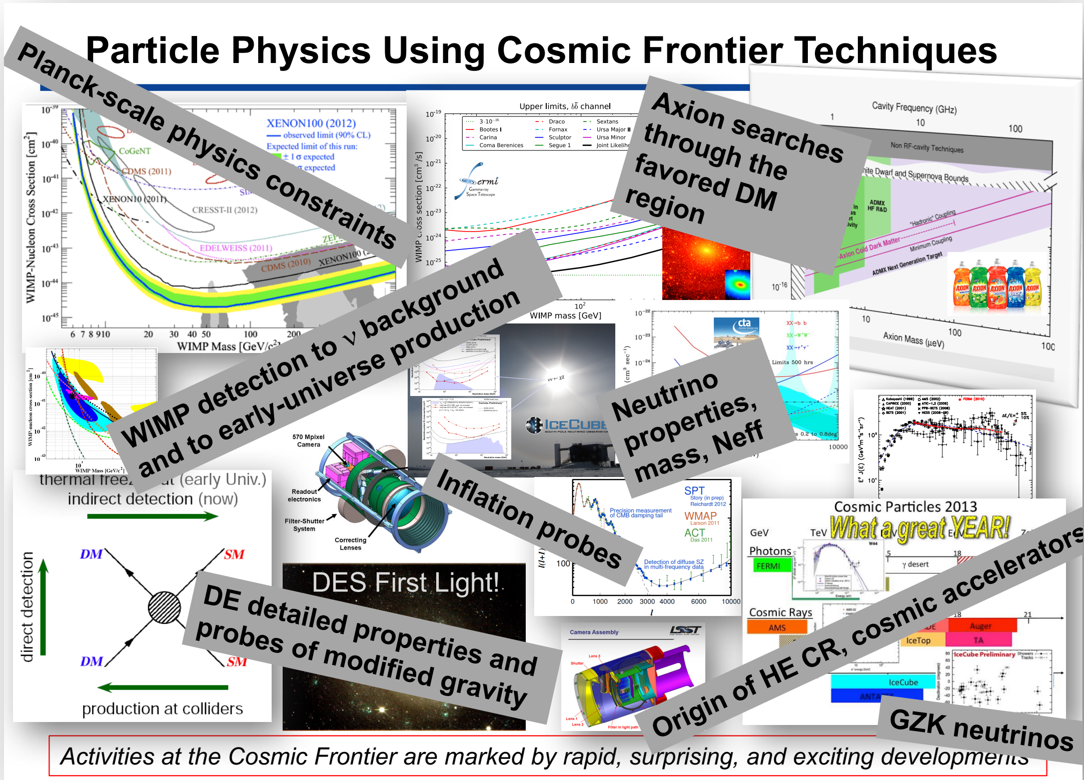
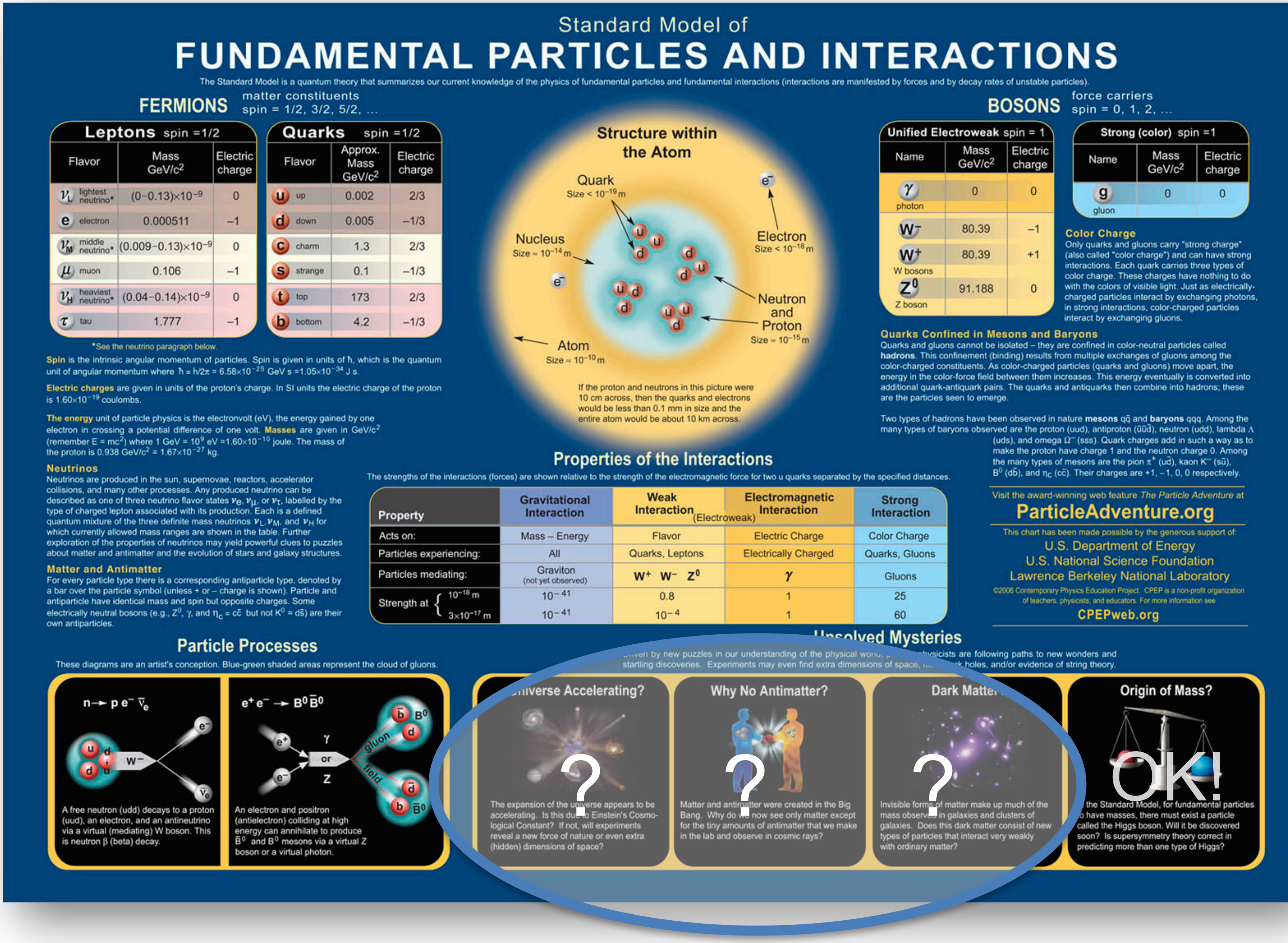
The Cosmic Frontier Landscape

SLAC Summer Institute 2017

S. Ritz
UCSC and SCIPP



The Standard Model (ca 2010)

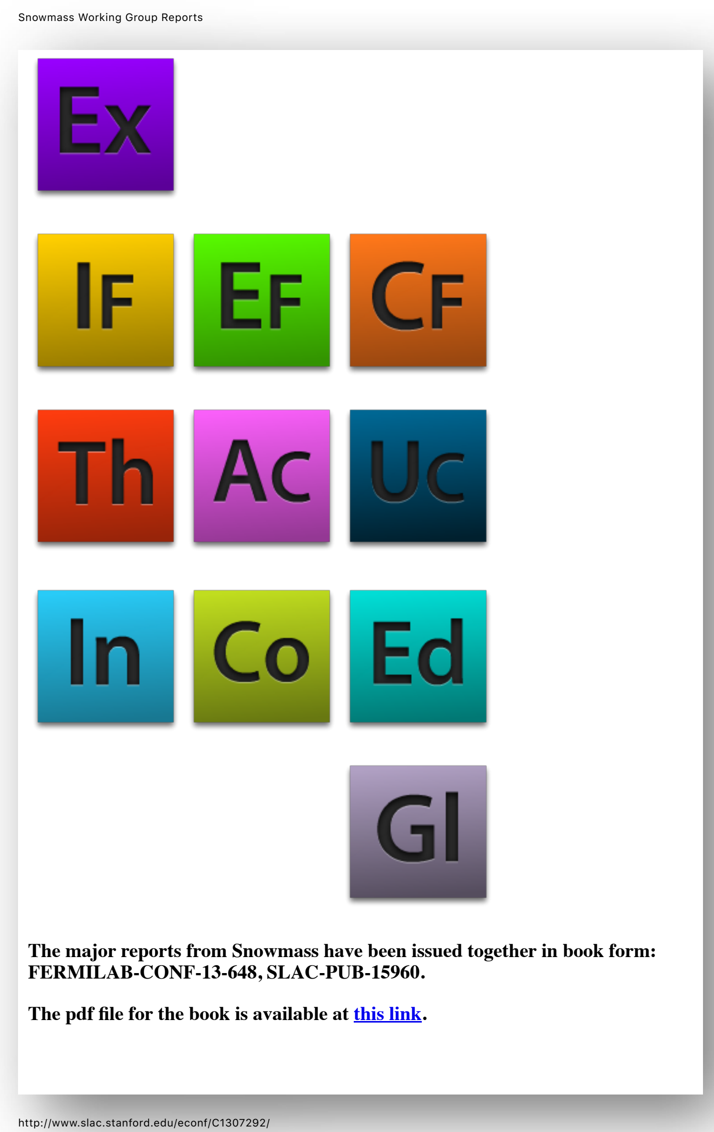


Snowmass and P5

The yearlong community-wide study, called Snowmass (2013):

- A vast number of scientific opportunities were investigated, discussed, and summarized in the Snowmass reports.

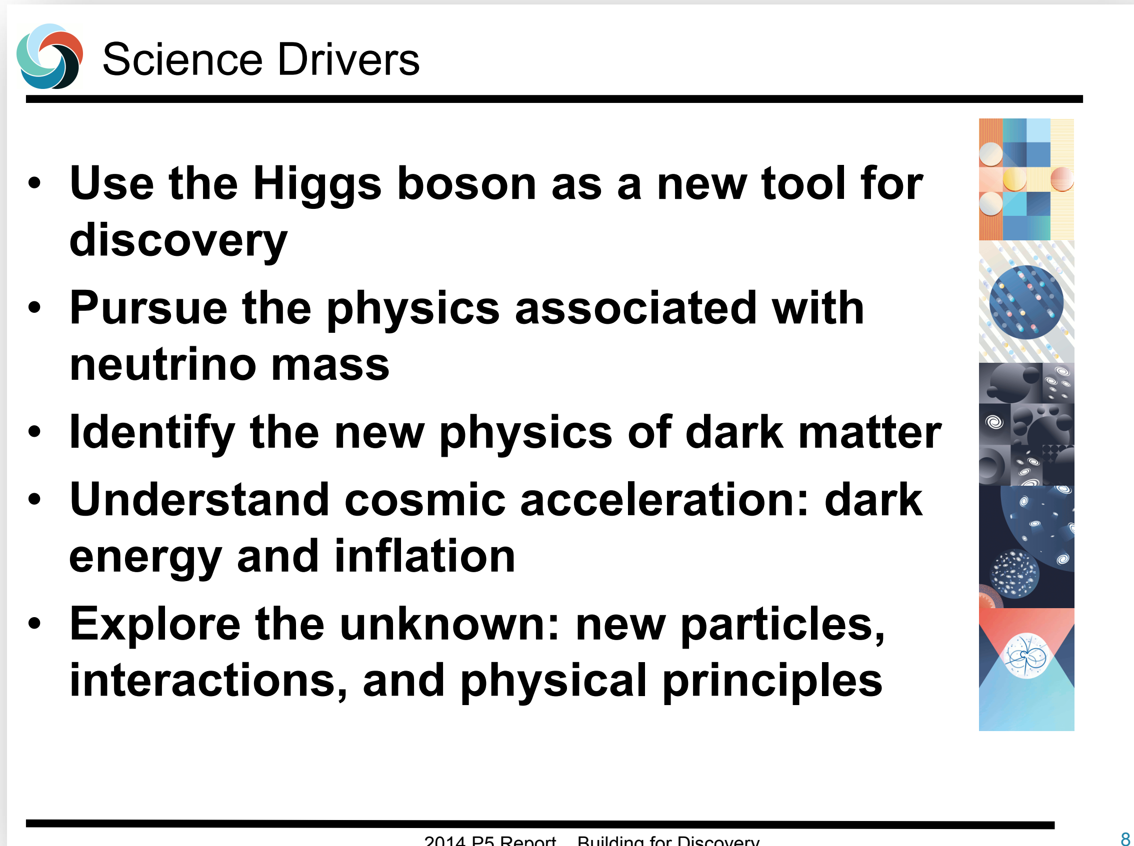
http://www.slac.stanford.edu/econf/C1307292/



Science Drivers for Particle Physics

The Particle Physics Project Prioritization Panel (P5) distilled the eleven groups of physics questions from Snowmass into five compelling, intertwined lines of inquiry that show great promise for discovery over the next 10 to 20 years:

Activities at the "Cosmic Frontier" address four of these



Science Drivers

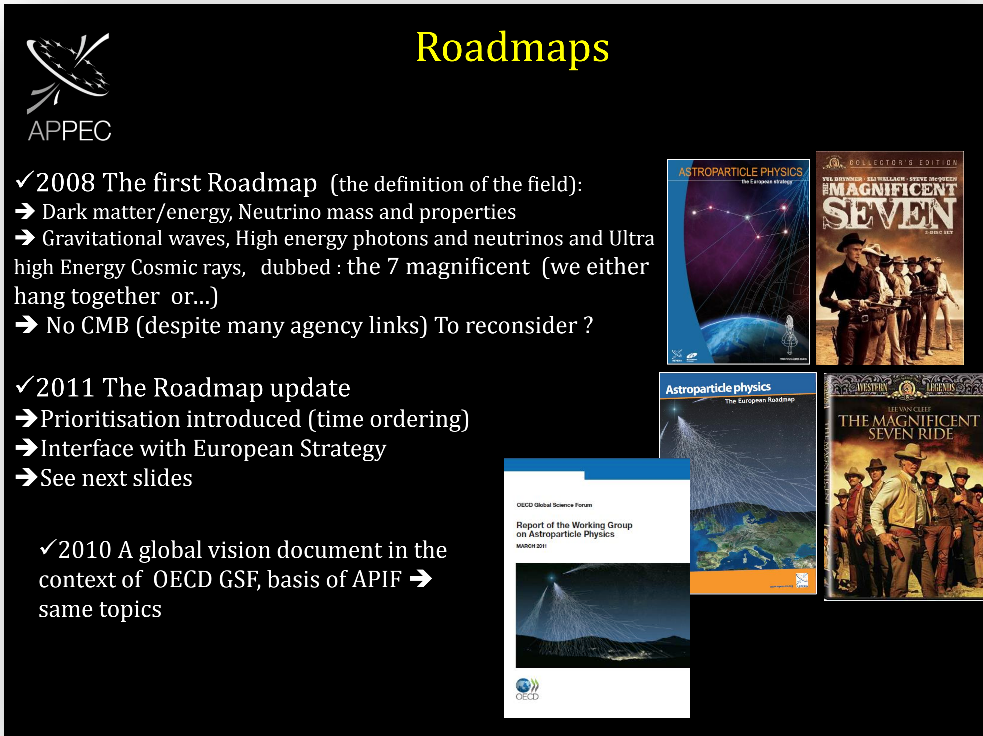
- **Use the Higgs boson as a new tool for discovery**
- **Pursue the physics associated with neutrino mass**
- **Identify the new physics of dark matter**
- **Understand cosmic acceleration: dark energy and inflation**
- **Explore the unknown: new particles, interactions, and physical principles**

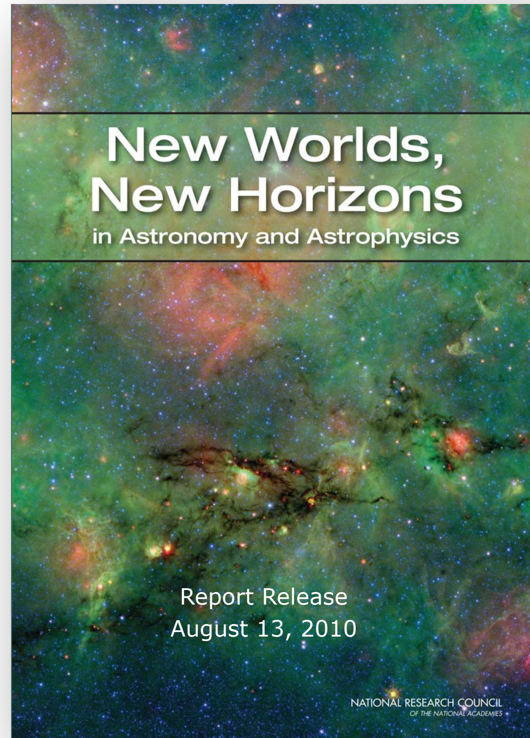
2014 P5 Report Building for Discovery 8

The vision for addressing each of the Drivers using a selected set of experiments – their approximate timescales and how they fit together – is given in the report.

International and Cross-discipline Planning

- Lots of planning and prioritization work already done prior to Snowmass/P5. Field is very much discovery driven, and evolves rapidly.





http://www.appec.org

http://sites.nationalacademies.org/bpa/BPA_049810

Common Threads: Theory and Technology Essential!

- Theory defines the physics drivers of the field, finds the deep connections among them, and helps to point in new directions.

- *New directions in science are launched by new tools much more often than by new concepts…The effect of a tool-driven revolution is to discover new things that have to be explained.* – F. Dyson

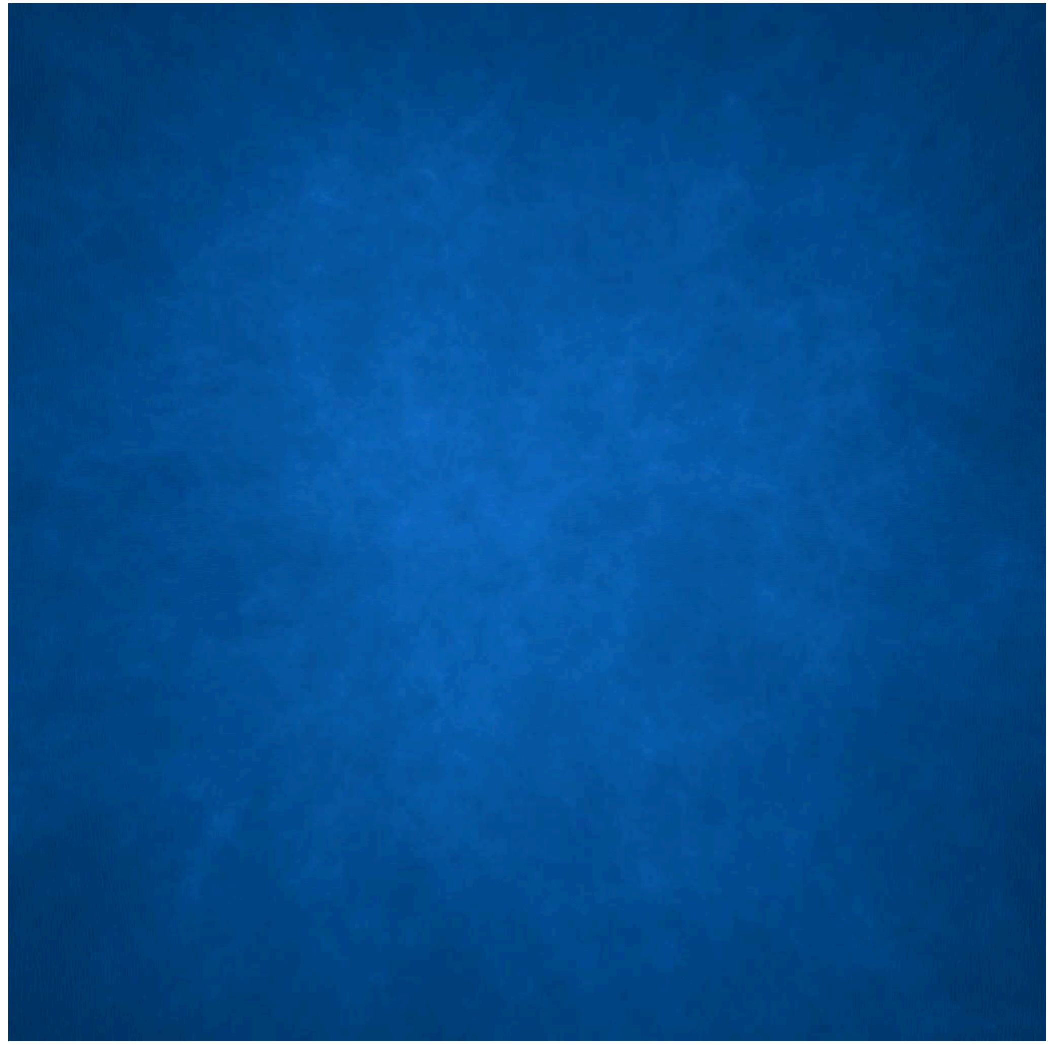
- Fields most promising for discovery at some moment have new leaps in measurement capability, new analysis techniques, accurate simulations, and clarity of theory to give meaning to the data.

- Projects need ecosystems to do science.

ΛCDM

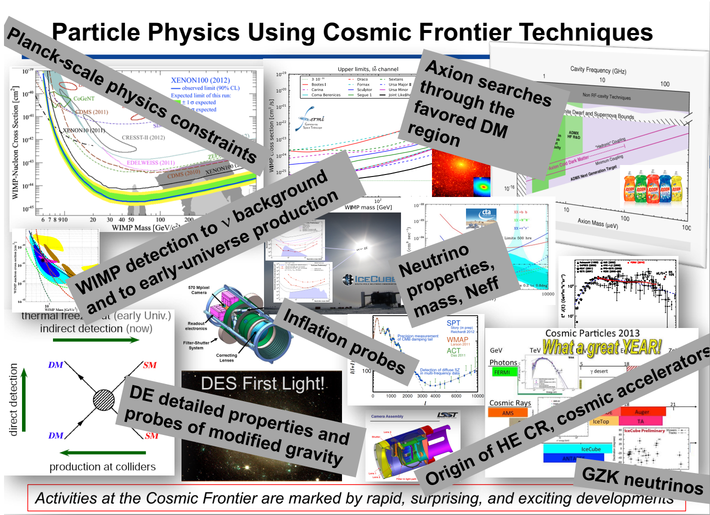
- Cold Dark Matter (CDM), cosmological constant (Λ), initial fluctuations, and gravity.
- With relatively few parameters, ΛCDM simulations describe the large scale structure remarkably well.
- Connecting the DM structure to the visible structure.

- **Just need to find out the identity of the Cold Dark Matter and Dark Energy…and what their presence is telling us.**



CLUES simulation

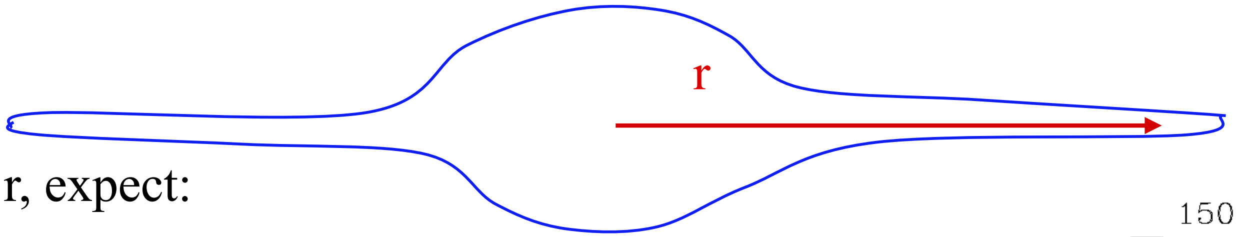
(courtesy of J. Primack)



Dark Matter (DM)

The Dark Matter Problem

Observe rotation curves for galaxies:

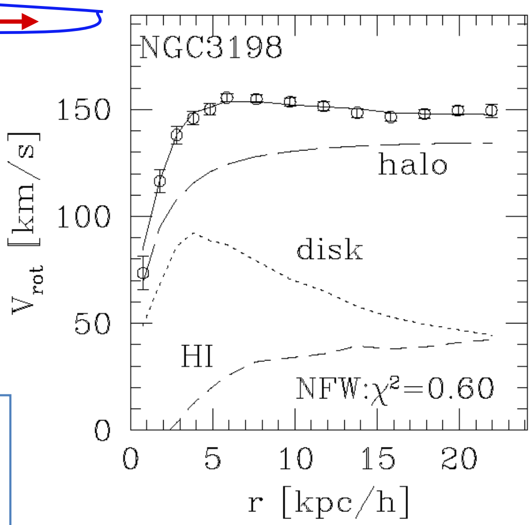


For large r, expect:

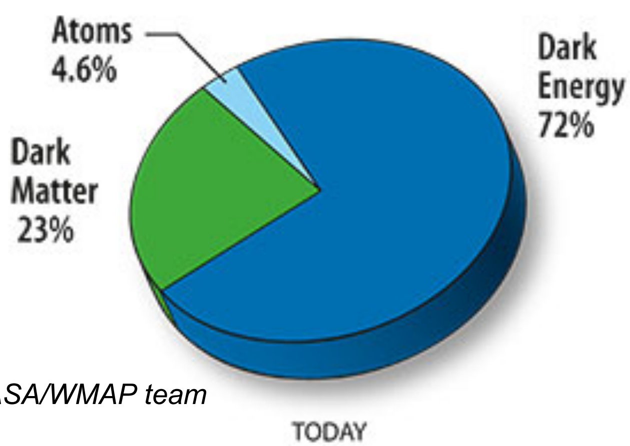
$$G\frac{M}{r^2} = \frac{v^2(r)}{r} \qquad v(r) \sim \frac{1}{\sqrt{r}}$$

see: flat or rising rotation curves

Begeman/Navarro

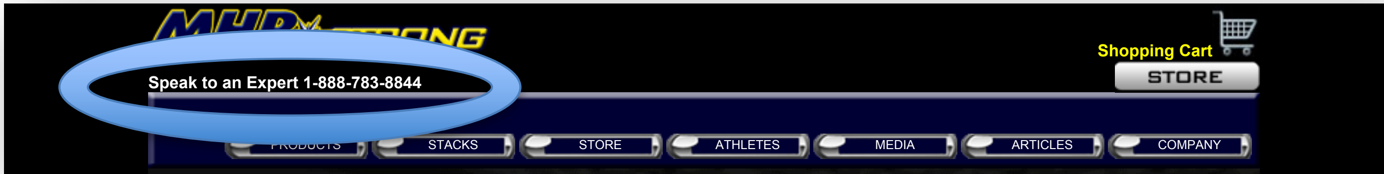


Hypothesized solution: visible galaxies are embedded in much larger haloes and structures of dark matter.



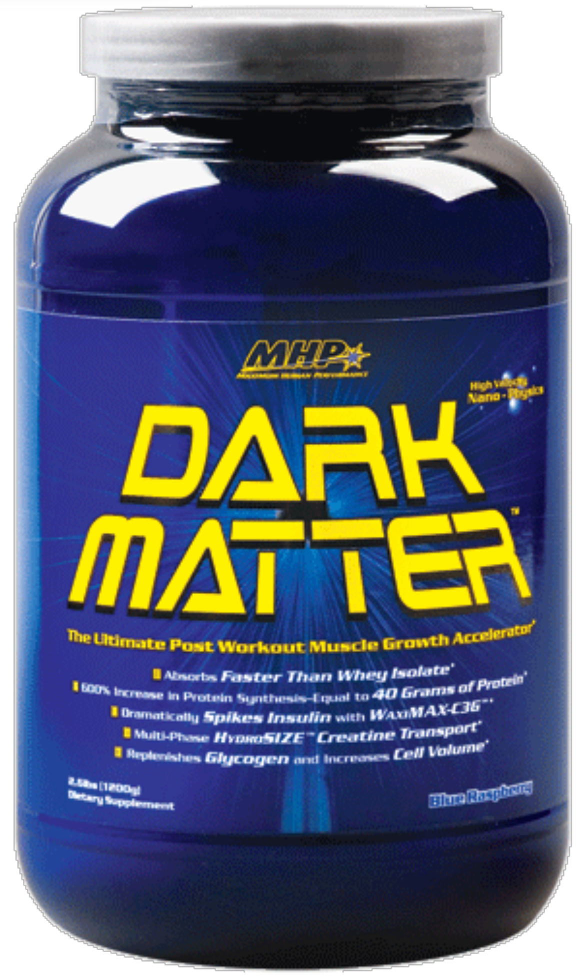
Credit: NASA/WMAP team

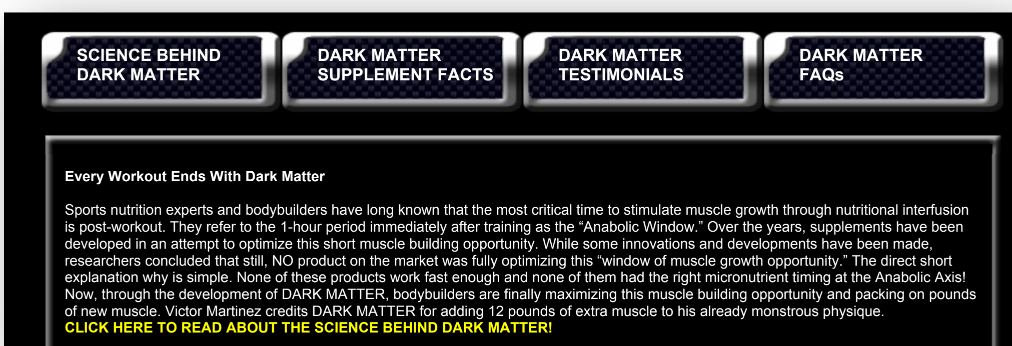
Bullet cluster



Dark Matter

A Quick Tour





DM Candidates and Topics

- Weakly Interacting Massive Particles (WIMPs)
  - Direct detection
  - Indirect detection
- Non-WIMPs
- DM Complementarity

- Strong reasons for optimism:
  - Extensions to the SM (e.g., SUSY, axions) that solve other problems also provide natural candidates for the DM.
  - Huge advances in instrumentation and techniques bring discovery within reach

- Remember:
  - No reason the DM should be just one thing. Could be whole sectors awaiting discovery.

arXiv:1707.04591v1 [hep-ph] 14 Jul 2017

US Cosmic Visions: New Ideas in Dark Matter 2017 : Community Report

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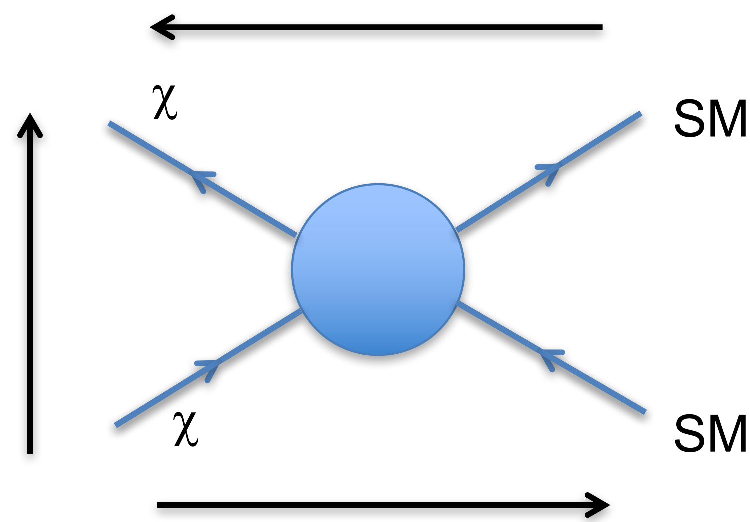
arXiv:1707.04591v1

See Feng, Schuster talks

WIMP Dark Matter

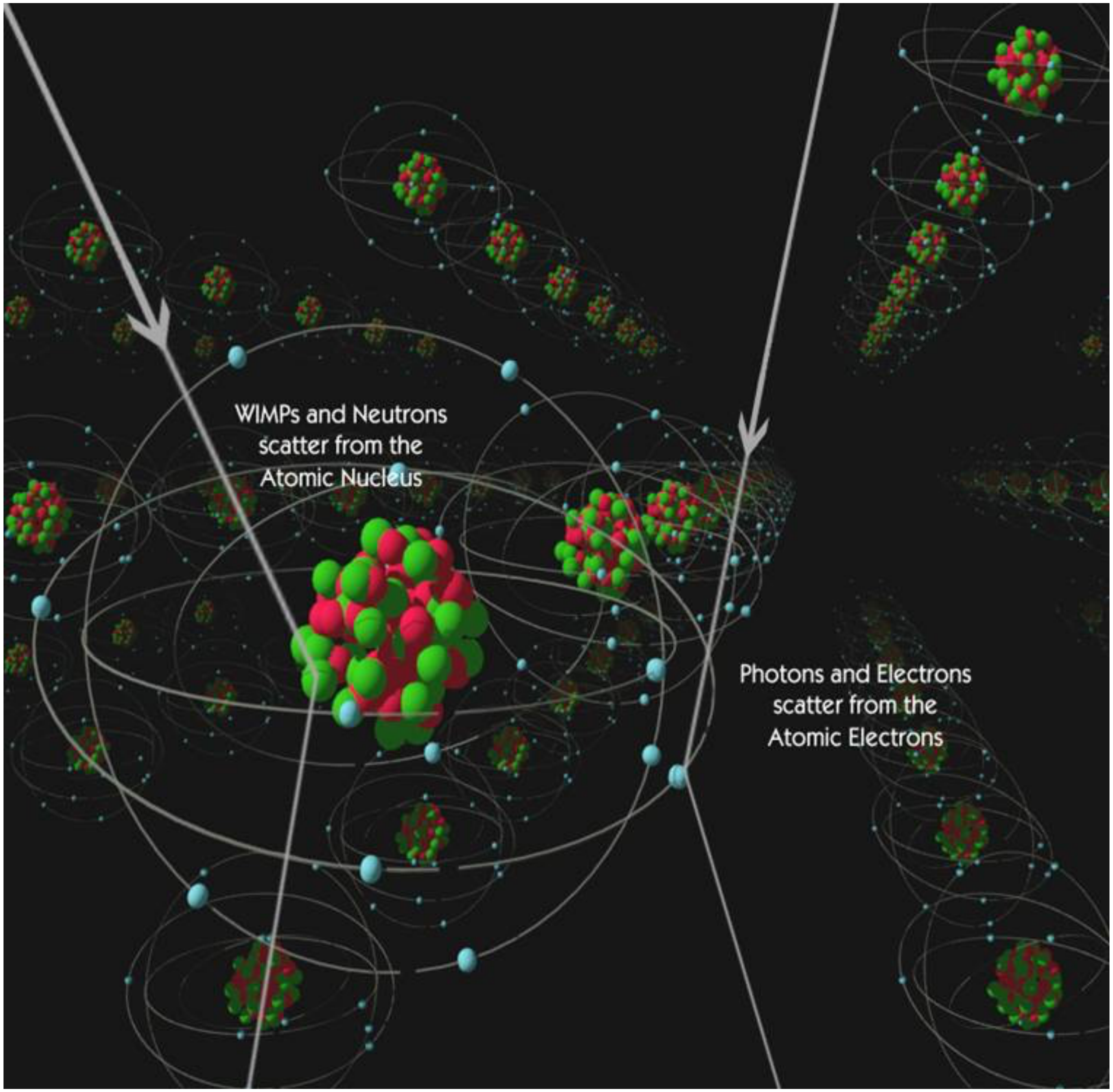
- Simplest picture:
  - Thermal production in the early Universe (left, right)
  - Direct Detection (up)
  - Indirect Detection (right)
  - Production at colliders (left)



- Provides natural scales for searches, particularly for Indirect Detection.

