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Closing in on Dark Matter

Tentative Conclusions

Status of the field

No clear cut signal: Should we be discouraged?
Theory/Observational spaces
More detailed models and comparison tools
More sensitive, better calibrated detectors
Importance of complementarity and

Potentially disruptive

DAMA
Low mass "WIMPs" ?
Galactic Center?
135GeV Fermi line?
Core of Dwarfs
Sterile neutrinos

Overall Impression

Excellent conference

Thanks to Jodi and her team: Stefan,Manoj,Jason,Jenni,Anyes

- Organization (+ Aspen Team: Jane Kelly, Patty Fox)
- Excellent scientific organization

Thanks to the speakers

Discussion outside the talks

A vibrant young community

Good snow

An impossible job!

64 talks:1 slide /talk >> 30 minutes

I cannot claim to understand all the details (> 2000 densed slides)

May be the most useful

A personal and partial point of view

- Status of the field
- Anomalies and their potential to be disruptive

Please email me (sadoulet at berkeley dot edu) if I keep propagating non sense

Should we be discouraged?

In spite of many predictions around the theme

"Are we at the brink of a discovery?" BS Science 2007, Bertone, the title of this conference

We have not seen no clear cut signal yet!

No missing energy at the LHC

No clear signal in direct detection

No unambiguous signal around the Galactic Center

No gamma ray from dwarfs

My own impression

1) Oversimplification of our theoretical models

We took a cartoon (mSUGRA) too seriously!

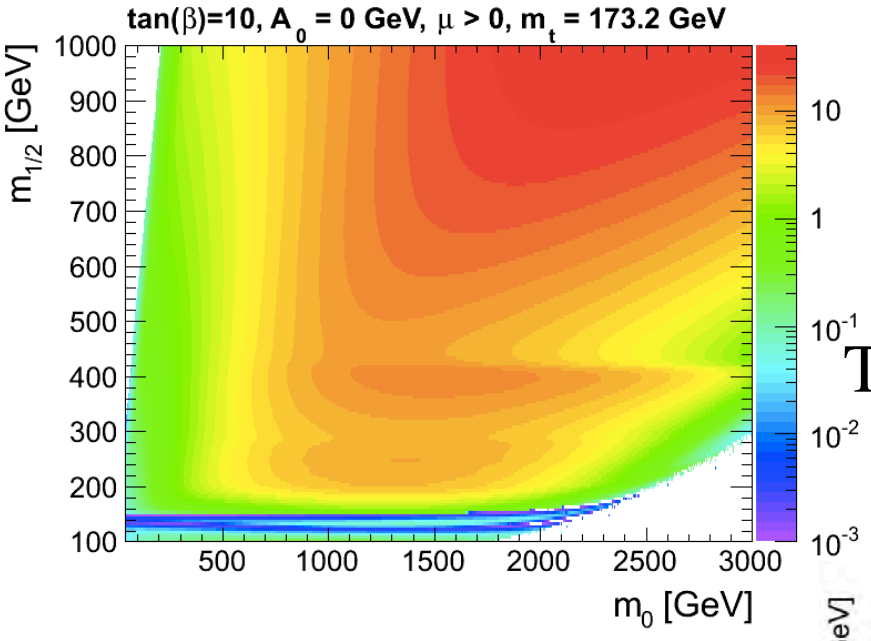
2) We need to be more professional in our measurements!

3)Separating (g)astrophysics from fundamental physics is challenging

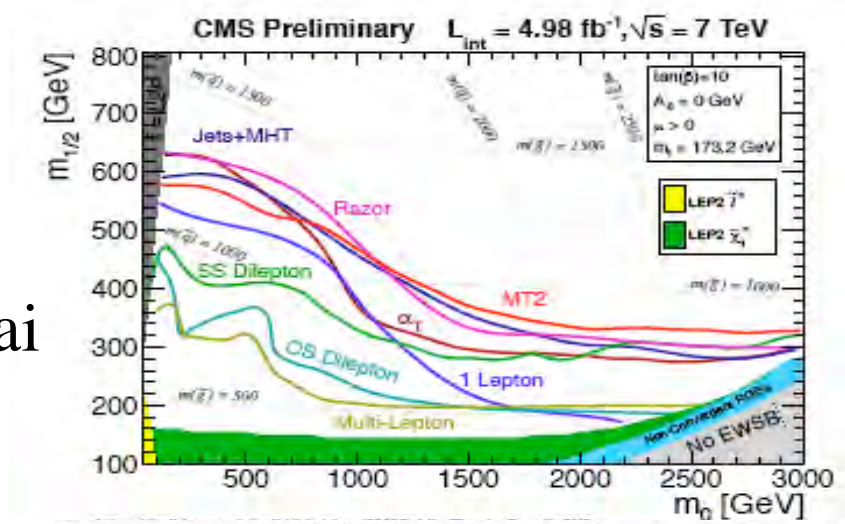
No Missing Energy at the LHC

mSUGRA≈CMSSM 4 parameter + sign

Useful simplification but easy to eliminate



Tai



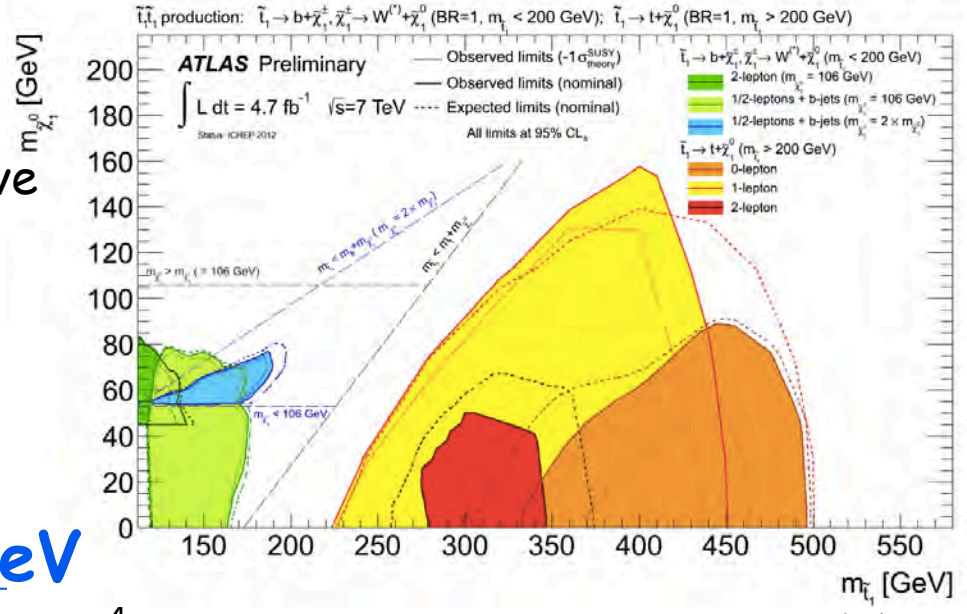
Natural supersymmetry

Do only what you really need to solve the hierarchy problem :

light s-top

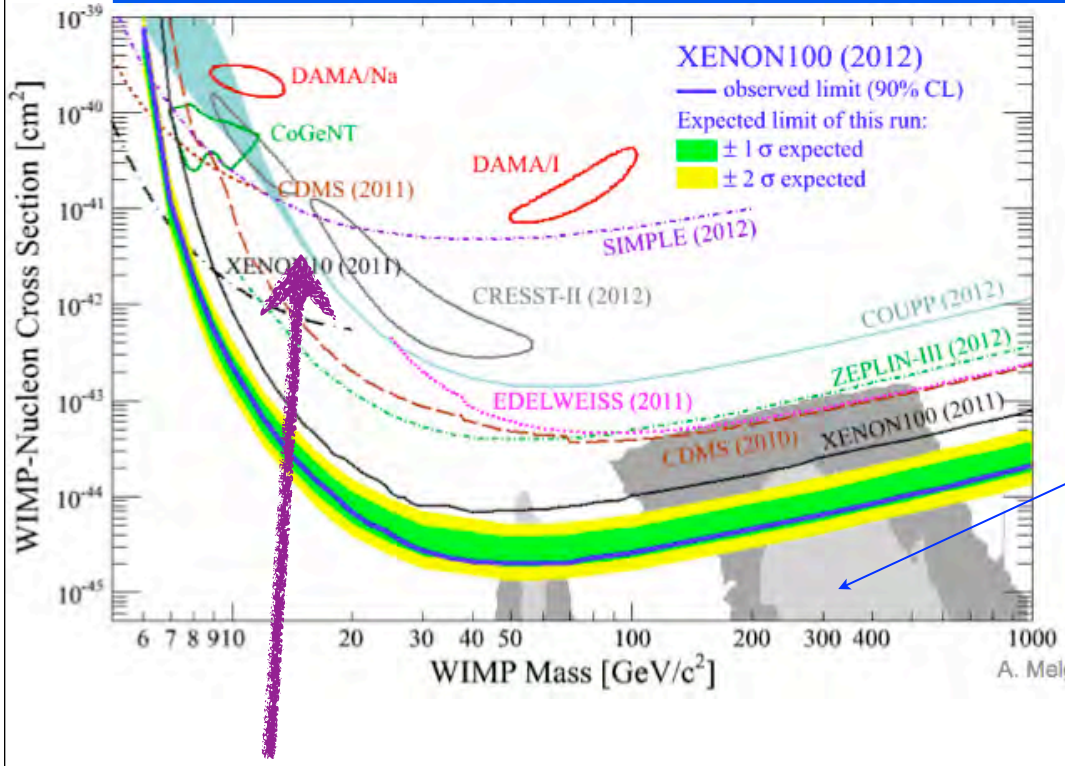
Much more open

But other problems (mh, B_s->γ)



