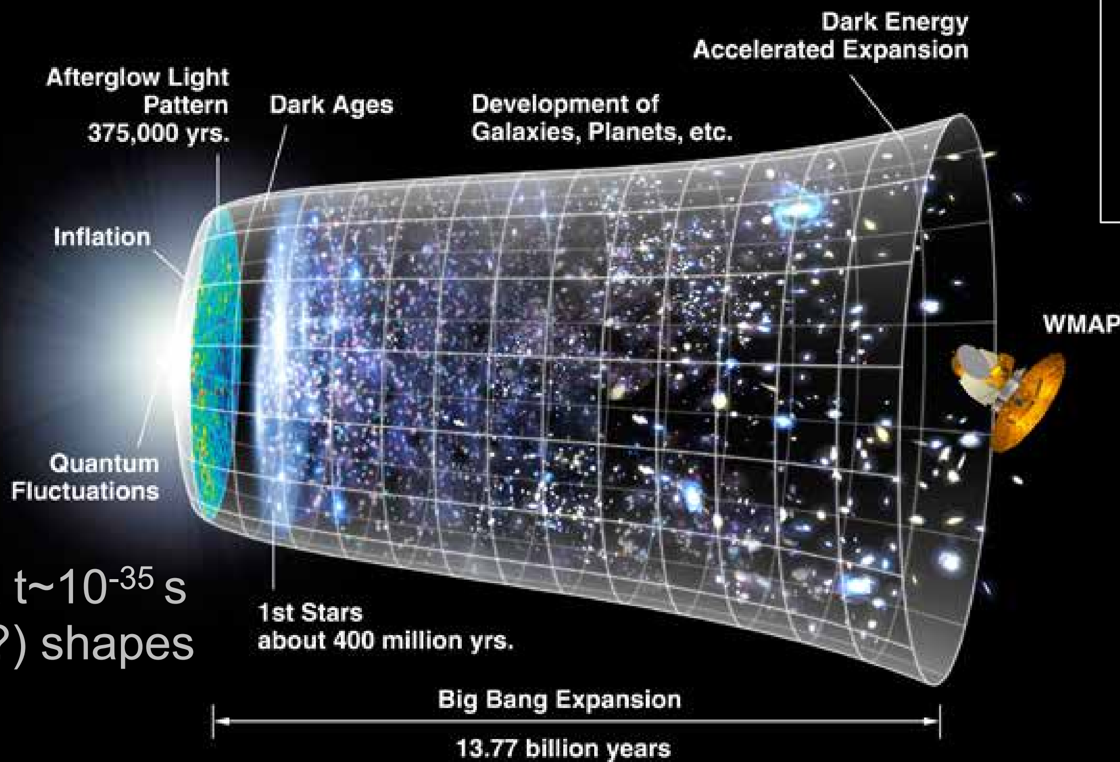
Summary of Snowmass Activities

***Part b**: CF5, CF6, Summary*

S. Ritz and J. Feng
For the Cosmic Frontier Group

Cosmic Surveys: The Big Picture

Detailed comparisons of different observations with much richer data sets will directly address these topics, and likely also provide more surprises.



Inflation at t~10^{-35} s (driven by ?) shapes the…

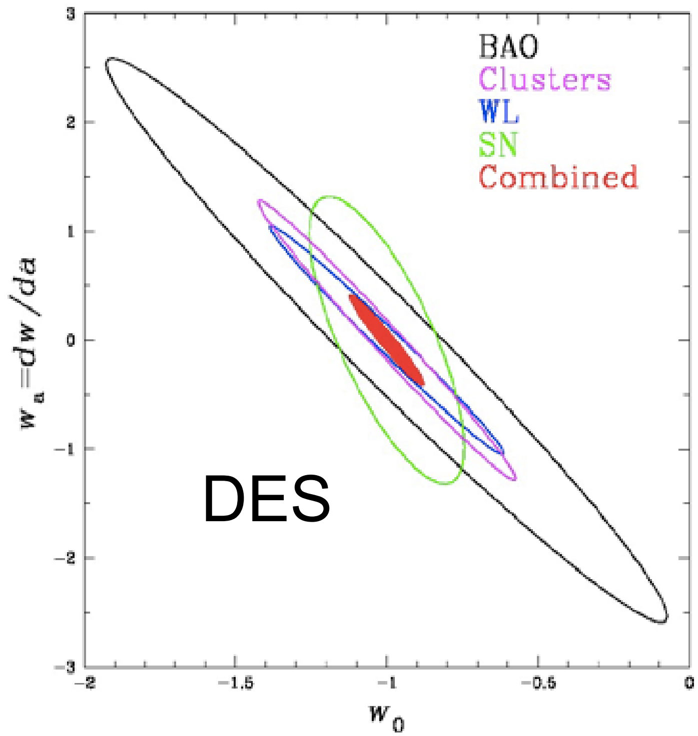
…CMB map at t~300,000 years, which, seeds structure formation driven by **Dark Matter** producing the growth of structure, which…

…is then driven by **Dark Energy...**

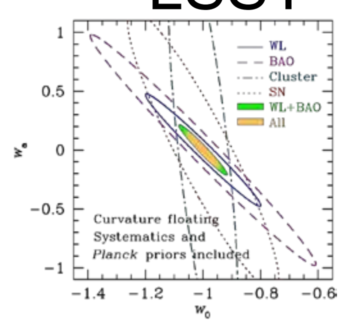
…and Neutrinos (N_{eff} and ($\Sigma m_\nu > 0$) have a significant impact on the growth of structure at small scales

Dark Energy

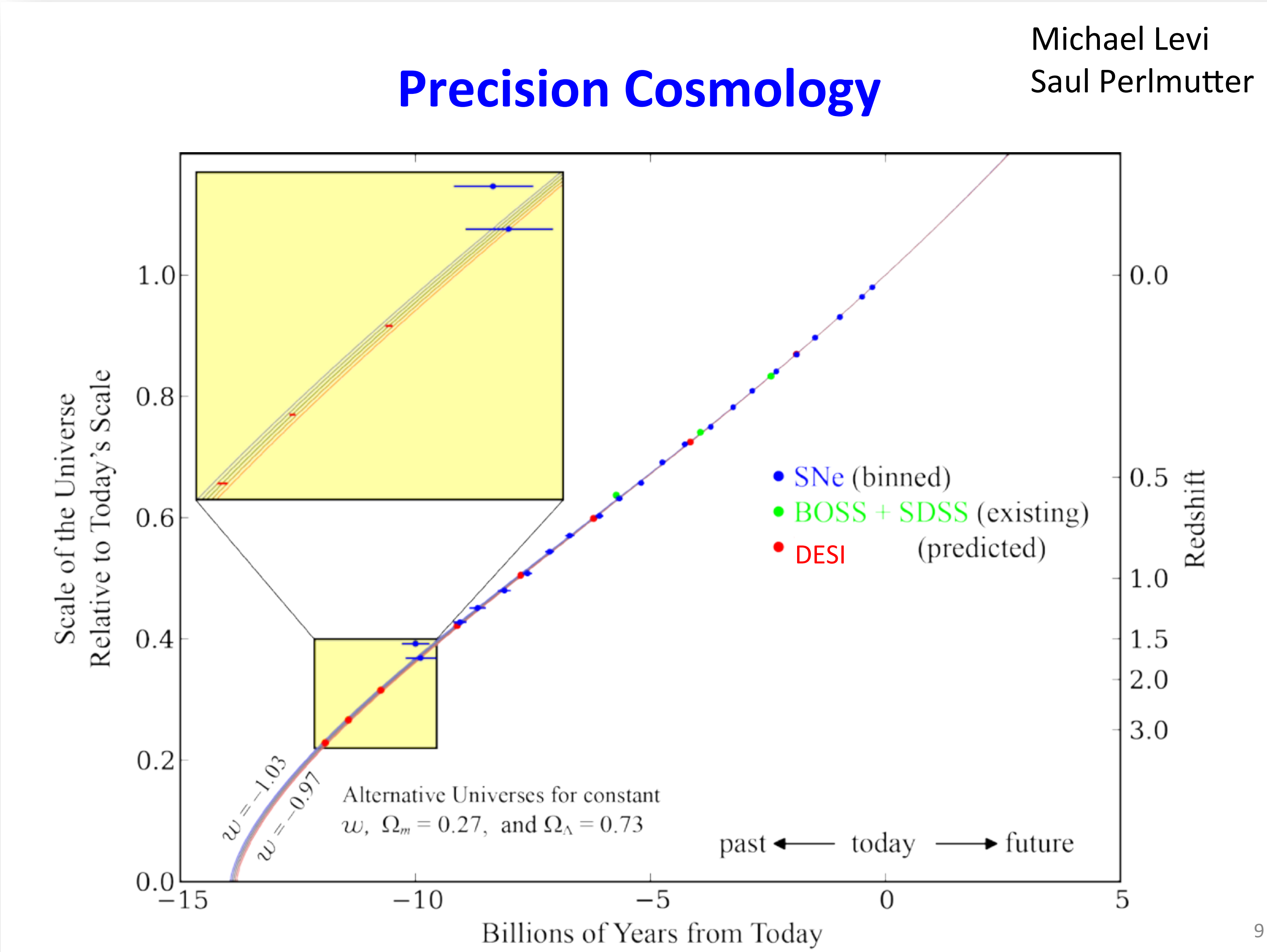
- Highlights of Snowmass work include
  - **Strategies to distinguish dark energy from modified gravity**
  - **Importance of upcoming complementary probes for determining the key cosmological parameters**
  - **Techniques and Issues**
  - **Facilities**
  - **"Why Study Dark Energy?"**
- Stage III (next up!) a big advance.
- Stage IV not "just" improved Figure of Merit – it's a new domain.
  - Stage III, IV plans result of intensive community processes



