Physics 129 LECTURE 14 February 25, 2014

Searching for Dark Matter

- Searching for WIMPs: Direct Detection
- Searching for WIMPs: Indirect Detection
- Warm Dark Matter - Sterile Neutrinos: Seen?
- WIMP Production at the LHC

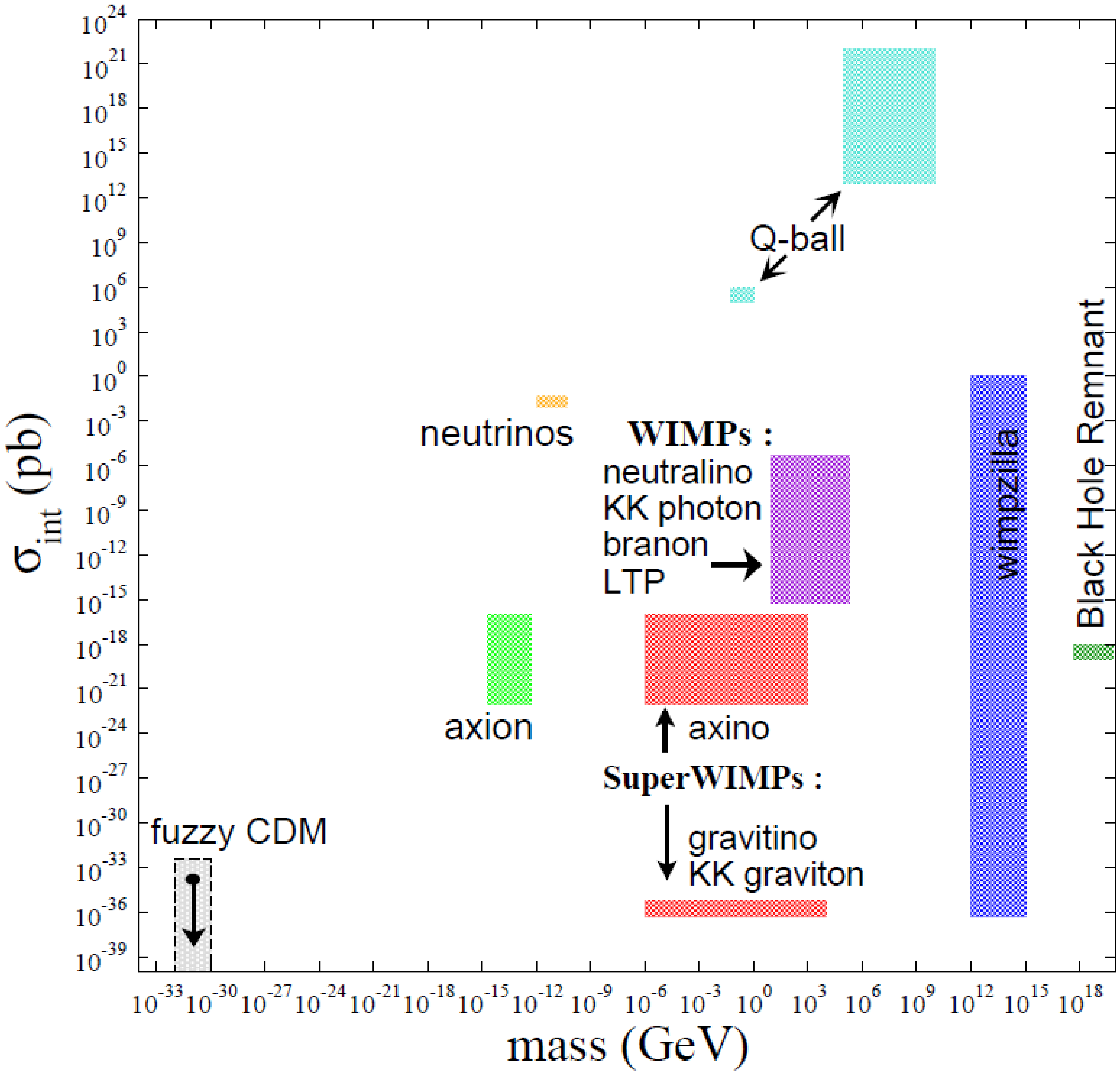
NOTE: The February 25, 2014, lecture is CANCELLED since I will be at the Dark Matter 2014 Conference at UCLA Wednesday - Friday February 26-28.

Many Dark Matter Candidates

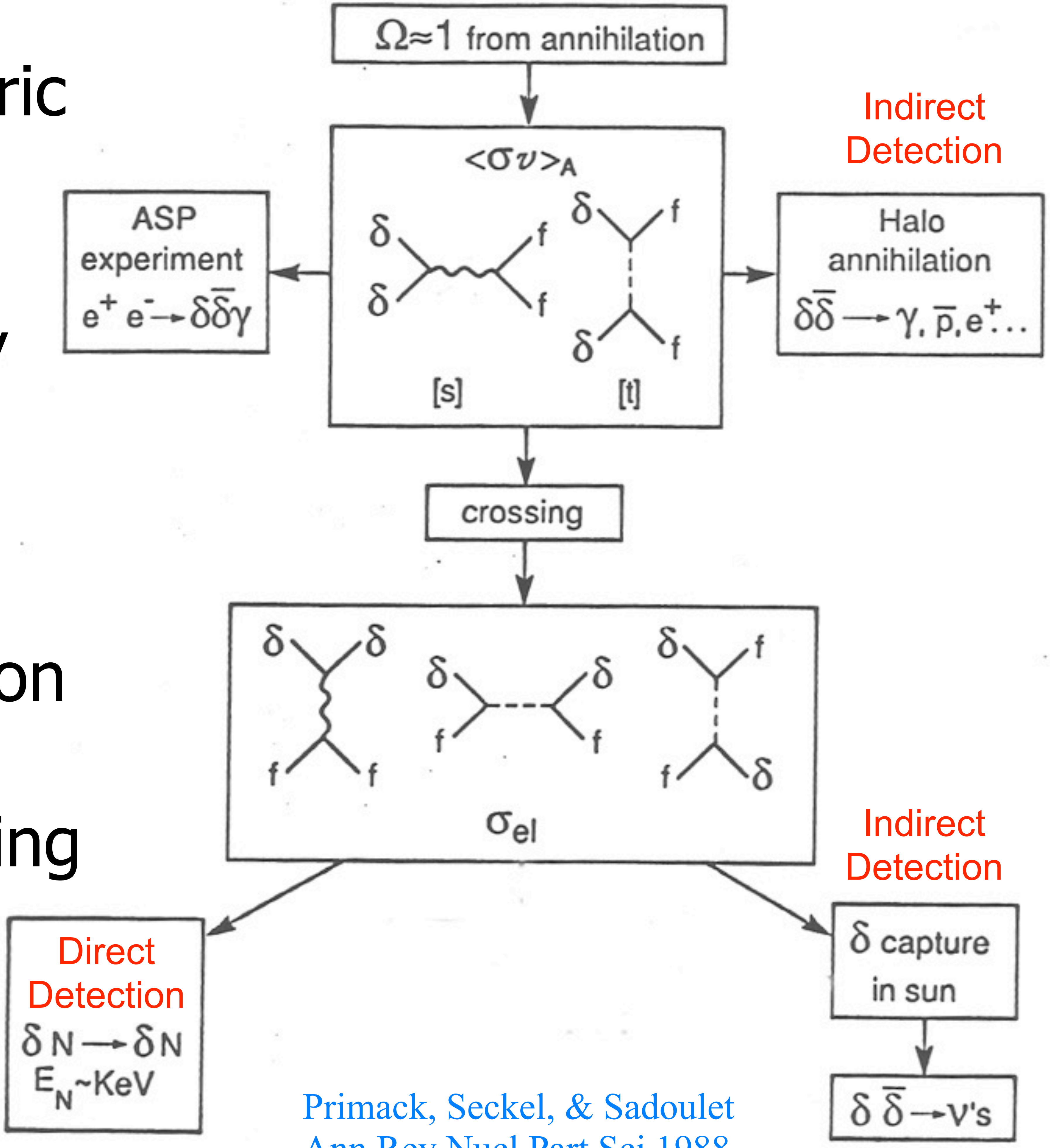
A plethora of candidates/ideas

- Q-balls
- SuperWIMPs
- Gravitinos
- Axions ..

Most searches focus onWIMPs, so I will also do so.



Supersymmetric WIMP (δ) annihilation is related by crossing to WIMP Direct Detection by Elastic Scattering



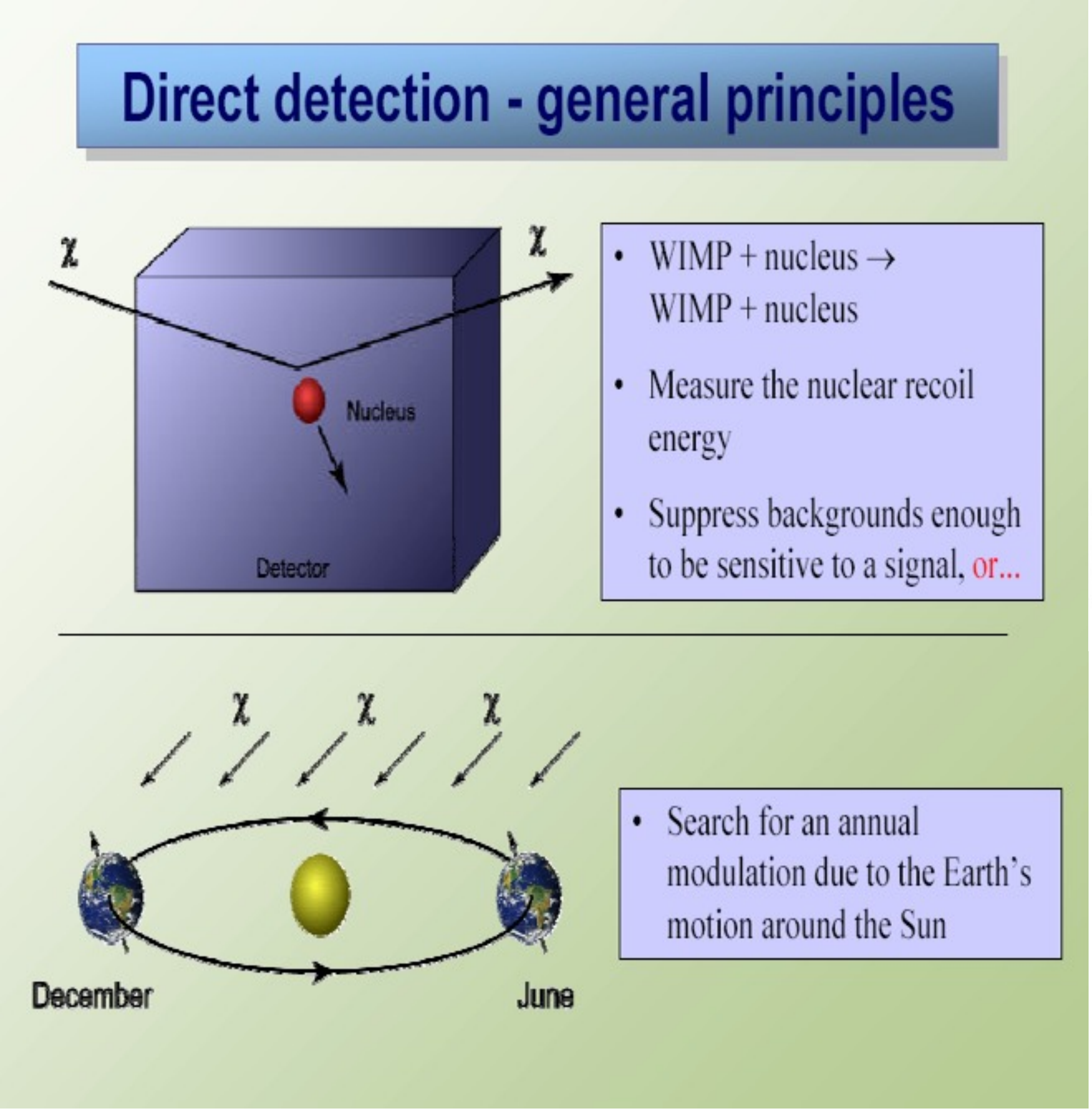
Indirect Detection

Indirect Detection

Direct Detection

Primack, Seckel, & Sadoulet
Ann Rev Nucl Part Sci 1988

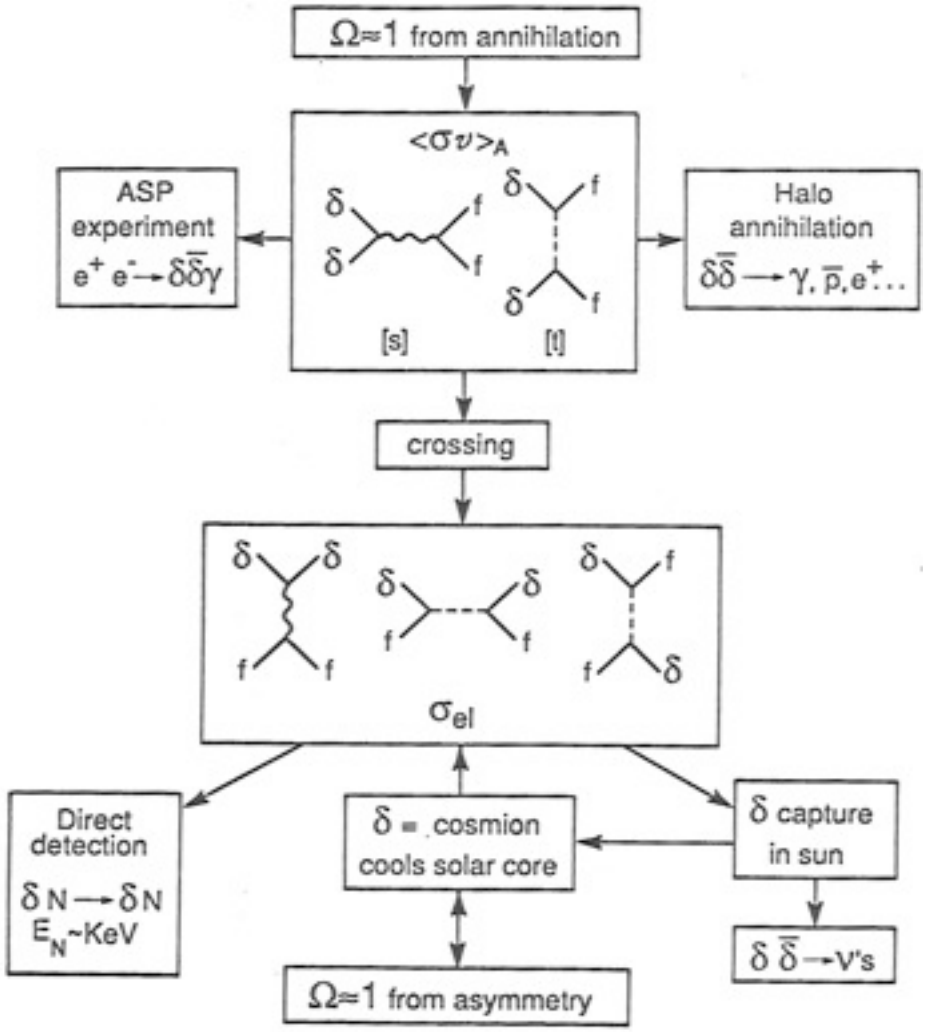
Experiments are Underway for Detection of WIMPs

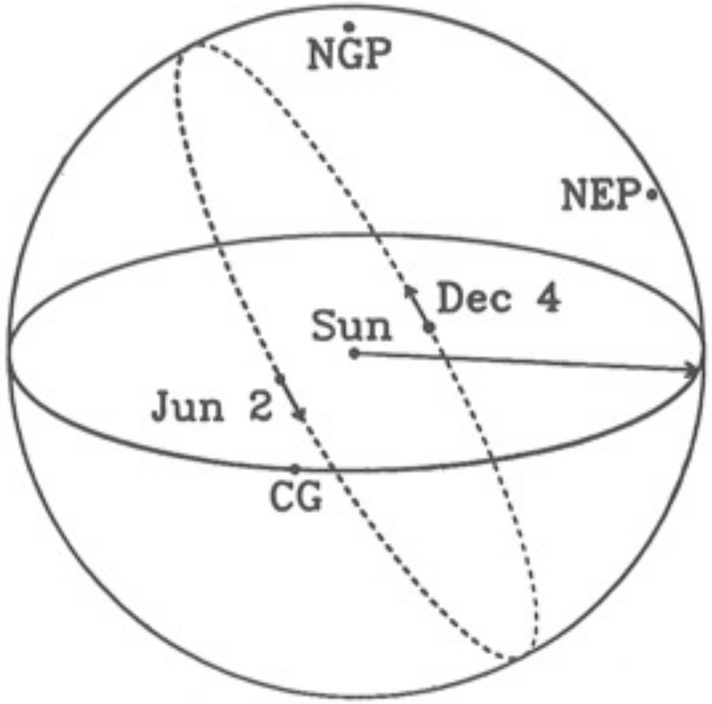


Direct detection - general principles

- WIMP + nucleus → WIMP + nucleus
- Measure the nuclear recoil energy
- Suppress backgrounds enough to be sensitive to a signal, or...

- Search for an annual modulation due to the Earth's motion around the Sun





Primack, Seckel, & Sadoulet (1987)

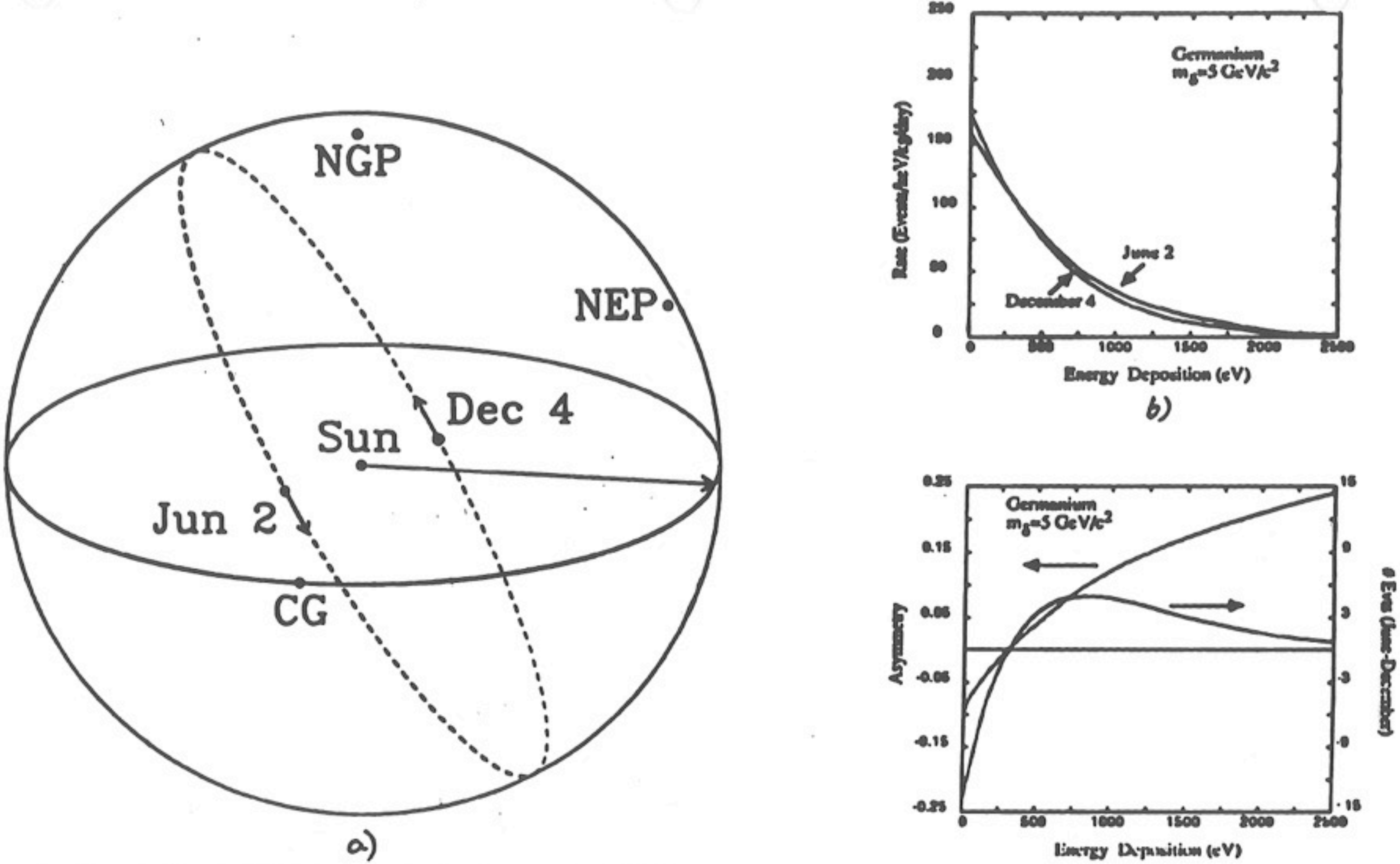
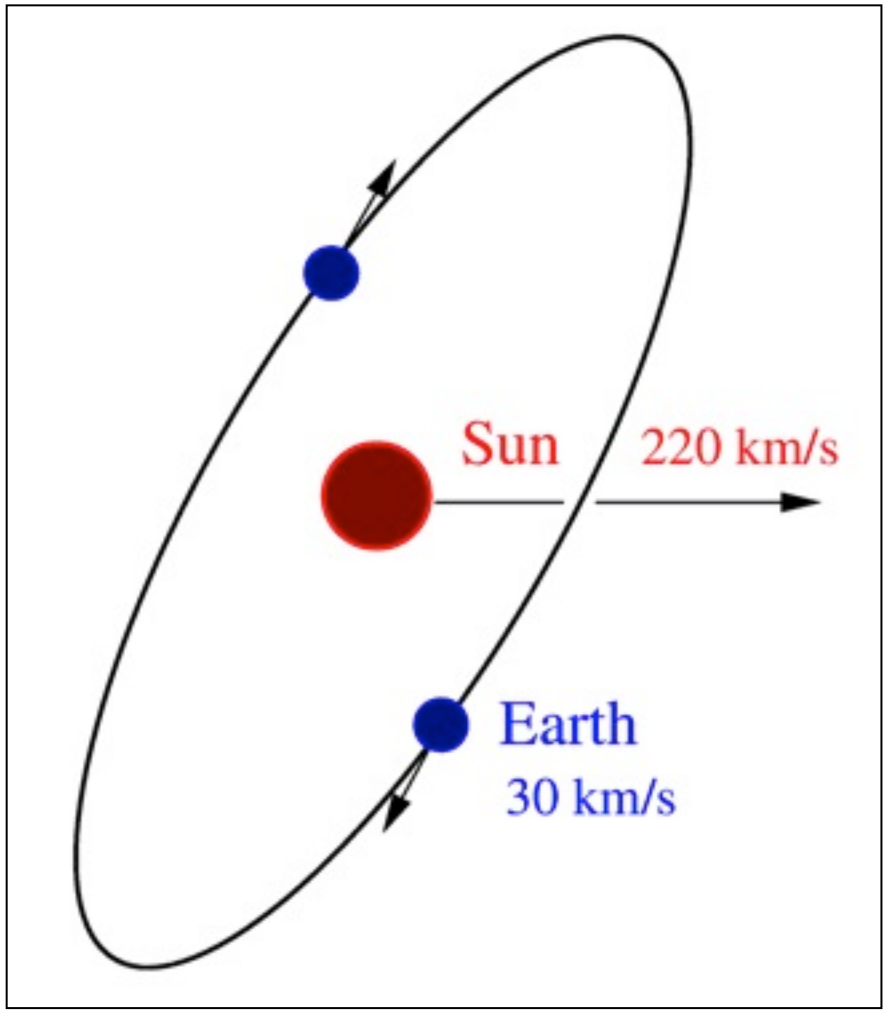


Figure 3. Annual effect in WIMP detection by elastic scattering. (a) Why expected: The solid line (darker in the front) shows the plane of the galactic disk and the Sun's orbit; the dashed circle is the orbit of the Earth (ecliptic plane). NGP and NEP are the north galactic and ecliptic poles. CG shows the direction toward the galactic center, and the long and short arrows show the Sun's and the Earth's velocities. The sum of the Sun's and Earth's velocities reaches its maximum on June 2 (248 km s^{-1}) and minimum on December 4 (219 km s^{-1}). (These velocities with respect to the galactic center are obtained neglecting the small eccentricity of the Earth's orbit, and assuming that the Sun's peculiar velocity is 16.5 km s^{-1} in the galactic direction $l = 53°$, $b = 25°$ with respect to the local standard of rest (cf. 118). Event rates in WIMP detectors actually depend on the Earth's velocity with respect to the DM halo, whose rotational velocity is uncertain.) (b) Rate for June 2 and December 4 vs. deposited energy. (c) June − December difference (right axis) and asymmetry (left axis) vs. deposited energy. Note that although the asymmetry increases with the energy deposition, the rate and therefore also the June − December rate difference both decrease at high energy deposition.

