Dark Matter Theory Wrap Up

Katherine Freese

- Director, Weinberg Institute for Theoretical Physics, Jeff & Gail Kodosky Chair,
- Prof of Physics, University of Texas, Austin
- Professor, Stockholm University

- Director Emerita, Nordita (Nordic Institute for Theoretical Physics, in Stockholm)

The Dark Matter Problem is 90 years old: Dates back to Knut Lundmark in 1930 and Fritz Zwicky in 1933

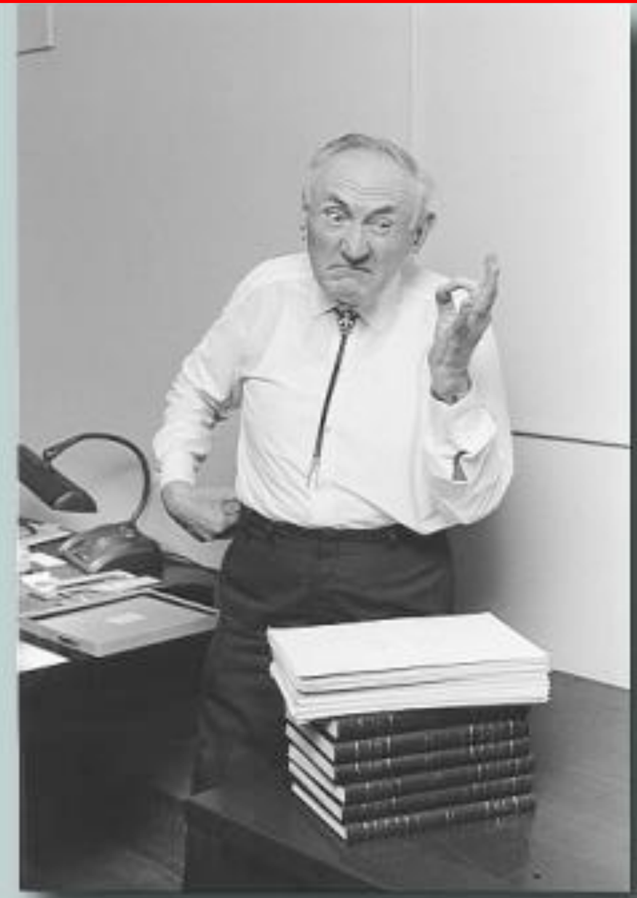
Knut Lundmark

Knut Lundmark as student in 1908

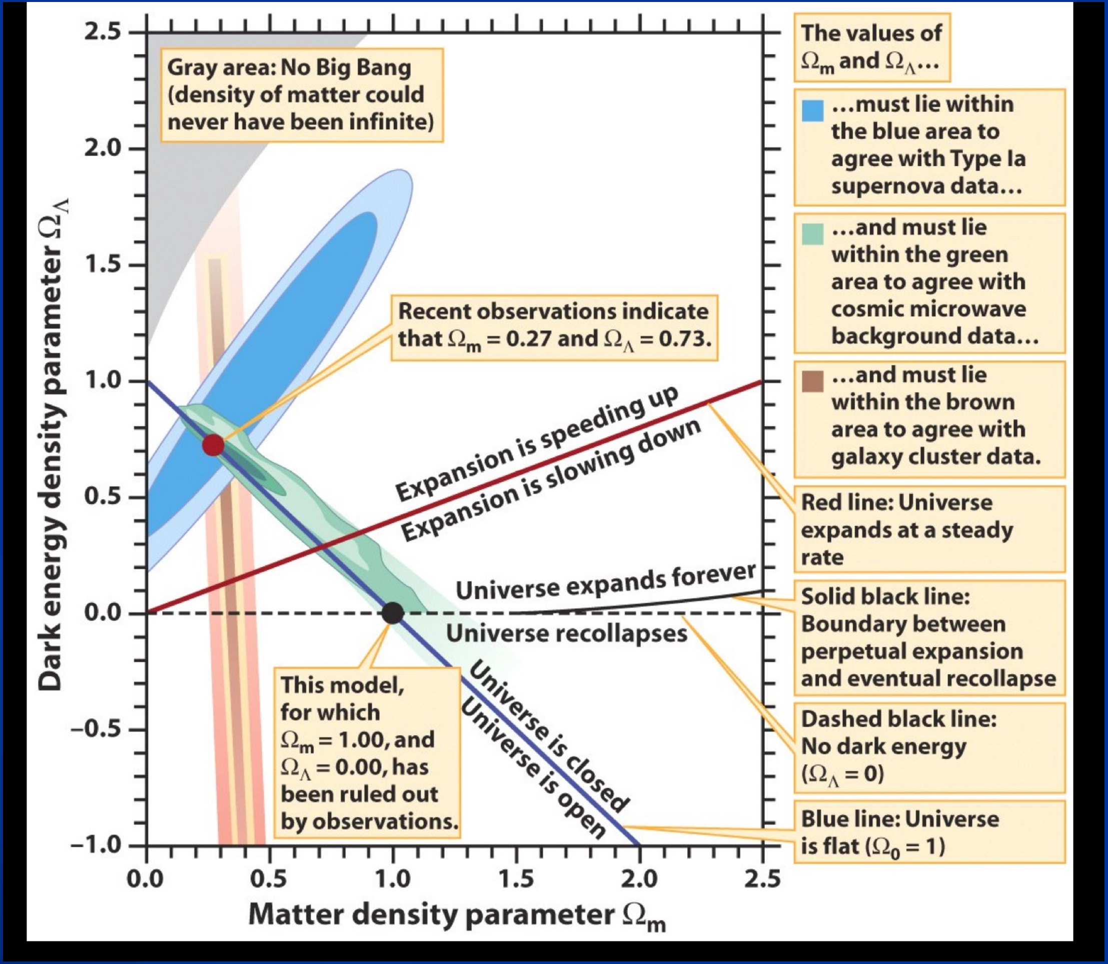
Galaxies in the Coma cluster were moving too rapidly.

Proposed Dunkle Materie as the explanation.

It's not stars, it doesn't shine.
It's DARK.



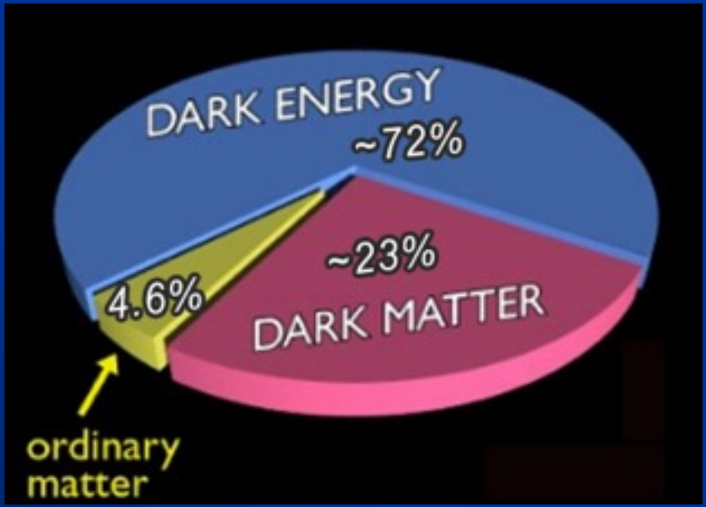
Concordance Cosmology

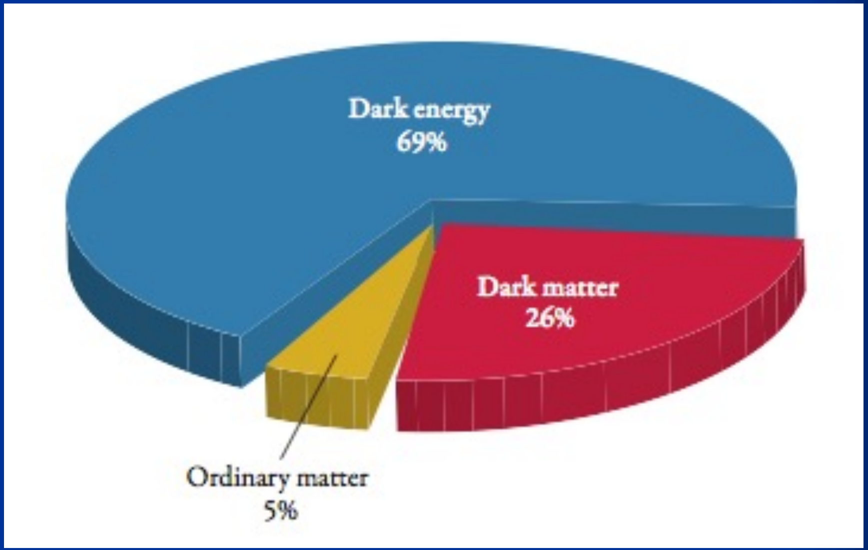


(talk of Marco Bruni)

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?

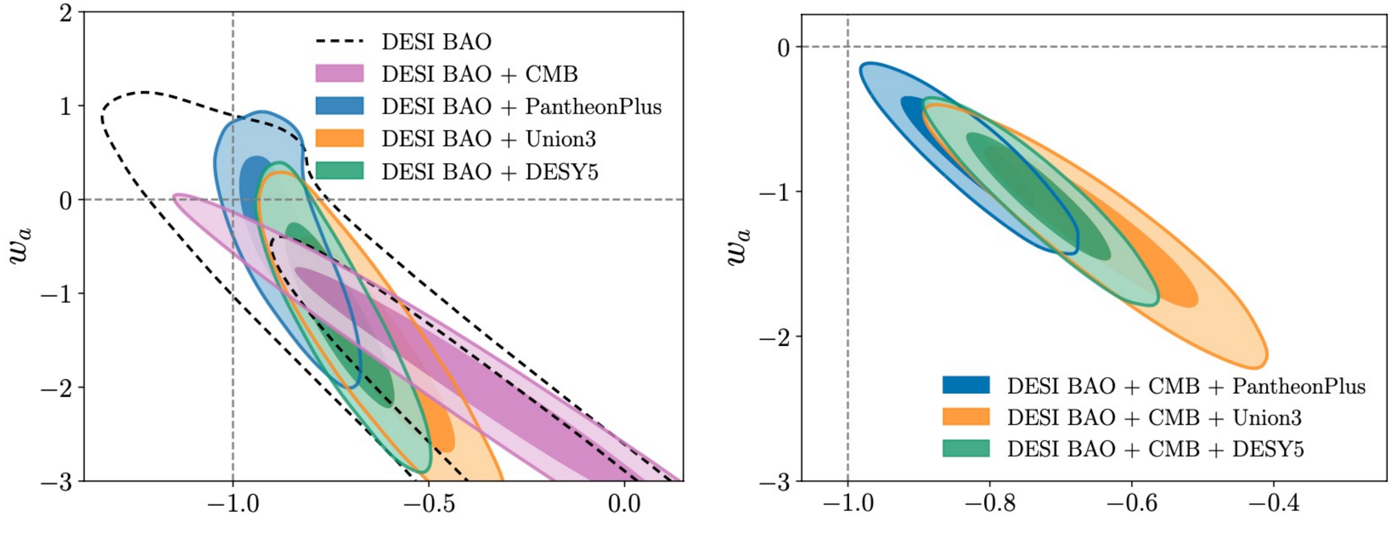
Outline: History, Surprising Results and Big new Results

- Surprising Results:
- Time dependence of Dark Energy in DESI??
- Hubble Tension ??
- Sigma_8 tension ??
- Negative Neutrino Mass from DESI??
- Too many and too massive early galaxies found in JWST to made sense in LCDM: some could be DARK STARS

- Big New Results of the Conference:
- COSINE-100 vs. DAMA
- XENON hits the neutrino fog

Time dependence of dark energy: DESI BAO results

- DESI baryon acoustic oscillation measurements favouring dynamical dark energy (assuming a time varying equation of state: $w(a) = w_0 + w_a\,(1 - a)$ at $\sim 3\sigma$ level the quadrant $w_0 > -1,\, w_a < 0$ is preferred).



[Adame et al., 2024]

From talk of Piero Ullio

Hubble Tension

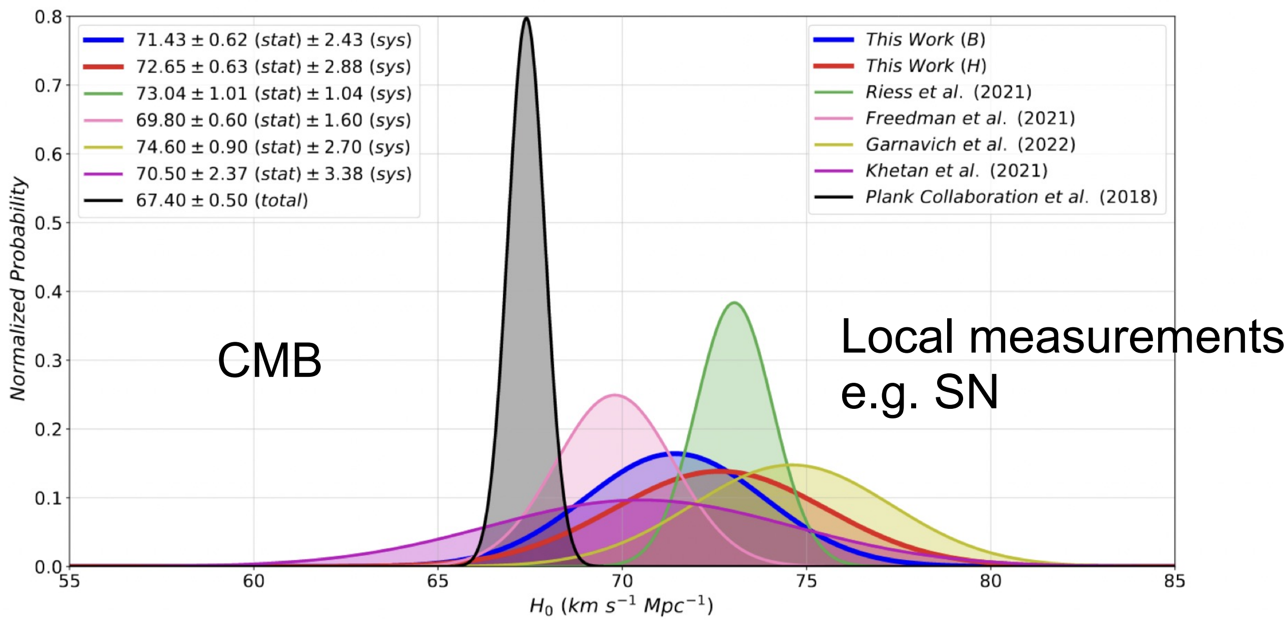


Figure 14. Probability distributions for H_0 for calibrations based on Cepheids [139], the TRGB [25] SBF from [85], compared to recent published values from the literature. The Planck Collaboration value from the CMB [11] shown in grey.

Freedman and Madore https://arxiv.org/pdf/2309.05618

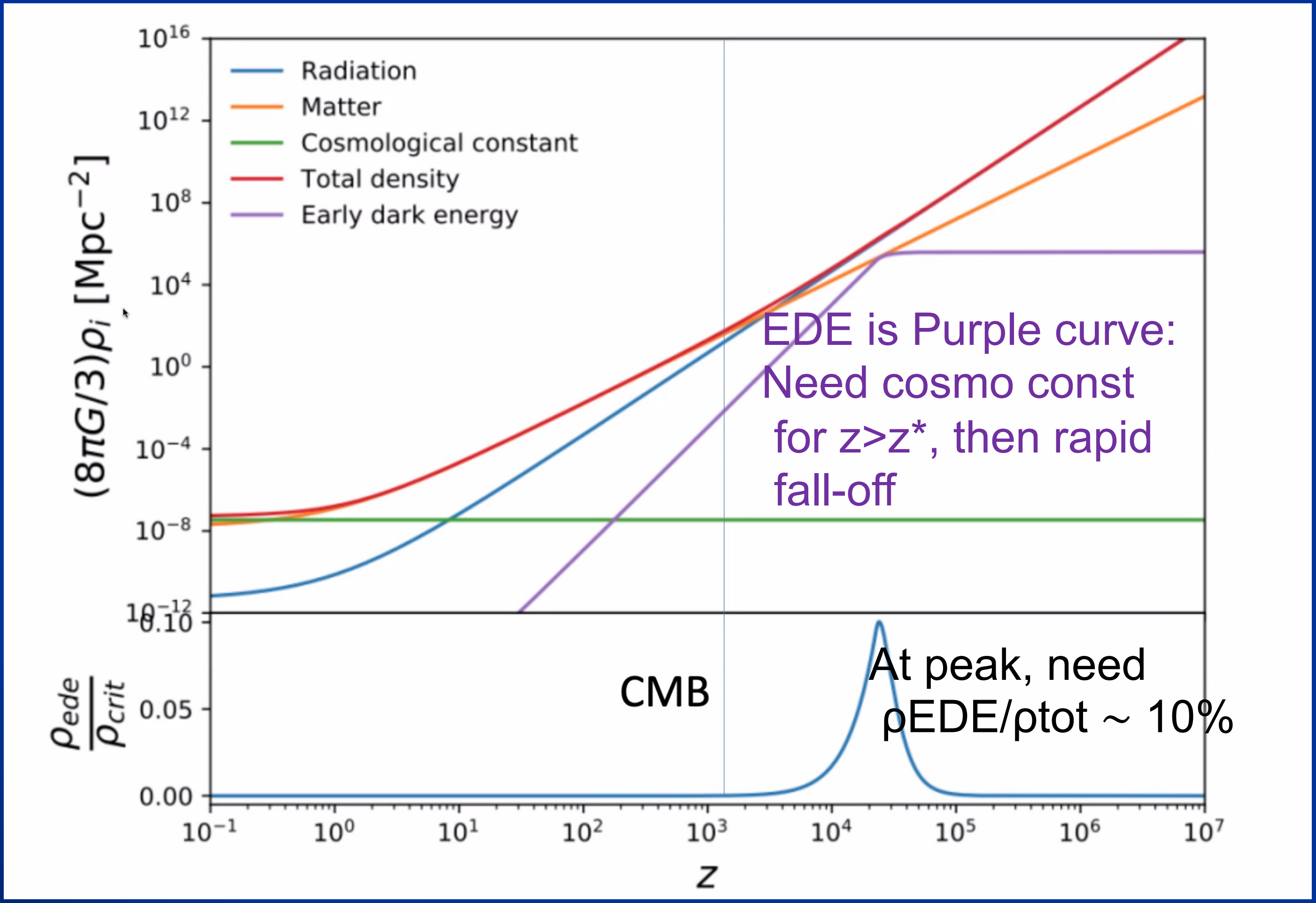
Use JWST data on Cepheids and tip of Red Giant Branch for callibration

Theory explanations of Hubble tension

- Very difficult!
- Late time solutions fail (Knox and Millea Hubble Hunters guide)
- Early time better: extra energy density speeds up universe expansion so that length scales including sound horizon are smaller when CMB is produced at z=1100. Thus to keep the Doppler peak at 1 degree, the inferred value of H0 is larger. How to get this:
- Dark radiation degrades fit to higher l
- my favorite: Early Dark Energy (Karwal and Kamionkowski). Our variant: Chain Early Dark Energy
- Problem: These approaches that help with the Hubble tension make the S8 tension worse

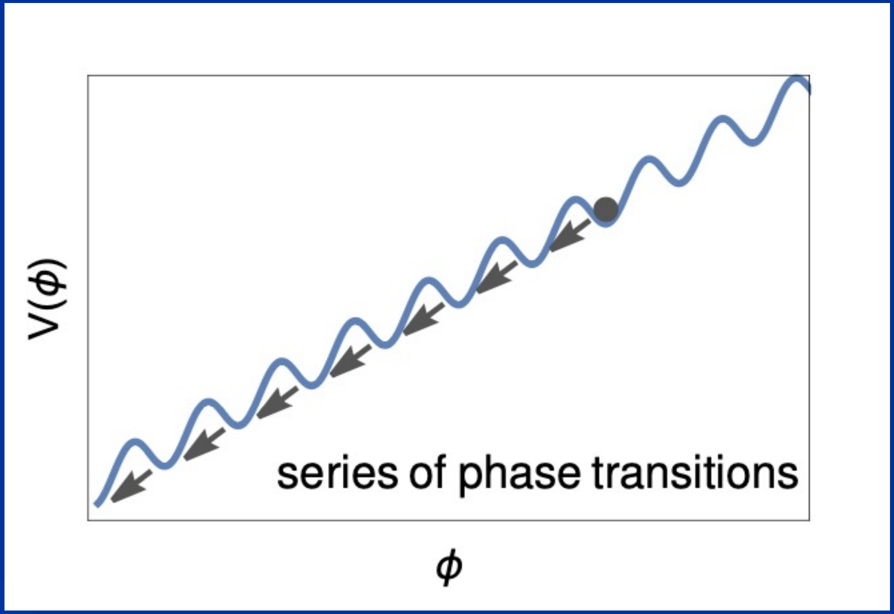
What's needed for Early Dark Energy

Plot from
Marc
Kamionkowski



n.b. PEAK is actually at z*=3500, right at matter/radiation equality
(Poulin etal 1811.04083)
My thoughts: looks like a phase transition!