LSST

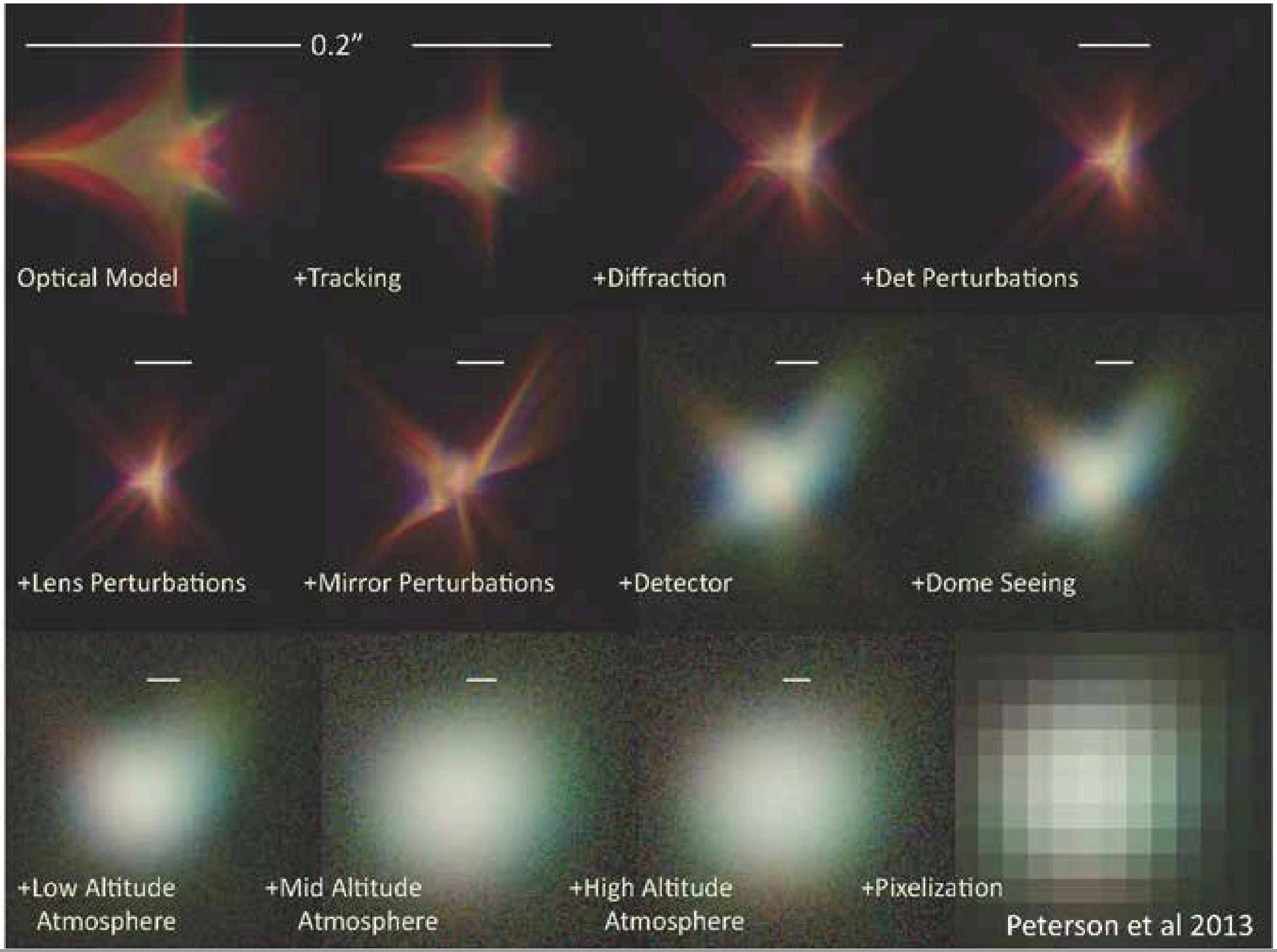


Much Better Data



Controlling Systematic Uncertainties

LSST Photon Simulator



10

Mapping the Universe

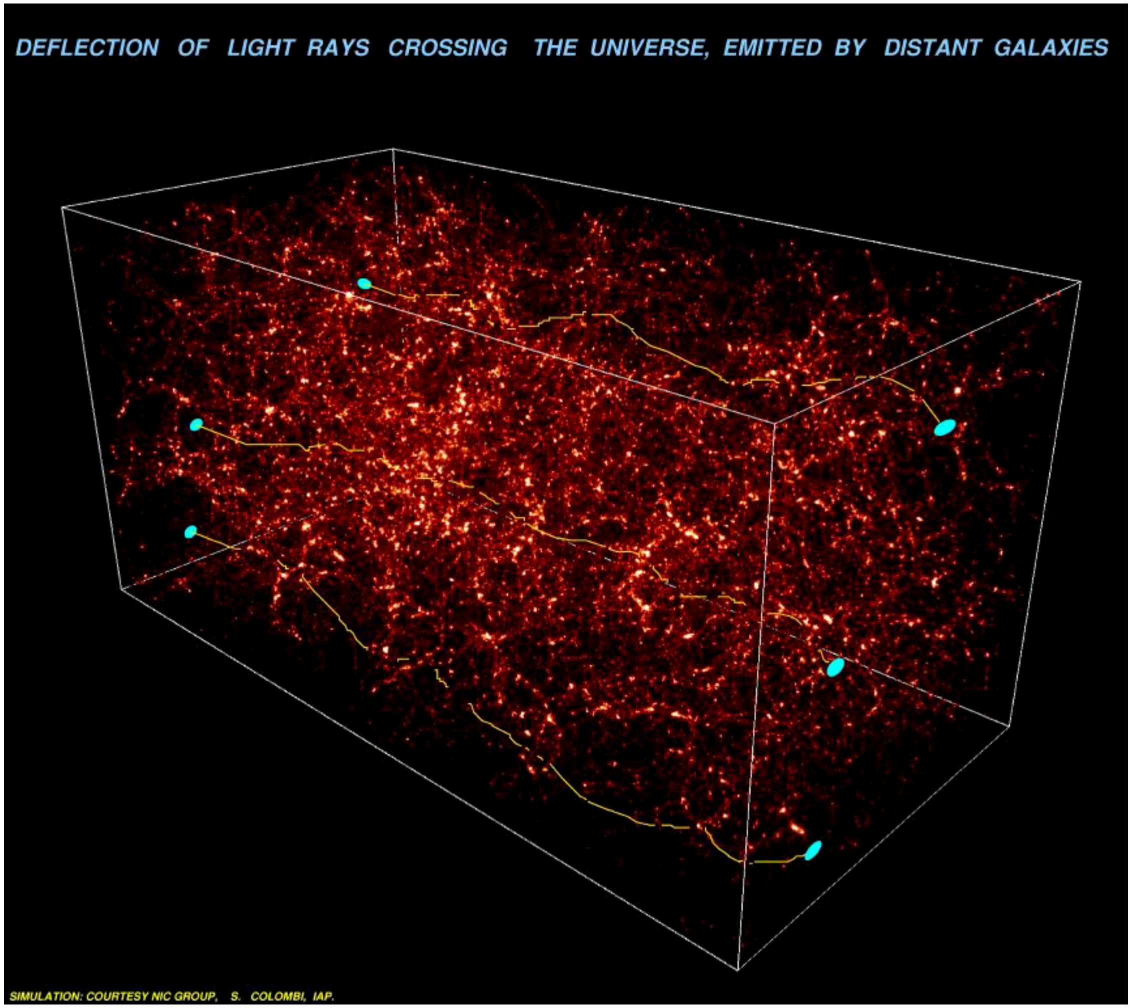
- Two observable fields
  - Matter Density
    - Growth of structure
  - Velocities
    - Response to the matter density
- Imaging and Spectroscopic surveys give different, complementary views
  - Imaging surveys : Lensing
  - Spectroscopic surveys : BAO/Redshift Distortions

Plus other complementary techniques: clusters, Sne, …

Weak Gravitational Lensing

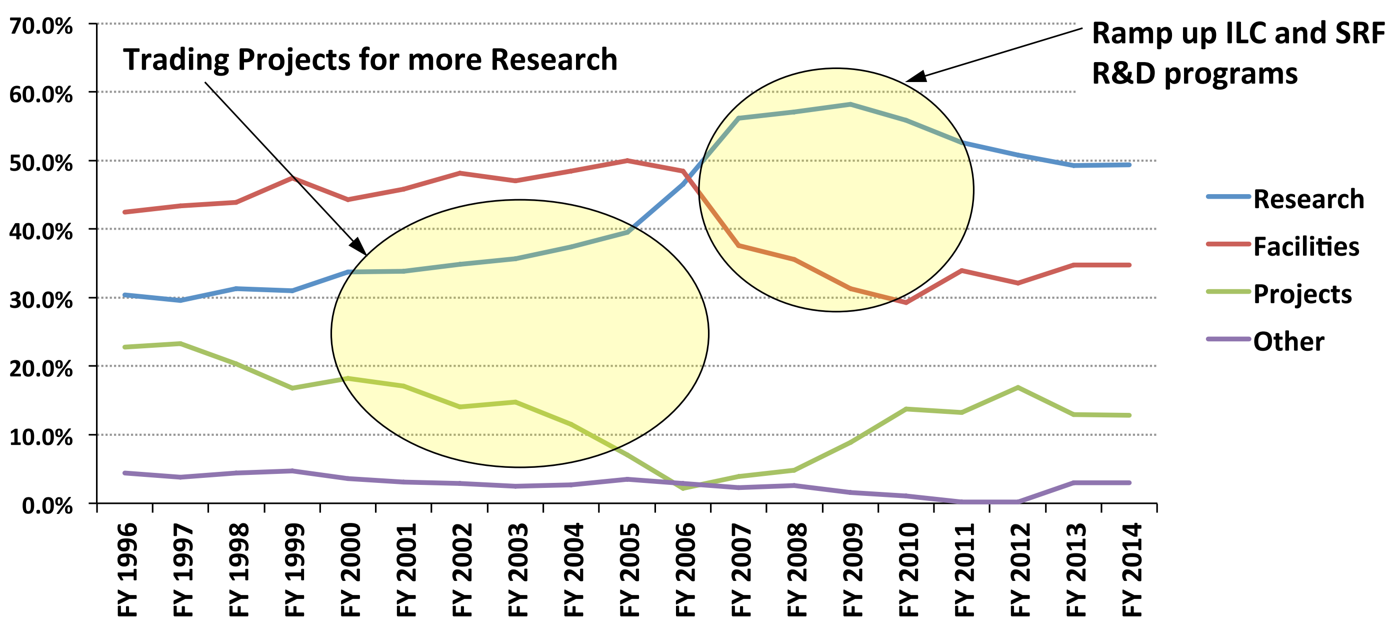
Galaxy shapes appear **sheared** due to **all matter** along line-of-sight

Measure **correlations** of those shears - not random



Weak Budgetary Lensing

HEP budget - Recent Funding Trends



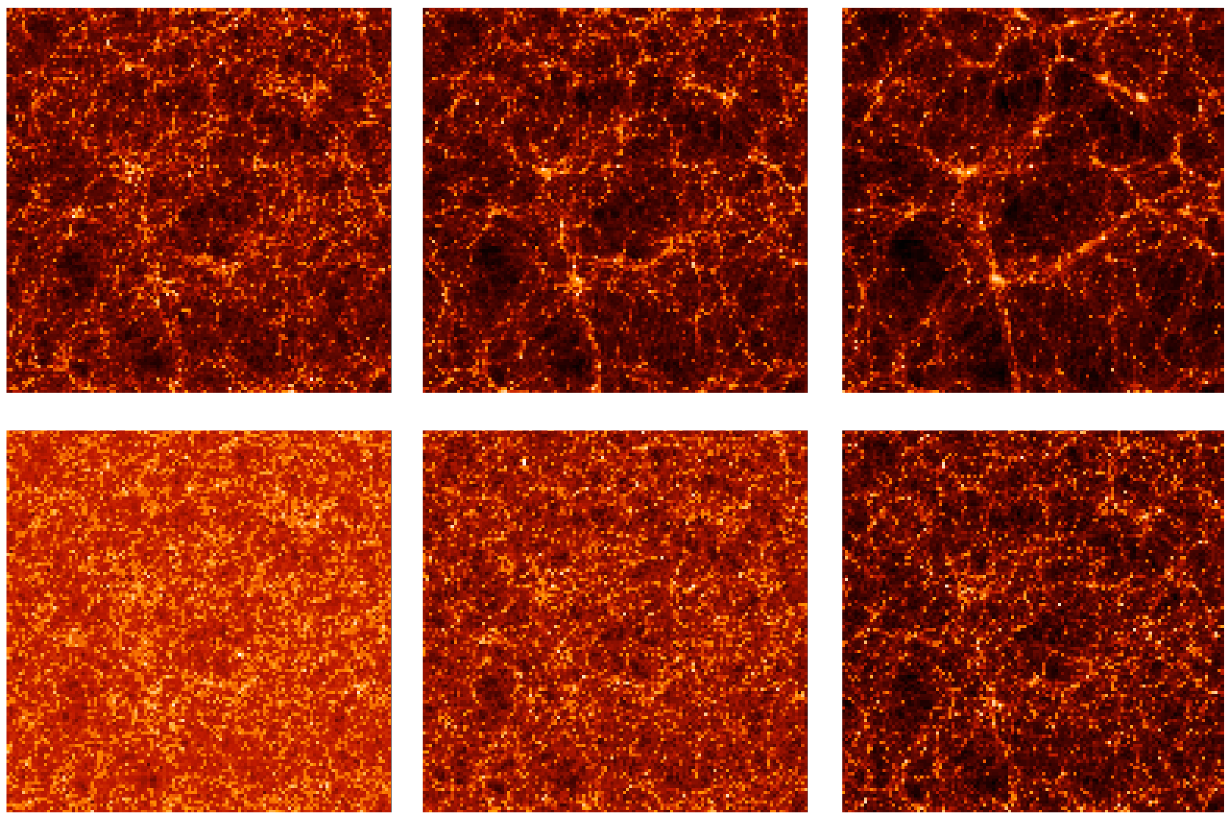
- In the late 90's the fraction of the budget devoted to projects was about 20%.
- Progress in many fields require new investments to produce new capabilities.
- The projects started in 2006 are coming to completion.
- New investments are needed to continue US leadership in well defined research areas.
- Possibilities for future funding growth are weak. Must make do with what we have.

