Bernard Sadoulet
Dept. of Physics /LBNL UC Berkeley
UC Institute for Nuclear and Particle Astrophysics and Cosmology (INPAC)

Dark Matter: Experiment

The Nature of Dark Matter:

Current understanding: observations/theoretical ideas

Axions

Current situation
Future (in particular ADMX: part of US Generation 2 program)
Far future: Path finders

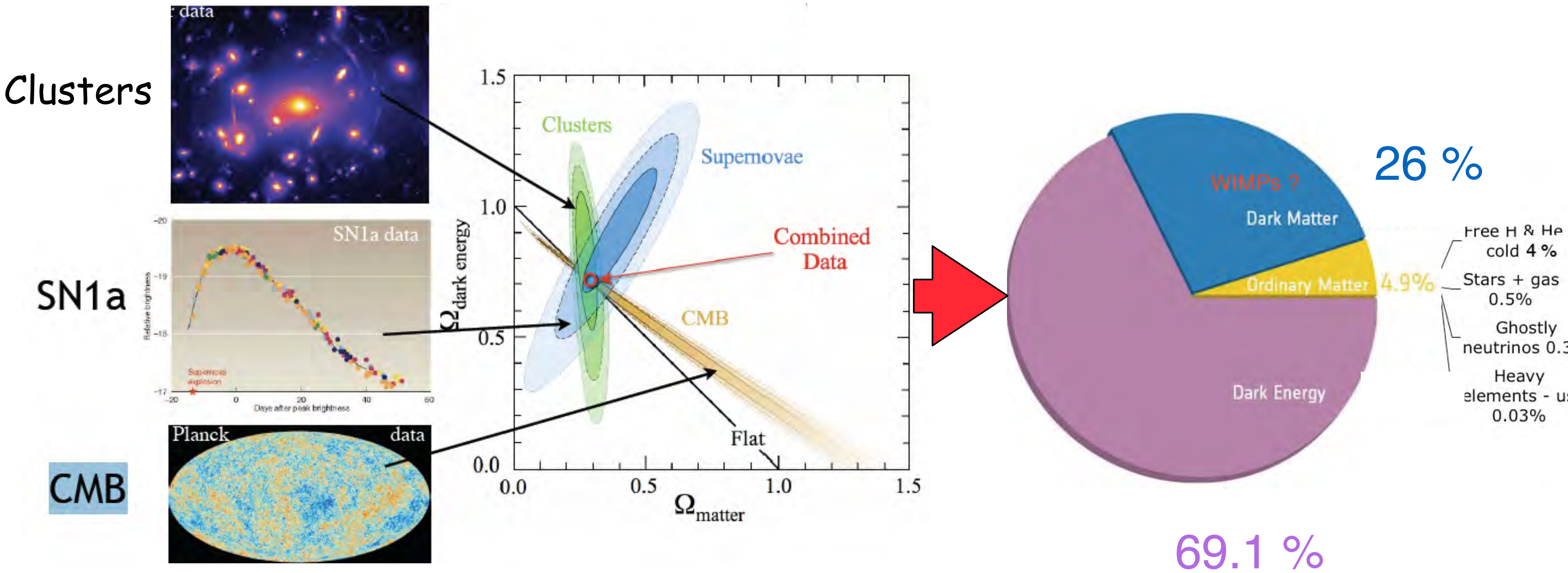
WIMP-like particles

Current situation: low and high mass
Immediate future (in particular Xe 1 ton + US Generation 2: LZ, CDMS)
Far future: R&D/Path finders

The Nature of Dark Matter

Current understanding: observations/paradigms

Dark Matter and its Nature



The nature of dark matter is a central problem of cosmology

≠ baryons

≠ light neutrinos

Is it made of particles produced in the early universe?

If yes: evidence for physics beyond standard model!

TeV scale or totally different origin?

Particle Physics:Favorite Possibilities

Axions <= Strong CP problem $10^{-6\ -3}$ eV

Peccei Quinn solution: dynamic restoration of CP

Weak scale WIMPs <= hierarchy problem 10^{11-12} eV

Freeze out when annihilation rate ≈ expansion rate

$$\Rightarrow \Omega_x h^2 = \frac{3\cdot 10^{-27}\, cm^3/s}{\langle \sigma_A v \rangle} \Rightarrow \sigma_A \approx \frac{\alpha^2}{M_{EW}^2} \equiv \text{Weak scale}$$

coincidence between Cosmology and Particle Physics

Dark Matter Hidden Sector: not necessarily weak scale

e.g., Asymmetric Dark Matter (Zurek) <-> Baryon-Antibaryon asymmetry

$$\frac{\rho_{\text{dark matter}}}{\rho_{\text{baryon}}} \approx 6 \Rightarrow M_{\text{dark matter}} \approx 6\ \text{GeV}/c^2$$

Dark Photon, atomic DM, Self Interacting

Intriguing but less predictive 10^{6-13} eV

Sterile neutrino in keV range ≈10^3 eV

with very small mixing angle (≠1 eV)

Recent inputs from Cosmology

Remarkable success of Lambda CDM

Cosmic Microwave Background
Large scale structure

Potential Problems at small scale

Observe Core instead of NFW cusp
Do not observe enough large satellites which should "too big to fail"
But: gravitational lensing and tidal streams (Carlsberg) may indicate lot of structure at small scale

Debate on whether this is "gastrophysics" or fundamental

Poor understanding/simulation of gas and feedback mechanisms
or new dark matter physics

Warm Dark Matter: few keV sterile neutrino with tiny mixing angles

Some excitement about an 3.5 keV X ray line (but ≤3σ) => 7keV sterile neutrino
seen in Andromeda, Perseus Cluster, co-added clusters
Balbul et al. arcXiv: 1402.2031 Boyarski et al. arXiv:1402.4119
but not in co-added dwarfs.
Could be it an atomic Xray line ? Should be clear with Astro-H!
Would probably have the same problem as CDM with cusp

Self Interactive Dark Matter:

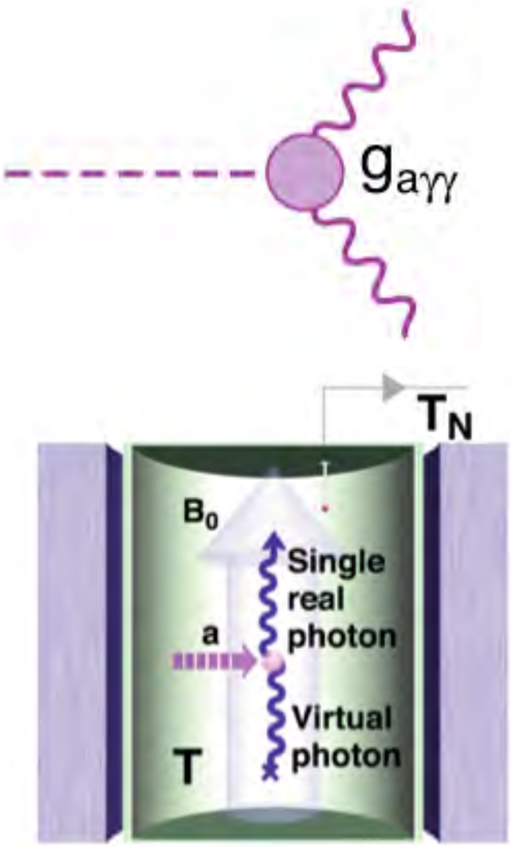
Could smooth the Dark Matter center distribution and indirectly solve "too big to fail"
barn/GeV/c^2 ≈OK with Bullet Cluster / Clusters anisotropy James Bullock and co.
Would clearly be a sign for a "Dark Sector"

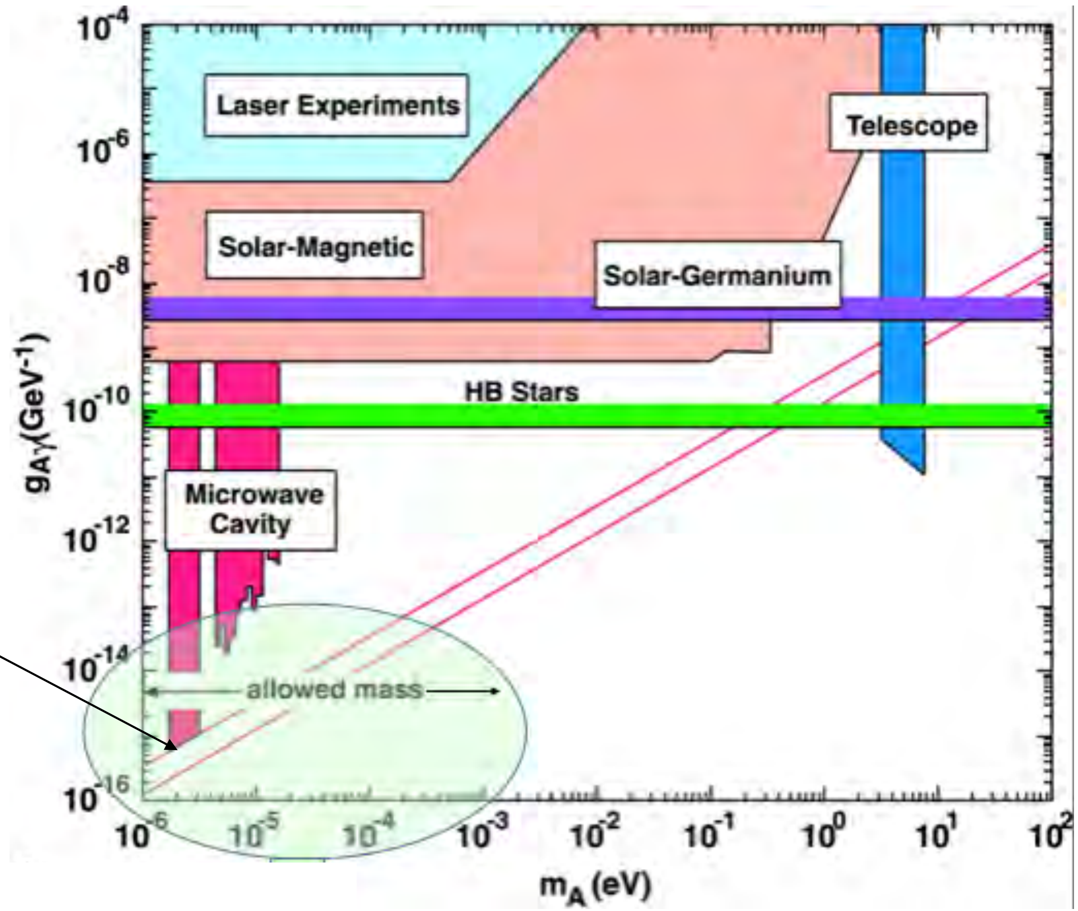
Axions

Axions <= Strong CP problem 10 $^{6\ -3}$ eV

see also F. Avignone's talk

Particle Detection Axions



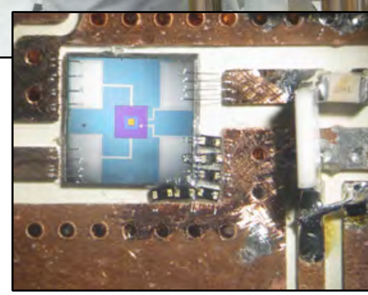


No detection so far but at the Cosmological limit

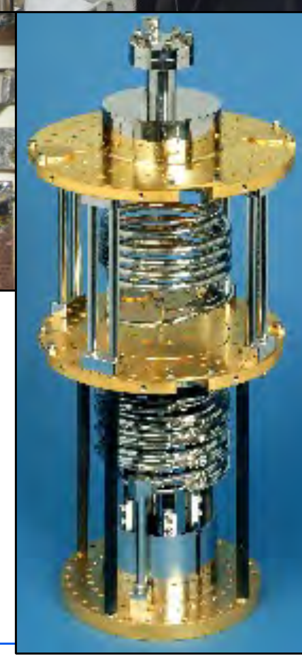
Gen 2 ADMX: Principle of Operation

ADMX is sensitive to sub-yoctowatts of microwave power

New ADMX experiment insert fabricated and being assembled



Dilution refrigerator and quantum-limited amplifiers provide sensitivity for the ADMX "Definitive Search"