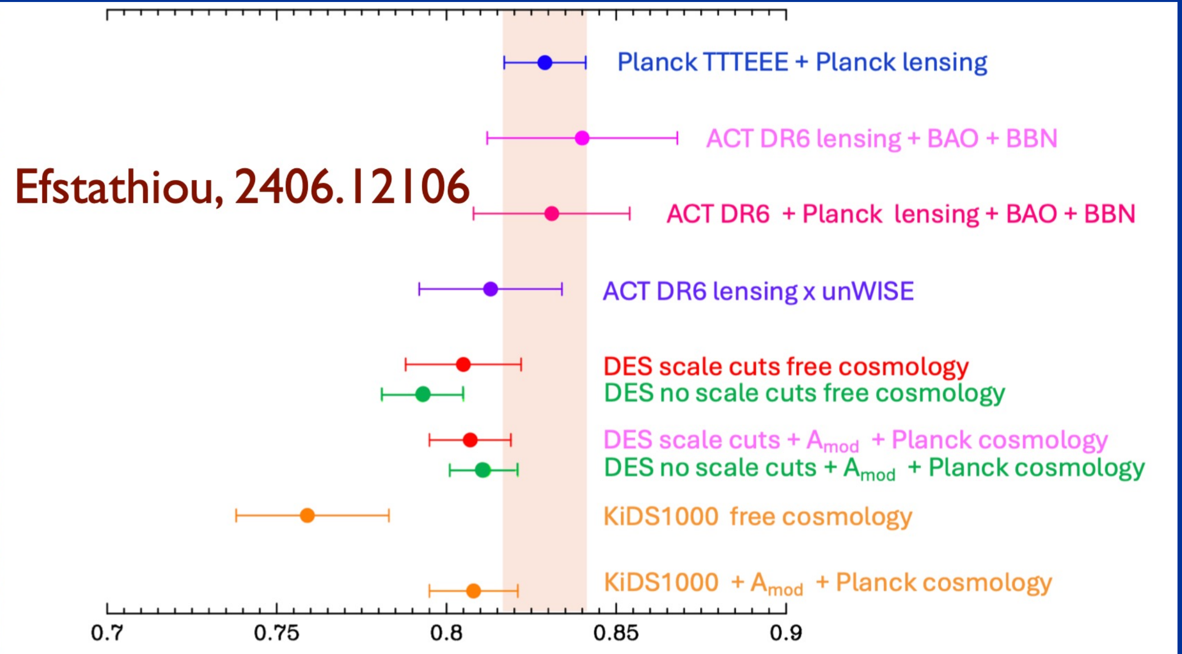
Chain EDE



K. Freese and Martin Winkler
arXiv: 2102.13655

S8 tension

Sigma8 quantifies amplitude of matter fluctuations on 8 Mpc scales



$$S_8 = \sigma_8(\Omega_m/0.3)^{0.5}$$

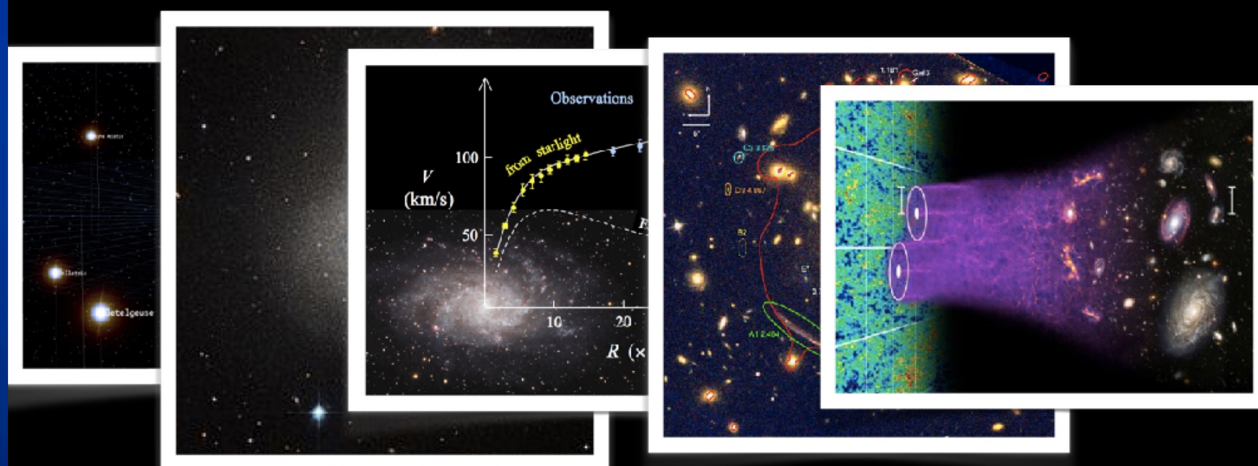
Figure 5. Summary of measurements of S_8 including new results from ACT DR6 CMB lensing measurements (Qu et al., 2024a) and ACT DR6 lensing cross-correlate with unWISE galaxies (Farren et al., 2024). The remaining entries show results for the DES and KiDS weak lensing surveys as described in the text.

CMB on linear scales, Weak galaxy lensing on nonlinear scales: need better understanding of baryonic feedback

Where is the dark matter?

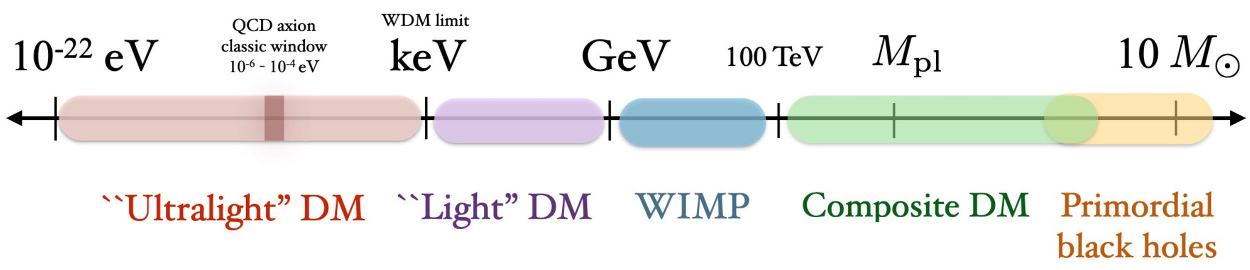
We have evidence for dark matter's existence on length scales spanning ~10 orders of magnitude…

~100 pc	~kpc	~100 kpc	~Mpc	>Gpc
Affects nearby stars	Dominates dwarf galaxies	Supports galaxy rotation	Fills galaxy clusters	CMB+ Large scale structure



Ciaran O'Hare

4



Important to remember

- All candidates basically work as dark matter in a broad sense (i.e. have mass+don’t interact much)
- But not all are “vanilla CDM”. Some forms of DM make structures in the Universe look a bit different (e.g. self-interacting DM, fuzzy DM, warm DM)
- They are generally speaking **not** mutually exclusive, in terms of existence, or as dark matter…
- Complementary probes exist, collider searches, fifth force experiments, light-shining through walls, helioscopes

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 are known to exist! But too light, ruin galaxy formation
- Sterile Neutrinos: no Standard Model interaction
- Primordial black holes
- Asymmetric Dark Matter
- Light Dark Matter, Fuzzy Dark Matter
- Self Interacting Dark Matter
- Q-balls
- WIMPzillas, Planck-scale DM

Neutrinos as Dark Matter? No

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

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

- 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

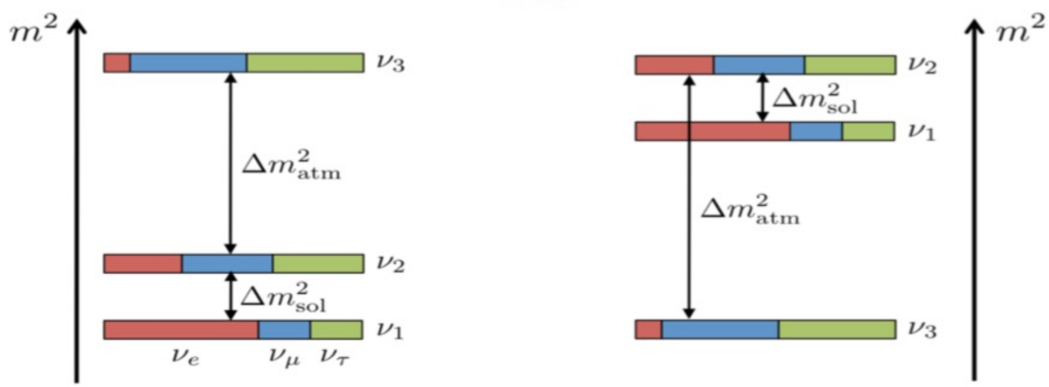
We know from the observation of neutrino oscillations that neutrinos have mass (Nobel prize 2015 to Kajita & McDonald!)
However, oscillations measure mass ***differences*** (with few % accuracy):

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

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

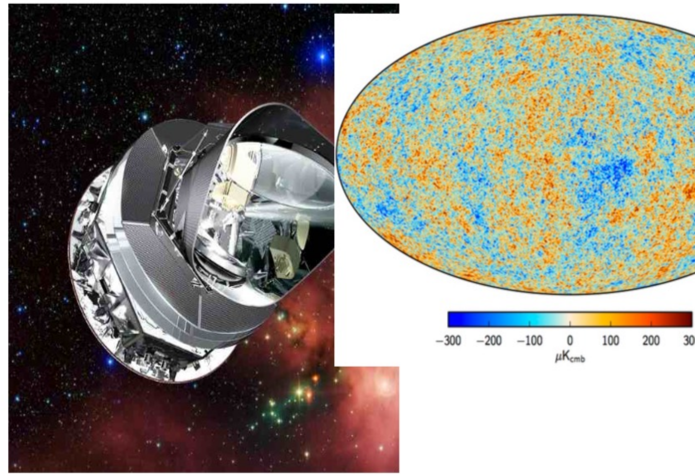
(depending on the hierarchy)

Figure credit: Juno Collaboration

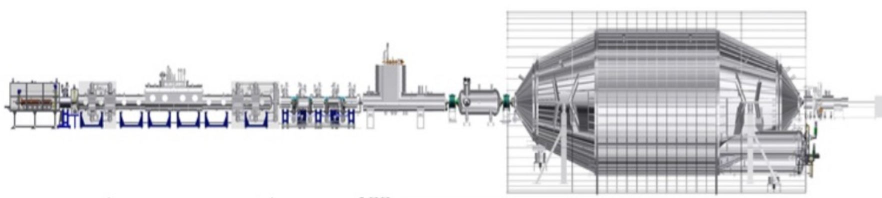
The tiny neutrino masses are a puzzle for the Standard Model of particle physics

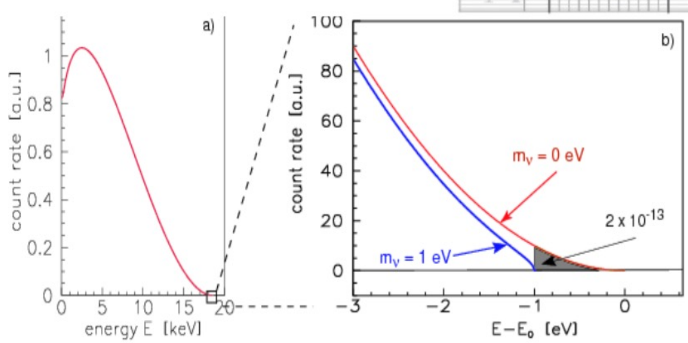
The absolute scale of neutrino masses can be measured in different ways

Cosmological observations (CMB, LSS)

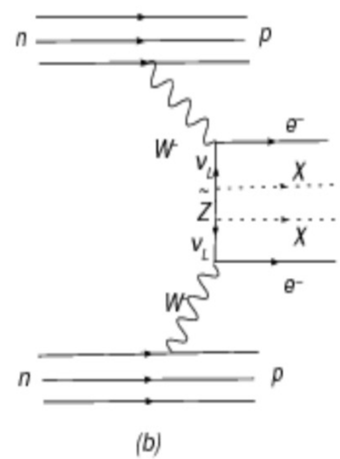


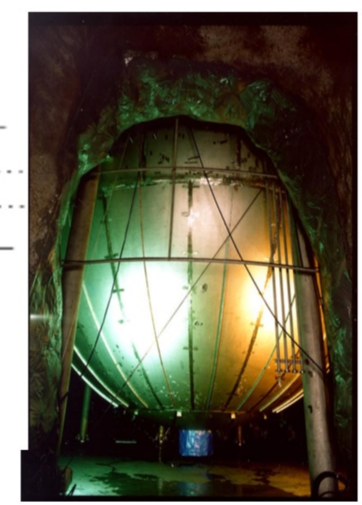
Neutrinoless double β decay





Kinematic measuremets (Tritium β decay)





PHYSICAL REVIEW LETTERS

Editors' Suggestion

Improved Limit on Neutrinoless Double-Beta Decay in ^{130}Te with CUORE

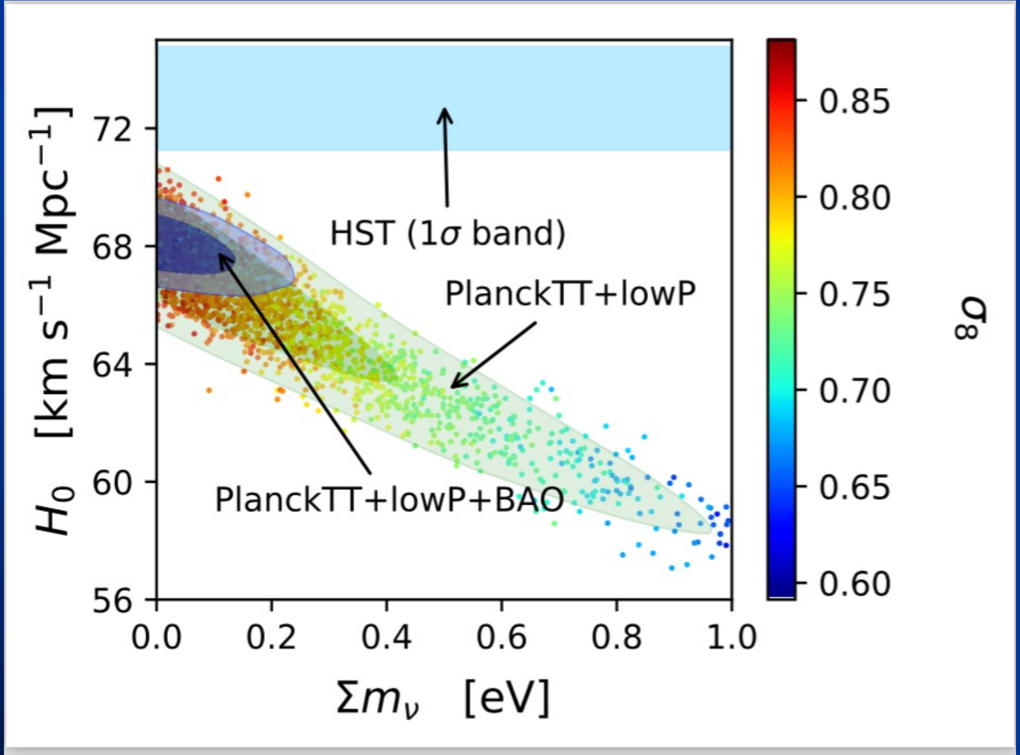
D. Q. Adams *et al.* (CUORE Collaboration)
Phys. Rev. Lett. **124**, 122501 – Published 26 March 2020

Doug Quincy Adams

ABSTRACT

We report new results from the search for neutrinoless double-beta decay in ^{130}Te with the CUORE detector. This search benefits from a fourfold increase in exposure, lower trigger thresholds, and analysis improvements relative to our previous results. We observe a background of $(1.38 \pm 0.07) \times 10^{-2}$ counts $/(\mathrm{keV\ kg\ yr})$ in the $0\nu\beta\beta$ decay region of interest and, with a total exposure of 372.5 kgyr, we attain a median exclusion sensitivity of 1.7×10^{25} yr. We find no evidence for $0\nu\beta\beta$ decay and set a 90% credibility interval Bayesian lower limit of 3.2×10^{25} yr on the ^{130}Te half-life for this process. In the hypothesis that $0\nu\beta\beta$ decay is mediated by light Majorana neutrinos, this results in an upper limit on the effective Majorana mass of 75–350 meV, depending on the nuclear matrix elements used.

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



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

Vagnozzi, Gerbino, KF etal arXIv:1701.0872

Planck Satellite: < 0.12 eV

DESI mν < 0.072 (0.113) 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

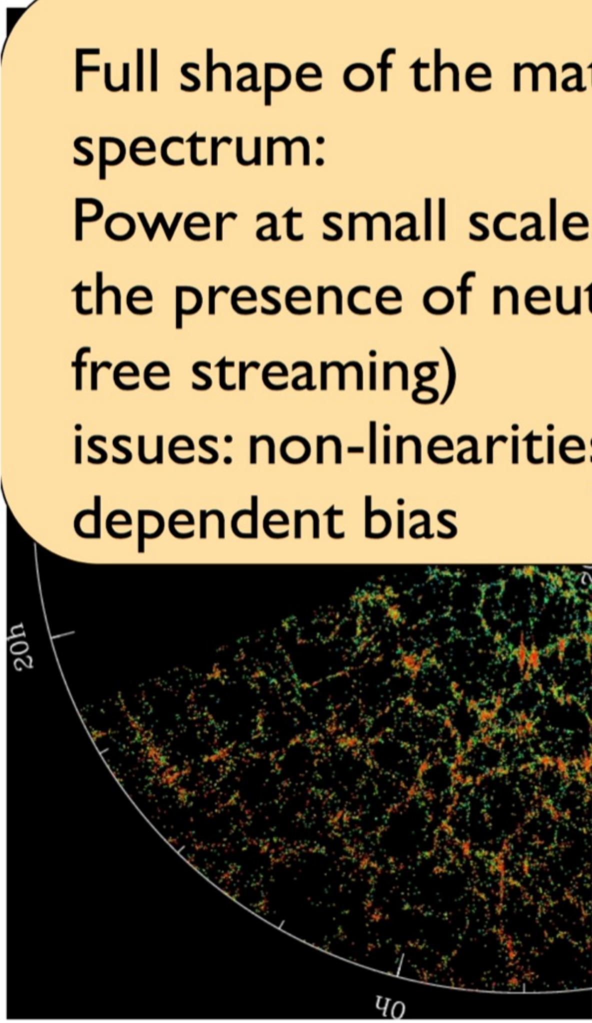
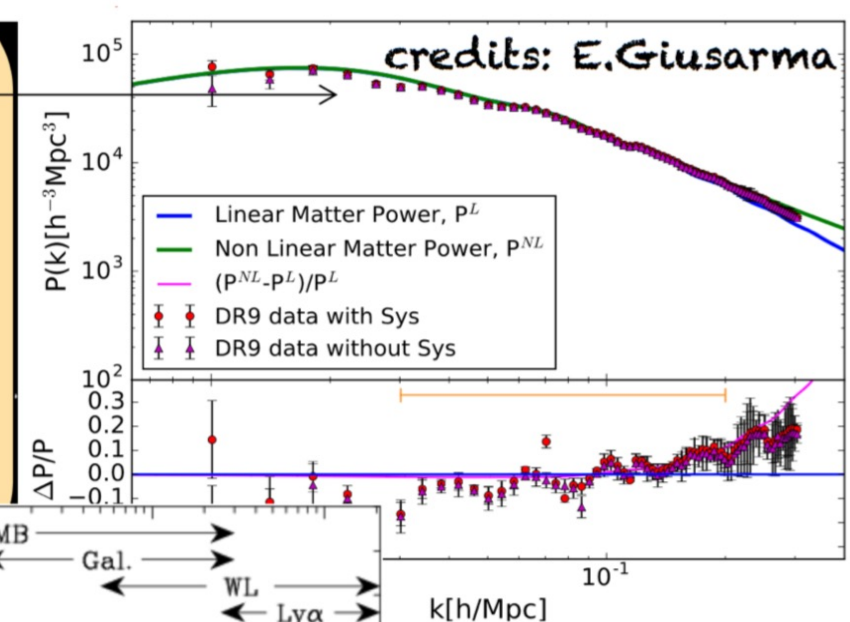
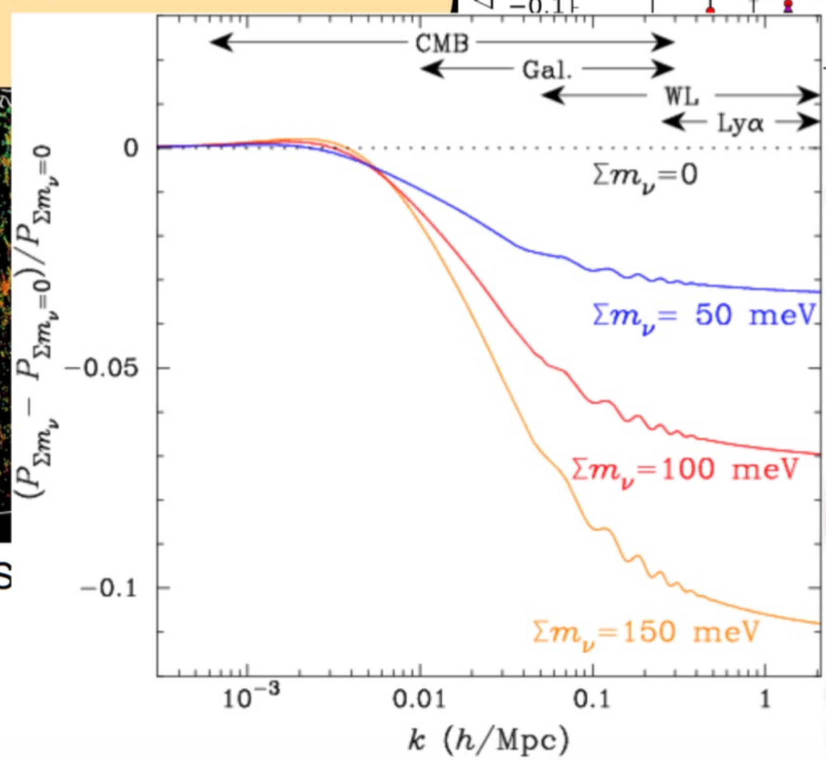
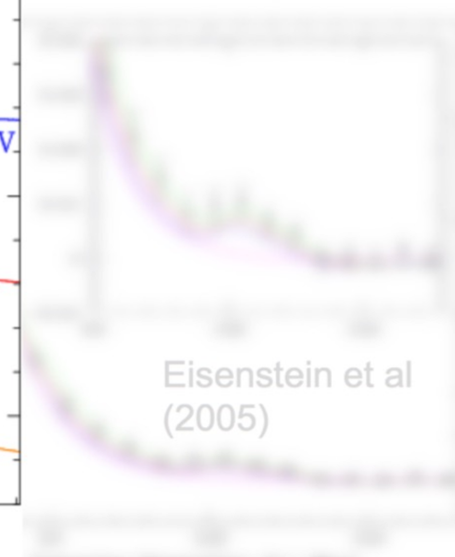


Image Credit: M. Blanton and the S






Eisenstein et al (2005)

DESI Collaboration 2024

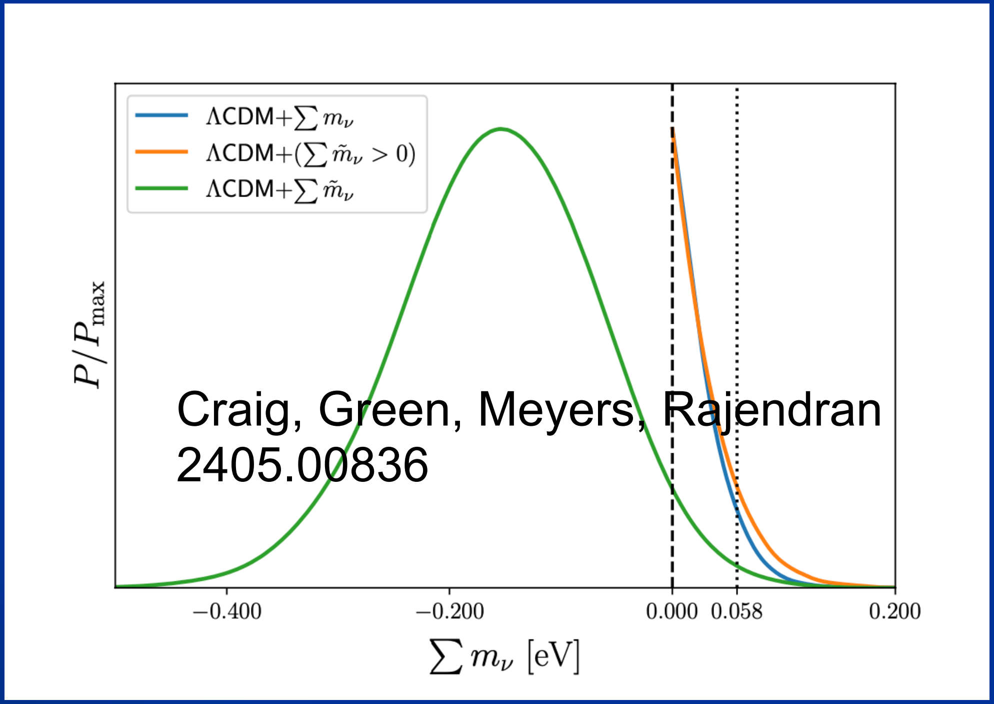
combining the DESI and CMB data yields an upper limit $\sum m_\nu < 0.072$ (0.113)

eV at 95% confidence for a $\sum m_\nu > 0$ $(\sum m_\nu > 0.059)$ eV prior.

