Dark Matter and Dark Stars

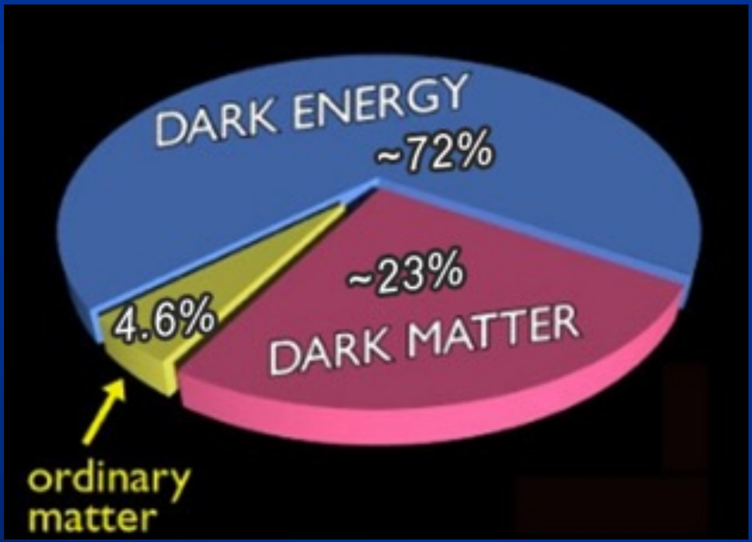
Katherine Freese

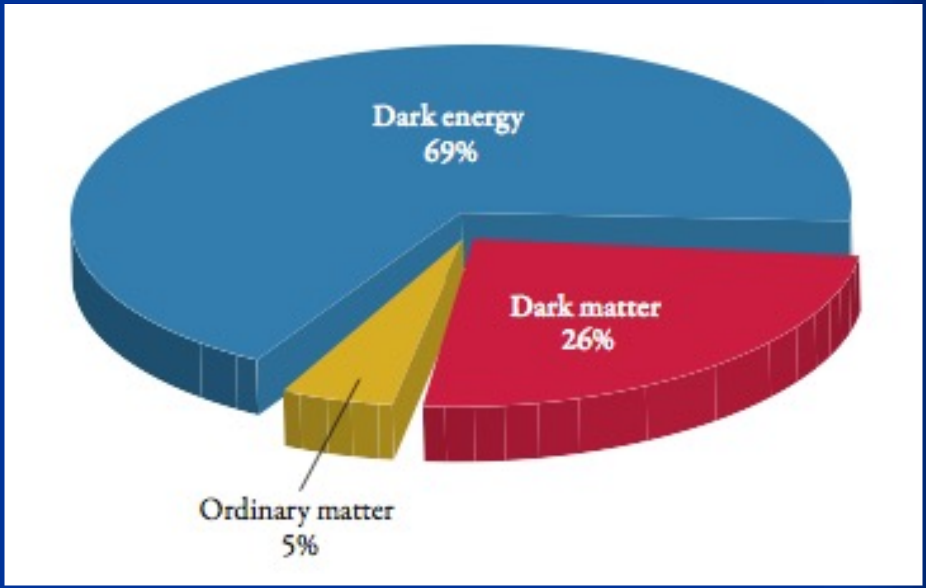
- Director, Weinberg Institute for Theoretical
- Physics, Jeff & Gail Kodosky Chair,
- Prof of Physics, University of Texas, Austin
- Guest Professor, Stockholm University

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

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:

- 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,

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

- 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.

PRIMORDIAL NUCLEOSYNTHESIS: A CRITICAL COMPARISON OF THEORY AND OBSERVATION

J. YANG,[1,2] M. S. TURNER,[2,3] G. STEIGMAN,[4] D. N. SCHRAMM,[2,3] AND K. A. OLIVE[3]

Received 1983 August 25; accepted 1983 December 20

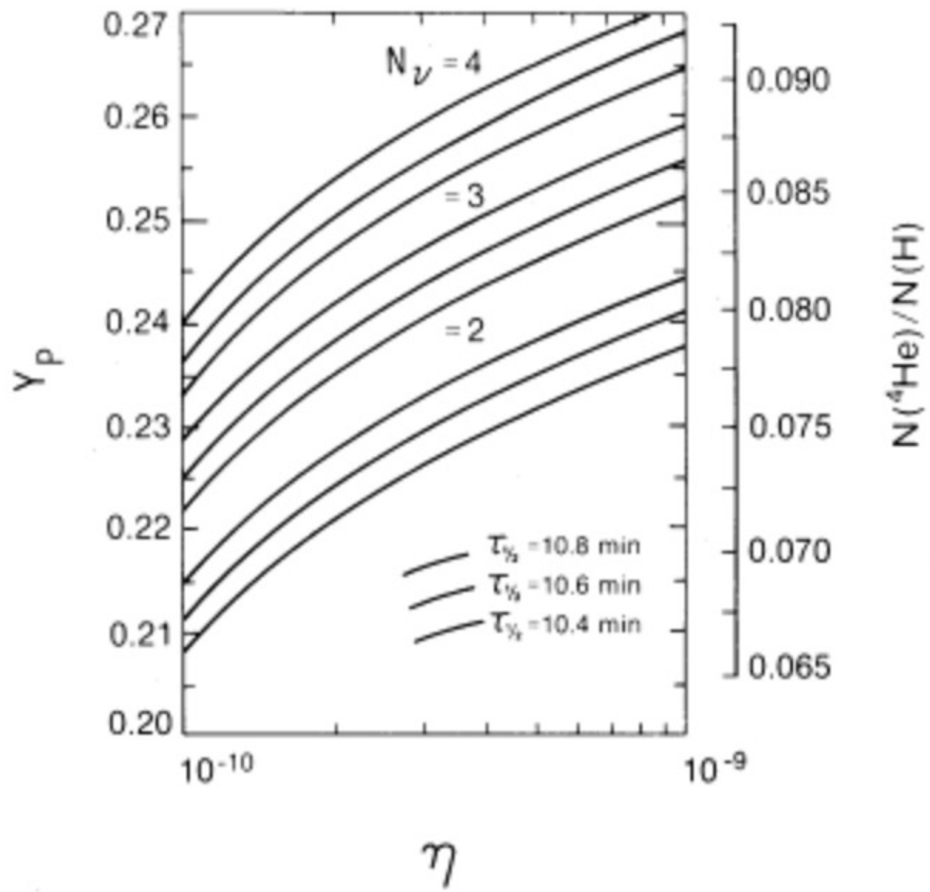


FIG. 1.—The abundance of ^{4}He (by mass and by number) as a function of the nucleon-to-photon ratio (η) for N_ν = 2, 3, 4 species of light, two-component neutrinos and for three choices for the neutron half-life ($\tau_{1/2}$ = 10.4, 10.6, 10.8 minutes).

Current Bounds on Number of Neutrino Species:

Planck TT+BAO gives Neff=3.15\pm0.23 at 68% CL.
If there are only 3 active neutrinos, the expected value is Neff=3.046

Therefore, models with Delta Neff=1 are ruled out at almost 3sigma level.

NEUTRINO MASS

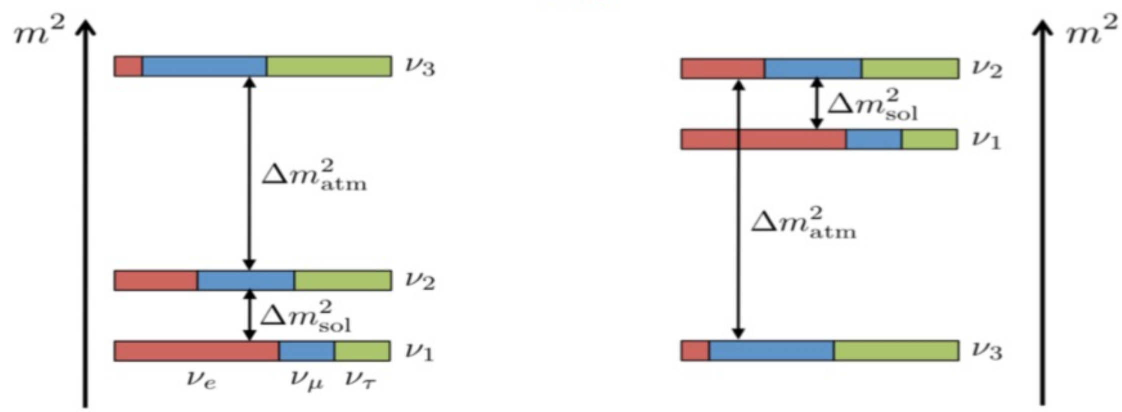
We know from the observation of neutrino oscillations that neutrinos have mass (Nobel prize 2015 to Kajita & McDonald!)
However, oscillations measure mass ***differences*** (with few % accuracy):

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

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

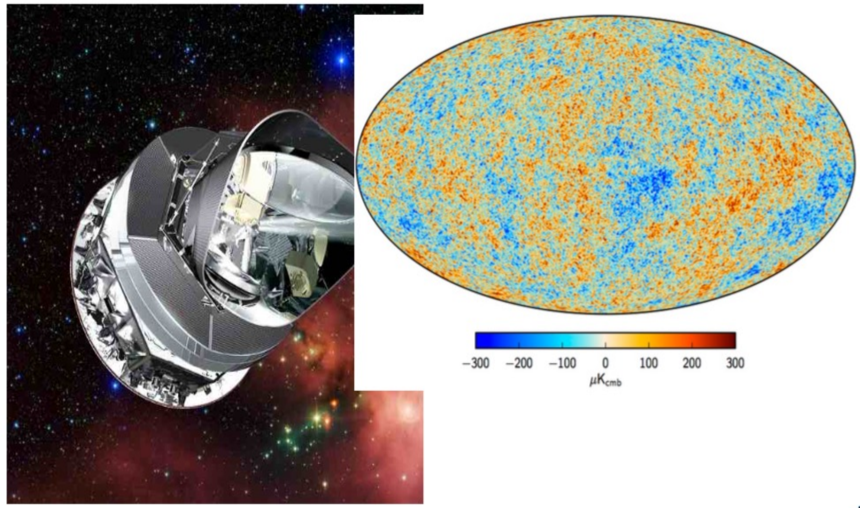
(depending on the hierarchy)

Figure credit: Juno Collaboration

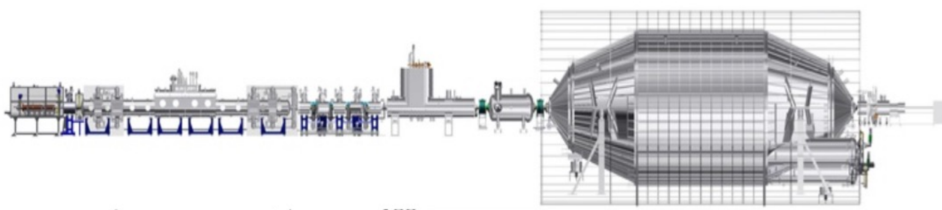
The tiny neutrino masses are a puzzle for the Standard Model of particle physics

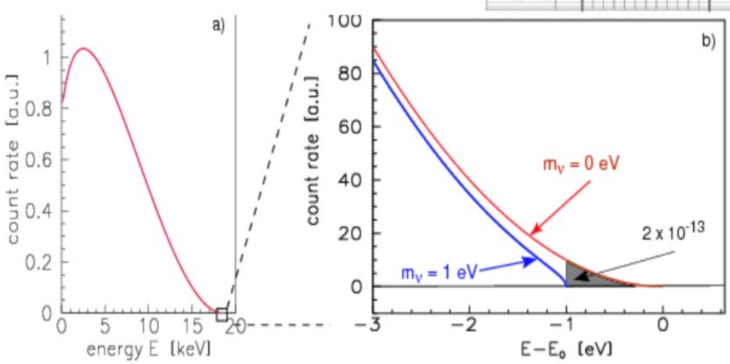
The absolute scale of neutrino masses can be measured in different ways

Cosmological observations (CMB, LSS)

