COSMIC FRONTIER

Jonathan Feng and Steve Ritz

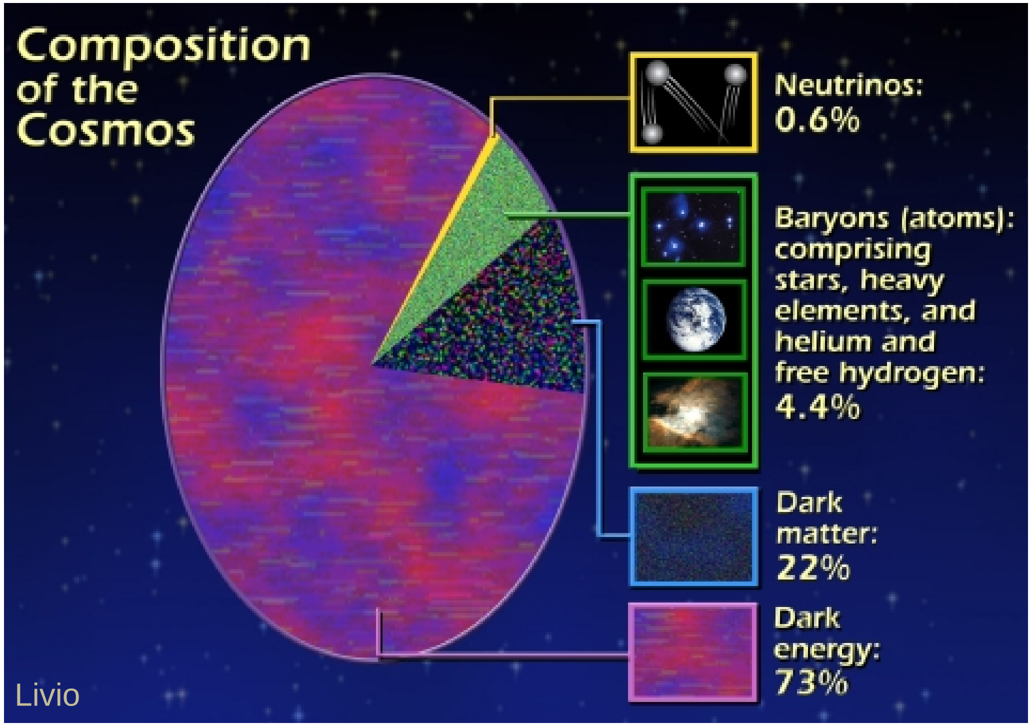
for the Cosmic Frontier Working Group

INTRODUCTION

Our understanding of the Universe has been transformed in recent years.

With the other Frontiers, the Cosmic Frontier now provides overwhelming evidence for new physics and powerful approaches to address many of our most fascinating questions:

- What is dark matter?
- What is dark energy?
- Why more matter than anti-matter?
- What are the neutrinos' properties?
- How did the Universe begin?
- What is the physics of the Universe at the highest energies?



CF WORKING GROUP STRUCTURE

For references and additional material, see
http://www.snowmass2013.org/tiki-index.php?page=Cosmic%20Frontier

- CF1: WIMP Dark Matter Direct Detection (Priscilla Cushman, Cristian Galbiati, Dan McKinsey, Hamish Robertson, Tim Tait)
  - A: Status and Science Case (Dan Bauer)
  - B: Defining the Parameter Space (Tim Tait)
  - C: Enabling Technology and Infrastucture (Bob Jacobsen)
- CF2: WIMP Dark Matter Indirect Detection (Jim Buckley, Doug Cowen, Stefano Profumo)
- CF3: Non-WIMP Dark Matter (Alex Kusenko, Leslie Rosenberg)
- CF4: Dark Matter Complementarity (Dan Hooper, Manoj Kaplinghat, Konstantin Matchev)

CF WORKING GROUP STRUCTURE

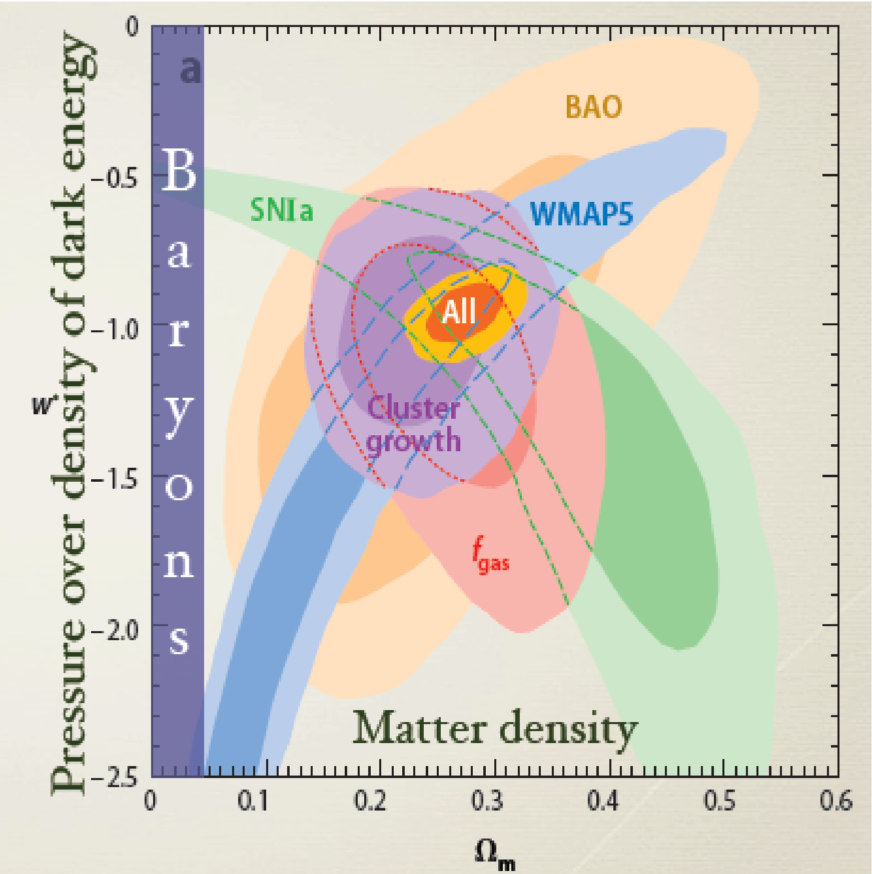
- CF5: Dark Energy and CMB (Scott Dodelson, Klaus Honscheid)
  - A: Distances (Alex Kim, Nikhil Padmanabhan)
  - B: Growth of Cosmic Structure (Dragan Huterer, David Kirkby)
  - C: Cross-Correlations (Jason Rhodes, David Weinberg)
  - D: Novel Probes of Gravity and Dark Energy (Bhuvnesh Jain)
  - E: Inflation Physics from CMB and Large Scale Structure (John Carlstrom, Adrian Lee)
  - F: Neutrino Physics from CMB and Large Scale Structure (Kev Abazajian, John Carlstrom, Adrian Lee)
  - G: Dark Energy Facilities (David Weinberg)
- CF6: Cosmic Particles and Fundamental Physics (Jim Beatty, Ann Nelson, Angela Olinto, Gus Sinnis)
  - A: Cosmic Rays, Gamma Rays and Neutrinos (Gus Sinnis, Tom Weiler)
  - B: The Matter of the Cosmological Asymmetry (Ann Nelson)
  - C: Exploring the Basic Nature of Space and Time (Aaron Chou, Craig Hogan)

PROCESS AND SUMMARIES

- Work done throughout the year, with weekly telecons with conveners and agency representatives, and several meetings
  - Community Planning Meeting, Fermilab, 11-13 October 2012
  - Cosmic Frontier Workshop, SLAC, 6-8 March 2013
  - SnowDARK: Non-WIMP Dark Matter, Snowbird, 22-25 March 2013
  - EF/IF/CF Theory Workshop, KITP Santa Barbara, 29-31 May 2013
  - Snowmass on the Mississippi, Minnesota, 29 July – 6 August 2013
- This work is being summarized at many levels
  - Contributed papers from collaborations, groups, individuals
  - 25-60 page summaries from CF1, CF2, CF3, CF4, CF5A, CF5B, CF5C, CF5D, CF5E, CF5F, CF5G, CF6 (~400 pages total)
  - 30-page Cosmic Frontier Summary
  - 30-page Snowmass Summary (CF contribution: 4 pages)
  - 6-page Snowmass Executive Summary (CF contribution: 2/3 page)
  - Trifold Snowmass Summary (CF contribution: 2 bullets)
- Many exciting scientific opportunities in the coming decades. Impossible to cover even all the highlights here; see the Snowmass colloquia, summary talks, and summary documents

DARK MATTER

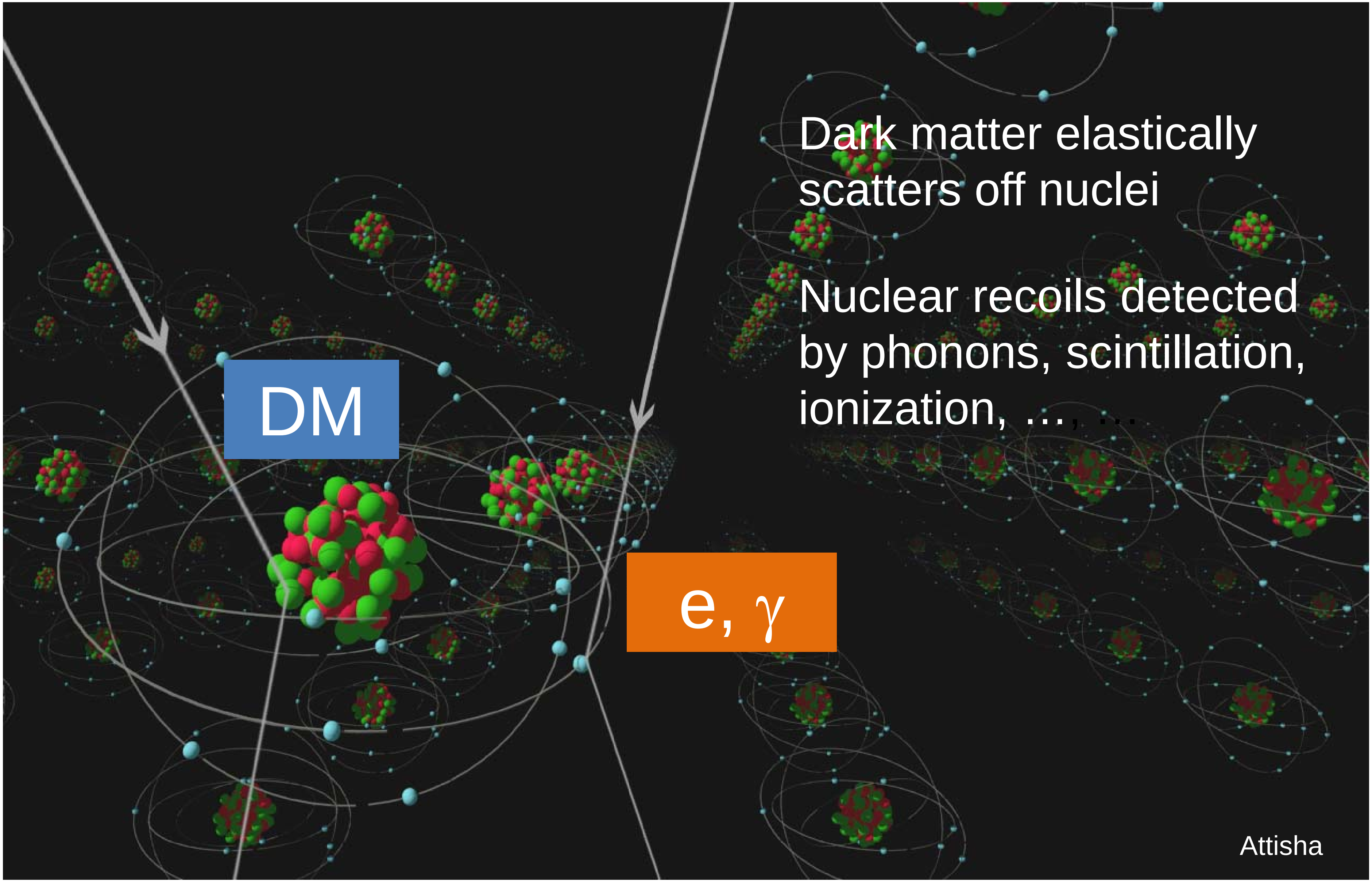
- Dark matter has **already been discovered** through
  - Galaxy clusters
  - Galactic rotation curves
  - Weak lensing
  - Strong lensing
  - Hot gas in clusters
  - Bullet Cluster
  - Supernovae
  - CMB
- We are entering the **decade of dark matter identification**



Allen et al, Annual Review of Astronomy and Astrophysics, vol. 49, pp. 409-470 (2011)

Mantz et al, Monthly Notices of the Royal Astronomical Society, Volume 406, Issue 3, pp. 1759-1772 (2010)