- Nature not so simple!
  - Present-era low-energy interactions could be suppressed, or complex phenomenology, or…

WIMP Direct Detection Principle



Goals include:

- Increase target mass
- Decrease detection energy threshold
- Improve background rejection
- Directionality information?

- DM-e scattering also important.

WIMP Direct Detection Experiments

Table of current and planned experiments (under construction)

Experiment	Status	Target	Technique	Location	Major Support
Cryogenic Solid State					
SuperCDMS Soudan	Current	9 kg Ge	Ionization, Phonons	Soudan	DOE, NSF
SuperCDMS SNOLab	Planned	200 kg Ge	Ionization, Phonons	SNOLab	DOE, NSF
SuperCDMS SNOLab	Planned	400 kg Ge	Ionization, Phonons	SNOLab	DOE, NSF
Edelweiss	Current	4 kg Ge	Ionization, Phonons	Modane	Europe
CRESST	Current	10 kg CaWO4	Scintillation, Phonons	LNGS	Europe
EURECA	Planned	Ge; CaWO4 O(100-1000kg)	Ionization+Phonons; Scintillation+Phonons	Europe	Europe
CoGeNT	Current	440 g Ge	Ionization	Soudan	DOE, NSF
C-4	Planned	5.2 kg Ge	Ionization	Soudan	DOE, NSF
TEXONO	Current	O(1kg)Ge	Ionization	KSNL	Taiwan
CDEX	Current	O(1-10kg)Ge	Ionization	CJPL	China
Liquid Xenon					
LUX	Current	350 kg LXe	Ionization, Scintillation	SURF	DOE, NSF, Europe
LZ	Planned	8000 kg LXe	Ionization, Scintillation	SURF	DOE, NSF, Europe
PandaX-1a	Current	125 kg LXe	Ionization, Scintillation	CJPL	China
PandaX-1b	Planned	500 kg LXe	Ionization, Scintillation	CJPL	China
PandaX-2	Planned	2400 kg LXe	Ionization, Scintillation	CJPL	China
XENON100	Current	62 kg LXe	Ionization, Scintillation	LNGS	DOE, NSF, Europe
XENON1T	Planned	2500 kg LXe	Ionization, Scintillation	LNGS	DOE, NSF, Europe
XENON10T	Planned	20000 kg LXe	Ionization, Scintillation	LNGS	DOE, NSF, Europe
XMASS-I	Current	835 kg LXe	Scintillation	Kamioka	Japan
XMASS-1.5	Planned	5000 kg LXe	Scintillation	Kamioka	Japan
XMASS-II	Planned	20000 kg LXe	Scintillation	Kamioka	Japan

http://www.snowmass2013.org/tiki-index.php?page=SLAC

Liquid Argon					
DarkSide-50	Current	50 kg LAr	Ionization, Scintillation	LNGS	DOE, NSF, Europe
DarkSide-G2	Planned	5000 kg LAr	Ionization, Scintillation	LNGS	DOE, NSF, Europe
ArDM	Current	1 ton LAr	Ionization, Scintillation	Canfranc	Europe
MiniCLEAN	Current	500 kg LAr/LNe	Scintillation	SNOLab	
DEAP-3600	Current	3600 ton LAr	Scintillation	SNOLab	Canada, UK
CLEAN	Planned	40 ton LAr/LNe	Scintillation	SNOLab	
Crystal and Annual Modulation					
DAMA/LIBRA	Current	NaI	Europe		
ELEGANT	Current	NaI	Japan		
DM-Ice	Planned	NaI			
Princeton NaI	Planned	NaI	LNGS		
ANAIS	Planned	250 kg NaI	Scintillation	Canfranc	Europe
CINDMS	Planned	100 kg CsI(Na)	Scintillation	China	
KIMS	Current	cesium iodide	Scintillation	Korea	
Superheated Liquids					
COUPP-60	Current	CF3I	Bubbles	SNOLab	DOE, NSF
COUPP-1T	Planned	CF3I	Bubbles	SNOLab	DOE, NSF
PICASSO	Current	C4F10	Bubbles	SNOLab	Canada
Picoupsso?	Planned	CF3I	Bubbles	SNOLab	DOE, NSF, Canada
SIMPLE Phase III	Current	1-2 kg C2ClF5	Bubbles	Canfranc	Europe
SIMPLE Phase IV	Planned	1000 kg C2ClF5	Bubbles	Canfranc	Europe
Directional Detection					
DRIFT-IId	Current	139 g CS2, CS4	Ionization	Boulby	US,UK
DRIFT-III	Planned	10s of kg CS2, CS4	Ionization	Boulby	US,UK
DMTPC	Current	CF4 gas	Ionization	WIPP	DOE
D^3	Planned		Ionization		
MIMAC	Planned		Ionization	Modane	
Newage	Planned		Ionization		Japan
New Ideas					
Columnar recombination	Planned	Xe gas	Ionization, Scintillation	Canfranc	
DAMIC	Current	Silicon	Ionization	SNOLab	
Liquid He-4	Planned	1-100 kg LHe	Ionization, Scintillation, Rotons	-	-
DNA	Planned	Gold	Broken DNA bonds	-	-
Nuclear emulsions	Planned	few 10s of kg emulsion	-	-	-

Snowmass Direct Detection Summary

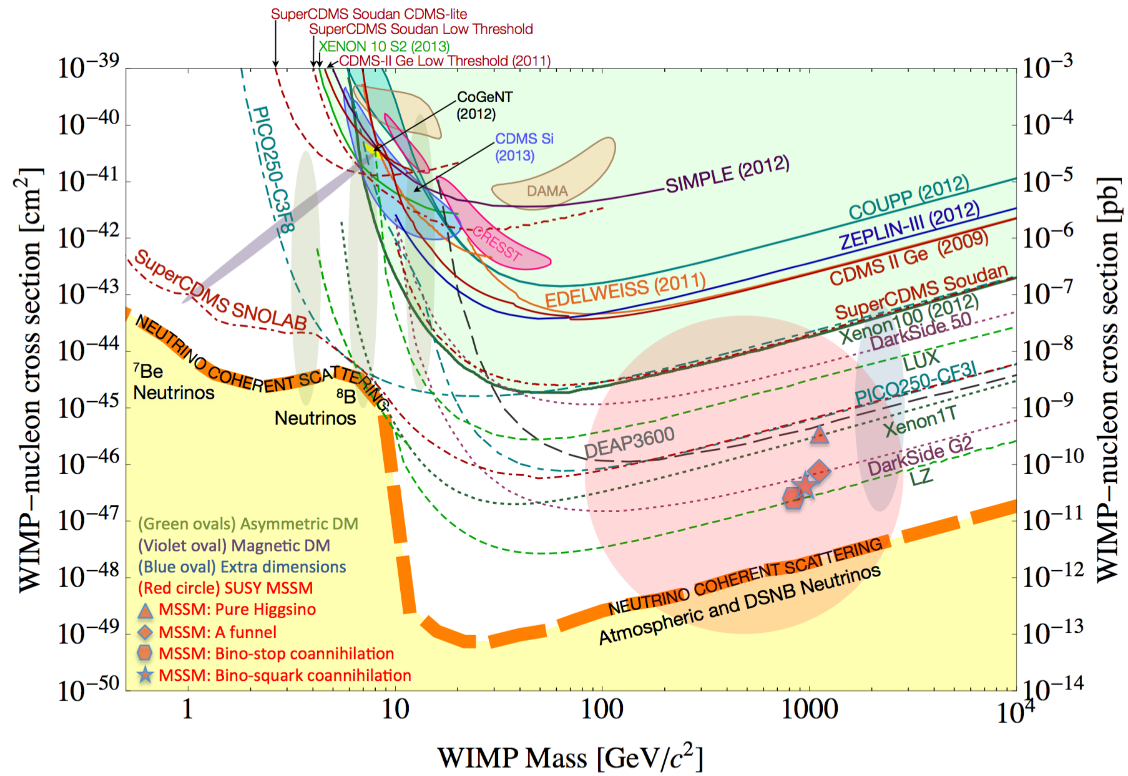


Figure 26. *A compilation of WIMP-nucleon spin-independent cross section limits (solid curves), hints for WIMP signals (shaded closed contours) and projections (dot and dot-dashed curves) for US-led direct detection experiments that are expected to operate over the next decade. Also shown is an approximate band where coherent scattering of ^8B solar neutrinos, atmospheric neutrinos and diffuse supernova neutrinos with nuclei will begin to limit the sensitivity of direct detection experiments to WIMPs. Finally, a suite of theoretical model predictions is indicated by the shaded regions, with model references included.*

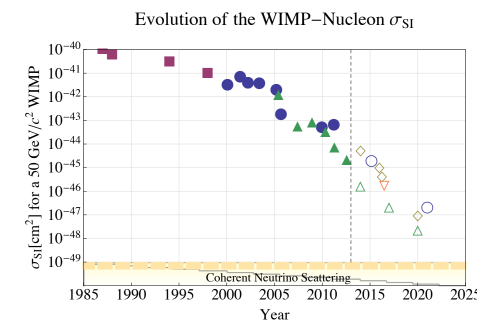


Figure 1. *History and projected evolution with time of spin-independent WIMP-nucleon cross section limits for a 50 GeV WIMP. The shapes correspond to technologies: cryogenic solid state (blue circles), crystal detectors (purple squares), liquid argon (brown diamonds), liquid xenon (green triangles), and threshold detectors (orange inverted triangle). Below the yellow dashed line, WIMP sensitivity is limited by coherent neutrino-nucleus scattering.*

Direct Detection Current Limits

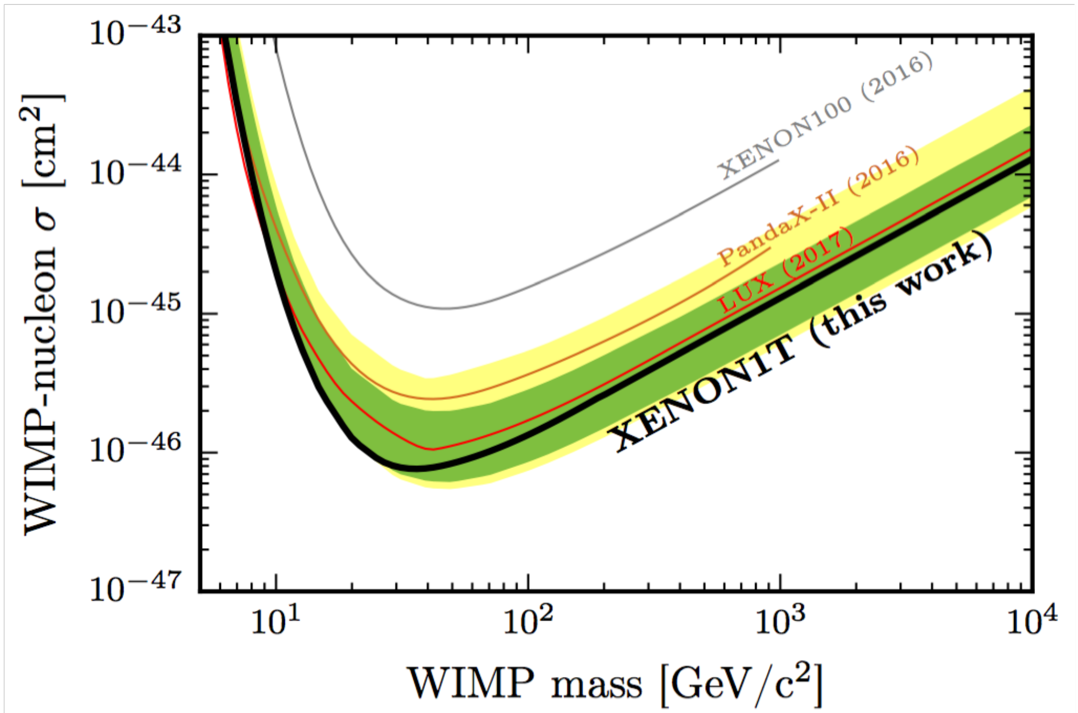


FIG. 4: The spin-independent WIMP-nucleon cross section limits as a function of WIMP mass at 90% confidence level (black) for this run of XENON1T. In green and yellow are the 1- and 2σ sensitivity bands. Results from LUX [26] (red), PandaX-II [27] (brown), and XENON100 [23] (gray) are shown for reference.

arXiv:1705.06655v2 and references therein

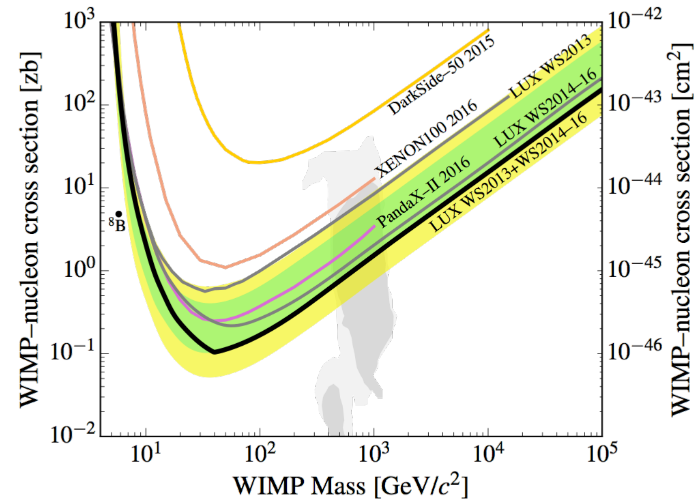


FIG. 3. Upper limits on the spin-independent elastic WIMP-nucleon cross section at 90% C.L. The solid gray curves show the exclusion curves from LUX WS2013 (95 live days) [9] and LUX WS2014–16 (332 live days, this work). These two data sets are combined to give the full LUX exclusion curve in solid black (“LUX WS2013+WS2014–16”). The 1– and 2–σ ranges of background-only trials for this combined result are shown in green and yellow, respectively; the combined LUX WS2013+WS2014–16 limit curve is power constrained at the -1σ level. Also shown are limits from XENON100 [44] (red), DarkSide-50 [45] (orange), and PandaX-II [46] (purple). The expected spectrum of coherent neutrino-nucleus scattering by ^{8}B solar neutrinos can be fit by a WIMP model as in [47], plotted here as a black dot. Parameters favored by SUSY CMSSM [48] before this result are indicated as dark and light gray (1– and 2–σ) filled regions.

arXiv:1608.07648v3

See Tunnell, Monzani talks

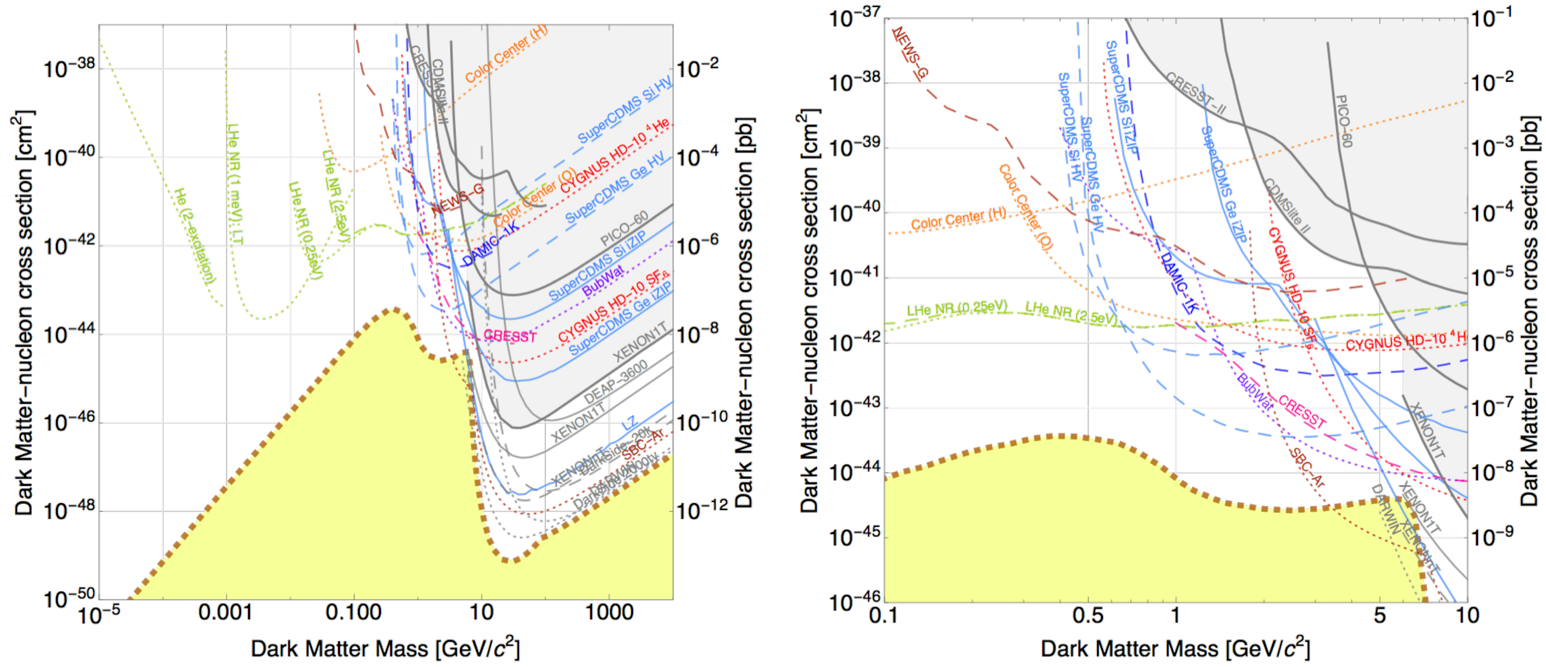


FIG. 8: **Left:** Constraints and projections (90% c.l.) for the **DM-nucleon scattering** cross section. Thick gray lines are current world-leading constraints [108, 116, 129, 130]. Projections are shown with solid/dashed/dotted lines indicating a short/medium/long timescale, respectively, with the same meaning as in Fig. 6. Blue lines denote the DoE G2 experiment projections. Yellow region denotes the WIMP-discovery limit from [131] extended to lower masses for He-based experiments. **Right:** As in left plot, but focused on the 100 MeV to 10 GeV DM mass range.

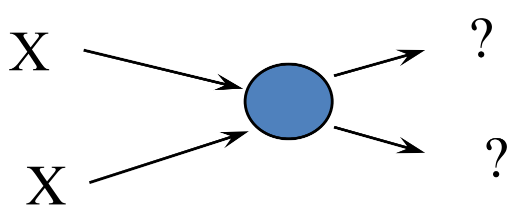
arXiv:1707.04591

- See later for spin-dependent limits
- See report for summary of DM-e scattering

See Monzani, Pyle, Dahl talks

Dark Matter Indirect Detection

DM particle interactions could produce an anomalous flux of cosmic particles ("indirect detection").



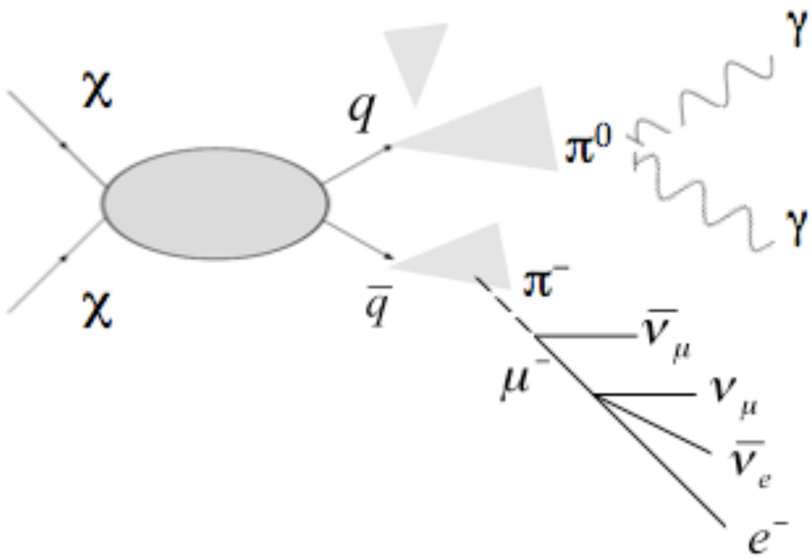
Anomalous gamma ray spectra and/or $\gamma\gamma$ or $Z\gamma$ "lines" and/or anomalous charged cosmic rays and/or neutrinos?

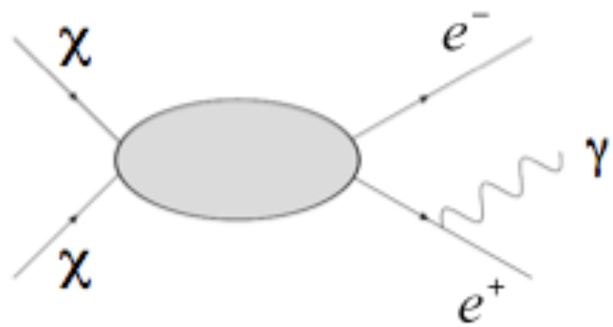
- If particles are stable: rate ~ (DM density)^2
- If particles unstable: rate ~ (DM density)

- Key interplay of techniques:
  - colliders
  - direct detection experiments underground
  - indirect detection (most straightforward: gamma rays and neutrinos)
    - Full sky coverage advantageous
    - Intensity highly model-dependent
    - Challenge is to separate signals from astrophysical backgrounds

See A. Albert talk

Indirect Detection: Dark Matter Annihilation





Prompt lepton pair production

+ “lines” from 2-body final states

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

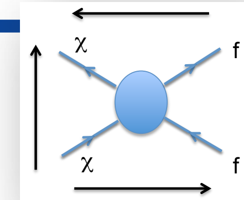
Astrophysical factor

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

Particle physics factor

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

WIMP Indirect Detection: Many Places to Look!



Galactic Center

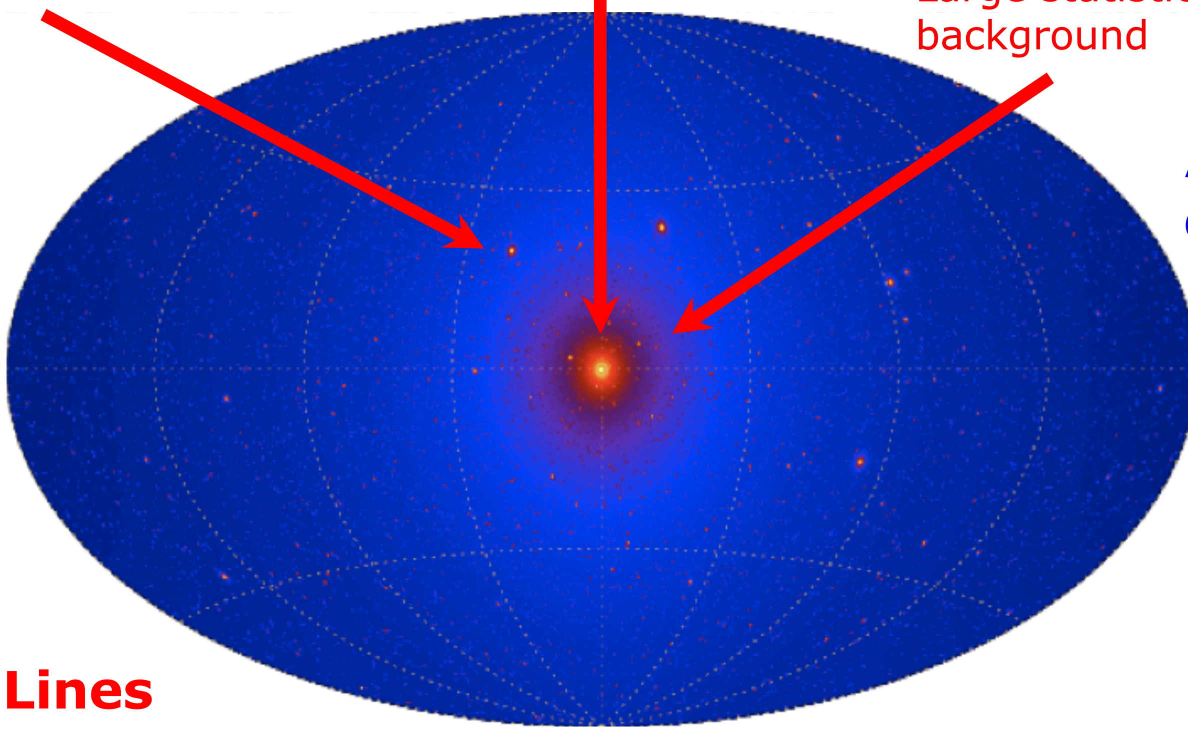
Good Statistics but source confusion/diffuse background

Satellites

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

Milky Way Halo

Large statistics but diffuse background



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.)

Spectral Lines

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

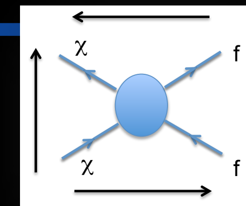
Extragalactic

Large statistics, but astrophysics, galactic diffuse background

Galaxy Clusters

Low background, but low statistics

WIMP Indirect Detection: Many Places to Look!