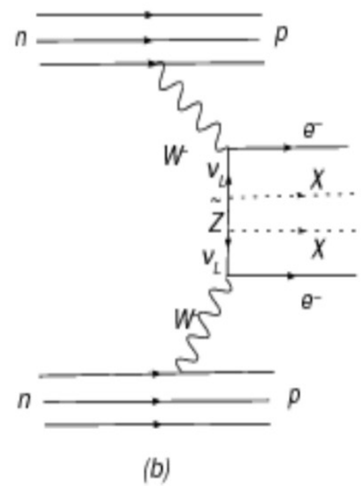


Neutrinoless double β decay





Kinematic measuremets (Tritium β decay)



The **absolute mass scale** can be measured through:

- tritium beta decay

$$m_\beta \equiv \left[\sum |U_{ei}|^2 m_i^2\right]^{1/2} < 1.1 \text{ eV @ 90\%CL}$$ (KATRIN)

- neutrinoless double beta decay

$$m_{\beta\beta} \equiv \left|\sum U_{ei}^2 m_i\right| \quad < 0.06 - 0.16 \text{ eV @ 90\%CL}$$

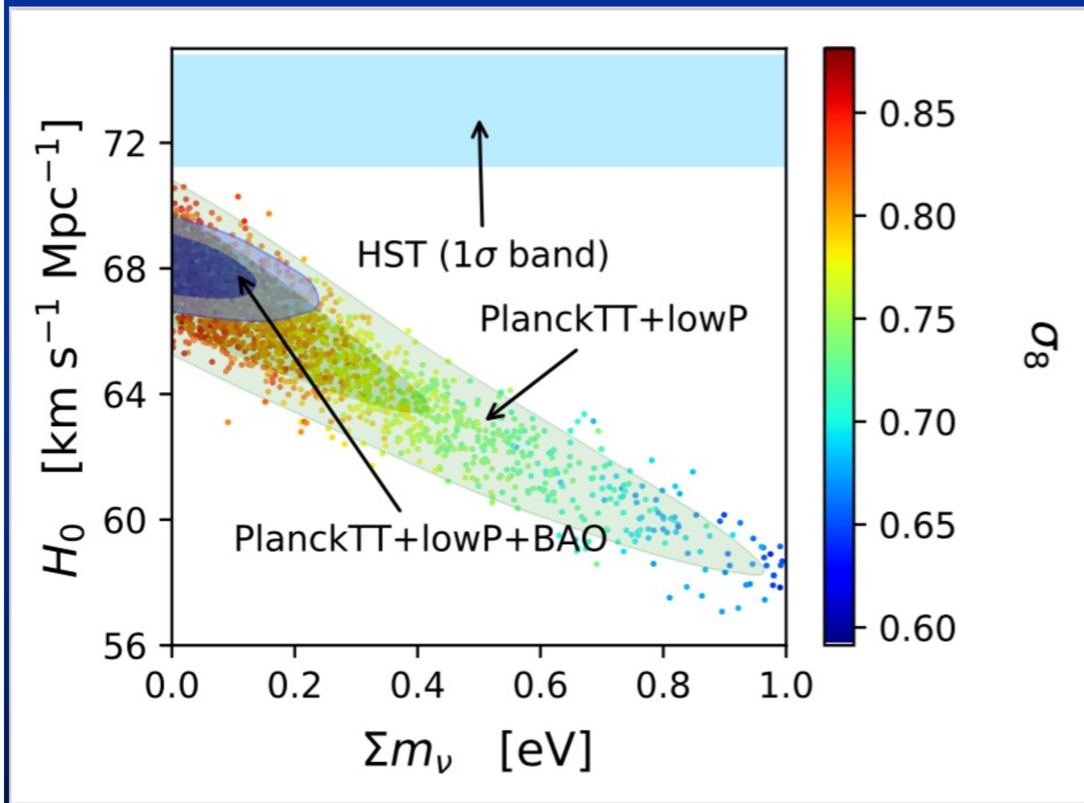
(Kamland-Zen)

- cosmological observations

$$\sum m_\nu \equiv \sum_i m_i \quad < 0.12 - 0.24 \text{ eV @ 95\%CL}$$

(Planck+…)

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

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

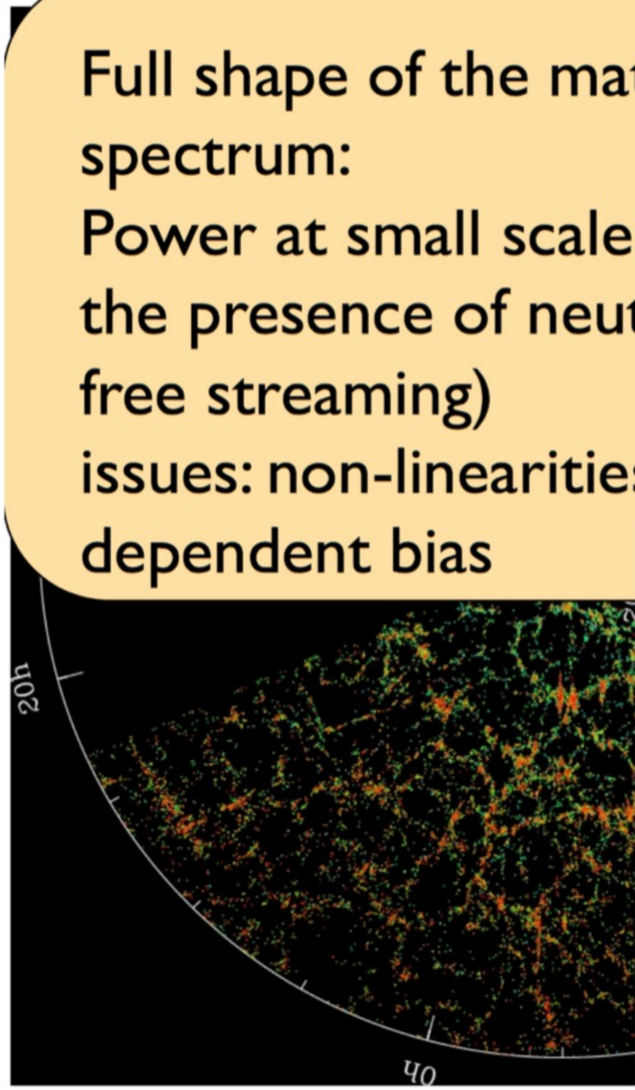
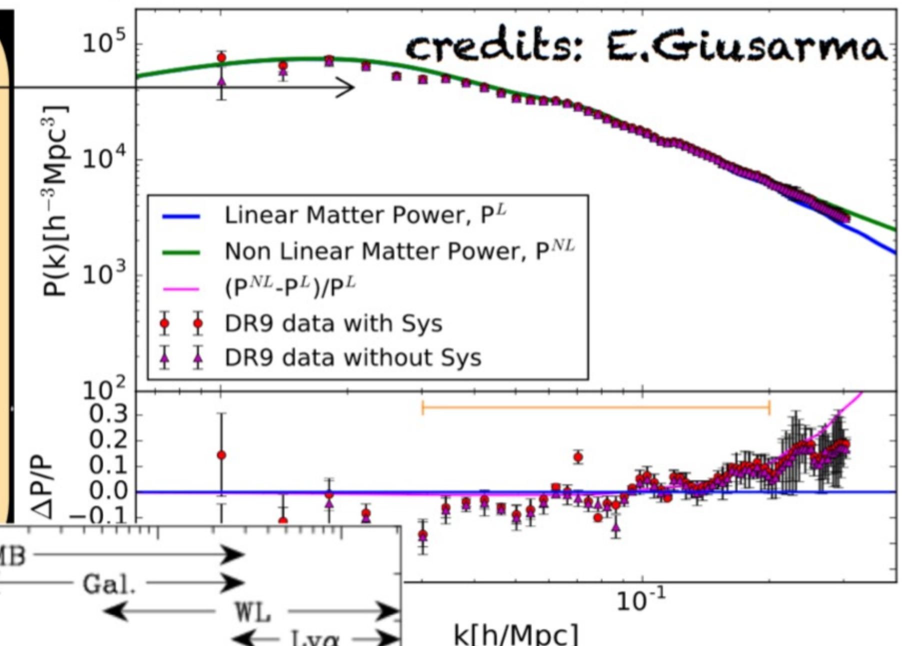
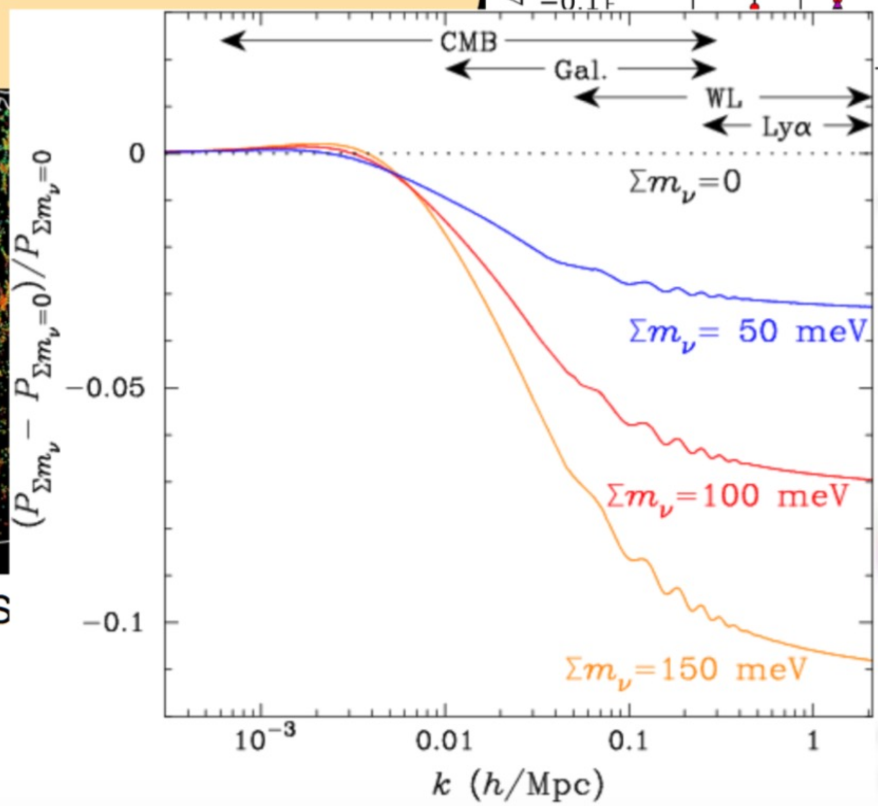


Image Credit: M. Blanton and the S

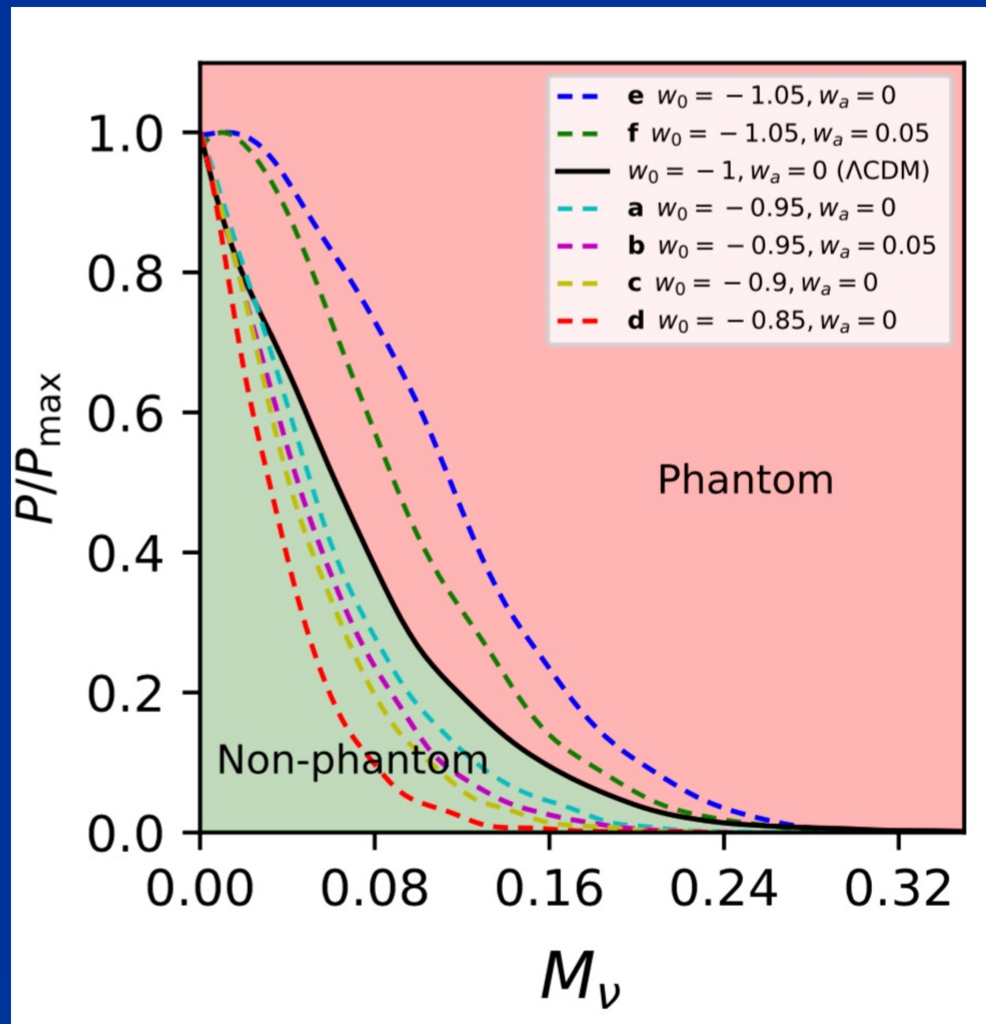




Neutrino Mass bounds are tighter for arbitrary dark energy with w>-1 (nonphantom) than for Lambda CDM

