Are
dark matter
and
dark energy
two aspects of a same problem?

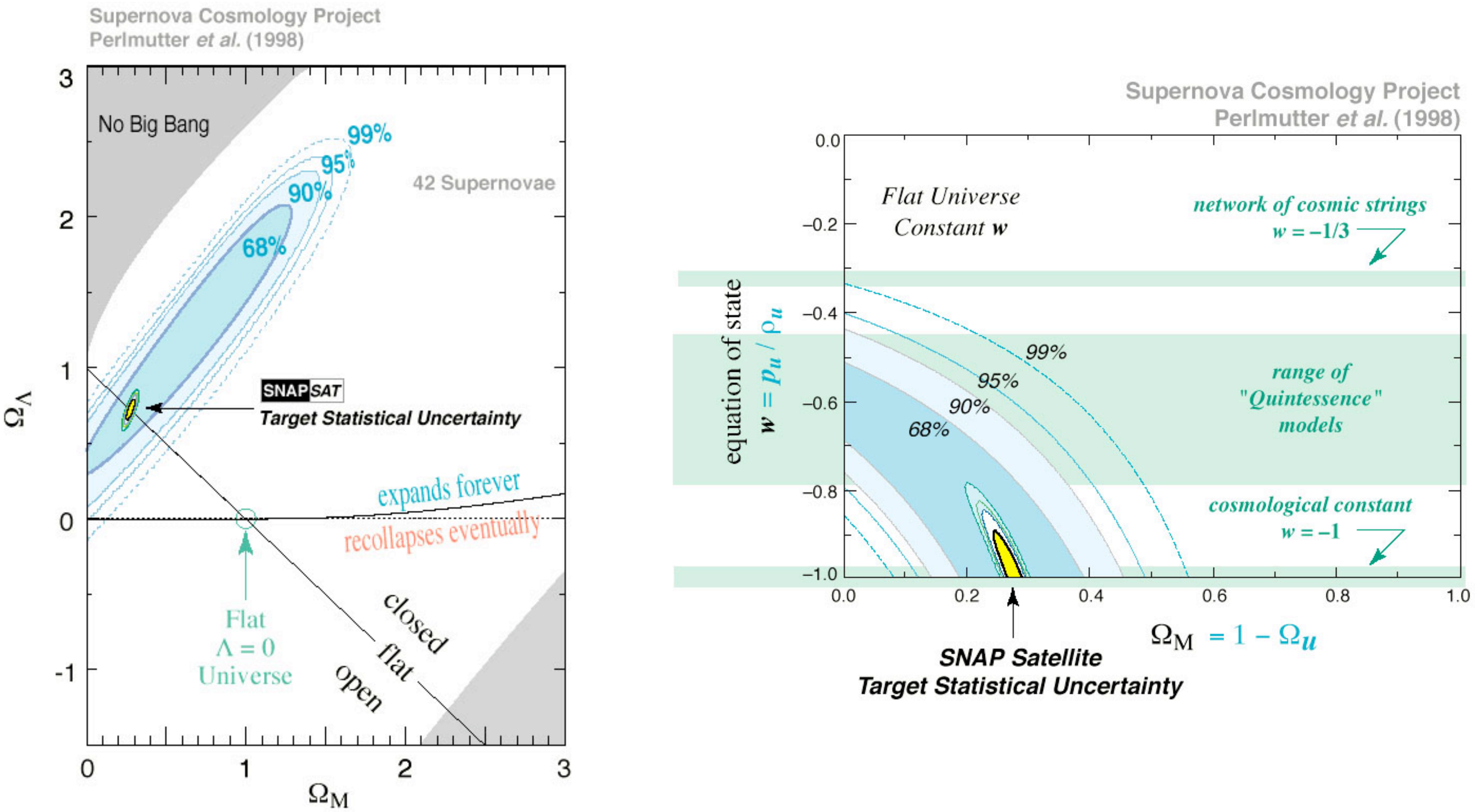
Celine Boehm

Cargese, nov-2008

LAPTH, UMR5108, Annecy-le-Vieux

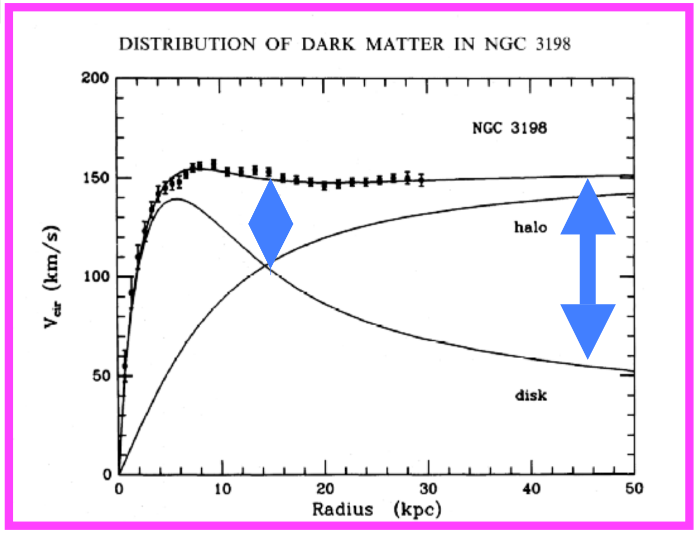
Evidence and (cosmo)“constraint” for dark energy

(Francis&Jerome’s talks)



Some evidence for DM

1



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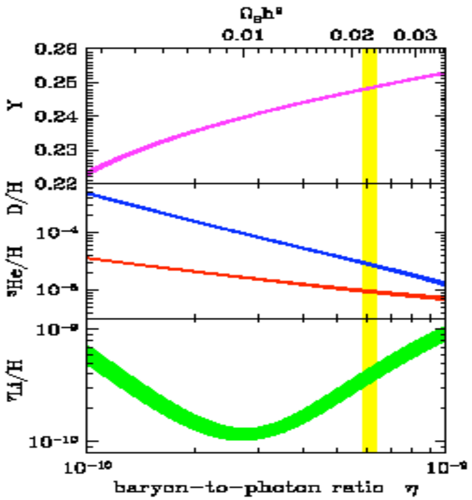
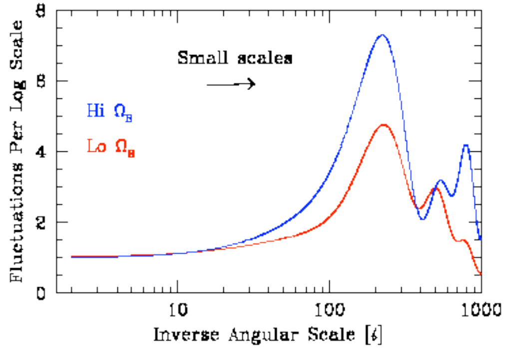


Baryonic matter represents less than 5% of the energy density of the Universe

3



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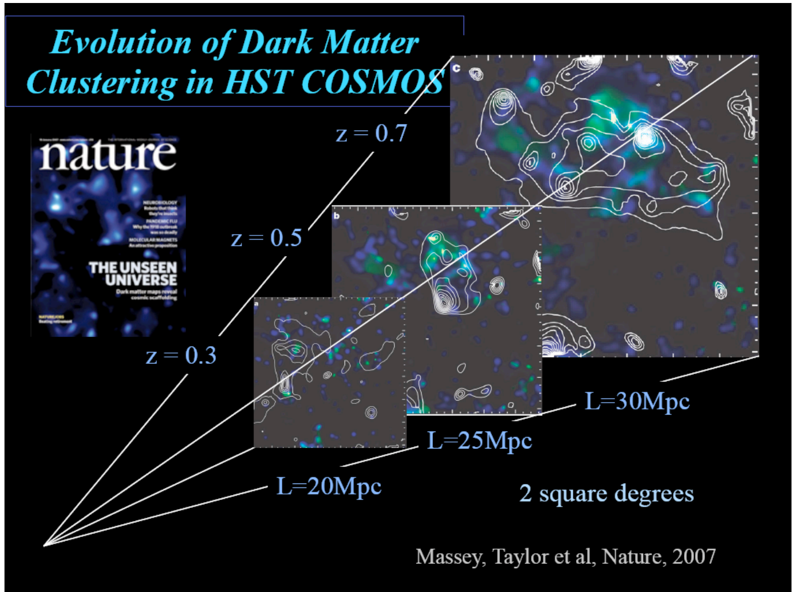
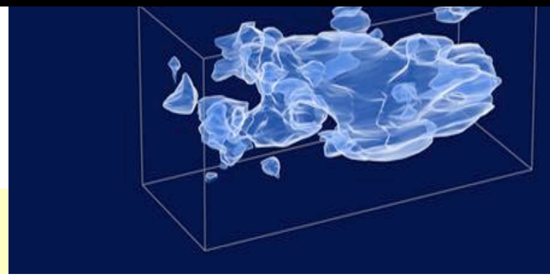




Lensing

Let us focus on DM

Any possible contestation?

- **Rotation curves of galaxies:**

  MOND is an alternative! (see Francoise's talk)

- **Nucleosynthesis:**

  No contestation, it is a very strong argument!

  (although most of the baryons are missing)

- **Structure formation:**

  Contestable under specific circumstances

  but in general difficult to explain without DM!

- **Lensing:**

  Contestable under specific circumstances

Well ….

What kind of DM candidates should we consider?

In absence of "direct" evidence…

EROS & MACHO

- Astrophysics: ~~MACHOs~~
- Modifying gravity: What kind of theories?
- Particle Physics: What kind of candidates?

What theor(y)/(ies) for modifying gravity?

MOND, its extensions and other scenarios

- **MOdified Newtonian Dynamics (MOND)**

$$\mathbf{F} = m\frac{\mathrm{d}^2\mathbf{r}}{\mathrm{d}t^2} = m\mathbf{a} \qquad \mathbf{a} = G\frac{M}{r^2}$$

$$\vec{F} = m.\mu\left(\frac{a}{a_0}\right).\vec{a} \qquad \begin{array}{l}\mu(x) = 1 \text{ si } x \gg 1 \\ \mu(x) = x \text{ si } |x| \ll 1\end{array} \qquad a = |\vec{a}| \qquad a = \frac{\sqrt{GMa_0}}{r} \quad a = \frac{v^2}{r} = \frac{\sqrt{GMa_0}}{r}$$

$$v = \sqrt[4]{GMa_0}$$

- **TeVeS (Bekenstein)**

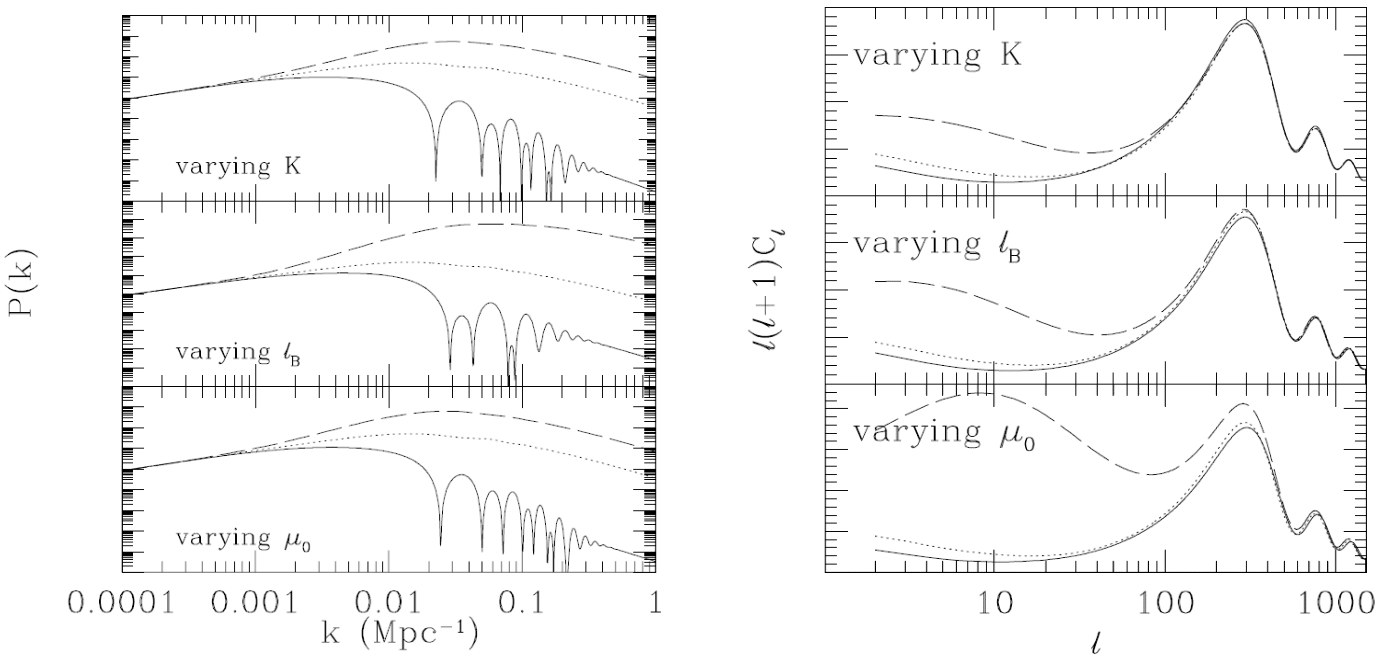
$$g_{\mu\nu} = e^{-2\phi}(\tilde{g}_{\mu\nu} + A_\mu A_\nu) - e^{2\phi} A_\mu A_\nu$$

$$S_s = -\frac{1}{16\pi G}\int d^4x\sqrt{-\tilde{g}}\,[\mu\ (\tilde{g}^{\mu\nu} - A^\mu A^\nu)\,\phi_{,\mu}\phi_{,\nu} + V(\mu)] \qquad S_v = -\frac{1}{32\pi G}\int d^4x\sqrt{-\tilde{g}}\Big[KF^{\alpha\beta}F_{\alpha\beta} - 2\lambda(A^\mu A_\mu + 1)\Big]$$

- **Other modifying gravity scenarios**
  - F(R) see Nathlie's talk

- **MOND:** suffer from Silk damping; no way to avoid it

- **Bekenstein:** Silk damping is counteracted but CMB 3^{rd} peak is difficult to fit

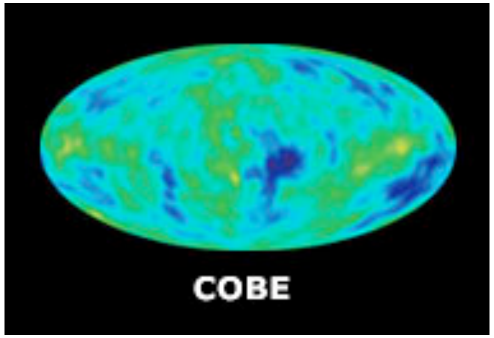


- **Others:** Smaller modifications but tests with solar system

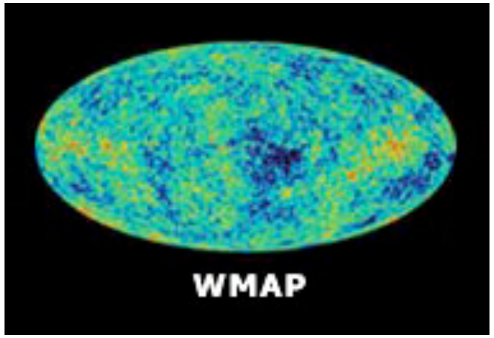
1967: Peebles assumed that objects (galaxies) originate from small energy density perturbations

galactic seeds

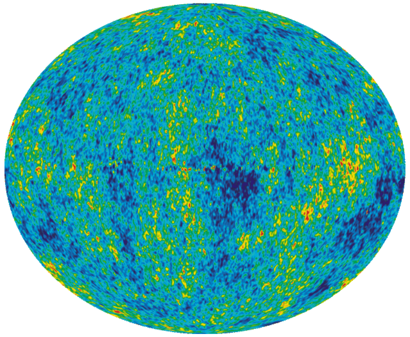
BUT do these fluctuations exist?