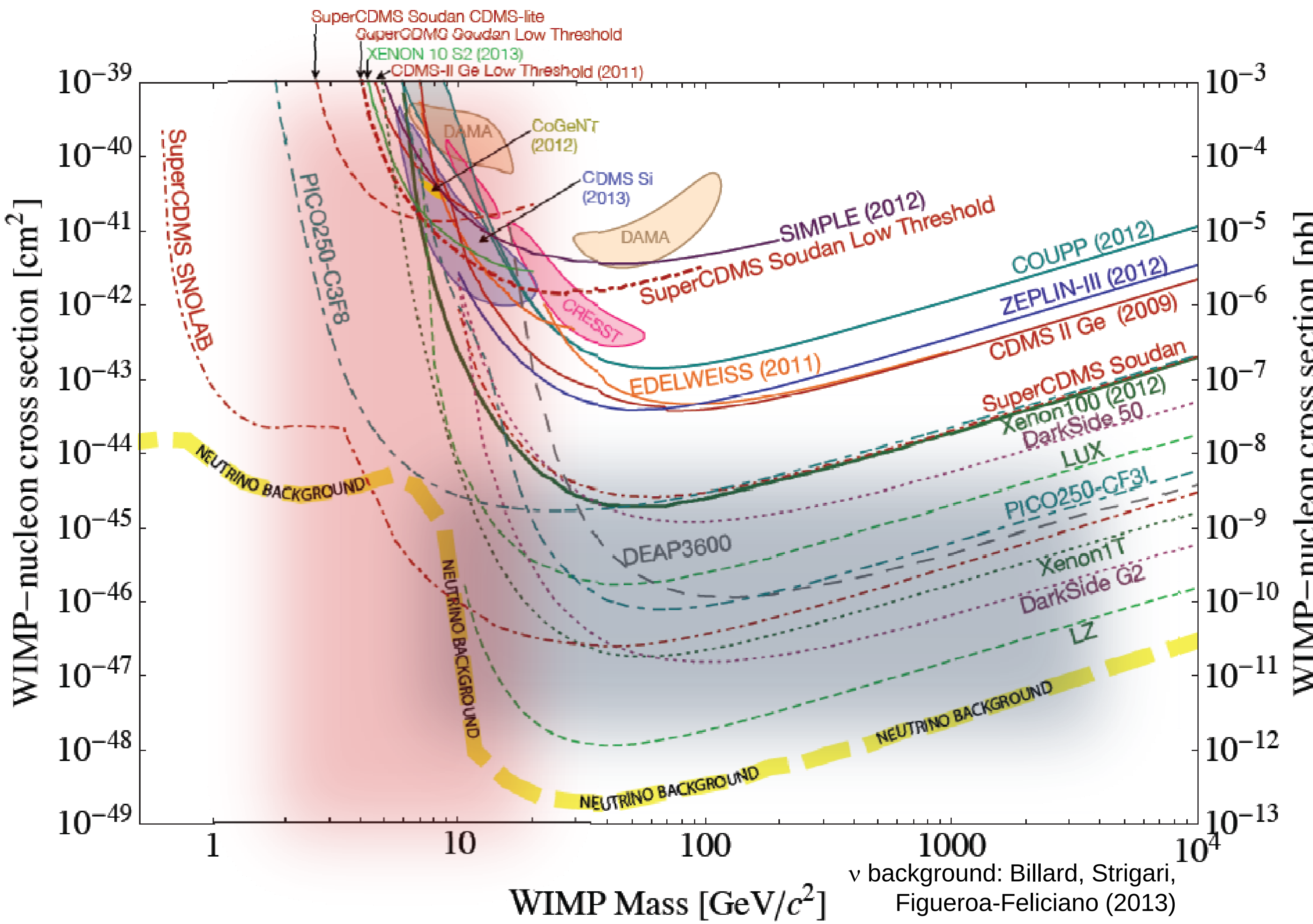
DIRECT DETECTION



Dark matter elastically scatters off nuclei

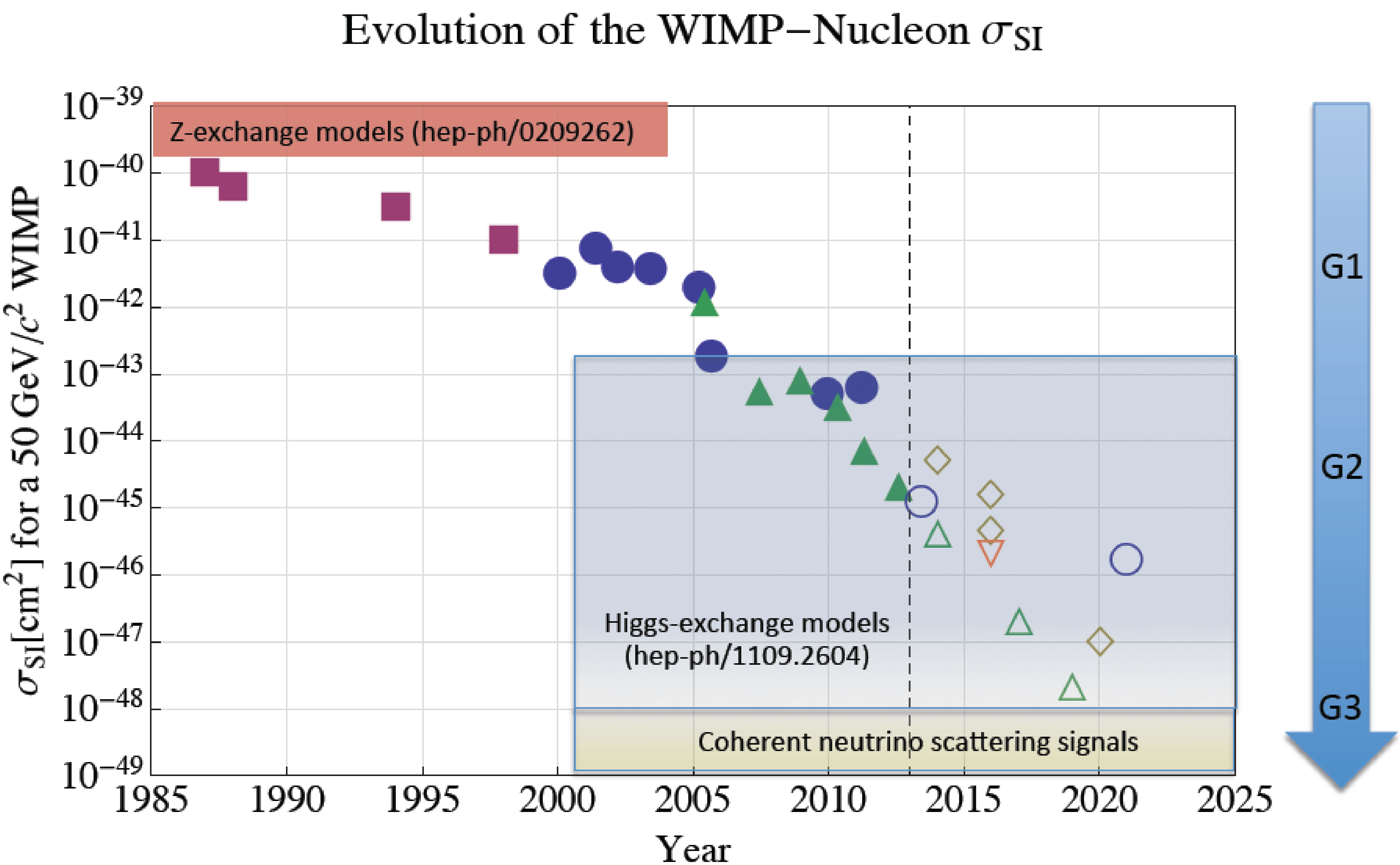
Nuclear recoils detected by phonons, scintillation, ionization, …, …

CURRENT STATUS AND FUTURE PROSPECTS



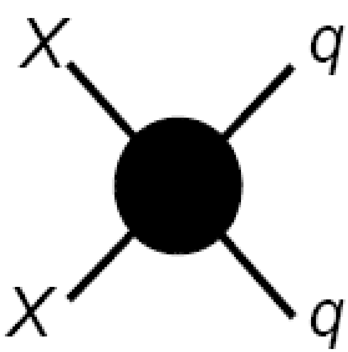
ν background: Billard, Strigari, Figueroa-Feliciano (2013)

MOORE'S LAW FOR DARK MATTER



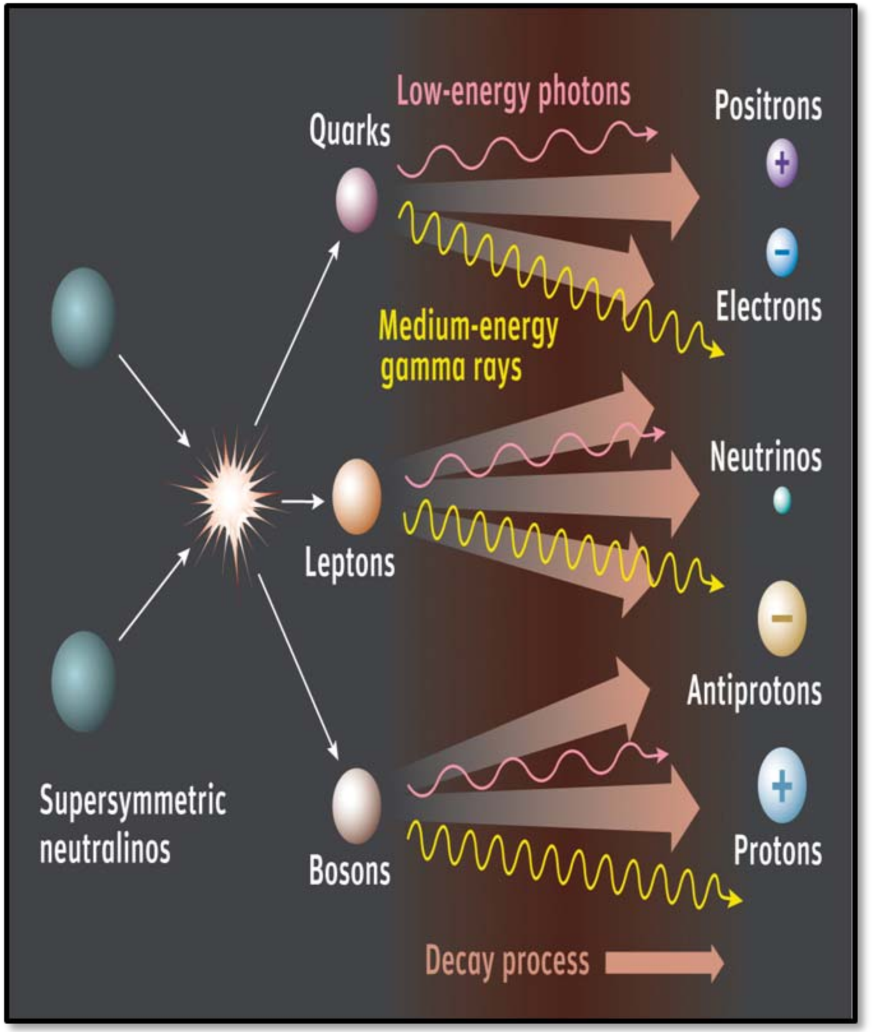
INDIRECT DETECTION

- Dark matter may pair annihilate in our galactic neighborhood to
  - Photons
  - Neutrinos
  - Positrons
  - Antiprotons
  - Antideuterons



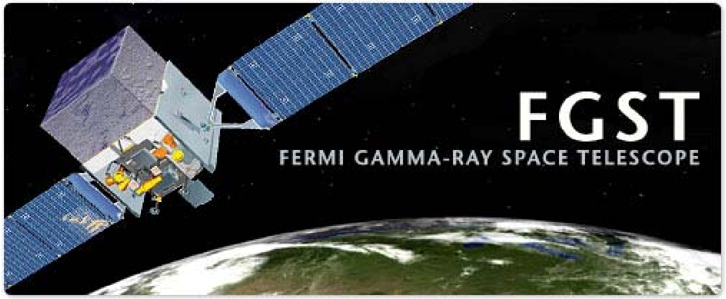
- The relic density provides a target annihilation cross section