Some tension with inverted hierarchy which requires sum of neutrino masses above 0.1 eV

arXiv:2404.03002

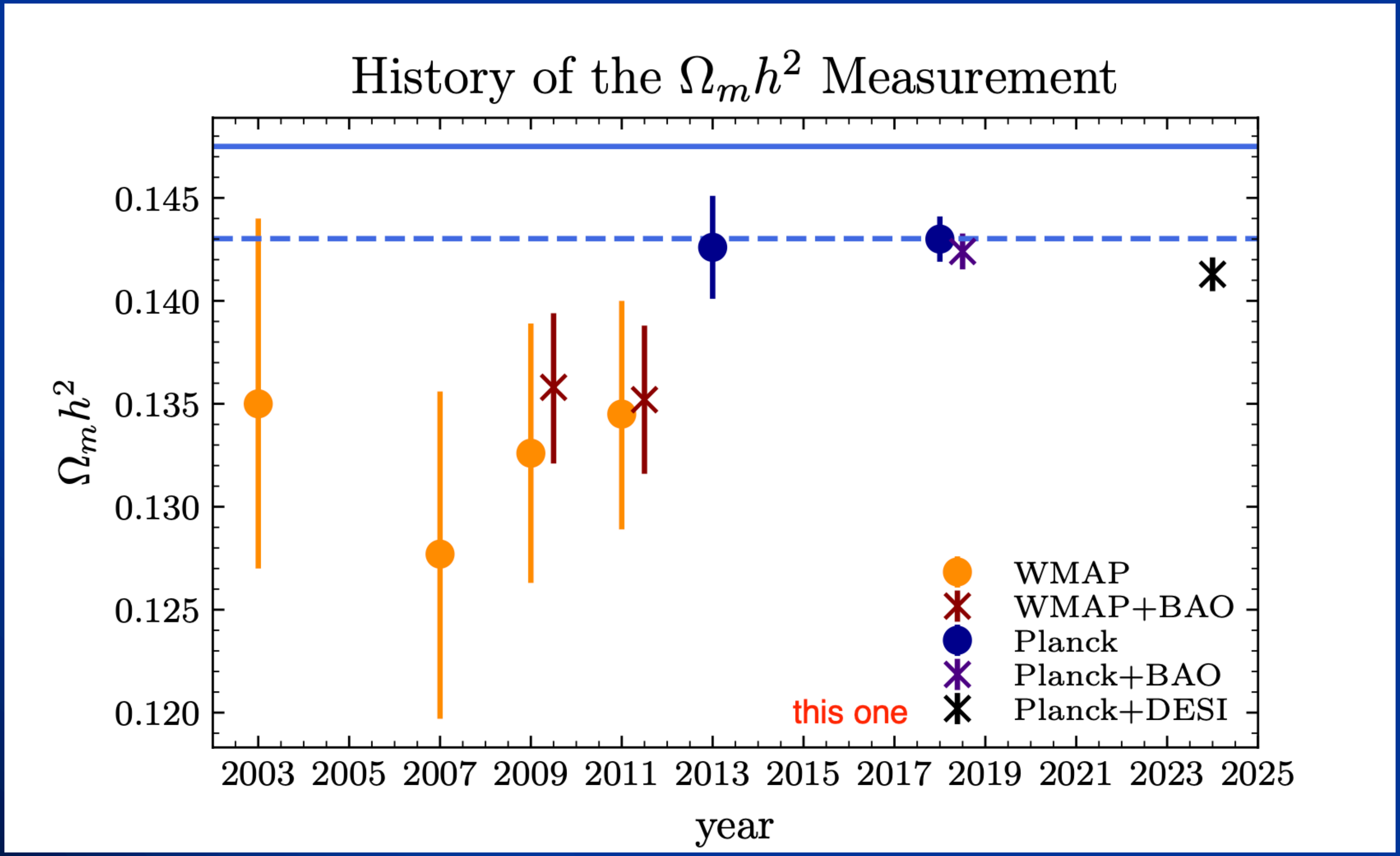
Negative Neutrino Mass from DESI results?



Craig, Green, Meyers, Rajendran
2405.00836

Of course not.

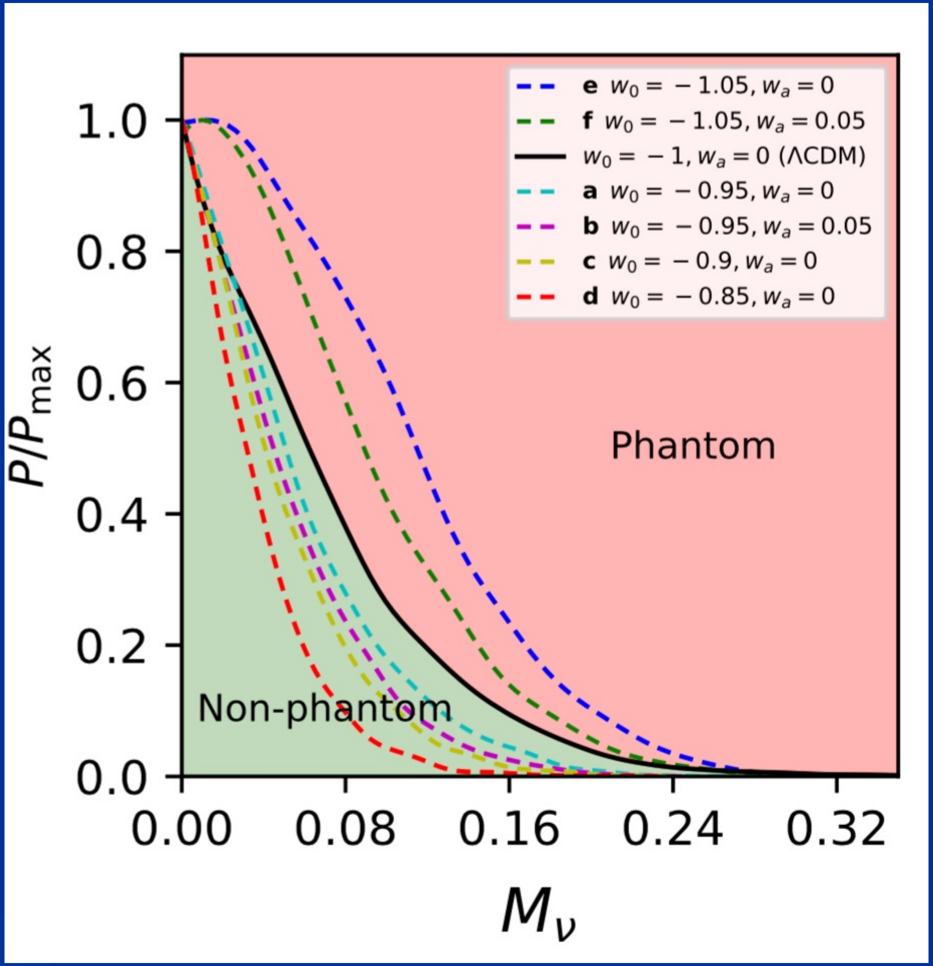
Systematics?
Problems with using BAO to get Omega_m h^2
Signs of new BSM physics that offset neutrino suppression of large scale structure ?
i.e. enhanced clustering of matter in the late universe due to long range forces
In the dark sector, eliminate the SM neutrinos via decay (or annihilation),
cool the neutrinos so that they behave like dark matter,
or change their mass over cosmological history.


History of the $\Omega_m h^2$ Measurement
0.145
0.140
0.135
0.130
0.125
0.120
$\Omega_m h^2$
2003 2005 2007 2009 2011 2013 2015 2017 2019 2021 2023 2025
year
WMAP
WMAP+BAO
Planck
Planck+BAO
Planck+DESI
this one

Neutrino Mass bounds are 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

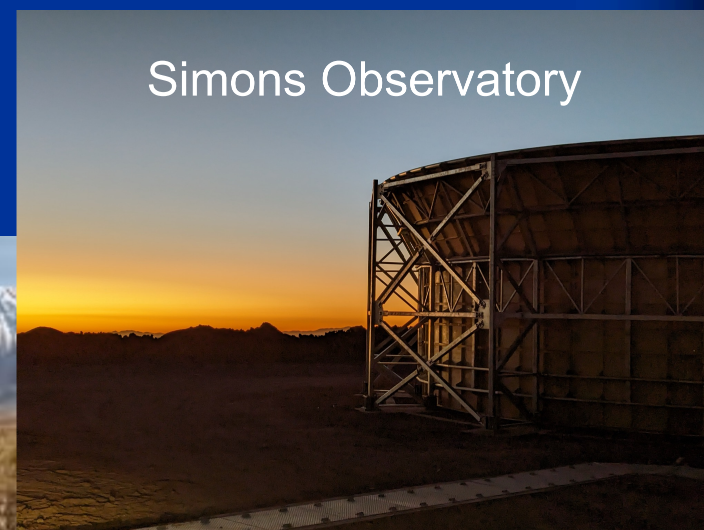
Ongoing Cosmic Microwave Background Experiments

My group has joined these two experiments

Jon Gudmundsson

Adri Duivenvoorden

SPIDER at South Pole



Nick Galitzki, new Prof at UT

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.

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.

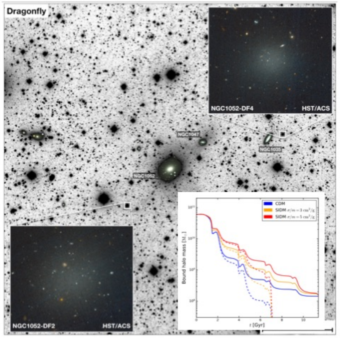
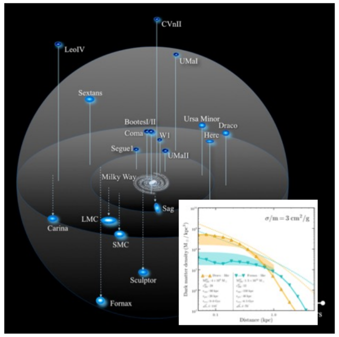
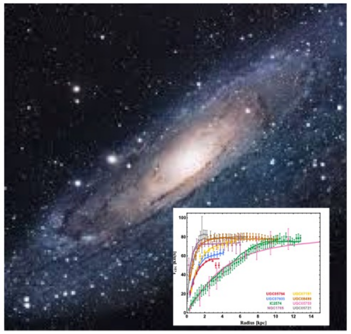
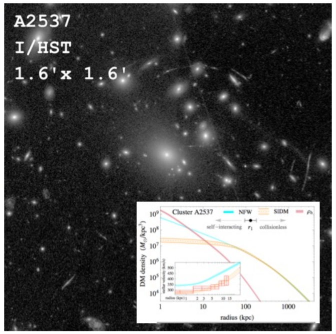
Vagnozzi, Gerbino, KF etal arXiv:1701.0872

Planck Satellite: < 0.12 eV

Candidates I'll discuss

- Self Interacting Dark Matter
- Primordial black holes
- Focus on theoretically well motivated CDM particle candidates:
- Axions
- WIMPs

SIDM From Dwarf to Cluster Scales

Ultra-diffuse galaxies (dark-matter-deficient)	Milky Way satellites	Spiral galaxies	Galaxy clusters
			
$M_{halo} <\sim 10^8\ M_\odot$	$M_{halo} \sim 10^8\ M_\odot$	$M_{halo} \sim 10^9 - 10^{13}\ M_\odot$	$M_{halo} \sim 10^{15}\ M_\odot$

- SIDM can explain diverse dark matter distributions over a wide range of galactic systems (halo masses $\sim 10^8 – 10^{15}\ M_\odot$)
- Bonus: seeding SMBHs
- Fundamental scales $\sim 10^{-12}$ cm vs galactic scales $\sim 10^{22}$ cm
- Measuring particle properties of dark matter without detecting it directly

From talk of

Haibo Yu;

See also

Parallel talk of

Daniel Gilman

Primordial Black Holes as Dark Matter?

- Primordial: they would have been born in the Universe's first fractions of a second, when fluctuations in the density led to small regions having enough mass to collapse in on themselves.
- One possibility: they formed at the transition in the early Universe when free quarks became bound together into protons, neutrons, etc. Pressure drop led to black holes.
- Resurgence of interest as possible explanation of gravitational waves seen in LIGO detector in 2016 due to merging black holes as massive as 30 suns.
- There could be millions of these between us and the center of the Milky Way.

Primordial Black Holes as Dark Matter

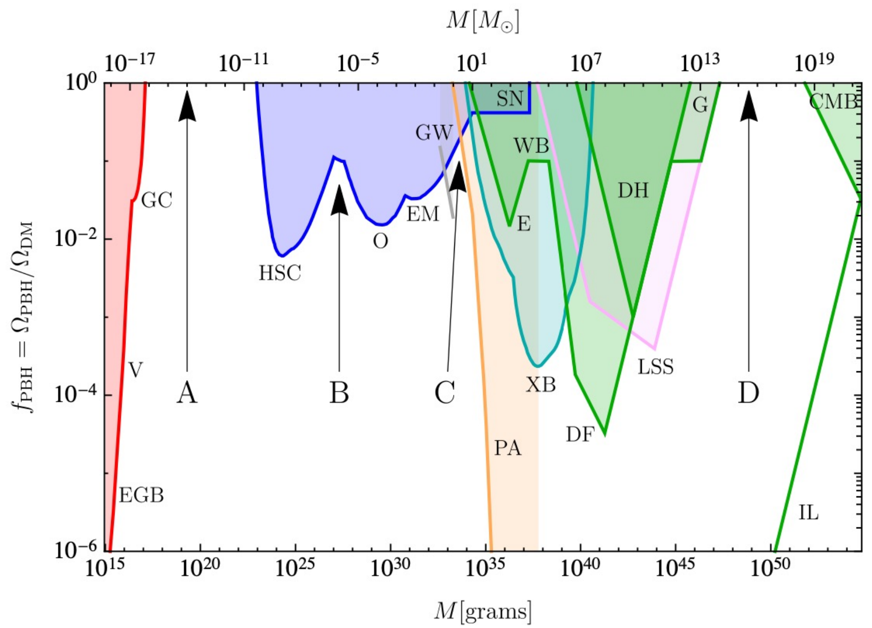


Figure 4: Constraints on $f(M)$ for a monochromatic mass function, from evaporations (red), lensing (blue), gravitational waves (GW) (gray), dynamical effects (green), accretion (light blue), CMB distortions (orange) and large-scale structure (purple), from Reference [1]. Evaporation limits come from the extragalactic γ-ray background (EGB), the Voyager positron flux (V) and annihilation-line radiation from the Galactic centre (GC). Lensing limits come from microlensing of supernovae (SN) and of stars in M31 by Subaru (HSC), the Magellanic Clouds by EROS and MACHO (EM) and the Galactic bulge by OGLE (O). Dynamical limits come from wide binaries (WB), star clusters in Eridanus II (E), halo dynamical friction (DF), galaxy tidal distortions (G), heating of stars in the Galactic disk (DH) and the CMB dipole (CMB). Large-scale structure constraints derive from the requirement that various cosmological structures do not form earlier than observed (LSS). Accretion limits come from X-ray binaries (XB) and Planck measurements of CMB distortions (PA). The incredulity limits (IL) correspond to one PBH per relevant environment (galaxy, cluster, Universe). There are four mass windows (A, B, C, D) in which PBHs could have an appreciable density.

Talks by

Paolo Pani

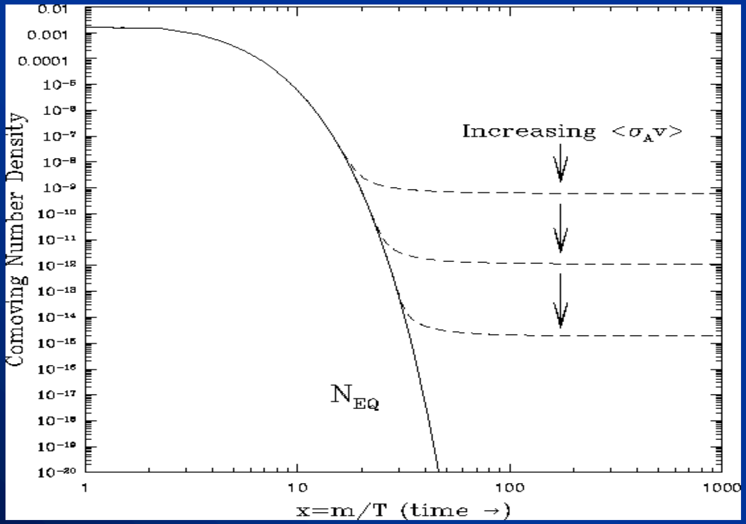
and

Alessandro Cuocco

From Carr and Kuhnel.
arxiv.org/pdf/2110.02821

Best motivated Dark matter candidates: cosmologists don't need to "invent" new particles

- 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)

Axions

- Axions automatically exist in a proposed solution to the strong CP problem in the theory of strong interaction. They are very light, weighing a trillionth as much as protons; yet they are slow-moving. Axions are among the top candidates for dark matter.

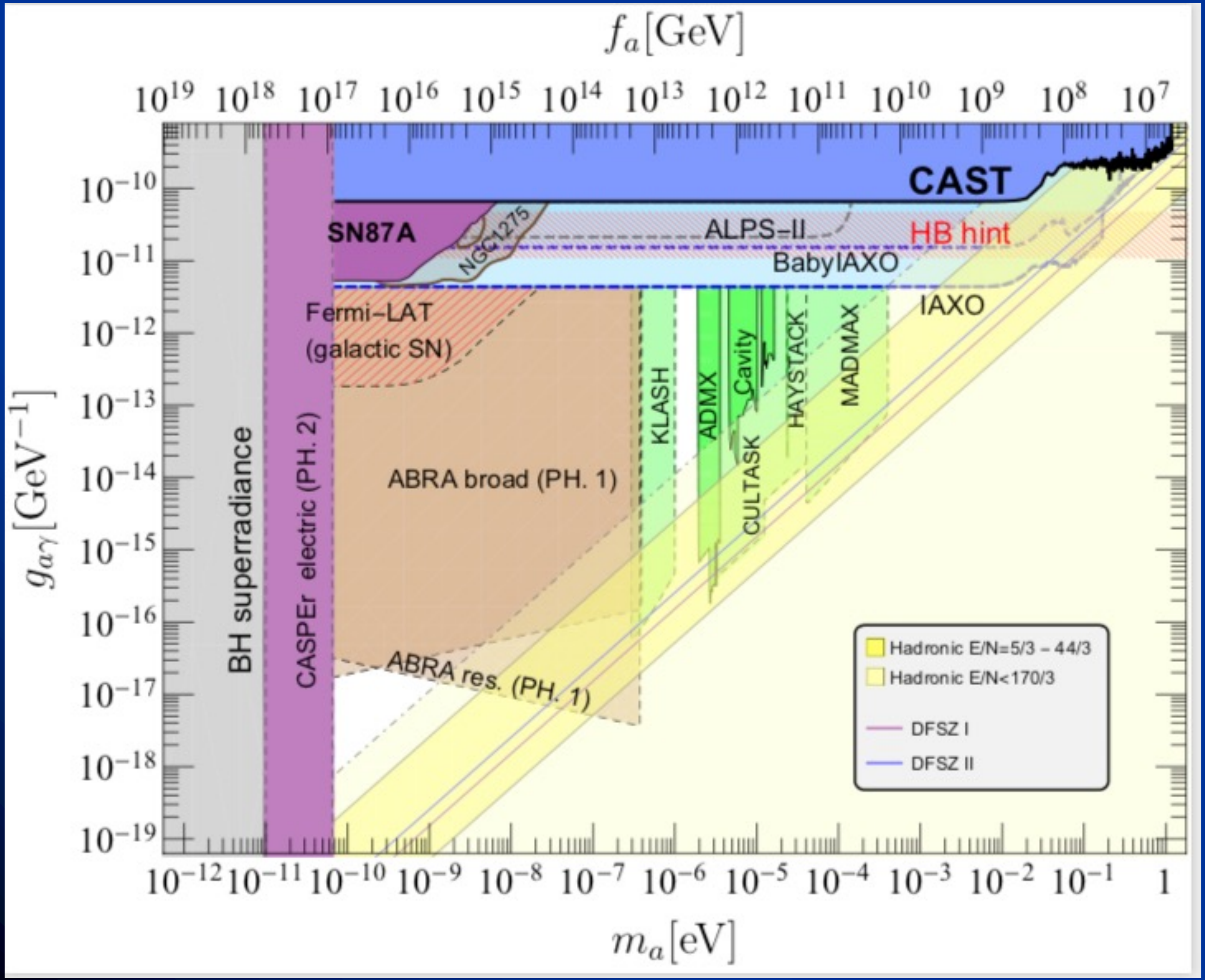
Steven Weinberg

Frank Wilczek

Steven Weinberg, 1933- July 23, 2021

- Driver of some of the most groundbreaking ideas of the last half century. One of the most important thinkers on the planet and a wonderful human being.
- Foundational work creating the Standard Model of Particle Physics.
- We will miss him terribly in Austin--
- A major loss for us and for the world!