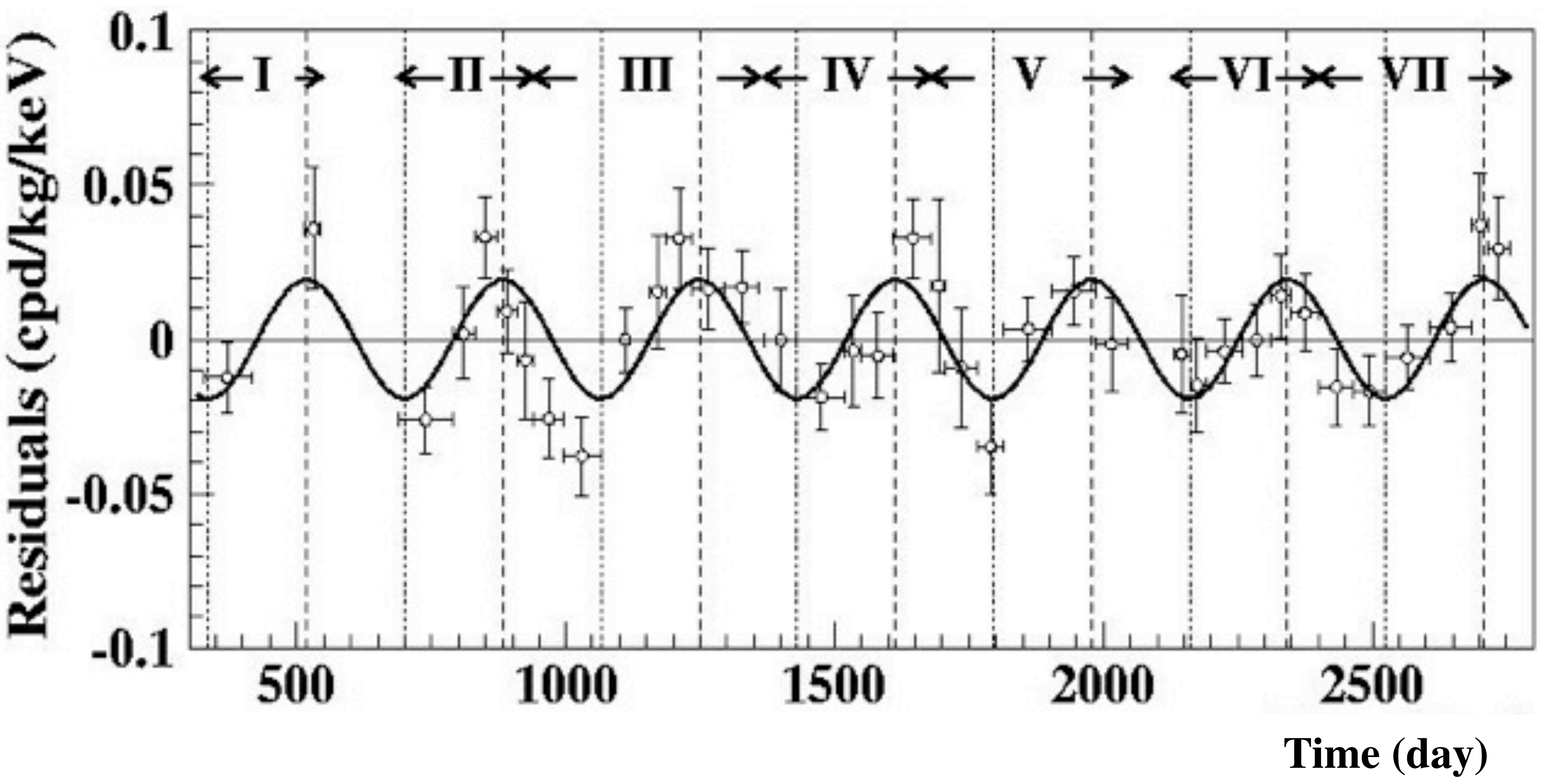
Primack, Seckel, & Sadoulet, Ann Rev Nucl Part Sci 1988

DAMA Evidence for WIMP detection



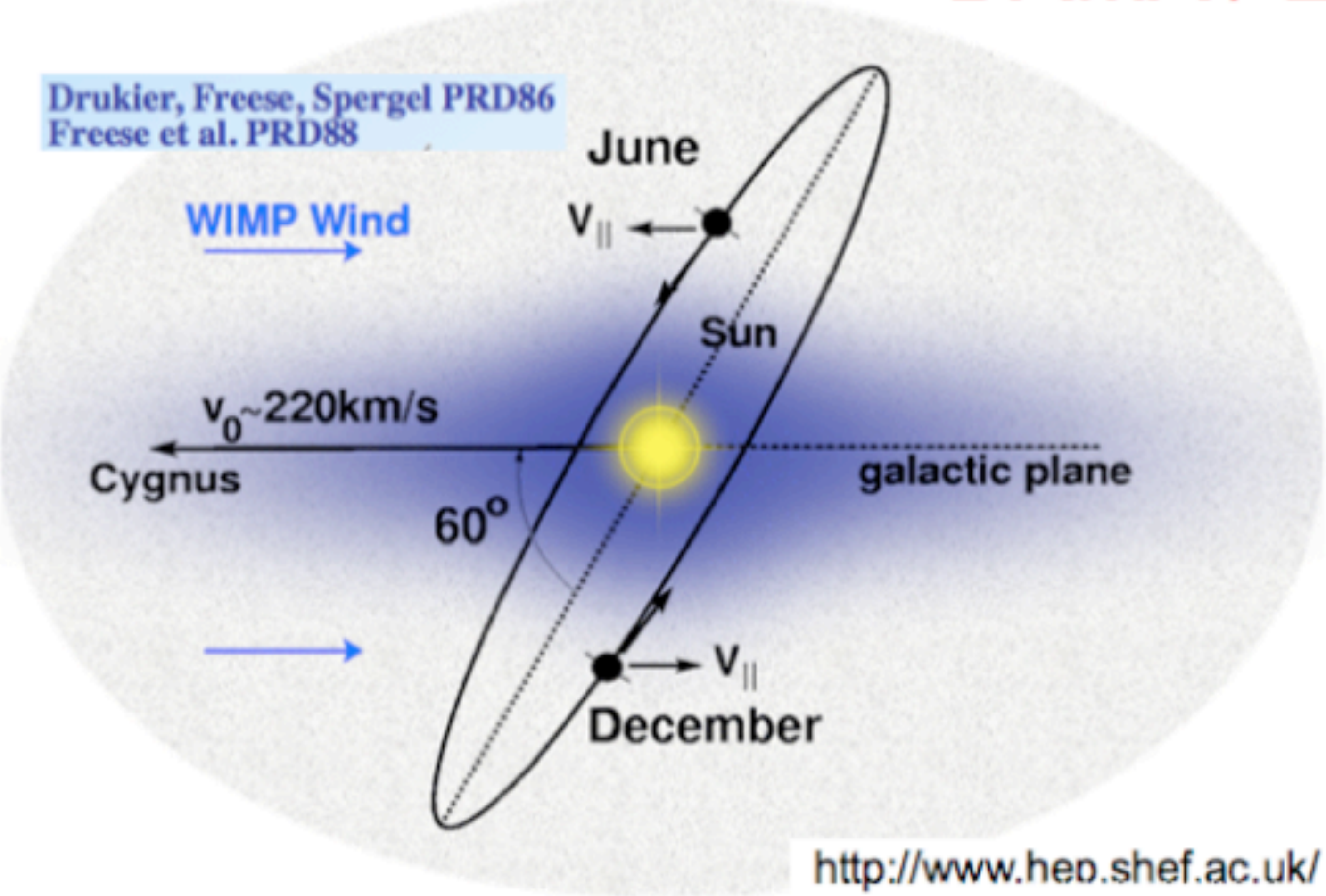
Annual modulation of WIMP signal a “smoking gun” signature

DAMA experiment in Gran Sasso (NaI scintillation detector) observes an annual modulation at a 6.3σ statistical CL, based on 110 ton-days of data [Riv. N. Cim. 26 (2003) 1–73]



- Detector stability ?
- Background stability ?

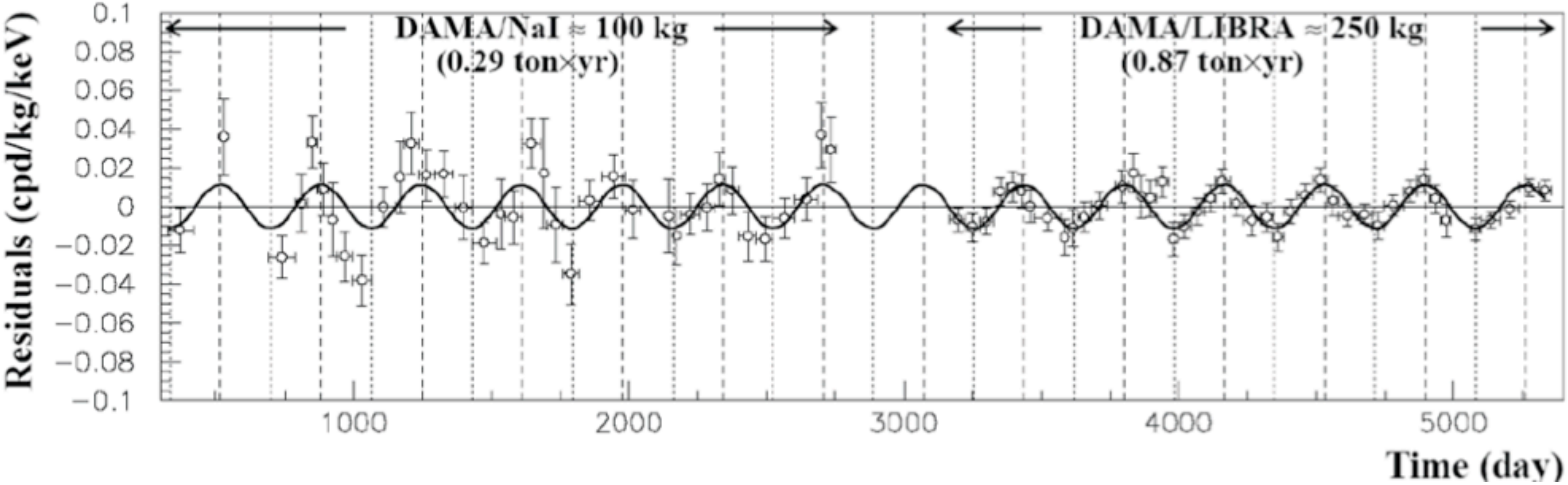
DAMA / LIBRA



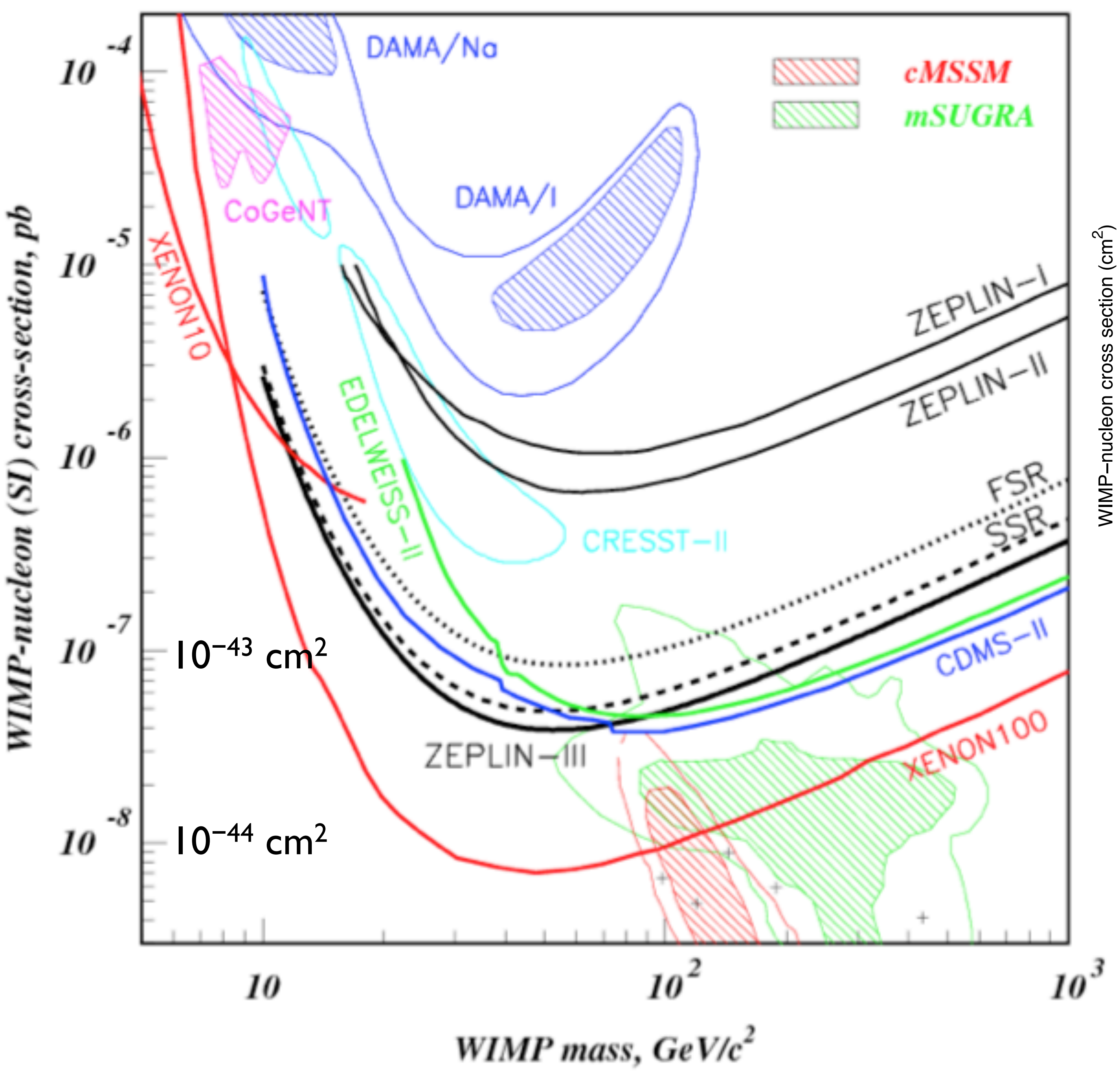
Drukier, Freese, Spergel PRD86
Freese et al. PRD88

http://www.hep.shef.ac.uk/

- Annual Modulation
  - Significance is 8.9σ
  - 1-2% effect in bin count rate
  - Appears in lowest energy bins
  - Can another experiment observe this effect?