1992



2002



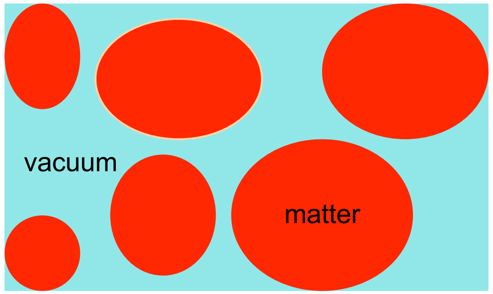
Latest WMAP

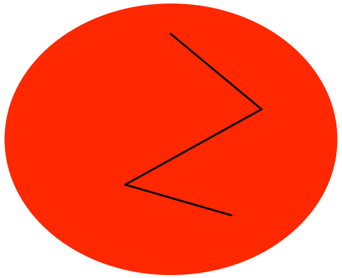
Silk Damping

1968: J. Silk's concluded that if perturbations exist then the content of such perturbations is dominated by baryons, then only a few galaxies can form

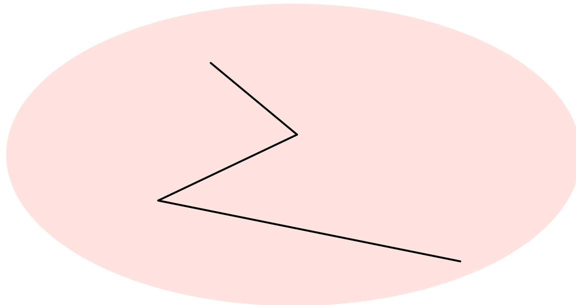
BUT

WHY?





Protons and photons have electromagnetic Interactions. Lead to accoustic oscillations when fluctuations enter the sound horizon



But eventually photons decouple while protons still interact with photons

Too low density to form loads of galaxies

Evidence that we need non-baryonic matter!!!
Birth of WIMPs (DM)

What kind of DM candidates?

Neutral, Weakly-Interacting Massive particles= WIMPS

OFTEN SAID:

WIMPS =Collisionless particles

WIMPS= Cold DM

(but neutrinos are WIMPs and HDM, so needs to be a bit careful)

But:

- How collisional can DM *be*?
- Can DM be also Warm? (and what would this mean?)

Generalisation of the Silk damping to DM

* Free-streaming scale
  (the relevant scale when DM has no interaction)

$$l_{fs(i)} \propto \int_{t_{dec(i)}}^{t} \frac{v_i \, dt}{a} \, .$$

- Free particles
- Leave the overdense regions
- Distance travelled depends on the time at which they became free and their velocity

* Collisional damping scale

$$l_{cd}^2 = \pi^2 \int^{t_{dec(dm)}} \frac{\zeta + \frac{4}{3}\eta + \lambda T \frac{\rho_m^2}{4 \not{\phi} \, \rho_r}}{\not{\phi} a^2} dt.$$

- Coupled particles
- Particles leave the fluctuations by following other species
- Depends on the interaction rate with these other species and number density

Classification of the DM properties

Scale factors

Decoupling — Non-relativistic — equality

Region I	$a_{dec(dm)} < a_{nr} < a_{eq(\gamma+\nu)}$
Region II	$a_{nr} < a_{dec(dm)} < a_{eq(\gamma+\nu)}$
Region III	$a_{nr} < a_{eq(\gamma+\nu)} < a_{dec(dm)}$
Region IV	$a_{dec(dm)} < a_{eq(\gamma+\nu)} < a_{nr}$
Region V	$a_{eq(\gamma+\nu)} < a_{dec(dm)} < a_{nr}$
Region VI	$a_{eq(\gamma+\nu)} < a_{nr} < a_{dec(dm)}$

Example of free-streaming calculations

Region I: Hot Dark Matter

Mass < MeV

$$l_{fs}^{(I)} = 0.51\, kpc\, {g'}_*^{-\frac{1}{2}}(T_{nr}) \left(\frac{m_{dm}\kappa_{dm}(T_{nr})}{1MeV}\right)^{-1}$$

Region II: Cold Dark Matter

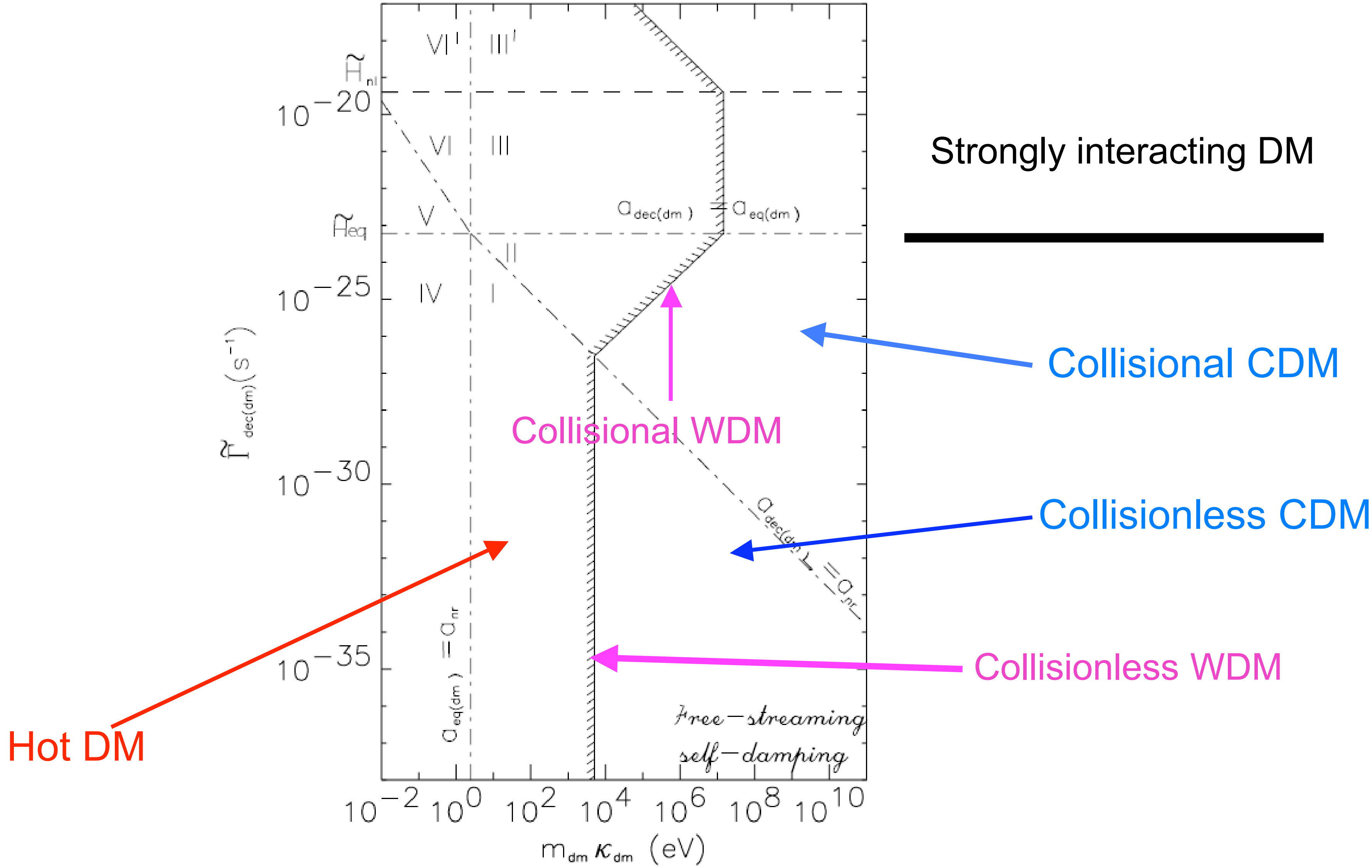
Interaction rate at equality

$$l_{fs}^{(II)} \sim\ 330\, kpc\ f\ {g'}_*^{-\frac{3}{4}}(T_{dec(dm)})$$

$$\left(\frac{m_{dm}\kappa_{dm}(T_{nr})}{1MeV}\right)^{-\frac{1}{2}} \left(\frac{\widetilde{\Gamma}_{dec(dm)}}{6\ 10^{-24}s^{-1}}\right)^{\frac{1}{2}}$$

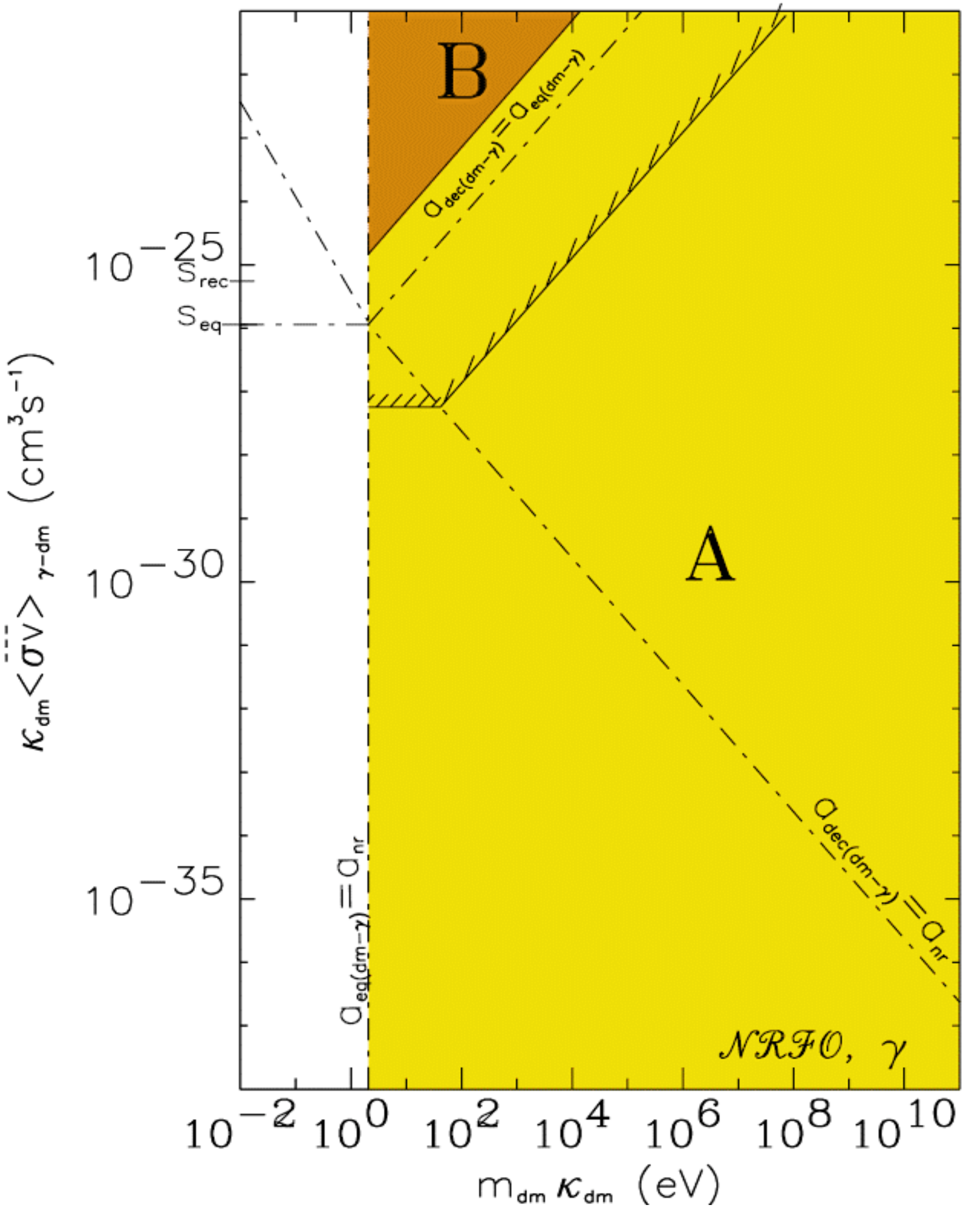
Mass > MeV

Constraints from free-streaming and self-damping



CB, R. Schaeffer (2001,2004)

Constraints from collisional damping

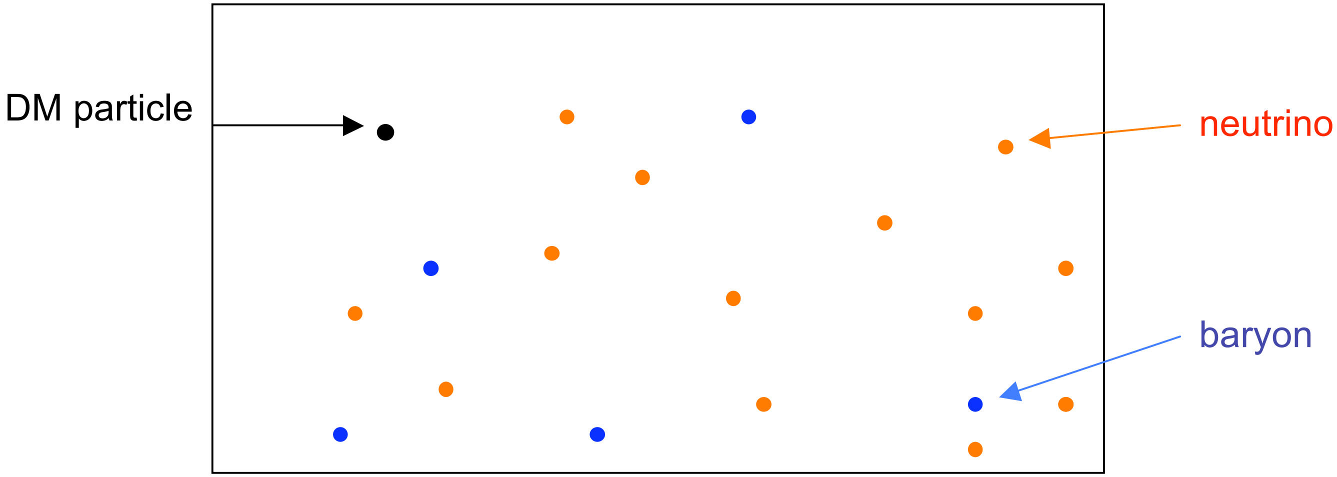


DM Mixed damping (CB, P. Fayet, R. Schaeffer 2001)