Galactic Center

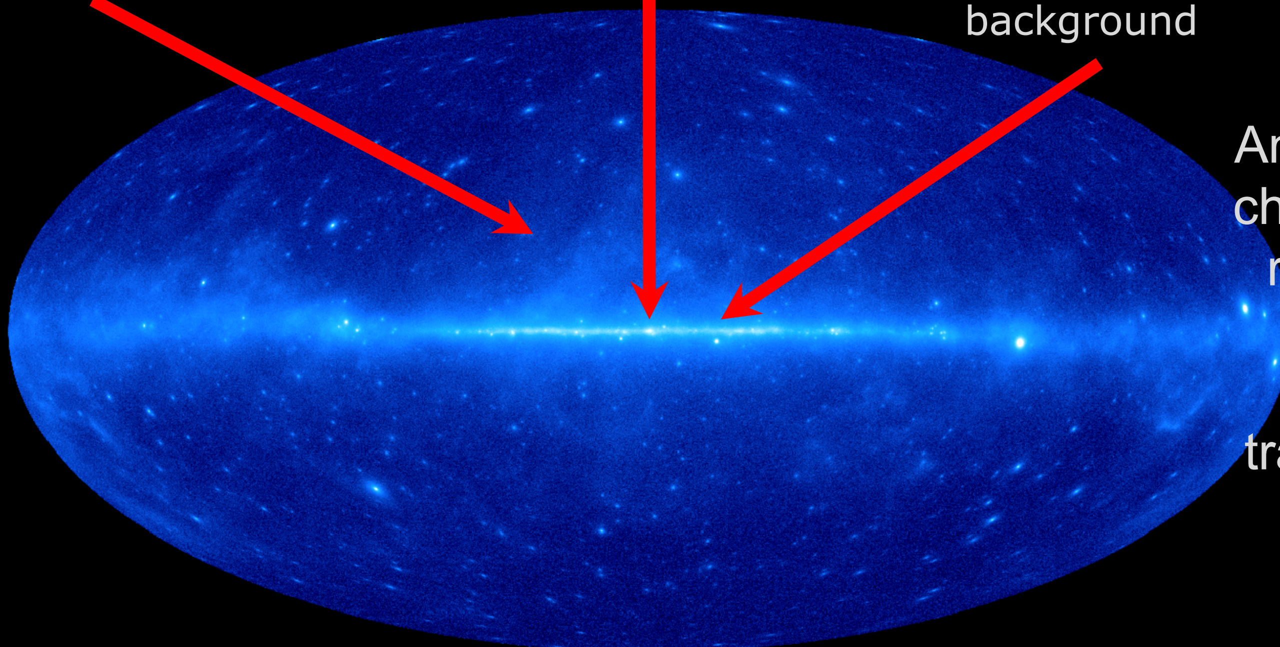
Good Statistics but source confusion/diffuse background

Satellites

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

Milky Way Halo

Large statistics but diffuse background



Fermi LAT All-sky Image

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

Spectral Lines

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

Extragalactic

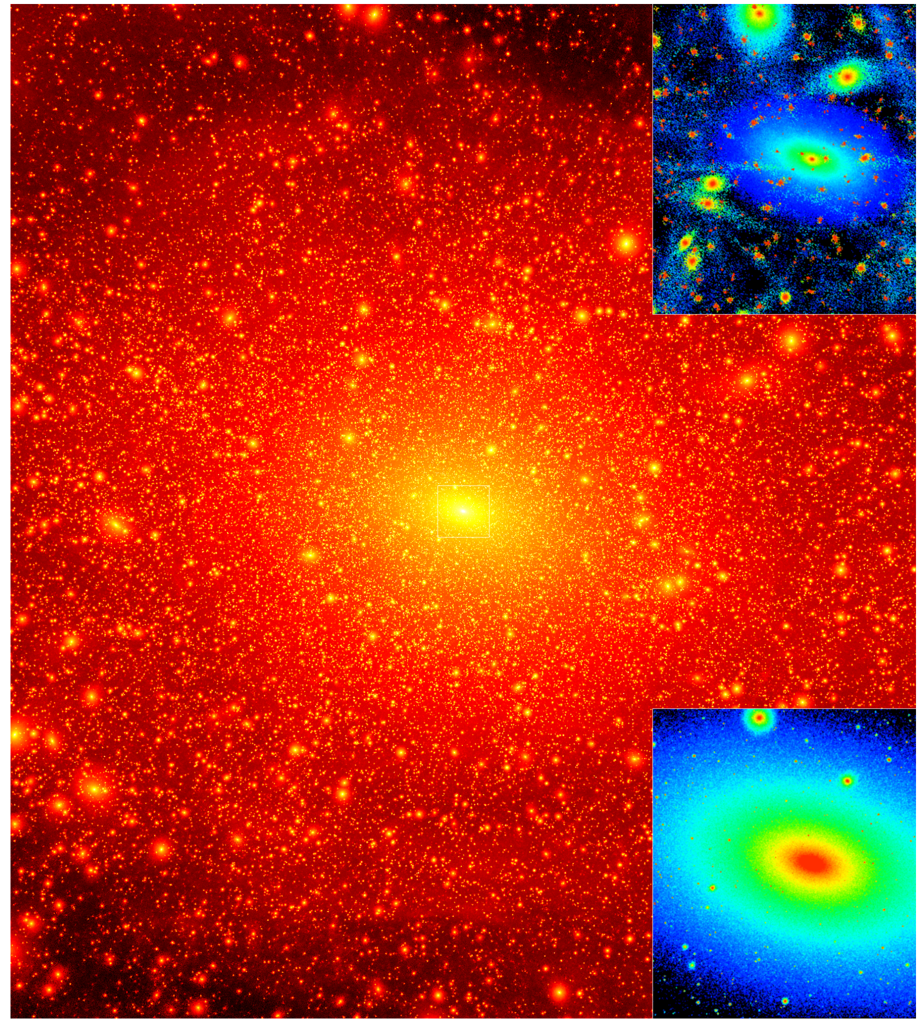
Large statistics, but astrophysics, galactic diffuse background

Galaxy Clusters

Low background, but low statistics

Dwarf Spheriodal (dSph) Galaxies

- Largest galactic substructures predicted (in ΛCDM)
- DM-dominated: mass-to-light ratios O(100-1000)
- Very low astrophysical backgrounds
  - no detected gas, low recent star formation activity
- SDSS and DES discovery of many more ultrafaint Milkyway satellites
  - more are welcome!
- Great opportunity for indirect DM signal searches!



Via Lactea II simulation

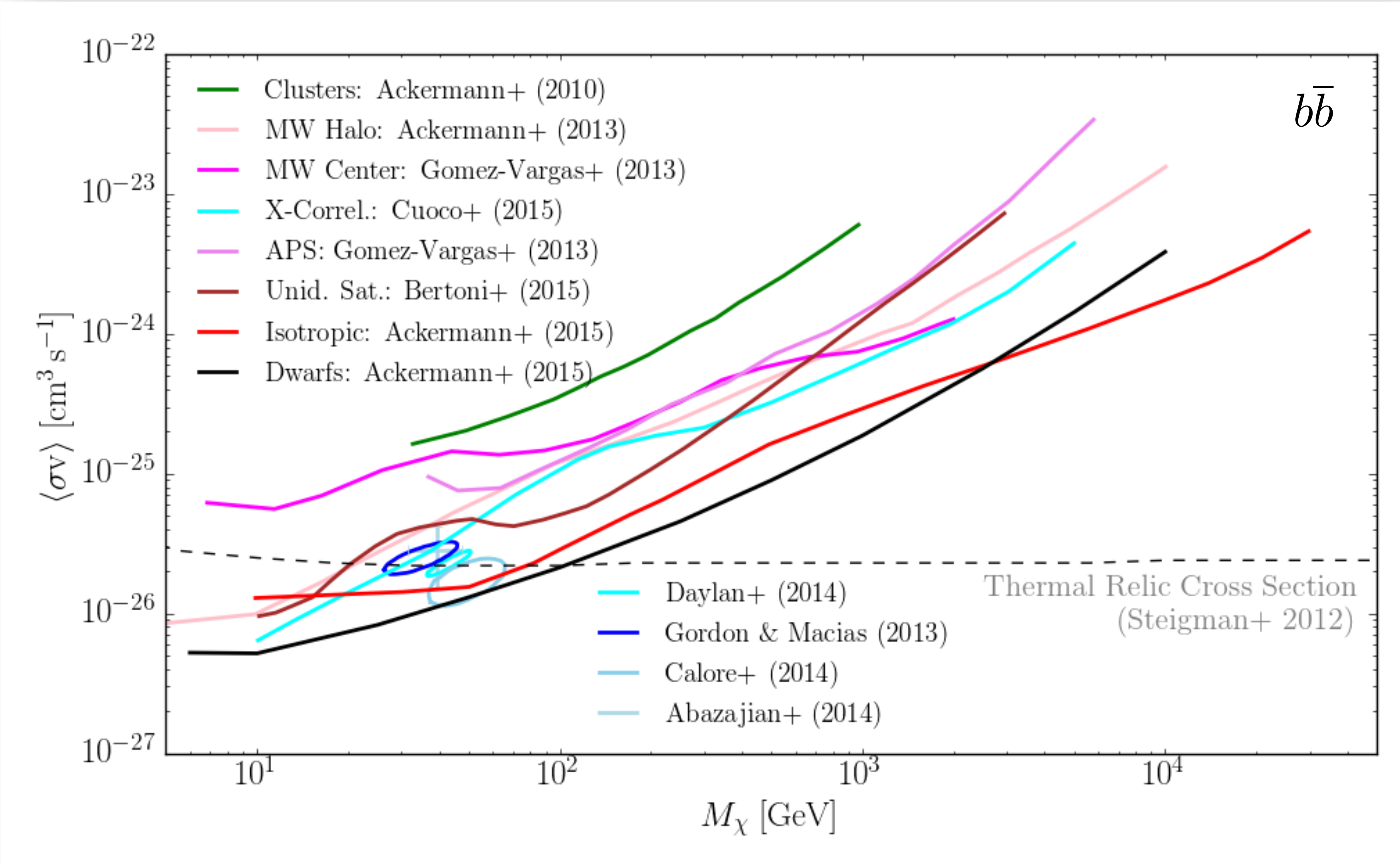
Indirect Detection Facilities

Indirect Detection Experiments

Status	Experiment	Target	Location	Major Support	Comments
Current	AMS	e+/e-, anti-nuclei	ISS	NASA	Magnet Spectrometer, Running
	Fermi	Photons, e+/e-	Satellite	NASA, DOE	Pair Telescope and Calorimeter, Running
	HESS	Photons, e-	Namibia	German BMBF, Max Planck Society, French Ministry for Research, CNRS-IN2P3, UK PPARC, South Africa	Atmospheric Cherenkov Telescope (ACT), Running
	IceCube/ DeepCore	Neutrinos	Antarctica	NSF, DOE, International: Belgium, Germany, Japan, Sweden)	Ice Cherenkov, Running
	MAGIC	Photons, e+/e-	La Palma	German BMBF and MPG, INFN, WSwiss SNF, Spanish MICINN, CPAN, Bulgarian NSF, Academy of Finland, DFG, Polish MNiSzW	ACT, Running
	PAMELA	e+/e-	Satellite		
	VERITAS	Photons, e+/e-	Arizona, USA	DOE, NSF, SAO	ACT, Running
	ANTARES	Neutrinos	Mediter-ranean	France, Italy, Germany, Netherlands, Spain, Russia, and Morocco	Running
Planned	CALET	e+/e-	ISS	Japan JAXA, Italy ASI, NASA	Calorimeter
	CTA	Photons	ground-based (site TBD)	International: MinCyT, CNEA, CONICET, CNRS-INSU, CNRS-IN2P3, Irfu-CEA, ANR, MPI, BMBF, DESY, Helmholtz Association, MIUR, NOVA, NWO, Poland, MICINN, CDTI, CPAN, Swedish Research Council, Royal Swedish Academy of Sciences, SNSF, Durham UK, NSF, DOE	ACT
	GAMMA-400	Photons	Satellite	Russian Space Agency, Russian Academy of Sciences, INFN	Pair Telescope
	GAPS	Anti-deuterons	Balloon (LDB)	NASA, JAXA	TOF, X-ray and Pion detection
	HAWC	Photons, e+/e-	Sierra Negra	NSF/DOE	Water Cherenkov, Air Shower Surface Array
	IceCube/ PINGU	Neutrinos	Antarctica	NSF, Germany, Sweden, Belgium	Ice Cherenkov
	KM3NeT	Neutrinos	Mediter-ranean	ESFRI, including France, Italy, Greece, Netherlands, Germany, Ireland, Romania, Spain, UK, Cyprus	Water Cherenkov
	ORCA	Neutrinos	Mediter-ranean	ESFRI, including France, Italy, Greece, Netherlands, Germany, Ireland, Romania, Spain, UK, Cyprus	Water Cherenkov

http://www.snowmass2013.org/tiki-index.php?page=WIMP+Dark+Matter+Indirect+Detection

A Sample of DM Limits



E. Charles et al, arXiv:1605.02016v2

See A. Albert talk

Gamma-ray Status and Prospects

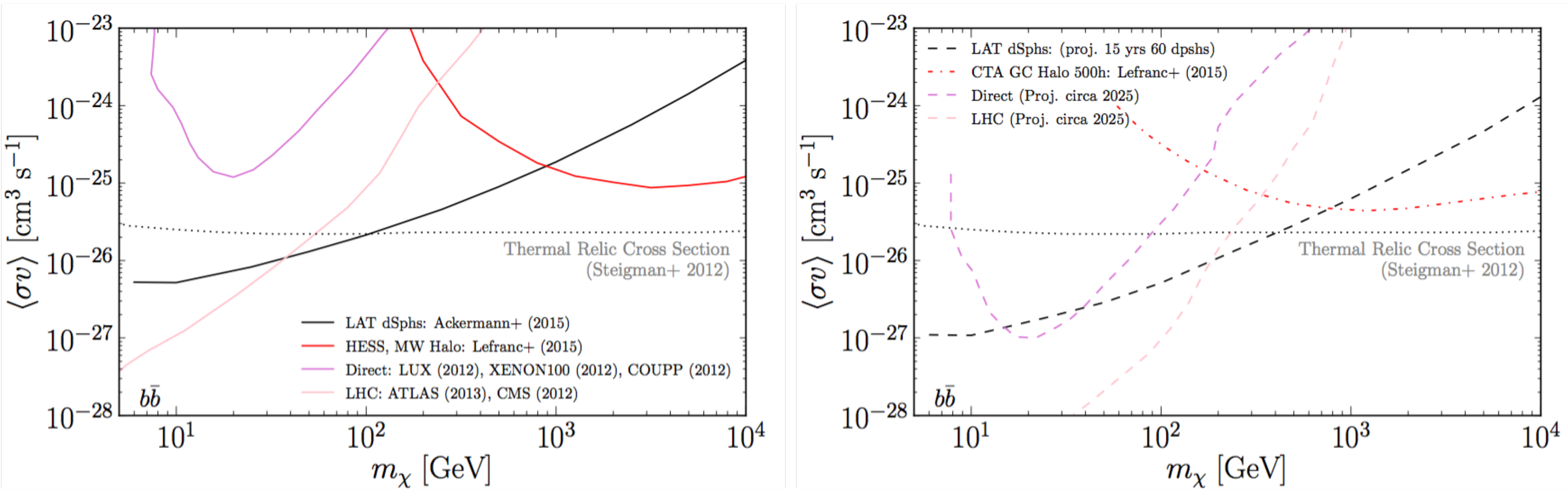


Figure 31: Comparison of best current (left) and projected (right) indirect-detection, direct-detection (spin-dependent) and collider-production limits on $\langle \sigma v \rangle$ in the $b\bar{b}$ channel. Conversion of direct-detection and collider limits to the $\langle \sigma v \rangle$ scale is based on the assumption of four particle contact interactions for the production/annihilation of DM. As noted in the text, this assumption is *quite uncertain* (potentially by orders of magnitude) and the comparisons shown here should be considered schematic. The current IACT limits are taken from Ref. [282]. Following Ref. [296], the direct-detection limits are taken from Ref. [304], and the projection was made using the expected LZ sensitivity. The collider-production limits are taken from Refs. [305, 306], and the projection was made for 300 fb^{-1} of data at 13 TeV [307].

E. Charles et al, arXiv:1605.02016v2

Gamma-ray Prospects

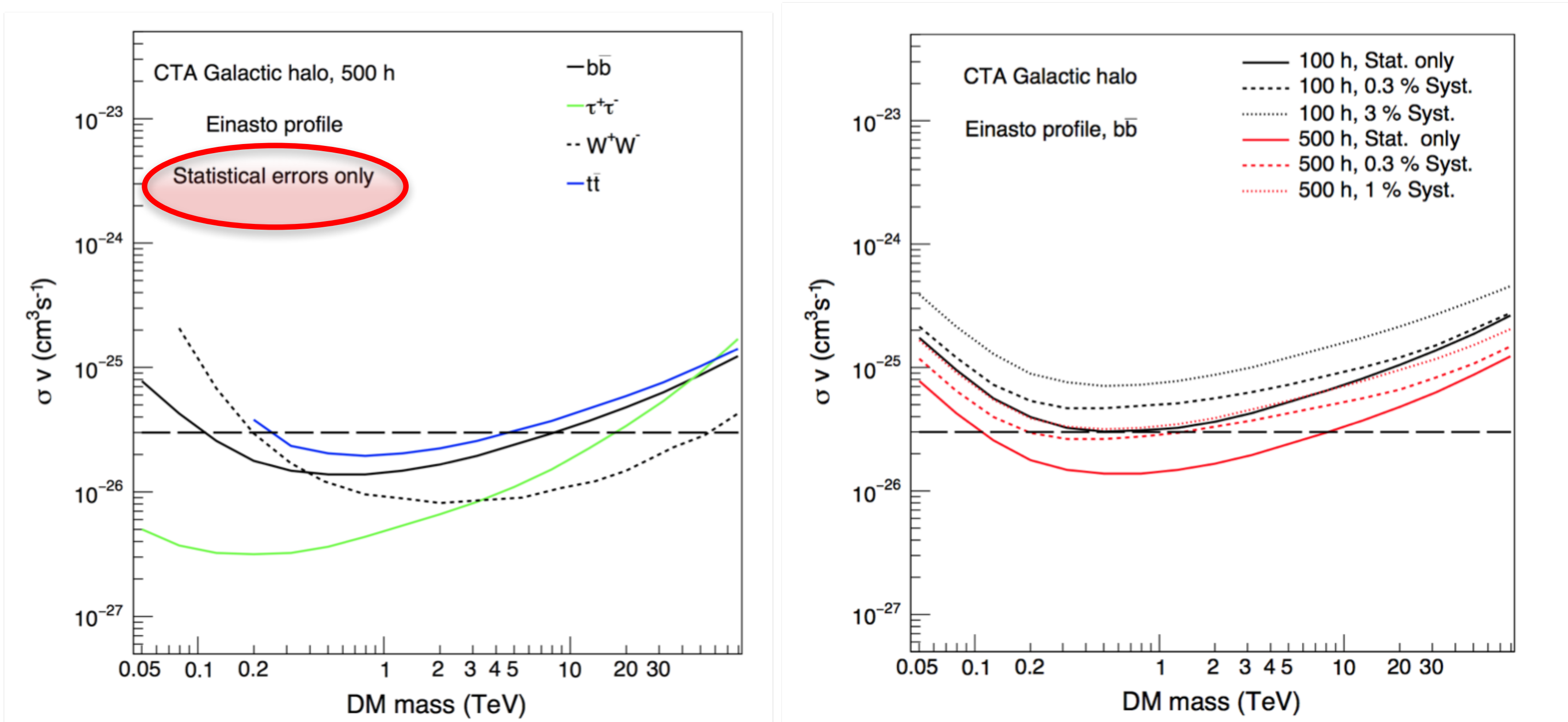
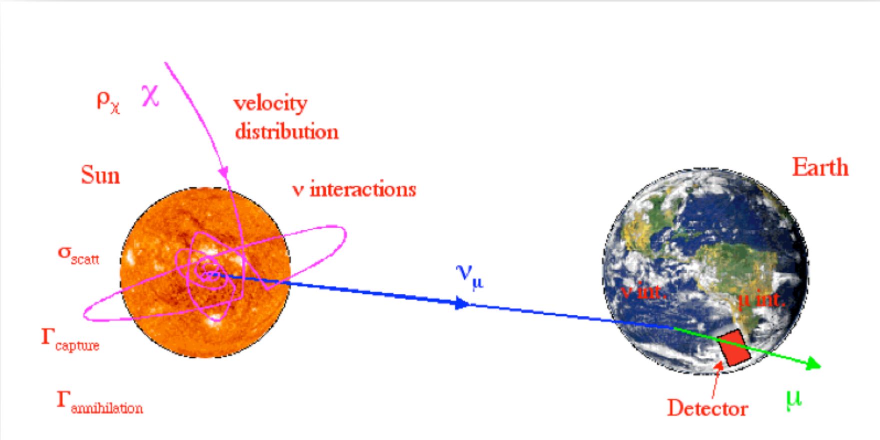


Figure 1: Left panel: CTA sensitivity from observation of the Galactic halo for the Einasto profile and for different annihilation modes as indicated. Only statistical errors were included. Right panel: CTA sensitivity for $b\bar{b}$ annihilation mode for the Einasto profile and for different conditions, black is for 100 hours of observation and red is for 500 hours. The solid lines are the sensitivities only taking into account the statistical errors while the dashed and dotted curves take into account systematics as indicated. The dashed horizontal lines approximate the level of the thermal relic cross-section.

A. Morselli et al ICRC 2017

HE Solar Neutrino Signals from WIMPs



12

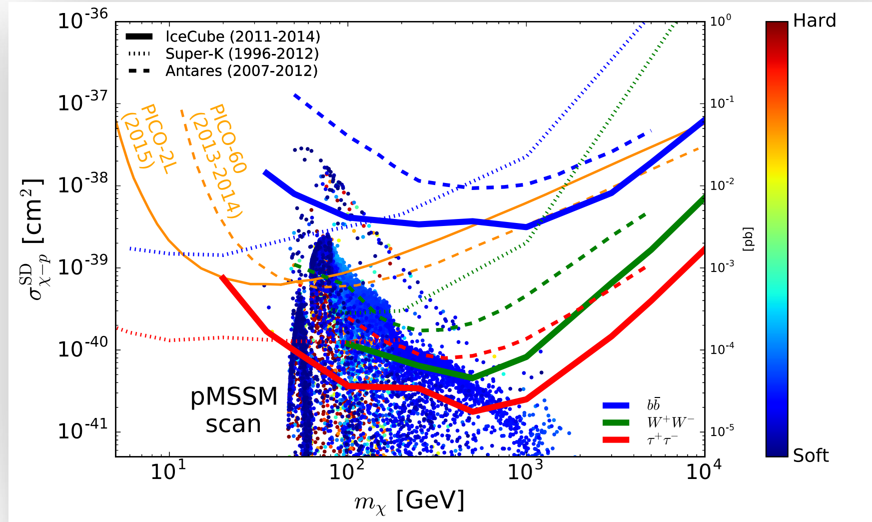


Fig. 7 Limits on $\sigma^{SD}_{\chi-p}$, compared to results from other neutrino detectors and direct detection experiments [34–37]. The IceCube limits have been scaled up to the upper edge of the total systematic uncertainty band. The colored points correspond to models from a scan of the pMSSM described in Section 7 and are shown color coded by the 'hardness' of the resultant neutrino spectrum. Points close to the red end of the spectrum annihilate predominantly into harder channels such as $\tau^+\tau^-$ and can hence be excluded by the IceCube red line.

IceCube **arXiv:1612.05949**

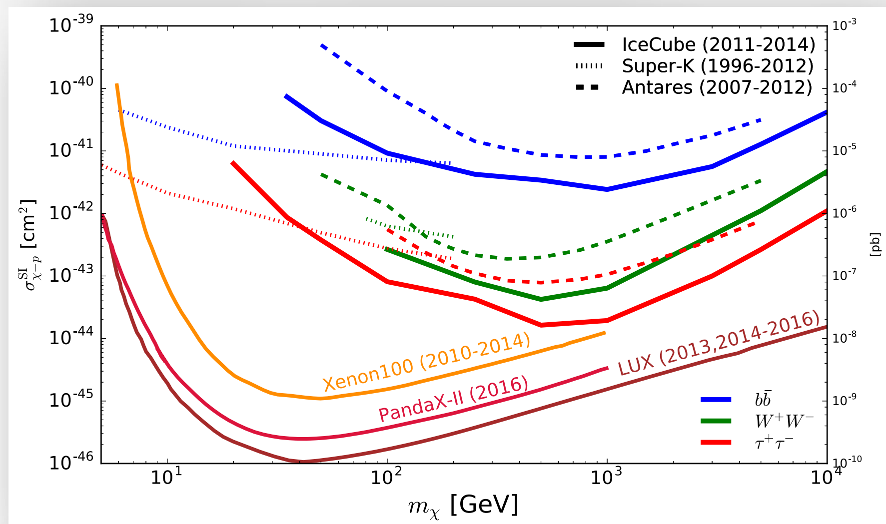
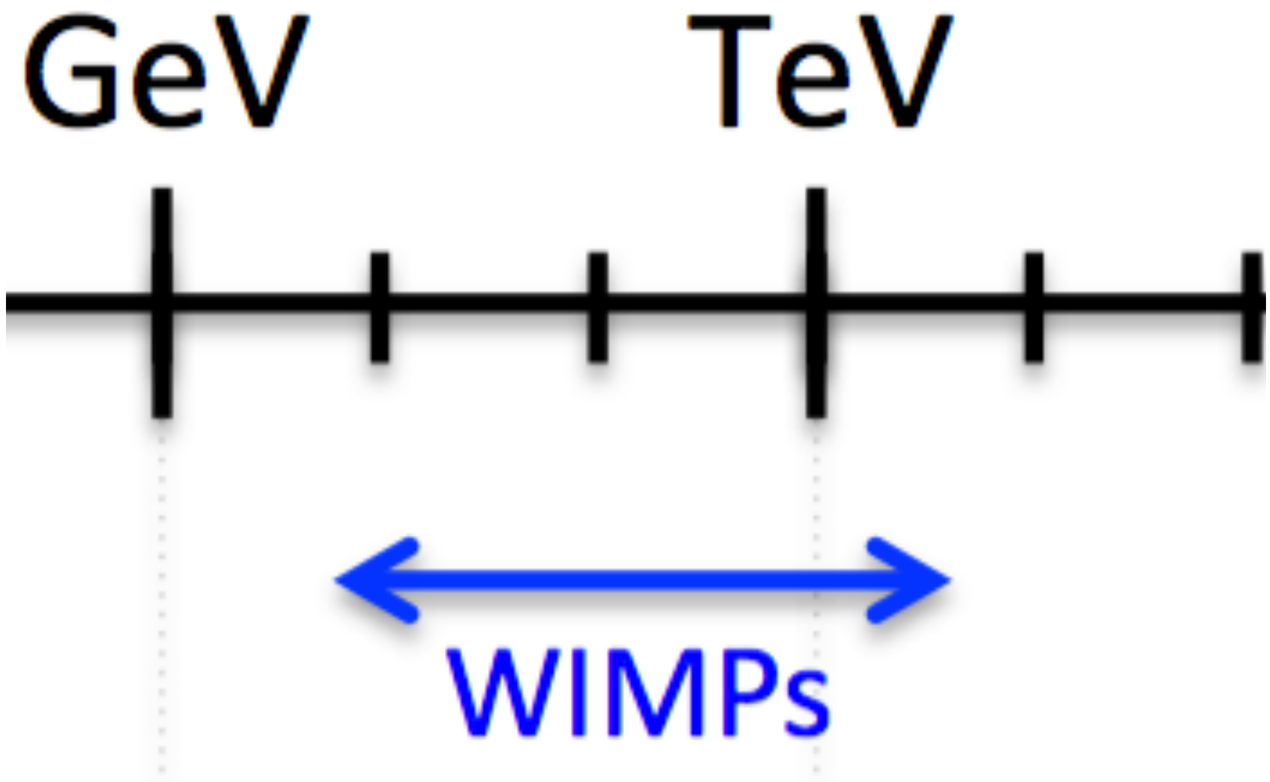


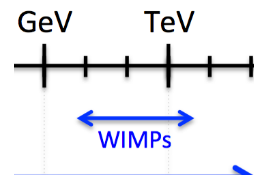
Fig. 8 Limits on $\sigma^{SI}_{\chi-p}$, compared to results from other neutrino detectors and direct detection experiments [34, 35, 38–40]. The IceCube limits include the systematic uncertainties.

See S. Klein talk

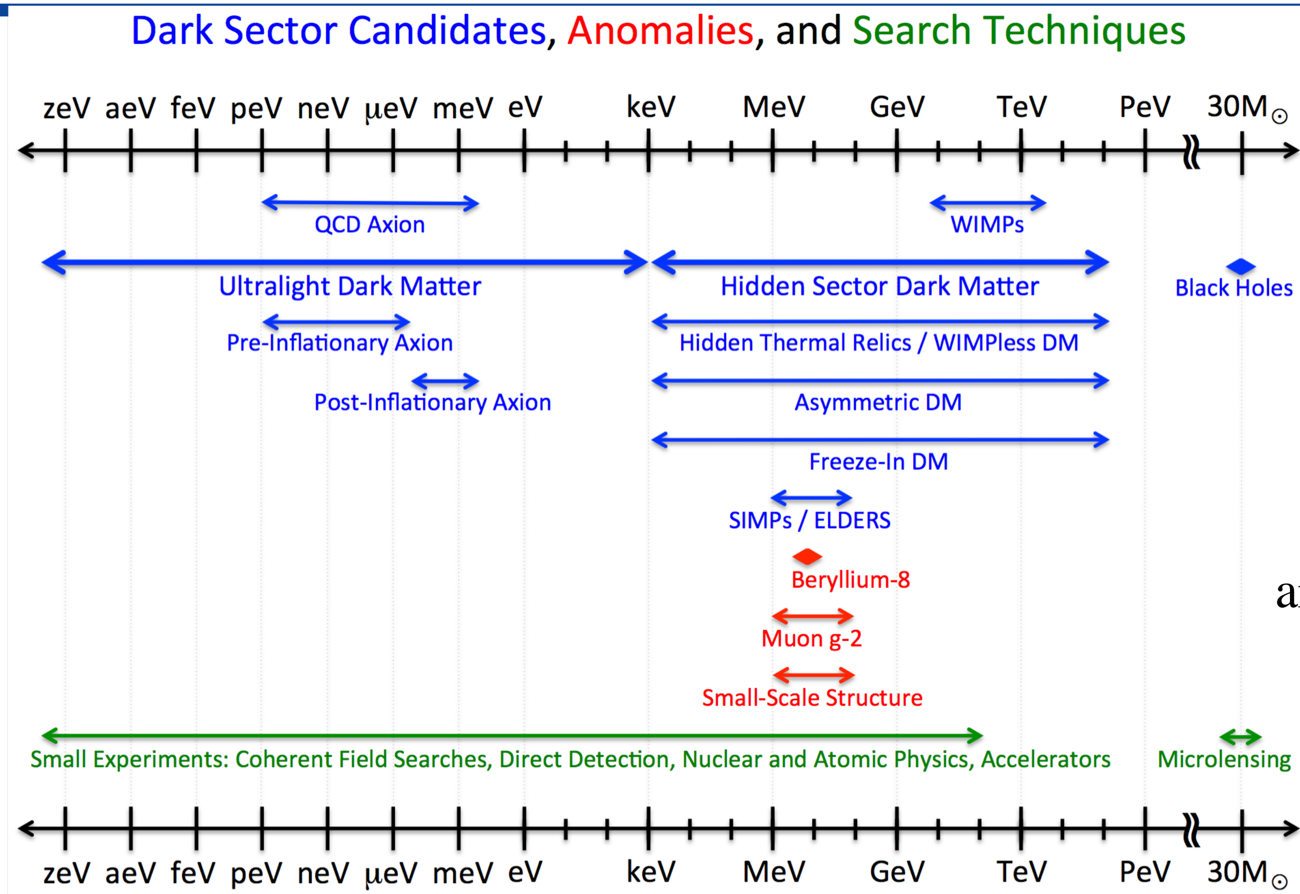
“Non-WIMPs” is a lot! DM Landscape



"Non-WIMPs" is a lot! DM Landscape



“Non-WIMPs” is a lot! DM Landscape



arXiv:1707.04591

FIG. 1: Mass ranges for dark matter and mediator particle candidates, experimental anomalies, and search techniques described in this document. All mass ranges are merely representative; for details, see the text. The QCD axion mass upper bound is set by supernova constraints, and may be significantly raised by astrophysical uncertainties. Axion-like dark matter may also have lower masses than depicted. Ultralight Dark Matter and Hidden Sector Dark Matter are broad frameworks. Mass ranges corresponding to various production mechanisms within each framework are shown and are discussed in Sec. II. The Beryllium-8, muon $(g-2)$, and small-scale structure anomalies are described in VII. The search techniques of Coherent Field Searches, Direct Detection, and Accelerators are described in Secs. V, IV, and VI, respectively, and Nuclear and Atomic Physics and Microlensing searches are described in Sec. VII.