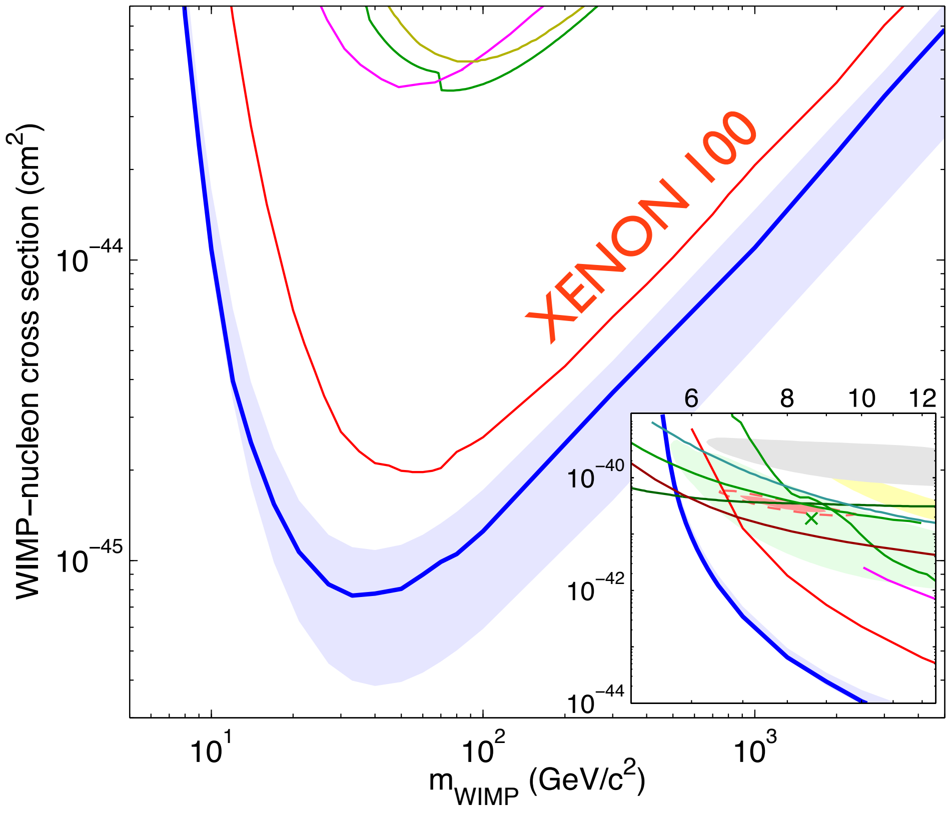
DAMA Interpretation vs. Other Limits



10^{-43} cm^2

10^{-44} cm^2

LUX Preliminary Upper Limits

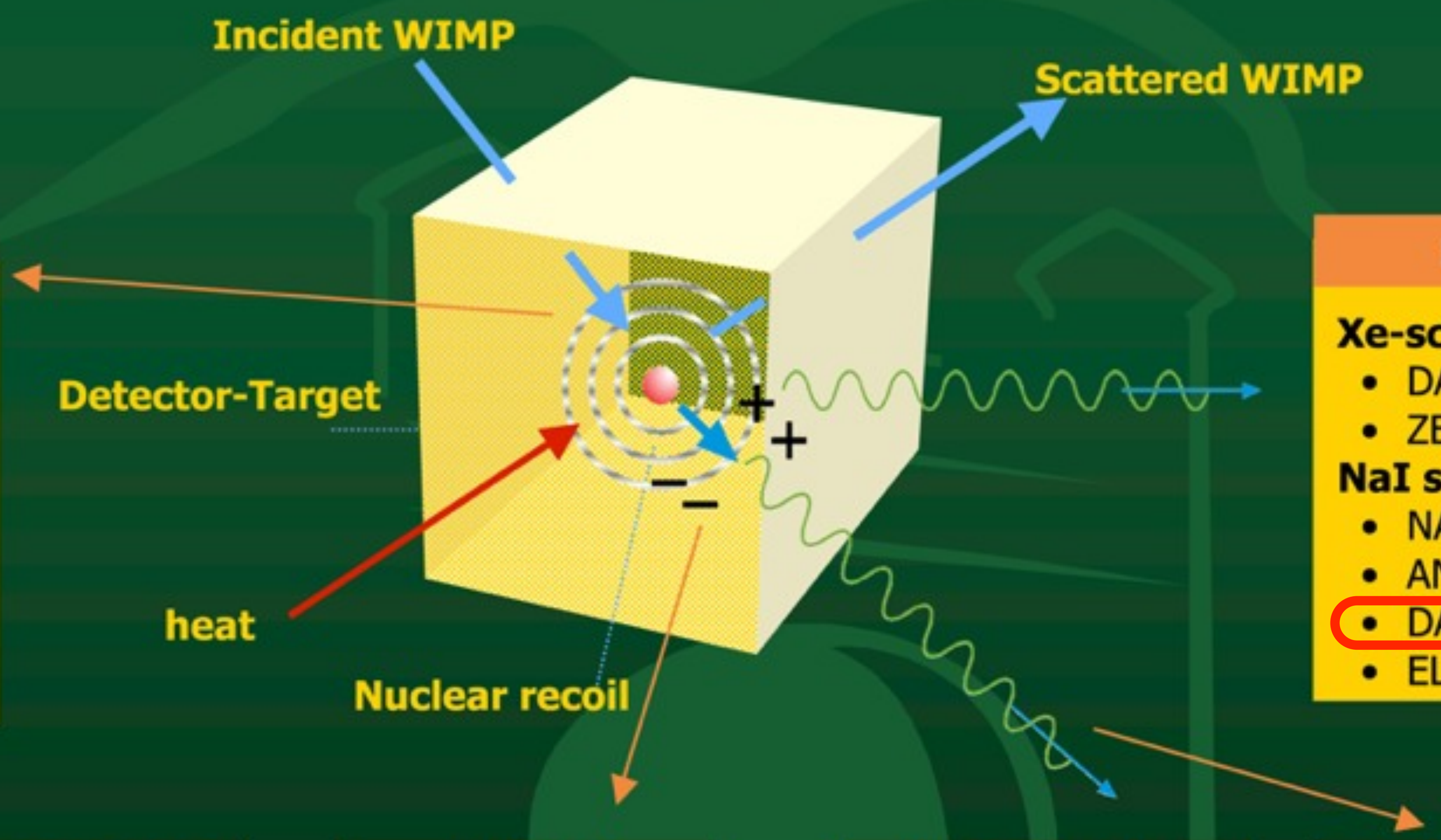


barn = 10^{-28} m^2 = 10^{-24} cm^2

picobarn = 10^{-12} barn

= 10^{-36} cm^2

Direct Detection Methods



HEAT

Bolometers:
- MiDBD
- ROSEBUD-I
- CRESST-I
- CUORICINO

Metastable p.det:
- SSD Micrograins
- SDD Droplets

LIGHT

Xe-scintillators:
- DAMA-Xe
- ZEPLIN-I

NaI scintillators:
- NAIAD
- ANAIS
- DAMA, LIBRA
- ELEGANTS

HEAT+CHARGE
- CDMS
- EDELWEISS

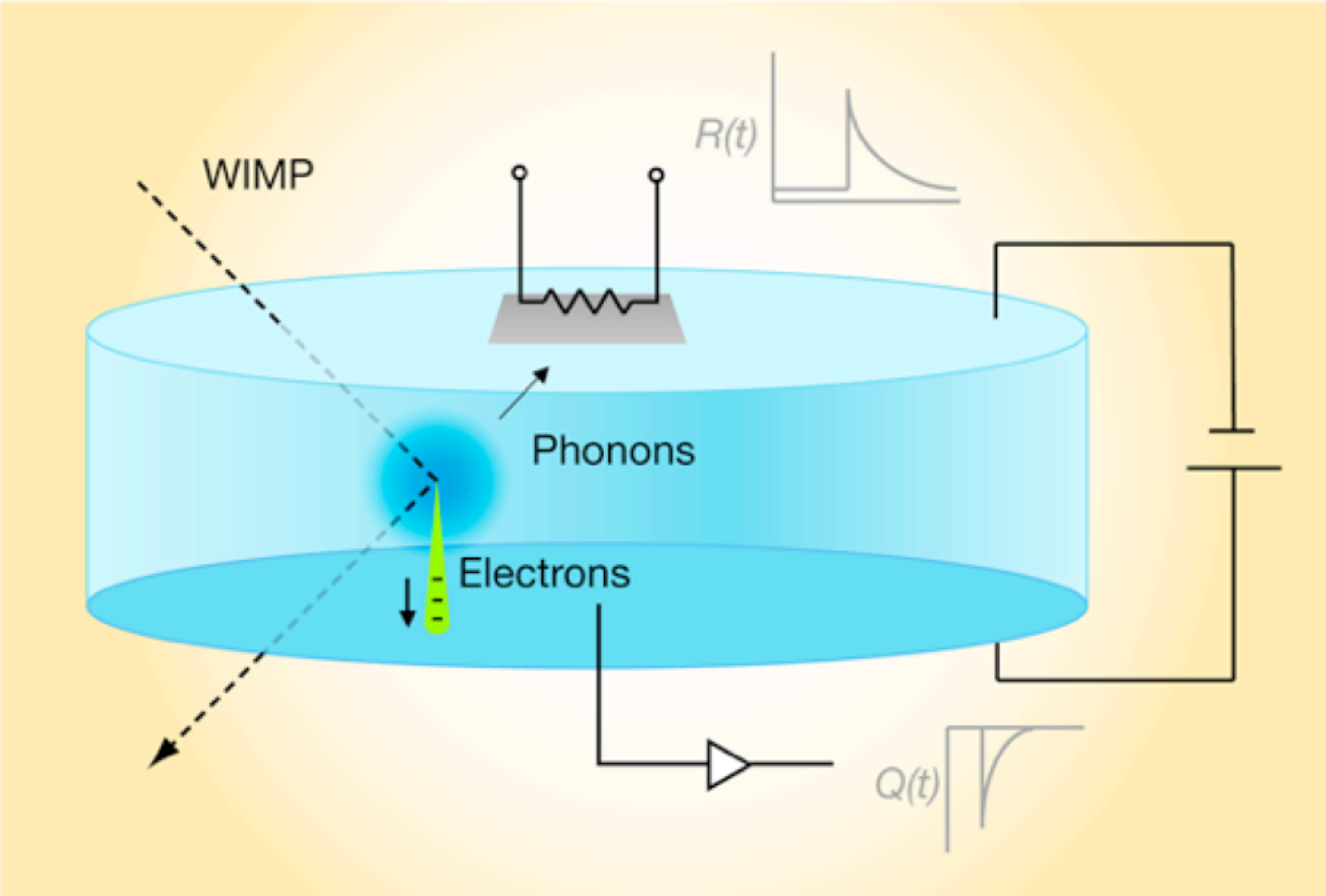
CHARGE

Ge-experiments:
- H/M
- IGEX
- GENIUS-TF

Tracking Chambers:
- DRIFT

HEAT+LIGHT
- ROSEBUD-II
- CRESST-II

LIGHT+CHARGE
- ZEPLIN-II
- X-MASS
- XENON100



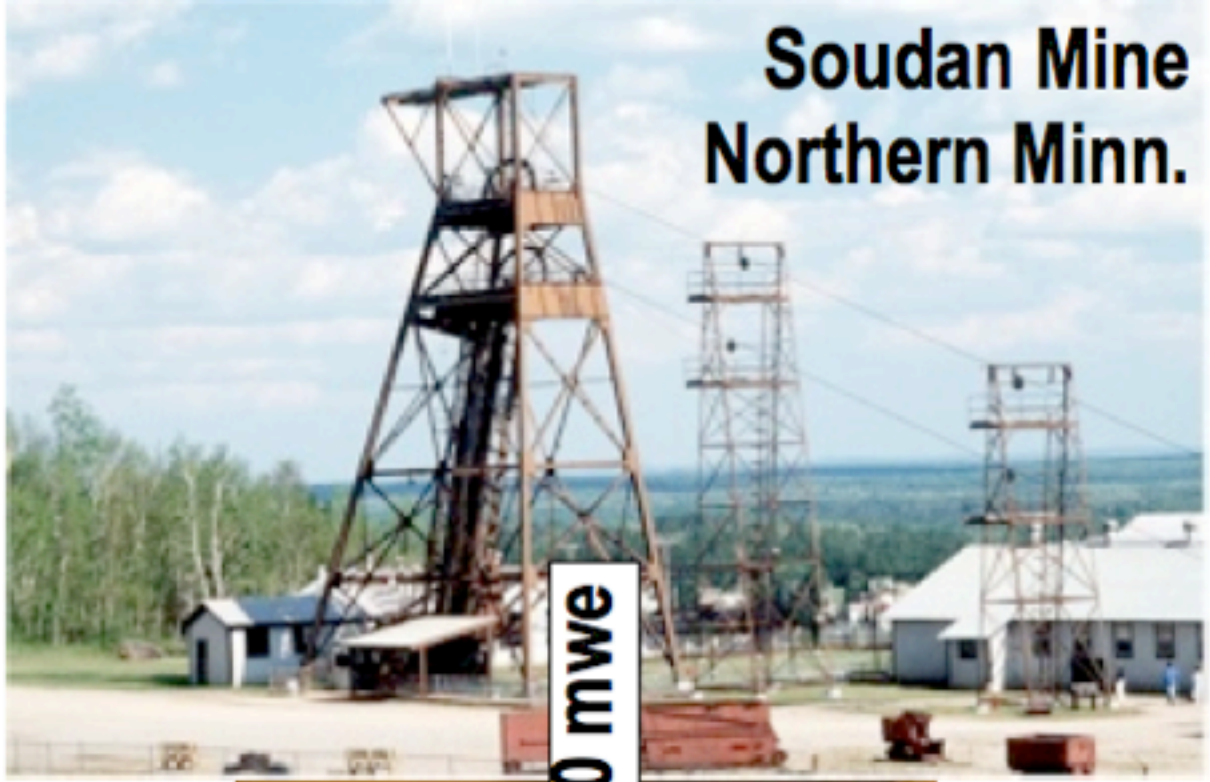
CDMS - Cryogenic DM Search

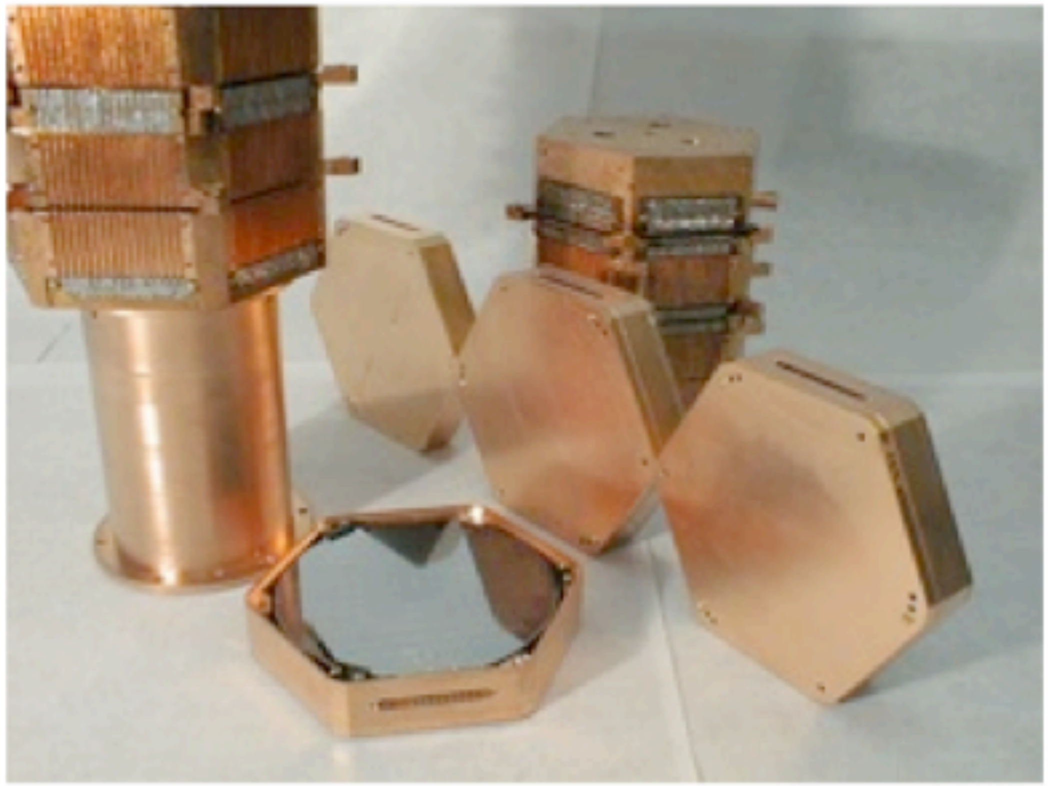
Berkeley-Stanford-led experiment has been at the forefront

Figure from: Perspective by Karl van Bibber http://physics.aps.org/viewpoint-for/10.1103/PhysRevLett.102.011301 on Z. Ahmed et al. CDMS Collaboration, “Search for Weakly Interacting Massive Particles with the First Five-Tower Data from the Cryogenic Dark Matter Search at the Soudan Underground Laboratory,” Phys. Rev. Lett. 102, 011301 (2009) – Published January 05, 2009

Schematic of an individual detector within CDMS. A WIMP scattering from a germanium nucleus produces a low-energy nuclear recoil, resulting in both ionization and athermal phonons. Charge carriers drift out to one face of the detector under the influence of a small electric field, and are detected with a sensitive amplifer [signal shown as Q(t)]. Phonons reaching the other face break Cooper pairs in a thin superconducting aluminum layer; the resulting quasiparticles heat a transition-edge sensor (TES) bonded to the aluminum layer, causing a measurable momentary change in its resistance R(t). In reality, the readout elements on both sides are highly segmented, and the relative timing of the ionization and phonon signals recorded, to provide good event localization.

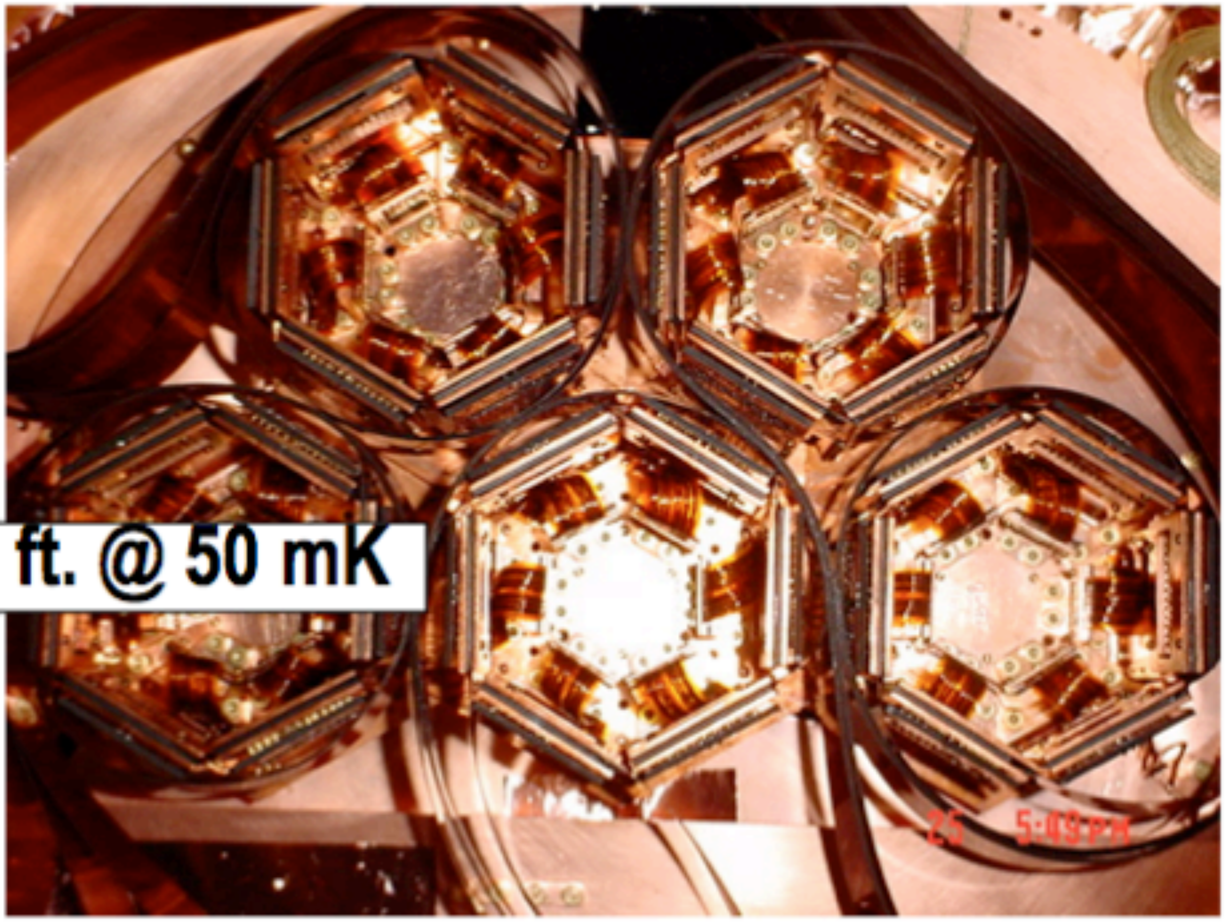
CDMS-II shielded underground detector array





2000 mwe

Cu ft. @ 50 mK



Slide from Sunil Golwal

From CDMS II to SuperCDMS and GEODM

CDMS II

⌀7.5cm x 1cm ZIP
0.25 kg/detector

16 detectors = 4 kg
2 yr, 1700 kg-d

SuperCDMS Soudan (G1)

⌀7.5cm x 2.5cm iZIP
0.64 kg/detector

15 detectors = 10 kg*
2 yr, 4000 kg-d

*iZIP has 2x larger fiducial efficiency than CDMS II ZIP

SuperCDMS SNOLAB (G2)

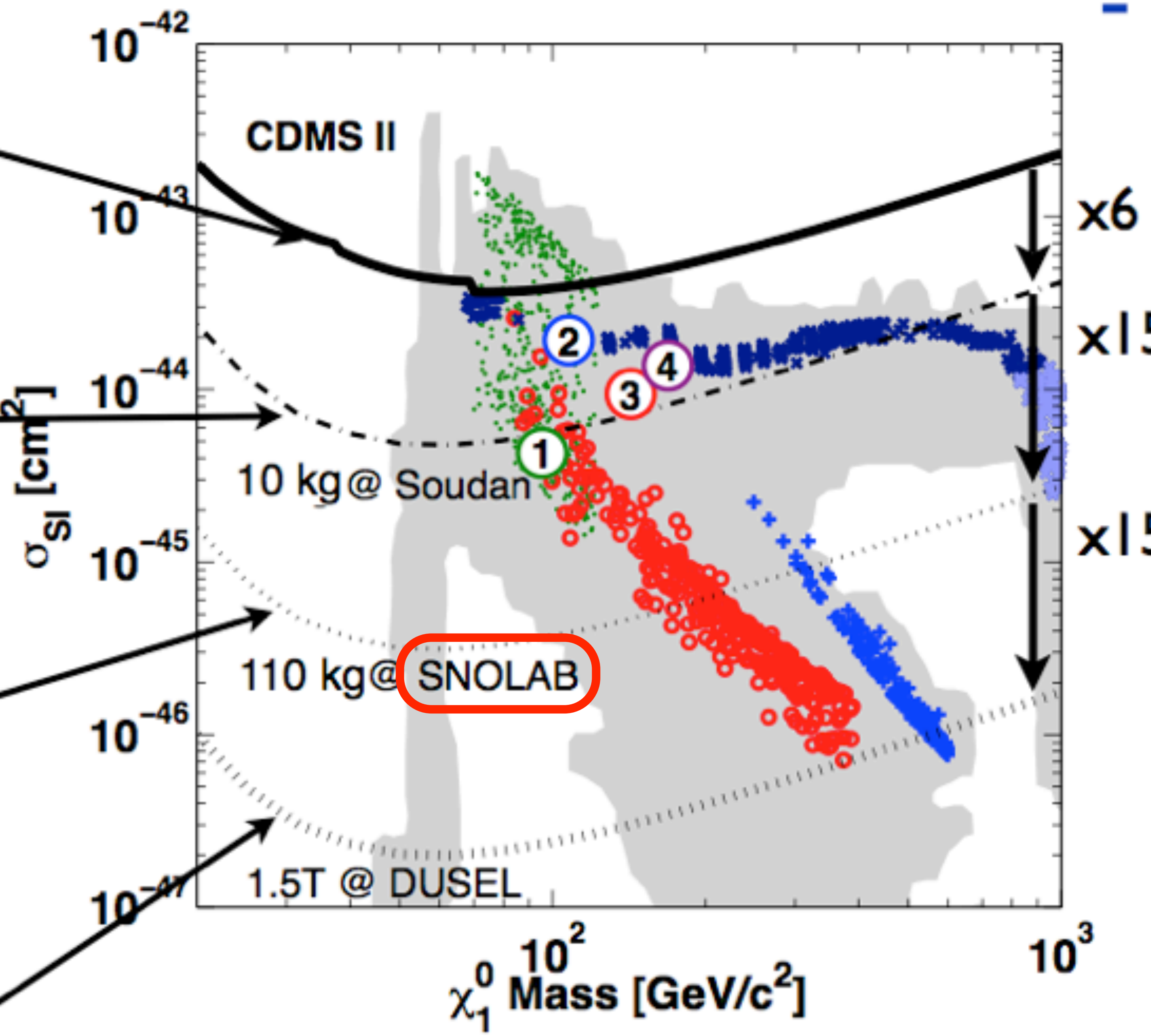
⌀10cm x 3.3cm iZIP
1.5 kg/detector

72 detectors = 110 kg
3 yr = 100,000 kg-d

GEODM (G3)

⌀15cm x 5cm iZIP
5.1 kg/detector

300 detectors = 1.5 T
3 yr, 1.5 M kg-d



Staged three-prong program to explore MSSM or study a signal:

- decreased backgrounds
- improved background rejection
- increase in mass/detector and decrease in cost/detector

< 1 event misid'd bgnd at each stage

SuperCDMS Future

Slide reformatted from
Sunil Golwala

- SuperCDMS Soudan (G1)
  - 15 iZIP detectors being commissioned, science running to begin soon
  - 2 yrs, ~4000 kg-d raw exposure expected
  - sensitivity will be set by residual radiogenic neutron background:
    - 5 x 10^{-45} cm^2 (0 events) to 8 x 10^{-45} cm^2 (expected bgnd)
- SuperCDMS SNOLAB (G2)
  - 2 SuperCDMS Soudan detectors with ^{210}Pb sources will establish rejection needed for SuperCDMS SNOLAB (~10^{-5})
  - R&D toward 10 cm x 3.3 cm detectors funded, actively pushing development of:
    - crystal quality demonstration from vendors with ionization-only tests
    - phonon sensor design
    - cryogenic electronics and hardware and 300K electronics
    - shielding/cryostat design incl. possible neutron veot
  - Will propose to 2012 NSF and DOE solicitations, hope for construction start FY14
- GEODM
  - Planning to continue in parallel “G3 long-term R&D” on 15-cm diameter crystals, multiplexed and alternate forms of phonon and ionization readout, shielding and cosmogenic neutron studies.