Time scale

2016-2019

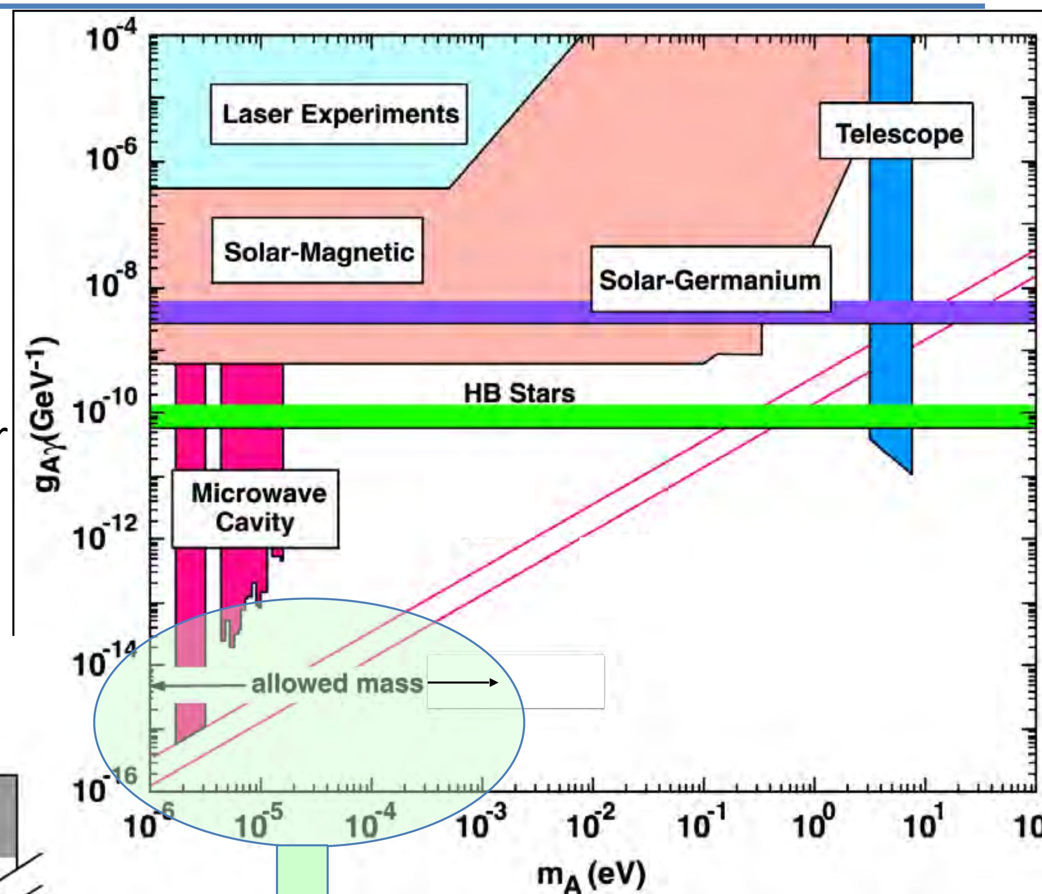
500MHz-10GHz

While one frequency band is searched, resonators for next frequency band are constructed

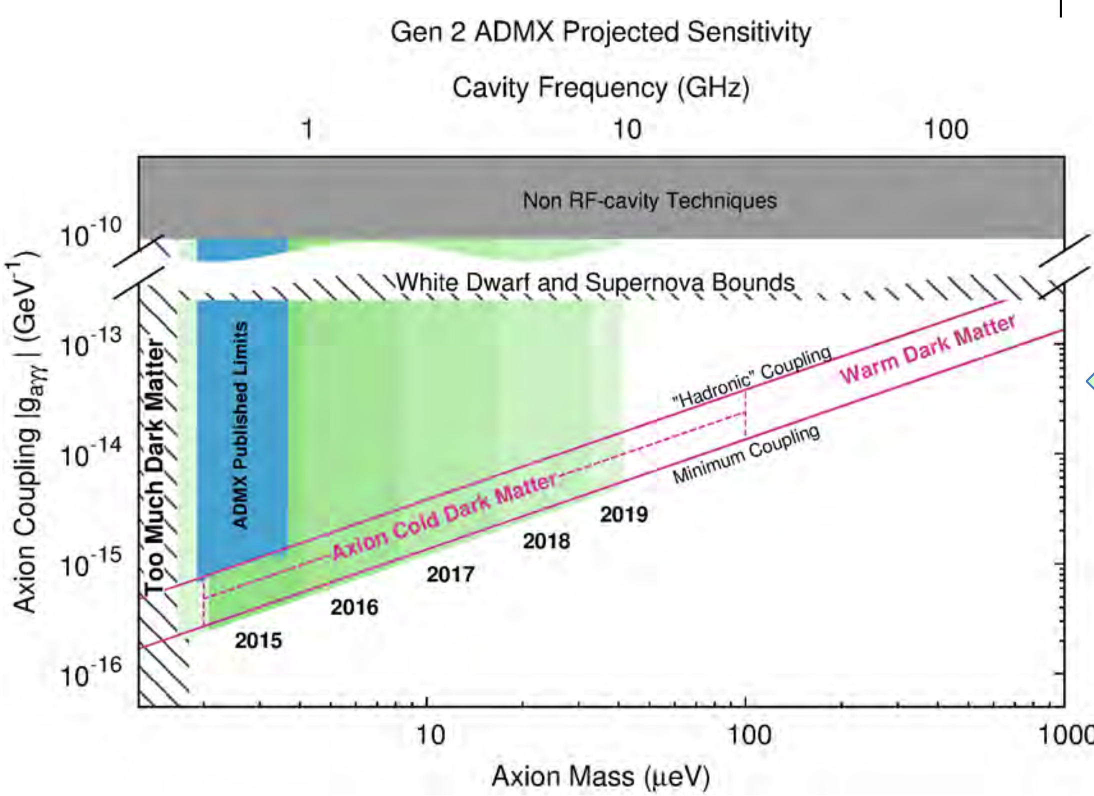
≈ $5M (DOE)

Gen 2 ADMX: Search Capability

U. Washington, LLNL, U. Florida, U.C. Berkeley, National Radio Astronomy Observatory, Sheffield U., Yale U., U. of Colorado
(+ new collaborators soon)



The dilution refrigerator in ADMX significantly speeds the dark-matter search, so that …



… ADMX has the sensitivity to either detect the dark-matter QCD axion or reject the hypothesis at high confidence. This is called the “Definitive Search”.

Axion Dark Matter eXperiment – High Frequency (ADMX-HF)

Yale – Berkeley – Colorado – LLNL

- ADMX-HF serves both as a
  - *Pathfinder Search* – First look at higher frequencies (5-25 GHz)
  - *Innovation Testbed* – R&D new cavity & amplifier technologies
- Funded by NSF & DOE ECRP; operates under MOU w. ADMX
- Technologies: NbTi magnet (9.4T), Josephson Parametric Amplifiers (≈ 1.5 × Standard Quantum Limit), Dilution refrigerator

