Mirror dark matter interpretations of DAMA, CoGeNT and CRESST experiments

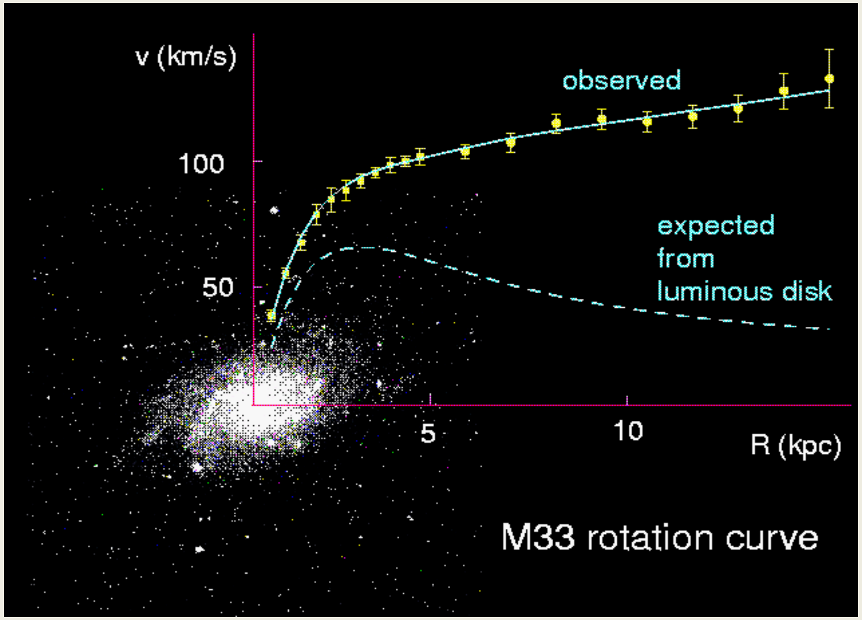
Robert Foot, University of Melbourne, CoEPP

Talk at PACIFIC Conference

5 September 2012

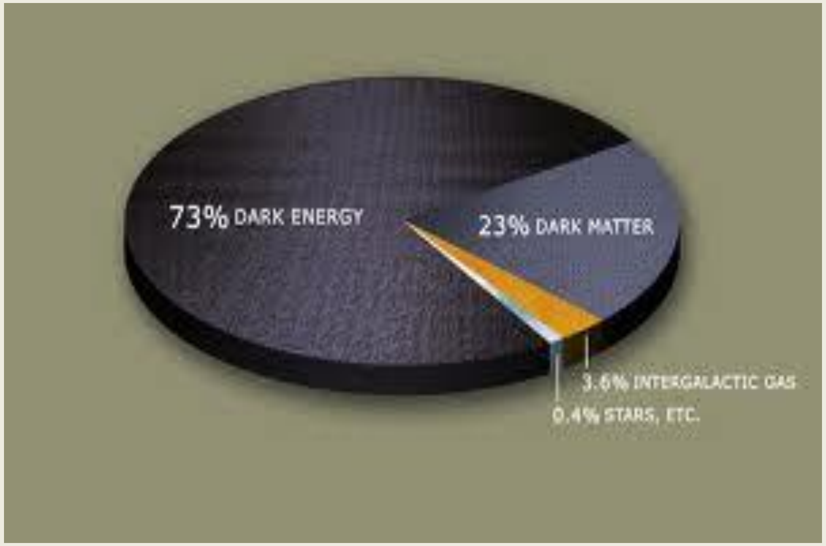
Evidence for non-baryonic dark matter

Rotation curves in spiral galaxies



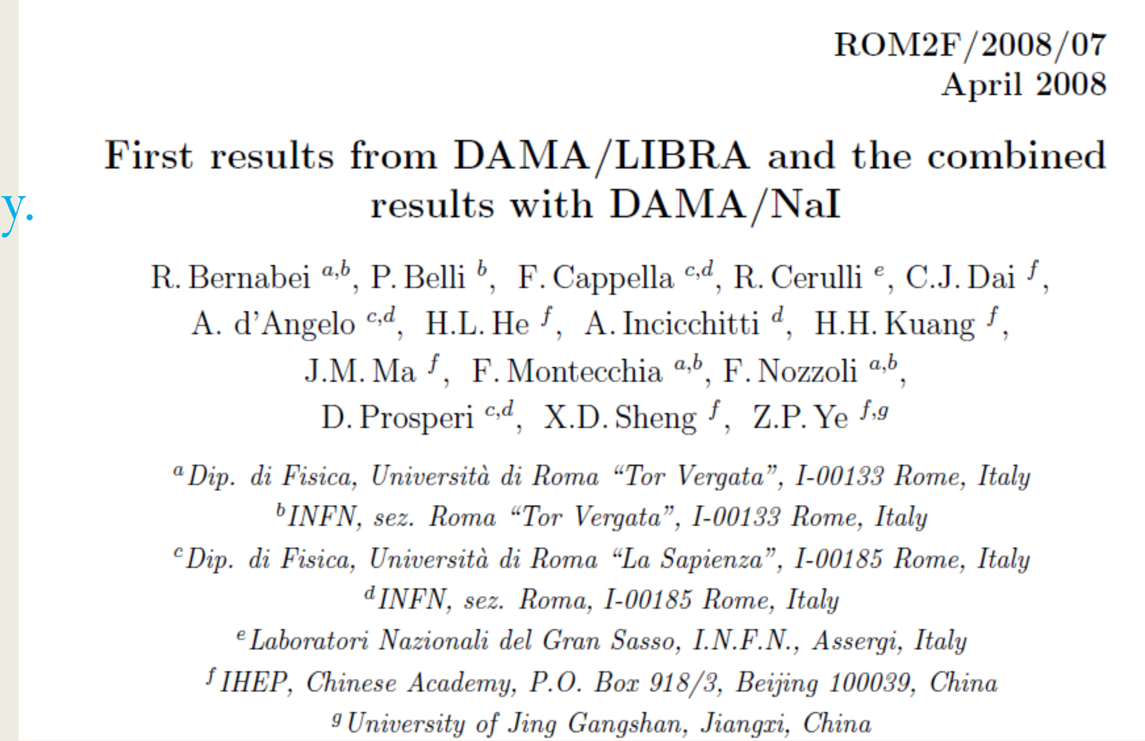
Lambda-CDM Model

Suggests 23% of the Universe consists of non-baryonic dark matter



DAMA/NaI and DAMA/Libra experiments

First claim of direct detection of dark matter!
More than 10 years already.



ROM2F/2008/07
April 2008

First results from DAMA/LIBRA and the combined results with DAMA/NaI

R. Bernabei [a,b], P. Belli [b], F. Cappella [c,d], R. Cerulli [e], C.J. Dai [f],
A. d'Angelo [c,d], H.L. He [f], A. Incicchitti [d], H.H. Kuang [f],
J.M. Ma [f], F. Montecchia [a,b], F. Nozzoli [a,b],
D. Prosperi [c,d], X.D. Sheng [f], Z.P. Ye [f,g]

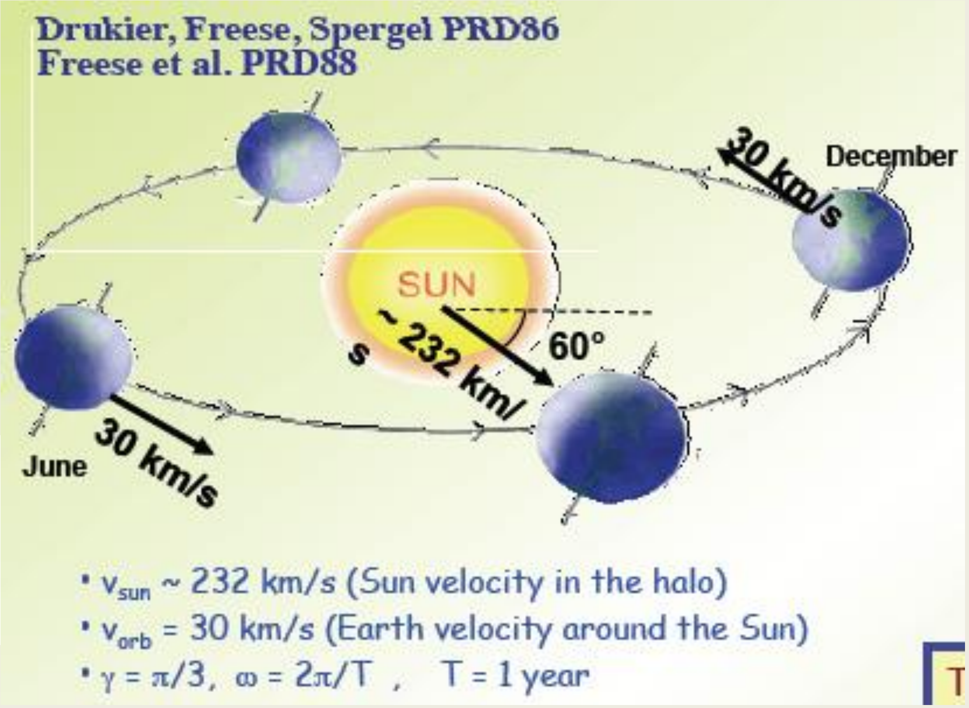
[a] *Dip. di Fisica, Università di Roma "Tor Vergata", I-00133 Rome, Italy*
[b] *INFN, sez. Roma "Tor Vergata", I-00133 Rome, Italy*
[c] *Dip. di Fisica, Università di Roma "La Sapienza", I-00185 Rome, Italy*
[d] *INFN, sez. Roma, I-00185 Rome, Italy*
[e] *Laboratori Nazionali del Gran Sasso, I.N.F.N., Assergi, Italy*
[f] *IHEP, Chinese Academy, P.O. Box 918/3, Beijing 100039, China*
[g] *University of Jing Gangshan, Jiangxi, China*

DAMA team have found evidence for dark matter with DAMA/NaI (100 kg NaI target) 1997-2003 and confirmed with more precision by DAMA/Libra (250 kg NaI target) 2003-2012

DAMA/NaI and DAMA/Libra experiments

Evidence from direct detection experiments, especially DAMA/LIBRA annual modulation signal