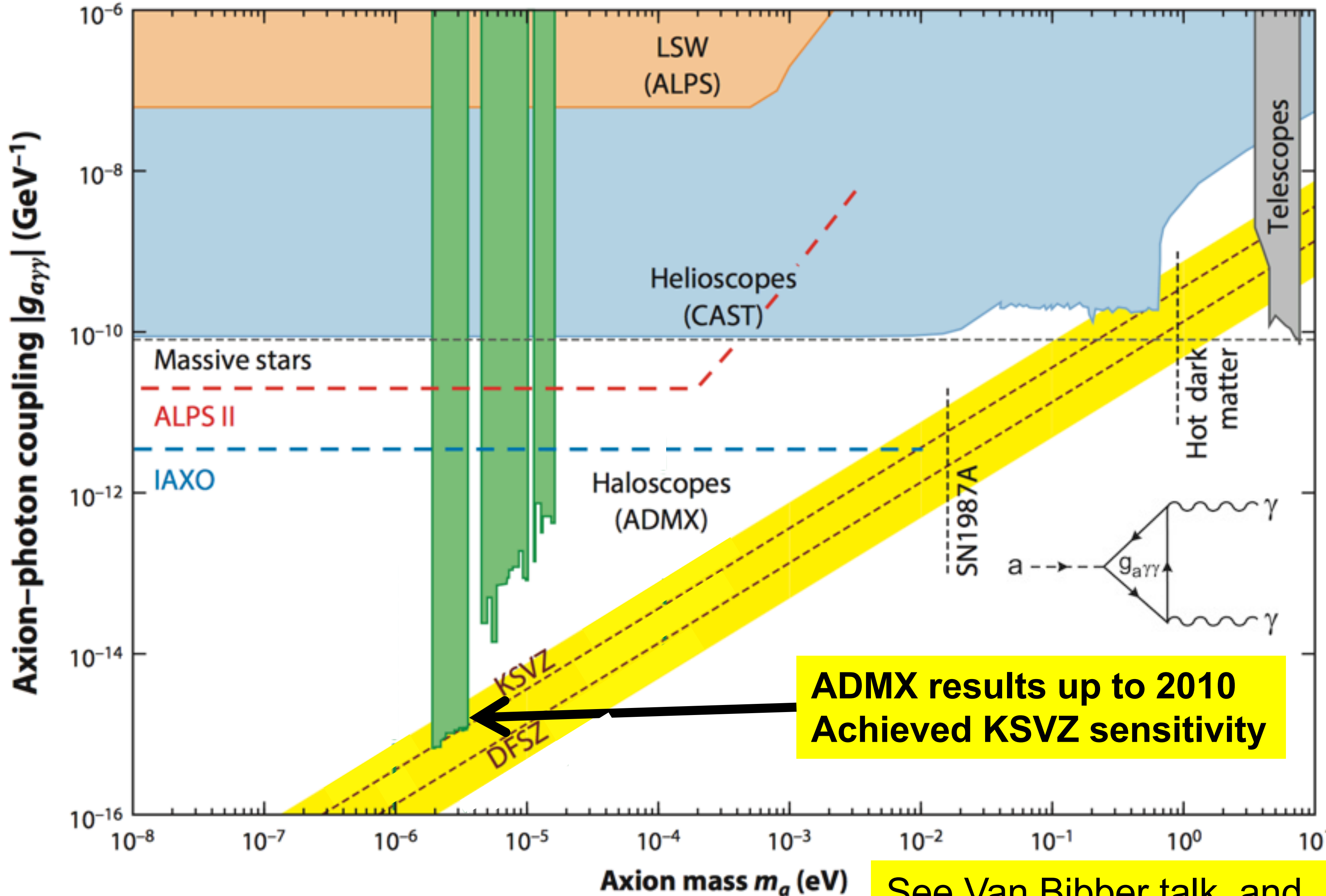
See Feng, Graham talks

Experiment	Machine	Type	E_{beam} (GeV)	Detection	Mass range (GeV)	Sensitivity	First beam	Ref.
Future US initiatives								
BDX	CEBAF @ JLab	electron BD	2.1-11	DM scatter	$0.001 < m_\chi < 0.1$	$y \gtrsim 10^{-13}$	2019+	[211, 212]
COHERENT	SNS @ ORNL	proton BD	1	DM scatter	$m_\chi < 0.06$	$y \gtrsim 10^{-13}$	started	[213, 214]
DarkLight	LERF @ JLab	electron FT	0.17	MMass (& vis.)	$0.01 < m_{A'} < 0.08$	$\epsilon^2 \gtrsim 10^{-6}$	started	[215]
LDMX	DASEL @ SLAC	electron FT	4 (8)*	MMomentum	$m_\chi < 0.4$	$\epsilon^2 \gtrsim 10^{-14}$	2020+	[216]
MMAPS	Synchr @ Cornell	positron FT	6	MMass	$0.02 < m_{A'} < 0.075$	$\epsilon^2 \gtrsim 10^{-8}$	2020+	[217]
SBN	BNB @ FNAL	proton BD	8	DM scatter	$m_\chi < 0.4$	$y \sim 10^{-12}$	2018+	[218, 219]
SeaQuest	MI @ FNAL	proton FT	120	vis. prompt	$0.22 < m_{A'} < 9$	$\epsilon^2 \gtrsim 10^{-8}$	2017	[220]
				vis. disp.	$m_{A'} < 2$	$\epsilon^2 \sim 10^{-14} - 10^{-8}$		
Future international initiatives								
Belle II	SuperKEKB @ KEK	e^+e^- collider	~ 5.3	MMass (& vis.)	$0 < m_\chi < 10$	$\epsilon^2 \gtrsim 10^{-9}$	2018	[203]
MAGIX	MESA @ Mami	electron FT	0.105	vis.	$0.01 < m_{A'} < 0.060$	$\epsilon^2 \gtrsim 10^{-9}$	2021-2022	[205]
PADME	DAΦNE @ Frascati	positron FT	0.550	MMass	$m_{A'} < 0.024$	$\epsilon^2 \gtrsim 10^{-7}$	2018	[206, 207]
SHIP	SPS @ CERN	proton BD	400	DM scatter	$m_\chi < 0.4$	$y \gtrsim 10^{-12}$	2026+	[208, 209]
VEPP3	VEPP3 @ BINP	positron FT	0.500	MMass	$0.005 < m_{A'} < 0.022$	$\epsilon^2 \gtrsim 10^{-8}$	2019-2020	[210]
Current and completed initiatives								
APEX	CEBAF @ JLab	electron FT	1.1-4.5	vis.	$0.06 < m_{A'} < 0.55$	$\epsilon^2 \gtrsim 10^{-7}$	2018-2019	[197, 198]
BABAR	PEP-II @ SLAC	e^+e^- collider	~ 5.3	vis.	$0.02 < m_{A'} < 10$	$\epsilon^2 \gtrsim 10^{-7}$	done	[191, 229, 230]
Belle	KEKB @ KEK	e^+e^- collider	~ 5.3	vis.	$0.1 < m_{A'} < 10.5$	$\epsilon^2 \gtrsim 10^{-7}$	done	[231]
HPS	CEBAF @ JLab	electron FT	1.1-4.5	vis.	$0.015 < m_{A'} < 0.5$	$\epsilon^2 \sim 10^{-7}$**	2018-2020	[232]
NA/64	SPS @ CERN	electron FT	100	MEnergy	$m_{A'} < 1$	$\epsilon^2 \gtrsim 10^{-10}$	started	[186]
MiniBooNE	BNB @ FNAL	proton BD	8	DM scatter	$m_\chi < 0.4$	$y \gtrsim 10^{-9}$	done	[188]
TREK	K^+ beam @ J-PARC	K decays	0.240	vis.	N/A	N/A	done	[201, 202]

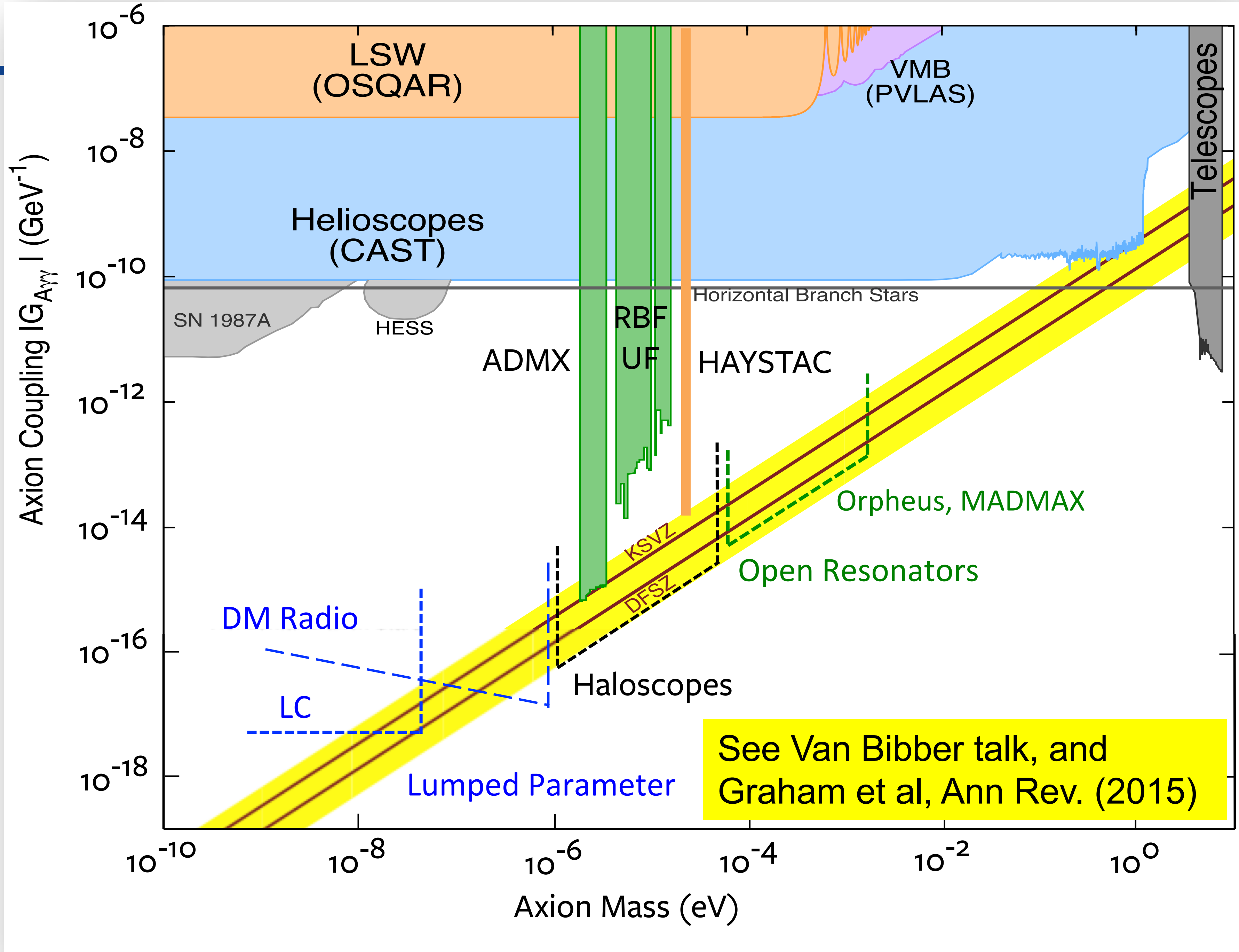
TABLE II: Summary table of current light DM experiments and future proposals. The sensitivities are quoted either for the kinetic mixing or the variable y, whichever is most relevant (see the text and the corresponding figures for more detailed predictions). The range quoted for experiments sensitive to both visible and invisible decays refers to the invisible case. Starting dates are subject to variations. *Legend:* beam dump (BD), fixed target (FT), dark matter scattering (DM scatter), missing mass (MMass), missing momentum (MMomentum), missing energy (MEnergy), prompt/displaced visible decays (vis). *Notes:* *LDMX beam energy is 4 GeV for phase I, and could be upgraded to 8 GeV for phase II. **Sensitivity to displaced vertices under study.

arXiv:1707.04591v1

Axion parameter space

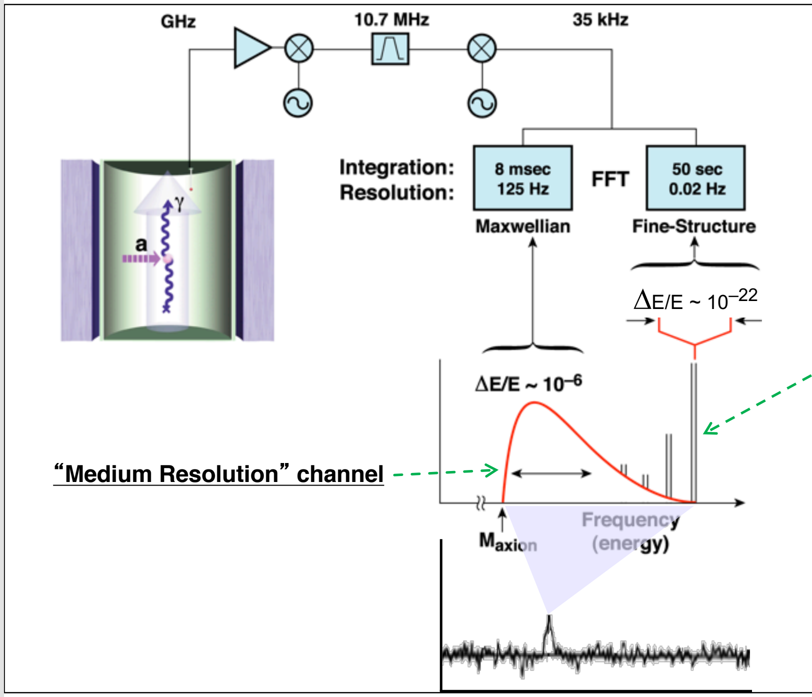


See Van Bibber talk, and Graham et al, Ann Rev. (2015)



LSW
(OSQAR)
VMB
(PVLAS)
Telescopes
Helioscopes
(CAST)
Horizontal Branch Stars
SN 1987A
HESS
RBF
UF
ADMX
HAYSTAC
Orpheus, MADMAX
KSVZ
DFSZ
Open Resonators
DM Radio
LC
Haloscopes
Lumped Parameter
See Van Bibber talk, and
Graham et al, Ann Rev. (2015)
Axion Coupling |G$_{A\gamma\gamma}$| (GeV^{-1})
Axion Mass (eV)
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}

The ADMX experimental layout
(original concept from P. Sikivie)



Local Milky Way density:

$\rho_{halo} \sim 450\ MeV/cm^3$

Thus for $m_a \sim 10\ \mu eV$:

$\rho_{halo} \sim 10^{14}\ cm^{-3}$

“High Resolution” channel

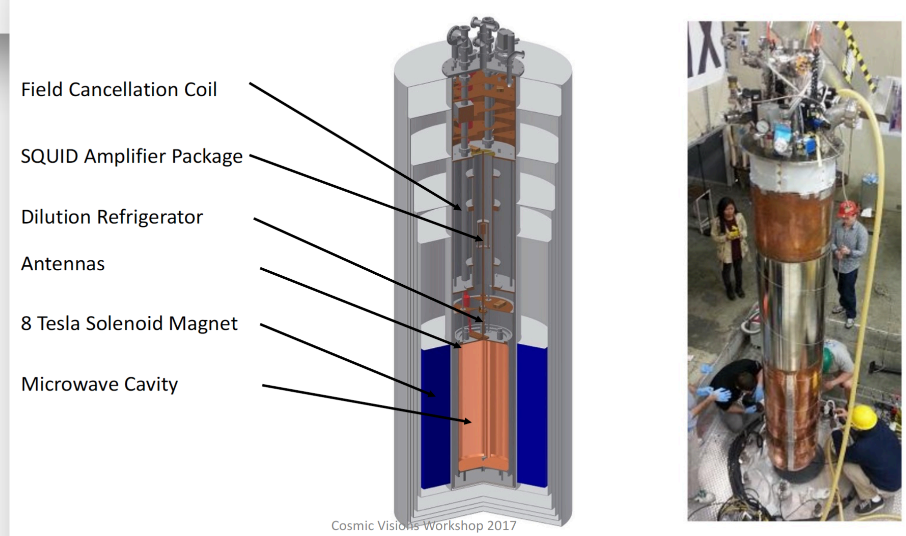
$\beta_{virial} \sim 10^{-3}$:

$\lambda_{De\ Broglie} \sim 100\ m$

$\Delta\beta_{flow} \sim 10^{-11}$:

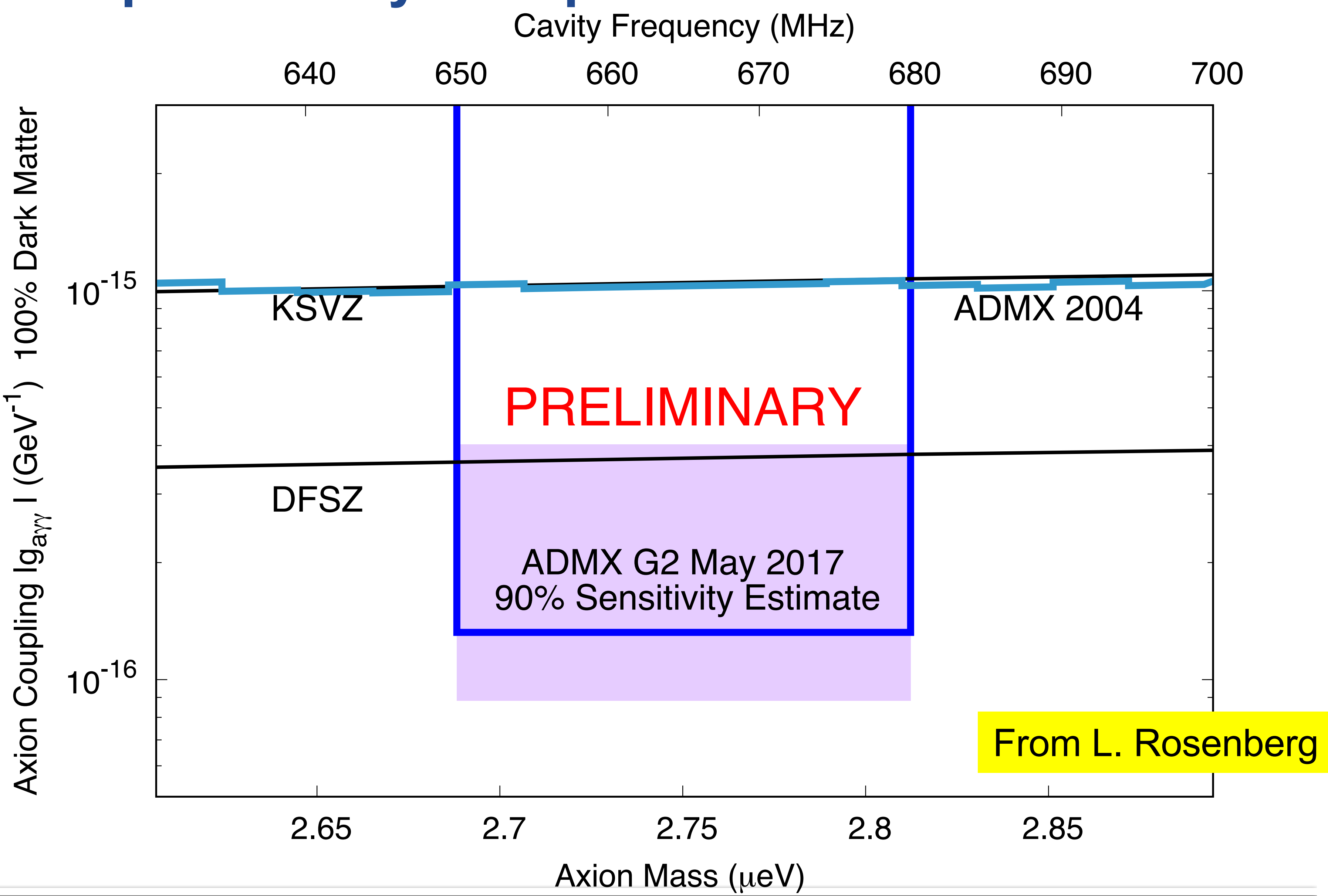
$\lambda_{Coherence} \sim 1000\ km$

ADMX experimental layout



Lawrence Livermore National Laboratory

Current preliminary limit plot



Making New Dark Matter

Generally not just one new particle but a sector.
Phenomenology can be complex.

arXiv:1703.05703v2 [hep-ex] 17 Mar 2017

CERN-LPCC-2017-01

Recommendations of the LHC Dark Matter Working Group: Comparing LHC searches for heavy mediators of dark matter production in visible and invisible decay channels

Andreas Albert,[1,*] Mihailo Backović,[2] Antonio Boveia,[3,*] Oliver Buchmueller,[4,*] Giorgio Busoni,[5,*] Albert De Roeck,[6,7] Caterina Doglioni,[8,*] Tristan DuPree,[9,*] Malcolm Fairbairn,[10,*] Marie-Hélène Genest,[11] Stefania Gori,[12] Giuliano Gustavino,[13] Kristian Hahn,[14,*] Ulrich Haisch,[15,16,*] Philip C. Harris,[7] Dan Hayden,[17] Valerio Ippolito,[18] Isabelle John,[8] Felix Kahlhoefer,[19,*] Suchita Kulkarni,[20] Greg Landsberg,[21] Steven Lowette,[22] Kentarou Mawatari,[11] Antonio Riotto,[23] William Shepherd,[24] Tim M.P. Tait,[25,*] Emma Tolley,[3] Patrick Tunney,[10,*] Bryan Zaldivar,[26,*] Markus Zinser[24]

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[10]Physics, King's College London, Strand, London, WC2R 2LS, UK

LHC DM WG: WG on Dark Matter Searches at the LHC | LPCC: LHC Physics Centre at CERN 8/10/17, 9:46

CERN Accelerating science Sign in Directory

LPCC: LHC Physics Centre at CERN

Welcome | About | LHC working groups | LHC publications | Events | Newsletter

LHC DM WG: WG on Dark Matter Searches at the LHC

To subscribe to the general WG mailing list, used to distribute announcements about meetings and available documents, go to
http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=lhc-dmwg
(http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=lhc-dmwg)

A second mailing list is used for more technical exchanges related to the ongoing work of the WG. To subscribe, go to
http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=lhc-dmwg-contributors
(http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=lhc-dmwg-contributors)

The LHC Dark Matter Working Group (LHC DM WG) brings together theorists and experimentalists to define guidelines and recommendations for the benchmark models, interpretation, and characterisation necessary for broad and systematic searches for dark matter at the LHC. As examples, the group develops and promotes well-defined signal models, specifying the assumptions behind them and describing the conditions under which they should be used. It works to improve the set of tools available to the experiments, such as higher- precision calculations of the backgrounds. It assists theorists with understanding and making use of LHC results.
The LHC DM WG develops and maintains close connections with theorists and other experimental particle DM searches (e.g. Direct and Indirect Detection experiments) in order help verify and constrain particle physics models of astrophysical excesses, to understand how collider searches and non-collider experiments complement one another, and to help build a comprehensive understanding of viable dark matter models.

The WG activity builds on the experience of the previous ATLAS-CMS Dark Matter Forum, whose findings are documented in this paper (https://arxiv.org/abs/1507.00966)

WG documents and meeting agendas: see links in the right menu

Topics currently under discussion:

- Recommendations for the definition of further simplified models, to be used in the analyses in preparation for the Winter 2017 conferences.

Conveners:

- ATLAS: C. Doglioni and A. Boveia
- CMS: K. Hahn and S.Lowette
- TH: U. Haisch and T. Tait
- LPCC: M. Mangano

https://lpcc.web.cern.ch/content/lhc-dm-wg-wg-dark-matter-searches-lhc

See talks by Toro, Gray, Eno, Stone, Jacobs

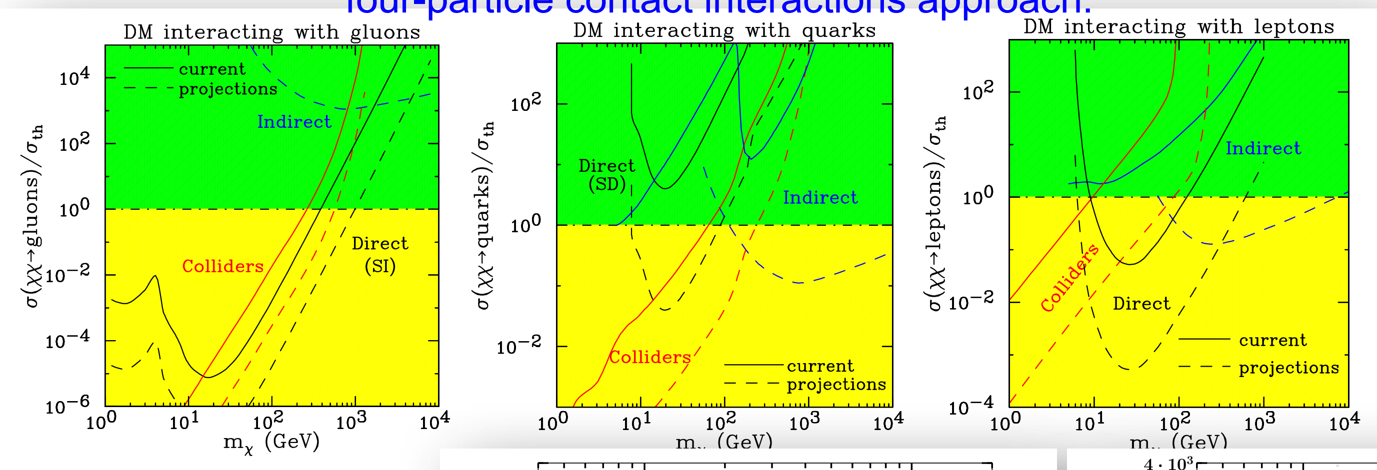
Dark Matter Complementarity

See arXiv:1305.1605

Direct Detection

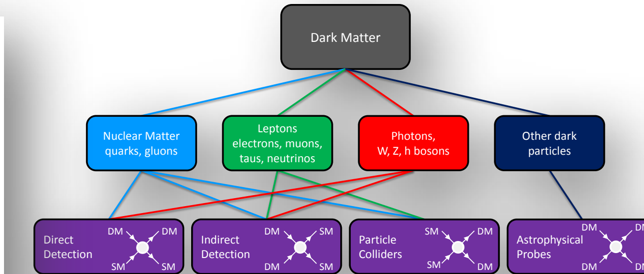
Relic scattering locally, at low energy. Push to larger target mass, lower backgrounds, directional sensitivity

four-particle contact interactions approach:



Accelerators

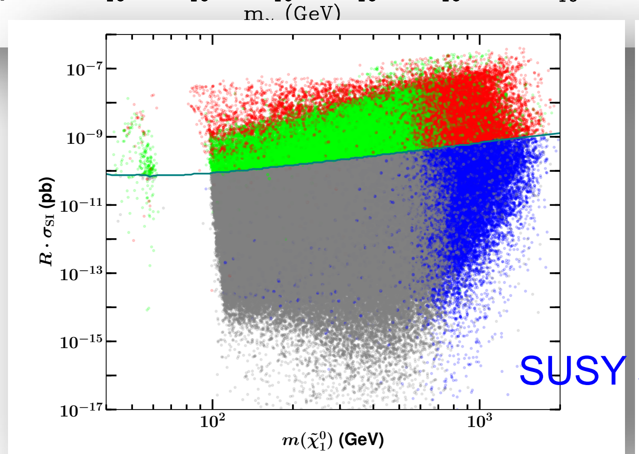
Direct production. Push to higher energy

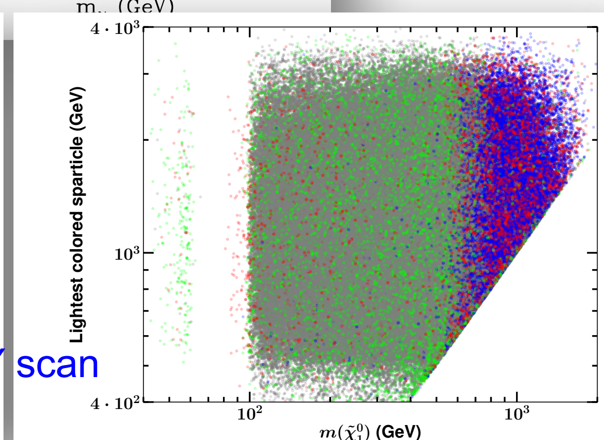


Observations

Push toward finding and studying galactic halo objects and large scale structure.

future direct detection, indirect detection or both. Plus maybe upgraded LHC only.





SUSY scan

Indirect Detection

Interactions (via annihilations, decays) with SM particles. Understand the astrophysical backgrounds in signal-rich regions, and reveal the distribution of dark matter.

Simulations

Large scale structure formation. Push toward larger simulations, finer details.

phenomenological Minimal Supersymmetric Standard Model (pMSSM)

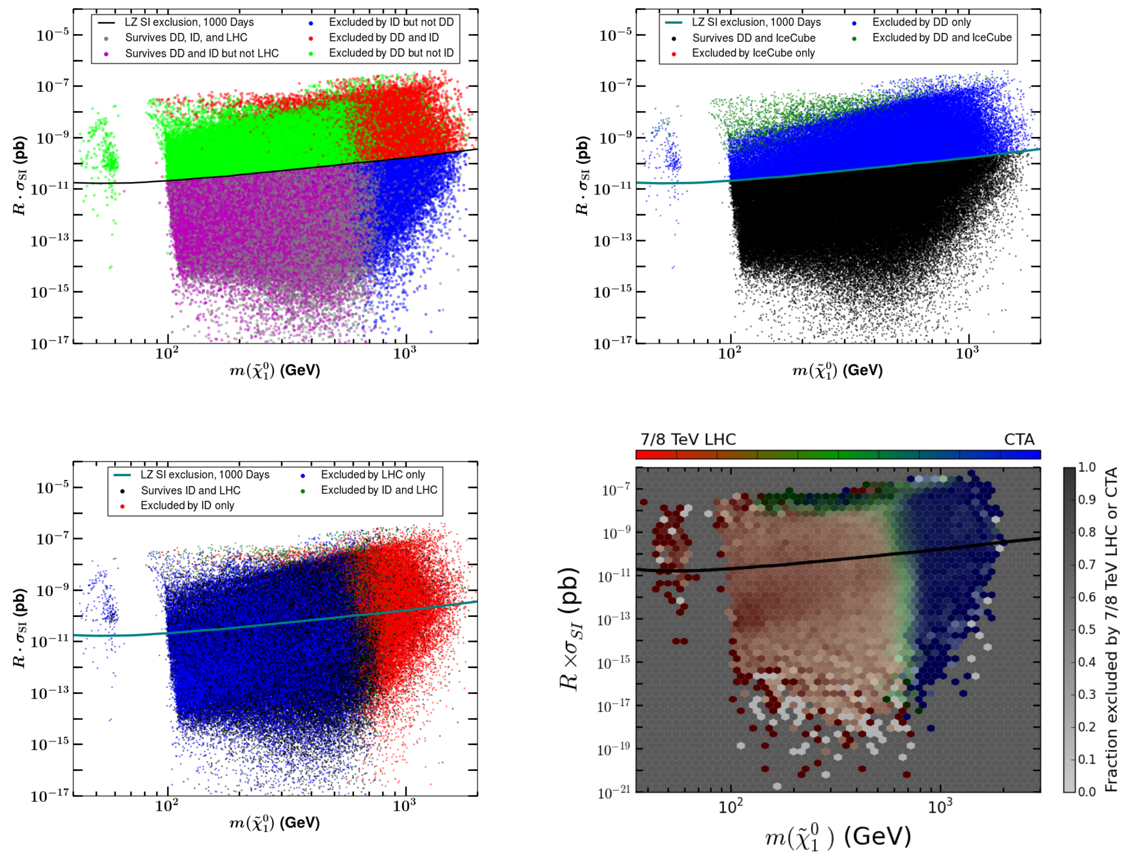


Figure 10: Comparisons of the sensitivity of the various searches, color-coded as indicated, in the LSP mass-scaled SI cross section plane for the pMSSM model sample as discussed in the text. The anticipated SI limit from LZ is shown as a guide to the eye.