Three-year goal – baseline exp't:
Cover 15 - 33 μeV @ ≈ 1.5 × KSVZ

Masses to 100 μeV, and coupling down to ≈ DFSZ with successful R&D program

WIMP-like particles

Weak scale WIMPs 100GeV-1TeV <= hierarchy problem

Dark Matter Hidden Sector: ≈ few GeV if asymmetric

wide mass region

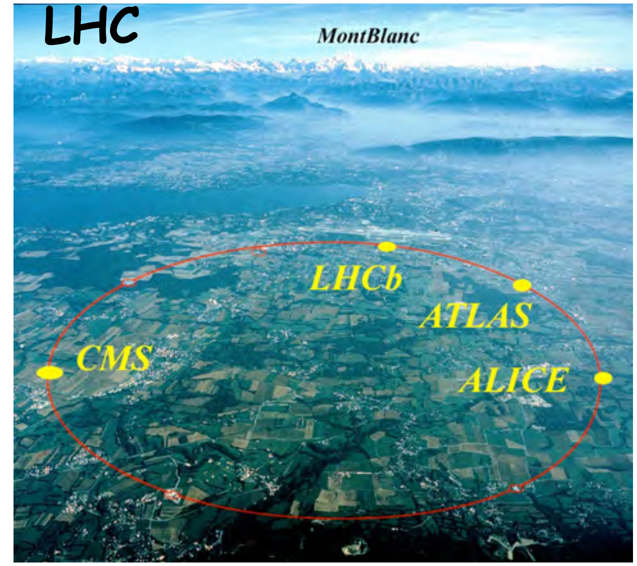
4 Complementary Approaches

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

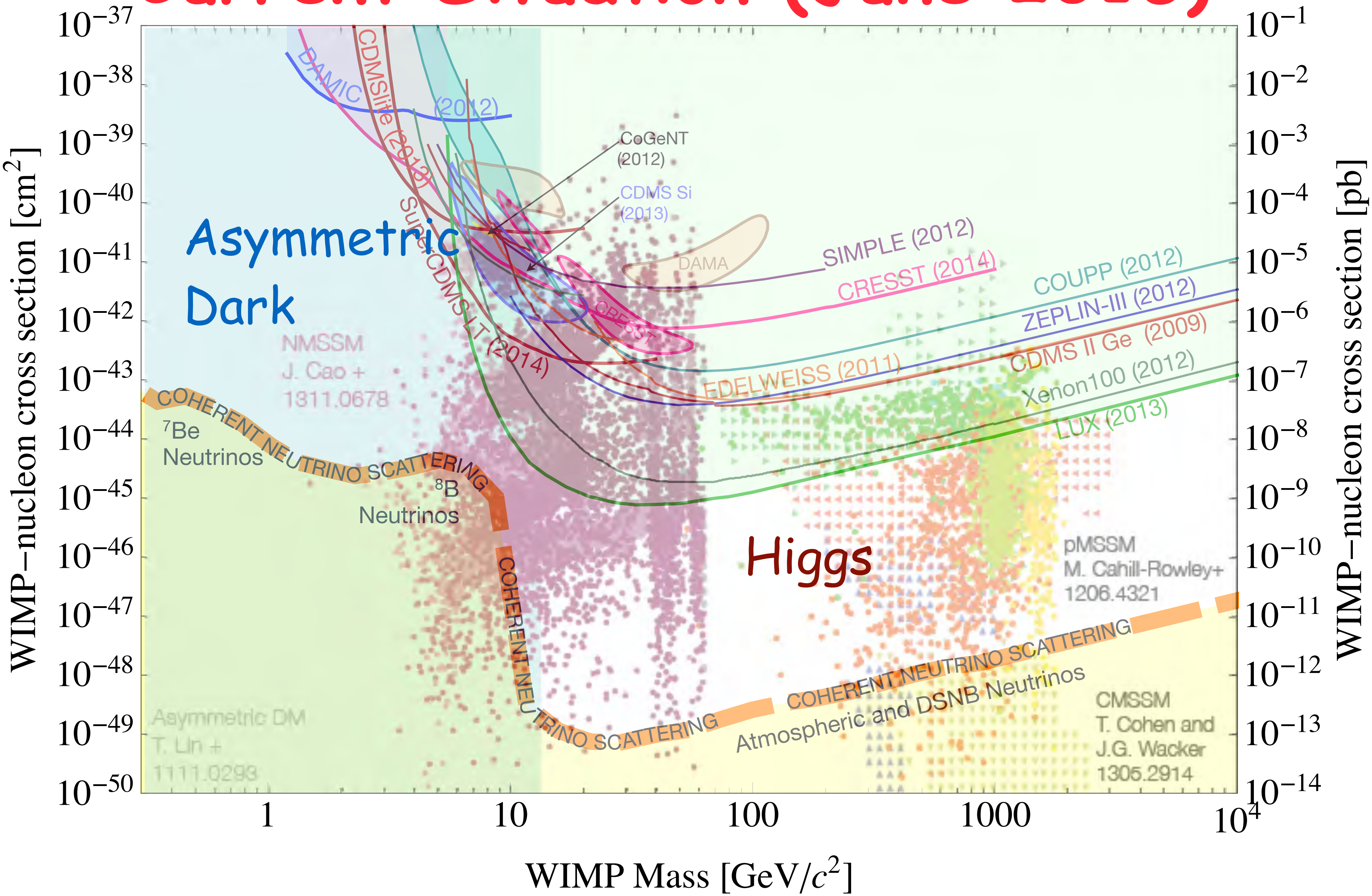
Fermi/GLAST

CDMS

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

Direct Detection

Current Situation (June 2015)



WIMP-like particles

Situation in low mass range (few GeV/c^2)

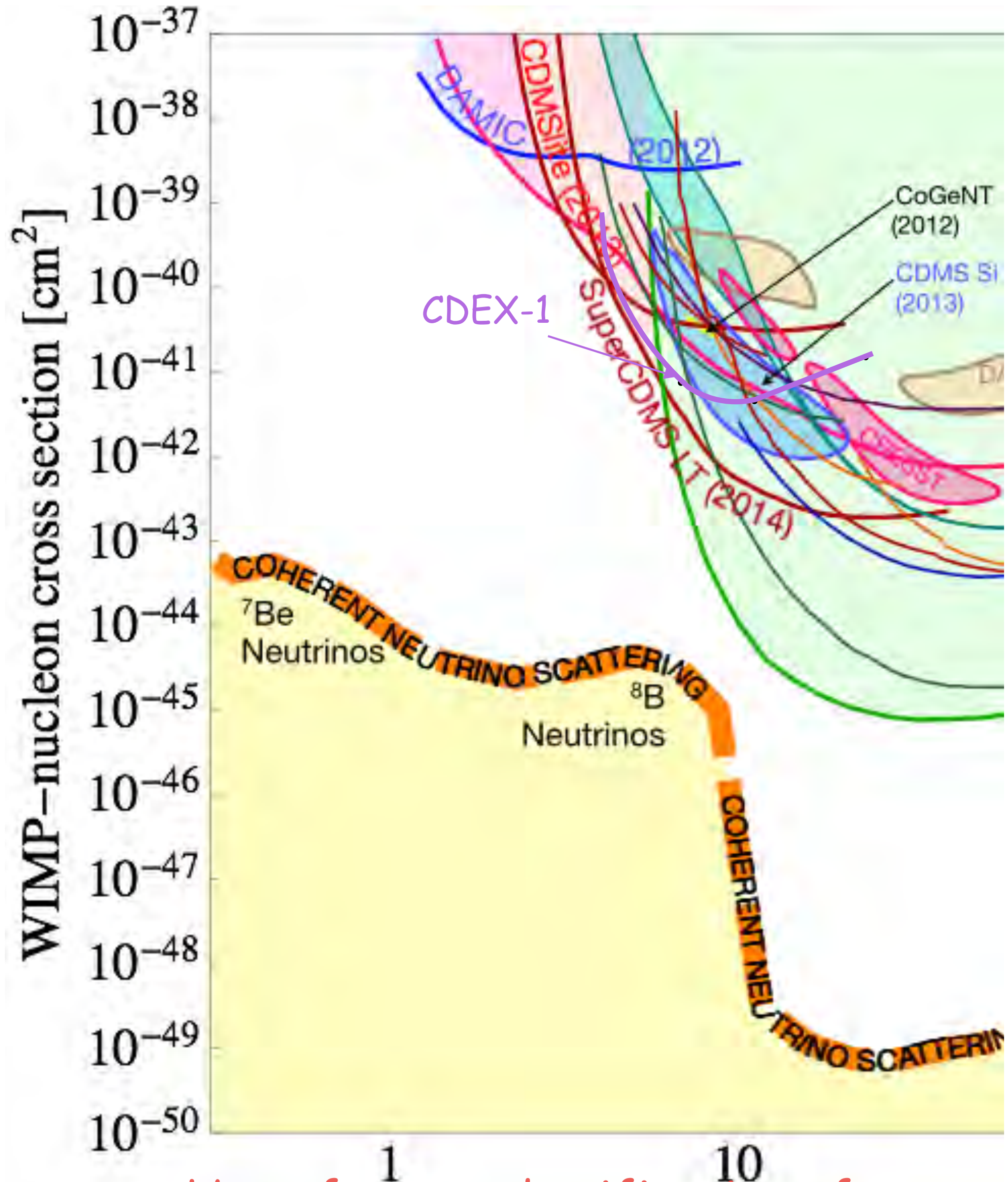
Low Mass Region

Optimistic

- Accumulation of claims in that region
- The exclusion by some experiments is based on unreliable calibration
- Just the region expected for asymmetric dark matter

Pessimistic

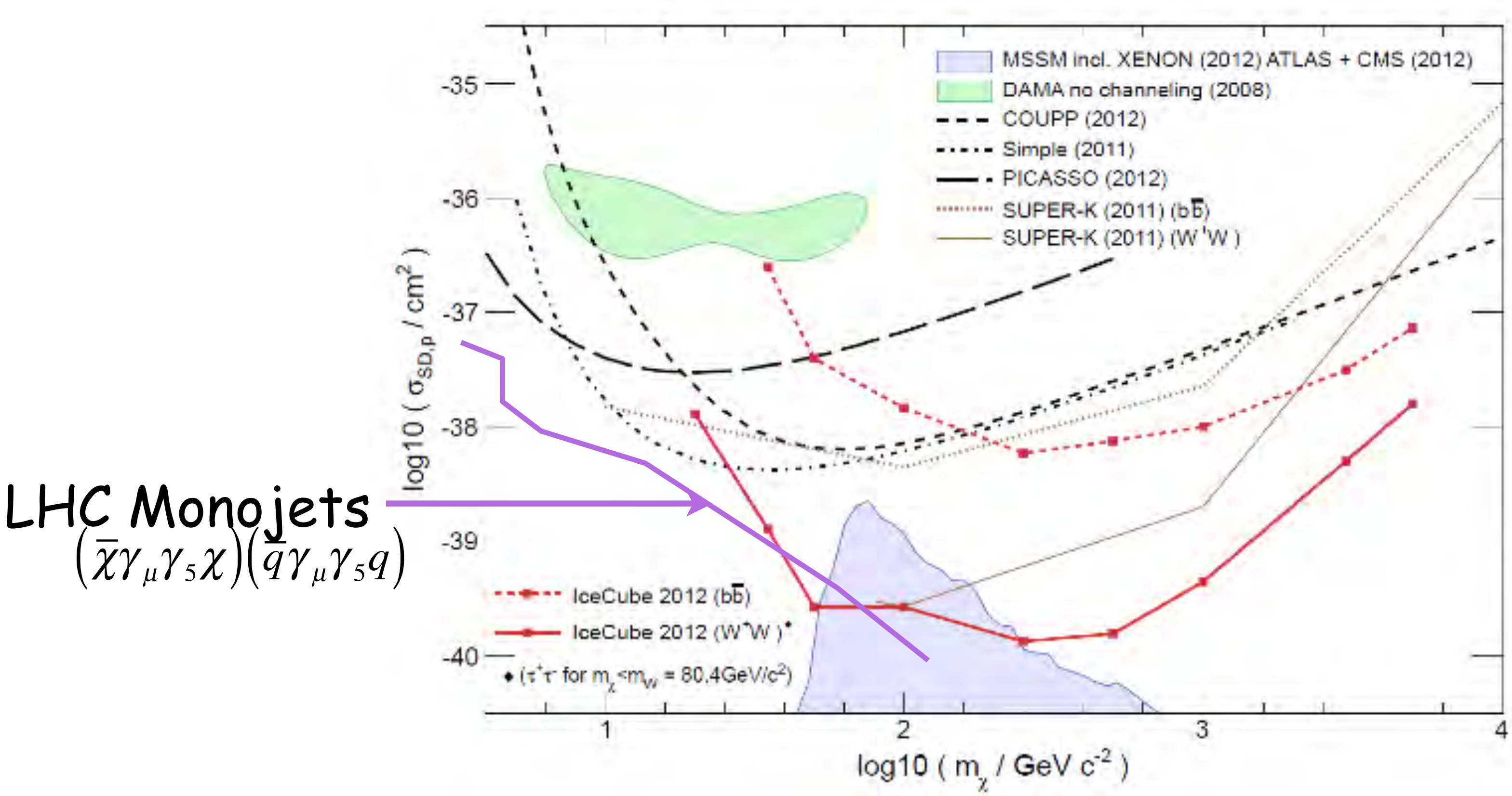
- Not compelling evidence
- Close to threshold: Outliers ?
- Excluded by
  - XENON100
  - LUX
  - SuperCDMS Soudan



Hope for grand unification of claims was clearly premature!