Dark Energy suppresses the growth of density fluctuations

(a=1/4 or z=3) 1/4 size of today | (a=1/2 or z=1) 1/2 size of today | (a=1 or z=0) Today

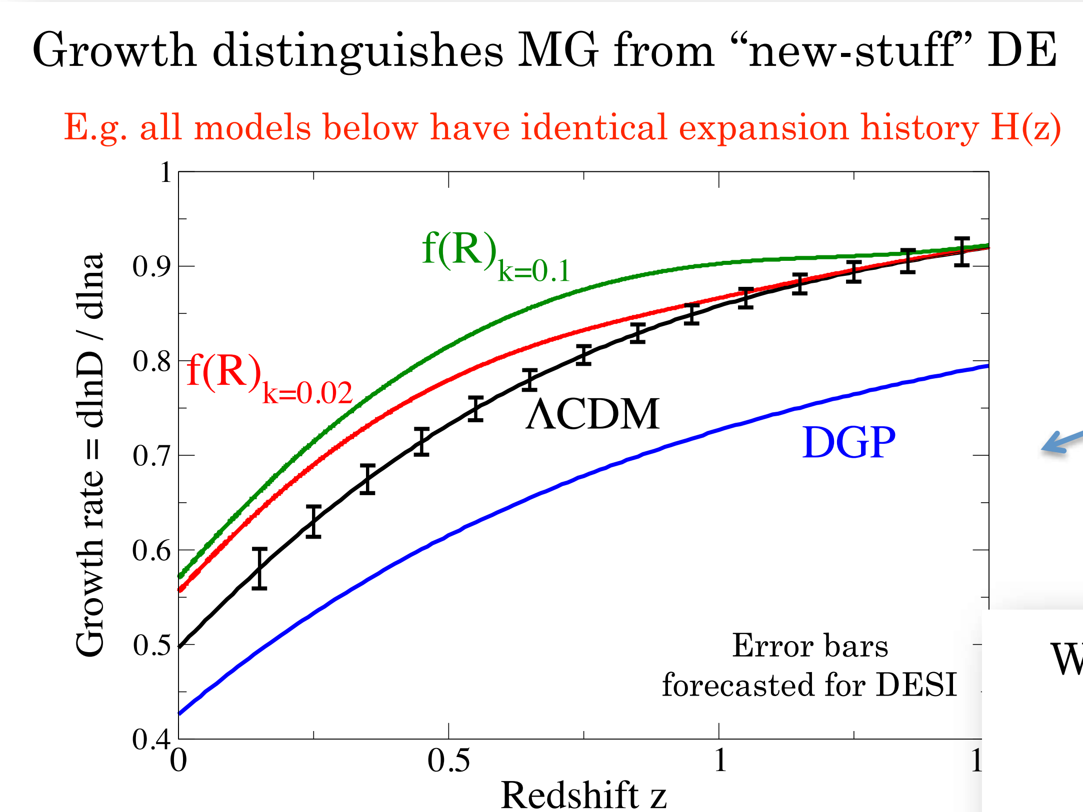
with DE

without DE

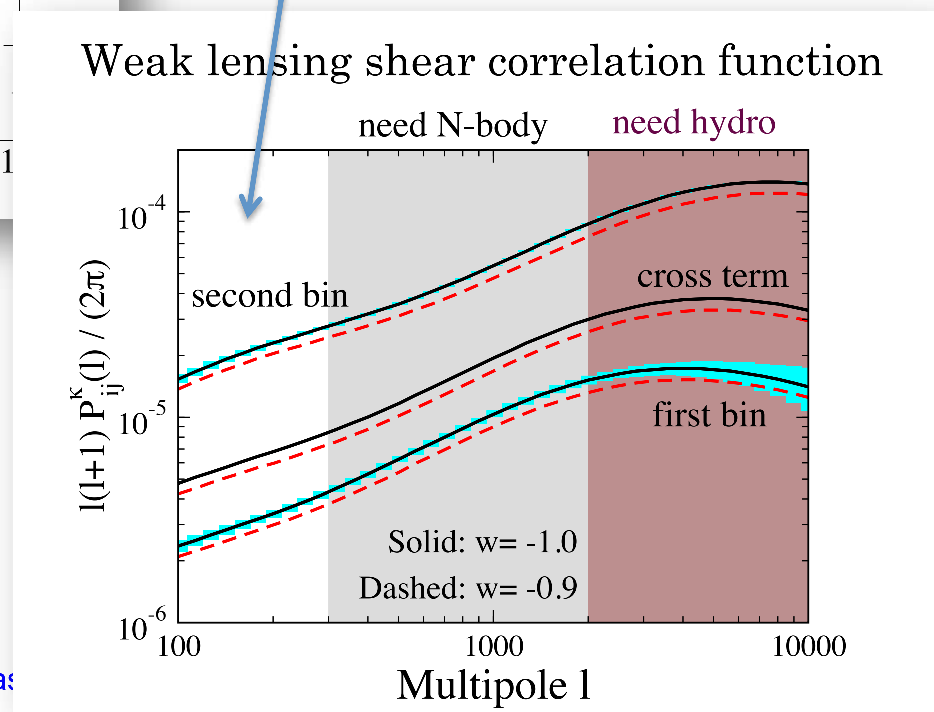


The Virgo Consortium (1996)

Two (of many) Examples



At large scales (>10 Mpc, *l<300*) and early times, predictions based on linear perturbations considered highly reliable (high-Q^2 analogy) at level of ~1%.

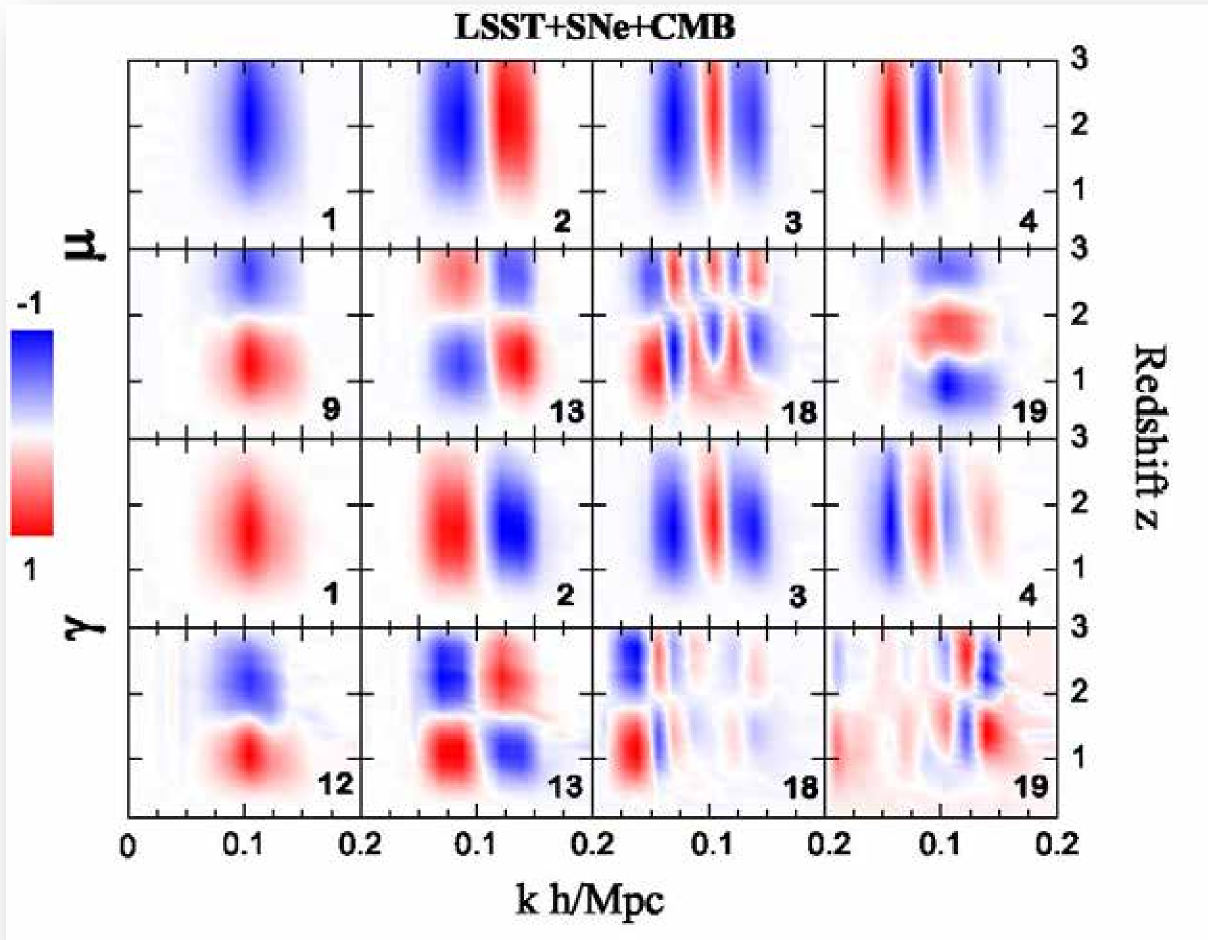


Smaller scales (<1 Mpc, *l >O(1000))* – also relevant to neutrino properties – more to do, but no show stoppers.

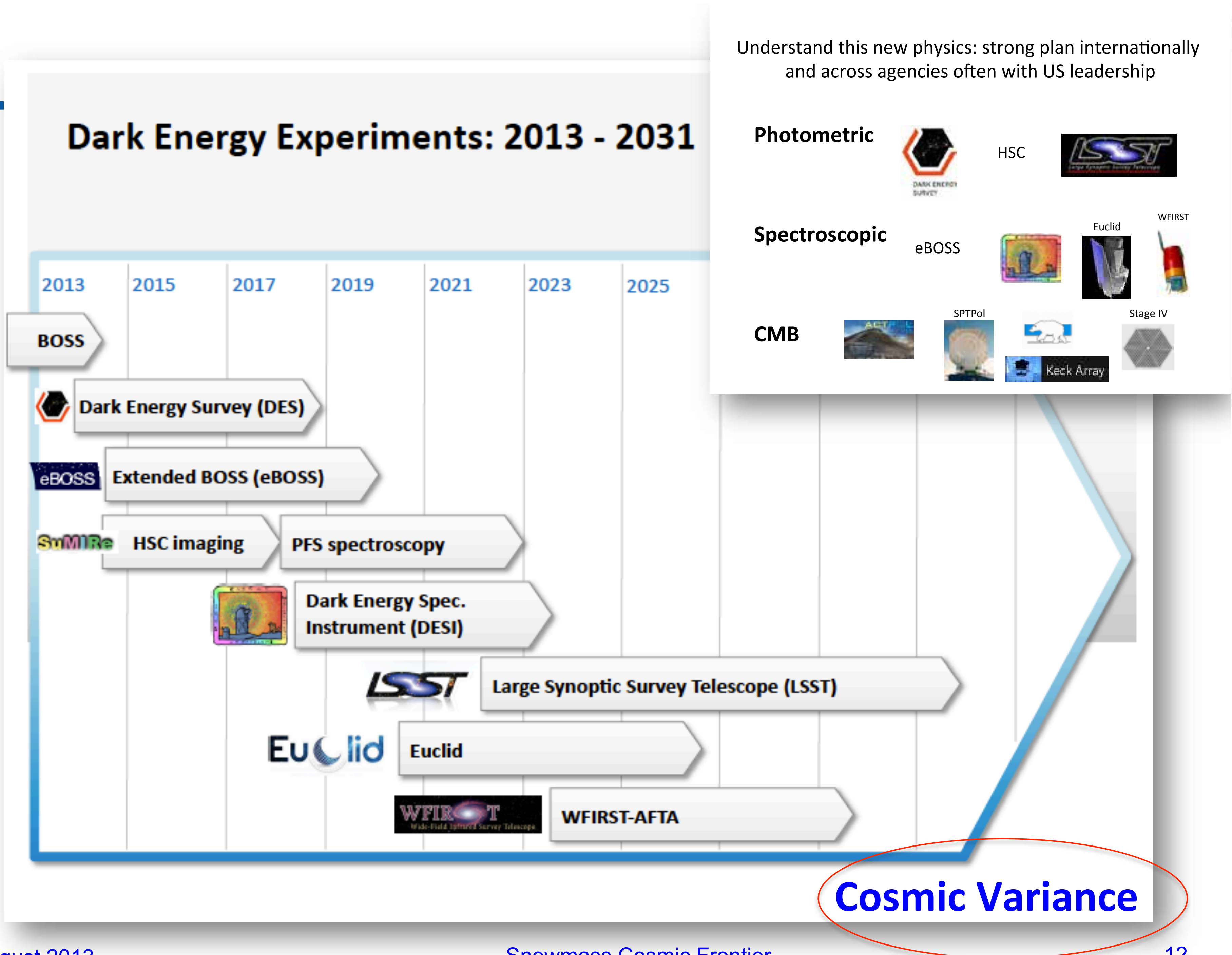
The same (DM) structures are probed in complementary ways.

It’s not just *w*!