MARTINA
GERBINO

SUNNY
VAGNOZZI



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

Upcoming Cosmic Microwave Background Experiments

My group has joined these two experiments

Jon Gudmundsson

Adri Duivenvoorden

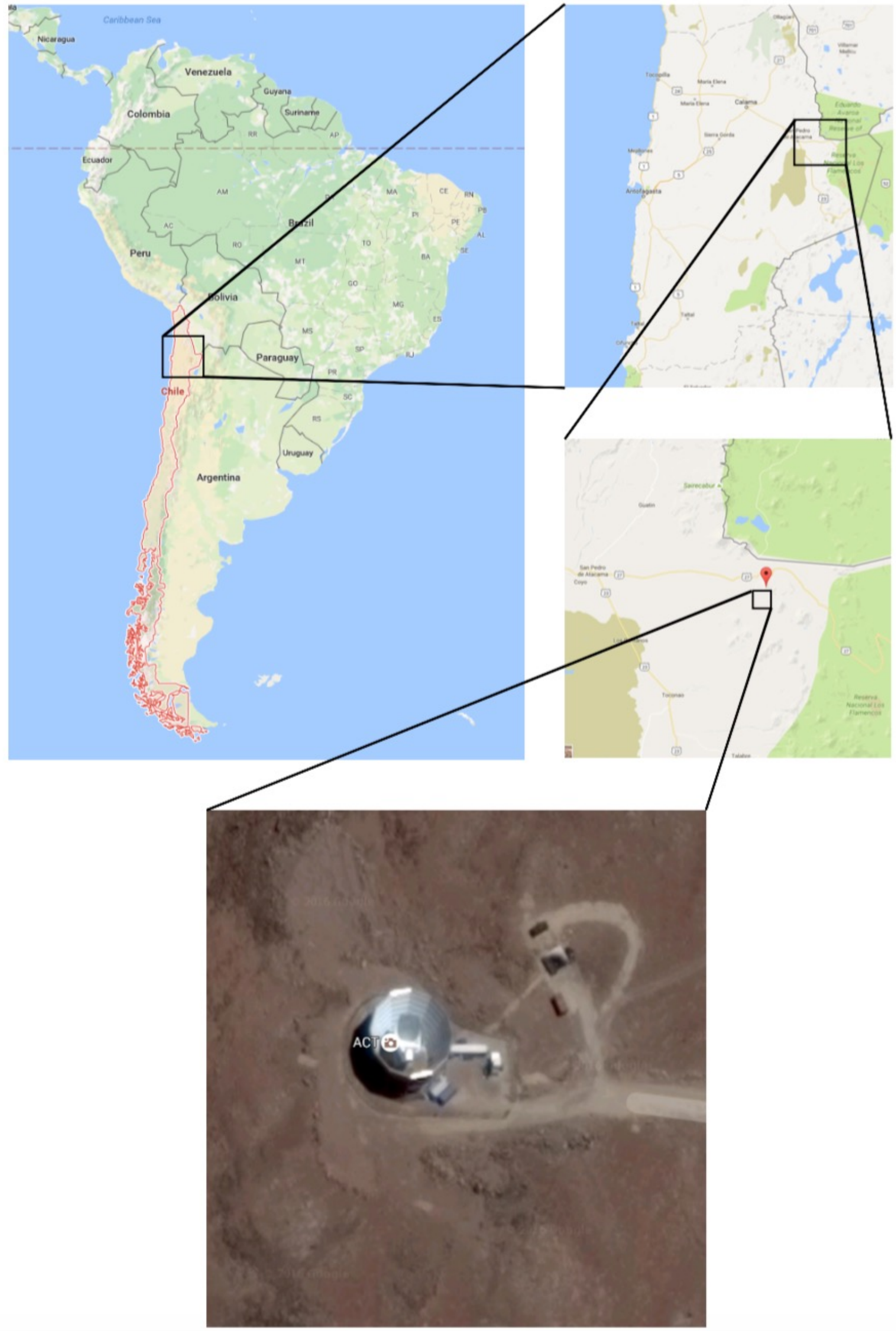
SPIDER at South Pole

Nick Galitzki, new Prof at UT

Simons Observatory

- 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 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.

Steffen Hagstotz

arXiv.org > astro-ph > arXiv:2003.02289

Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 4 Mar 2020]

Bounds on light sterile neutrino mass and mixing from cosmology and laboratory searches

For m_nu < keV

Steffen Hagstotz, Pablo F. de Salas, Stefano Gariazzo, Martina Gerbino, Massimiliano Lattanzi, Sunny Vagnozzi, Katherine Freese, Sergio Pastor

We provide a consistent framework to set limits on properties of light sterile neutrinos coupled to all three active neutrinos using a combination of the latest cosmological data and terrestrial measurements from oscillations, β-decay and neutrinoless double-β decay ($0\nu\beta\beta$) experiments. We directly constrain the full $3+1$ active-sterile mixing matrix elements $|U_{\alpha 4}|^2$, with $\alpha \in (e, \mu, \tau)$, and the mass-squared splitting $\Delta m^2_{41} \equiv m^2_4 - m^2_1$. We find that results for a $3+1$ case differ from previously studied $1+1$ scenarios where the sterile is only coupled to one of the neutrinos, which is largely explained by parameter space volume effects. Limits on the mass splitting and the mixing matrix elements are currently dominated by the cosmological data sets. The exact results are slightly prior dependent, but we reliably find all matrix elements to be constrained below $|U_{\alpha 4}|^2 \lesssim 10^{-3}$.
Short-baseline neutrino oscillation hints in favor of eV-scale sterile neutrinos are in serious tension with these bounds, irrespective of prior assumptions. We also translate the bounds from the cosmological analysis into constraints on the parameters probed by laboratory searches, such as m_β or $m_{\beta\beta}$, the effective mass parameters probed by β-decay and $0\nu\beta\beta$ searches, respectively. When allowing for mixing with a light sterile neutrino, cosmology leads to upper bounds of $m_\beta < 0.09$ eV and $m_{\beta\beta} < 0.07$ eV at 95\% C.L, more stringent than the limits from current laboratory experiments.

2) What is the Dark Matter? Candidates:

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- ---
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- Light Dark Matter
- Self Interacting Dark Matter
- Q-balls
- WIMPzillas

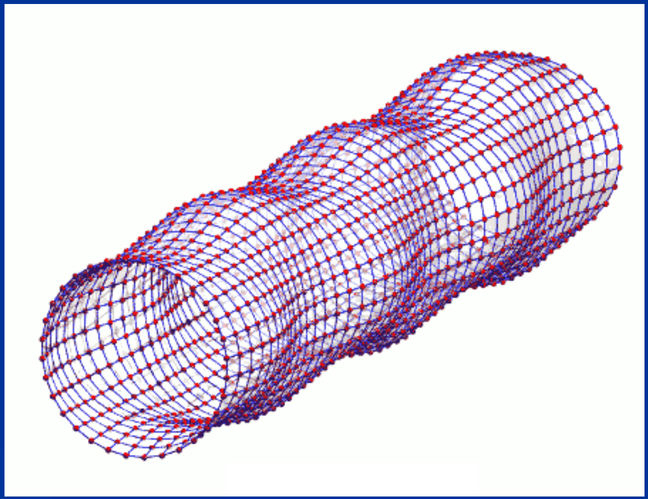
Florian Kuhnel
Primordial
Black Holes

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.

Gravitational Waves

- Gravitational waves alternately stretch and squeeze space-time both vertically and horizontally as they propagate.



Detection of Gravitational Waves by LIGO

Two arms, 4km each, length of one increases while the other decreases – by a fraction of the size of a proton -- when gravitational waves come by that stretch the spacetime differently in perpendicular directions

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]

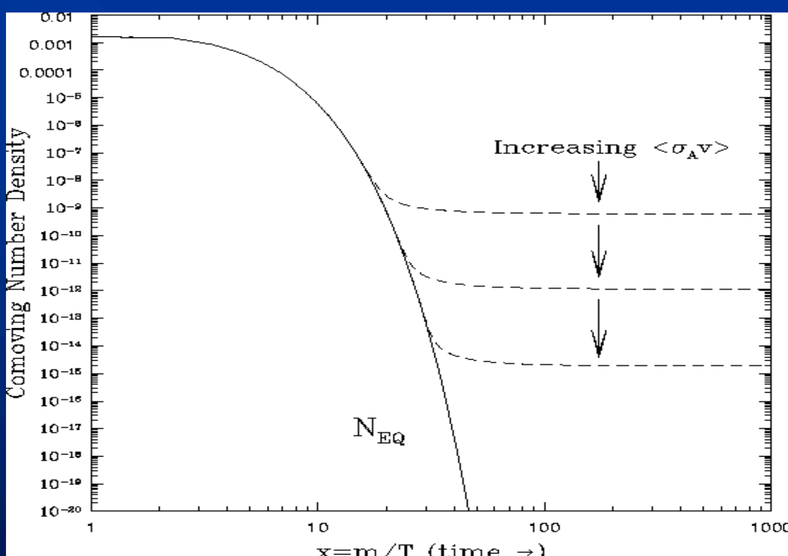
[1] *Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles St., Baltimore, MD 21218, USA*

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

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

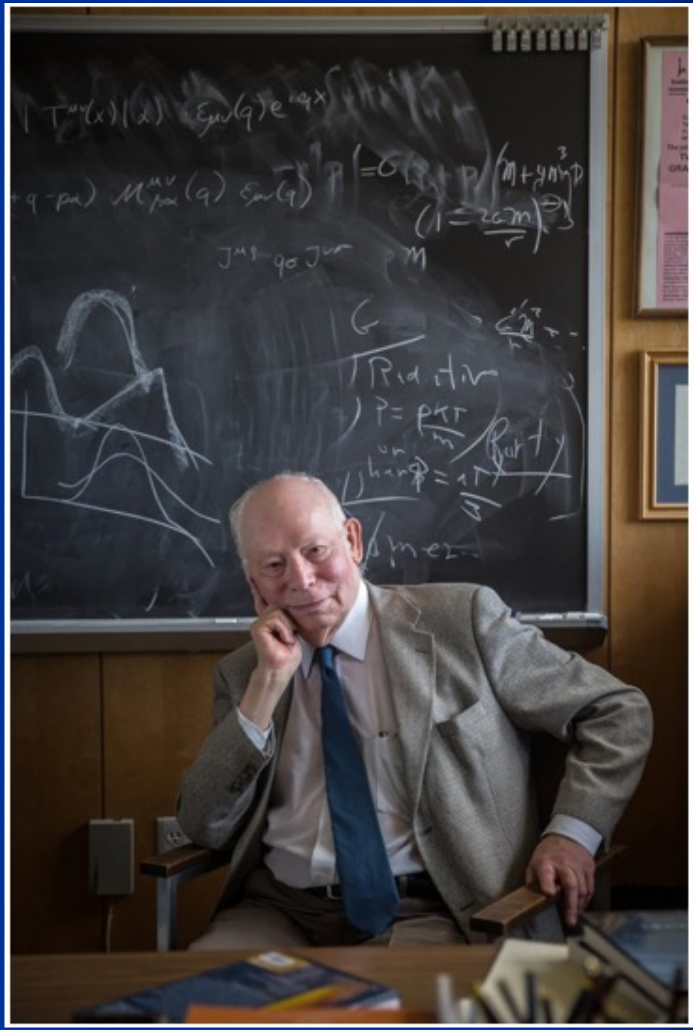
- Axions automatically exist in a proposed solution to the strong CP problem in the theory of strong interaction. They are very light, weighing a trillionth as much as protons; yet they are slow-moving. Axions are among the top candidates for dark matter.