Spin dependent limits (e.g. p)

Finally entering SUSY region



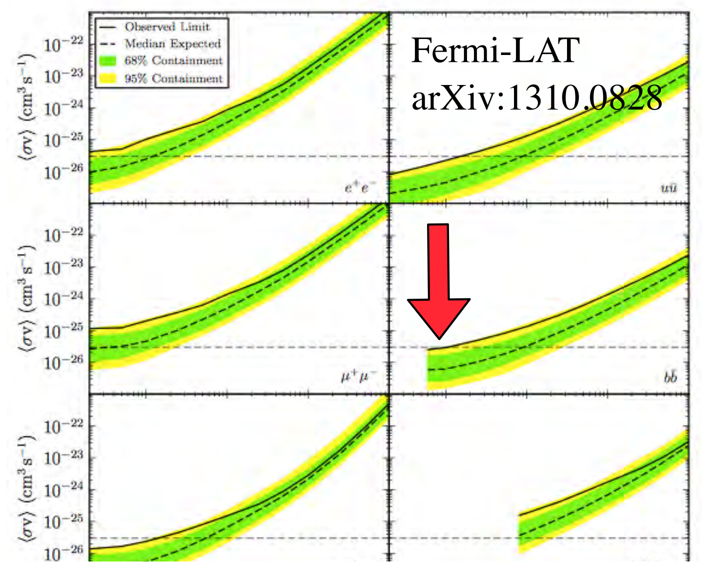
$(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma_\mu\gamma_5 q)$

Indirect Detection

No significant evidence from dwarf galaxies

although limit at small masses higher than expected sensitivity in all channels arXiv:1310.0828

see also arXiv:1503.02641

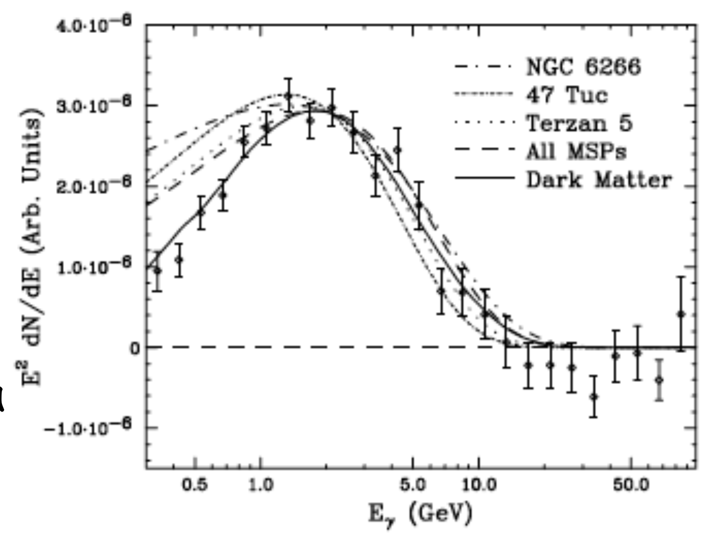


10-30 GeV/c^2 towards Galactic Center?

arXiv: 1402.6703 Standard question:

Is it dark matter or standard astrophysics: millisecond pulsar

also tension with most recent Fermi data



also 135 GeV/c^2 line:

would need strange couplings: no continuum, large $\gamma\gamma$ cross section

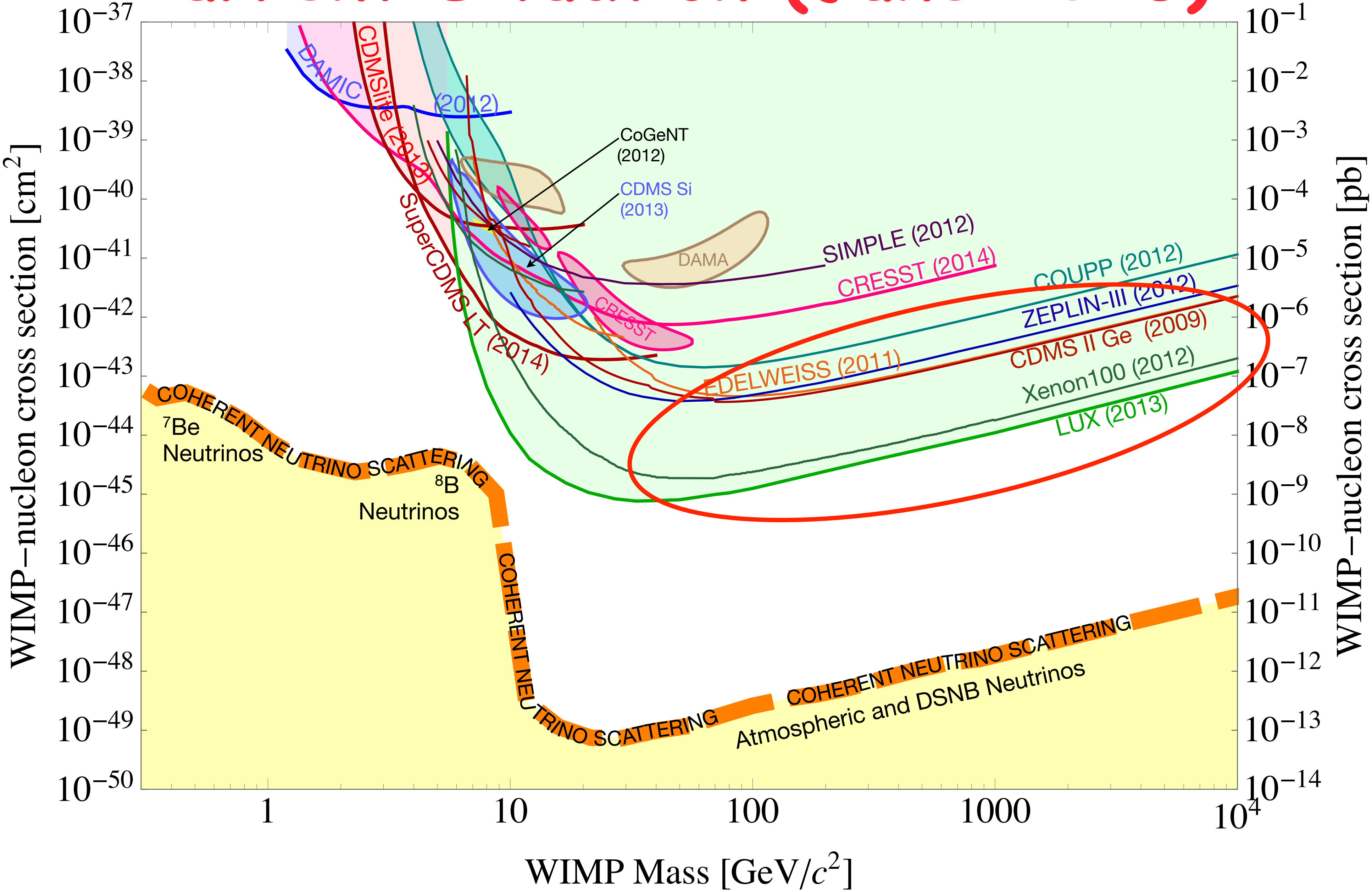
statistical significance decreasing?

WIMP-like particles

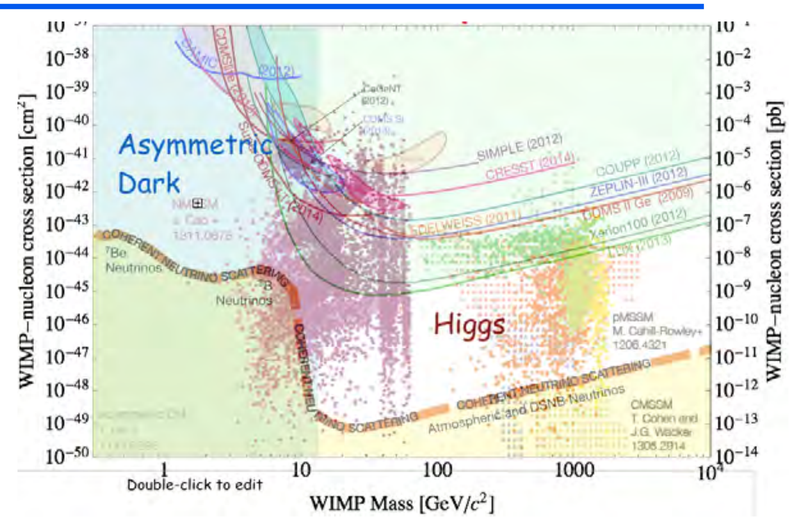
Situation at high mass range (few GeV/c^2)

Direct Detection

Current Situation (June 2015)



Recent Input from Particle Physics



Higgs at 126 GeV/c

No sign for supersymmetry

CMSSM too simple ->pMSSM,NSSM
Crisis of naturalness?

No evidence from mono-jets,mono-γ's

Note: Limits only apply with high mass mediator
Dark Sector models have typically low mass mediators
Complementarity with "Dark Photon" searches

Basic complementarity

LHC probes well:
- monojets if high mass mediated
- masses below $m_H/2$: produced in Higgs
- intermediate mass in decay of gluinos (≈6x LSP), but needs to produce it!

Direct Detection do not mind light mediators and only looses linearly at high mass

WIMP-like particles

Future

Current Situation 2015

Some closed contours: discovery?

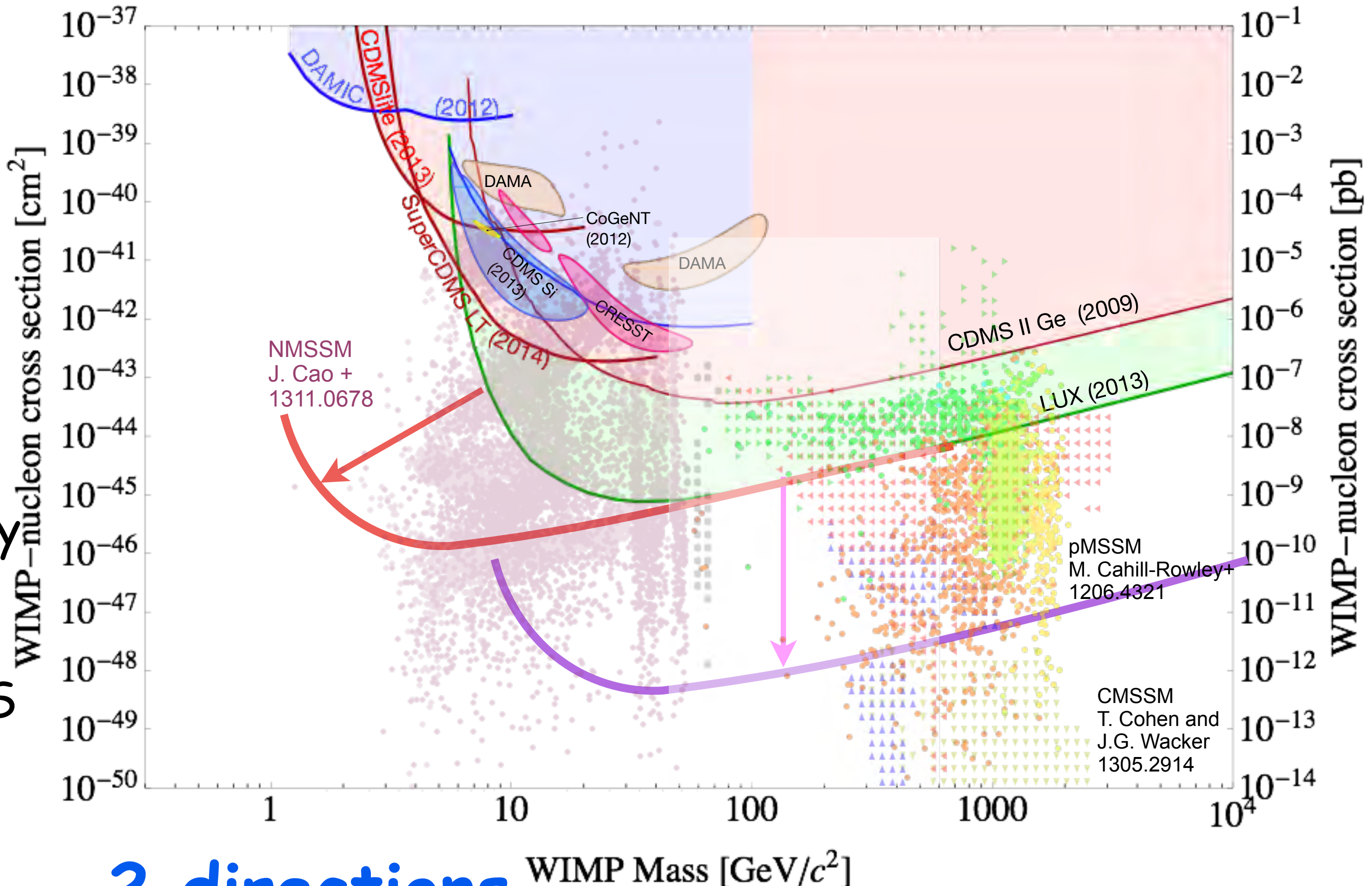
More likely misunderstood backgrounds

No discovery at LHC

Mass of supersymmetry pushed to higher energy: Unnatural?