$$\langle \sigma_A v \rangle \sim 3 \times 10^{-26}\ \text{cm}^3/\text{s}$$

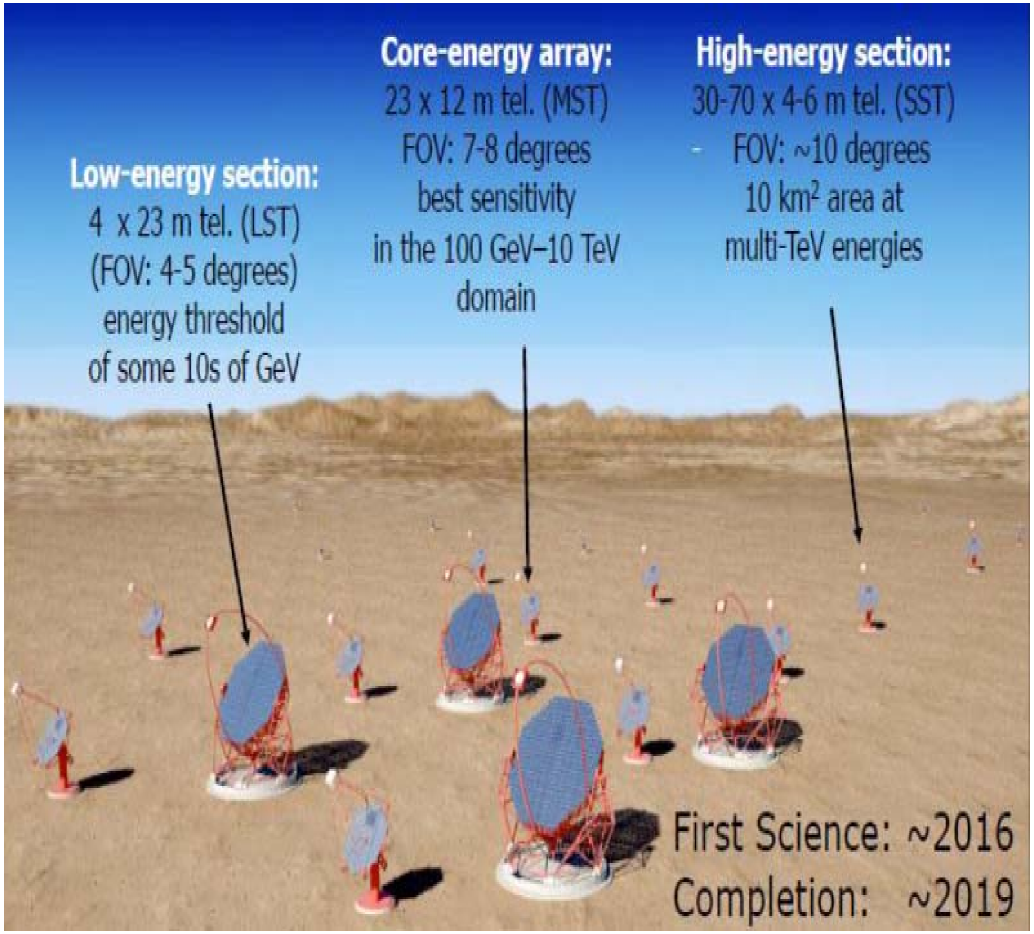


INDIRECT DETECTION: PHOTONS

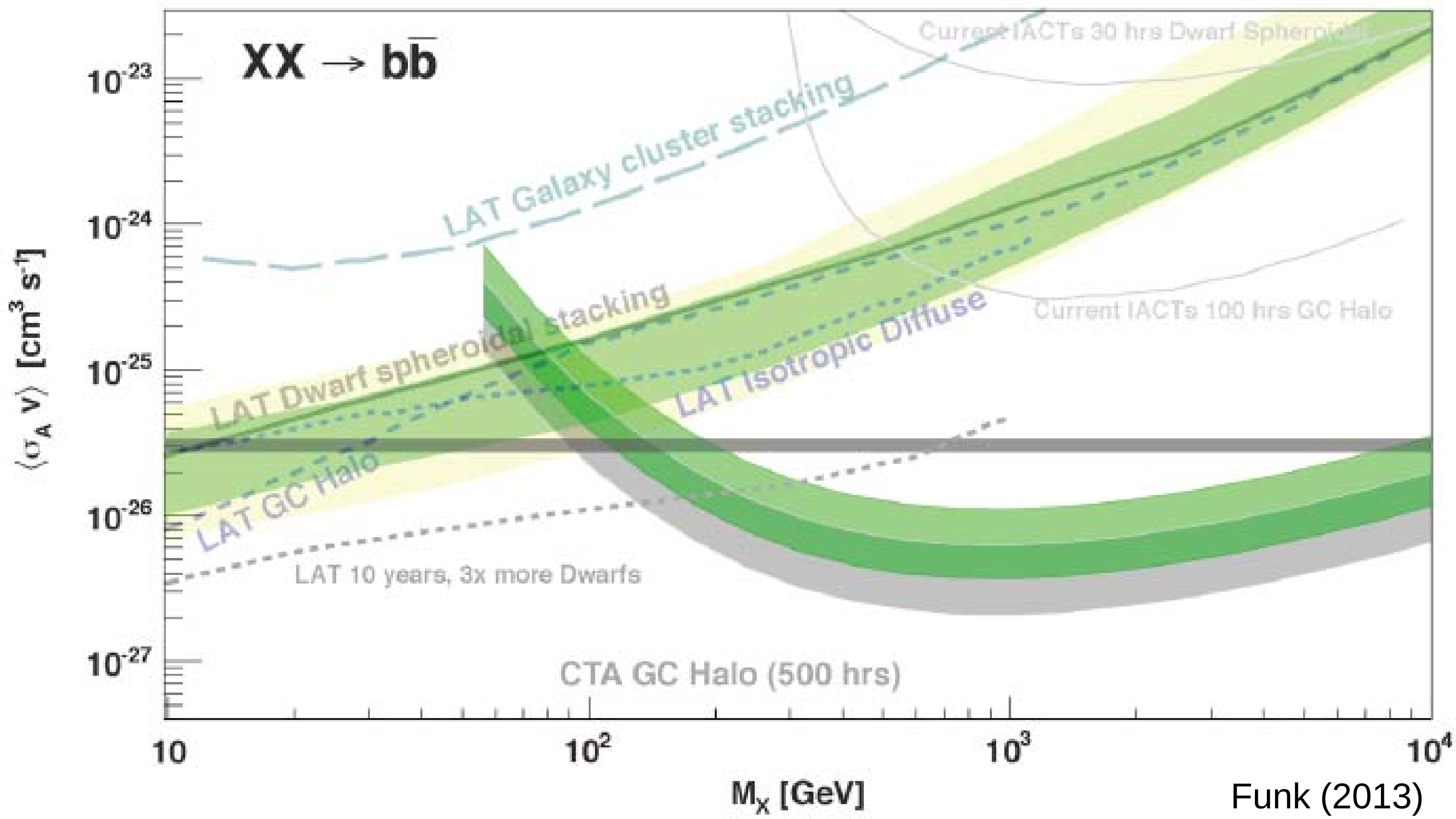
Current: Veritas, Fermi-LAT, HAWC, Magic, HESS, …



Future: Cerenkov Telescope Array (CTA)



INDIRECT DETECTION: PHOTONS



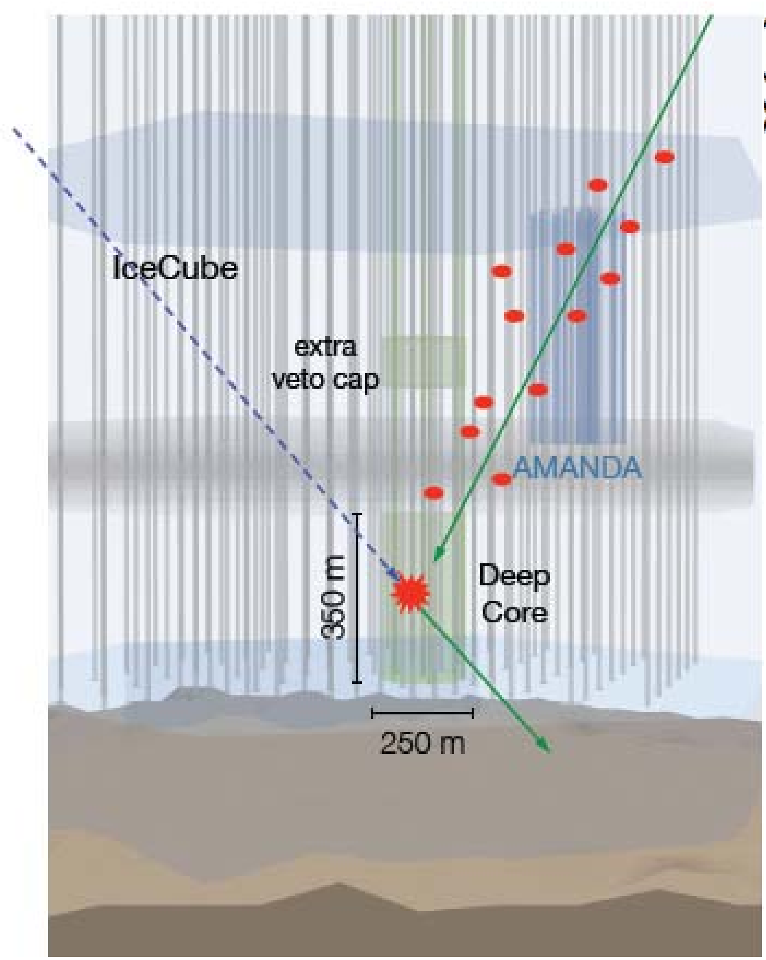
Funk (2013)

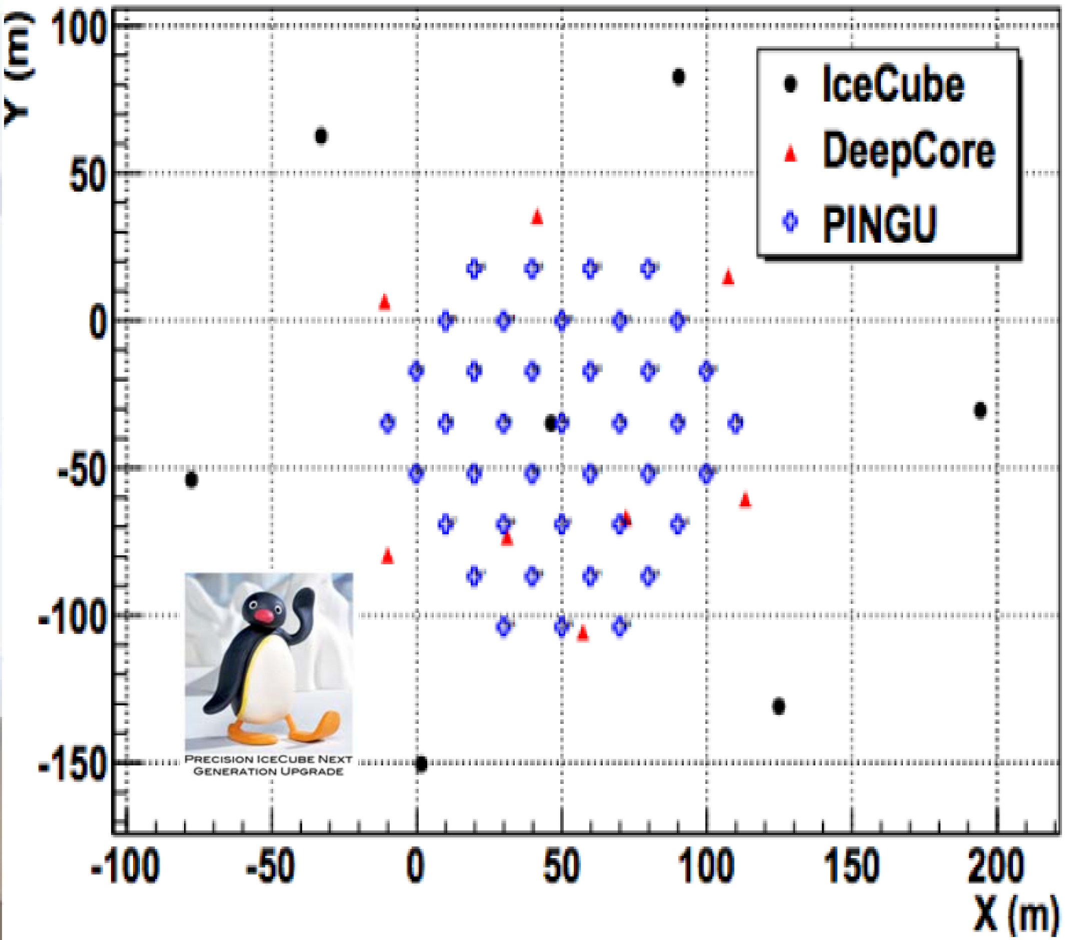
- Fermi-LAT has excluded a light WIMP with the target annihilation cross section for certain annihilation channels
- CTA extends the reach to WIMP masses ~ 10 TeV