Bounds on Axions and ALPs



From review by Luca di Luzio, Giannotti, Nardi, Luca Visinelli 2003.01100

WHY WIMPS? “WIMP MIRACLE”

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

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

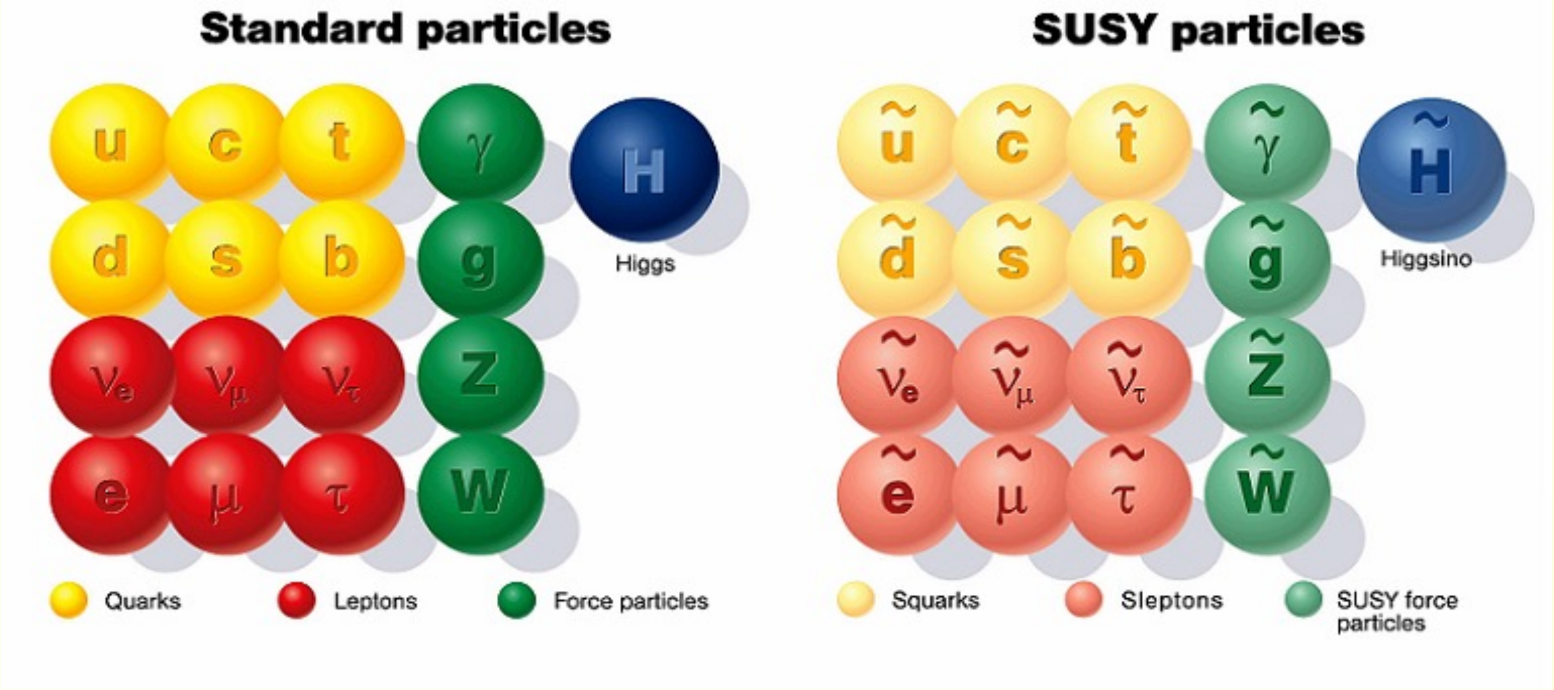
n.b. thermal WIMPs

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

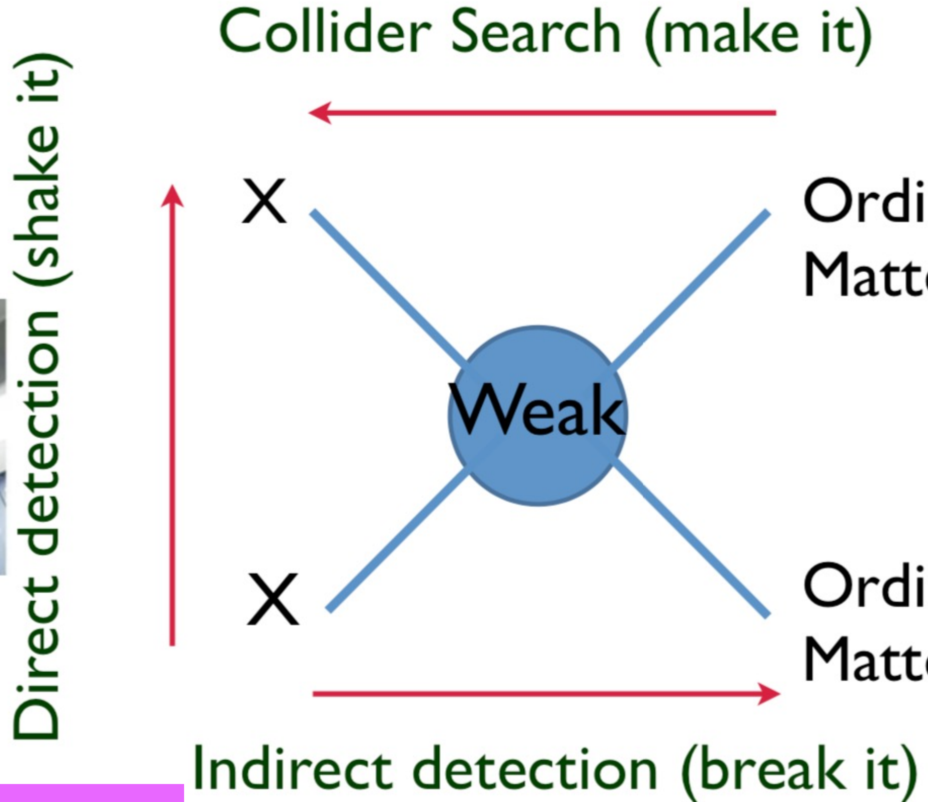
Second reason we favor WIMPS: in particle theories, eg supersymmetry

- Every particle we know has a partner

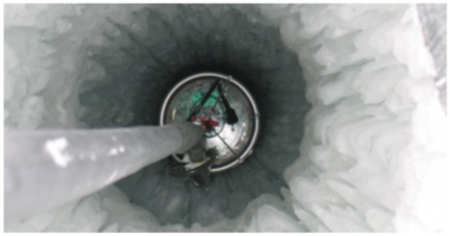


- The lightest supersymmetric particle may be the dark matter.

THREE PRONGED APPROACH TO WIMP DETECTION

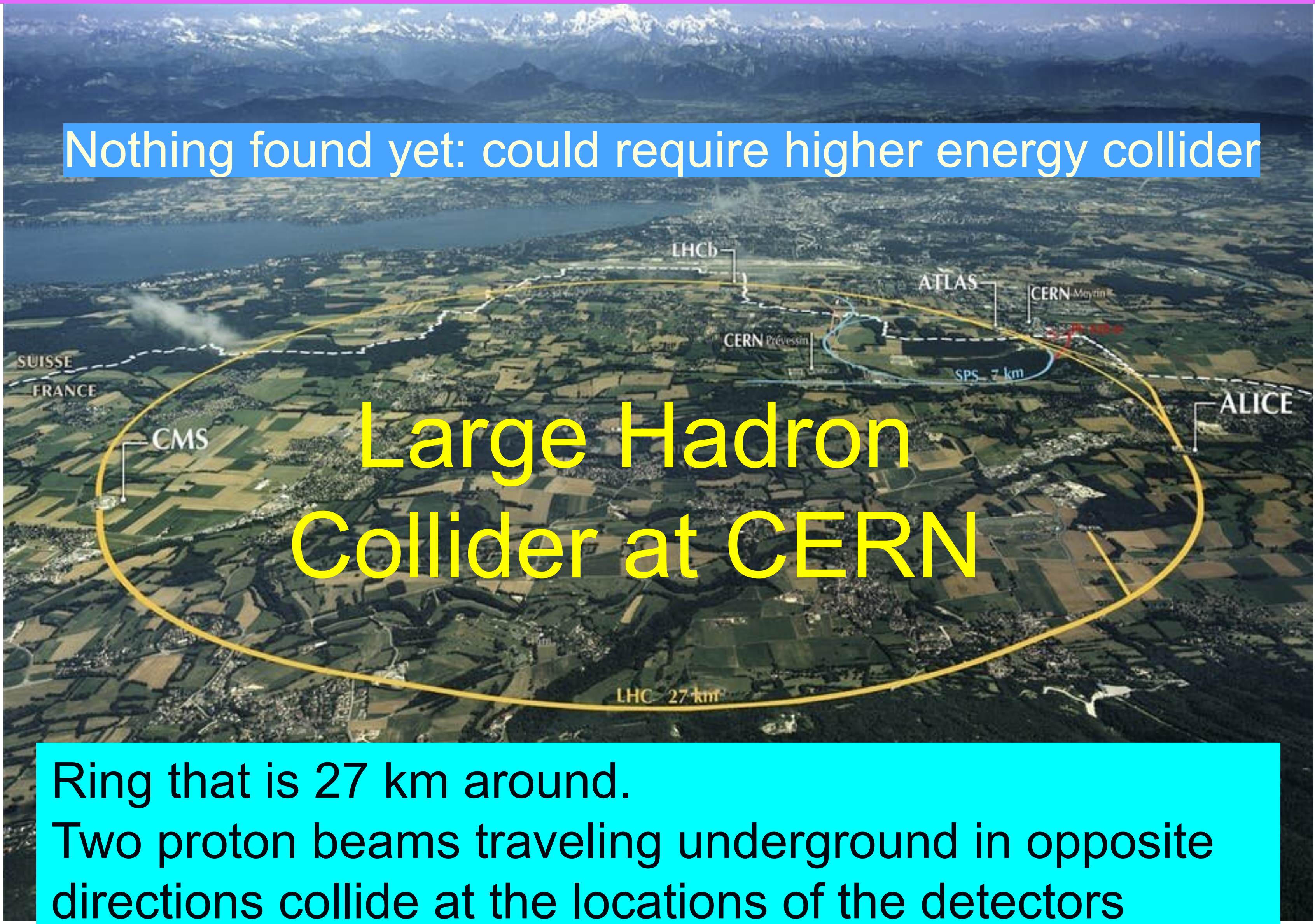


FOURTH PRONG: DARK STARS



FIRST WAY TO SEARCH FOR WIMPS

Nothing found yet: could require higher energy collider

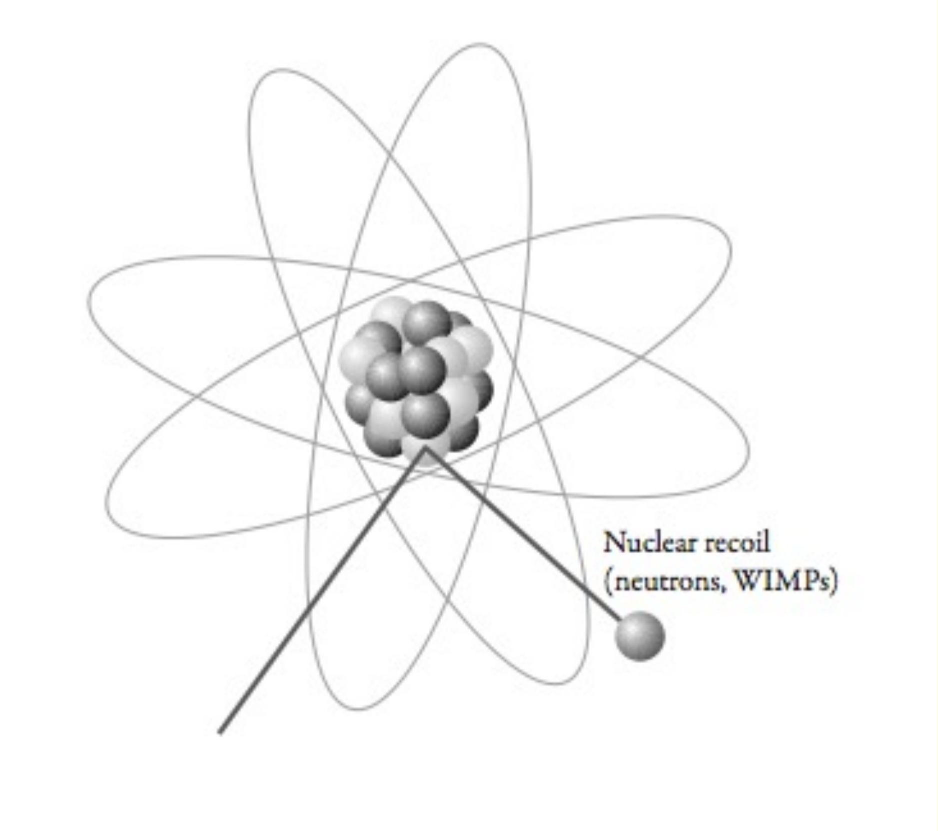


Large Hadron Collider at CERN

Ring that is 27 km around.
Two proton beams traveling underground in opposite directions collide at the locations of the detectors

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!

How did I get into Dark Matter?

PhD Advisor at Univ of Chicago, David Schramm
One of the founders of astroparticle physics

Drukier and Stodolsky (1984)

proposed neutrino detection via weak scattering off nuclei

Andrzej Drukier

GOODMAN AND WITTEN (1986) turned same approach to DM detection

The Back Page

Email | Print

Cold War Human Radiation Experiments: A Legacy of Distrust

By Mark Goodman

The April 1995 APS Meeting in Washington DC marked two significant anniversaries in the history of ionizing radiation and health. A special session celebrated the 100th anniversary of Roentgen's discovery of x rays. Since this discovery, ionizing radiation and radioactive tracer materials have become ubiquitous tools in medical research, diagnosis, and treatment. Another session, which I organized, marked the 50th anniversary of the first use of nuclear energy for military purposes and delved into the darker history of Cold War human radiation research.

In December 1993, Energy Secretary Hazel O'Leary learned of a newspaper article by an Albuquerque reporter about people who had plutonium injected into their bodies to study the resulting risks. O'Leary was shocked, and called for an outside investigation of these and other experiments that had come to light. She persuaded President Clinton to establish the Advisory Committee on Human Radiation Experiments, to report on human radiation experiments performed by the Department of Energy and other agencies implicated in similar activities. This committee of experts in medical science, biomedical ethics and related fields released its final report in October.

The Advisory Committee's report has been well-received in general, although some have expressed disappointment with its failure to condemn certain experiments and scientists. Reaching consensus on the ethical judgment of past actions proved quite difficult given the limits of available information. But the committee was widely praised for the way it carried out its two other main tasks, providing a public accounting of the events of the past and making recommendations for the future based on lessons from these events.

I was not a member of this committee, but served on its staff. The staff was responsible for most of the historical research, and drafted findings and recommendations for consideration by the committee. My work focused on experiments involving the deliberate release of radioactive materials into the environment.

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 $v_{\rm esc}$,

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

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,

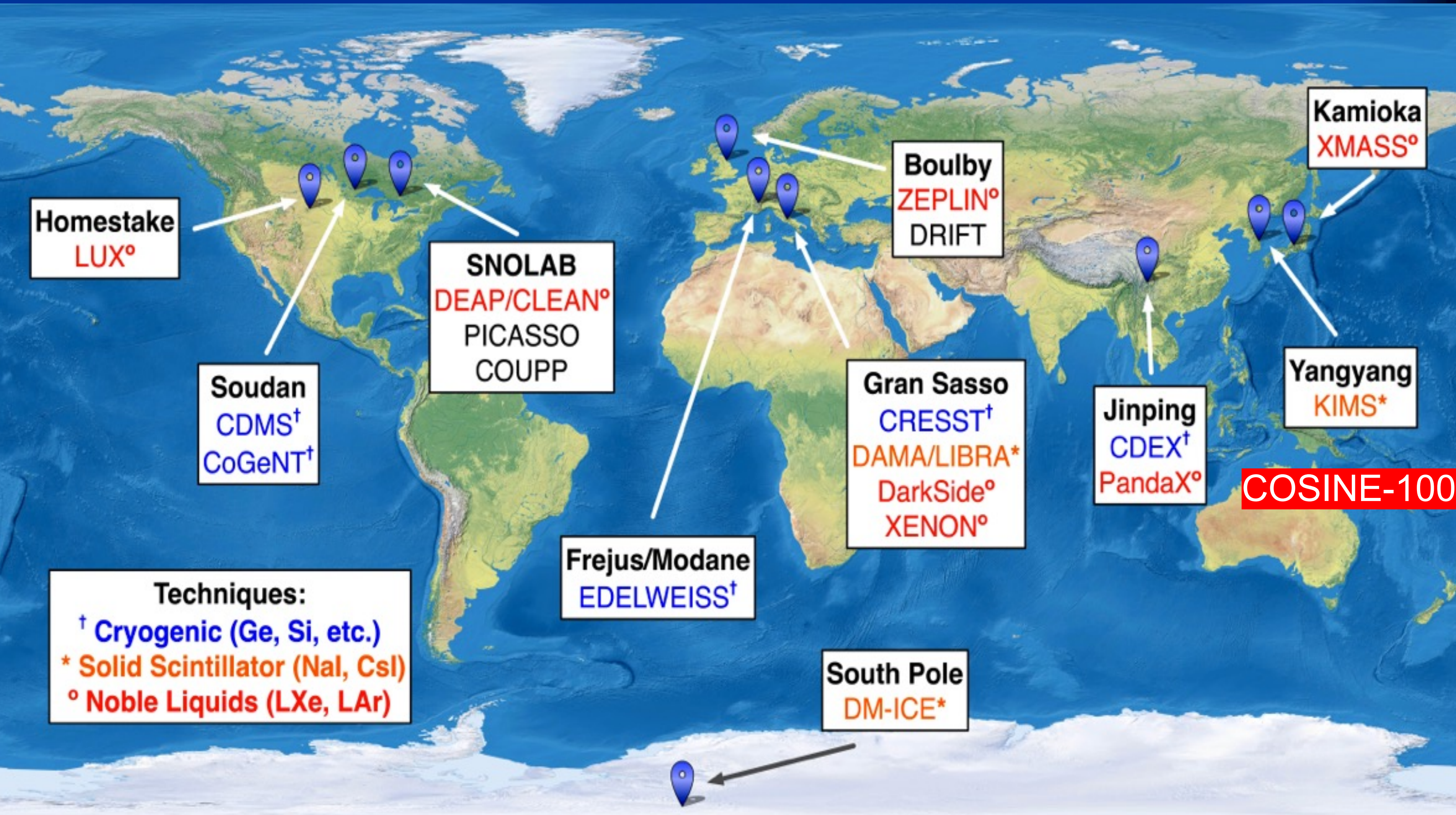
$$\overline{v}_0 = \sqrt{2/3}\,\sigma_v,$$

Typical particle speed is about 270 km/sec.

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

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

UNDERGROUND DARK MATTER LABORATORIES WORLDWIDE



WIMP detectors must be in underground laboratories

Need to shield from Cosmic Rays

XENON experiment in Gran Sasso Tunnel

XENON

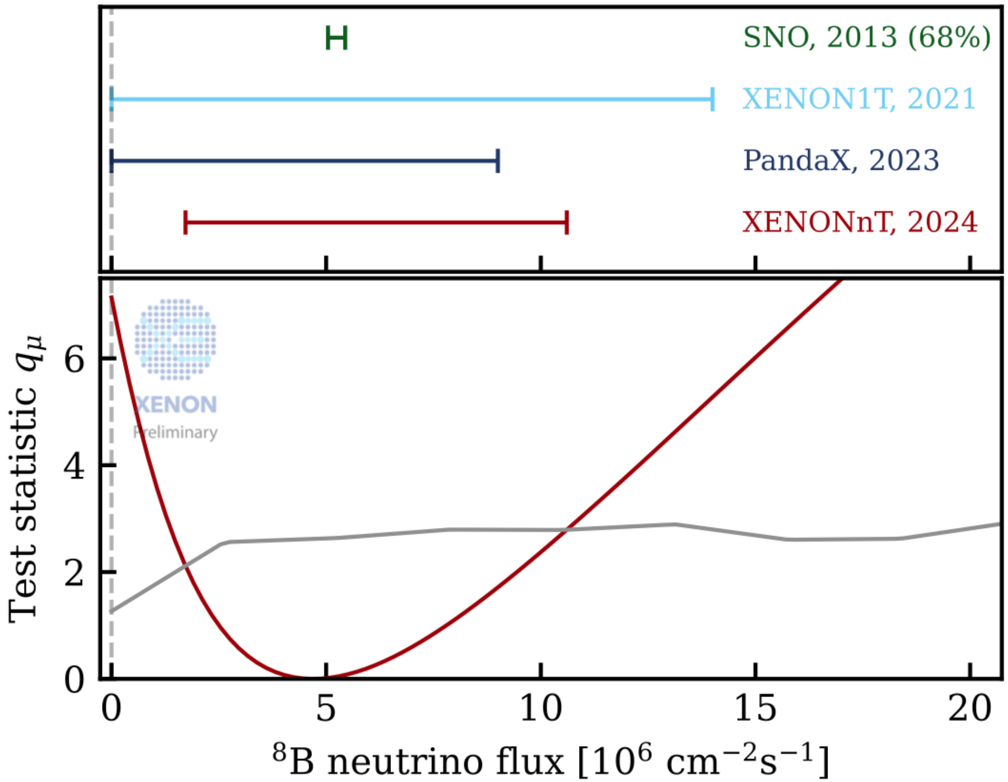
清華大學
Tsinghua University

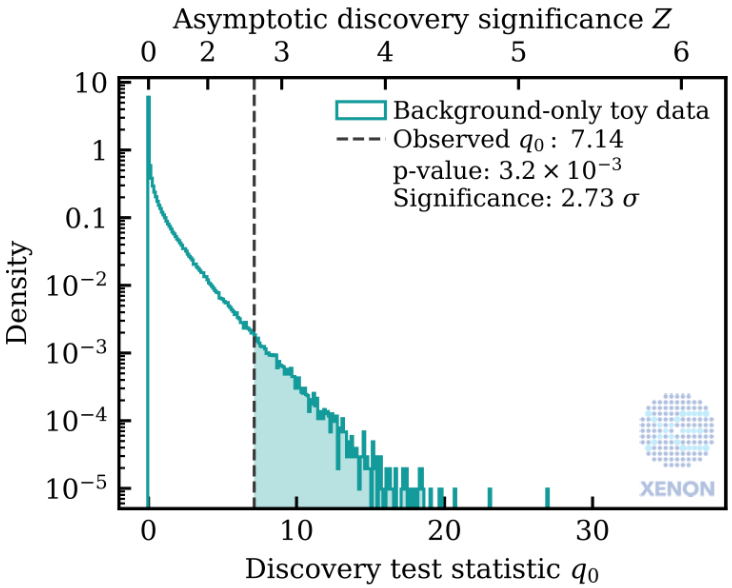
First Measurement of Coherent Elastic Neutrino Nucleus Scattering of Solar ^8B Neutrinos in XENONnT

Fei Gao, Tsinghua University
on behalf of the XENON Collaboration

15th International Workshop on the Identification of Dark Matter
July 8-12, 2024, L'Aquila

XENONnT Solar ^{8}B CEvNS Search Results

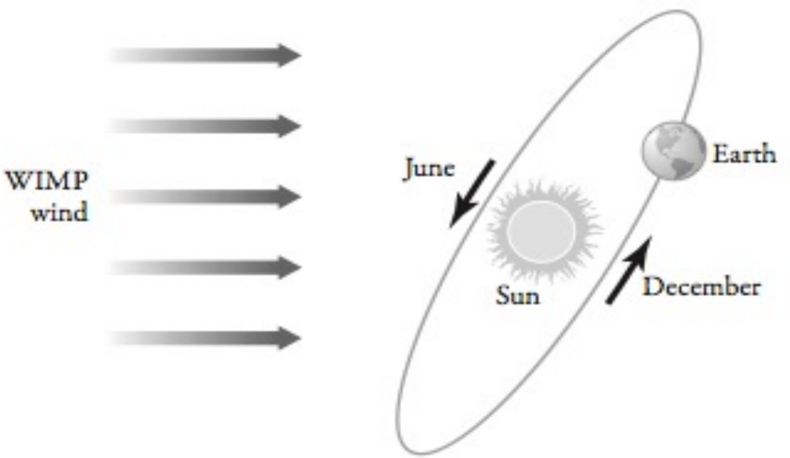


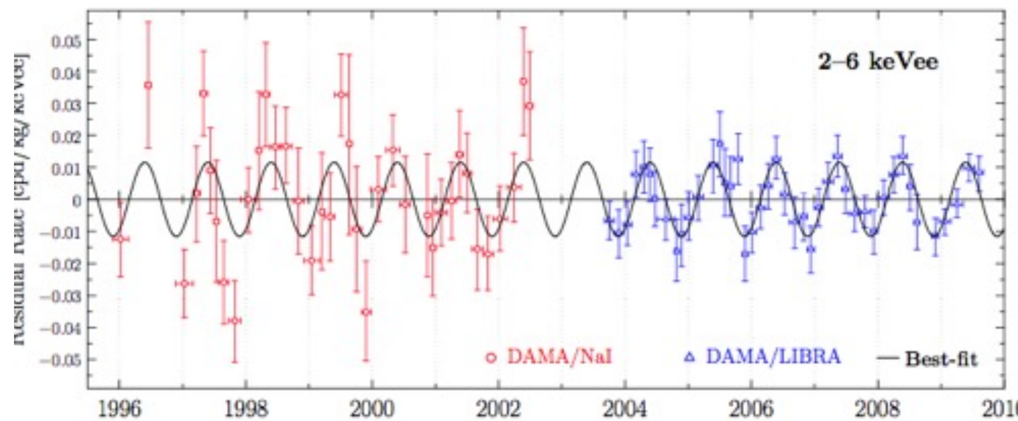


- We have measured the solar ^{8}B neutrinos via CEvNS in XENONnT at 2.73σ
- The first CEvNS measurement with Xe!
- The first astrophysical neutrino measurement via CEvNS

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??

