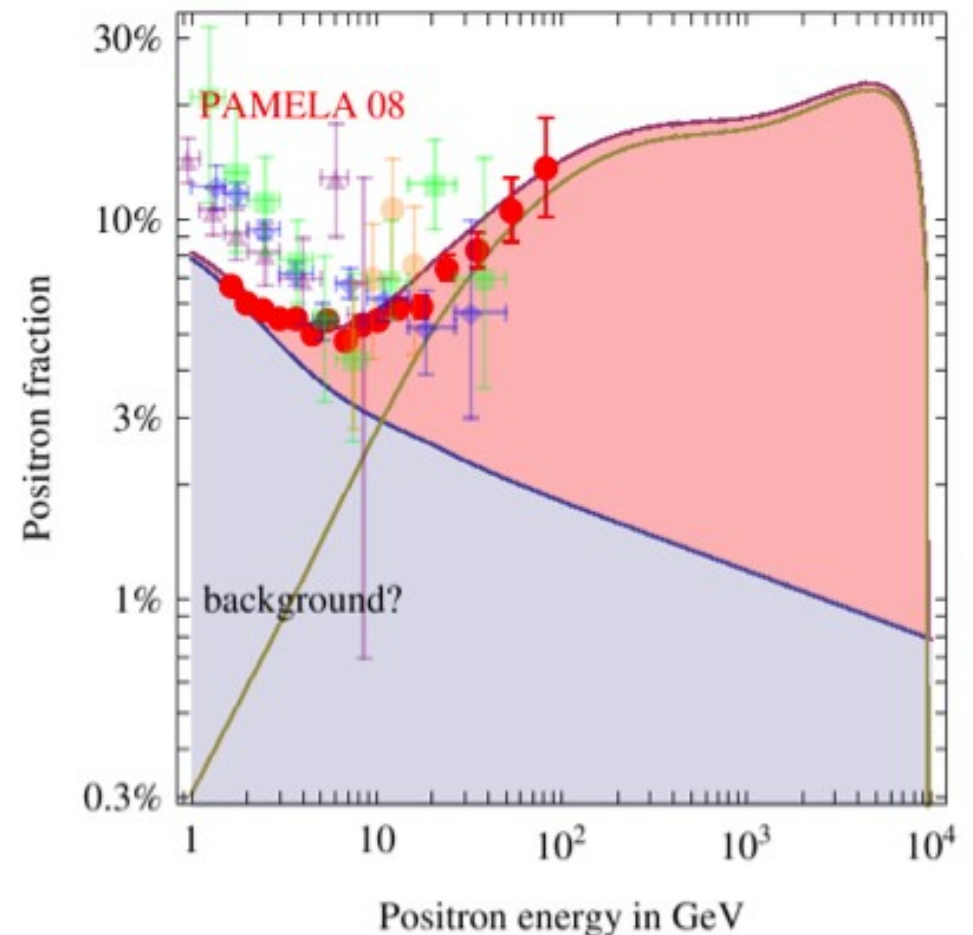
Pamela results (released October 28 2008)



$$DM + DM \rightarrow \dots \rightarrow e^+ e^- \dots$$



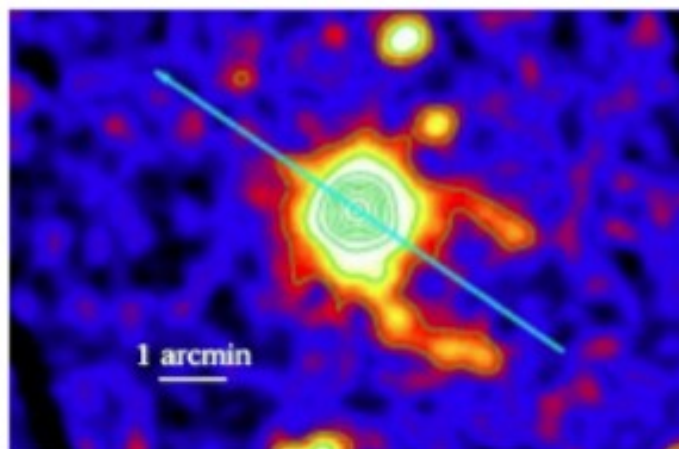
$$M_{DM} = 150 \text{ GeV into } W^+W^-$$



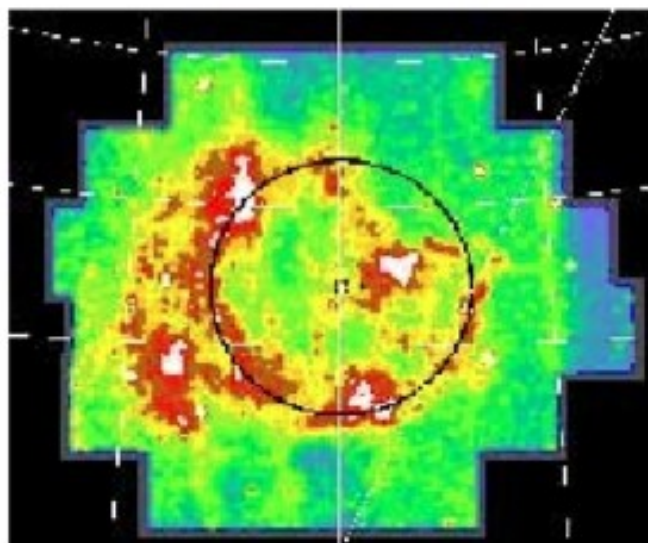
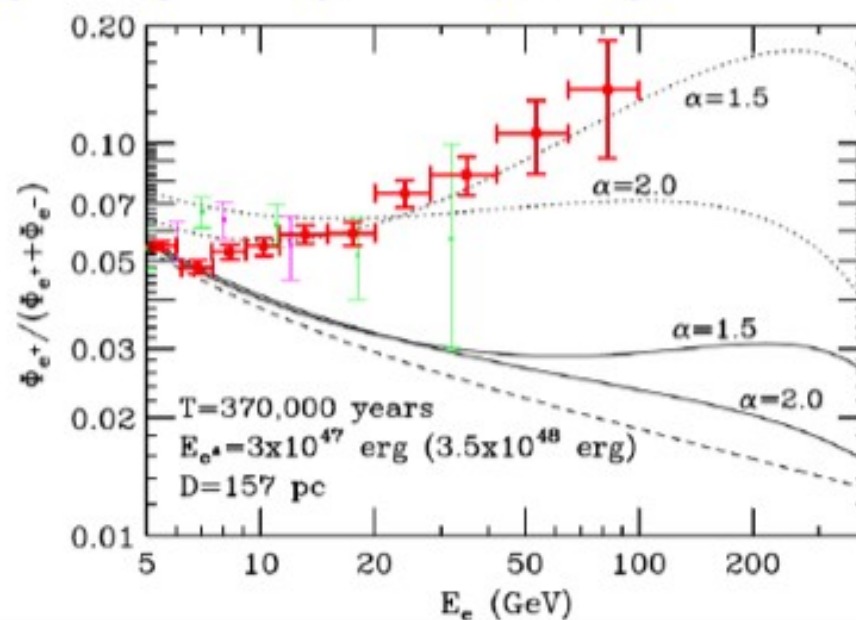
$$M_{DM} = 10 \text{ TeV into } W^+W^-$$