Simplified models ->600 GeV

Direct Detection



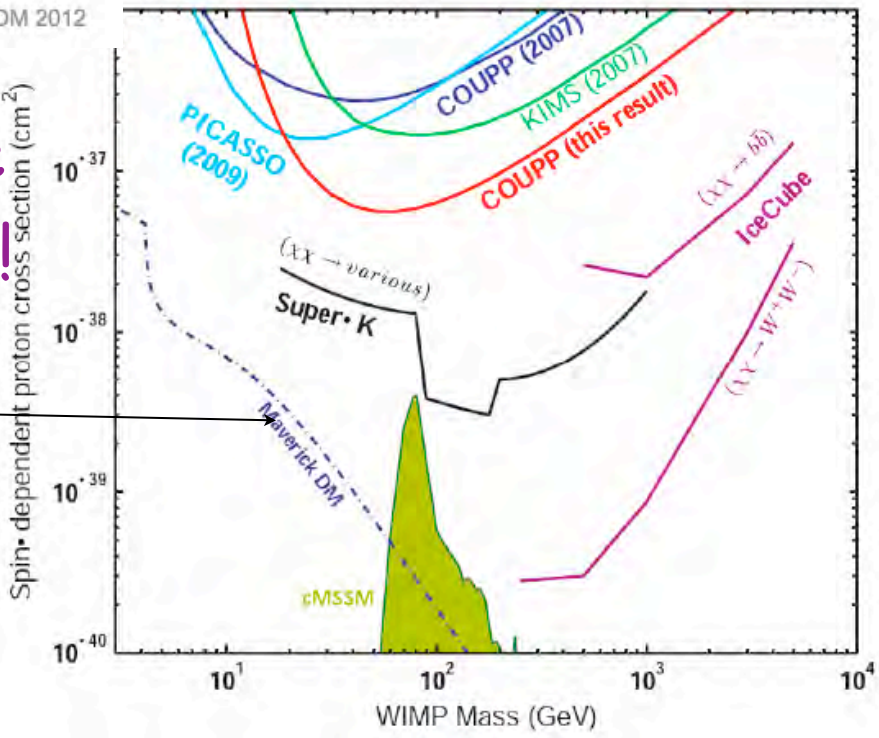
CMSSM≈mSUGRA Focal point region

No threshold for Direct Detection

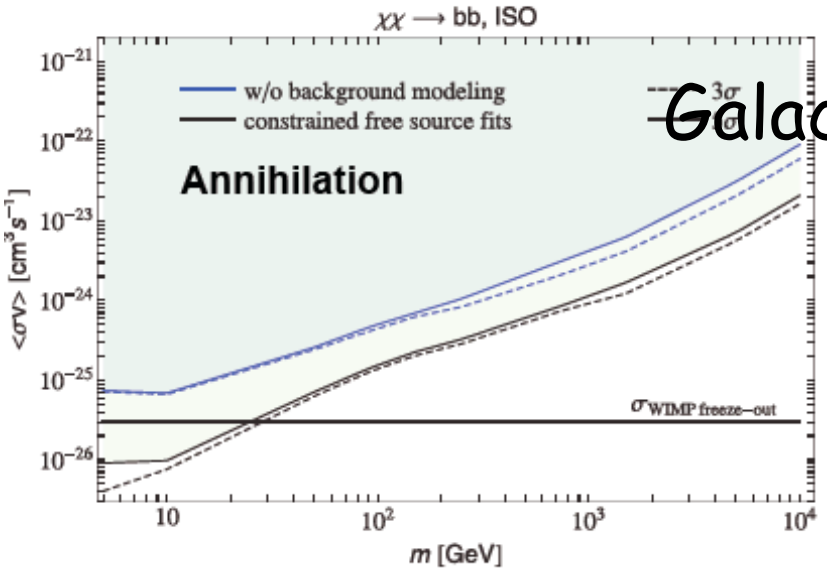
This does not project the image that we know what we are doing!

LHC Monojets

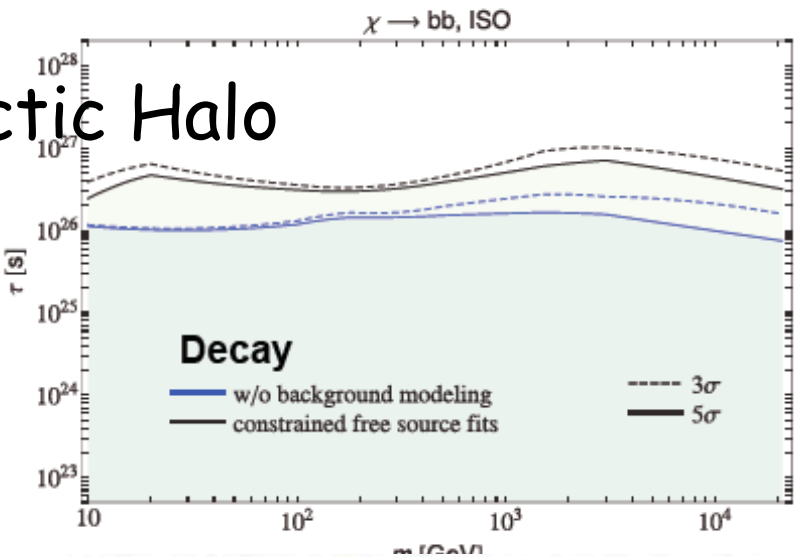
$$\left(\bar{\chi}\gamma_\mu\gamma_5\chi\right)\left(\bar{q}\gamma_\mu\gamma_5 q\right)$$

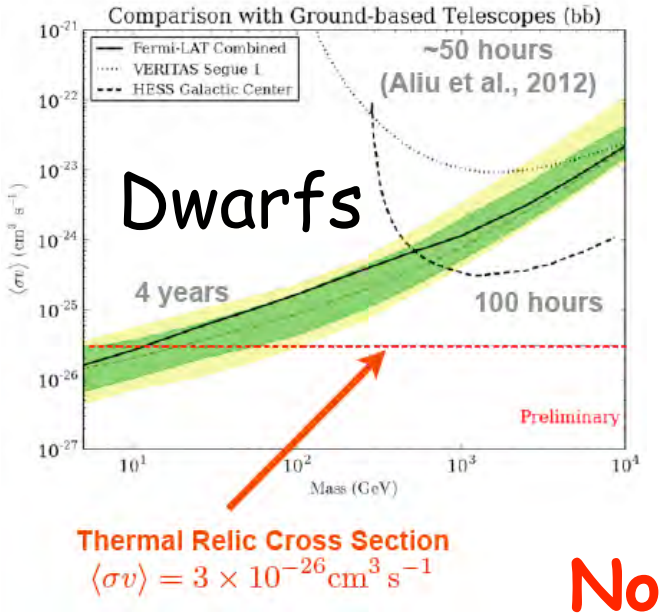


Dark Matter Annihilation (Fermi)



Galactic Halo

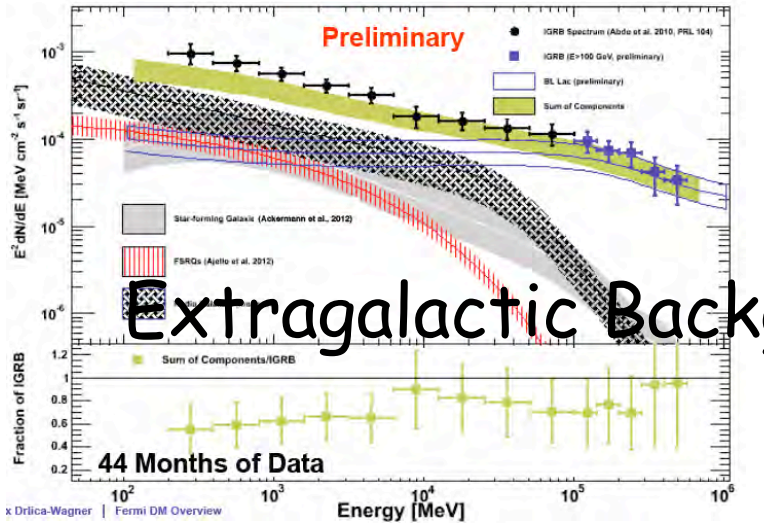




Dwarfs

Thermal Relic Cross Section

$\langle \sigma v \rangle = 3 \times 10^{-26} \mathrm{cm}^3\,\mathrm{s}^{-1}$



Extragalactic Background

No clear signal

Minor gripe: While presentation in terms of $b\bar{b}$, $\tau\bar{\tau}$,$W\bar{W}$ channels is simple realistic model is a mix -> less restrictive limits

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My own impression

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2) We need to be more professional in our measurements!