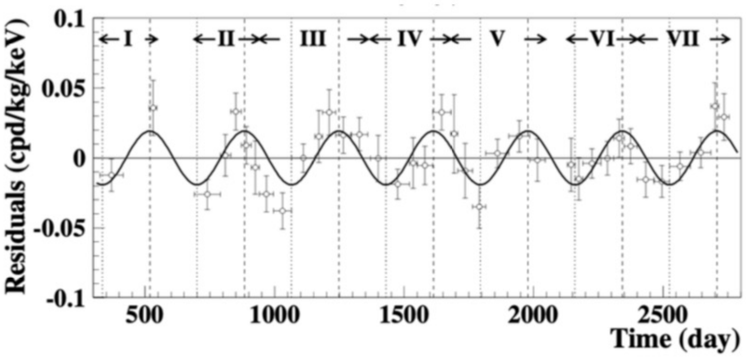


Figure 24: Experimental residual rate of the *single–hit* scintillation events measured by DAMA/NaI in the (2–6) keV energy interval as a function of the time (exposure of 0.29 ton $\times$ yr) . The superimposed curve is the cosinusoidal functional forms $A\cos\omega(t-t_0)$ with a period $T=\frac{2\pi}{\omega}=1$ yr, a phase $t_0=152.5$ day (June 2^{nd}).

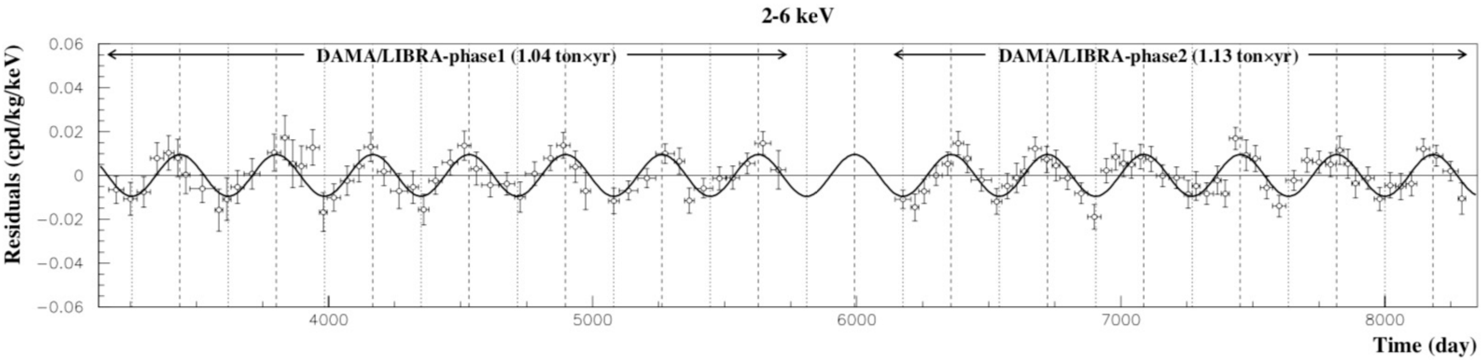
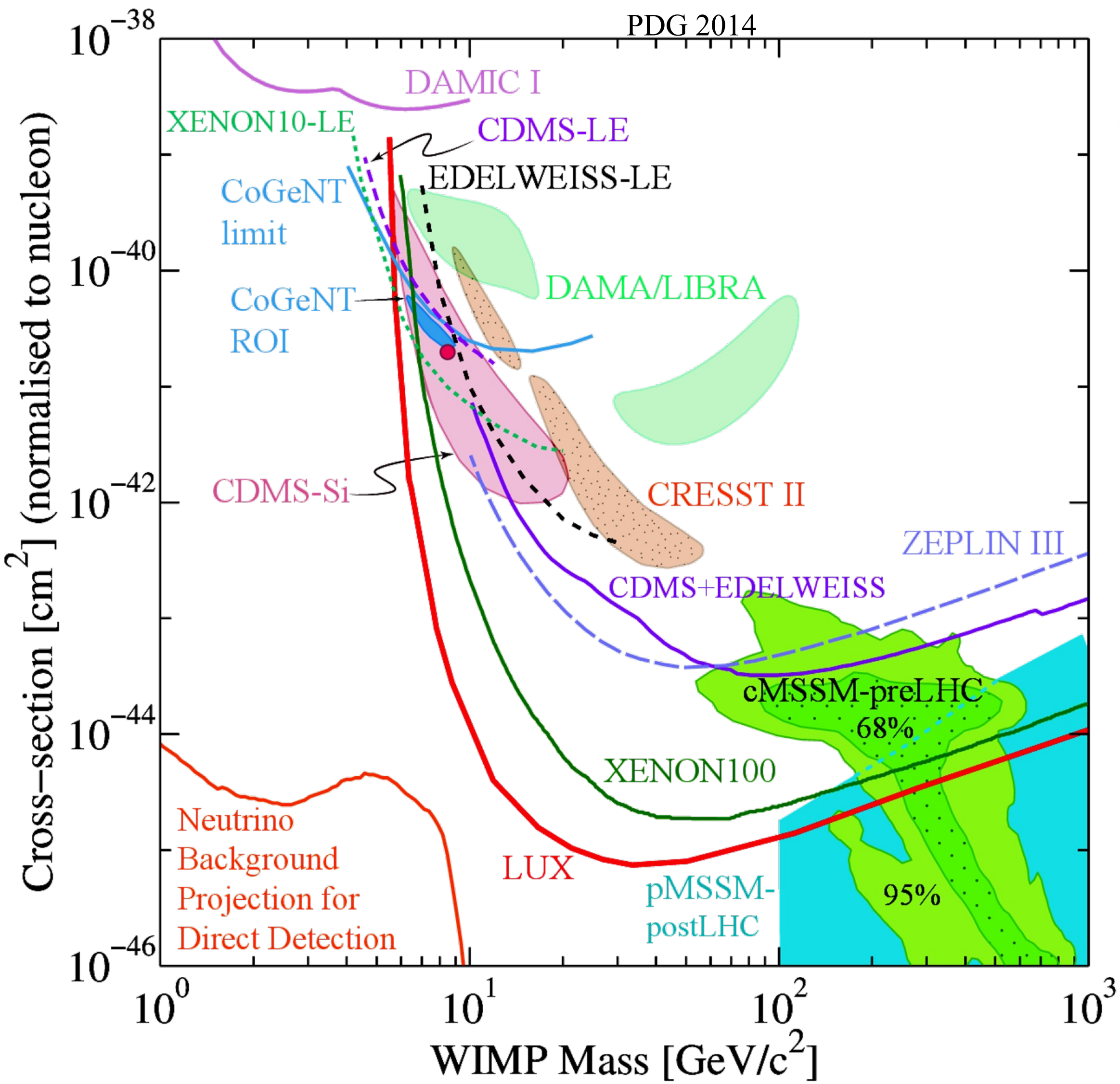


Figure 25: Experimental residual rate of the *single–hit* scintillation events measured by DAMA/LIBRA–phase1 and DAMA/LIBRA–phase2 in the (2–6) keV energy intervals as a function of the time. The superimposed curve is the cosinusoidal functional forms $A\cos\omega(t-t_0)$ with a period $T=\frac{2\pi}{\omega}=1$ yr, a phase $t_0=152.5$ day (June 2^{nd}) and modulation amplitude, A, equal to the central value obtained by best fit on the data points of DAMA/LIBRA–phase1 and DAMA/LIBRA–phase2. For details see caption of Fig. 23.

Bounds on Spin Independent WIMPs



BUT:

--- it's hard to compare results from different detector materials (DAMA is NaI vs. Xenon or Ge etc)

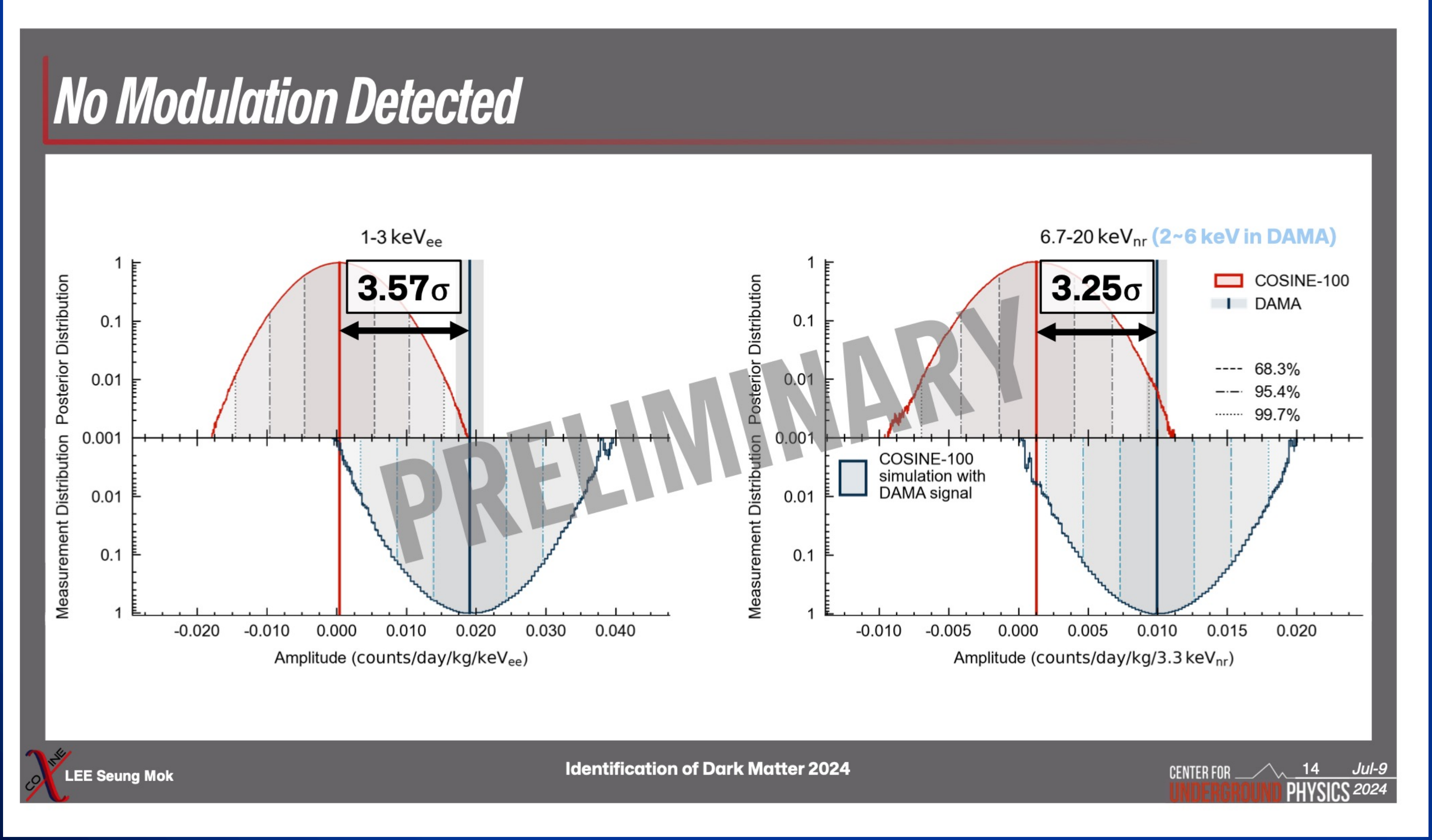
To test DAMA

- DAMA data down to keV imply DAMA all by itself is not compatible with SI scattering

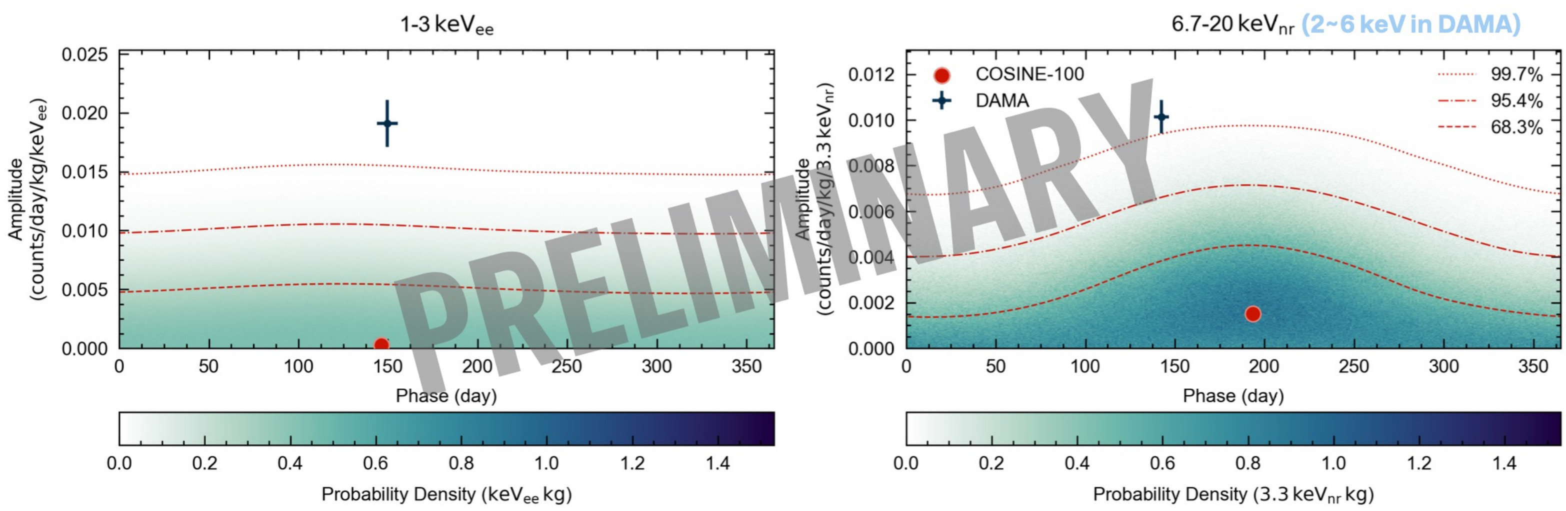
Baum, Freese,Kelso 2018

- Other groups are using NaI crystals:
- COSINE-100
- SABRE
- ANAIS
- COSINUS

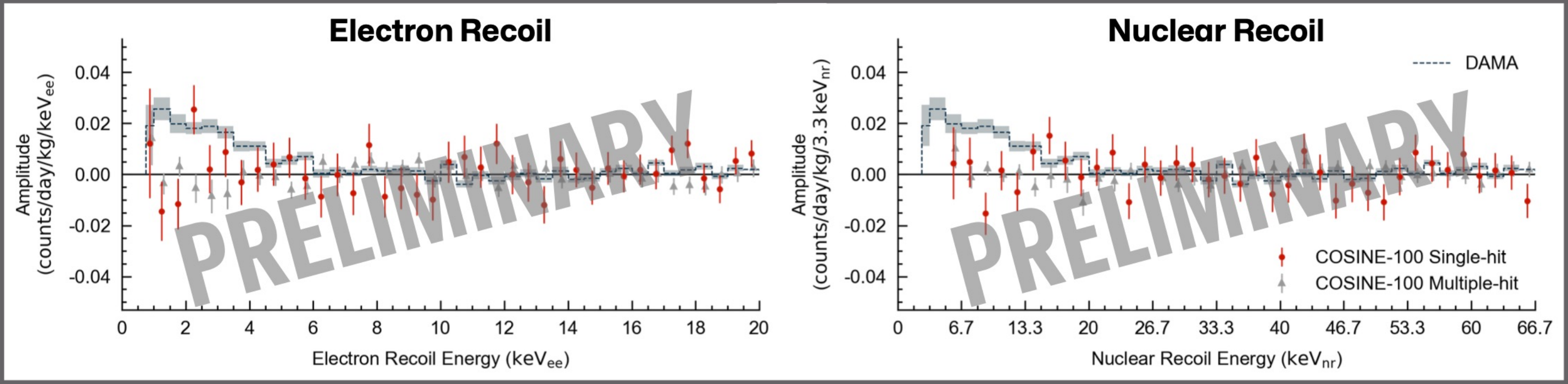
COSINE-100 does not confirm DAMA annual modulation



No Modulation Detected



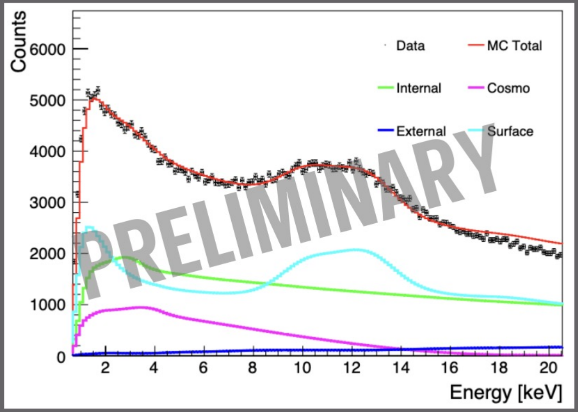
No Modulation Detected

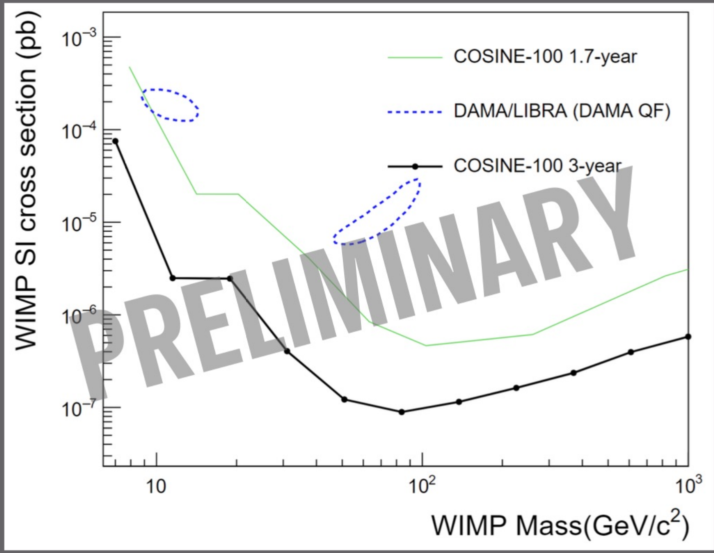


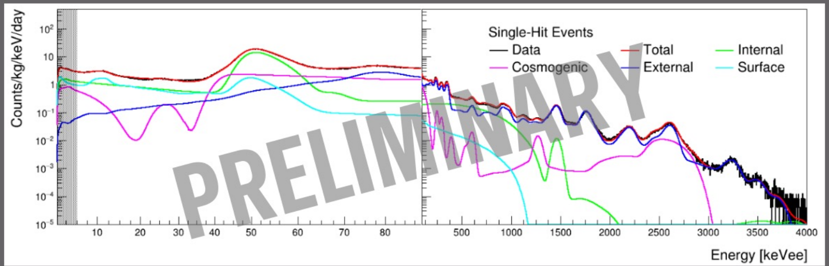
E (keV$_{ee}$)	A (counts/day/kg/keV$_{ee}$)	
	COSINE-100	DAMA/LIBRA
1~3	0.0004 ± 0.0050	0.0191 ± 0.0020
1~6	0.0017 ± 0.0029	0.01048 ± 0.00090
2~6	0.0053 ± 0.0031	0.00996 ± 0.00074

E (keV$_{nr}$)	A (counts/day/kg/3.3 keV$_{nr}$)	
	COSINE-100	DAMA/LIBRA
6.7~20	0.0013 ± 0.0027	0.00996 ± 0.00074

No DAMA-like WIMPs in NaI(Tl) Spectrum

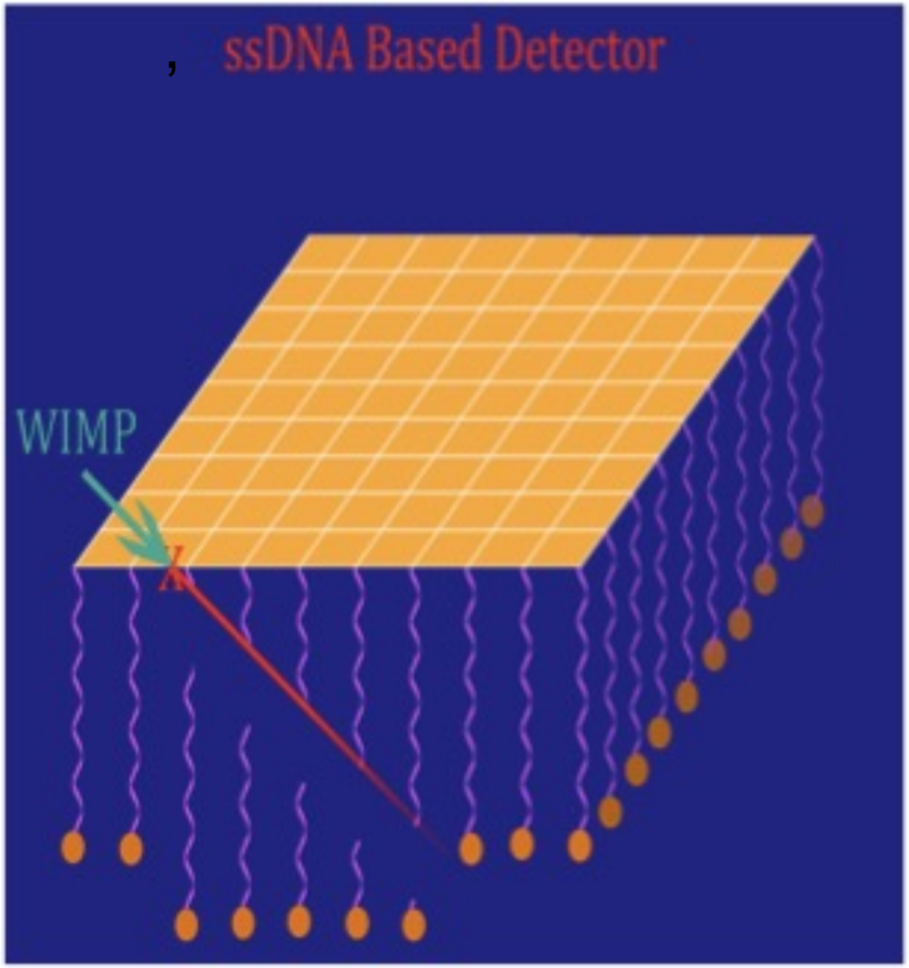






DNA/RNA Tracker: directional detector with nanometer resolution

- 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

article in New Scientist

Digging for dark matter

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

Projected sensitivity of paleodetectors

2106.06559 (w Tom Edwards)

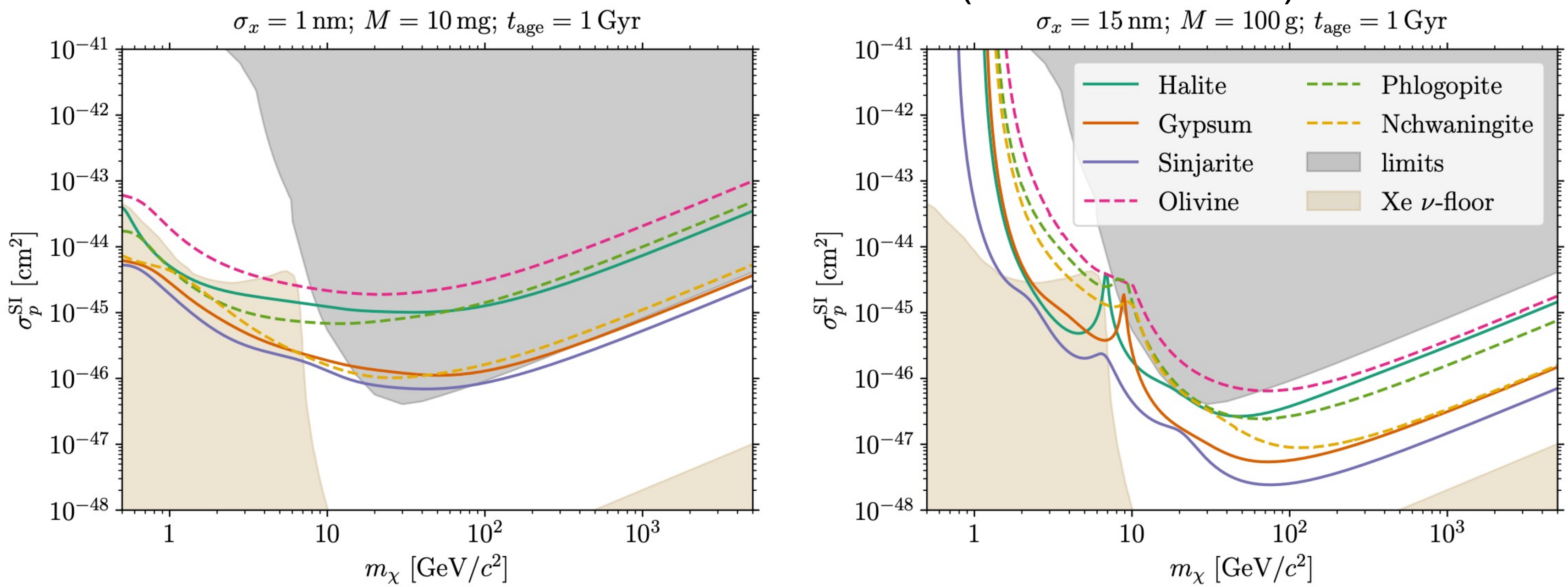


Figure 3. Projected 90 % confidence level upper limits in the WIMP mass (m_χ) – spin-independent WIMP-nucleus scattering cross section (σ_p^{SI}) plane in the high-resolution (sample mass $M = 10\,\mathrm{mg}$, track length resolution $\sigma_x = 1\,\mathrm{nm}$; left panel) and high-exposure ($M = 100\,\mathrm{g}$, $\sigma_x = 15\,\mathrm{nm}$; right panel) readout scenarios. The different lines are for different target materials as indicated in the legend, see Table 1. The gray-shaded region of parameter space is disfavored by current upper limits from direct detection experiments [12, 14, 17, 105, 150], while the sand-colored region indicates the *neutrino floor* for a Xe-based experiment [151]. Colors and linestyles are the same in both panels.