Cahill-Rowley et al arXiv:1405.6716

19-parameter space scan

Dark Matter Complementarity

See arXiv:1305.1605

Direct Detection
Relic scattering locally, at low energy. Push to larger target mass, lower backgrounds, directional sensitivity

Accelerators
Direct production. Push to higher energy

Observations
Push toward finding and studying galactic halo objects and large scale structure.

Indirect Detection
Interactions (via annihilations, decays) with SM particles. Understand the astrophysical backgrounds in signal-rich regions, and reveal the distribution of dark matter.

Simulations
Large scale structure formation. Push toward larger simulations, finer details.

DM Candidates and Topics

- Main messages:
  - Importance of low-threshold direct detection capabilities for hidden-sector and ultralight DM candidates
  - A small number of low-cost fixed-target experiments can broadly explore sub-GeV dark matter and associated forces at relevant sensitivities
  - Much of the QCD axion parameter space can be explored over the coming decade
  - Existing data in other subfields (anomalies, LIGO mergers,…) may be providing important clues about dark sector physics
  - Interactions between theorists and experimentalists have been particularly fruitful in this area. Healthy support for theory is essential.
  - Can have hidden-sector DM that was in thermal equilibrium with the Standard Model sector in the early universe but that evade existing constraints.

arXiv:1707.04591v1 [hep-ph] 14 Jul 2017

US Cosmic Visions: New Ideas in Dark Matter 2017 : Community Report

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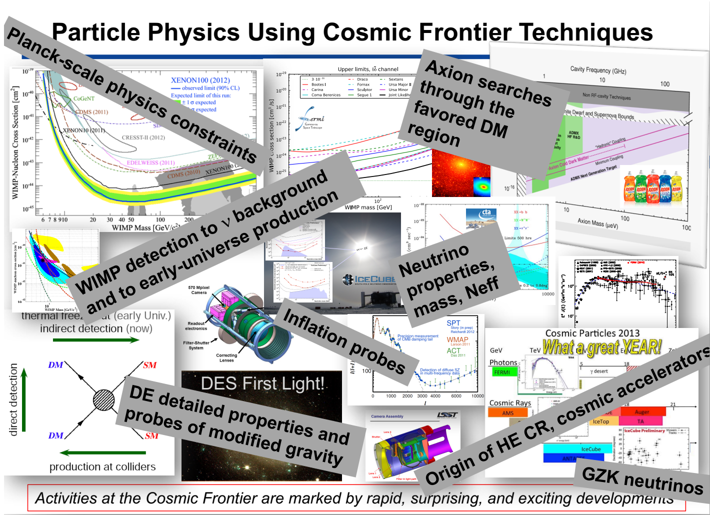
arXiv:1707.04591v1

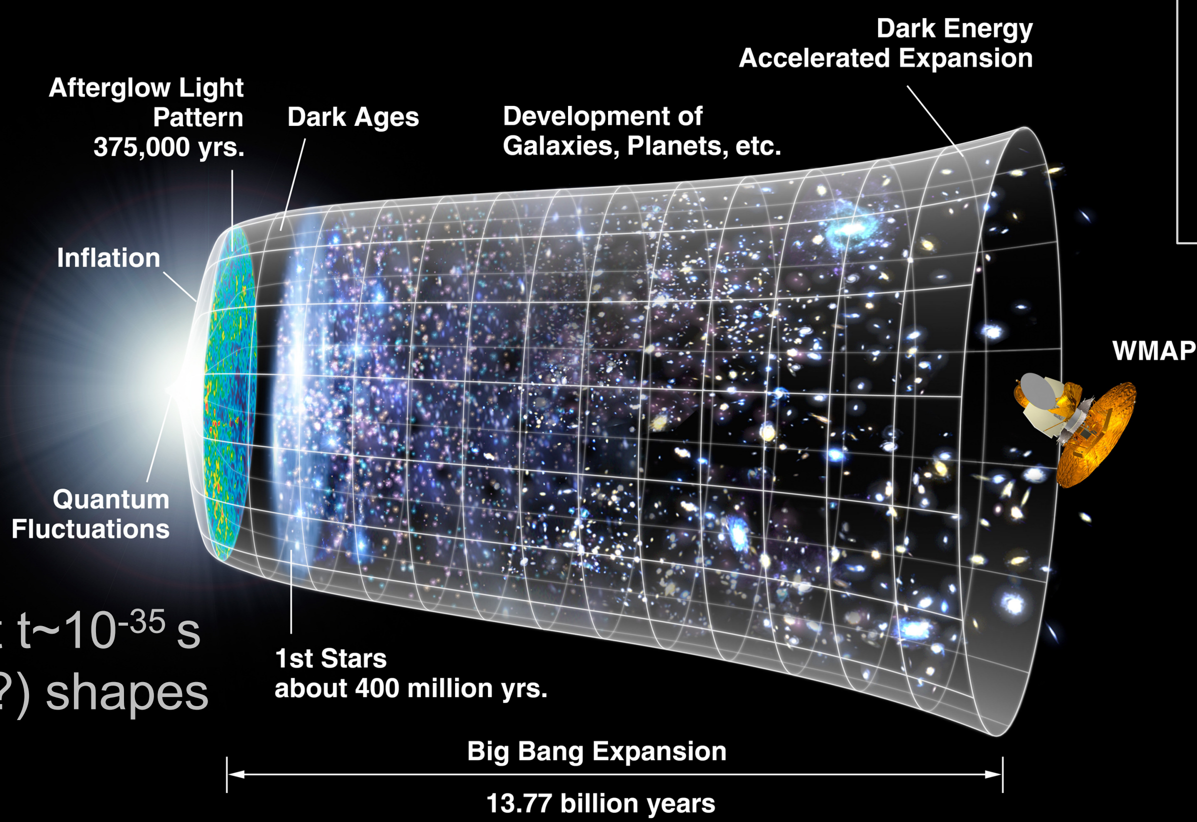
See Feng, Schuster talks



Cosmic Surveys

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 $t \sim 10^{-35}$ s (driven by ?) shapes the…

See Frieman and Battaglia talks; Olive, Grossman talks

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

Aside: Neutrino Mass Measurements

To measure the mass of a feather…

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

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

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

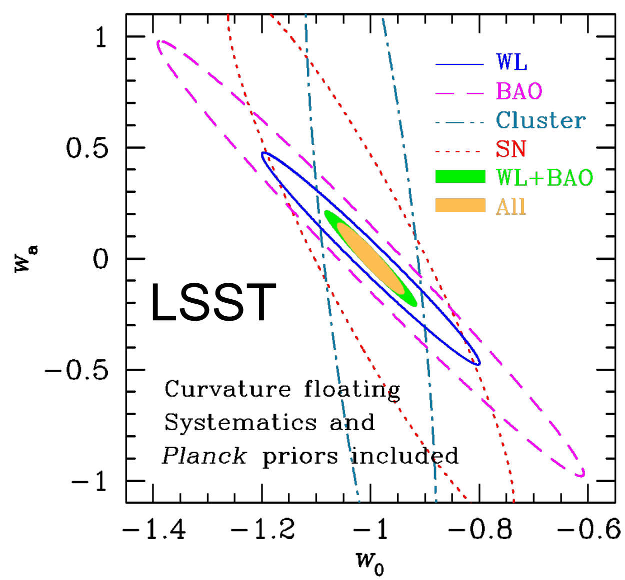
Cosmic Surveys for Dark Energy

Two observable fields:
- Matter density: growth of structure
- Velocities: distance-redshift

Imaging and spectroscopic surveys provide complementary views. Together, they enable a variety of primary techniques:
- Supernovae
- Baryon Acoustic Oscillations (BAO)/Redshift distortions (RSD)
- Weak Lensing
- Clusters

The combination is powerful:
- Precision
- Consistency checks
- Distinguishing DE from modified gravity

Future "Stage IV" Facilities (early 2020's):
- LSST
- MS-DESI spectroscopic survey
- From space:
  - Euclid
  - WFIRST/AFTA



See talks by Krause, Trodden, Wechsler, Kim, Mantz, Marshall, McGaugh, Frieman arXiv:1604.07626v1 [astro-ph.CO] 26 Apr 2016

Cosmic Visions Dark Energy: Science

Scott Dodelson, Katrin Heitmann, Chris Hirata, Klaus Honscheid, Aaron Roodman, Uroš Seljak, Anže Slosar, Mark Trodden

Executive Summary

Cosmic surveys provide crucial information about high energy physics including strong evidence for dark energy, dark matter, and inflation. Ongoing and upcoming surveys will start to identify the underlying physics of these new phenomena, including tight constraints on the equation of state of dark energy, the viability of modified gravity, the existence of extra light species, the masses of the neutrinos, and the potential of the field that drove inflation. Even after the Stage IV experiments, DESI and LSST, complete their surveys, there will still be much information left in the sky. This additional information will enable us to understand the physics underlying the dark universe at an even deeper level and, in case Stage IV surveys find hints for physics beyond the current Standard Model of Cosmology, to revolutionize our current view of the universe. There are many ideas for how best to supplement and aid DESI and LSST in order to access some of this remaining information and how surveys beyond Stage IV can fully exploit this regime. These ideas flow to potential projects that could start construction in the 2020's.

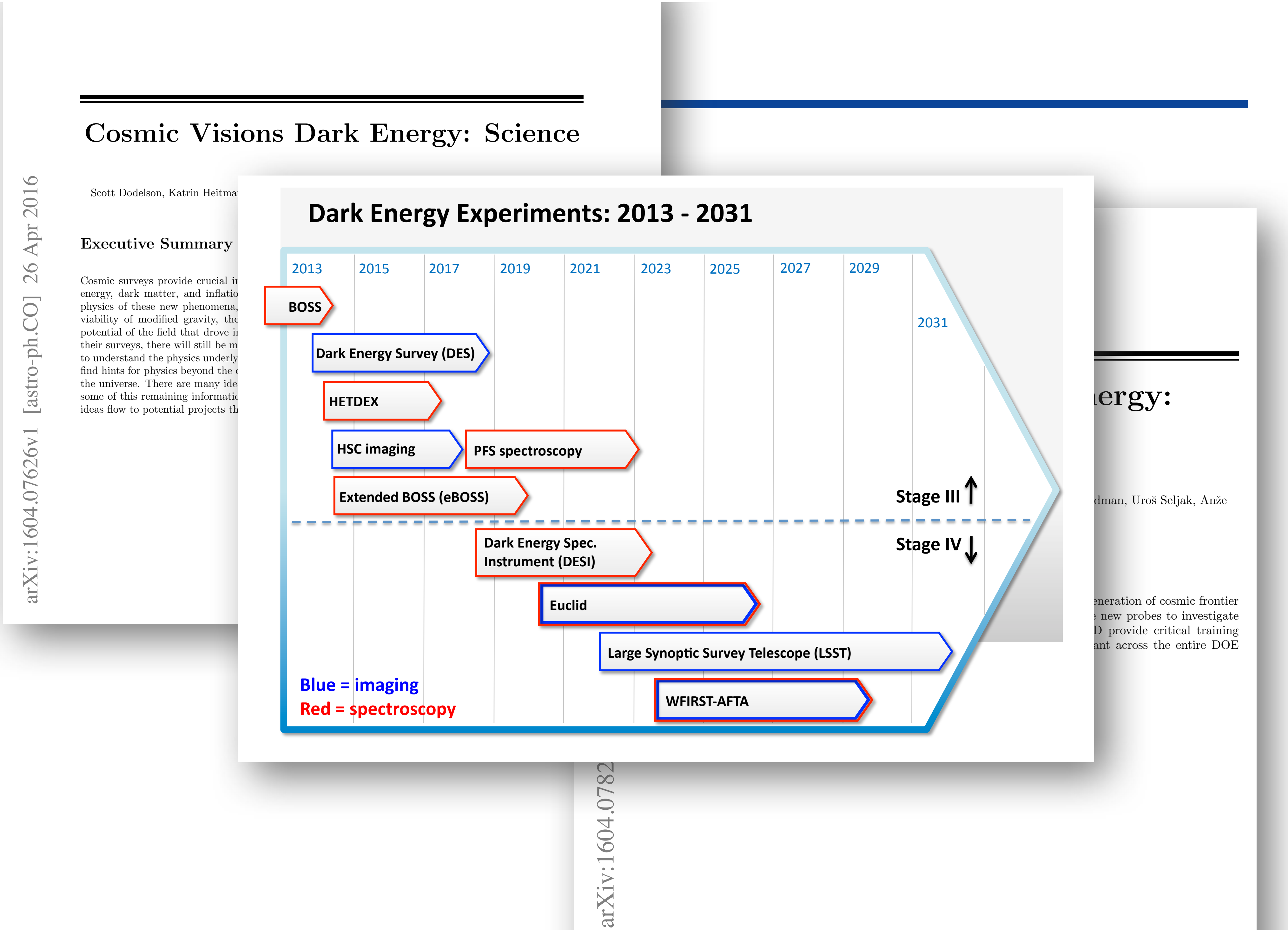
arXiv:1604.07821v2 [astro-ph

Cosmic Visions Dark Energy: Technology

Scott Dodelson, Katrin Heitmann, Chris Hirata, Klaus Honscheid, Aaron Roodman, Uroš Seljak, Anže Slosar, Mark Trodden

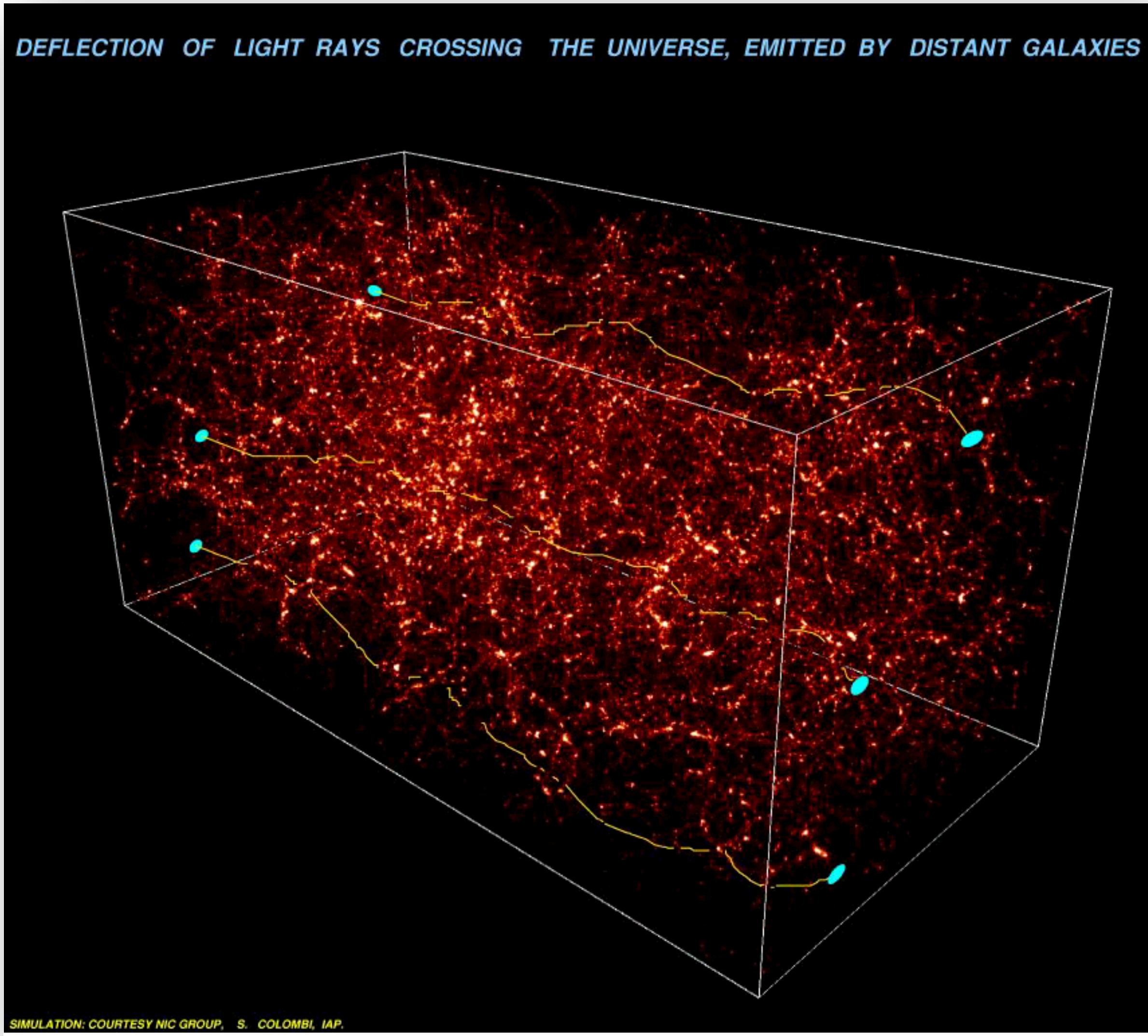
Executive Summary

A strong instrumentation and detector R&D program has enabled the current generation of cosmic frontier surveys. A small investment in R&D will continue to pay dividends and enable new probes to investigate the accelerated expansion of the universe. Instrumentation and detector R&D provide critical training opportunities for future generations of experimentalists, skills that are important across the entire DOE HEP program.



Cosmic Visions Dark Energy: Science
Scott Dodelson, Katrin Heitma
Executive Summary
arXiv:1604.07626v1 [astro-ph.CO] 26 Apr 2016
Dark Energy Experiments: 2013 - 2031
2013
2015
2017
2019
2021
2023
2025
2027
2029
2031
BOSS
Dark Energy Survey (DES)
HETDEX
HSC imaging
PFS spectroscopy
Extended BOSS (eBOSS)
Stage III
Stage IV
Dark Energy Spec. Instrument (DESI)
Euclid
Large Synoptic Survey Telescope (LSST)
WFIRST-AFTA
Blue = imaging
Red = spectroscopy
ergy:
dman, Uroš Seljak, Anže
arXiv:1604.0782

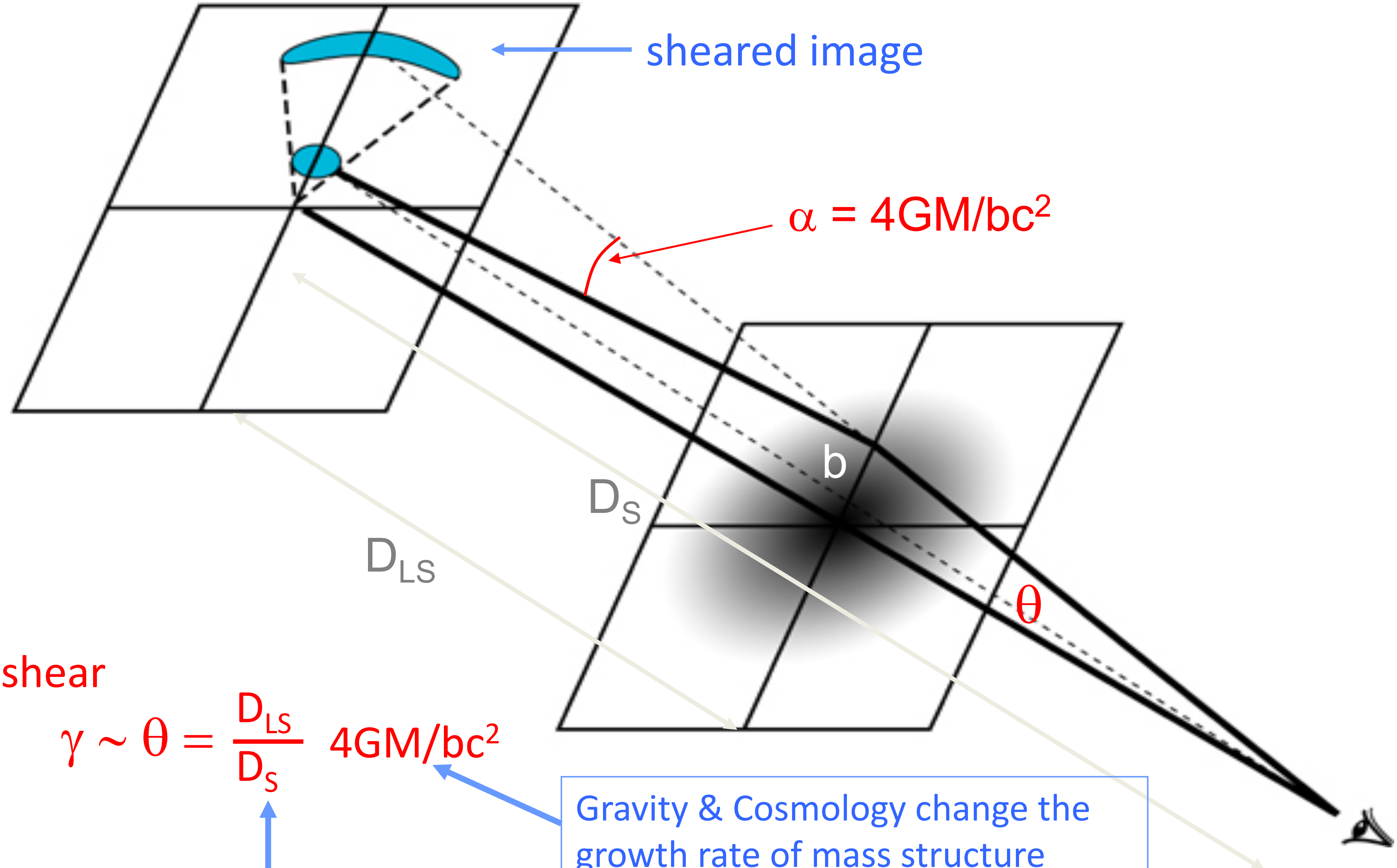
Weak Gravitational Lensing



- Dark Energy affects the rate of growth of structure.
  - Together with distance-redshift measurements, can look for DE evolution, and test alternative models of gravity.
- Galaxy shapes appear sheared due to all the (dark) matter along the line of sight.
- Measure correlations of the shears – not random.
- Measurements over different distance scales and over cosmic time provide many tests. Deviation from expectation in any one of many bins could signal a breakdown of the ΛCDM paradigm.

Challenging: shear-shear correlations O(10^{-4} - 10^{-7})

See M. Schneider talk



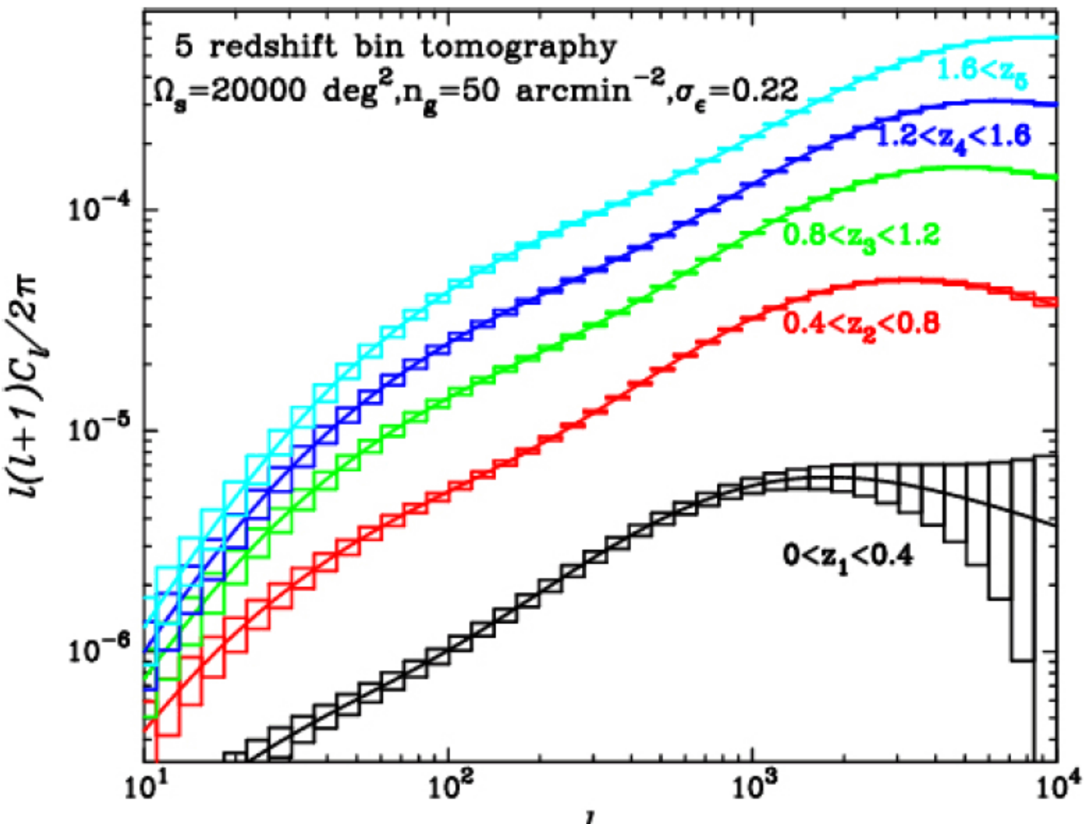
shear

$$\gamma \sim \theta = \frac{D_{LS}}{D_S}\; 4GM/bc^2$$

Gravity & Cosmology change the growth rate of mass structure

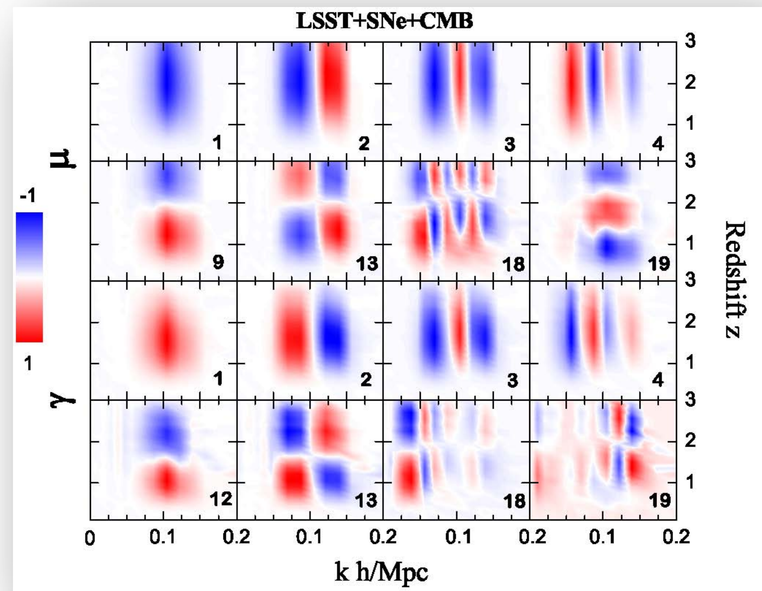
Cosmology changes geometric distance factors

Cosmic Shear Power Spectra



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

Many cross-correlation tests. It's not just w and ellipses!



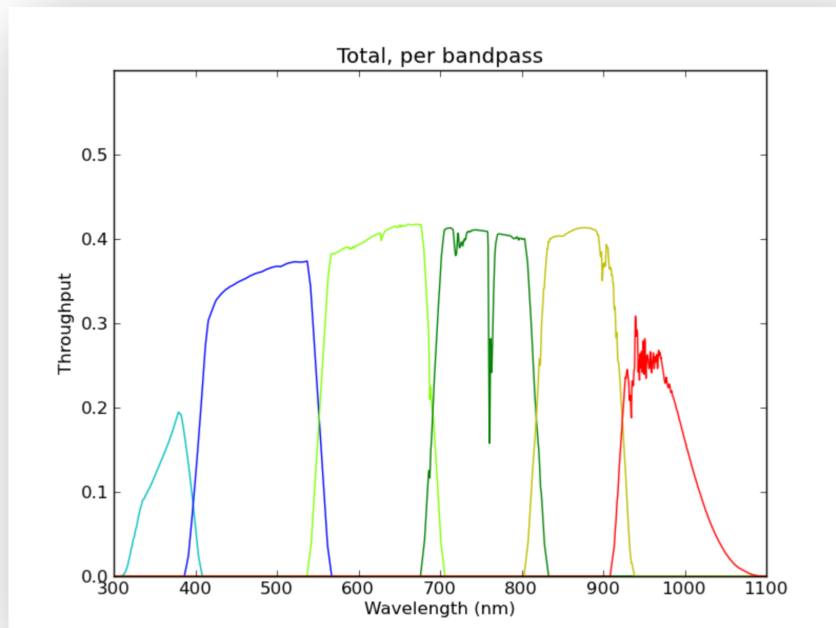
arXiv:1111.3960 *Hojjati et al. 2012*

Failure in any one of these could signal a breakdown of the ΛCDM paradigm

- Study growth as a function of *k*
- Can decompose into "modes", linear combinations of D(k,z) that are best probed by surveys

Using Imaging Surveys for Weak Lensing

- For a large number of galaxies:
  - Measure their shapes precisely for shear-shear correlations
    - Repeat the measurements many times (~100 in each color for LSST) to overcome atmospheric and other effects and to check for other systematics
  - Measure their redshifts (distances) photometrically, typically with broadband filters



Very Recent Results from DES!

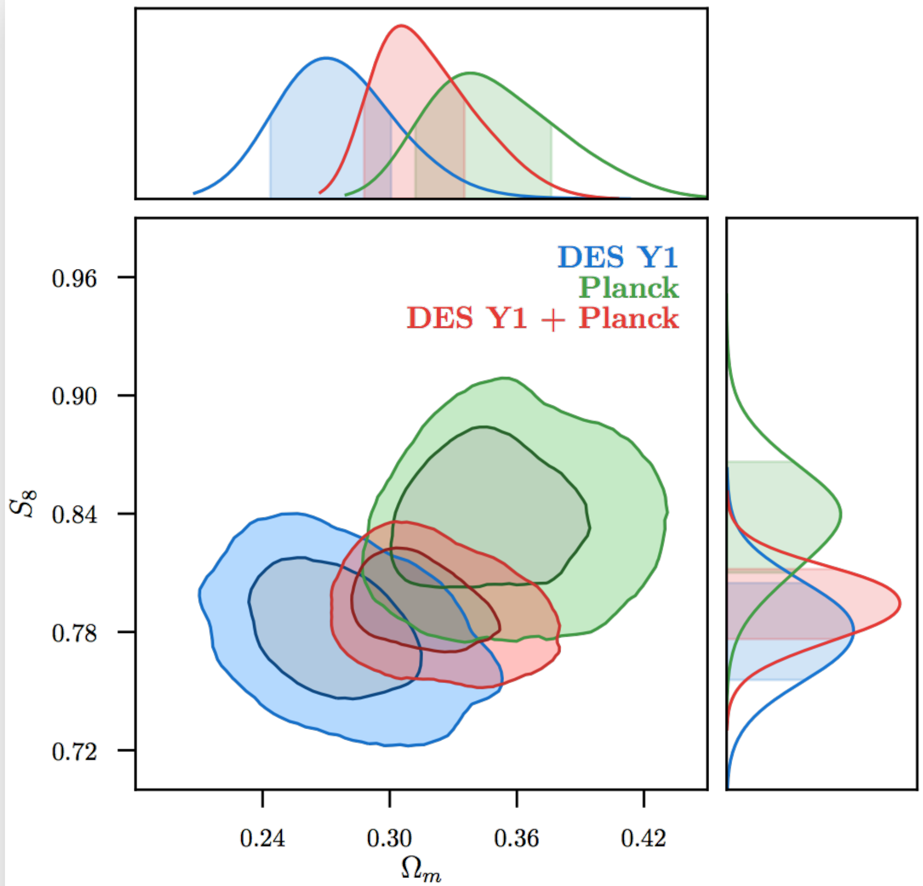


FIG. 10. ΛCDM constraints from the three combined probes in DES Y1 (blue), Planck with no lensing (green), and their combination (red). The agreement between DES and Planck can be quantified via the Bayes factor, which indicates that in the full, multi-dimensional parameter space, the two data sets are consistent (see text).