Figure from Cirelli, Strumia & Raidal

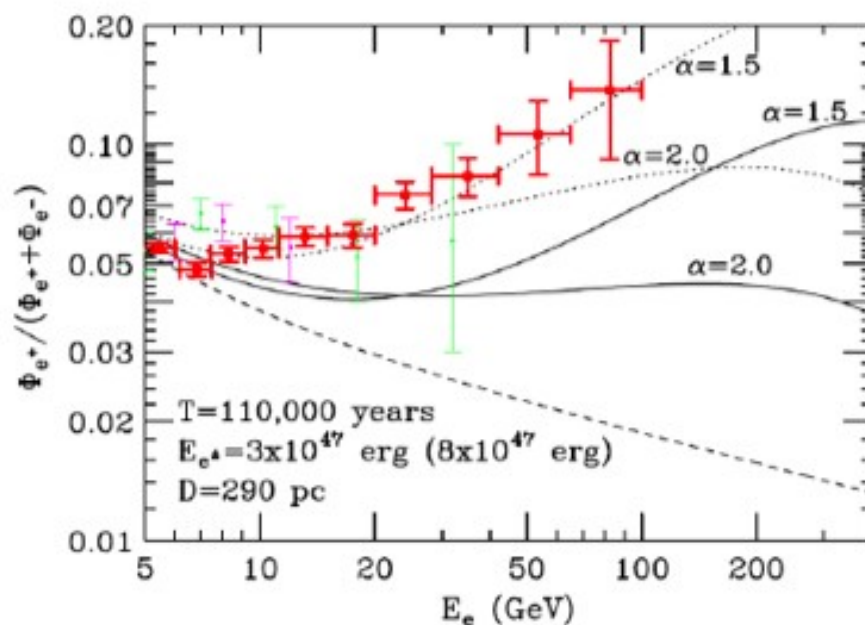
Geminga



$$dN_e/dE_e \propto E_e^{-\alpha} \exp(-E_e/600\text{GeV})$$

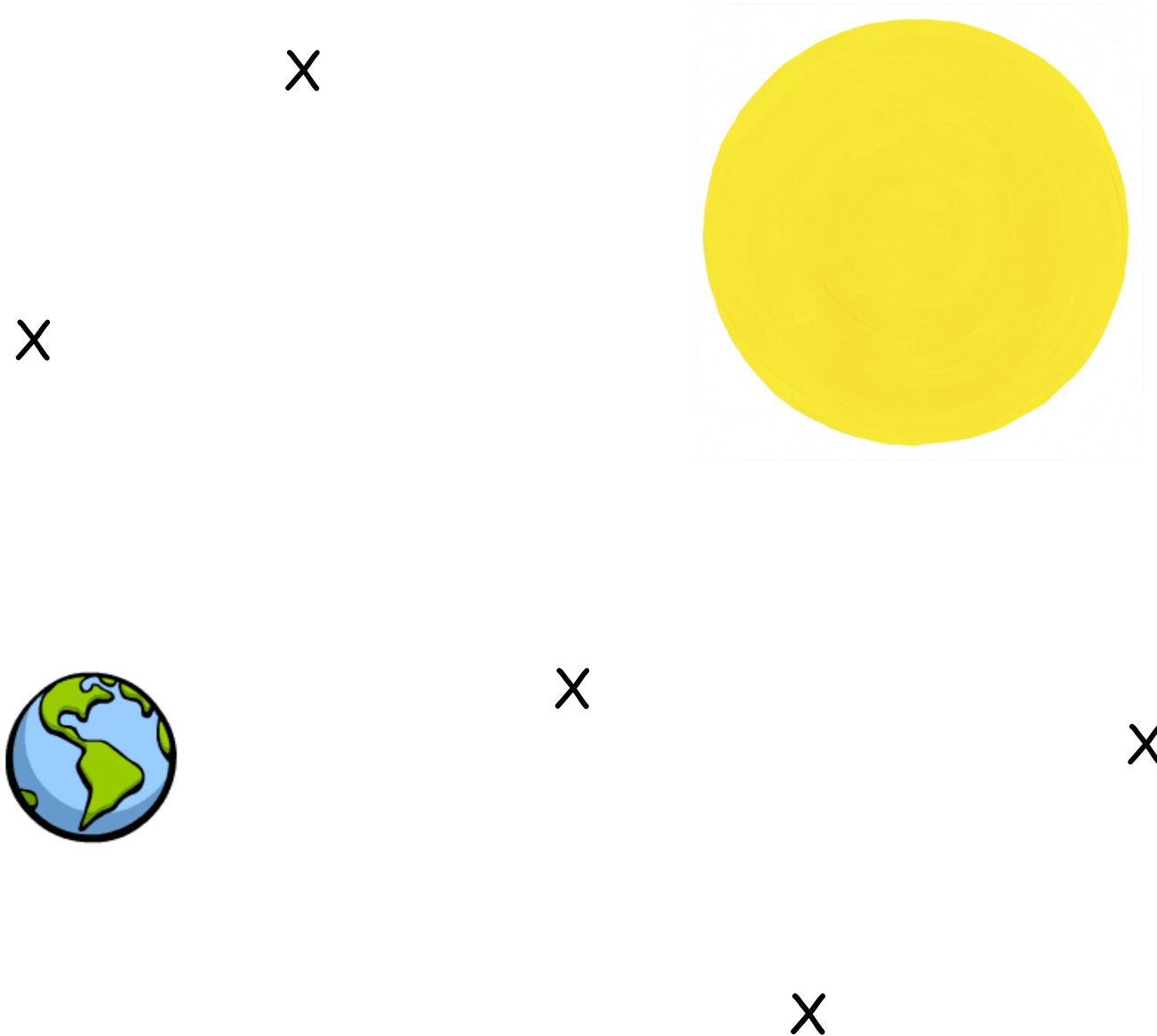


B0656+14



Hooper, Blasi, Serpico

Neutrinos





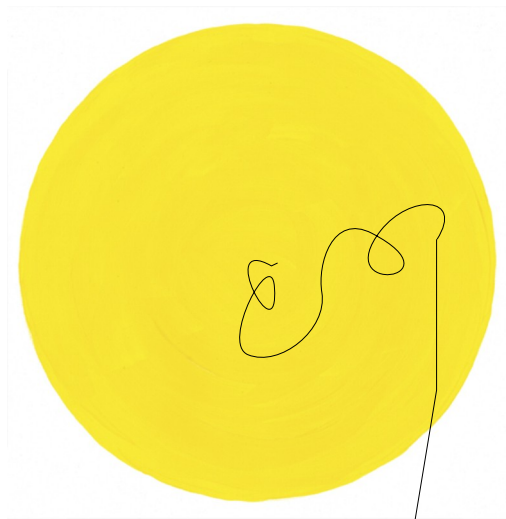
X

X

X

X

X





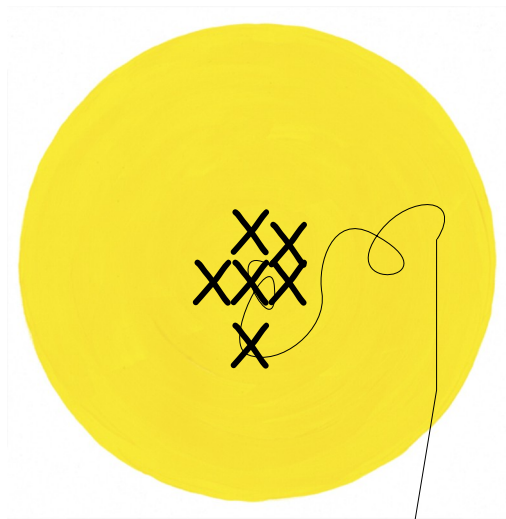
X

X

X

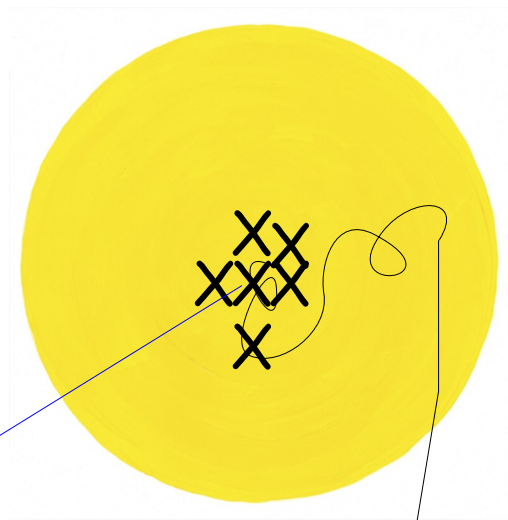
X

X





GeV ν flux !!!

