What's Exciting in Cosmology?

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OUTLINE

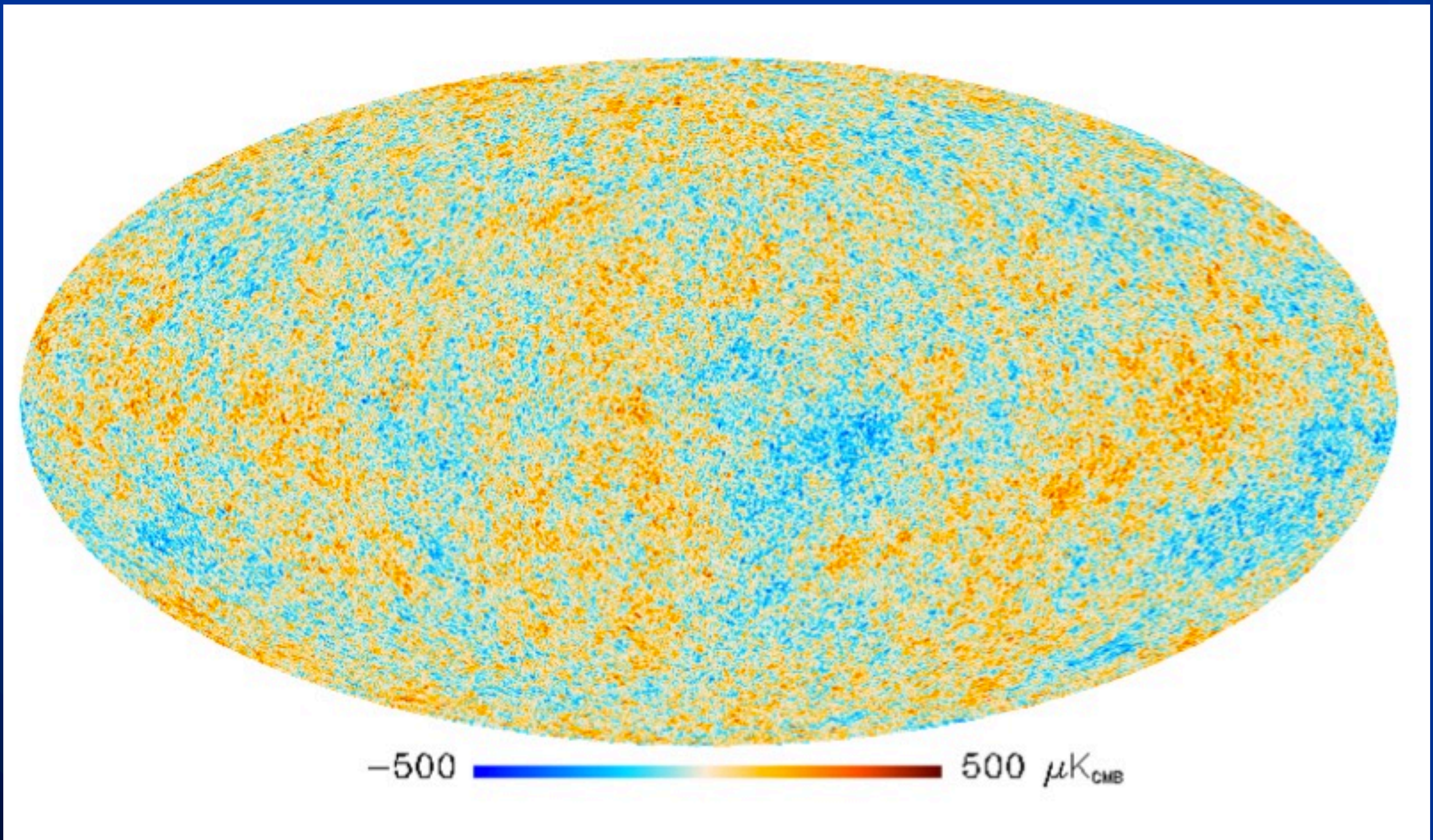
- Hubble Tension
  - Is it real?
  - Proposed solution: Early Dark Energy
- Dark Matter
  - Neutrino Mass from Cosmology
  - Candidates:
    - Primordial Black Holes in LIGO?
    - axions: detectors very active
    - WIMPs: multi-pronged approach
    - Light Dark Matter: many searches on the way
    - Sterile neutrinos: 3.5 keV x-ray line?
  - Learning about nature of DM using GAIA data
- Dark Energy

ENORMOUS PROGRESS OVER THE LAST CENTURY

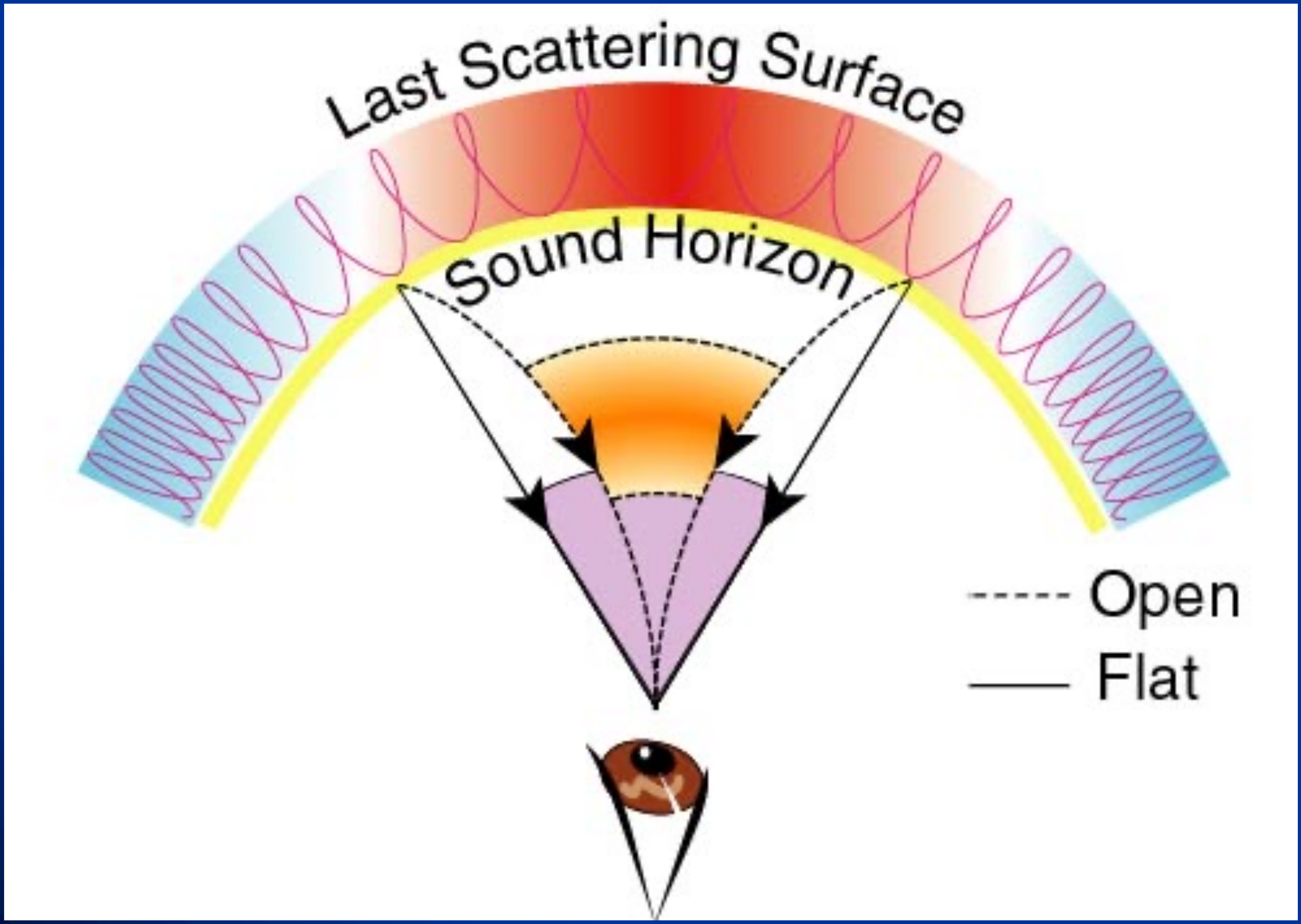
At the turn of the Millenium, recent experiments answered BIG QUESTIONS:

- We know the geometry of the universe
- We know the energy density of the universe
- We know the age of the Universe
- We understand the physics all the way to the edge of the observable universe (the horizon)
- BUT many questions remain: what is the universe made of (dark matter and dark energy)? How did it begin? How will it end?

The Universe according to ESA's Planck Space Telescope

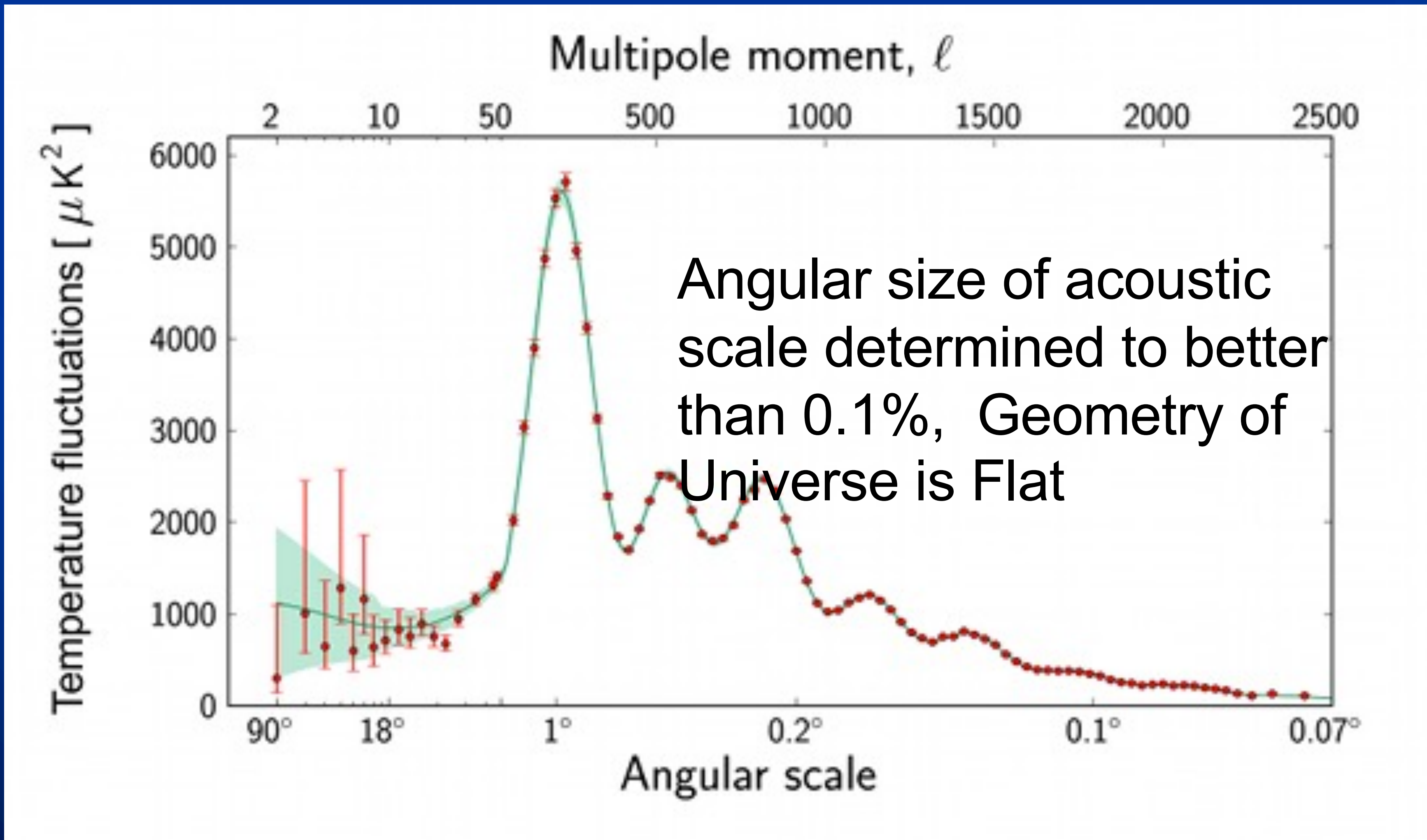


How can Microwave Background tell us about geometry?



Planck Satellite

(7 acoustic peaks)



Angular size of acoustic scale determined to better than 0.1%, Geometry of Universe is Flat

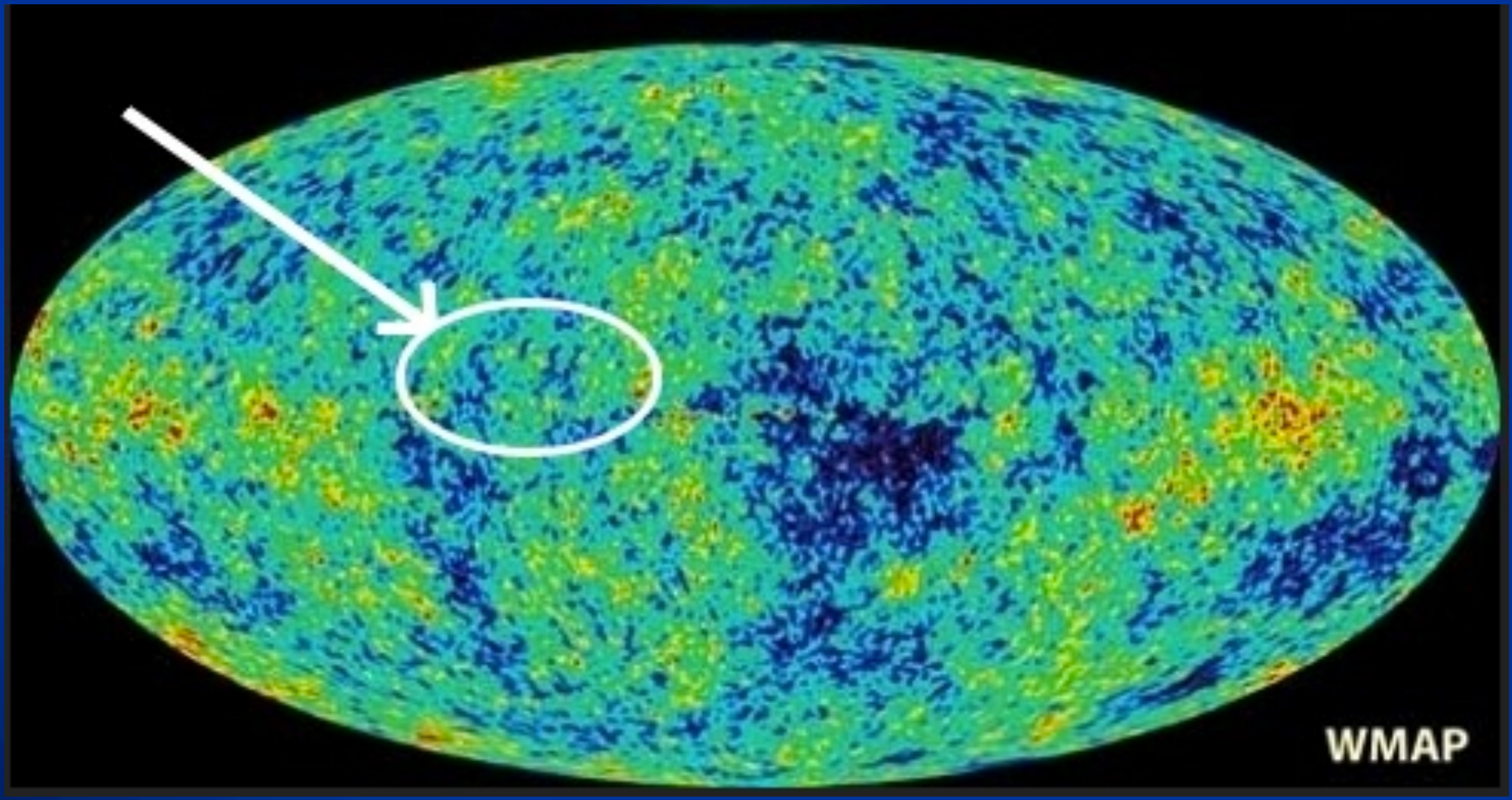
Implies energy density of the Universe is

$$\rho = \rho_c = 10^{-29}\ \text{gm/cm}^3$$

Cosmological Parameters from Planck

	Planck (CMB+lensing)		*Planck*+WP+highL+BAO	
Parameter	Best fit	68 % limits	Best fit	68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04150	1.04141 ± 0.00067	1.04148	1.04147 ± 0.00056
τ	0.0949	0.089 ± 0.032	0.0952	0.092 ± 0.013
n_s	0.9675	0.9635 ± 0.0094	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057	3.0973	3.091 ± 0.025
Ω_Λ	0.6964	0.693 ± 0.019	0.6914	0.692 ± 0.010
σ_8	0.8285	0.823 ± 0.018	0.8288	0.826 ± 0.012
z_{re}	11.45	$10.8^{+3.1}_{-2.5}$	11.52	11.3 ± 1.1
H_0	68.14	67.9 ± 1.5	67.77	67.80 ± 0.77
Age/Gyr	13.784	13.796 ± 0.058	13.7965	13.798 ± 0.037
$100\theta_*$	1.04164	1.04156 ± 0.00066	1.04163	1.04162 ± 0.00056
r_{drag}	147.74	147.70 ± 0.63	147.611	147.68 ± 0.45
$r_{drag}/D_V(0.57)$	0.07207	0.0719 ± 0.0011		

SH initials in WMAP satellite data

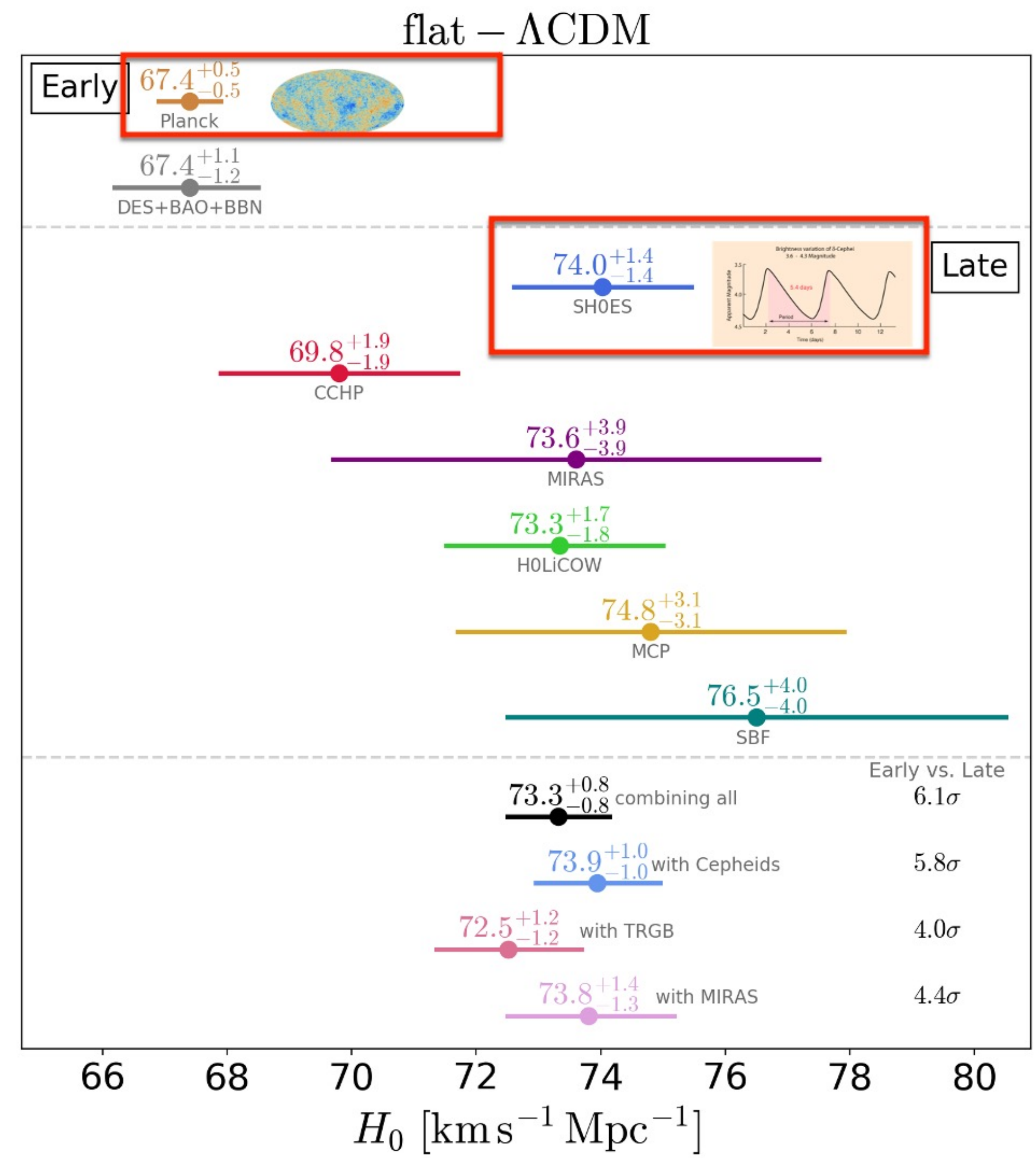


I. One one of most exciting developments in cosmology: Hubble tension

- What are the data? Is the tension real, or just systematics or dust or …?

- Proposed resolutions: hard to explain
- Most interesting proposal: Early Dark Energy

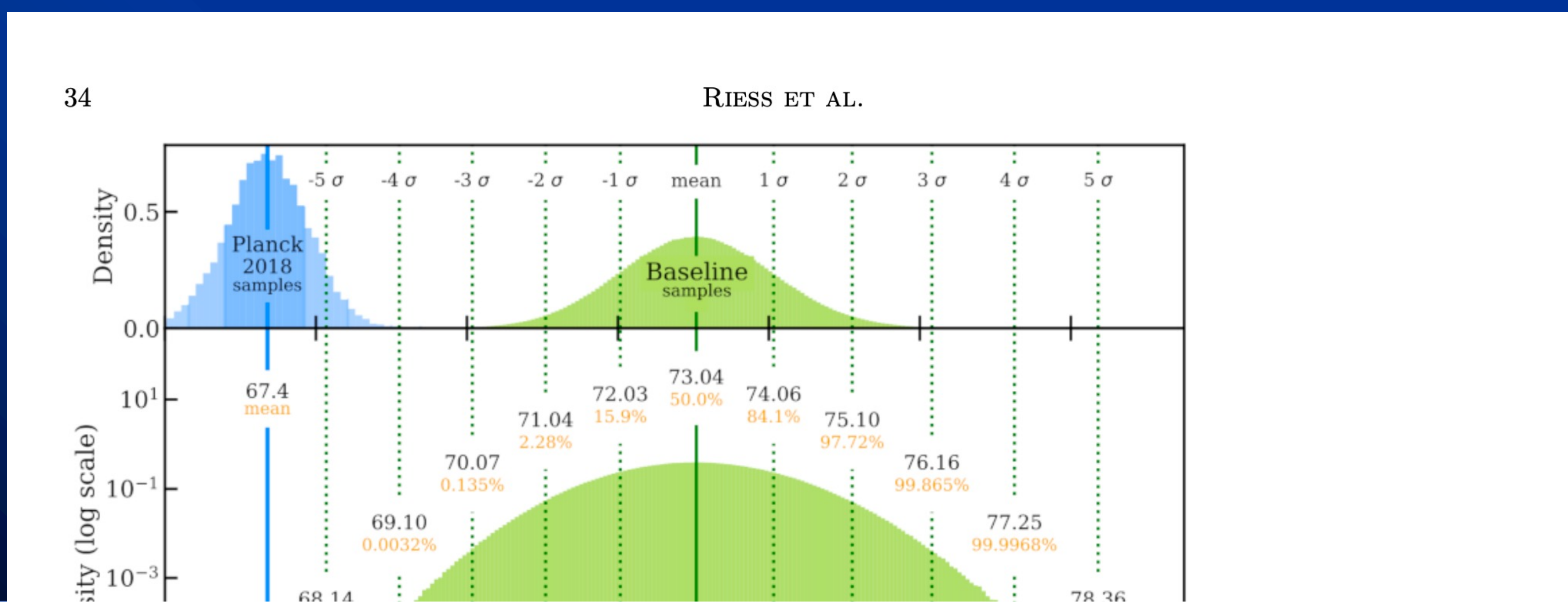
Hubble Tension



Verde, Treu & Riess arXiv:1907.10625

Claim: 5 sigma discrepancy between CMB and SN

Riess etal 2112.04510
observations from the Hubble Space Telescope (HST) of Cepheid variables in the host galaxies of 42 Type Ia supernovae (SNe Ia) used to calibrate the Hubble constant (H0).



Tip of Red Giant Branch
(Wendy Freedman 2106.15656)

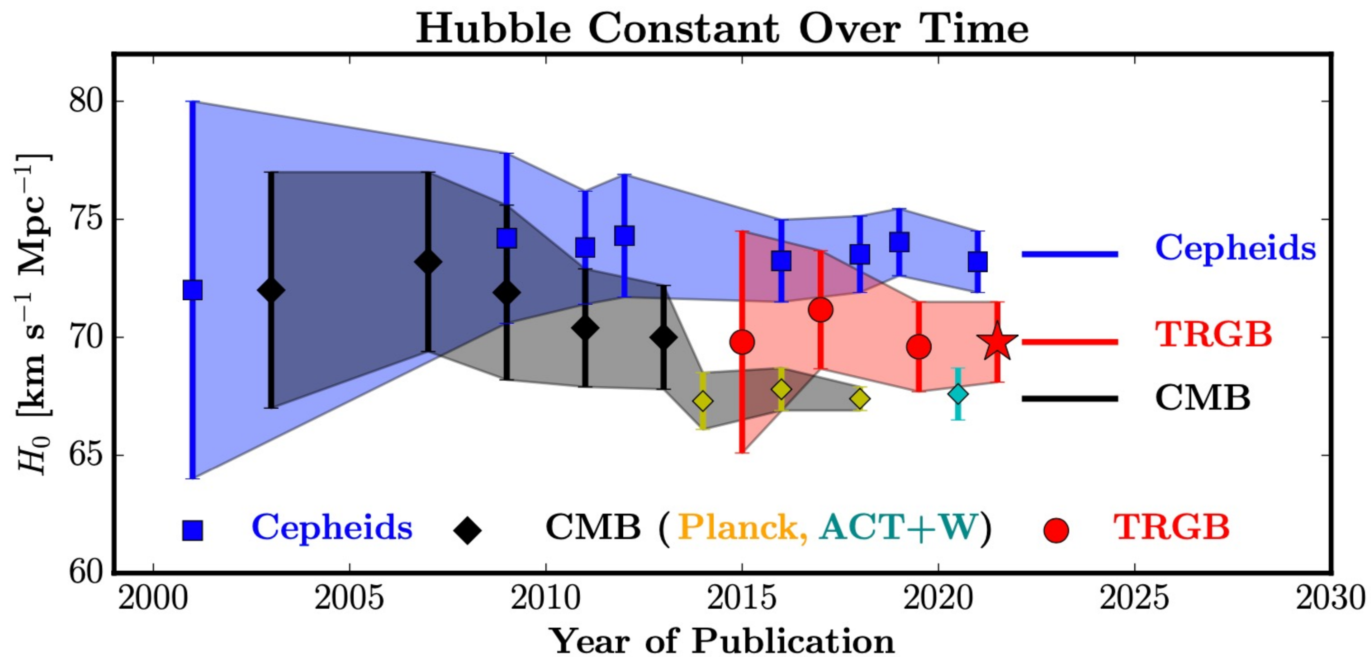
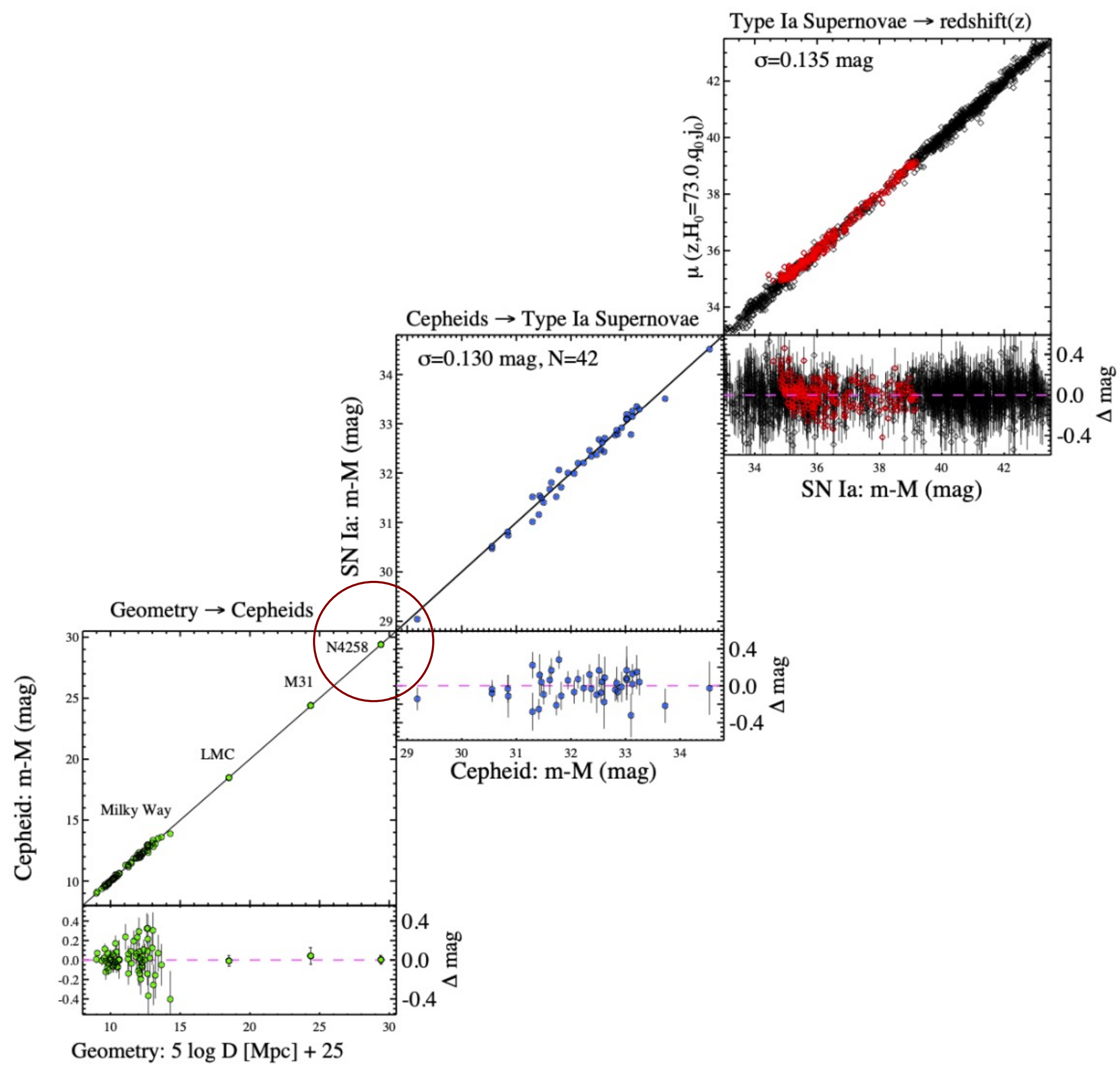


Figure 11. A summary of Hubble constant values in the past two decades, based on Cepheid variables (blue squares), the TRGB (red filled circles and star), and estimates based on measurements of fluctuations in the CMB (WMAP: black filled diamonds; Planck: yellow diamonds; ACT + WMAP: cyan diamond). The CMB H_0 values assume a flat Λ CDM model. The CMB and Cepheid results straddle a range of 67 to 74 $\mathrm{km\,s^{-1}\,Mpc^{-1}}$, with the TRGB results falling in the middle, and overlapping the CMB results. The tension between the CMB and TRGB results amounts to only 1.3σ.