or more complex NMSS

or dark sector



2 directions

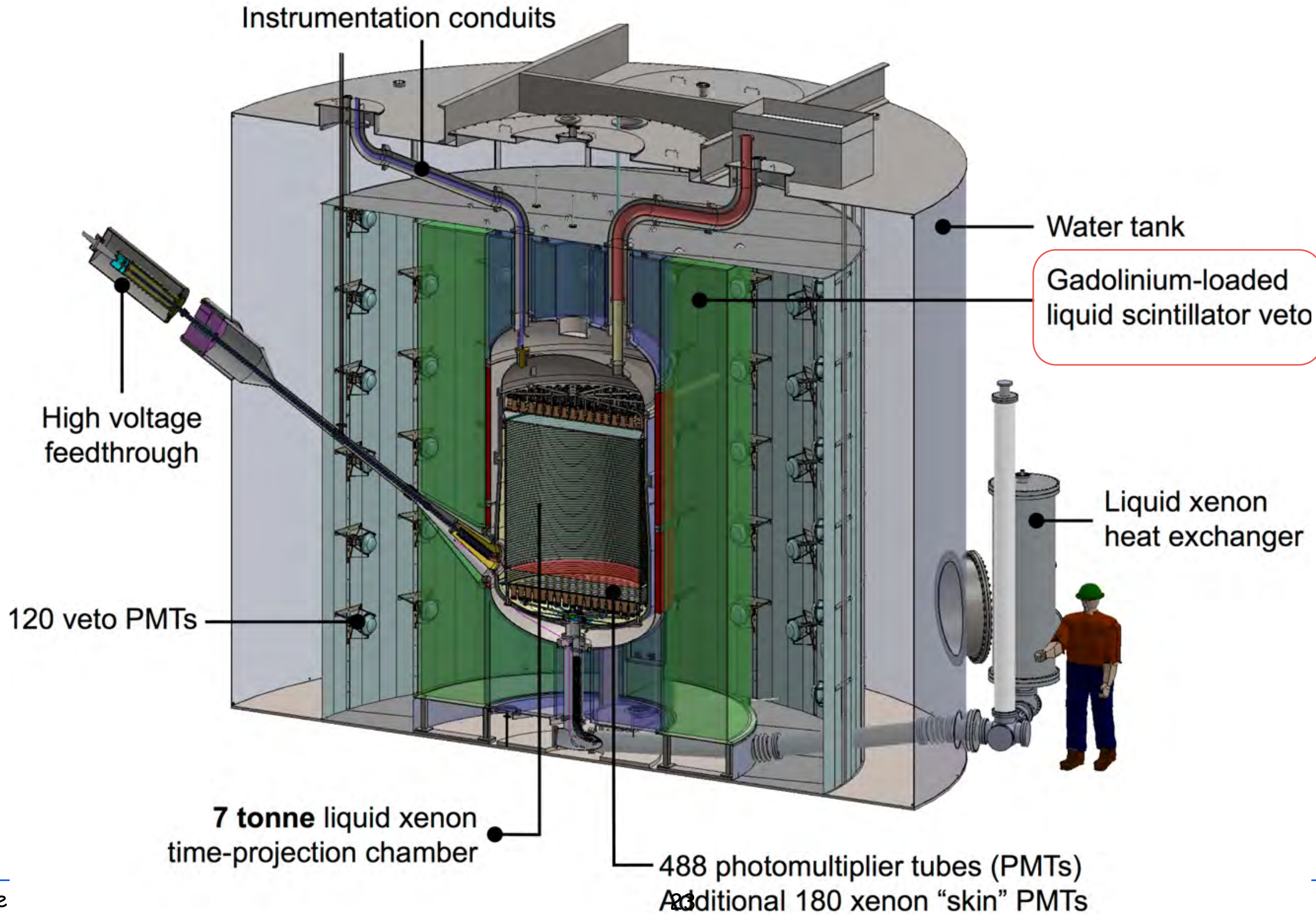
1. Improve sensitivity at large mass

2. Improve sensitivity at small mass

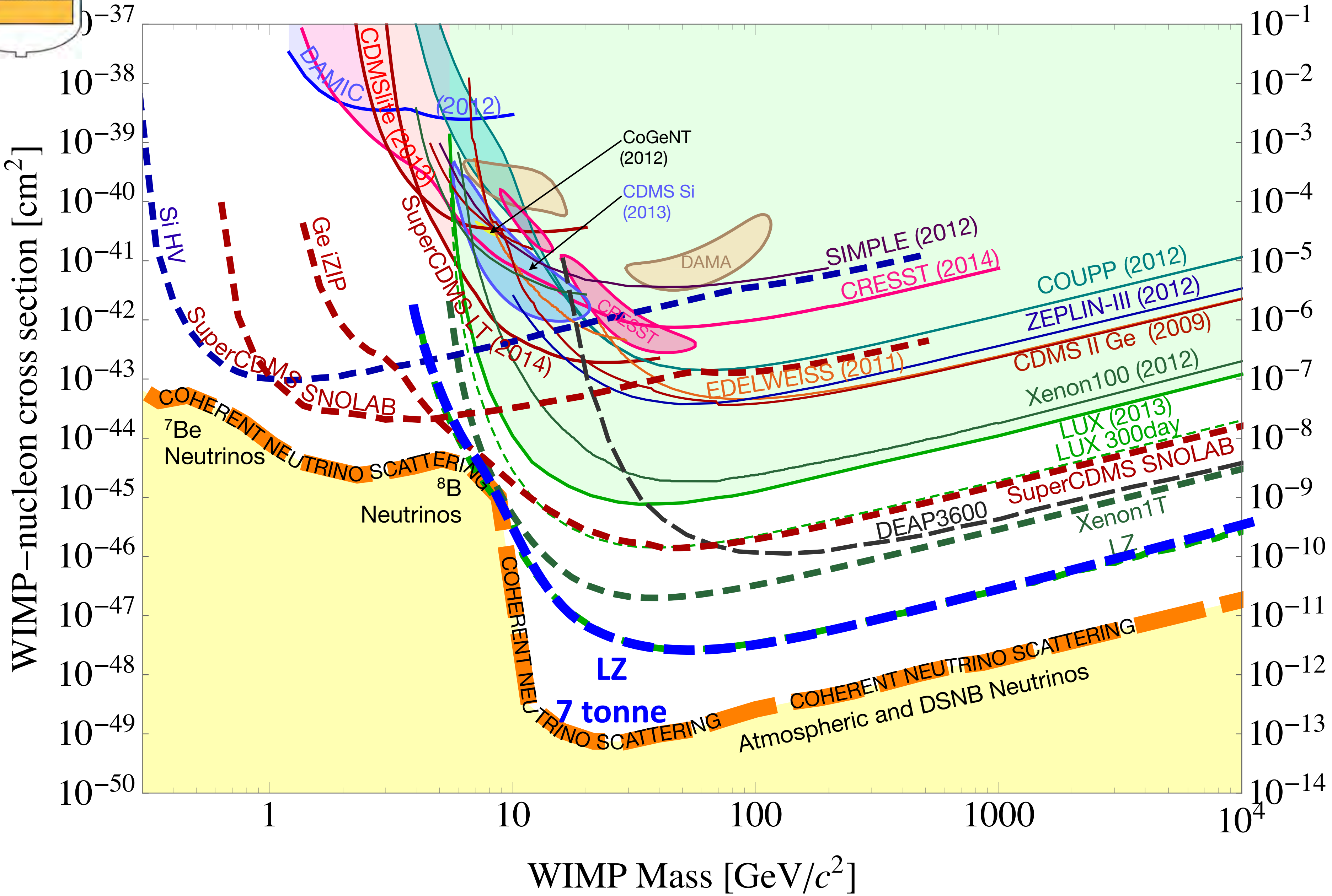
US G2: LZ

(+ Xenon 1 Ton, approved 2012)

Replaces LUX at the Sanford Underground Research Facility (SURF)