Mineral Detection of Neutrinos and Dark Matter. A Whitepaper

Recoiling nuclei lead to defects:
Nm Fission tracks, vacancies in crystal lattice, etc

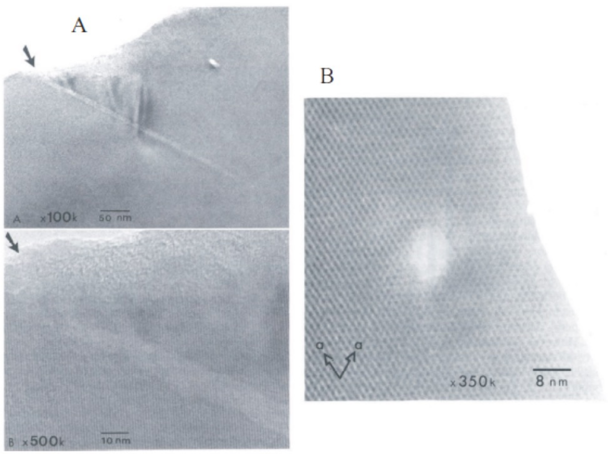


Figure 1: TEM-images of latent fission-tracks in apatite. *Left (A)*: Images taken parallel to the flight trajectory (light grey). *Right (B)*: Image taken perpendicular to the flight trajectory. Core of a fission-track is visible in the central part of the image. Figure taken from Ref. [90].

Color Centers:
Vacancies in crystal lattice,
e pairs fill in, get excited and fluoresce,
the crystal changes color

Biannual Conferences
Trieste 2022
Wash DC 2024

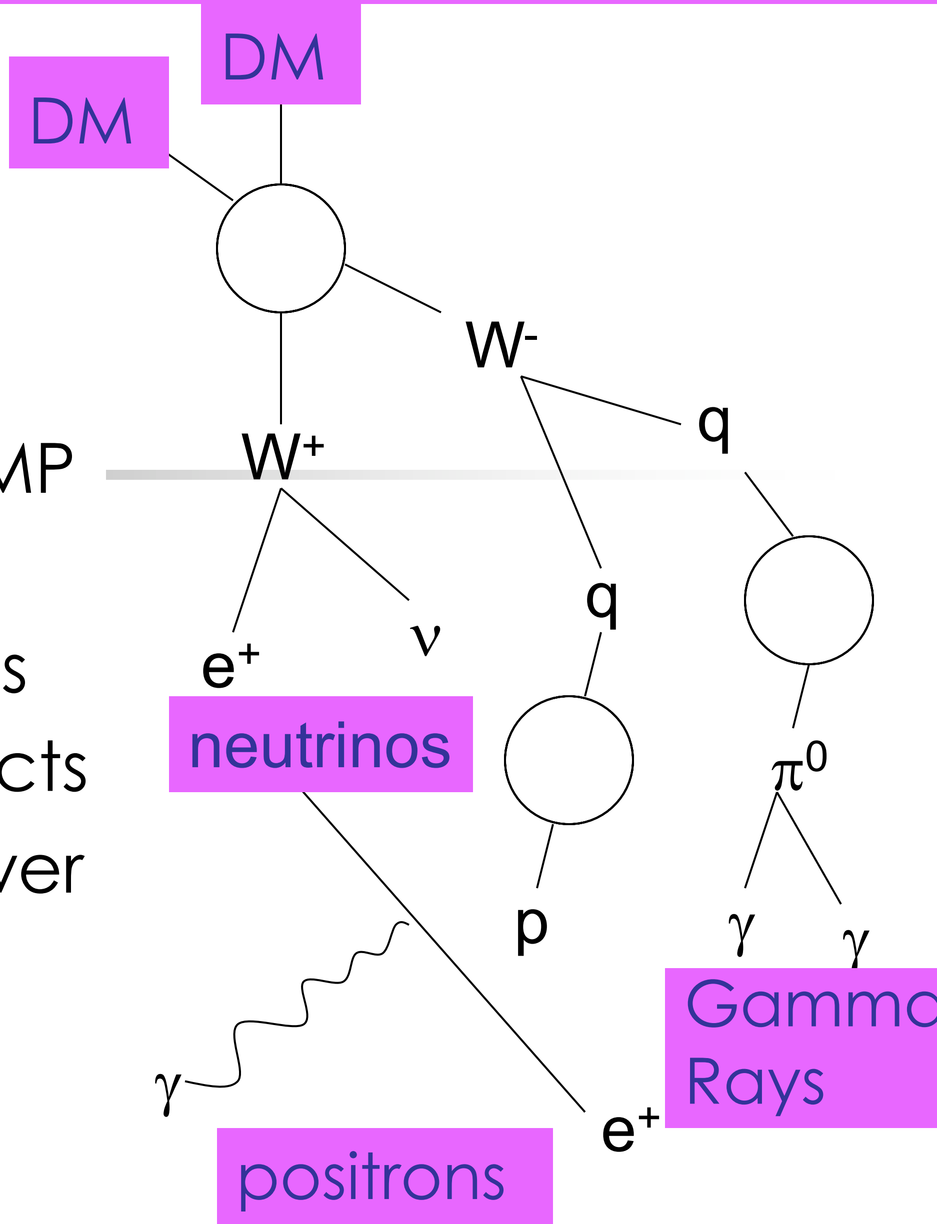
Useful for DM, SN neutrinos, CR,
Nuclear nonproliferation, etc
Active experimental effort

https://arxiv.org/pdf/2301.07118.pdf

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)

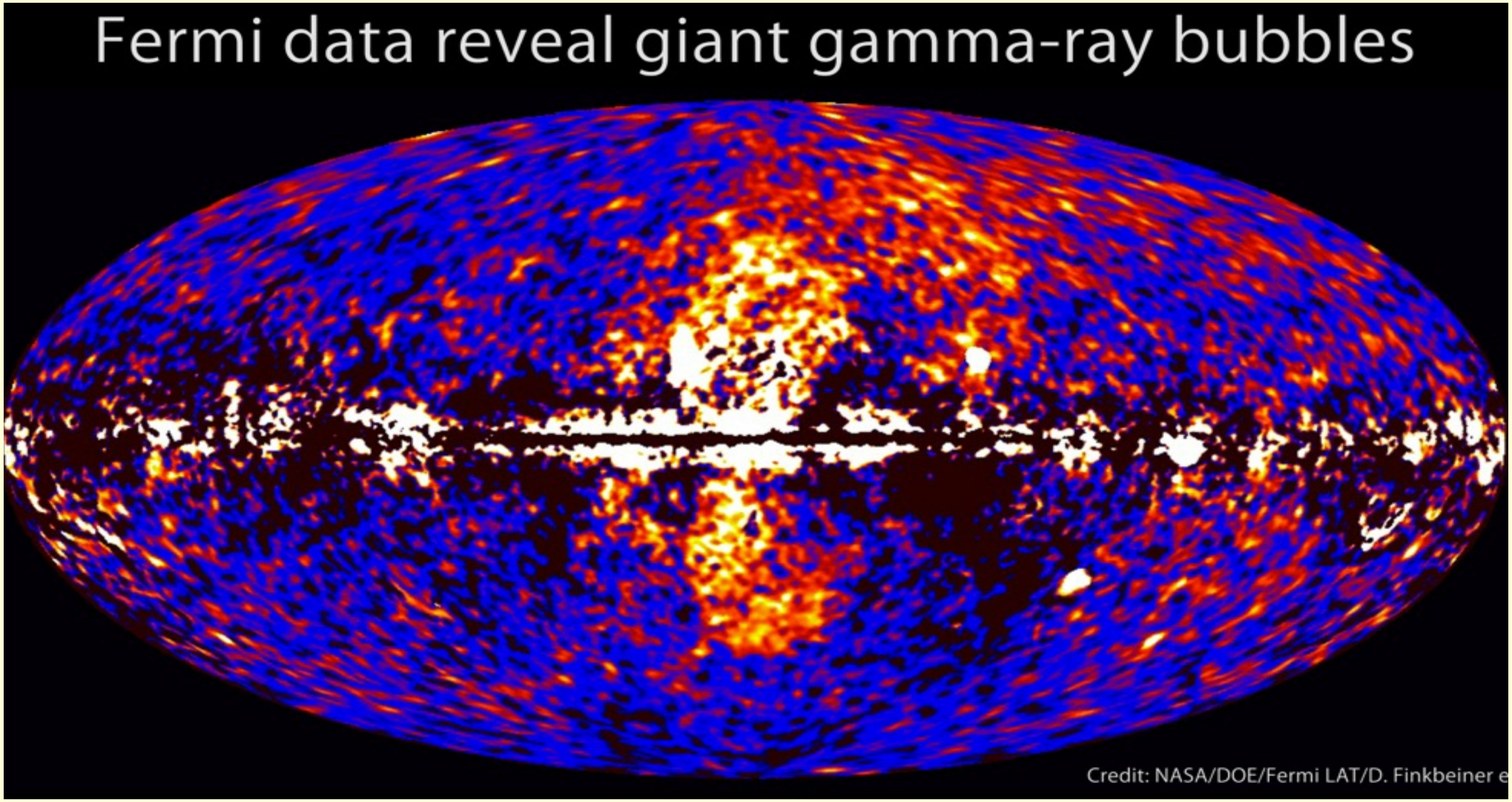


INDIRECT DETECTION of HIGH ENERGY PHOTONS (GAMMA-RAYS)

Are they from DM annihilation?

THE FERMI SATELLITE

The gamma ray sky

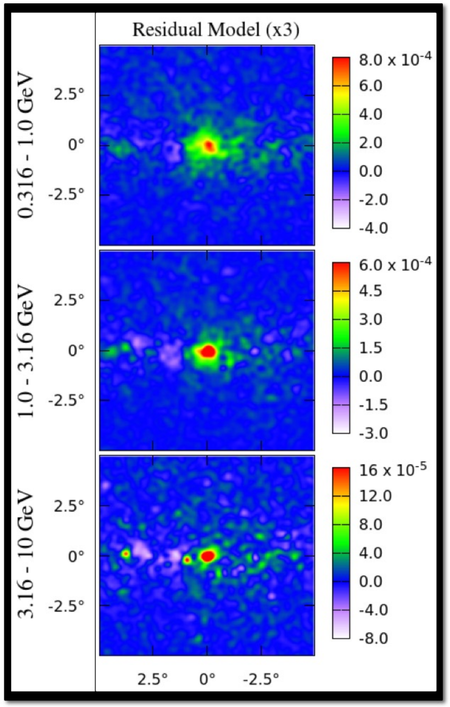


Doug Finkbeiner (Fermi Bubbles)

Talk of Dan Hooper

The Galactic Center Gamma-Ray Excess

- The Fermi data contains an excess of GeV-scale emission from the direction of the Inner Galaxy, relative to *all models* of known astrophysical backgrounds
- This signal is bright and highly statistically significant – its existence is not in dispute
- It is very difficult to explain this signal with known astrophysical sources or mechanisms
- The observed characteristics of this signal are consistent with those expected from annihilating dark matter

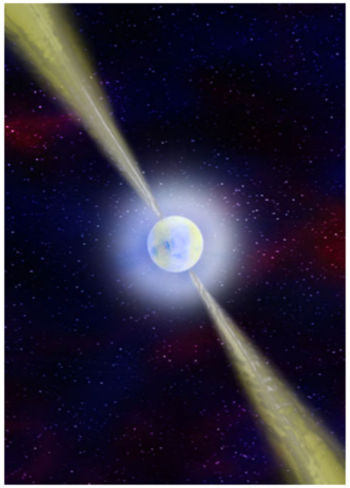


Among other references, see:
DH, Goodenough (2009, 2010)
DH, Linden (2011)
Abazajian, Kaplinghat (2012)
Gordon, Macias (2013)
Daylan, DH, et al. (2014)
Calore, Cholis, Weniger (2014)
Murgia, et al. (2015)
Ackermann et al. (2017)

Fermi

- The spectrum of the excess is well fit by a ~20-65 GeV particle annihilating to quarks or gluons

Millisecond Pulsars and The Galactic Center Gamma-Ray Excess



Arguments in Favor of Pulsars:

- The gamma-ray spectrum of observed pulsars
- ~~Claims of small-scale power in the gamma-ray the Inner Galaxy~~
- ~~Claims that the excess traces the Galactic Bulge/Bar~~

Arguments Against Pulsars:

- The lack of pulsars detected in the Inner Galaxy
- The lack of low-mass X-ray binaries in the Inner Galaxy

- To date, Fermi has detected only three gamma-ray sources that could potentially be pulsars located within a few kpc of the Galactic Center (PSR J1747-4036, J1649-3012, J1833-3840)

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

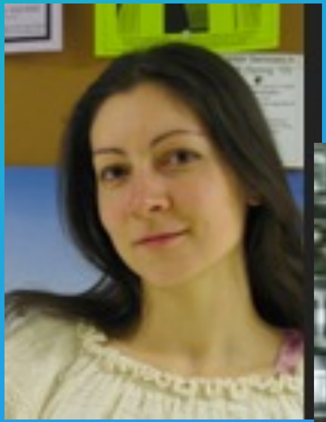
Collaborators

Doug Spolyar

Paolo Gondolo

Luca Visinelli

Pearl Sandick



Tanja Rindler-Daller

Peter Bodenheimer

Cosmin Ilie

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 ten billion times as bright as the Sun. We have found candidates 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 200 million years after the Big Bang in the centers of protogalaxies --- 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.

The Bottom Line

- JWST found ~ 700 high redshift objects with z > 10. They call them "galaxy candidates"
- Too many galaxies for Lambda CDM
- Are some of them Dark Stars?
- NIRSPEC on JWST has spectra for 9 of these; so far 5 are on the arxiv or published..

(W/out spectra, can't be sure of redshift; some are low redshift)

- Specifically, JADES has four. So far, these are the ones we have studied. (JWST Advanced Extragalactic Survey)
- OUR RESULTS: Three of the four hi-z JWST objects we studied are consistent with Dark Stars
- New data: one of them has metal lines (not a DS?) .

The role of Weakly Interacting Massive Particles (WIMPs) or Self Interacting Dark Matter

- Re WIMPs:

  Mass 1Gev-10TeV (canonical 100GeV)

  Annihilation cross section (WIMPS):

$$<\sigma v>_{ann} = 3\times10^{-26}\, cm^3/\sec$$

Same annihilation that leads to correct WIMP abundance in today's universe

Same annihilation that gives potentially observable signal in FERMI, PAMELA, AMS

Dark Matter Heating

Heating rate:

$$Q_{ann} = n_\chi^2 < \sigma v > \times\, m_\chi \qquad = \frac{\rho_\chi^2 < \sigma v >}{m_\chi}$$

Fraction of annihilation energy deposited in the gas:

$$\Gamma_{DMHeating} = f_Q\, Q_{ann}$$

f_Q:

1/3 electrons

1/3 photons

1/3 neutrinos

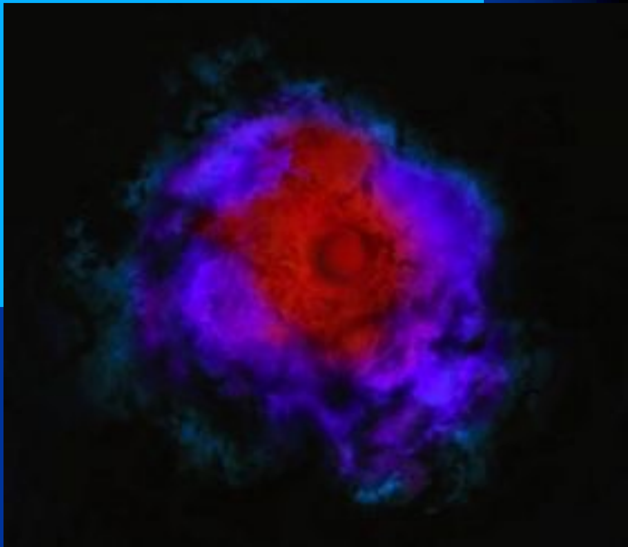
Dark Matter Power vs. Fusion

- DM annihilation is (roughly) 100% efficient in the sense that all of the particle mass is converted to heat energy for the star
- Fusion, on the other hand, is only 1% efficient (only a fraction of the nuclear mass is released as energy)
- Fusion only takes place at the center of the star where the temperature is high enough; vs. DM annihilation takes place throughout the star.

Three Conditions for Dark Stars
(Spolyar, Freese, Gondolo 2007 aka Paper 1)

- I) Sufficiently High Dark Matter Density ?
- 2) Annihilation Products get stuck in star ?
- 3) DM Heating beats H2 Cooling ?