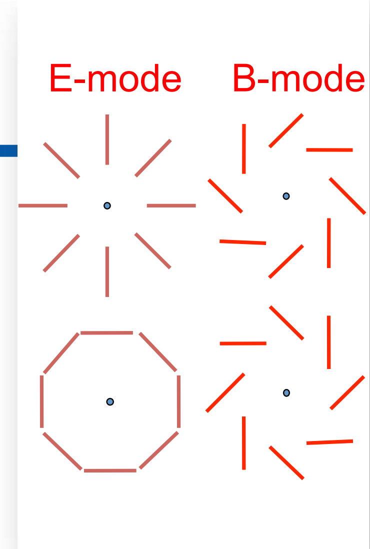
- Study growth as a function of *k*
- Can decompose into “modes”, linear combinations of D(k,z) that are best probed by surveys
- **Failure in any one of these modes to agree with GR could signal a breakdown of the dark energy paradigm**



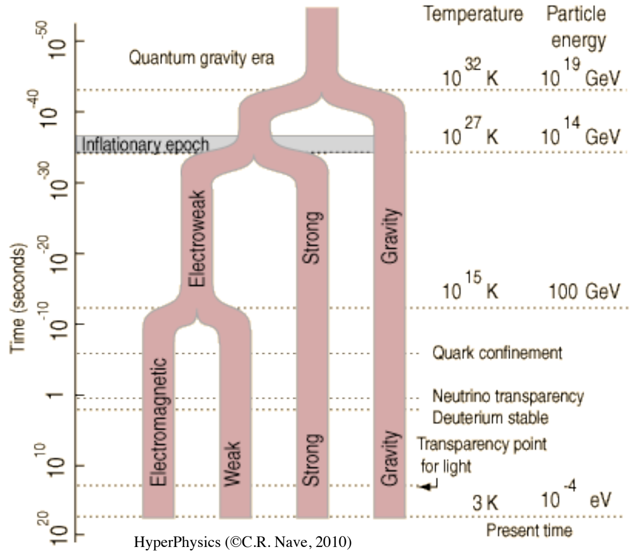
Hojjati et al. 2012


Dark Energy Experiments: 2013 - 2031
2013
2015
2017
2019
2021
2023
2025
BOSS
Dark Energy Survey (DES)
eBOSS
Extended BOSS (eBOSS)
SuMIRe
HSC imaging
PFS spectroscopy
Dark Energy Spec. Instrument (DESI)
LSST
Large Synoptic Survey Telescope (LSST)
Euclid
Euclid
WFIRST
WFIRST-AFTA
Understand this new physics: strong plan internationally and across agencies often with US leadership
Photometric
HSC
Spectroscopic
eBOSS
Euclid
WFIRST
CMB
SPTPol
Keck Array
Stage IV
Cosmic Variance

CMB Opportunities

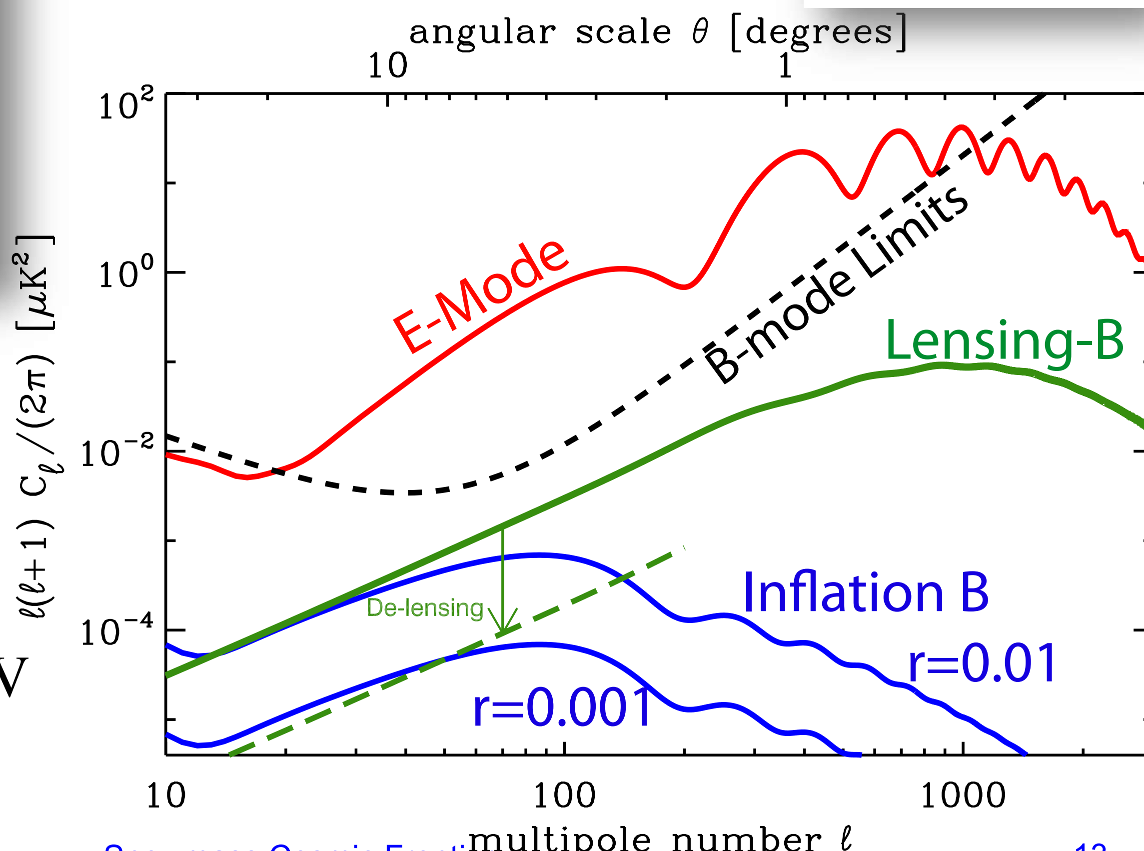


Early universe as an HEP lab



Gravitational waves from Inflation leave an imprint on the CMB B-mode polarization

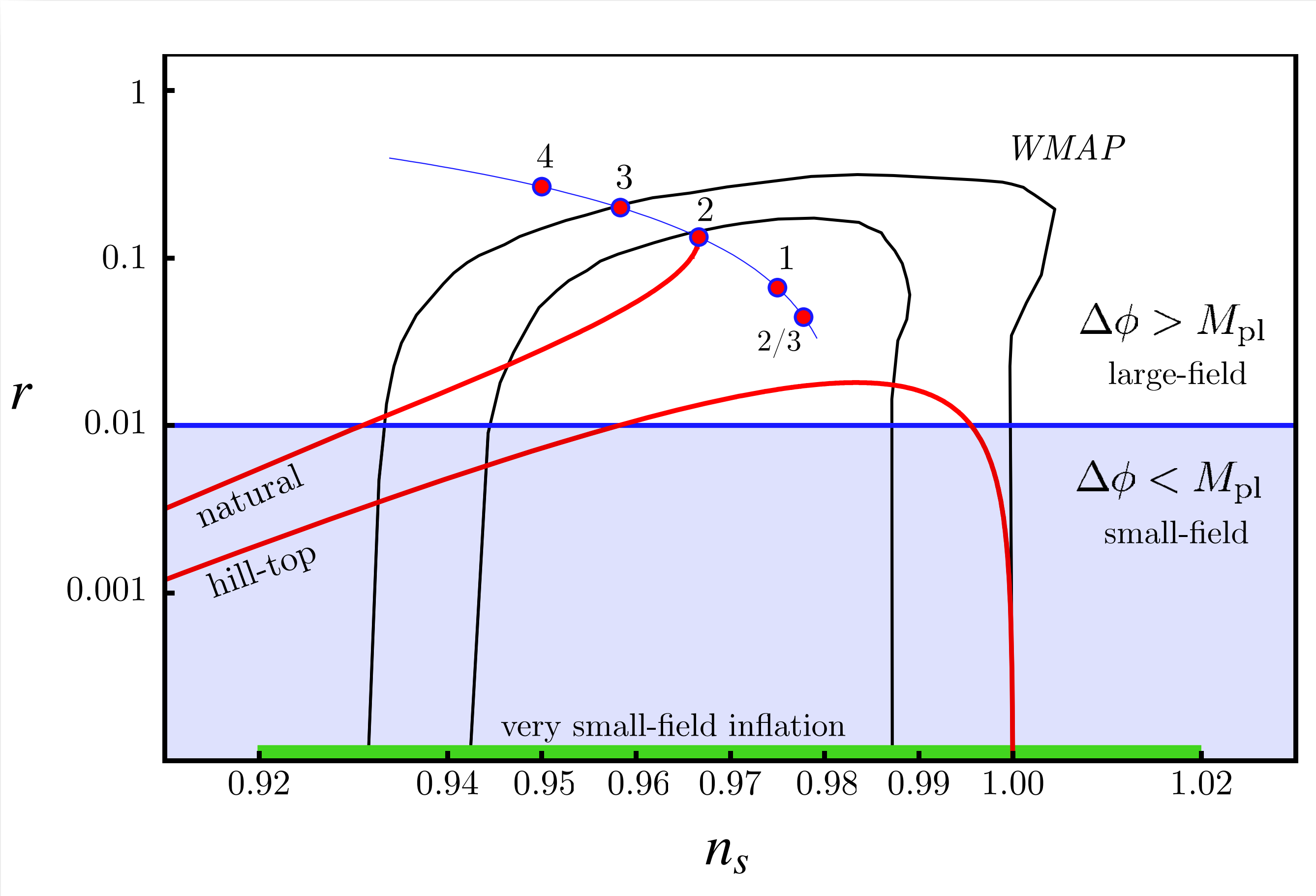
$$E_{\text{inf}} = 1.06 \times 10^{16} \left(\frac{r}{0.01} \right)^{1/4} \quad \text{GeV}$$



Goals of r=0.001 Scale

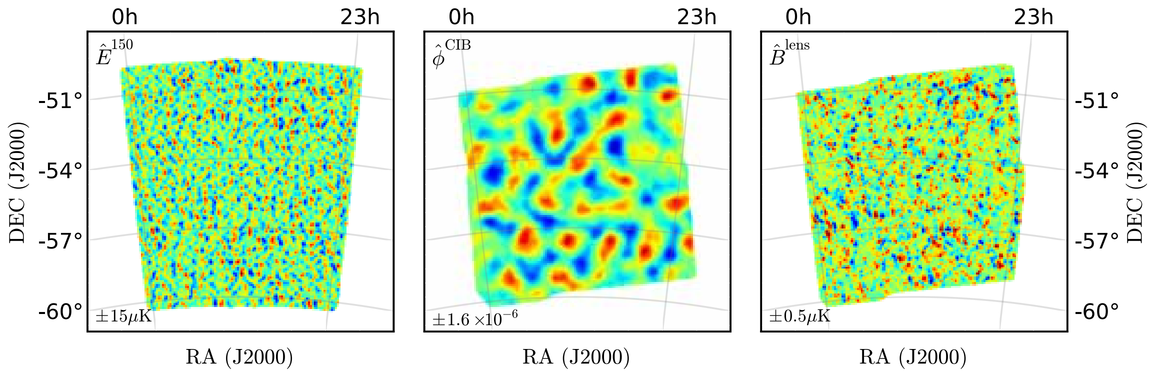
- Detection:
  - Unambiguous confirmation of the Inflationary paradigm
  - Determine energy scale of inflation
- Upper Limit:
  - Rule out large field inflation

- Two classes of Inflation Models
  - Large Field -- $\Delta\phi > m_{pl}$
  - Small Field -- $\Delta\phi < m_{pl}$



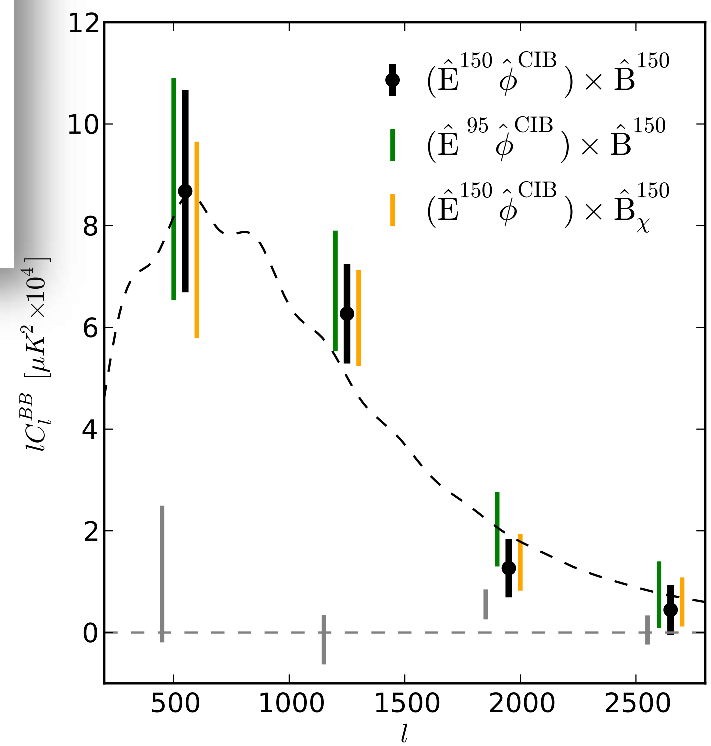
B-mode Polarization Due to Lensing Detected

