An Undetectable Universe: the experimental quest in the laboratory

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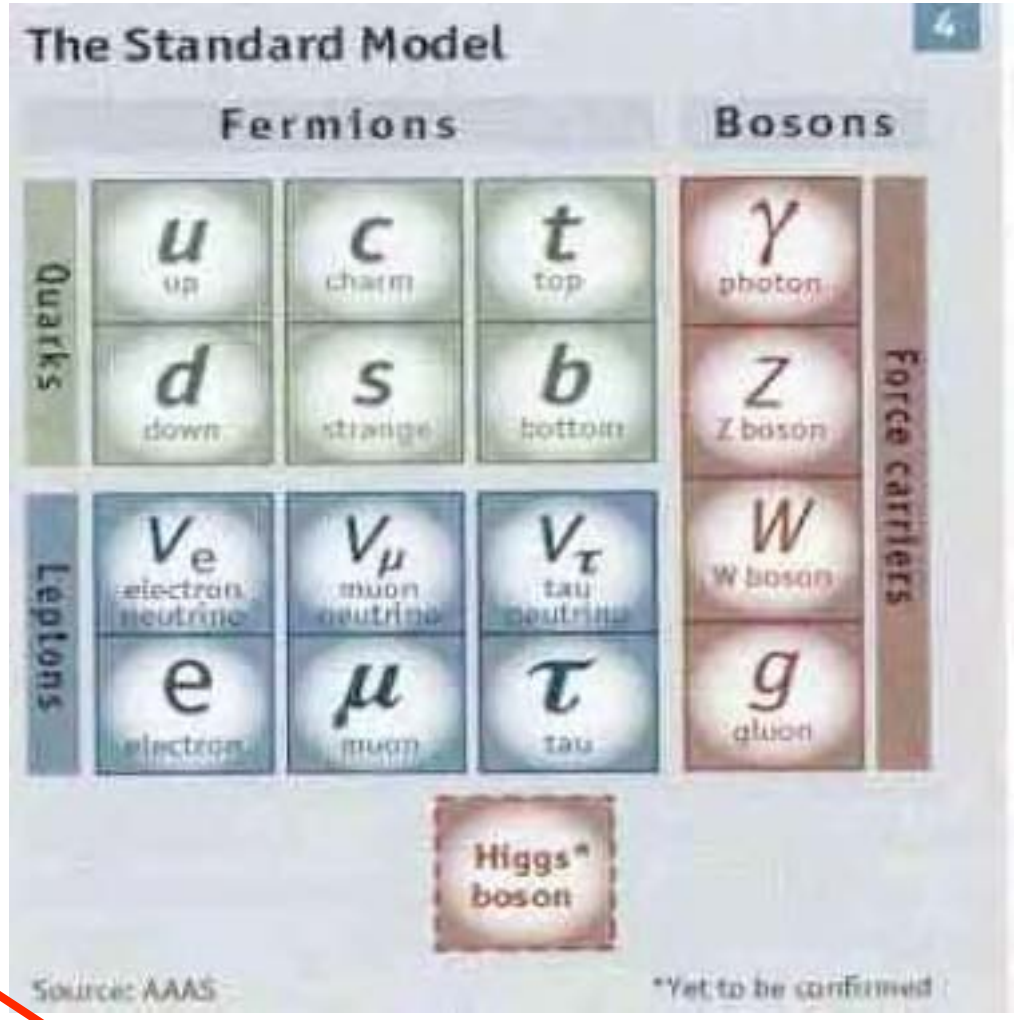
From optical astronomy to astro-particle physics

- Luminous matter accounts for only a tiny fraction of the total mass density of the Universe and only about a tenth of the ordinary matter (baryons).
- While stars are very interesting and pretty to look at — and without them, astronomy wouldn't be astronomy and we wouldn't exist — they represent a tiny fraction of the cosmic mass budget, only about 0.5 % of the total energy and mass of the Universe.
- As we have known for several decades, the bulk of the constituents of the Universe are dark and only indirectly observable through induced effects.
- In order to know more, the scientific activity of optical Astronomy needs to be extended in a variety of ways. Particle physics provides attractive solutions for instance with
  - accelerator experiments on the Standard Model and beyond
  - non accelerator experiments that may shed further light for instance on relic elementary particles left over from the Big Bang in sufficient numbers to account for a significant fraction of critical density.
- The earliest optical event (CBR) has occurred 300'000 years after the big bang. But a huge amount of facts had occurred before then: they can be emulated today recreating the phenomena with high energy collisions.

The Standard Model "saga"

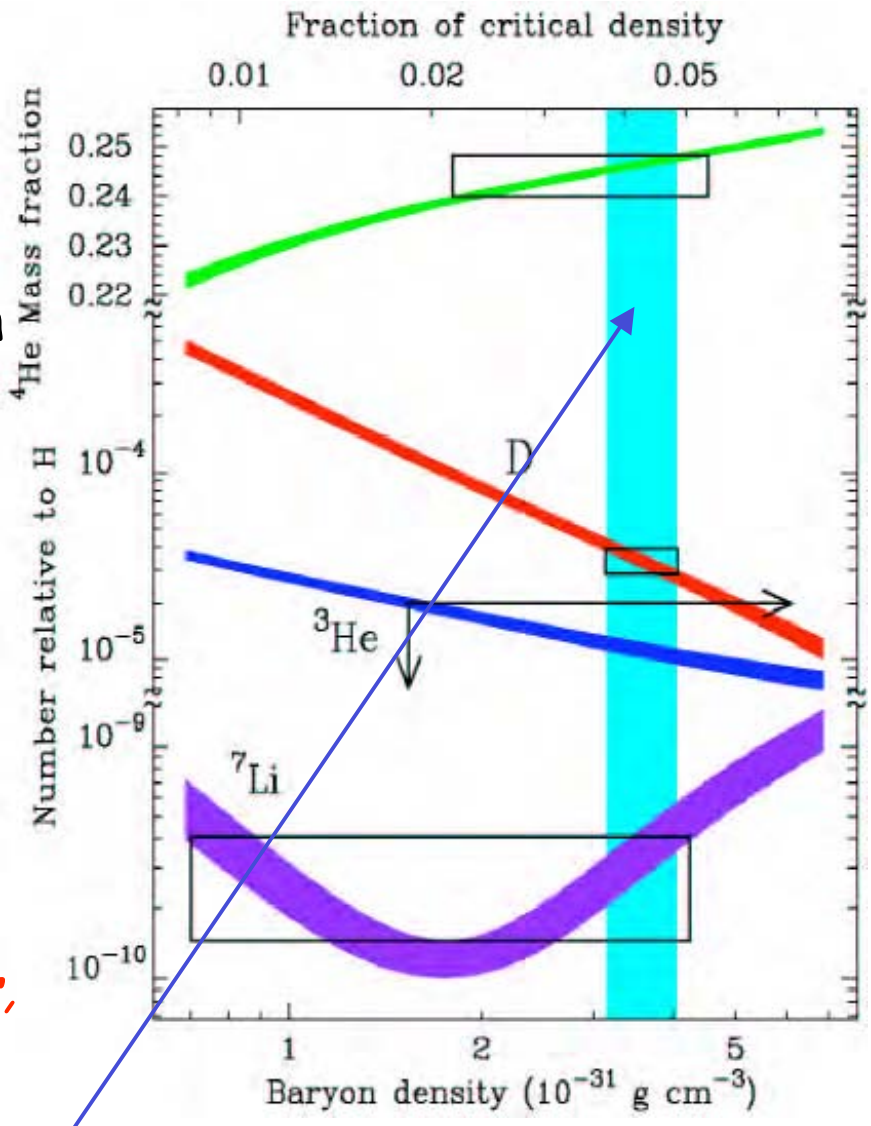
- Universe emerged from an explosion in a vacuum that occurred 13.7 billion years ago
- 10^{-12} sec: electromagnetism separated from the weak nuclear force; hot quark-gluon plasma and leptons were dominant
- 10^{-6} sec: hadrons are formed
- 1-3 sec: lepton/antilepton annichilate
- 3 - 20 min: protons and neutrons began to combine to form atomic nuclei (BBN).



We are here with LHC !!

Big Bang Nucleo-synthesis (BBN)

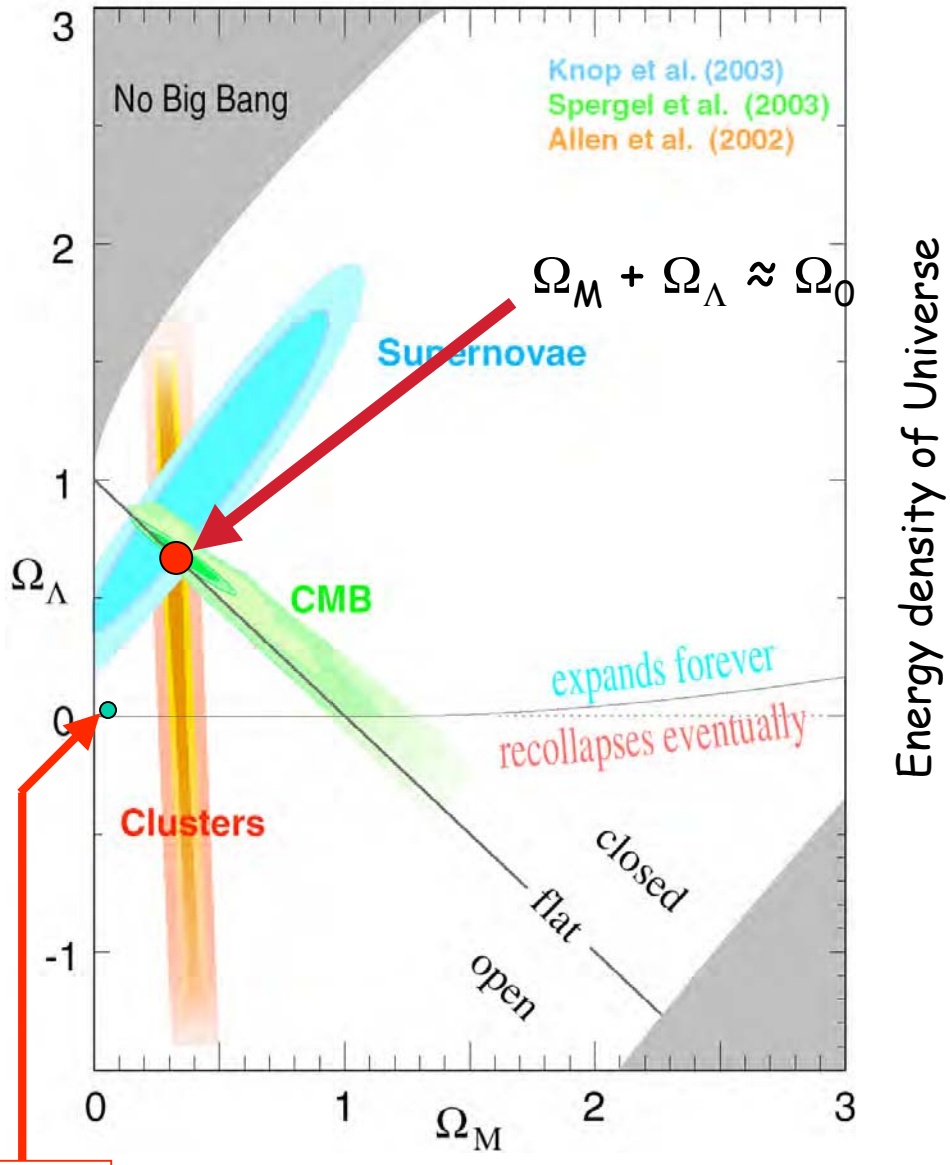
- For more than twenty years big-bang nucleo-synthesis had provided a key test of the baryon density, Ω_B.
- The situation has greatly improved when Burles and Tytler clarified matters, based on the deuterium abundance measured in four high-red shift hydrogen clouds seen in absorption against distant QSOs.
- The Burles-Tytler measurement turned the previous factor 3 into a 10% determination of baryon density : $\Omega_B h^2 = 0.02 \pm 0.002$.
- The evidence for such very profound conclusion has been mounting for almost two decades: there is much more matter than there are baryons, and thus, *baryonic matter, e.g. the ordinary matter as generated by BBN, is not the dominant form of matter of the Universe*.



$\Omega_{BBN} = 0.044 \pm 0.004$

The over-all concordance.

- There is no doubt that even a normally conservative person would say that we are witnessing today a turning point in Cosmology as important as in 1964, when the Cosmic Background Radiation (CBR) was discovered.
- The density and composition of both matter and energy in the Universe are of fundamental importance.
- With the recent discovery of an invisible energy component in the empty space, about as large as the total matter of the Universe multiplied by c^2 (e.g. the non zero value of Ω_Λ) we have now for the first time a credible model for structure formation that is consistent with all the data at hand.