Rungs of Distance Ladder



Dust Corrections

The Hubble Tension Bites the Dust:
Sensitivity of the Hubble Constant Determination to Cepheid Color Calibration

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ABSTRACT

Motivated by the large observed diversity in the properties of extra-galactic extinction by dust, we reanalyse the Cepheid calibration used to infer the local value of the Hubble constant, H_0, from Type Ia supernovae. Unlike the SH0ES team, we do not enforce a universal color-luminosity relation to correct the near-IR Cepheid magnitudes. Instead, we focus on a data driven method, where the measured colors of the Cepheids are used to derive a color-luminosity relation for each galaxy individually. We present two different analyses, one based on Wesenheit magnitudes, a common practice in the field that attempts to combine corrections from both extinction and variations in intrinsic colors, resulting in $H_0 = 66.9 \pm 2.5$ km/s/Mpc, in agreement with the Planck value. In the second approach, we calibrate using color excesses with respect to derived average intrinsic colors, yielding $H_0 = 71.8 \pm 1.6$ km/s/Mpc, a $2.7\,\sigma$ tension with the value inferred from the cosmic microwave background.

Hence, we argue that systematic uncertainties related to the choice of Cepheid color-luminosity calibration method currently inhibits us from measuring H_0 to the precision required to claim a substantial tension with Planck data.

2105.11461

How to solve the Hubble Tension

- $H0 \simeq 67$ km $s-1$ $Mpc-1$ inferred from CMB

  vs

  $H0 \simeq 74$ km $s-1$ $Mpc-1$ from late time measurements

e.g. supernova redshifts

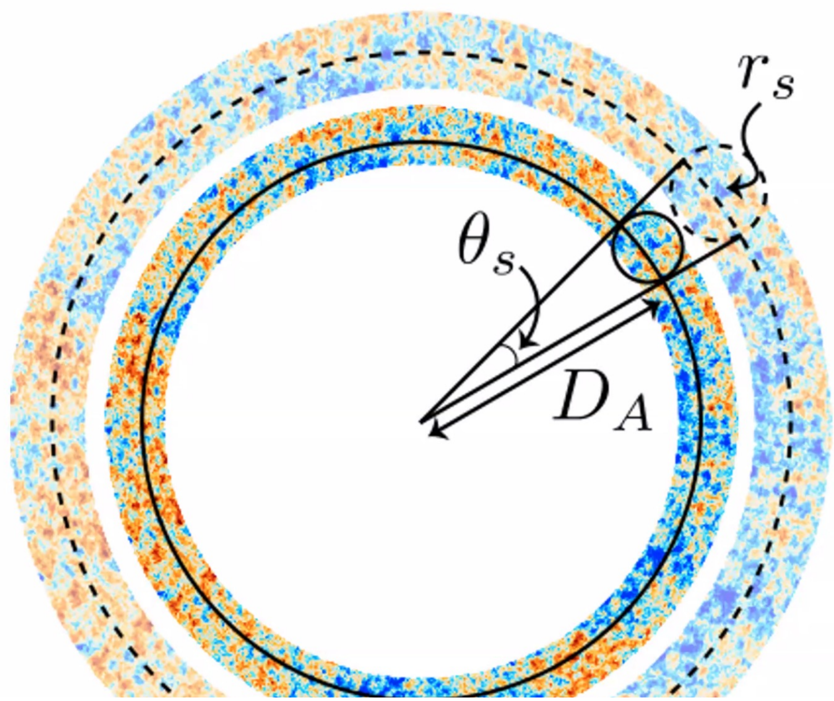
Many proposed resolutions, most fail, see Knox and Millea's Hubble Hunters Guide

"We single out the set of solutions that increase the expansion rate in the decade of scale factor expansion just prior to recombination as the least unlikely. "

Additional Energy Density before CMB helps with Hubble tension

- It speeds up the Universe’s expansion, so that length scales are smaller when reach temperature of CMB. In particular sound horizon rs is smaller at recombination. Thus to keep the Doppler peak at 1 degree, the inferred value of H0 is larger.

$$\theta_s = \frac{r_s}{D_A}$$



Keep Doppler Peak at 1 degree

$$\theta_s = \frac{r_s}{D_A}$$

$$D_A = \frac{c}{H_0} \int_{t_{rec}}^{t_0} \frac{dt/t_0}{[\rho(t)/\rho_0]^{1/2}}$$

$$r_s = \frac{1}{H_{\rm rec}} \int_0^{t_{\rm rec}} \frac{c_s(t)\, dt/t_{\rm rec}}{[\rho(t)/\rho(t_{\rm rec})]^{1/2}}$$

$$H_0 = H_{\rm rec} \frac{\int_{t_{\rm rec}}^{t_0} \frac{c\, dt/t_0}{[\rho(t)/\rho_0]^{1/2}}}{\int_0^{t_{\rm rec}} \frac{c_s(t)\, dt/t_{\rm rec}}{[\rho(t)/\rho(t_{\rm rec})]^{1/2}}}$$

To increase H_0, can

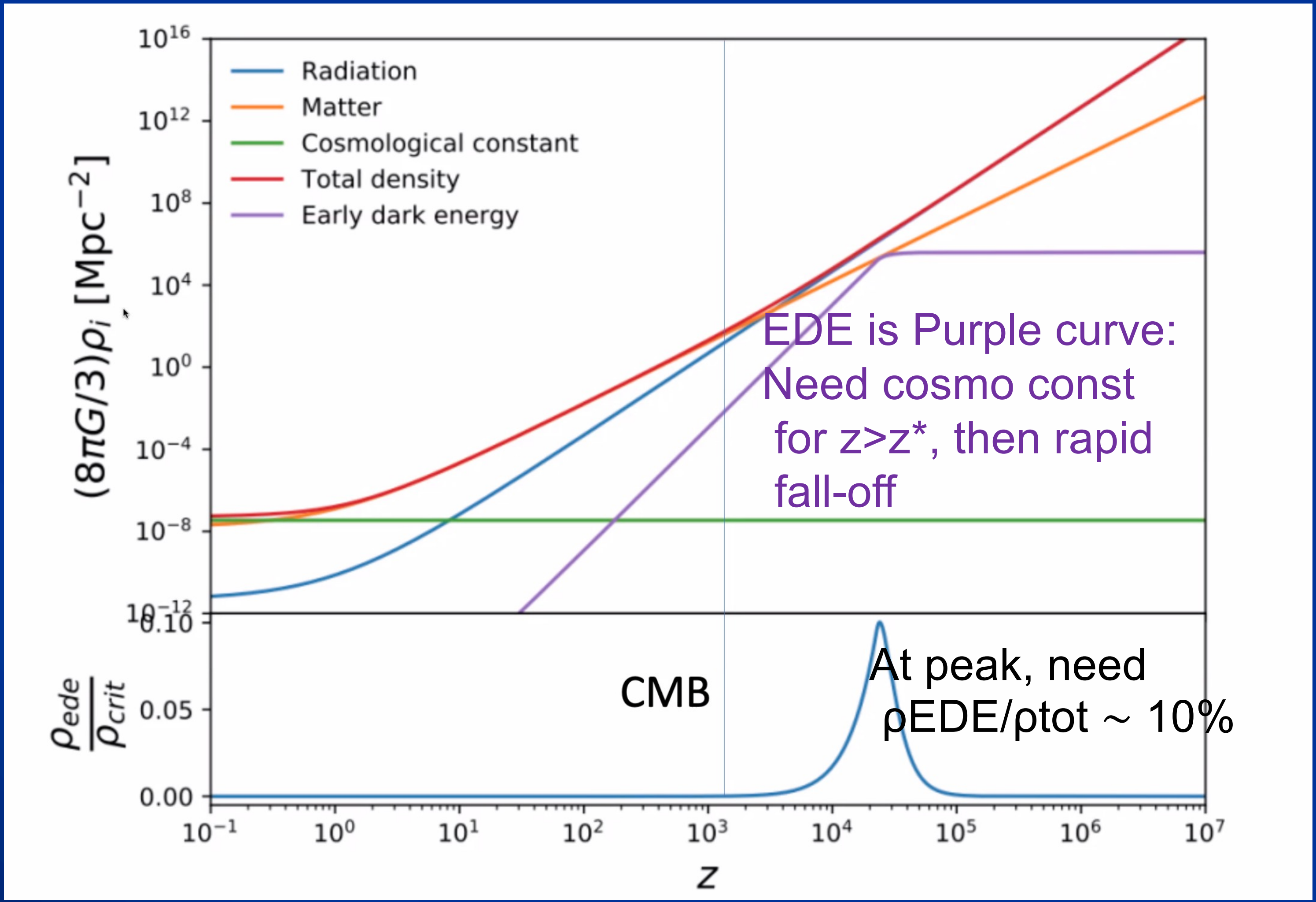
- Decrease matter density at late times
- Decrease sound speed in early Universe
- Increase matter density at early times

Additional Energy before CMB

- Dark Radiation doesn't work. Degrades fits to higher-l CMB peaks and polarization and BAO
- Early Dark Energy seems to match all CMB and Large Scale Structure Data
- The original model of Kamionkowski and others:
- A scalar field initially displaced from it minimum, stays there due to Hubble friction, once H = mphi, phi oscillates around the minimum, turns out you need non-generic potentials to get rapid enough decrease
- $V \propto (1 - \cos(\varphi/f))$^n with $n \geq 2$

What's needed for EDE to work

Plot from Marc Kamionkowski's talk



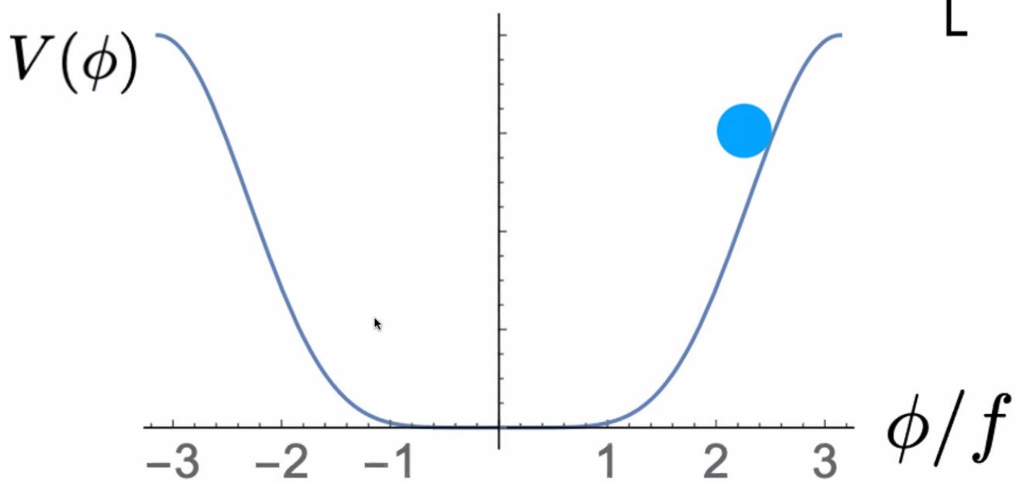
BETTER FIT TO DATA FOR PEAK AT Z*=3500, RIGHT AT MATTER/RADIATION EQUALITY

(Poulin etal 1811.04083)

The original oscillating EDE model

A scalar field initially displaced from it minimum, stays there due to Hubble friction, once H = mphi, phi oscillates around the minimum,
turns out you need non-generic potentials to get rapid enough decrease

$$V(\phi) \propto \left[1 - \cos\left(\frac{\phi}{f}\right)\right]^n$$

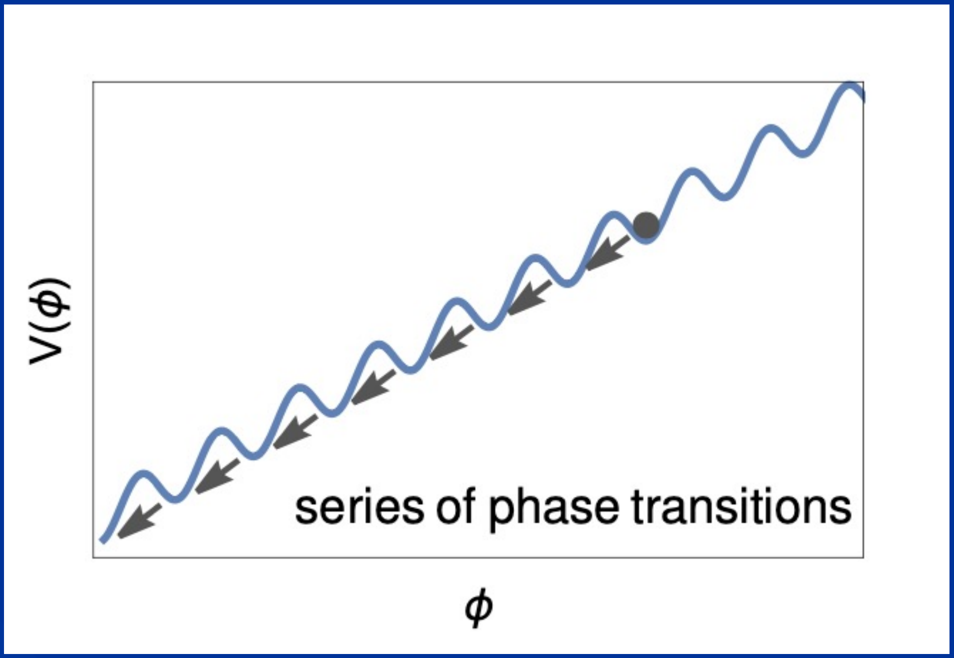


Behaves like cosmological constant at late times; decays as $(\mathrm{scale\,factor})^{(2n-2)/(2n+2)}$ at late times (MK, Pradler & Walker, 2014)

Idea: use First Order Phase Transition for EDE

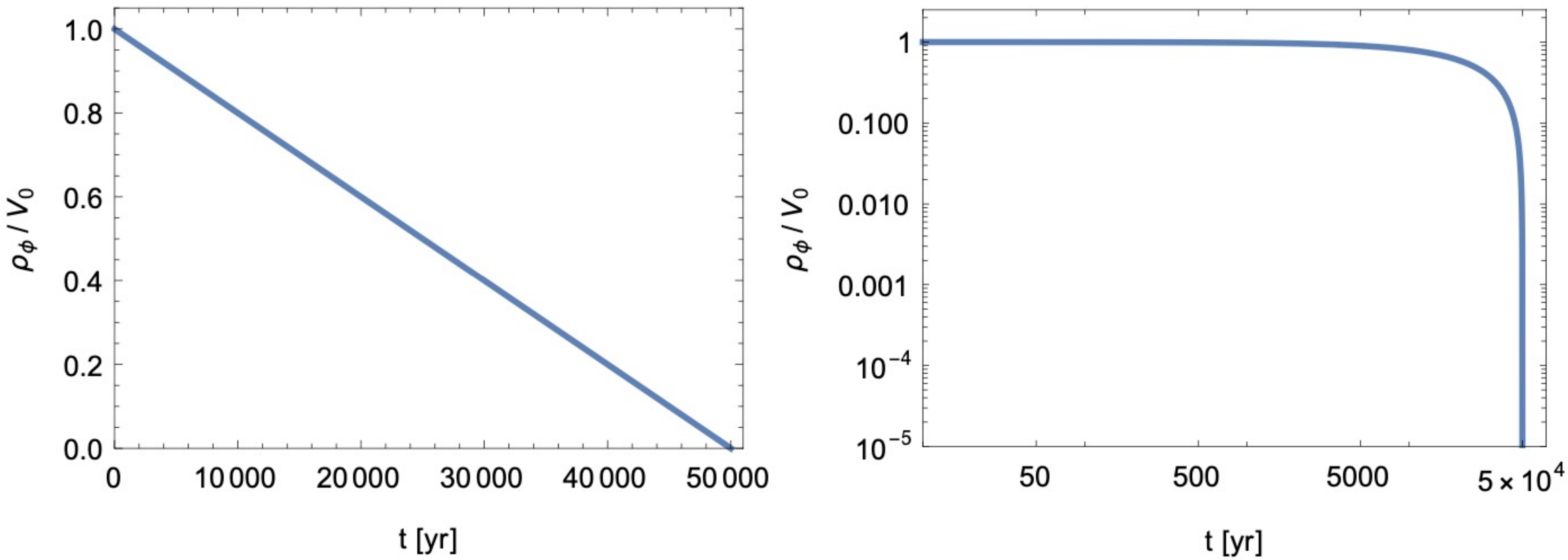
- Single phase transition doesn't work, due to large anisotropies produced by large bubbles in conflict with CMB
- Just as in inflation, need fast phase transition right at z*
- two ways to do it.
- Double Field (based on Adams and Freese 1990;
- Sloth and Niedermann call it New EDE)
- Chain EDE: series of phase transitions (Freese and Winkler 2021)

Chain EDE



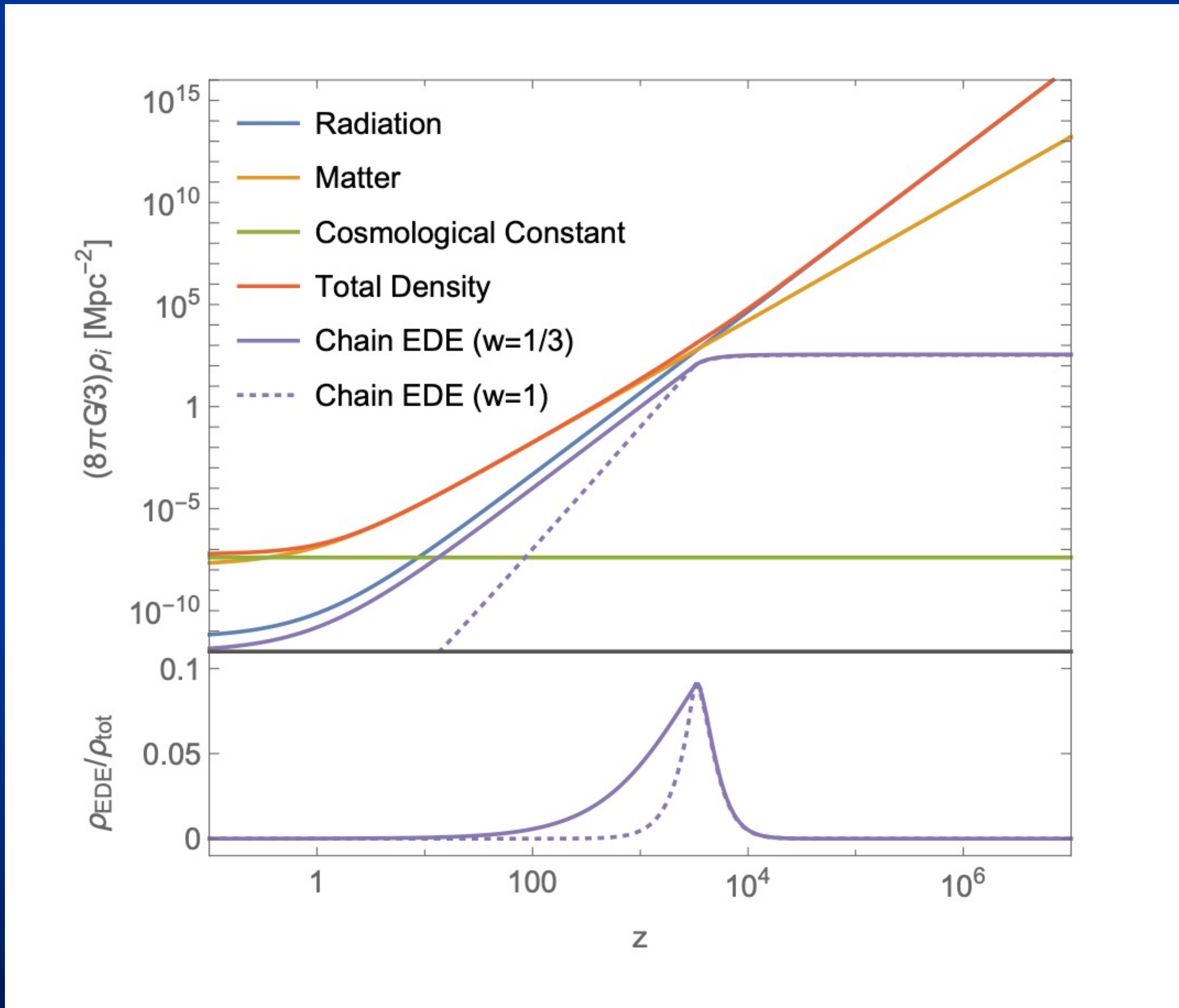
K. Freese and Martin Winkler
arXiv: 2102.13655

Chain EDE: Automatically get right behavior of vacuum energy with time.

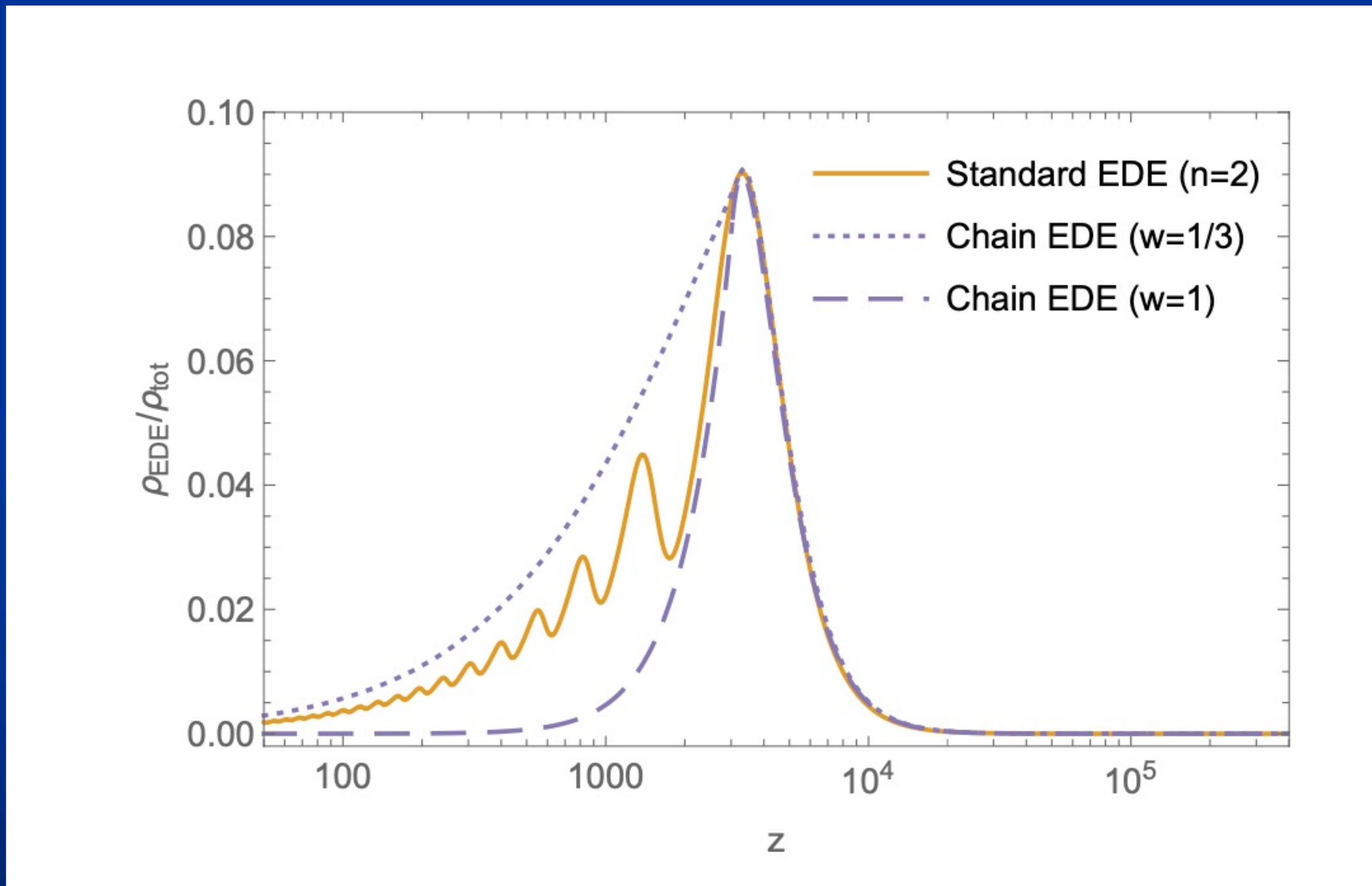


a linear decrease of ρ_ϕ looks almost like a step-function in a log-log plot

Our Final Result



Comparing to previous EDE models (which match all data)



Standard EDE (n=2) has been shown to fit CMB, BAO, SN with

$H_0 \simeq 71.6\,\mathrm{km\ s^{-1}\ Mpc^{-1}}$ In agreement with local measurements

Early Dark Energy as a proposed resolution to the Hubble Tension

- $H0 \simeq 67$ km $s{-}1$ $Mpc{-}1$ inferred from CMB

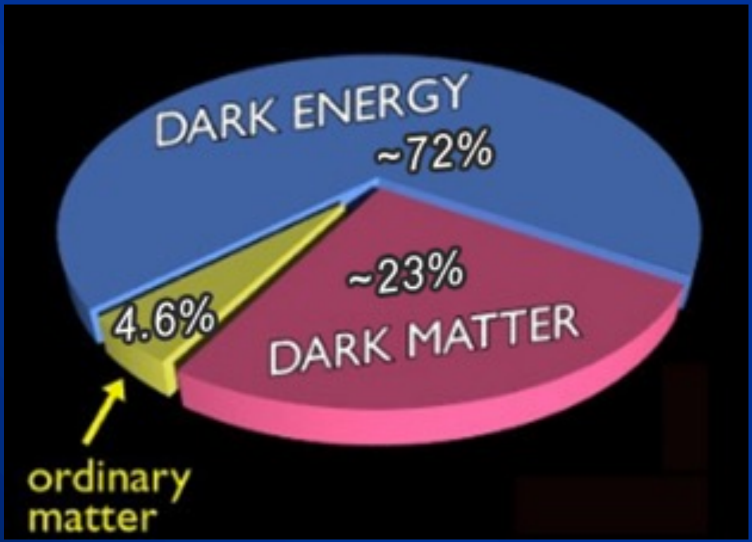
  vs

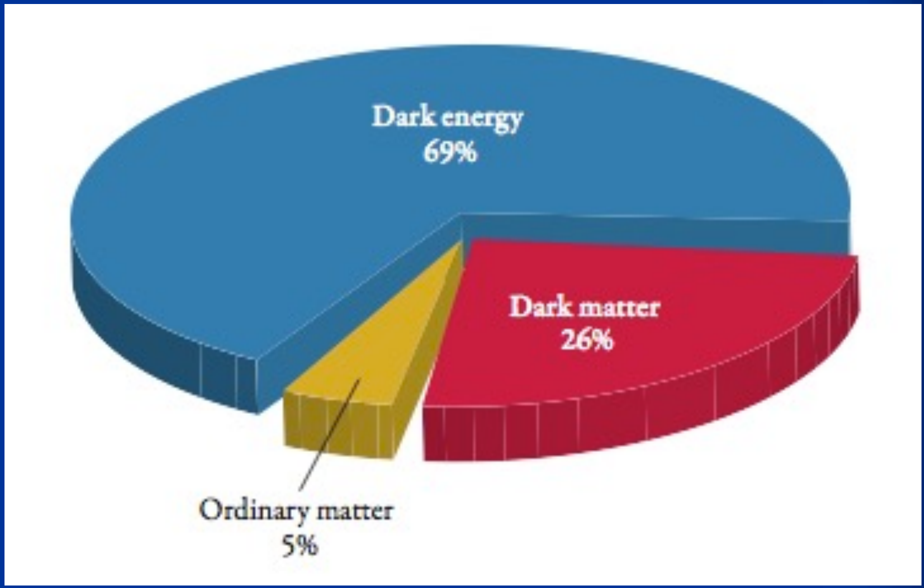
  $H0 \simeq 74$ km $s{-}1$ $Mpc{-}1$ from late time measurements e.g. supernova redshifts

Tantalizing: a cosmological constant that shuts off right at matter/radiation equality

II. More Dark Matter (Planck vs. WMAP)

- WMAP: 4.7% baryons, 23% DM, 72% dark energy
- PLANCK: 4.9% baryons, 26% DM, 69% dark energy





Less than 5% ordinary matter.