See J. Frieman talk

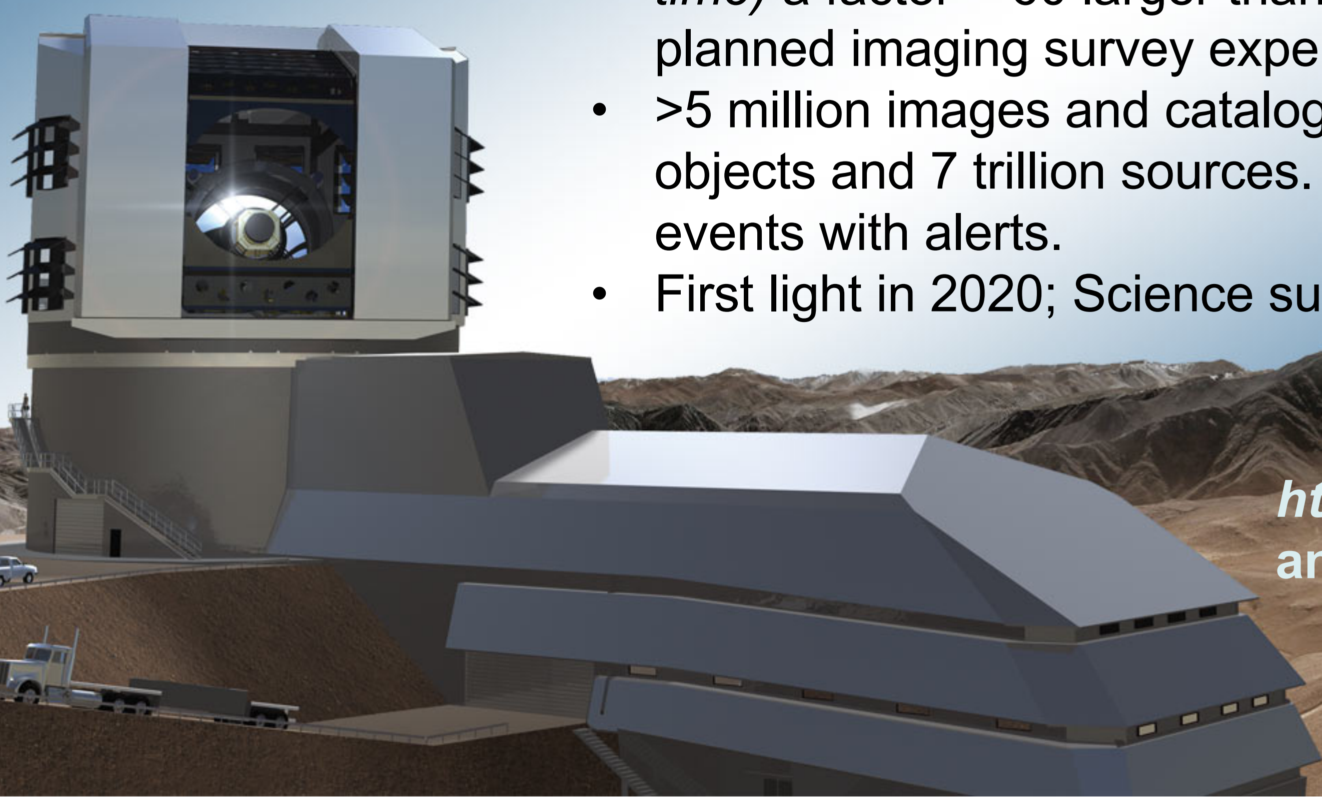
arXiv:1708.01530v1

The Large Synoptic Survey Telescope

A new, integrated survey system designed to conduct a decade-long, deep, wide, fast time-domain survey of the optical sky.

8-meter class wide-field ground based telescope, a 3.2 Gpixel camera, and an automated data processing system.

- *integrated étendue (collecting area x field of view x time)* a factor ~ 60 larger than any other current or planned imaging survey experiment.
- >5 million images and catalogs with >37 billion objects and 7 trillion sources. Billions of time-domain events with alerts.
- First light in 2020; Science survey starts in 2022.



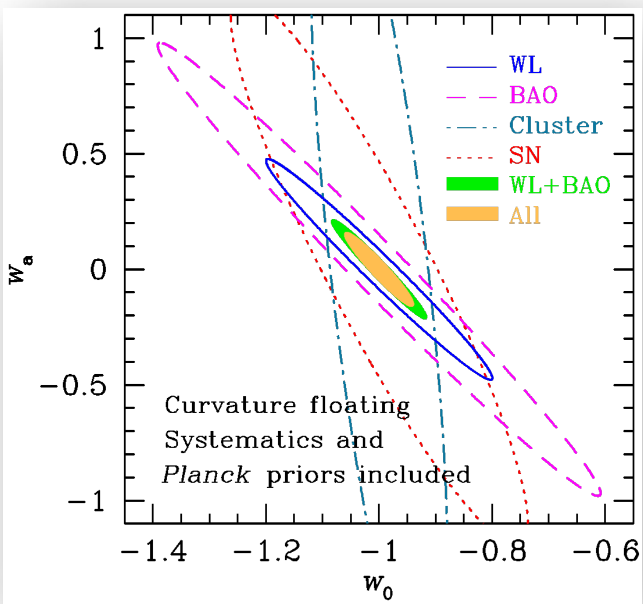
http://www.lsst.org/lsst/
and links therein

The Science Enabled by LSST

- Time domain science
  - Novae, supernovae, GRBs
  - Source discovery and characterization
  - Discovery
- Dark energy multiple probes

http://www.lsst.org/files/docs/sciencebook/SB_Whole.pdf

- A census of moving objects
  - Asteroids and comets
  - Proper motions of stars
- Mapping the structure and evolution of the Milky Way
  - Tidal streams
  - Galactic structure



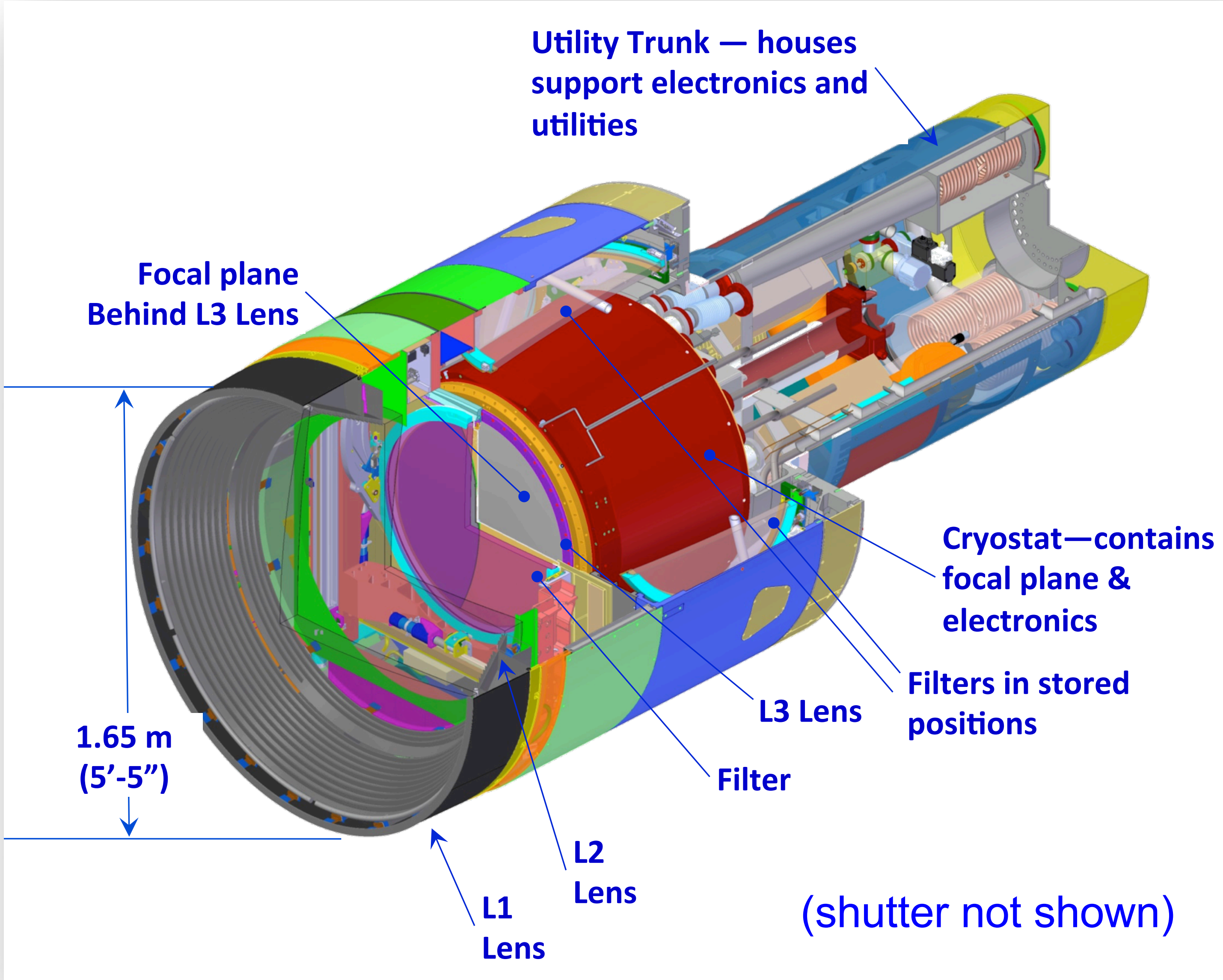
$w(a) = w_0 + (1-a)w_a \qquad a = (1+z)^{-1}$

Dark Energy affects both the expansion history and the rate of growth of structure.

- **Growth of structure measurements provide much more than just shrinking the error ellipse: test ΛCDM paradigm over wide range of distance scales and over cosmic time**
- **Also sensitive to Σm_ν at ~0.03eV precision => may also resolve the neutrino mass hierarchy**

3.2 Gigapixel Camera

- 10 micron pixels, 0.2 arcsec/pixel
- Focal plane diameter 634mm:189 science CCDs (4kx4k, each segmented into 16 parallel readout chains), arranged in 21 rafts, plus corner rafts
- 6 filters: *ugrizy* (320nm to 1050 nm)
- Nominal operation: dual 15-second exposures, 2 second readout
- ~5 million exposures in 10-year survey, average 15TB per night



A DOE particle physics project, managed at SLAC

DESI:

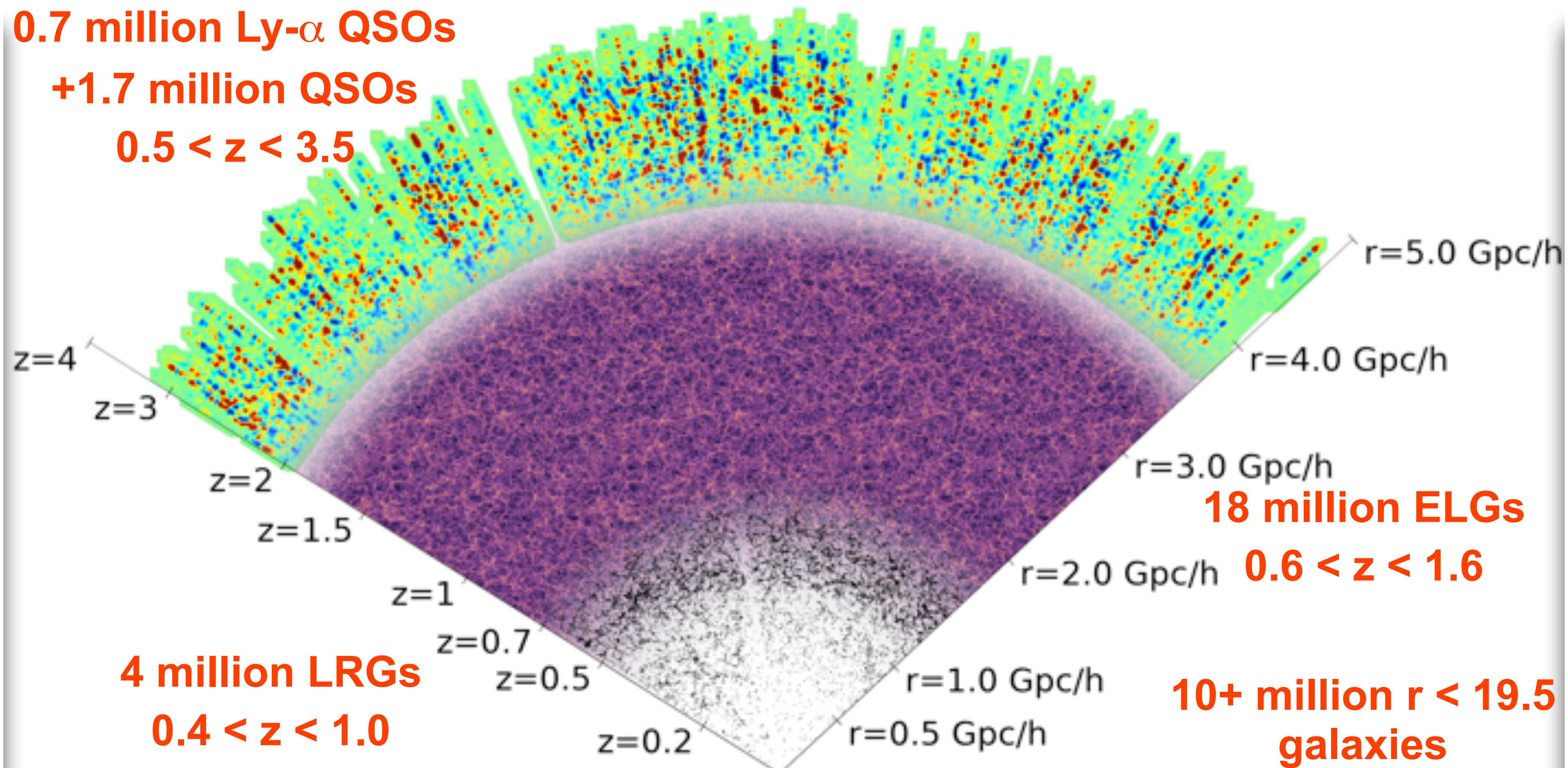
The Dark Energy Spectroscopic Instrument

- new instrument: 5000 fibers, 8 deg^2 FOV, 10 3-arm spectrographs with R=2000-5500, 350-980nm
- 14000 sq. degree spectroscopic survey, 2019+5 years
- 35 million galaxy & quasar spectra— more than an order of magnitude increase in # of spectra and volume probed compared to current state-of-the-art
  - Dark Time Survey: 4 M LRGs, 17M ELGs, 2.5M QSOs
  - Will do a survey of >10 million bright galaxies ($r < 20$) and >10 million Milky Way stars in bright time
- Uses Baryon Acoustic Oscillations to and Redshift-Space Distortions to map expansion rate and growth of structure

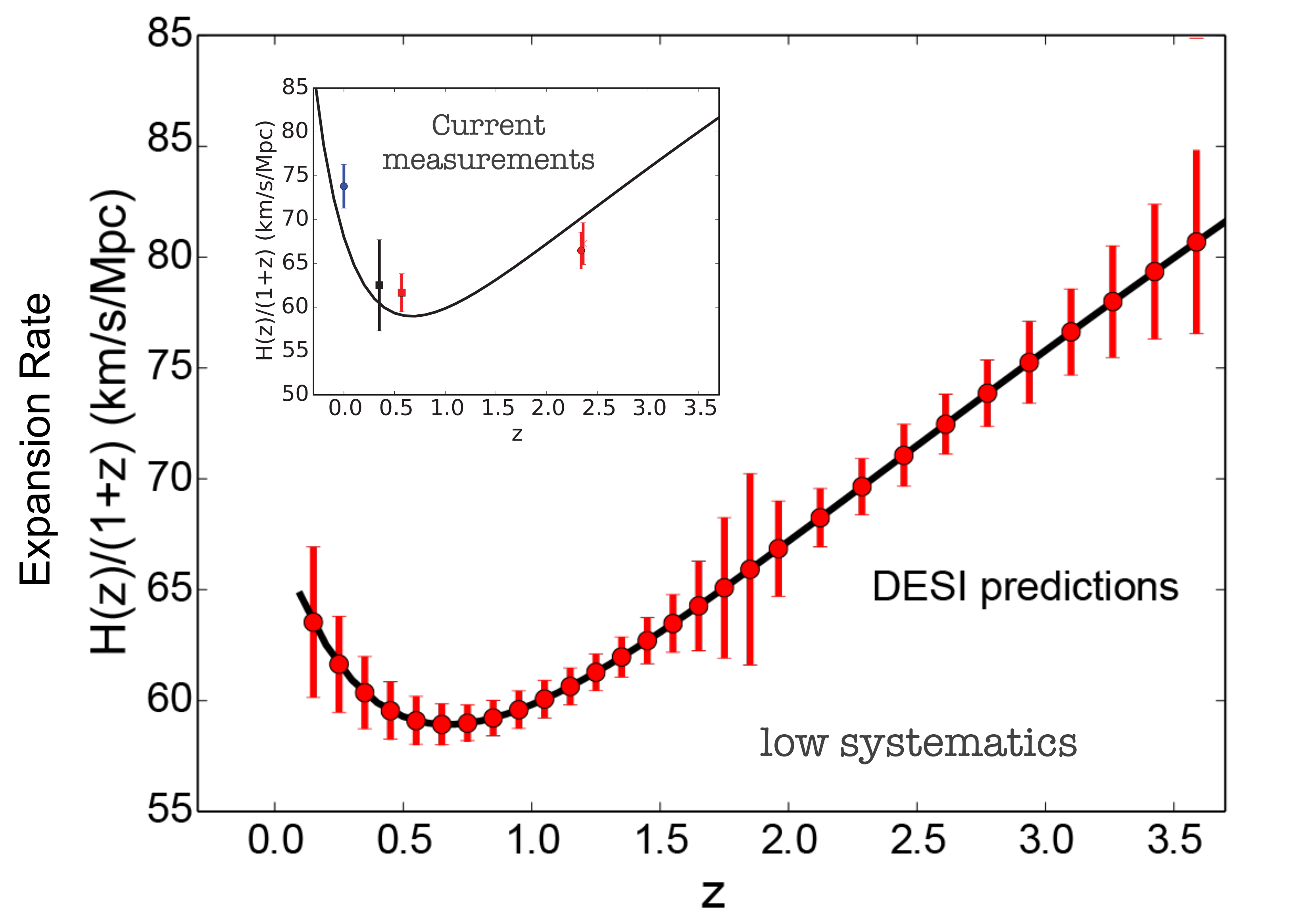
See R. Wechsler talk

Overview of the DESI Survey

- Four target classes in dark time spanning redshifts z=0.4 → 3.5 (LRGs, ELGs, QSOs)
- Additional Bright Galaxy Survey will target all 10+ M galaxies with r < 19.5 (z=0-0.4)
- Will measure the distance scale to < 0.3% out to z~1, < 0.4% out to z ~ 2.
- Will measure the Hubble parameter to ~1% out to z ~ 2.

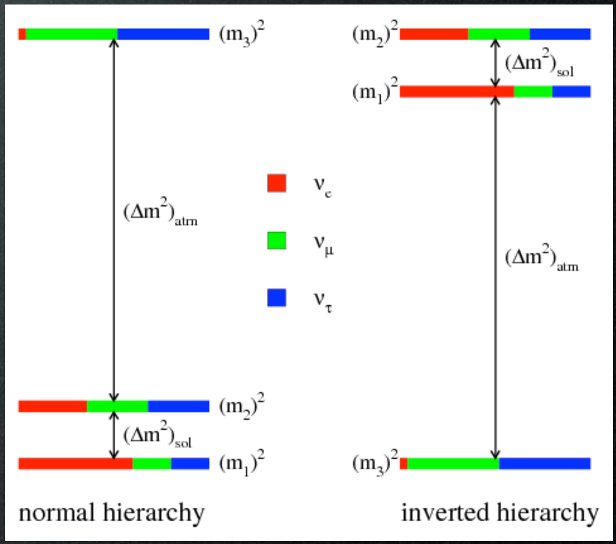


DESI is designed for BAO: accurate measurements of the H(z) and D(z)



Measuring Σm_ν

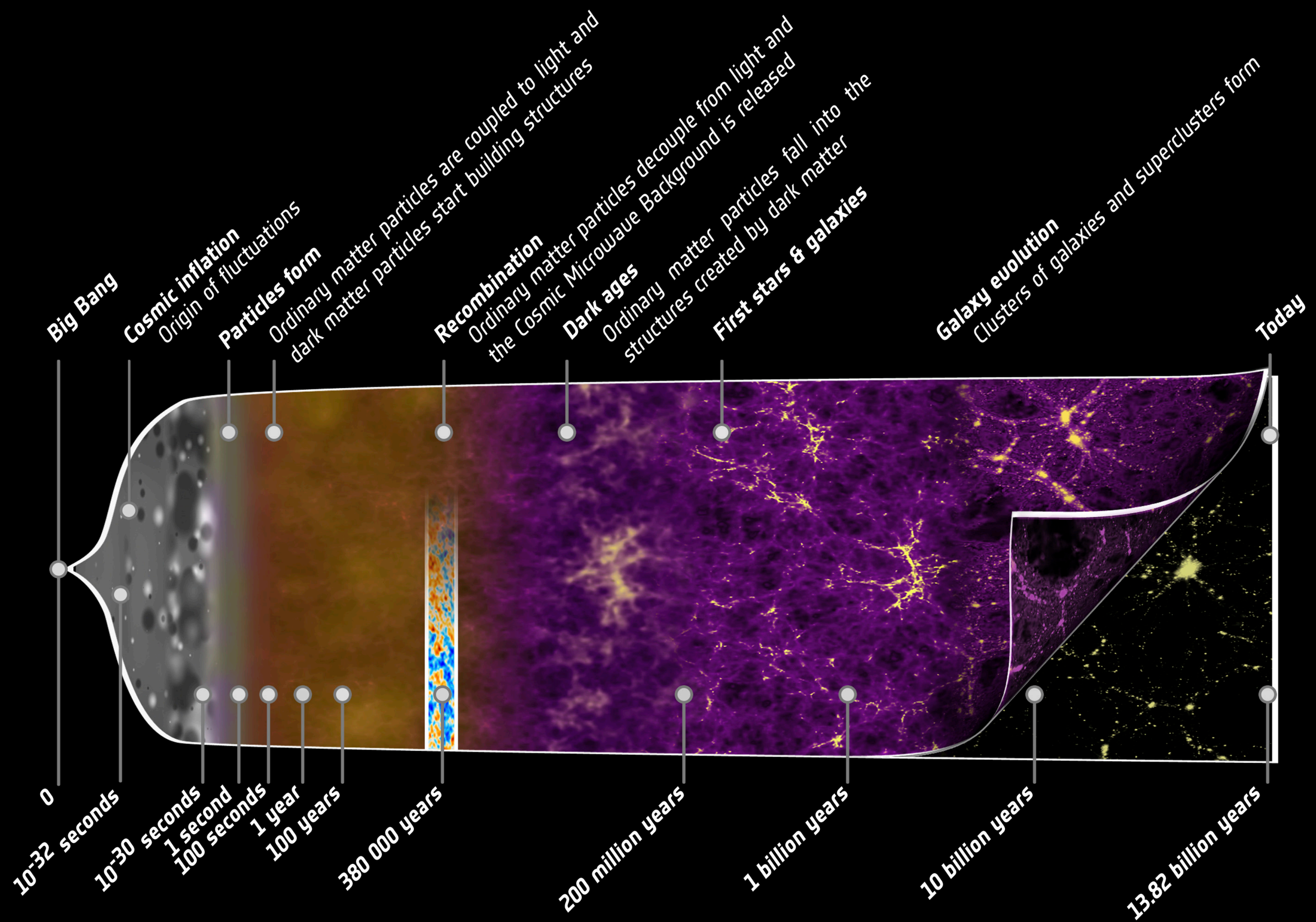
- … and possibly the neutrino hierarchy.
  - The shape of the power spectrum encodes information about neutrino masses. Massive neutrinos suppress cosmic structure growth.
  - DESI + CMB can measure an error of 0.017 eV in the sum of the masses if we can use the power spectrum to k = 0.2, enough to distinguish the normal and inverted hierarchy of mass states.
  - Extra relativistic species (e.g. sterile neutrinos) can also be measured by LSS+CMB



Data	$\sigma_{\Sigma m_\nu}$ [eV]
Planck	0.350
Planck+DESI BAO	0.090
Gal ($k_{\max} = 0.1$)	0.024
Gal ($k_{\max} = 0.2$)	0.017

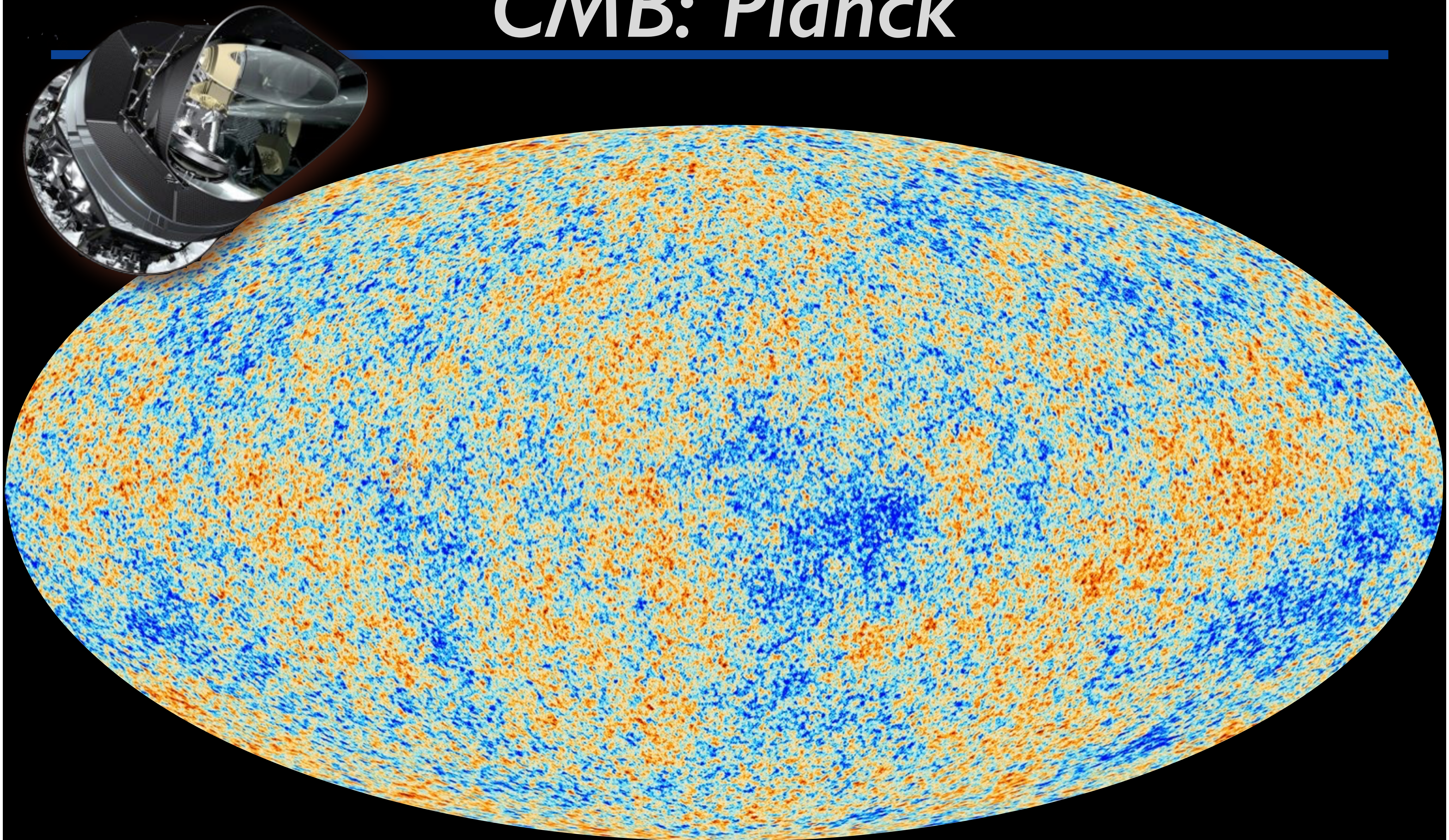
conservative

optimistic



Credit: Planck Science Team

CMB: Planck



CMB Temperature Fluctuations (TT) Power Spectrum

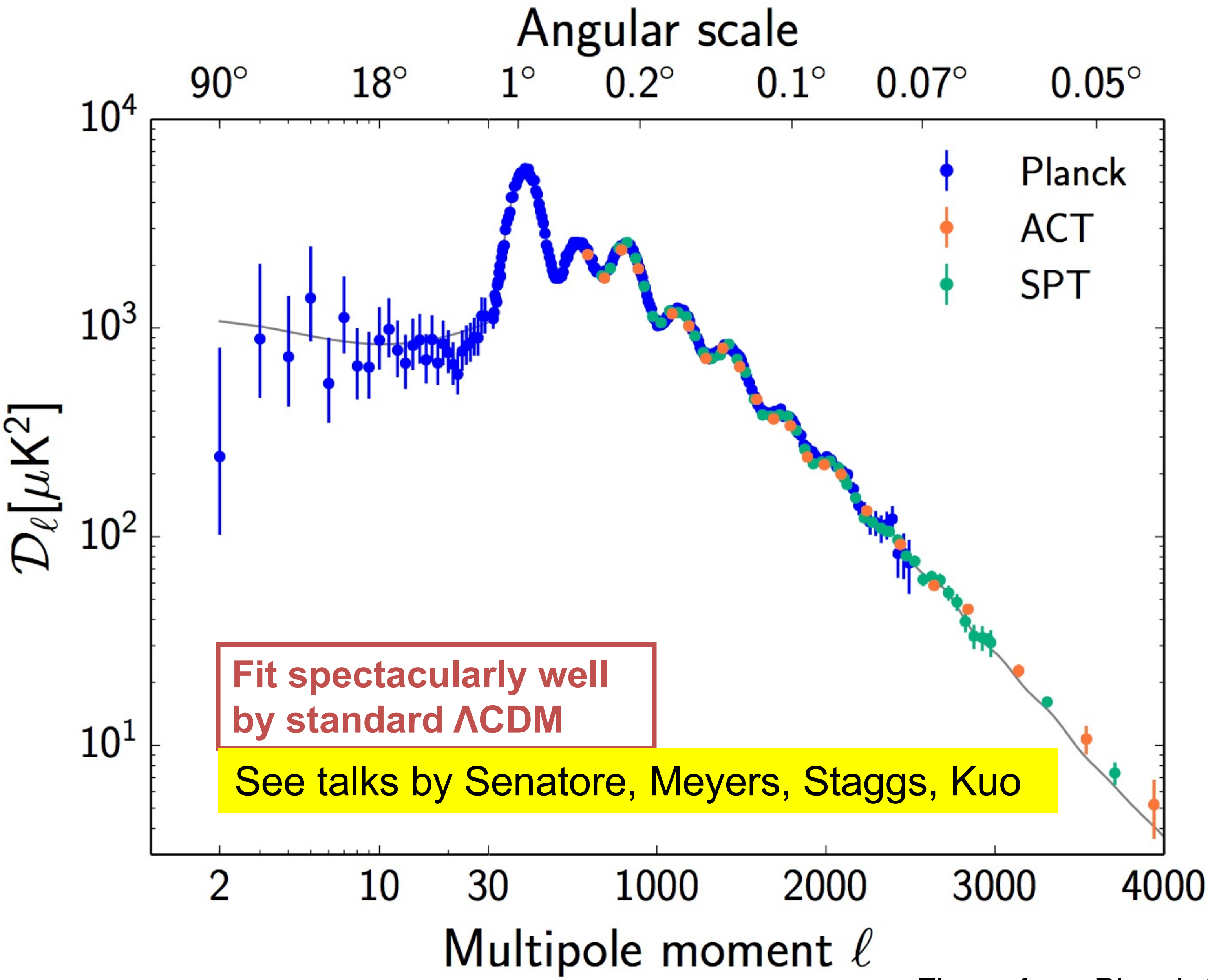


Figure from Planck 2015 Results XI

arXiv:1610.02743v1 [astro-ph.CO] 10 Oct 2016

CMB-S4 Science Book
First Edition

CMB-S4 Collaboration

August 1, 2016

- Exhortations
- Inflation
- Neutrinos
- Light Relics
- Dark Matter
- Dark Energy
- CMB lensing
- Data Analysis, Simulations & Forecasting