Steven Weinberg

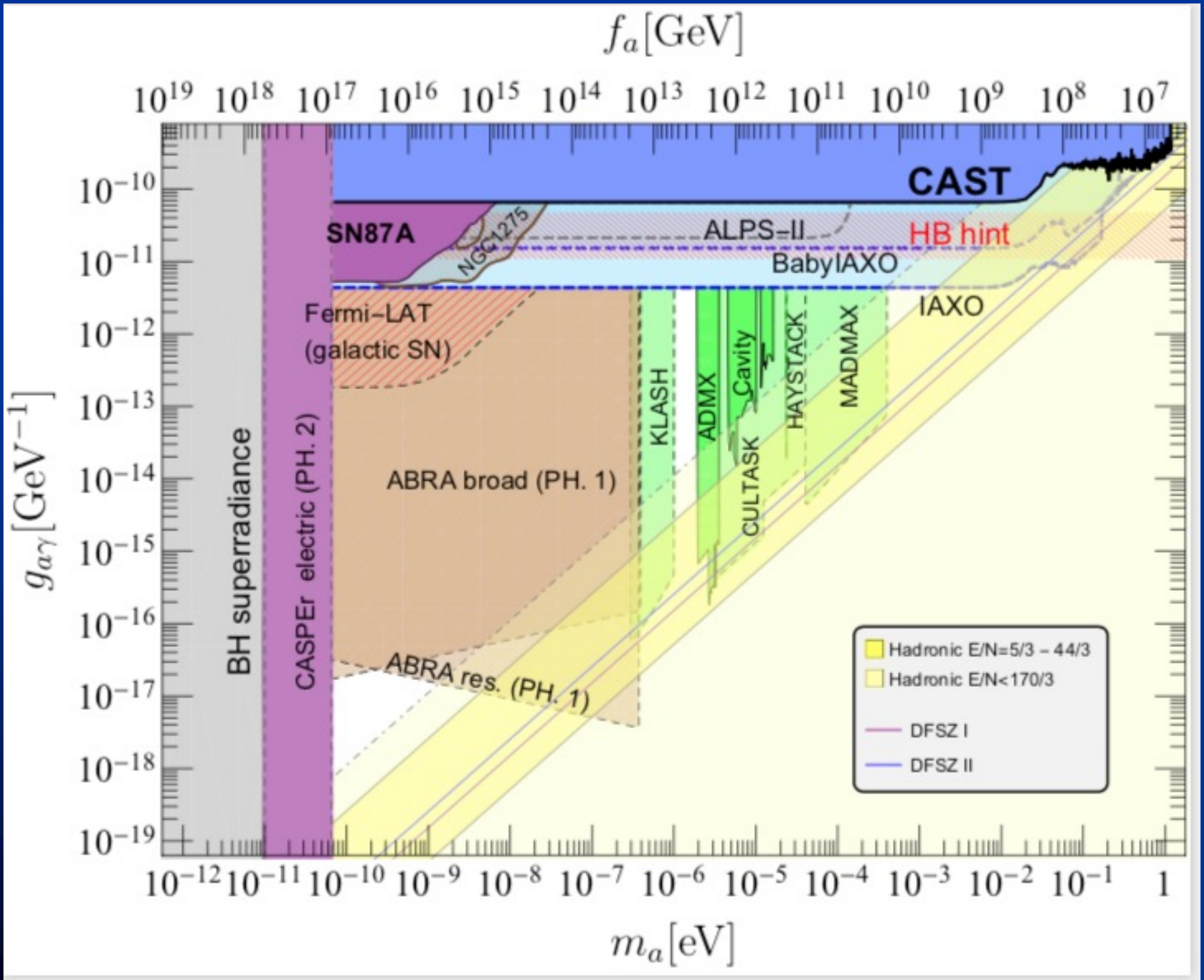
Frank Wilczek

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 at University of Texas --
- A major loss for us and for the world!



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.

$$\Omega_\chi h^2 = \frac{3\times10^{-27}\ cm^3/\mathrm{sec}}{<\sigma v>_{ann}}$$

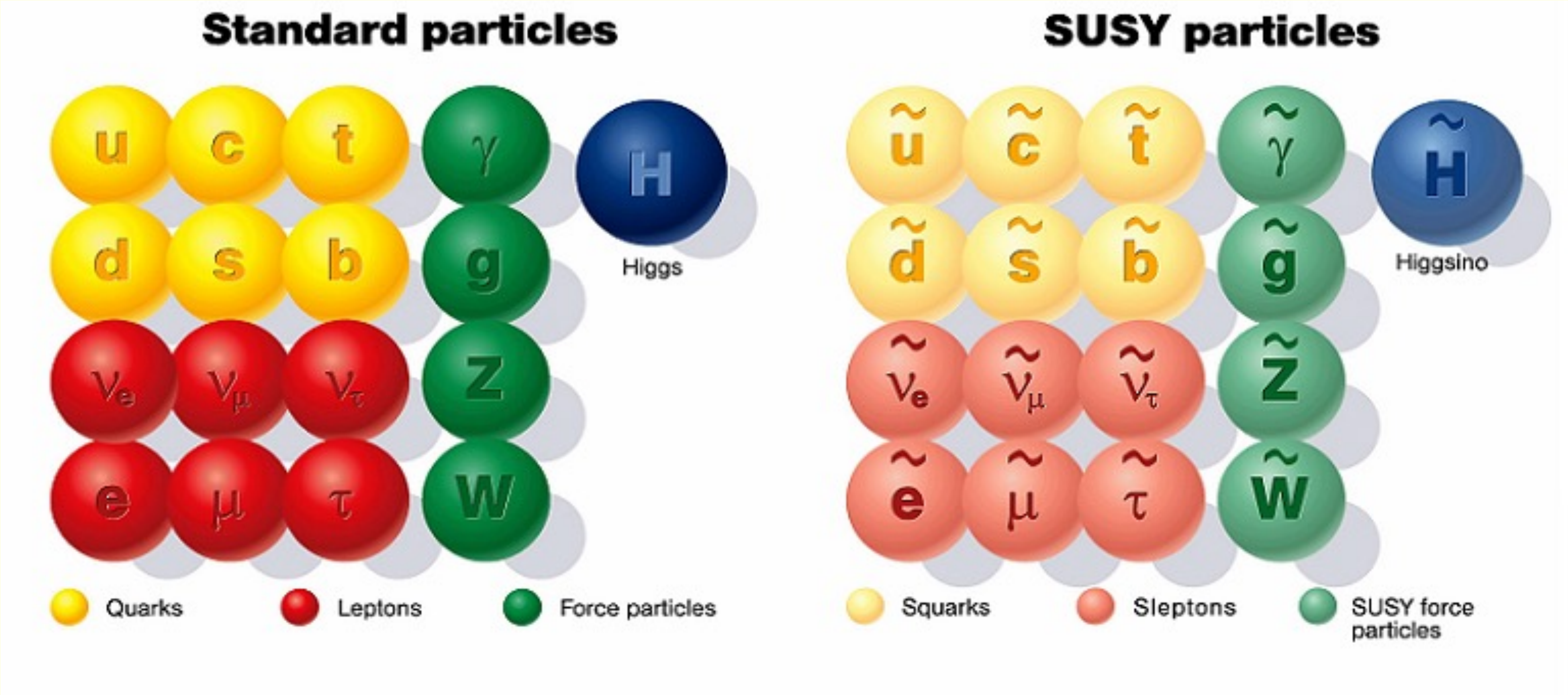
n.b. thermal WIMPs

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

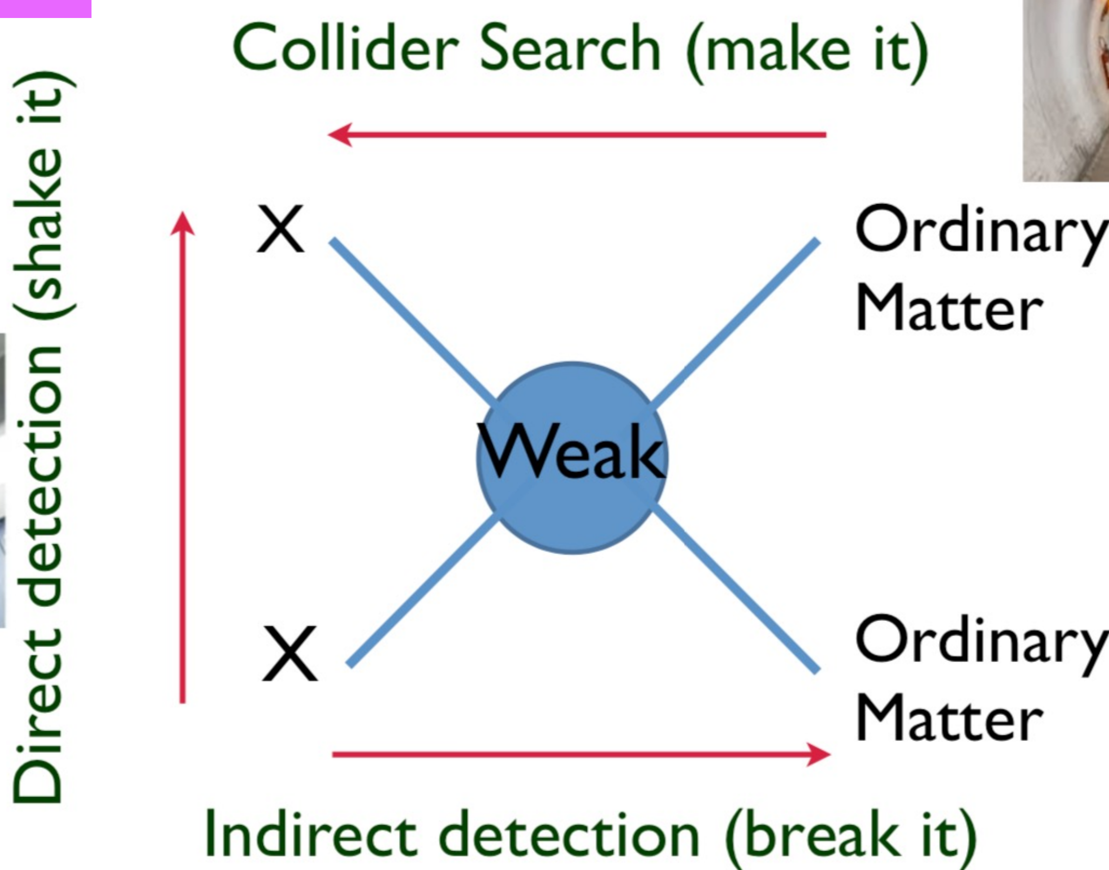
Second reason we favor WIMPS: in particle theories, eg supersymmetry

- Every particle we know has a partner

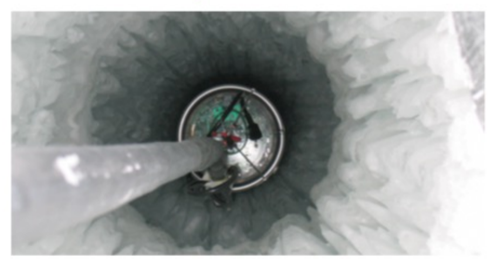


- The lightest supersymmetric particle may be the dark matter.