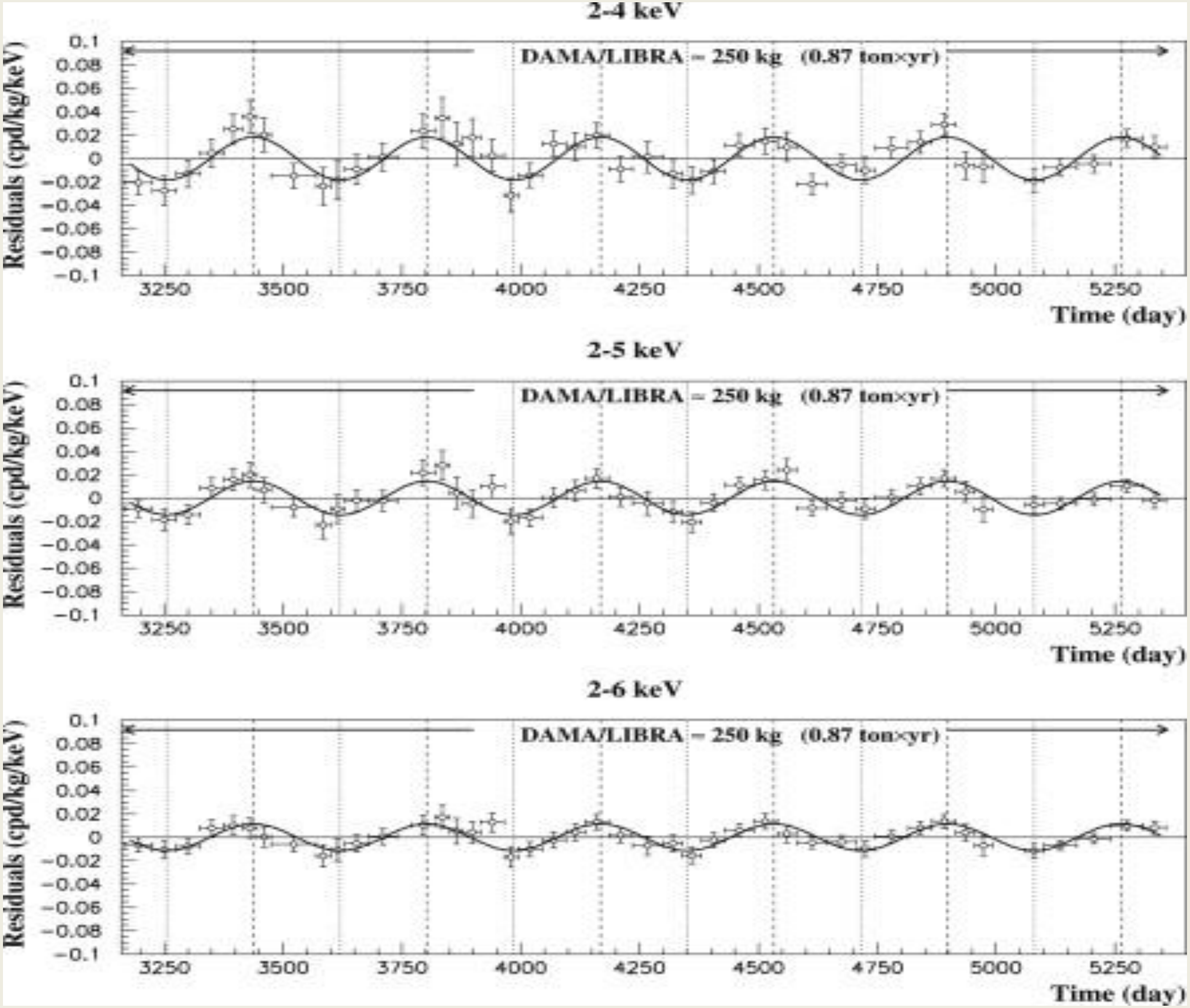
$$R(v_E) = R(v_\odot) + \left(\frac{\partial R}{\partial v_E}\right)_{v_\odot} \Delta v_E \cos\omega(t - t_0)$$


Drukier, Freese, Spergel PRD86
Freese et al. PRD88

- v_{sun} ~ 232 km/s (Sun velocity in the halo)
- v_{orb} = 30 km/s (Earth velocity around the Sun)
- $\gamma = \pi/3$, $\omega = 2\pi/T$, T = 1 year

Phase and Period of modulation are predicted! $t_0 = 152$ (June 2), T = 1 year.

$$\begin{aligned} T &= 0.999 \pm 0.002 \text{ year} \\ t_0 &= 146 \pm 7 \text{ day.} \end{aligned}$$


2-4 keV
DAMA/LIBRA ≈ 250 kg (0.87 ton×yr)
Residuals (cpd/kg/keV)
0.1
0.08
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
−0.1
3250
3500
3750
4000
4250
4500
4750
5000
5250
Time (day)
2-5 keV
DAMA/LIBRA ≈ 250 kg (0.87 ton×yr)
Residuals (cpd/kg/keV)
Time (day)
2-6 keV
DAMA/LIBRA ≈ 250 kg (0.87 ton×yr)
Residuals (cpd/kg/keV)
Time (day)

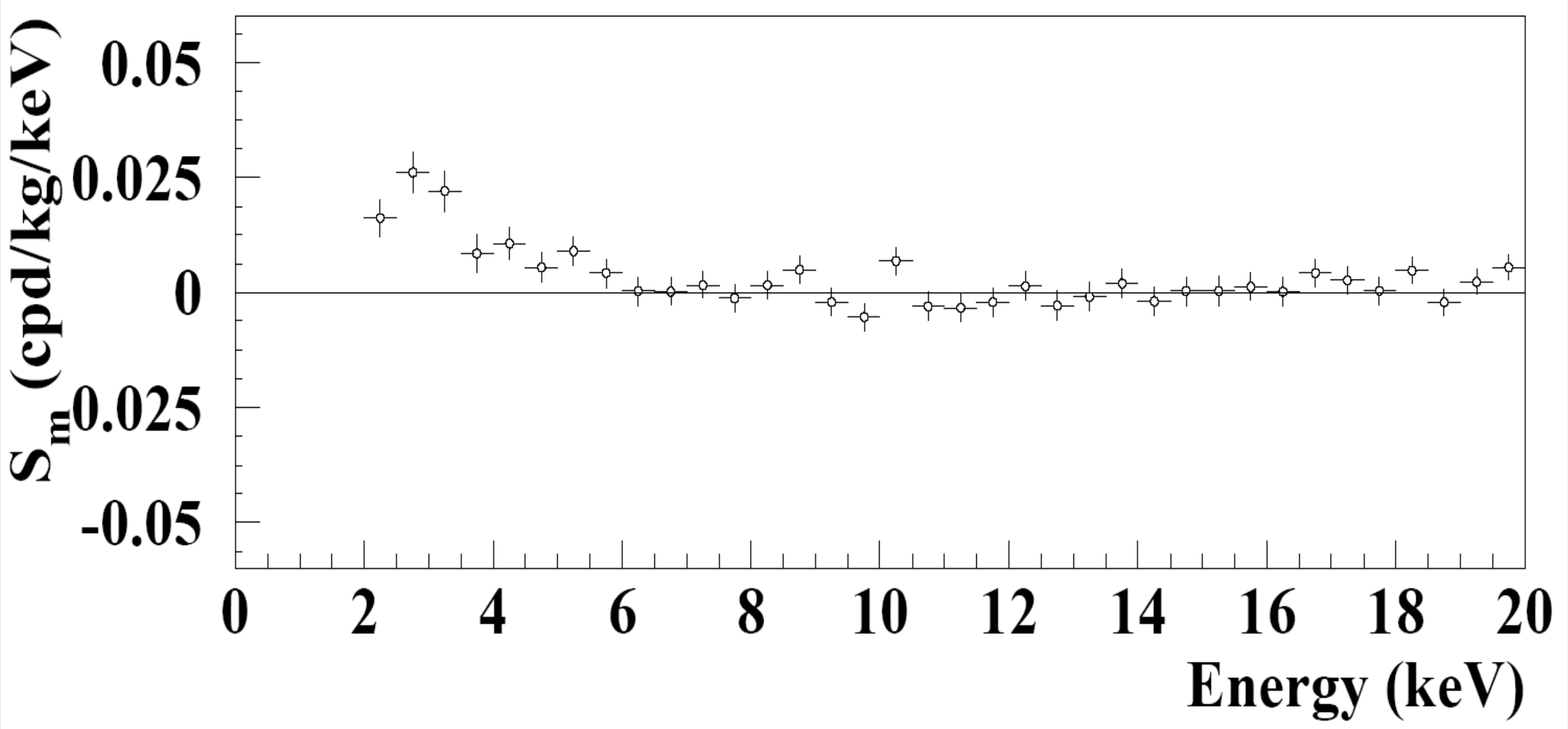
Energy distribution of the modulation amplitudes

$$R(t) = S_0 + S_m \cos[\omega(t - t_0)]$$

here $T = 2\pi/\omega = 1$ yr and $t_0 = 152.5$ day

DAMA/NaI (7 years) + DAMA/LIBRA (6 years)

total exposure: 425428 kg×day ≈1.17 ton×yr



Modulation is present in the 2-6 keV energy interval.

What is dark matter?

A simple idea... assume dark matter belongs to a hidden sector exactly isomorphic to the standard model

$$\mathscr{L} = \mathscr{L}_{SM}(e,u,d,\gamma,\ldots) + \mathscr{L}_{SM}(e',u',d',\gamma',\ldots)$$

RF, H. Lew and R. R. Volkas, PLB,91

Concept discussed prior to standard model by Lee and Yang and others.

If left and right fields interchanged in the hidden sector, theory has exact parity symmetry, x → -x

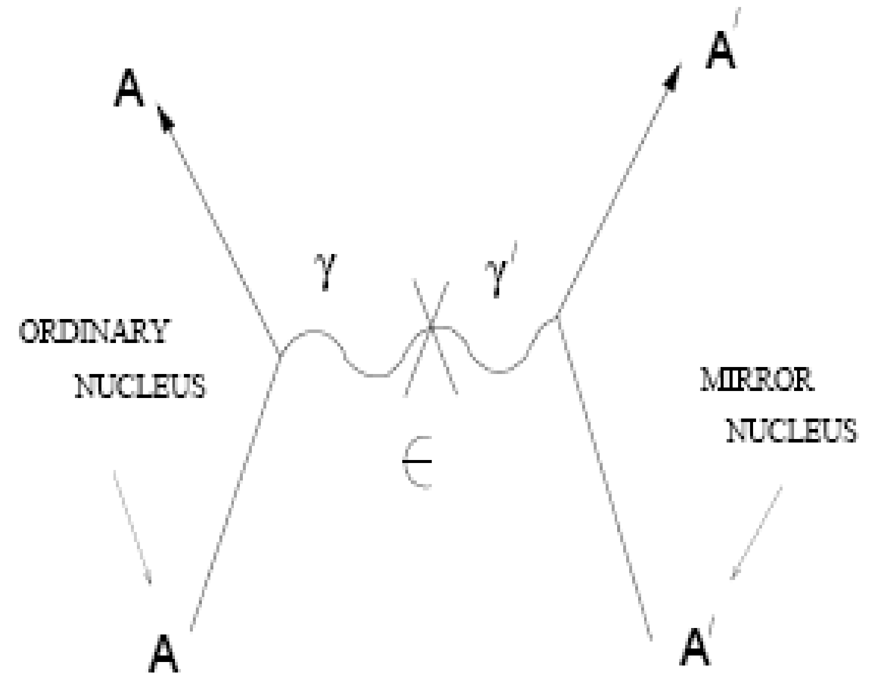
The e', H', He', … particles in the hidden (mirror) sector are stable and provide an interesting dark matter candidate.

The ordinary and mirror particles form two almost decoupled sectors which couple to each other via gravity and possibly by the renormalizable interactions:

$$\mathcal{L}_{mix} = \frac{\varepsilon}{2} F^{\mu\nu} F'_{\mu\nu} + \lambda \phi^{\dagger} \phi \phi'^{\dagger} \phi'$$

$$\frac{d\sigma}{dE_R} = \frac{\lambda}{E_R^2 v^2}$$

$$\lambda \equiv \frac{2\pi\epsilon^2 Z^2 Z'^2 \alpha^2}{m_A} F_A^2(qr_A) F_{A'}^2(qr_{A'})$$



Dark matter = mirror matter

Successful cosmology requires asymmetric initial conditions:

$$T' << T \quad \text{and} \quad n_{b'} = 5\, n_b$$

With such initial conditions the theory exactly mimics standard cold dark matter on large scales, i.e. successful LSS and CMB.

Berezhinai, Comelli and Villante, PLB 01,
Ignatiev and Volkas, PRD 03
Ciarcelluti, IJMP 05.

On smaller scales mirror dark matter is radically different to standard cold dark matter because it is self-interacting, dissipative and multi-component.

Mirror dark matter on small scales: Galactic halos

Observations suggest that galactic halo is a pressure supported plasma consisting of e', H', He', O', Fe',...

Volkas and R.F. astro-ph/0407522;
Silagadze and R.F. astro-ph/0404515

Such a plasma would radiatively cool unless heat source exists.