INDIRECT DETECTION: NEUTRINOS

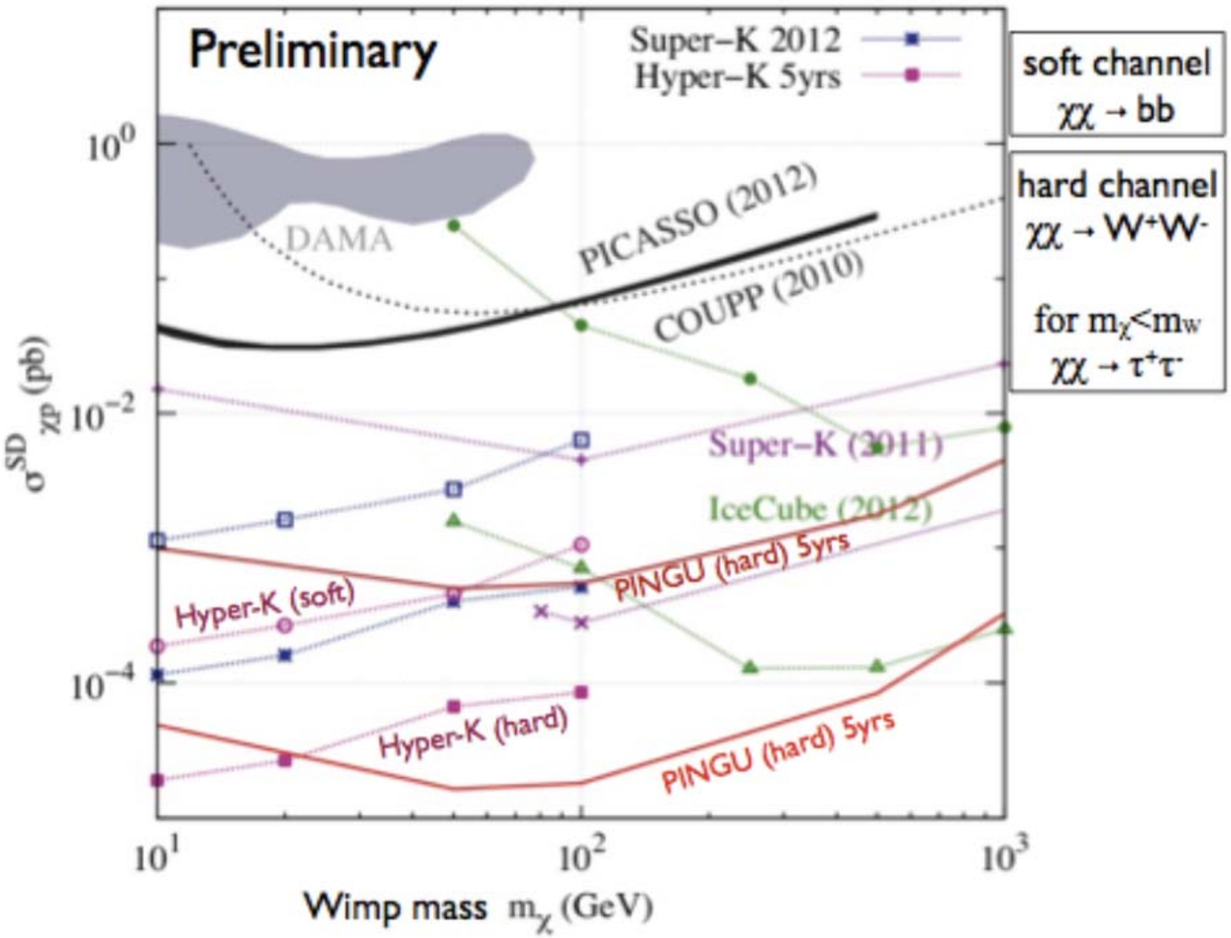
Current: IceCube/DeepCore, ANTARES

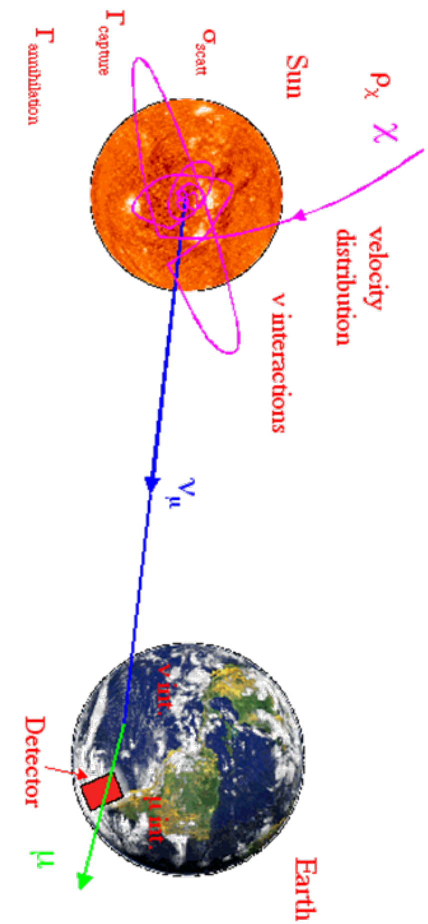
Future: PINGU, …





INDIRECT DETECTION: NEUTRINOS

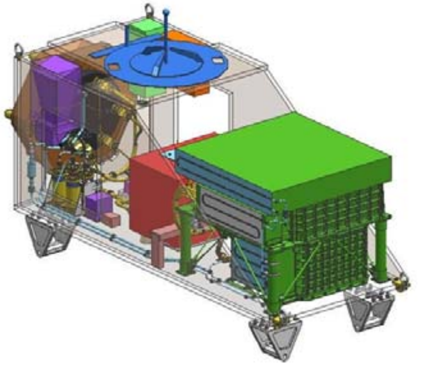


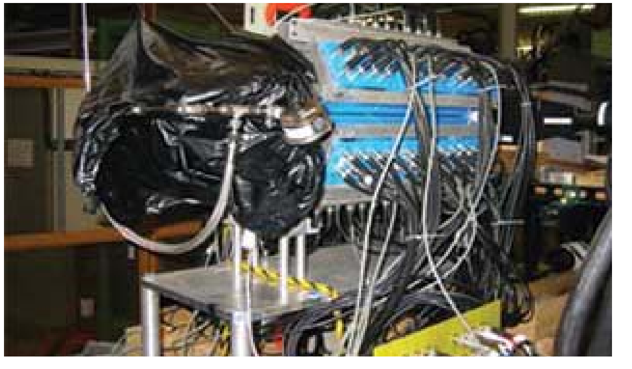


Future experiments like PINGU may discover the smoking-gun signal of HE neutrinos from the Sun, or set stringent σ_{SD} limits, extending the reach of IceCube/DeepCore

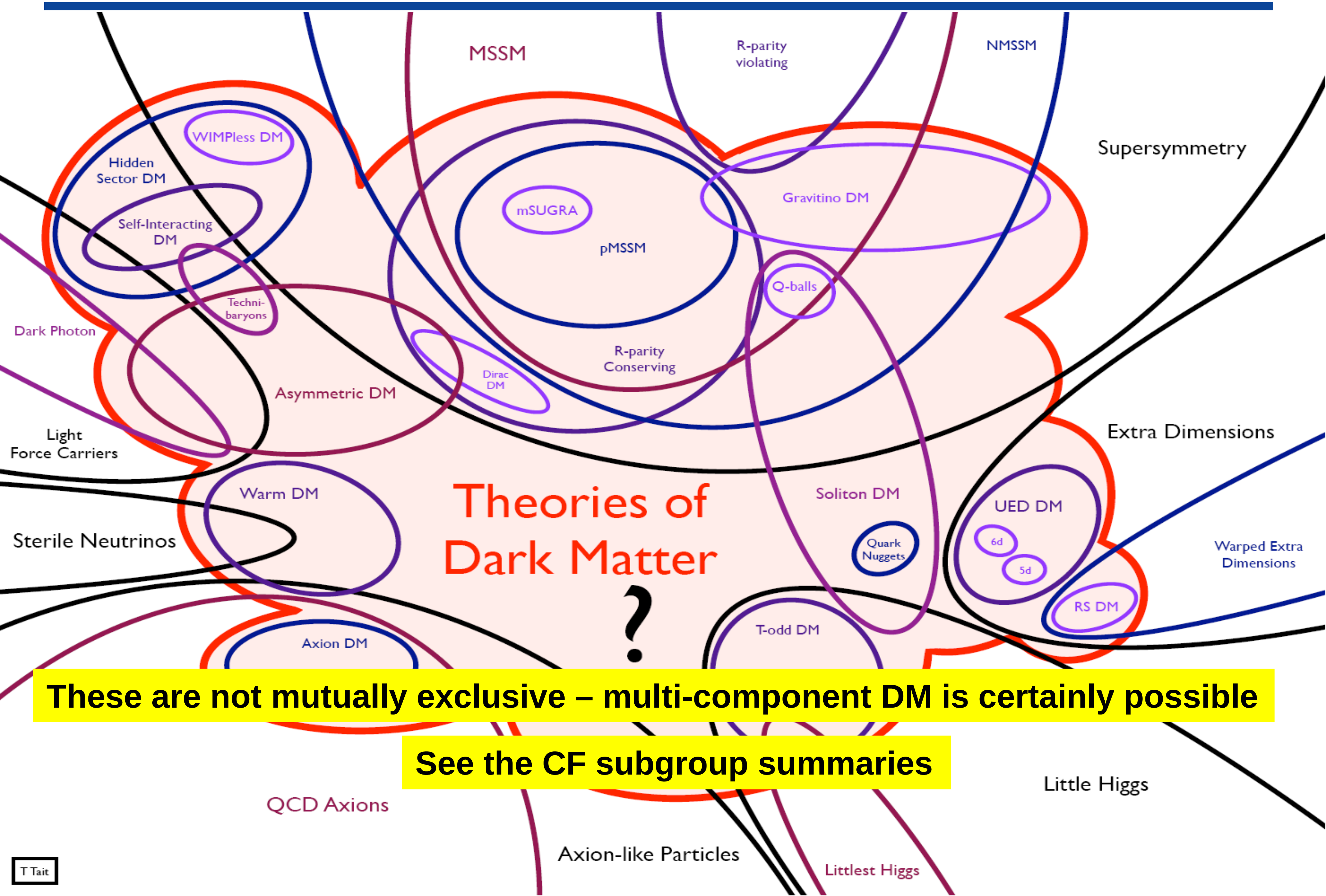
INDIRECT DETECTION: ANTI-MATTER

- Positrons (PAMELA, Fermi-LAT, AMS, CALET)
- Anti-Protons (PAMELA, AMS)
- Anti-Deuterons (GAPS)





NON-WIMP DARK MATTER



These are not mutually exclusive – multi-component DM is certainly possible

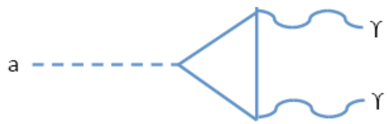
See the CF subgroup summaries

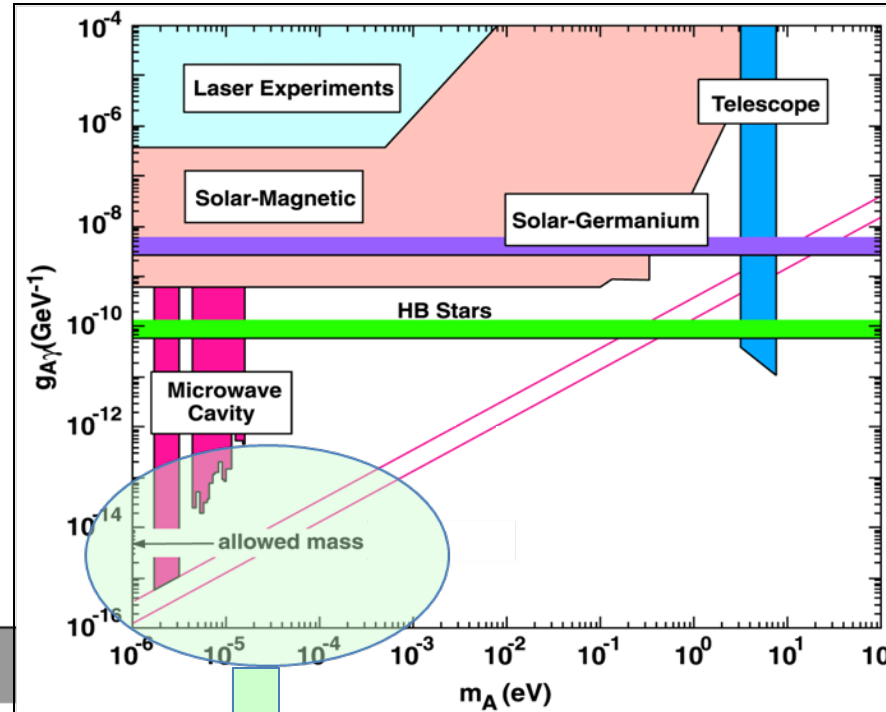
AXIONS

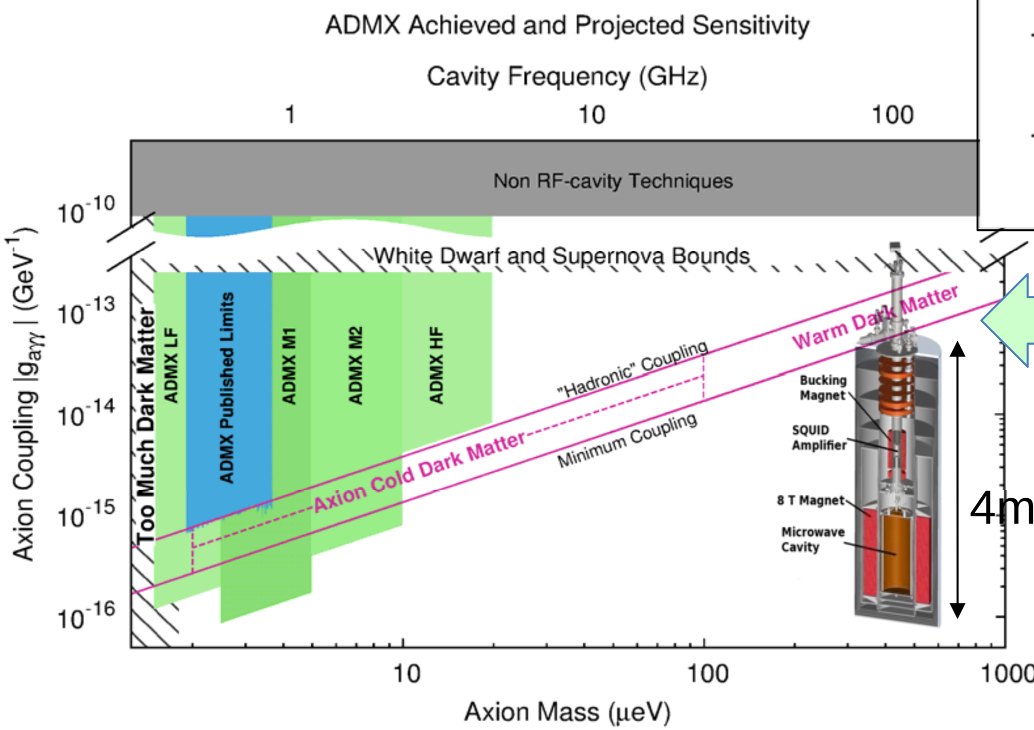
Strongly motivated by strong CP problem

$$\theta_{CP} \frac{g_3^2}{32\pi^2} \epsilon^{\mu\nu\rho\sigma} G^{\alpha}_{\mu\nu} G^{\alpha}_{\rho\sigma} \qquad \theta_{CP} < 10^{-10}$$

A natural solution implies axion particles, which couple to two photons



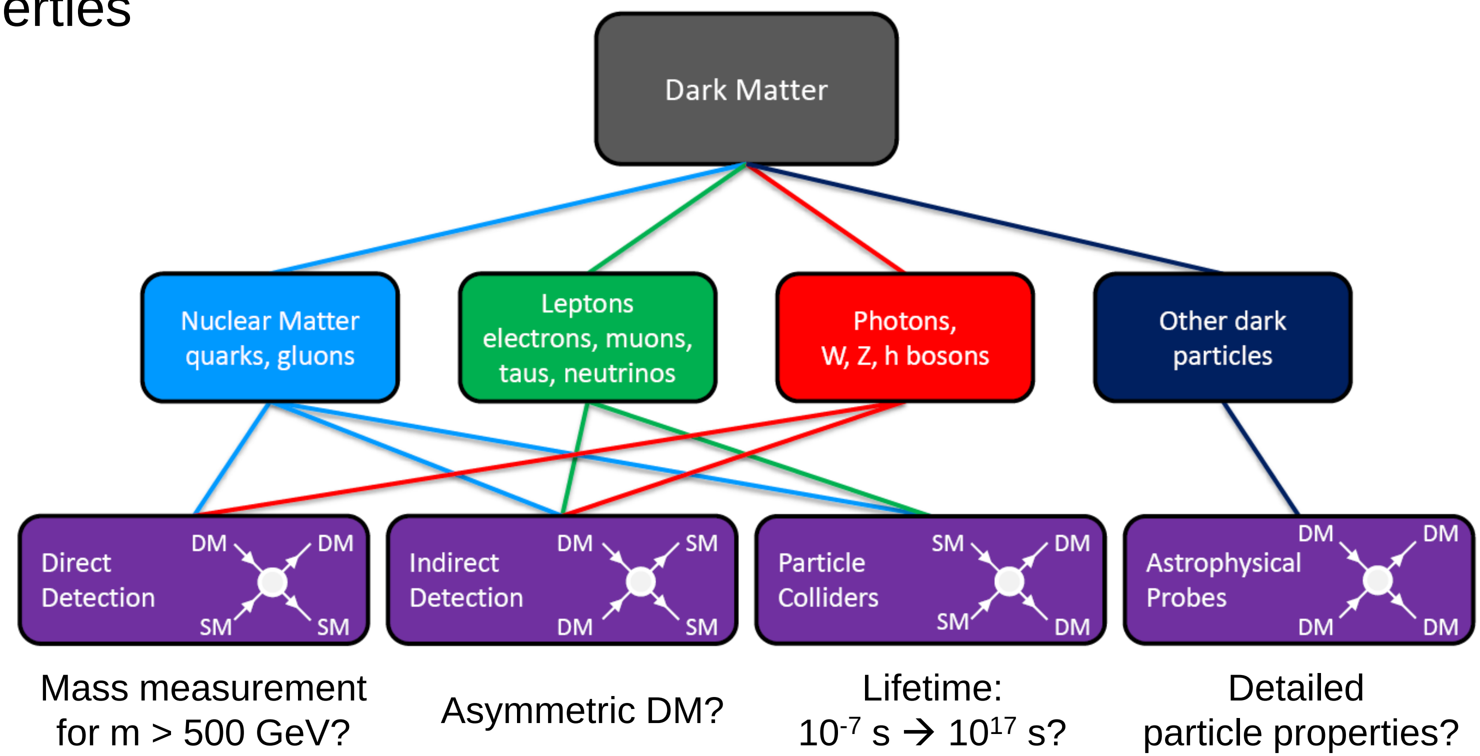




- Favored mass: μeV to meV
- ADMX is projected to cover the first of these three decades in its first year of operations, and the second decade over the following two years