THREE PRONGED APPROACH TO WIMP DETECTION



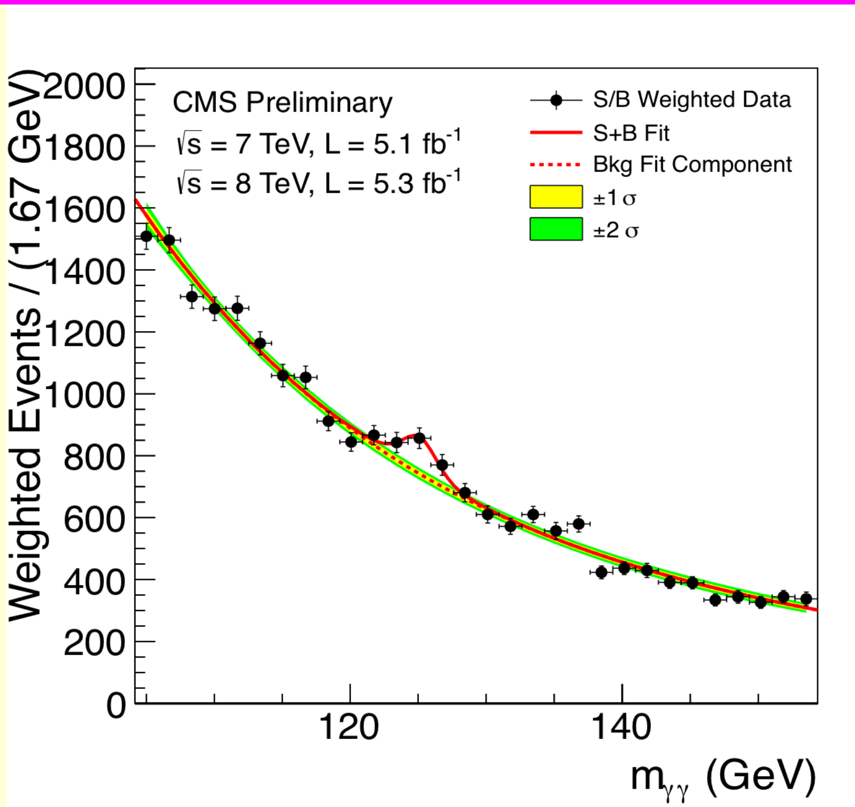
FOURTH PRONG: DARK STARS



FIRST WAY TO SEARCH FOR WIMPS

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

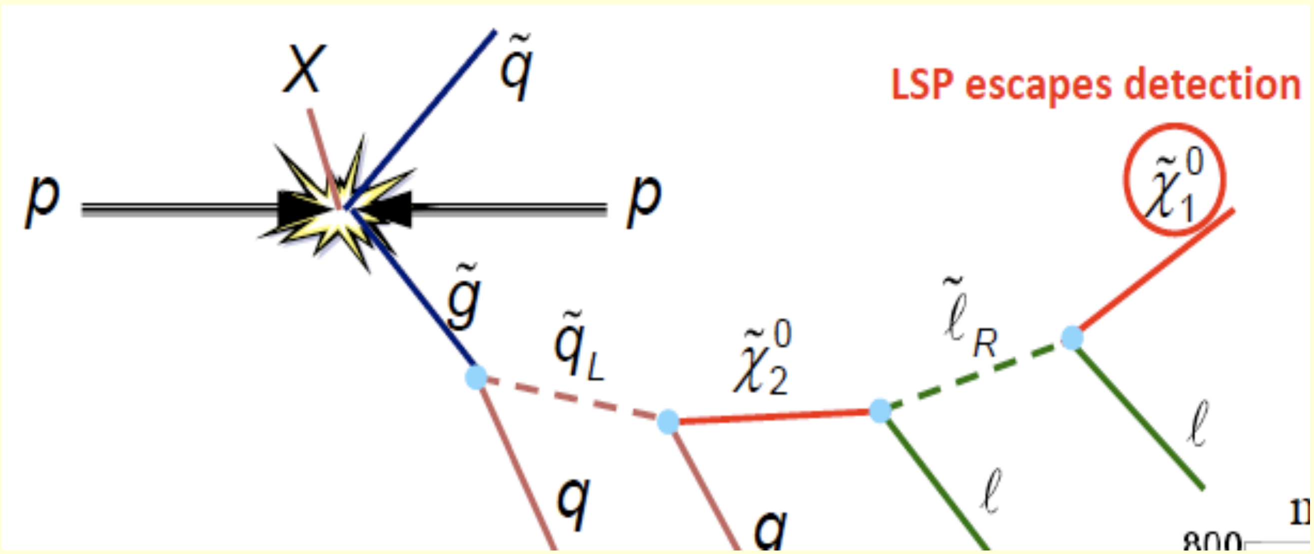
LHC's first success
Discovery of Higgs boson
weighing 125 GeV



Key role of Higgs:
imparts mass
to other particles

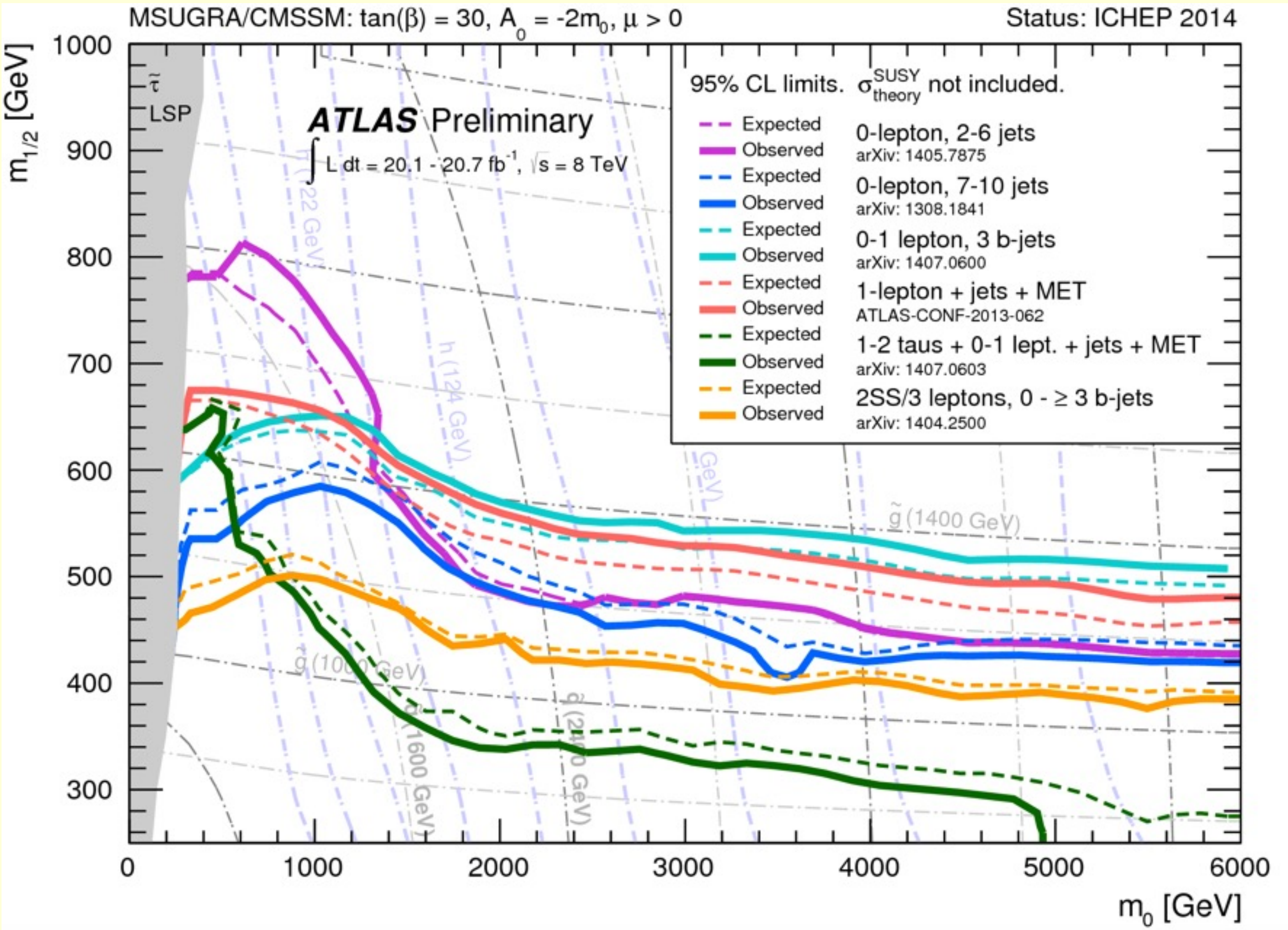
Second major goal of LHC: search for SUSY and dark matter

- Two signatures: Missing energy plus jets



- Nothing seen yet: particle masses pushed to higher masses

ATLAS bounds on CMSSM



Comments on DM at LHC

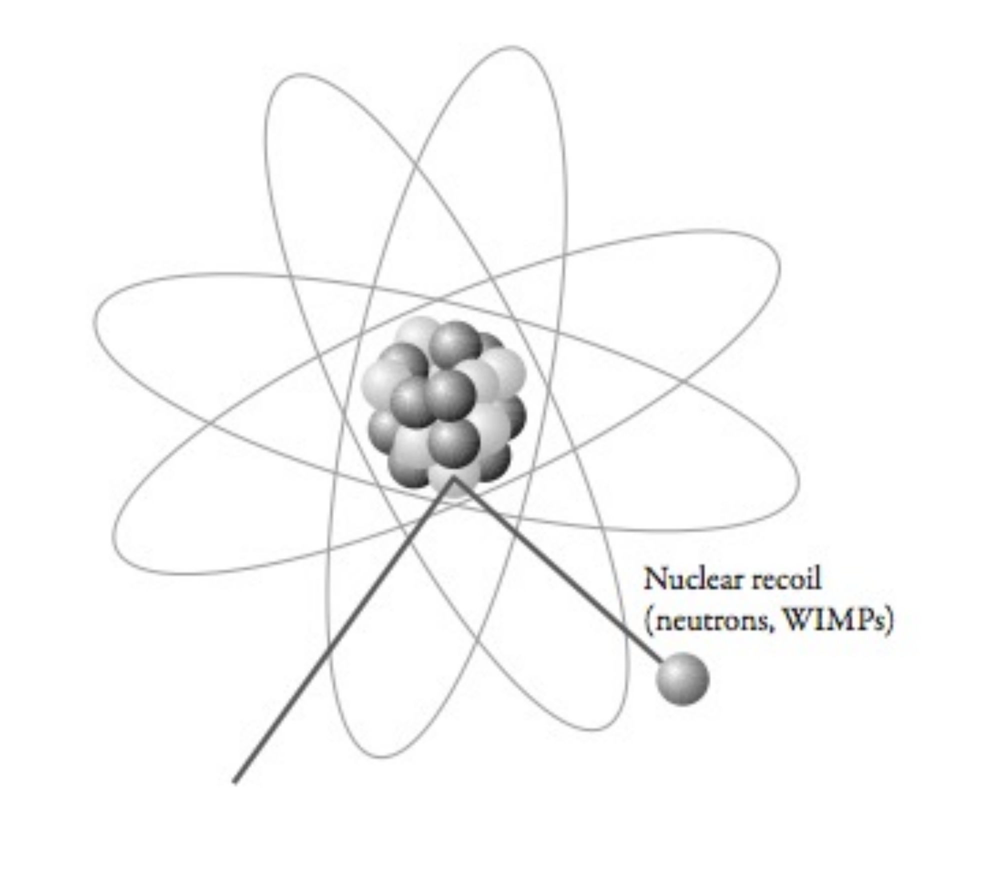
- If the LHC sees nothing,
  can SUSY survive? Yes.
- It may be at high scale,
- It may be less simple than all scalars and all fermions at one scale
- Even is SUSY is found at LHC, we still won't know if particles are long-lived; to see if it's dark matter, need other approaches

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!

How did I get into Dark Matter?