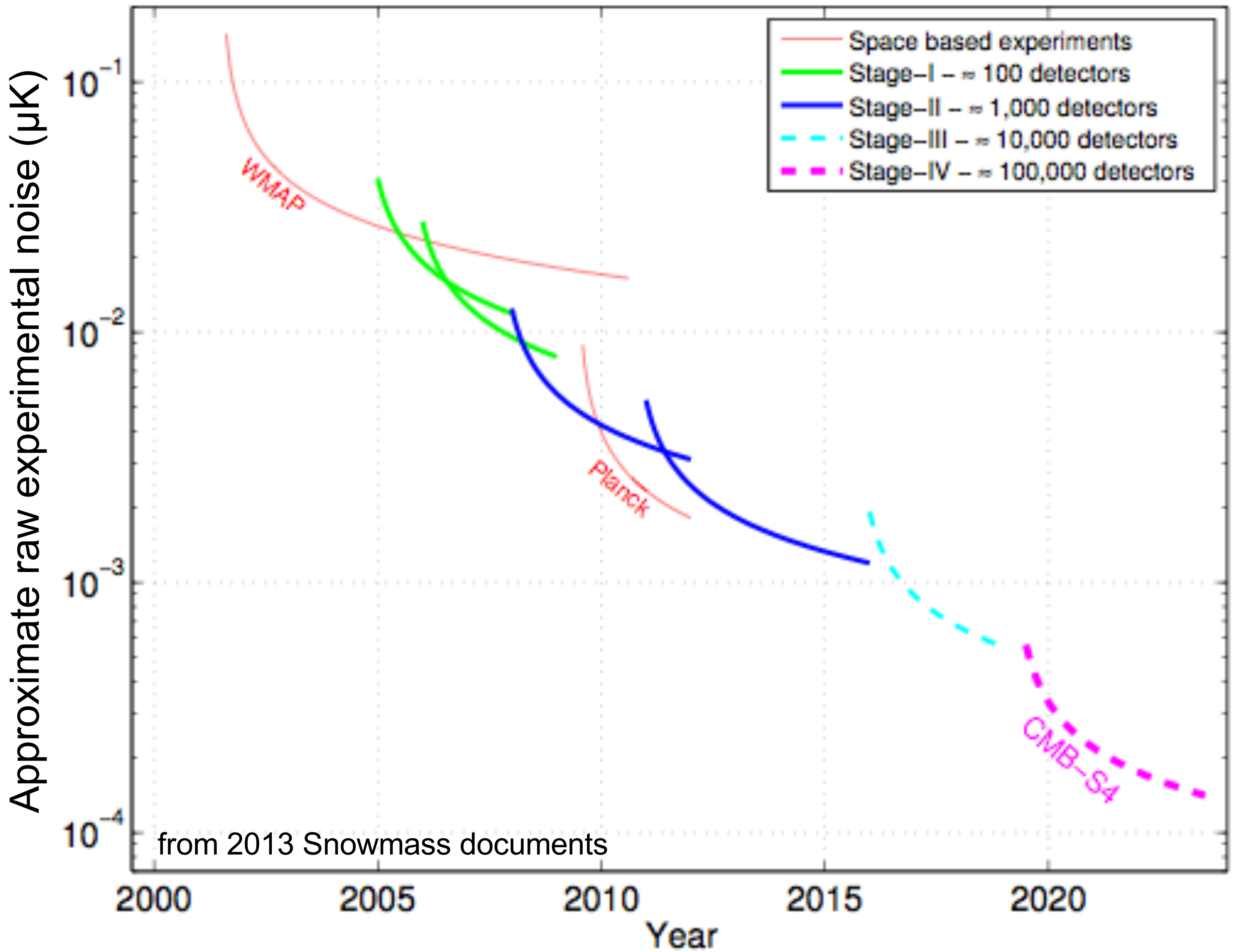
SCIENCE NEWS EVENTS **DOCS & TALKS** COLLABORATION CDT JOB POSTINGS CMB-S4 WIKI

Docs & Talks

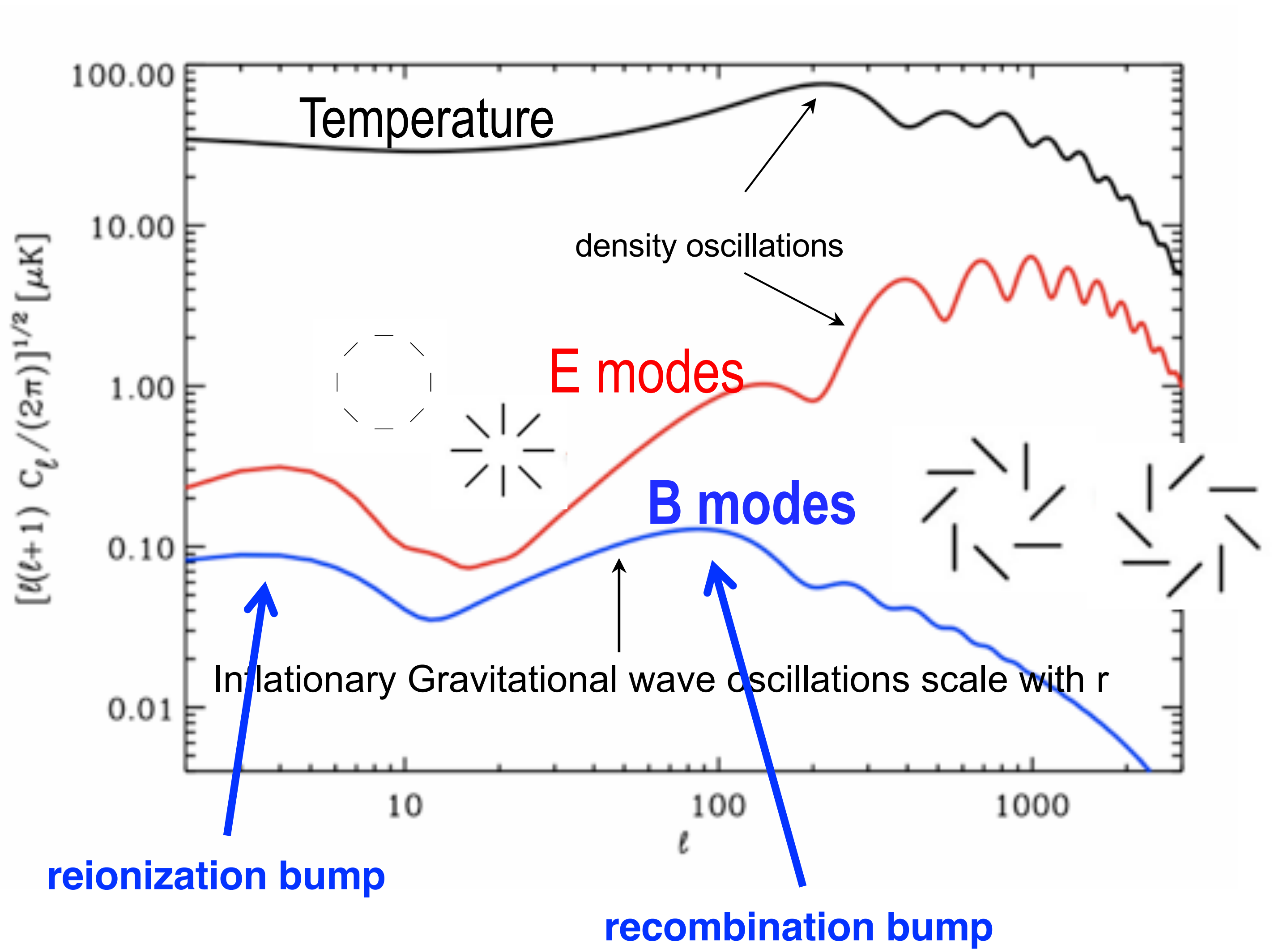
1. CMB-S4 Technology Book, First Edition
   Maximilian H. Abitbol, Zeeshan Ahmed, Darcy Barron, Ritoban Basu Thakur, Amy N. Bender, Bradford A. Benson, Colin A. Bischoff, Sean A. Bryan, John E. Carlstrom, Clarence L. Chang, David T. Chuss, Ari Cukierman, Tijmen de Haan, Matt Dobbs, Tom Essinger-Hileman, Jeffrey P. Filippini, Ken Ganga, Jon E. Gudmundsson, Nils W. Halverson, Shaul Hanany, Shawn W. Henderson, Charles A. Hill, Shuay-Pwu P. Ho, Johannes Hubmayr, Kent Irwin, Oliver Jeong, Bradley R. Johnson, Sarah A. Kernasovskiy, John M. Kovac, Akito Kusaka, Adrian T. Lee, Salatino Maria, Philip Mauskopf, Jeff J. McMahon, Lorenzo Moncelsi, Andrew W. Nadolski, Johanna M. Nagy, Michael D. Niemack, Roger C. O'Brient, Stephen Padin, Stephen C. Parshley, Clement Pryke, Natalie A. Roe, Karwan Rostem, John Ruhl, Sara M. Simon, Suzanne T. Staggs, Aritoki Suzuki, Eric R. Switzer, Keith L. Thompson, Peter Timbie, Gregory S. Tucker, Joaquin D. Vieira, Abigail G. Vieregg, Benjamin Westbrook, Edward J. Wollack, Ki Won Yoon, Karl S. Young, Edward Y. Young
   arXiv:1706.02464
2. CMB-S4 Science Book, First Edition
   Kevork N. Abazajian, Peter Adshead, Zeeshan Ahmed, Steven W. Allen, David Alonso, Kam S. Arnold, Carlo Baccigalupi, James G. Bartlett, Nicholas Battaglia, Bradford A. Benson, Colin A. Bischoff, Julian Borrill, Victor Buza, Erminia Calabrese, Robert Caldwell, John E. Carlstrom, Clarence L. Chang, Thomas M. Crawford, Francis-Yan Cyr-Racine, Francesco De Bernardis, Tijmen de Haan, Sperello di Serego Alighieri, Joanna Dunkley, Cora Dvorkin, Josquin Errard, Giulio Fabbian, Stephen Feeney, Simone Ferraro, Jeffrey P. Filippini, Raphael Flauger, George M. Fuller, Vera Gluscevic, Daniel Grin, Evan Grohs, Jason W. Henning, J. Colin Hill, Renee Hlozek, Gilbert Holder, William Holzapfel, Wayne Hu, Kevin M. Huffenberger, Reijo Keskitalo, Lloyd Knox, Arthur Kosowsky, John Kovac, Ely D. Kovetz, Chao-Lin Kuo, Akito Kusaka, Maude Le Jeune, Adrian T. Lee, Marc Lilley, Marilena Loverde, Mathew S. Madhavacheril, Adam Mantz, David J. E. Marsh, Jeffrey McMahon, Pieter Daniel Meerburg, Joel Meyers, Amber D. Miller, Julian B. Munoz, Ho Nam Nguyen, Michael D. Niemack, Marco Peloso, Julien Peloton, Levon Pogosian, Clement Pryke, Marco Raveri, Christian L. Reichardt, Graca Rocha, Aditya Rotti, Emmanuel Schaan, Marcel M. Schmittfull, Douglas Scott, Neelima Sehgal, Sarah Shandera, Blake D. Sherwin, Tristan L. Smith, Lorenzo Sorbo, Glenn D. Starkman, Kyle T. Story, Alexander van Engelen, Joaquin D. Vieira, Scott Watson, Nathan Whitehorn, W.L. Kimmy Wu
   arXiv:1610.02743

ence Foundation
WHERE DISCOVERIES BEGIN

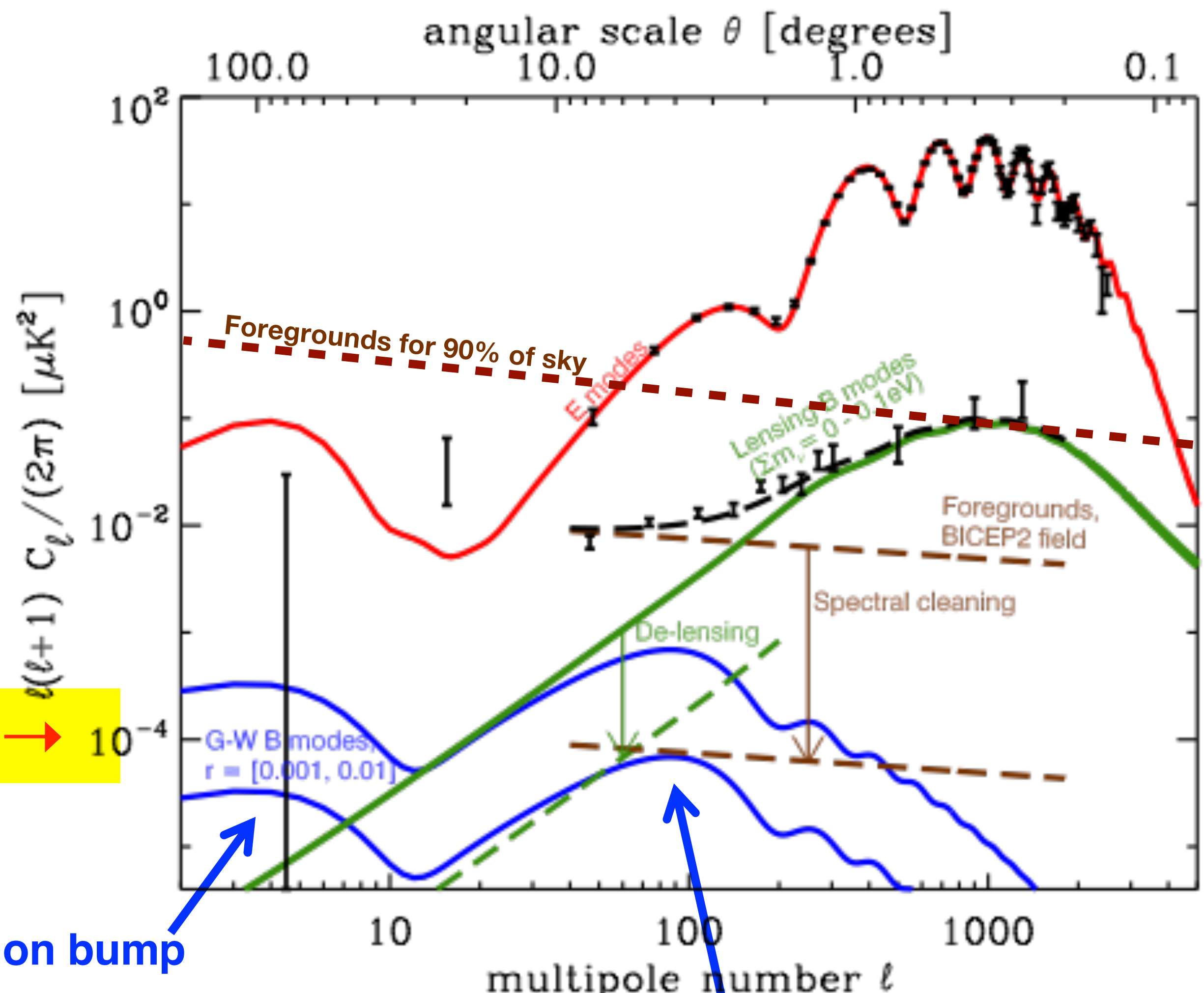
ENERGY.GOV


Space based experiments
Stage–I – ≈ 100 detectors
Stage–II – ≈ 1,000 detectors
Stage–III – ≈ 10,000 detectors
Stage–IV – ≈ 100,000 detectors
WMAP
Planck
CMB–S4
Approximate raw experimental noise (μK)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
2000
2005
2010
2015
2020
Year
from 2013 Snowmass documents

CMB Polarization



The Path Forward



10 nK →

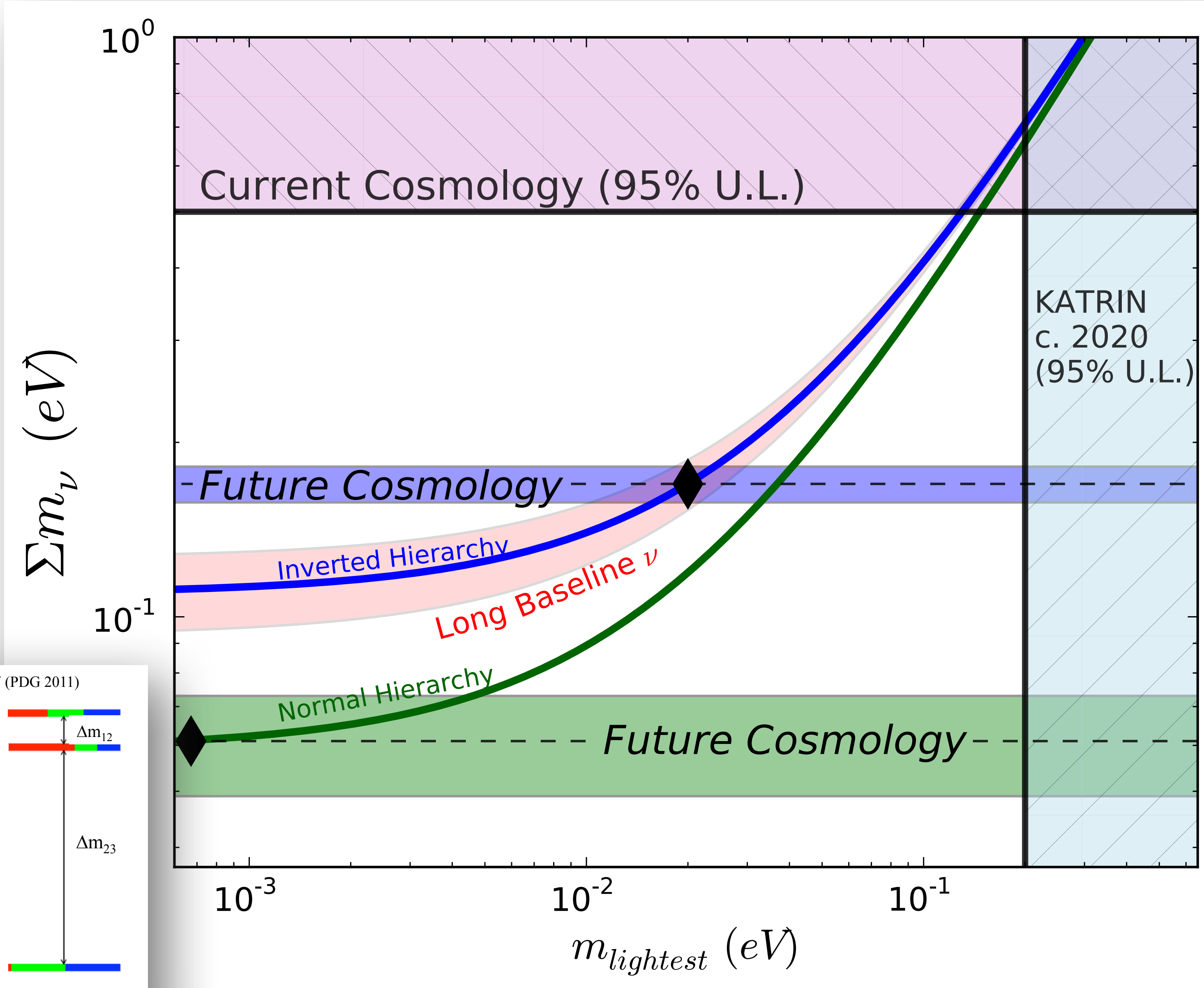
E modes

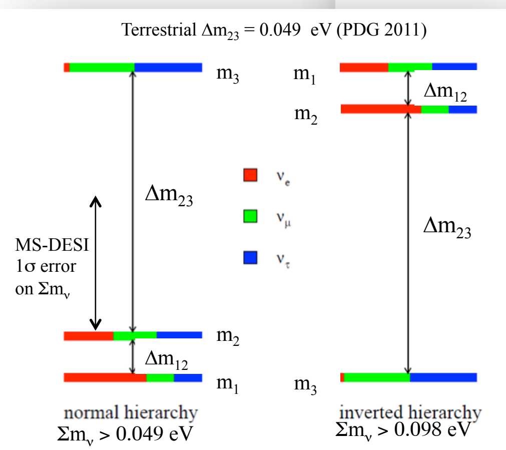
lensing
B modes

inflationary
gravity wave
B modes

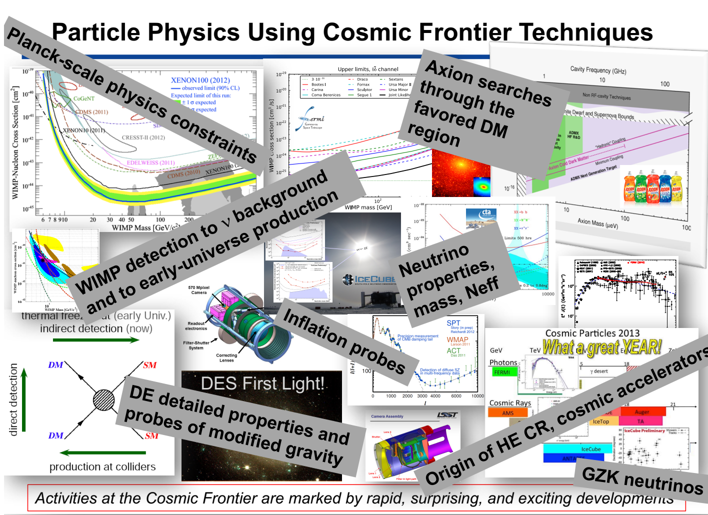
reionization bump
CLASS exploring from the ground; target of LiteBIRD, PIXIE , CORE satellites proposals

recombination bump
key target of ground experiments, incl. CMB-S4





Snowmass arXiv:1309.5383 and arXiv:1103.5083



Neutrinos, Cosmic Rays

Snowmass/P5 Neutrino Questions

- What is the origin of neutrino mass? Why are they so light compared to other matter particles?
- How are the neutrino masses ordered?
- What are the neutrino masses?
- Do neutrinos and antineutrinos oscillate differently?
- Are there additional neutrino types and interactions?
- Are neutrinos their own antiparticles?

- Complementarity of many techniques

See Friedland, Kaufman, Tanaka talks

Recent IceCube Result 6-56 GeV

arXiv: 1707.07081

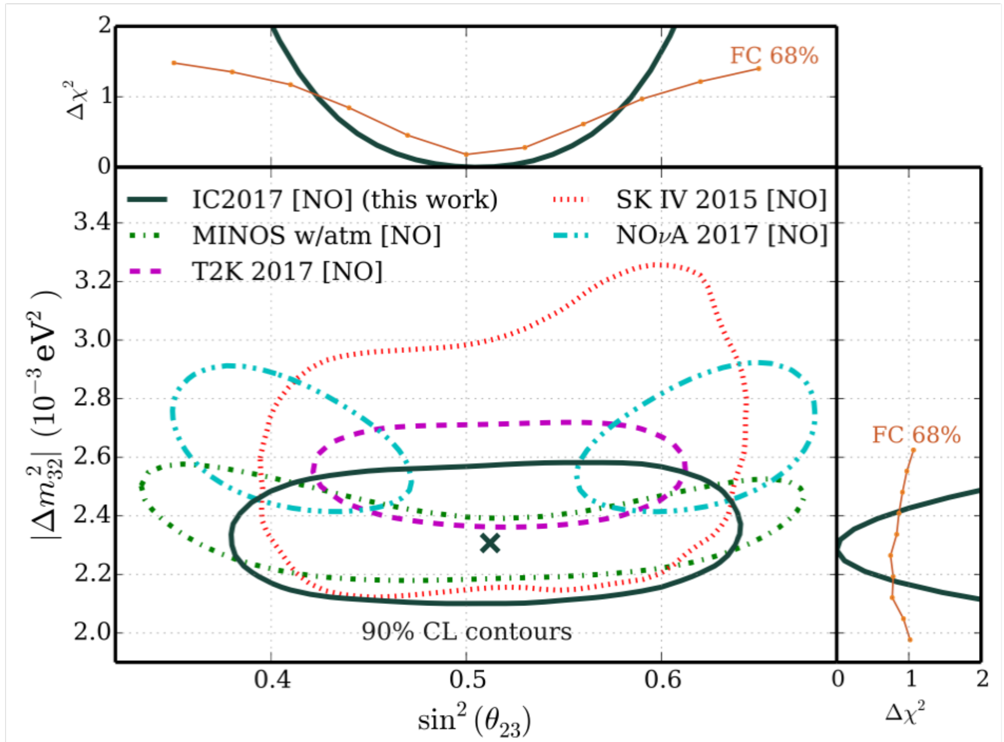


FIG. 3. The 90% allowed region from this work (solid line) compared to other experiments [12–14, 16] (dashed lines). The cross marks our best-fit point. The outer plots show the results of the 1-D projections after profiling over the other variables along with the 68% CL $\Delta\chi^2_c$ threshold estimated using the Feldman-Cousins method [47].

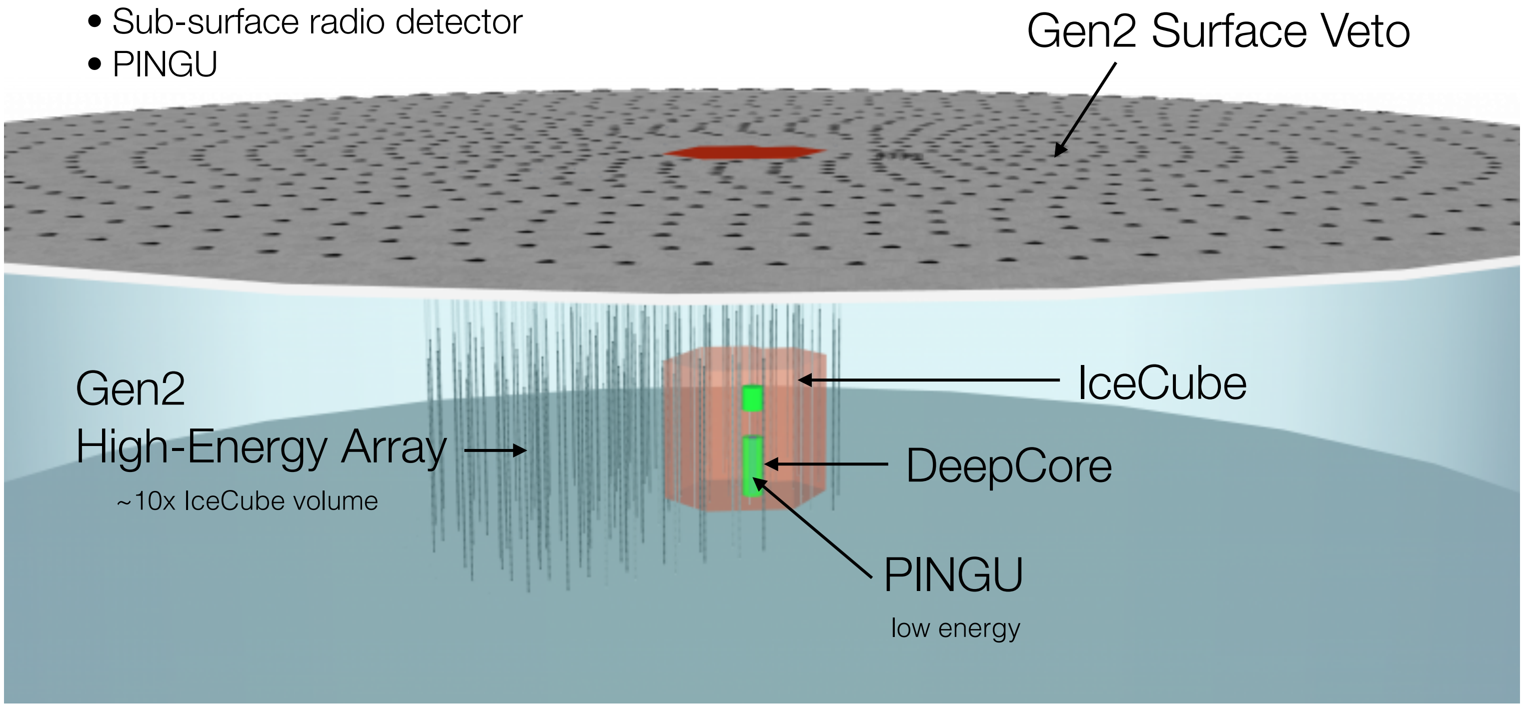
See S. Klein, Tanaka talks

IceCube-Gen2 Planning

IceCube-Gen2 Facility

A wide band neutrino observatory (MeV – EeV) using several detection technologies – optical, radio, and surface veto – to maximize the science

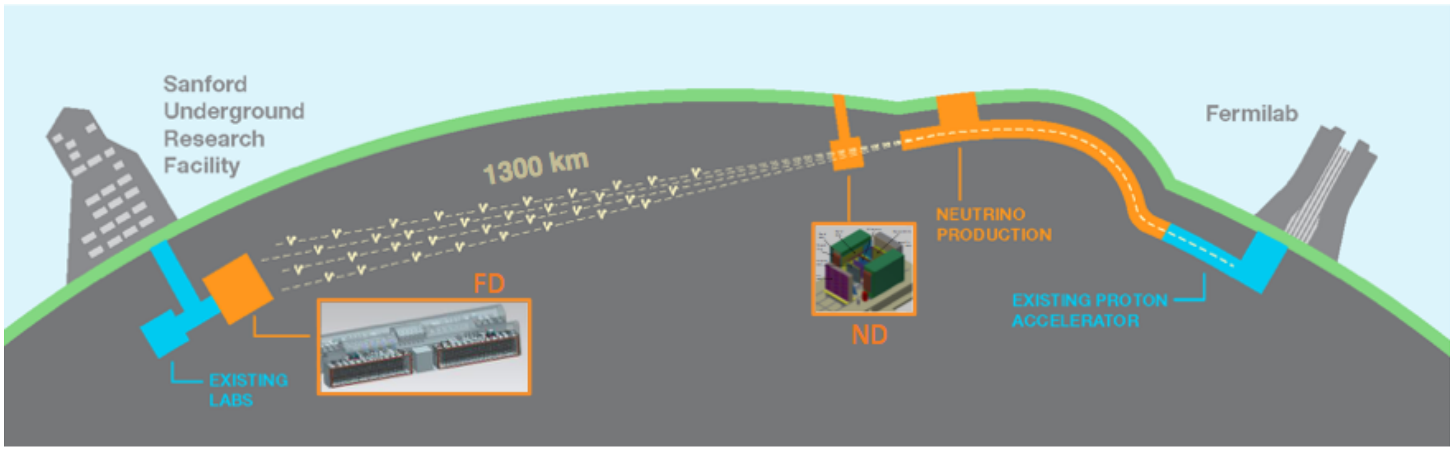
Multi-component observatory:
- Gen2 High-Energy Array
- Surface air shower detector
- Sub-surface radio detector
- PINGU