3)Separating (g)astrophysics from fundamental physics is challenging

Tentative conclusions: No

1) LHC not done yet 8TeV(results this year), 14TeV

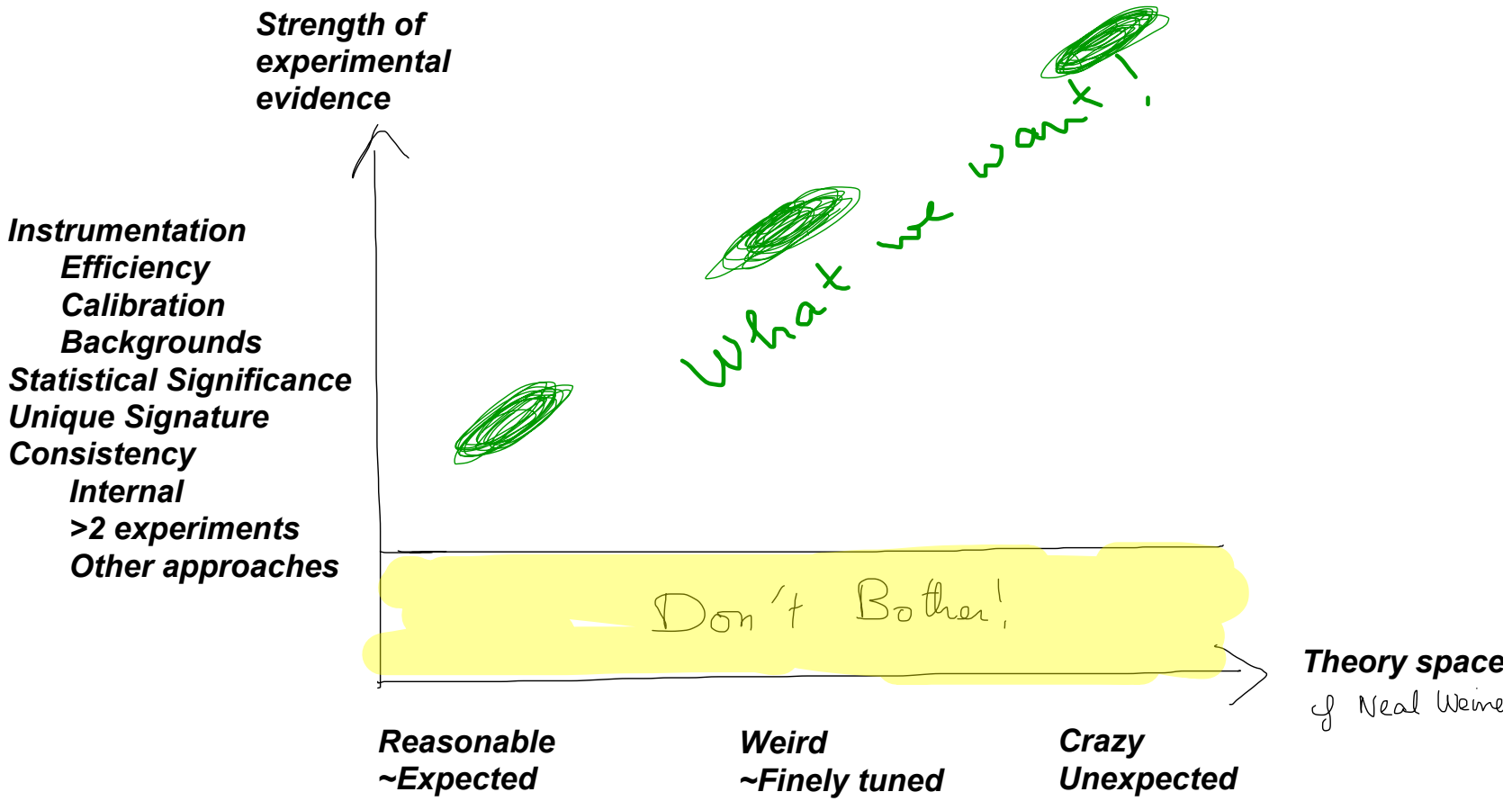
2) "The announcement of SUSY's demise is premature" Howie Baer(Mark Twain)

3) But we need to look at alternatives

Interaction between Theory and Experiment

What about the proliferation of experimental anomalies and new theory models

Adding a dimension to Neal Weiner's axis



Our Problem:The truth is not given

We are fundamentally Bayesian

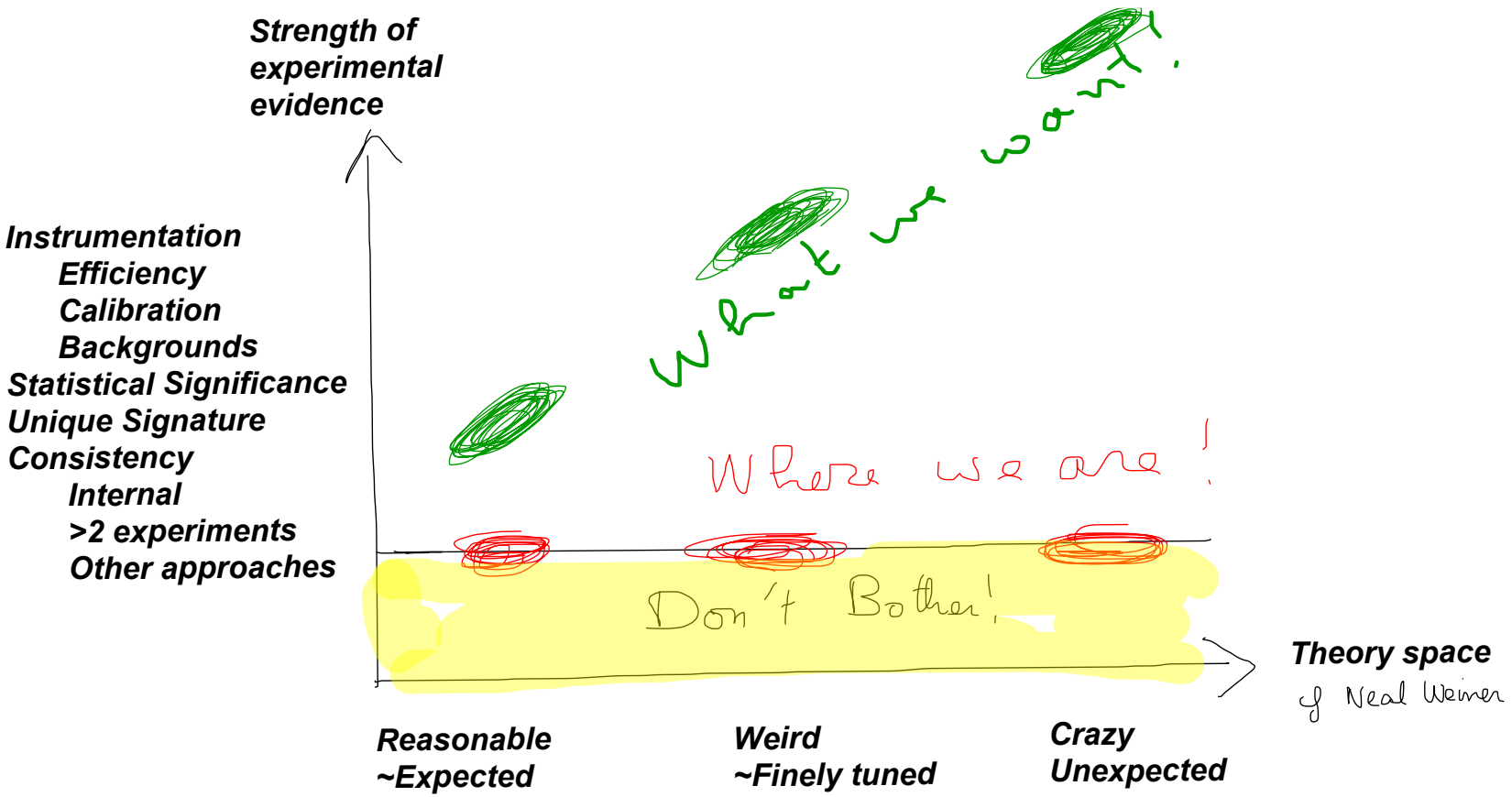
Final probability = a priori probability x measurement

Our understanding = a priori ideas about reality x hard facts from our interactions with reality

Emmanuel Kant!