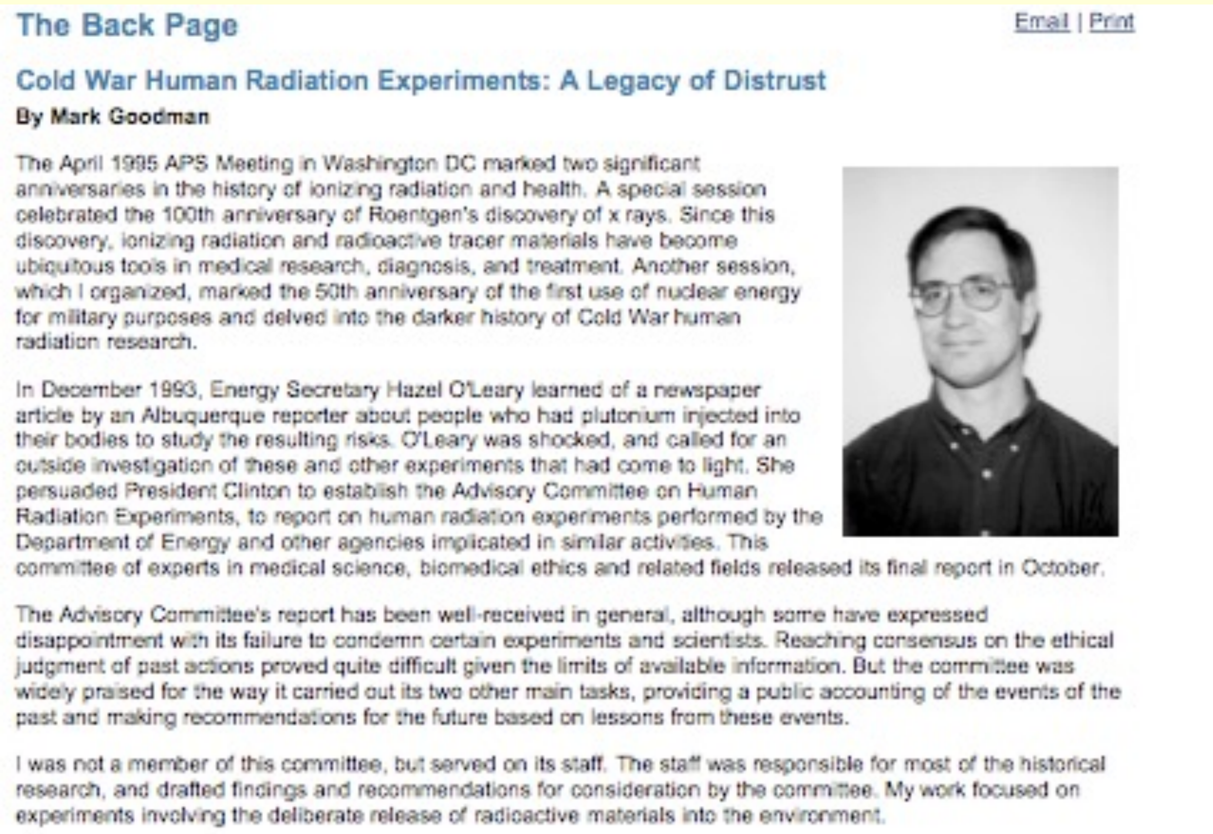
PhD Advisor at Univ of Chicago, David Schramm
ADVICE to students: Find a great mentor

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

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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 $v_{\rm esc}$,

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

Here

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

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

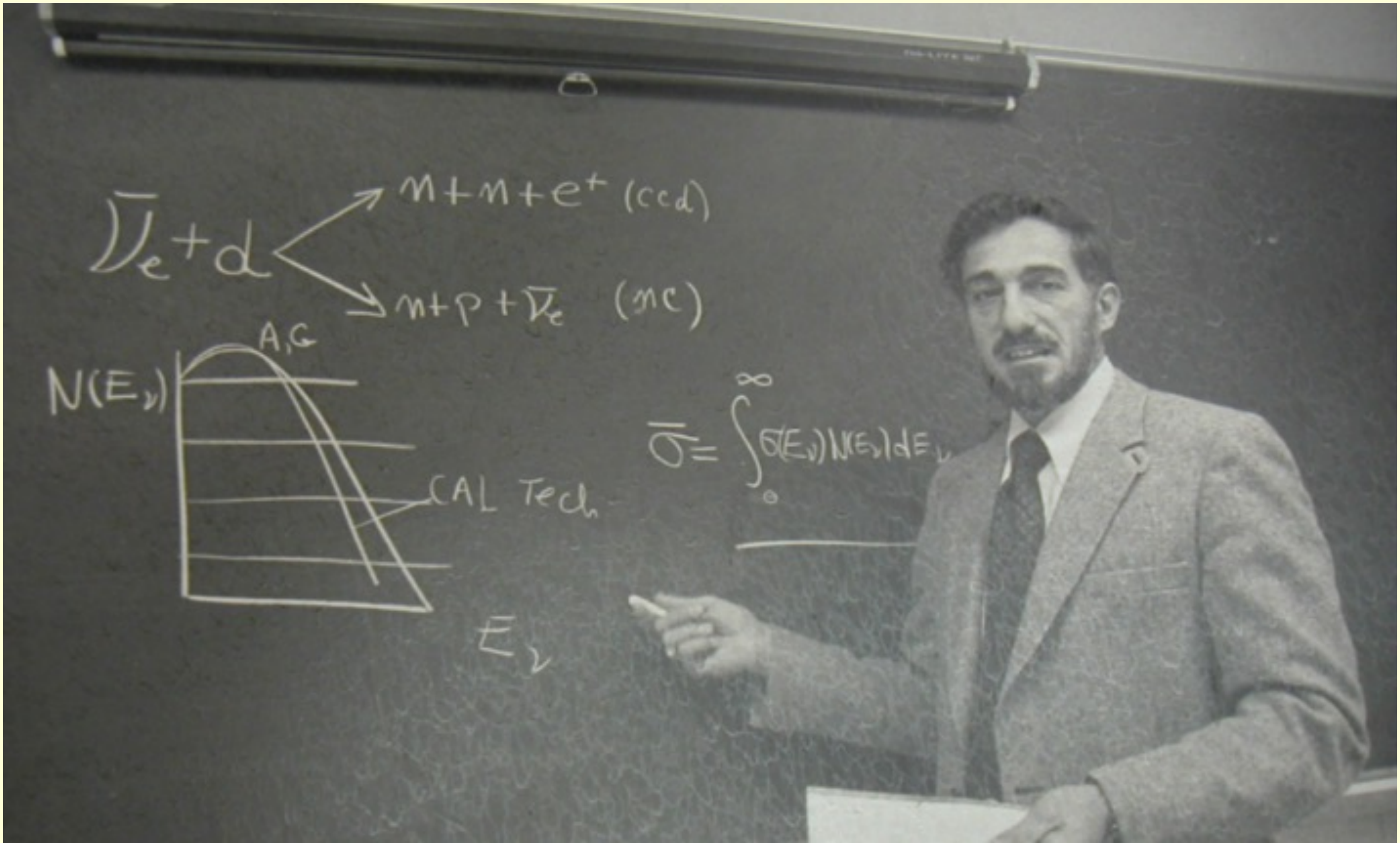
$$\overline{v}_0 = \sqrt{2/3}\,\sigma_v,$$

Typical particle speed is about 270 km/sec.

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

$E_0 = 2\mu^2 v_c^2/M$ so

But what about testing the theories?
Along comes Frank Avignone!
New Chair of Physics at USC in 1979
Neutrino guy (or so he thought)



The Lure of the Dark Side: First Dark Matter Search in the Homestake Mine in the early 80s

LIMITS ON COLD DARK MATTER CANDIDATES FROM AN ULTRALOW BACKGROUND GERMANIUM SPECTROMETER

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Received 5 May 1987

An ultralow background spectrometer is used as a detector of cold dark matter candidates from the halo of our galaxy Using a realistic model for the galactic halo, large regions of the mass–cross section space are excluded for important halo component particles. In particular, a halo dominated by heavy standard Dirac neutrinos (taken as an example of particles with spin-independent Z^0 exchange interactions) with masses between 20 GeV and 1 TeV is excluded. The local density of heavy standard Dirac neutrinos is <0.4 GeV/cm^3 for masses between 17.5 GeV and 2 5 TeV, at the 68% confidence level.

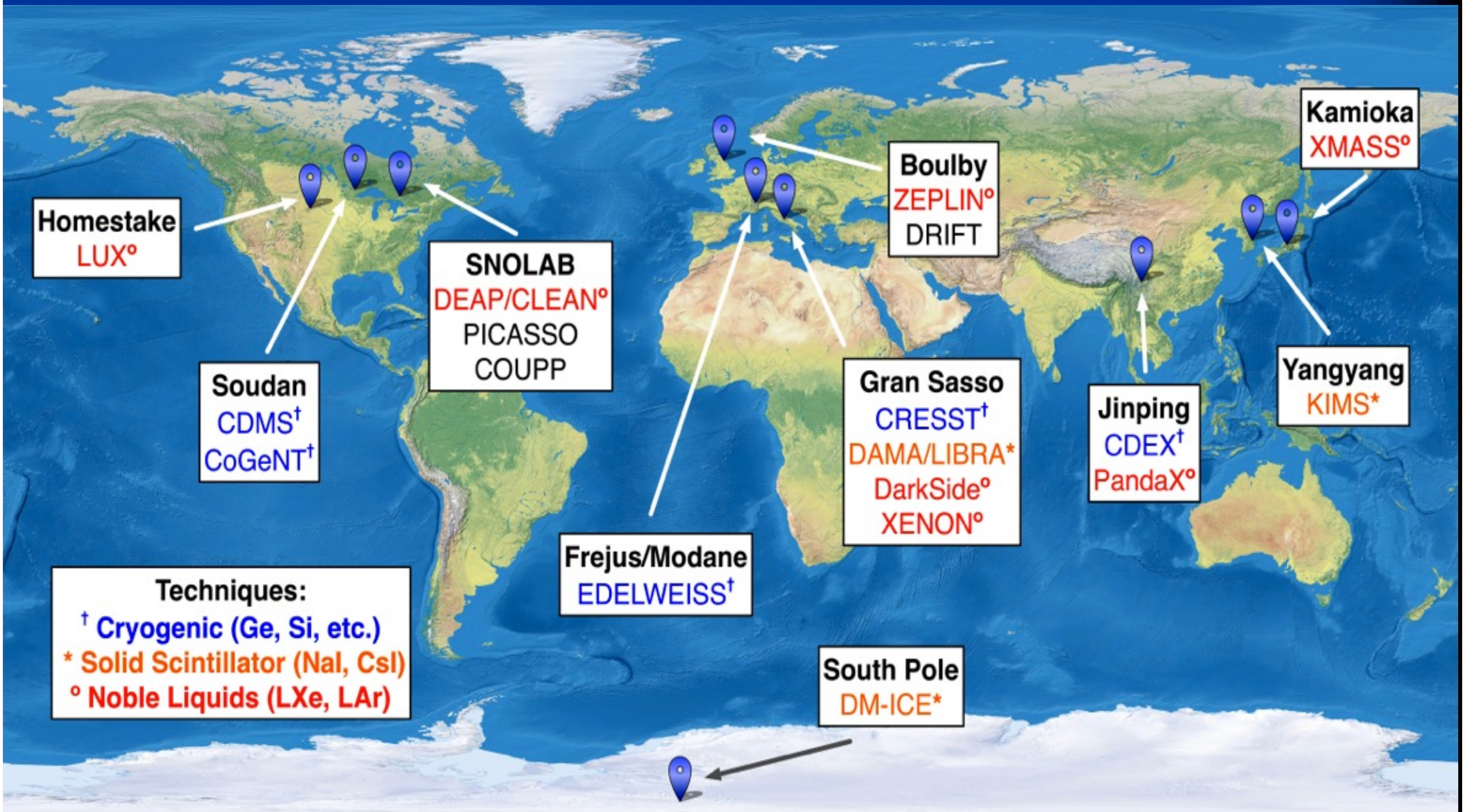
Frank and Anne in front of the Nobel Museum in Stockholm