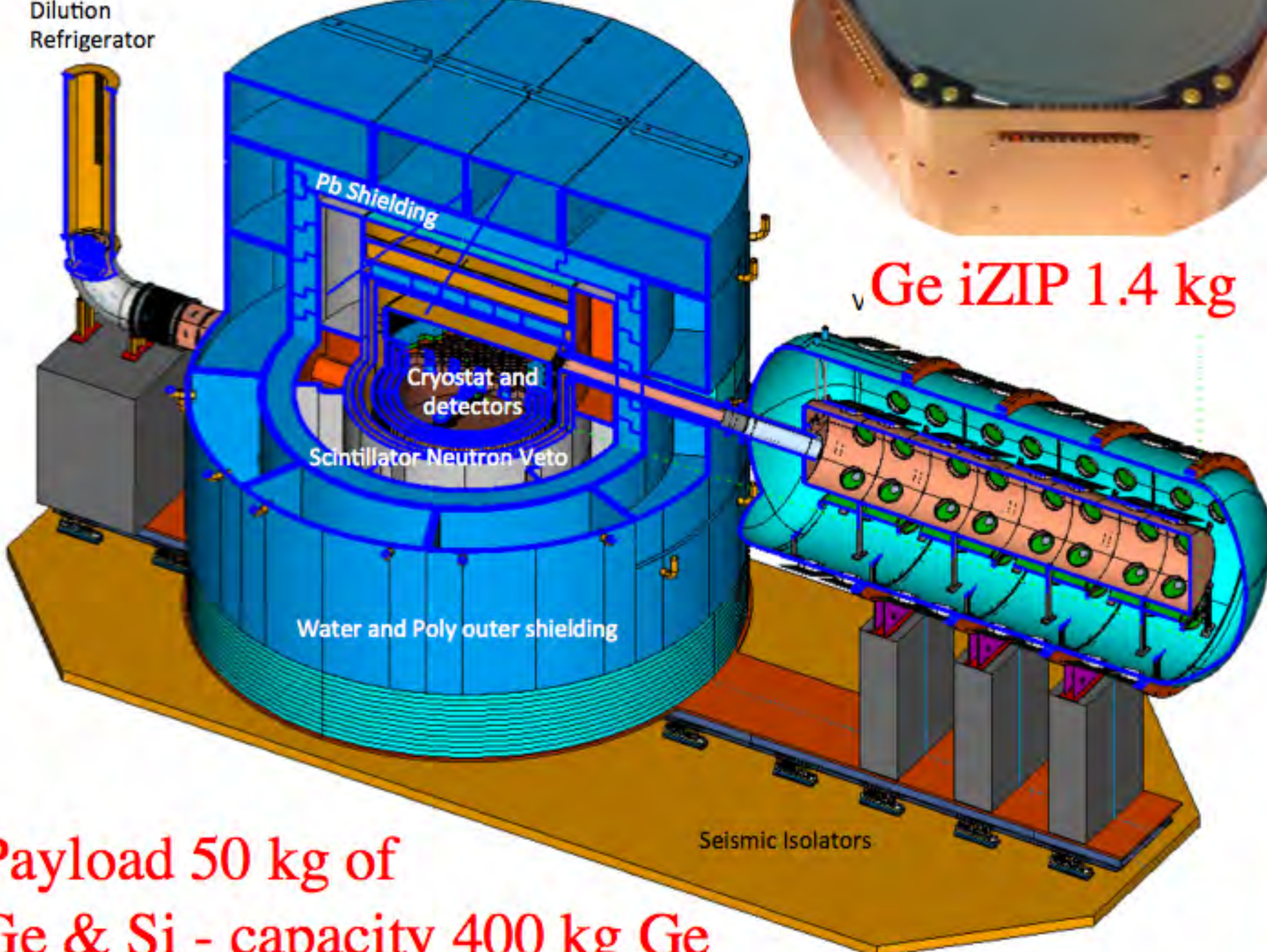


LZ on Snowmass über Plot



SuperCDMS SNOLAB Experiment

- SNOLAB 6010 mwe



Ge iZIP 1.4 kg

Payload 50 kg of
Ge & Si - capacity 400 kg Ge

Ge Tower 8.4 kg

SuperCDMS SNOLAB

Low temperature Ge/Si detector

Focus

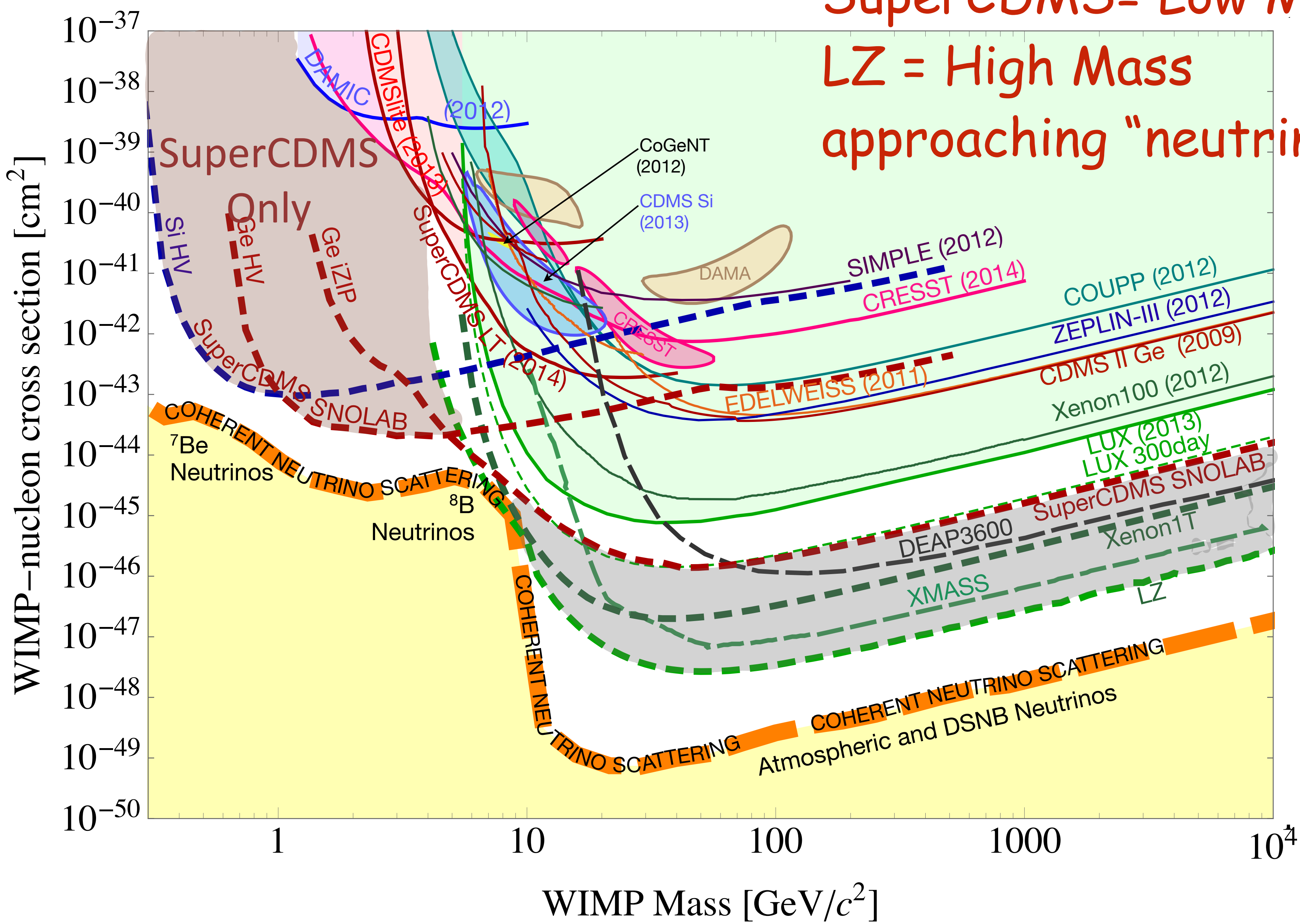
- Low mass 0.3-10GeV/c^2
  - Above 5 GeV/c^2 6 towers ≈50kg Ge full nuclear recoils recognition through ionization (σ=100eV) + athermal phonon (σ=50eV). Surface rejection demonstrated for a run of 7 years.
  - 0.3-5 GeV/c^2, 1 tower of e.g., 3 Ge, 3 Si, CDMS HV (Luke Neganov amplification of ionization). No discrimination. Background limited after 1 year
- High mass
  - Complementary role to confirm a discovery by say LUX 300 days with different technology, different background sensitivity and different target

Cryostat able to house 400kg => upgrade paths

- Current discussions with EURECA to increase target mass/diversity within the same tower geometry (evaluation of feasibility of operating at 15mK)
  - Edelweiss 30kg re-equipped with HEMT to decrease threshold, Potentially additional Ge payload -> ≈200kg
  - CRESST $CaWO_4$.
- Possibility of rapidly increasing the mass with CDMS technology if there is a serious hint for a signal at medium or high mass.
- Follow up of a possible hint at small mass: if we can improve the phonon to better than 20eV we begin to recover discrimination (Matt Pyle)

US G2 WIMP Sensitivity

SuperCDMS= Low Mass
LZ = High Mass
approaching "neutrino floor"



US G2: Complementarity between LZ and SCDMS

High Mass-Low Mass

Different technologies with different susceptibility to backgrounds.

Need of course for the two experiments to have both sensitivity to the signal claimed

WIMPs

At high mass, CDMS-LZ overlap if relatively high cross sections ≈ LUX 300 days

But Edelweiss III

DEAP 3600 should be able to do that sooner

XENON 1T

Around 10 GeV very similar

^{8}Boron solar neutrinos

Cross check between two experiments

Complementarity with solar neutrino-electron scattering which should be unambiguously observable deep inside LZ.

Time scale and budgets

Technically could deploy 2018

Problems are budget: LZ $34M DOE (+21K), SuperCDMS $13M DOE $12M NSF $3M CFI

Absolute value + profile

US G2: Technical Challenges (My opinion)

Radiopurity

LZ: very large extrapolation: 2.5 orders of magnitude.

Although "it is just chemistry", fairly challenging.

Potential leaching of radioactive products in the liquid. Adapt methods of SuperK, Borexino, Kamland etc.

CDMS has demonstrated surface rejection for this stage for the region where it has nuclear recoil discrimination (mass above 5GeV/c^2). But:

- Needs to improve radio purity of surrounding material by ≈200, not to have neutrons from fission!
- For CDMS-HV: control of ^{32}Si, cosmogenic ^{3}H in Ge/Si, Cu activation lines

Thresholds -> Low Mass +^{8}B solar neutrinos

LZ: control few electrons emission from surface/grid

CDMS:

- Intermediate mass: importance of ionization (σ=100eV) . Athermal phonon (σ=50eV) for fiducial region control
- CDMS HV Athermal phonon (σ=50eV) + structure able to withhold voltage without carrier injection

Complementarity of US G2 with other expts 1.

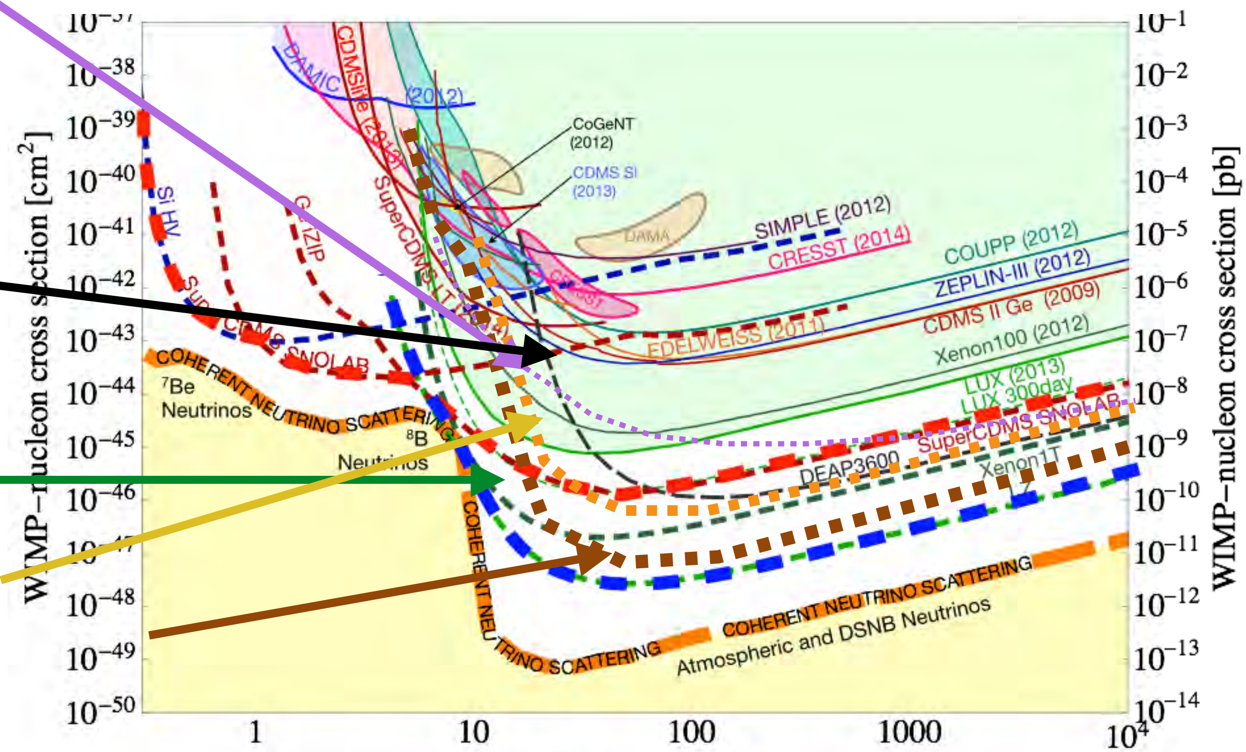
LUX and SuperCDMS Soudan,
Edelweiss III (data taking 7/14)
Doubling energy of LHC
More stats Fermi + IceCube
CTA in a few years