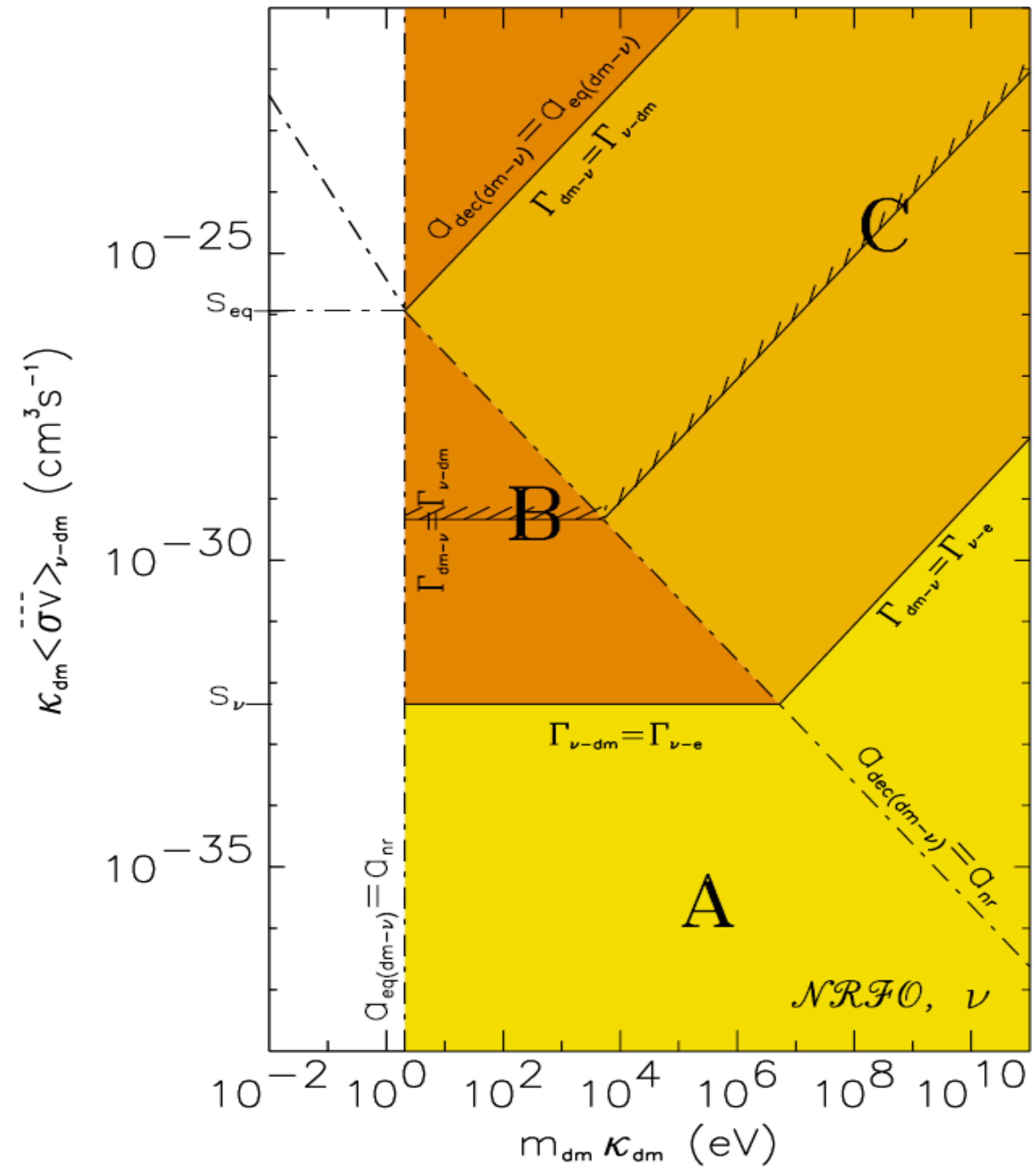
(the same as for protons in the tight regime, after the photons decouple)

The baryons stay coupled to photons but photons free-stream

$$\boxed{l_{id}^2 = \frac{2\,\pi^2}{3} \int^{t_{dec(i)}} \frac{\rho_i\, v_i^2}{\phi\, a^2\, \Gamma_i} \left(1 + \Theta_i\right)\, dt + \frac{2\pi^2}{3} \int_{t_{dec(i)}}^{t_{dec(dm-i)}} \frac{\rho_i\, v_i^2}{\phi\, a^2\, H} \left(1 + \Theta_i\right)\, dt \ .}$$

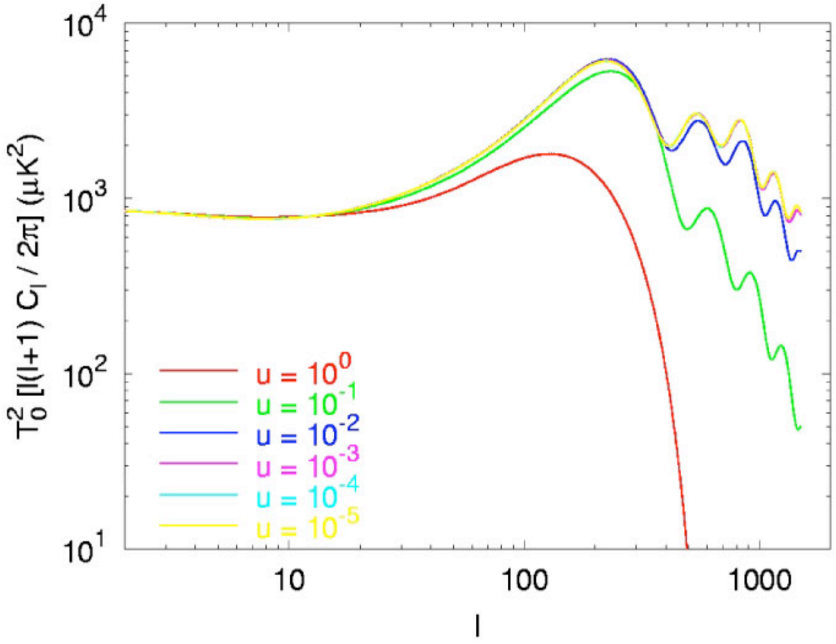


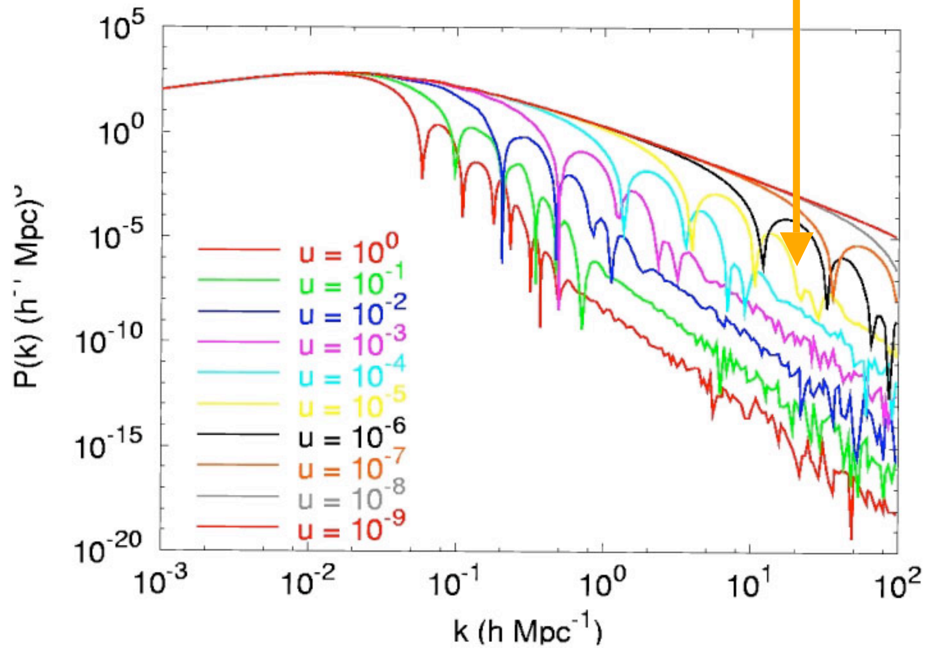
Constraints from mixed damping



Maximal DM interactions with photons?

U = sigma_(dm photon)/sigma_(Thomson)





Planck could constrain
the DM interactions

So in short for
what kind of part. phys DM
candidates should we
consider:

Very light

Hot DM = e.g. neutrinos

gravity + DM velocity

Excluded!

massive

CDM = collisional but wimps
SUSY LSP, KK, XDM, MDM,LDM

just gravity

Very popular!

Warm DM = *collisionless* neutrinos with m=1 keV

*coll*isional dm with m~ 1 MeV

gravity + DM velocity (+DM interactions)

Not popular and yet ...

+ all sorts (including self-interacting DM) as long as FS and collisonal damping length are not too large

Any other constraint?

1. Relic density

2. Direct Detection

3. Indirect Detection

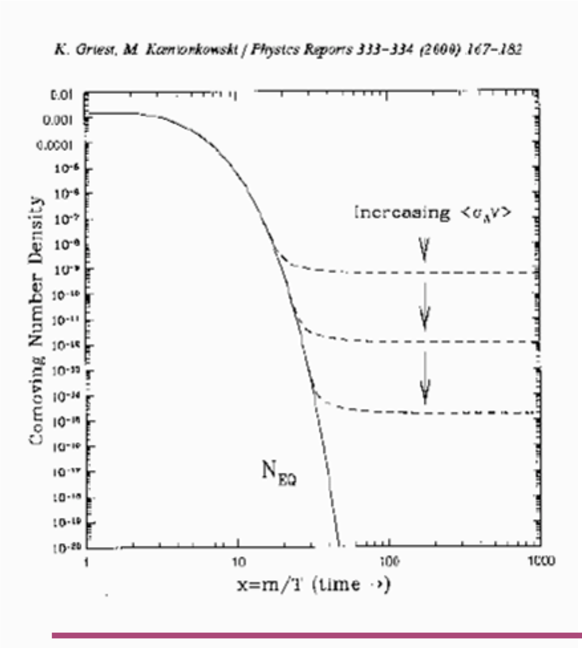
4. Laboratory

Relic density

Hut, Lee-Weinberg (1977)

The proportion of DM cannot exceed 100% of the energetic content of the Universe

DM + SM matter + DE = 100%



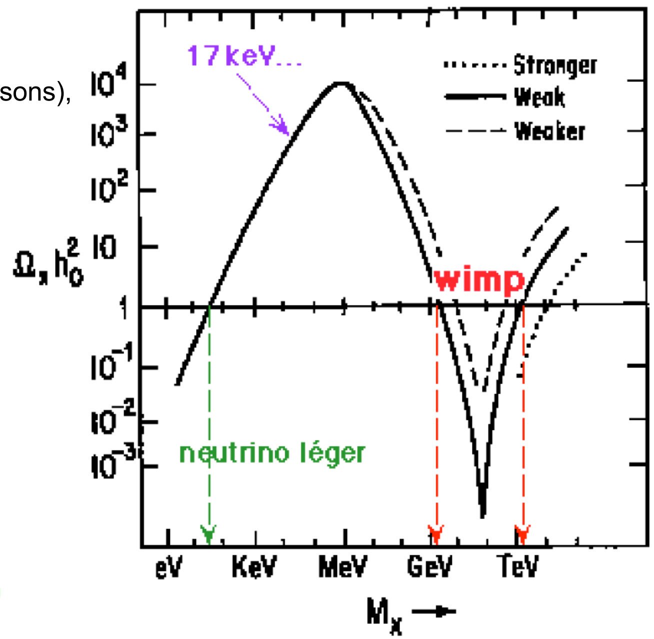
Pure ``cosmology''

One range of cross sections always give the right relic density!

It is about 10^{-35}-10^{-37} cm^2… like weak interactions

- With a ``Standard'' Model (heavy neutrinos exchanging heavy gauge bosons), one obtains the following window but that is **assuming a cross section that is proportional to the dark matter mass**

$$\boxed{\sigma\, v \propto \frac{m_{dm}^{2}}{m_{w}^{4}}}$$



Pure ``particle physics''

The Lee-Weinberg limit:

- Annihilating DM particles must be heavy with a mass between]1 GeV- 1 TeV]

- In agreement with *supersymmetry*

- BUT there is one massively important assumption

- They took fermionic particles!

- With scalar particles, there is no limit anymore!

- Lee-Weinberg:

$$\sigma\, v \propto \frac{m_{dm}^{\;2}}{m_w^{\;4}}$$

- Scalar particles:

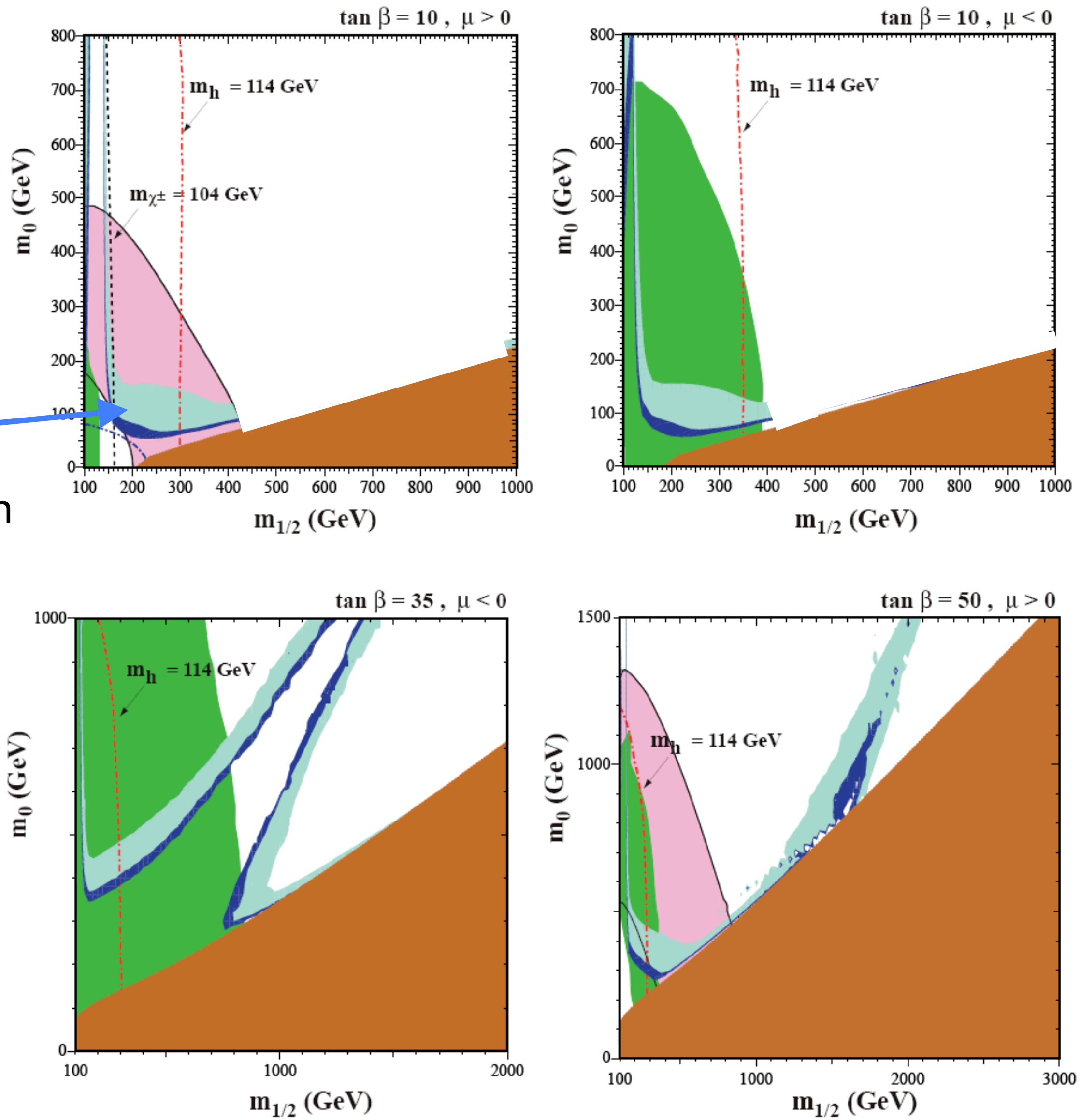
$$\sigma v \propto \frac{c_l^2 c_r^2}{m_F^2}$$

Independent of the DM mass

Light particles (MeV) are allowed by the relic density argument!

Is the relic density constraint constraining?