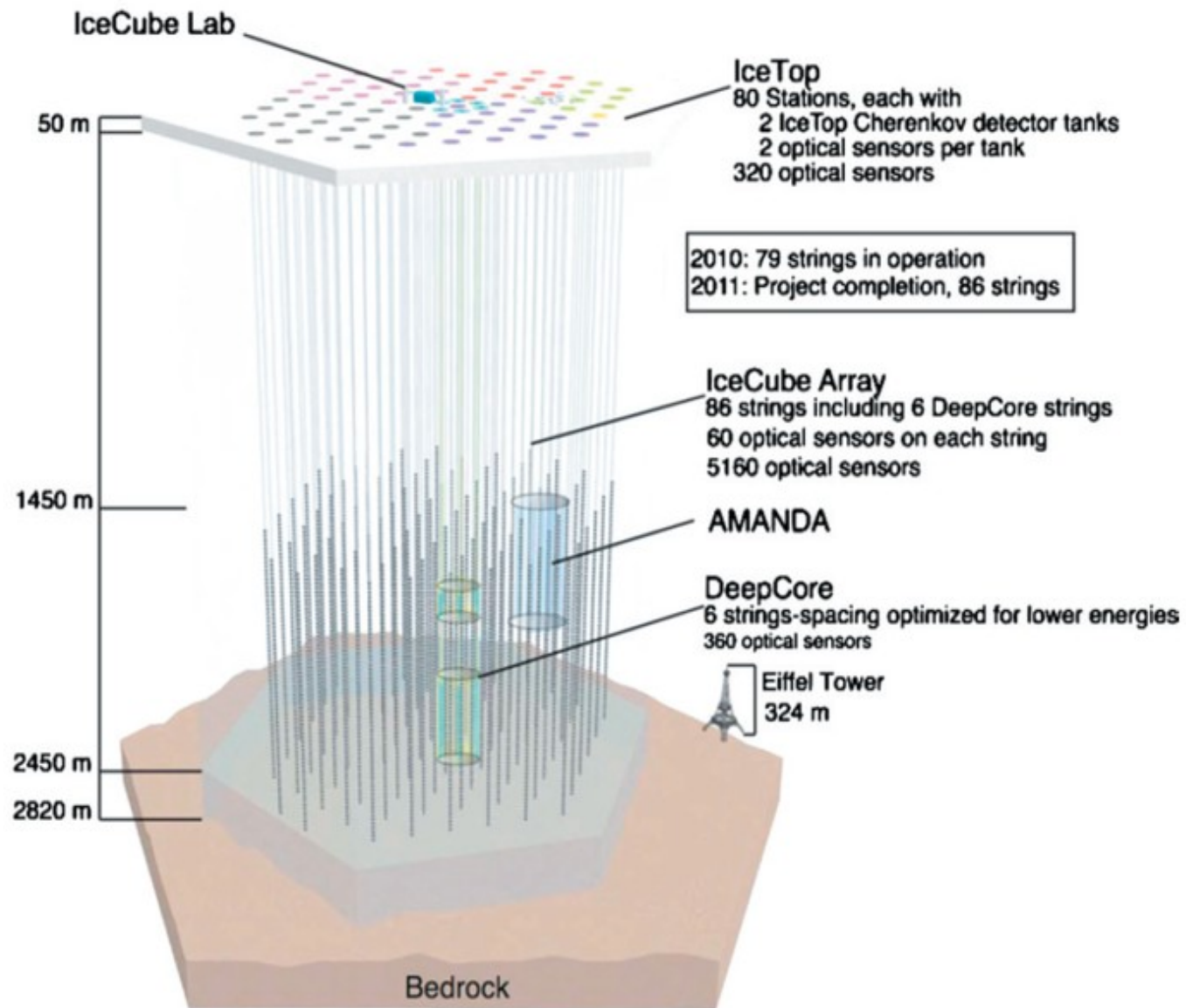


X

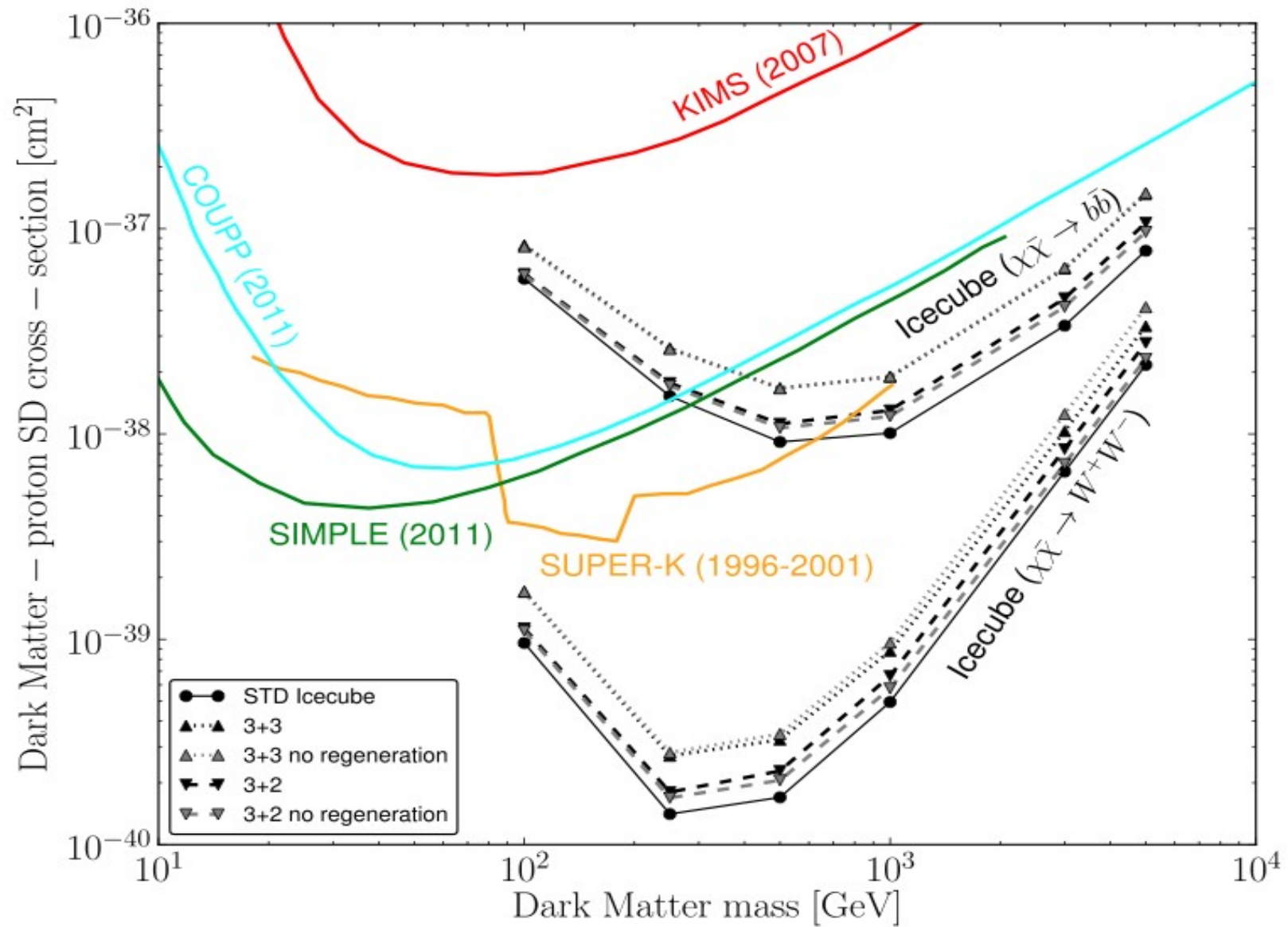
X

X