Ordinary supernova can potentially supply the required energy if the kinetic mixing has strength :

$$\epsilon \sim 10^{-9}$$

~ half of supernova core collapse energy goes into mirror e'

Importantly, if kinetic mixing exists can detect mirror particles in experiments

Kinetic mixing interaction, with $\epsilon \sim 10^{-9}$ means ordinary and mirror particles can interact with each other and can therefore be detected!

$$\frac{dR}{dE_R} = N_T n_{A'} \int \frac{d\sigma}{dE_R} \frac{f_{A'}(\mathbf{v}, \mathbf{v}_E)}{k} |\mathbf{v}| d^3 v$$

Rate depends on halo distribution function

$$\begin{aligned} f[i] &= e^{-\frac{1}{2} m_i \mathrm{v}^2 / T} \\ &= e^{-\mathrm{v}^2 / \mathrm{v}_0^2 [i]} \end{aligned}$$

Temperature can be determined from condition of hydrostatic equilibrium

$$\frac{dP}{dr} = -\rho g$$

$$P = \sum n_i T, \ \rho = \sum m_i n_i, \ g = \frac{G}{r^2} \int^r \rho \, dV = \frac{\mathrm{v}_{rot}^2}{r}$$

Solving this equation leads to $T = \frac{1}{2}\overline{m}v_{rot}^2$

Galactic rotation velocity

Mean mass of particles in halo

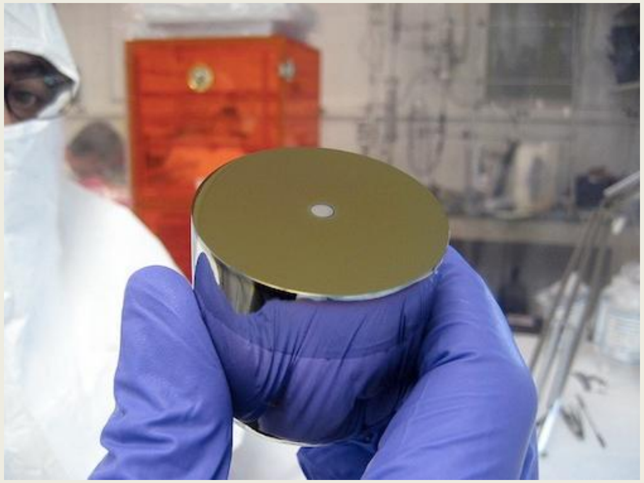
And hence $v_0^2[i] = v_{rot}^2 \frac{\overline{m}}{m_i}$

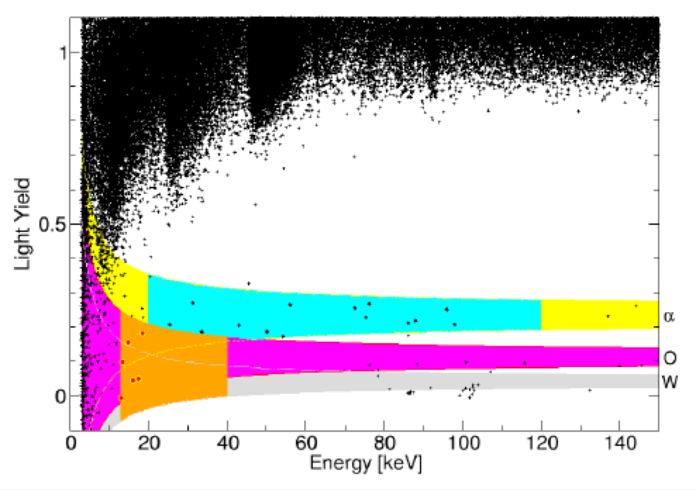
The key point is that heavy particles have narrow velocity dispersion

If $m_i \gg \overline{m}.$ **then** $v_0^2[i] \ll v_{rot}^2$

This can help explain why DAMA sees a signal and higher threshold experiments such as CDMS and XENON100 do not!

The CoGeNT and CRESST experiments, like DAMA, also have low energy thresholds and they also see a possible dark matter signal.





Many sensitive, but higher threshold experiments such as XENON100 and CDMS have yet to find any dark matter signal.

Can mirror dark matter explain these results?

References: R. F. arXiv: hep-ph/0308254 and more recent analysis: R.F. arXiv 1203.2387; arXiv: 1106.2688; 1008.0685.

DAMA experiment measures annual modulation

$$R(v_E) = R(v_\odot) + \left(\frac{\partial R}{\partial v_E}\right)_{v_\odot} \Delta v_E \cos\omega(t - t_0)$$

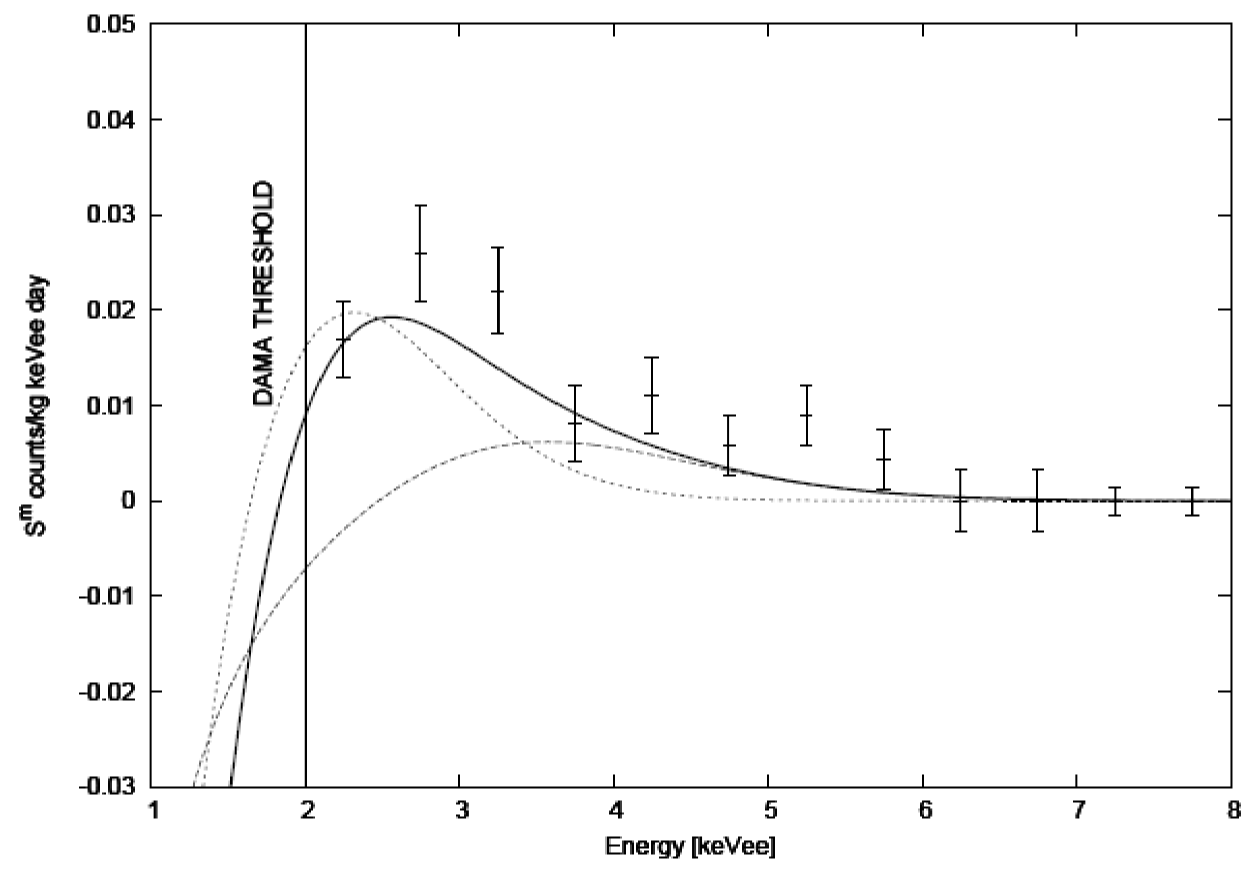
Mirror dark matter can fit the energy dependence of the DAMA modulation

Shown is fit for an example:

$$A' = \mathrm{Fe}'$$

$$v_{rot} = 200\ \mathrm{km/s},$$

$$\epsilon\sqrt{\xi_{Fe'}} = 2.2 \times 10^{-10}$$



CoGeNT spectrum quite uncertain due to surface event correction.

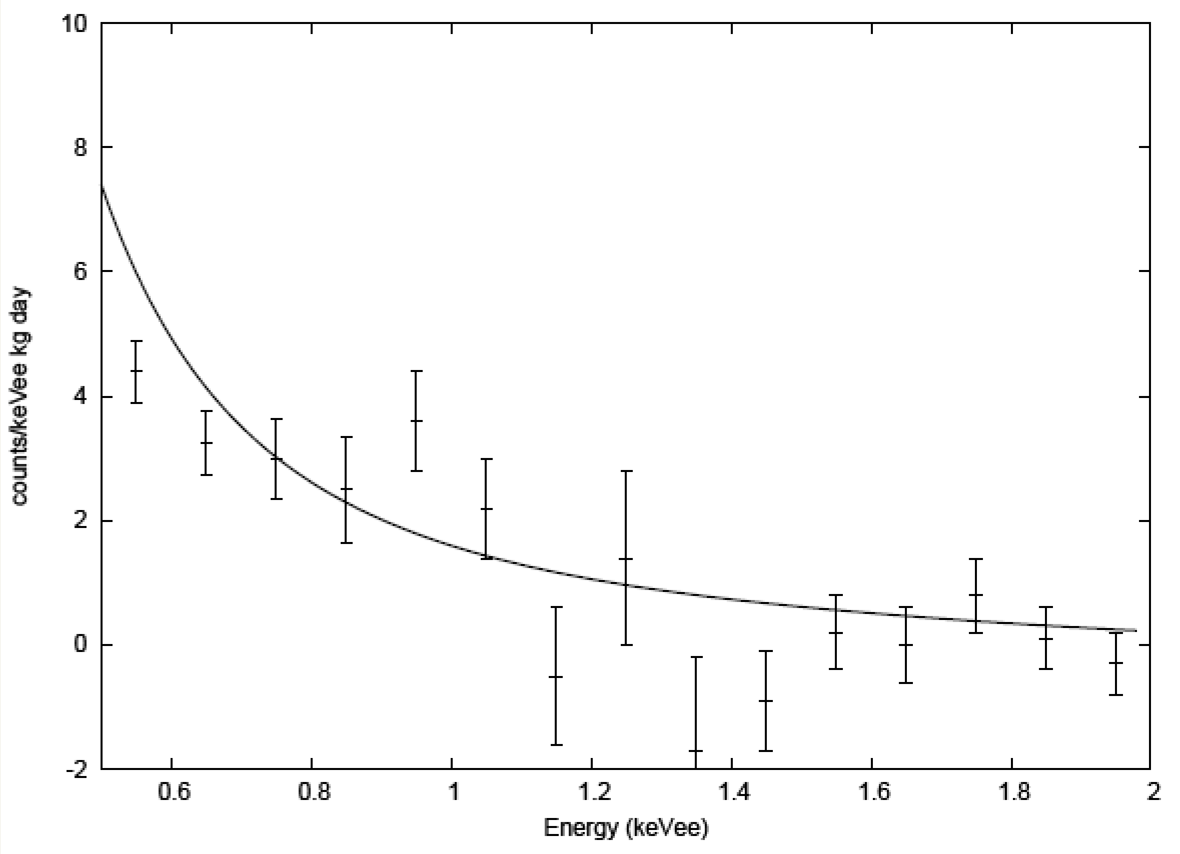
Mirror dark matter can fit the energy dependence of the CoGeNT spectrum