Example with SUSY



Susy constrained
to the bulbe region

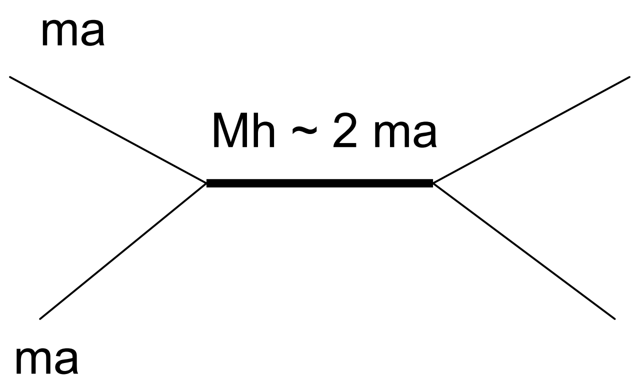
Ellis et al

But exceptions to relic density constraint

- Co-annihilation

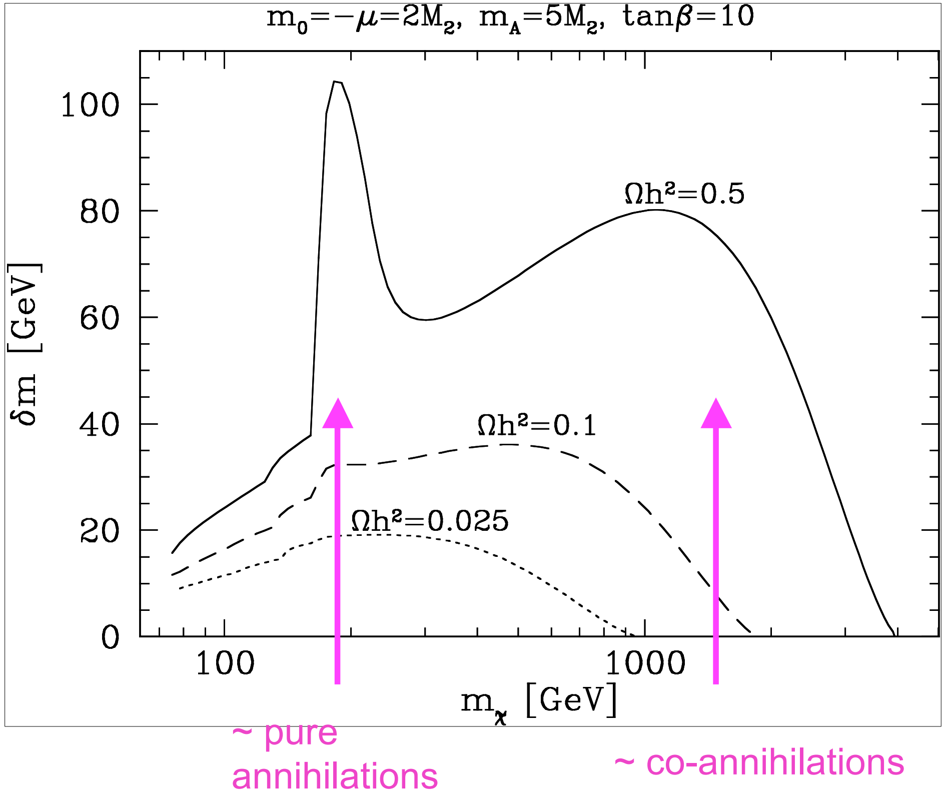
$$\frac{dn_i}{dt} = -3Hn_i - \sigma v_{ann}(n_i^2 - n_{i,0}^2) - \sigma v_{co-ann}(n_i n_j - n_{i,0} n_{j,0})$$
$$\frac{dn_j}{dt} = -3Hn_j - \sigma v_{ann}(n_j^2 - n_{j,0}^2) - \sigma v_{co-ann}(n_i n_j - n_{i,0} n_{j,0}) - \Gamma_j (n_j - n_{j,0})$$

- Resonances



- Focus point

Coannihilations, etc



$$n \propto (mT)^{3/2} e^{-\beta m}$$

Enables to consider very large neutralino masses

Coa interactions enables to reduce the DM number density

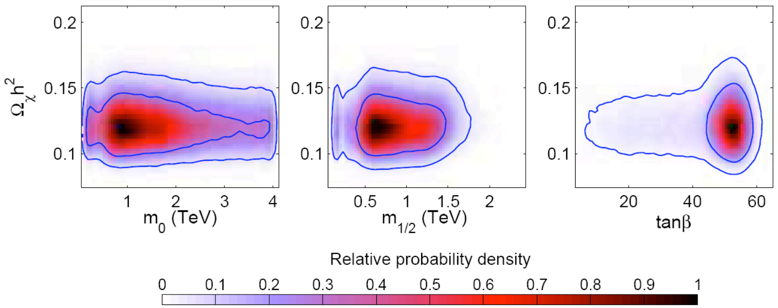


Figure 6: The 2–dim relative probability density $p(\Omega_\chi h^2, \theta_i|d)$, where $\theta_i = m_0$, $m_{1/2}$ and $\tan\beta$. Note that the measured value of $\Omega_\chi h^2$, Eq. (3.10), has been included in computing the relative probability density.

Direct detection

Direct Detection Principles

Inspired from Druckier & Stodolski
Goodman&Witten (1985)

- **Counting rates**

$$dN = Flux * S * dt$$

$$Flux = \sigma v * n_{dm} * n_p * d \ \ with \ \ n_p = \frac{\rho_p}{m_p}$$

$$Since \ \ \rho_p = \frac{Z}{A} * \mathrm{N}_a * \rho_{material} \ \ and \ \ \rho_{material} = \frac{M_{material}}{Volume}, \ we \ have:$$

$$dN = \sigma v * n_{dm} * \frac{Z}{A} * \mathrm{N}_a * M_{material} * dt$$

Needs very massive detector

- **Type of interactions**
  - *Spin dependent:* sensitive to the spin of the nuclei (coherent cross section J(J+1) with J=L+S)
  - *Spin independent:* insensitive to the spin of the nuclei

Annual modulation

Drukier,Freese,Spergel

$$v_{Earth} = v_{sun} + v_{orb} \cos\gamma \cos[w(t - t_0)]$$

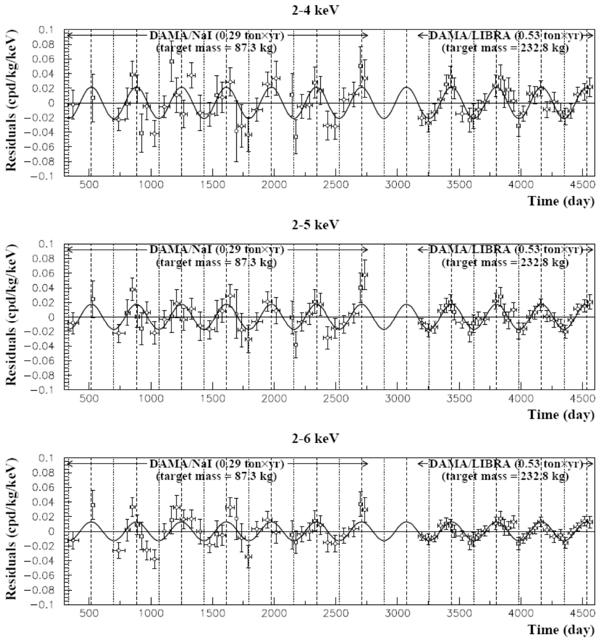
with

$v_{orb} \approx 30\,km/s$ (earth orbital velocity around the Sun)

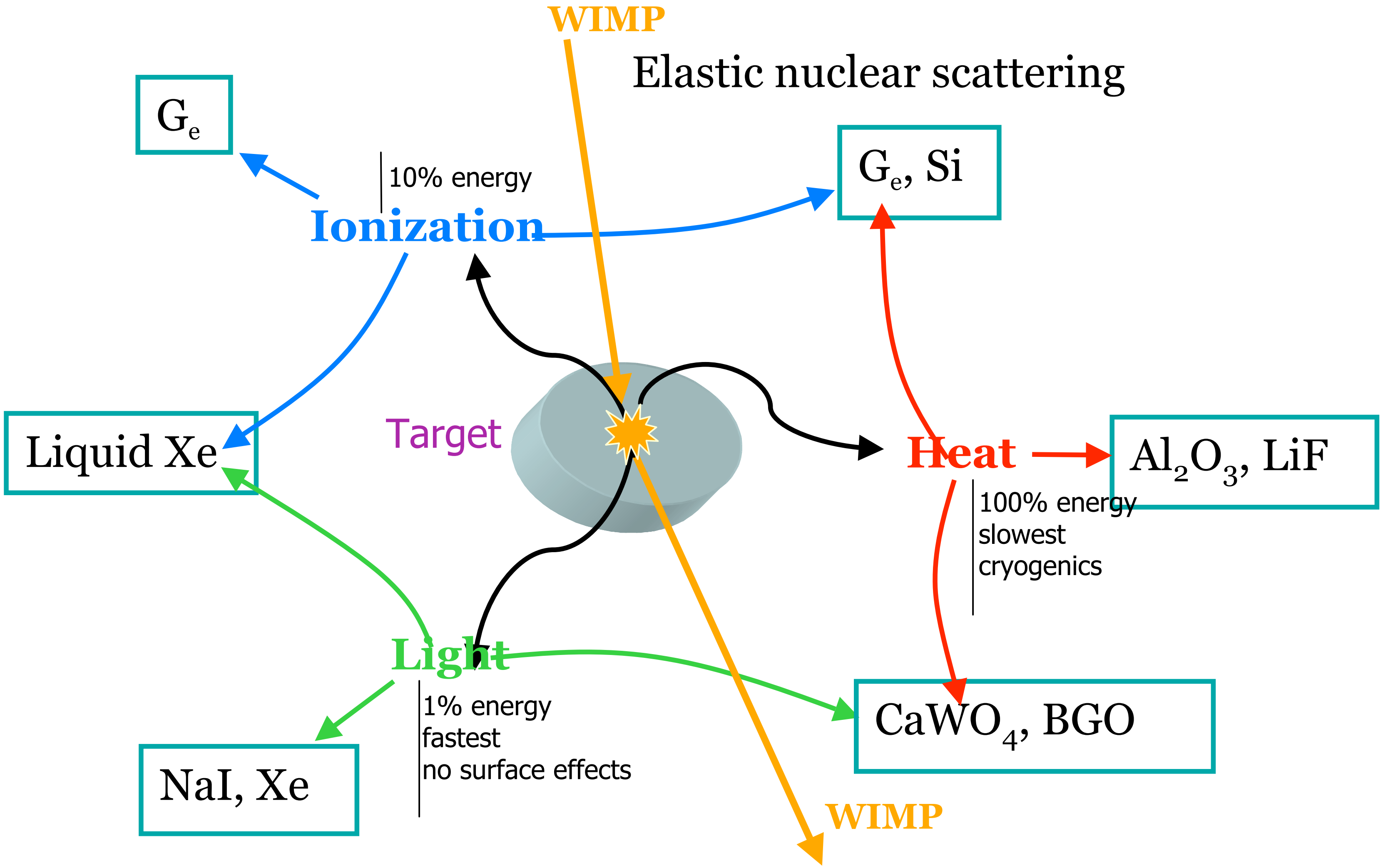
$\gamma = 60°$ (the inclination of the Earth orbital plane with respect to the galactic plane)

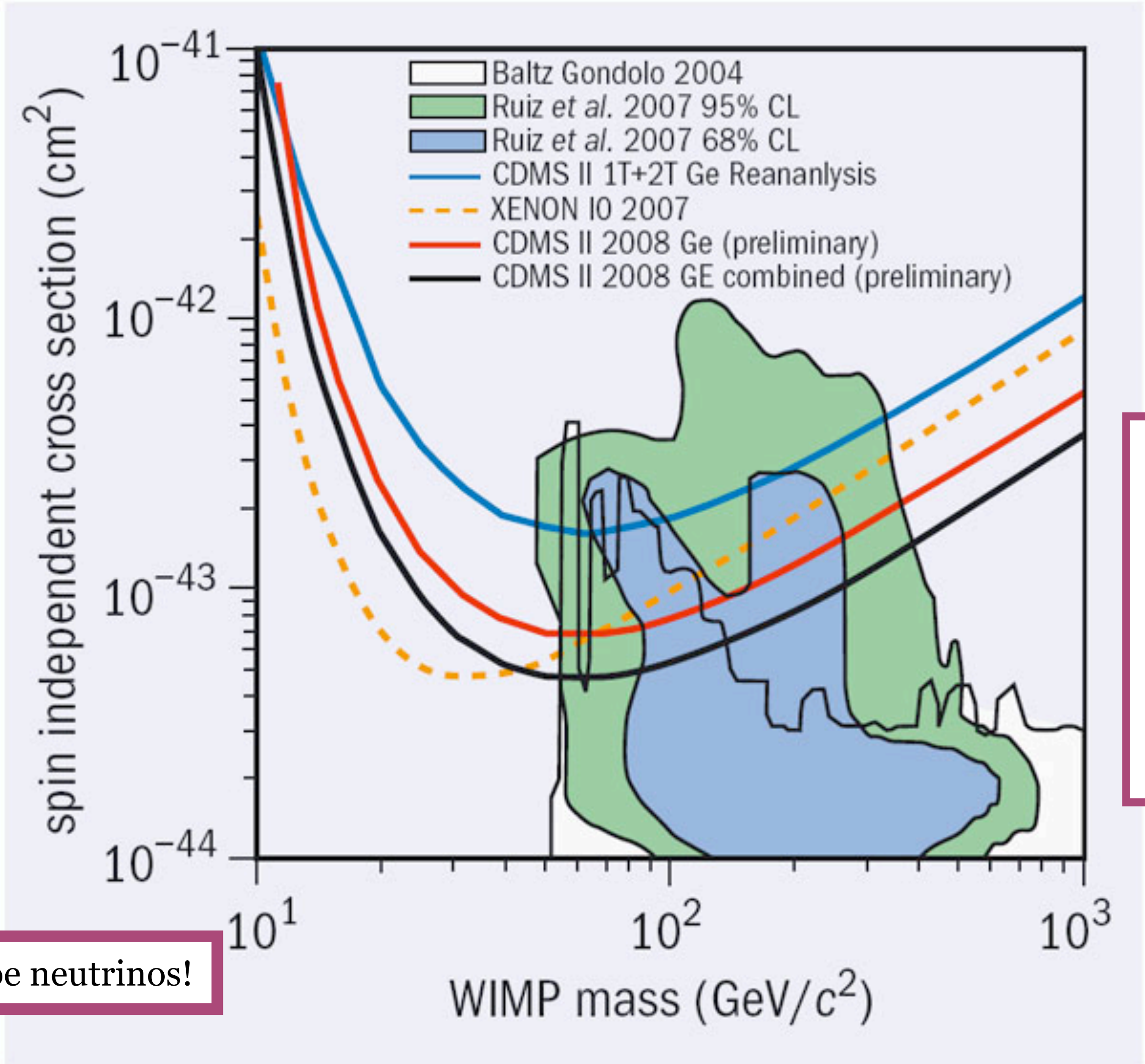
$w = (2\pi/365)\,radian/day$

t_0 the 2nd of June (half a year!)