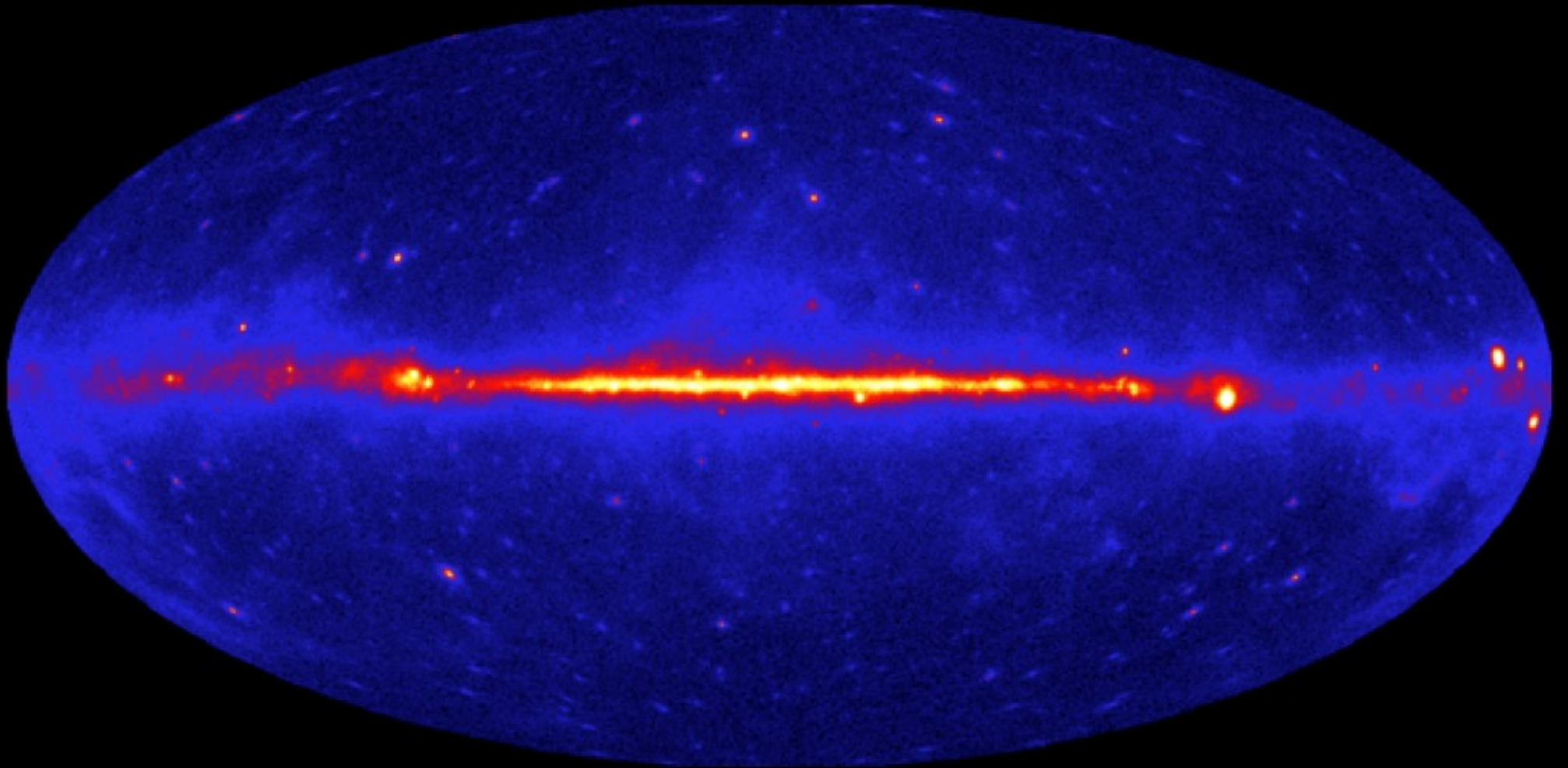
ICECUBE, the Biggest Dark Matter Detector In The World