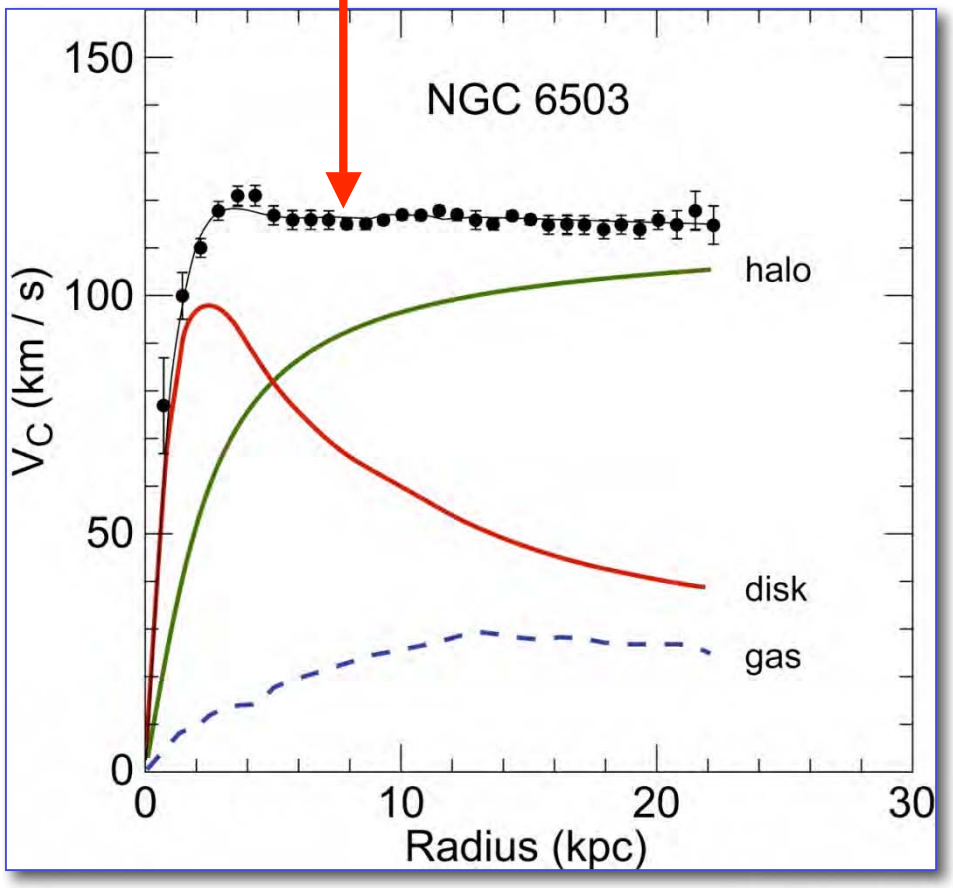


$\Omega_{BBN} = 0.044 \pm 0.004$

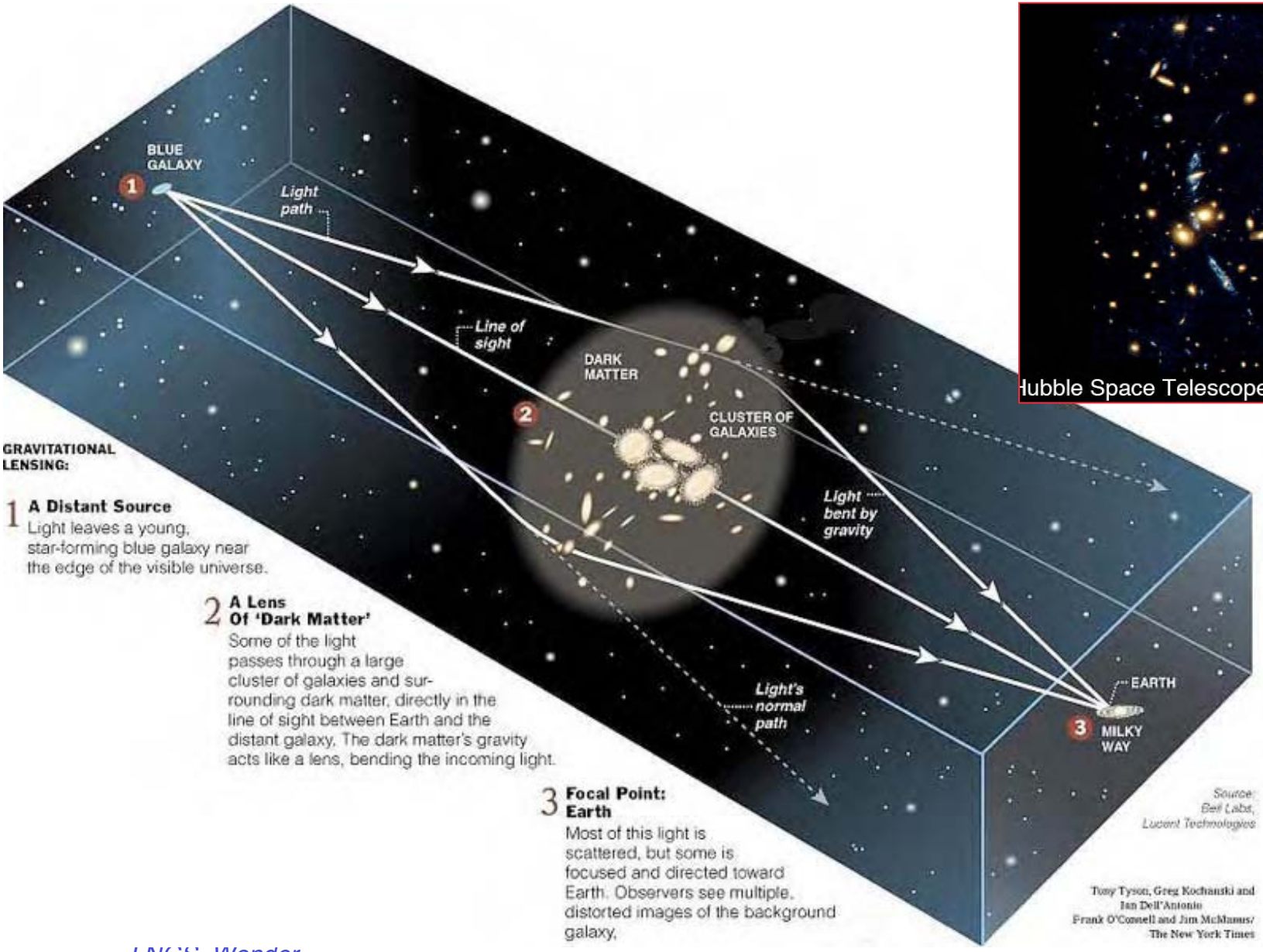
Evidence for Dark matter:Galactic rotation curves

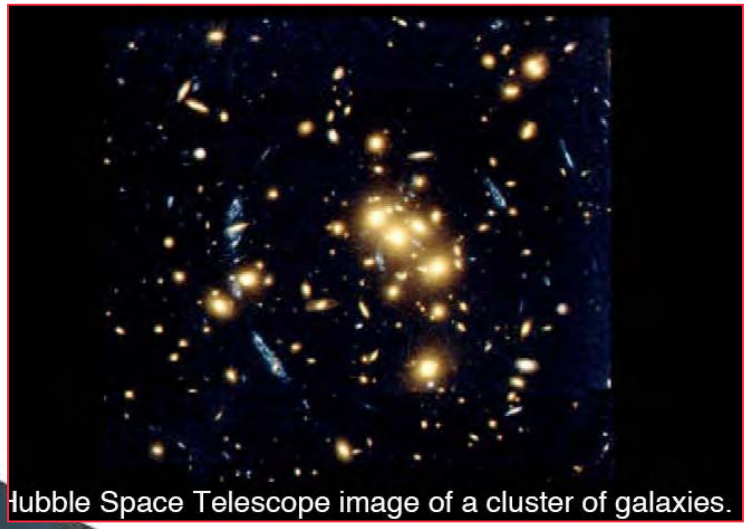
- Doppler measurements in spiral galaxies.
  - Observe: v(r)
  - if v is constant,then: M ≈ r
  - **Needs "dark matter"**