Shown is fit for an example:

$$A' = \mathrm{Fe}'$$

$$v_{rot} = 200\ \mathrm{km/s},$$

$$\epsilon\sqrt{\xi_{Fe'}} = 2.2 \times 10^{-10}$$



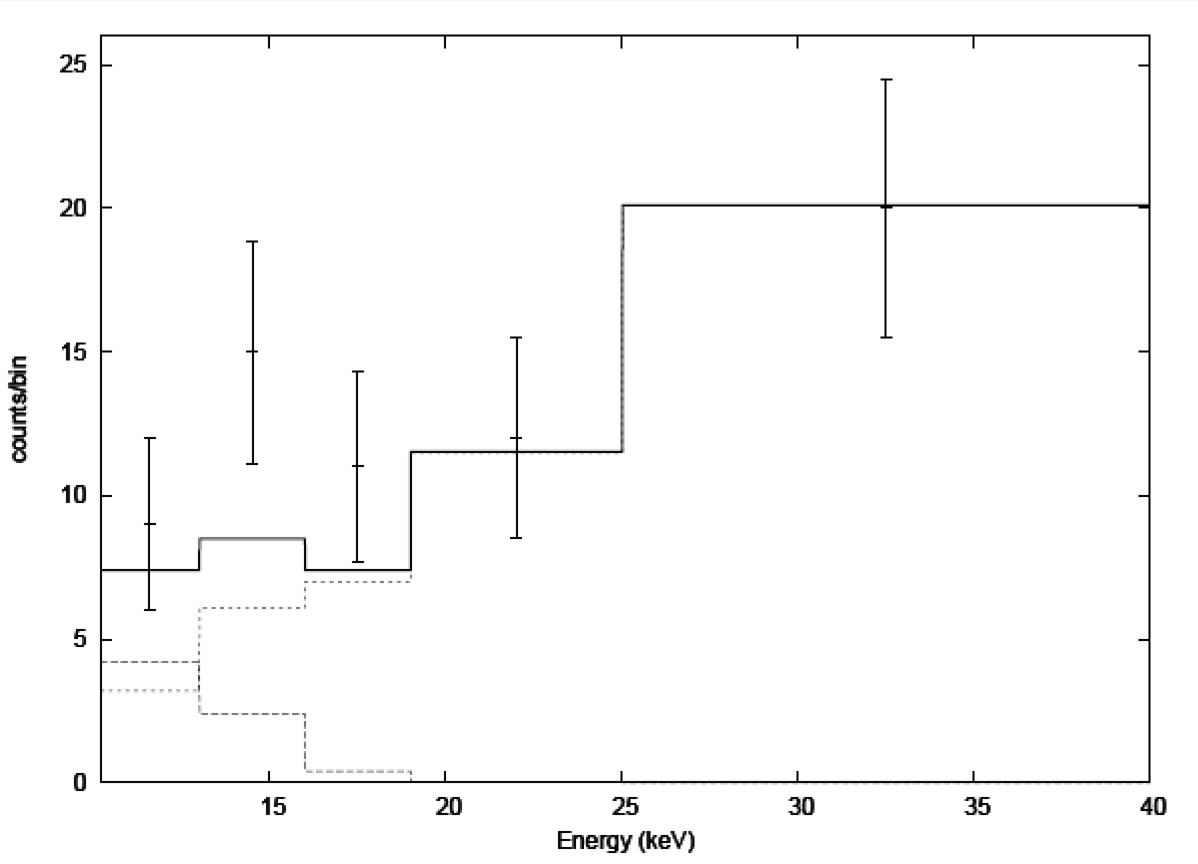
Mirror dark matter can fit the CRESST-II spectrum.

Shown is fit for an example:

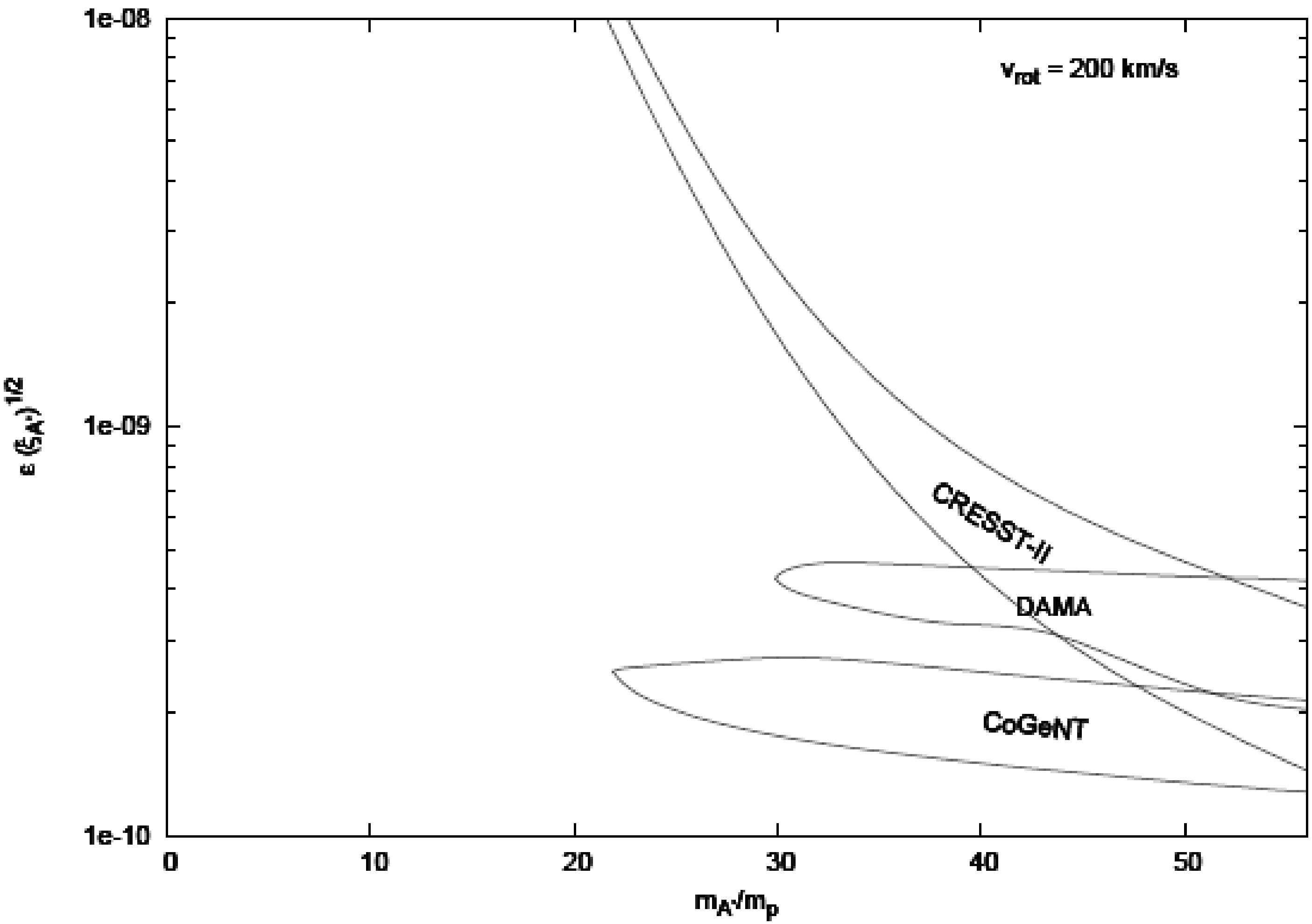
$$A' = \mathrm{Fe}'$$

$$v_{rot} = 200\ \mathrm{km/s},$$

$$\epsilon\sqrt{\xi_{Fe'}} = 2.2 \times 10^{-10}$$



Combined fit of DAMA, CoGeNT and CRESST-II



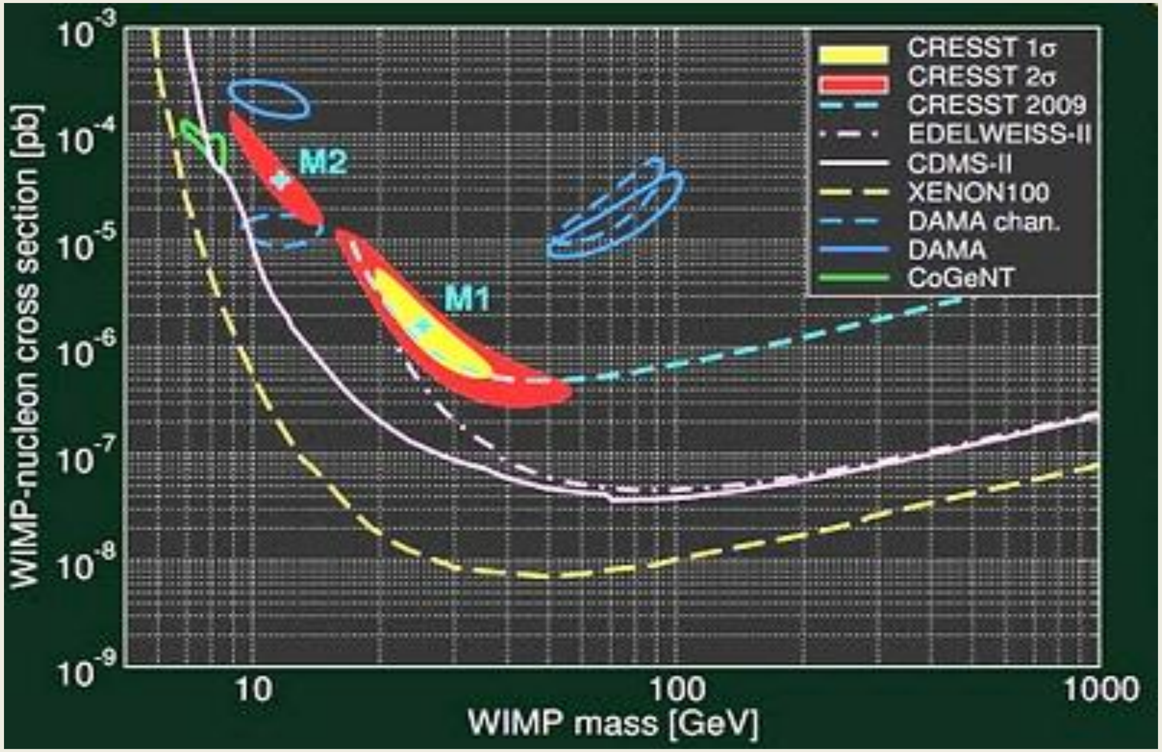
Mirror dark matter different to standard WIMP models

1) Mirror dark matter is necessarily light < 52 GeV

2) Mirror dark matter interacts via Rutherford scattering, rather than contact interactions

3) Mirror dark matter is multi-component which leads to narrow velocity dispersion.