SNOLAB
MINING FOR KNOWLEDGE
CREUSER POUR TROUVER... L'EXCELLENCE

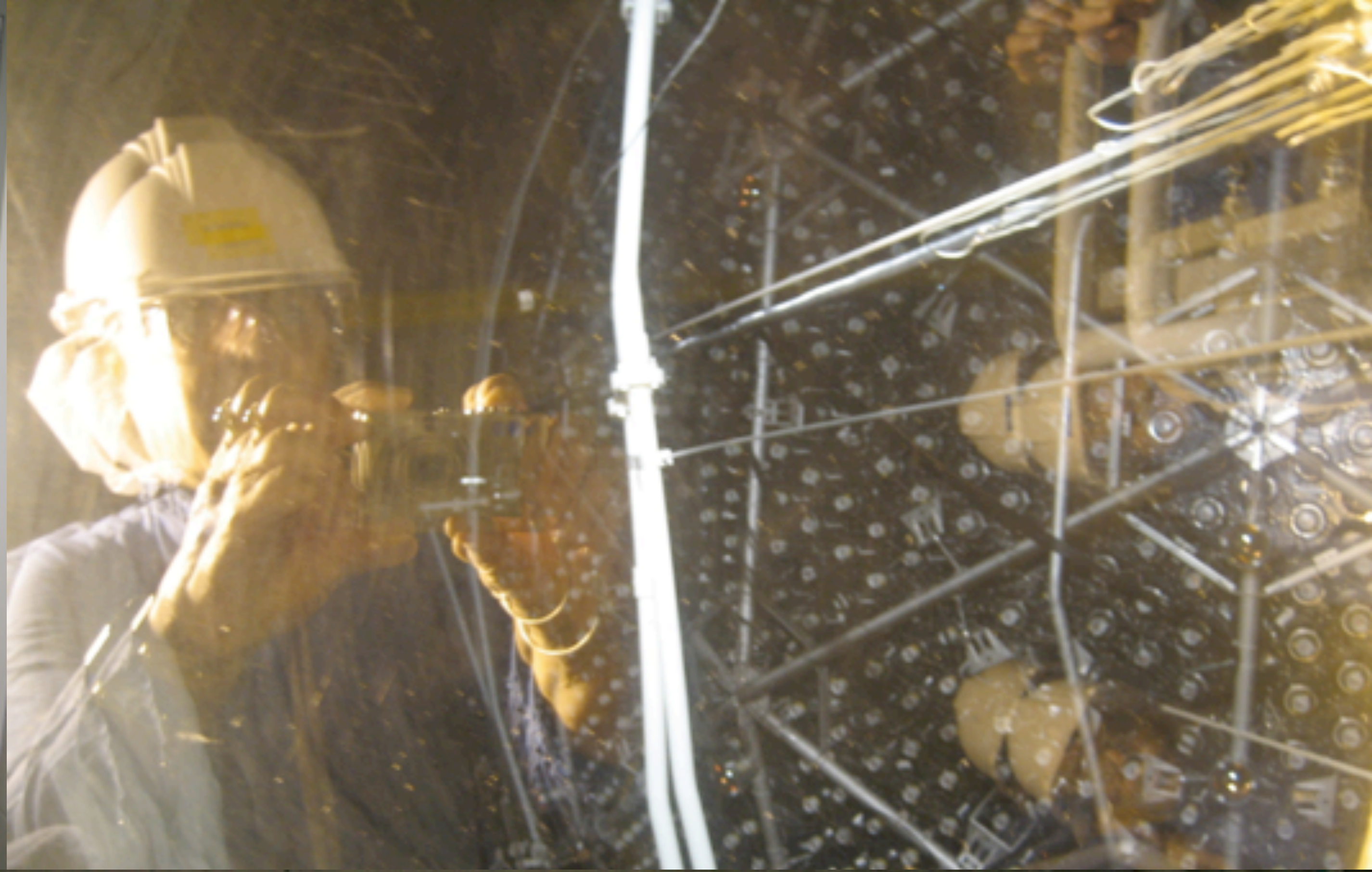

SURFACE


4000 LBS MAX
X5


AUG 9
SNO


USE AIR SHO
IMUM
OPLE
N
HOWER
OFF

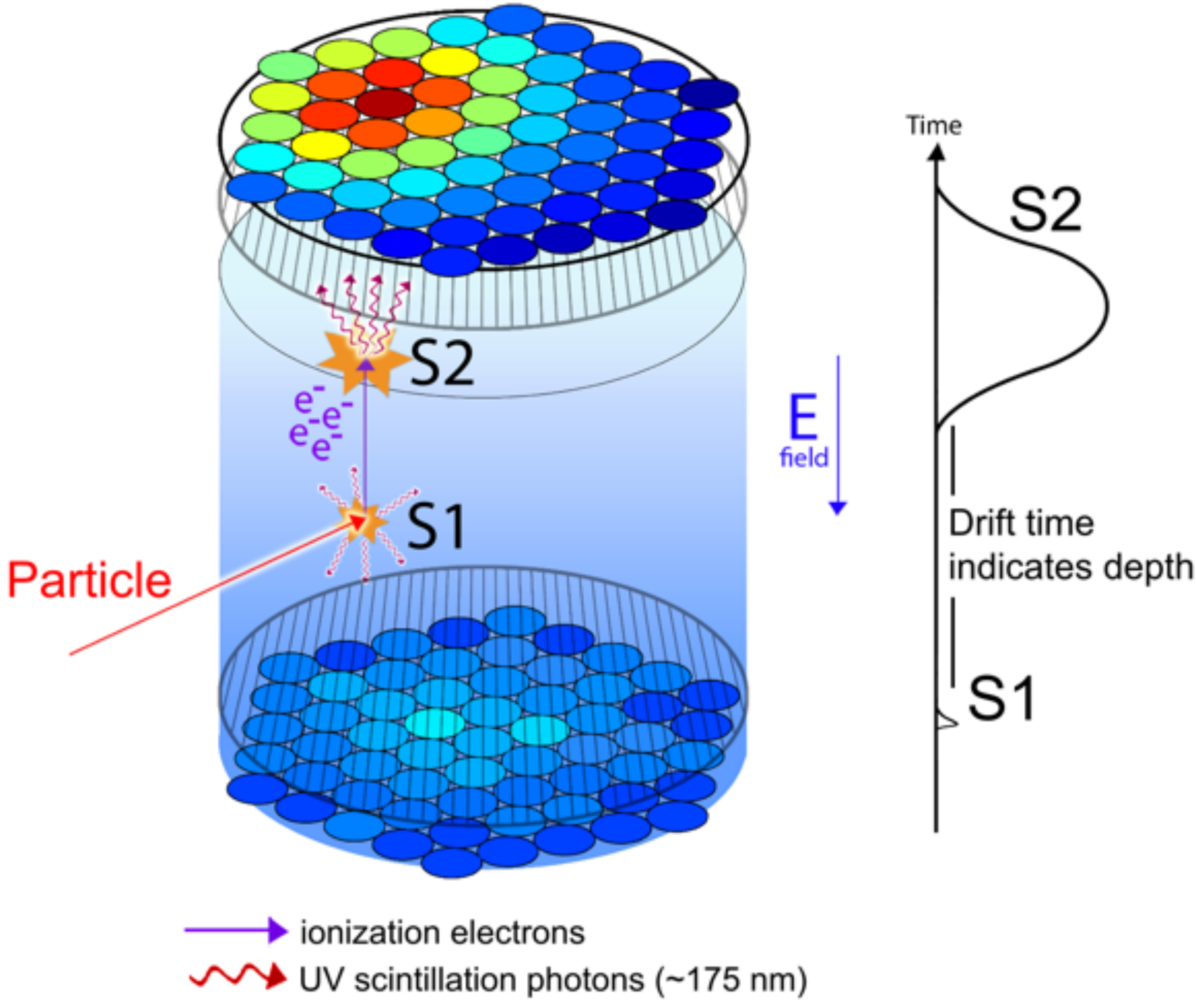

USE AIR SHOWER

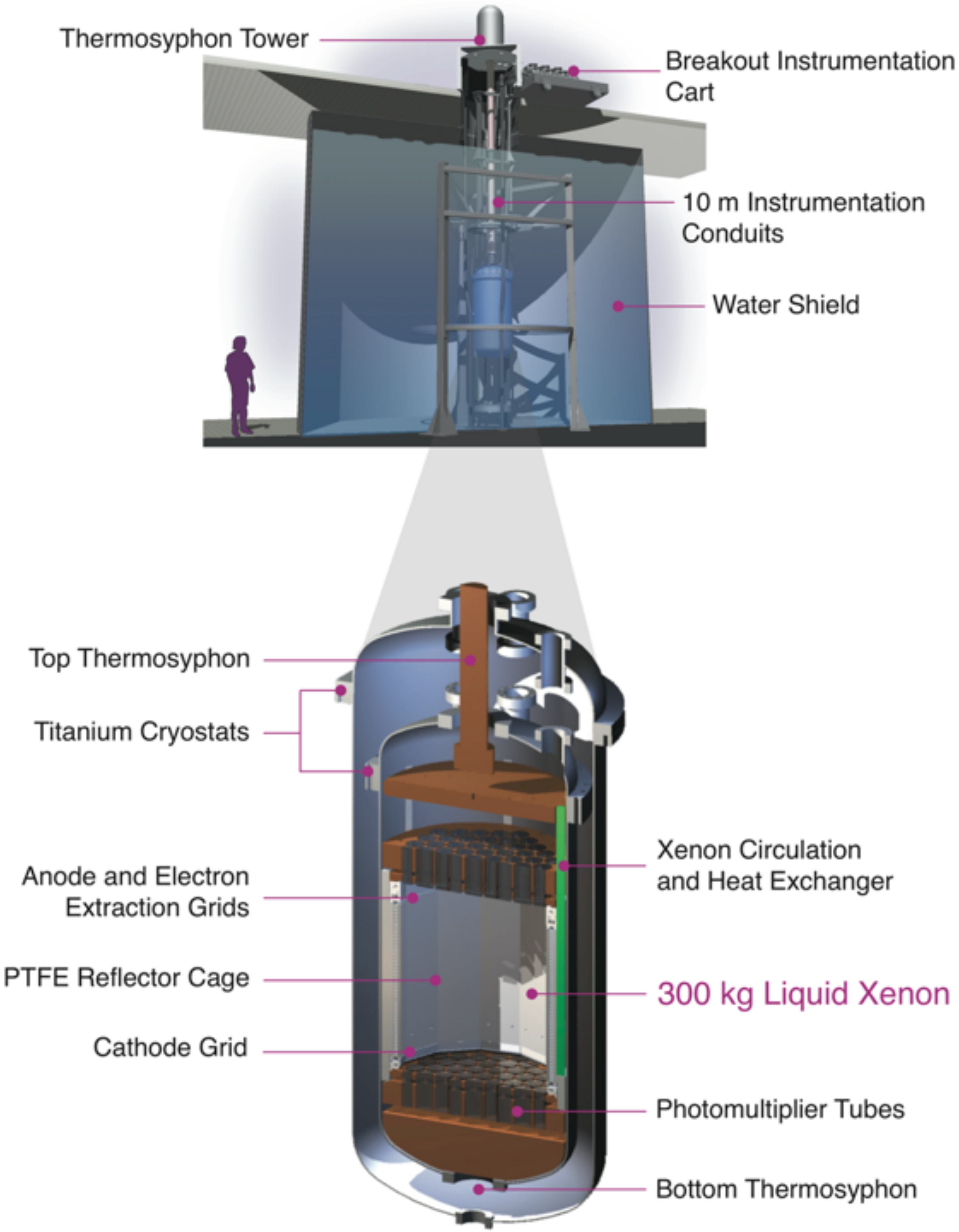


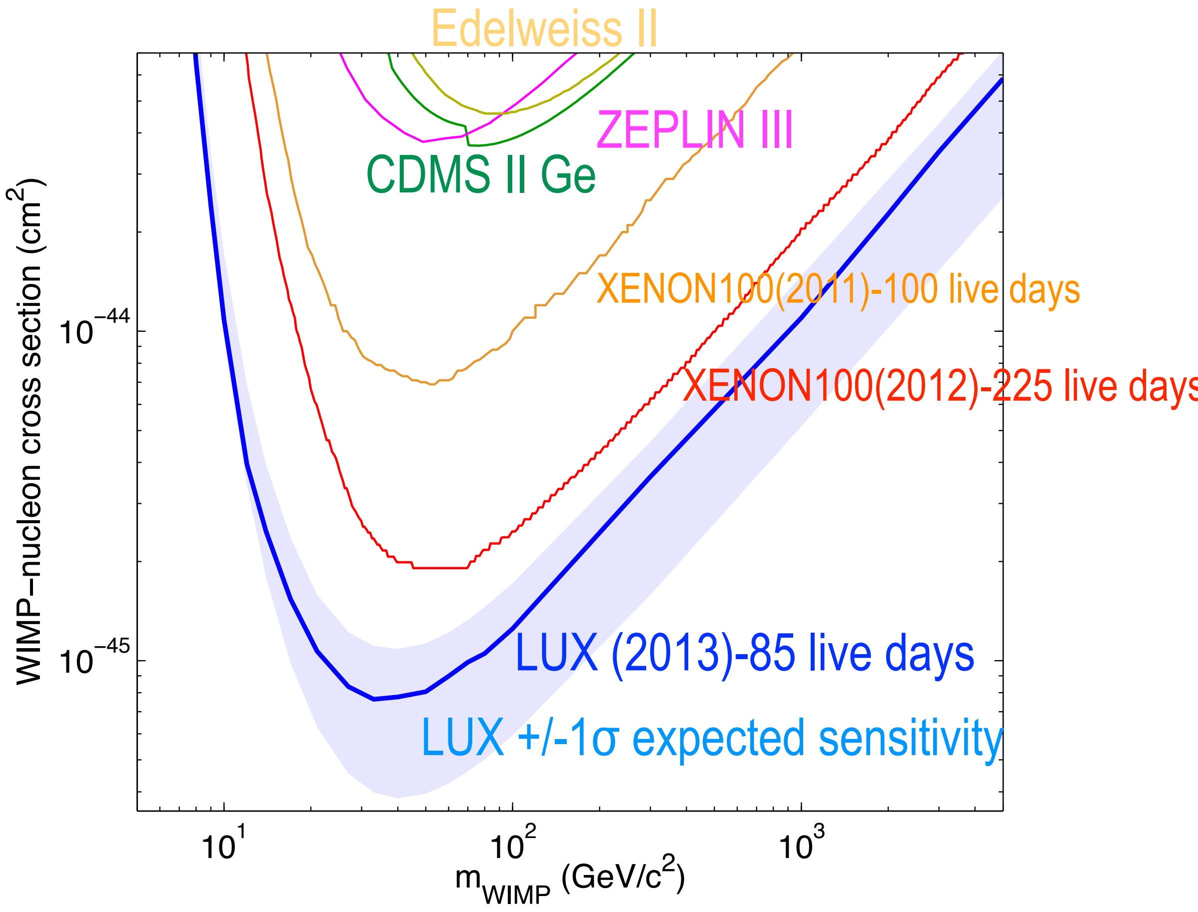

SEARCH FOR DARK MATTER WITH Picasso
THE DARK MATTER PROBLEM
THE PICASSO EXPERIMENT
RESULTS AND FUTURE PLANS

The LUX Dark Matter Detector

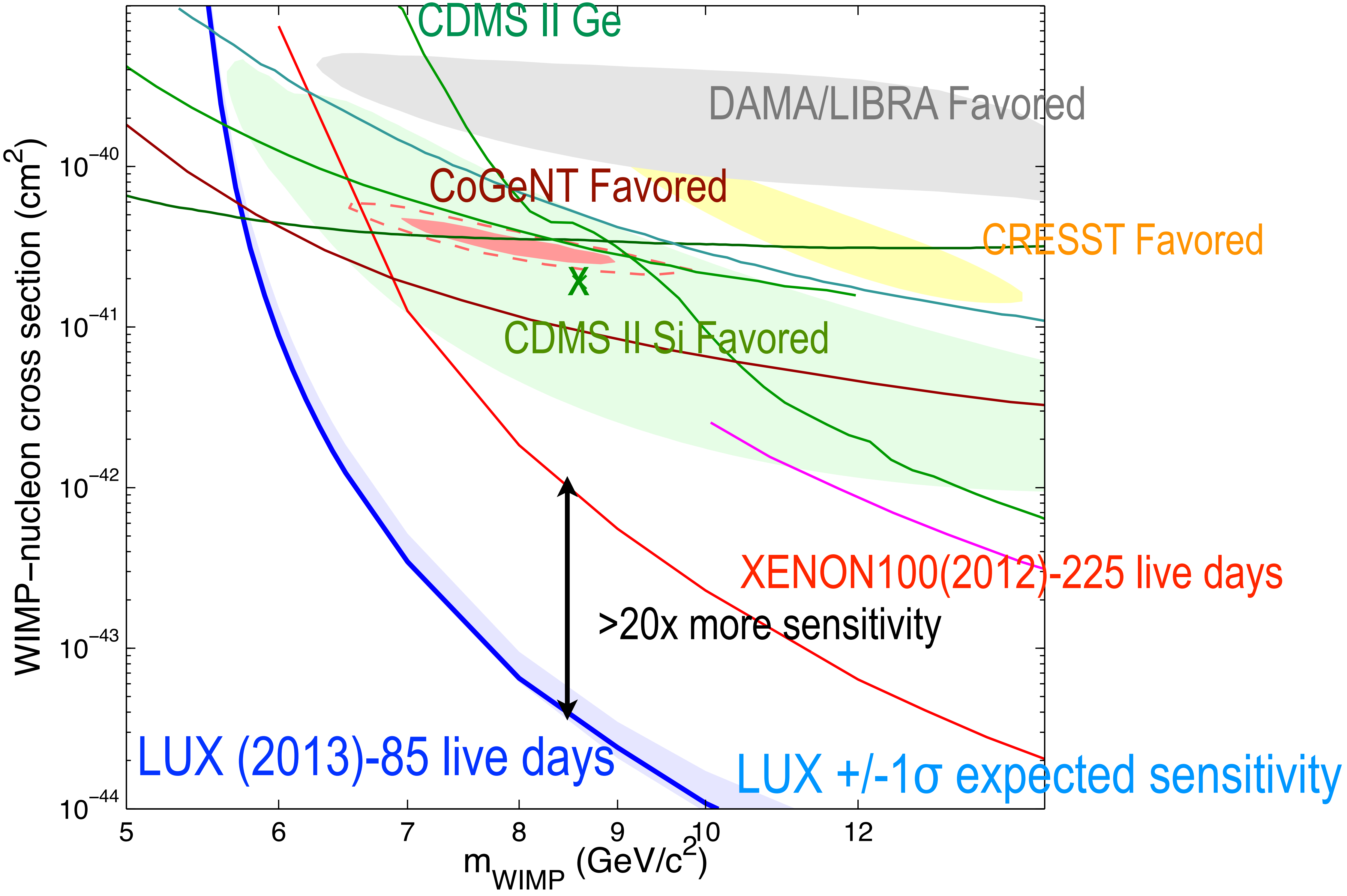
- What is LUX?
  - a particle detector
  - a monolithic wallless fiducial region within 370 kg Xe TPC
  - viewed by 122 Photomultiplier Tubes
  - able to reconstruct (x,y,z) for each event
  - exceptional self-shielding from outer xenon layer
  - discrimination between electronic and nuclear recoils (99.6%)
- How would LUX see dark matter?
  - it detects scintillation photons and ionized electrons created by particle interactions
  - if dark matter interacted with a xenon atom, energy transferred to that atom would be visible to LUX
  - $\alpha_1 \sim O(0.10)$ and $\alpha_2 \sim O(10)$ are the amplification factors for each quanta
  - n_γ and n_e are the fundamental measured quantities




Thermosyphon Tower
Breakout Instrumentation Cart
10 m Instrumentation Conduits
Water Shield
Top Thermosyphon
Titanium Cryostats
Anode and Electron Extraction Grids
PTFE Reflector Cage
Cathode Grid
Xenon Circulation and Heat Exchanger
300 kg Liquid Xenon
Photomultiplier Tubes
Bottom Thermosyphon

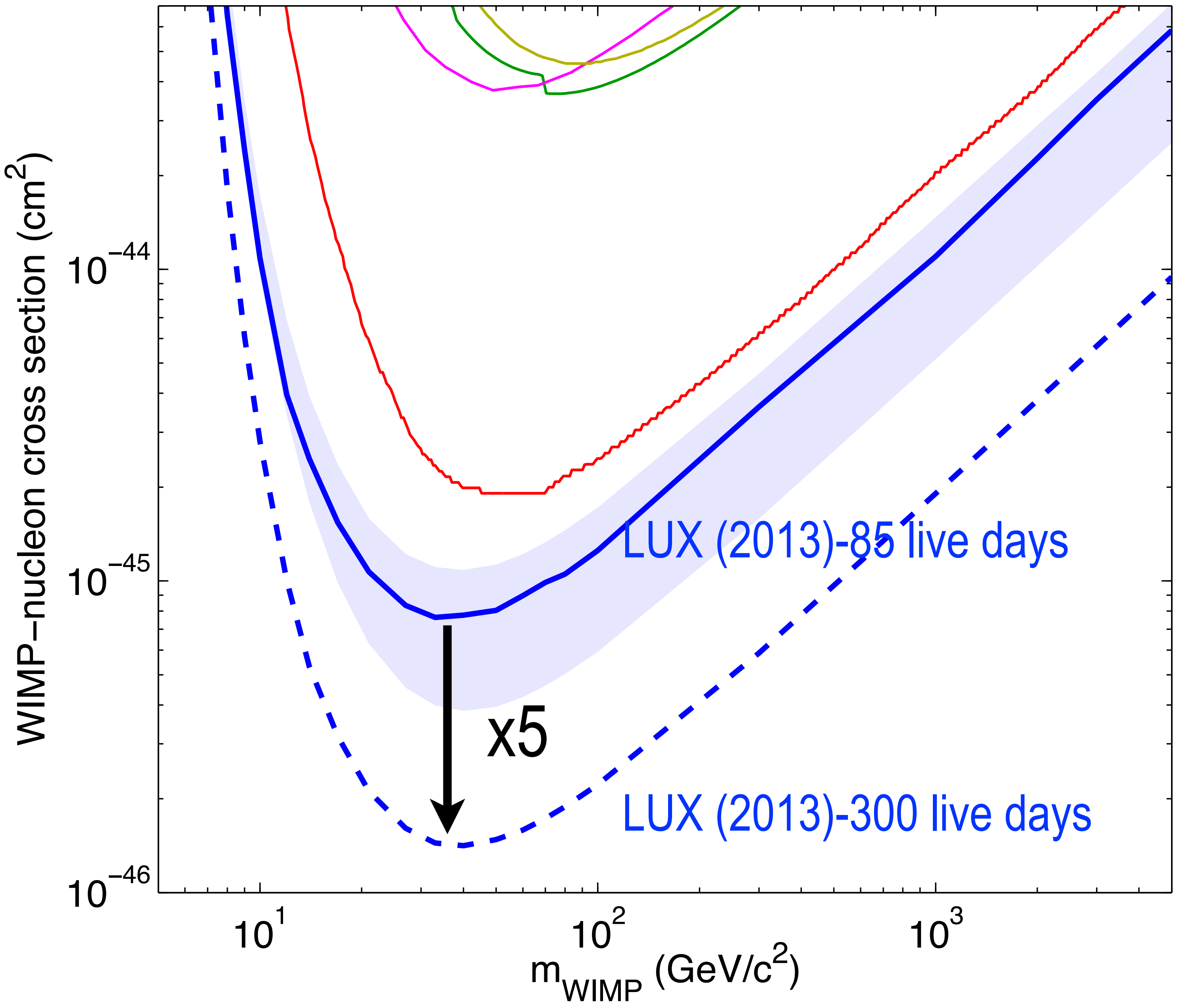

Edelweiss II
ZEPLIN III
CDMS II Ge
XENON100(2011)-100 live days
XENON100(2012)-225 live day
LUX (2013)-85 live days
LUX +/-1σ expected sensitivity
WIMP–nucleon cross section (cm^2)
10^{-44}
10^{-45}
10^1
10^2
10^3
m_{WIMP} (GeV/c^2)

Low Mass WIMPs - Fully Excluded by LUX



Projected LUX 300 day WIMP Search Run

- We intend to run LUX for a new run of 300 days in 2014/15
    - Extending sensitivity by another factor 5
    - Even though LUX sees no WIMP-like events in the current run, it is still quite possible to discover a signal when extending the reach
    - LUX does not exclude LUX
- WIMPs remain our favored quarry
- LZ 20x increase in target mass
    - If approved plans to be deployed in Davis Lab in 2016+



past
(2005 - 2007)

XENON10

Achieved (2007) $\sigma_{SI}=8.8 \times 10^{-44}$ cm^2

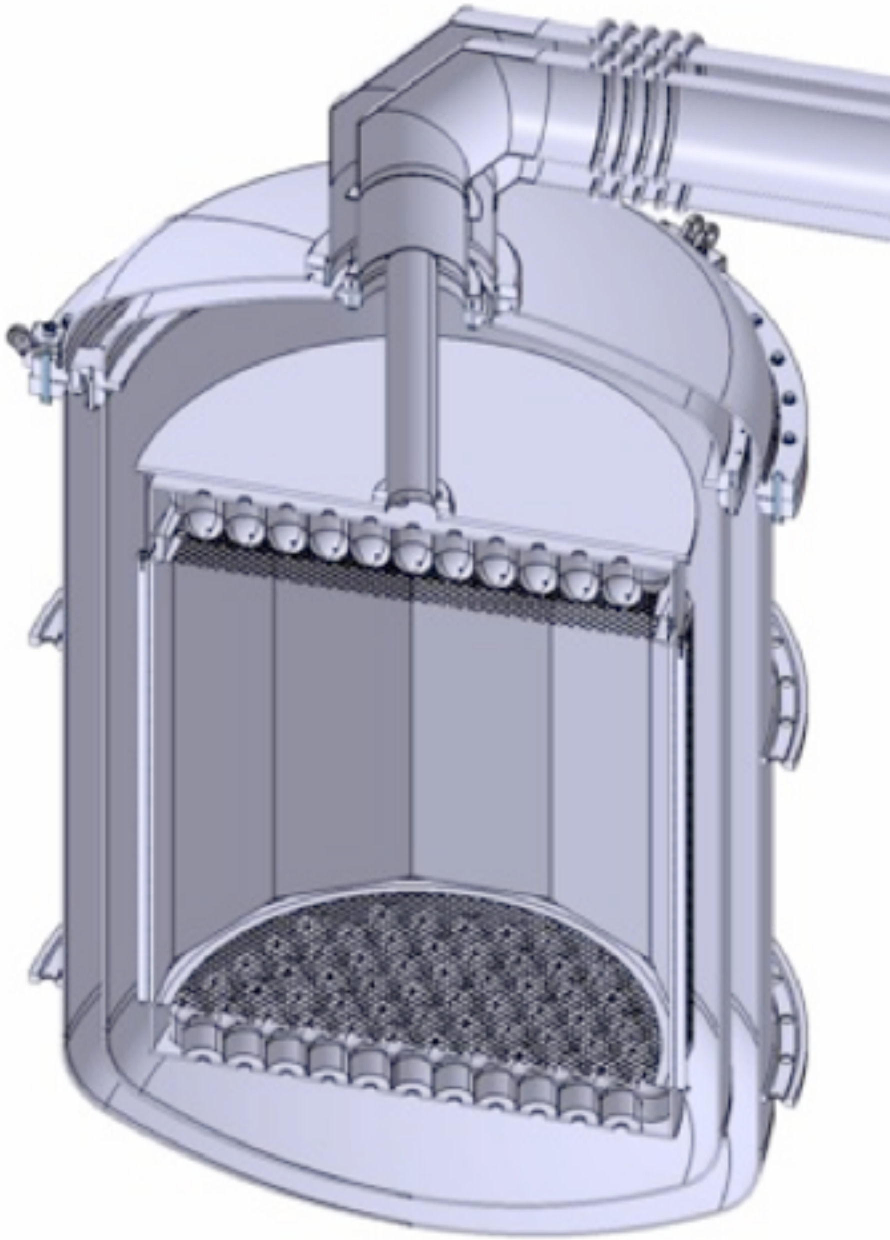
Phys. Rev. Lett. **100**, 021303 (2008)
Phys. Rev. Lett. **101**, 091301 (2008

current
(2007-2012)

XENON100

Achieved (2011) $\sigma_{SI}=7.0 \times 10^{-45}$ cm^2
Projected (2012) $\sigma_{SI} \sim 2 \times 10^{-45}$ cm^2

future
(2012-2017)



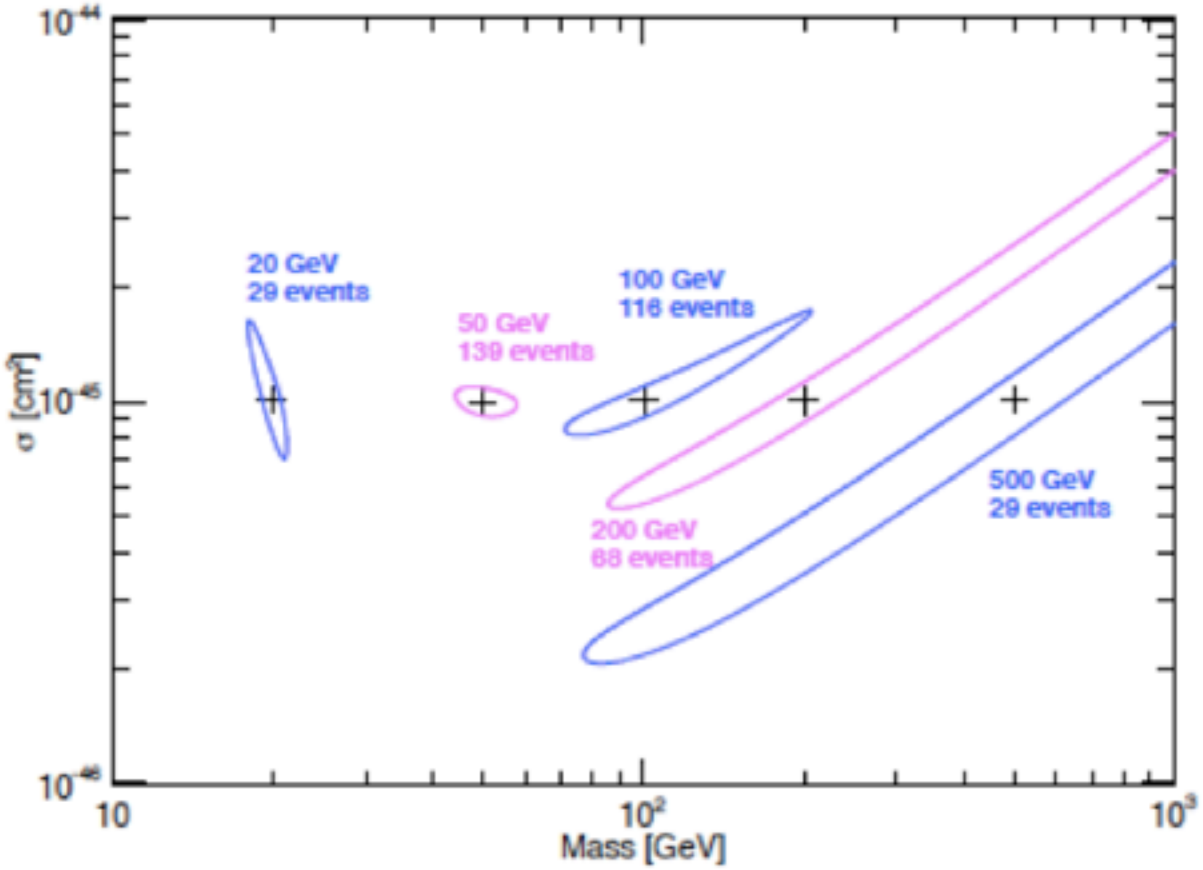
XENON1T

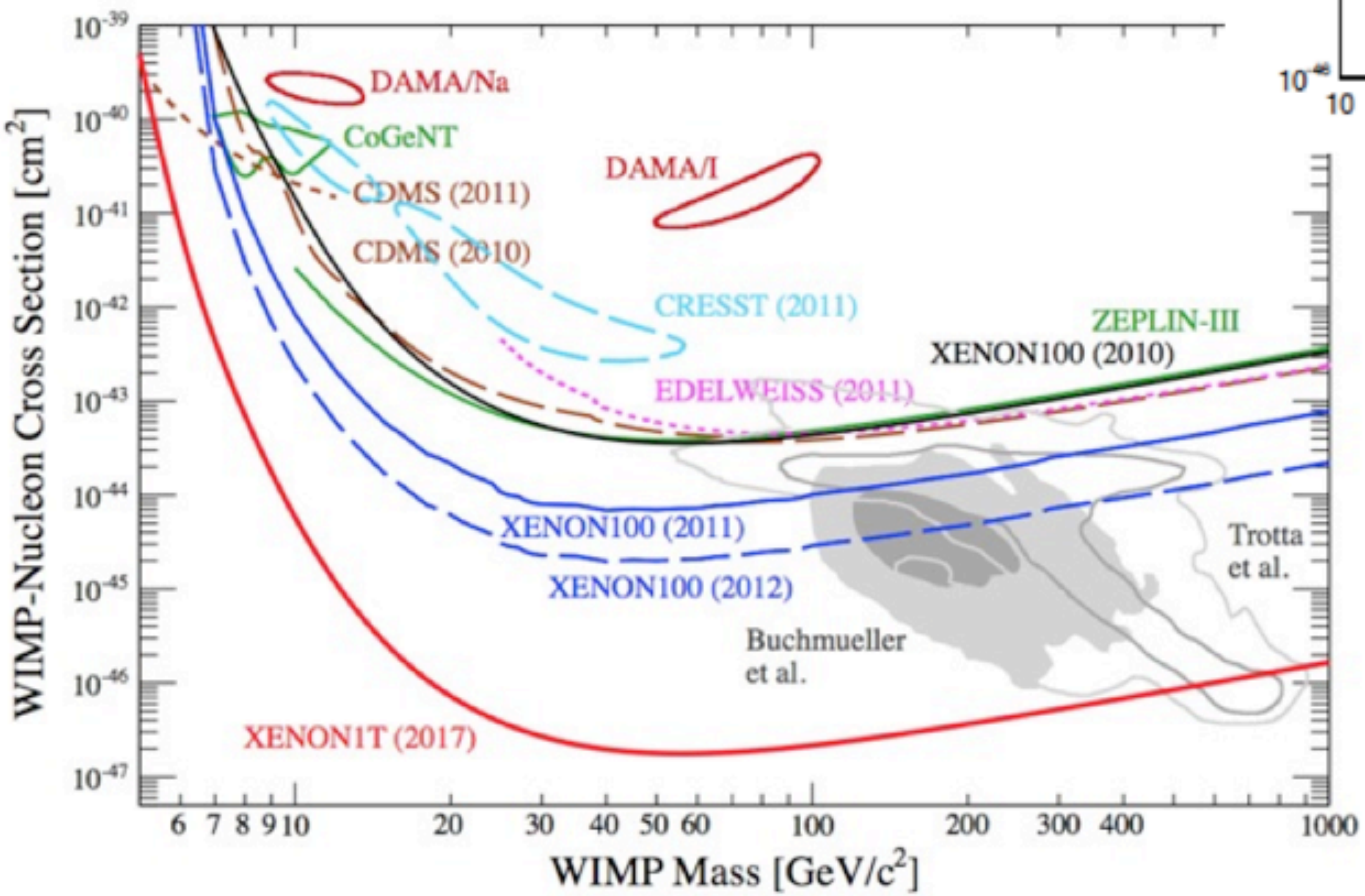
Projected (2017) $\sigma_{SI} \sim 10^{-47}$ cm^2