What is the dark matter? What is the dark energy?

What is the Dark Matter? Candidates:

- Top candidates for Dark Matter:
- WIMPs (SUSY or extra dimensions)
- Axions (exist automatically in solution to strong CP problem)
- ---
- Neutrinos (too light, ruin galaxy formation)
- Sterile Neutrinos: no Standard Model interaction
- Primordial Black Holes
- Asymmetric Dark Matter
- Light Dark Matter
- Self Interacting Dark Matter
- Q-balls
- Scalar Field Dark matter

Neutrinos as Dark Matter? No But cosmology teaches us about the mass!

- Nearly relativistic, move large distances, destroy clumps of mass smaller than clusters
- Too light,

$$\Omega_\nu h^2 = \frac{\sum m_\nu}{93.5\mathrm{eV}}$$

- 50 eV neutrinos would “close” the Universe.
- BUT
- The sum of the neutrino masses adds to roughly 0.1 eV
- Neutrinos contribute ½% of the mass of the Universe.

NEUTRINO MASS

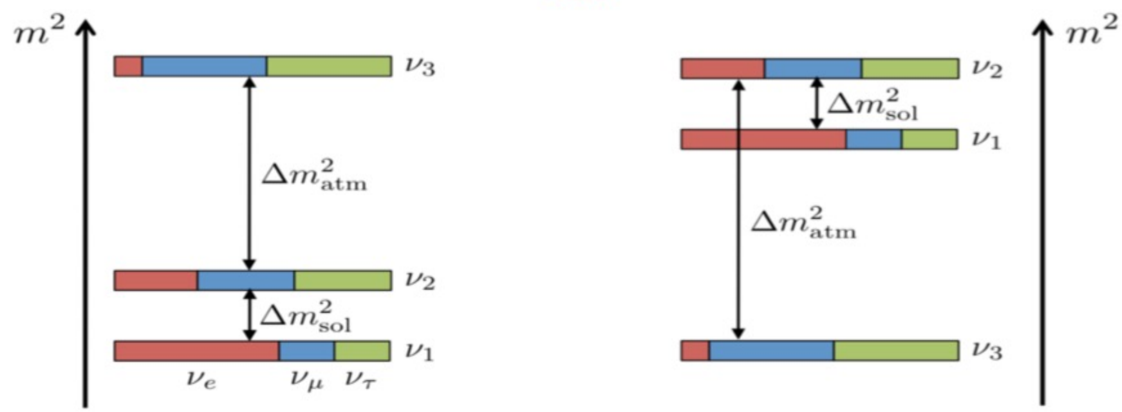
We know from the observation of neutrino oscillations that neutrinos have mass (Nobel prize 2015 to Kajita & McDonald!)
However, oscillations measure mass ***differences*** (with few % accuracy):

$\Delta m^2_{21} = 7.6 \times 10^{-5}\ \mathrm{eV}^2$

$|\Delta m^2_{31}| = 2.5 \times 10^{-3}\ \mathrm{eV}^2$ (NH)
$2.4 \times 10^{-3}\ \mathrm{eV}^2$ (IH)

We do not know yet the mass pattern (hierarchy) nor the absolute mass scale

normal hierarchy (NH) **vs.** **inverted hierarchy (IH)**



$\Sigma m_\nu > 0.06$ eV

$\Sigma m_\nu > 0.10$ eV

Oscillations put a ***lower limit*** on the mass scale

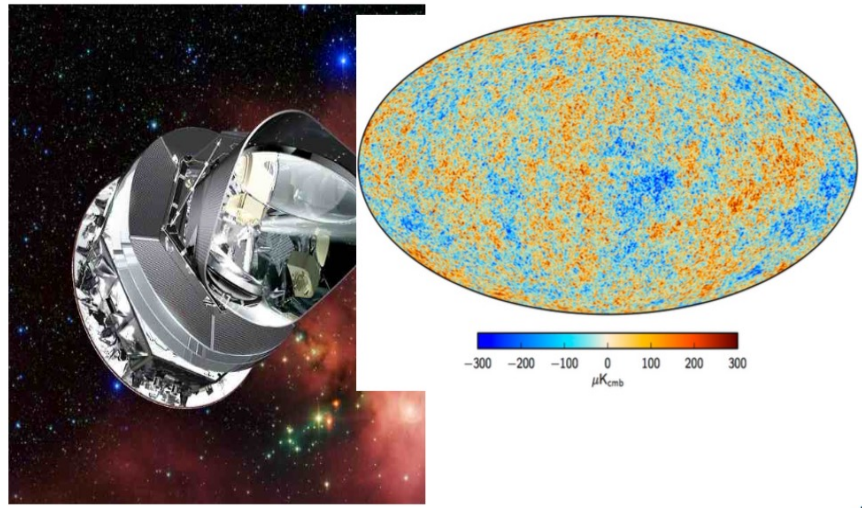
(depending on the hierarchy)

Figure credit: Juno Collaboration

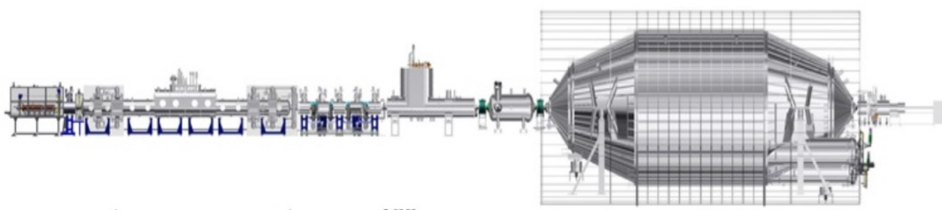
The tiny neutrino masses are a puzzle for the Standard Model of particle physics

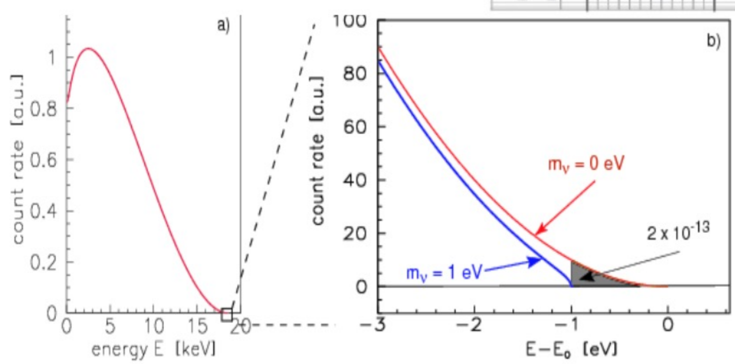
The absolute scale of neutrino masses can be measured in different ways

Cosmological observations (CMB, LSS)

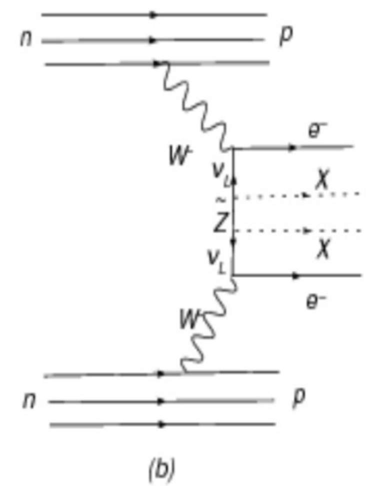


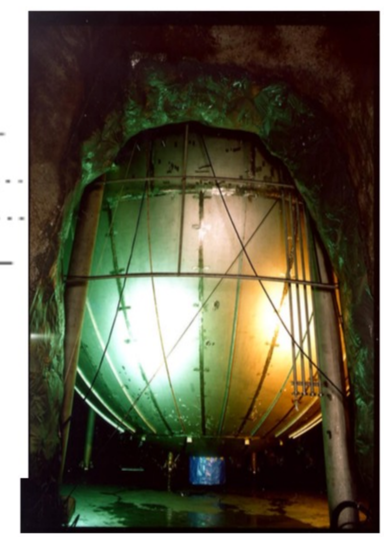
Neutrinoless double β decay



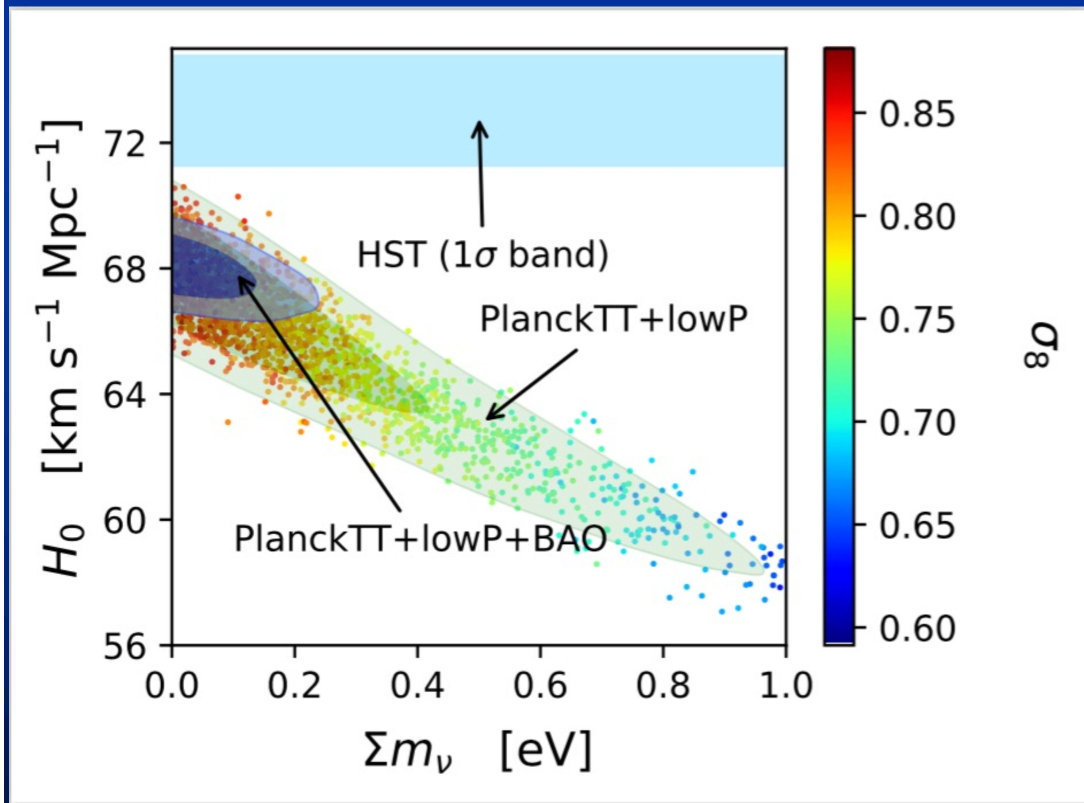


Kinematic measuremets (Tritium β decay)





Cosmological data (CMB plus large scale structure) bound neutrino mass



$$\sum m_\nu < 0.15 \text{ eV}$$
at 95% C.L.

Vagnozzi, Gerbino, KF etal
arXIv:1701.0872

Planck Satellite: < 0.12 eV

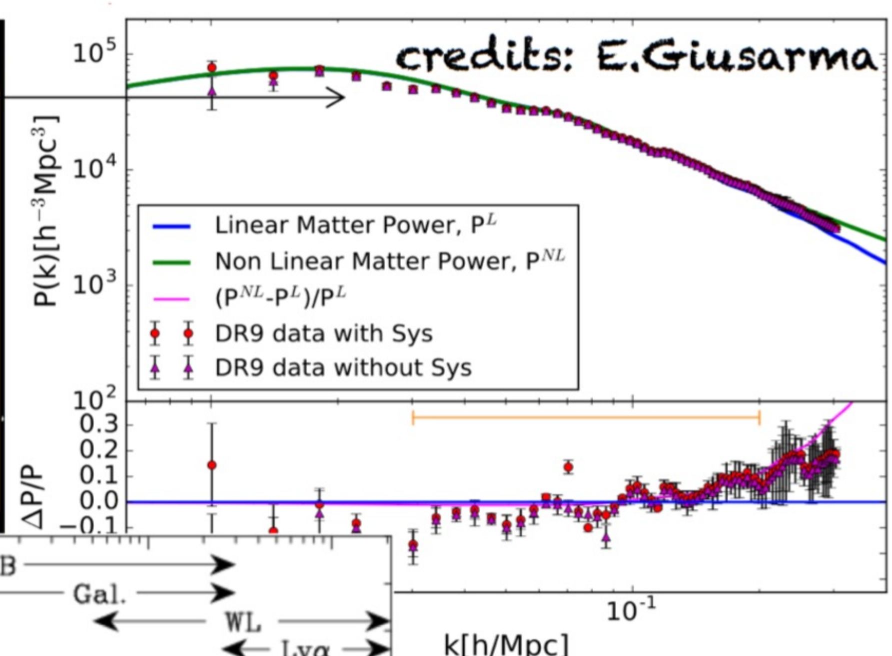
Assumes standard Lambda CDM
If w>-1, stronger bounds

From oscillations: >0.06 eV

Giusarma, KF etal arXiv:1405:04320
Neutrino Properties in Particle Data Group's Review of Particle Properties

LARGE SCALE STRUCTURES

Full shape of the matter power spectrum:
Power at small scales is affected by the presence of neutrinos (due to free streaming)
issues: non-linearities, scale-dependent bias



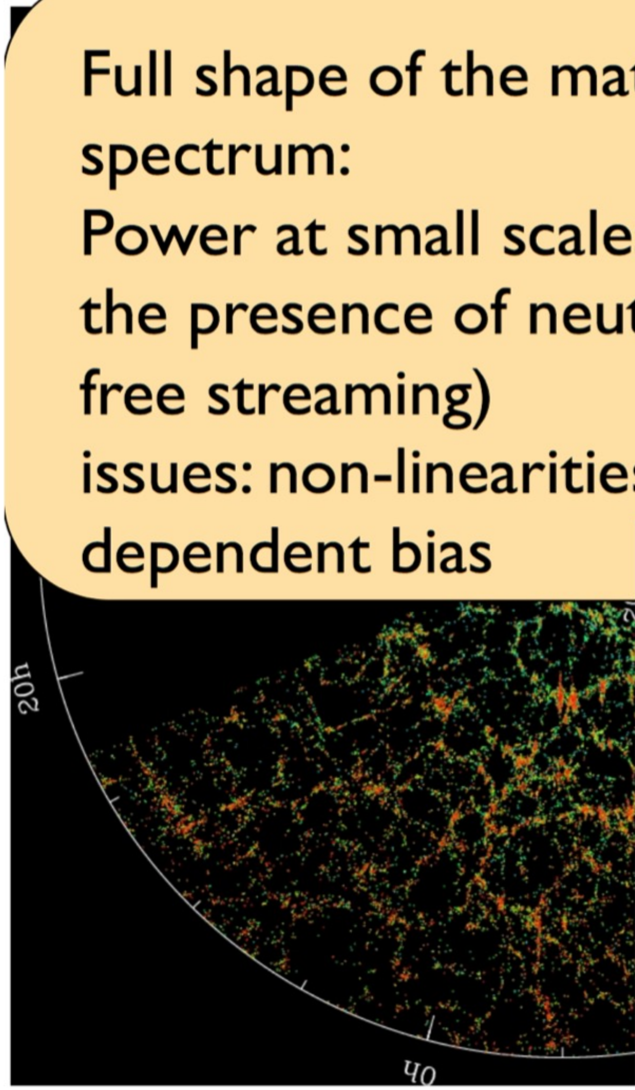
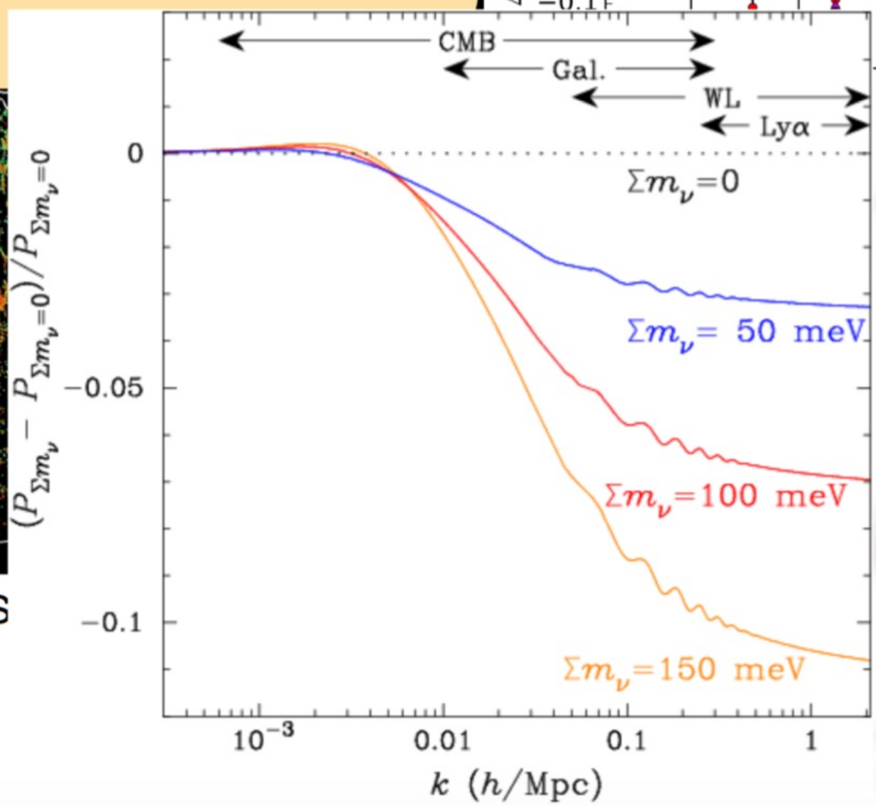


Image Credit: M. Blanton and the S

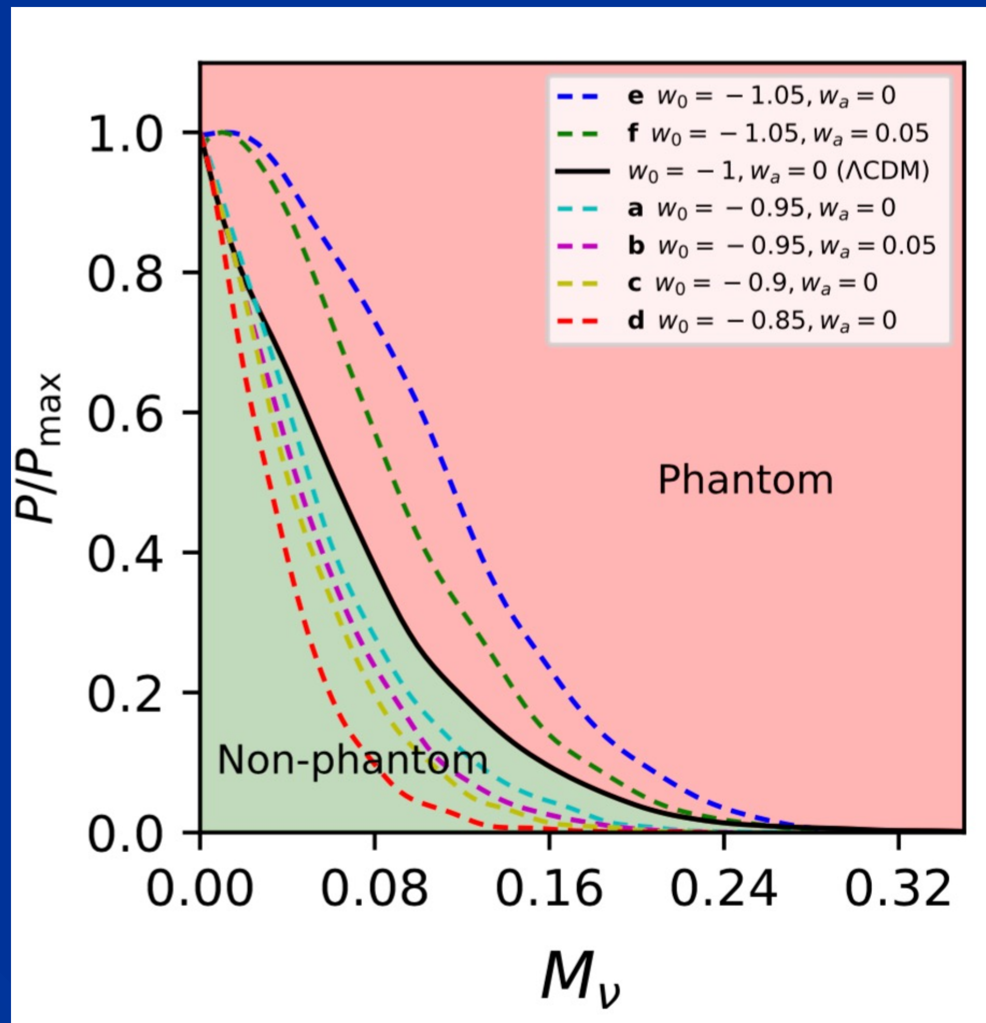


Eisenstein et al (2005)

Neutrino Mass bounds are valid beyond LCDM. In fact they're tighter for arbitrary dark energy with w>-1 (nonphantom) than for Lambda CDM.

MARTINA GERBINO

SUNNY VAGNOZZI



Vagnozzi, Gerbino, KF, etal http://lanl.arxiv.org/pdf/1801.08553

Neutrino Mass close to being measured (for the 3 active neutrinos)

- From oscillation experiments:

- $\sum m_\nu$ > 0.06 eV (Normal Hierarchy)
- > 0.1 eV (Inverted Hierarchy)

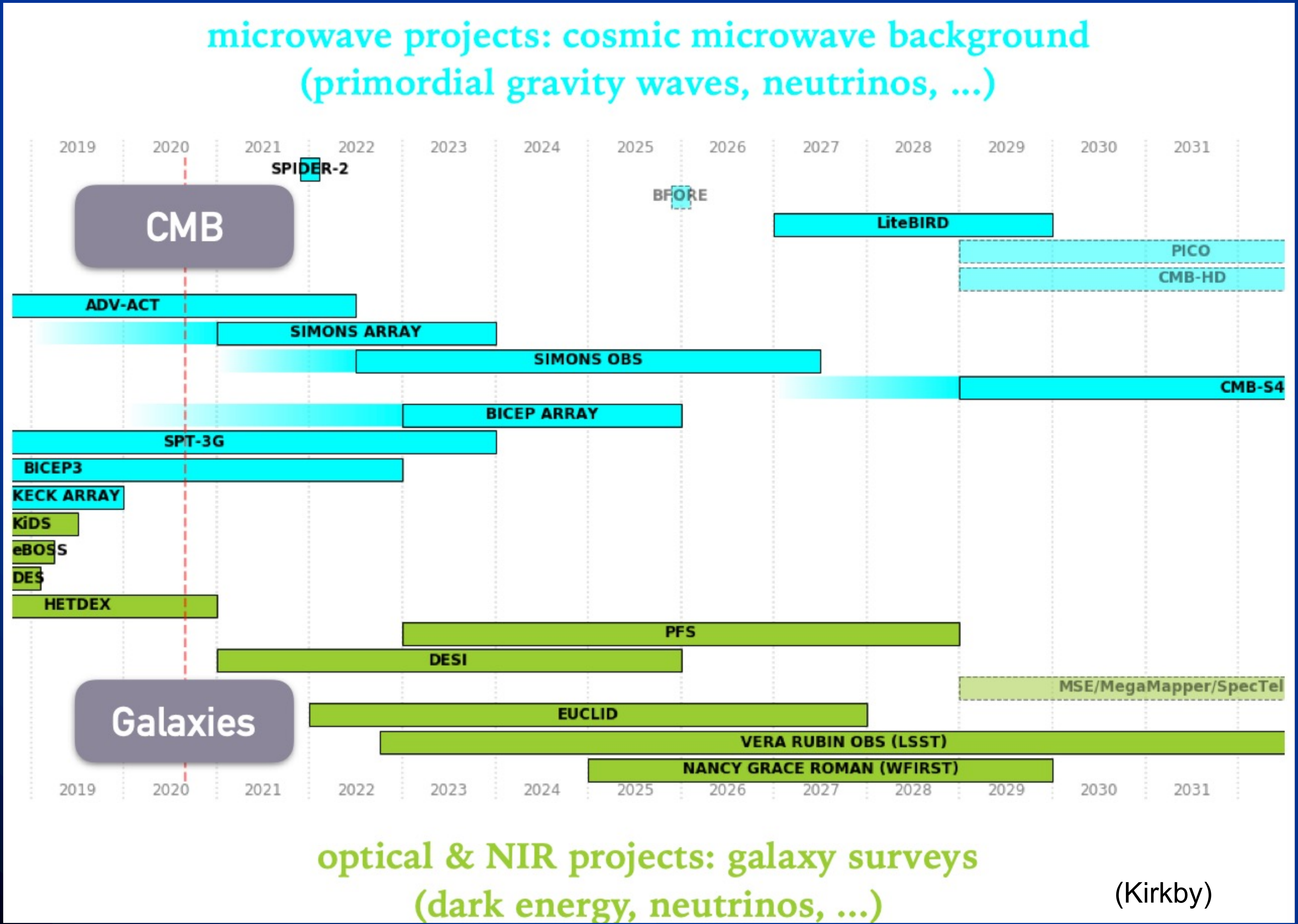
- From cosmology (CMB + Large Scale Structure +BAO)

$\sum m_\nu$ < 0.15 eV at 95% C.L.

Vagnozzi, Gerbino, KF etal
arXiv:1701.0872

Planck Satellite: < 0.12 eV

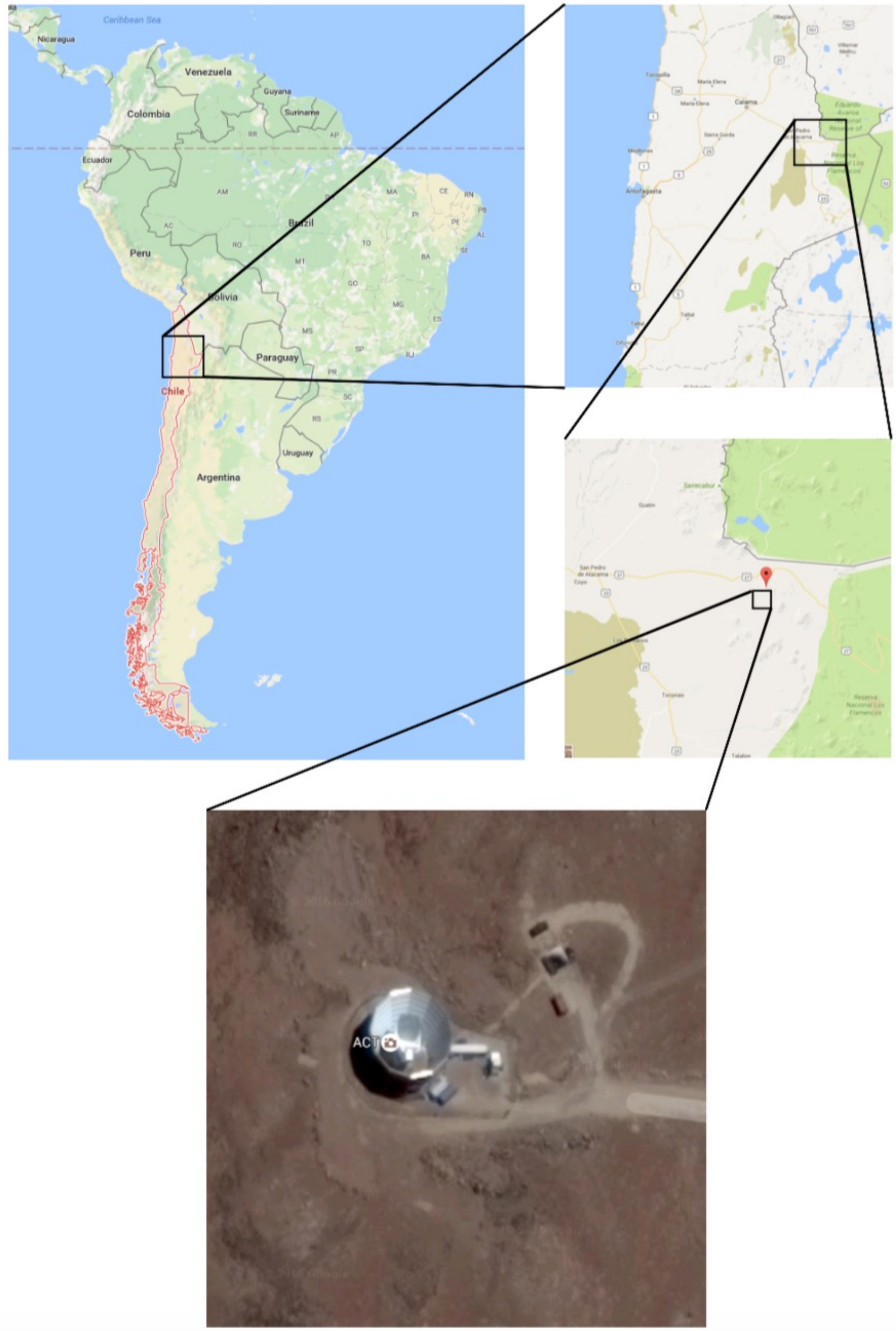
Cosmological Observations in 2020s



Simons Observatory

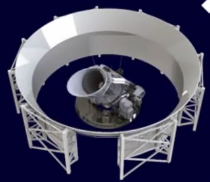
- The Simons Observatory will be located in the high Atacama Desert in Northern Chile at 5,200 meters (17,000 ft) above sea level.