Parameter space in standard wimp model



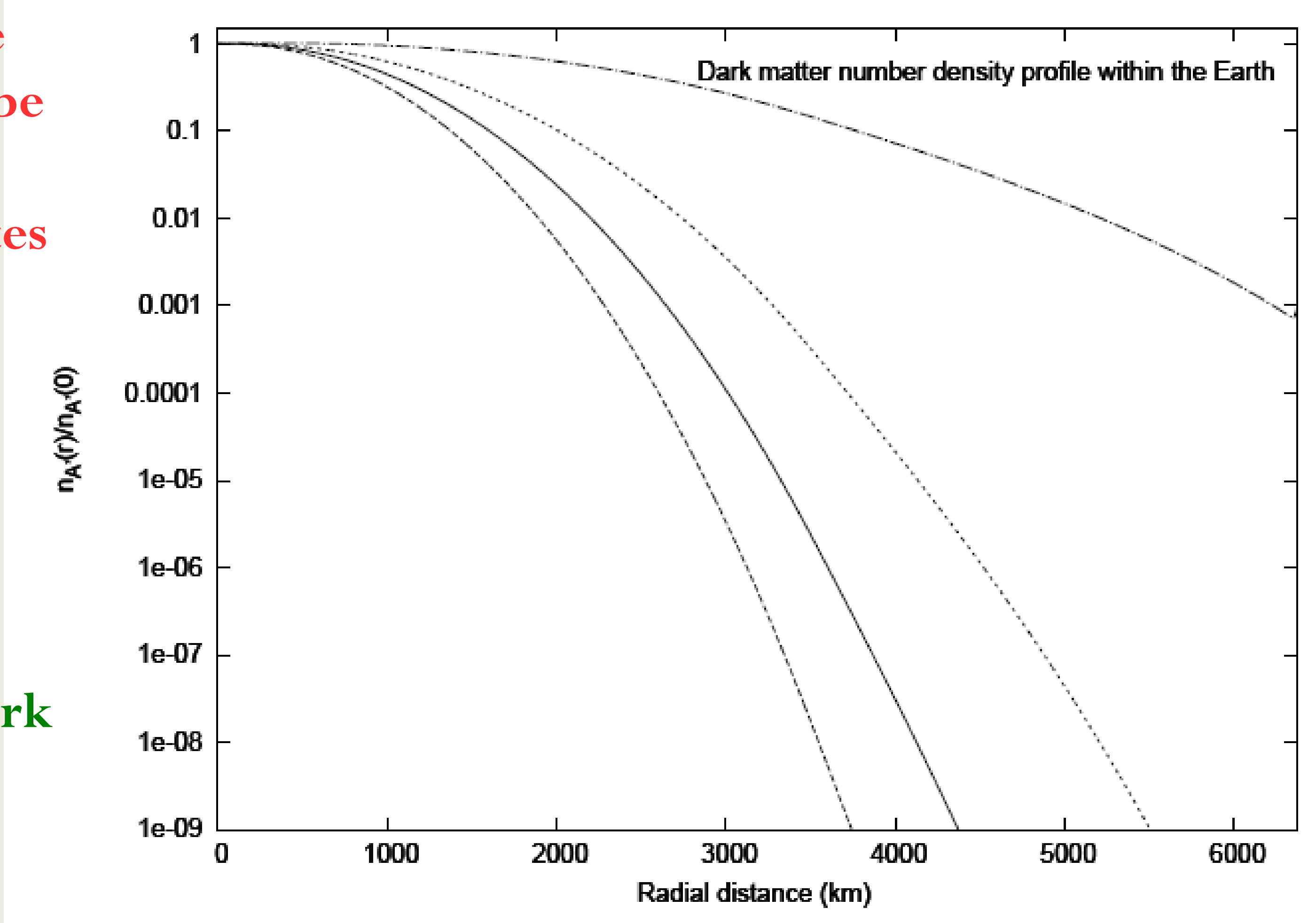
Diurnal signal

(R.F. arXiv: 1110.2908)

Mirror dark matter, and other self interacting dark matter candidates, can accumulate in the Earth.

In this case, the halo wind can be blocked, and dark matter rates in experiments suppressed

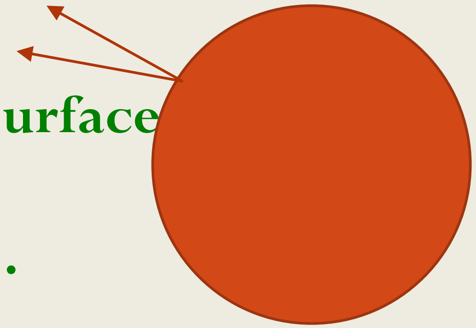
The level of suppression depends on the direction of dark matter flux.

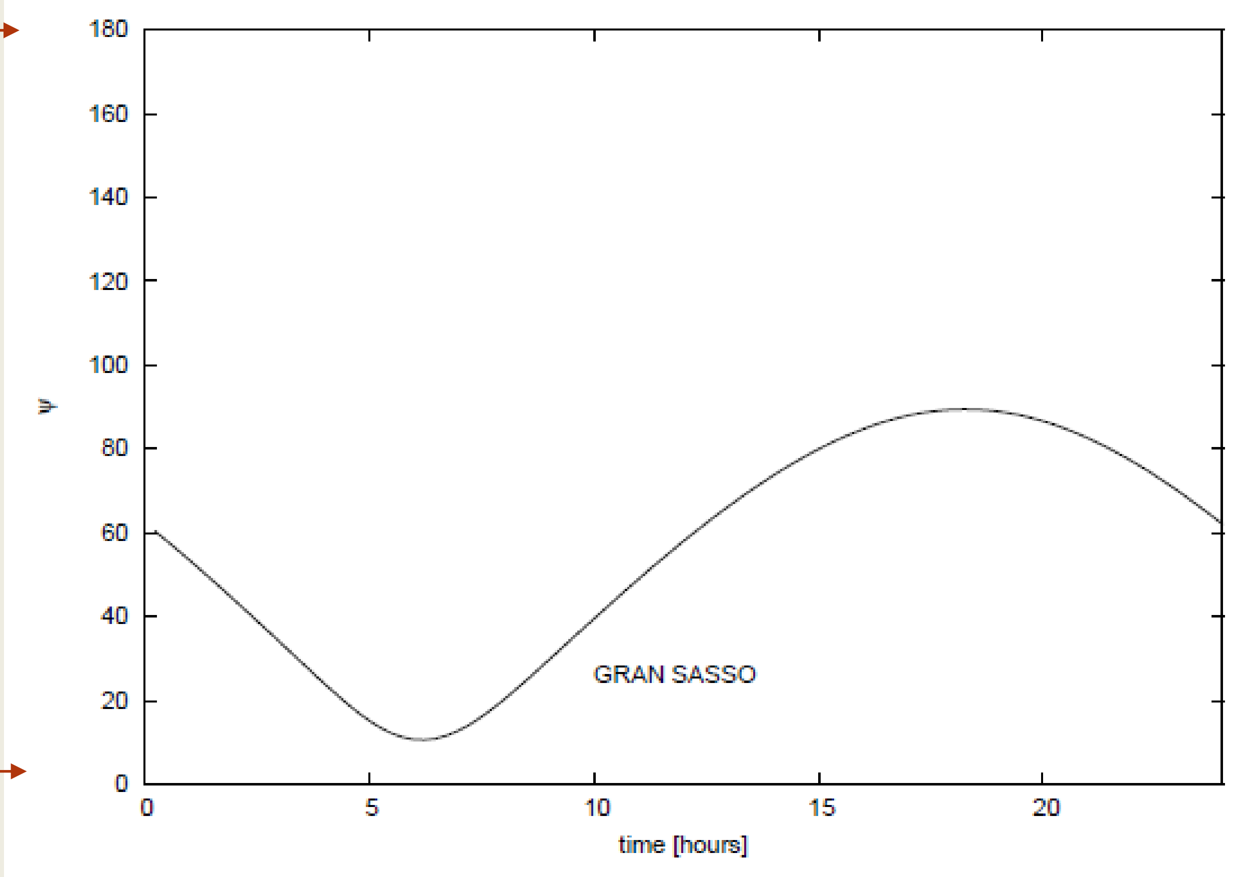


Diurnal signal

The angle between Earth's motion through the halo and normal to Earth's surface

This angle changes as the earth rotates….



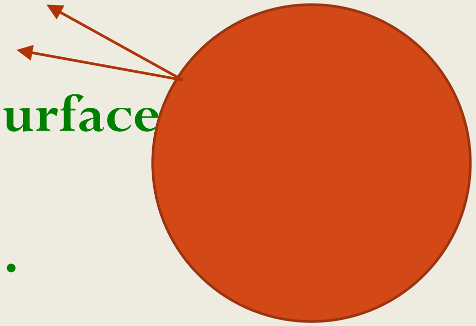


Dark matter wind through Earth’s core

Dark matter wind directly above

Diurnal signal

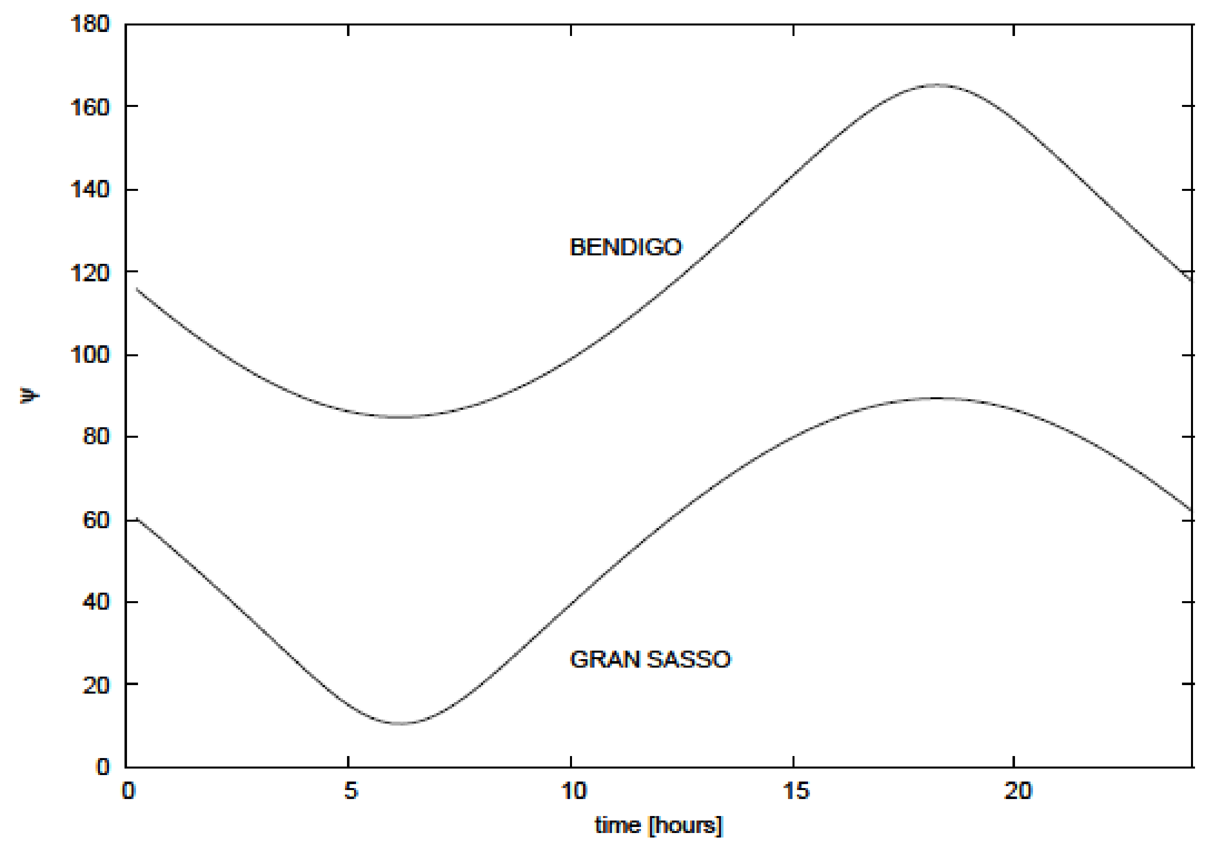
The angle between Earth's motion through the halo and normal to Earth's surface



This angle changes as the earth rotates….