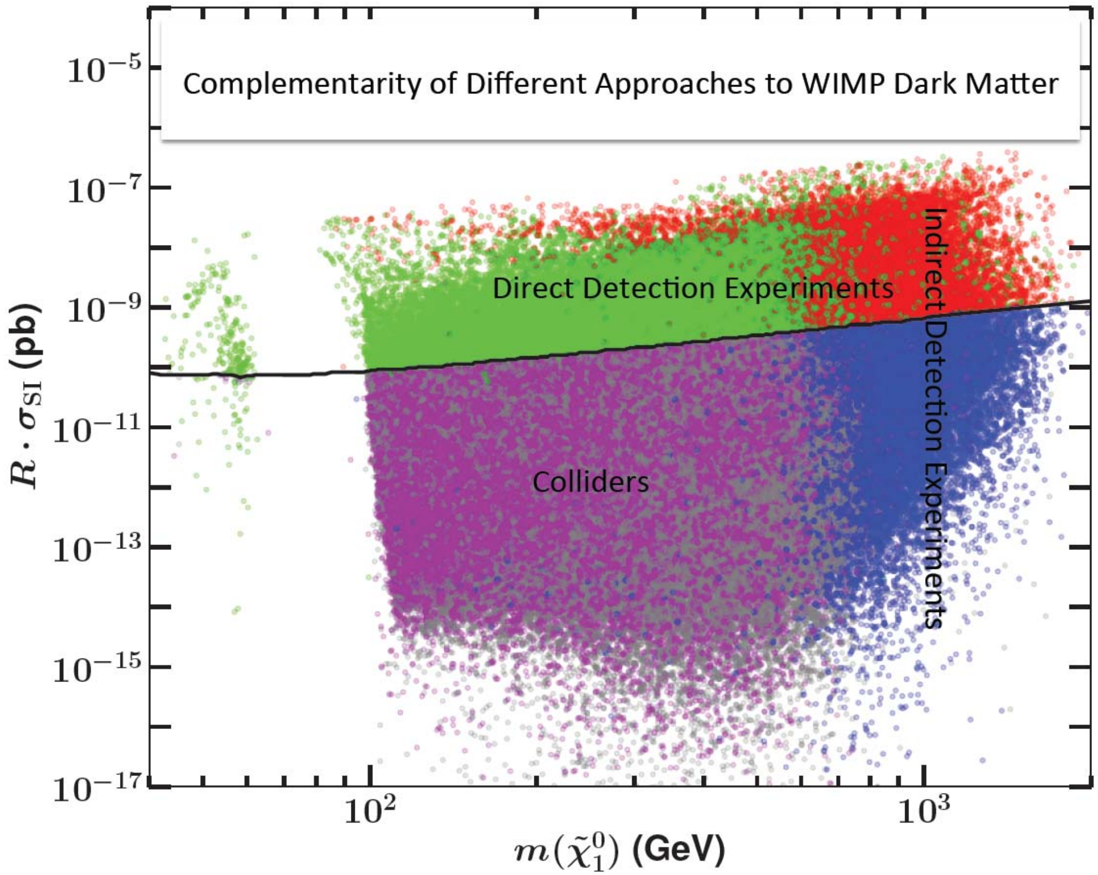
DARK MATTER COMPLEMENTARITY

- Before a signal: Different experimental approaches are sensitive to different dark matter candidates with different characteristics, and provide us with different types of information – complementarity at all levels
- After a signal: we are trying to identify a quarter of the Universe: need high standards to claim discovery and follow-up studies to measure properties



COMPLEMENTARITY: FULL MODELS

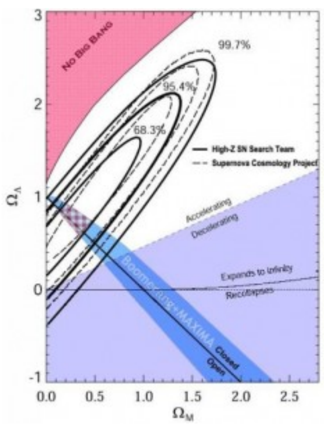
pMSSM 19-parameter scan of SUSY parameter space



- Complementarity for SUSY models; also for DM effective theories
- Many promising approaches to dark matter, and any compelling signal will have far-reaching implications

DARK ENERGY

- Stunning discovery of the accelerating Universe

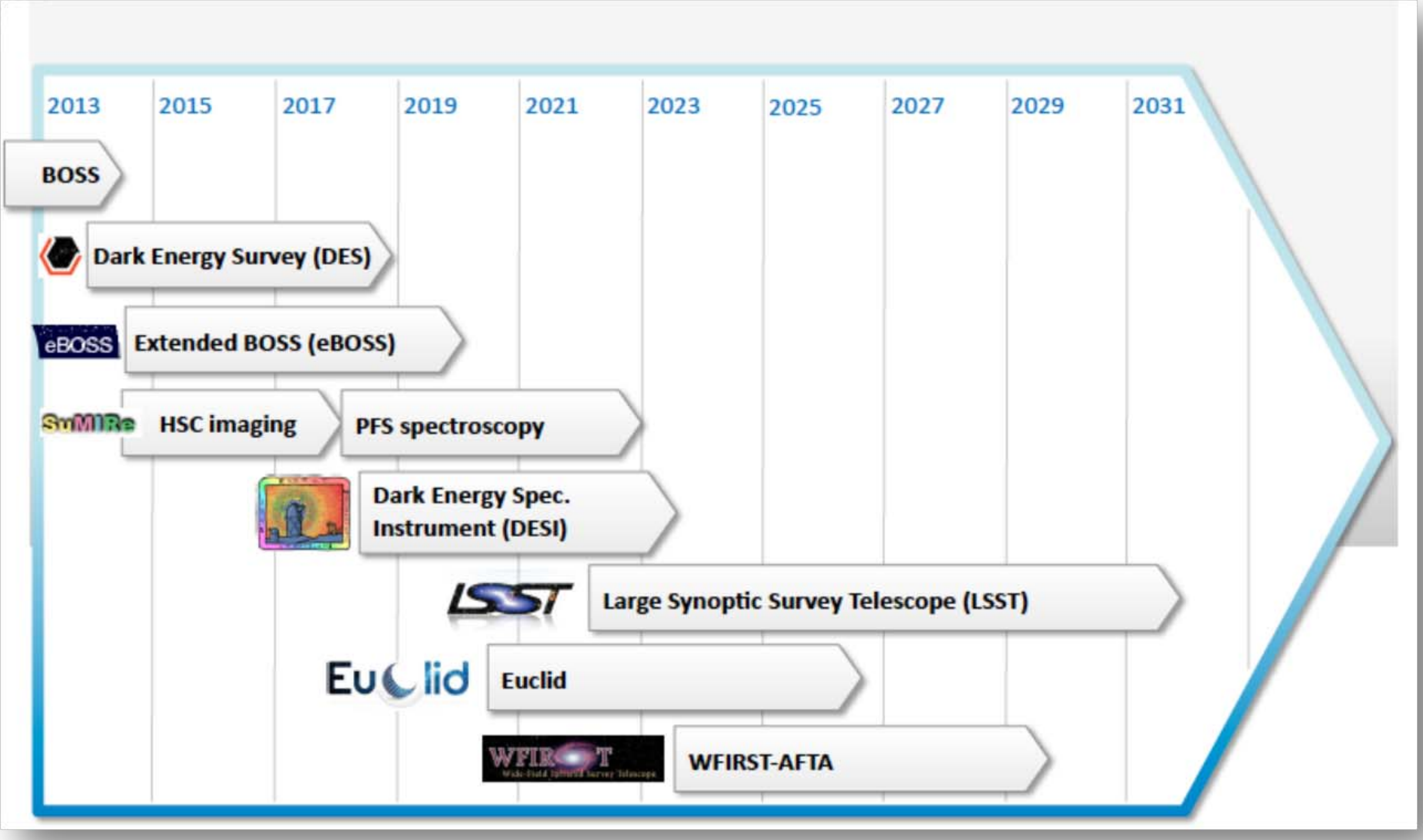


- Can be accommodated in the standard model (ΛCDM). At the same time, it's deeply troubling: the most prosaic explanation is a cosmological constant that is 10^{120} times smaller than naive expectations, immensely fine-tuned, and unnatural.

- There are no compelling theoretical ideas, but many interesting directions are being pursued. Is it vacuum energy? An evolving field? Evidence of the multiverse? A modification of general relativity? Detailed probes of its properties are required (cf. Higgs boson).

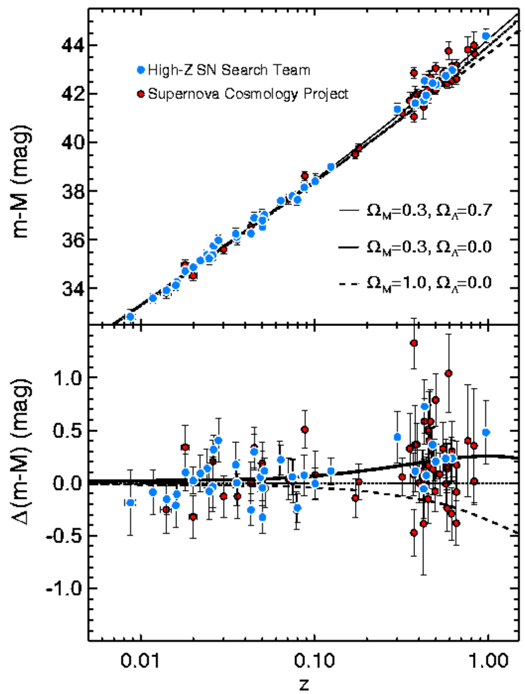
THE DARK ENERGY PROGRAM

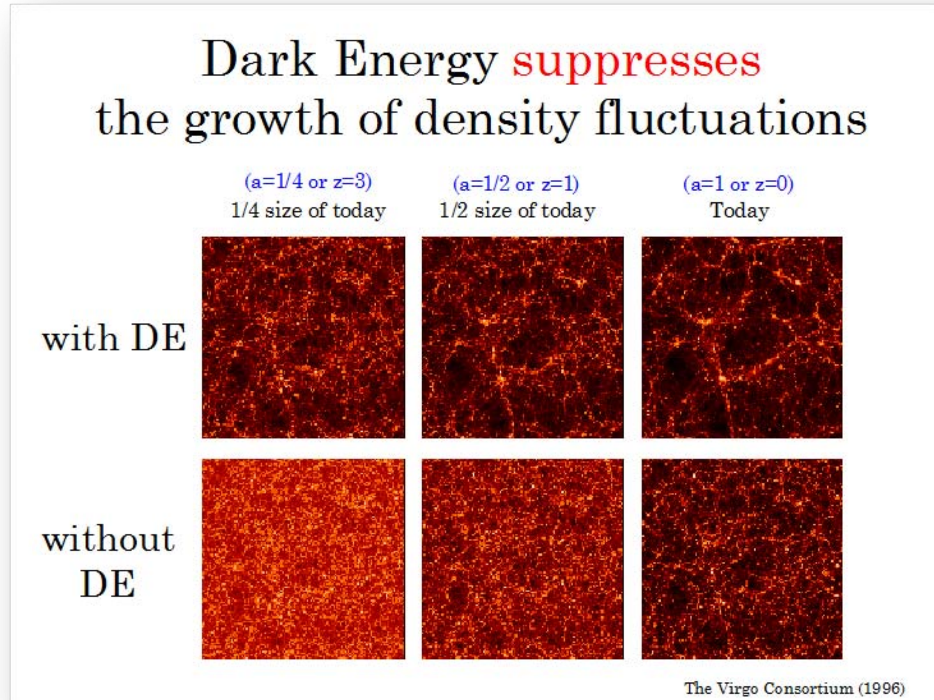
- Well-reviewed, based on intensive community processes
- International with U.S. leadership