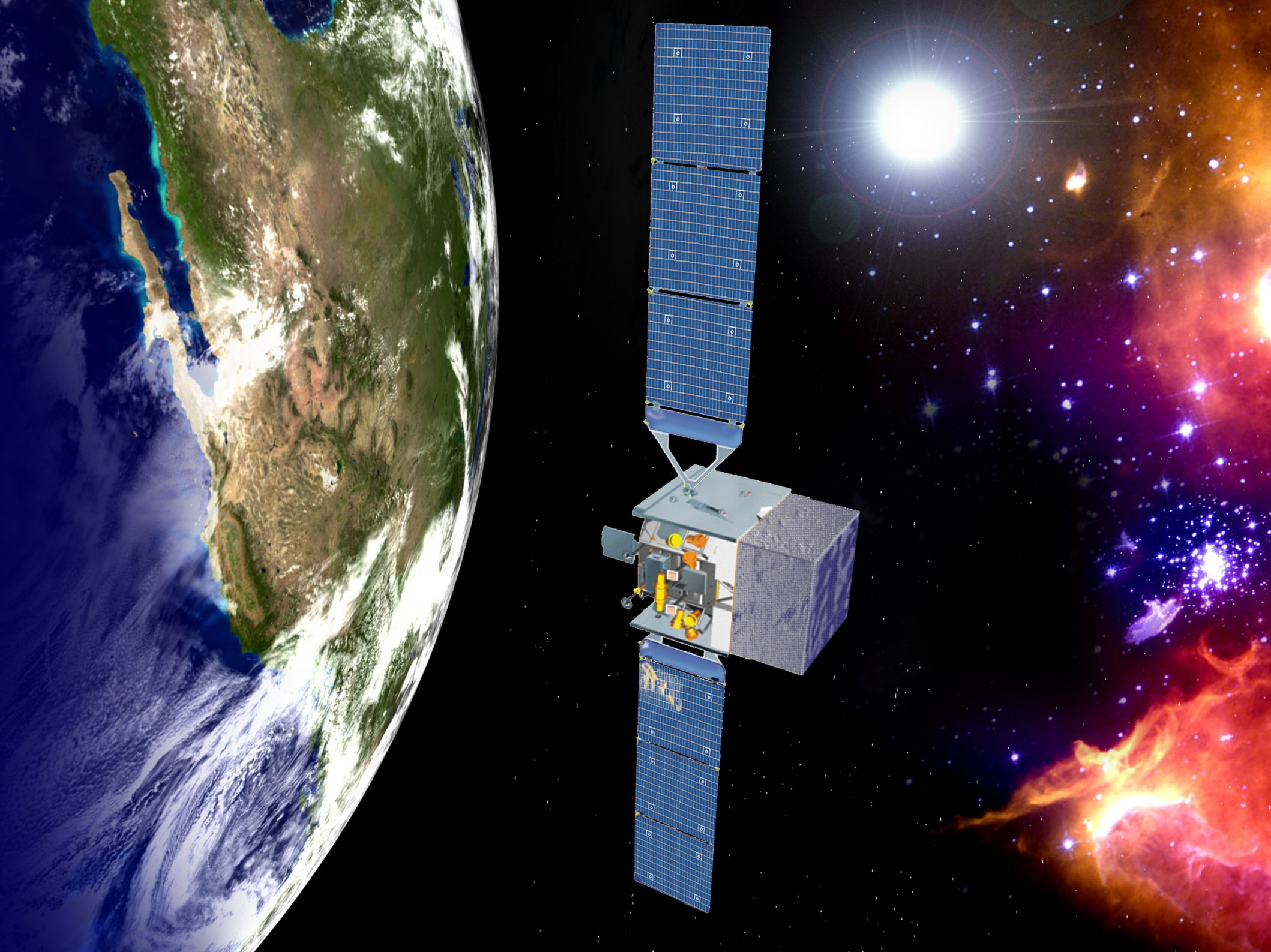


No signal seen, so ICECUBE sets exclusion limits...



Gamma rays (the sky as seen by Fermi-LAT)