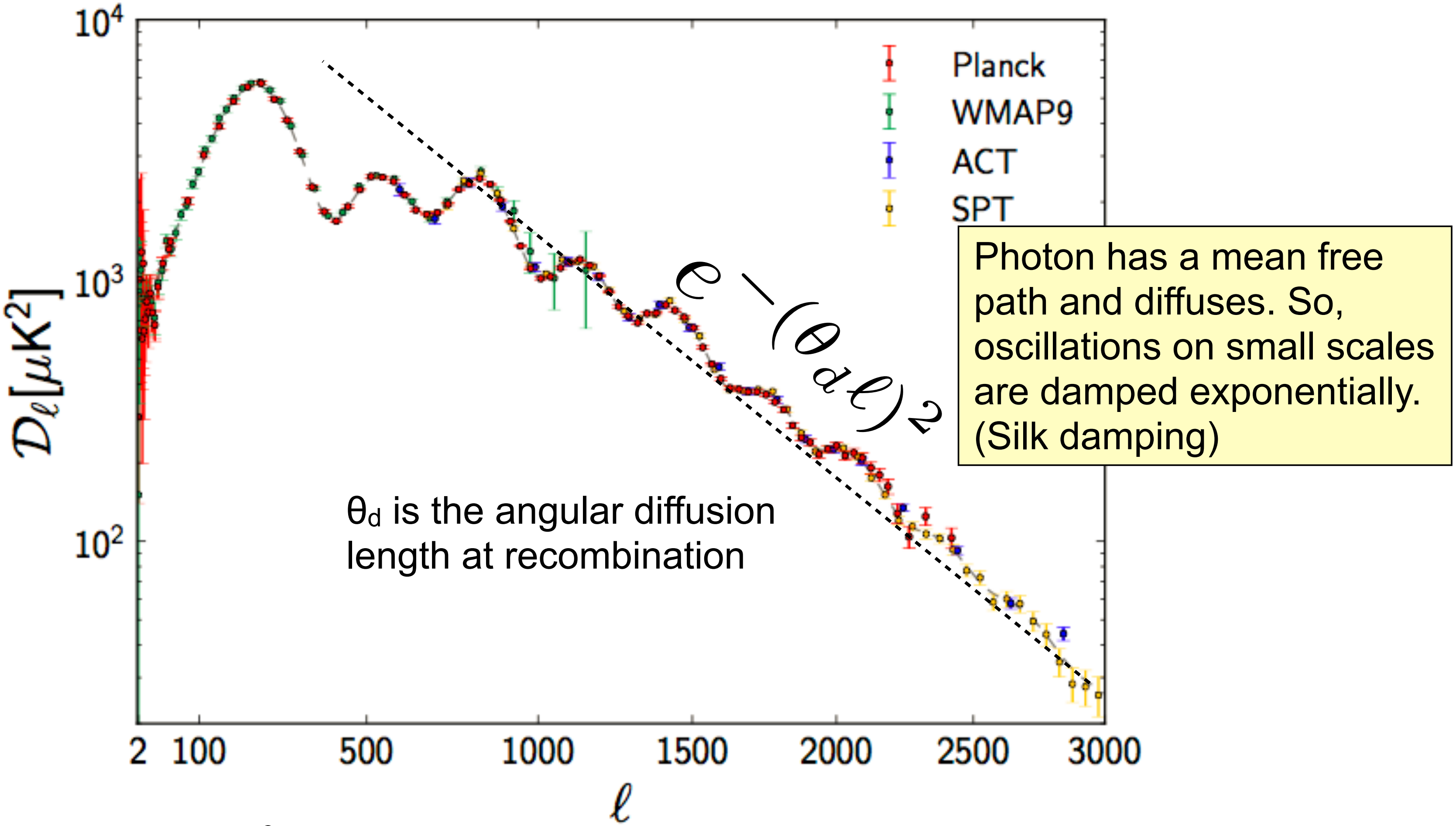
Detection of B-mode Polarization in the Cosmic Microwave Background with Data from the South Pole Telescope



First measurement of lensing B modes (last week!) using three-point EBϕ from SPTpol + Herschel-SPIRE maps of the cosmic infrared background.

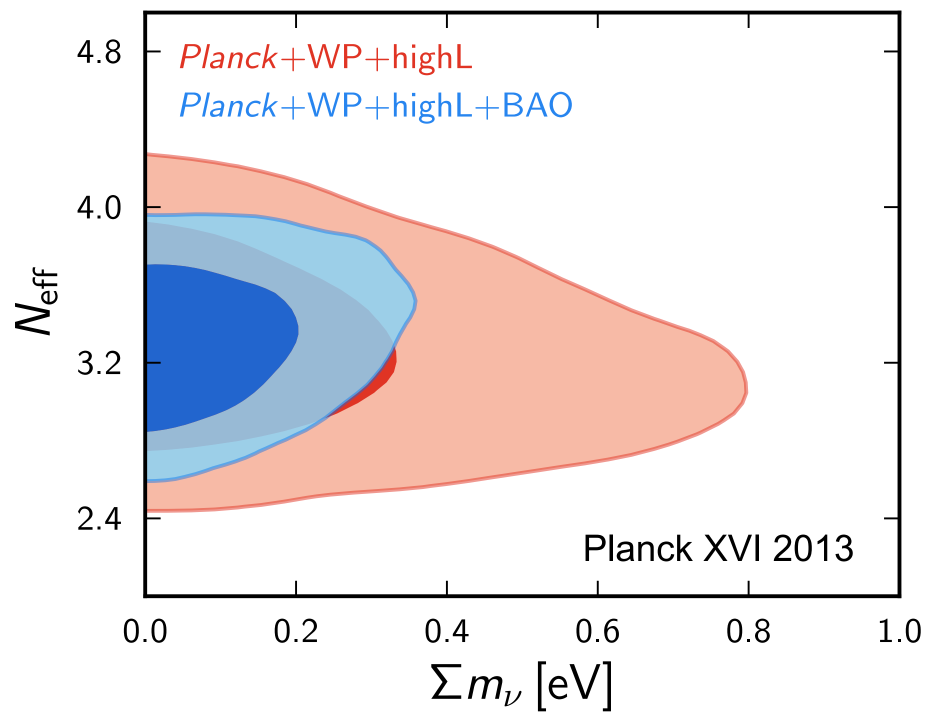
An important milestone





Note $\frac{r_d}{r_s} = \frac{\theta_d}{\theta_s} \propto H,^{0.5}$ so ratio is sensitive energy density.

Constraining model extensions:
joint N_{eff} and Σm_ν constraints



$\sigma(N_{eff})$ = 3.30±0.27

$\sigma(\Sigma m_\nu)$ < 0.23eV at 95% C.L.

N_{eff} is the effective number of relativistic species.
For standard 3 neutrinos N_{eff} =3.046.
It measures the extra energy relative to the photons.

Aside: Neutrino Mass Measurements

To measure the mass of a feather…

…get a large number of them and measure their combined effects

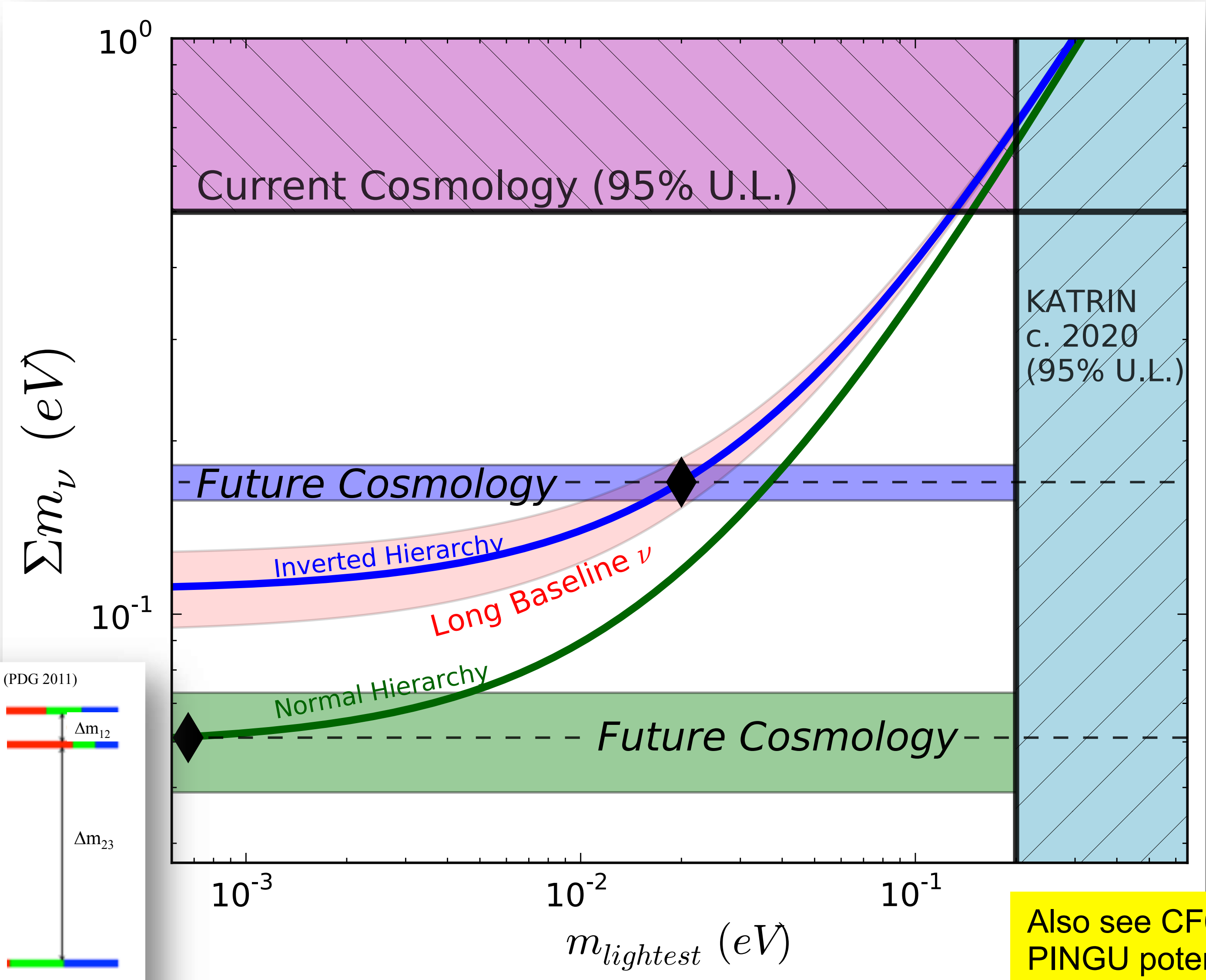
…get a large number of them and measure their combined effects

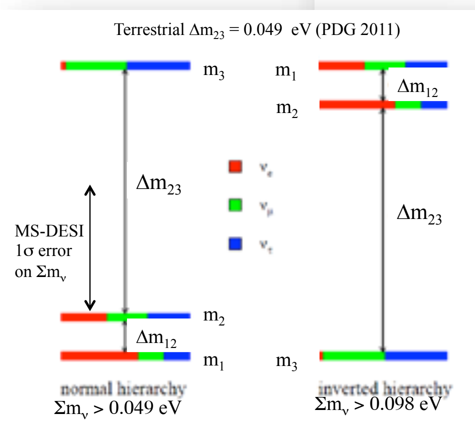
arXiv: 1103.5083 and CF5 summary

DATASET	$\sigma\left(\sum m_\nu\right)$ [meV]	$\sigma\left(N_{\rm eff}\right)$
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.