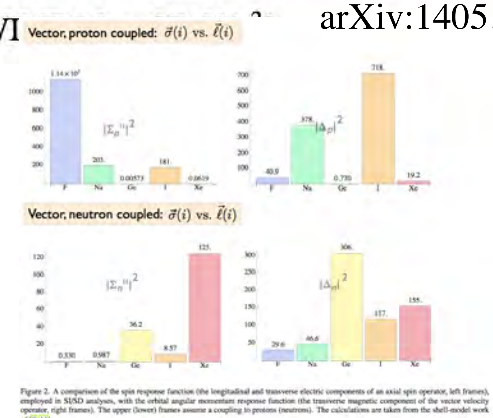
Intense competition!

DEAP 3600
Physics starting early 2015
≈ XENON 1T at high mass

XENON1T
Commissioning late 2015

XMASS
XMASS 1.5 Operation in 2017
≈ XENON1T at high mass
+ XMASS 2 Operation ≈2019?
close to LZ at high mass





Reasonable complementarity of Nuclei

But we are missing nuclei (F, I) with unpaired protons, which is most sensitive to axial couplings and velocity dependent effects
cf Haxton, Zurek

Complementarity of US G2 with other expts 2.

Low mass

CDEX, C-4

SuperCDMS Soudan

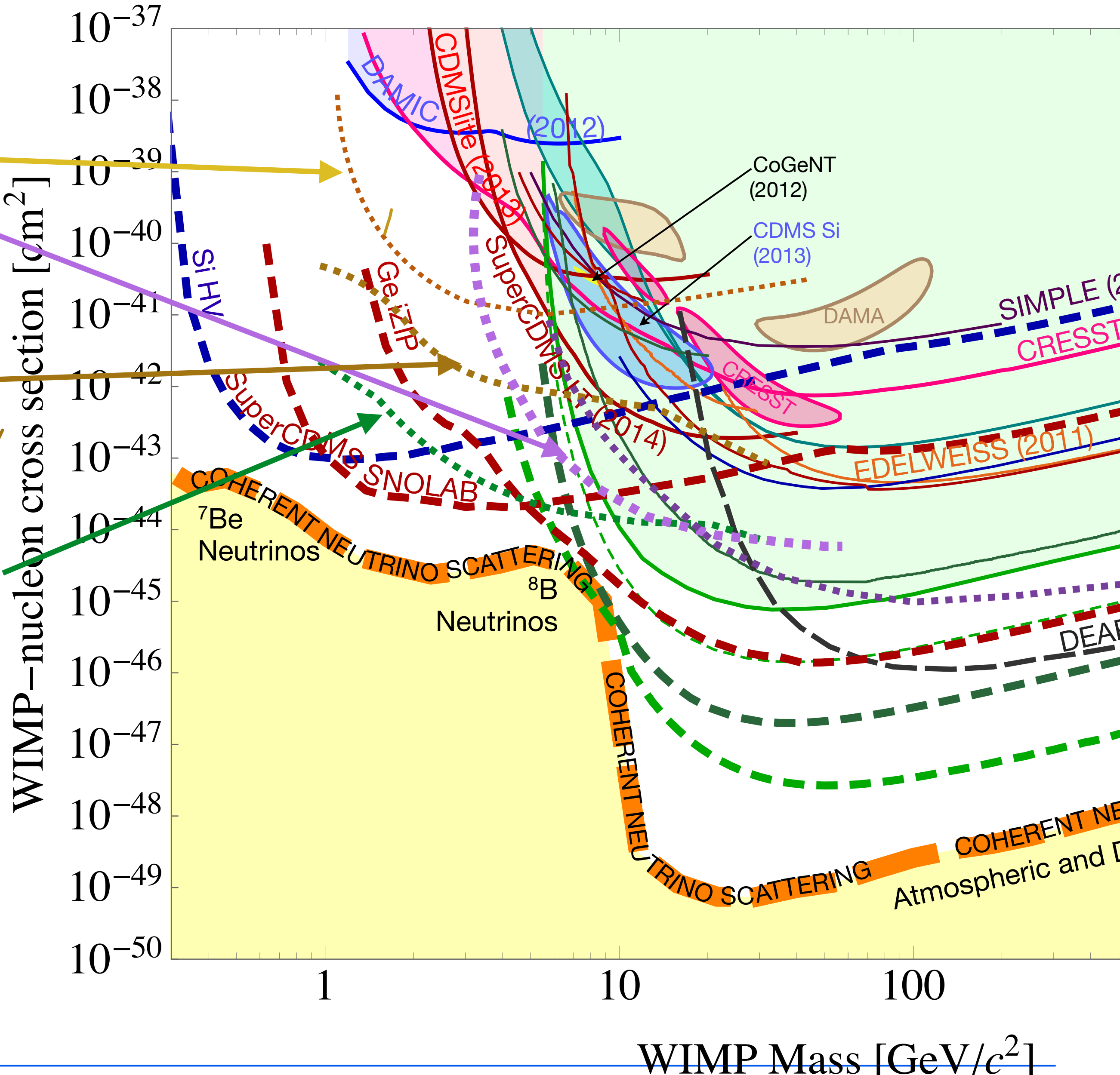
DAMIC

Edelweiss III Low Mass

CRESST

50kg days Gran Sasso
20g detectors
with current radioactivity

1000kg days, 100x purity
EURECA/CDMS?



B.Sadoulet

The Preparation of Generation 3

How do we get ready for a breakthrough?

Generation 3

Goals

- In case of discovery:
  - High statistics (with negligible background) both for Cosmology (velocity distribution) and Particle Physics (cross sections, mass, coupling to nucleus)
  - Directionality
  - Eventually Dark Matter Observatory
- In case of conflicting results: clean up with better detectors, higher purity and rejection
- In case of no discovery in direct detection (even if convincing evidence at LHC or in Indirect Detection): Cover the full observational space
  - Down to the neutrino floor
  - Lower masses

How to maximize chances of success and timeliness?

Maintain diversity of approaches

Support R&D of promising directions

Pathfinders/demonstration project

Learn from difficulties encountered in G2: e.g. backgrounds / outliers

G3 R&D recommended by P5 (≥ 1 US G3)

Implementation and time scales. Be ready for breakthrough!

Combination of upgrades ≈ 2018?

new set ups (US, elsewhere) ≈ early 2020's?

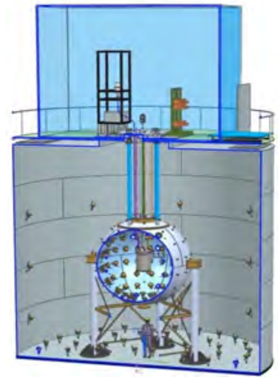
Probably need new cavity at Homestake or SNOLAB.

cf. HEPAP facility report.

PathFinders: Liquid Argon

Dark Side 50l

Currently running in Gran Sasso
in CTF (Borexino)
High efficiency neutron veto
Will test underground Argon (depleted in ^{39}Ar)



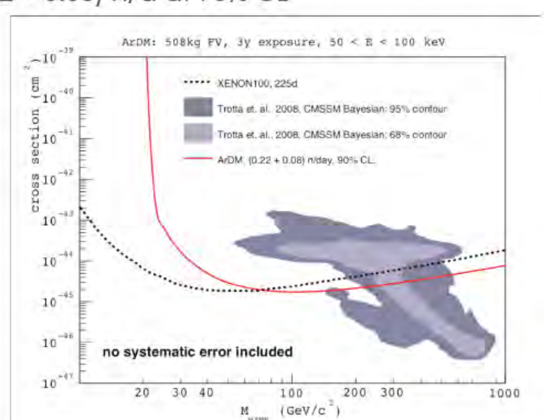
Mini Clean Goals in addition to DEAP 3600

- Single phase Liquid Argon
  - 2014: Detector construction complete
  - 2015: Natural Ar & ^{39}Ar Spike Run
- 4π coverage to maximize light-yield at threshold …
  - 3D Position Reconstruction
  - Particle-ID via Pulse-shape discrimination (PSD)
- Radon-reduced assembly

ArDM

Start in data-taking mode in scintillation only mode
Ready to rapidly install the TPC after first run

Projected sensitivity of ArDM for a background expectation of (0.22 + 0.08) n/d at 90% CL



Generation 3 Aspirations

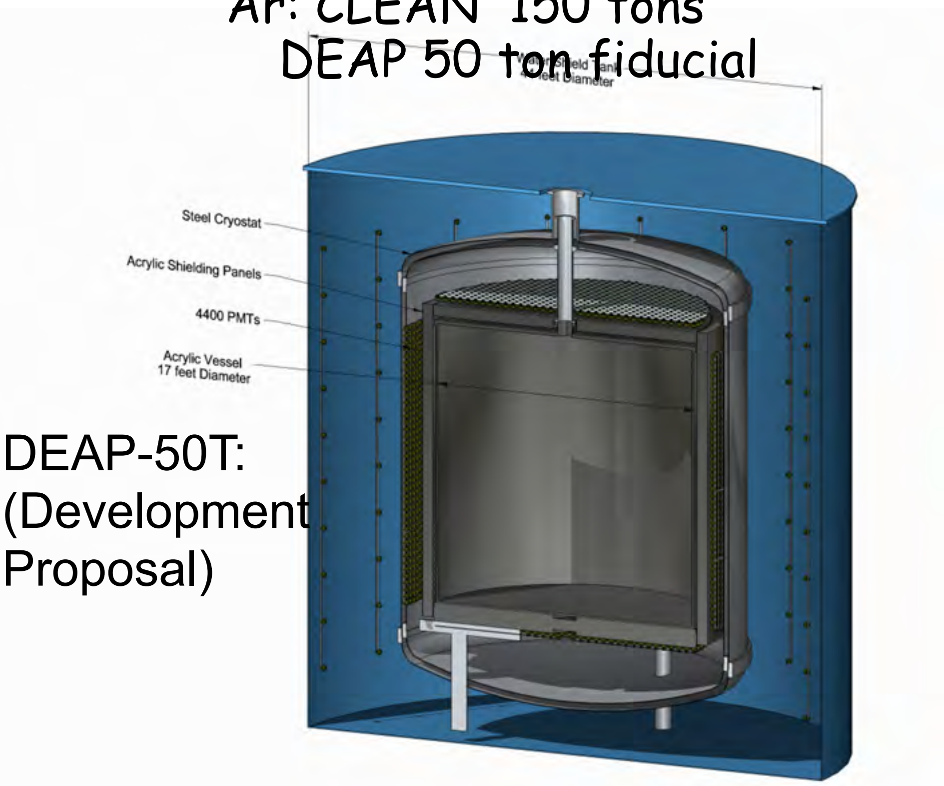
Crystals

CDEX 1 ton in new cavities in the Chinese Jin Ping laboratory (7000m.w.e.)