The XENON1T Science Case

a statistically significant WIMP signal after 2.2 ton-years of data

~100 events if cross section at 10^{-45} cm^2





two orders of magnitude improvement in SI cross-section sensitivity w/r to XENON100

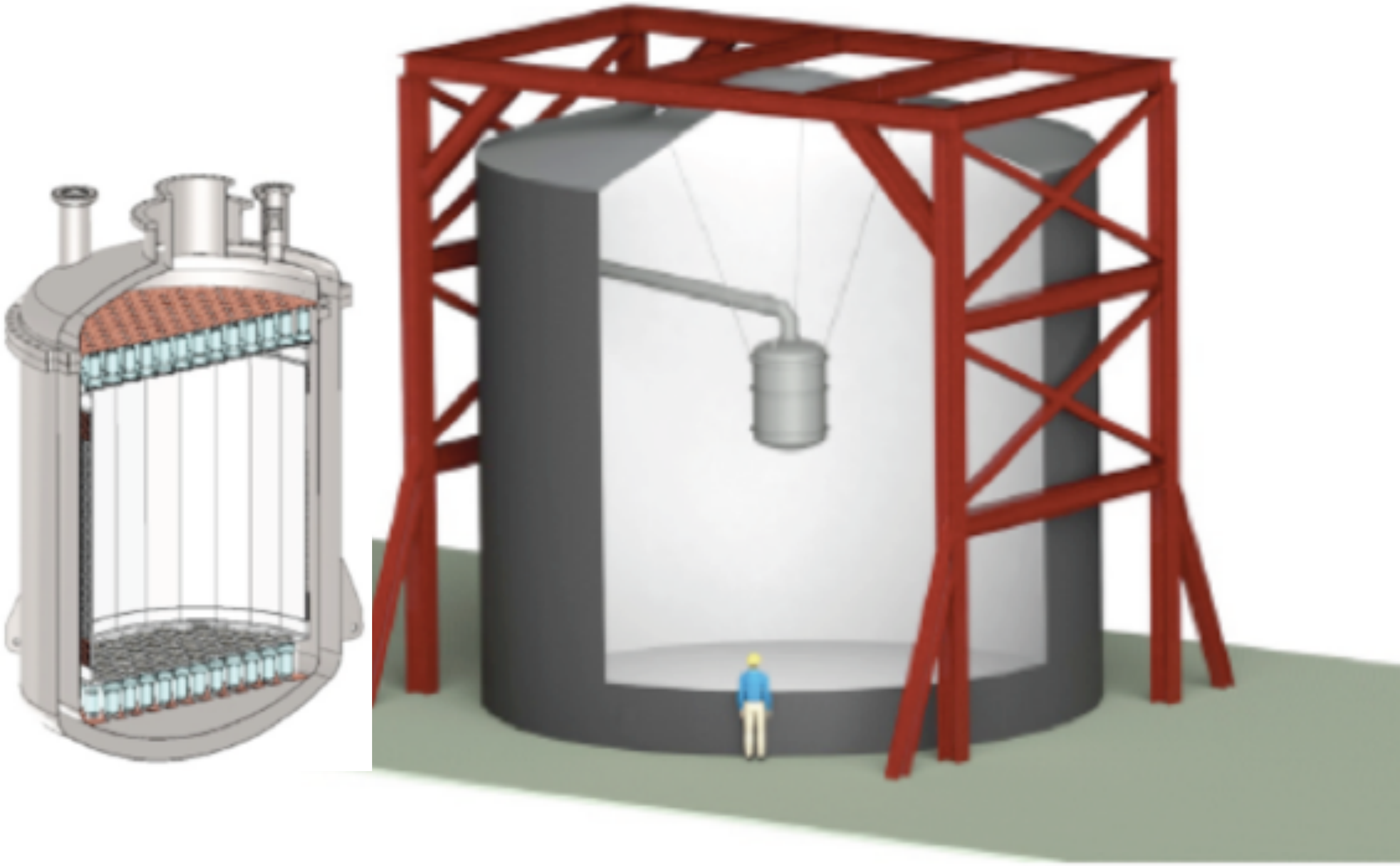
XENON1T: OVERVIEW

- Detector: 1m drift TPC with 2.2 ton LXe target
- Shield: ~10 m x 10 m Water Cherenkov Muon Veto
- Background: 0.01 mdru (100 lower than XENON100
- Location: approved by INFN for LNGS Hall B
- Capital Cost: ~11 M$ (50% US and 50% non-US)
- Status: Construction start in Fall 2012
- Science Run: projected to start in 2015
- Sensitivity: 2 x 10^{-47} cm^2 at 50 GeV with 2.2 ton-years

COLUMBIA RICE UCLA PURDUE ZURICH COIMBRA

LNGS INFN MPIK BOLOGNA SJTU

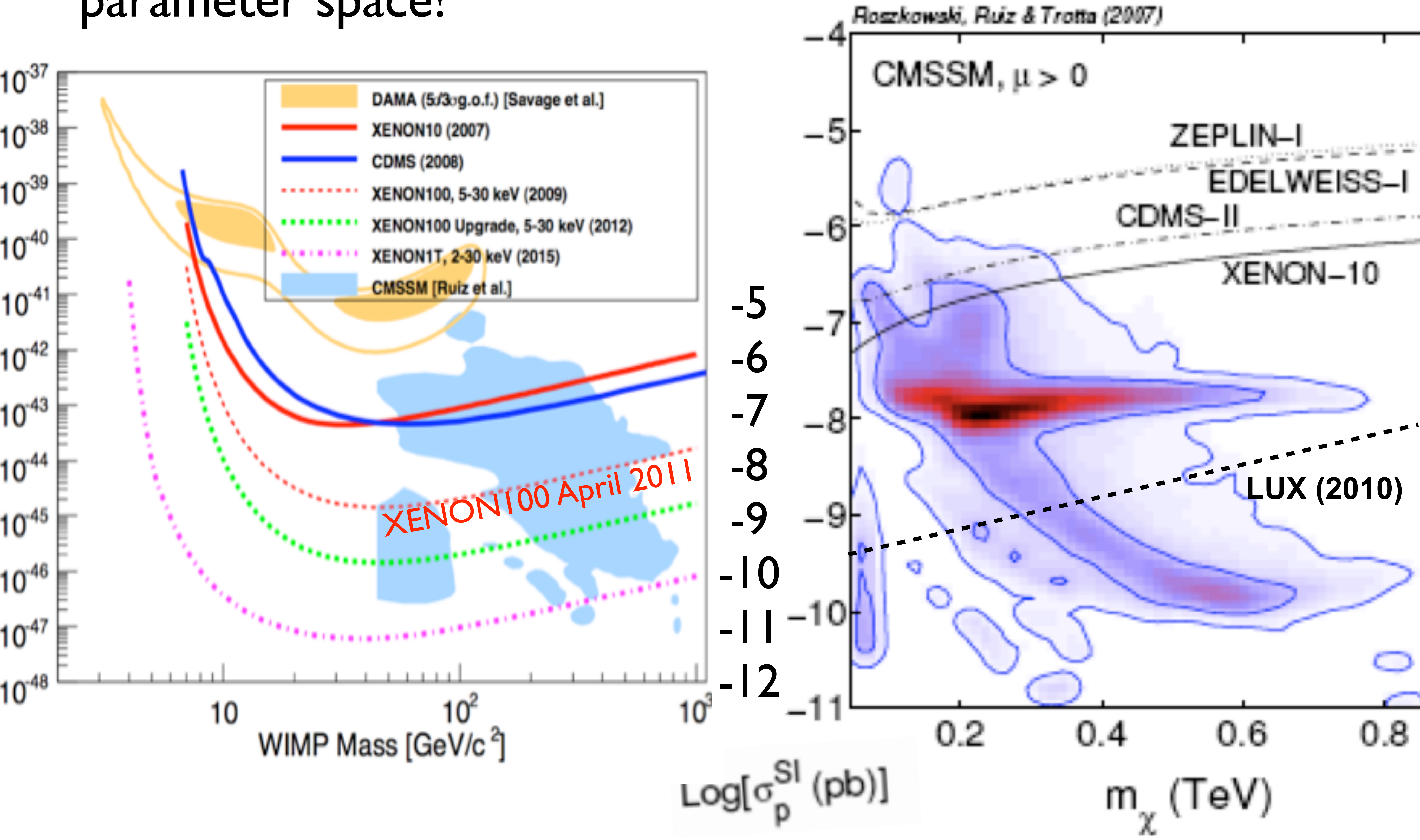
MUENSTER SUBATECH NIKHEF WEIZMANN



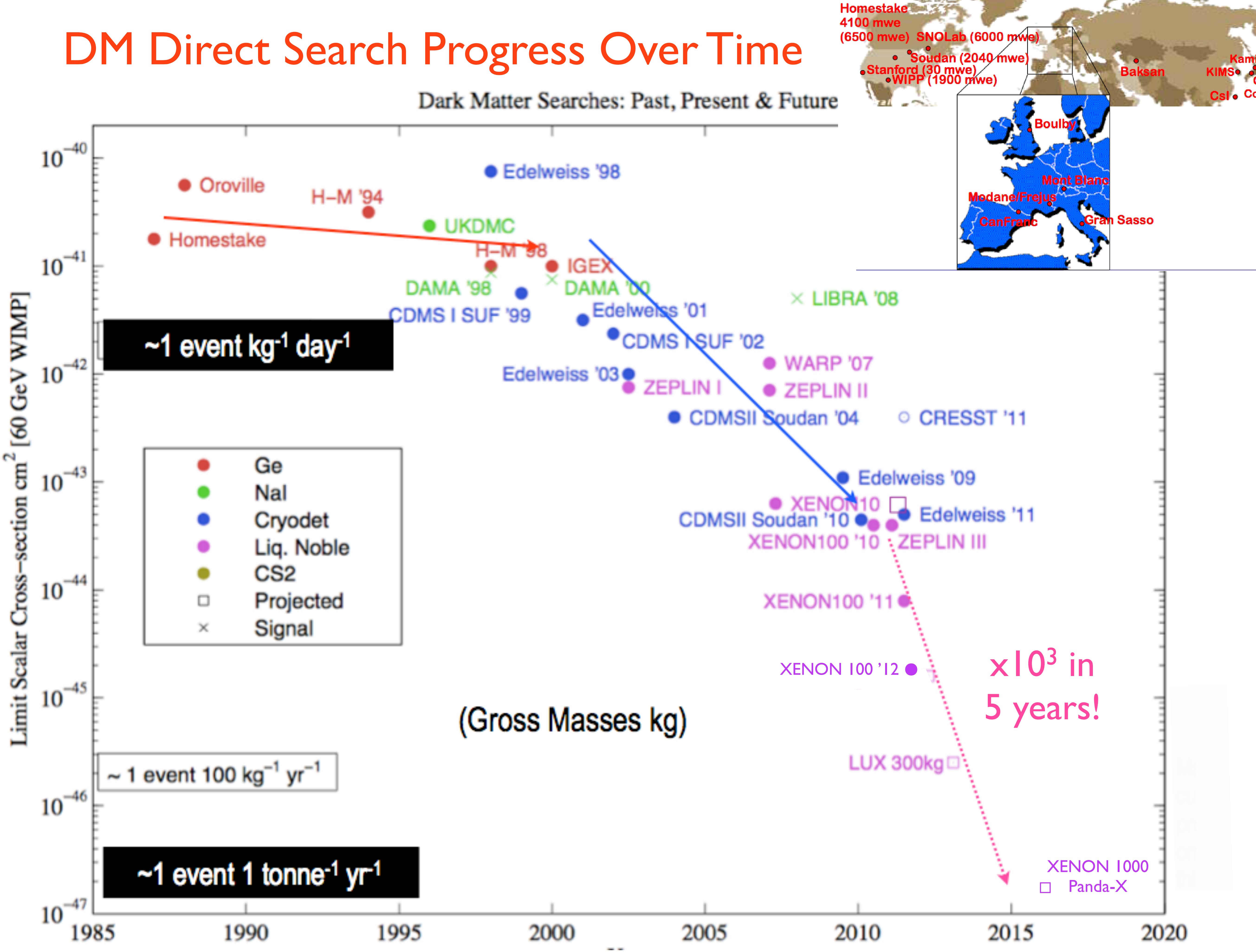
LNGS Underground Laboratory – Hall B

LNGS Underground Laboratory – Hall B

By ~2015 Direct Detection could probe most of the CMSSM (constrained minimal supersymmetric standard model) and mSUGRA (minimal supergravity) WIMP parameter space!

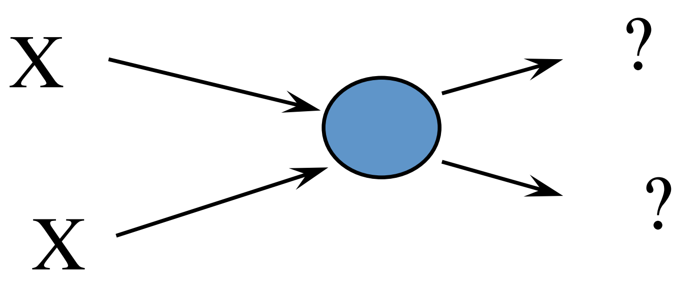


DM Direct Search Progress Over Time



Indirect Detection of Dark Matter

Some important models in particle physics could also solve the dark matter problem in astrophysics. If correct, these new particle interactions could produce an anomalous flux of cosmic particles (“indirect detection”).



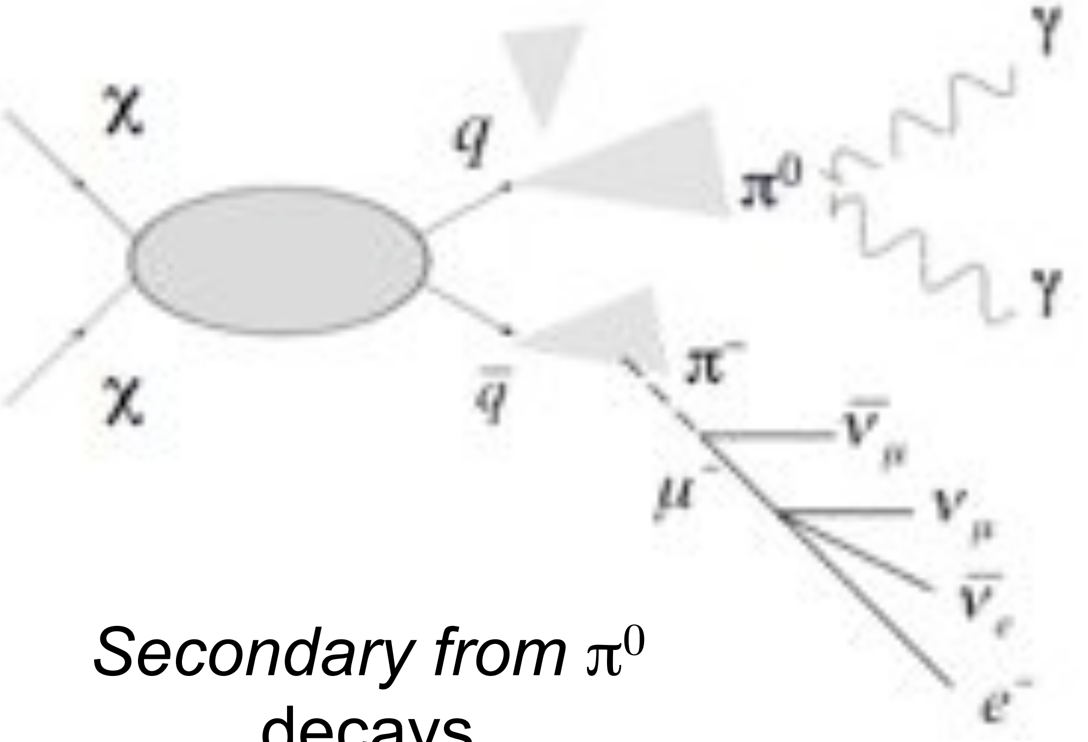
Anomalous gamma ray spectra and/or $\gamma\gamma$ or $Z\gamma$ “lines” and/or anomalous charged cosmic rays and/or neutrinos?

- If particles are stable: rate ~ (DM density)^2
- If particles unstable: rate ~ (DM density)

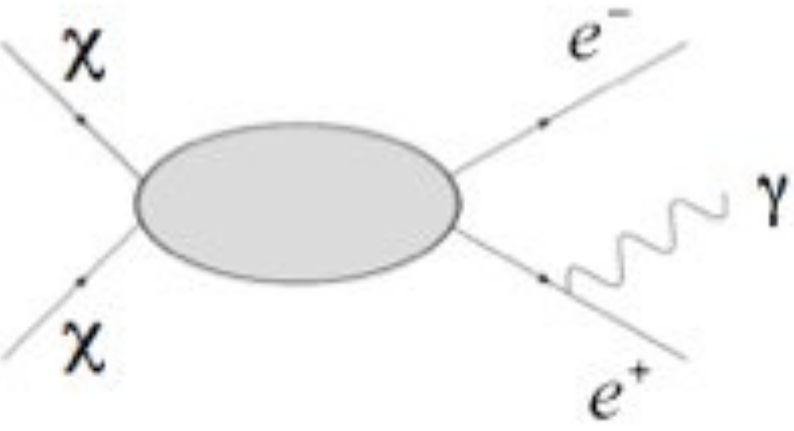
- Key interplay of techniques:
  - colliders (TeVatron, LHC)
  - direct detection experiments underground
  - indirect detection (most straightforward: gamma rays and neutrinos)
    - Full sky coverage look for clumping throughout galactic halo, including off the galactic plane (if found, point the way for ground-based facilities)
    - Intensity highly model-dependent
    - **Challenge is to separate signals from astrophysical backgrounds**

Steve Ritz

Gamma rays from Dark Matter annihilation



Secondary from π^0
decays



Prompt lepton
pair production

+ “lines” from 2-body final states

$$\Phi_{WIMP}(E,\Psi)=J(\Psi)\times\Phi^{PP}(E)$$

Astrophysical
factor

$$J(\Psi)=\int_{l.o.s} dl(\Psi)\,\rho^2(l)$$

Particle physics
factor

$$\Phi^{PP}(E)=\frac{1}{2}\frac{\langle\sigma v\rangle}{m^2_{WIMP}}\sum_f\frac{dN_f}{dE}B_f$$

Steve Ritz

Dark Matter: Many Places to Look!

Galactic Center

Good Statistics but source confusion/diffuse background

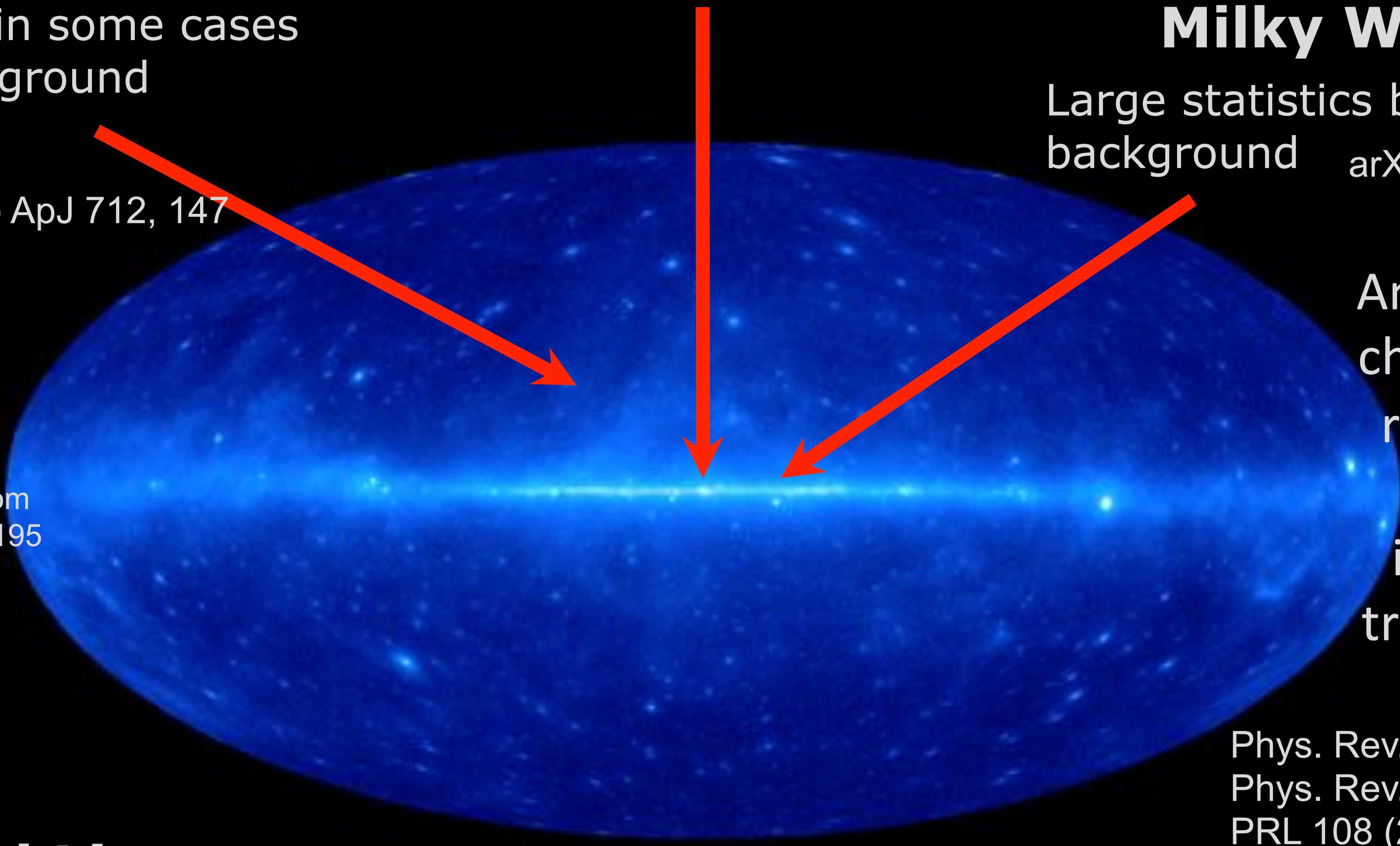
Satellites

Low background and good source id, but low statistics, in some cases astrophysical background

JCAP 1204 (2012) 016
ApJ 747, 121 (2012)
PRL 107, 241302 (2011) ApJ 712, 147 (2010)
JCAP 01 (2010) 031
ApJ 718, 899 (2010)

Milky Way Halo

Large statistics but diffuse background arXiv:1205.6474



All-sky map of gamma rays from DM annihilation arXiv:0908.0195 (based on Via Lactea II simulation)

And anomalous charged cosmic rays (little/no directional information, trapping times, etc.)