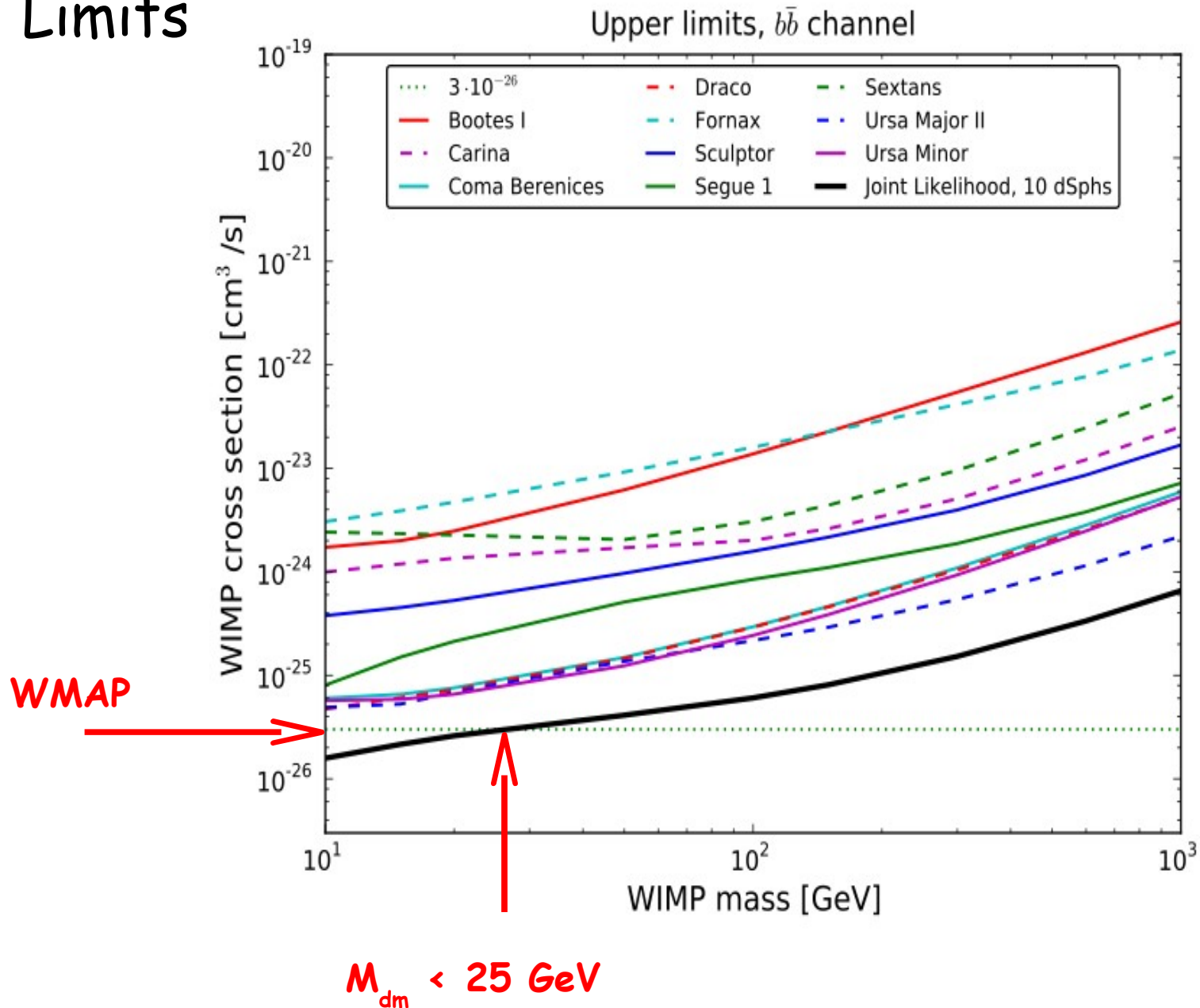


Observation by Fermi-LAT of

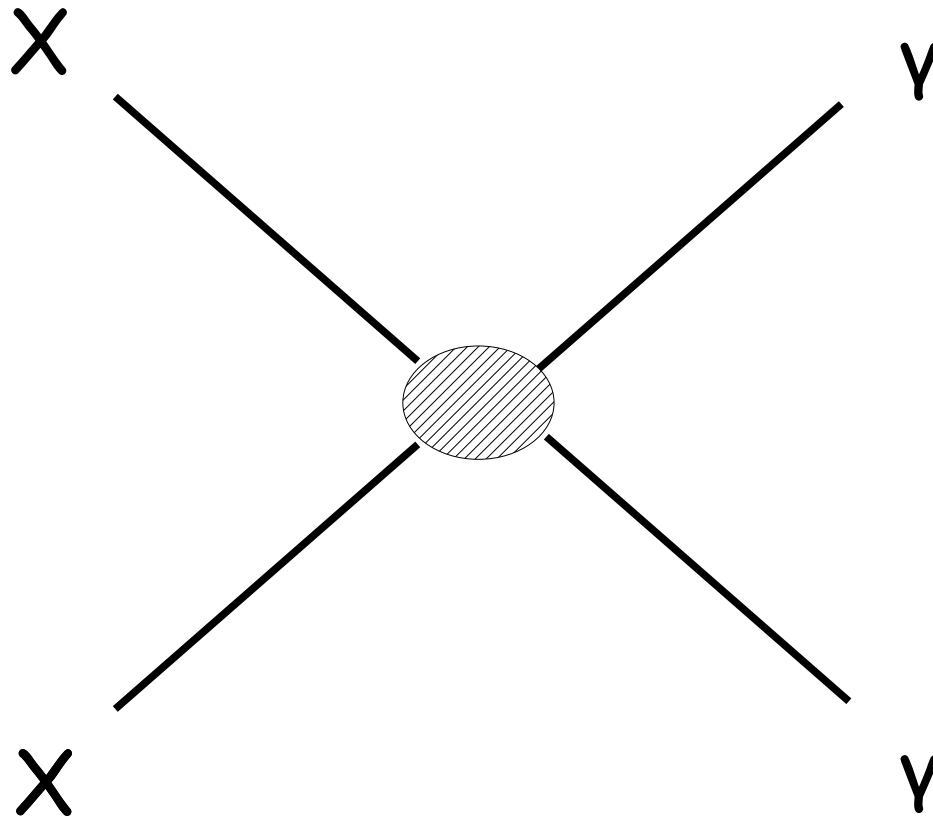
Dwarf Spheroidal Galaxies = Satellites of the Milky Way

- + Large Mass/Luminosity ratio (lot of DM there?)
- + Low astrophysical activity (low gamma-ray background)
- Only few dSphs (low statistics)