arXiv: 1103.5083 and CF5 summary





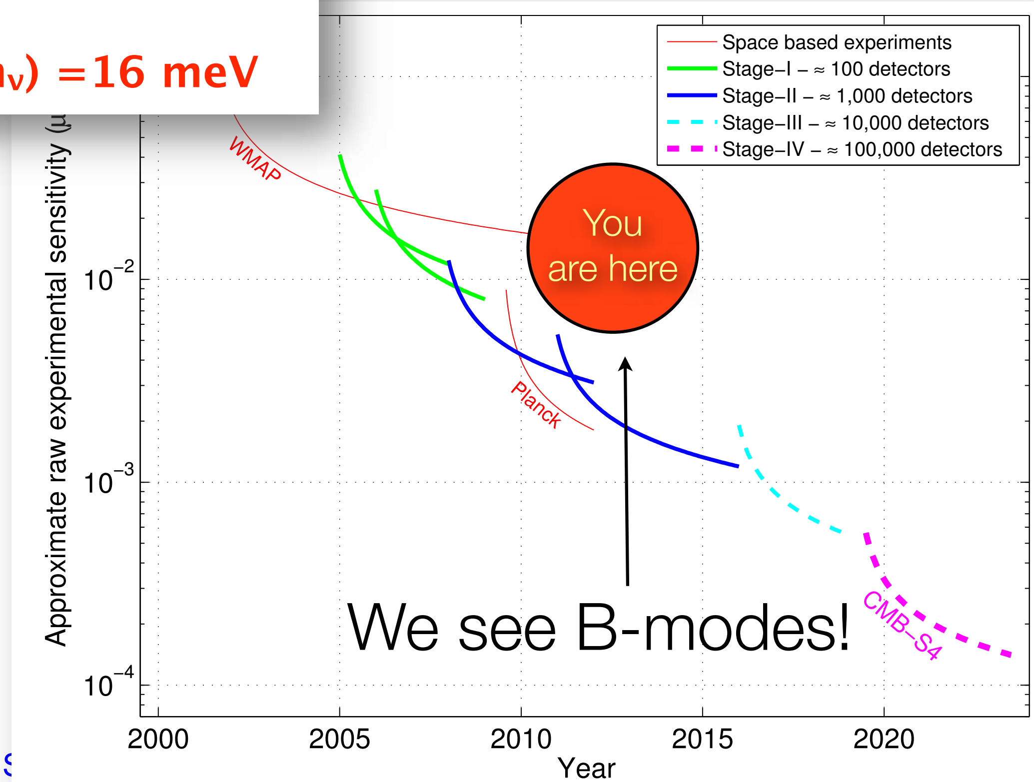
Also see CF6:
PINGU potential to determine hierarchy
arXiv:1306.5846v1

CMB timeline

- 2009: r < 0.7 (BICEP) Chiang et al, 0906.1181

- 2013: r ≲ 0.1 from Inflationary B-modes (BICEP 2) ?
- 2013: Stage II experiments detect lensing B-modes
- 2013-2016: Stage II experiments
  $\sigma(r)\sim0.03$, $\sigma(N_{eff})\sim0.1$, $\sigma(\Sigma m_\nu)\sim0.1$eV
- 2016-2020: Stage III experiments
  $\sigma(r)\sim0.01$, $\sigma(N_{eff})\sim0.06$, $\sigma(\Sigma m_\nu)\sim0.06$eV;

- 2020-2025: **Stage IV goal to reach**
  $\sigma(r) = 0.001$, $\sigma(N_{eff}) = 0.025$, $\sigma(\Sigma m_\nu) = 16$ meV



National lab and HEP community involvement in CMB-S4

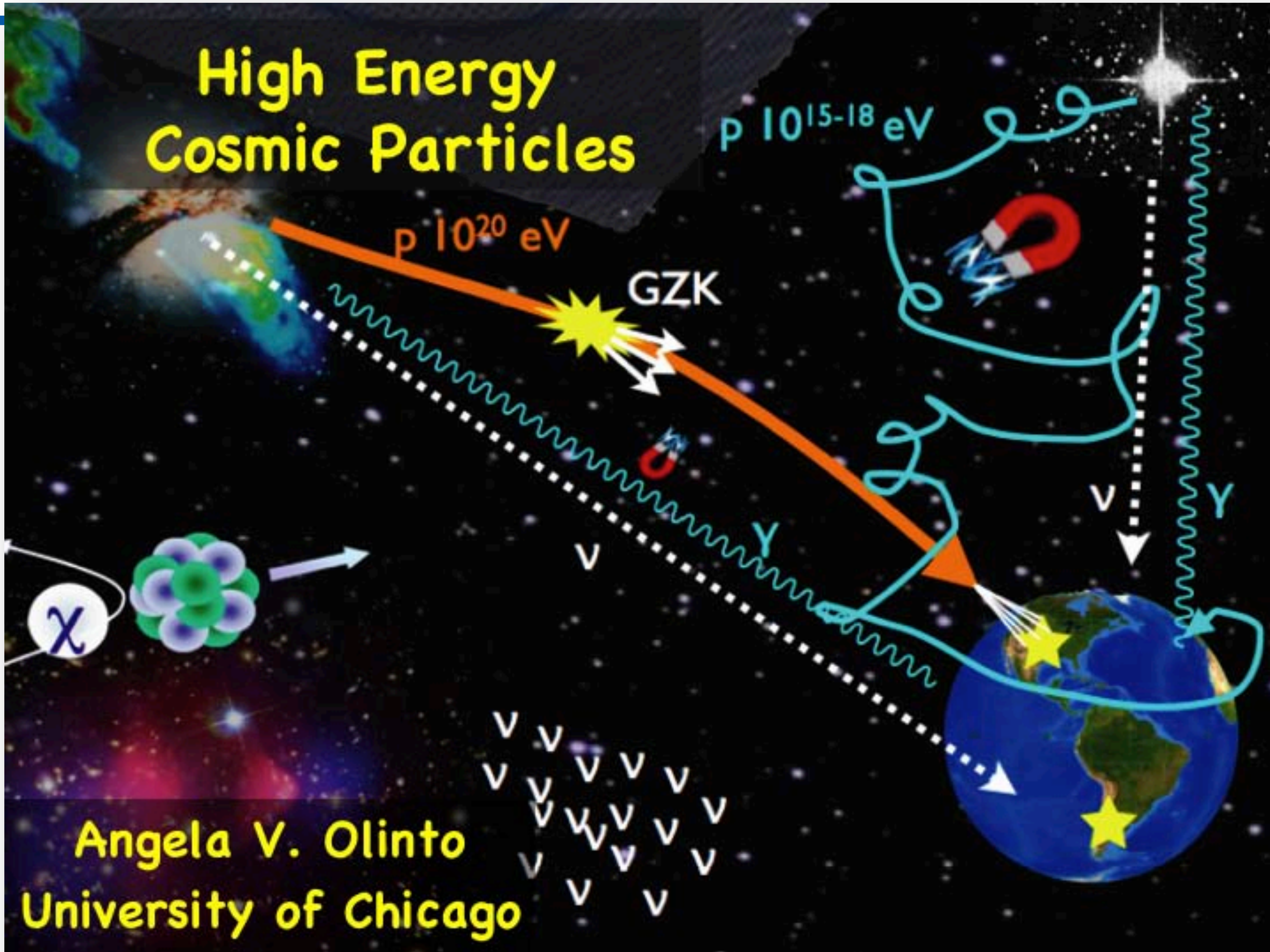
- **CMB-S4 requirements exceed capabilities of University-based experiments**
  - –Focal-plane Arrays and Readout
    - Improved Production Reliability
    - Increased Production Volume and Throughput
      - –500,000 detectors ~ 300 silicon arrays
    - Multiplexed TES Readout
    - Large Cryogenic Optics
  - –Computing Infrastructure and Analysis tools
    - ~10,000 x *Planck* data size (~ 3 TB/day)
  - –Project Organization/Management

CF5 Findings

- Cosmic Surveys are sensitive to fundamental physics
  - discovery of the accelerating universe
  - strong evidence for an epoch of early expansion near GUT scale
  - indirect detection of cosmic neutrino background
  - compelling evidence for non-baryonic dark matter
- To date only a tiny fraction of the available information has been explored
- Strategic, valuable information, accessible to experiments, remains unmined…but that will soon change.
- Great potential to discover something fundamentally new

CF5 Main Messages

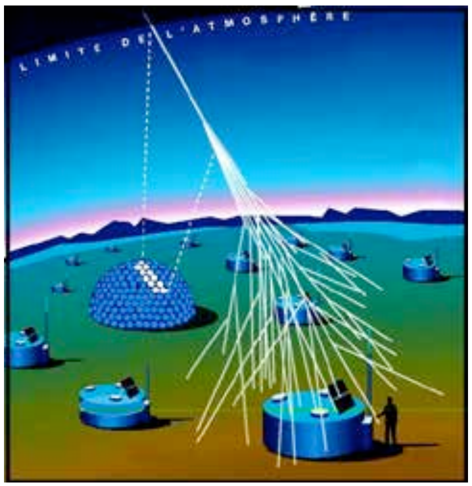
- **Remain a Leader in Dark Energy**
  - A combination of imaging and spectroscopic surveys is needed to pinpoint the new physics driving the accelerations
  - Current suite of surveys, Stage III, will be the first to implement the vision of multiple probes and small systematics.
  - The next stage is 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.


High Energy
Cosmic Particles
p 10^{15-18} eV
p 10^{20} eV
GZK
γ
ν
ν
γ
χ
Angela V. Olinto
University of Chicago

EeV Neutrino Beam: the GZK Process

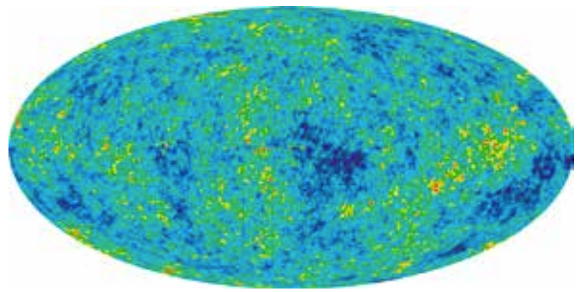
$$p + \gamma_{cmb} \rightarrow \Delta^+ \rightarrow n + \pi^+$$
$$\rightarrow \mu^+ + \boxed{\nu_\mu}$$
$$\rightarrow e^+ + \boxed{\bar{\nu_\mu} + \nu_e}$$

cosmic rays



+

CMB

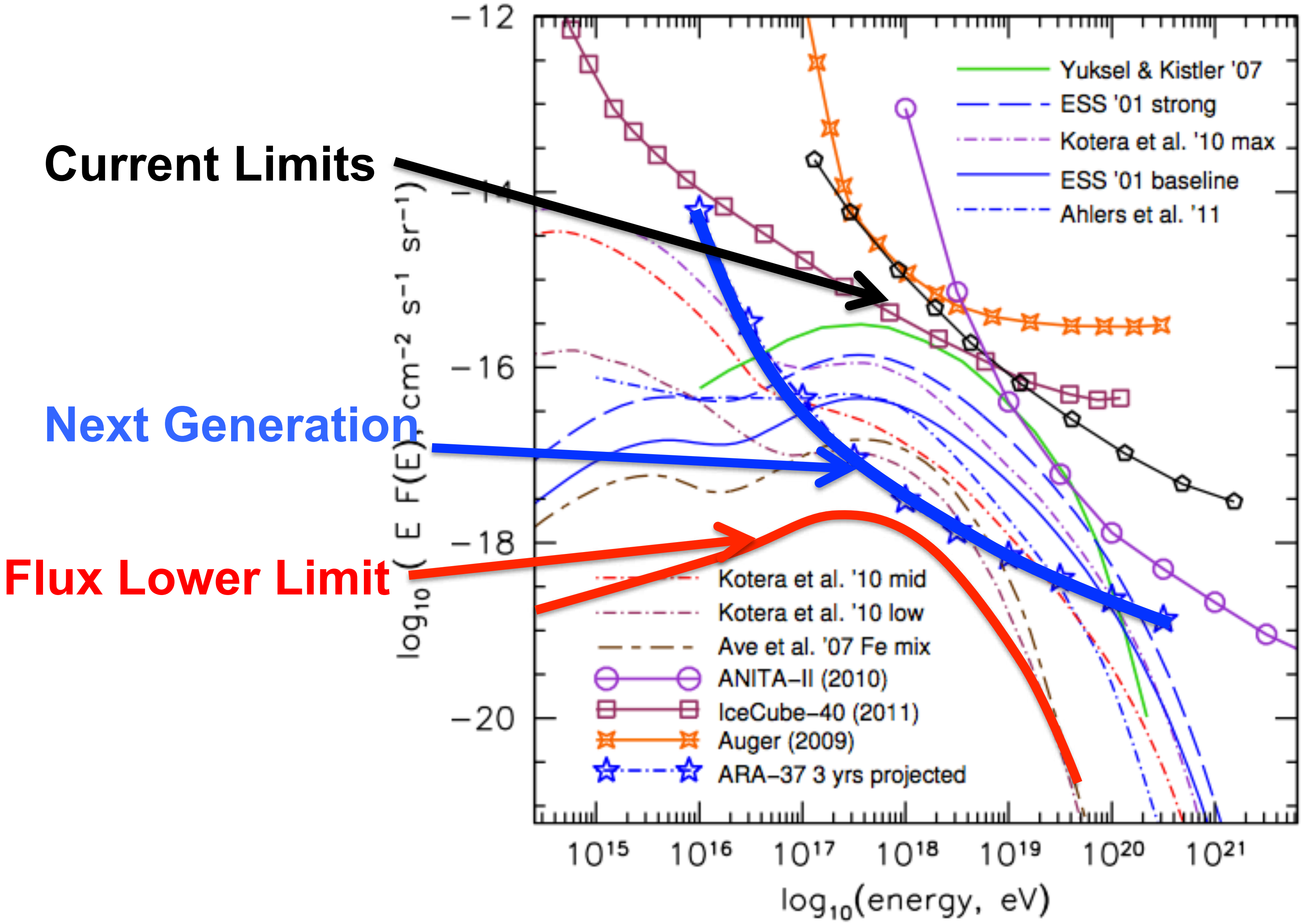


= Neutrino Beam!