Phys. Rev. D84, 032007 (2011
Phys. Rev. D82, 092003 (2010
PRL 108 (2012)

Spectral Lines

No astrophysical uncertainties, good source id, but low sensitivity because of expected small BR

Phys. Rev. D, In press (2012)
Phys. Rev. Lett. 104, 091302 (2010)

Galaxy Clusters

Low background, but low statistics

JCAP 05 (2010) 025

Extragalactic

Large statistics, but astrophysics, galactic diffuse background JCAP 04 (2010) 014

Steve Ritz

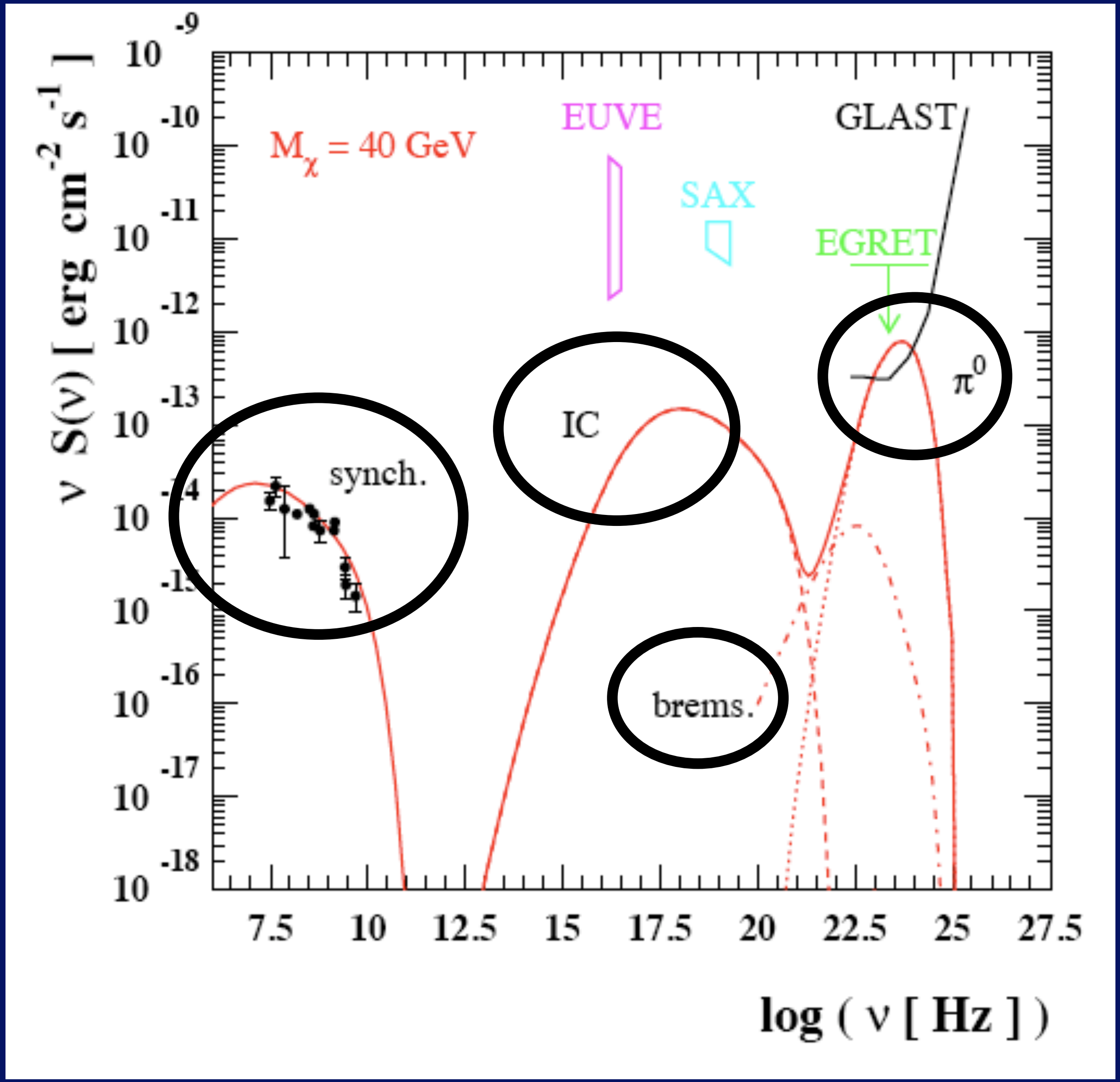
Observing Dark Matter

- Dark matter annihilation/decay can lead to a broad spectrum of emission.

Gamma-ray: π^0 decay,
direct production

X-ray: IC scattering of CMB by
energetic e^+e^- produced

Radio: synchrotron emission in
a magnetic field



Example spectrum of DM annihilation in the Coma cluster (Colafrancesco et al. 2006)

Gamma-Ray Searches with Fermi

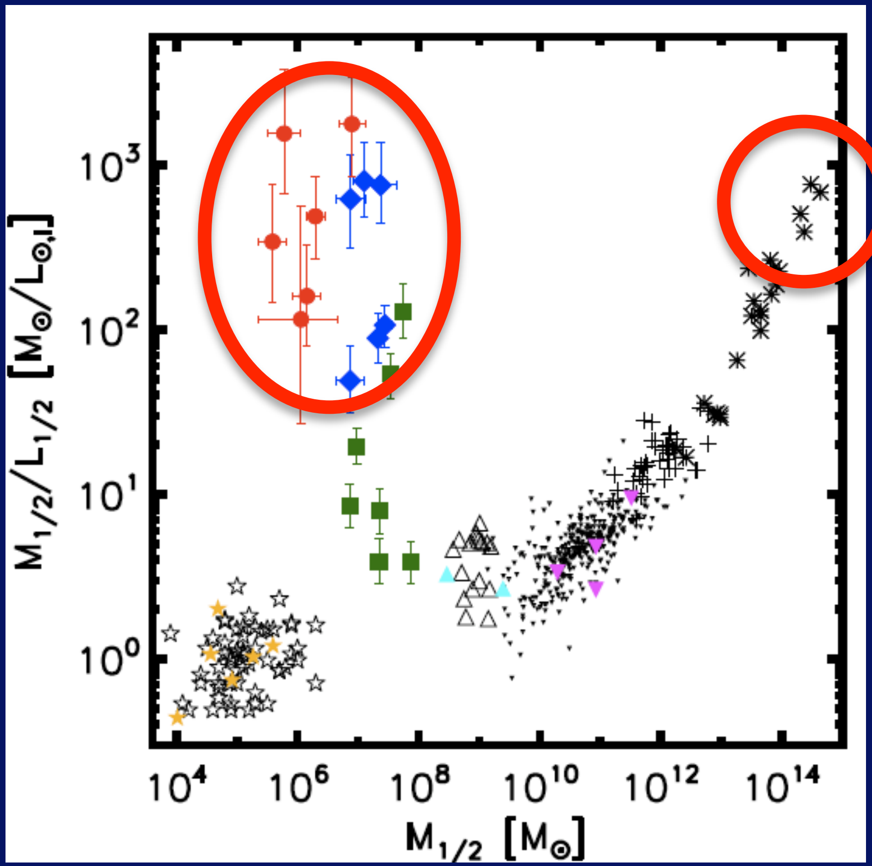
Dwarf spheroidal galaxies give strong constraints on dark matter annihilation.

Clusters of galaxies constrain:

- dark matter decay
- leptophilic dark matter when IC emission dominate (models fitting the PAMELA positron excess)

(Abdo et al. 2010; Ackermann et al. 2010; Dugger, Jeltema, & Profumo 2010; Ackermann et al. 2011)

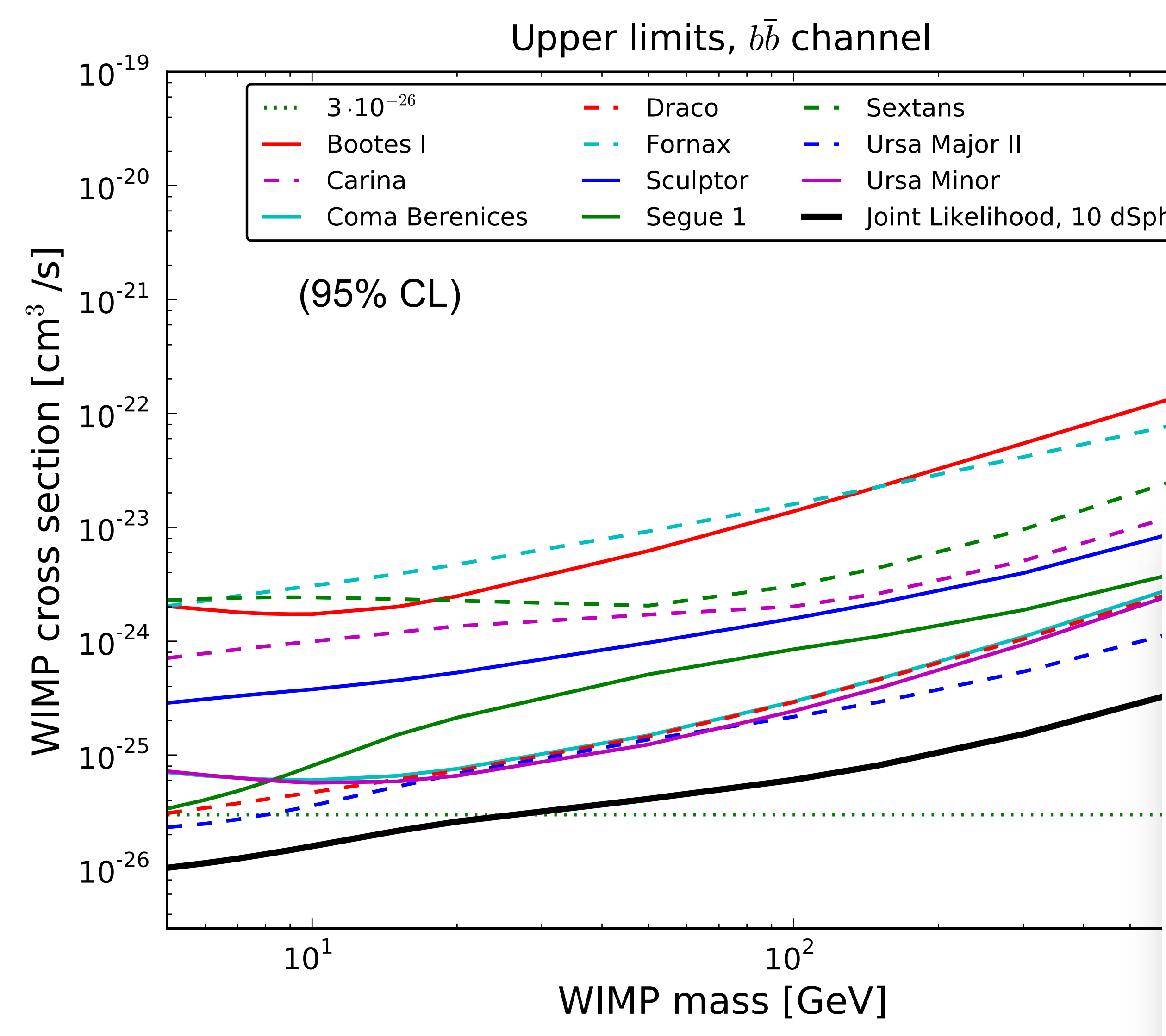
dwarfs clusters

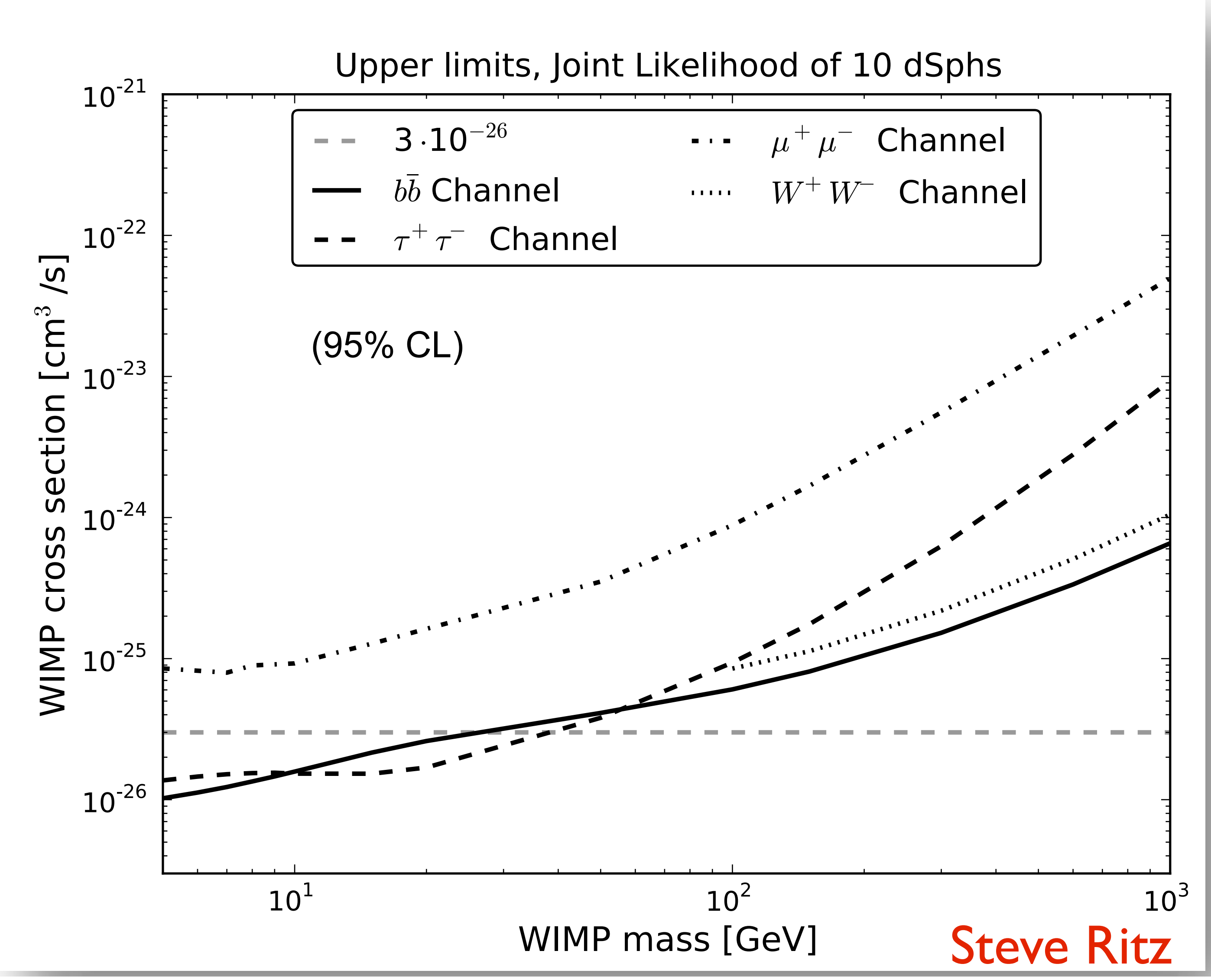


Wolf et al. 2009

Combining dSph Limits

PRL 107(2011)
arXiv:1108.3546v2



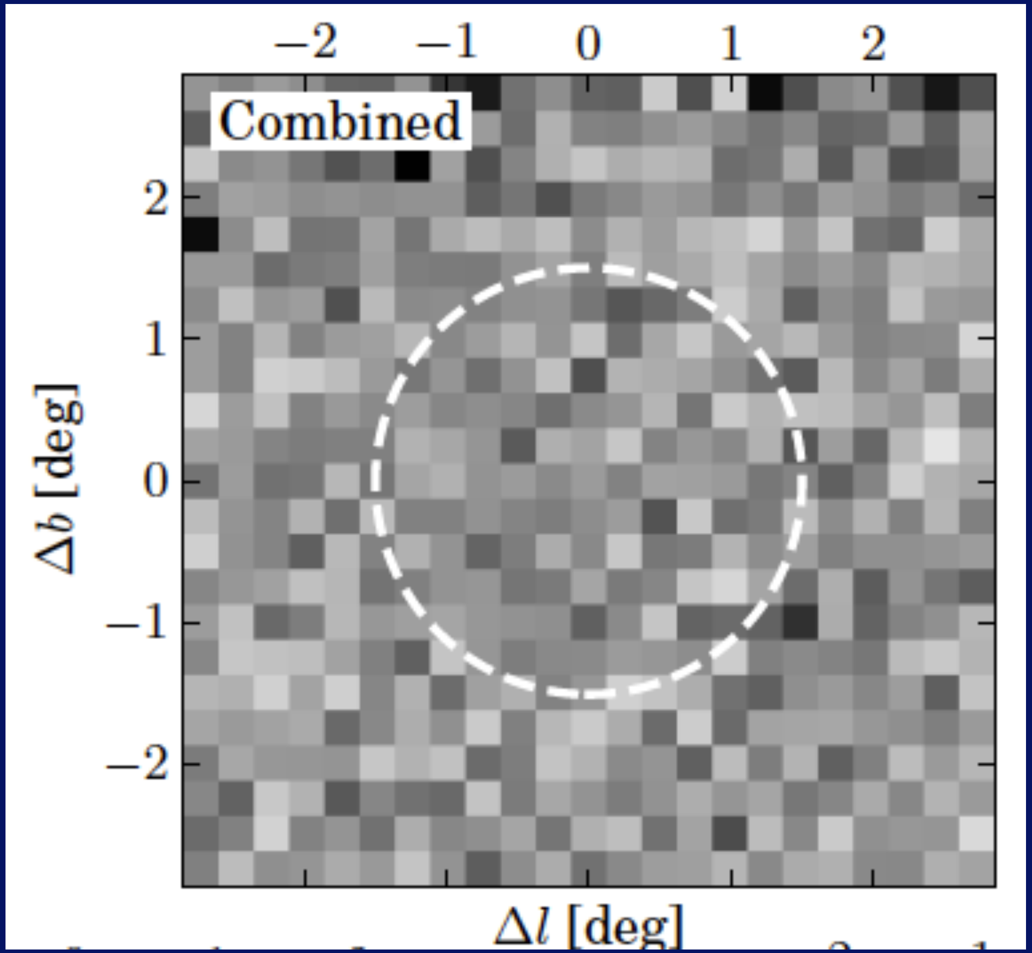


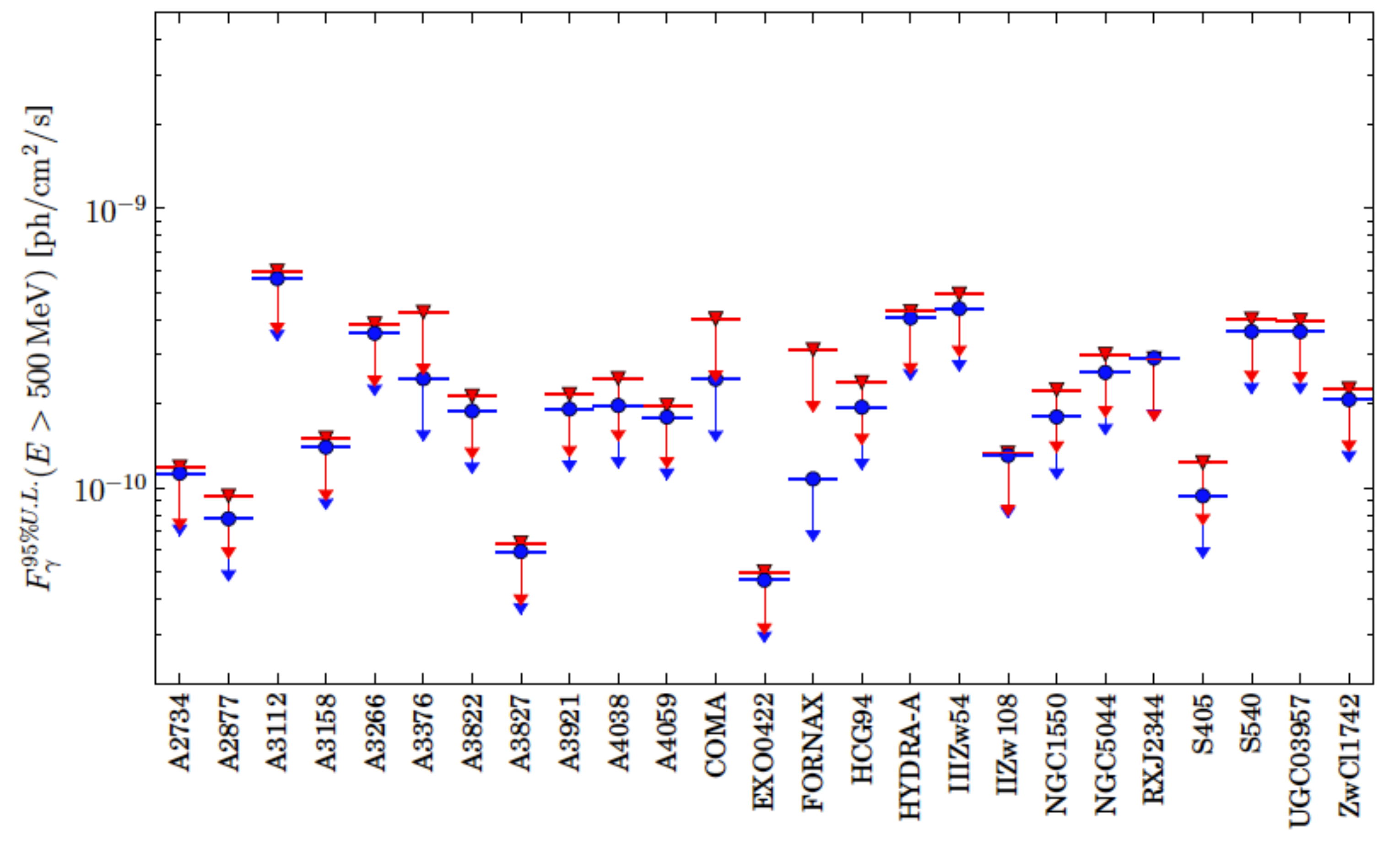
Steve Ritz

Now getting to very interesting sensitivity ranges!

Upcoming from Fermi: Cluster Stacking

- Fermi does not detect gamma-ray emission from clusters even for a joint fit of 50 clusters with 4 years of data.





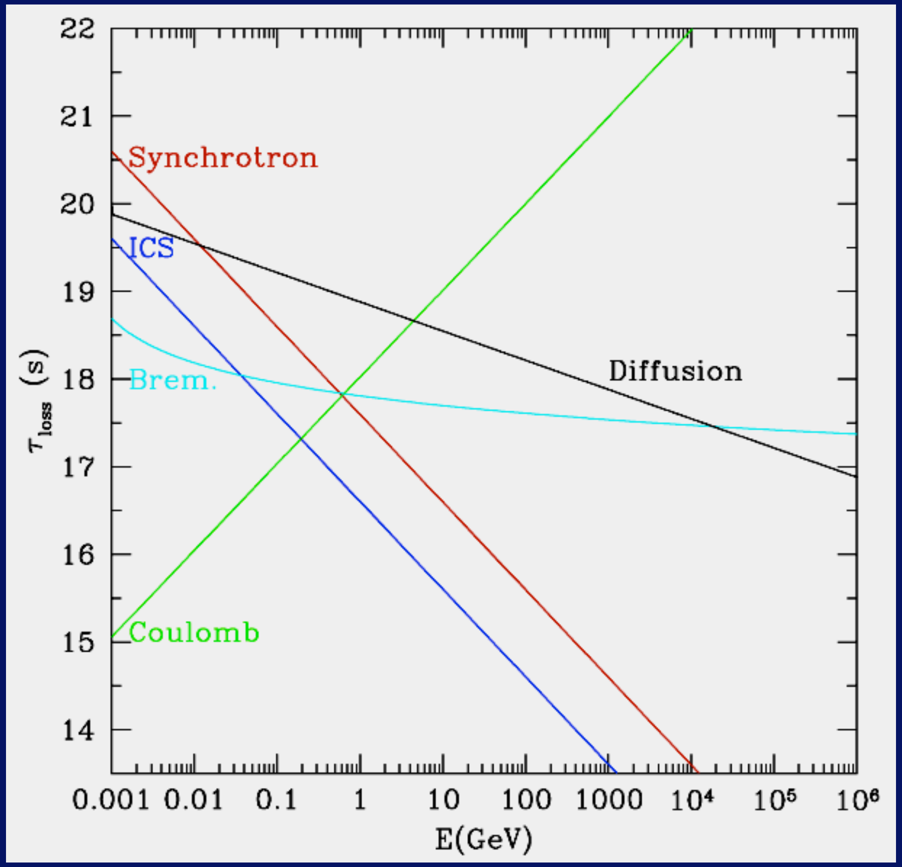
Ackermann et al. 2013, arXiv:1308.5654

Tesla Jeltema

Multiwavelength Dark Matter Searches

- Clusters are excellent targets for searches for secondary synchrotron and IC radiation:

  1. The energy loss timescale is much shorter than the diffusion time
  2. They have large-scale magnetic fields

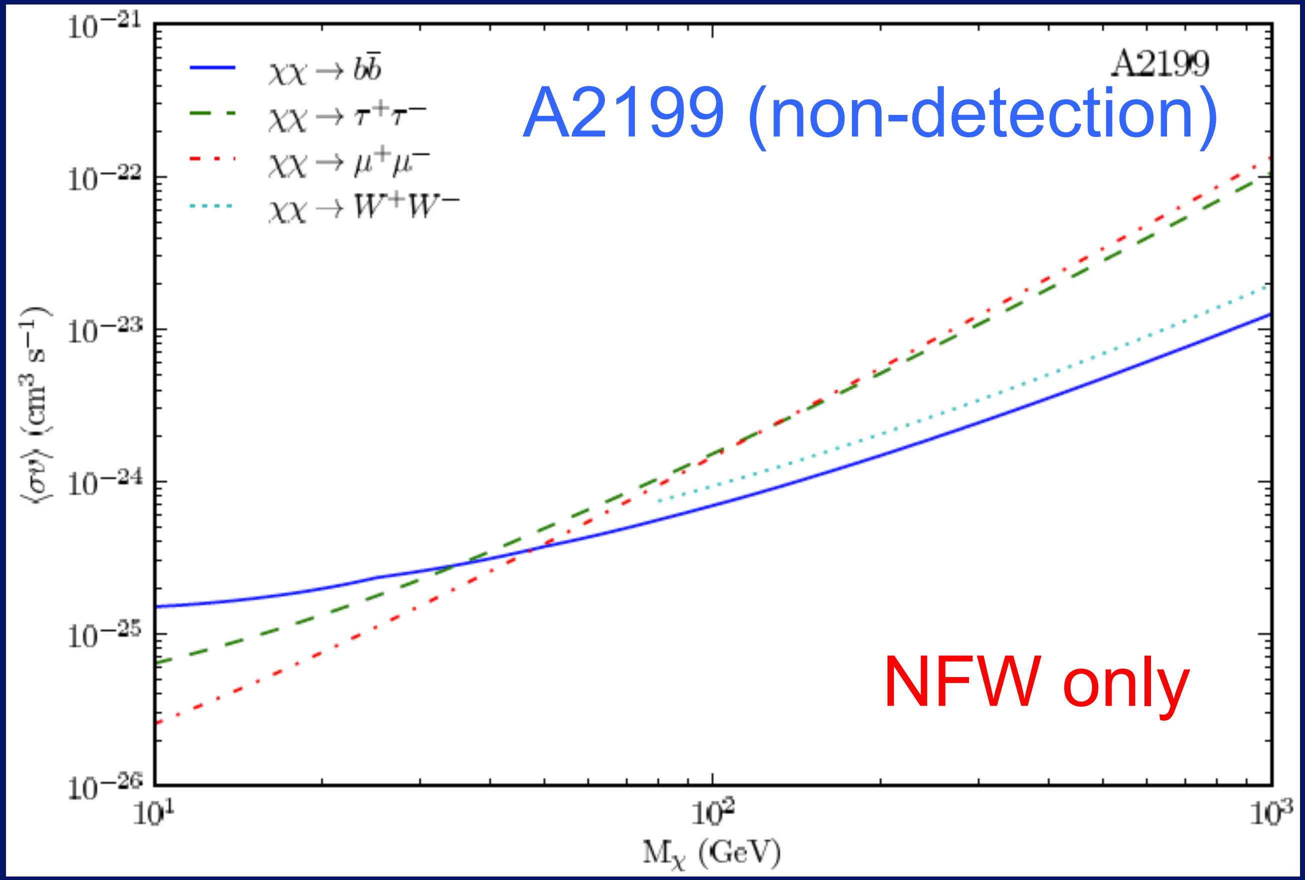


Colafrancesco et al. 2006

Tesla Jeltema

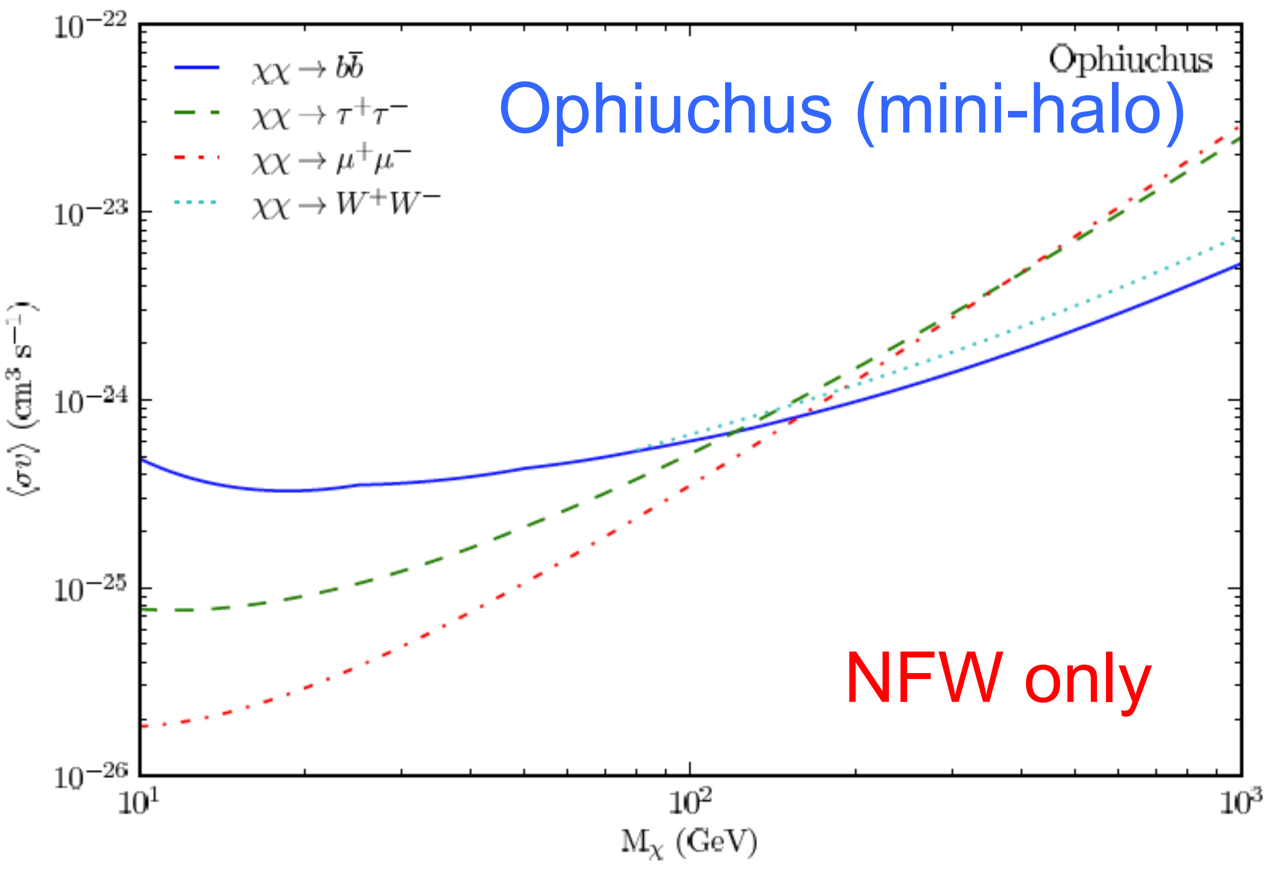
Radio Observations of Clusters

- The non-detection or weak detection of radio emission from nearby clusters places stronger limits on DM annihilation than current Fermi
- At low mass, limits approach thermal cross-section even for conservative density profile



A2199 (non-detection)

NFW only

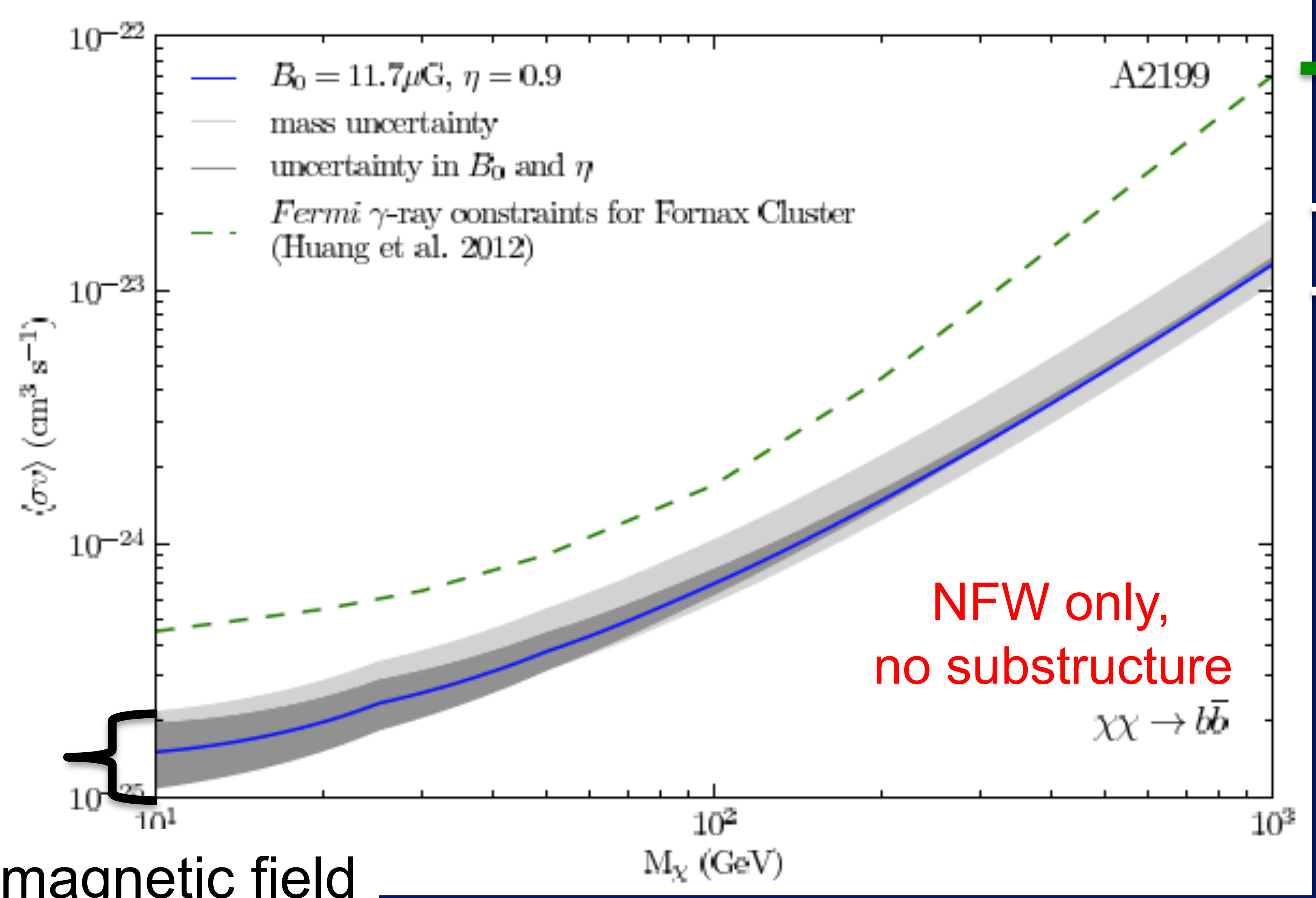


Ophiuchus (mini-halo)

NFW only

Storm, Jeltema, Profumo, & Rudnick 2013

Dark Matter Annihilation Limits



best Fermi cluster limits

cluster mass uncertainty

NFW only, no substructure

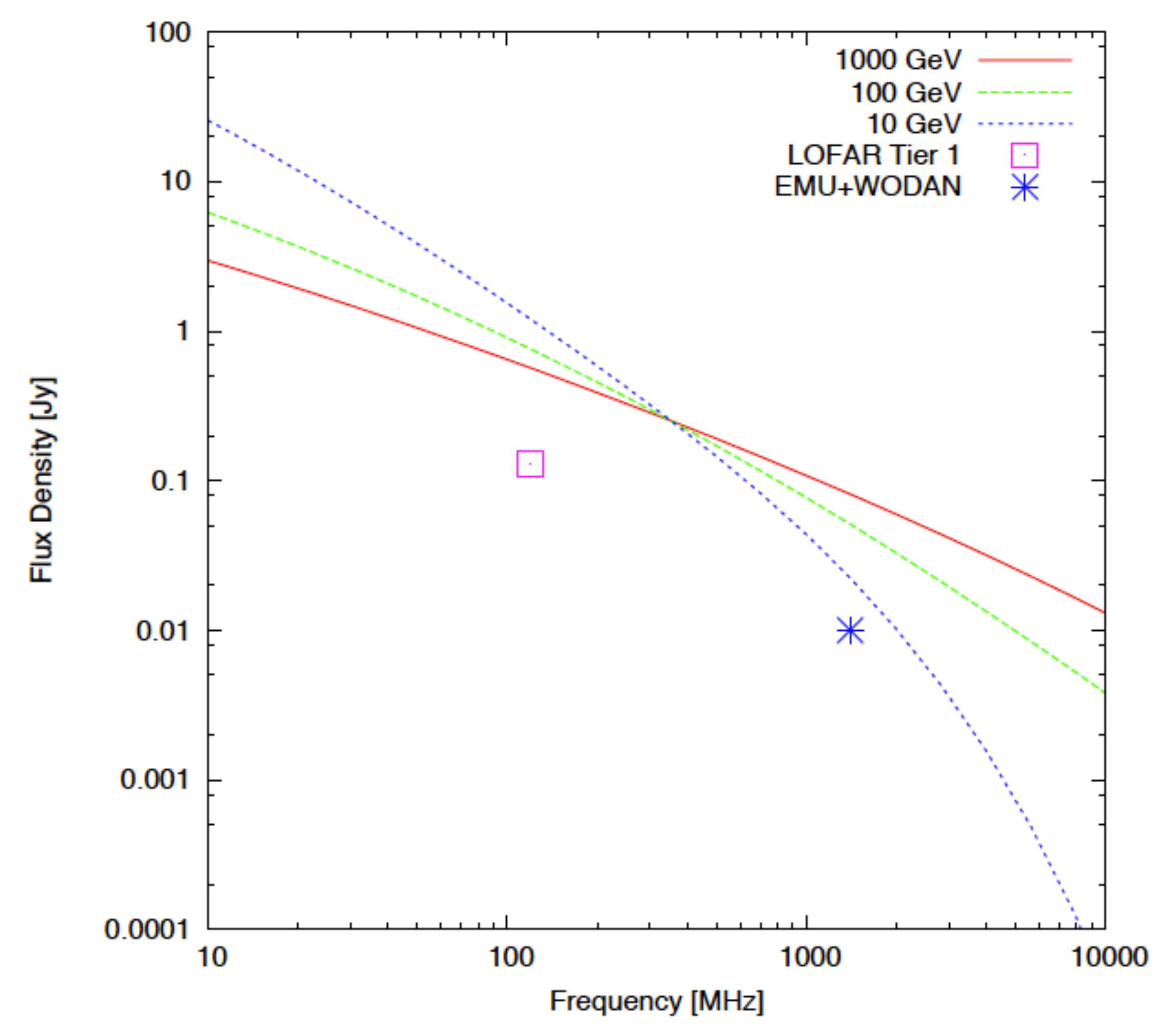
magnetic field uncertainty

Storm, Jeltema, Profumo, & Rudnick 2013

Future Radio Observations

Large near term gains from:

- ➢ New low frequency capabilities (LOFAR, LWA)
- ➢ Increased sensitivity at GHz frequencies (ASKAP, APERTIF, MeerKAT)



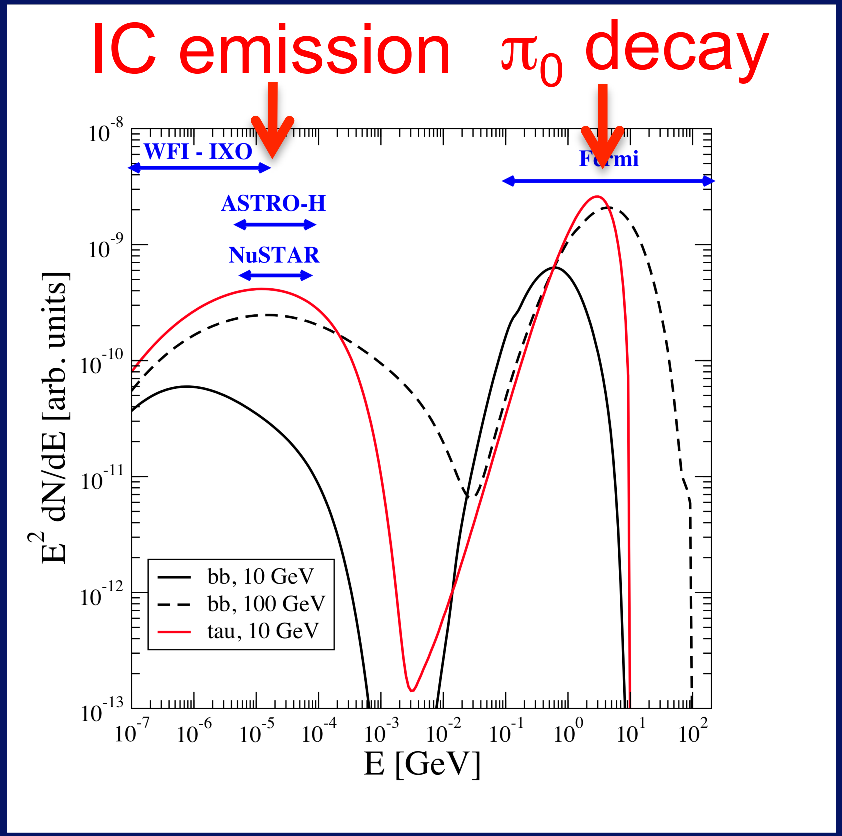
Order of magnitude gains from planned surveys alone!

Tesla Jeltema

X-ray Emission from Dark Matter

- ➢ For a range of DM models, IC emission from the scattering of the CMB by the $e^+ e^-$ produced peaks in the hard X-ray band.

- ➢ Again clusters are a good target – diffusion negligible, thermal X-ray emission drops off steeply at high energy


IC emission π_0 decay

Jeltema & Profumo 2012

- ➢ Planned X-ray telescopes will have (at best) similar sensitivity to Fermi.

Dark Matter Summary

- Observations of clusters across the electromagnetic spectrum can probe dark matter models

- Gamma-ray: Strong constraints on decay and leptophilic models, upcoming gains from stacking

- Radio: Current constraints are competitive with gamma-ray in some cases, and new facilities are imminent

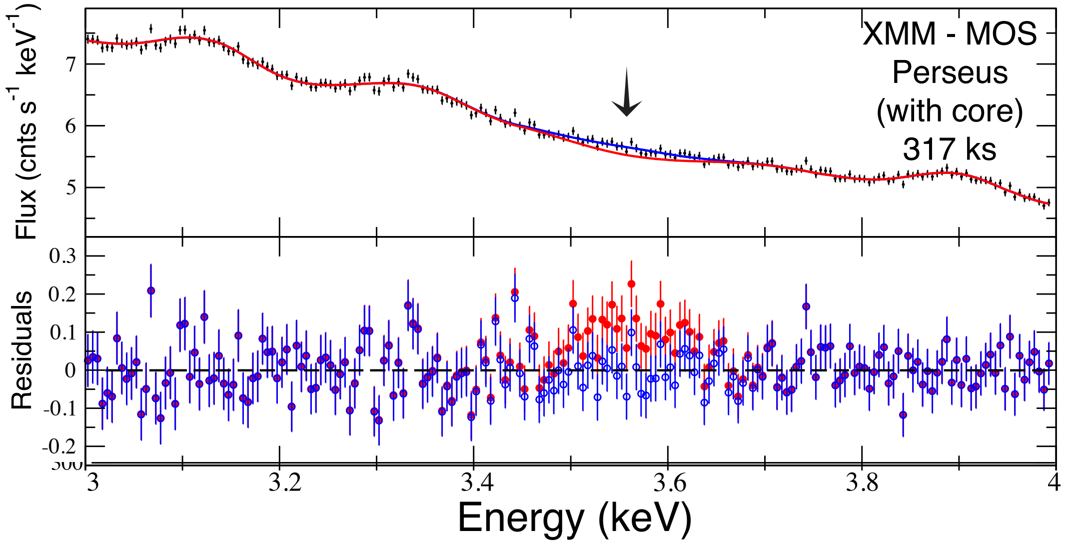
- X-ray: limits are not currently competitive, but could be with an appropriately planned telescope.

- A multiwavelength approach is highly complementary to future high energy gamma-ray searches

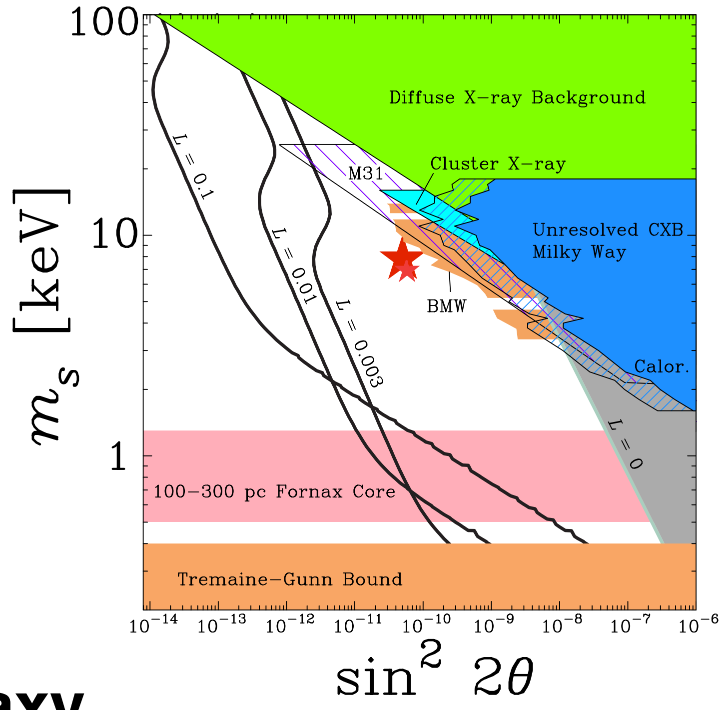
There is new evidence for WDM with $m_\nu^{\rm sterile} \approx 7$ keV from detection of 3.5 keV X-rays. Will this be consistent with high-z galaxies, gravitational lensing flux anomalies, and breaks in cold stellar streams?

DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS arXiv:1402.2301

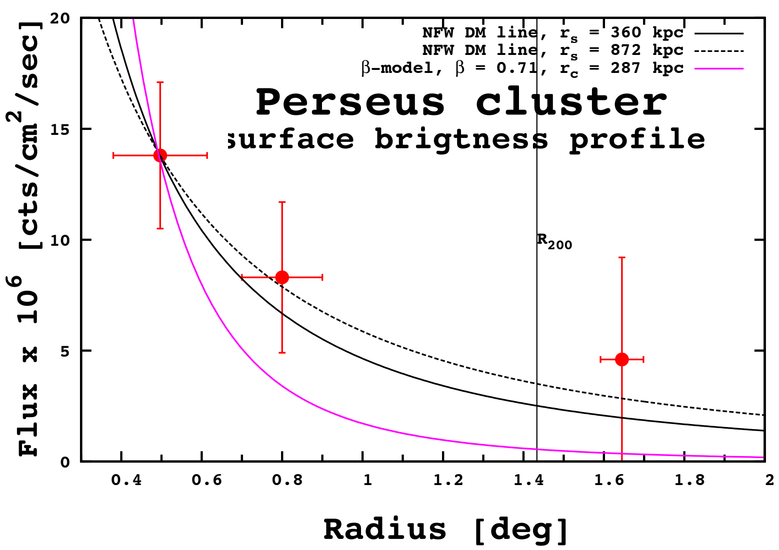
Esra Bulbul, Maxim Markevitch, Adam Foster, Randall K. Smith, Michael Loewenstein, and Scott W. Randall

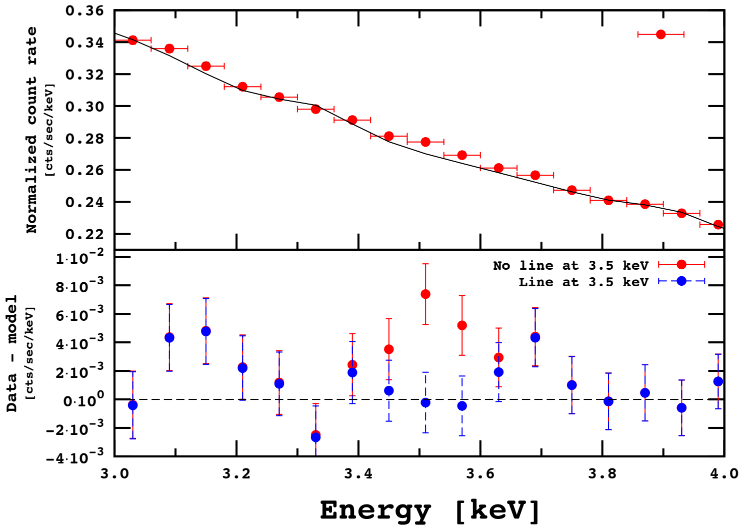


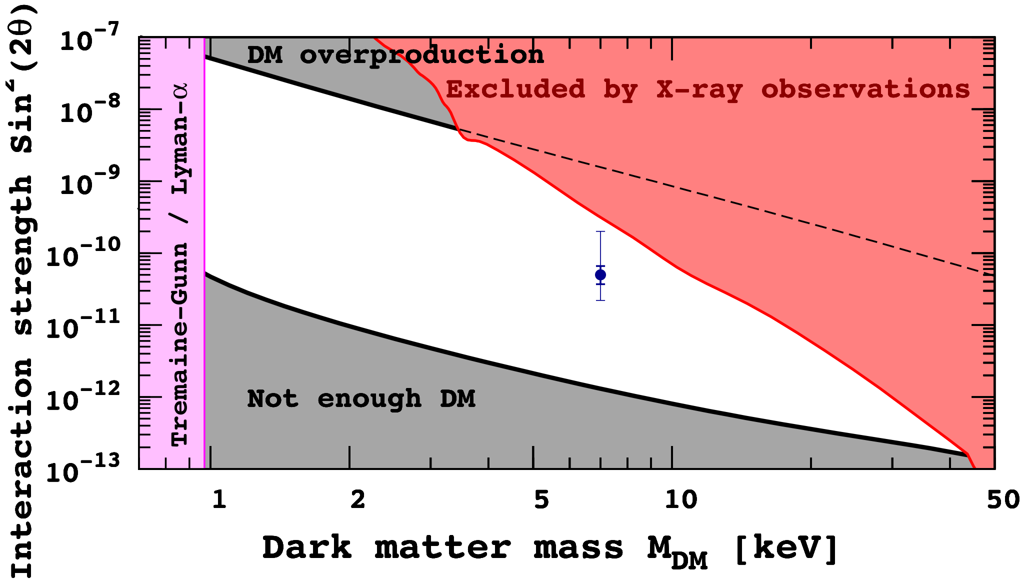
Recent constraints on sterile neutrino dark matter production models (Abazajian+07). Lines in black show theoretical predictions assuming sterile neutrinos are the dark matter with lepton number L = 0, L = 0.003, L = 0.01, L = 0.1. The ★ is consistent with upper limits.