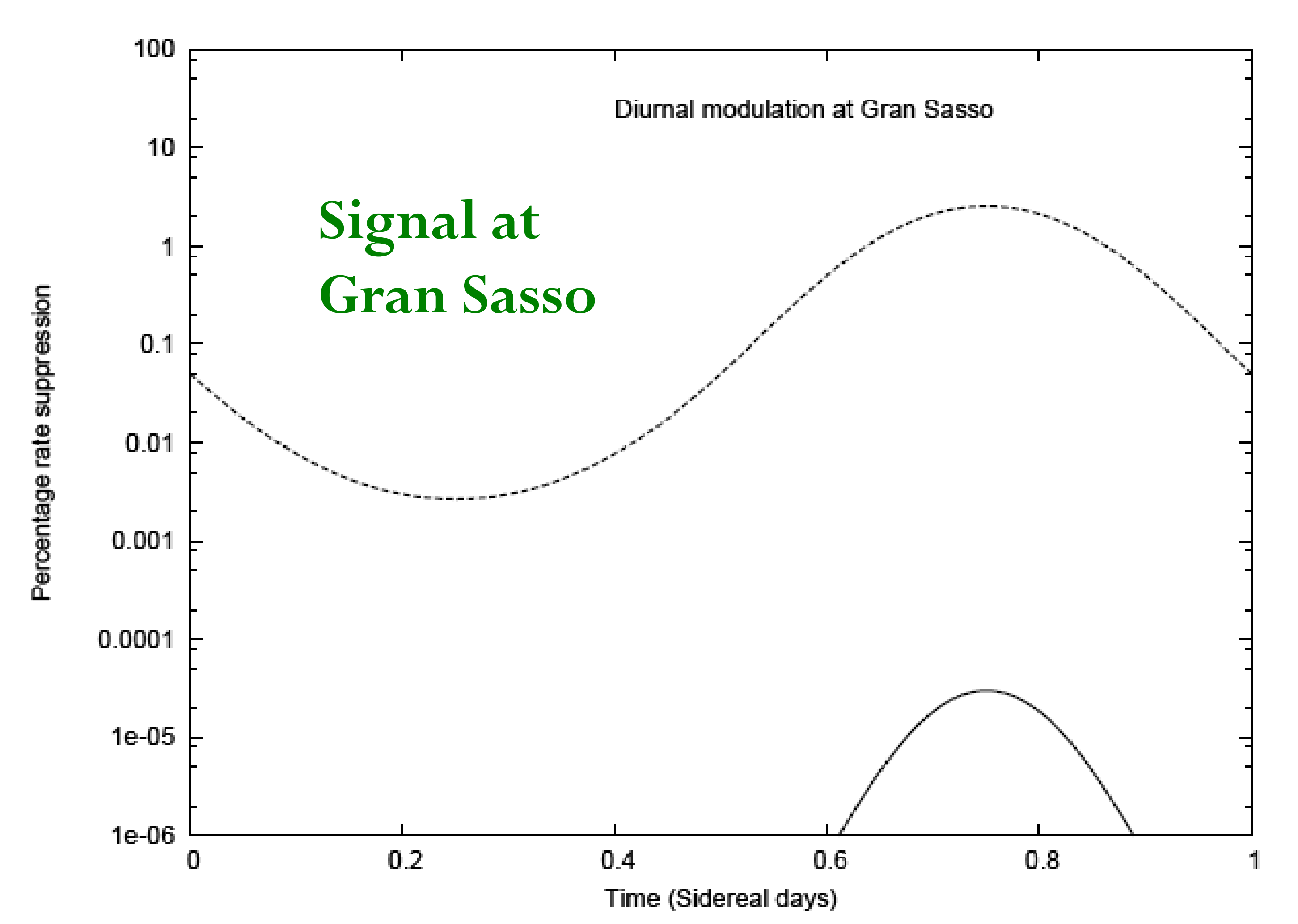
Dark matter wind through Earth's core

Dark matter wind directly above



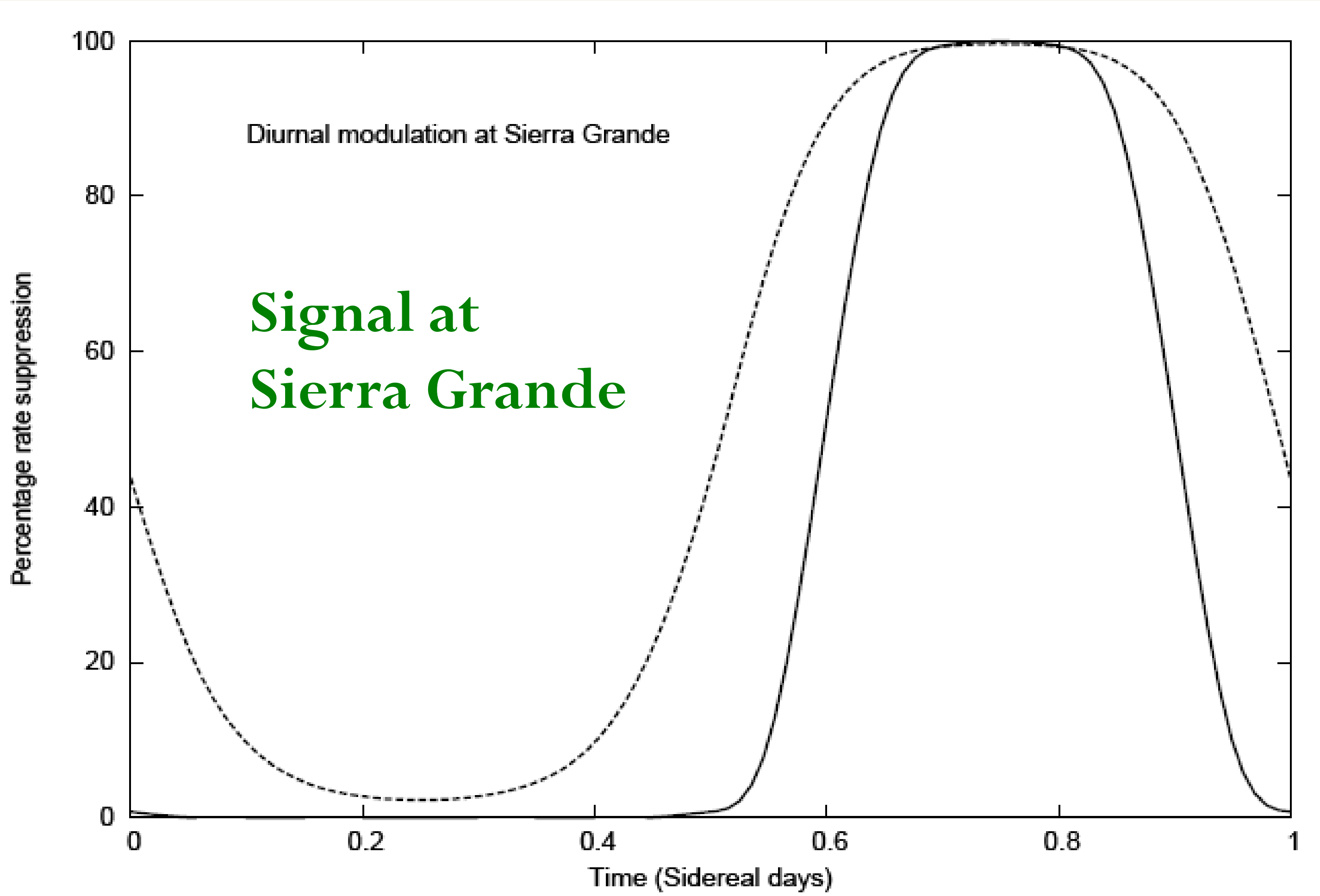
Diurnal signal

For northern hemisphere, diurnal variation is typically very small…



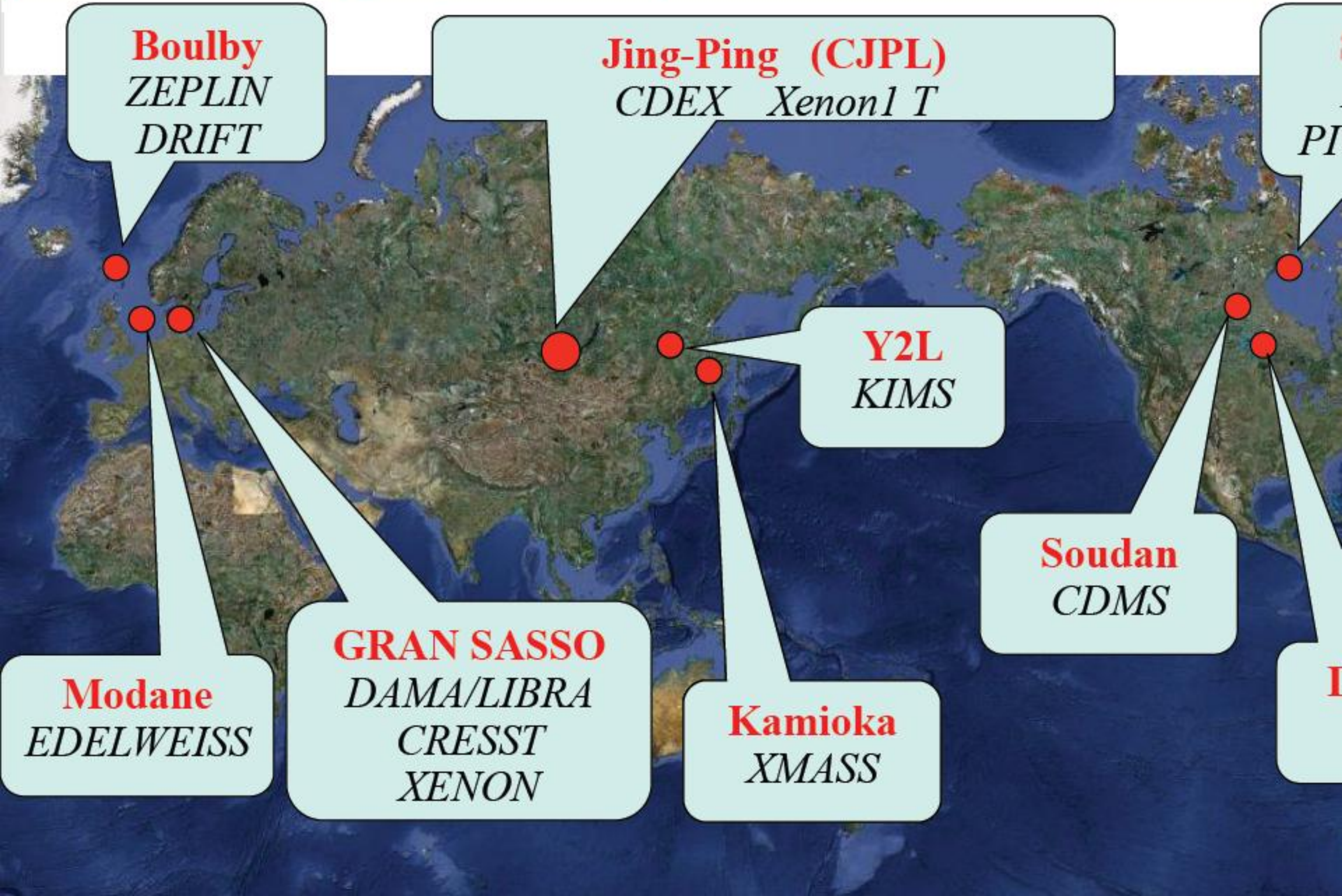
Diurnal signal

For Southern hemisphere, diurnal variation is typically very big...