Both influenced strongly by our preconceptions and the data

Where are we?



At the moment, at most indications

The fundamental tension:

1) The Reasonable

Occam->Von Neuman-> Fermi

Keep the number of tooth-fairies to the minimum

Stay under our comfortable lamppost!

Our beloved lamppost! = EW Scale

The fundamental tension:

2) The Explorers

Explore the paradigm space

Have the courage to leave the lamppost and enter the dark forest.

There is no guarantee that Nature is simple!

After all, the ultimate goal of science: The destruction of current paradigm

Scientific Revolution: Thomas Kuhn

My own feeling:

Exploration (<- anomalies) is fine but:

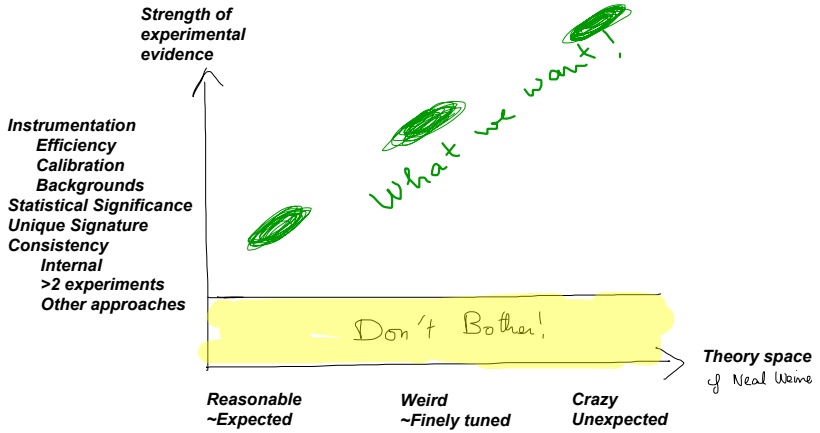
Let us first cross check the experiment

internal + external ≥2 Expts

Let us then unravel the astrophysics

Then we can invoke new particle physics:

The more exotic, the heavier the burden of proof



Where are we? Th: 4 Different Models

The old timers + unsolved moduli problem

Axions:

Dynamical restoration of CP invariance in QCD

although a lot of details glossed over, in particular $\theta \approx 1$ (time of inflation, impact of supersymmetry) + topological defects

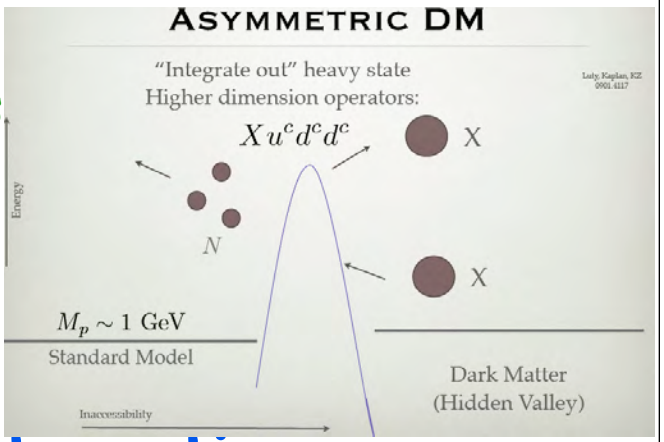
May combine Baer!

WIMPs

Hierarchy problem in particle physics

Relic density for thermalized massive particles

although lot of parameters in MSSM,



Gaining respectability!

A complex dark sector with self interaction

Symmetric (relic density) or asymmetric (if ≈same as matter => $M_\chi \approx 7$GeV)

Possibility of a light mediator (Weiner), dark photon

But interaction with the standard sector ≈ arbitrary

Sterile neutrino

Right handed neutrino related to neutrino mass and baryogenesis

But scale is not fixed a priori (eV, keV or >100GeV)

Where are we with experiments?

Getting more professional

Calibration

Scintillation and ionization yield for direct detection

Analysis methods

Most Direct Detection experiments are now blind

Number of trials

Likelihood methods

But beware of the systematics in the background shape assumed

Making rapid progress

Rapid increase in planned detector sensitivity

Example: Direct Detection (sensitivity ≠mass: background and rejection)

Indirect: Impressed by Gamma 400 and CTA

But progress is always slower than we hope

Important and innovative R&D

e.g., Axion: at HF with parametric amplifiers

square km array for axion

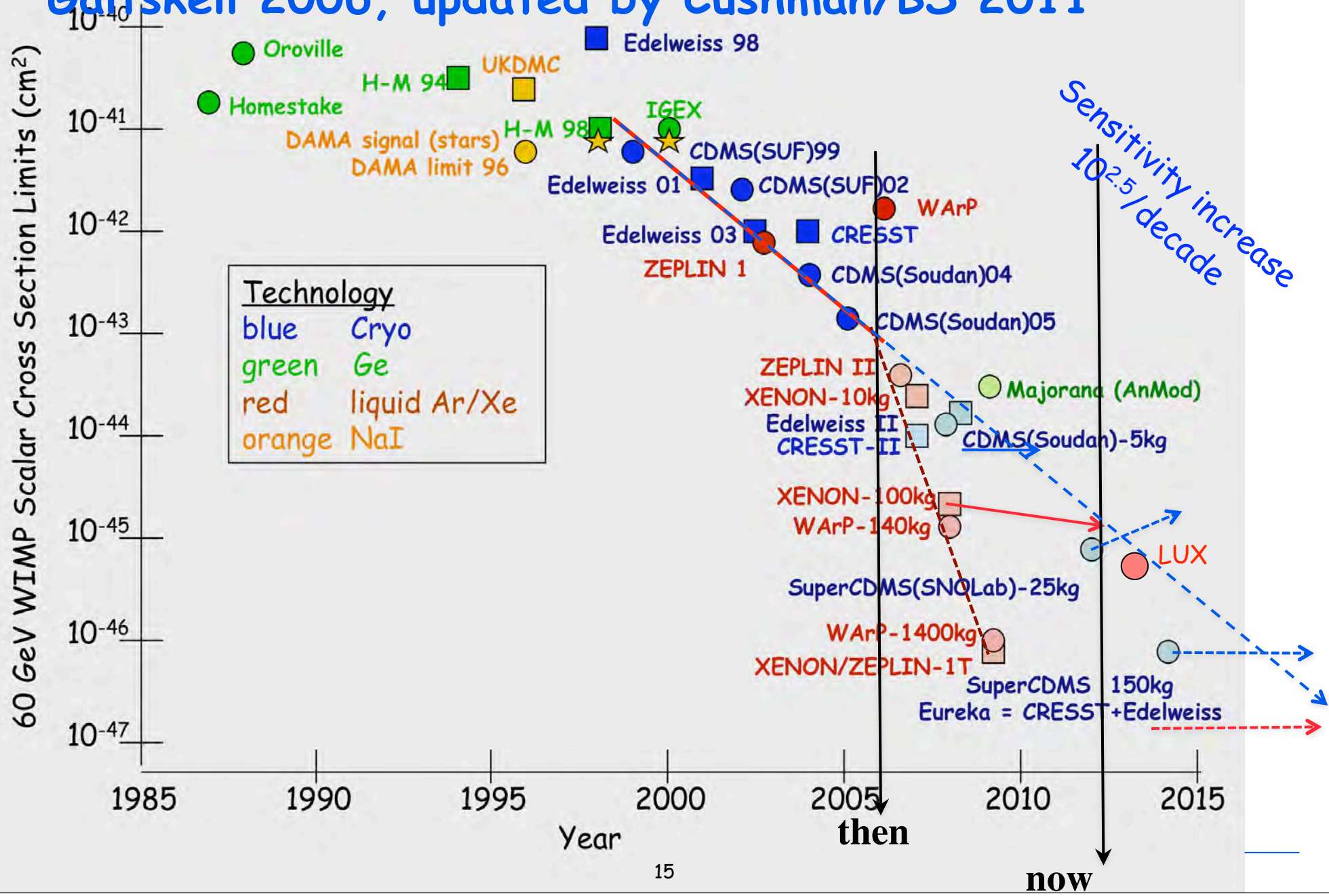
WIMP direct detection:

sensitivity at small energy : CDMS lite, low Tc TES

directional detectors

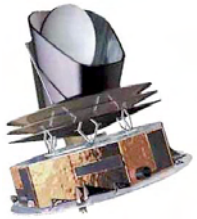
Hopes and Progress

Gaitskell 2006, updated by Cushman/BS 2011



4 Complementary Approaches

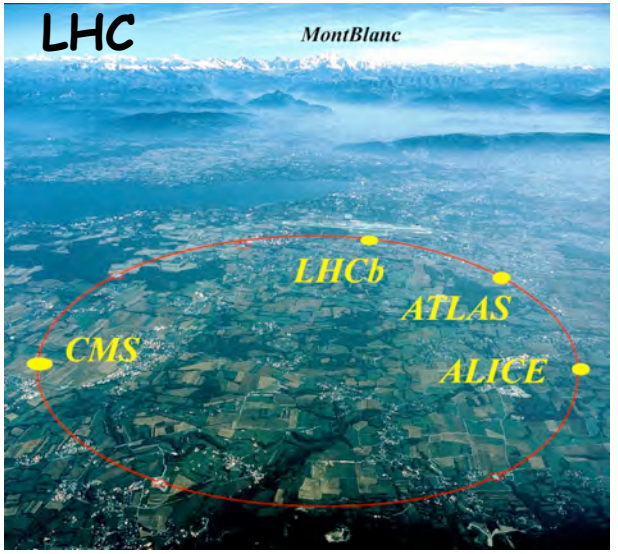
Cosmological Observations



Planck

Keck telescopes

Dark Matter
Galactic Halo (simulation)