DARK ENERGY PROBES

- Dark energy impacts both geometry and growth of structure

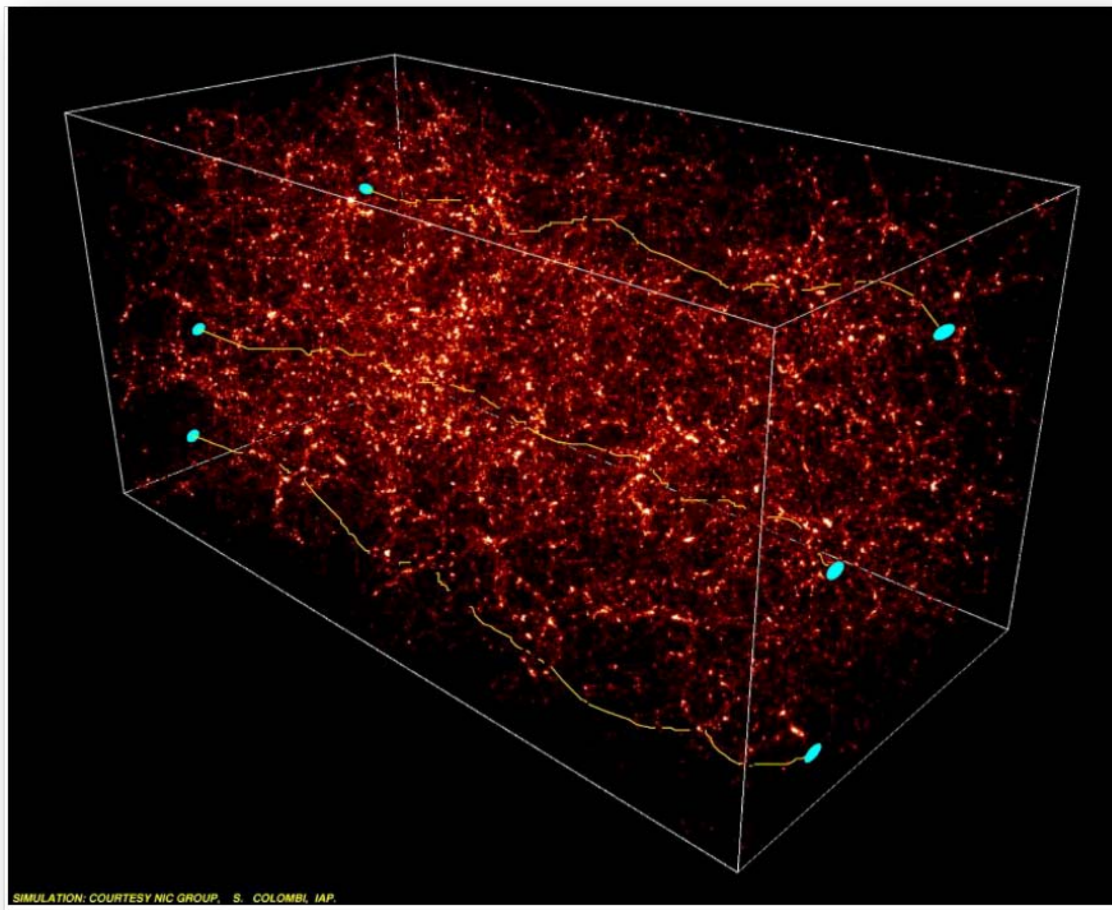




- Snowmass work stressed the importance of complementary probes through supernovae, baryon acoustic oscillations, clusters, weak lensing, and redshift space distortions

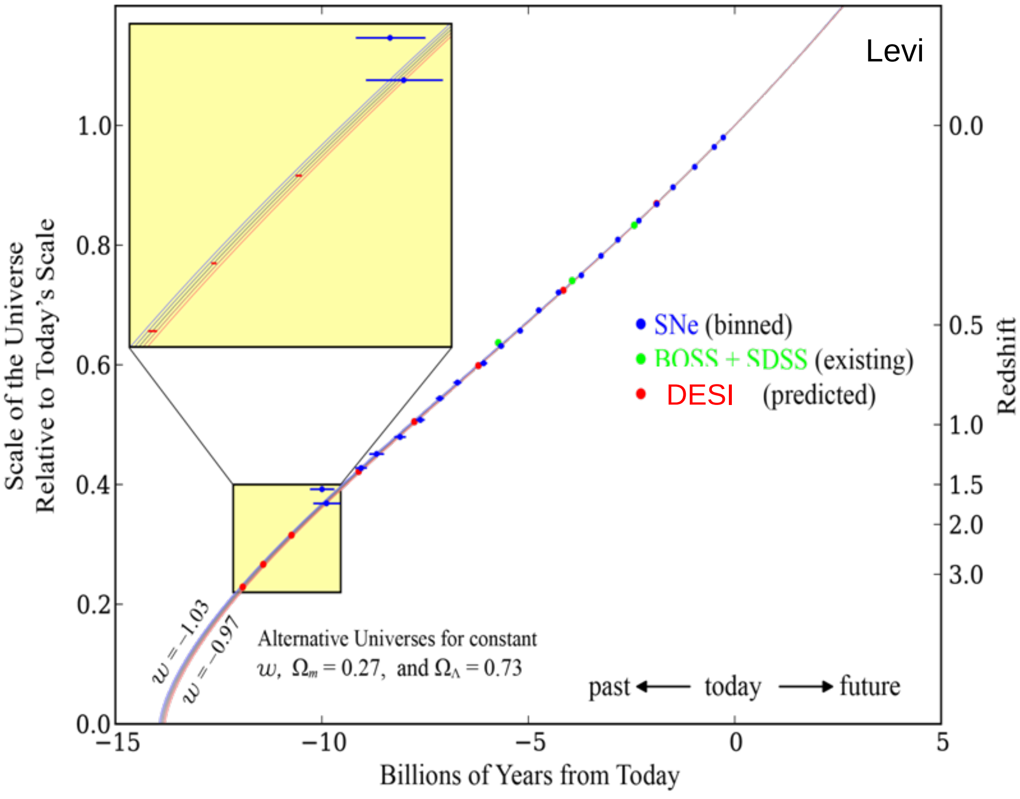
WEAK GRAVITATIONAL LENSING

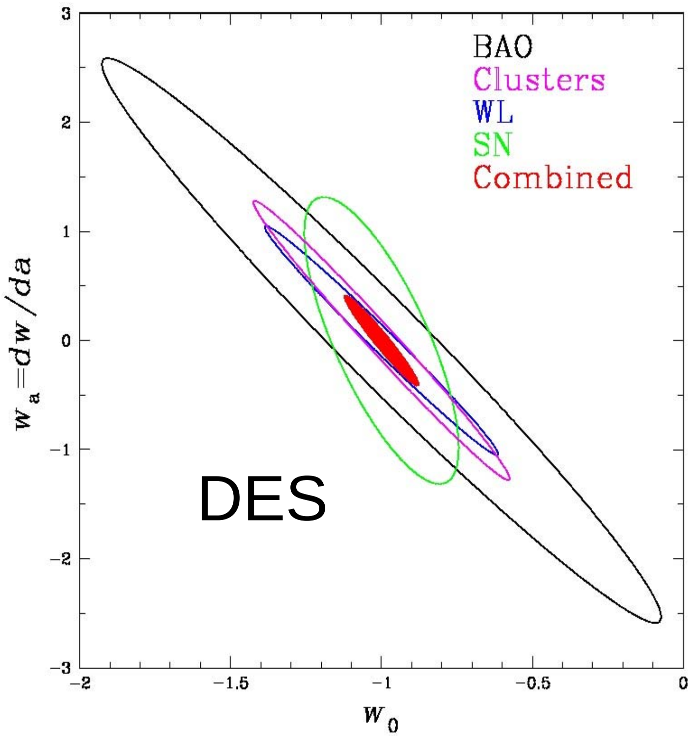
- Images of distant galaxies distorted by gravitational bending of light
- Probes the distribution of dark matter, its evolution with time, and the influence of dark energy on the growth of structure



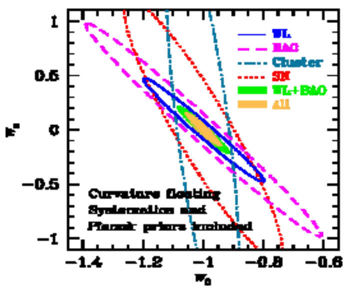
PRECISION DARK ENERGY

- Stage III and Stage IV will take us into the era of precision dark energy, with stringent constraints on w_0, w_a



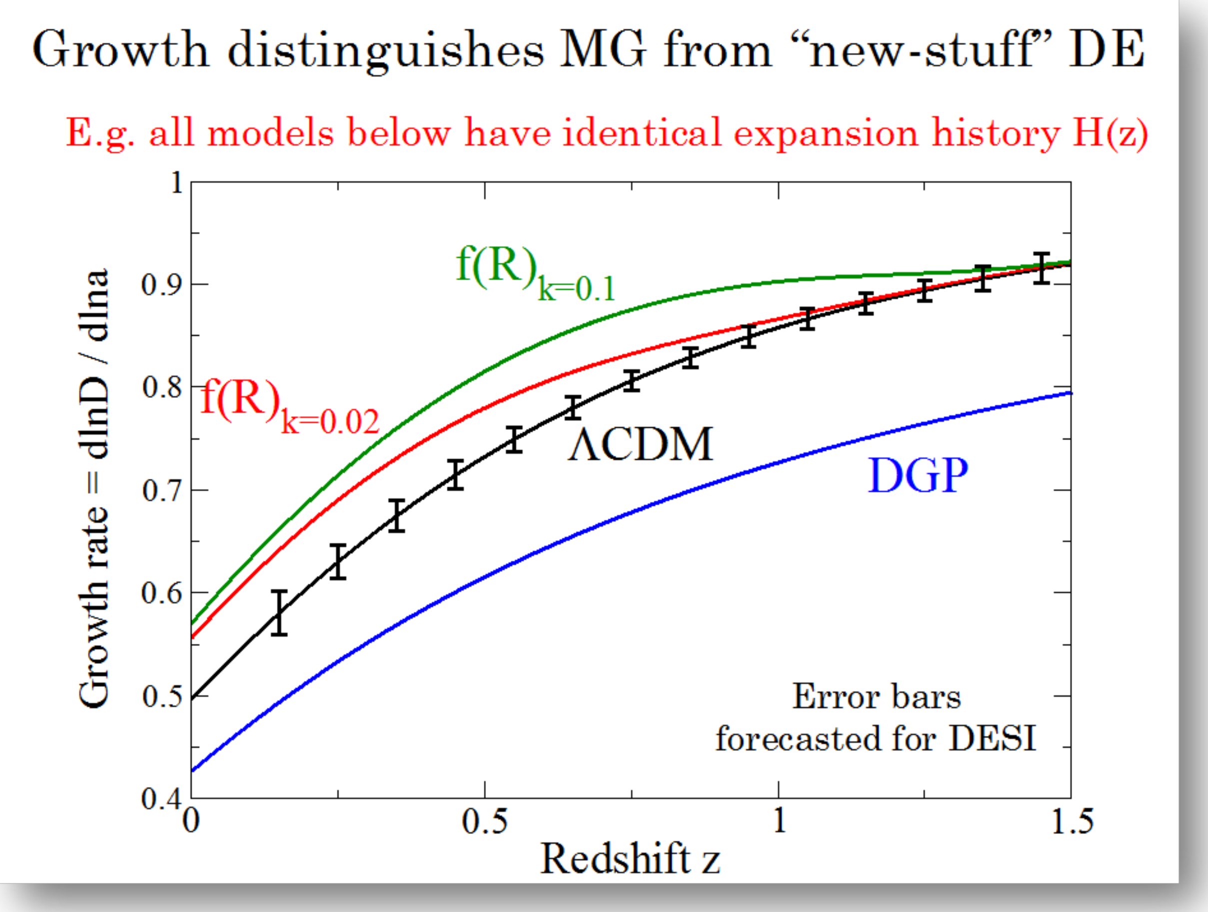


LSST



MODIFIED GRAVITY

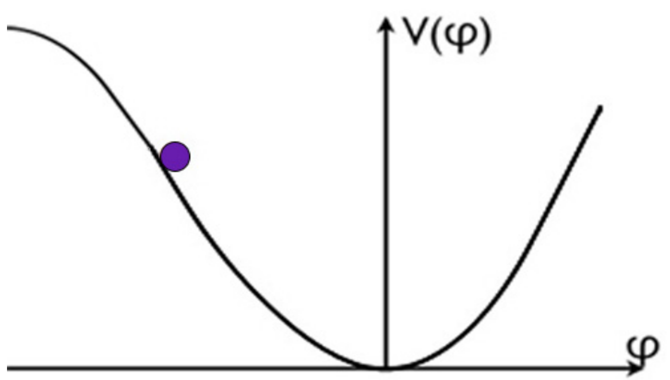
But it's not just about measuring w_0 and w_a now. Modified gravity can be distinguished from vacuum energy by comparing distances and growth of structure, and also novel probes

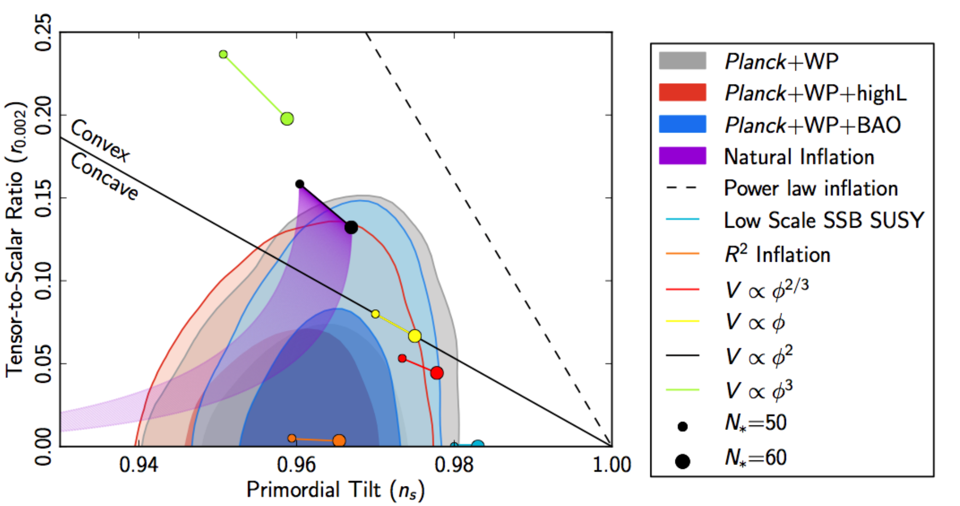


INFLATION AND CMB

- Inflation, originally proposed to solve the flatness and horizon problems, is now the leading theory for the primordial origin of structure
- Many possible inflation models, but we are now entering the era when these are being tested (physics at 10^{-32} s after the Big Bang!)
- CMB B-modes probe inflation scale (r ~ 0.1 to 0.001), with implications for GUT-scale inflation, large field inflation, …

$$E_{\text{inf}} = 1.06 \times 10^{16} \left(\frac{r}{0.01} \right)^{1/4} \text{ GeV}$$





NEUTRINO COSMOLOGY

- Cosmology constrains the effective number of neutrinos N_{eff}

$$\rho_R = \left(1 + N_{\text{eff}} \frac{7}{8} \left(\frac{4}{11}\right)^{4/3}\right) \rho_\gamma$$

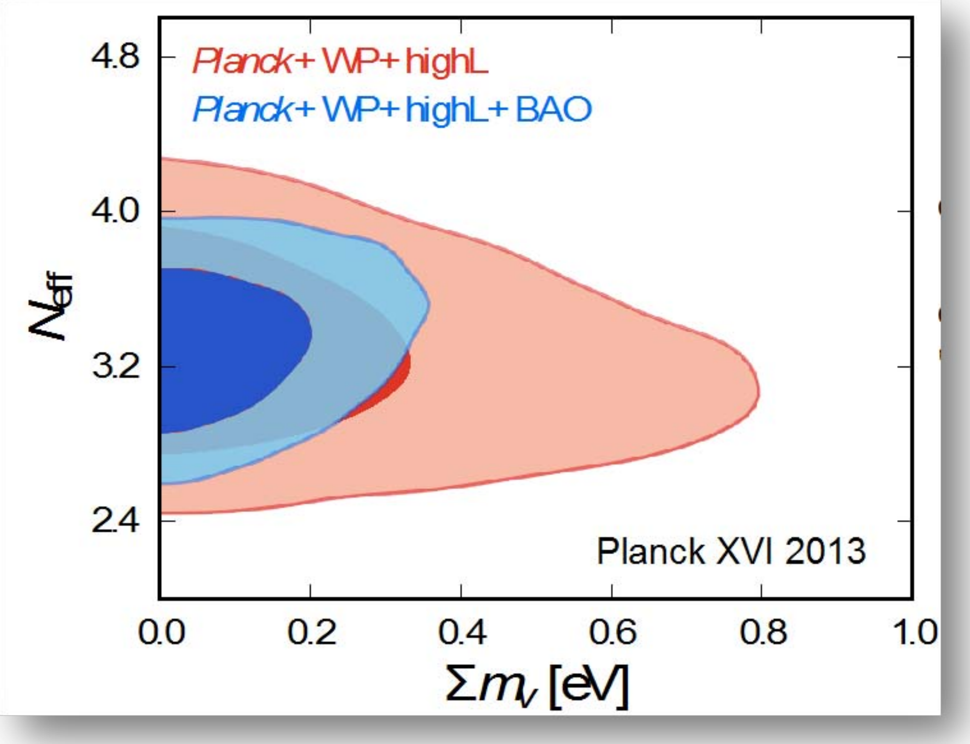
N_{eff} = 3.046 in the SM with 3 active neutrinos.