- The large existing structure is the Atacama Cosmology Telescope (ACT) and the smaller ones are PolarBear/Simons Array



Simons Observatory

2018 2019 2020 2021 2022 2023



Small aperture telescope platform

Design	Manufacture	Validation	Ship and site testing

Small aperture telescope 1

Design	Manufacture	Validation	Integration and testing	Ship and site testing

Scientific Observations

- Analysis pipeline development
- Calibration strategy

Simons Observatory Science Goals

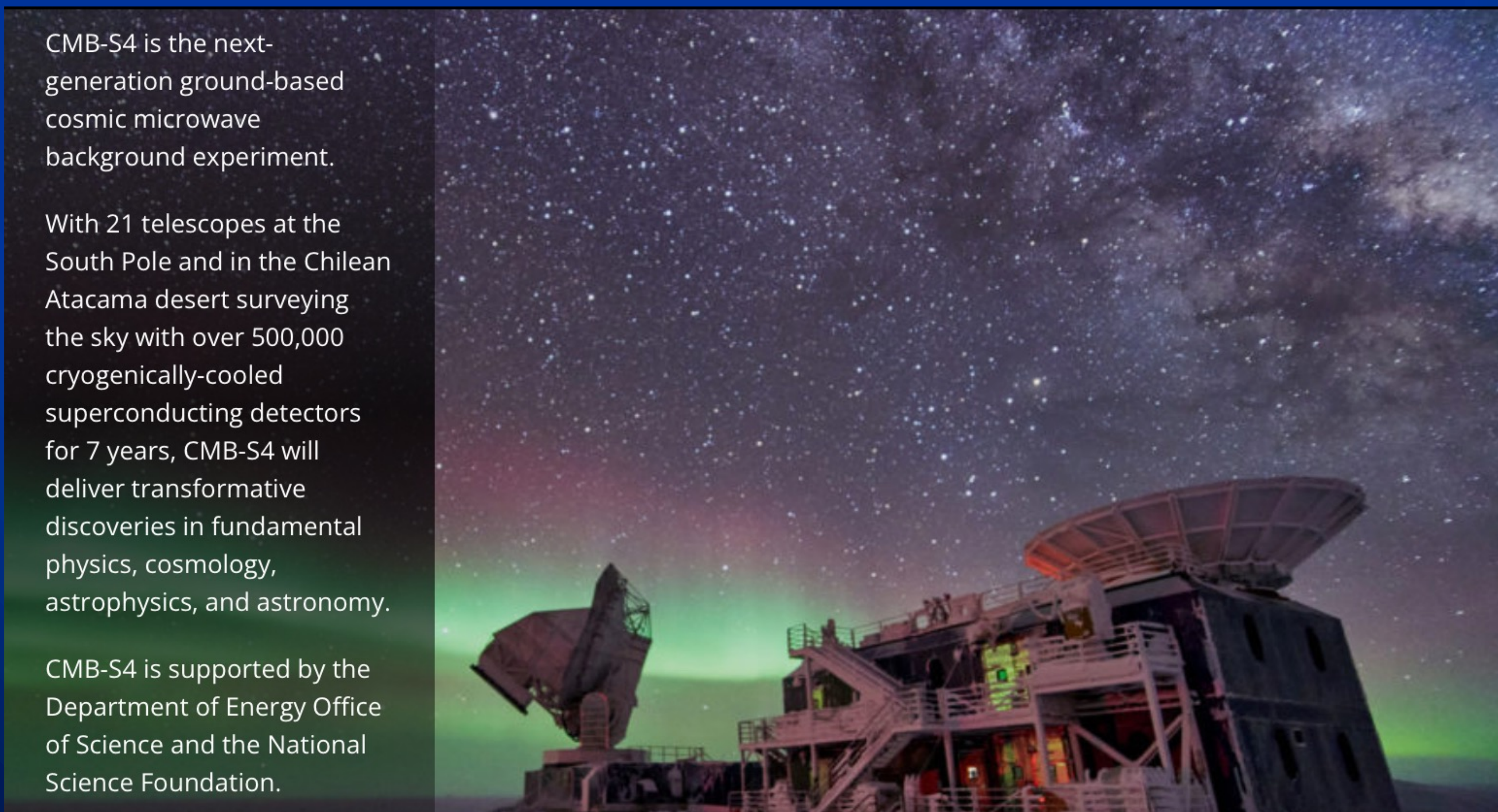
Table 9
Summary of SO key science goals[a]

	Parameter	SO-Baseline[b] (no syst)	**SO-Baseline**[c]	SO-Goal[d]	Current[e]	Method
Primordial perturbations	r	0.0024	**0.003**	0.002	0.03	BB + ext delens
	$e^{-2\tau}\mathcal{P}(k=0.2/\mathrm{Mpc})$	0.4%	**0.5%**	0.4%	3%	$TT/TE/EE$
	$f_{\mathrm{NL}}^{\mathrm{local}}$	1.8	**3**	1	5	$\kappa\kappa \times$ LSST-LSS + 3-pt
		1	**2**	1		kSZ + LSST-LSS
Relativistic species	N_{eff}	0.055	**0.07**	0.05	0.2	$TT/TE/EE + \kappa\kappa$
Neutrino mass	Σm_ν	0.033	**0.04**	0.03	0.1	$\kappa\kappa$ + DESI-BAO
		0.035	**0.04**	0.03		tSZ-N $\times$ LSST-WL
		0.036	**0.05**	0.04		tSZ-Y + DESI-BAO
Deviations from Λ	$\sigma_8(z=1-2)$	1.2%	**2%**	1%	7%	$\kappa\kappa$ + LSST-LSS
		1.2%	**2%**	1%		tSZ-N $\times$ LSST-WL
	H_0 (ΛCDM)	0.3	**0.4**	0.3	0.5	$TT/TE/EE + \kappa\kappa$
Galaxy evolution	η_{feedback}	2%	**3%**	2%	50-100%	kSZ + tSZ + DESI
	p_{nt}	6%	**8%**	5%	50-100%	kSZ + tSZ + DESI
Reionization	Δz	0.4	**0.6**	0.3	1.4	TT (kSZ)

[a] All of our SO forecasts assume that SO is combined with *Planck* data.

Detection of "r" would be detection of gravitational waves from inflation: Smoking gun for inflation? Would tell us which model is right and would be a probe of physics possibly all the way to the Planck scale.

CMB S4 (next generation)



What is the Dark Matter? Candidates:

- Cold Dark Matter candidates w/ strong theoretical motivation:
- WIMPs (SUSY or extra dimensions)
- Axions (exist automatically in solution to strong CP problem)
- ---
- Neutrinos (too light, ruin galaxy formation)
- Sterile Neutrinos: no Standard Model interaction
- Primordial black holes
- Asymmetric Dark Matter
- Light Dark Matter
- Self Interacting Dark Matter
- Q-balls
- WIMPzillas

Florian Kuhnel
Primordial
Black Holes

Primordial Black Holes in LIGO

Did LIGO detect dark matter?

Simeon Bird,* Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, and Adam G. Riess[1]

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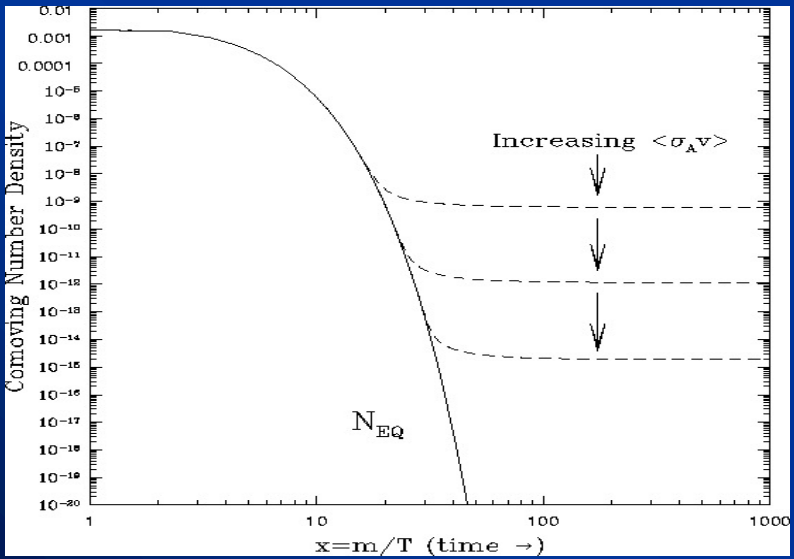
We consider the possibility that the black-hole (BH) binary detected by LIGO may be a signature of dark matter. Interestingly enough, there remains a window for masses $20\,M_\odot \lesssim M_{\rm bh} \lesssim 100\,M_\odot$ where primordial black holes (PBHs) may constitute the dark matter. If two BHs in a galactic halo pass sufficiently close, they radiate enough energy in gravitational waves to become gravitationally bound. The bound BHs will rapidly spiral inward due to emission of gravitational radiation and ultimately merge. Uncertainties in the rate for such events arise from our imprecise knowledge of the phase-space structure of galactic halos on the smallest scales. Still, reasonable estimates span a range that overlaps the $2-53$ Gpc^{-3} yr^{-1} rate estimated from GW150914, thus raising the possibility that LIGO has detected PBH dark matter. PBH mergers are likely to be distributed spatially more like dark matter than luminous matter and have no optical nor neutrino counterparts. They may be distinguished from mergers of BHs from more traditional astrophysical sources through the observed mass spectrum, their high ellipticities, or their stochastic gravitational wave background. Next generation experiments will be invaluable in performing these tests.

30 May 2016

Dark Matter: Good news: cosmologists don't need to "invent" new particle

- Weakly Interacting Massive Particles (WIMPS). e.g.,neutralinos



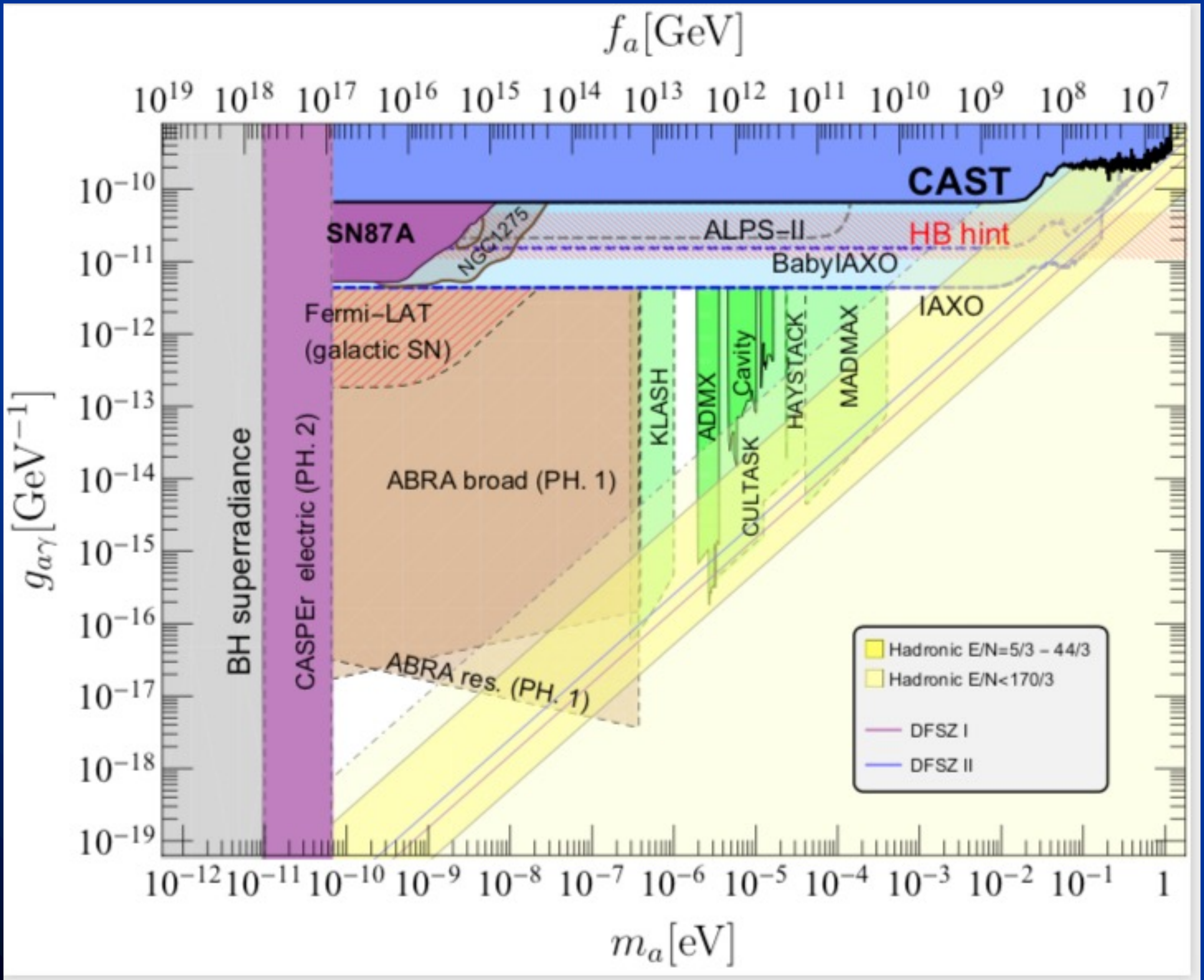
- Axions

$m_a \sim 10^{-(3\text{-}6)}$ eV

arise in Peccei-Quinn solution to strong-CP problem

(Weinberg; Wilczek; Dine, Fischler, Srednicki; Zhitnitskii)

Bounds on Axions and ALPs



From review by
Luca Visinelli
2003.01100

Among theTop candidates for Dark Matter : WIMPs

- Weakly Interacting Massive Particles
- Billions pass through your body every second (one a day—month hits)
- No strong nuclear forces
- No electromagnetic forces
- Yes, they feel gravity
- Of the four fundamental forces, the other possibility is weak interactions
- Weigh 1-10,000 GeV

Two reasons we favor WIMPs: First, the relic abundance

Weakly Interacting Massive Particles Many are their own antipartners. Annihilation rate in the early universe determines the density today.

$$\Omega_\chi h^2 = \frac{3\times 10^{-27}\ cm^3/\sec}{<\sigma v>_{ann}}$$

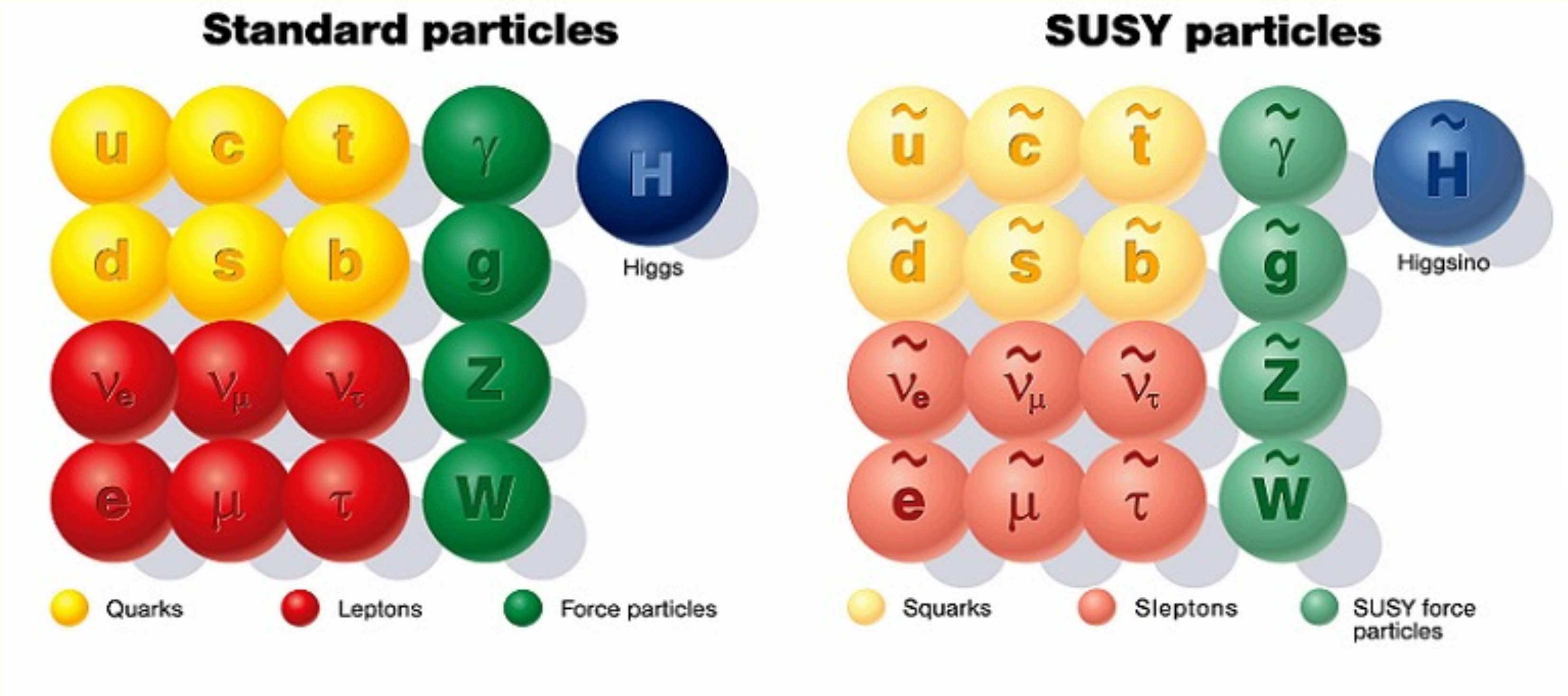
n.b. thermal WIMPs

This is the mass fraction of WIMPs today, and gives the right answer if the dark matter is weakly interacting

WIMP mass: GeV – 10 TeV

Second reason we favor WIMPS: in particle theories, eg supersymmetry

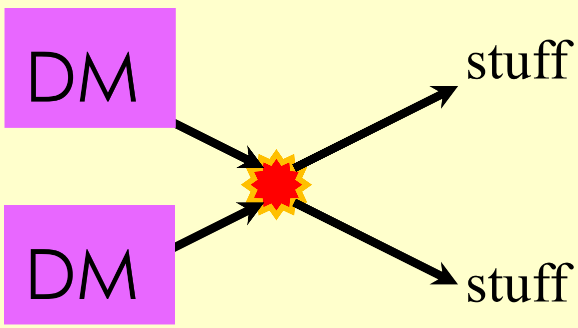
- Every particle we know has a partner



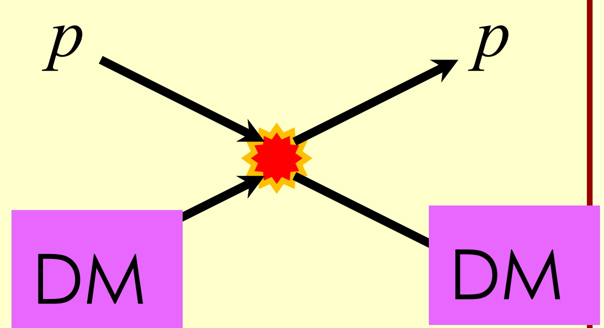
- The lightest supersymmetric particle may be the dark matter.

THREE PRONGED APPROACH TO WIMP DETECTION

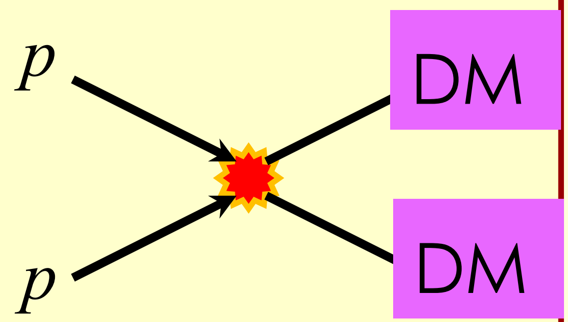
Interactions with Standard Model particles



Annihilation



Scattering



Production

Indirect Detection:
Halo (cosmic-rays),
capture in Sun (ν’s)

Direct Detection:
Look for scattering
events in detector

Accelerators:
LHC

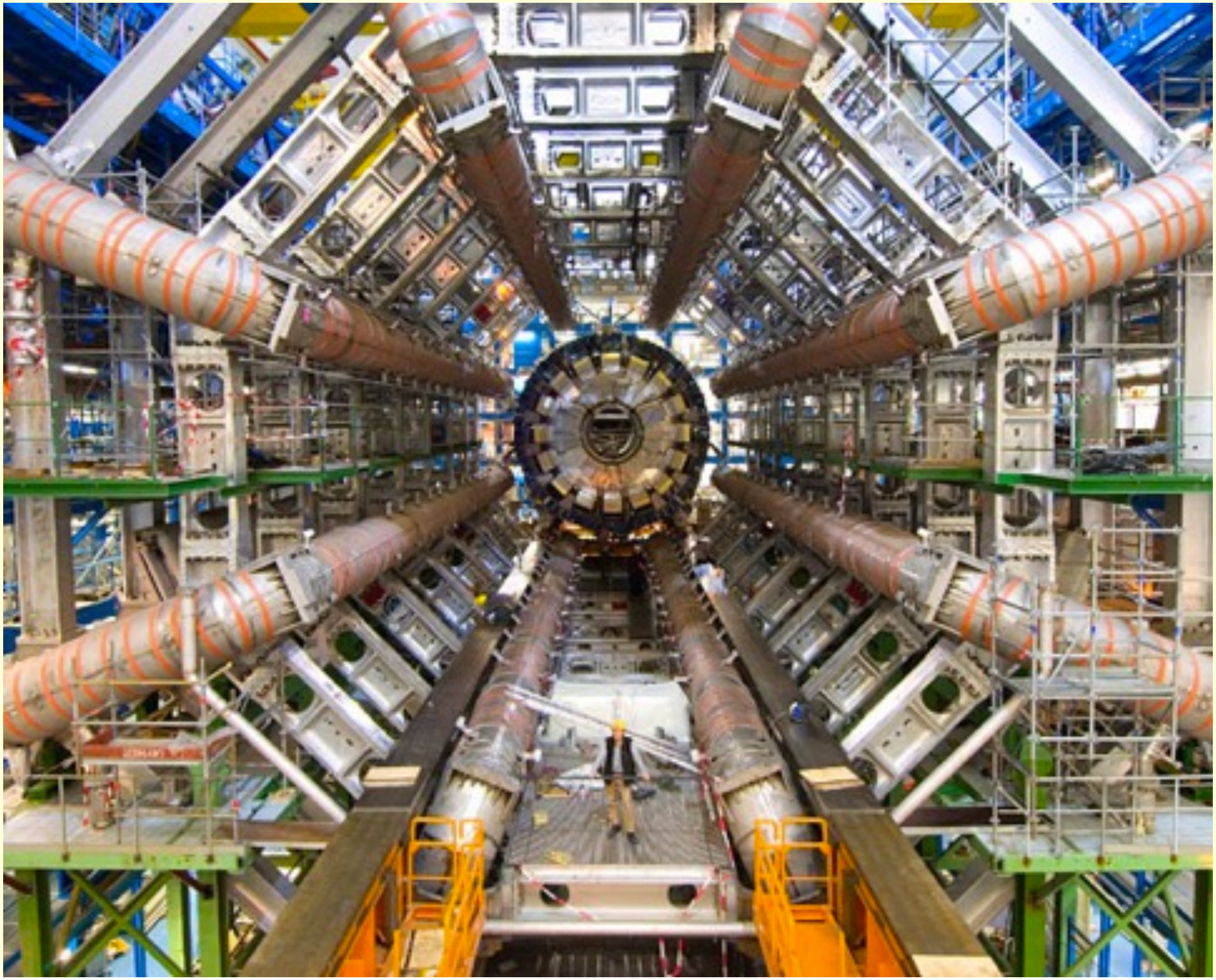
FOURTH PRONG: DARK STARS

FIRST WAY TO SEARCH FOR WIMPS

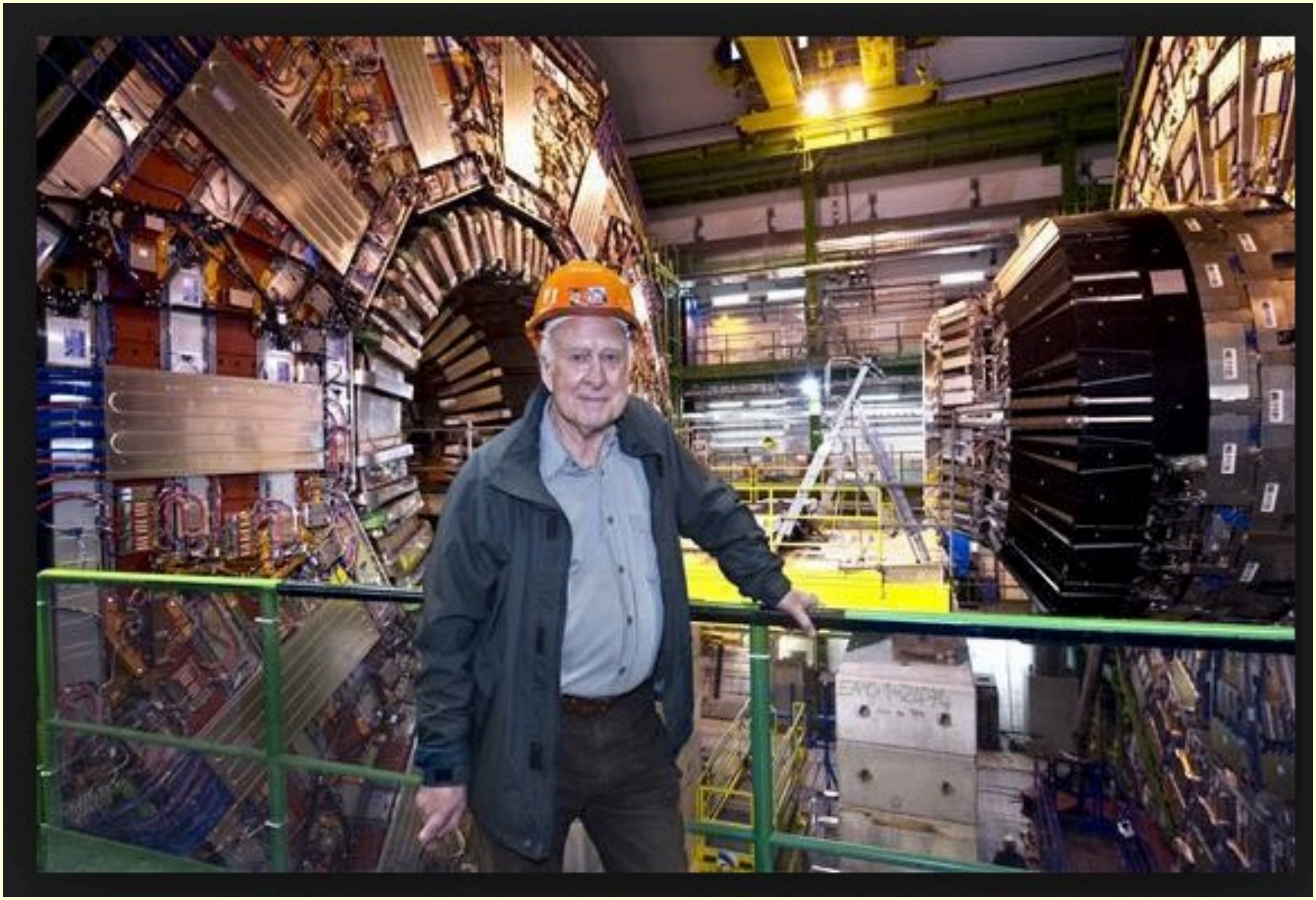
Ring that is 17 miles around.
Two proton beams traveling underground in opposite directions. Collide at four intersection points where there are detectors.