Credit: V. Sanglard

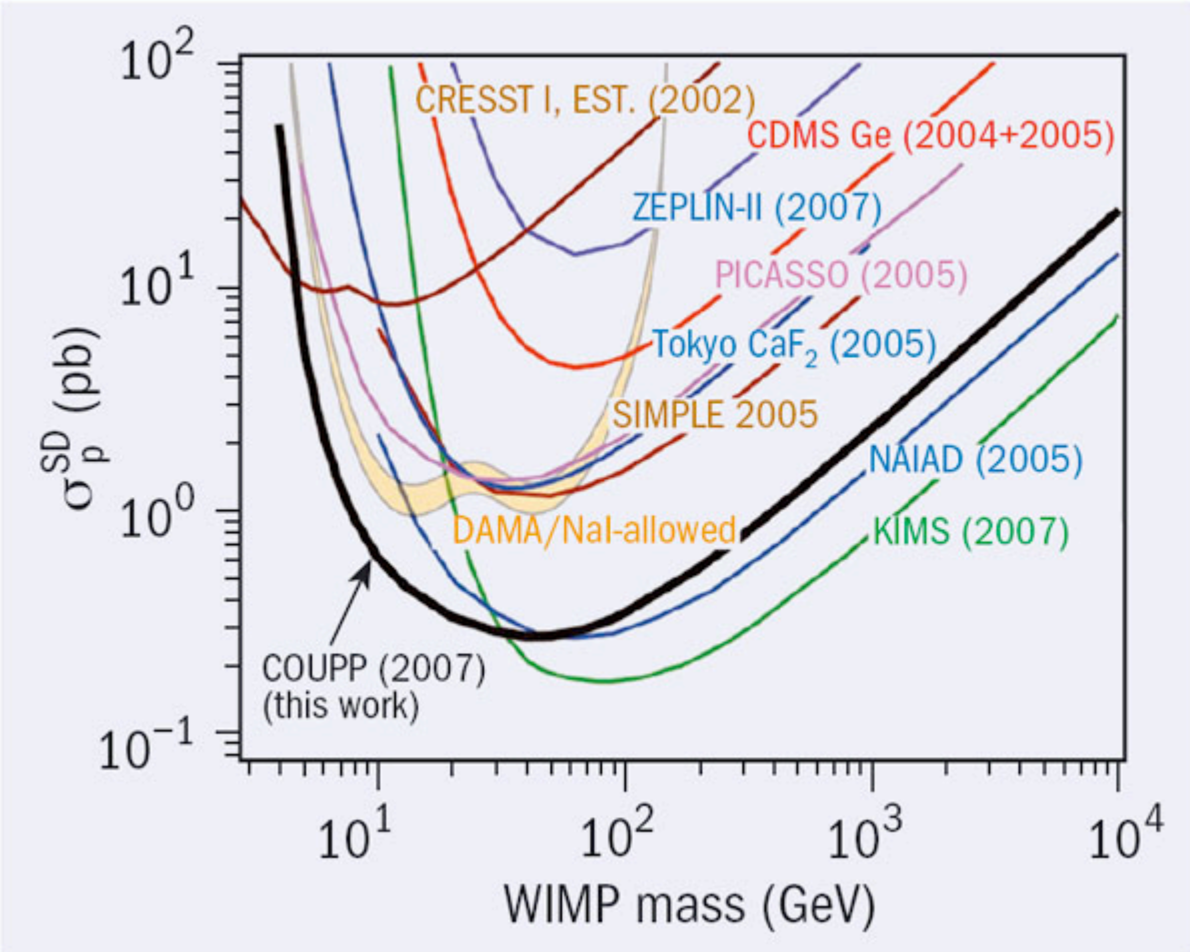




SUSY saved
by coannihilations,
focus point region,
Higgs pole…

Mechanisms "used"
to uncorrelate the
relic density criterion
from direct detection

Soon able to probe neutrinos!



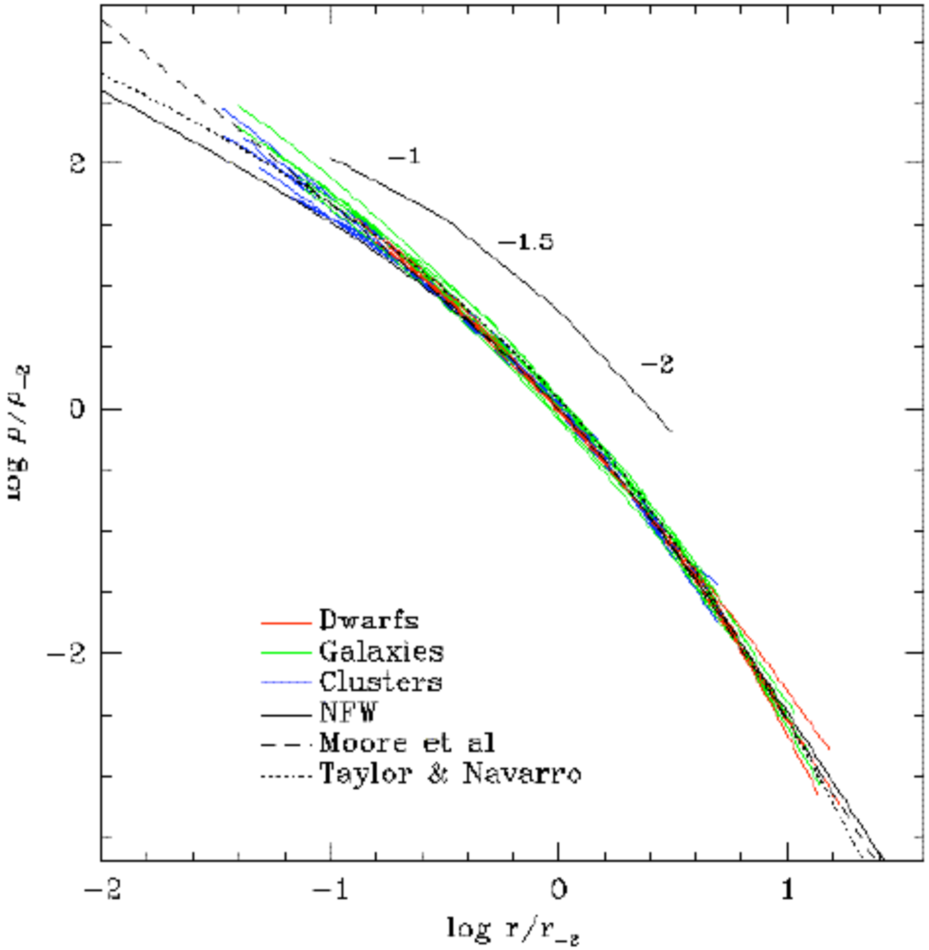
Exclude DAMA but DAMA/LIBRA just claimed a 8sigma discovery of an annual modulation signal....

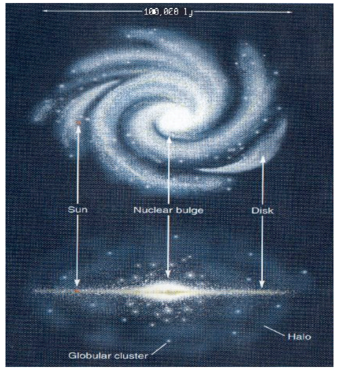
So (apart from DAMA) there is no manifestation of DM candidates in Direct Detection experiments!

Indirect Detection

3 types of messengers

$$\rho = n * m$$





NFW = Navarro-Frenk-White

$$\rho = \frac{\rho_0}{\left(\frac{r}{r_c}\right)^{1.5} \times \left(1 + \left(\frac{r}{r_c}\right)^2\right)}$$

Moore

$$\rho = \frac{\rho_0}{\left(\frac{r}{r_c}\right) \times \left(1 + \left(\frac{r}{r_c}\right)^2\right)}$$

Halo with a ~ spherical symmetry (triaxial)

1. DM annihilations into 2 photons
2. DM annihilations into cosmic rays/anti matter
3. DM annihilations into neutrinos
4. Radiative decays + decays in cosmic rays/anti matter

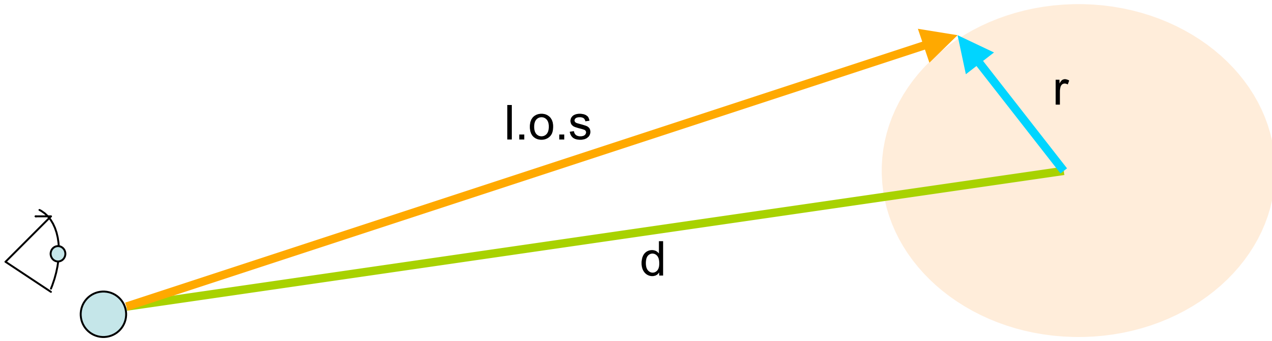
DM DM -> $\gamma\ \gamma$

DM DM -> e^+
e^-,ppbar..

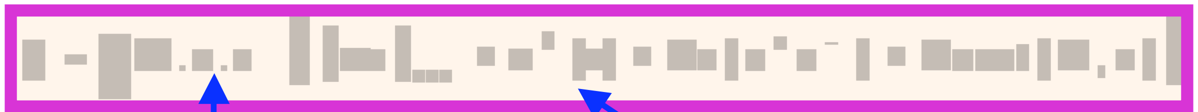
DM DM -> $\nu\ \nu$

Celine Boehm 44

The basic way (assuming no propagation, no loss):



Production of the particles that one want to detect



$$l_{\pm} = d\cos\alpha \pm \sqrt{r^2 - d^2\sin^2\theta_{res}}$$

(the numerical way)

$$r = \sqrt{l^2 + d^2 - 2\,d\,l\cos\theta_{res}}$$

(the analytic way)

How to compute a flux (bis)

- **Propagation**

losses source

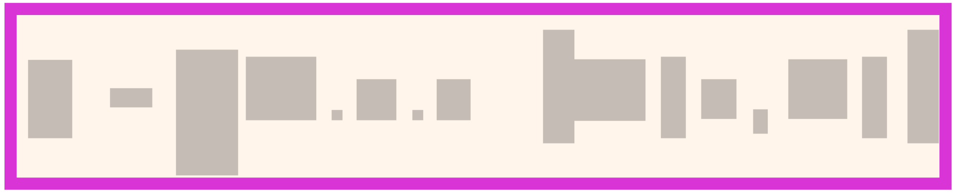
$$\partial_t N(r,E) = K(E)\,\nabla^2 N(r,E) + \partial_E \big(b(E) N(r,E)\big) + Q(r,E)$$

$$\boxed{K(E) = K_0 \frac{d_B^{2/3}}{B_\mu^{1/3}} \left(\frac{E}{\{E_0 = 1\ \mathrm{GeV}\}}\right)^{1/3}}$$

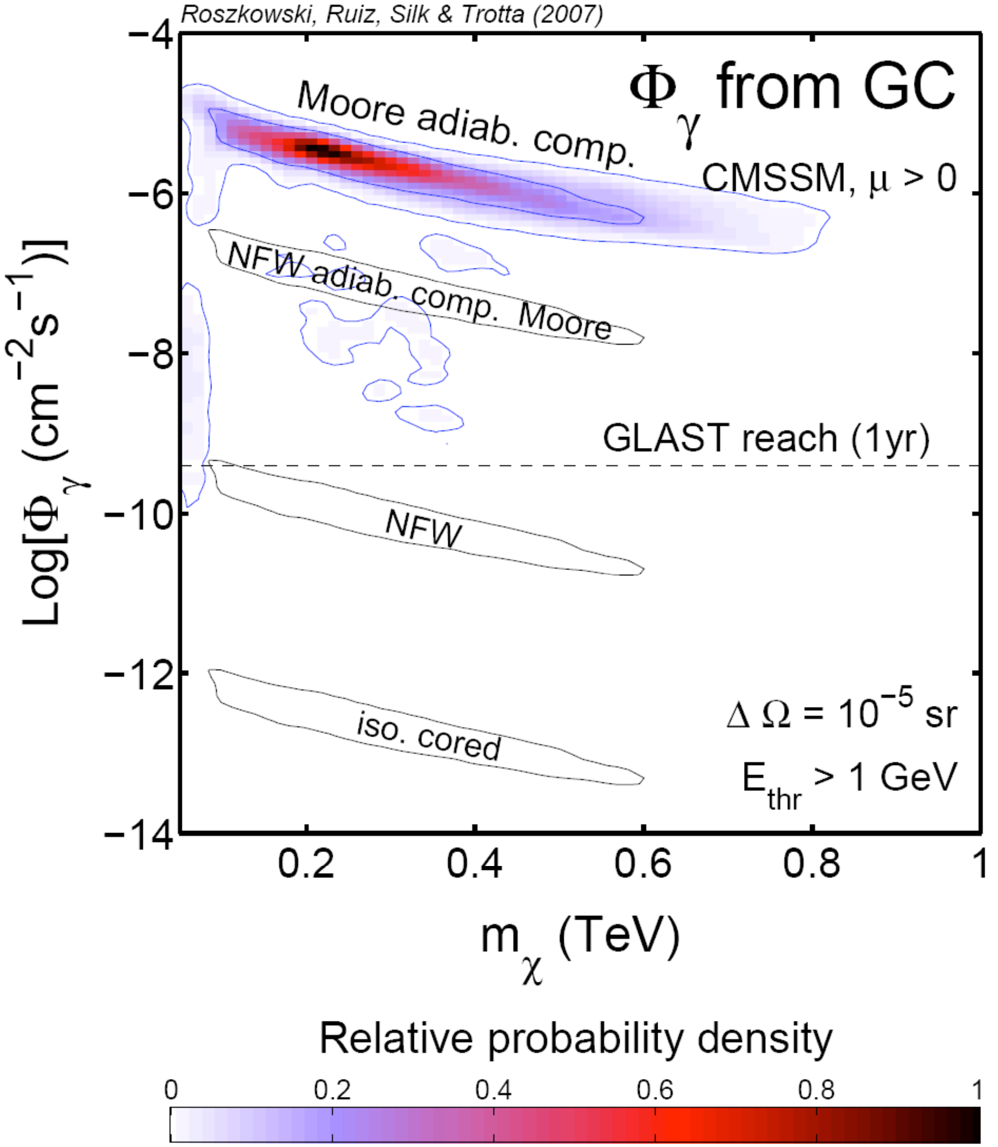
Depends on the magnetic field

- **Boost** (hidden in the source term Q(r,E), related to presence of e.g. clumps)

- **Losses** (term in b(E))



A SUSY example



Have we seen DM particles already?