- Also, neutrinos, once hot, are now cold:

$T_{CNB} << m_\nu \sim 50$ meV

The transition impacts structure formation, and cosmology also constrains the sum of neutrino masses

$$\Omega_\nu h^2 \simeq \frac{\sum m_\nu}{94 \text{ eV}}$$



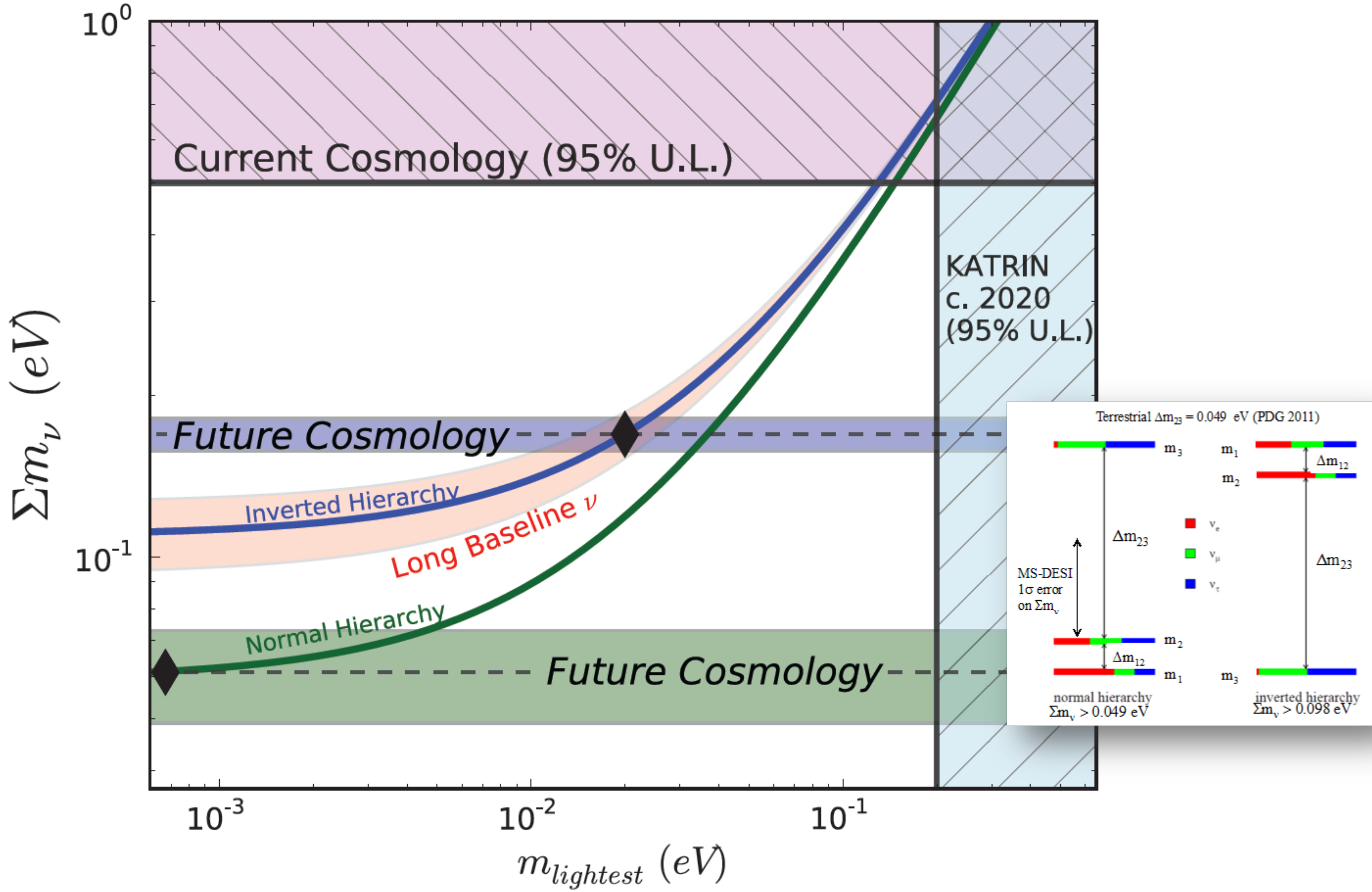
NEUTRINO COSMOLOGY PROSPECTS

- Future CMB + LSS experiments will have greatly improved sensitivities

DATASET	$\sigma(\sum m_\nu)$ [meV]	$\sigma(N_{\rm eff})$
TODAY:		
Planck + BOSS BAO	100	0.34
2020:		
Planck + eBOSS galaxy clustering	36/52	0.13/0.16
Stage-III CMB + BOSS BAO	60	0.06
2025:		
Planck + DESI galaxy clustering	17/24	0.08/0.12
Planck + LSST	23	0.07
Stage-IV CMB + DESI BAO	16	0.02

Cosmic constraints are complimentary to terrestrial experiments, and will be at a sensitivity that they can precisely test predictions; either confirming the standard model or indicating new physics.

NEUTRINO COSMOLOGY PROSPECTS



COSMIC SURVEYS SUMMARY

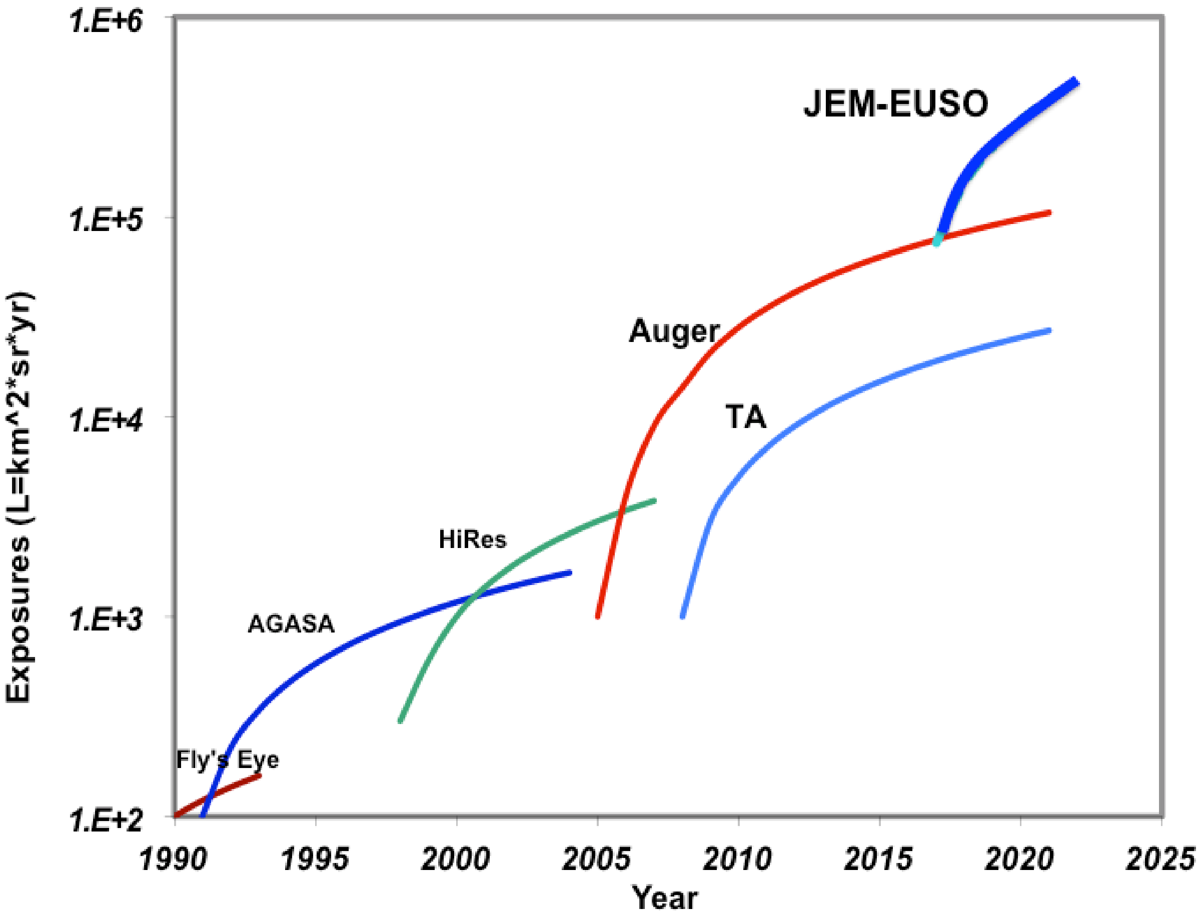
- **Remain a Leader in Dark Energy**
  - A combination of imaging and spectroscopic surveys is needed to pinpoint the new physics driving the accelerations
  - Current suite of surveys, Stage III, will be the first to implement the vision of multiple probes and small systematics
  - The next stage is needed to complete this program and to achieve percent-level uncertainties
- **Build a Stage IV CMB Polarization Experiment**
  - The community understands that next generation experiment will require a nation-wide coherent effort
  - Moving to hundreds of thousands of detector elements will require the involvement of the national labs working with the university community
- **Extend the Reach**
  - With small investments the DE program can be augmented in important ways

THE MATTER—ANTI-MATTER ASYMMETRY

- Physics beyond the standard model to explain why 10^8+1 quarks for every 10^8 antiquarks in very early universe
- Possibilities within popular theories beyond the standard model
  - ➡ *Leptogenesis*: decay of very heavy right handed neutrinos
  - ➡ *Electroweak Baryogenesis:* new bosons providing 1st order phase transition (light right handed top squark, 2 Higgs doublets, …)
  - ➡ *Affleck-Dine:* evolution and decay of squark/slepton condensate
  - ➡ many others
- Need nonstandard CP violation: → look for new source
  - ➡ Electric Dipole Moments
  - ➡ CPV in long baseline neutrino oscillations
- A 3 Frontier Problem

COSMIC PARTICLES AND FUNDAMENTAL PHYSICS

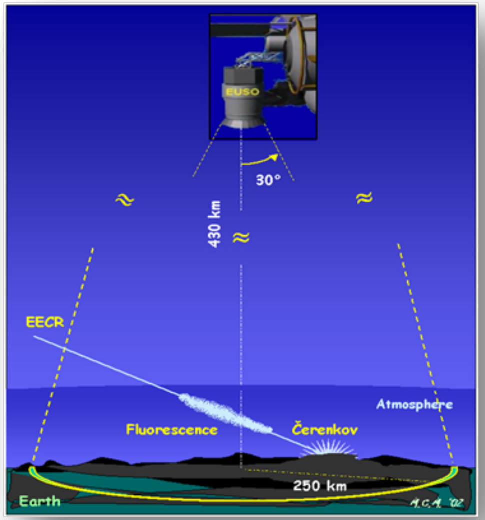
Outstanding mysteries of ultrahigh energy cosmic rays: sources, composition, fundamental particle physics



Events above 60 EeV:

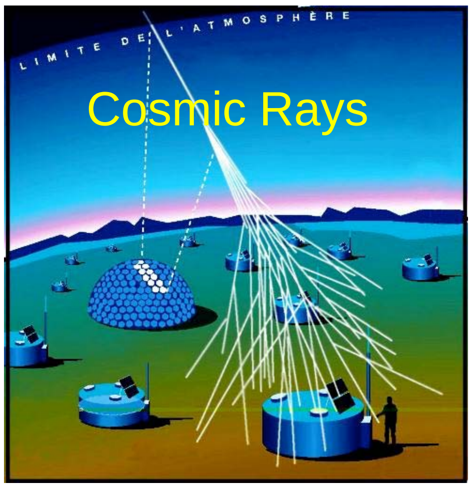
1 every 10 s on Earth

200 per year
seen by JEM-EUSO



ULTRAHIGH ENERGY (GZK) NEUTRINOS

$$p + \gamma_{cmb} \rightarrow \Delta^+ \rightarrow n + \pi^+$$
$$\rightarrow \mu^+ + \nu_\mu$$
$$\rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$



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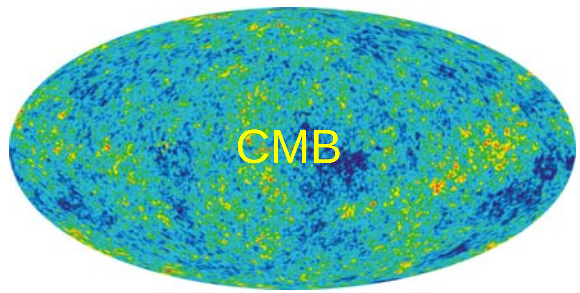


= Neutrino Beam!