WIMP production on Earth

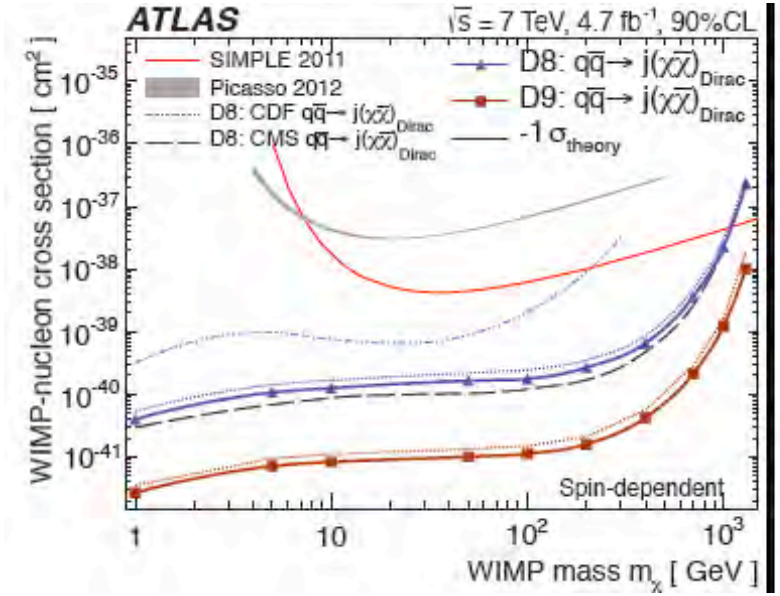
VERITAS, also HESS, Magic + IceCube (ν)

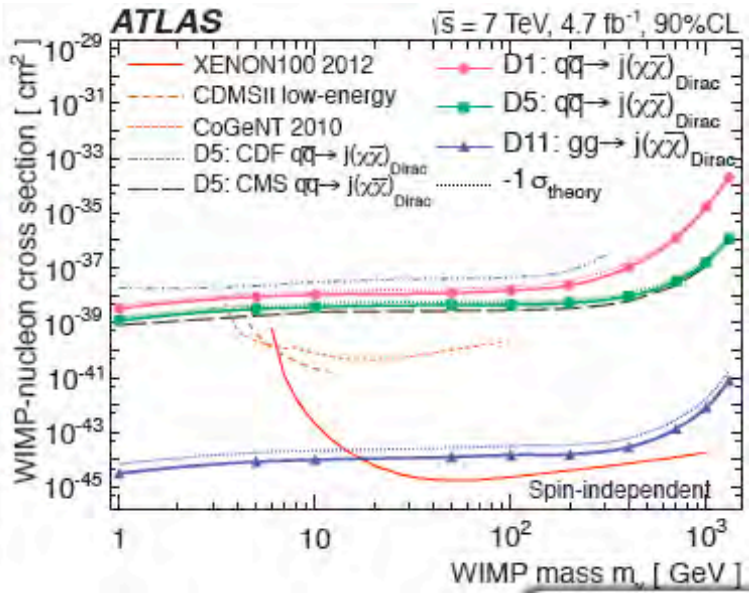
WIMP annihilation in the cosmos

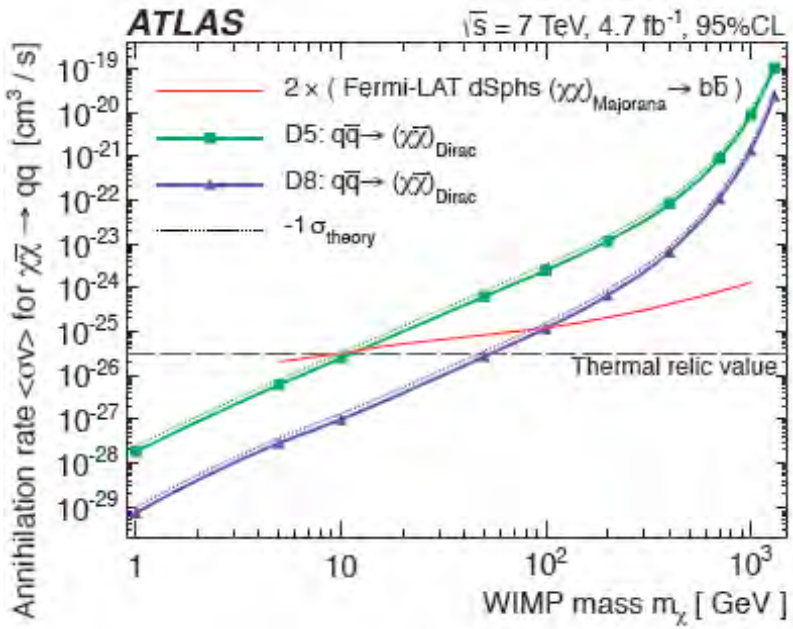
Fermi/GLAST

VIMP scattering on Earth:e.g. CDMS, Xenon 100,etc.

LHC<-> Direct and Indirect Detection



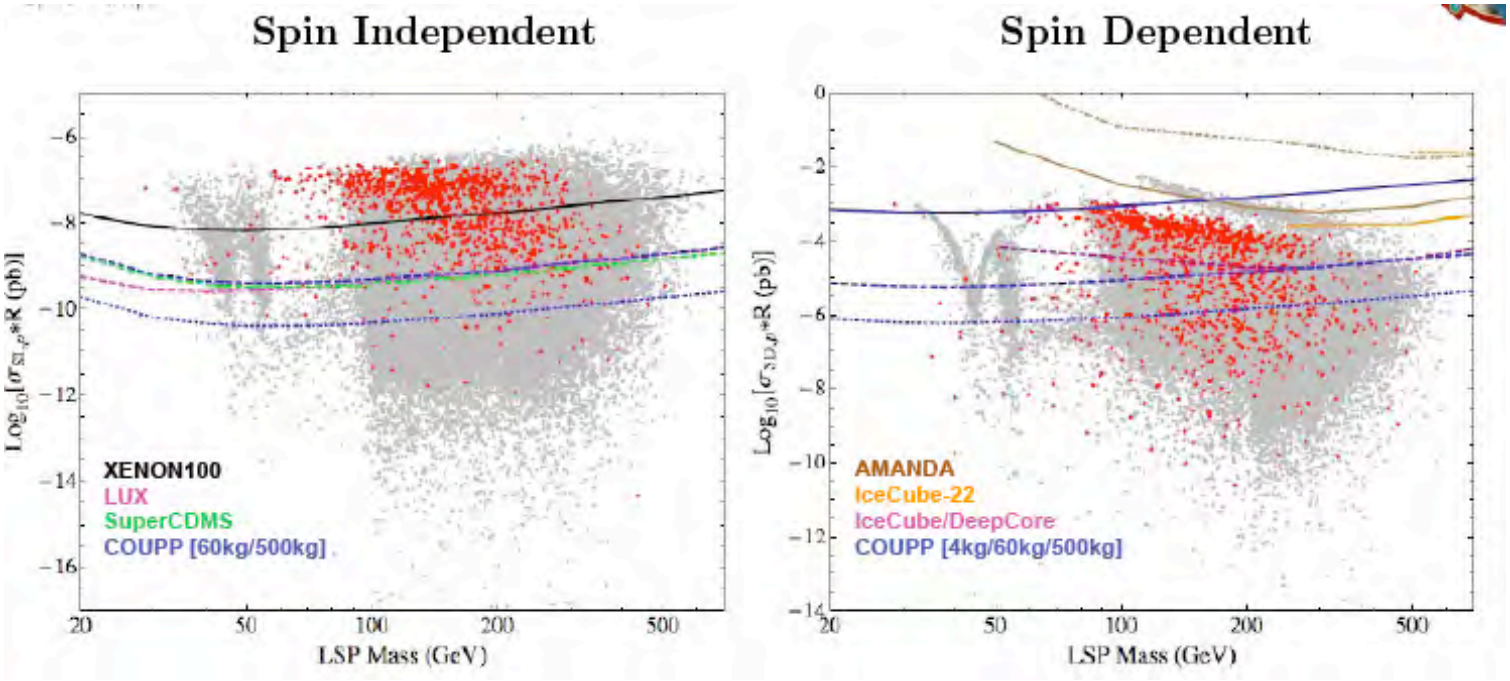




Monojets/Monophotons

Tim Tait et al, Paddy Fox et al:
Effective theory with various operators
But: Physical interpretation?
limits of formalism(e.g., E<<M)

Complementarity Direct-Indirect



pMSSM model scan (19-dimensional scan of the MSSM) shown in gray

red = models which the LAT may be sensitive to over a 10 year mission

Complementraity and cross checking

What will it take to convince ourselves and the scientific community that we have a signal?