Major disagreement with"naïve" Kepler's laws



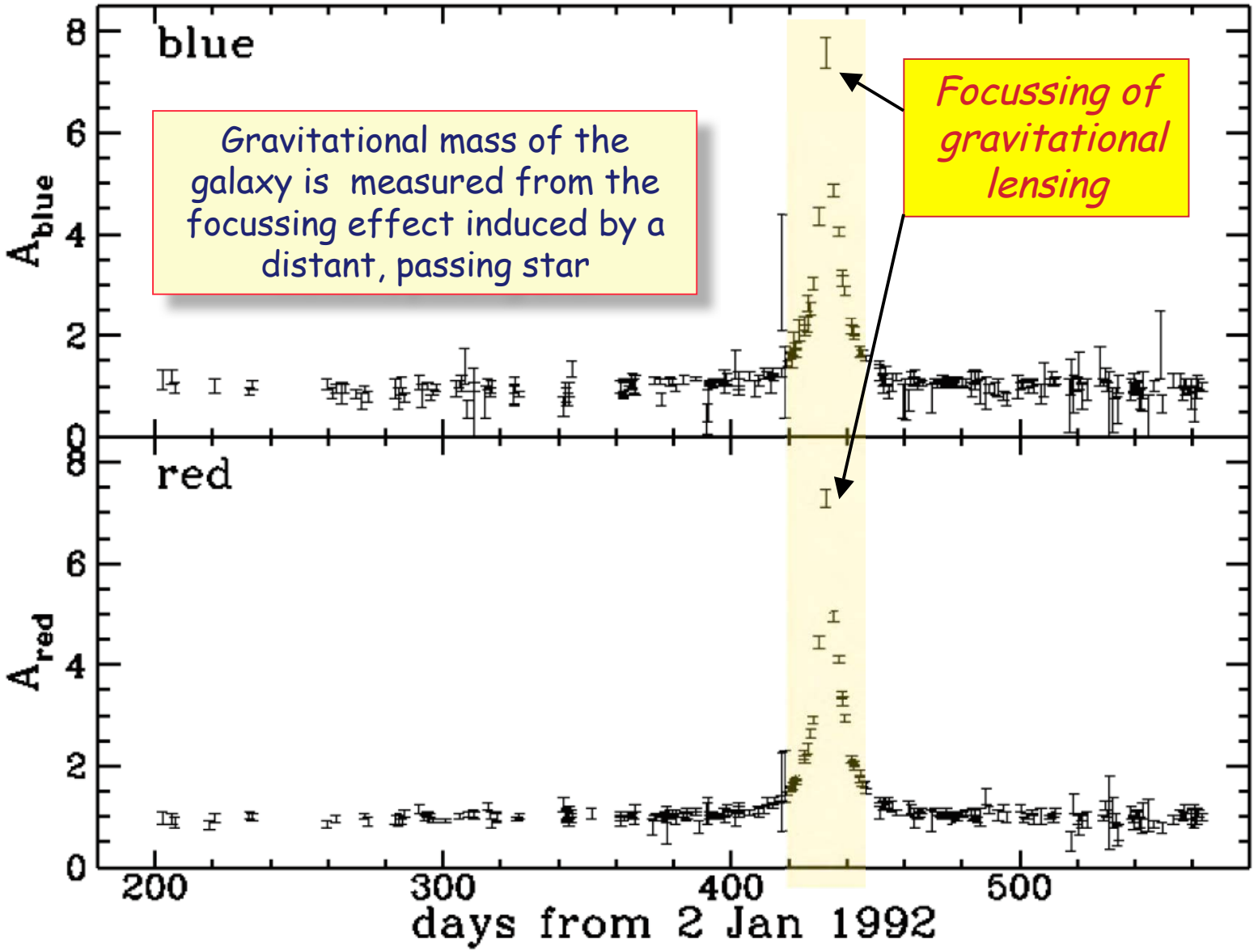
Gravitational Lensing



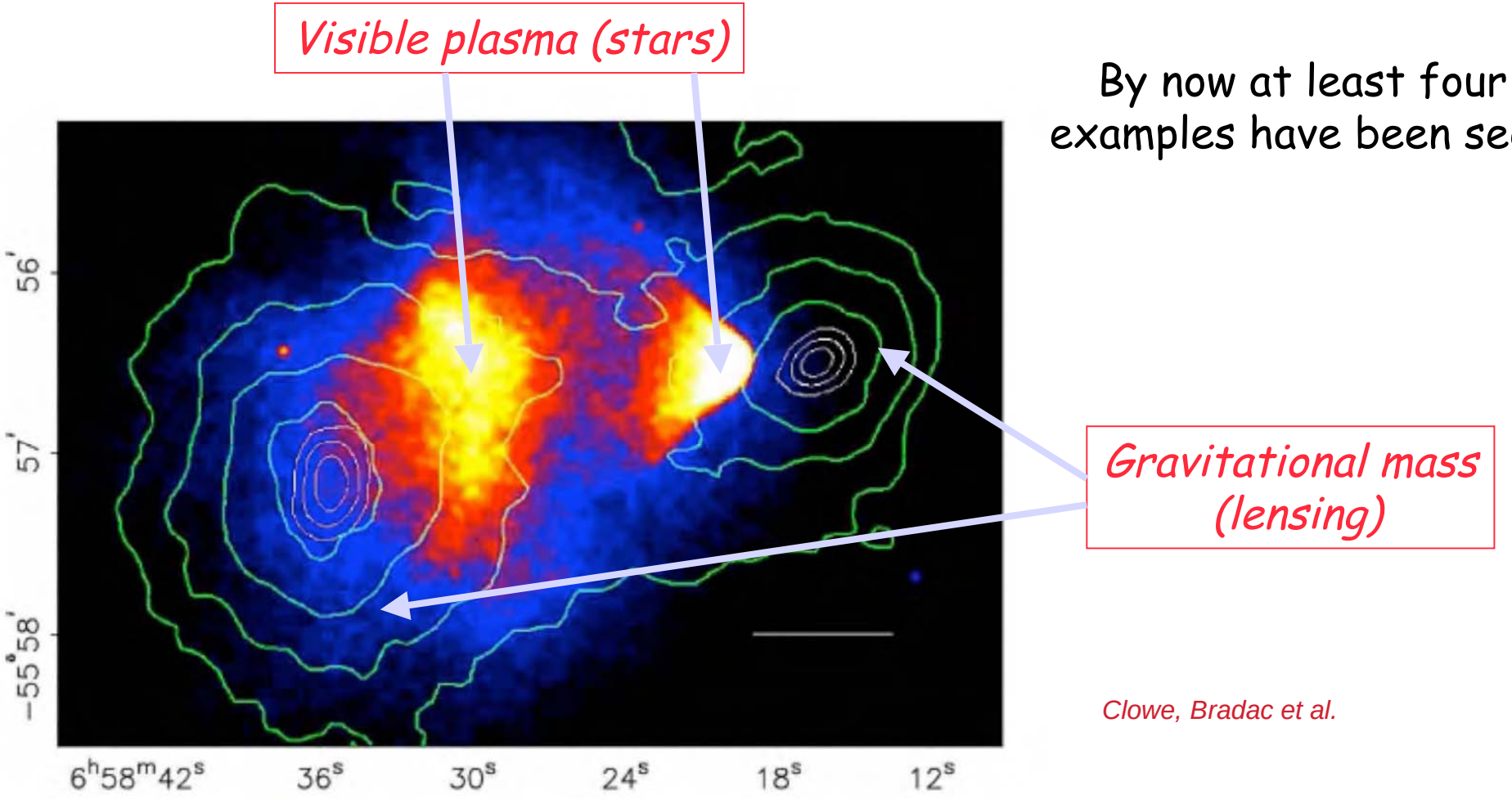


Hubble Space Telescope image of a cluster of galaxies.

Observing the gravitational lensing



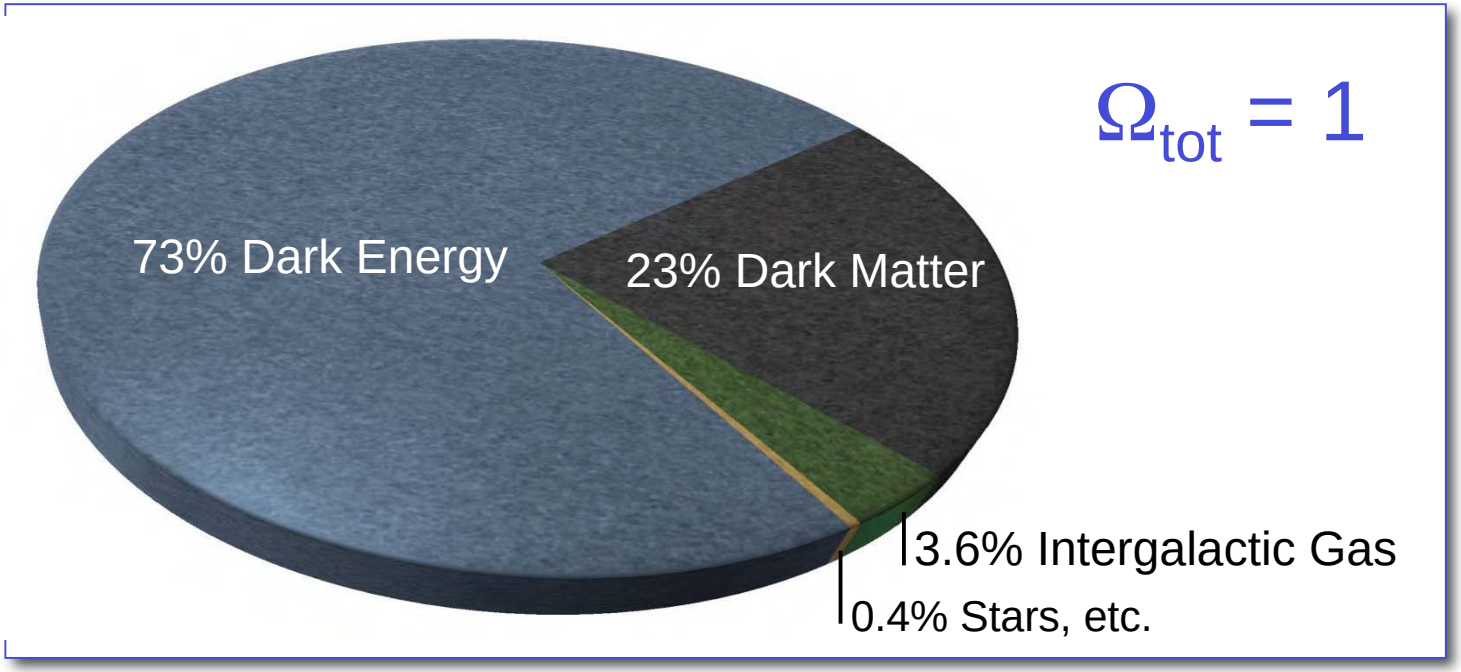
Weak lensing observations of cluster merger



- The gravitational potential does not trace the plasma distribution, the dominant baryonic mass component; the majority of the matter in the system is unseen.

A FIRST, INESCAPABLE CONCLUSION

- Only about 4 % of the Universe is ordinary, hadronic matter (inanimate and living) of which we are made of and that we perceive.
- The remaining 96% is invisible and completely unknown.



This is a major experimental result of immense consequences

Dark Matter : an elementary particle ?

- All present evidence *is now limited to gravitational effects.*
- A key question is which kind of interaction may be connected to DM and in particular the possible *existence of an electro-weak coupling to ordinary matter.*
- This is not a necessity: for instance other forms of "classical" fields with purely gravitational effects may be possible alternatives.
- "Popular" bets are, at the moment, the lightest SUSY particle (the Neutralino) and the Axion.
- Dark matter and dark energy: a common physical origin ?

- Kaluza-Klein DM inUED
- Kaluza-Klein DM in RS
- **Axion**
- Axino
- Gravitino
- Photino
- SM Neutrino
- Sterile Neutrino
- Sneutrino
- Light DM
- Little Higgs DM
- Wimpzillas
- Q-balls
- Mirror Matter
- Champs (charged DM)
- D-matter
- Cryptons
- Self-interacting
- Superweakly interacting
- Braneworls DM
- Heavy neutrino
- **NEUTRALINO**
- Messenger States in GMSB
- Branons
- Chaplygin Gas
- Split SUSY
- Primordial Black Holes

A fervent imagination !

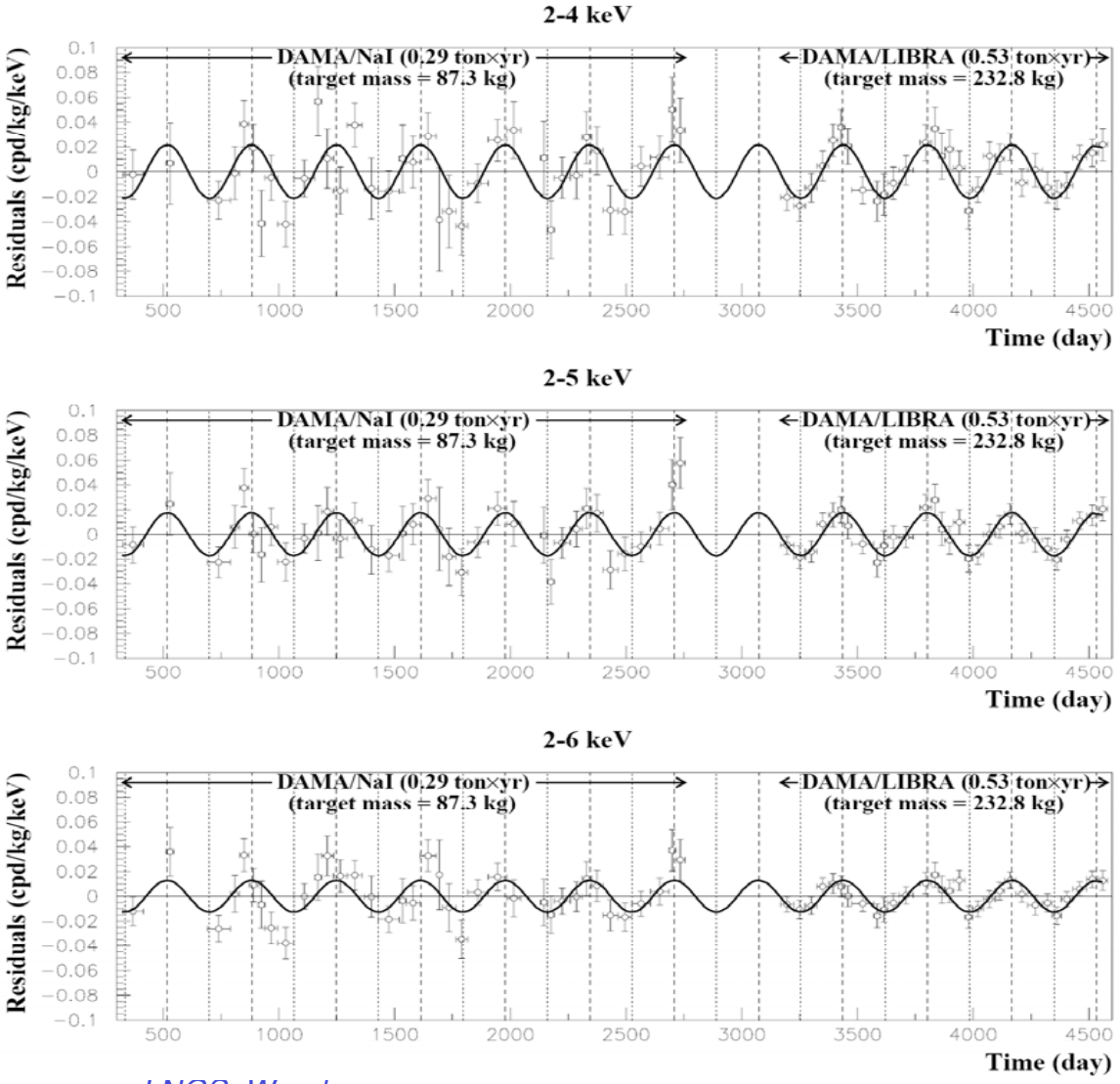
An undetectable Universe present in the laboratory ?

- Particle physics may provide an attractive solution to the non baryonic dark matter problem: relic elementary particles left over from the Big Bang.
- Long-lived or stable particles with very weak interactions can remain from the earliest moments of particle democracy in sufficient numbers to account for a significant fraction of critical density.
- Dark matter (and energy) must have participated to the evolution of the Universe, presumably in a comparable, but different way than ordinary matter. Indeed the dark matter has been main driving force throughout its evolution.
- The experimental search in the laboratory for a such new forms of matter outside of the Standard Model is an extremely exciting programme.