Discovery of GZK neutrinos within reach over the next decade

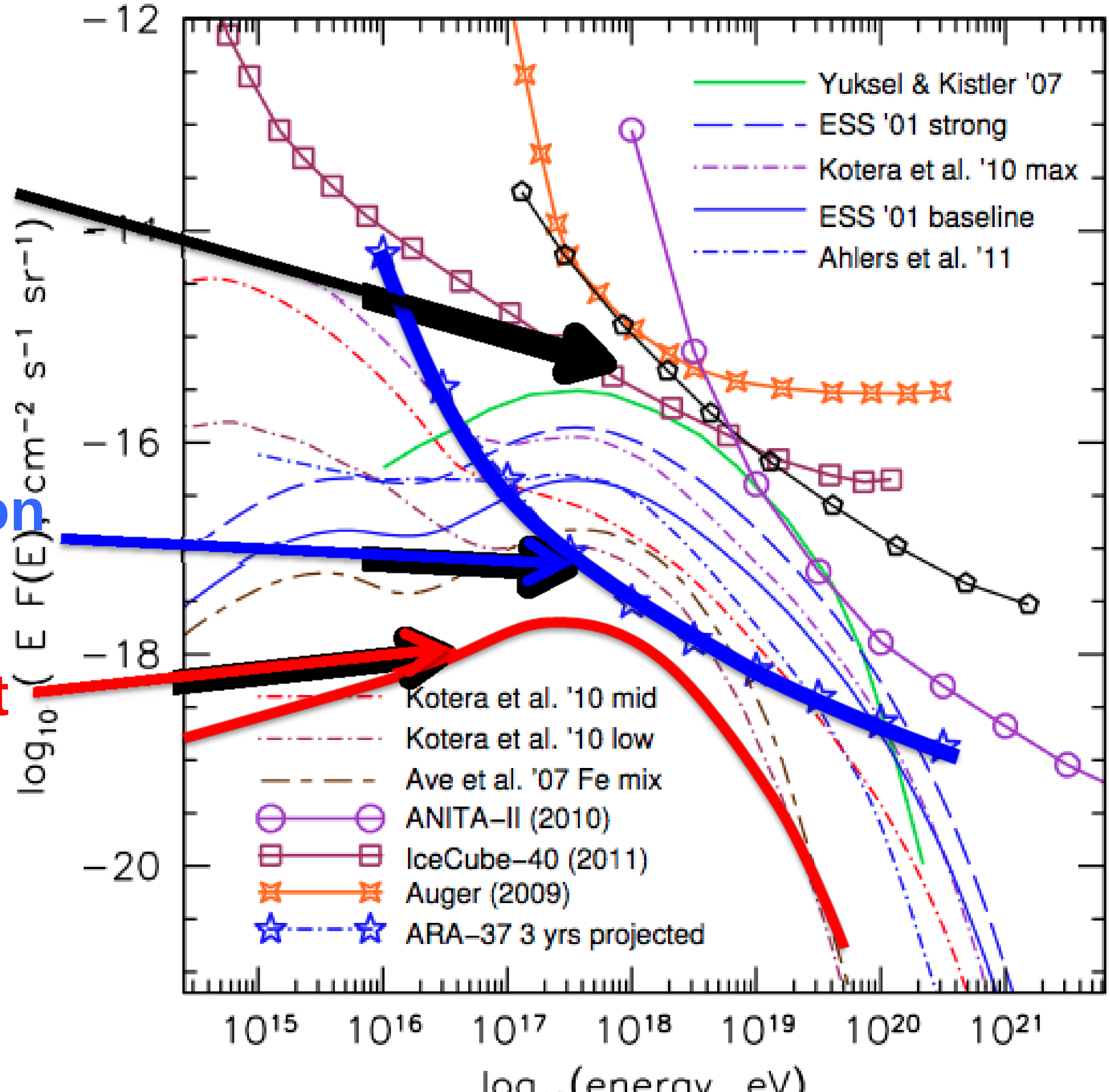
- Determine the origin of the highest energy particles
- Measure E_{COM} ~ 100 TeV neutrino interactions via ratio of upward to downward neutrino showers
- Test Lorentz invariance

GZK NEUTRINO PROSPECTS: ARIANNA, ARA

Current Limits

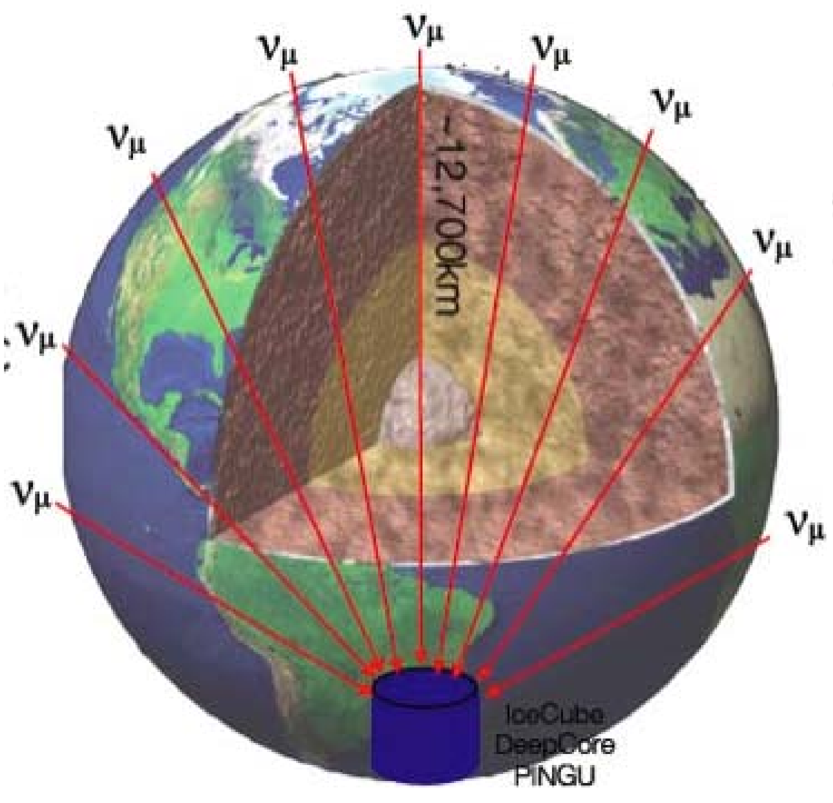
Next Generation

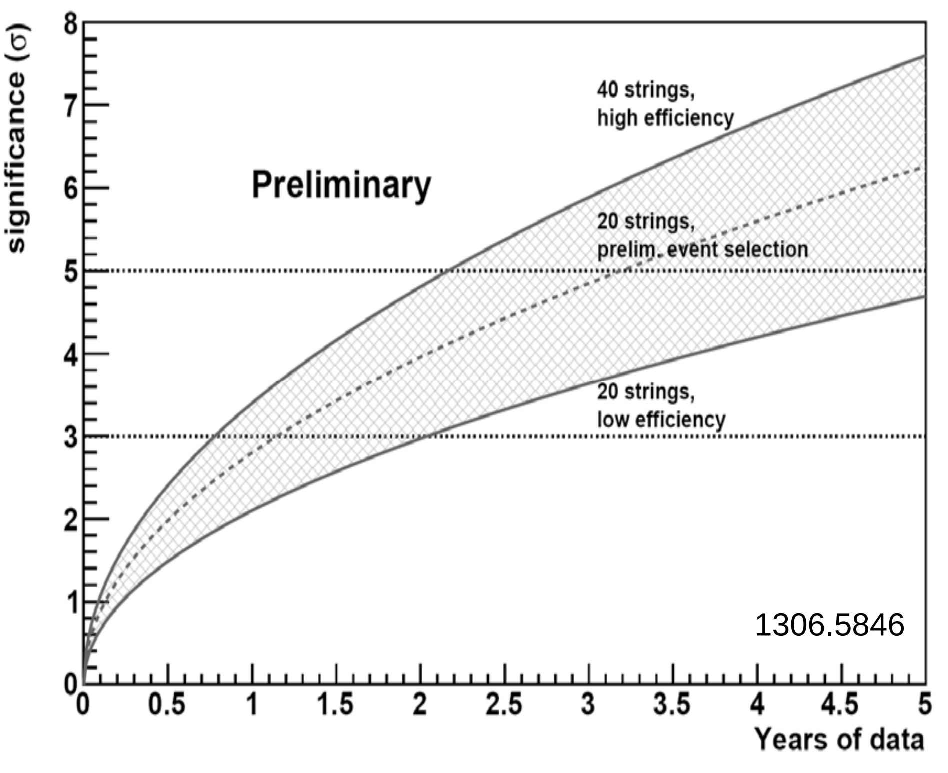
Flux Lower Limit



NEUTRINO MASS HIERARCHY

- PINGU, IceCube infill array, could provide significant neutrino mass hierarchy information, complementing long baseline and reactor neutrino experiments





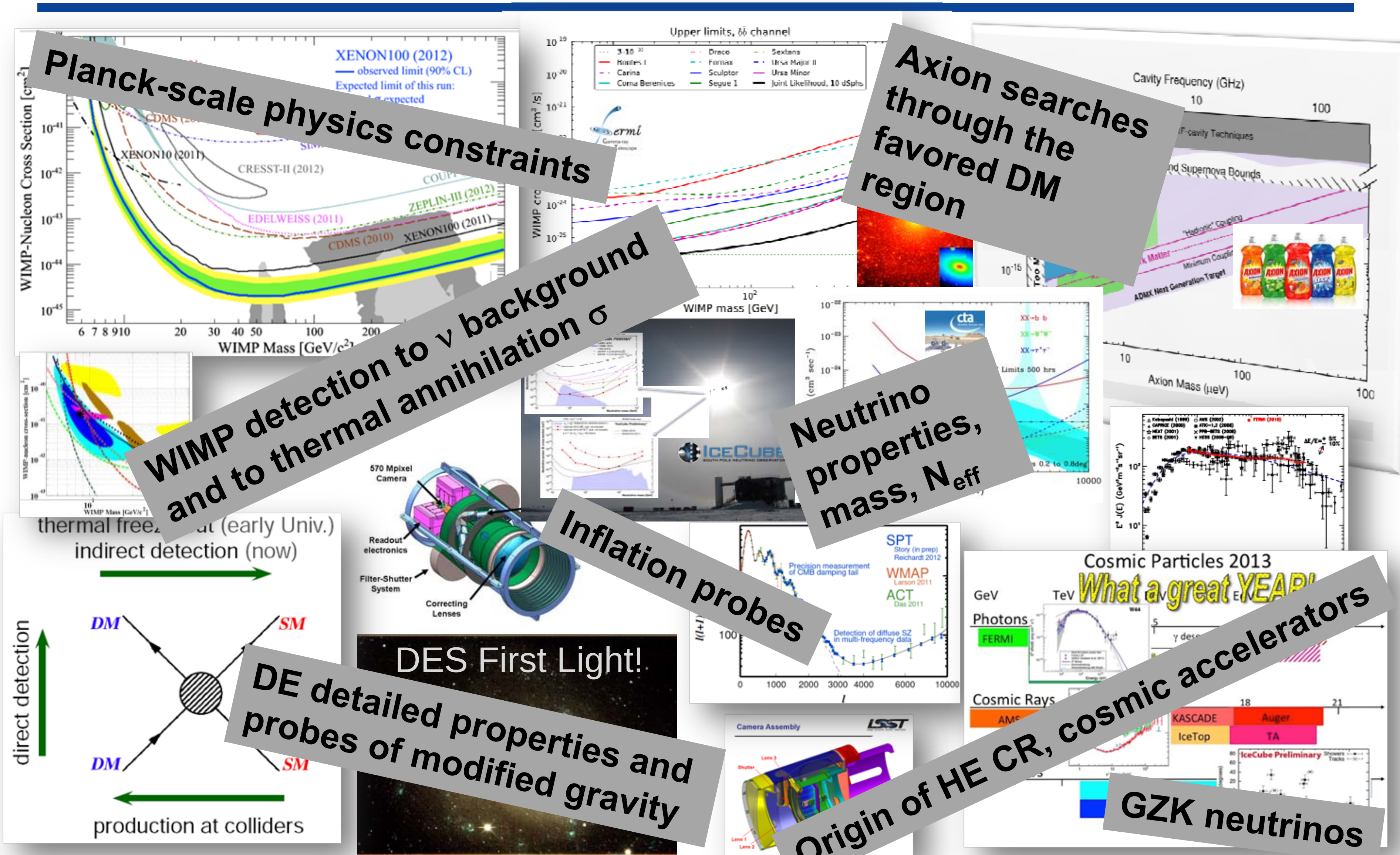
COSMIC PARTICLES SUMMARY

- Matter asymmetry: EDMs, CP violation in neutrino sector, and inflation scale are key measurements
- Neutrino mass hierarchy possible with SN neutrinos (LBNE) and atmospheric neutrinos (PINGU)
- Origin of highest energy particles in the universe (multi-messenger campaign)
- Fundamental physics accessible with next generation instruments
- Control of astrophysical systematics in era of precision VHE gamma-ray astrophysics (CTA)
- Neutrino interactions at high energies to be measured with GZK neutrinos (ARIANNA, ARA, …)
- 300 TeV COM interactions to be measured with UHECRs (JEM-EUSO)
- Probing Planck scale physics is now possible

COSMIC FRONTIER SUMMARY

- Together with the other frontiers, the Cosmic Frontier provides to particle physics:
  - Clear evidence for physics beyond the Standard Model
  - Profound questions of popular interest
  - Frequent new results, surprises, with broad impacts
  - A large discovery space with unique probes
  - Important cross-frontier topics
  - Full range of project scales, providing flexible programmatic options
  - U.S. leadership

THE COSMIC FRONTIER MENU



Activities at the Cosmic Frontier are marked by rapid, surprising, and exciting developments