GEODM 1.5 ton | combined? Focusing on G2 for the time being
EURECA 1 ton | SNOLAB or Modane

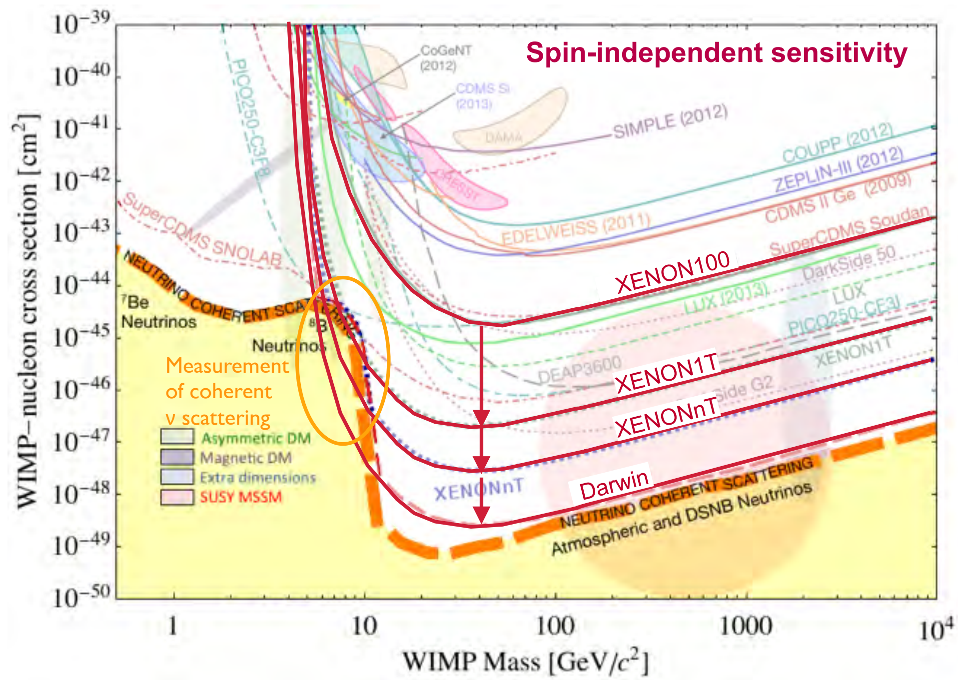
Noble Liquids

Ar: CLEAN 150 tons
DEAP 50 ton fiducial



DEAP-50T:
(Development
Proposal)

XENON: e.g. upgrade of
XENON 1T
then Darwin Xe+Ar



Bubble chambers similar to PICO

The challenges of low mass

Extension of current schemes

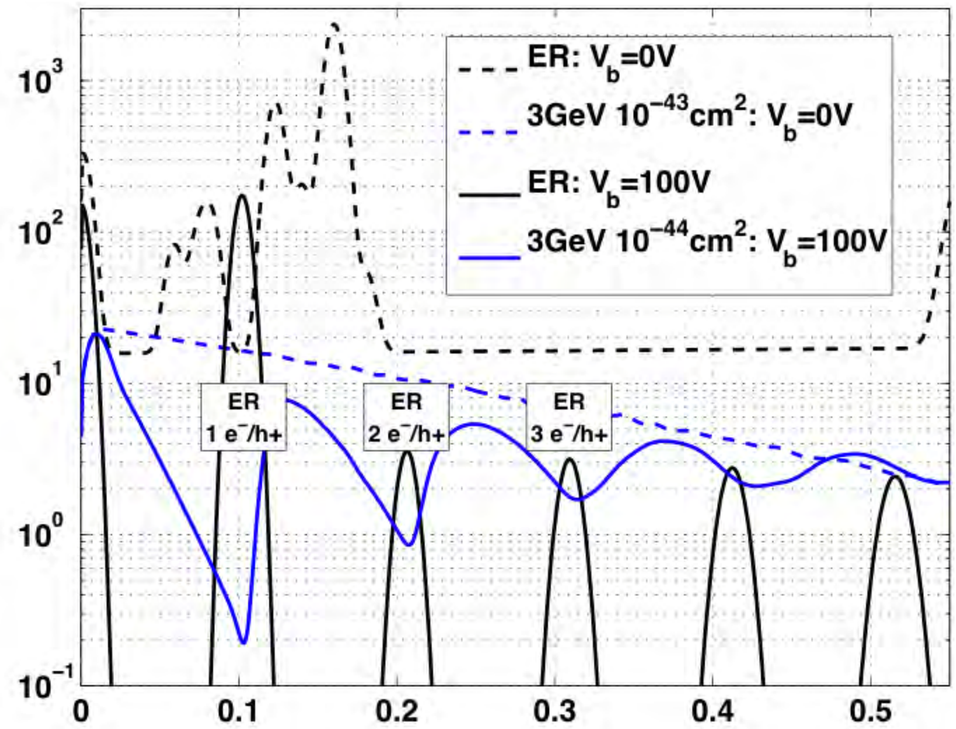
Increase of sensitivity

- phonon optimization (CDMS/Matt Pyle, CRESST)
- but need also ionization (CDMS) or photon (CRESST)

Give up discrimination (less important at low mass)

- S2 only for Xenon 2-phase detectors
- CDMS-HV (CDMS-light) hole-electron pair -> phonons

Important note: below $\sigma_{pt} \approx 10$ eV, restore ER/NR discrimination (Pyle)

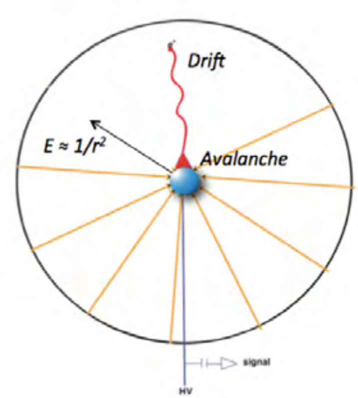


Other schemes

DAMIC (thick CCDs): ultimate ionization detectors

Spherical Proportional counters (G. Gerbier, I. Giomataris)

DNA (Drukier)

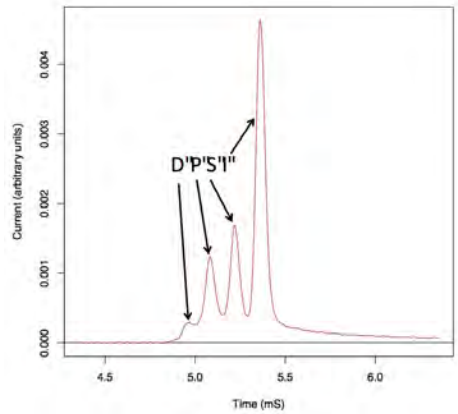


PathFinders: Directional Detectors

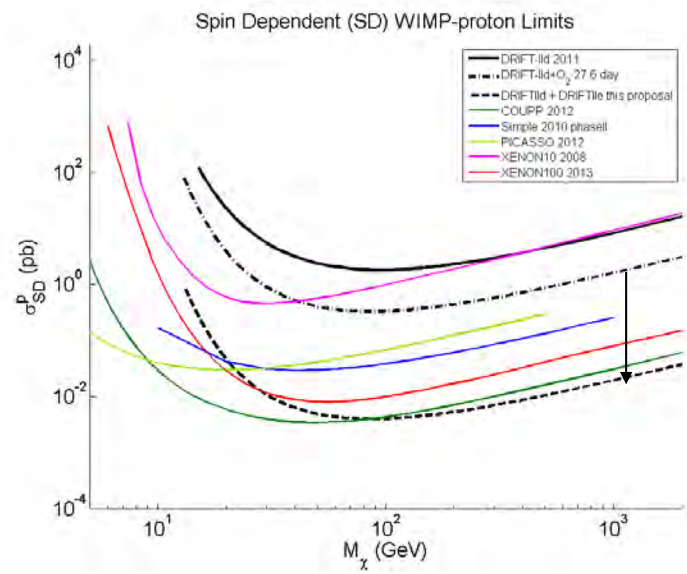
Low Pressure Gas TPC Challenge:

At 100 torr: 100g/m^3 Instrument >>1,000m^3 with mm^3 pixels. Start with m^3
z measurement (in particular to get rid of cathode radioactivity)

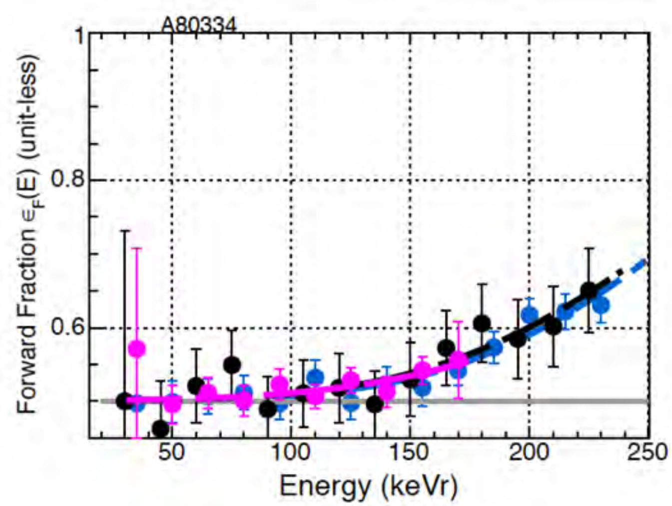
In the US: DRIFT



The addition of O_2 to a $CS\text{-}CF_4$ mixture produces minority peaks with separation proportional to distance. + texturing of electrode: background free on 75% F fiducial volume



DMTPC



Measurement of directional sensitivity with 25 cm drift using neutrons.

Currently constructing 1,000L detector for use underground

Other approaches:

Columnar recombination (Nygren)
DNA detectors (Drukier)

Where is this going?

Importance of the 13 TeV LHC run (starting now)

- Discovery of supersymmetry
  - Why so high scale?
  - Is this responsible for Dark Matter: detect in Cosmos
- No supersymmetry
  - End of the naturalness concept?
  - Even larger importance of direct detection -> Dark Sector (low mass)
  - High mass inaccessible to LHC + indirect detection

Think out of the box!

As indicated by Lisa Randall: much broader theoretical framework

4 prong approach=>

complementary coverage
constrain theory speculations
even if purely gravitational interactions