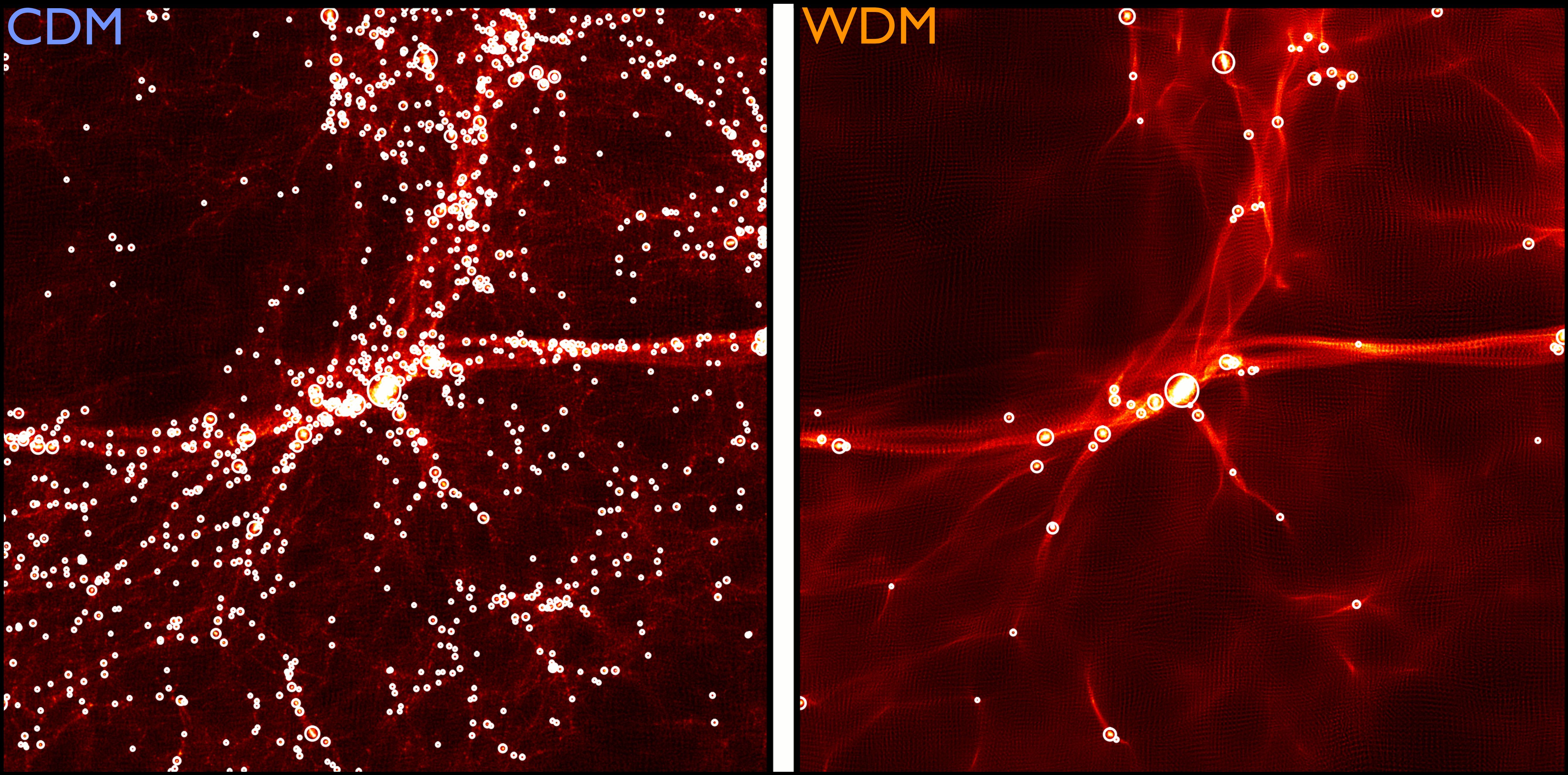


An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus cluster arXiv:1402.4119 A. Boyarsky, O. Ruchayskiy, D. Iakubovskyi and J. Franse





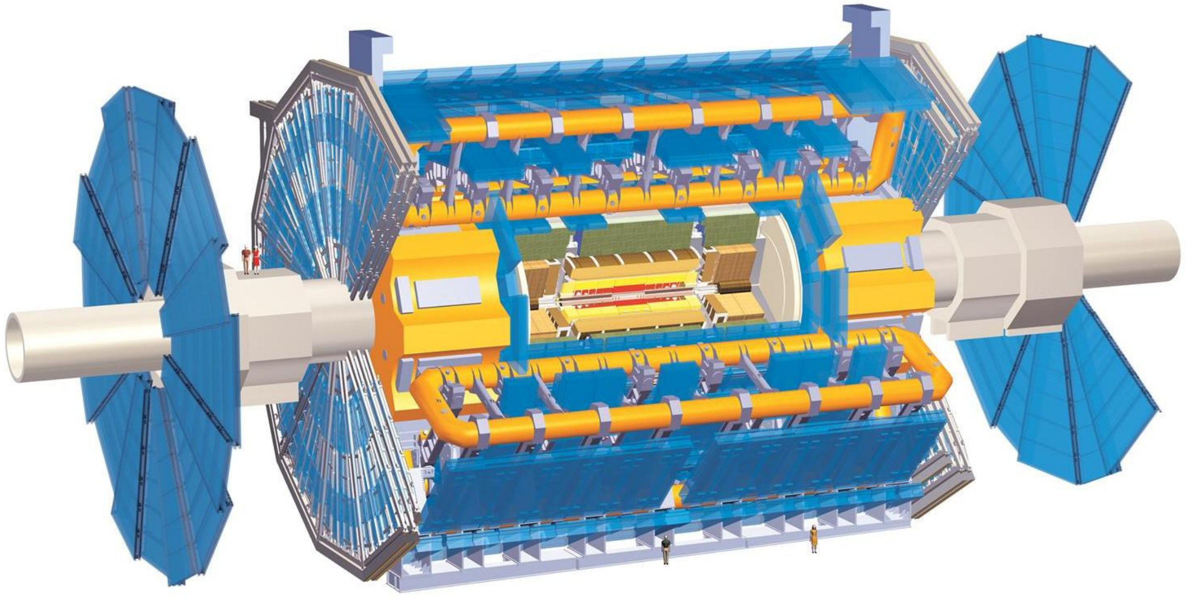




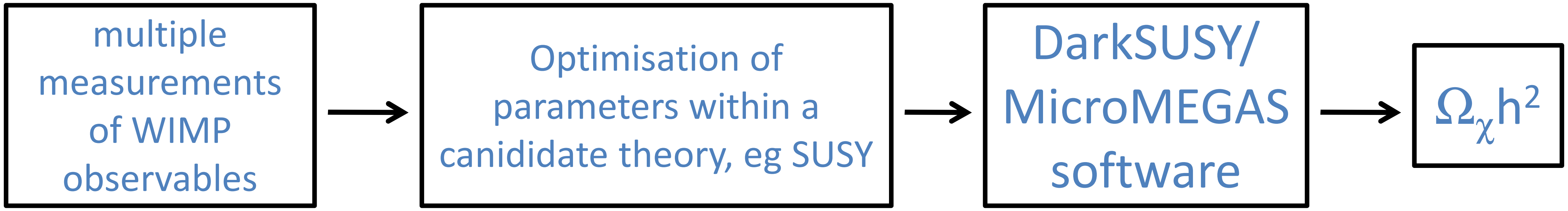
WDM simulation at right has no “too big to fail” subhalos, but it is inconsistent at $>10\sigma$ with Ultra Deep Field galaxy counts. It also won’t have the subhalos needed to reionize the universe unless $m_\nu^{\mathrm{thermal}} \gtrsim 2.6$ keV (or $m_\nu^{\mathrm{sterile}} \gtrsim 15$ keV) assuming an optimistic ionizing radiation escape fraction (Schultz, Onorbe, Abazajian, Bullock14). And the new Ly-α forest analysis (Viel+13) excludes $m_\nu^{\mathrm{thermal}} \lesssim 2$ keV at 4σ.

The LHC – an essential component of the DM story

- If DM is made of WIMPs, they will be produced at LHC in abundance
- Indirect DM detection using principally missing E_T signatures
- Unique role of LHC: multiple measurements allow understanding of underlying theory, determination of identity of DM

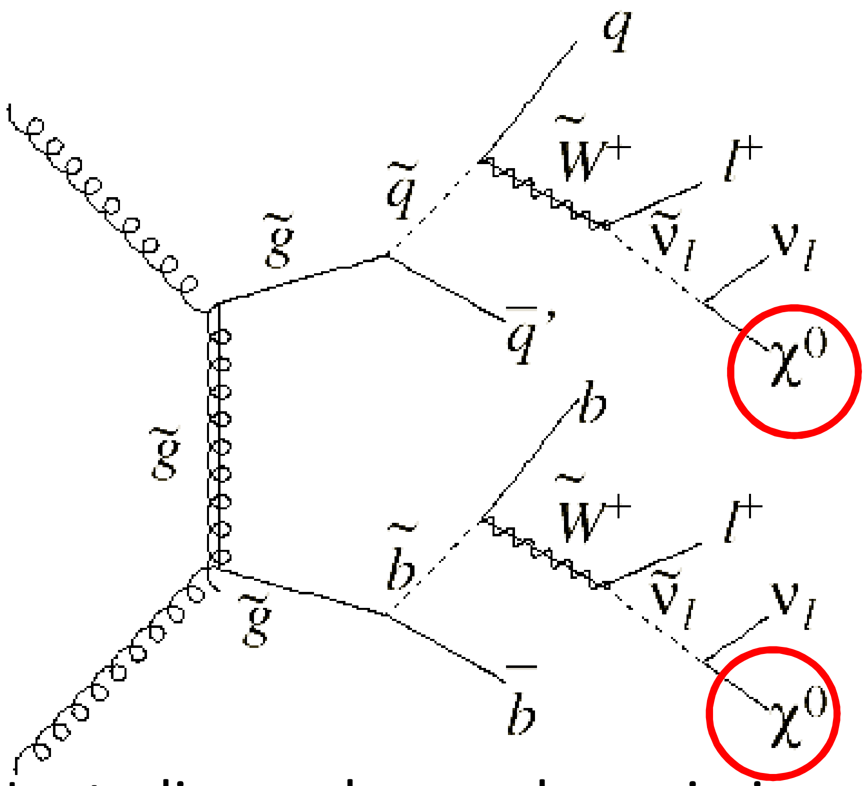


ATLAS Detector

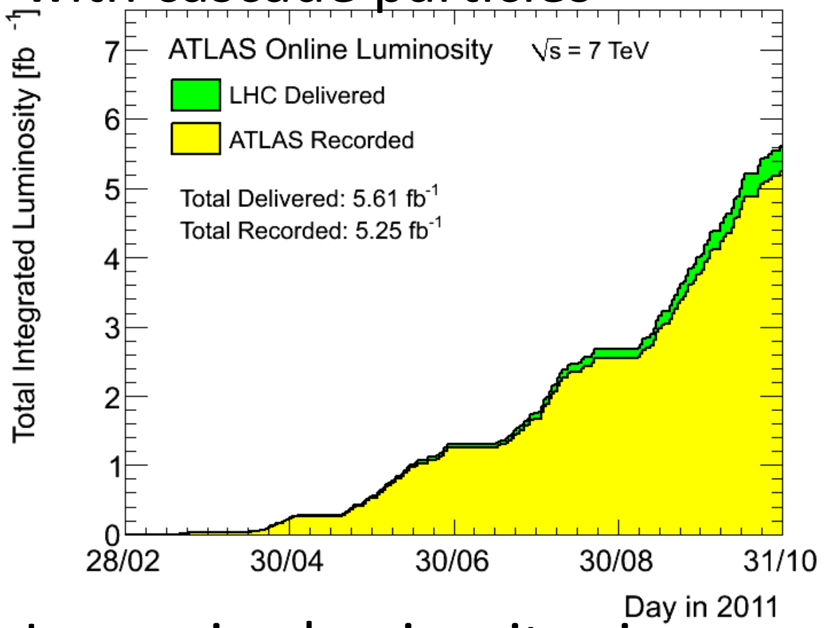


multiple measurements of WIMP observables → Optimisation of parameters within a canididate theory, eg SUSY → DarkSUSY/ MicroMEGAS software → $\Omega_\chi h^2$

Search strategies for SUSY at the LHC



Neutralinos observed as missing transverse energy in association with cascade particles



Increasing luminosity gives sensitivity to higher masses and rare processes.

Jet multiplicity + kinematics

Lepton multiplicity + kinematics

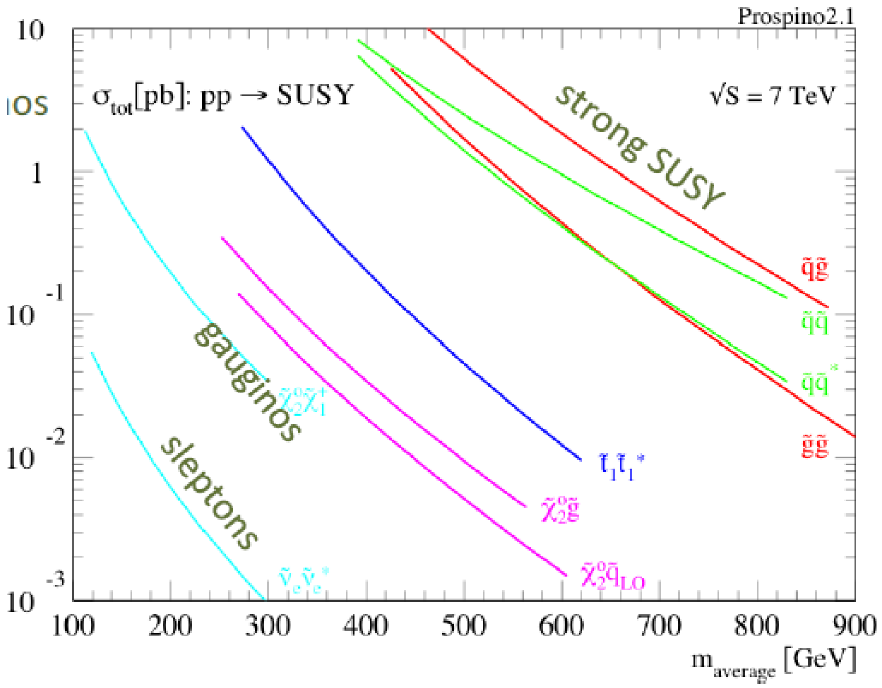
+ global event quantities

$$E_T^{miss} = -\left|\sum_i \vec{E}_T\right| \qquad m_{eff} = E_T^{miss} + \sum_i p_T^{jet}$$

$$H_T = \sum_i p_T^{jet}$$

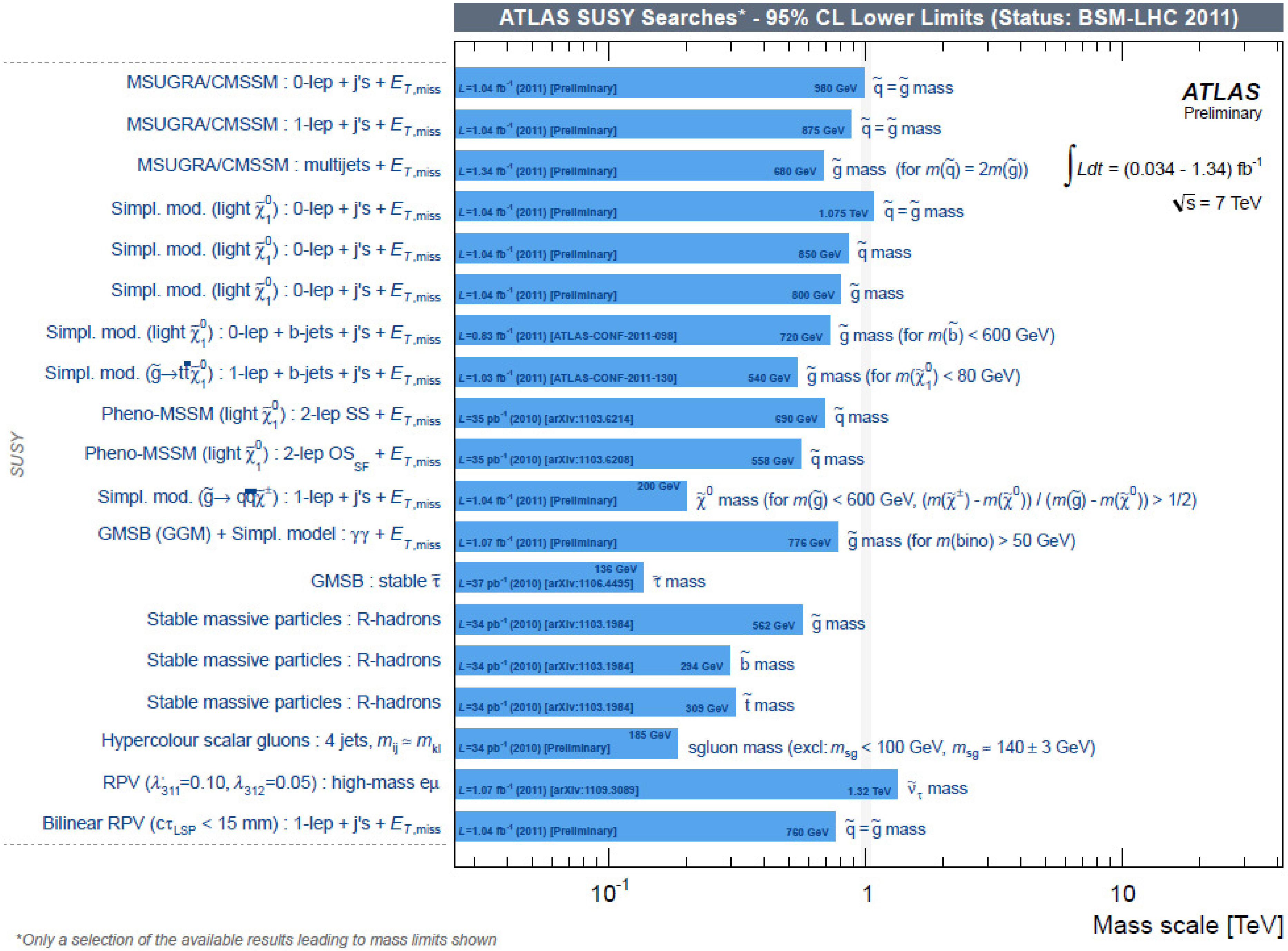
α_T exploits angular relation between jets....

……



Growing sensitivity for non-strong SUSY.

A body of searches already performed



Albeit with model dependence – limits starting to push SUSY up to and beyond 1 TeV

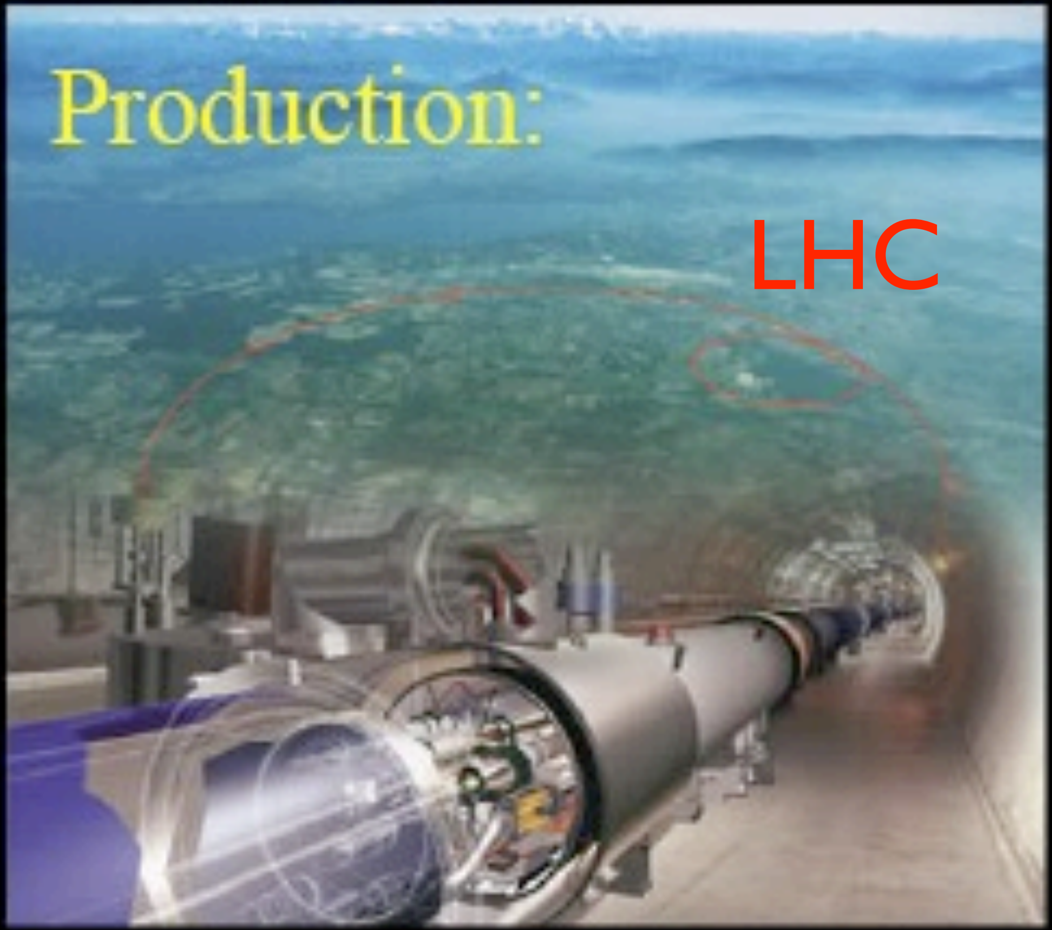
Note that a detection of missing mass, energy, and momentum at the LHC is not proof that the invisible particle is the dark matter. The particle needs only to have a lifetime of $\sim 10^{-9}$ s to escape the Atlas and CMS detectors.

It will be the dark matter particle if direct and/or indirect detection experiments see the same mass and interaction pattern.

Thus all three approaches must be pursued: production, direct detection and indirect detection.

Four roads to dark matter: *catch it, infer it, make it, weigh it*

Direct:



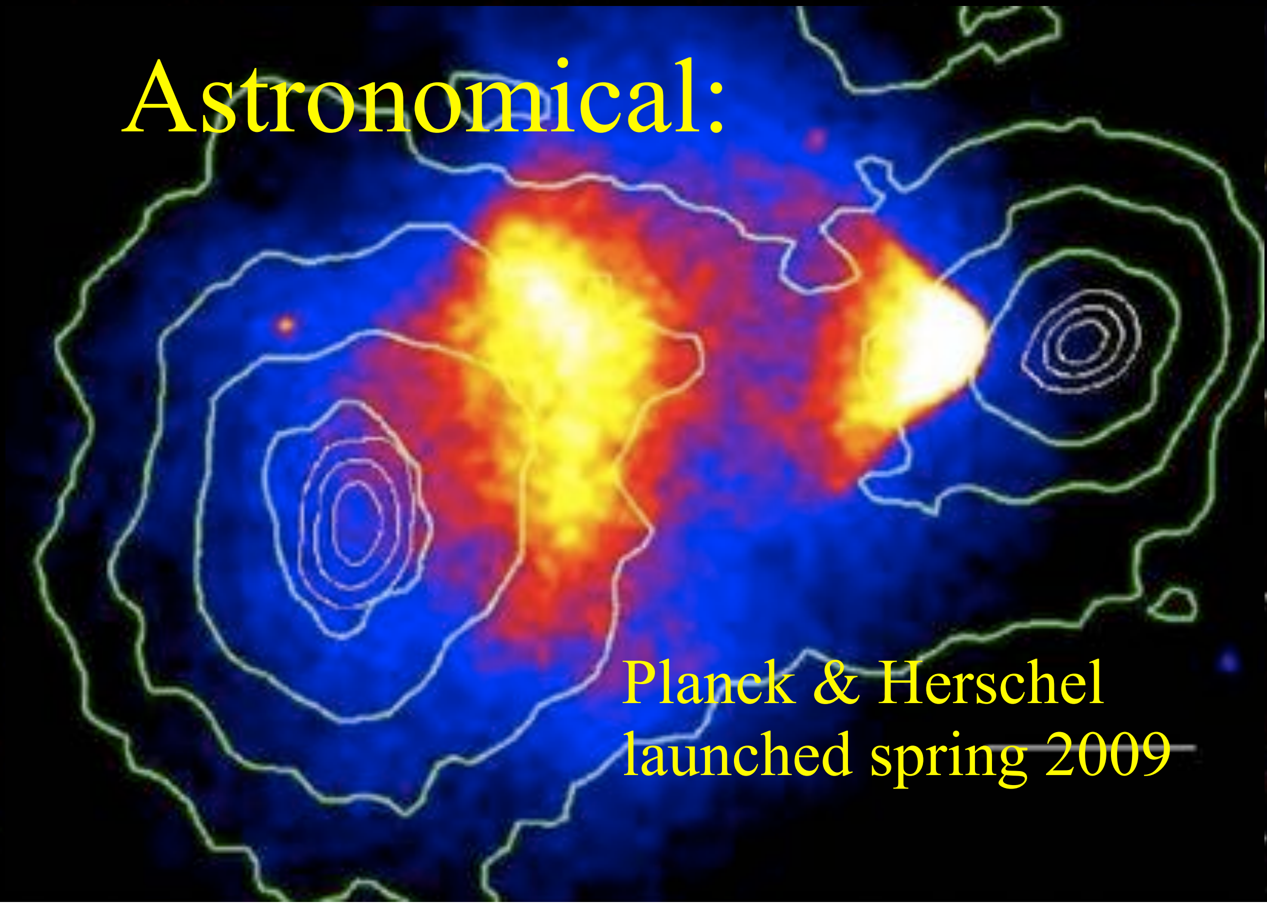
Production:

LHC

With all
these
upcoming
experiments,
the next
few years
will be very
exciting!

Indirect:

Fermi (GLAST) launched
June 11, 2008



Astronomical:

Planck & Herschel
launched spring 2009