See S. Klein talk

DUNE

"Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) Conceptual Design Report Volume 2: The Physics Program for DUNE at LBNF" (arXiv:1512.06148)



- **Deep Underground Neutrino Experiment**: 40 kton LAr TPC far detector at 1480 m depth (4300 mwe) at SURF measuring neutrino spectra at 1300 km in a **wide-band** high purity ν_μ beam with peak flux at 2.5 GeV **operating at ~1.2 MW** and upgradeable to 2.4 MW
- **4 x 10 kton (fiducial) modules** (single and/or dual-phase) with ability to detect LBL oscillations, SN burst neutrinos, nucleon decay, atmospheric νs…
- Detectors will be ready before the beam arrives ⇨ **good opportunity to start with non-accelerator physics!**

E. Blucher talk

Core-collapse Supernovae

- Core-collapse supernova are a huge source of neutrinos of all flavors
- Gravitational binding energy: $E_B \approx 3 \times 10^{53}$ erg
  - 99% neutrinos
  - 1% kinetic energy of the exploding matter
  - 0.01% light
- Neutrino emission lasts ~10 sec
- Expected SNs in our Galaxy (d ≈ 10 kpc) : 1-3 SN/century

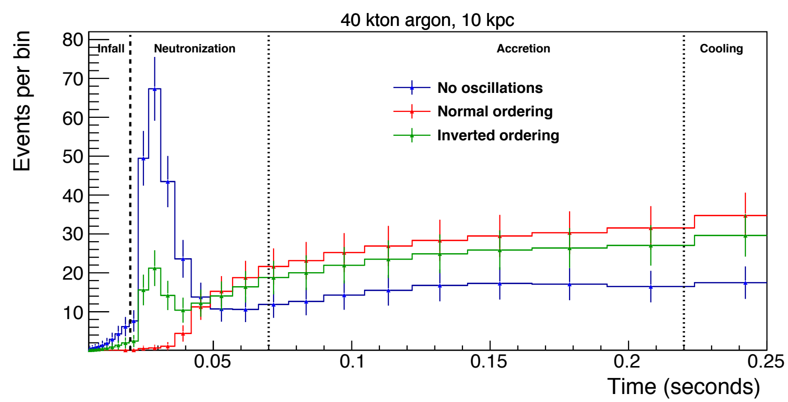
- Measurement of the neutrino energy spectra, flavor composition and time distributions from SN will provide **information about**:
  - **Supernova physics**: Core collapse mechanism, SN evolution in time, cooling of the proto-neutron star, nucleosynthesis of heavy nuclei, black hole formation
  - **Neutrino (other particle) physics**: ν flavor transformation in SN core and/or in Earth, collective effects, ν absolute mass, other ν properties: sterile vs, magnetic moments, axions, extra dimensions, …

- Neutrinos detected from SN1987A

6 July 8, 2017 Inés Gil-Botella I Astroparticle Physics

Neutronization burst

Because of its sensitivity to electron neutrinos, LAr TPCs can provide unique information bout the early breakout pulse from next galactic SN



Garching model, MSW transitions only, total events (mostly ν_e)

The time structure of the SN signal during the first few tens of ms after the core bounce can provide a clear indication if the ν_e burst is present or absent, allowing to **distinguish between different mixing scenarios**

12 July 8, 2017 Inés Gil-Botella I Astroparticle Physics at DUNE

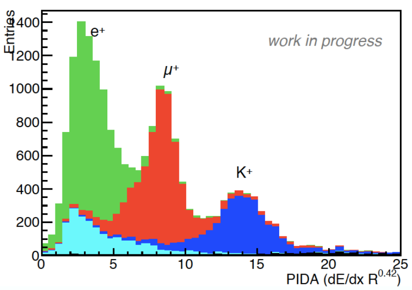
Nucleon decay channels

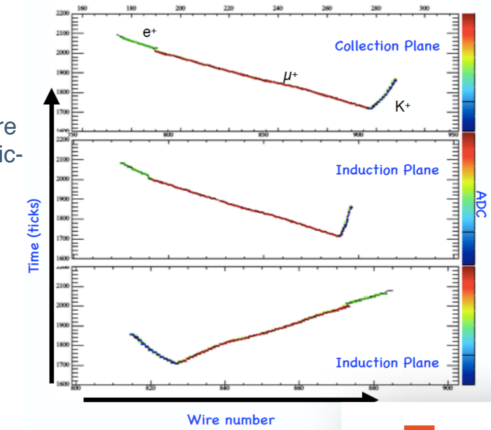
- **Many possible decay modes** (≈ 90 identified)
  - Proton decay modes, neutron decay modes, n-nbar oscillation modes
- The strength of LAr: kaon modes, e.g. **p → $\bar{\nu}$ K⁺ (SUSY motivated)**
- Kaons clearly identified by dE/dx and decay chain in LAr TPCs
- Main background: atmospheric neutrinos where a proton is misidentified as kaon or cosmogenic-induced kaons

$p \to K^+ \bar{\nu}$

$K^+ \to \mu^+ \bar{\nu}_\mu$

$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$

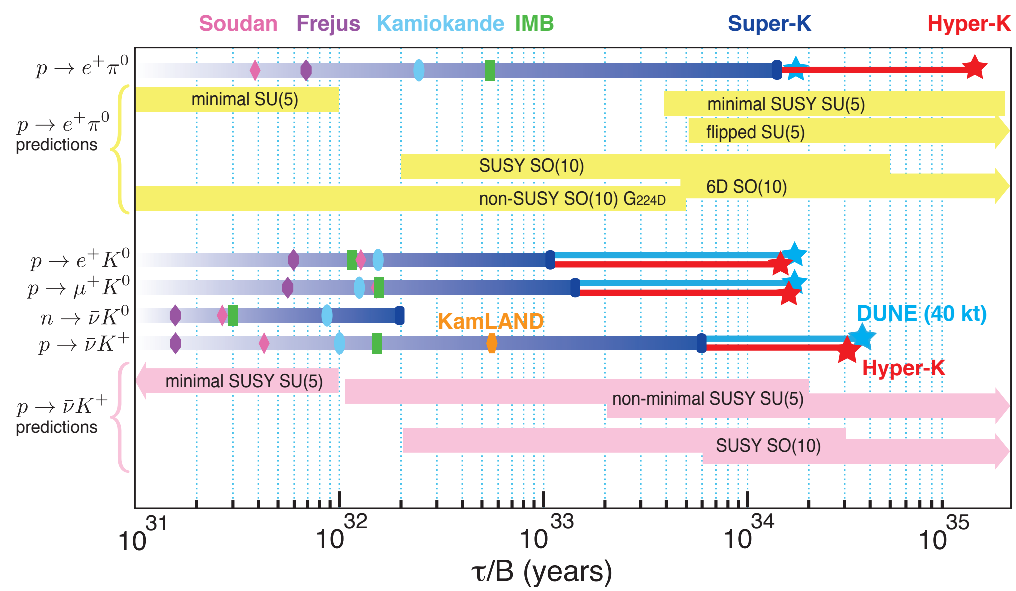




Simulation and reconstru... decay at DUNE

Experimental Limits and Theoretical Predictions

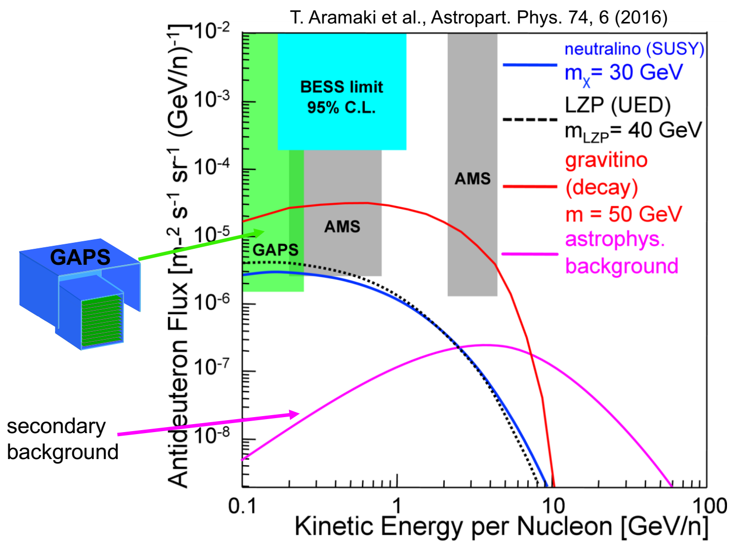
Example "benchmark" decay modes, but **many others will also be searched**

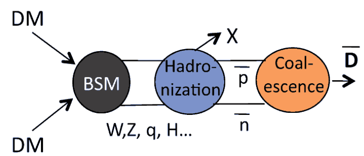


GAPS

Antideuteron Searches

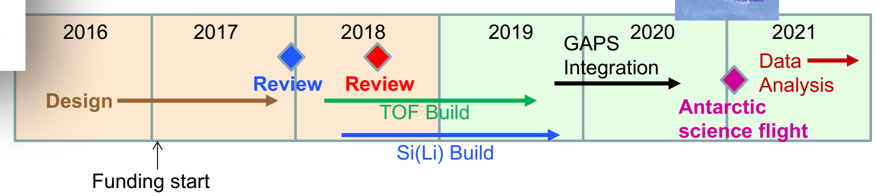
Anti-D's can be produced by BSM dark matter, and unlike e^-, e^+, $\bar{p}$, they are essentially background free:





Anti-D's are the most important unexplored indirect detection technique !

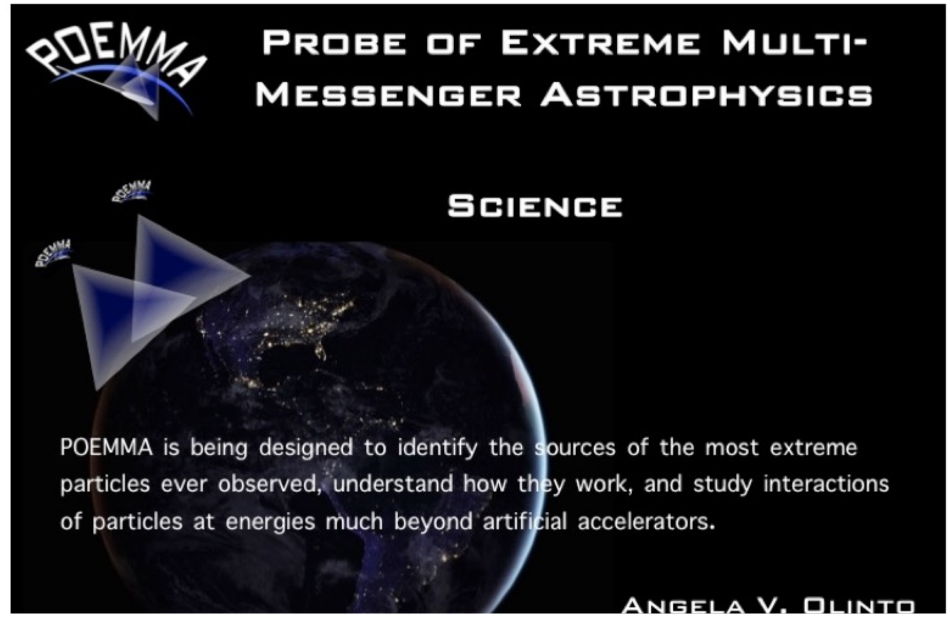
Timeline & Summary

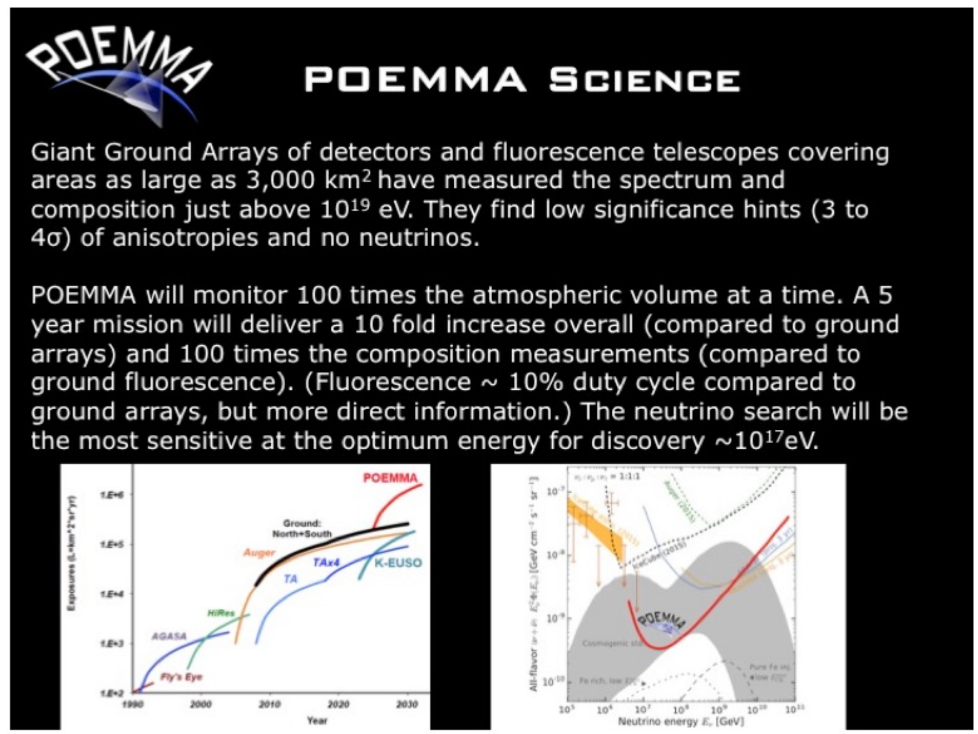


- Discovery of antideuterons in cosmic rays would a very significant result.
- GAPS is specifically designed for low-energy anti-D's and antiprotons
- Technique is different and complementary to AMS; if AMS sees some events, GAPS can confirm and go deeper.
- Prototype GAPS flight – completely successful, verified detector operation
- Rapid timeline from funding start to GAPS construction, integration and first science flight in late 2020

Note: Two advertised postdoctoral positions, see:
https://inspirehep.net/record/1505690 https://inspirehep.net/record/1495582

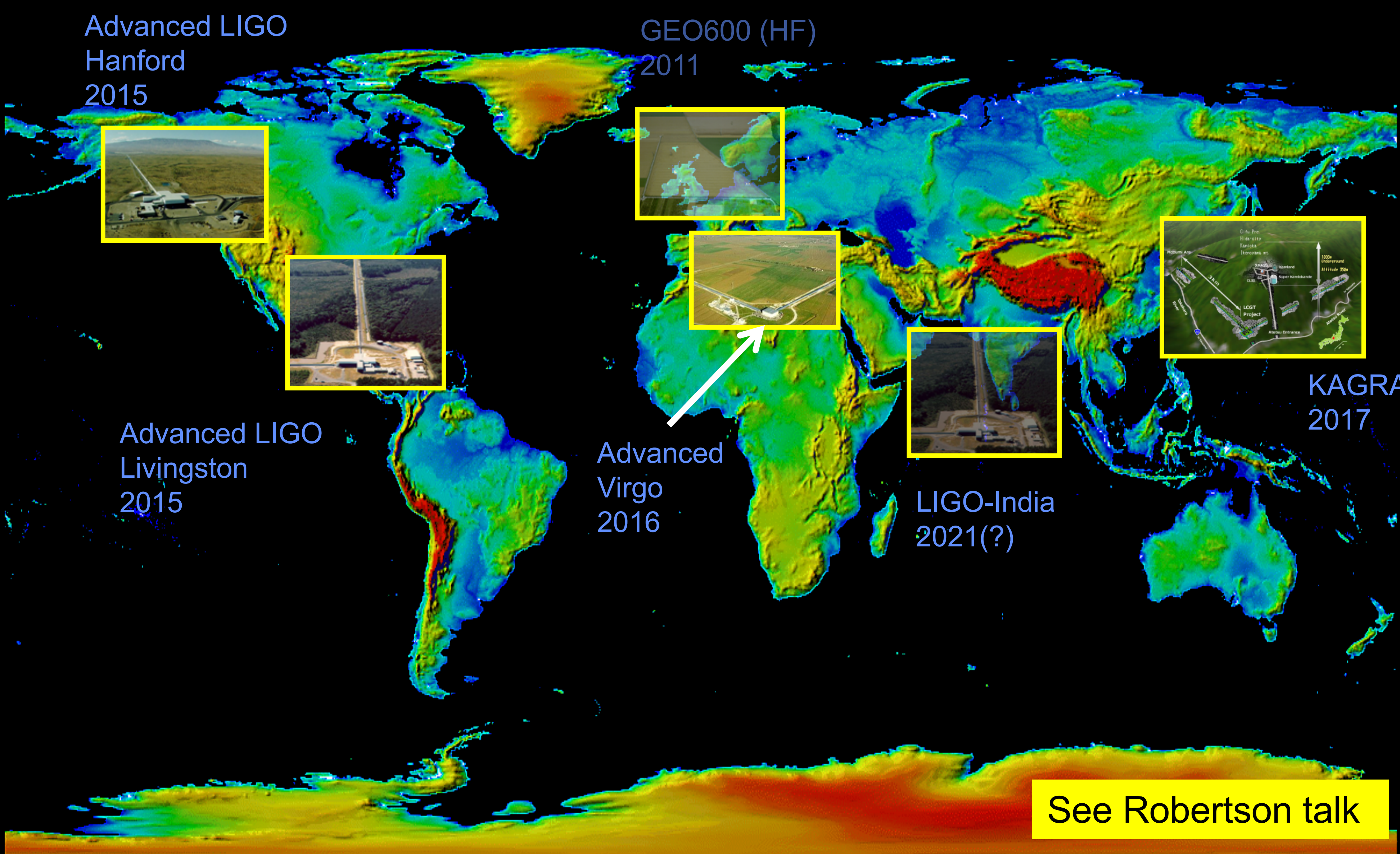
Highest Energy Cosmic Rays





D. Reitze

The Advanced GW Detector Network

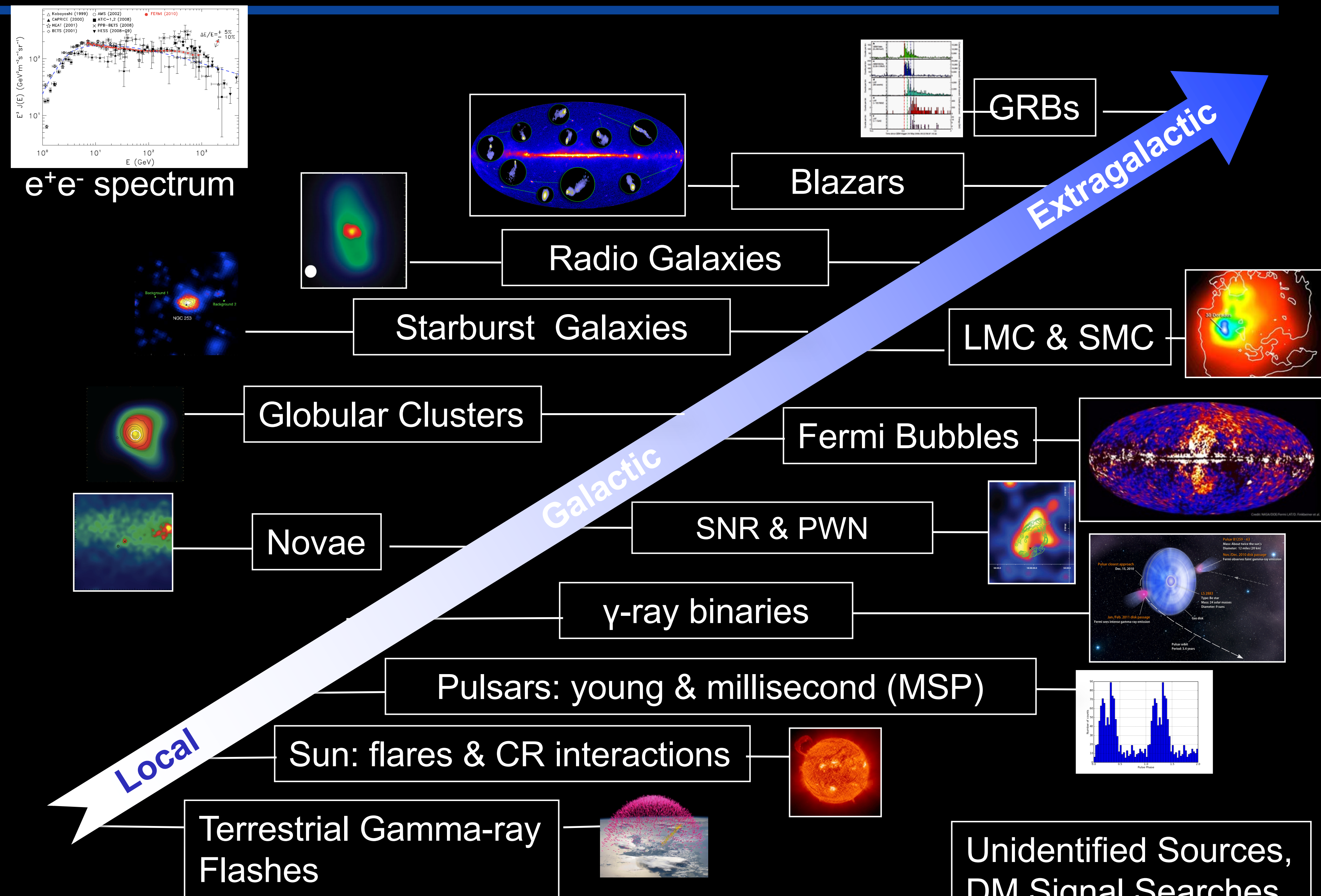


Cosmic Observations

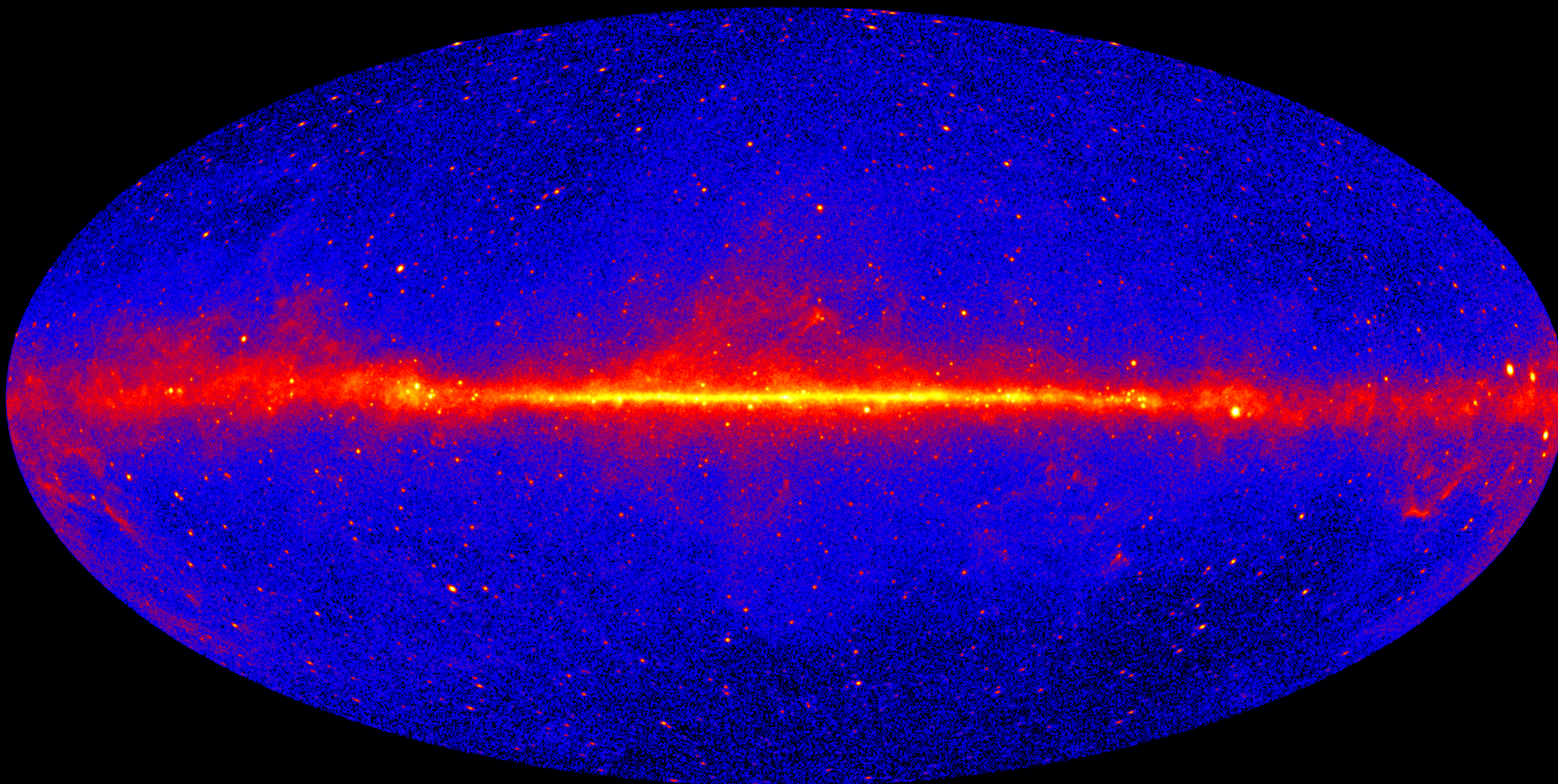
- **Together with the other Frontier areas in Particle Physics**, the Cosmic Frontier provides:
  - Clear evidence for physics Beyond the Standard Model
  - Many surprises. Profound questions.
  - Frequent new results, with broad impacts.
  - Large discovery space.
  - Important cross-frontier topics (*e.g.*, neutrinos, DM, …)
  - Full range of project scales, providing flexible programmatic options.

- Many of these experiments do great science at the boundary between particle physics and astrophysics or even more broadly. Best done in partnership.

Expanding Classes of Fermi-LAT Sources



7 years, E>1 GeV




Happy Birthday, Fermi!
➢ 9 years, >50,000 orbits
➢ >100 billion events downlinked
➢ Many hundreds of papers

Strong Agency Support

PA Program Scope & Currently Supported Projects

- Direct Dark Matter Detection – WIMP and non-WIMP experiments
  SuperCDMS at SNOLAB, XENON100/1T, LUX, DArkSide-50, PICO, DRIFT, DM-Ice, SABRE, DAMIC, HAYSTAC (ADMX-HF), ALPS2 and Light mass DM experiments
- Indirect Dark Matter Detection
  VERITAS, HAWC, IceCube
- Cosmic Ray, Gamma Ray, and UHE Neutrino Observatories
  IceCube, VERITAS, HAWC, Auger, Telescope Array, CTA, ARA, ARIANNA
- Cosmic Microwave Background
  SPT and BICEP
- Neutrino Properties
  Double Chooz, Project 8, IceCube, IsoDAR, CHANDLER
- Solar, SuperNova and Geo-Neutrinos
  Borexino, SNEWS
- Detector R&D
  NaI/CsI, LiSc/QuDots

AST

Polar Programs

June 5, 2017 HEPAP

HEP Cosmic Frontier Experiments (April 2017)

Activity	Location	Science	Current Status	# Collaborators	# Institutions	# Countries
Extended Baryon Oscillation Spectroscopic Survey (BOSS)	APO in New Mexico	dark energy stage III (spectroscopic)	operations started 2015	230 (150 US, 40 HEP)	(22 US, 8 HEP)	7
Dark Energy Survey (DES)	CTIO in Chile	dark energy stage III (imaging)	operations started Sept. 2013	300	25 (13 US, 9 HEP)	6
Large Synoptic Survey Telescope (LSST) - Dark Energy Science Collaboration (DESC)	Cerro Pachon in Chile	dark energy stage IV (imaging)	science studies, planning	232 (200 US, 134 HEP)	53 (41 US, 16 HEP)	3
Large Synoptic Survey Telescope (LSST) - LSSTcam Project	Cerro Pachon in Chile	dark energy stage IV (imaging)	FY14 Fab. start; CD3 Aug2015	142 (111 US, 111 HEP)	17 (11 US, 11 HEP)	2
Dark Energy Spectroscopic Instrument (DESI)	KPNO in AZ	dark energy stage IV (spectroscopic)	FY15 fab start; CD3 June 2016	179 (93 US, 74 HEP)	39 (21 US, 19 HEP)	9
DM-G1: Large Underground Xenon (LUX)	SURF in South Dakota	dark matter - WIMP search	Operations ended in 2016	102 (86 US, 64 HEP)	18 (15 US, 13 HEP)	3
DM-G1: Super Cryogenic Dark Matter Search (SuperCDMS-Soudan)	Soudan in Minnesota	dark matter - WIMP search	Operations ended in 2016	83 (72 US, 44 HEP)	20 (17 US, 7 HEP)	3
DM-G2: ADMX-G2	Univ Washington	dark matter - axion search	Operations started Jan. 2017	31 (29 US, 20 HEP)	8 (7 US, 4 HEP)	2
DM-G2: SuperCDMS-SNOLAB	SNOLab in Canada	dark matter - WIMP search	FY15 fab start; CD1 Dec. 2015	90 (74 US, 47 HEP)	22 (17 US, 7 HEP)	5
DM-G2: LZ	SURF in South Dakota	dark matter - WIMP search	FY15 fab start; CD3 Feb. 2017	154 (118 US, 107 HEP)	28 (18 US, 17 HEP)	3
SPT-3G	South Pole	CMB stage 3	Operations started Feb. 2017	59	9 (7 US,5 HEP)	3
Very Energetic Radiation Imaging Telescope Array System (VERITAS)	FLWO in AZ	gamma-ray survey	HEP ops completed 2016	109 (76 US, 28 HEP)	20 (16 US, 5 HEP)	4
Pierre Auger Observatory	Argentina	cosmic-ray	HEP ops completed 2016	436 (61 US, 18 HEP)	90 (17 US, 6 HEP)	17
Fermi Gamma-ray Space Telescope (FGST) Large Area Telescope (LAT)	space-based	gamma-ray survey	June 2008 launch; operating	362 (153 US, 58 HEP)	115 (38 US, 3 HEP)	22
Alpha Magnetic Spectrometer (AMS-02)	space-based (on ISS)	cosmic-ray	May 2011 launch; operating	600	60 (6 US, 2 HEP)	16
High Altitude Water Cherenkov (HAWC)	Mexico	gamma-ray survey	Operations started Jan. 2015	111 (54 US, 8 HEP)	28 (17 US, 3 HEP)	2

Final Thoughts

- Cultural differences among communities are not necessarily impediments, but rather reinforcing capabilities enabling important new opportunities. We’re lucky to have each other!
- Strong international and multicultural cooperation.
- Great leaps in capabilities have broad and surprising impacts, *e.g.*,
  - Sloan and DES Dwarf Spheroidal galaxies discoveries opening new opportunities for indirect DM signal searches.
  - Fermi all-sky sensitivity => millisecond pulsars for use by Nanograv for gravitational wave searches
  - …
- Great leaps in measurement capabilities demand new analysis approaches *and* new theory.
- What a wonderful time – so much great data and new results!