Model Independent Annual Modulation

DAMA/NaI (7 years) + DAMA/LIBRA (4 years) Total exposure: 300555 kg×day = 0.82 ton×yr

experimental single-hit residuals rate vs time and energy



$A\cos[\omega(t-t_0)]$; continuous lines: t_0 = 152.5 d, T = 1.00 y

2-4 keV

A=(0.0215±0.0026) cpd/kg/keV

χ^2/dof = 51.9/66 **8.3 σ C.L.**

Absence of modulation? No

χ^2/dof=117.7/67 ⇒ P(A=0) = 1.3×10^{-4}

2-5 keV

A=(0.0176±0.0020) cpd/kg/keV

χ^2/dof = 39.6/66 **8.8 σ C.L.**

Absence of modulation? No

χ^2/dof=116.1/67 ⇒ P(A=0) = 1.9×10^{-4}

2-6 keV

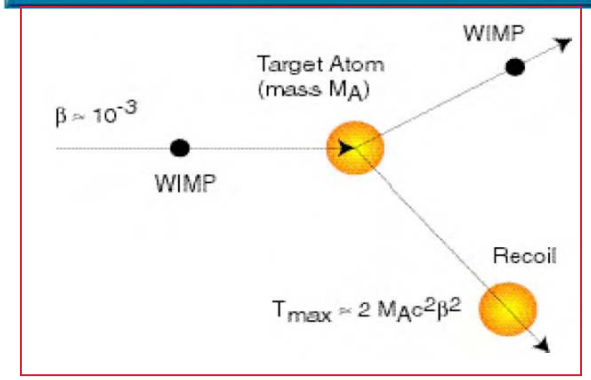
A=(0.0129±0.0016) cpd/kg/keV

χ^2/dof = 54.3/66 **8.2 σ C.L.**

Absence of modulation? No

χ^2/dof=116.4/67 ⇒ P(A=0) = 1.8×10^{-4}

Competition in underground experiments



More than 20 experiments running or in construction

No evidence for WIMPS so far, except for DAMA/LIBRA

DAMA/LIBRA

Italy

WARP

CUORICINO

USA

CRESST II

EDELWEISS II

France

Germany

UK

ZEPLIN I

ZEPLIN III

ZEPLIN II

NaIAD

DRIFT I

Bubble Chamber

HDMS/Genino

Russia

Japan

XMASS (DM)

LiF

ELEGANTS V & VI

PICASSO

Canada

USA

CDMS II

XENON

MAJORANA (DM)

IGEX

Spain

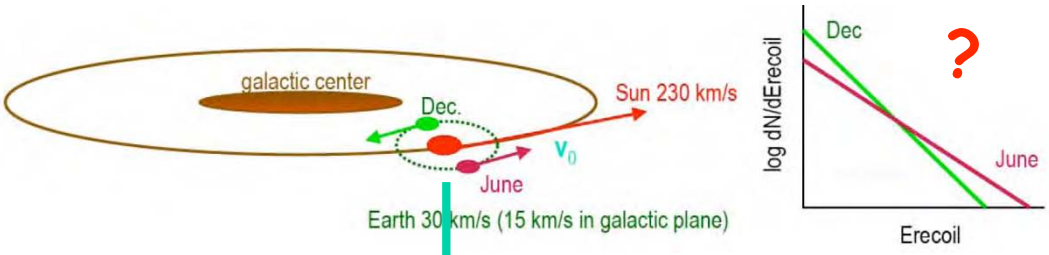
ANAIS

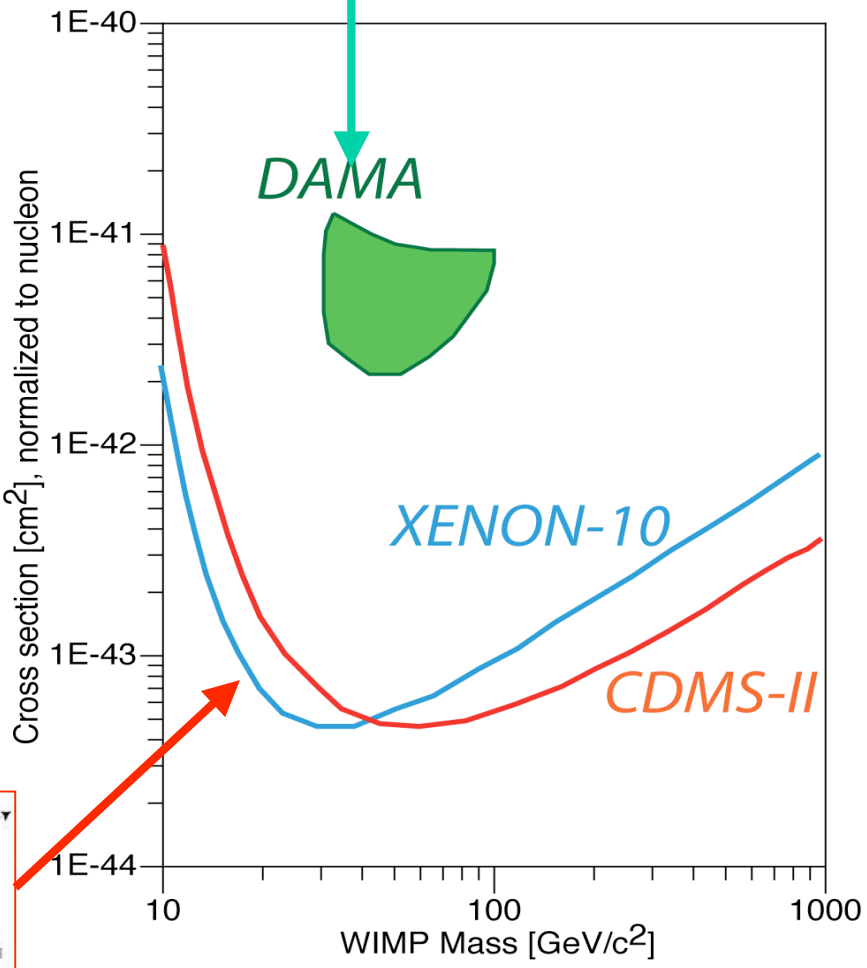
ArDM

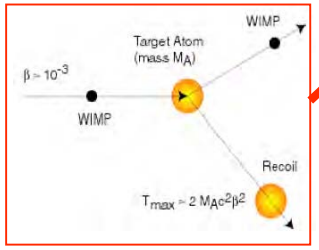
ROSEBUD

The DAMA/LIBRA is not due to naïve WIMP recoils

- Striking contrast between DAMA/LIBRA signal from model independent annual modulation signal and upper limits due to naïve WIMP recoil events.
- The reason of this disagreement is so far essentially unexplained.
- A number of exotic alternatives have been put forward, which may reconcile the absence of the quoted signal in the direct experiments.
- A new annual modulation experiment with about x 10 sensitivity is in progress at the LNGS laboratory (WARP-CHRONOS).



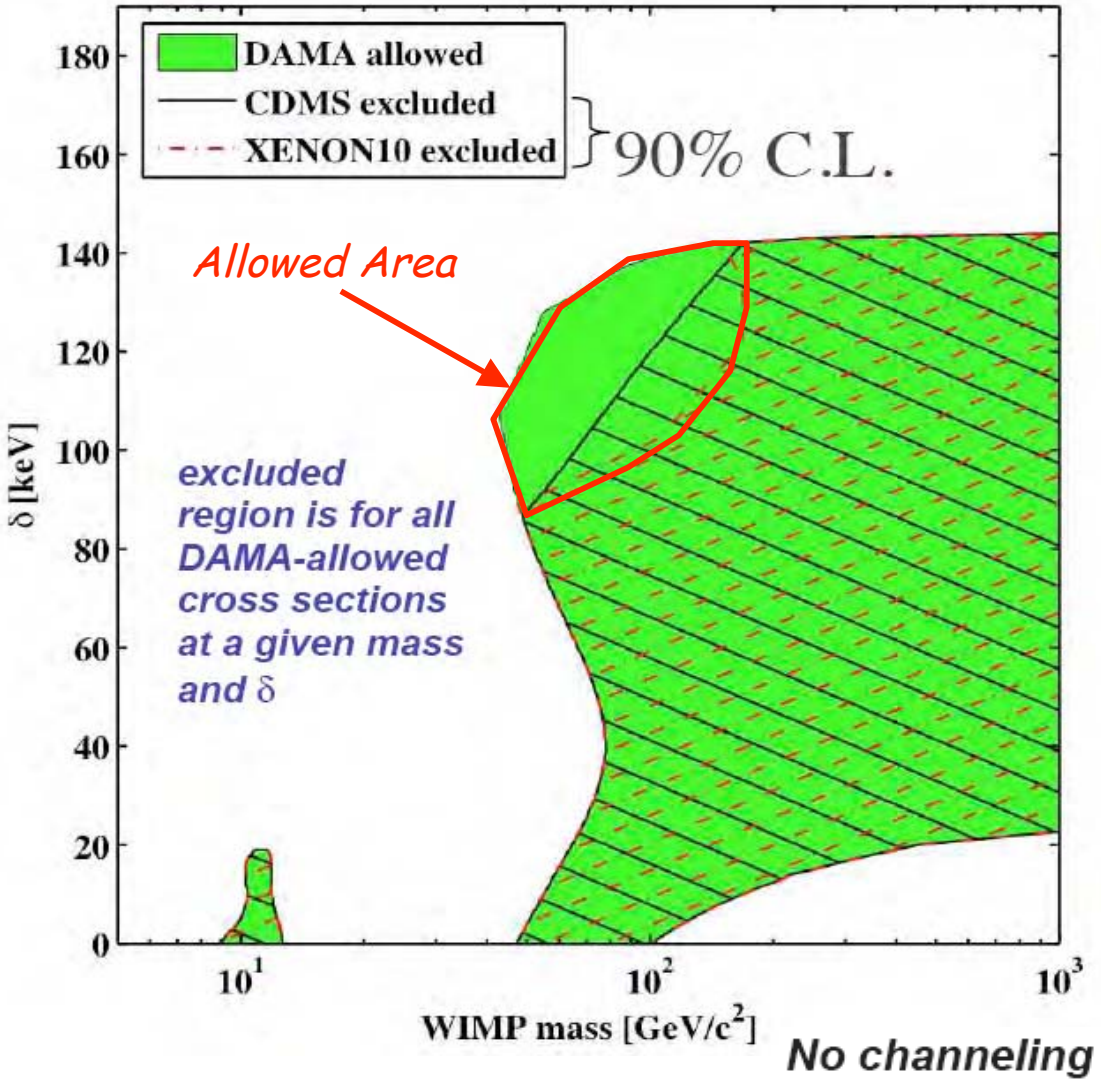




Inelastic Dark Matter ?

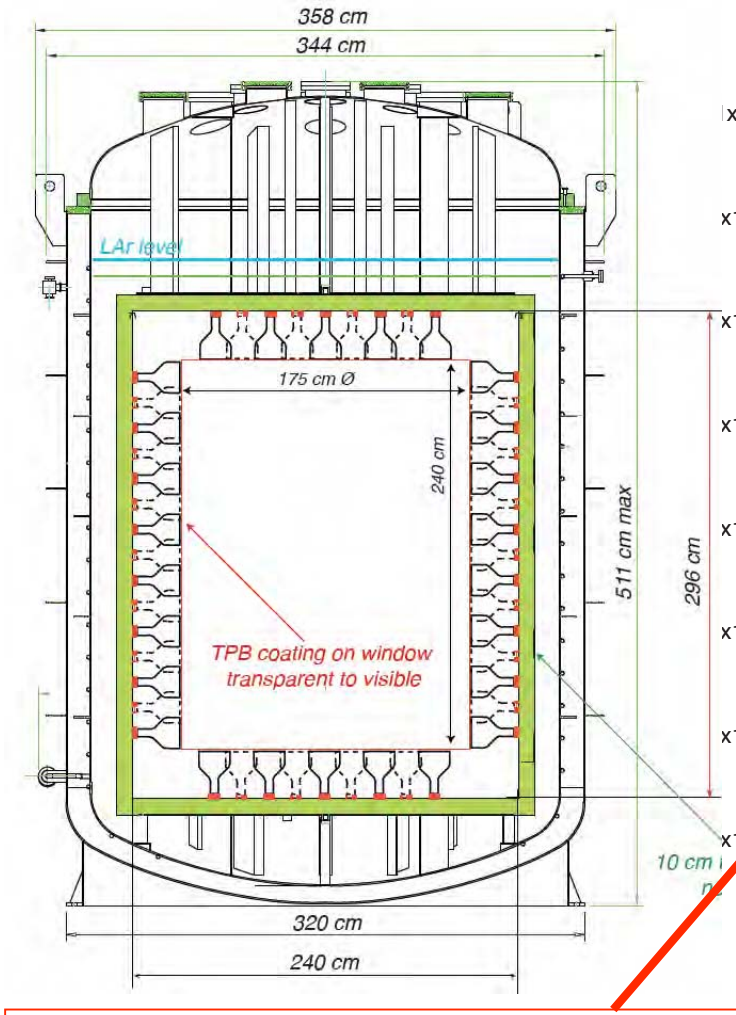
- Has been invoked by Weiner et al. to explain DAMA/LIBRA data [Phys. Rev. D 64, 043502 (2001)]
- Scattering occurs via transition of WIMP to excited state (with mass splitting δ)
- Spectrum peaks at higher recoil energies
- DAMA, allowed regions (at 90% C.L.) [JCAP 04 (2009) 010]

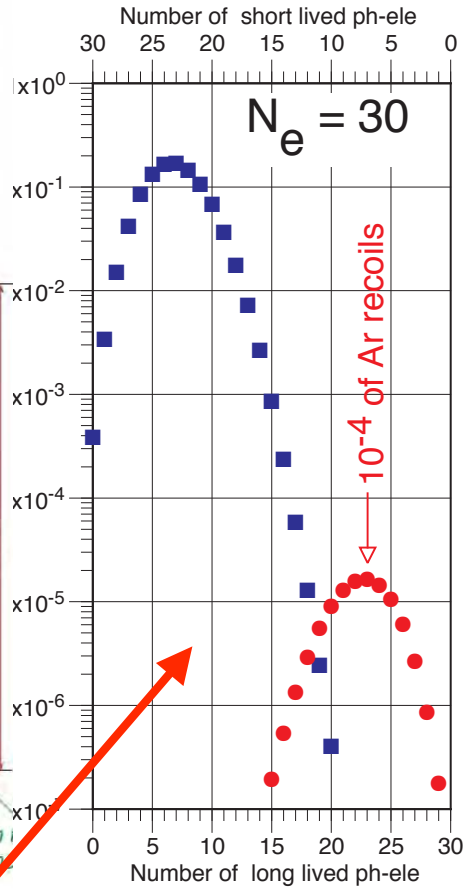
Source: B. Sadoulet



The WARP-Chronos setup

- The experiment will record in essence a DAMA-like modulated recoil spectrum in LAr as a function of the energy of the recoil in the interval above about 25-30 keV.
- The fiducial mass of WARP (8 ton x year) is after one single yearly cycle about a factor ten larger than the whole DAMA/LIBRA exposure of 0.82 ton x year.