Doug Adams

WIMP detectors must be in underground laboratories

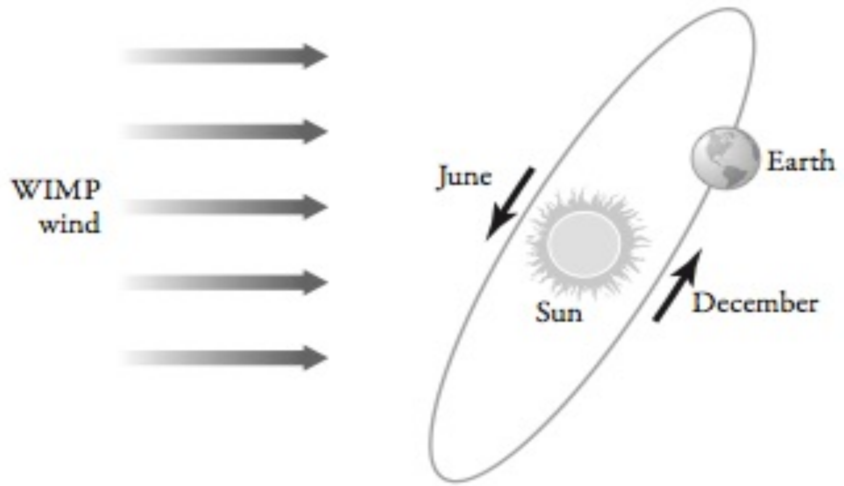
SNOLAB in Canada, 2 km below ground,
reduces cosmic rays that would overwhelm the detector
by a factor of 50 million. Location of DEAP 3600, SUPERCDMS, PICO, DAMIC

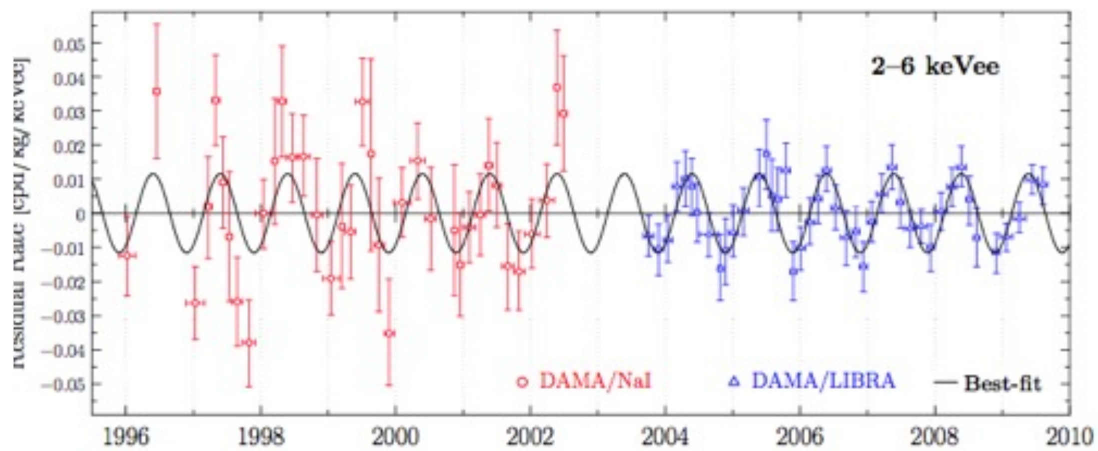
UNDERGROUND DARK MATTER LABORATORIES WORLDWIDE



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??

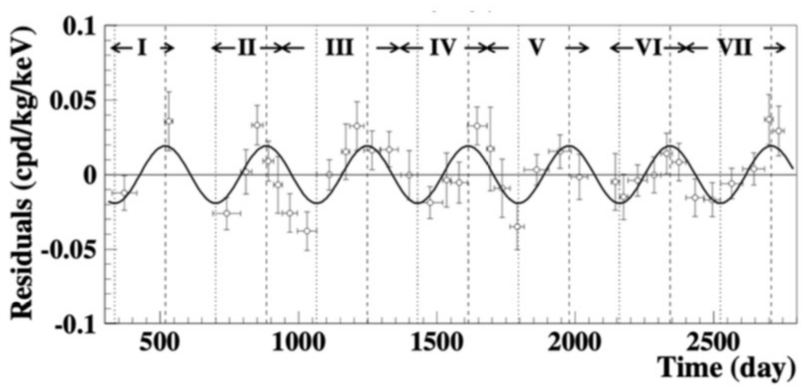


Figure 24: Experimental residual rate of the *single–hit* scintillation events measured by DAMA/NaI in the (2–6) keV energy interval as a function of the time (exposure of 0.29 ton $\times$ yr) . The superimposed curve is the cosinusoidal functional forms $A\cos\omega(t-t_0)$ with a period $T=\frac{2\pi}{\omega}=1$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

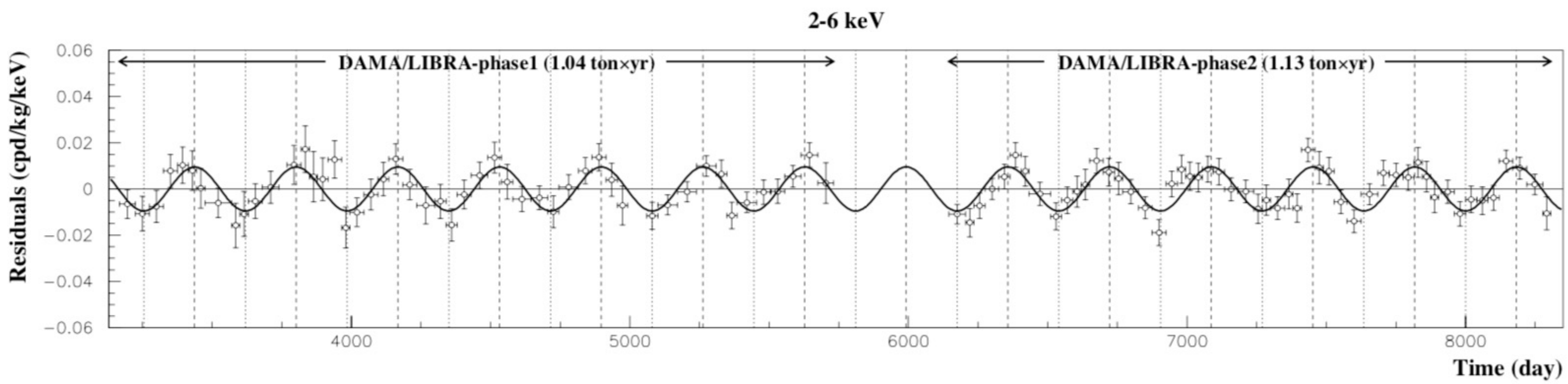


Figure 25: Experimental residual rate of the *single–hit* scintillation events measured by DAMA/LIBRA–phase1 and DAMA/LIBRA–phase2 in the (2–6) keV energy intervals as a function of the time. The superimposed curve is the cosinusoidal functional forms $A\cos\omega(t-t_0)$ with a period $T=\frac{2\pi}{\omega}=1$ 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.

Two Issues with DAMA

- 1. The experimenters won't release their data to the public

"If you can bear to hear the truth you've spoken twisted by knaves to make a trap for fools, you'll be a Man my son!"

(quote from Rudyard Kipling on the DAMA webpage)

- 2. Comparison to other experiments:

null results from XENON, CDMS, LUX.

But comparison is difficult because experiments are made of different detector materials!

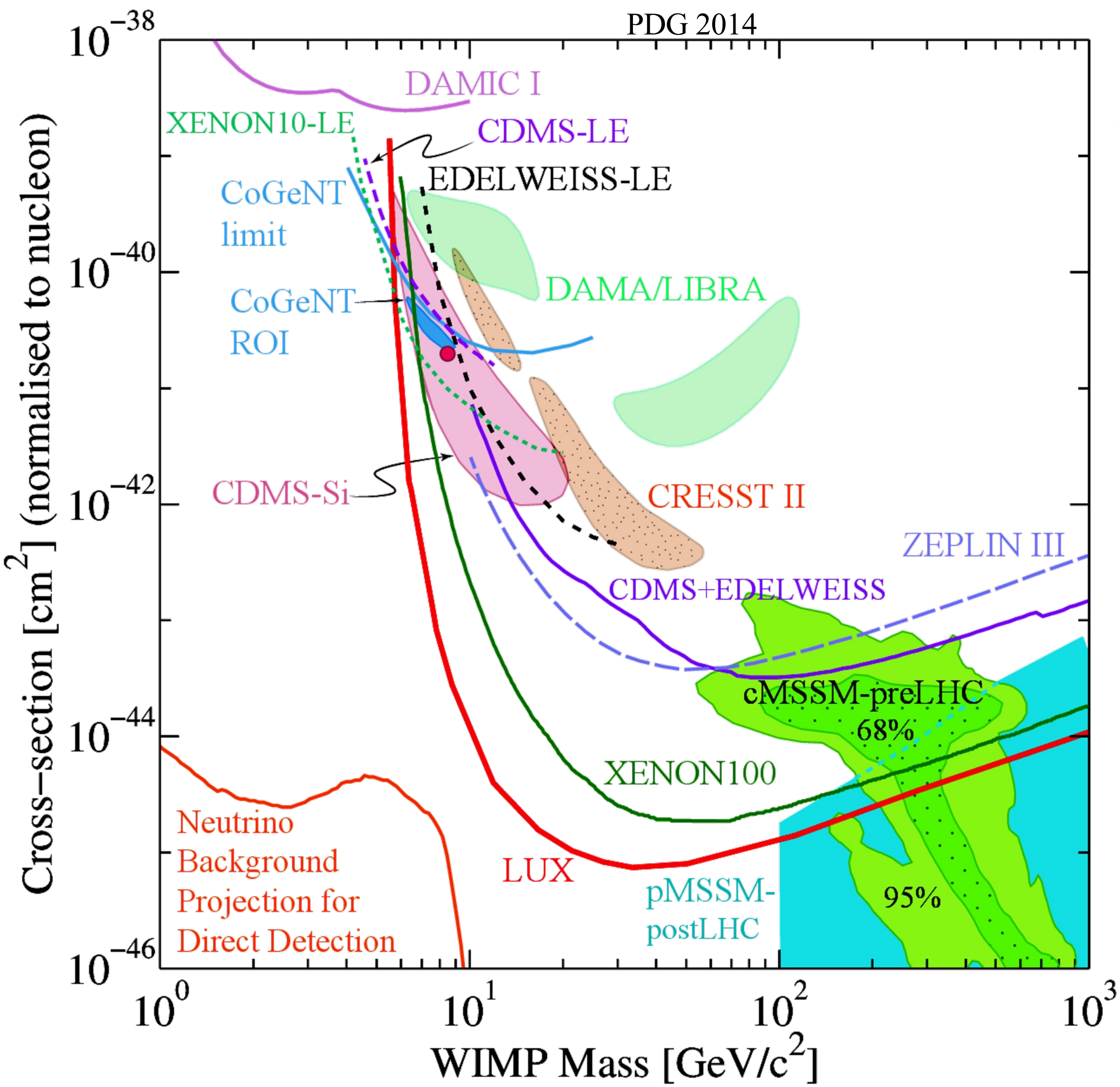
“I’ m a Spaniard caught between two Italian women”