High quality experiments

Statistical sensitivity: Blind. Number equivalent to "5 sigmas" ≈6 events for background of 0.4 events. Fold in uncertainty on background.

Clear separation from background, unique signature, demonstration of absence of outliers

At least two experiments

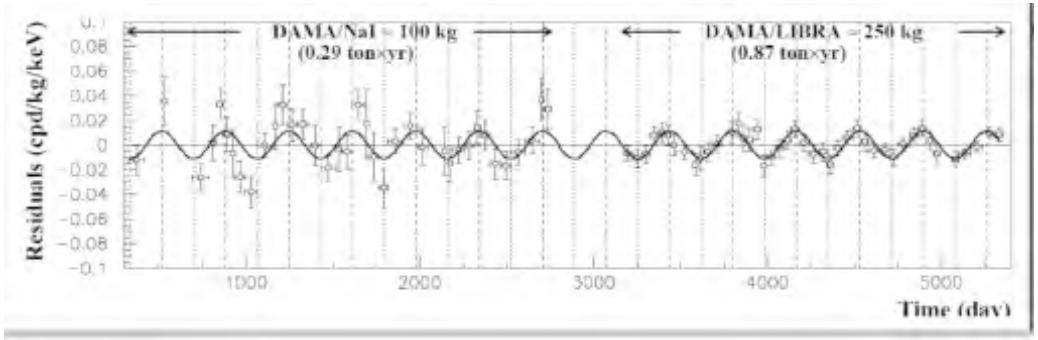
Each with blind analysis, high level of discrimination, understanding of backgrounds. Should be fully statistically compatible.

Better: very different technologies, different types of backgrounds

We need each other (even if we ask critical questions about each other)

Obviously cannot be of too dissimilar sensitivity (Gaitskell/Sadoulet)

DAMA



Clearly modulation

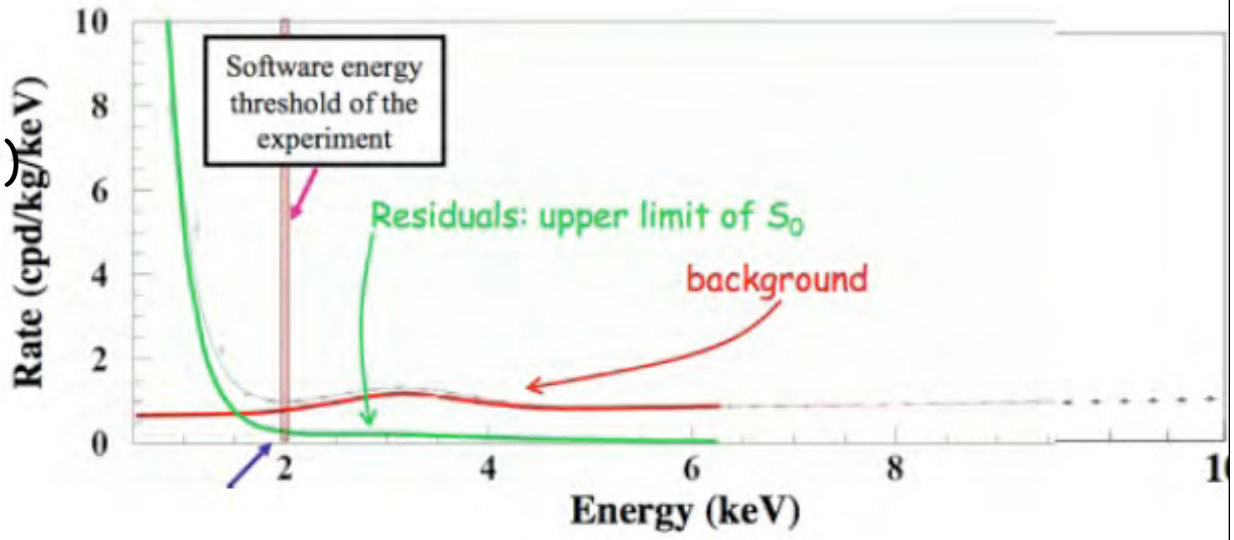
although not blind

Is it a signal?

incompatible with other experiments (New: KIMs)

Saturates single rate

=>Unphysically large modulation



If true important!

Can it be instrumental?

Unstability in threshold: modulation appears smaller in LIBRA than in DAMA?

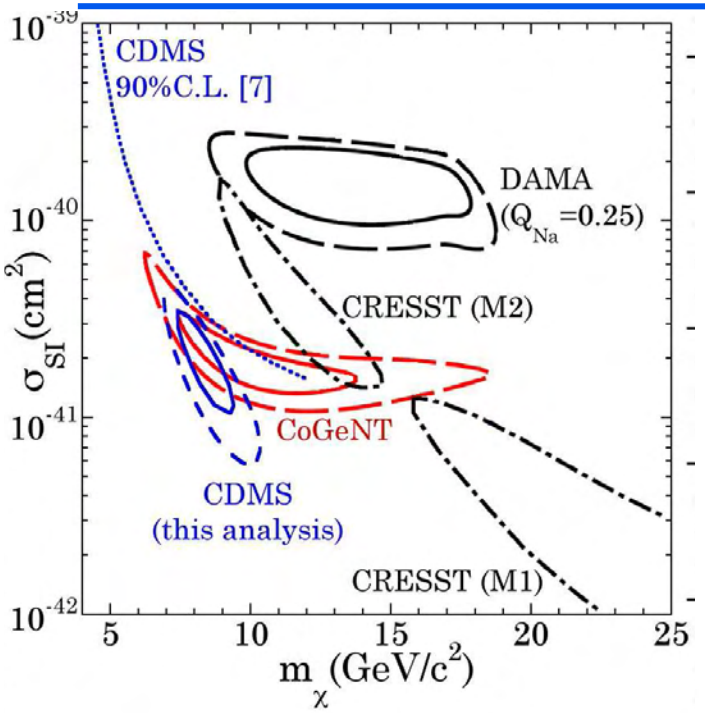
Delayed pulses from muons (not neutrons, but defects): problems single rate +phase

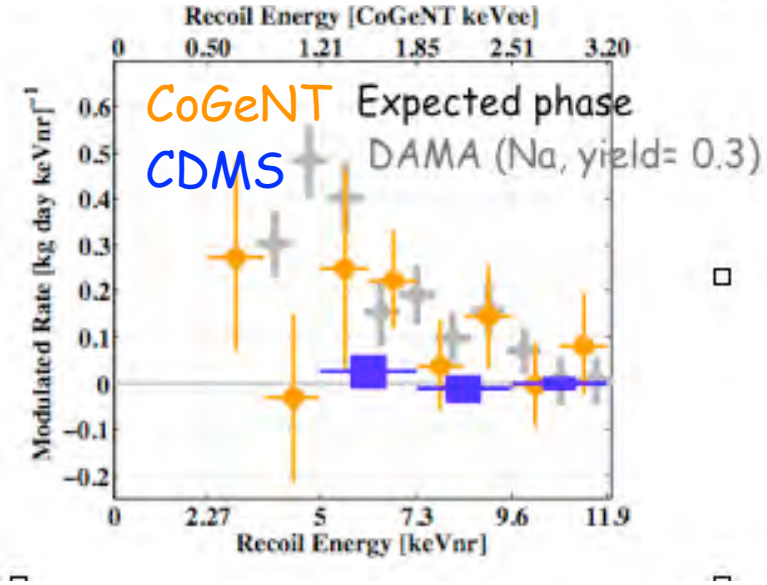
Awkward to the community: What to do?