Two components of scintillation yield, $\tau_{singlet}$ = 7ns and τ_{riplet} = 1.5 μs, with different relative intensities for electron and nuclear recoils.

A SECOND, ESSENTIAL CONCLUSION

- The DAMA/LIBRA effect has now been confirmed to a high degree of evidence: but its origin is still wide opened.
  - Is the effect due to a cosmological effect, as hinted by the nature of its maximum corresponding to the expected galactic speed variations of the solar system ?
  - If so, is the effect due to collisions with electrons or with nuclear recoils ?
  - Is the cosmological effect confirmed, performing an analogue measurement in the Southern Hemisphere, when the summer/winter local cycles are reversed ?
  - Is the effect persisting with materials of different Z and with different experimental configurations ?
  - Can the effect be enhanced detecting the directionality of the observed recoils or with other methods ?

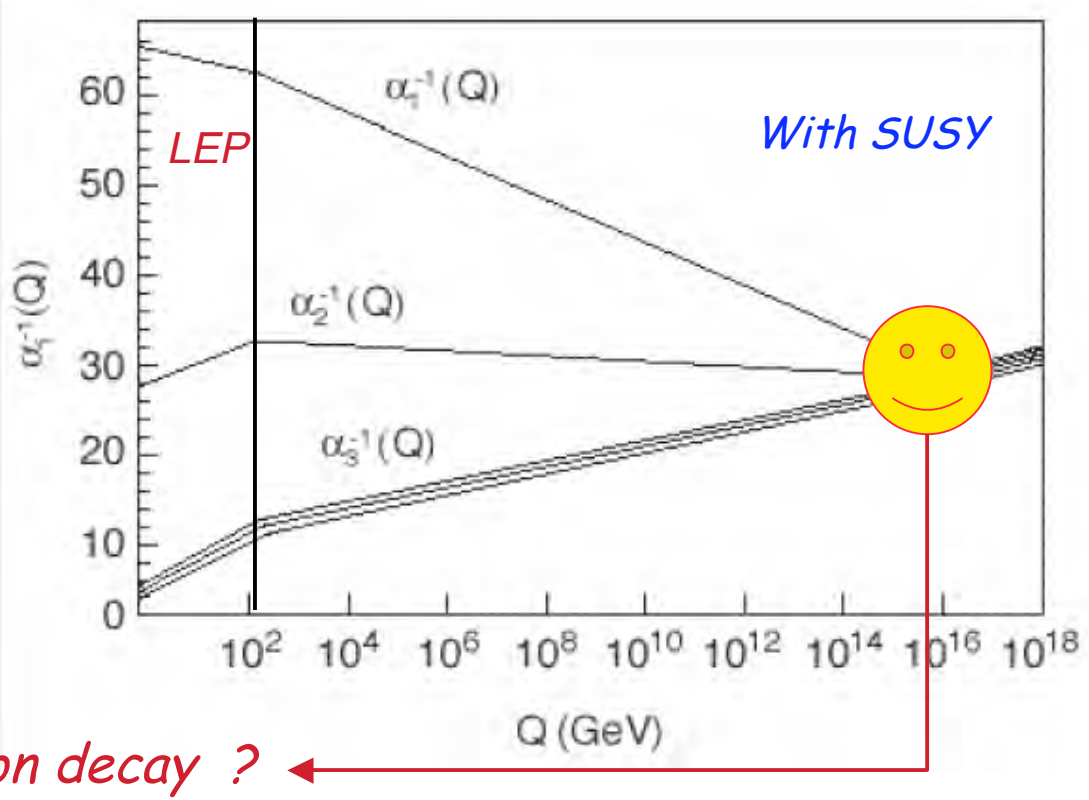
The DAMA/LIBRA anomaly must be repeated and understood

We know that the Electro-weak Theory is incomplete

- It does not account for the fermion spectrum masses, quark & lepton mixings
- No explanation for generations
- Right-handed neutrinos are absent
- Neutrino mass may have a new origin
- CP-violation is accommodated, not accounted for
- Known CP-V doesn't readily account for matter excess
- No viable dark-matter candidates:We do not know the nature of dark matter, nor whether a single species dominates.
- If dark-matter particles interact with weak-interactions, the needed relic abundance generically results for M_{dark} = 100 GeV to 1 TeV
- One really wrong prediction: vacuum energy density too high by x 10^{54}
- No candidate explanation for dark energy

Running coupling constants from LEP

- Running coupling constants are modified above SUSY threshold, and the three main interactions converge to a common Grand Unified Theory at about 10^{16} GeV but provided that SUSY is there at a not too high masses

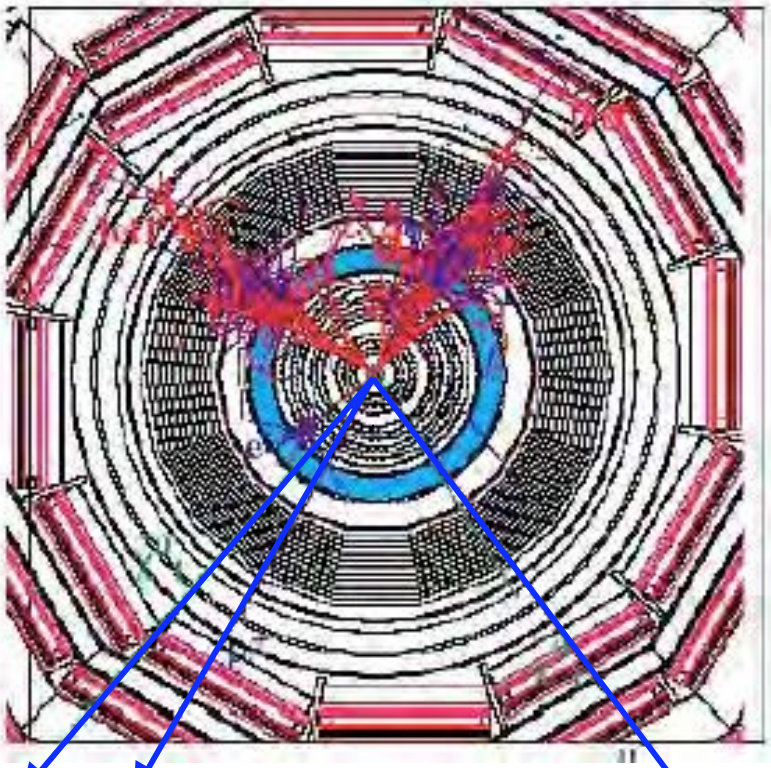


- A doubling the elementary particles occurring at the LHC, the *so-called "no failure" theorem*, has been widely supported by the theoretical physics community.
- A "low mass" *elementary* Higgs is predicted as precursory to the existence of SUSY physics, *a real blessing for LHC*.

LHC as source of SUSY ?

- The experimental signature of a SUSY type particle is generally very characteristic and it deeply affects the number and the kinematical configuration of large $p_\perp$ events

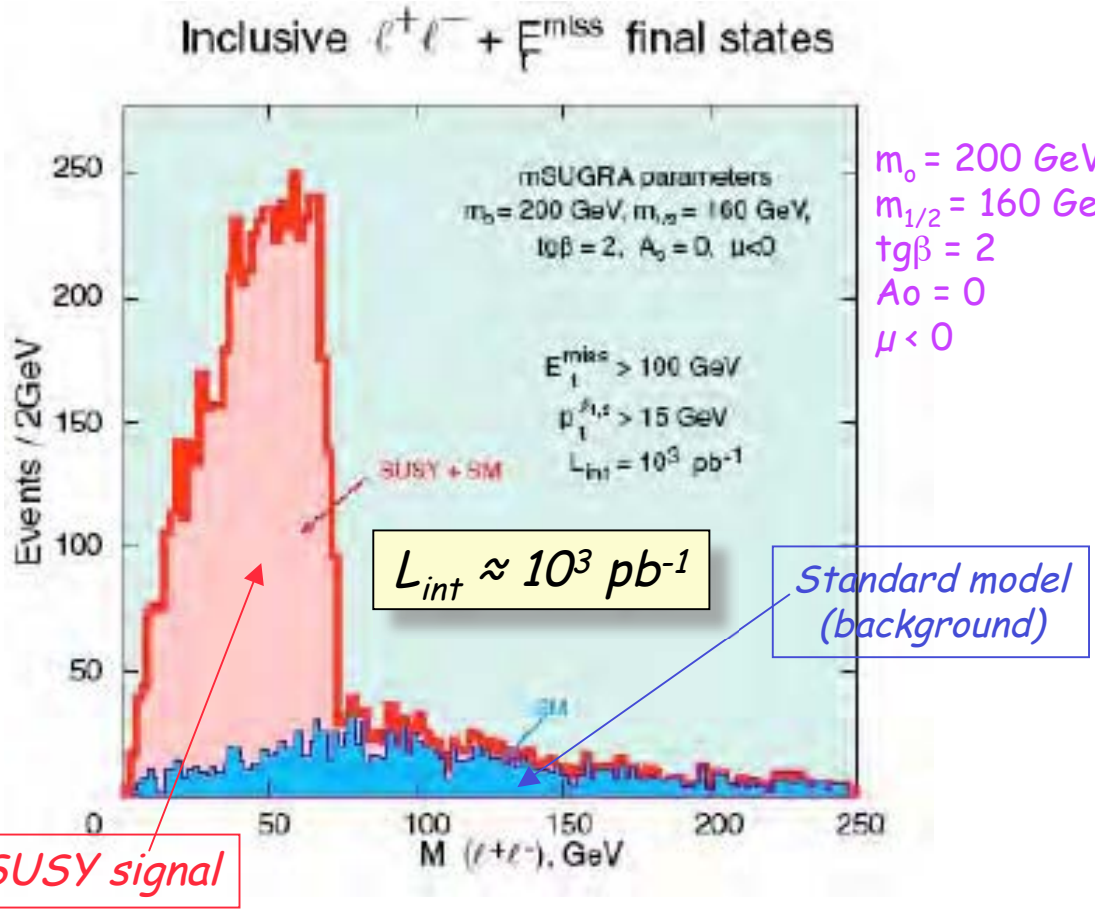
SUSY event with 3 lepton + 2 Jets signature



Lepton(s)

Lepton

2 leptons $p_\perp$>15 GeV+ $E_{\perp miss}$> 100 GeV



m_0 = 200 GeV
$m_{1/2}$ = 160 GeV
tgβ = 2
Ao = 0
μ < 0

$L_{int} \approx 10^3$ pb^{-1}

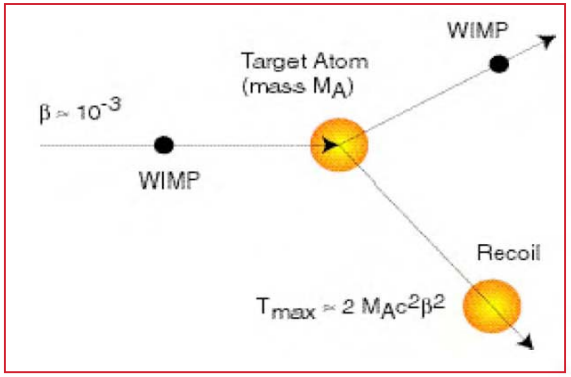
Standard model (background)