ATLAS detector:
Fabiola Gianotti, spokesperson for Higgs searches
now Director General at CERN

ATLAS Detector at CERN

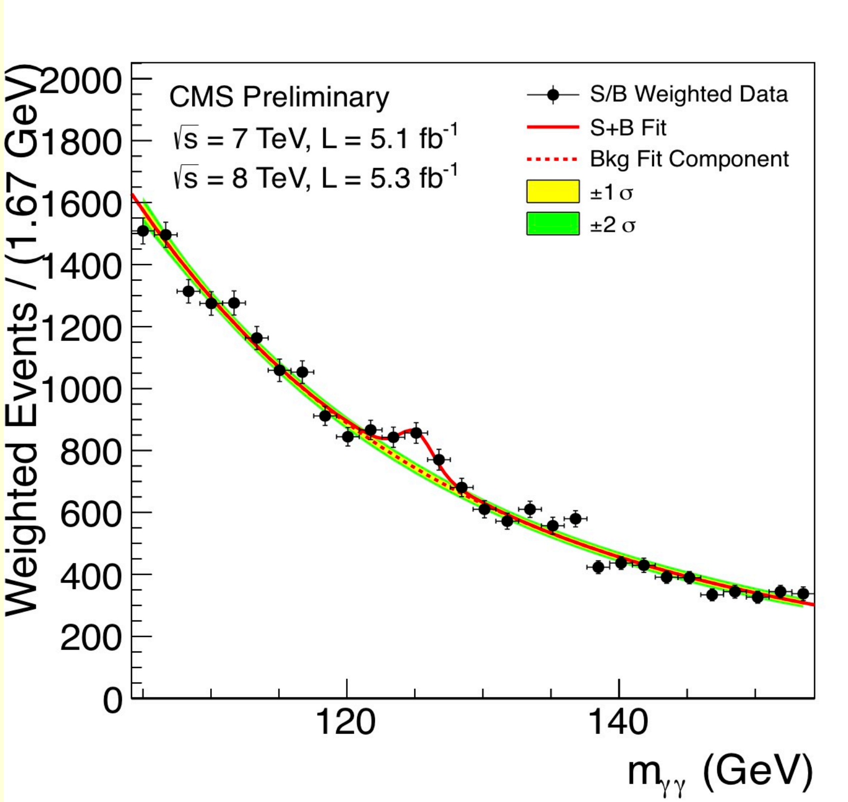


Peter Higgs and CMS detector



LHC's first success Discovery of Higgs boson

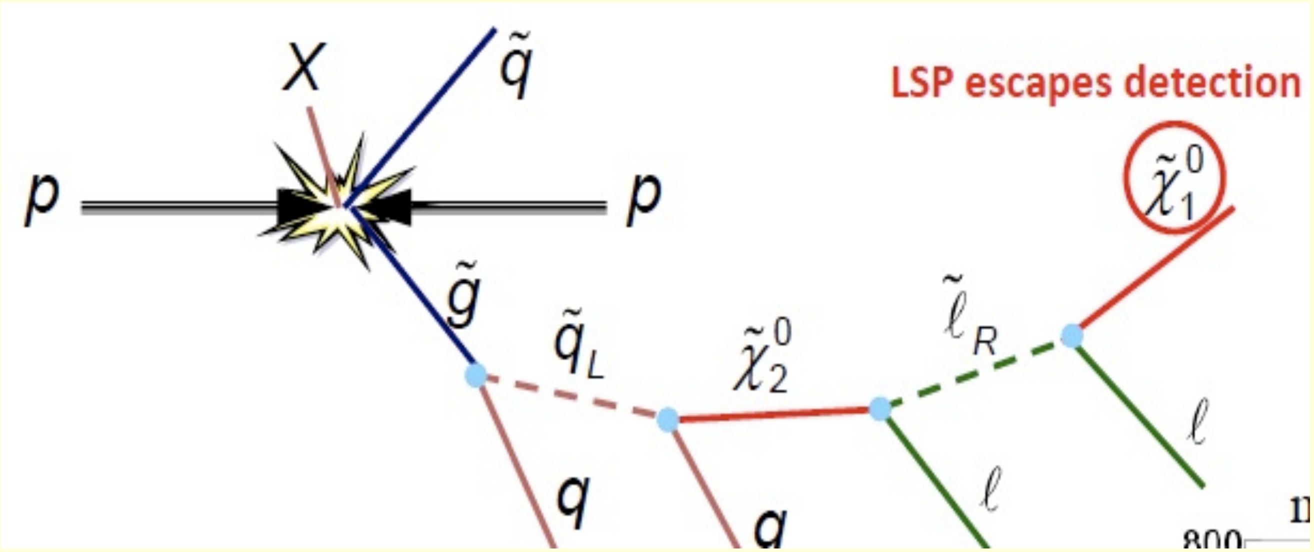
weighing 125 GeV



Key role of Higgs:
imparts mass
to other particles

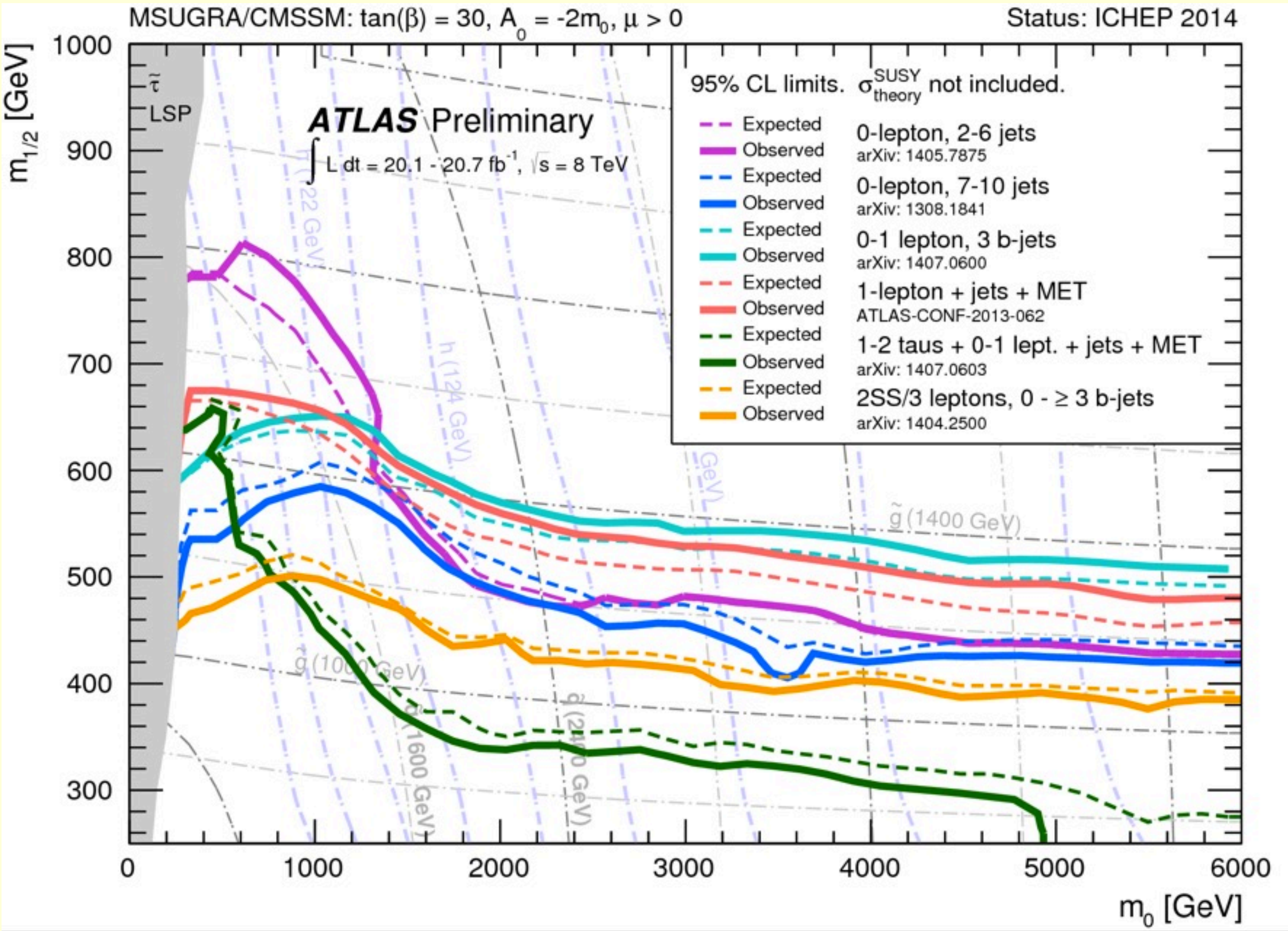
Second major goal of LHC: search for SUSY and dark matter

- Two signatures: Missing energy plus jets



- Nothing seen yet: particle masses pushed to higher masses

ATLAS bounds on CMSSM



Comments on DM at LHC

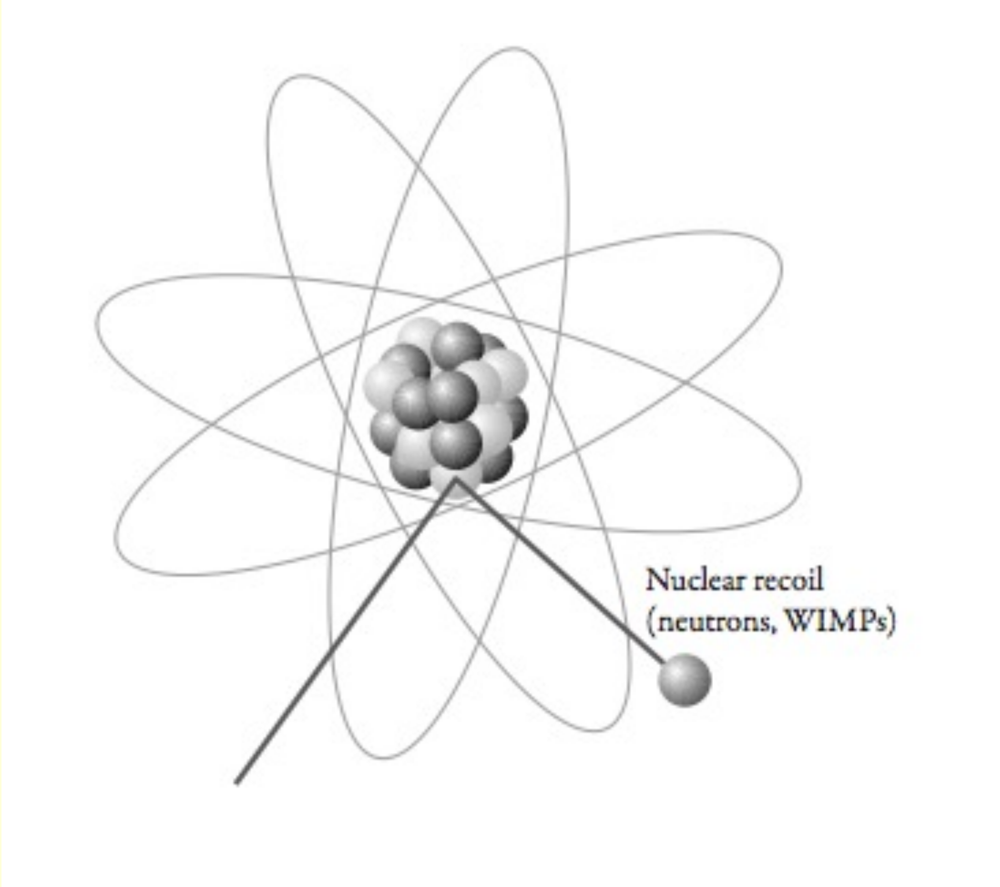
- If the LHC sees nothing, can SUSY survive? Yes.
- It may be at high scale,
- It may be less simple than all scalars and all fermions at one scale, e.g. NUHM (Pearl Sandick)
- Even is SUSY is found at LHC, we still won't know if particles are long-lived; to see if it's dark matter, need other approaches

SECOND WAY TO SEARCH FOR WIMPS

DIRECT DETECTION
Laboratory EXPERIMENTS

DIRECT DETECTION OF WIMP DARK MATTER

A WIMP in the Galaxy travels through our detectors. It hits a nucleus, and deposits a tiny amount of energy. The nucleus recoils, and we detect this energy deposit.



Expected Rate: less than one count/kg/day!

Drukier, Freese, & Spergel (1986)

We studied the WIMPs in the Galaxy and the particle physics of the interactions to compute expected count rates, and we proposed annual modulation to identify a WIMP signal

Event rate

(number of events)/(kg of detector)/(keV of recoil energy)

$$\frac{dR}{dE} = \int \frac{N_T}{M_T} \times \frac{d\sigma}{dE} \times nv\, f(v,t)\, d^3v$$

$$= \frac{\rho\sigma_0 F^2(q)}{2m\mu^2} \int_{v>\sqrt{ME/2\mu^2}} \frac{f(v,t)}{v} d^3v$$

Spin-independent $\sigma_0 = \frac{A^2\mu^2}{\mu_p^2}\sigma_p$

Spin-dependent $\sigma_0 = \frac{4\mu^2}{\pi} \left| \langle S_p \rangle G_p + \langle S_n \rangle G_n \right|^2$

Canonical DM distribution in halo

use a Maxwellian distribution, characterized by an rms velocity dispersion σ_v, to describe the WIMP speeds, and we will allow for the distribution to be truncated at some escape velocity $v_{\rm esc}$,

$$\widetilde{f}(\mathbf{v}) = \begin{cases} \frac{1}{N_{\rm esc}} \left(\frac{3}{2\pi\sigma_v^2}\right)^{3/2} e^{-3\mathbf{v}^2/2\sigma_v^2}, & \text{for } |\mathbf{v}| < v_{\rm esc} \\ 0, & \text{otherwise.} \end{cases}$$

Here

$$N_{\rm esc} = \mathrm{erf}(z) - 2z\exp(-z^2)/\pi^{1/2},$$

with $z \equiv v_{\rm esc}/\overline{v}_0$, is a normalization factor. The most probable speed,

$$\overline{v}_0 = \sqrt{2/3}\,\sigma_v,$$

Typical particle speed is about 270 km/sec.

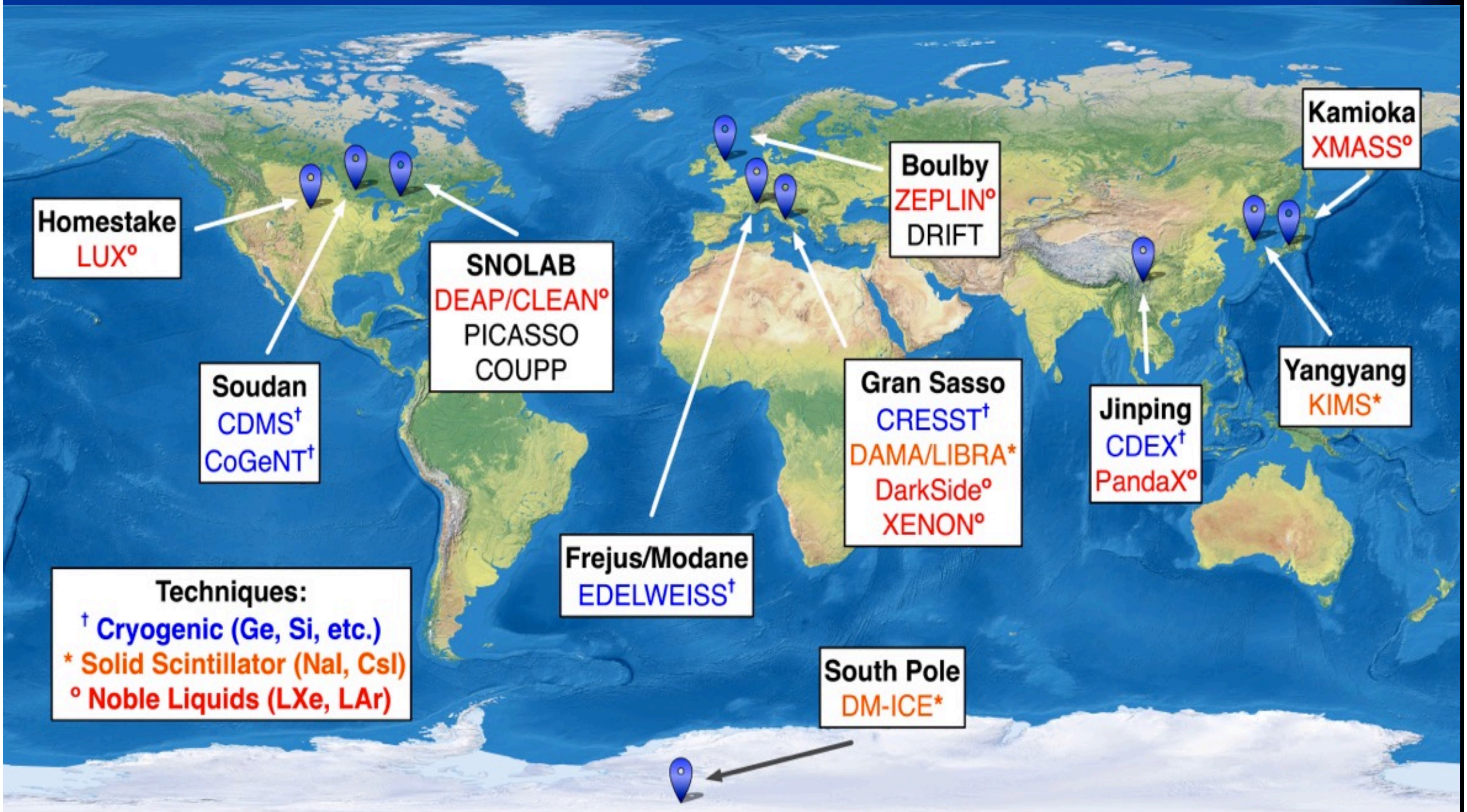
$$dR/dE \propto e^{-E/E_0}$$

$$E_0 = 2\mu^2 v_c^2/M \text{ so}$$

WIMP detectors must be in underground laboratories

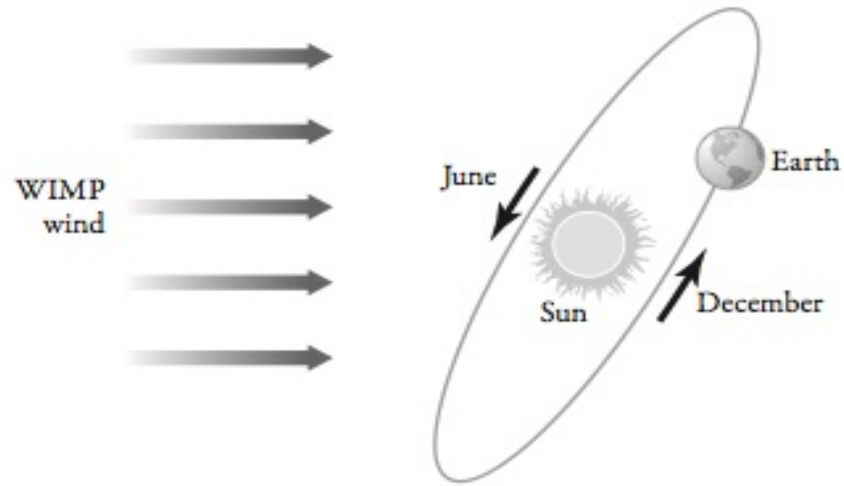
SNOLAB in a mine in Canada, 2 km below ground,
reduces cosmic rays that would overwhelm the detector
by a factor of 50 million.   Location of SUPERCDMS experiment.

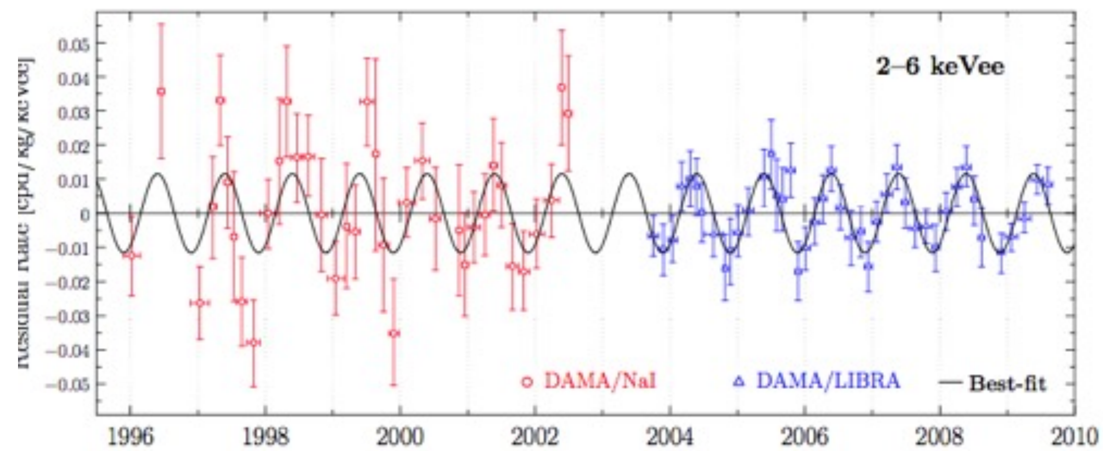
UNDERGROUND DARK MATTER LABORATORIES WORLDWIDE



DAMA annual modulation

Drukier, Freese, and Spergel (1986);
Freese, Frieman, and Gould (1988)

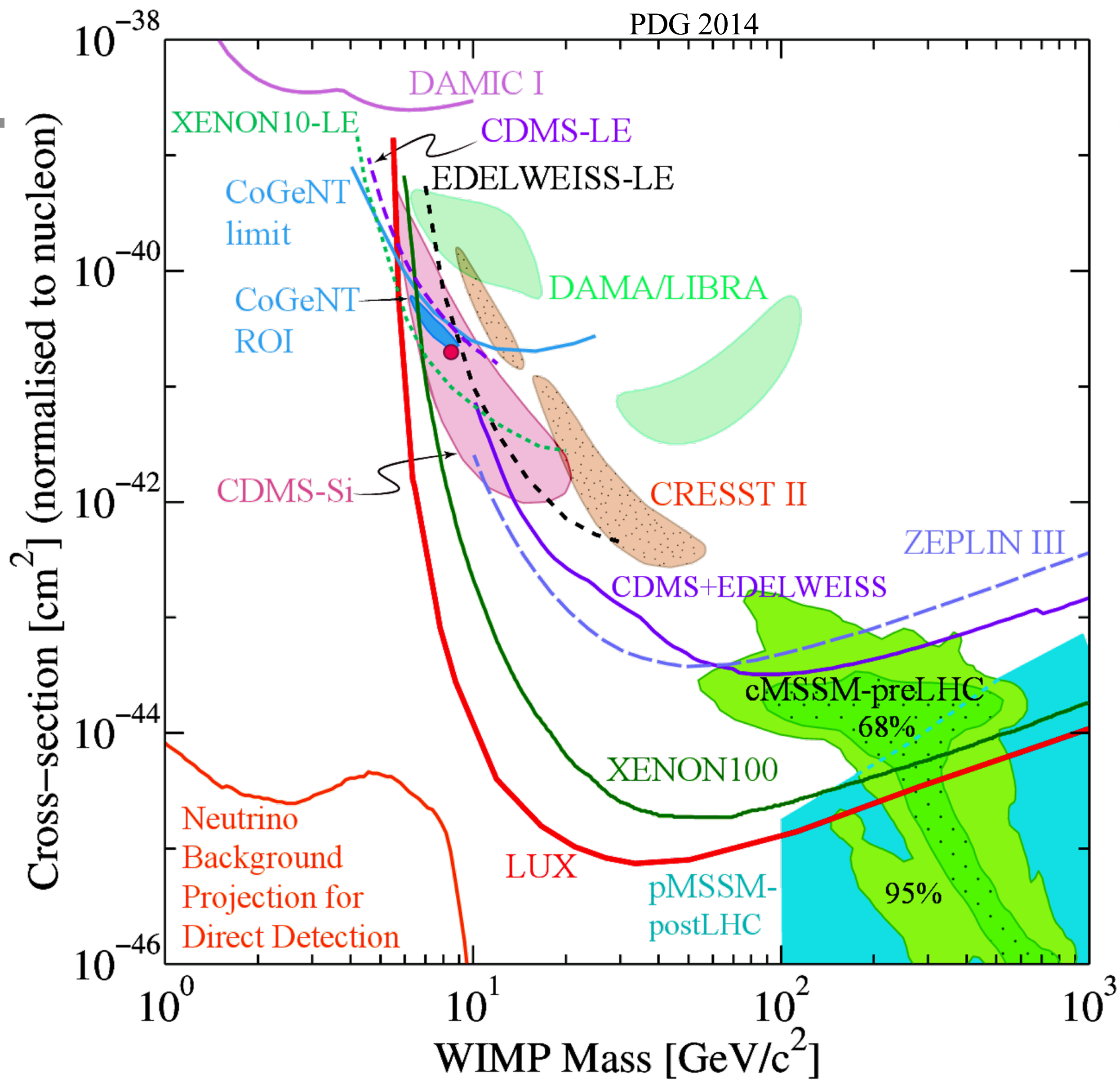




NaI crystals in Gran Sasso Tunnel under the Apennine Mountains near Rome.

Data do show modulation at 12 sigma! Peak in June, minimum in December (as predicted). Are these WIMPs??