Signal at Sierra Grande

Underground Experiments World-Wid



Boulby
ZEPLIN
DRIFT

Jing-Ping (CJPL)
CDEX Xenon1 T

PI

Y2L
KIMS

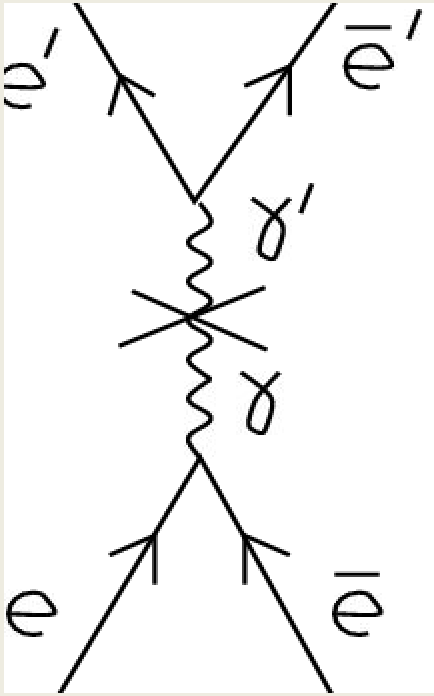
Soudan
CDMS

Modane
EDELWEISS

GRAN SASSO
DAMA/LIBRA
CRESST
XENON

Kamioka
XMASS

Implications of kinetic mixing $\epsilon \sim 10^{-9}$ for early Universe



Kinetic mixing can excite
mirror electron/positron in early Universe via:

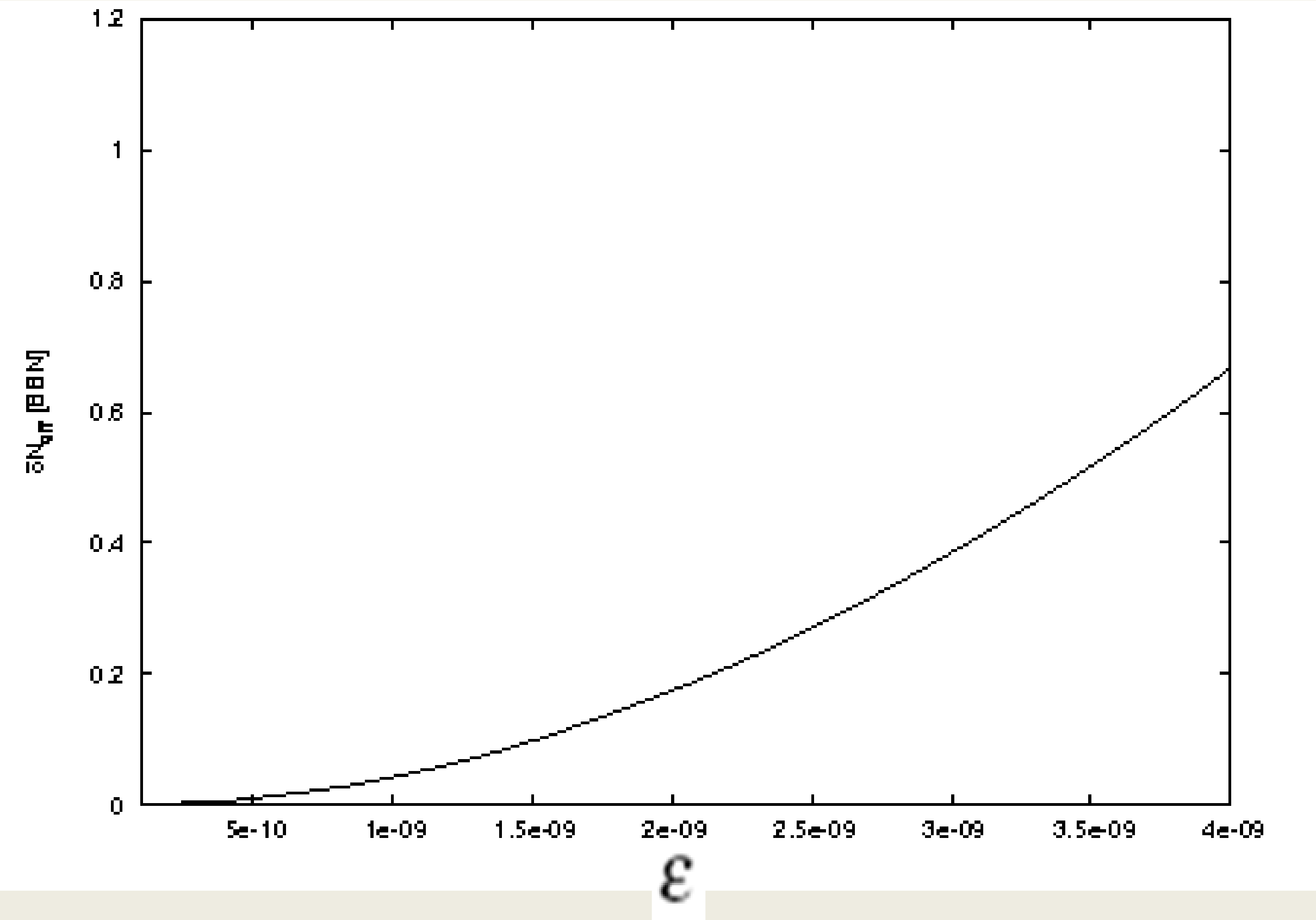
Leads to mirror entropy production, with asymptotic Temperature ratio of:

$$x \equiv \frac{T'_\gamma}{T_\gamma} \simeq 0.31 \left(\frac{\epsilon}{10^{-9}}\right)^{1/2}$$

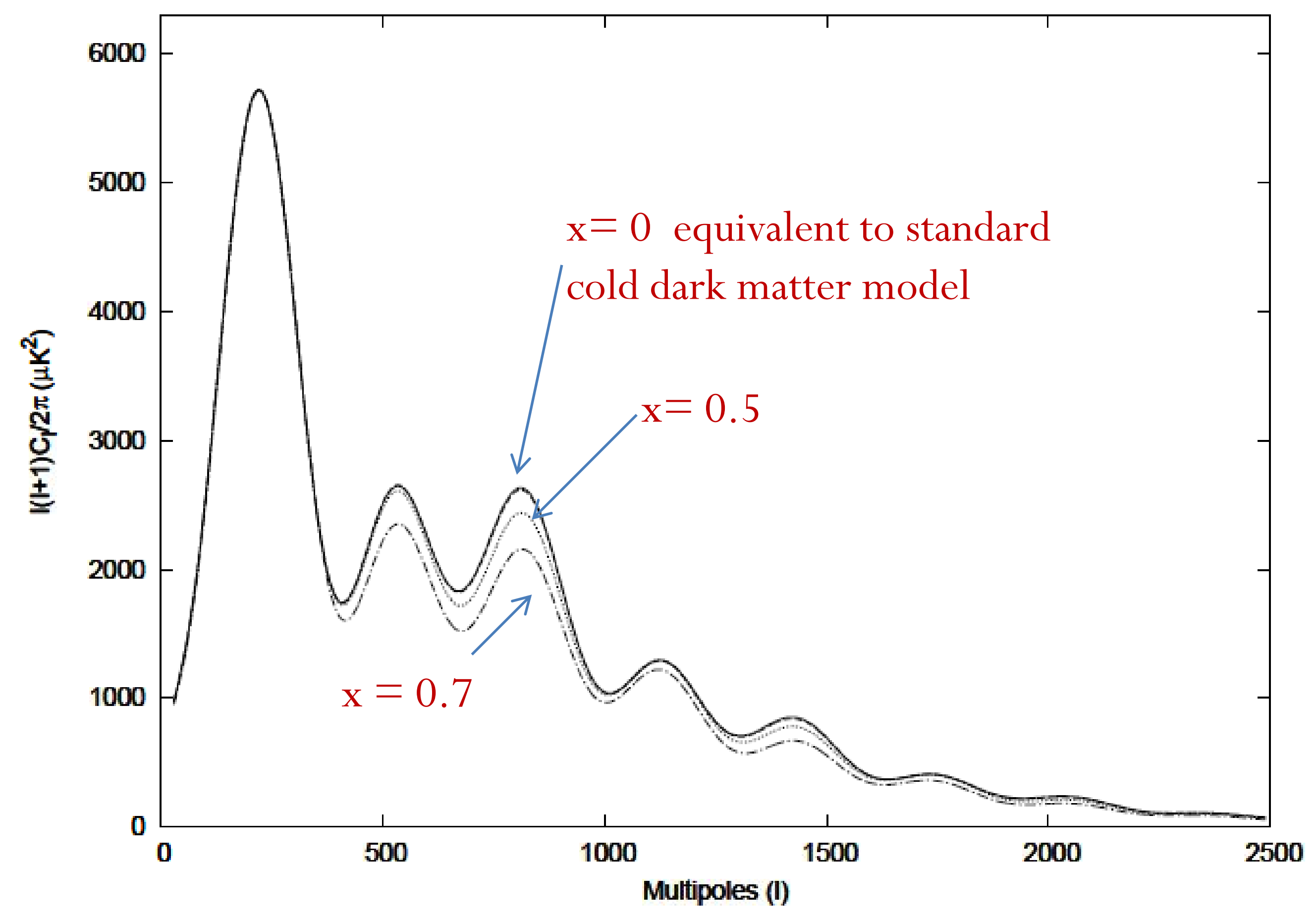
Excitation of mirror degree's of freedom can have implications for BBN. Also important for CMB, but acoustic oscillations of mirror baryon fluid more important effect.

References: Carlson and Glashow, PLB 87,
Ciarcelluti and RF. arXiv: 0809.4438
RF. arXiv:1111.6366 and arXiv 1208.6022.

Implications of kinetic mixing for BBN



Implications of kinetic mixing for CMB



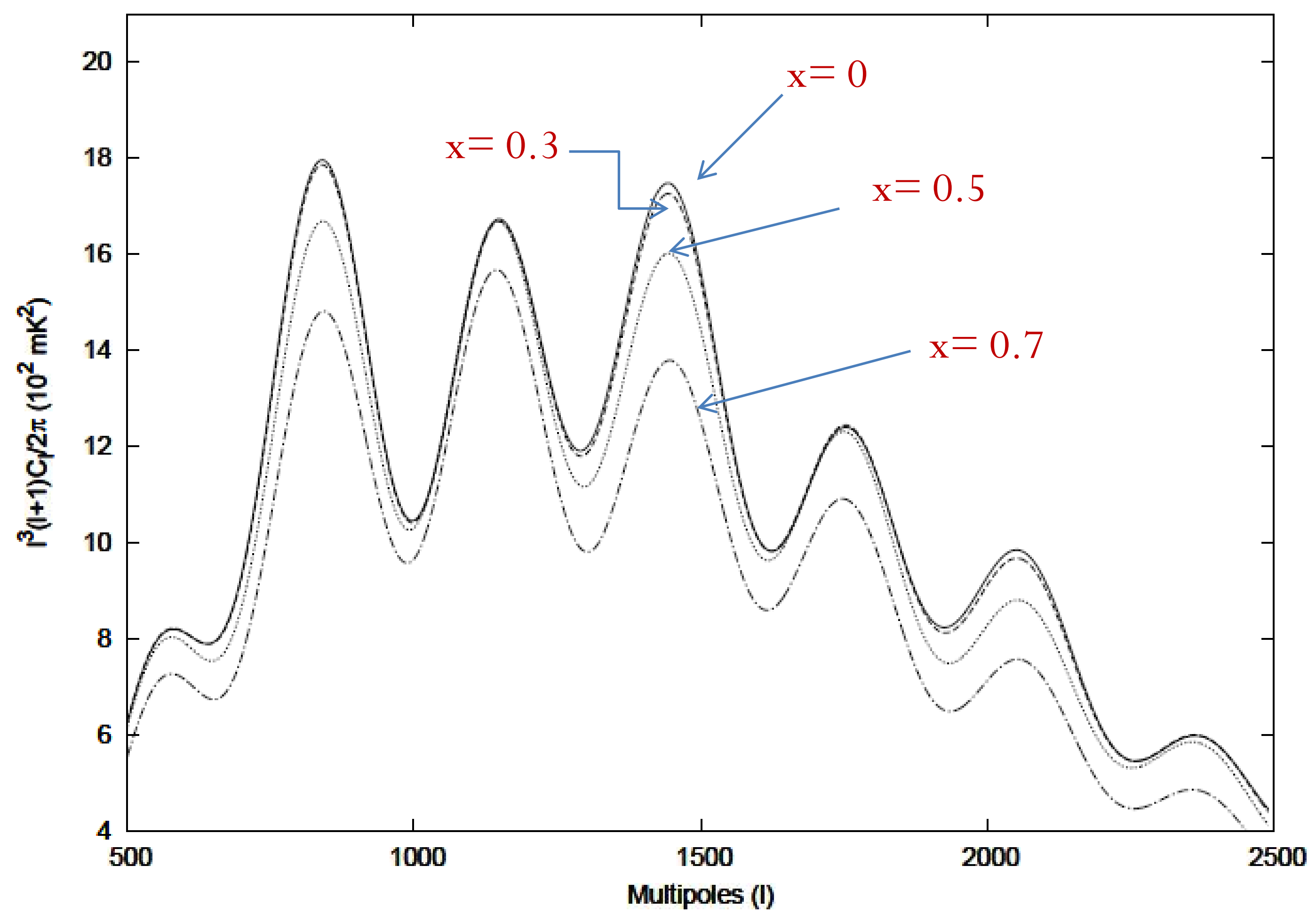
x= 0 equivalent to standard cold dark matter model