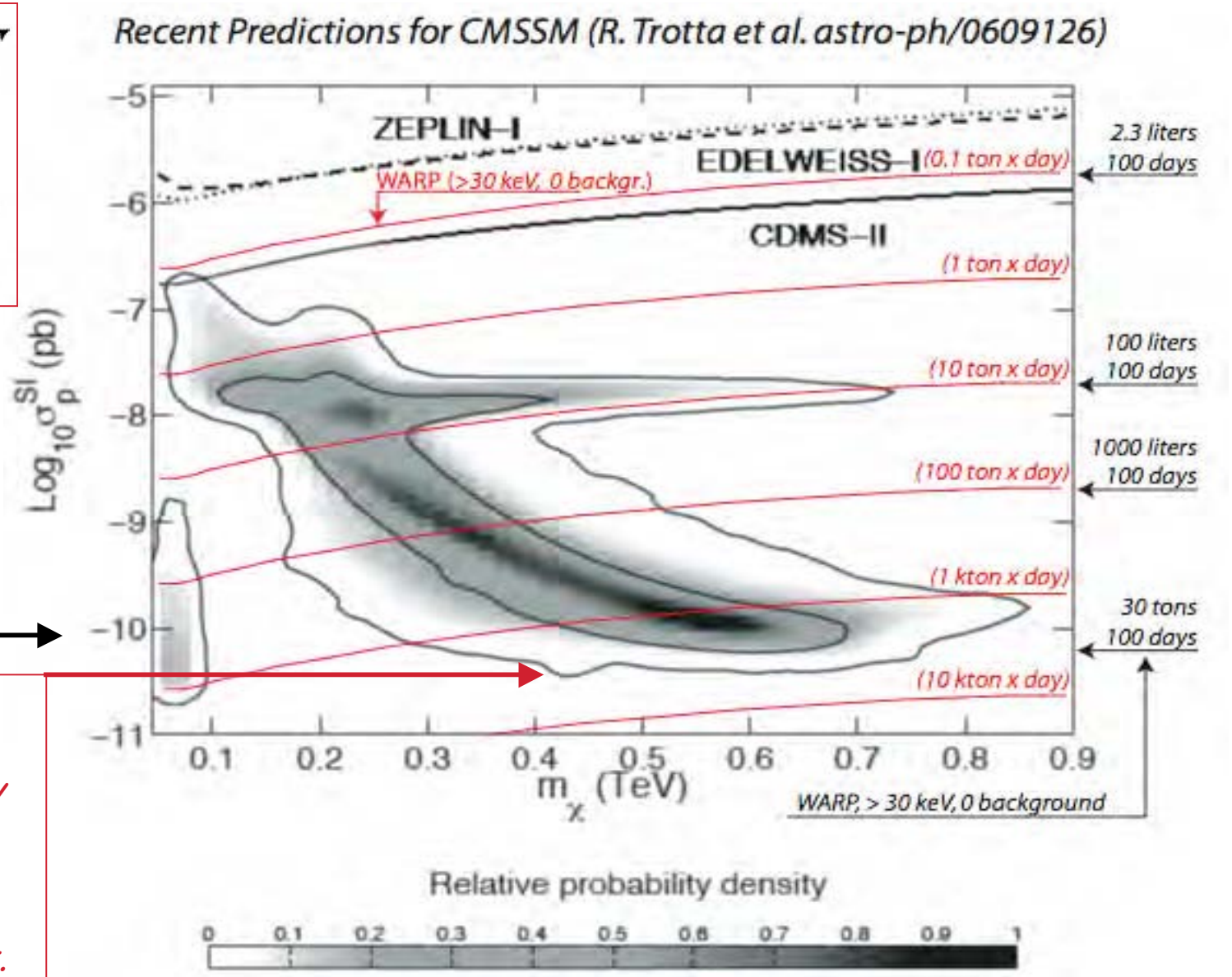
SUSY signal

SUSY: the source of non-baryonic matter ?

- The relation between dark matter and SUSY matter is far from being immediate: however the fact that such SUSY particles may also eventually account for the non baryonic dark matter is therefore either *a big coincidence or a big hint*.
- It must be noted that any heavy relic particle may behave as CDM and a host of exotic possibilities have been suggested.
- *Lest we become overconfident, we should remember that nature has many options for particle generated dark matter, some of which less "costly" than SUSY.*
- However in order to be also the origin of dark mass, the lowest lying neutral SUSY particle must be able to survive the 13 billion years of the Universe The lifetime of an otherwise fully "permitted" SUSY particle weak decay is typically $\approx 10^{-18}$ sec !
- We need to postulate some strictly conserved quantum number (R-symmetry) capable of an almost absolute conservation, with a forbidness factor well in excess of $4x10^{+17} / 10^{-18} = 4x10^{35}$!!!

Predictions of relic Susy/WIMP





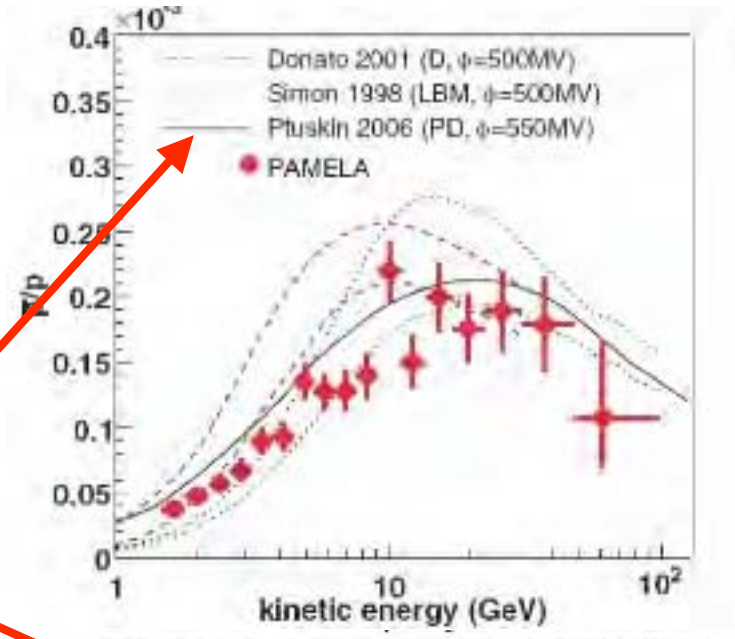
10^{-46} cm^2 →

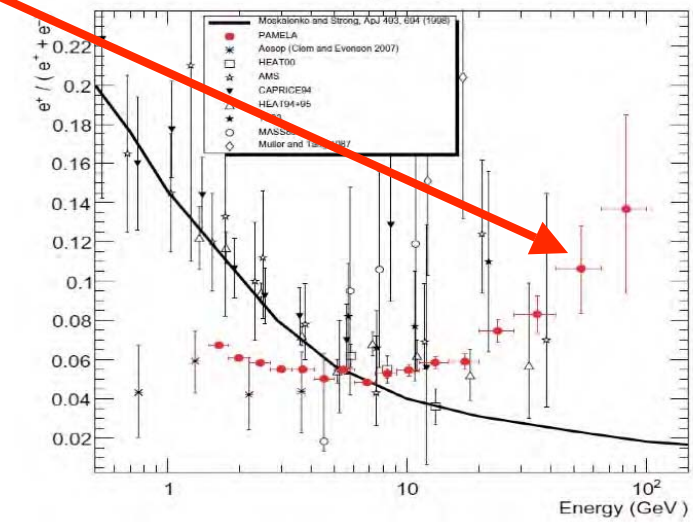
The "ultimate" WIMP detector requires some 10-30 active tons, a very strong rejection of cosmic neutron backgrounds and a vast international investment.

Typical recoil threshold for elastic nuclear recoils > 30 keV

Looking for WIMPs annihilation from space:PAMELA,AMS

- Neutralino are Majorana fermions and will annihilate with each other in the halo, with production of particles and antiparticles, the latter providing an observable signature of annihilations that produce antiprotons and positrons.
- The pbar/p flux ratio appears in agreement with the standard secondary production models.
- A positron excess is however observed, either
  - young pulsars or SNR or non-standard processes
  - more exotic explanations, like DM annihilations.
- This result puts strong constraints on DM models since they usually do not predict an asymmetry between leptonic and hadronic production. *Most dark matter candidates will also generate an unacceptably large flux of cosmic ray antiprotons (!)*



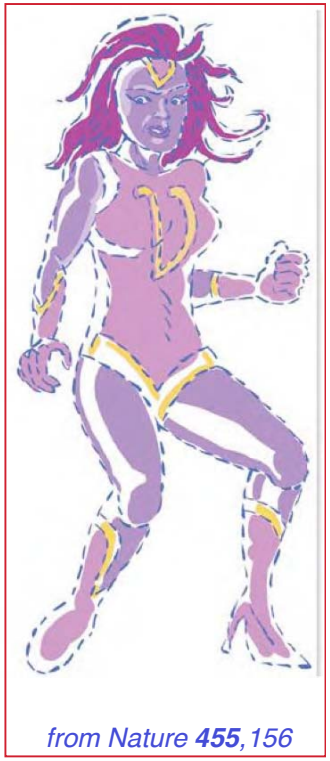


Neutrinos !?

- Neutrinos have been the origin of an impressive number of "Surprises". It has been demonstrated that the sum of the strengths of the coupling of different ν is very close to 3. But it is only assuming that neutrinos, in similarity to charged leptons, have unitary strengths that the *resulting number of neutrinos is 3.* The situation may be altered by the additional presence of sterile neutrinos.
- The experimentally measured weak coupling strengths are only rather poorly known, leaving room for many other alternatives.
- It is only because the masses of known neutrino species are so small, that their contribution to the Dark Matter of the Universe can be neglected. The additional presence of *massive sterile neutrinos* may contribute to Dark Matter.

A THIRD CONCLUSION: DO NOT FORGET EXOTIC NEUTRINOS

- Are neutrino a simple carbon copy repetition of quarks?
  - Masses were once taken as zeros "by ignorance"
  - Oscillations are an extension of C+KM quark mixing
  - Matter oscillations are due to neutral currents
- But this is't all ! Important discoveries are ahead:
  - CP violation in the lepton sector
  - Majorana or Dirac ν's;ν-less β-decay,ν-masses
  - Sterile neutrino and other "surprises"
  - Right handed neutrinos and see-saw mechanisms



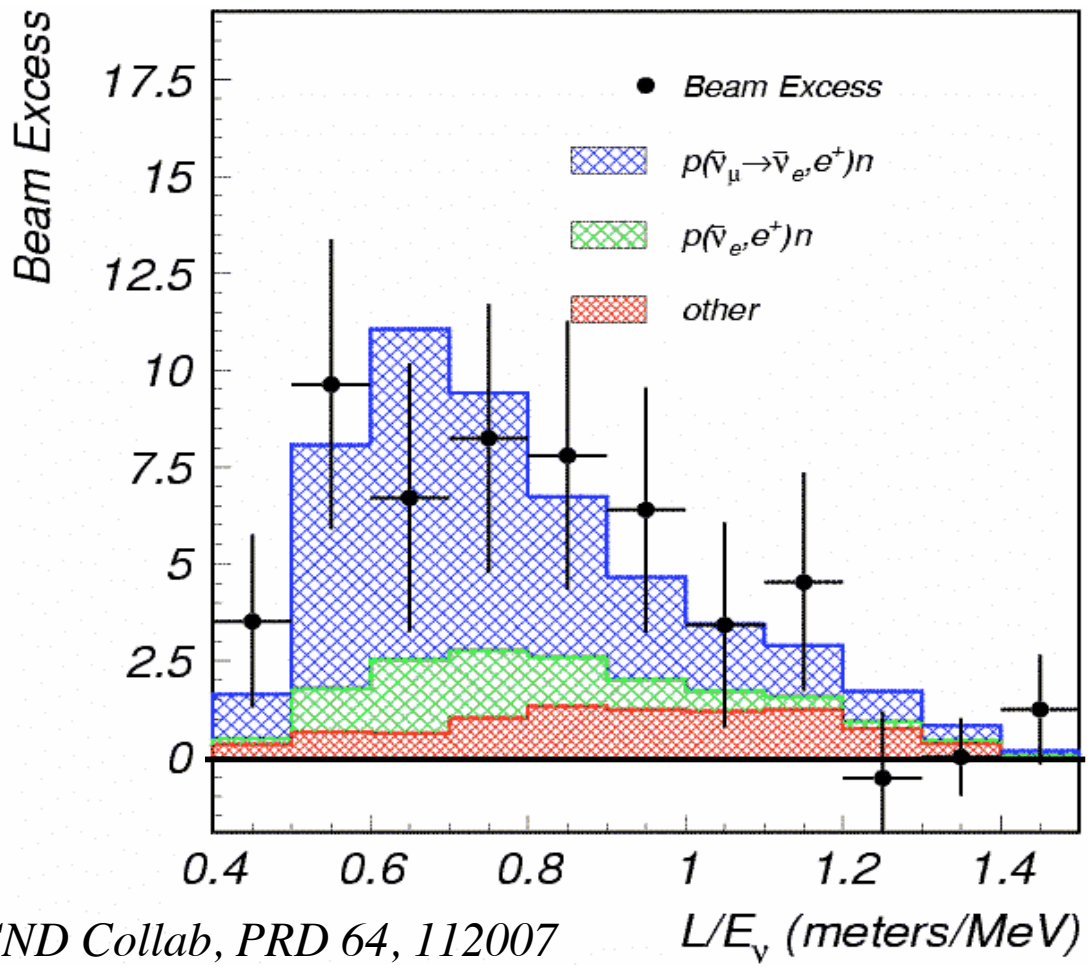
*from Nature **455**,156*

If a neutrino like object of the mass > a few MeV is found, it will be necessarily a main contributor to Dark Matter.