New Phase



DS Basic Properties

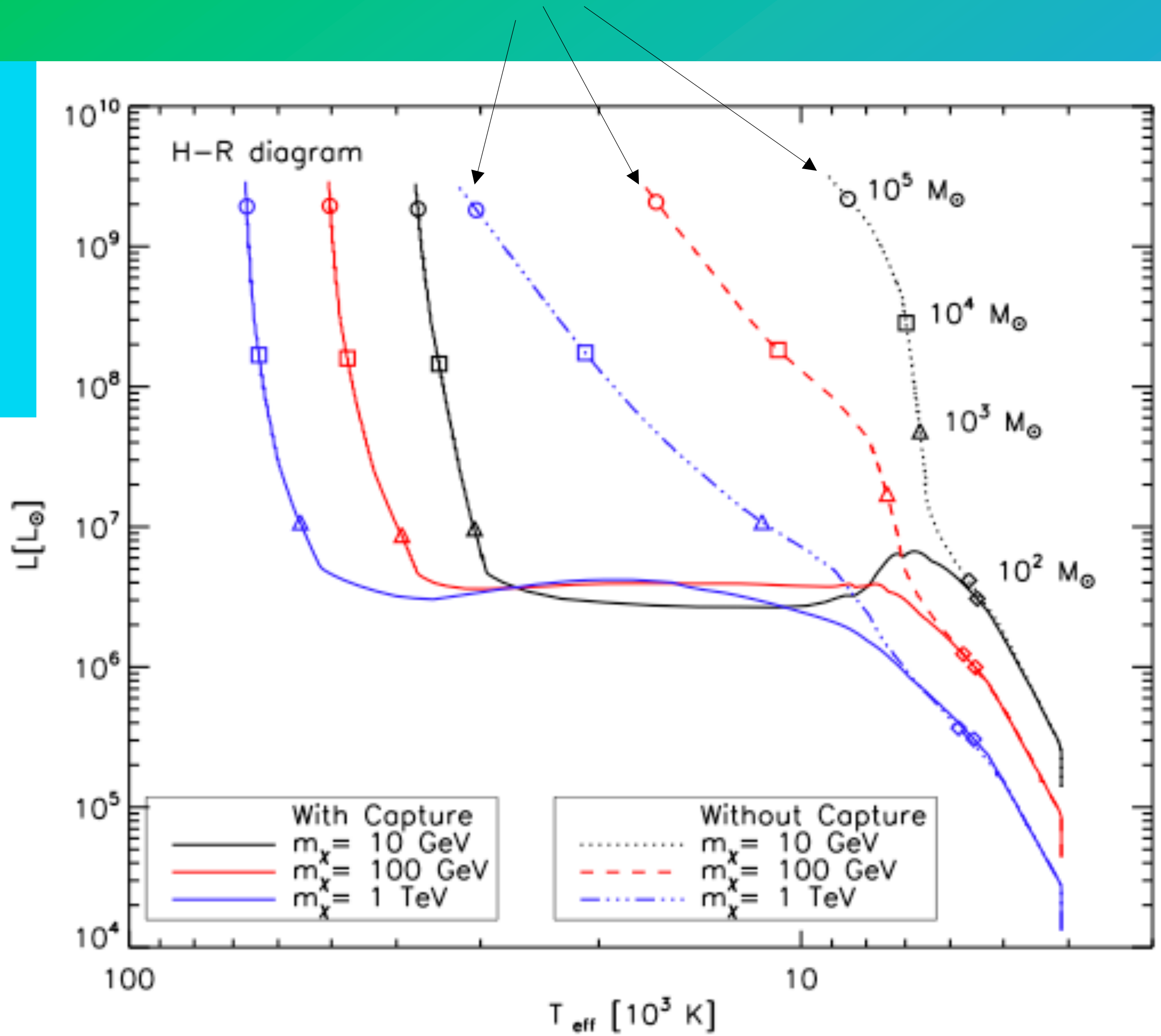
- We find that DS are big puffy objects:
  - Massive: can grow to $10^7\ M_\odot$
  - Large- 10 a.u. (radius of Earth's orbit around Sun)
  - Luminous: up to $10^{10}\ L_\odot$
  - Cool: 10,000 K vs. 100,000 K plus
    - Will not reionize the universe.
  - Long lived: more than 10^6 years, even till today?.
  - With Capture or nonCircular orbits, get even more massive, brighter, and longer lived

Building up the mass

- Start with a few $M_\odot$ Dark Star, find equilibrium solution
- Accrete mass, one $M_\odot$ at a time, always finding equilibrium solutions
- N.b. as accrete baryons, pull in more DM, which then annihilates
- Continue until you run out of DM fuel
- VERY LARGE FIRST STARS. Then, star contracts further, temperature increases, fusion will turn on, eventually make black hole
- The largest ones collapse directly to black holes

Super Massive DS due to extended adiabatic contraction since reservoir has been replenished due to orbital structure

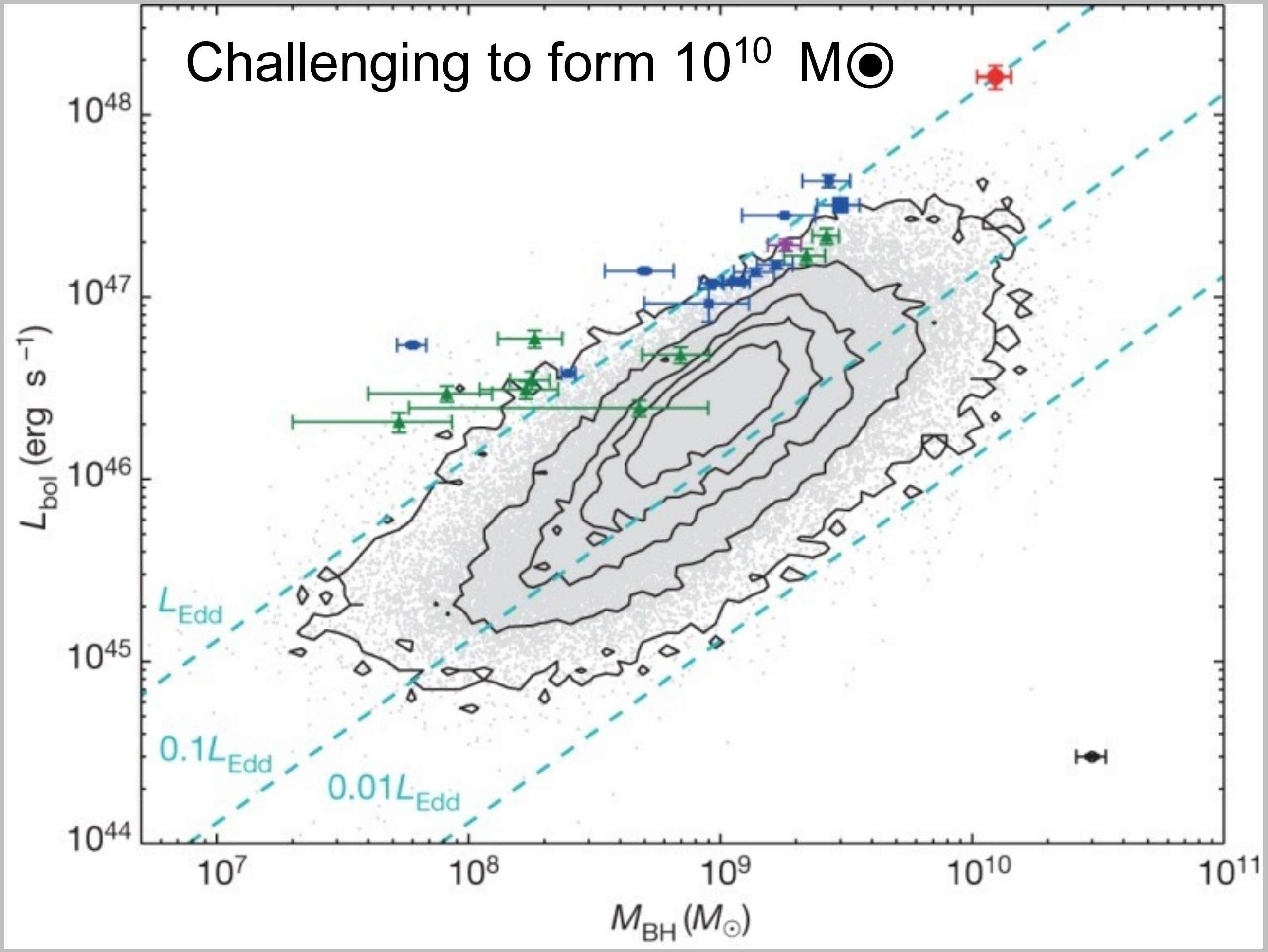
Assuming all of the baryons can accrete in a 10^6 $M_\odot$ halo



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 directly to BH
- Less massive ones live a million years, then collapse to Black Holes
- Helps explain observed black holes:
- (i) in centers of galaxies
- (ii) billion solar mass BH in the early Universe: the BIG BLACK HOLE PROBLEM
- (iii) intermediate mass BH

SupperMassive Black holes from Dark Stars
Very Massive progenitor Million Solar Masses at z=6
Challenging to form supermassive BH this early



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

nature

An 800 million solar mass black hole in a significantly neutral universe at redshift 7.5

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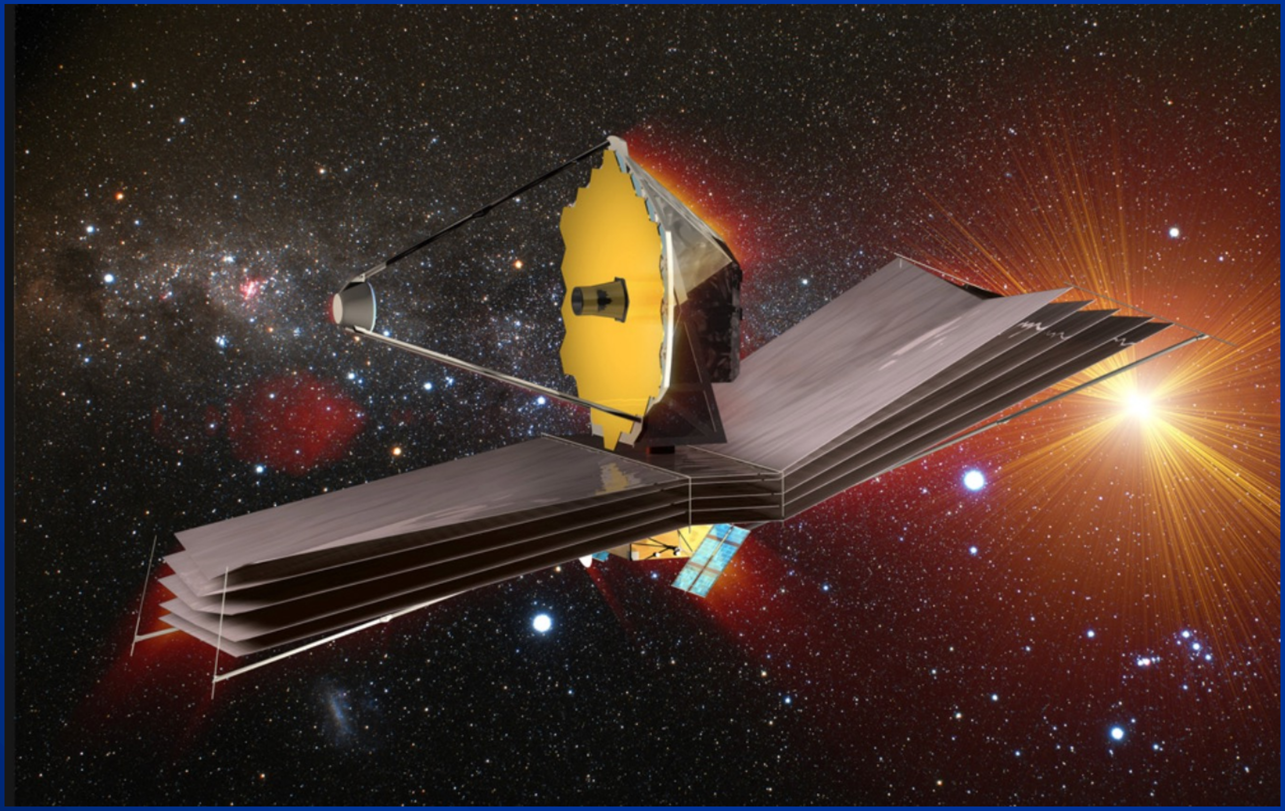
ABSTRACT

Quasars are the most luminous non-transient objects known, and as such, they enable unparalleled studies of the universe at the earliest cosmic epochs. However, despite extensive efforts from the astronomical community, the quasar ULAS J1120+0641 at $z = 7.09$ (hereafter J1120+0641) has remained as the only one known at $z > 7$ for more than half a decade[1]. Here we report observations of the quasar ULAS J134208.10+092838.61 (hereafter J1342+0928) at a redshift of $z = 7.54$. This quasar has a bolometric luminosity of $4 \times 10^{13} L_{\odot}$ and a black hole mass of $8 \times 10^{8} M_{\odot}$. The existence of this supermassive black hole when the universe was only 690 Myr old, i.e., just 5% its current age, reinforces early black hole growth models that allow black holes with initial masses $\gtrsim 10^{4} M_{\odot}$[2,3] or episodic hyper-Eddington accretion[4,5]. We see strong evidence of the quasar's Lyα emission line being absorbed by a Gunn-Peterson damping wing from the intergalactic medium, as would be expected if the intergalactic hydrogen surrounding J1342+0928 is significantly neutral. We derive a significant neutral fraction, although the exact value depends on the modeling. However, even in our most conservative analysis we find $\bar{x}_{\rm HI} > 0.33$ ($\bar{x}_{\rm HI} > 0.11$) at 68% (95%) probability, indicating that we are probing well within the reionization epoch.

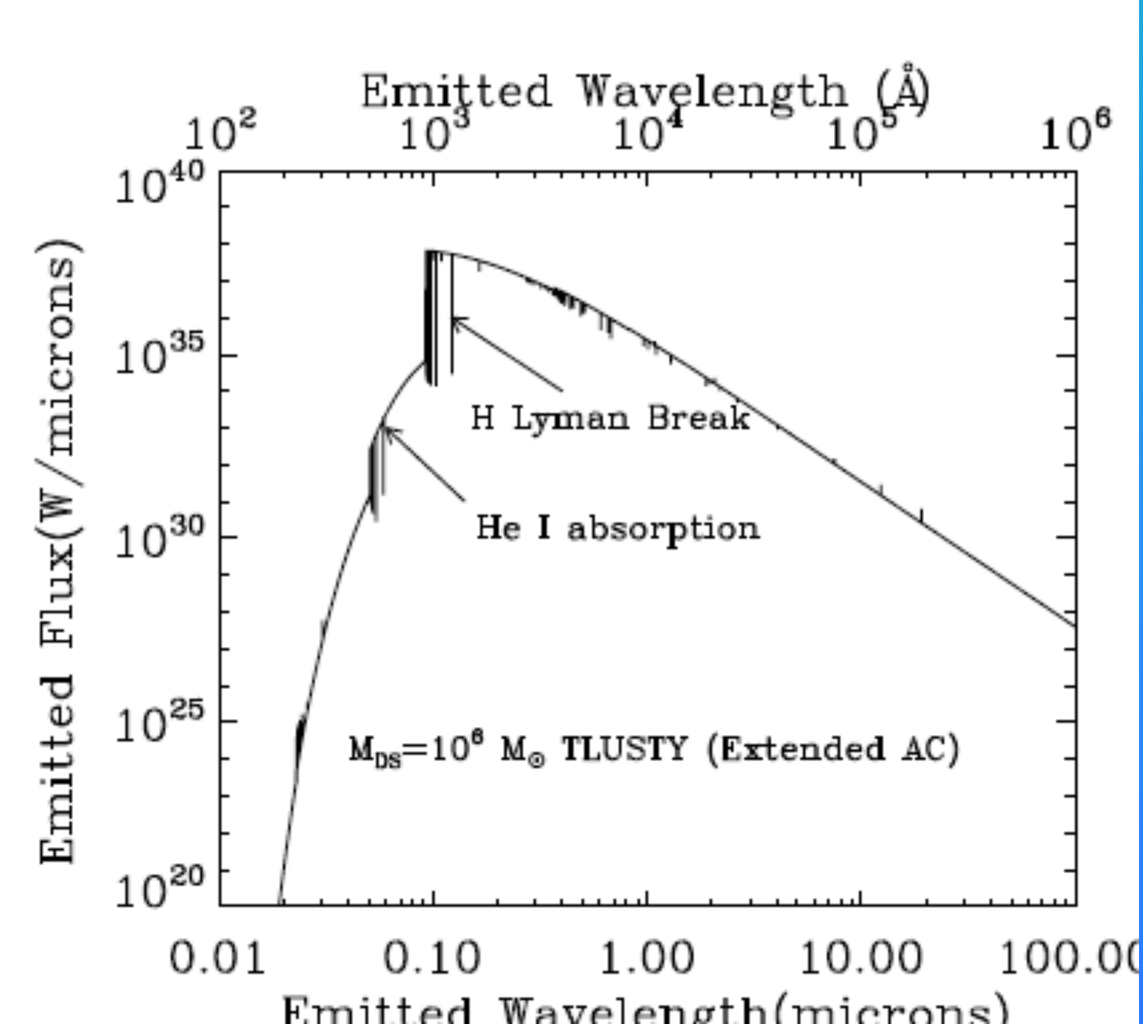
James Webb Space Telescope



Has JWST discovered Supermassive Dark Stars:
They would be a billion times brighter than the Sun
But the same temperature as the Sun. Unique signature.

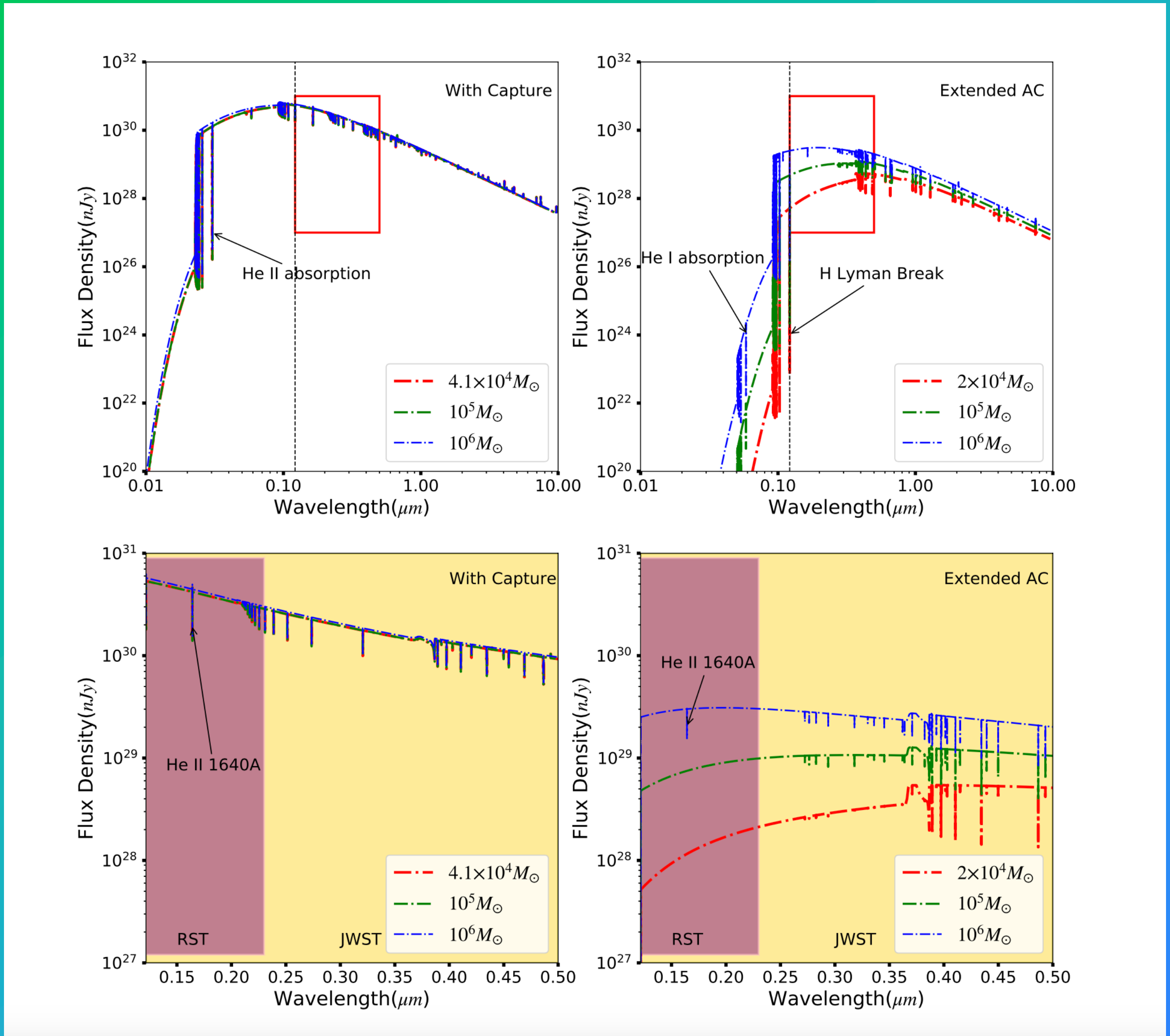
OBSERVING DARK STARS

DS Spectrum from TLUSTY (stellar atmospheres code)



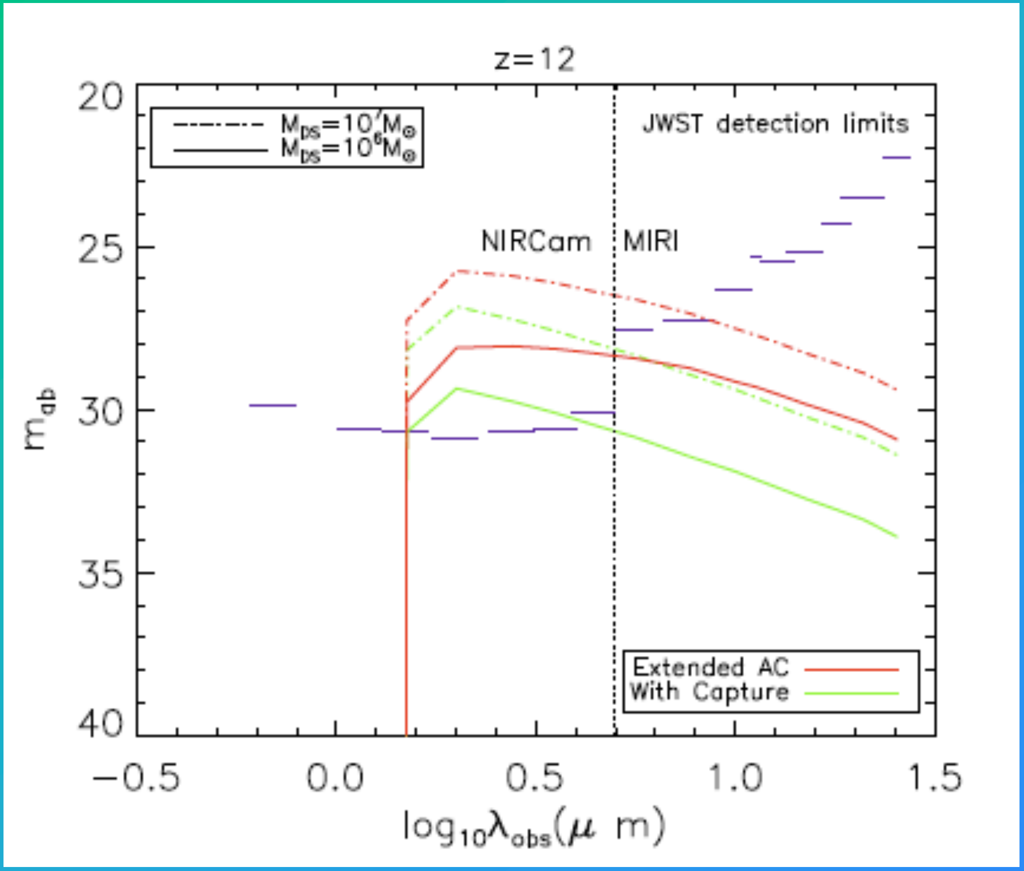
n.b. DS are made of hydrogen and helium only