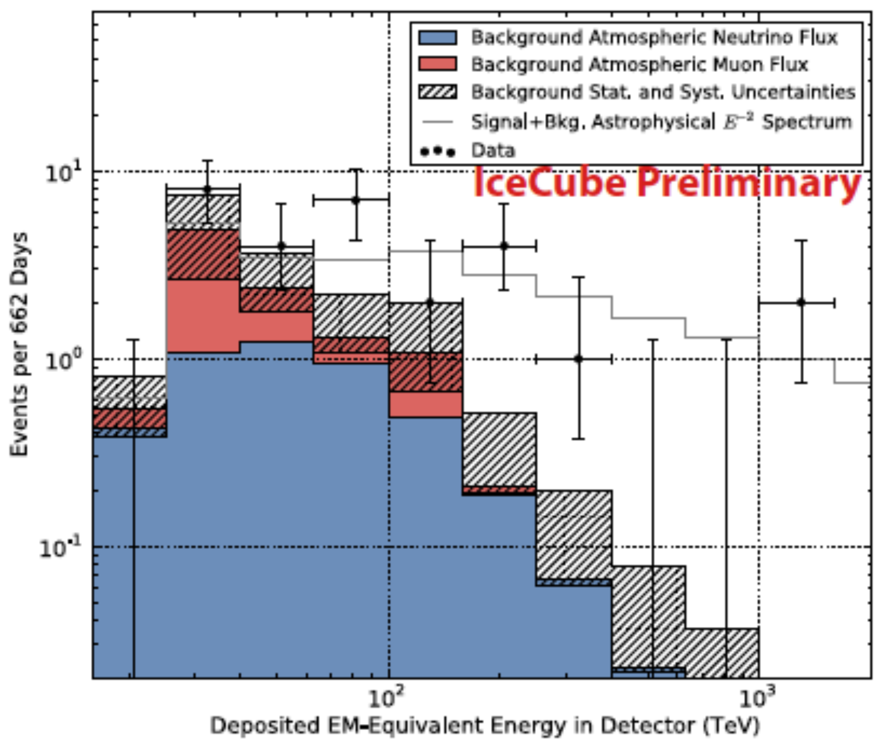
Discovery of GZK neutrinos within reach over the next decade

- to measure 100 TeV c.m. neutrino interactions via ratio of upward to downward neutrino showers.
- to determine the Origin of the Highest Energy Particles

Next Generation GZK Neutrino Detectors



Have the first High Energy Astrophysical Neutrinos been observed by IceCube?



28 events with a spectrum harder than that expected for any atmospheric backgrounds.

Cascade-dominated as expected.

Southern events more abundant as expected due to Earth antenuation

Spectrum slightly softer than E^{-2}

Insufficient statistics to identify sources; currently compatible with isotropy.

More to come as IceCube runs…

PINGU

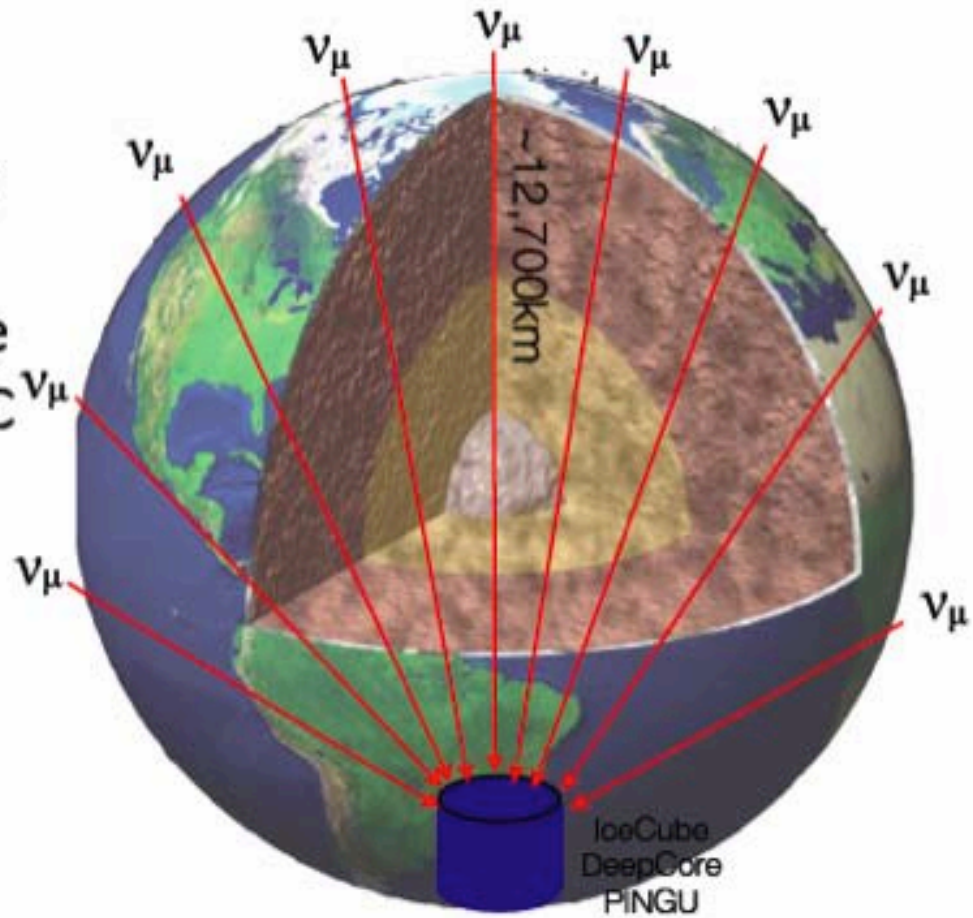
arXiv:1306.5846v1

Atmospheric neutrinos provide many values of L and E

Very large baselines for probing matter effects (~12,700 km)

Add ~40 strings inside DeepCore

20-25m string spacing (73 for DC and 125 for IC)



Could provide very significant hierarchy information with a few years of running, improving δ_{CP} range probed by NOvA + T2K

Photon Dispersion Limits from GRB 090510

Fermi, Nature, vol 462, p331 (plus comment on p291)

17

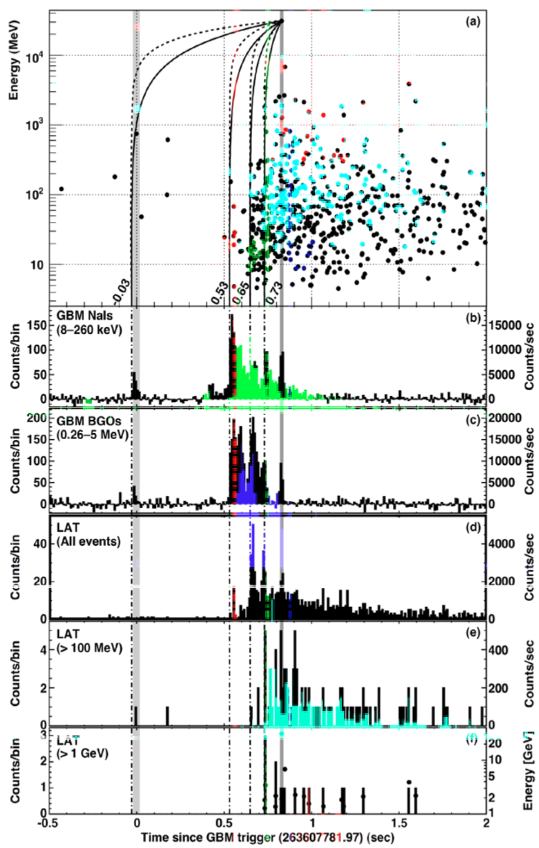
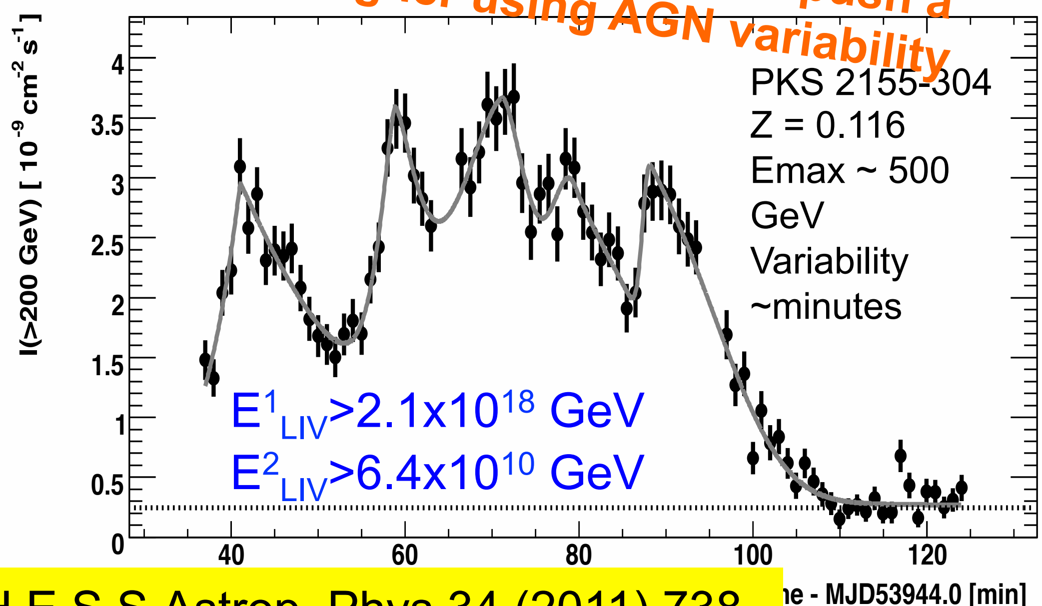


Figure 1. Panel (a): energy vs. arrival time w.r.t the GBM trigger time for the 160 LAT photons that passed the transient off-line event selection (*red*) and the

Table 2 | Limits on Lorentz Invariance Violation

#	$t_{start} - T_0$ (ms)	Limit on $\|\Delta t\|$ (ms)	Reasoning for choice of t_{start} or limit on Δt or $\|\Delta t/\Delta E\|$	E_l[†] (MeV)	Valid for s_n*	Lower limit on $M_{QG,1}/M_{Planck}$
(a)[◇]	−30	< 859	start of any < 1 MeV emission	0.1	1	> 1.19
(b)[◇]	530	< 299	start of main < 1 MeV emission	0.1	1	> 3.42
(c)[◇]	*648*	< 181	start of main > 0.1 GeV emission	100	1	> 5.63
(d)[◇]	730	< 99	start of > 1 GeV emission	1000	1	> 10.0
(e)[♦]	—	< 10	association with < 1 MeV spike	0.1	±1	> 102
(f)[♦]	—	< 19	If 0.75 GeV[‡] γ-ray from 1[st] spike	0.1	−1	> 1.33
(g)[♠]	$\|\Delta t/\Delta E\|$ < 30 ms/GeV		lag analysis of > 1 GeV spikes	—	±1	> 1.22

Next-generation facilities could push a factor ~10 higher using AGN variability



$E^1_{LIV} > 2.1 \times 10^{18}$ GeV

$E^2_{LIV} > 6.4 \times 10^{10}$ GeV

H.E.S.S.Astrop. Phys 34 (2011) 738

How many UHECRs > 60 EeV?