Perhaps

...the 511 keV line

observed from the centre of the galaxy

Electron/Positron background

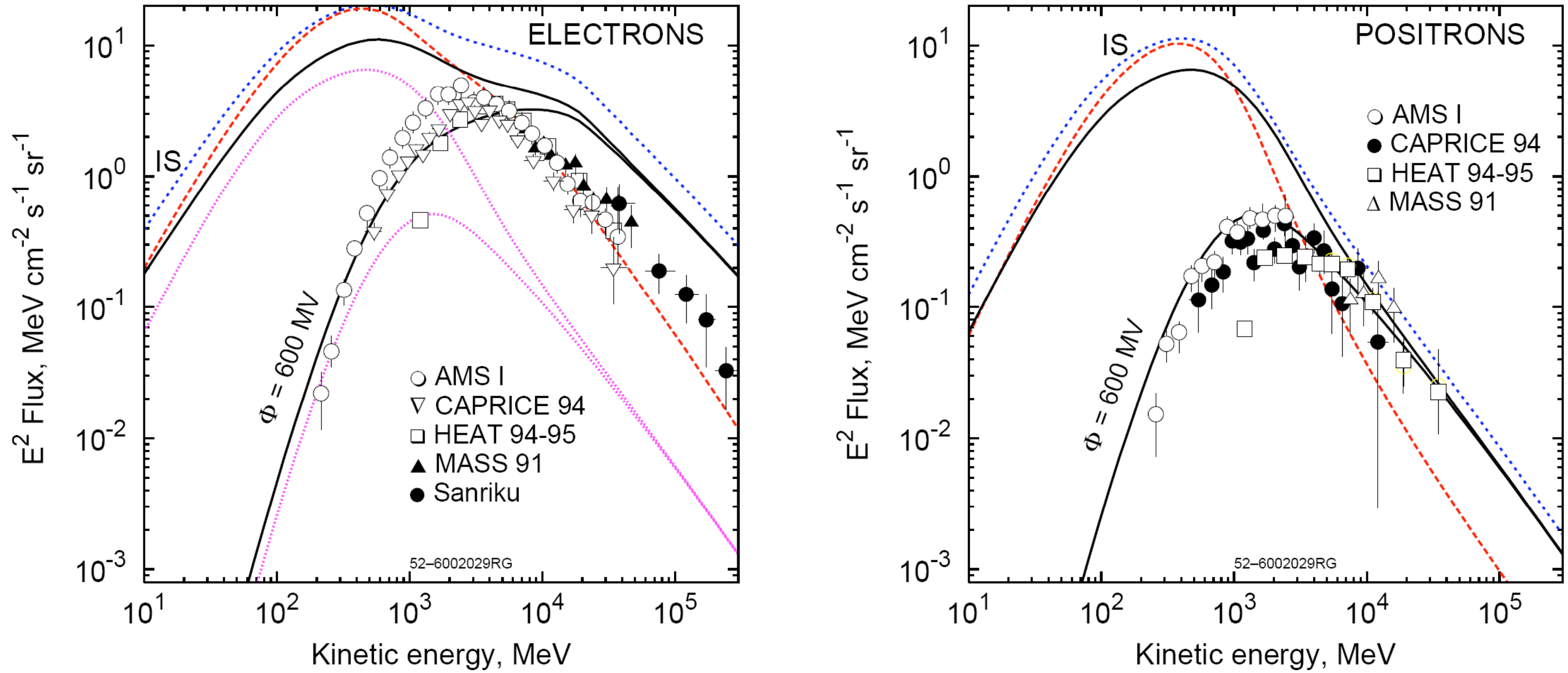


FIG. 2.— Spectra of CR electrons and positrons in the Galactic plane, as predicted by the adopted optimised GALPROP model. *Left:* Total (primary + secondary) and secondary electrons; *Right:* Secondary positrons. Interstellar spectra (IS): $R = 0$ kpc (red long dashes), $R = 4$ kpc (blue short dashes), $R = 8.5$ kpc (black solid), also shown modulated to 600 MV. Secondary electrons are shown separately as magenta lines (IS and modulated) on the left panel at $R = 8.5$ kpc.

Electron/Positron background +uncertainties

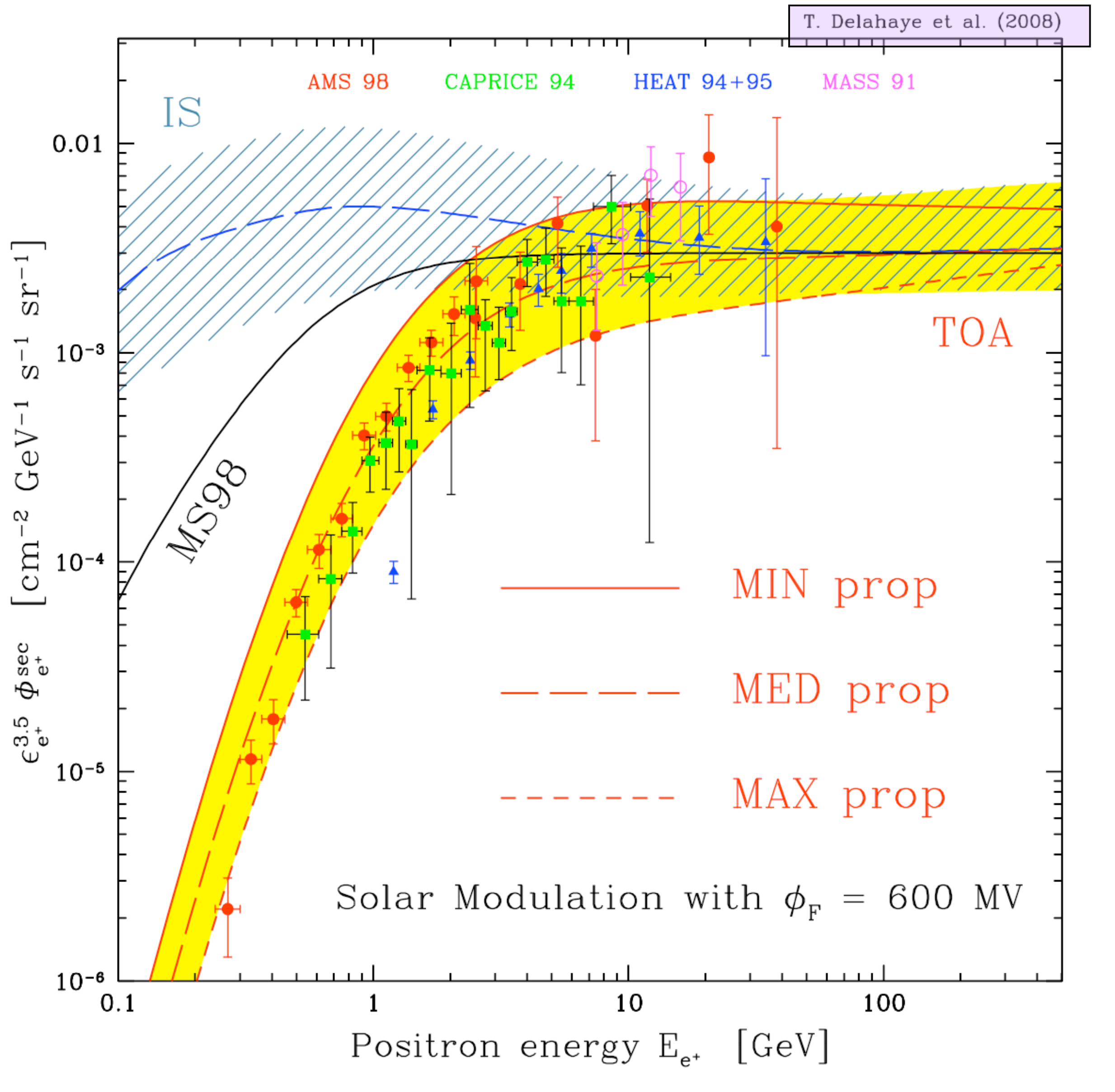
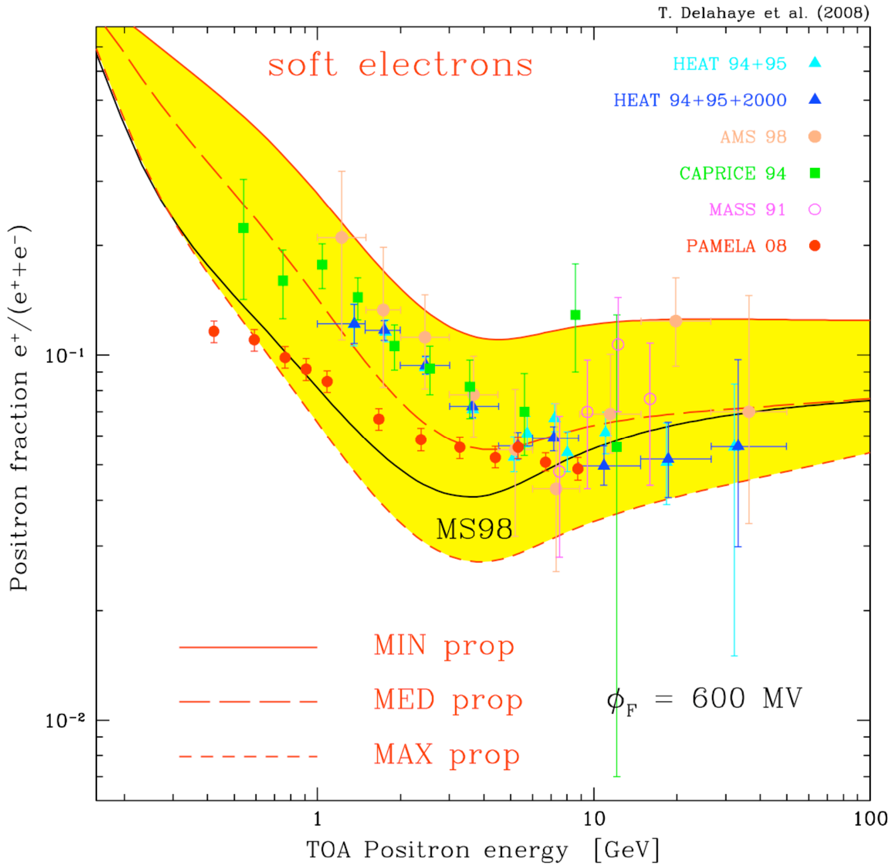
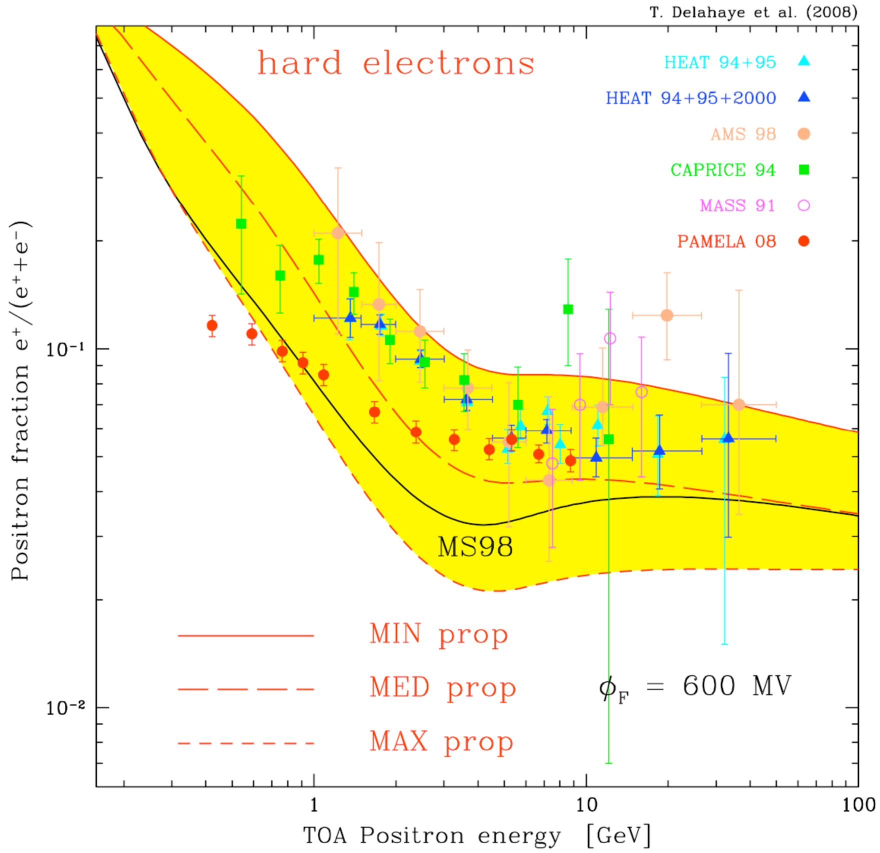


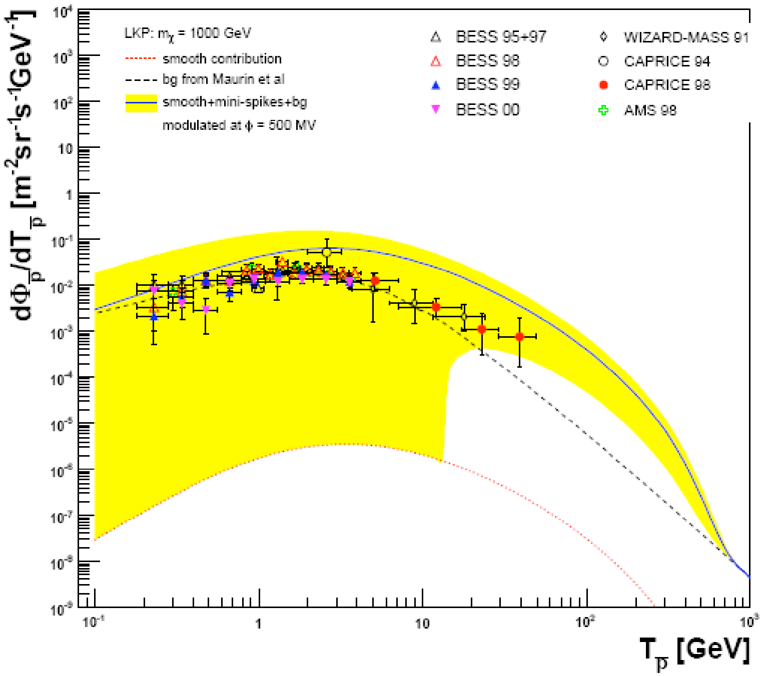
Fig. 4. Secondary positron flux as a function of the positron energy. The blue hatched band corresponds to the CR propagation uncertainty on the IS prediction whereas the yellow strip refers to TOA fluxes. The dashed curves feature our reference model with the Kamae et al. (2006) parameterization of nuclear cross sections, the Shikaze et al. (2007) injection proton and helium spectra and the MED set of propagation parameters. The MIN,MED and MAX propagation parameters are displayed in Tab. 1. Data are taken from Boezio et al. (2000), Barwick et al. (1997), Alcaraz et al. (2000) and Grimani et al. (2002).

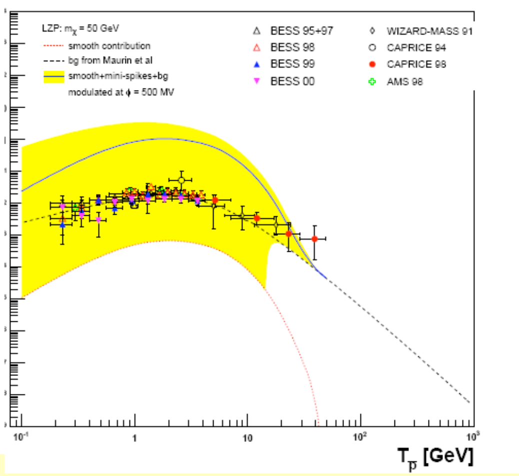
Positron fraction!