Bounds on Spin Independent WIMPs

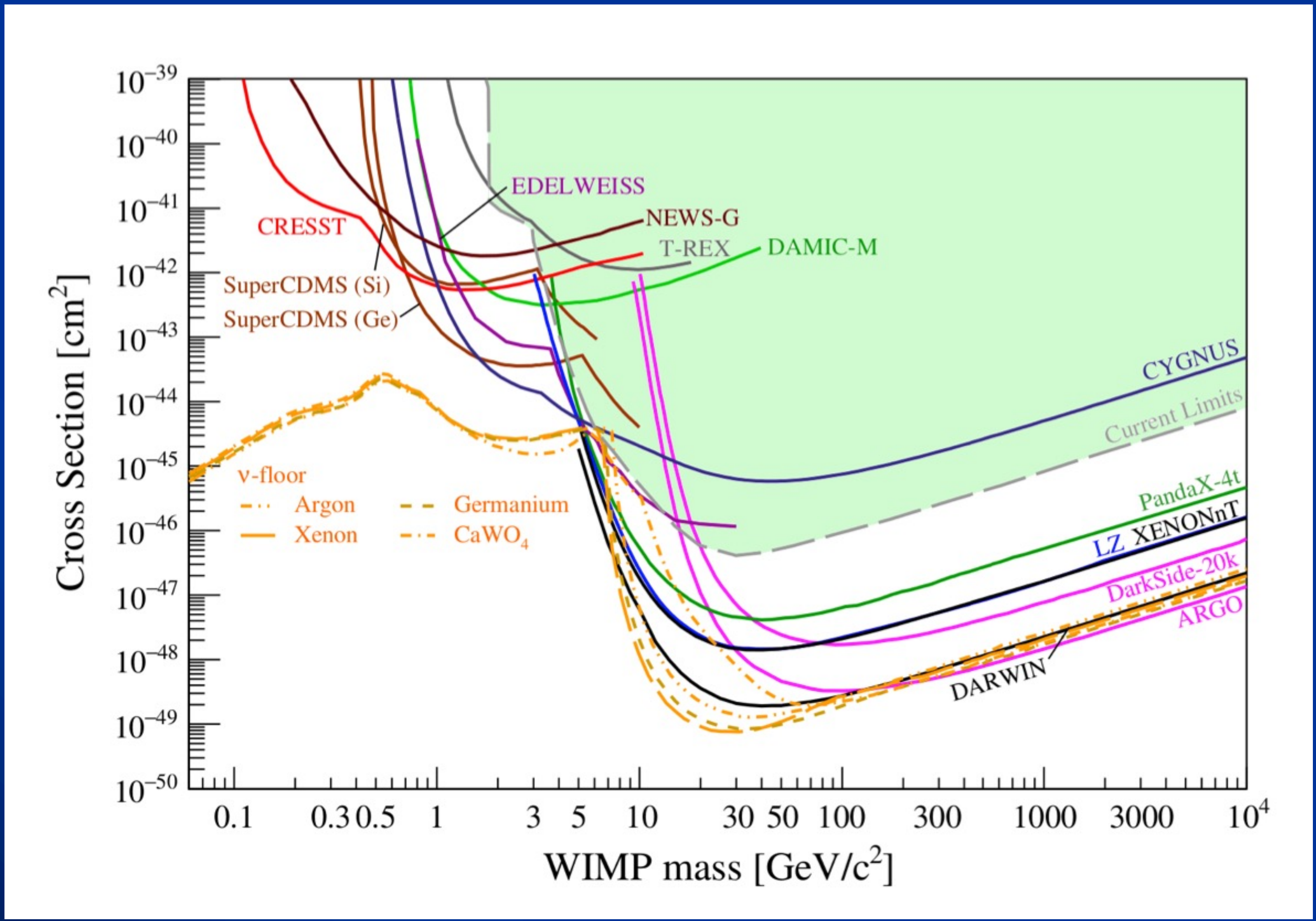


BUT:

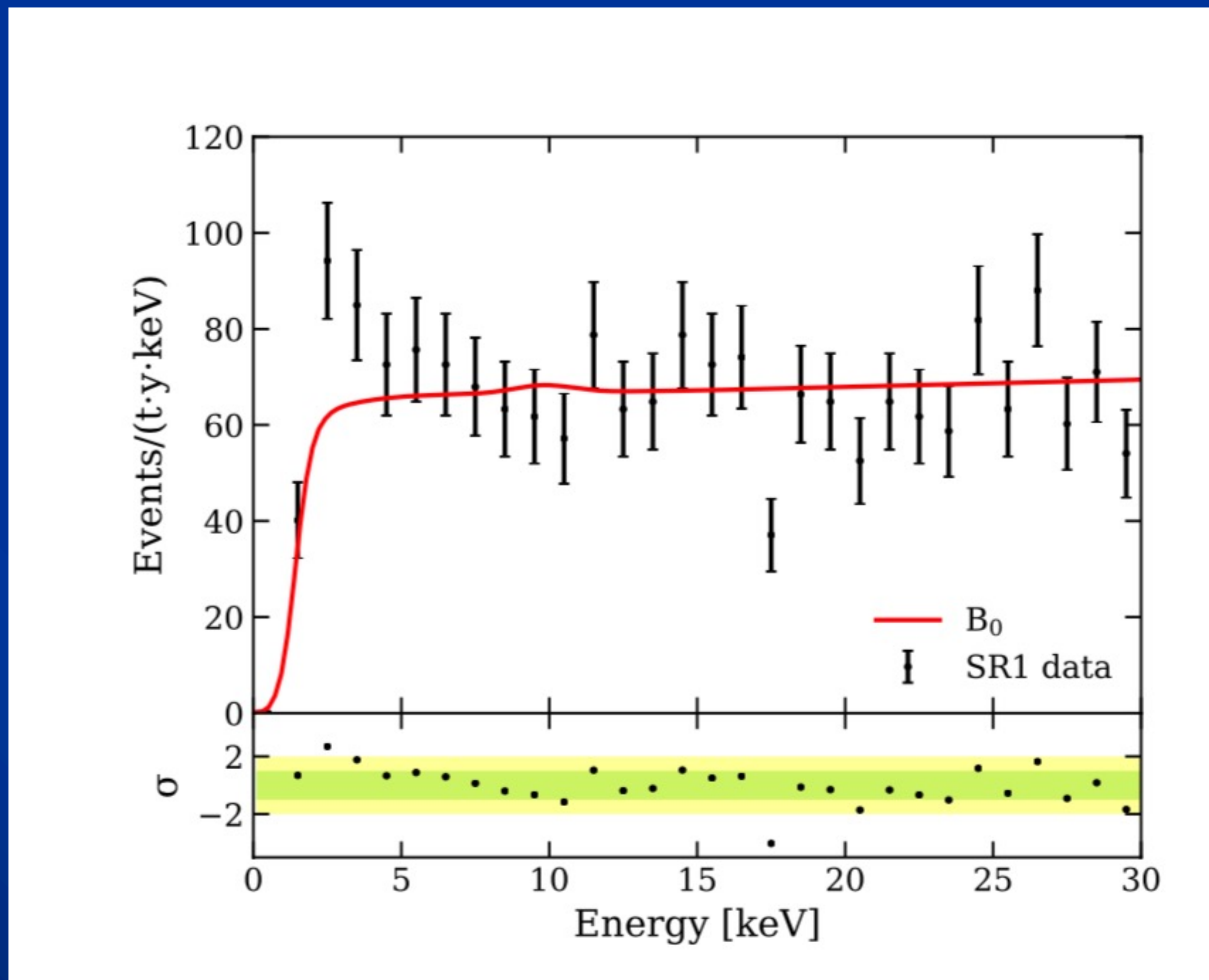
--- it's hard to compare results from different detector materials

--- can we trust results near threshold?

Future experiments

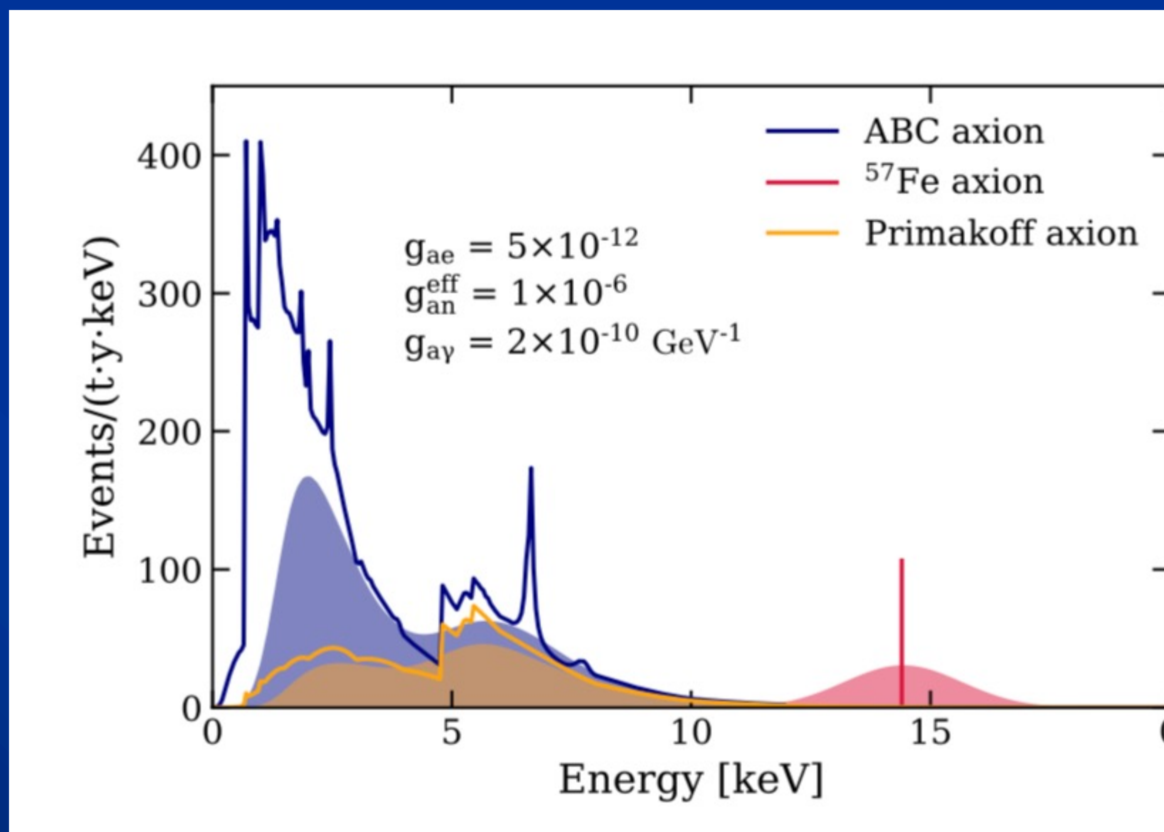


XENON 1T excess at 2-3 keV



Most new particle explanations of XENON 1T excess are ruled out.

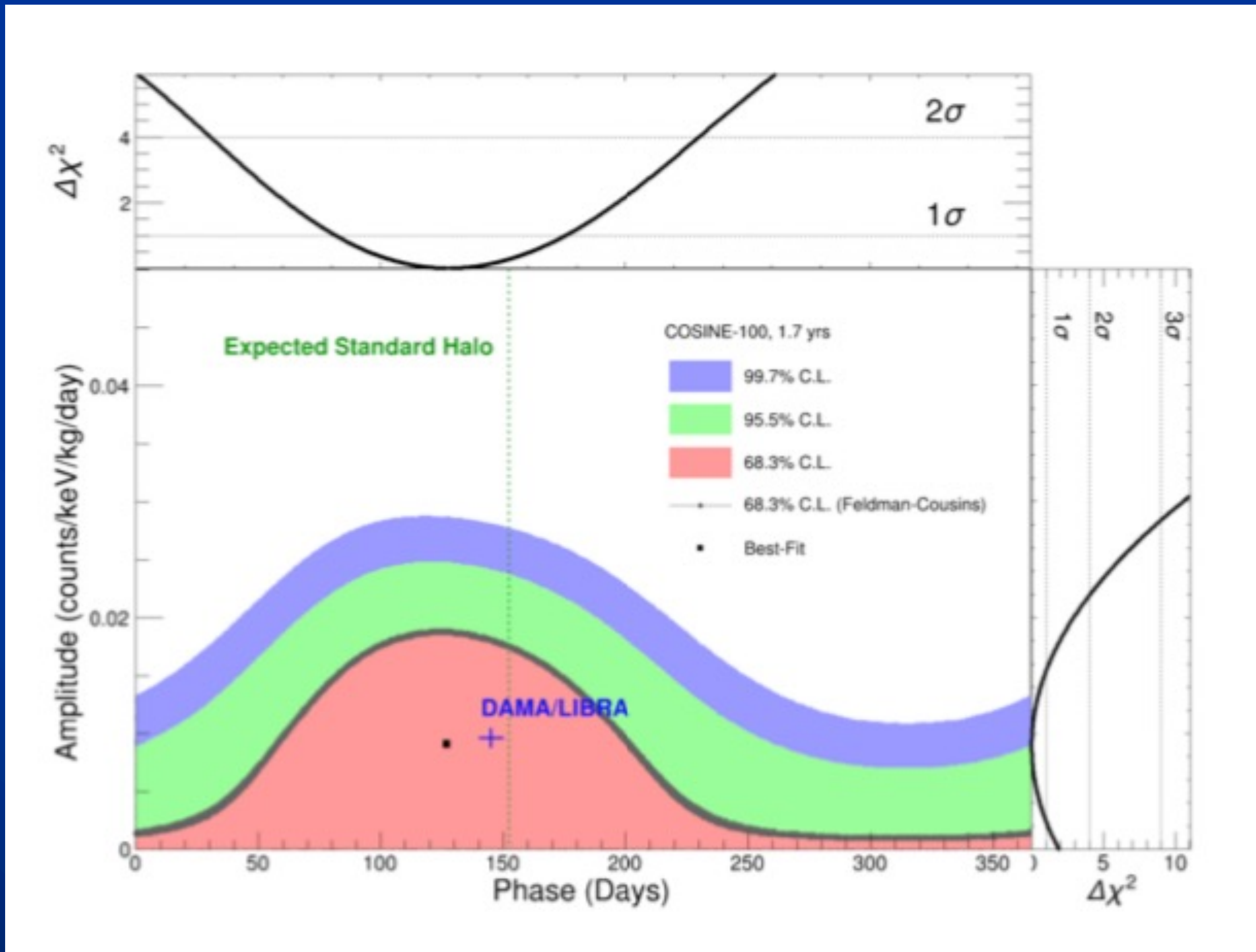
The one with the right spectrum is axions from the Sun, but this interpretation is ruled out by stellar cooling of white dwarfs and horizontal branch stars.



To test DAMA within next 5 years

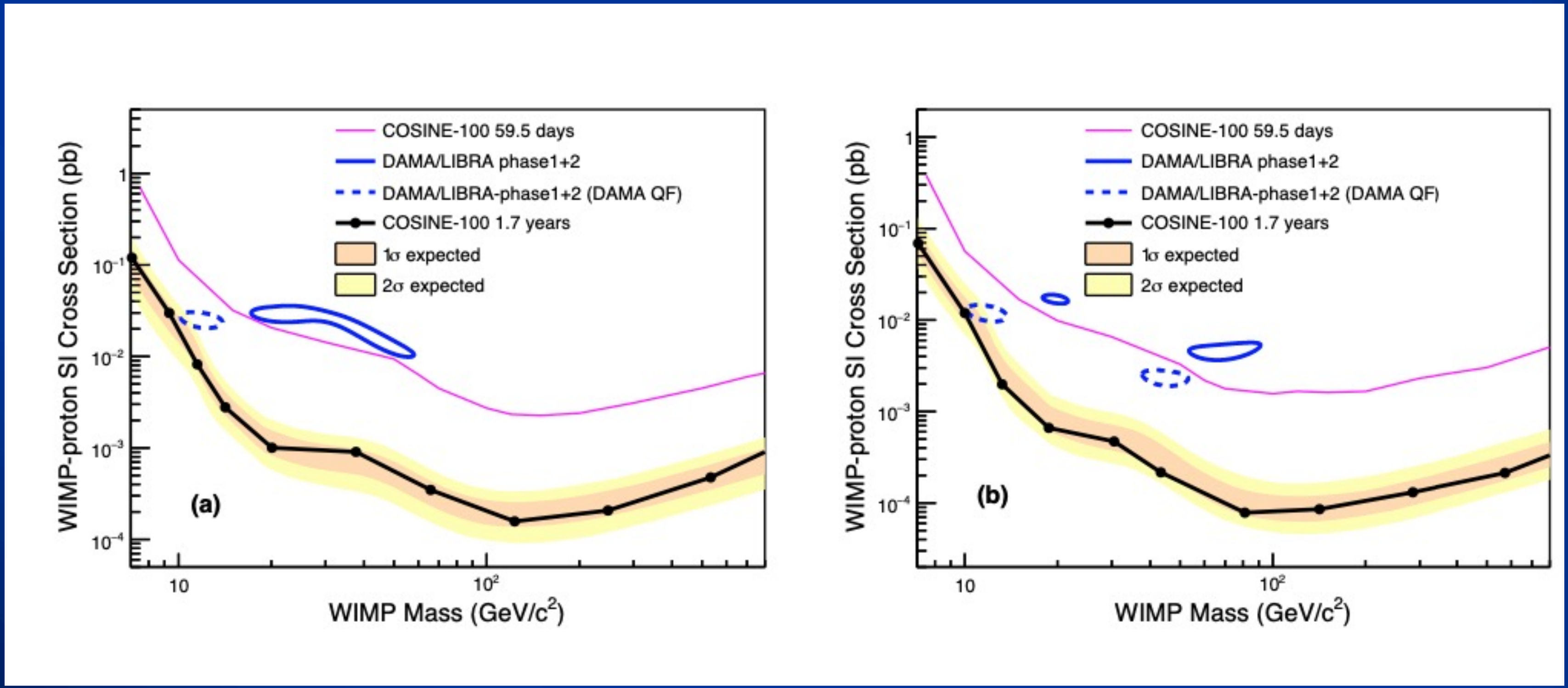
- The annual modulation in the data is still there after 13 years and still unexplained.
- New DAMA data down to keV still see modulation (DAMA all by itself is not compatible with SI scattering) Baum, Freese,Kelso 2018
- Other groups are using NaI crystals:
- COSINE-100 has data, will have an answer within 3-5 years
- SABRE (Princeton) with Australia
- ANAIS (has data)

COSINE-100 1.7 years of data



https://arxiv.org/pdf/1903.10098.pdf

COSINE-100 on isospin violating interactions



https://arxiv.org/pdf/2104.03537.pdf

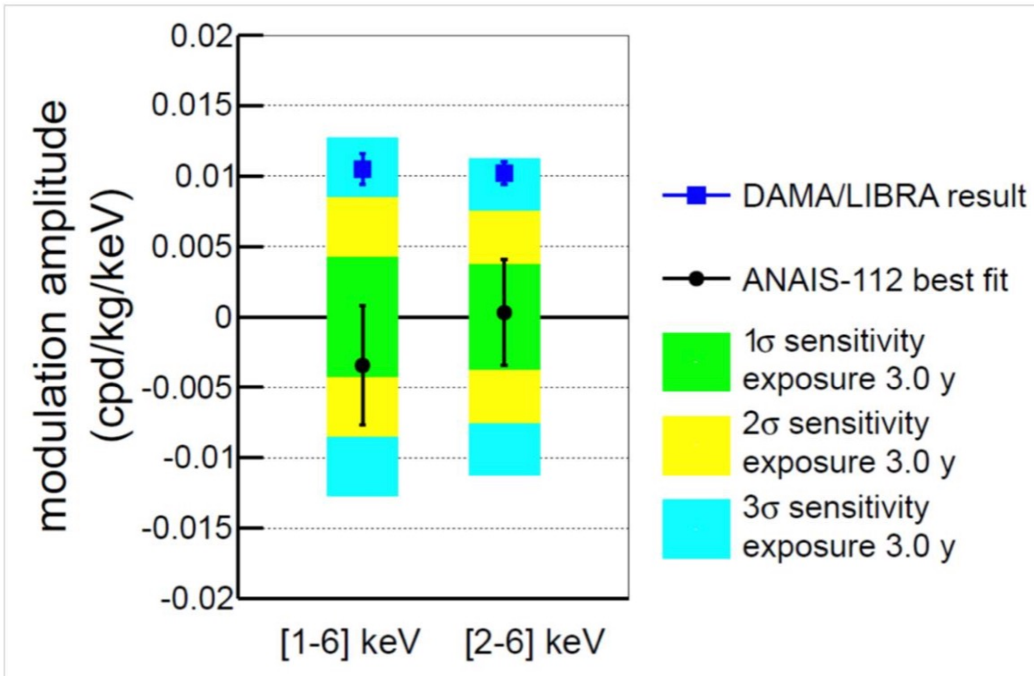
New ANAIS-112 results on annual modulation – three years exposure

Posted on **03/03/2021**

ANAIS-112 experiment is taking data at Canfranc Underground Laboratory since August 2017 in order to test DAMA/LIBRA signal. Updated results for three years and 112.5 kg, together with complementary analysis and consistency checks have been posted in arXiv this week:

https://arxiv.org/abs/2103.01175

We confirm our sensitivity estimates and tension with DAMA/LIBRA results (for 2.7 / 2.5 sigma sensitivities in the two energy regions considered).



Tweet

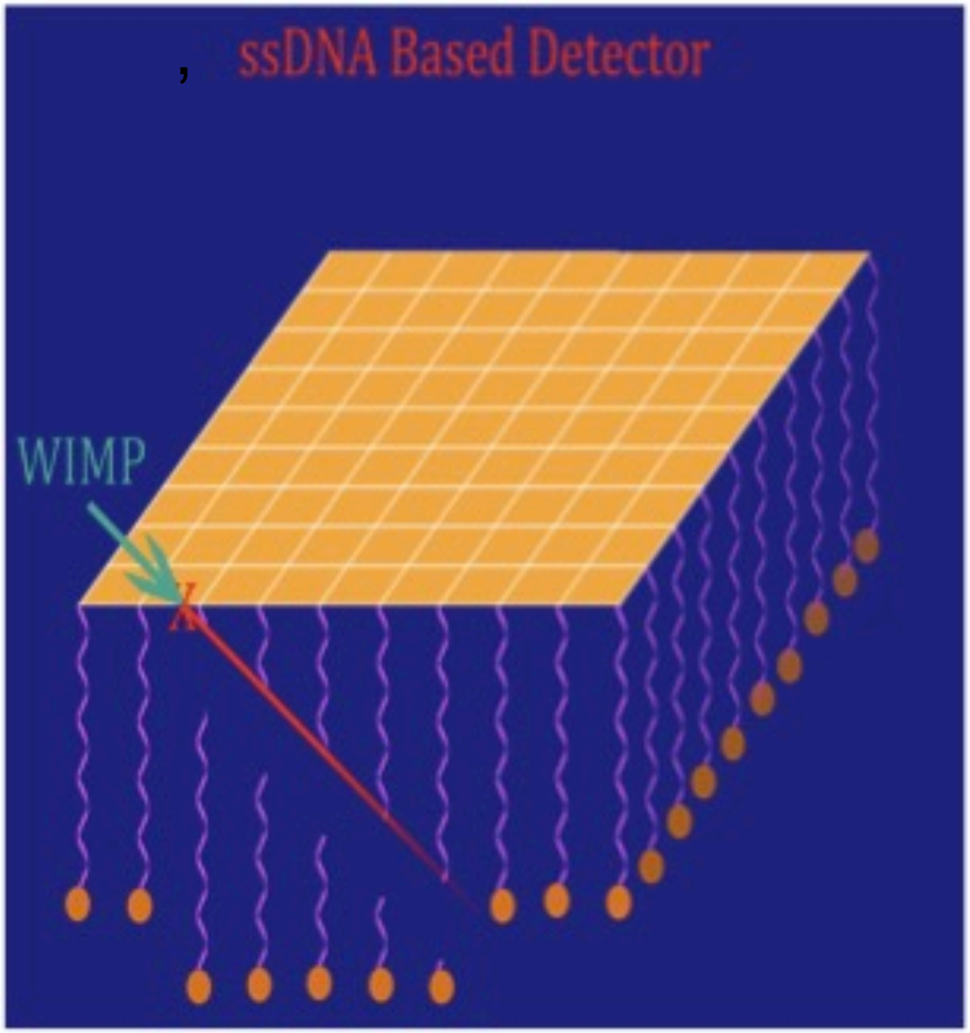
Posted in **News**

Status of DM searches

- Difficulty: comparing apples and oranges, since detectors are made of different materials.
- Theory comes in: Spin independent scattering, Spin dependent, try all possible operators, mediators, dark sector, etc.
- Interesting avenue: nuclear physics. (Fitzpatrick, Haxton, etal)

DNA/RNA Tracker: directional detector with nanometer resolution

- 1 kg Gold, 1 kg ssDNA, identical sequences of bases with an order that is well known



BEADED CURTAIN OF ssDNA

WIMP from galaxy knocks out Au nucleus, which traverses DNA strings, severing the strand whenever it hits.

Drukier, KF, Lopez, Spergel, Cantor, Church, Sano

Paleodetectors

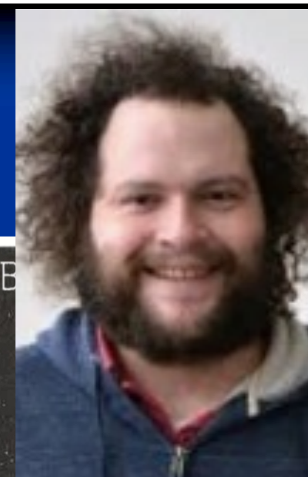
WIMPs leave tracks in ancient minerals from 10km below the surface of the Earth.

Collecting tracks for 500 Myr.

Backgrounds: Ur-238 decay and fission

Take advantage of nanotools: can identify nanometer tracks in 3D

Baum, Drukier, Freese, Gorski, Stengel arXiv:1806.05991



Pat Stengel

Sebastian Baum

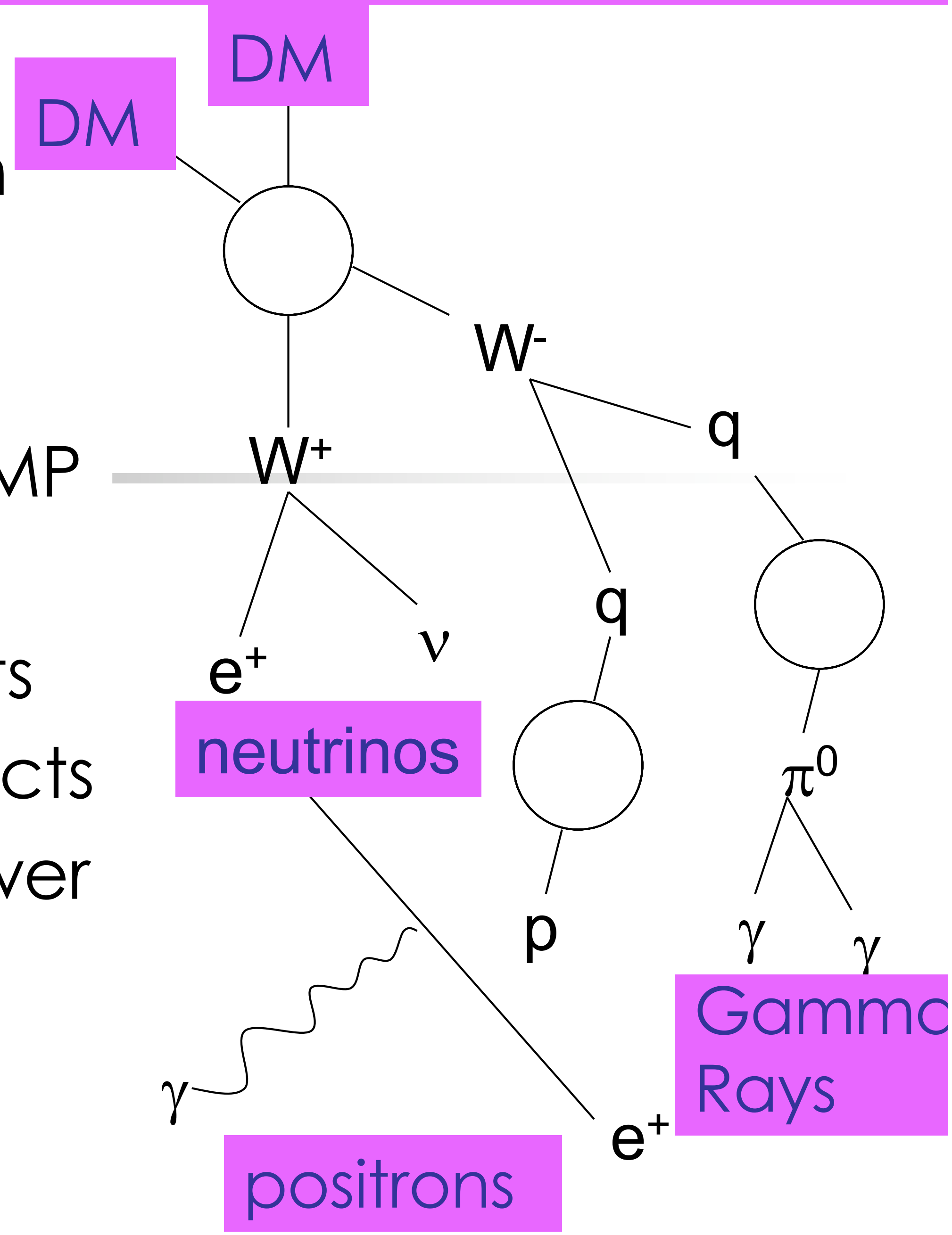
Despite making up most of the universe, we still haven't detected dark matter. A clue could lie buried in ancient rocks, says physicist Sebastian Baum

MOST of our universe is missing. Observations of the smallest galaxies to structures spanning the entire universe show that ordinary matter – the stuff that makes up you, me and everything we see in the cosmos around us – accounts for only one-fifth of all matter. The remaining 80 per cent is a mystery. After decades trying to hunt down this

Third Way to Search for WIMPs: Indirect Detection of WIMP Annihilation

Many WIMPs are their own antiparticles, annihilate among themselves:

- 1) Early Universe gives WIMP miracle
- 2) Indirect Detection expts look for annihilation products
- 3) Same process can power Stars (dark stars)



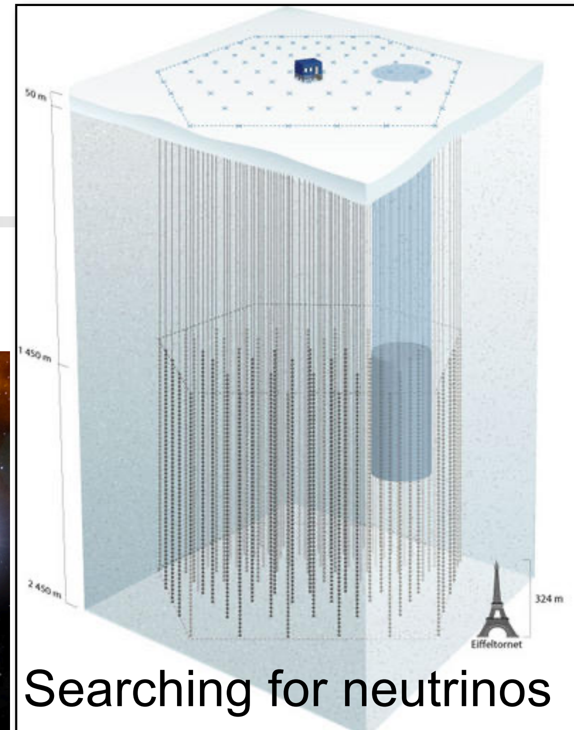
Indirect Detection: looking for DM annihilation signals

AMS aboard the International Space Station

Found
excess e+

FERMI

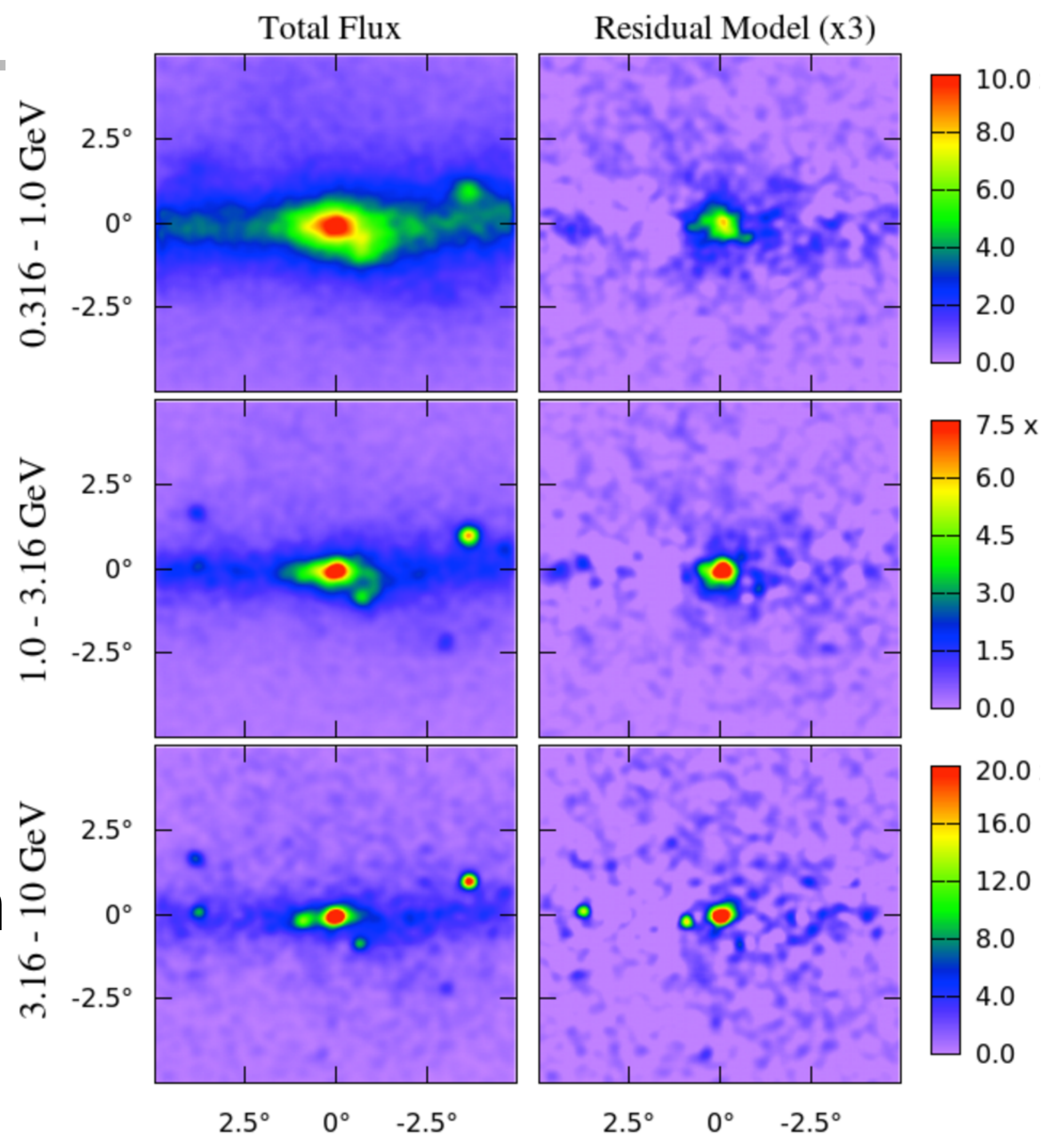
IceCube
At the South Pole



Fermi/LAT gamma-ray excess

Goodenough & Hooper (2009)

Daylan, Finkbeiner, Hooper, Linden
Portillo, Rodd, Slatyer (2014)



Towards galactic center:

- Model and subtract astrophysical sources
- Excess remains
- Spectrum consistent with (30 GeV, $\chi\chi \rightarrow$ b-bbar)

BUT also consistent with astrophysical point sources. Status unclear.