Auger + TA ~ 30 events/yr

40 years to reach 1,000

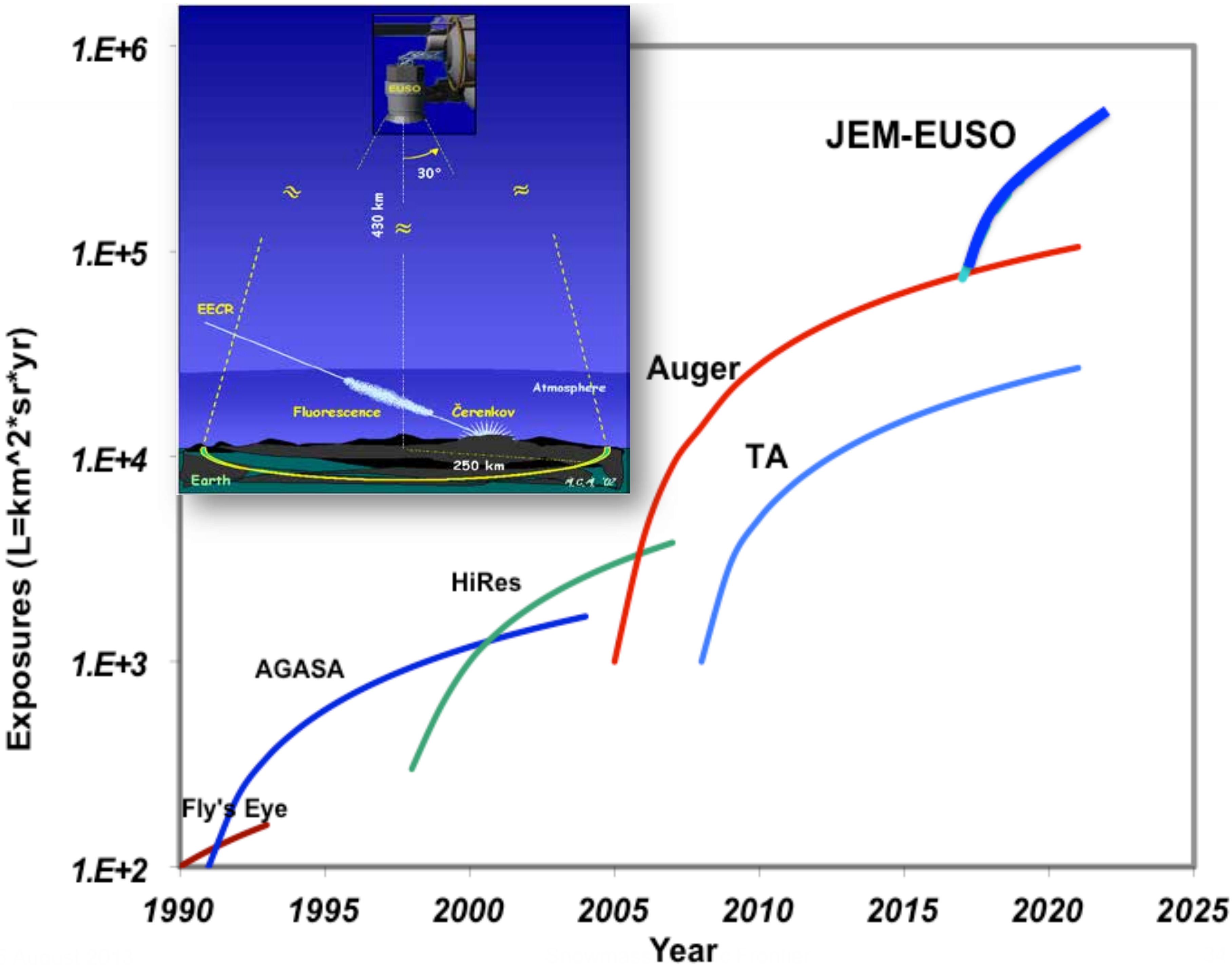
JEM-EUSO

~200 events > 60 EeV/ yr

Earth - surface ~ 5 10^8 km^2

~3.4 10^6 events/yr

1


EUSO
30°
430 km
EECR
Atmosphere
Fluorescence
Čerenkov
250 km
Earth
JEM-EUSO
Auger
TA
HiRes
AGASA
Fly's Eye
1.E+6
1.E+5
1.E+4
1.E+3
1.E+2
Exposures (L=km^2*sr*yr)
1990
1995
2000
2005
2010
2015
2020
2025
Year

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

Sunday, August 4, 2013

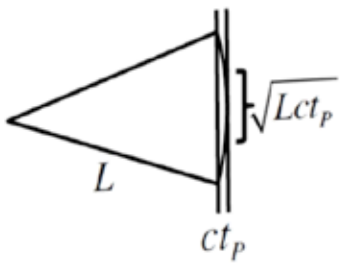
Holometer

from Craig Hogan

Planckian quantum-geometrical position uncertainty

- Gravitational theory suggests that quantum geometrical degrees of freedom have information with Planck areal density
- Information on spatial position is much less than in field theory; limits angular or transverse degrees of freedom
- Quantum geometry may not respect locality or separation of scales; geometrical position uncertainty may be much larger than the Planck length
- Introduces new source of noise in macroscopic position detectable with nonlocal measurements of position of massive bodies in two directions
- May be relevant to new physics of Dark Energy

There may be no such thing as a massive body at rest



Uncertainty in transverse position defined with Planck frequency waves; much larger than Planck length at macroscopic separation L

Friday, August 2, 2013

Fermilab Holometer Experimental Concept

Measure correlated optical phase fluctuations in a pair of isolated but collocated power recycled 40-meter Michelson interferometers

- exploit the spatial coherence of entangled quantum-geometrical noise
- measure at high frequencies (MHz) where other correlated noise is small
- Sensitive to nonlocal entanglement of quantum-geometrical position states

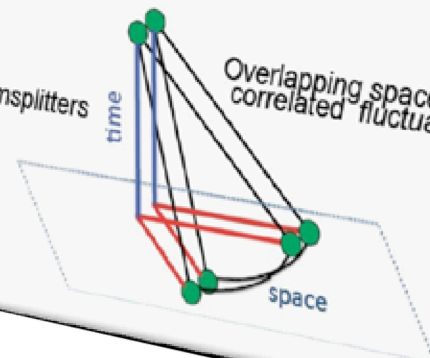
Sensitivity goal: measure or rule out spectral density of transverse position noise given by the Planck time:

$$h^2 \approx \frac{\langle \hat{x}_\perp^2 \rangle}{cL_a} = t_P/\sqrt{4\pi} = (1.23 \times 10^{-22}\mathrm{Hz}^{-1/2})^2$$

World lines of beamsplitters

Overlapping spacetime volumes -> correlated fluctuations

Experiment is now built, currently in commissioning stage



- Expect results soon!

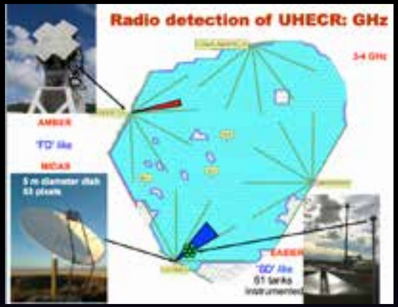
CF-6 Summary

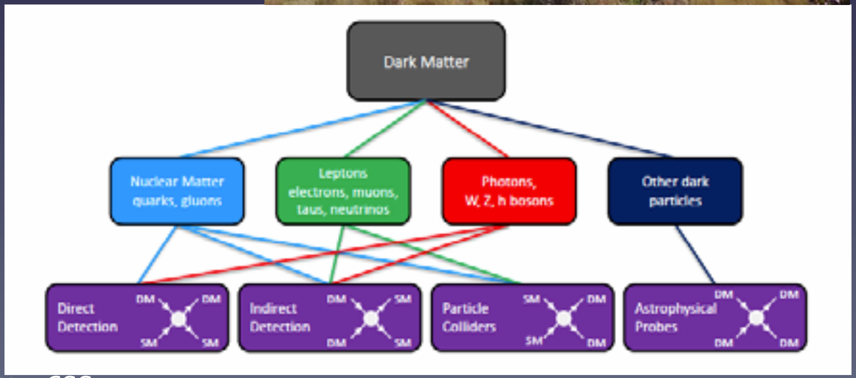
- Baryogenesis: EDMs, CP violation in neutrino sector, and inflation scale are key measurements
- Neutrino mass hierarchy possible with SN neutrinos (LBNE) and atmospheric neutrinos (PINGU)
- Origin of highest energy particles in the universe (multi-messenger campaign)
- Fundamental physics accessible 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 C-M interactions to be measured with UHECRs (JEM-EUSO)
- Probing Planck scale physics is now possible

Instrumentation Investments Important!

Cosmic Frontier Challenges

- UHE-CR
  - Low rates at high energy
  - R&D: Radio Detection, detection of air shower from space
- UHE-neutrinos
  - R&D: Need development of new antennas, low noise amplifiers for detection of Cherenkov radio emission
- Gamma rays
  - R&D: Cherenkov and water tank arrays, Low-cost photosensors/low-power digitizers
  - Distributed timing across large arrays
- Dark Energy
  - R&D path: Low-resolution spectroscopy and spectroscopic capability to wide field optical surveys
- Dark Matter
  - Large program looking for larger mass, lower thresholds and directionality
- CMB
  - R&D path towards readout of large cryogenic multi-chroic arrays

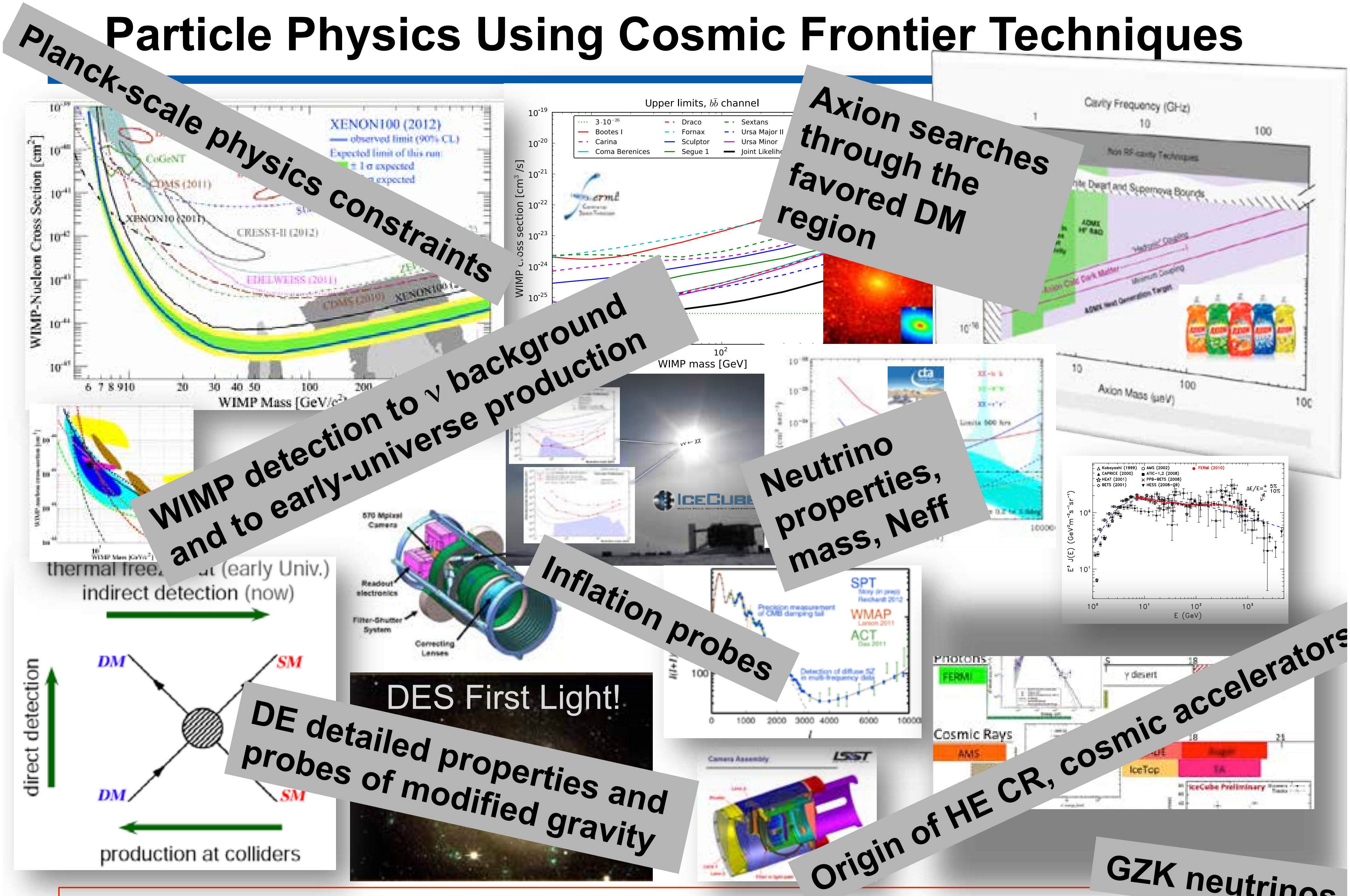




A Big Message

- **Together with the other Frontier areas**, 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.
  - Large discovery space with unique probes.
  - Important cross-frontier topics
  - Full range of project scales, providing flexible programmatic options.
  - **US Leadership**

Particle Physics Using Cosmic Frontier Techniques



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