In my view this is still an open alternative !

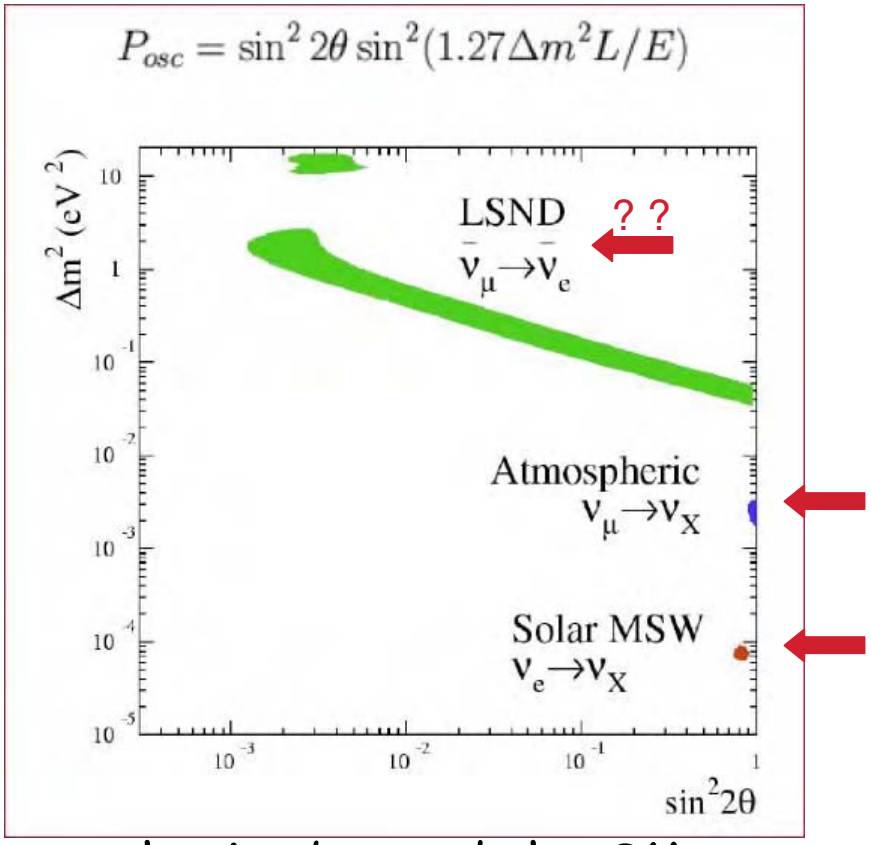
The LSND Experiment: antineutrino oscillations ?

LSND has observed an excess of $\bar{\nu}_e$ events in a $\bar{\nu}_\mu$ beam, 87.9 ± 22.4 ± 6.0 **(3.8σ)**



LSND Collab, PRD 64, 112007

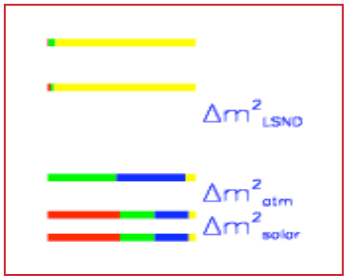
Points -- LSND data
Signal (blue)
Backgrounds (red, green)



- 3 oscillation signals, if confirmed, require new physics beyond the SM

Many theoretical hypothesis…..

3+2 Sterile Neutrinos — Sorel, Conrad, & Shaevitz (PRD70(2004)073004)



← Additional, sterile neutrinos ?

← Standard neutrinos

MaVaNs & 3+1 — Hung (hep-ph/0010126)

Sterile Neutrino — Kaplan, Nelson, & Weiner (PRL93(2004)091801

CPT Violation & 3+1 Sterile Neutrino — Barger, Marfatia, & Whisnant (PLB576(2003)303)

Quantum Decoherence — Barenboim & Mavromatos (PRD70(2004)093015)

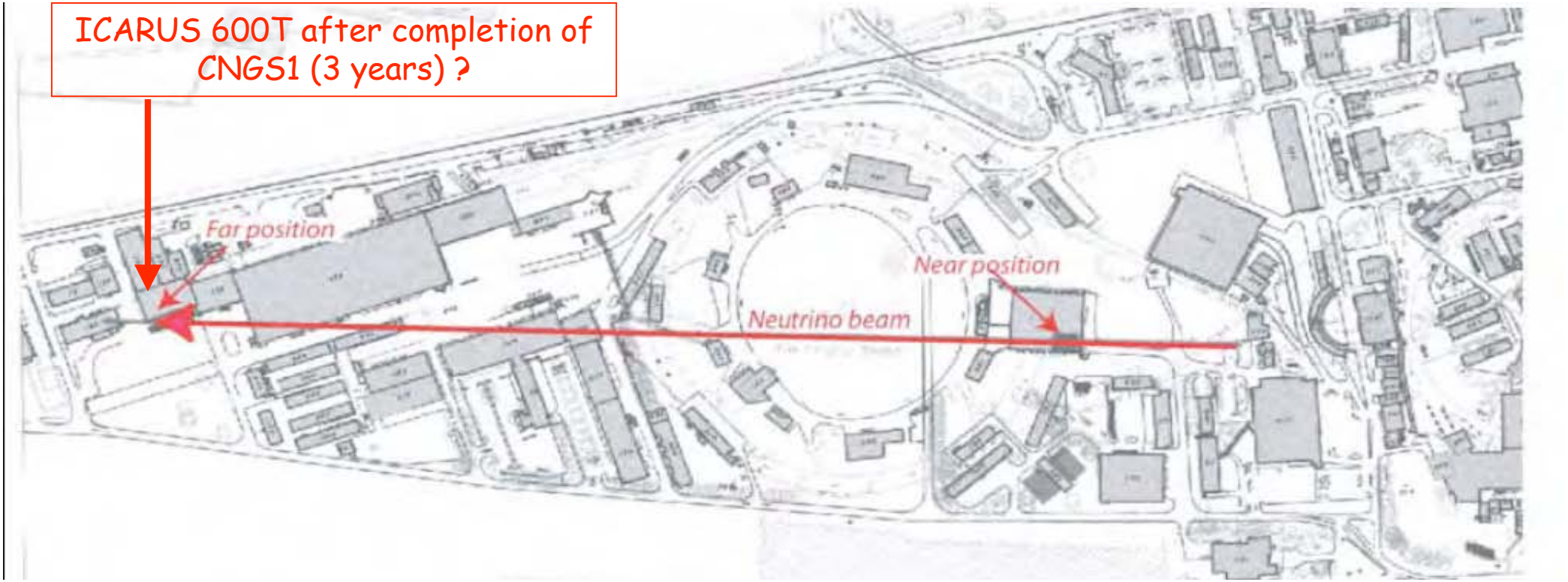
Lorentz Violation — Kostelecky & Mewes (PRD70(2004)076002)
Katori, Kostelecky, Tayloe (hep-ph/0606154)

Extra Dimensions — Pas, Pakvasa, & Weiler (PRD72(2005)095017)

Sterile Neutrino Decay — Palomares-Ruiz, Pascoli, & Schwetz (JHEP509(2005)48)

And so on….

The new PS neutrino beam

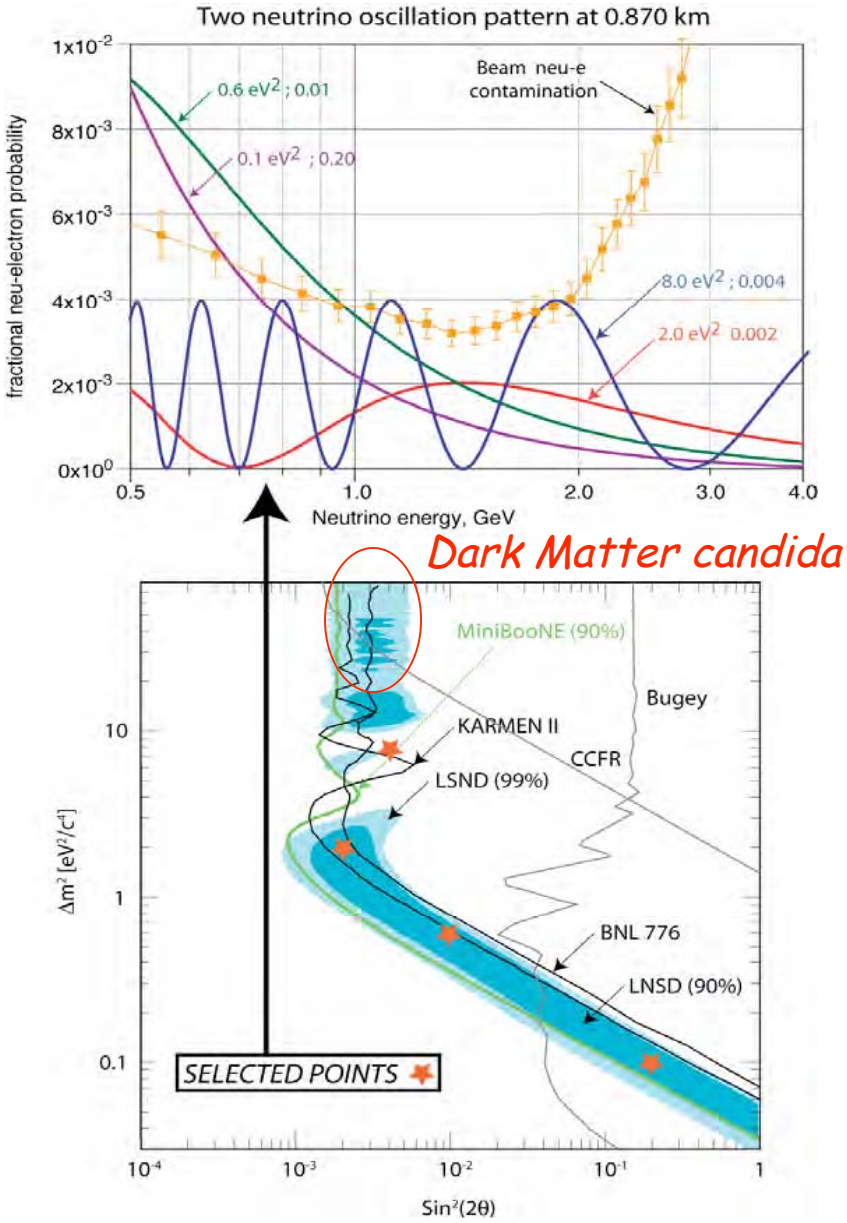


- The PS proton beam at 19.2 GeV/c is extracted via TT2, TT1 and TT7.
- The magnetic horn is designed to focus particles of momentum≈2GeV/c.
- The decay tunnel is about 50 m long, followed by an iron beam stopper

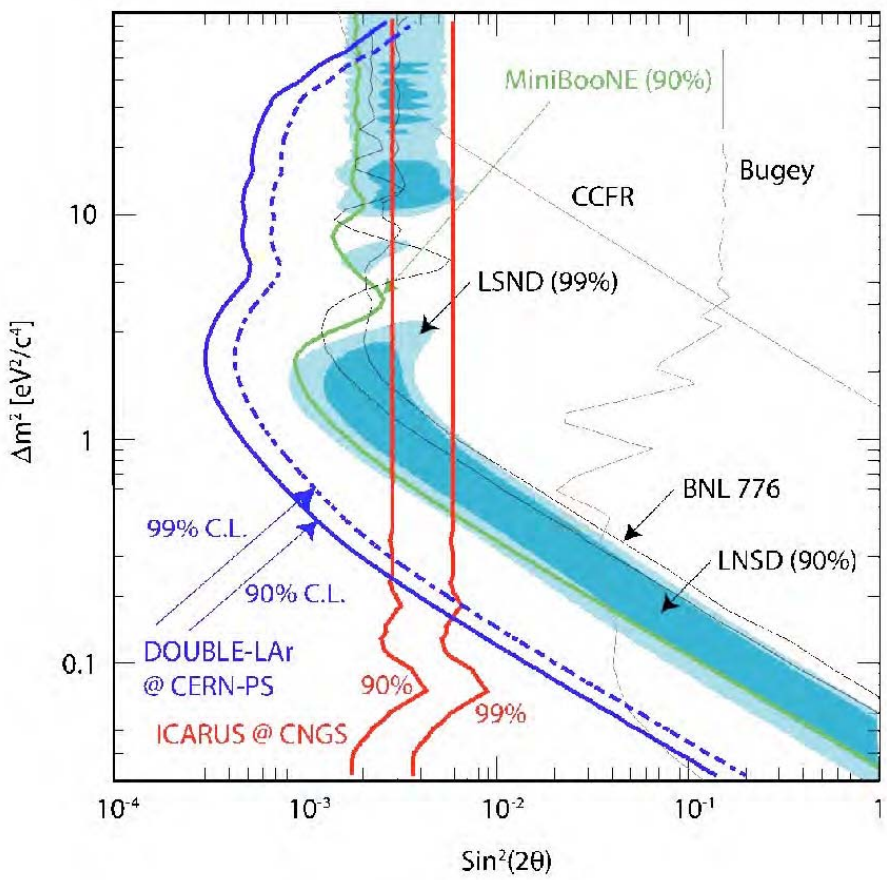
Two positions are foreseen for the detection of the neutrinos
The far (main) location at 850 m from the target (600T);
The near location at a distance of 127 m from the target (100T).