Possible evidence for WIMP detection :

- Direct Detection:
  DAMA annual modulation
  (but XENON, LUX)
- Indirect Detection:
  FERMI gamma ray excess near galactic center

FOURTH WAY TO SEARCH FOR WIMPS

Dark Stars:
Dark Matter annihilation can power the first stars

Fourth Way: Find Dark Stars (hydrogen stars powered by dark matter) in James Webb Space Telescope, sequel to Hubble Space Telescope

W Doug Spolyar, P. Gondolo

Dark Stars

The first stars to form in the history of the universe may be powered by Dark Matter annihilation rather than by Fusion. Dark stars are made almost entirely of hydrogen and helium, with dark matter constituting 0.1% of the mass of the star).

- This new phase of stellar evolution may last millions to billions of years
- Dark Stars can grow to be very large: up to ten million times the mass of the Sun. Supermassive DS are very bright, up to a billion times as bright as the Sun. **These can be seen in James Webb Space Telescope.**
- Once the Dark Matter runs out, the DS has a fusion phase before collapsing to a big black hole: **IS THIS THE ORIGIN OF SUPERMASSIVE BLACK HOLES?**

Basic Picture

- The first stars form at z=10-20 in 10^6 Msun minihaloes, right in the DM rich center.
- As a gas cloud cools and collapses en route to star formation, the cloud pulls in more DM gravitationally.
- DM annihilation products typically include e+/e- and photons. These collide with hydrogen, are trapped inside the cloud, and heat it up.
- At a high enough DM density, the DM heating overwhelms any cooling mechanisms; the cloud can no longer continue to cool and collapse. A Dark Star is born, powered by DM.

DS in James Webb Space Telescope

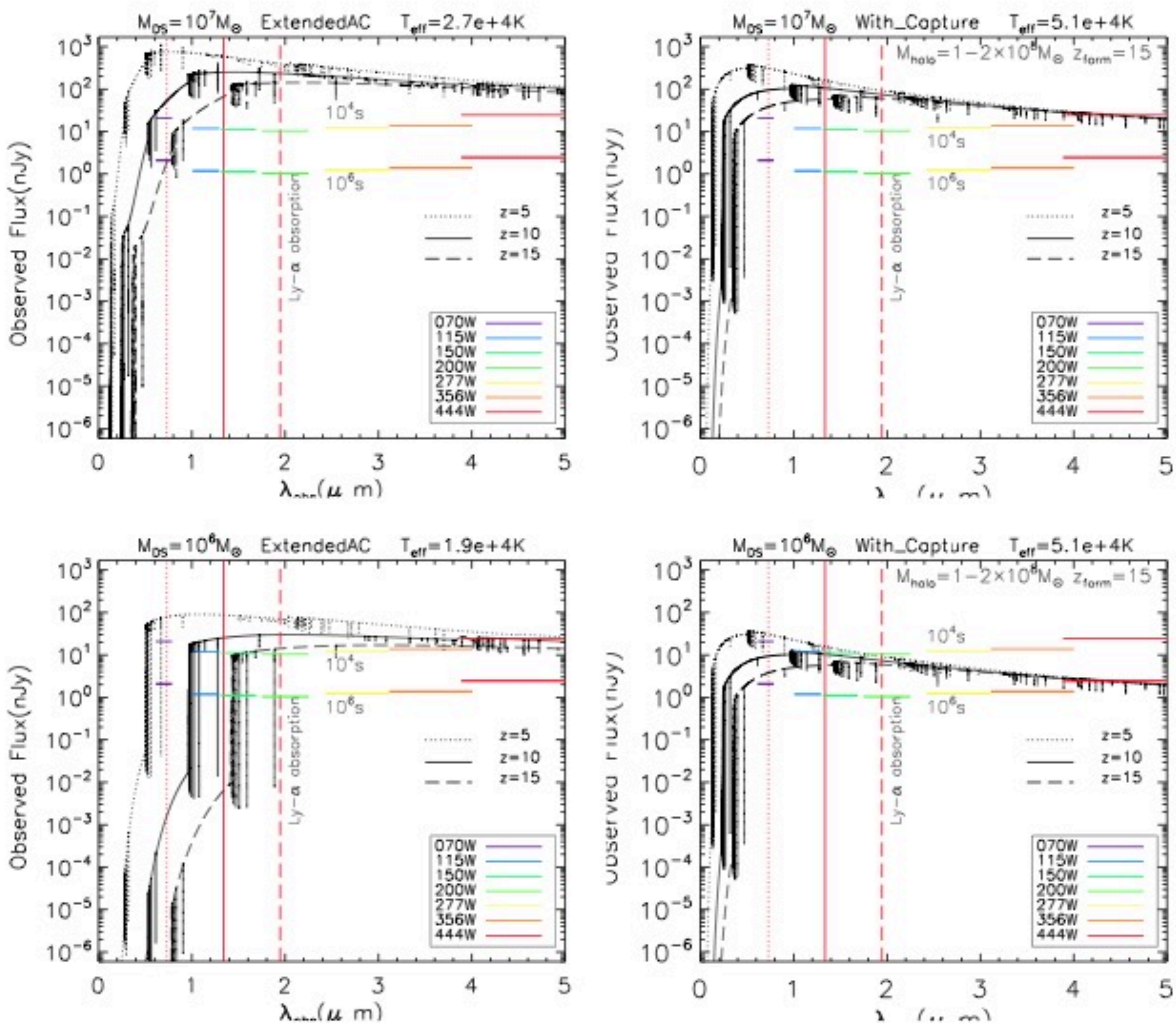
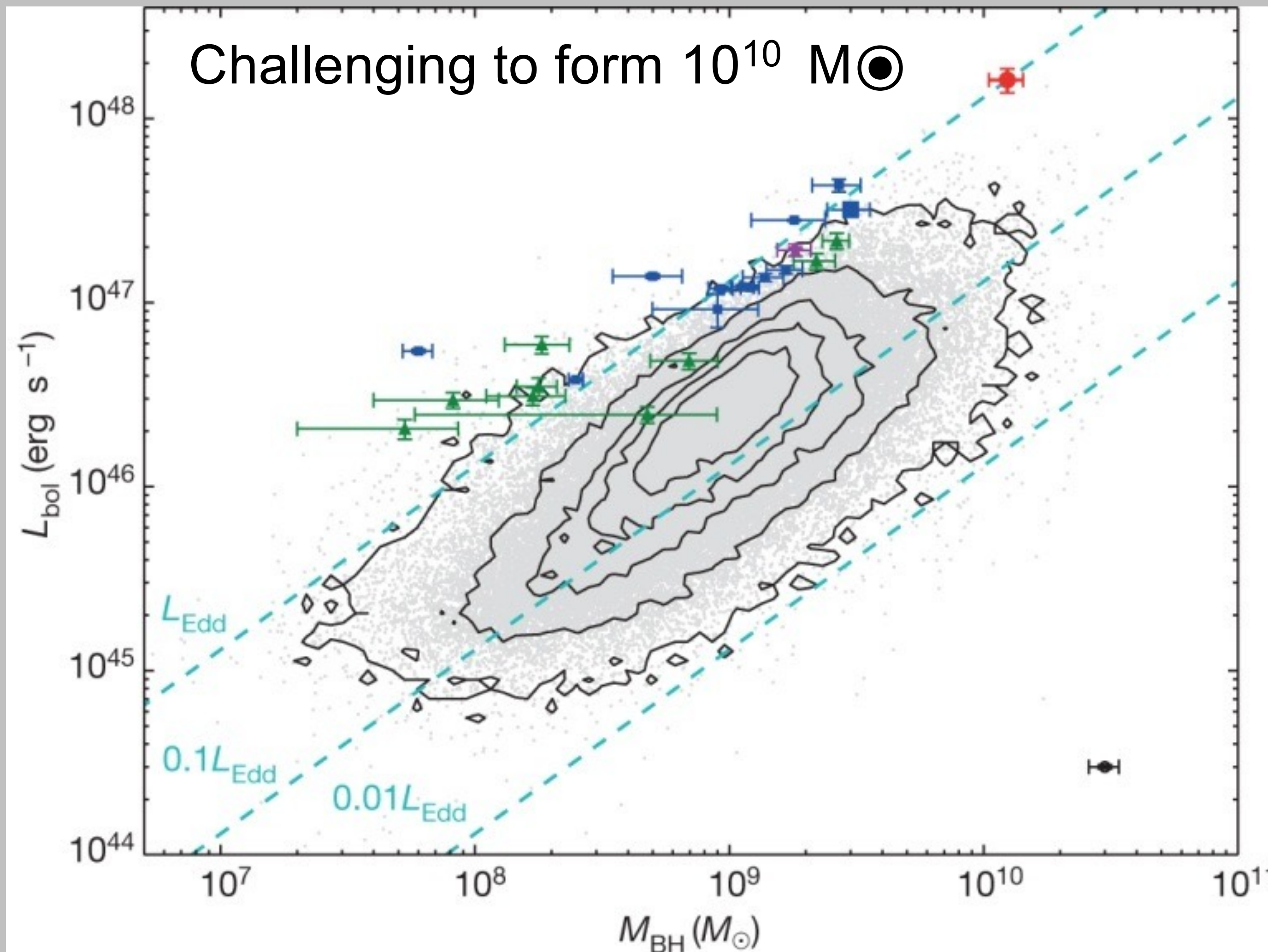


Figure 7. Spectra for supermassive DSs formed at $z_{\rm form} = 15$ (formation redshift)

What happens next? BIG BLACK HOLES

- Star reaches $T=10^7$K, fusion sets in.
- A. Heger finds that fusion powered stars heavier than 153,000 solar masses are unstable and collapse to BH
- Less massive Pop III star lives a million years, then becomes a Black Hole
- Helps explain observed black holes:
- (I) in centers of galaxies
- (ii) billion solar mass BH at z=6 (Fan, Jiang)
- (iii) intermediate mass BH
-

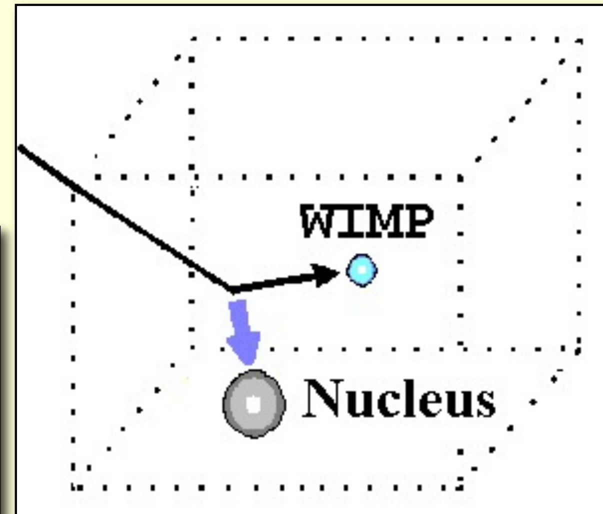
SupperMassive Black holes from Dark Stars
Very Massive progenitor Million Solar Masses at z=6
No other way to form supermassive BH this early



X-B Wu *et al. Nature* **518**, 512-515 (2015) doi:10.1038/nature14241

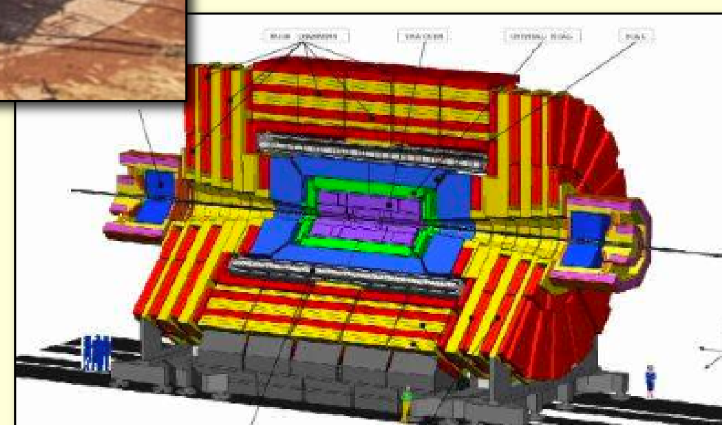
nature

WIMP Hunting:
Good chance of detection this decade



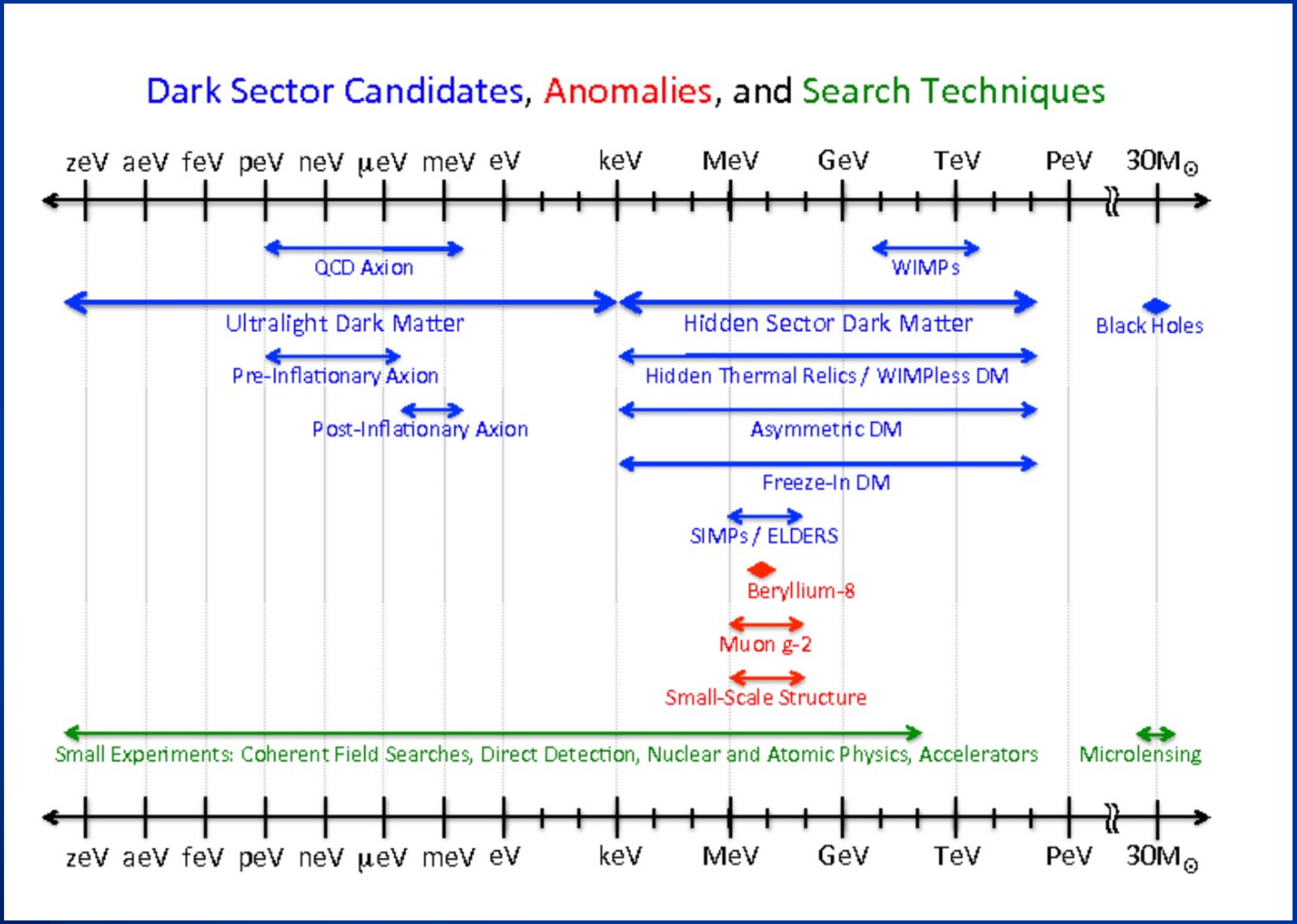
- **Direct Detection**

- **Indirect Detection**
- **Collider Searches**

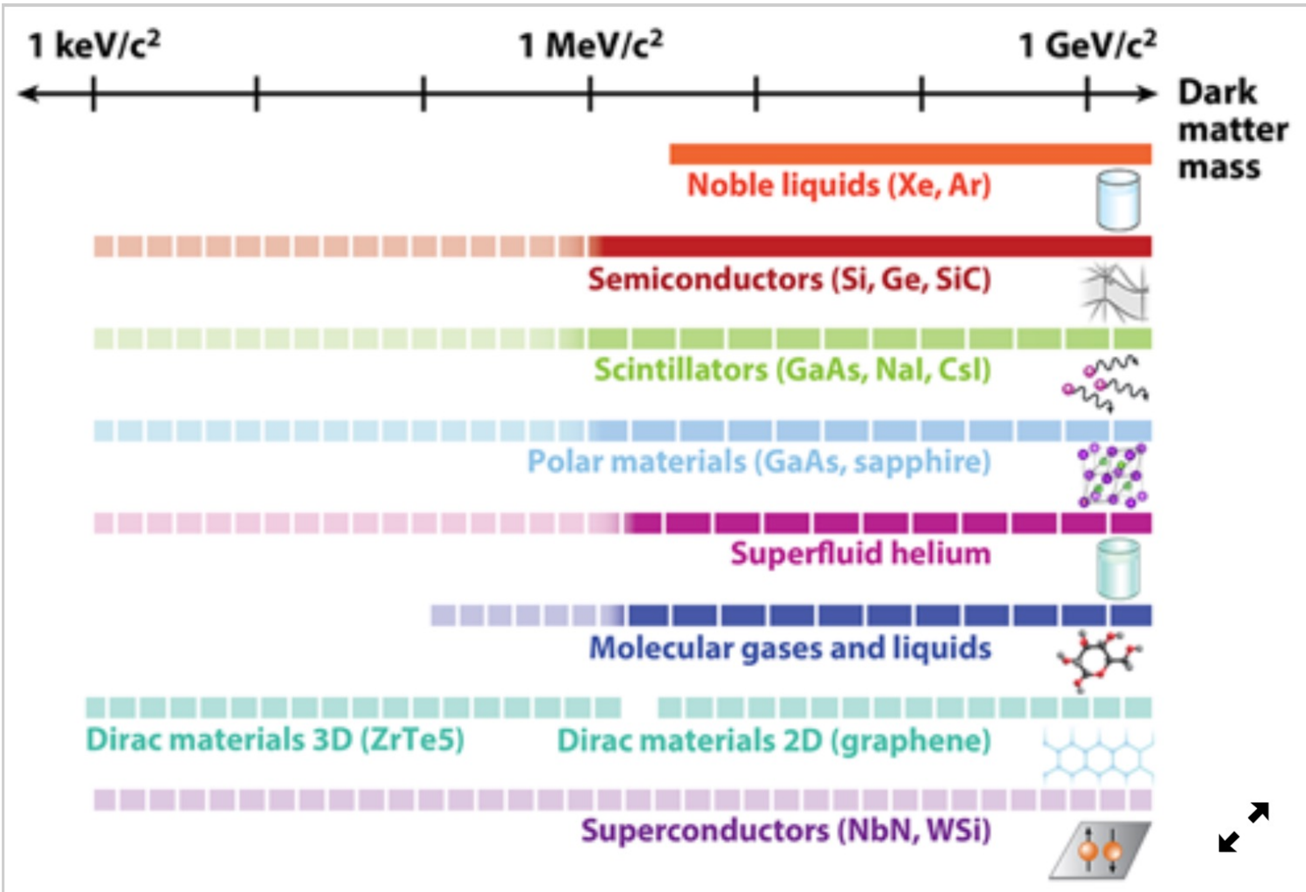


Looking for Dark Stars

Light Dark Matter



New Detector Technologies



R. Essig/Stony Brook University; APS/Carin Cain

Another intriguing signal: 3.5 keV line. From sterile neutrino?

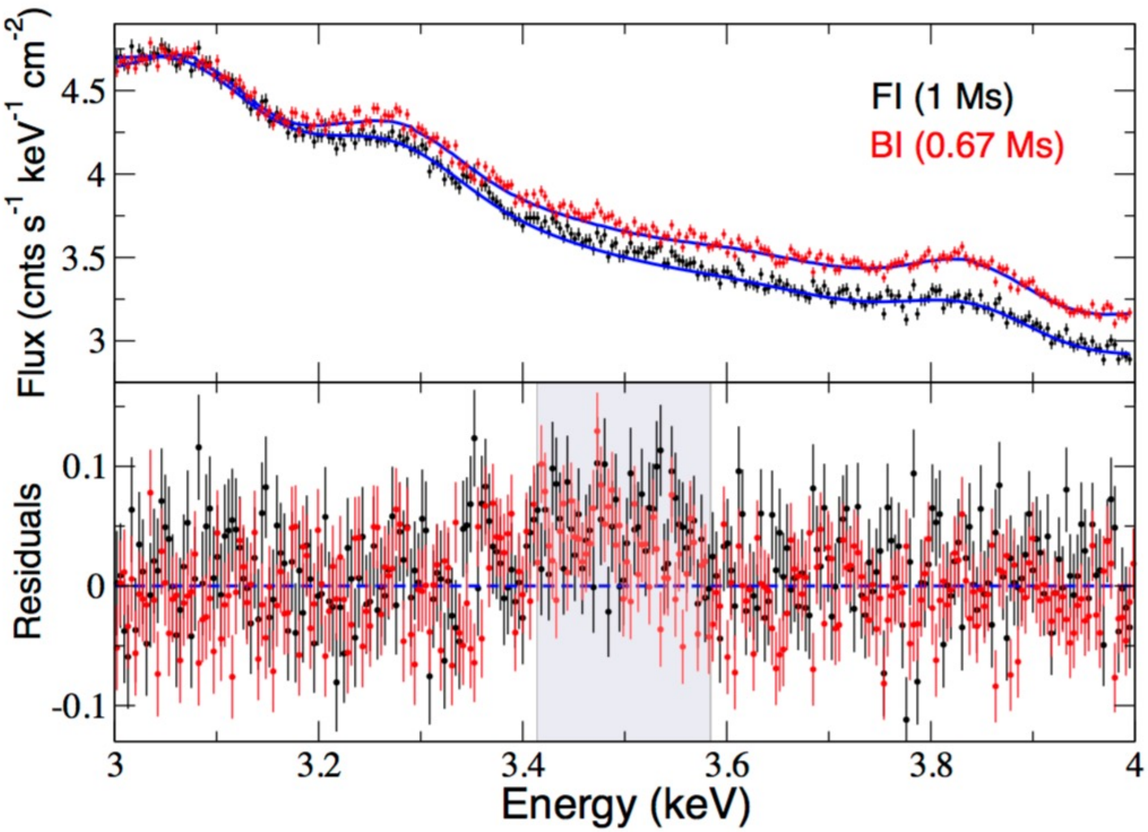
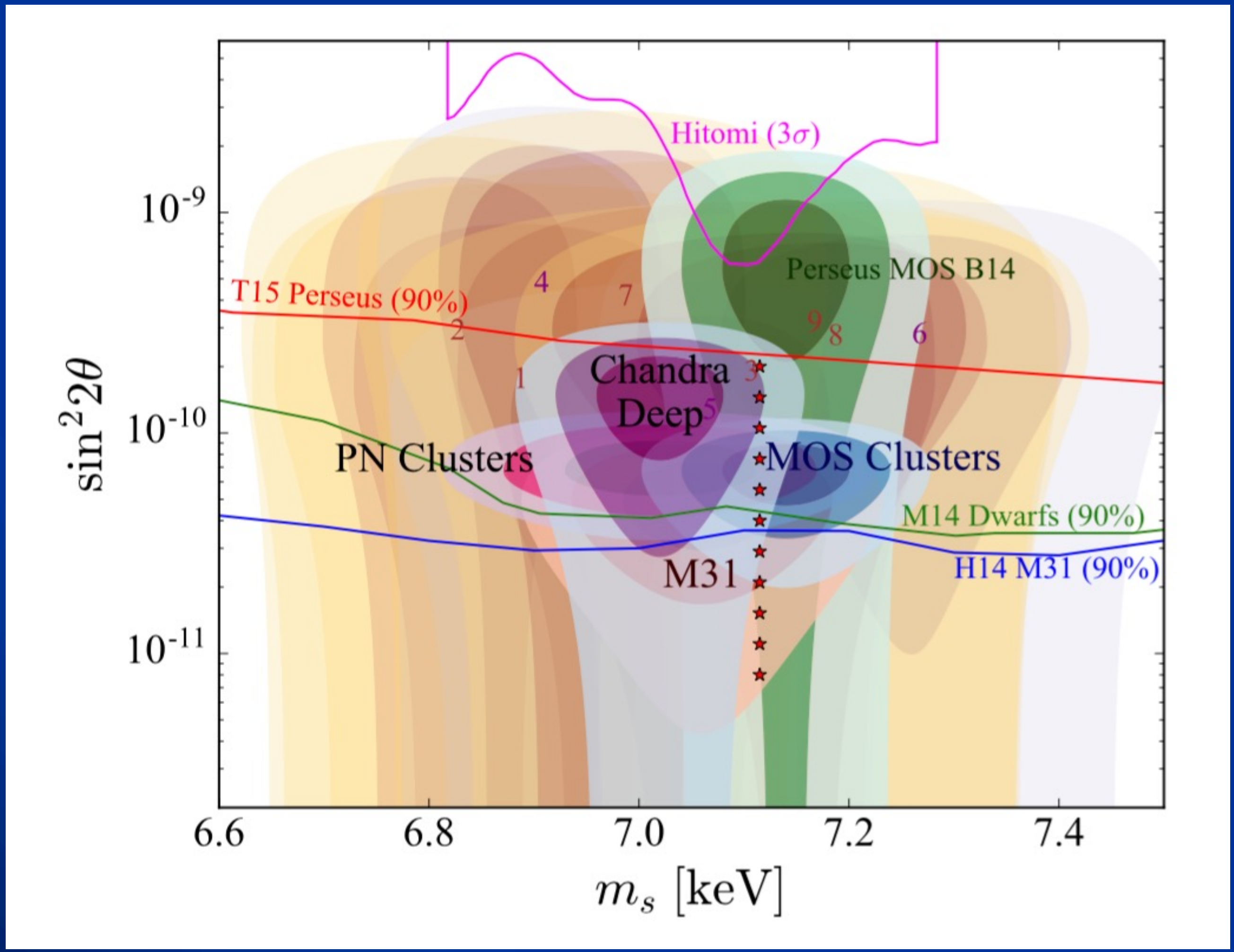


Figure 2. Observed *Suzaku* FI and BI Spectrum of the Perseus cluster core (Region 1). The residuals around 3.5 keV (redshifted) are visible clearly (shaded area in the bottom panel). The model shown in the figure includes contributions from the nearby K XVIII, Cl XVII, and Ar XVII lines.