Dark Star spectra

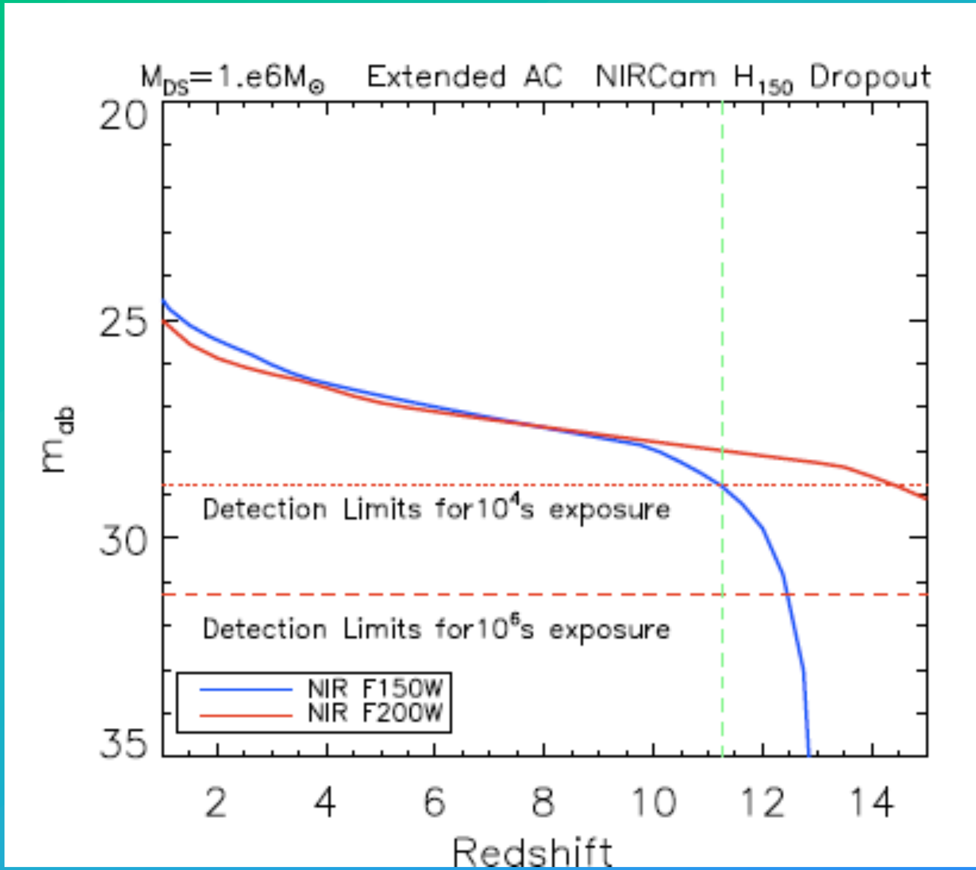


Assumes z =10 object

Dark Stars in JWST

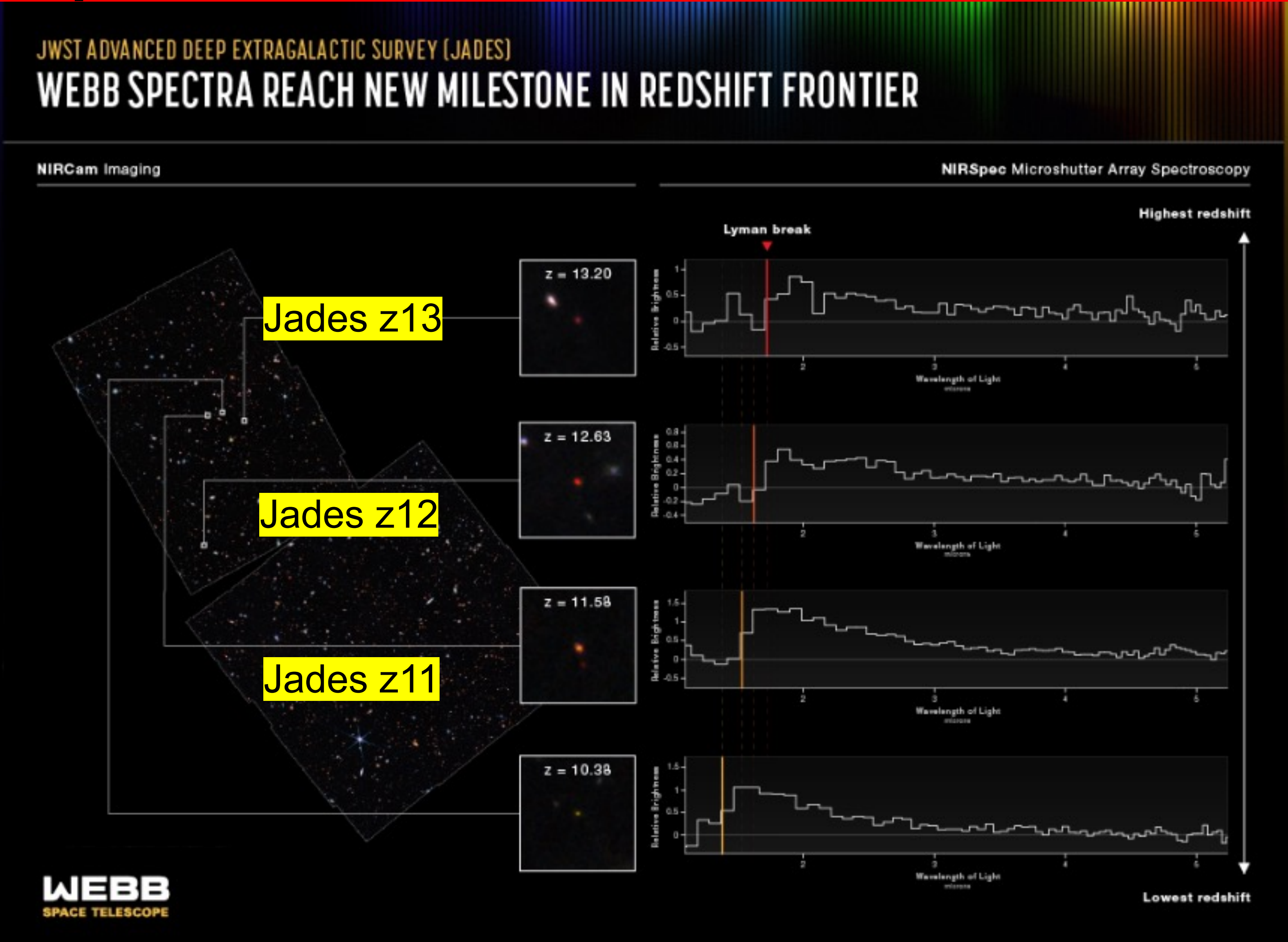


Million solar mass SMDS as H-band dropout



(see in 2.0 micron but not 1.5 micron filter, implying it's a z=12 object)

Of 5 objects in JWST data with spectra: 3 could be Dark Stars!



Cosmin Ilie

Colgate University

Jillian Paulin

Criteria for hi-z objects to be Supermassive Dark Star candidates

- 1) Point object (SMDS) vs. resolved (galaxy)
- 2) DS spectra match data. We used photometric data (not noisy spectra for which data are not public).
- 3) Dark stars predict HeII1640 absorption line vs. galaxies predict emission line and a lot of other lines too. Spectra are too noisy so far but will get better with longer exposure.

All four JADES objects could be point objects

- Authors fit to spectral SEDs plus to galaxy profile (Sersic) and claimed best fit sizes of 0.04” and 0.02”, ~ the size of one NIRCam pixel, and one order of magnitude below the resolution limit ~0.1”

SMDS fits to JWST photometric data (brightness in 9 wavelength bands)

- Jillian Paulin did MCMC to optimize chi^2 for Dark Matter mass m= 100GeV with three parameters:
- Mass of SMDS $(10^4, 10^5, 10^6) M_\odot$
- Redshift of object
- Magnification due to lensing

n.b. could be mu=10,

or, most lines of light have mu < 1

(Wang, Holz, Wald)

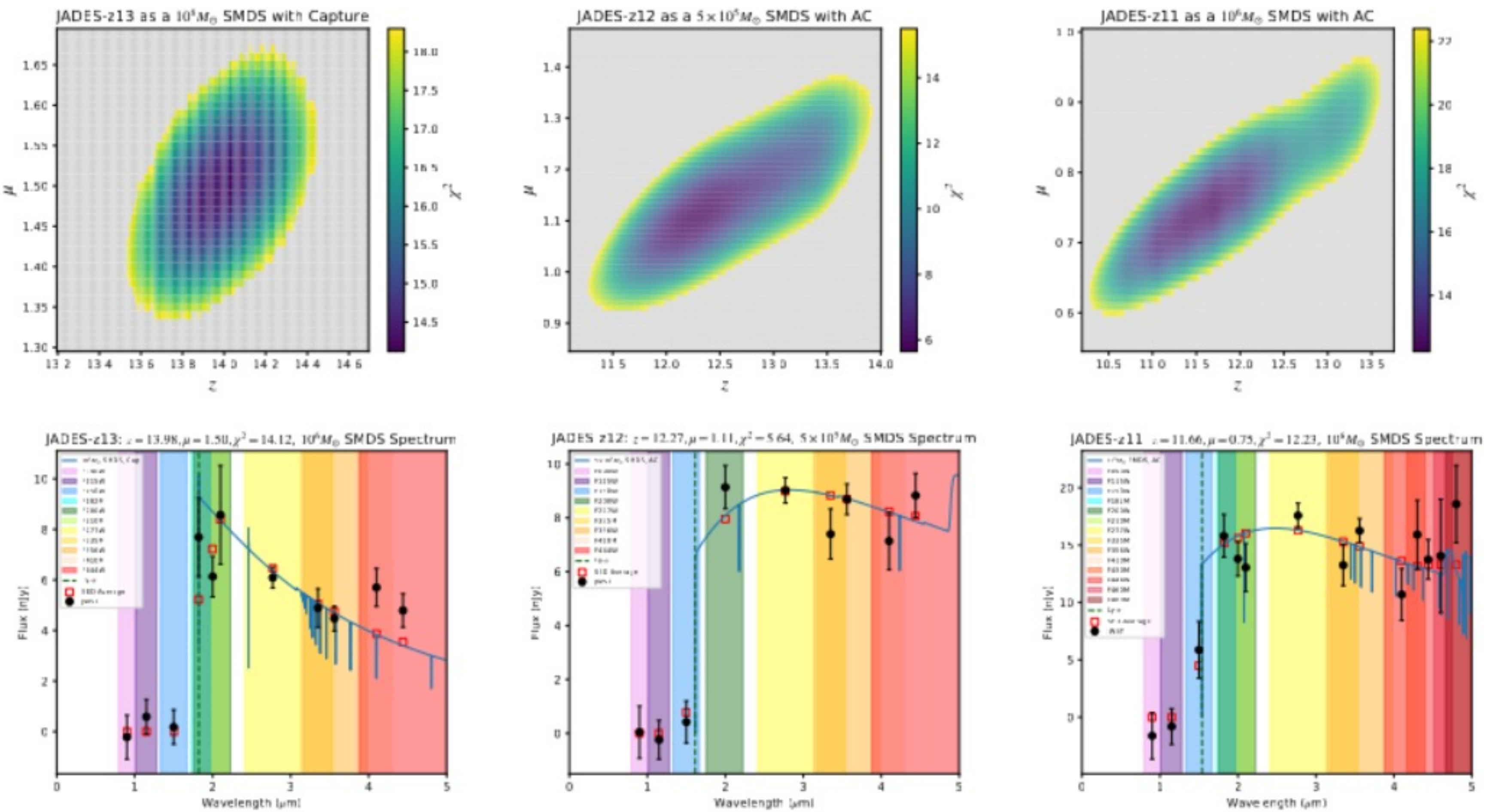
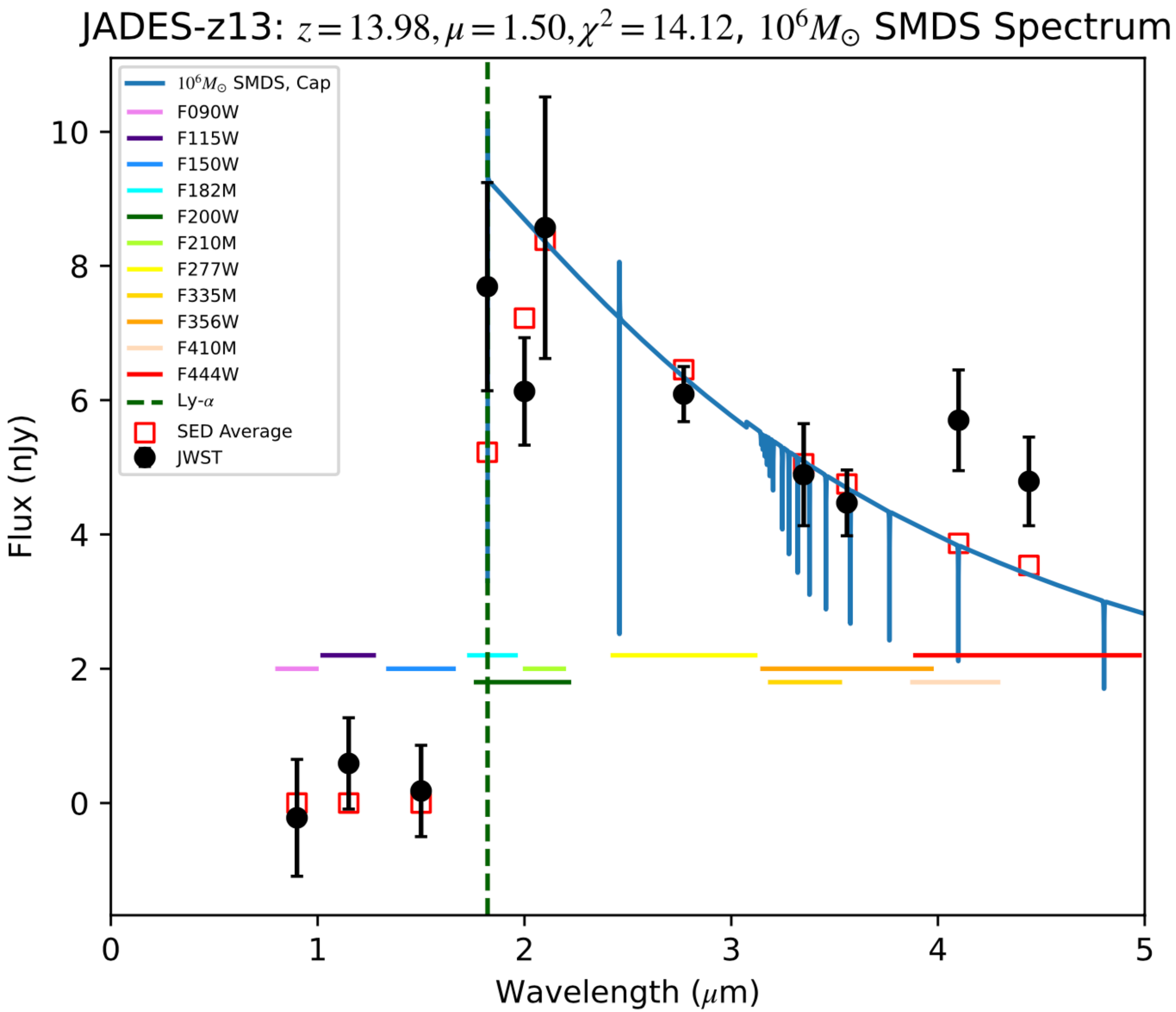


FIG. 1. (Top Row) Optimal fit regions in the z vs μ (magnification) parameter space for Supermassive Dark Star fits to JADES-GS-z11-0 , JADES-GS-z12-0 , and JADES-GS-z13-0 photometric data. The heatmap is color coded according to the value of the χ^2, and is cut off (grayed out) at the critical value corresponding to 95% CL. In addition to labeling the object, the title in each panel includes the the mass and formation mechanism for the SMDSs model considered. (Bottom Row) For each case we plot our best fit SEDs against the photometric data of [25] in each band (color coded and labeled in legend).



JADES-z13: $z = 13.98, \mu = 1.50, \chi^2 = 14.12,\ 10^6 M_\odot$ SMDS Spectrum
$10^6 M_\odot$ SMDS, Cap
F090W
F115W
F150W
F182M
F200W
F210M
F277W
F335M
F356W
F410M
F444W
Ly-α
SED Average
JWST
Flux (nJy)
Wavelength (μm)
0
2
4
6
8
10
1
3
5

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GNz11: An object with beautiful spectrum: a galaxy

A. J. Bunker et al.: JADES Spectroscopy of GN-z11

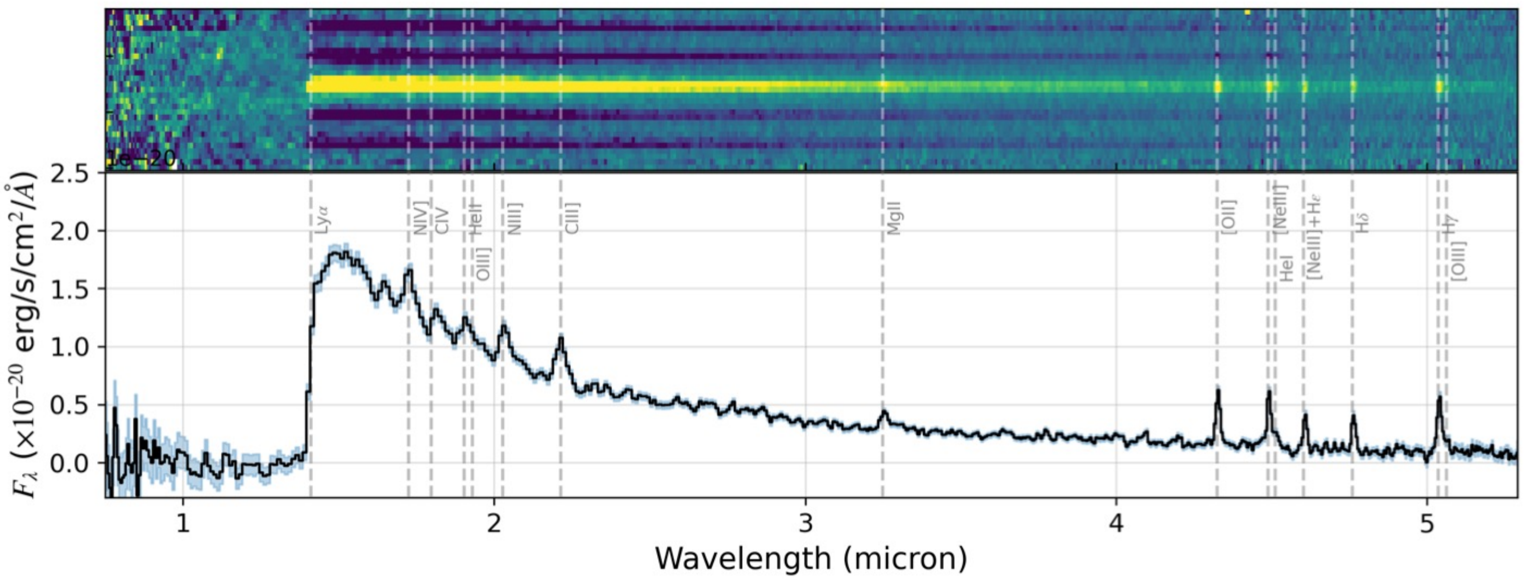


Fig. 1. 2D (top) and 1D (bottom) spectra of GN-z11 using PRISM/CLEAR configuration of NIRSpec. Prominent emission lines present in the spectra are marked. The signal to noise ratio (SNR) of the continuum is high and the emission lines are clearly seen in both the 1D and 2D spectra.

Best bet to distinguish SMDS vs. early galaxies

- HeII 1640 absorption line is smoking gun for SMDS.
- Need to get better spectra: take data for a longer time, find a highly magnified object
- Also: Since SMDS are point object, maybe find Airy (diffraction) pattern if it's a strong signal (magnified bright object)
- Also: at lambda>5 micron, spectra differ!

The Bottom Line

- JWST has found ~ 700 high redshift objects with z > 10. They call them "galaxy candidates"
- Too many galaxies for Lambda CDM
- Are some of them Dark Stars?
- NIRSPEC on JWST has spectra for 9 of these; so far 5 are on the arxiv or published..

(W/out spectra, can't be sure of redshift; some are low redshift)

- Specifically, JADES has four. So far, these are the ones we have studied. (JWST Advanced Extragalactic Survey)
- OUR RESULTS: Three of the four hi-z JWST objects we studied are consistent with Dark Stars
- New data: one of them has metal lines (not a DS?) .

Roman Space Telescope

- SMDS are also visible in RST which has MUCH larger field of view, making them easier to find.
- Find them with RST, then go study them with JWST which has much better angular resolution (n.b. JWST also goes to higher wavelength and hence higher z).
- Paper with Saiyang Zhang (student) and Cosmin Ilie

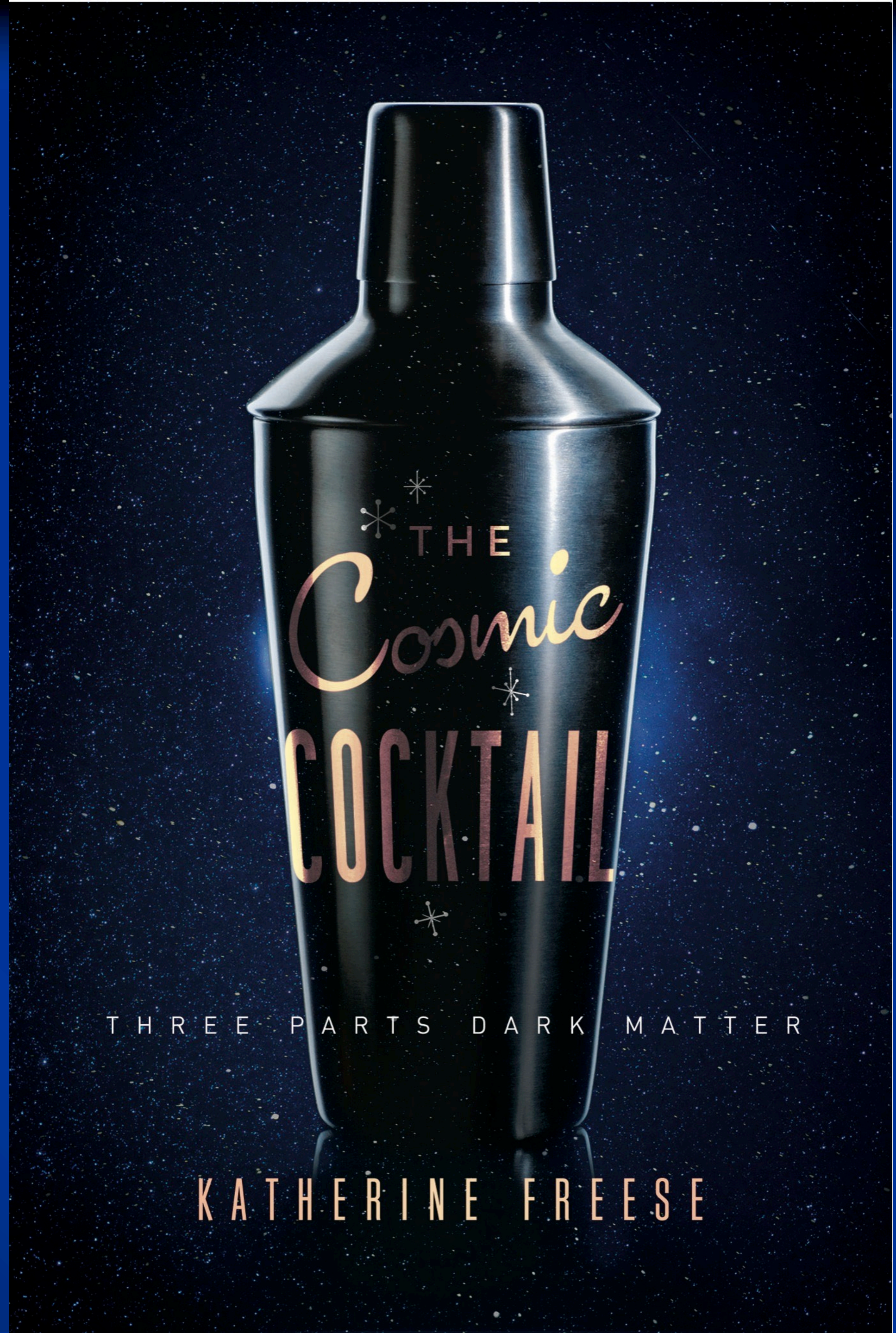
Dark Stars (conclusion)

- The dark matter can play a crucial role in the first stars. Though made of hydrogen and helium, they may be powered by DM heating rather than fusion
- Dark stars may be very massive (up to ten million $M_{\odot}$) and bright (up to ten billion solar luminosities), and can be precursors to Supermassive Black Holes
- SMDS may already have been discovered by JWST; need to find He absorption line as smoking gun
- SMDS are also detectable in Roman Space Telescope
- WIMPs and their properties could first be detected by discovering Dark Stars

Summary: Surprising Results and Big new Results

- Surprising Results:
- Time dependence of Dark Energy in DESI??
- Hubble Tension ??
- Sigma_8 tension ??
- Negative Neutrino Mass from DESI??
- Too many and too massive early galaxies found in JWST to made sense in LCDM: Could be DARK STARS

- Big New Results of the Conference:
- COSINE-100 vs. DAMA
- XENON hits the neutrino fog


THE
Cosmic
COCKTAIL
THREE PARTS DARK MATTER
KATHERINE FREESE