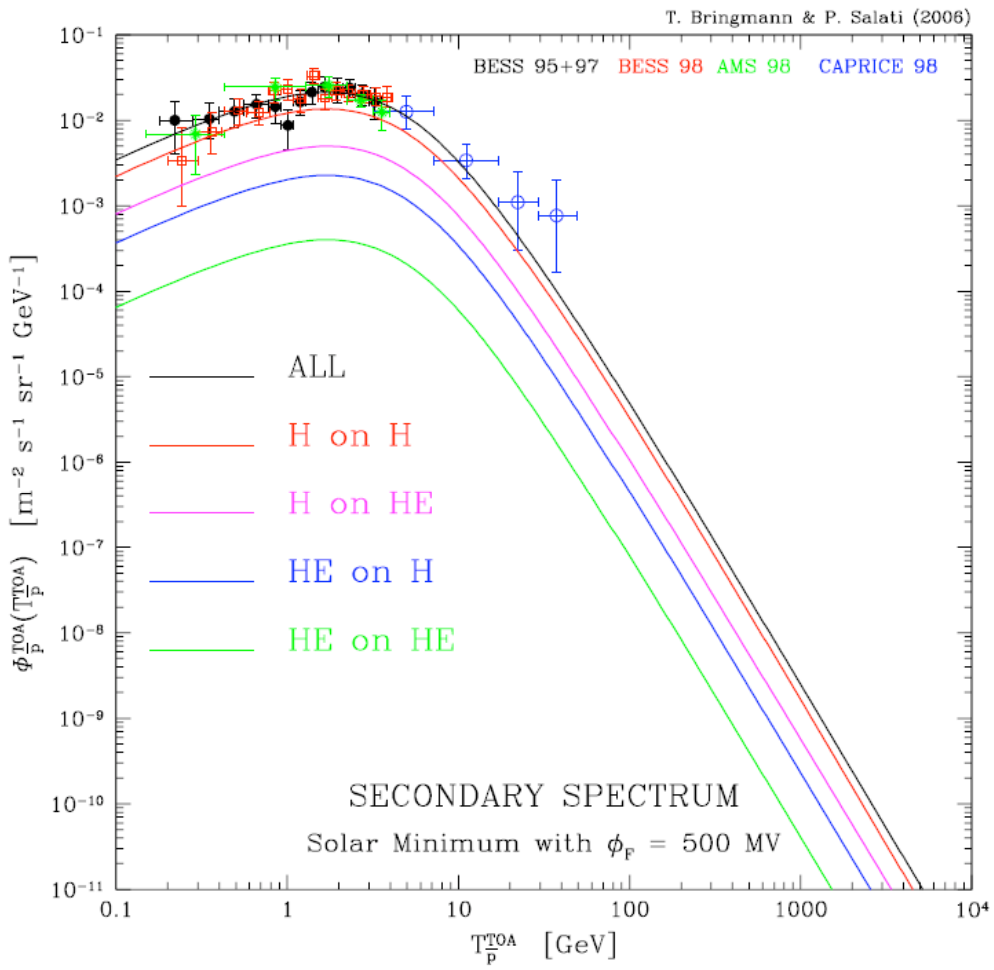




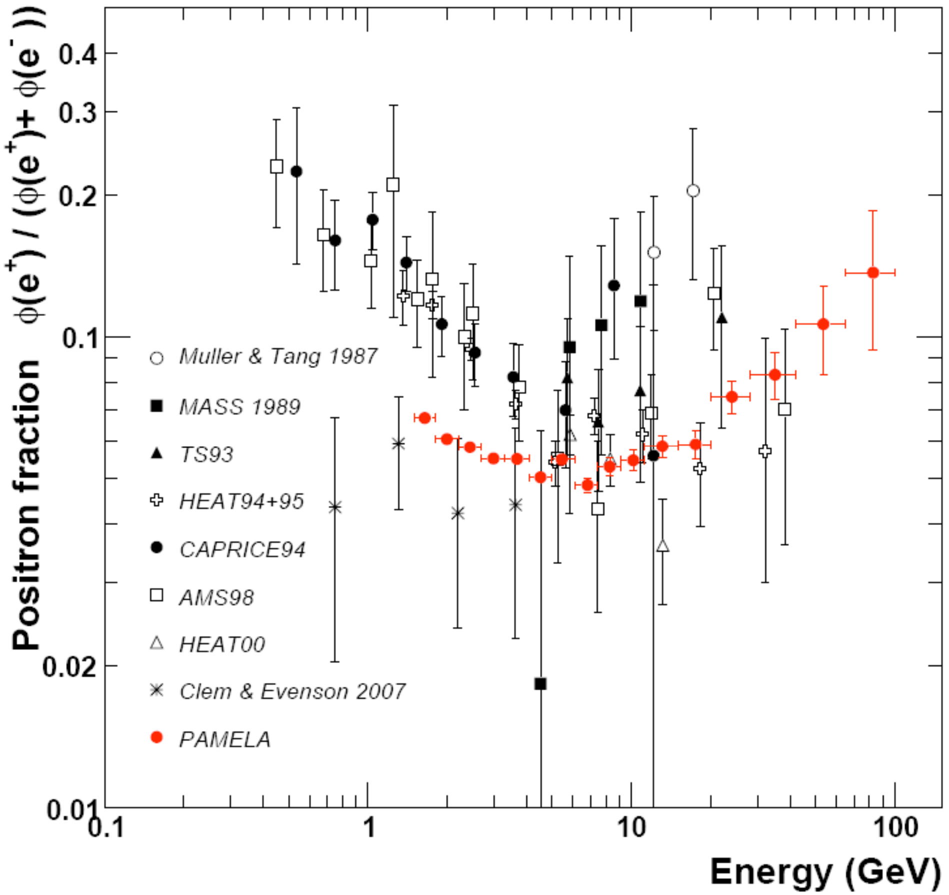
Proton and anti proton background



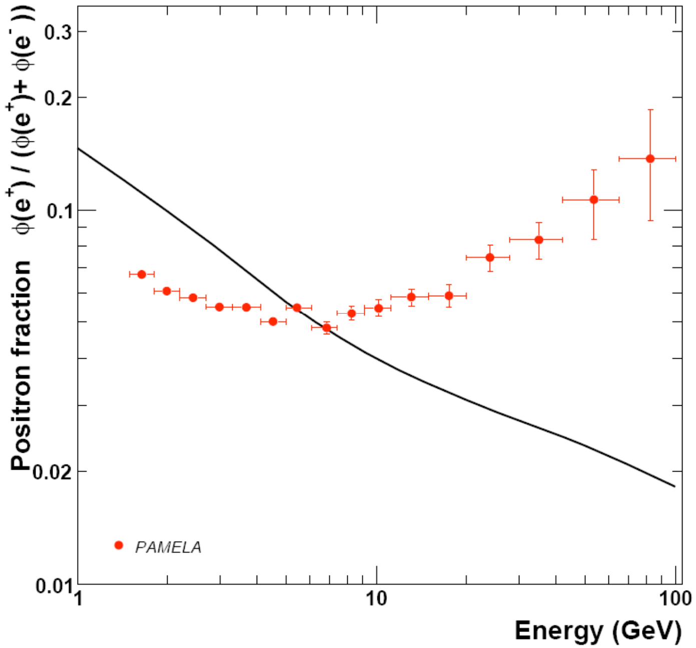




PAMELA DATA

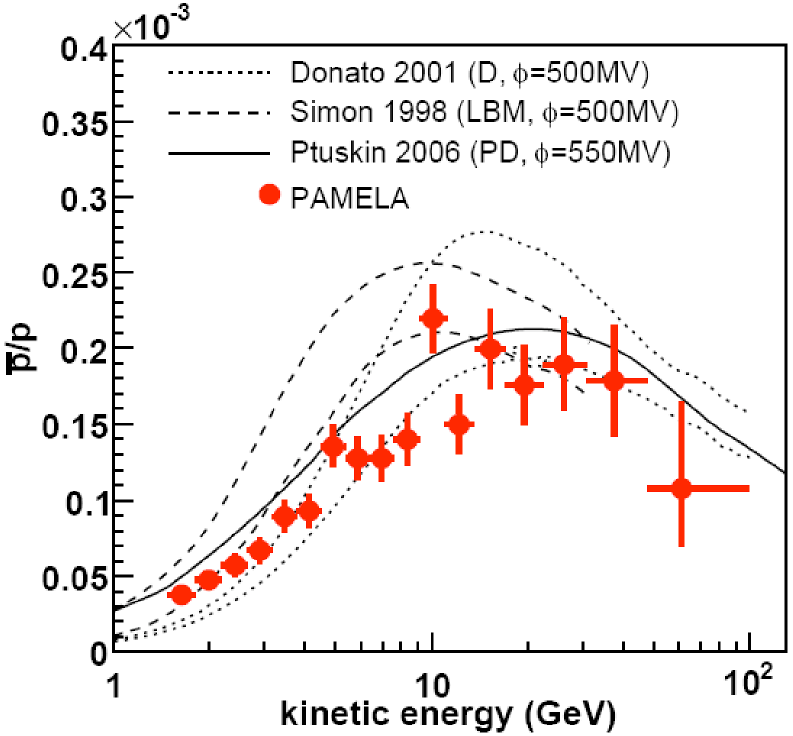


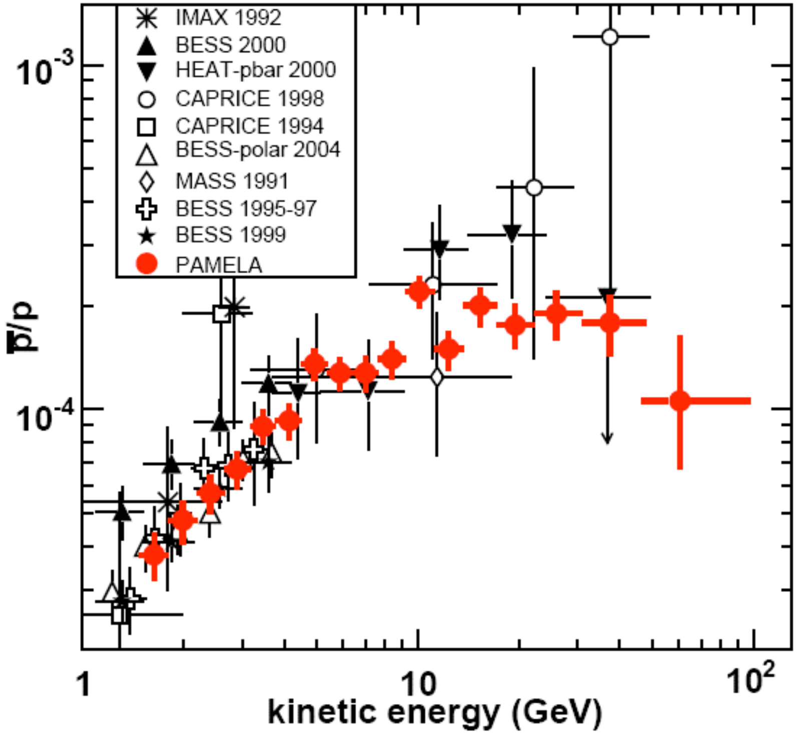
Positron fraction φ(e+) / (φ(e+)+ φ(e-))
0.4
0.3
0.2
0.1
0.02
0.01
0.1
1
10
100
Energy (GeV)
Muller & Tang 1987
MASS 1989
TS93
HEAT94+95
CAPRICE94
AMS98
HEAT00
Clem & Evenson 2007
PAMELA



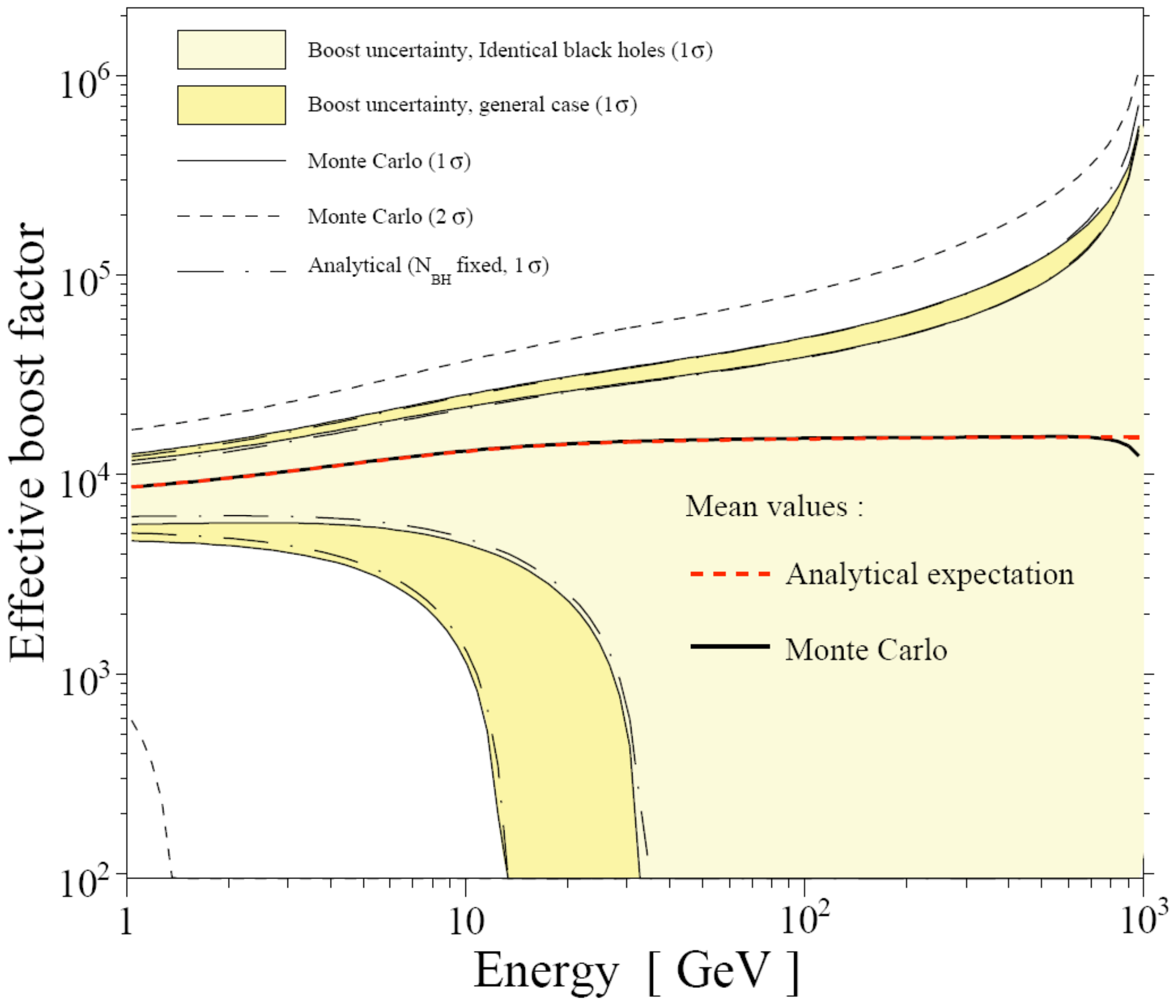
Positron fraction φ(e+) / (φ(e+)+ φ(e-))
0.3
0.2
0.1
0.02
0.01
1
10
100
Energy (GeV)
PAMELA

But nothing new with anti-proton





Boost factor

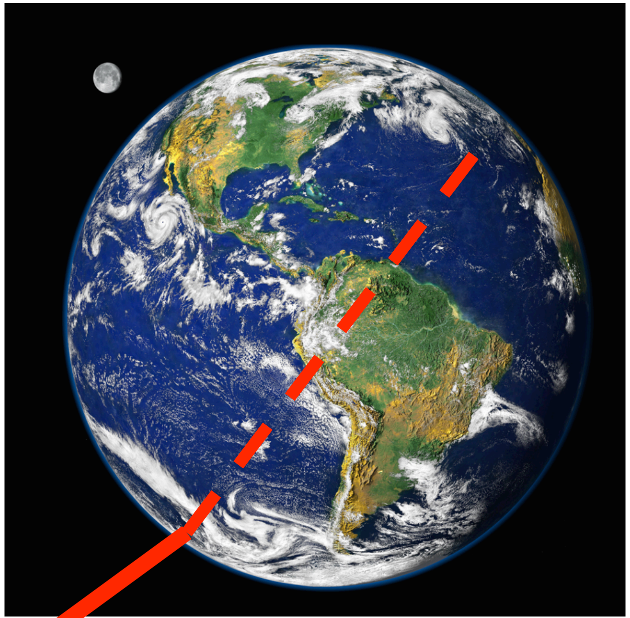


So perhaps the high energy positrons reveal dark matter but maybe not….given the anti-proton data!