Perseus Cluster in Suzaku x-ray satellite

(Franse, Bulbul, etal 2016)

X-ray line detections consistent with sterile neutrino dark matter as well as 90% C.L. bounds



From review of Abazajian 2017

Very Controversial

WHAT'S HOT IN DARK MATTER? Unexplained signals.

WIMPS:

- DAMA annual modulation (but XENON, LUX)
- Indirect Detection:

    NO: The HEAT/PAMELA/FERMI/AMS positron excess

    FERMI gamma ray excess near galactic center

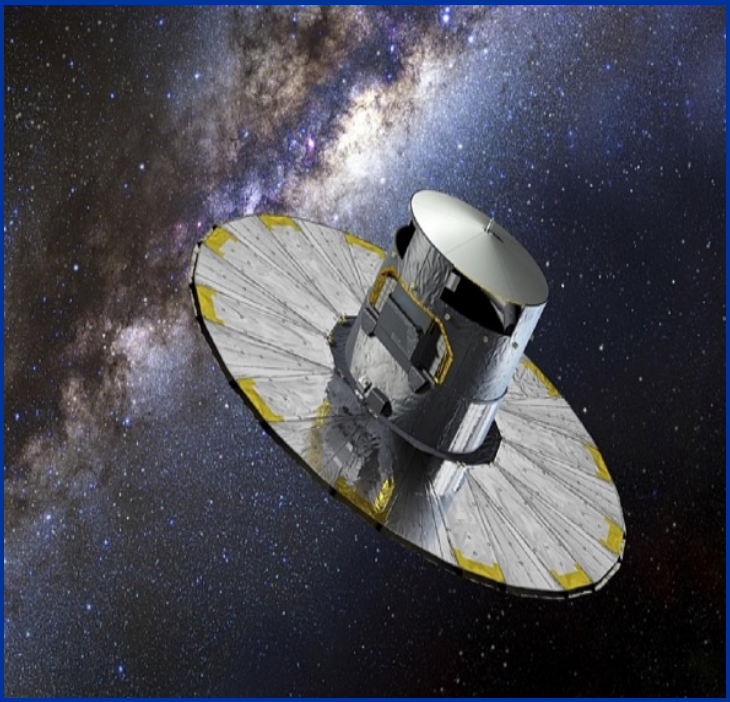
- ---

7 keV Sterile neutrinos

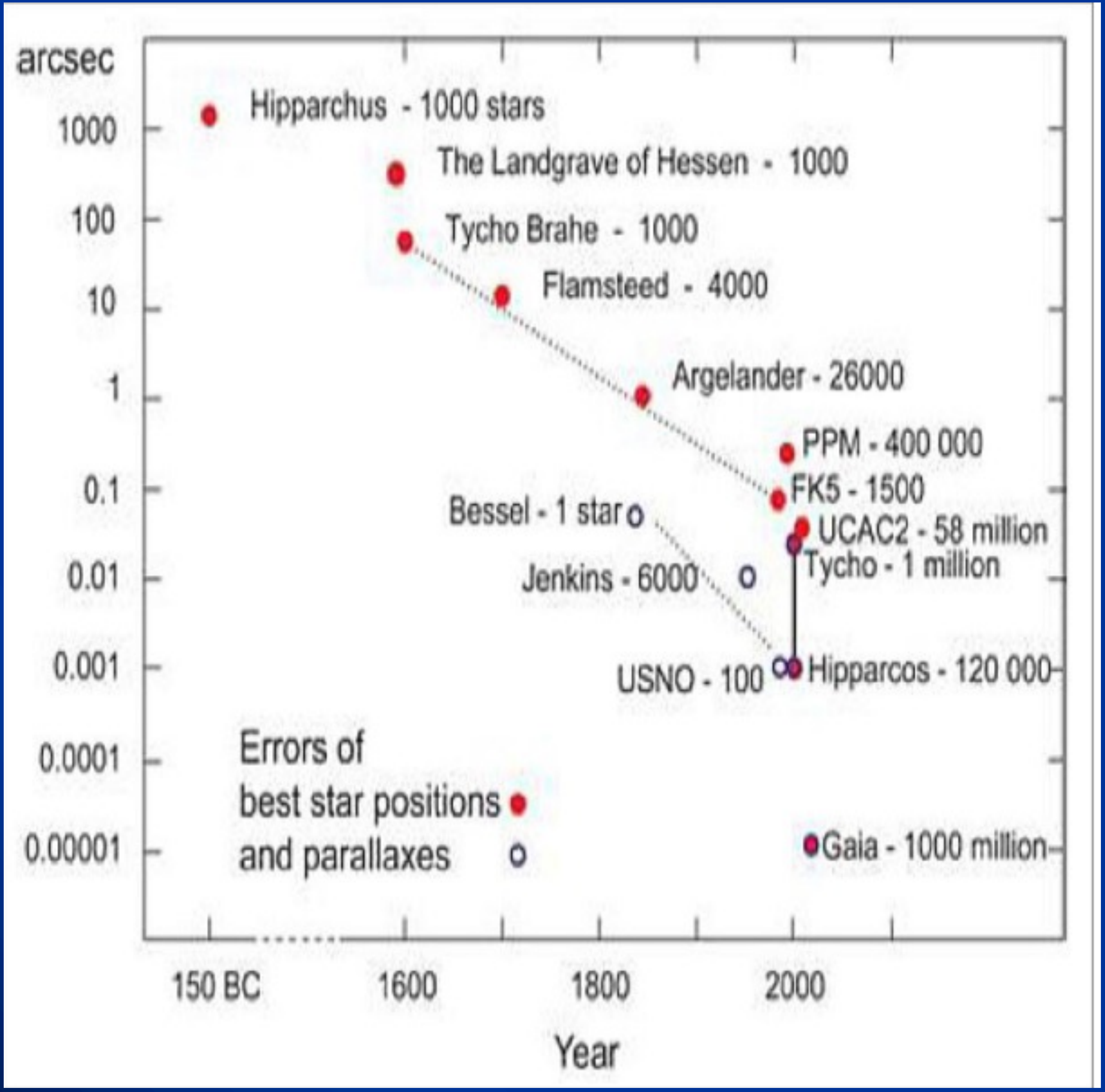
- 3.5 keV x-ray line in Perseus, M31, and GC

- MeV dark matter 511 keV line in INTEGRAL DATA

New ways to test nature of DM: use GAIA data

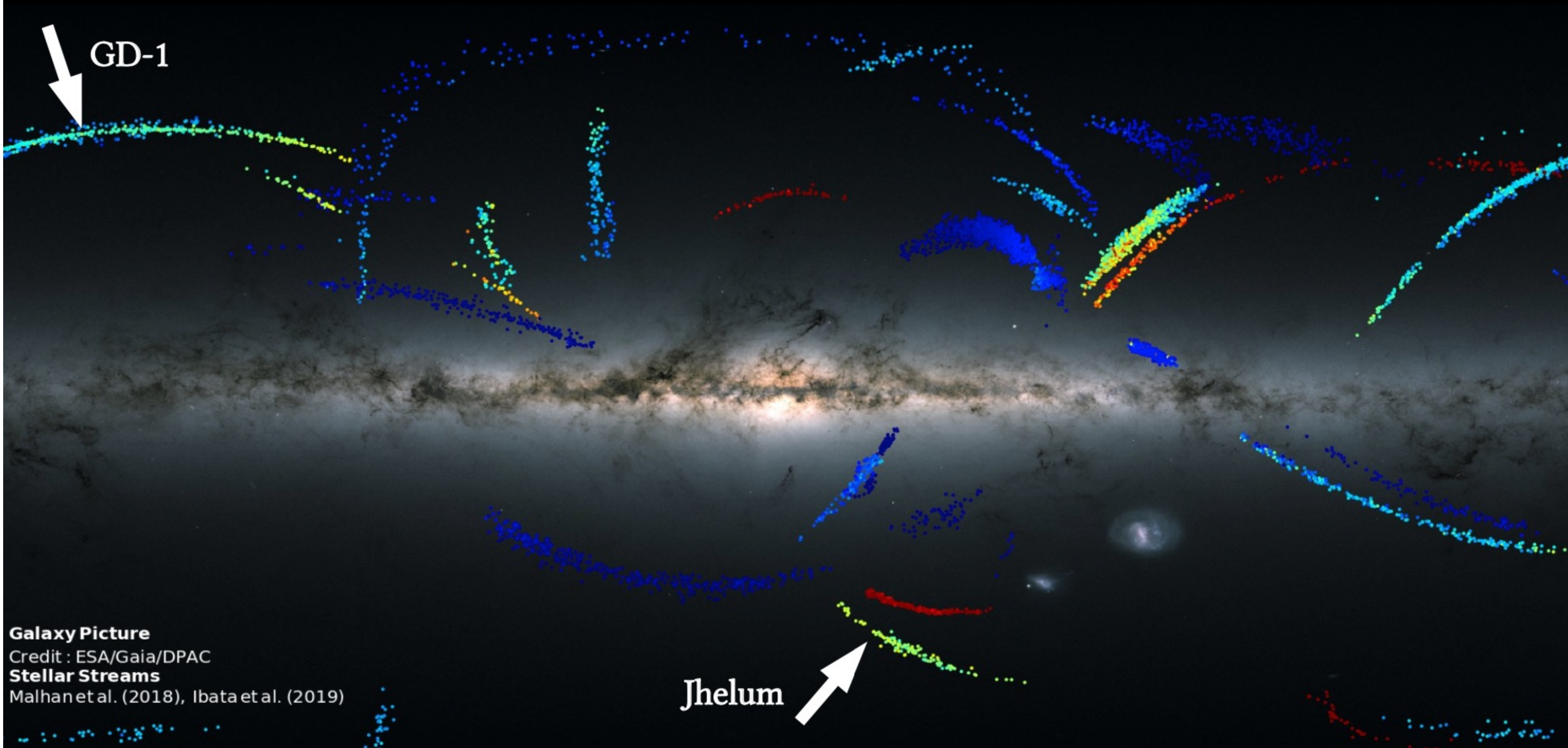


Measures positions and velocities of 1.3 billion stars in the Milky Way. Stellar kinematics determined by gravitational potential of Dark Matter


arcsec
1000
100
10
1
0.1
0.01
0.001
0.0001
0.00001
Hipparchus - 1000 stars
The Landgrave of Hessen - 1000
Tycho Brahe - 1000
Flamsteed - 4000
Argelander - 26000
PPM - 400 000
FK5 - 1500
UCAC2 - 58 million
Tycho - 1 million
Bessel - 1 star
Jenkins - 6000
USNO - 100
Hipparcos - 120 000
Gaia - 1000 million
Errors of
best star positions
and parallaxes
150 BC
1600
1800
2000
Year

Stellar Streams in the Milky Way

Question: Can the present day physical properties of such accreted GC streams provide information about the DM density of their parent subhalos?



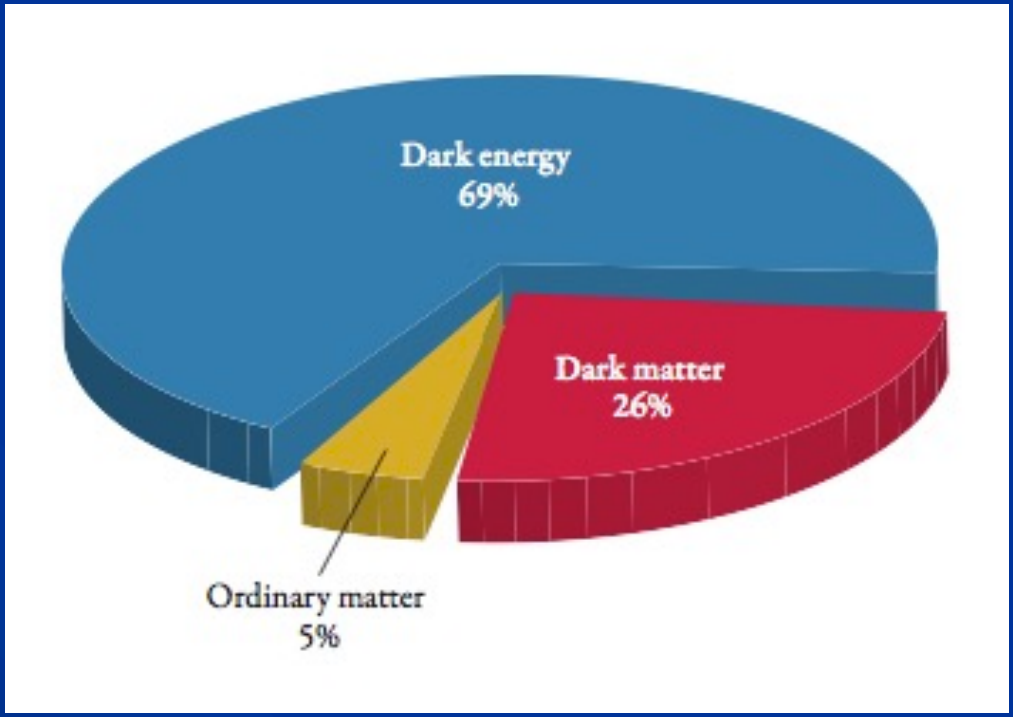
GAIA tests Cold Dark Matter hypothesis

- 1) Cored vs. cuspy (as predicted by CDM) subhalos produce streams of different widths (Malhan, KF, Valluri)
- 2) Gaps in streams: learn about low mass subhalos
- 3) Shape of Milky Way Halo:
  CDM predicts triaxial. (Vasiliev, Valluri)
- 4) Subhalos that passed through MW disk left residual observable oscillations (Spolyar, Widrow)
- 5) Better estimates of local dark matter density
  ~0.3 GeV/cm^3 (Pablo Fernandez deSalas, Sofia Sivertsson) using Jeans equation

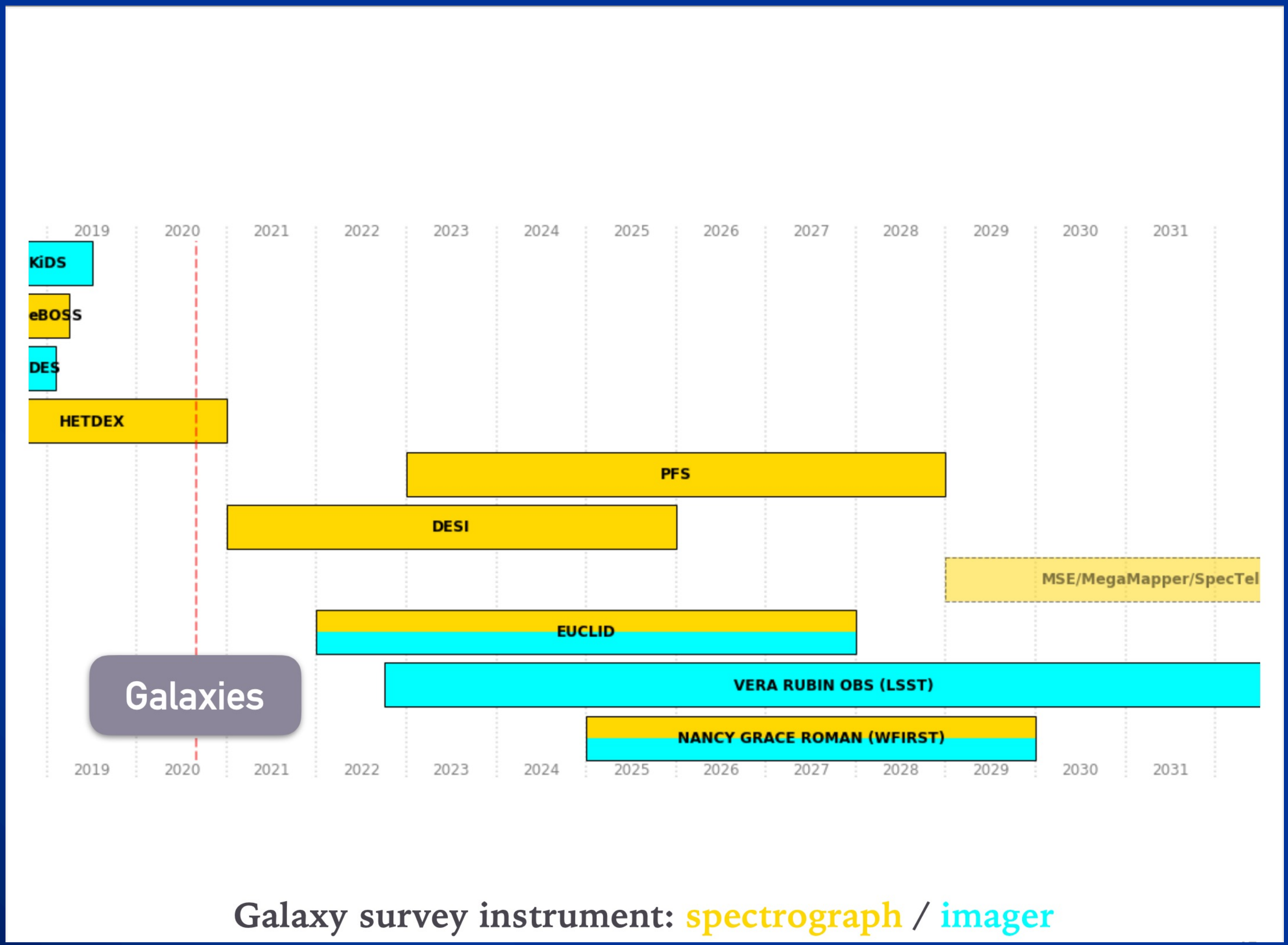
Dark Matter Summary

- 1) Neutrino mass ~ 0.1 eV. We are close to knowing the answer. Cosmology is very powerful.
- 2) WIMP searches: what is going on with DAMA? COSINE-100, ANAIS, Sabre are testing it.
- 3) Dark Stars: the first stars could have been powered by Dark Matter rather than by fusion. Powered by WIMPs or SIDM or …
- 4) Hints of sterile neutrinos?
- 4) New ways to test nature of DM: GAIA satellite and stellar streams as a test of Cold Dark Matter

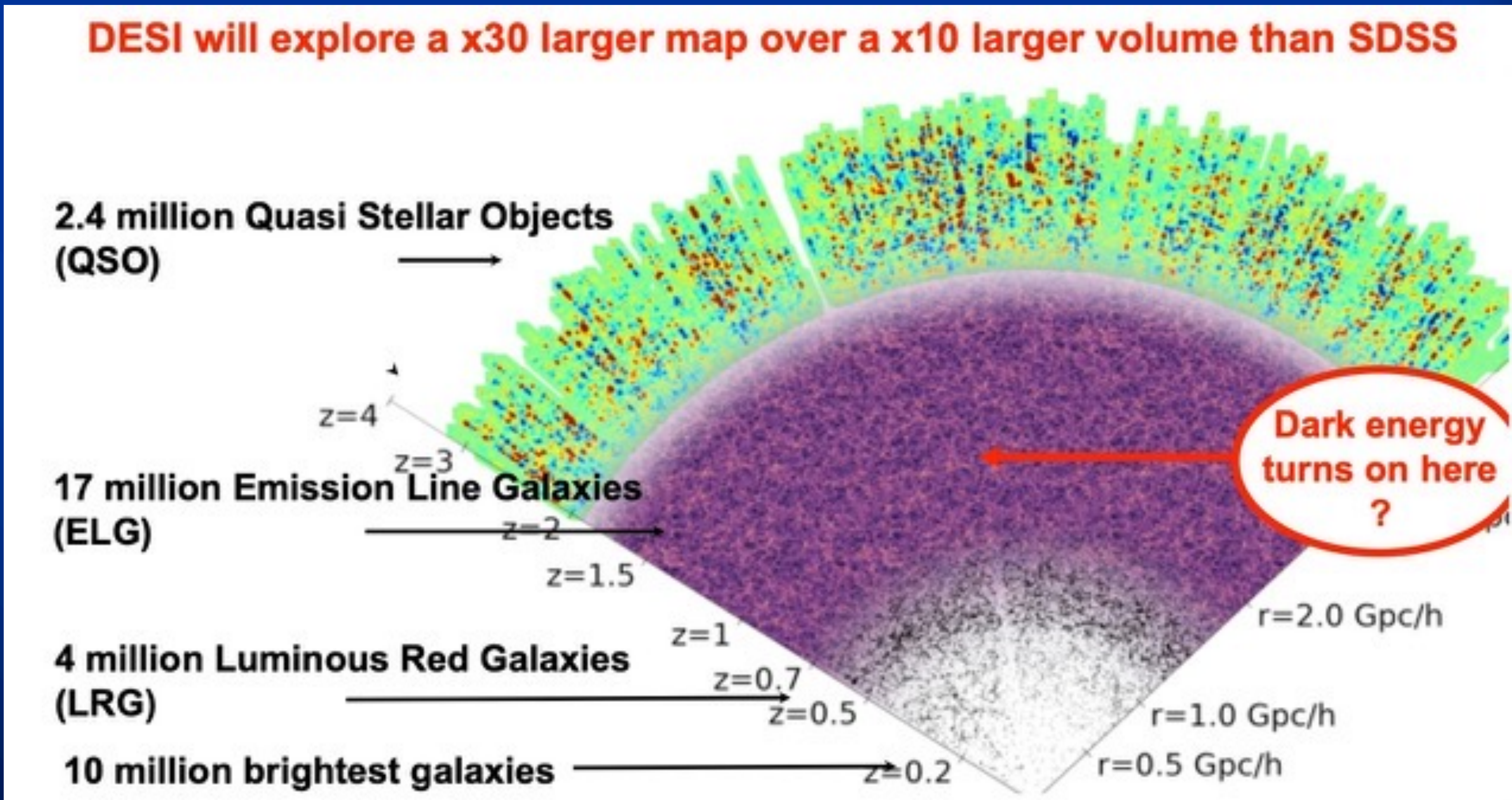
3) Even stranger: Dark Energy



Current and Future Surveys and Dark Energy



DESI taking data now

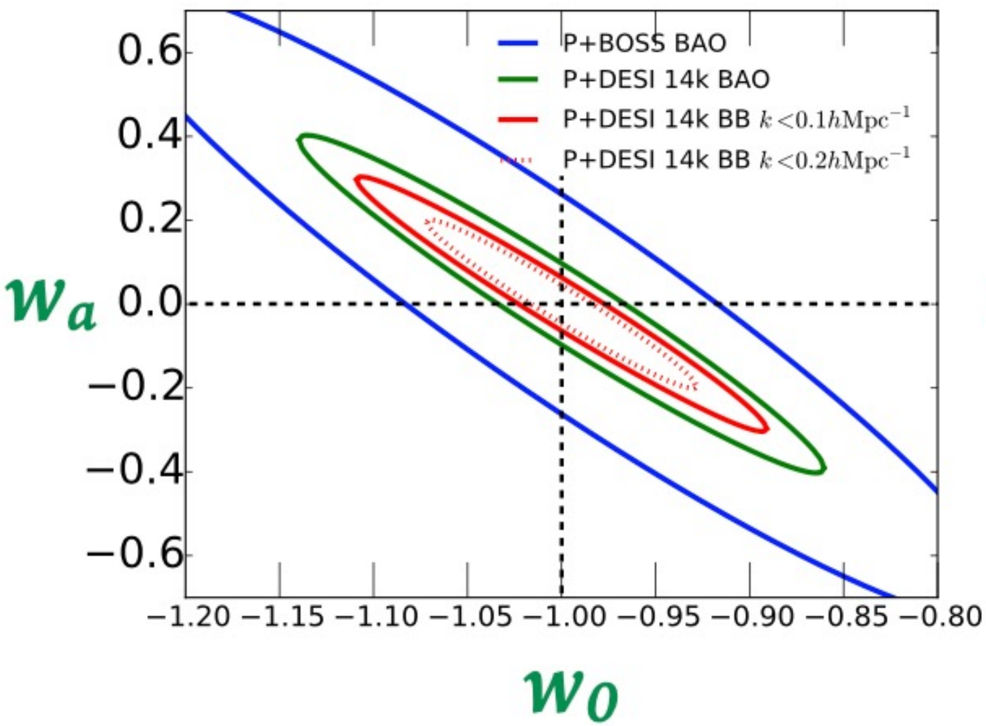


DESI will get 30M redshifts (it used to be hard to get one!)

GALAXIES: DARK ENERGY FORECASTS

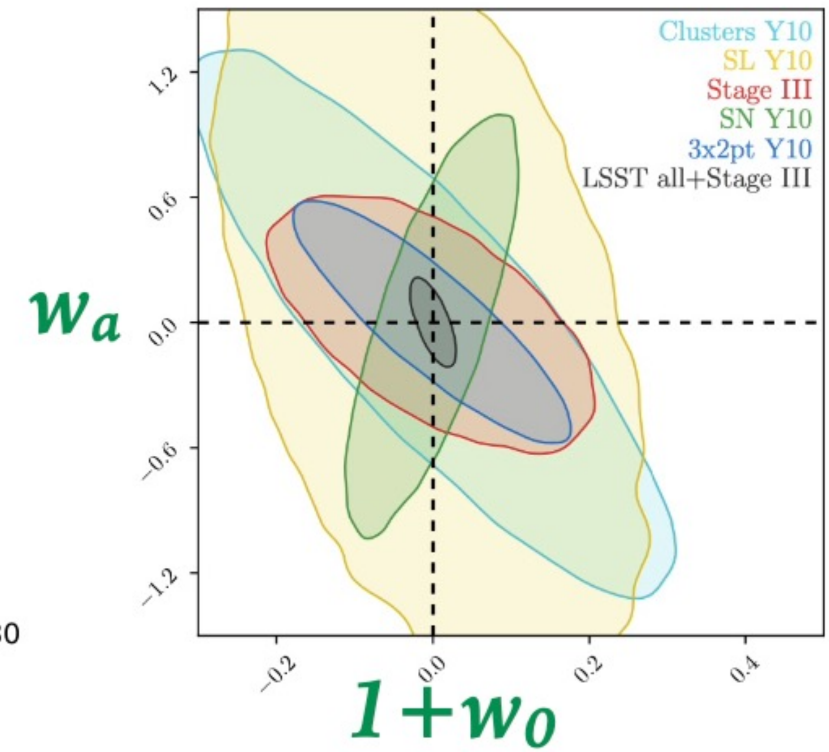
expect percent-level test of w_0=-1 during 2020s

$$w(a) = w_0 + w_a(1\text{-}a)$$



DESI forecast

https://arxiv.org/abs/1611.00036



Vera Rubin Obs (DESC) forecast

https://arxiv.org/abs/1809.01669

Gravitational Waves and Dark Energy: Standard Sirens

GW and multimessenger provide four main tests of DE and gravity:

Gravitational wave astronomy opens new possibilities to probe gravity and DE. For readers unfamiliar with the basics of GWs, we provide a short introduction in section 3. For the purpose of cosmology, the most promising GW events are those that can be observed by other messengers (either EM waves or neutrinos). There are four main tests one can do with multi-messenger GW events:

- *Standard sirens (section 4):* the amplitude of GWs is inversely proportional to its luminosity distance. If a counterpart of the GW is observed, a redshift measurement of the source is possible and the cosmic expansion history can be constrained. For close by sources, only the Hubble constant is measured. Future standard sirens measurements could help resolving the present tension in H_0 (see Figure 8).
- *GW speed (section 5):* the propagation speed of GWs follows from the dispersion relation. Once the location of a GW event is known, it is possible to compare the speed of GWs with respect to the speed of light. Many alternative gravity theories predict that GWs propagate at a different speed either by modifying the effective metric in which GWs propagate, by inducing a mass for the graviton or by introducing higher order terms in the dispersion relation.
- *GW damping (section 6):* modified gravity interactions can also alter the amplitude of GWs. In addition to the cosmic expansion, effective friction terms can damp GWs. This introduces an inequality between the GW and the EM luminosity distance that can be tested.
- *Additional polarizations (section 7):* in alternative theories of gravity, there could be additional modes propagating. These extra polarizations could be directly tested if the source is localized and there is a network of detectors online. Moreover, these modes could mix with the tensor perturbations leading, for instance, to GW oscillations.

https://www.frontiersin.org/articles/10.3389/fspas.2018.00044/full#F8

The panel on “The Dark Side of the Universe” at the World Science Festival in NY in June 2011

The three women representing Dark Matter are, from the right, Katherine Freese, Elena Aprile, and Glennys Farrar. Continuing to the left are three men representing Dark Energy: Michael Turner, Saul Perlmutter and Brian Greene (co-host of the Festival).

“Dark matter is attractive, while dark energy is repulsive!”