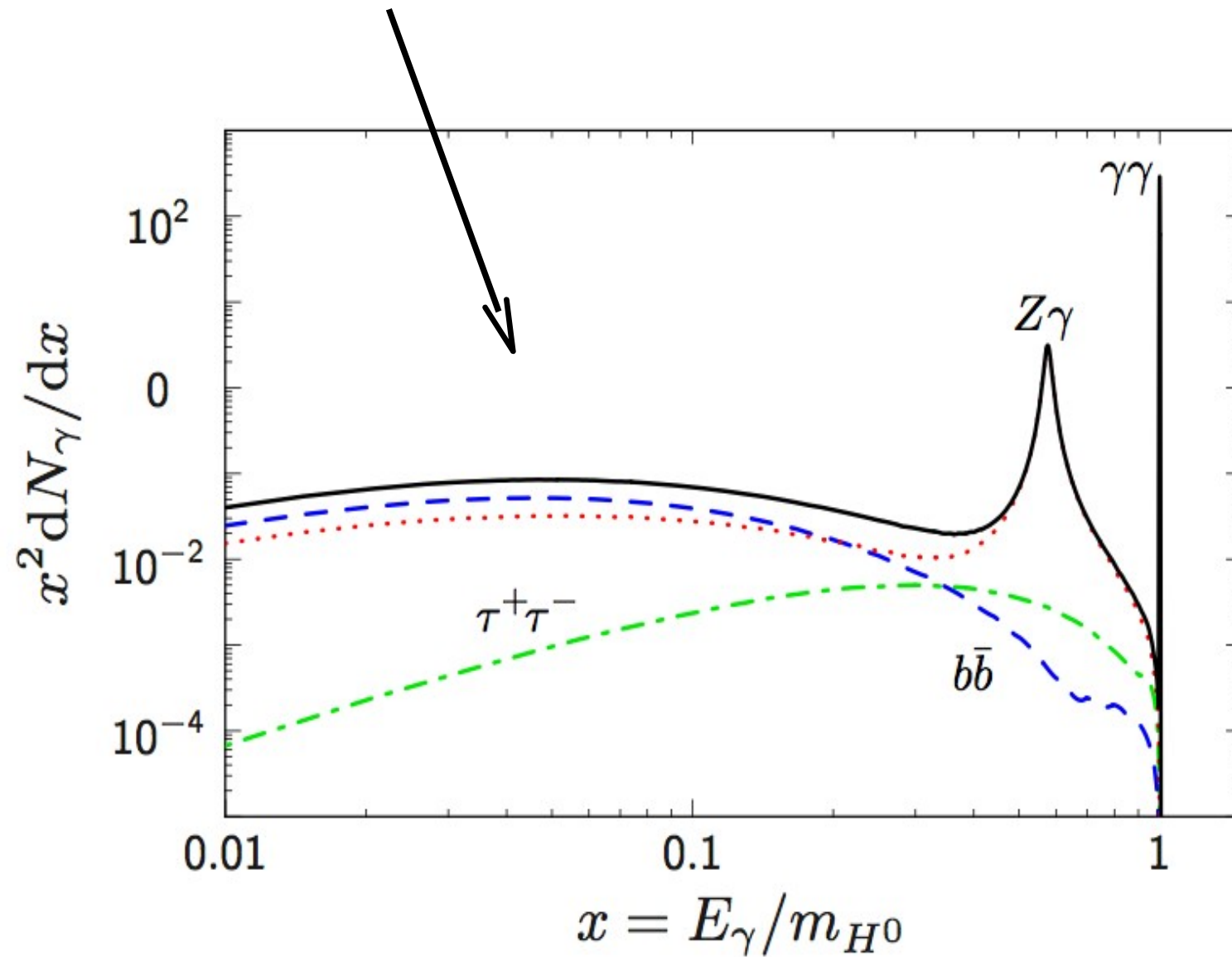
No signal seen, so Fermi-LAT sets Exclusion Limits



A gamma-ray line?

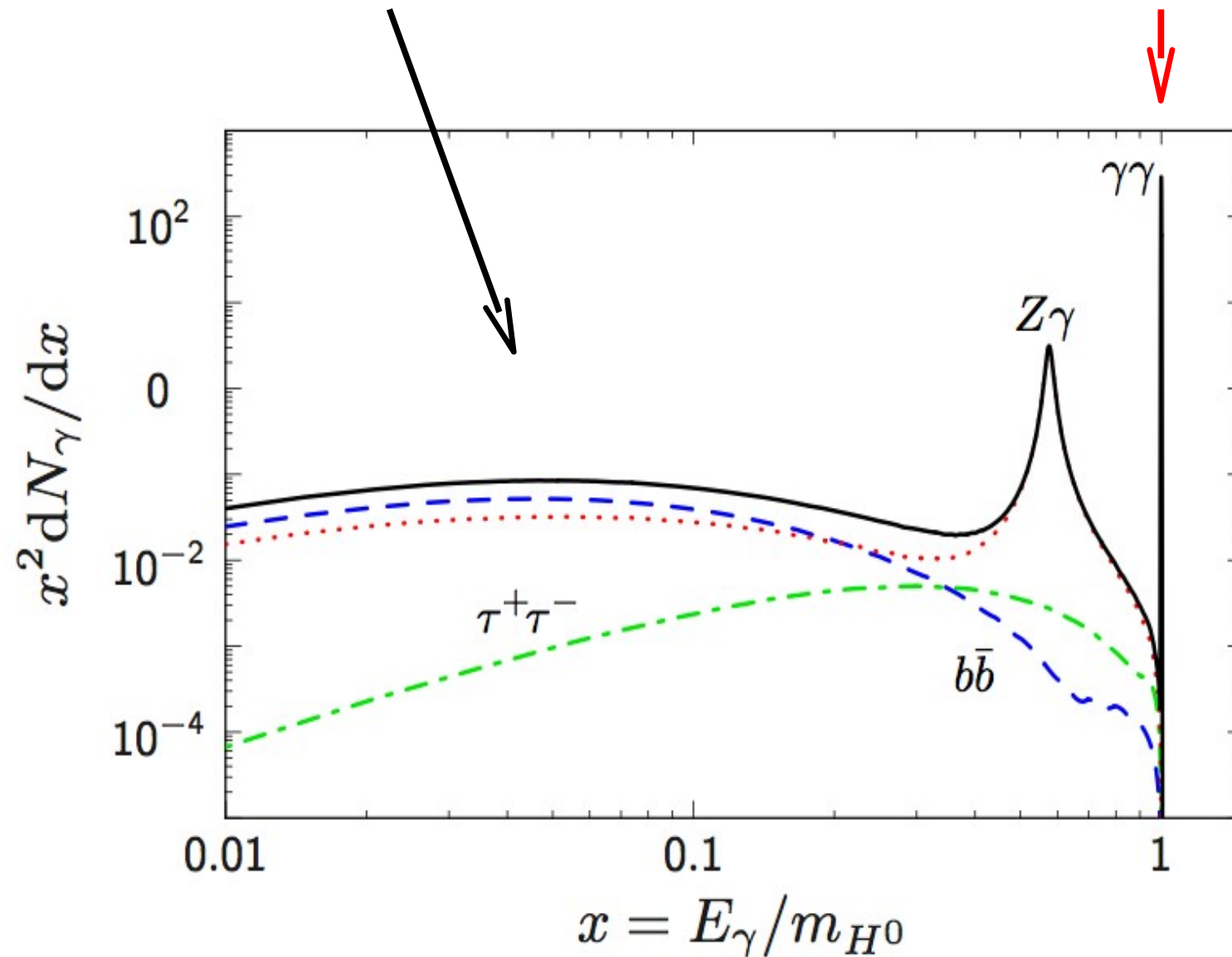


Continuous spectrum
(essentially γ -ray from π^0 decay)