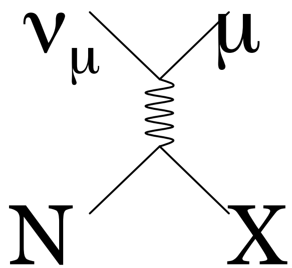
Could mean that DM annihilates predominantly into electrons, that it is heavier than a few TeV or simply that DM is not responsible for this signal..

Neutrino detection

Neutrino-muon conversion



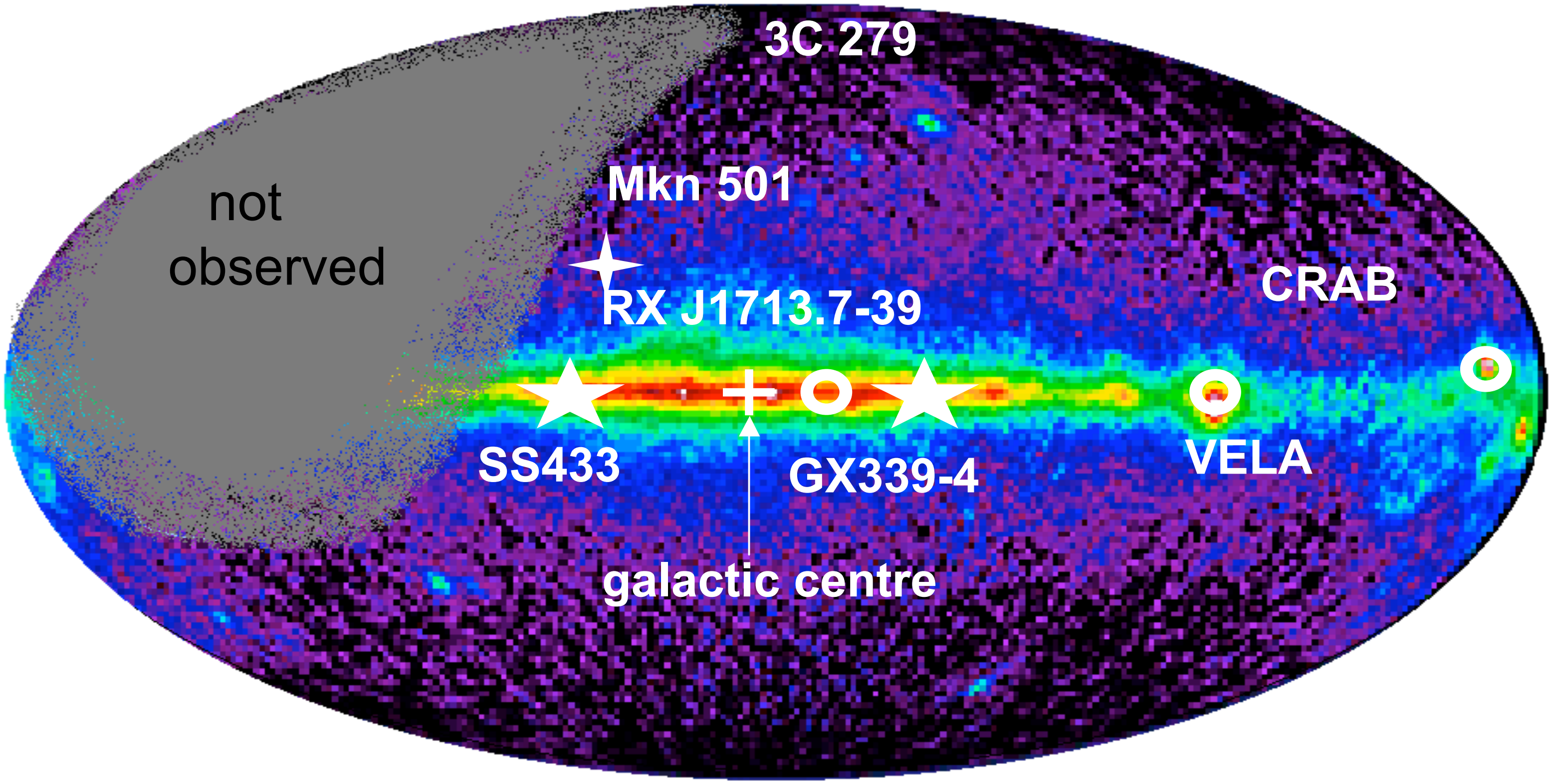
$$dN(\theta) = flux * surface(\theta) * d\Omega * R$$
$$d\Omega = 2\pi \sin\theta \, d\theta$$



For dE/dx of the muons, see PDG

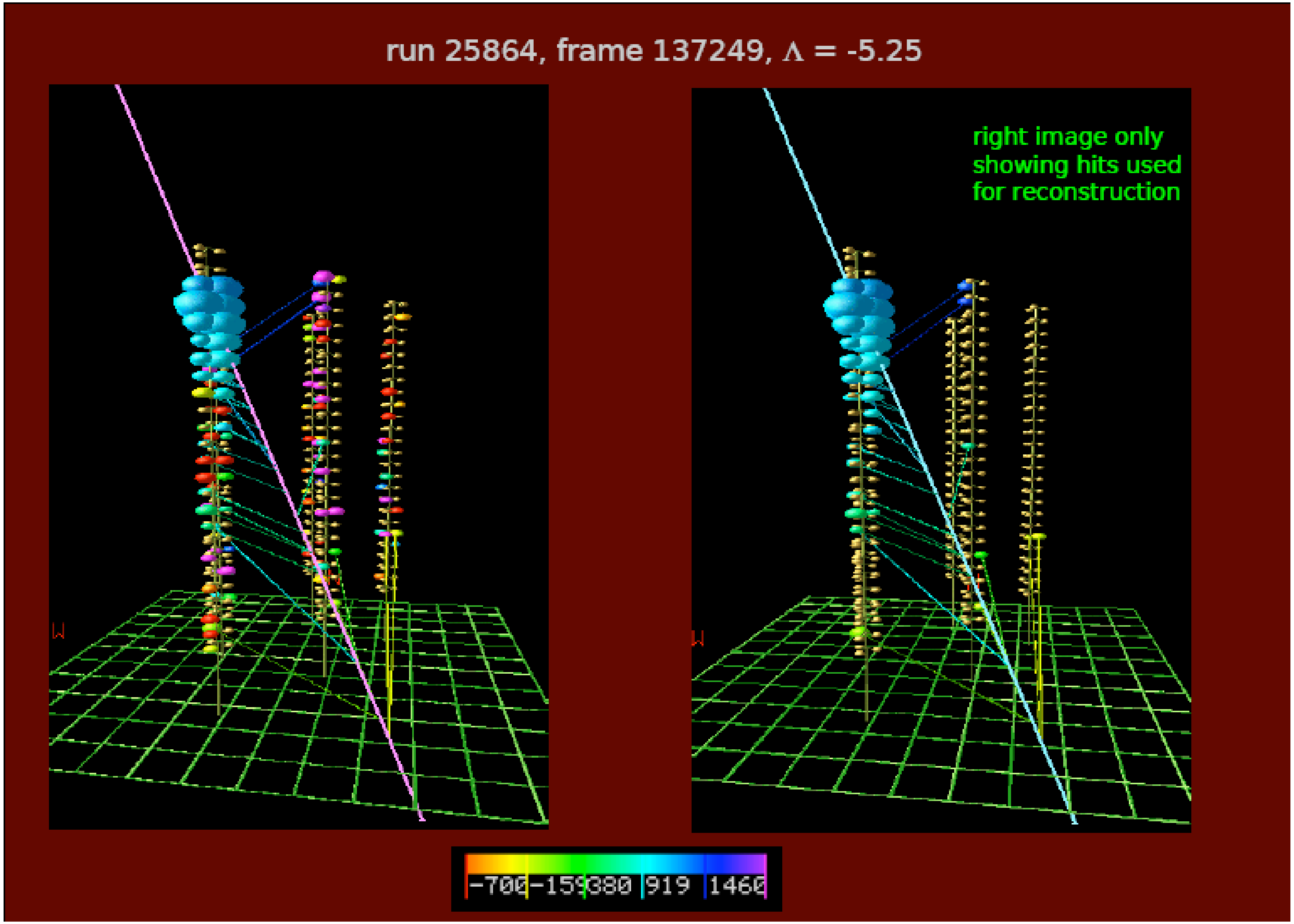
Visible Sky for ANTARES

(courtesy Gabrielle Lelaizant)



ICECUBE is in the south pole. Cannot see well the galactic centre but still

(courtesy Gabrielle Lelaizant)



Celine Boehm

In the absence of strong evidence for
DM signatures in experiments,
we may have to reconsider
the hypothesis that
DM is not a simple substance.

So is there a link between DM and DE?

Many people try…

- Spintessence (Boyle, Caldwell,Kamionkowski)
- Interacting DM-DE (Peebles and Farrar)
- Phantom cosmology (F(R))
- Unified DE-DM model (Bertolami et al)
- Strongly interacting DM and DE
- …

Spintessence

Take a complex scalar field

$$\phi(x,t) = \phi_1(x,t) + i\phi_2(x,t)$$
$$= R(x,t)e^{i\Theta(x,t)}$$

Evolves in a potential: $V(\phi) = monotically\ \ function\ of\ \phi$

Simplest solution are
So the field is spinning at a frequency thetadot.

$$\phi(t) = R\,e^{iwt}$$
$$V'(R) = Rw^2$$

$$\ddot{R} + 3H\dot{R} + V'(R) = \frac{Q^2}{a^6 R^3}$$

$$\rho = \frac{1}{2}(\dot{R}^2 + R^2\dot{\Theta}^2) + V$$

$$p = \frac{1}{2}(\dot{R}^2 + R^2\dot{\Theta}^2) - V$$

$$V(R) = V_0\left(\frac{R}{R_0}\right)^n \quad or \quad V(R) = \frac{m^2}{2}R^2 + \frac{\lambda}{4}R^4$$

For general potential:
w= (n-2)/(n+2)
When n=2, w=0 so DM present
Formation of Q-balls.

For quartic+quadratic V:
If R2 dominates, DM
Otherwise if lambda>0 w=1/3 but tends to 0
and if lambda<0, there is a solution where w=0

For potential: $-1/3\ R^2\ V'' < RV' < R^2 V''$
quintessence and decay into
Q-balls

Interacting DM-DE

$$S_{de} = \int d^4x \sqrt{-g}\,[\frac{1}{2}\phi_{,\nu}\phi^{,\nu} - V(\phi)]$$

$$V(\phi) = \frac{k}{\phi^{\alpha}}$$

$$S_{fermionicDM} = \int d^4x \sqrt{-g}\,[i\bar{\psi}\gamma\partial\psi - y(\phi - cst)\bar{\psi}\psi]$$

$$\frac{\delta m}{m} \propto y * \frac{density\ contrast}{\phi_b}$$

They considered small contrast so dm/m is small.
However DM acquires its mass thanks to the DE field
This varies a bit from the LCDM model

Unified DE-DM

Bertolami et al

$$L = -A^{\frac{1}{1+\alpha}}\left[1-\left(g^{\mu\nu}\theta_{,\mu}\theta_{,\nu}\right)^{\frac{1+\alpha}{2\alpha}}\right]^{\frac{\alpha}{1+\alpha}}$$

$$\boxed{\begin{aligned} p &= -\frac{A}{\rho^{\alpha}} \\ \rho &= \left[A + \frac{B}{a^{3(1+\alpha)}}\right]^{\frac{1}{1+\alpha}} \end{aligned}}$$

Cosmological cst

DM

Generalized Chaplygin gaz

(see Hugo's talk)

Can separate the two components with time and do cosmology

DM is still a ~ CDM fluid

Conclusion

DM generally treated separately from DE

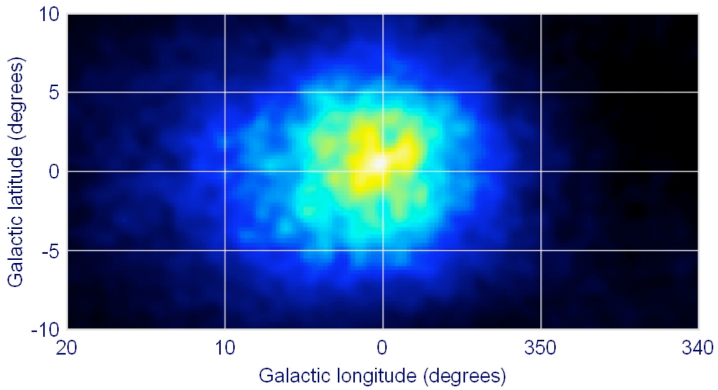
Yet nature of DM remains mysterious

Possible positive signal (PAMELA, INTEGRAL) but
may favour “outsider” candidates

No detection in DD or collider experiments (indirectly or directly)

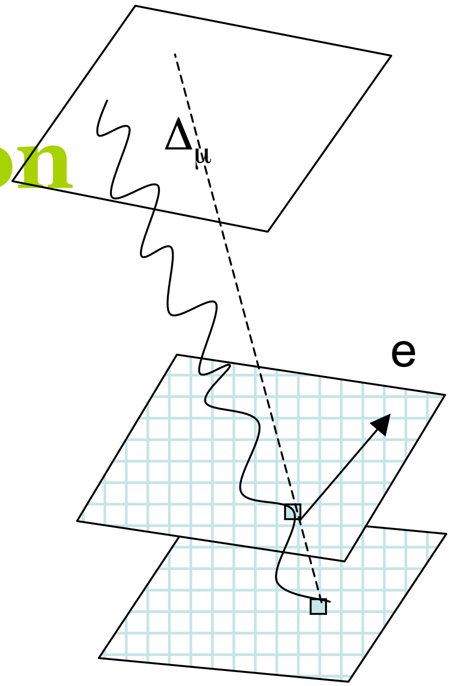
Connection to DE done “by hand” in general (except for unified DE-DM?)
But DM and DE both present and difficult to find.

Is the key in modifying gravity ???…



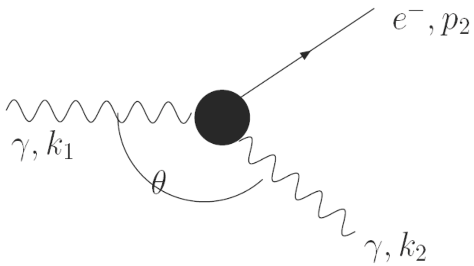
511 keV SPI/INTEGRAL image obtained using this principle

Principle
Compton



ΔE = Ee-me
(electron scattered out)

Measures the photon energy



$$p_1.k_1 = m\ E_{k_1},$$

$$p_1.k_2 = m\ E_{k_2}$$

$$\boxed{E_{k_2} = \frac{E_{k_1}}{1 + \frac{E_{k_1}}{m}(1 - \Delta_\mu)}}$$

$\Delta\mu$ = angle between the 2 photons

Where

$\Delta E = E_{k2} - E_{k1}$
$= E_{p2} - E_{p1}$