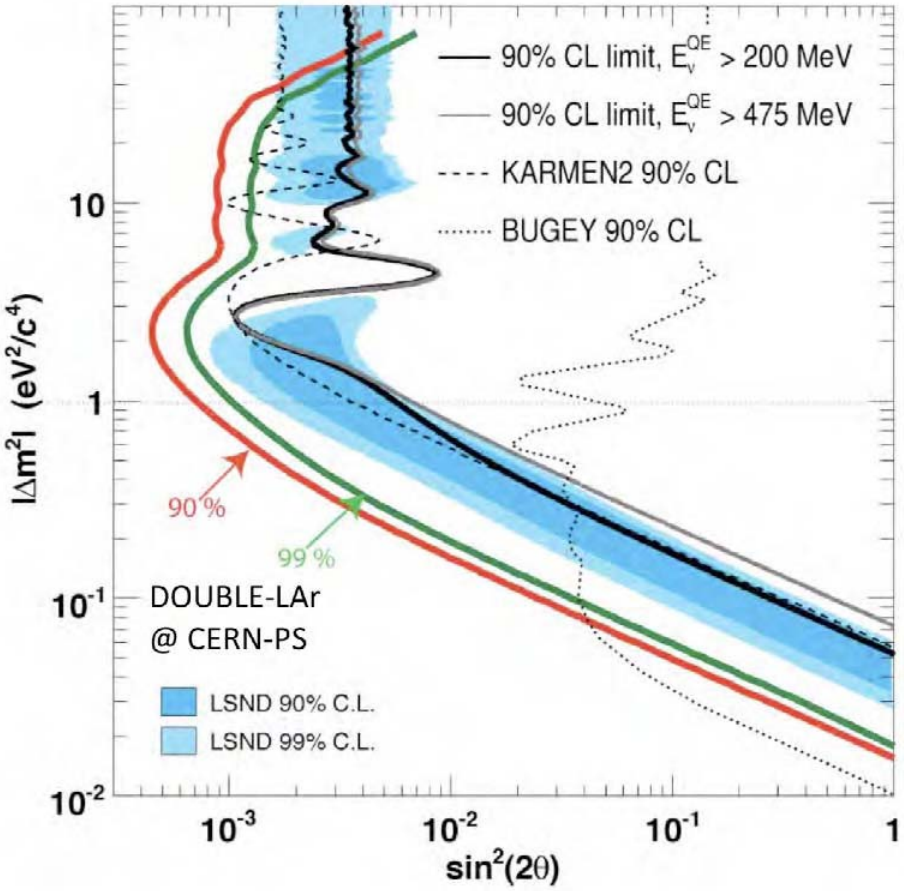
New features of the CERN proposal

- It appears that the present proposal, unlike LNSD and MiniBooNE, can *determine both the mass difference and the value of the mixing angle.*
- Very different and clearly distinguishable patterns are possible depending on the actual values in the (Δm^2 – $\sin^2 2\theta$) plane.
- The intrinsic ν_e background due to the beam contamination is also shown.
- The magnitude of the LNSD expected oscillatory behaviour, for the moment completely unknown, is in all circumstances well above the background, also considering the very high statistical impact and the high resolution of the experimental measurement.



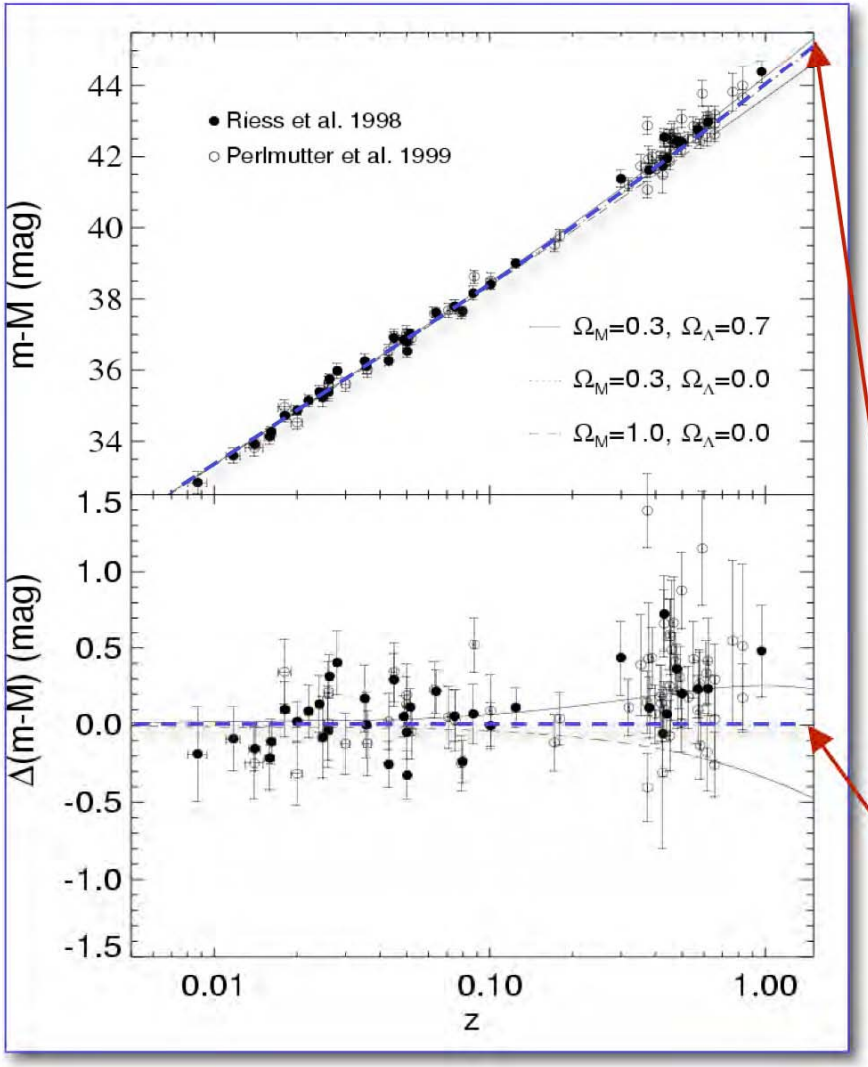
Comparing sensitivities





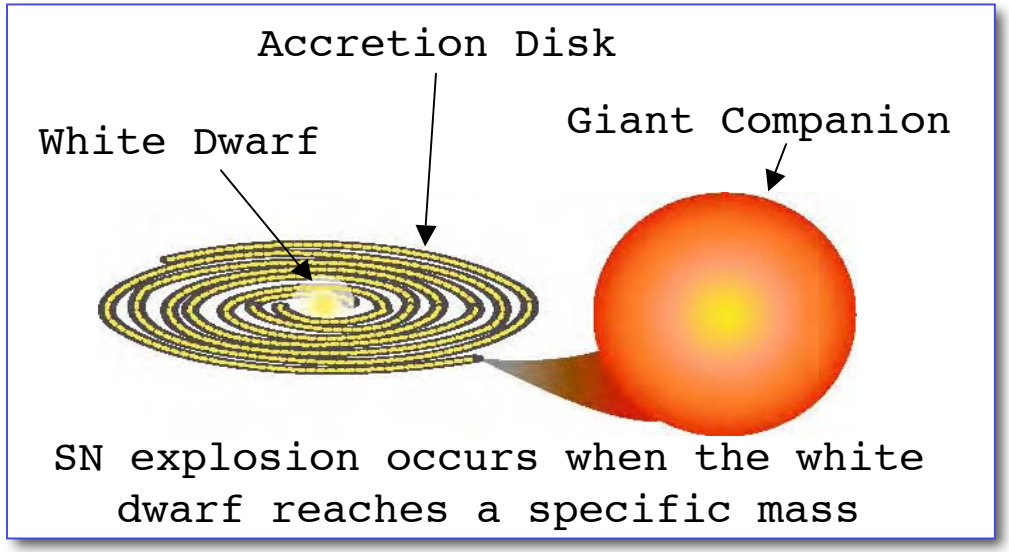
Expected sensitivity for the proposed experiment exposed at the CERN-PS neutrino beam (left) and anti-neutrino (right) for 2.5 10^{20} pot. The LSND allowed region is fully explored both for neutrinos. In the neutrino case, the expectations from CNGS2/ICARUS T600 at LNGS are also shown.

Evidence of $\Omega_\Lambda \neq 0$: Dark Energy ?



Constant expansion rate

Regression velocity of Type 1A SN



- Redshift measurements of Type 1A SN indicate an accelerated expansion at large z

Dominant contribution to the matter / energy content of the Universe due to some form of energy characterized by negative pressure

Dark Energy

- There is also evidence of a significant (actually dominant) contribution to the matter / energy content of the Universe due to some form of energy characterized by negative pressure: Dark Energy.
- Can be accommodated into the Einstein's equation in the form of Cosmological Constant:

$$8\pi \cdot \mathcal{G} \cdot \mathcal{T}_{\mu\nu} = \mathcal{R}_{\mu\nu} - \frac{1}{2}\mathcal{R} \cdot \mathcal{g}_{\mu\nu} \quad \boxed{+ \Lambda \cdot \mathcal{g}_{\mu\nu}}$$

- Very difficult to interpret in the framework of particle physics (v.e.v. some 10^{50} larger than the actual value of Λ) and also in terms of cosmological arguments (the observed quasi-equality between Dark Energy and Matter densities hard to justify on the basis of general arguments).

A few comments about Dark Energy.

- Several increasingly accurate Astronomical observations have strengthened the evidence that today's Universe is dominated by an exotic nearly homogeneous energy density with negative pressure. The empty space still contains lots of invisible energy.
- The simplest candidate is a cosmological term in Einstein's field equations. Independently of the nature of this energy, the constant $\Lambda \neq 0$ is not larger than the critical cosmological density $\Omega_o \approx 1$, and thus incredibly small by particle physics standards. This is a profound mystery, since we expect that all sorts of vacuum energies contribute to the effective cosmological constant.
- Since the vacuum energy density is constant in time, while the matter energy density decreases as the Universe expands, why are the two comparable at about the present time, tiny in the early Universe and very large in the distant future ?
- The problem of the value of Λ is one of the greatest questions of the Universe, all along from its introduction in 1917 by Einstein: it has now become widely clear that we are facing a deep mystery and *that the problem will presumably stay with us for along time.*

Conclusions

- Frank Wilczek (Nobel in Physics, 2004) has said that *"only the LHC stands a real chance of breaking the existing paradigm"* and Nature magazine has named it *"the unstoppable collider".*
- However I believe that one cannot predict where and if the next major discoveries/surprises may come from. Ultimately the LHC and the other major subjects of investigation are competing with each other, a sort of David and Goliath confrontation.
- The discovery of a SUSY—in my view very speculative, in spite of the "insurances" of the theoretical community — may be the promise for a real "bonanza" for the present (and future) colliders; however its relation to dark matter is by no mean obvious or granted.
- Likewise the neutrino sector may reserve for us incredible new discoveries. Proton decay may be in the domain of experimental discovery,opening the experimental observation of a grand Unification of all forces. Gravitational waves are about to be discovered in the laboratory and in space.
- Events from space and underground have an immense role to play in the future. Now that LHC is at last on the verge of operation, European physics and CERN should concentrate again some of the efforts and funding also on a broader range of other activities in a wider collaborative effort over the many other "unthinkable ideas".

Thank you !