x= 0.5

x = 0.7

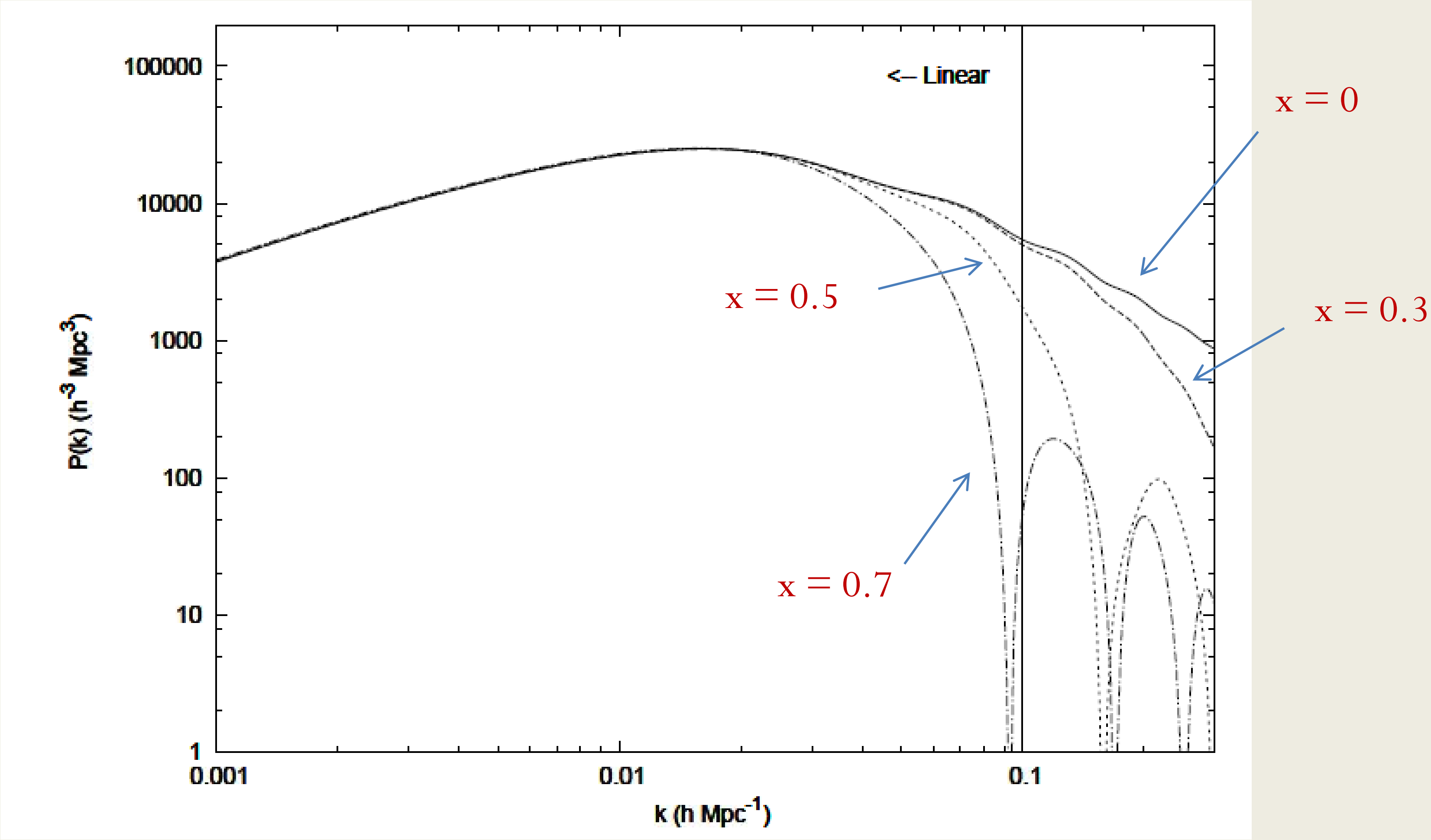
Current observations limit x = T'/T < 0.5, some interesting hint for x ~ 0.4 from observed damping of the CMB tail. Will be tested by PLANCK.

The CMB tail: Mirror dark matter predicts damping of higher odd peaks. Observable at PLANCK if $x = T'/T > 0.3$



Matter power spectrum also suggests x = T'/T < 0.3-0.5

x



x = 0

x = 0.5

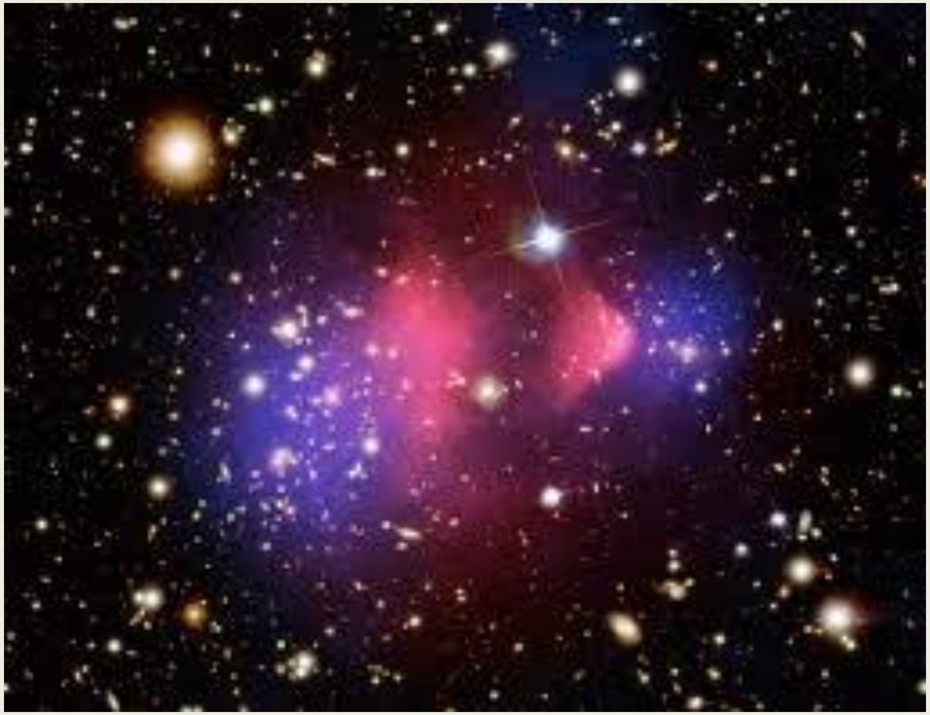
x = 0.3

x = 0.7

Bullet cluster constraints on mirror dark matter?

Suggests dark matter is not self interacting OR self interacting and dissipative so that it is very clumpy. Mirror dark matter can be clumpy enough to be ok ;)

Another issue: self interactions can make halo too spherical? But asymmetries due to e.g.
a) dark disk,
b) asymmetric heating of halo from SN,
c) partial collapse of halo?
d) mirror magnetic fields… can explain deviations from perfect spherical halos…



One should also remember that standard cold dark matter does not work very well on small scales, especially cusp/core problem…self interactions can help here!

Spergel and Steinhardt, PRL 2000.

Conclusions

Evidence for non-baryonic dark matter from rotation curves in galaxies, and precision cosmology.

The DAMA experiment may have actually detected galactic dark matter! Support from CoGeNT and CRESST-II !

Mirror dark matter can explain the experiments. Appears consistent with all observations, and might also show up in the CMB when PLANCK results released.

More generic hidden sector dark matter also compatible with the experiments. Require only a hidden sector with two or more stable particles charged under an unbroken gauged U(1)' (or broken at scale < 1 MeV), kinetically mixed with standard $U(1)_Y$

An experiment in the southern hemisphere is highly desirable to

a) Confirm that the DAMA annual modulation is not related to seasons or detector location.

b) Search for Diurnal variation – completely unexplored territory...

Backup slides

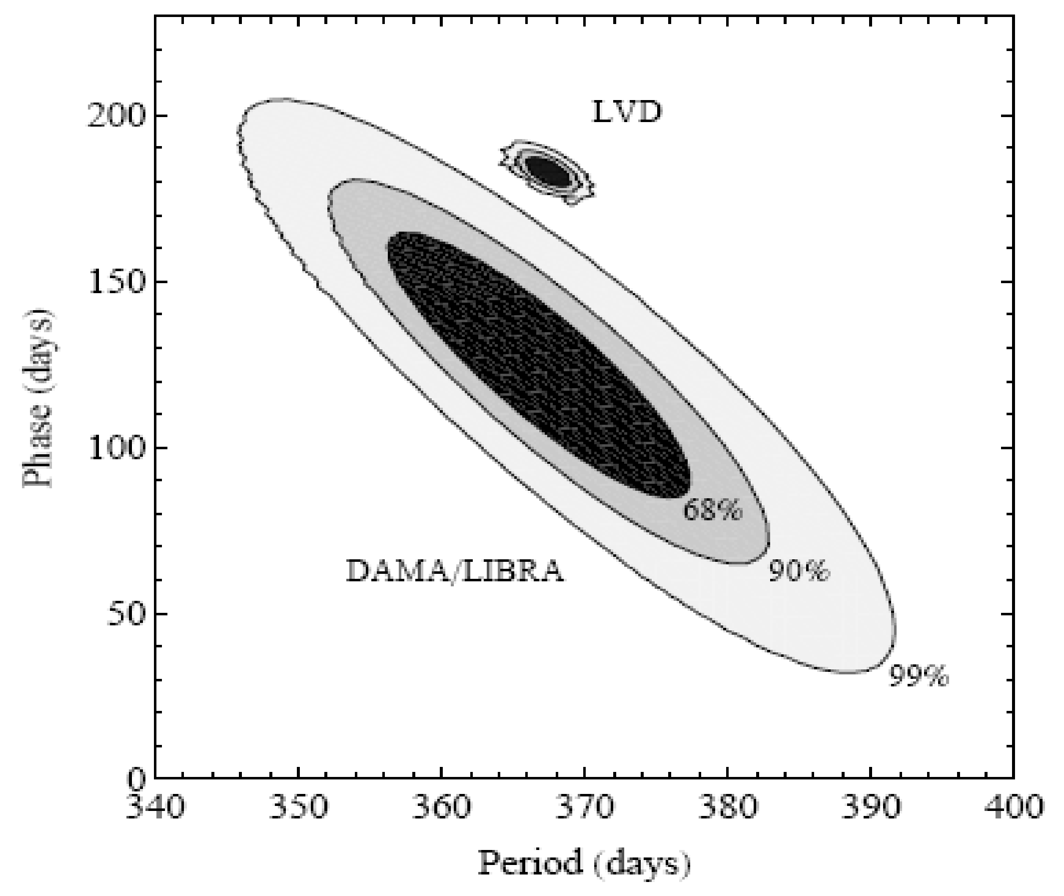
Energy lost to radiative cooling is:

$$L^{halo}_{energy-out} = \Lambda \int_{R} n_{e'}^2 4\pi r^2 dr \sim 10^{44}\ \mathrm{erg/s\ for\ Milky\ Way}$$

Energy produced from kinetic mixing induced e'$^+$, e'$^-$ production in ordinary supernova core:

$$L^{SN}_{heat-in} \sim \frac{1}{2} \times 3 \times 10^{53}\ erg \frac{1}{100\ years} \sim 10^{44}\ \mathrm{erg/s\ for\ Milky\ Way}$$

Matching heat-in = energy lost, requires $\epsilon \sim 10^{-9}$



Chang et al, ArXiv: 1111.4222

Clearly, phase doesn't quite work out.

Also estimates of DAMA background rate from muons, reviewed in arXiv: 1202. 4179, are more than 2 orders of magnitude too small to account for DAMA signal.

Can backgrounds possibly give annual modulation?

Only possibility appears to be muon flux which is known to modulate annually, due to variations in the atmosphere due to temperature .. summer/winter