Lower threshold: LIBRA has changed Phototubes to high QE + background model

Experiment by other groups: DM-Ice,ANAIS,KIMS, Princeton

Low WIMP Mass Region (DD)





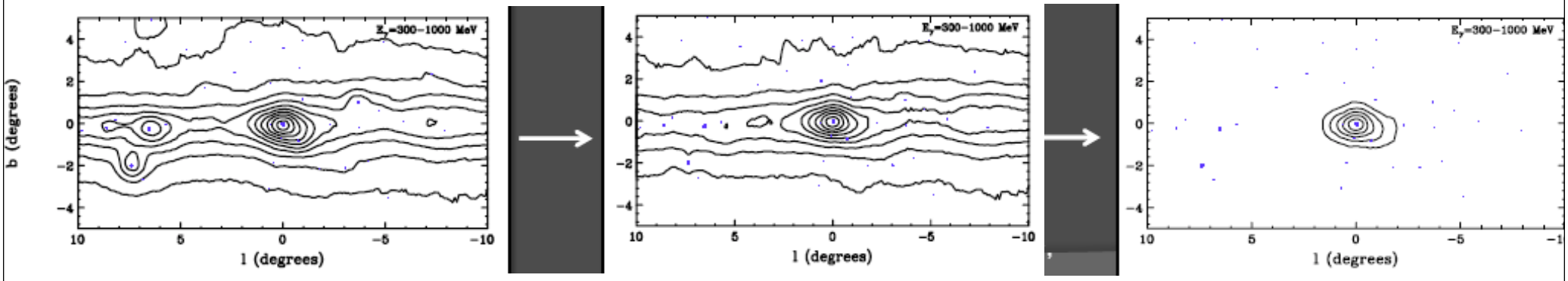
Trying to make sense of the various claims

- CoGeNT evolving (surface events): no more claim
- CRESST likely ^{206}Pb
- CDMS interpreted by Collar/Fields: similar effect in multiple

Very large modulations

- CDMS does not see modulation (but needs to go below)
- Statistical significance of CoGeNT marginar (2.8 sigma) => more statistics
- Control of systematics is essential

What about the Galactic Center?



2 independent analysis

Hooper,Linden

Abazadjian,Klapinghat

More or less agree on conclusions

Could be dark matter annihilation: spatial shape, cross section, spectrum

But could be Millisecond Pulsars

or Cosmic rays interaction

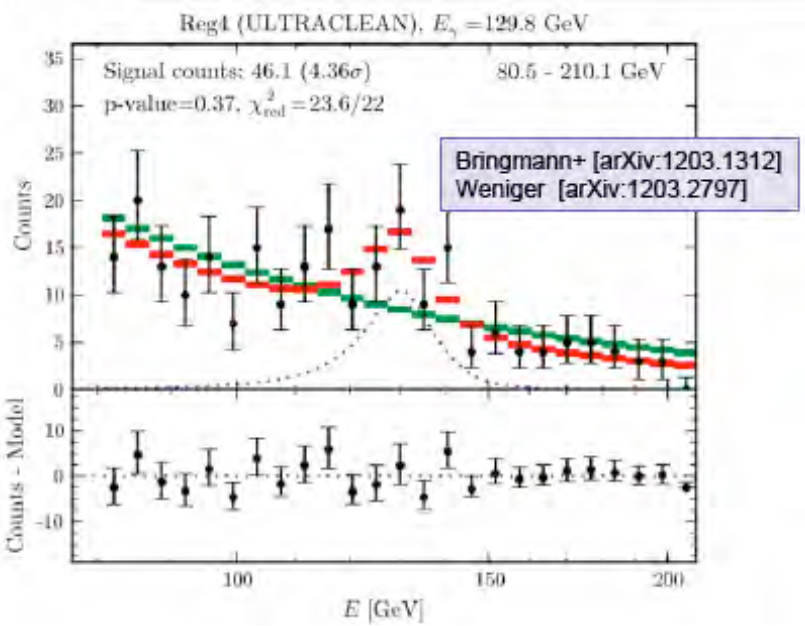
How will we ever know whether astrophysics or Particle Physics?

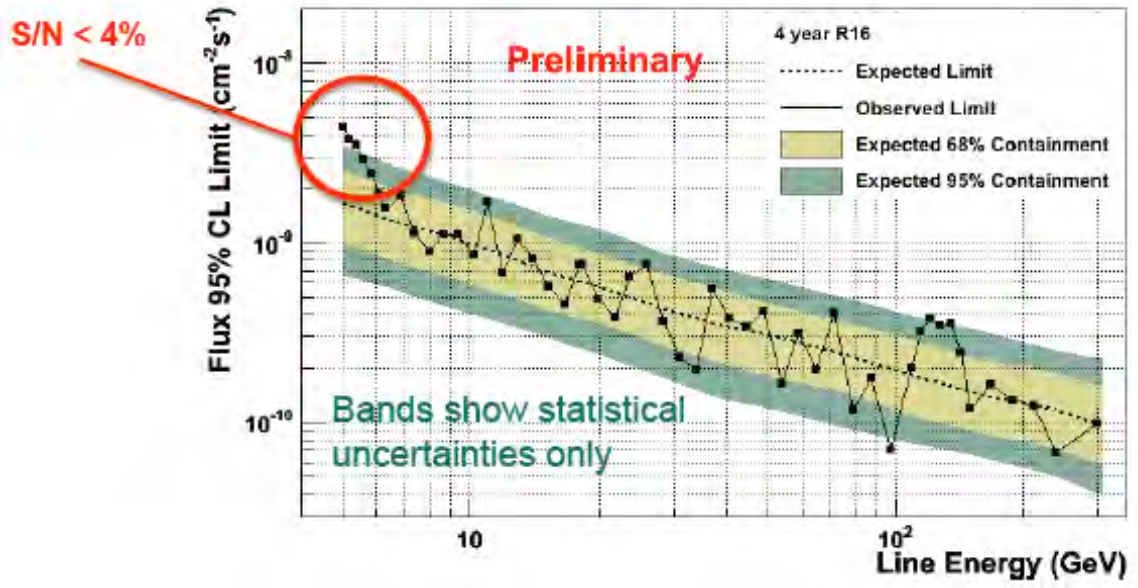
Better spectrum

Higher spatial resolution? Gamma 400? CTA?

Same type of remarks about TeV positron excess

Fermi 135 GeV Gamma Line





Very few events ≈15

+ Fundamental difficulty: how do we determine the number of trials

Can it be instrumental?

A priori smooth efficiency (MC) but

Use the limb as efficiency calibrator : 30 events; large error bars

"Signal" appears toward the limb and the sun (Daniel Whiteson)

Can it be due to change of reconstruction algorithm in this energy region?

What could it be if it is real?

Not ordinary WIMP (large cross section/absence of continuum)

Dark Sector with light mediator or more generally structure (Weiner et al.)

Decay of heavy right handed neutrino (Bergstrom)

Fermi 135 GeV Gamma Line

How will we make progress?

- More Fermi data (improve observational strategy?)
- Better understanding of detector response
- HESS II this spring: better angular resolution and effective area but worse energy resolution
  - Very different systematics

We should know soon!

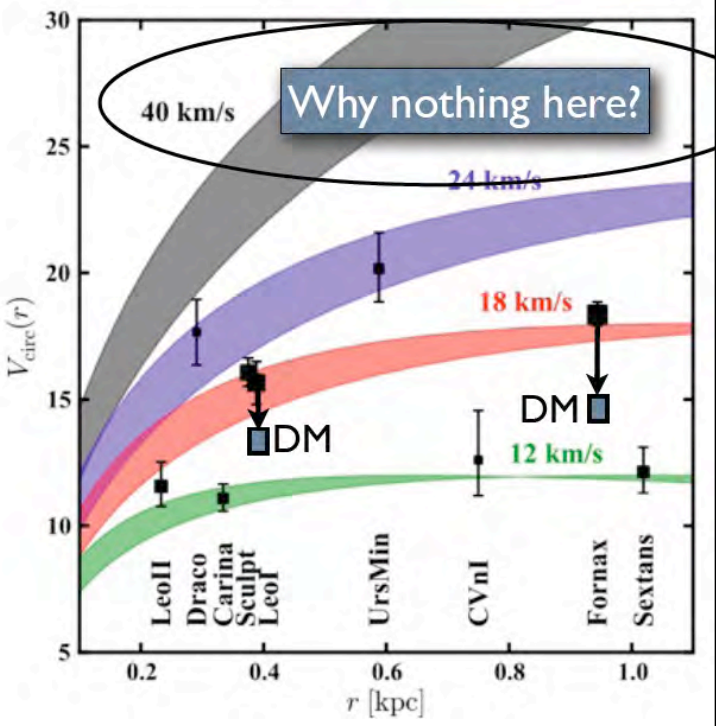
Dwarf Spheroidals

2 distinct but related problems

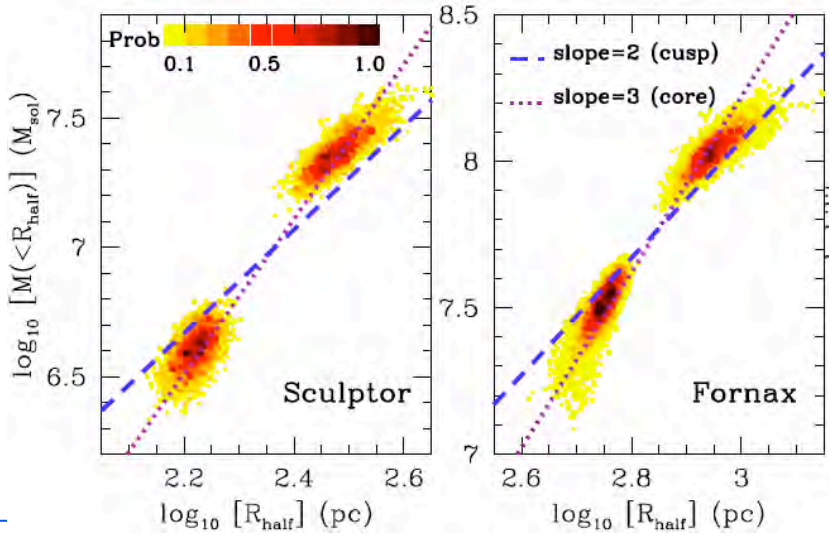
1) The number of satellites
but we keep discovering small ones

Not enough large mass satellites: Too big to fail

Frenk et al.
Bullock et al.