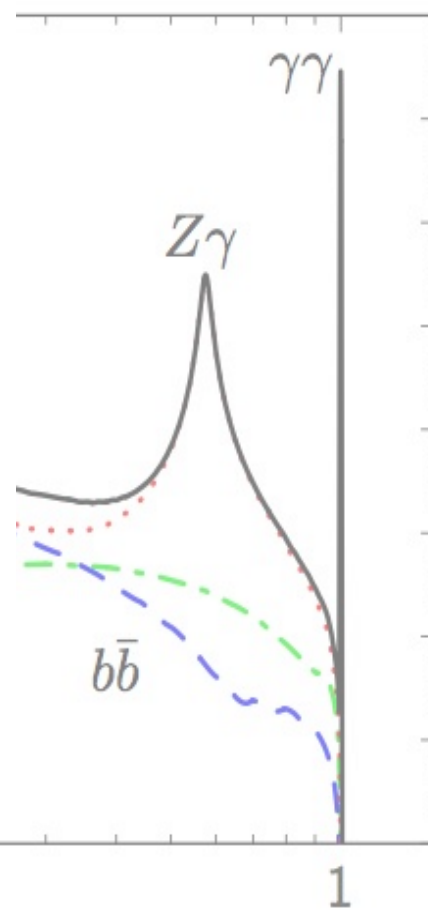
Continuous spectrum
(essentially γ -ray from π^0 decay)

A Gamma-ray Line
($E_\gamma = M_X ?$)





A Gamma-ray Line
($E_\gamma = M_\chi$?)



0.01

0.1

1

$$x = E_\gamma / m_{H^0}$$

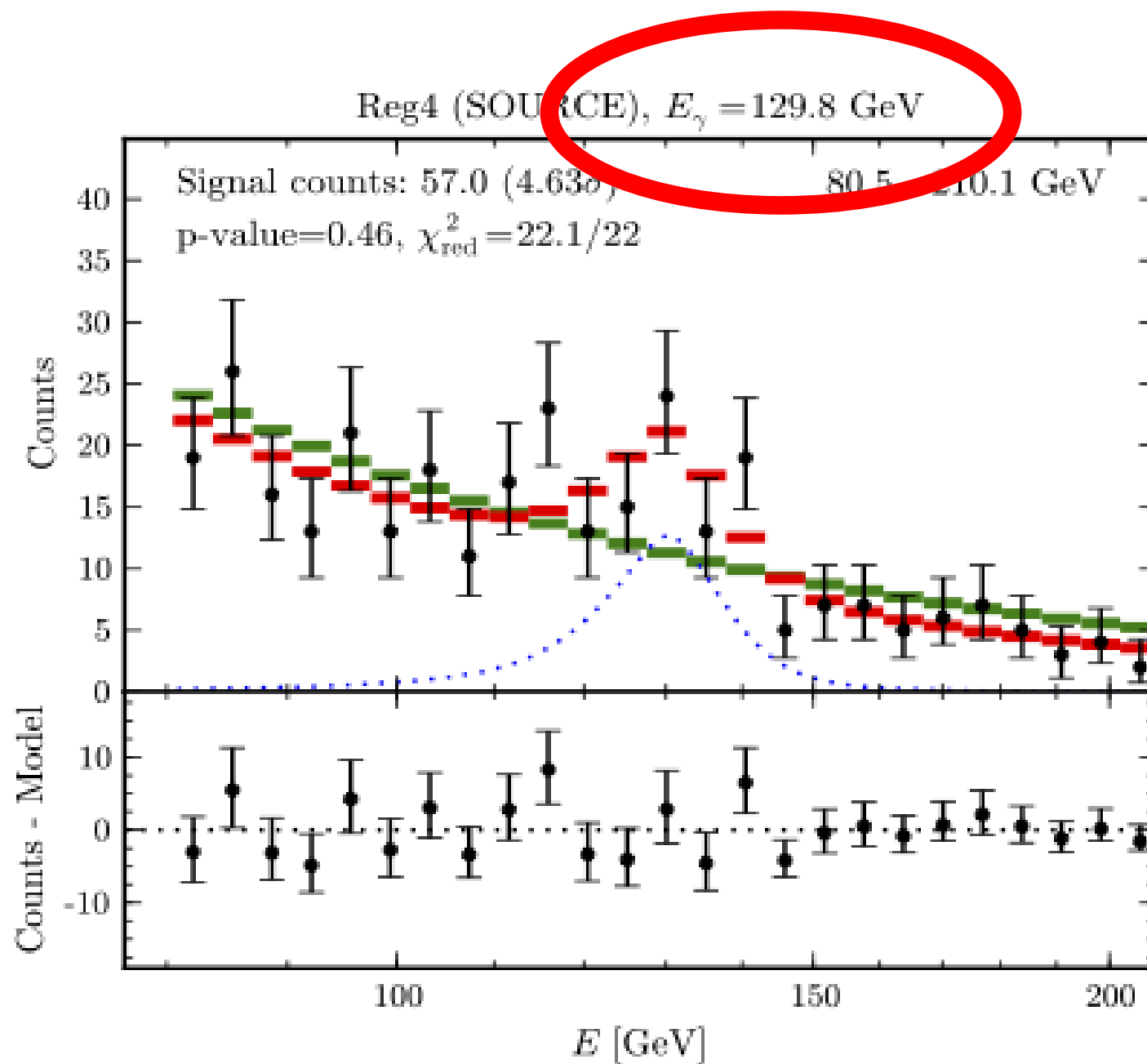


Figure from C. Weniger (1204.2797)

General Summary

- * Convincing **Gravitational** evidences for DM
(both astro and cosmo)

- * We, particle physicists, believe that it is made of (a) **new particle(s)**

- * Which one(s), we don't know (yet)

* If we are lucky, DM has Weak Interactions (the WIMP paradigm)

* Opens the possibility for **DIRECT DETECTION** (some clues, but contradicting and altogether not very convincing, yet)

* Beautiful complementarity with
PRODUCTION @ COLLIDERS
and **INDIRECT DETECTION**

* There are positive Smoking Guns
signal

* Beautiful complementarity with
PRODUCTION @ COLLIDERS
and **INDIRECT DETECTION**

* There are positive Smoking Guns
signals

* Likely « Pétards Mouillés » but
this is sometime how discoveries
happens