2) The density profile: NFW or core?
Basic degeneracy between velocity anisotropy and density profile
Walker and Penarrubia: break the degeneracy for Fornax and Sculptor with two populations of stars -> Core! (Matt Walker)



B.Sadoulet

Is this the end of Lambda CDM?

2 ways to fix it?

either astrophysics or particle physics

Astrophysics

Change Mass of the Milky Way: but other problems (M31, LMC,Leo proper motion)

Baryon ejection

In practice very difficult to eject enough (energetics with current stars) (F. Governato, Justin Read): need high feedback efficiency and several cycles

Relative velocity of dark matter and baryons?

Particle Physics

- Heavy (≈ keV) sterile neutrino: but suppress the small systems first!

Isn't the mass distribution still cuspy ? (difficult to simulate Justin Read)

- Strongly interacting dark matter:

$$\frac{\sigma}{m} \approx 0.1 \left(g / cm^2\right)^{-1} \approx 0.18 \text{ barns}/ \left(\text{GeV}/c^2\right) \qquad \text{(Bullock's group)}$$

introduces core without other consequences (OK with Bullet Cluster, triaxial halos)

"too big to fail" problem is alleviated indirectly:

Simulated systems are spread out and appear less massive within $R_{1/2}$

Easier disruption (need full simulation)

Important issue: Needed

More velocity+metallicity measurements (in progress)

Improvement of simulations (baryons, sterile neutrinos, Strongly InteractingDM)

Sterile neutrinos

Theoretically

Seesaw mechanism

Split SeeSaw 3 scales (Kusenko)

Leptogenesis -> baryon anti baryon asymmetry

Maybe evidence in lab

LSND and MiniBoone now compatible

Deficit of reactor neutrino

Deficit of source neutrinos

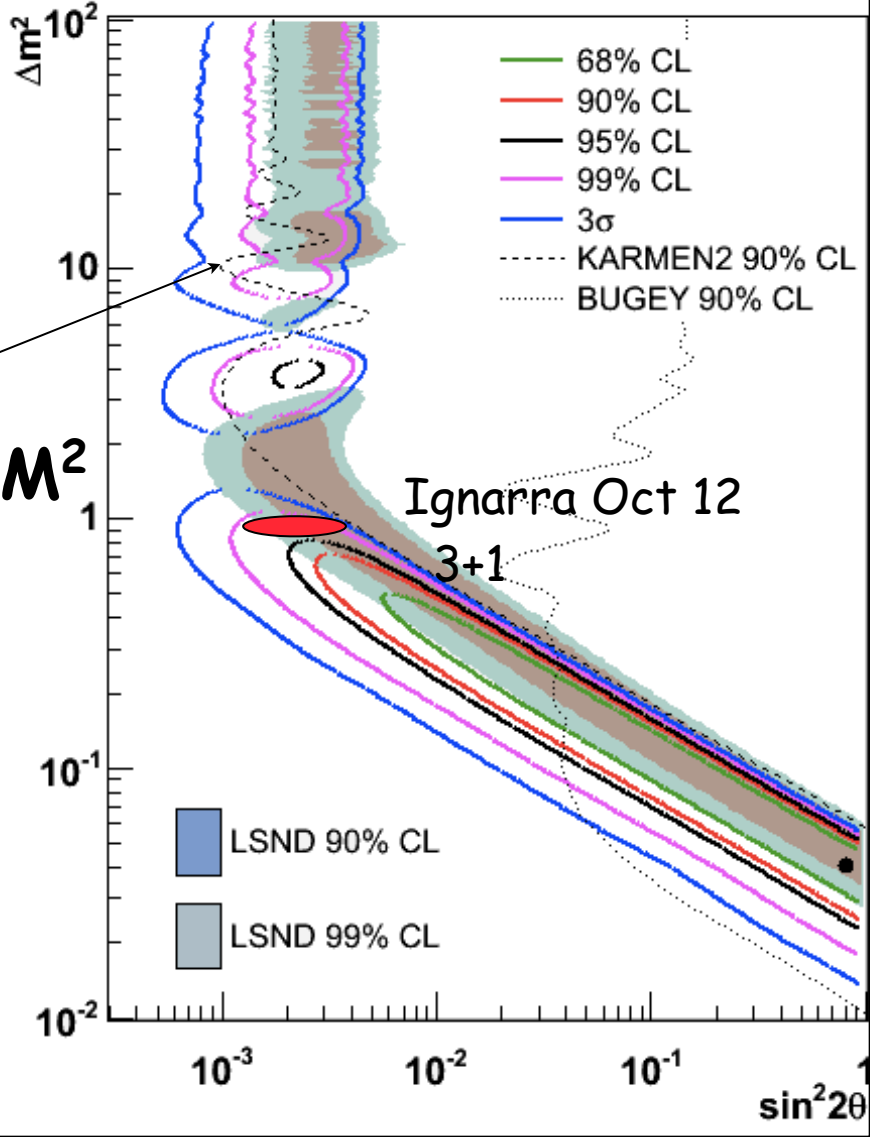
Note: Karmen excludes large DM^2

not keV neutrino! Best fit ≈ 1 eV

Not what we need for dwarfs!

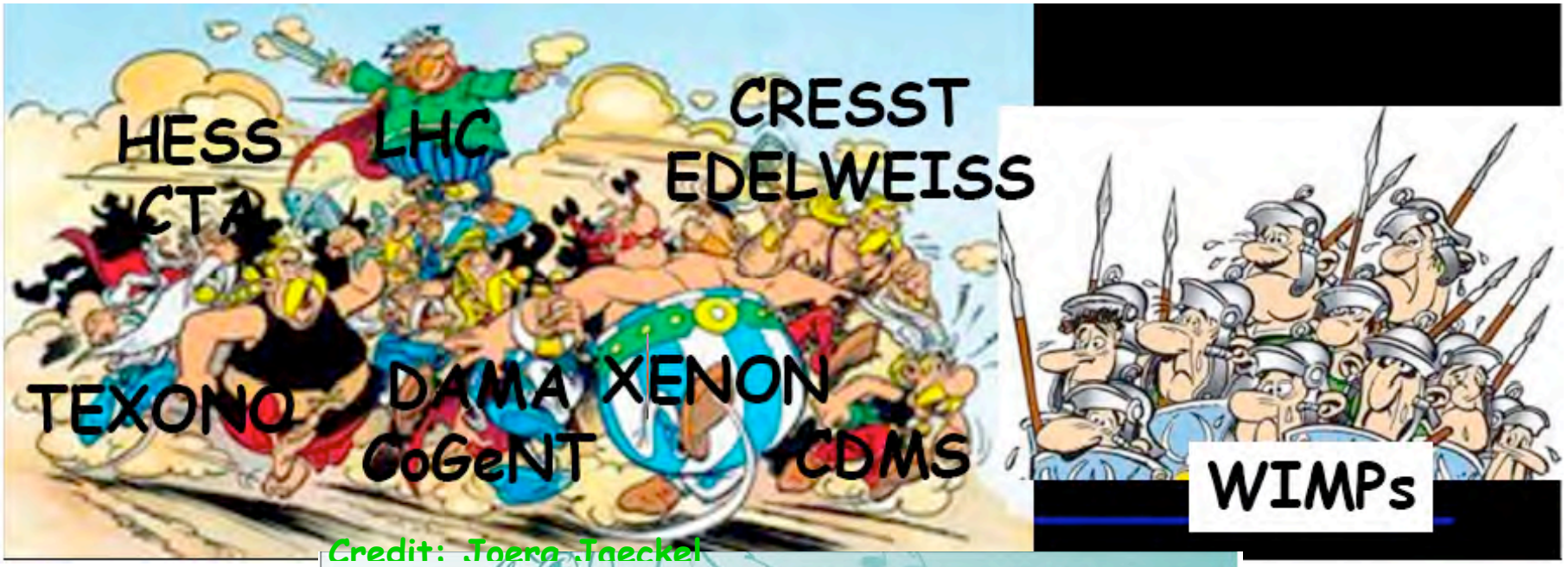
But may be explain N_{eff} (relativistic) from BBN

Would not show up in CMBR



Dark Matter: An Exciting Time!

Credit: Joerg Jaeckel



Credit: Joerg Jaeckel