Rita Bernabei,
DAMA

Juan Collar,
PICO

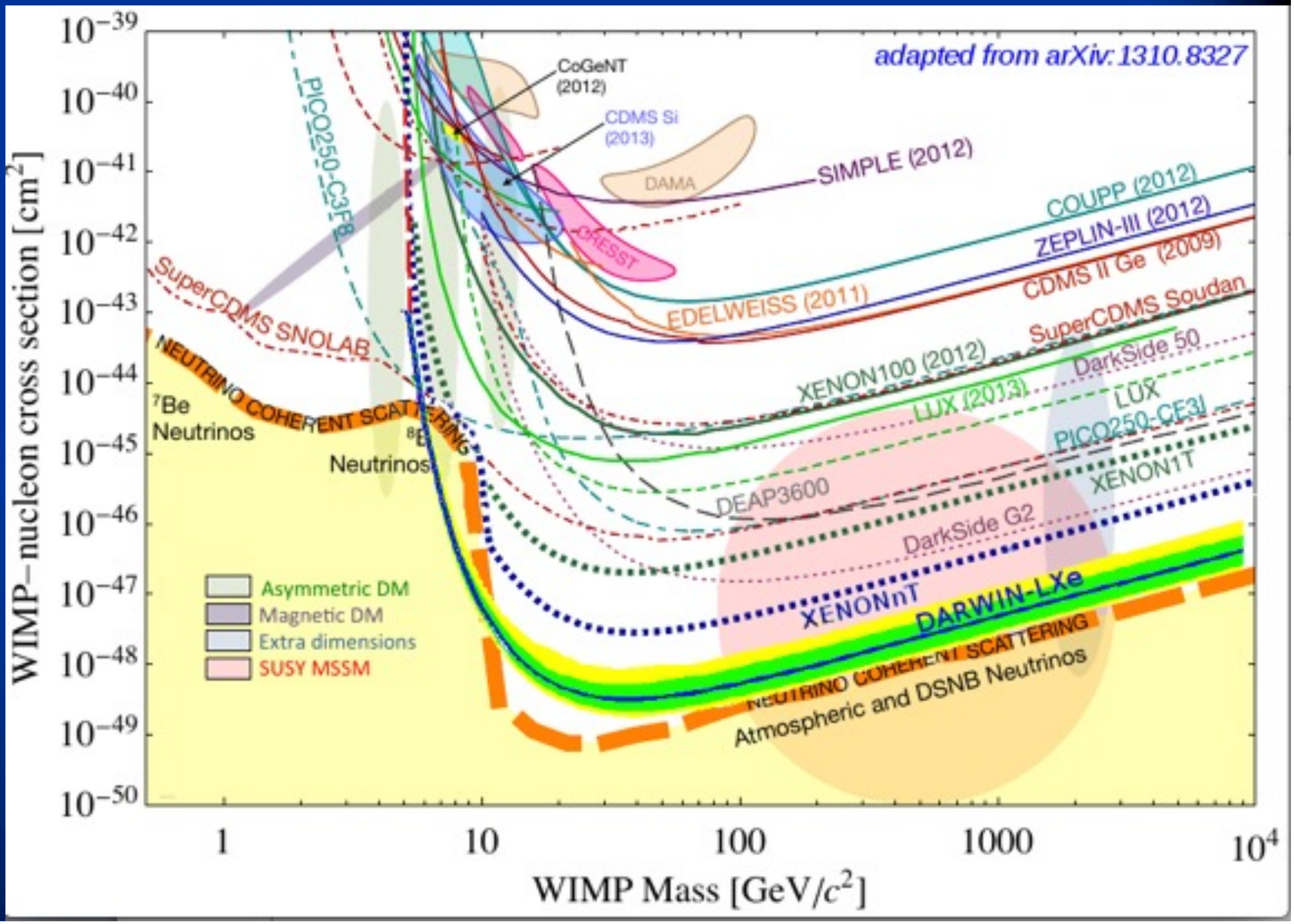
Elena Aprile, XENON

Bounds on Spin Independent WIMPs



BUT:
--- it's hard to compare results from different detector materials
--- can we trust results near threshold?

Future experiments



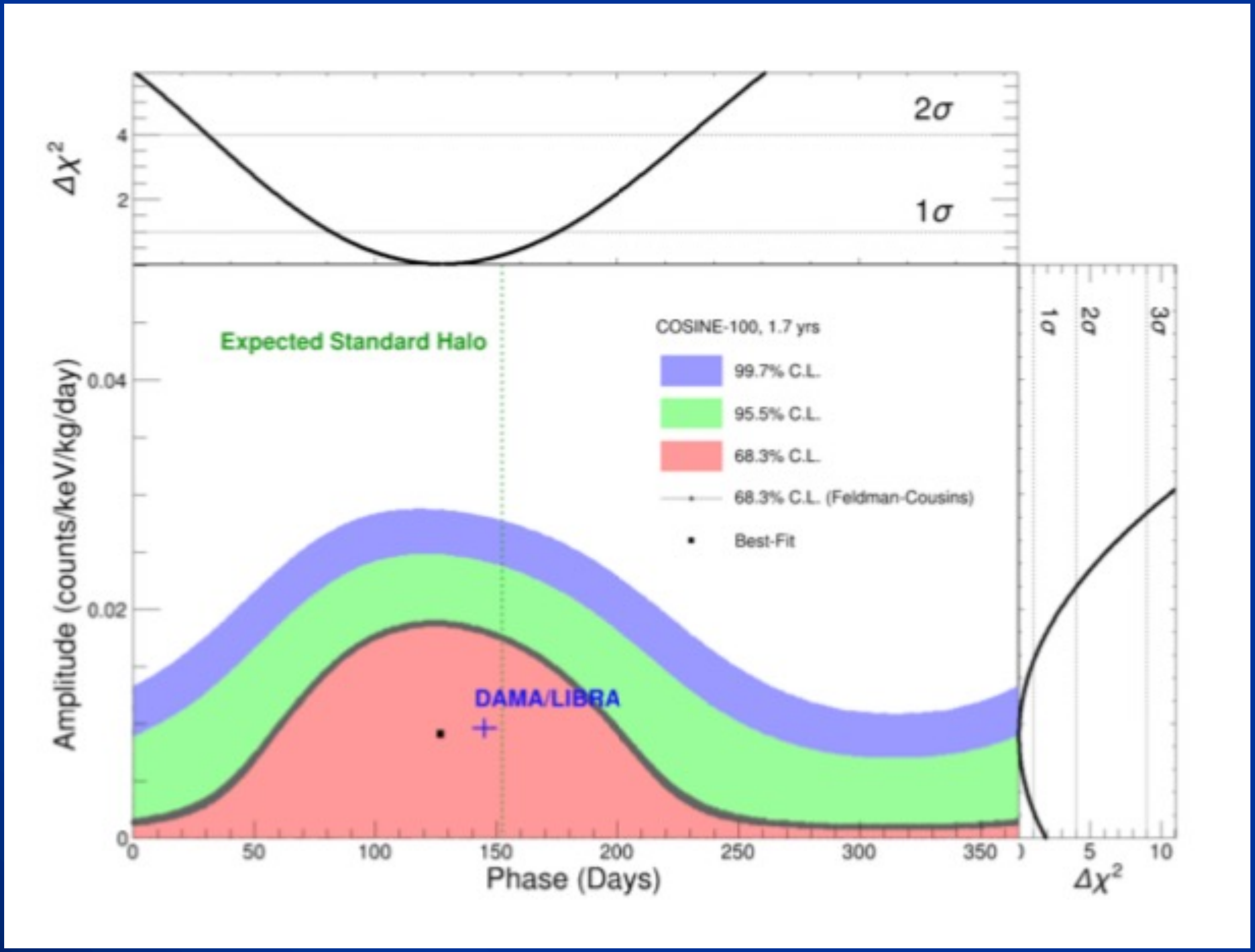
To test DAMA within next 5 years

- 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

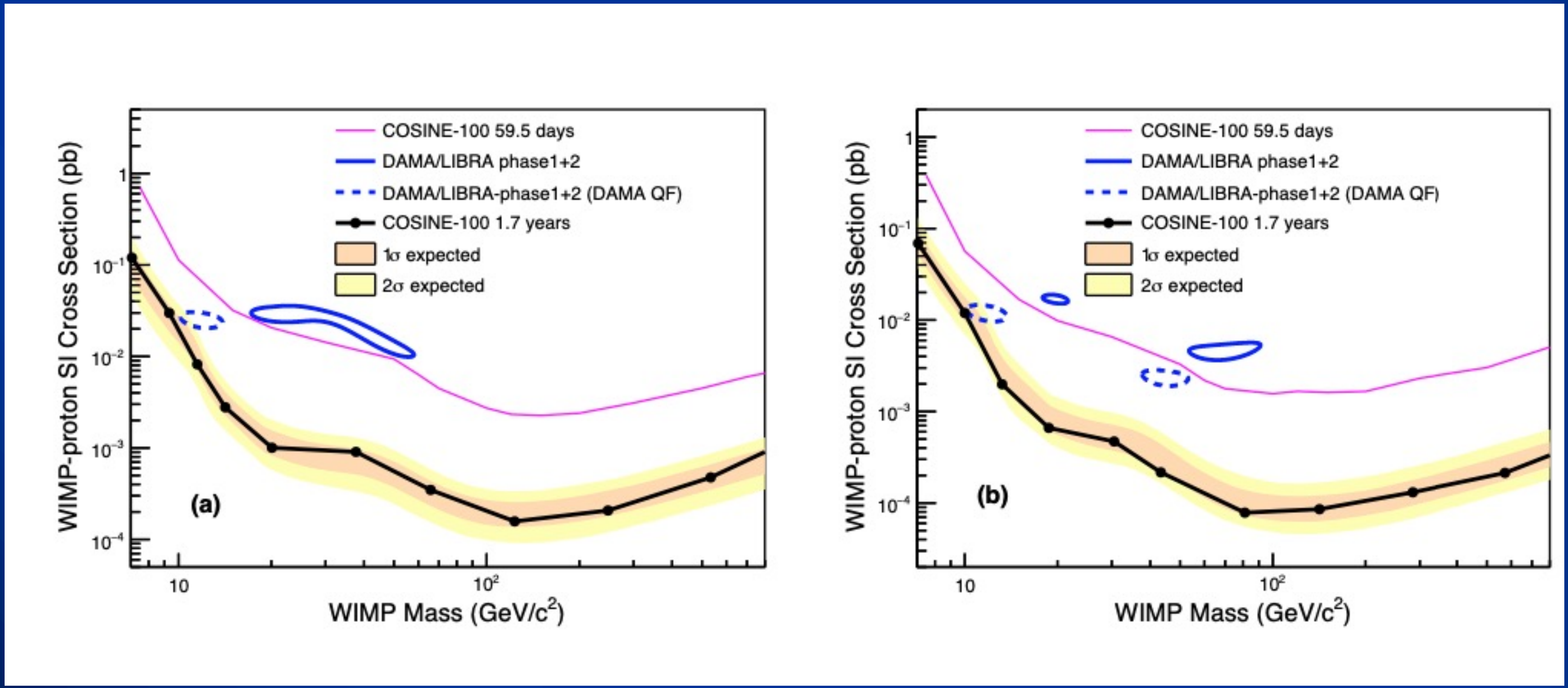
- Other groups are using NaI crystals:
- COSINE-100 has 1.7 years of data release, will have an answer within 3-5 years
- SABRE (Princeton) with Australia
- ANAIS
- COSINUS

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

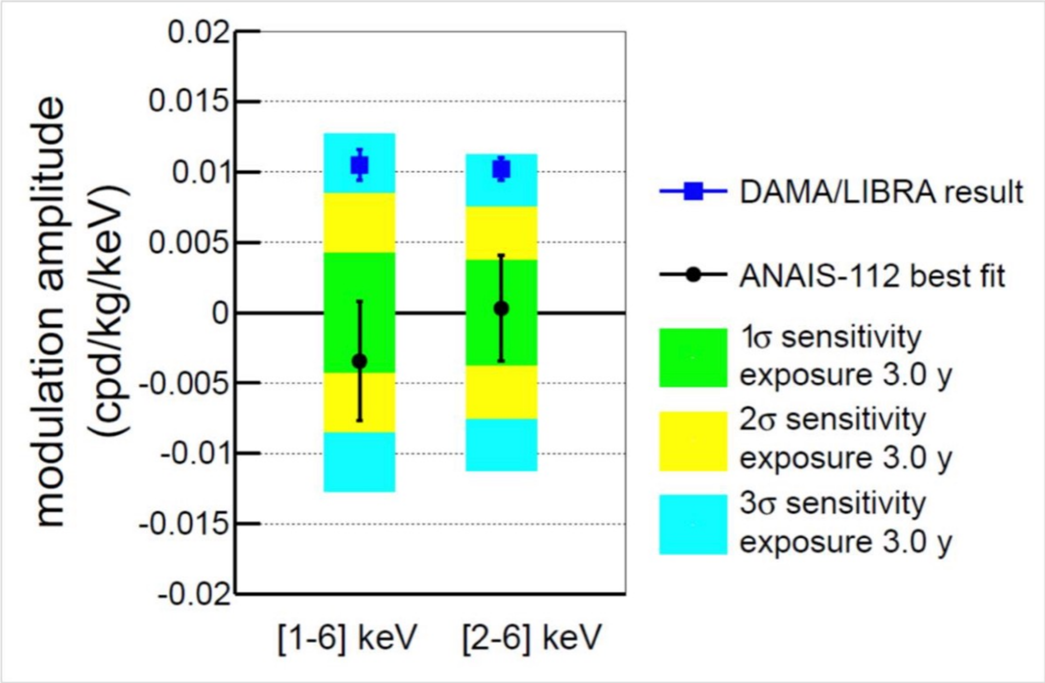
New ANAIS-112 results on annual modulation – three years exposure

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)

To go beyond the neutrino floor

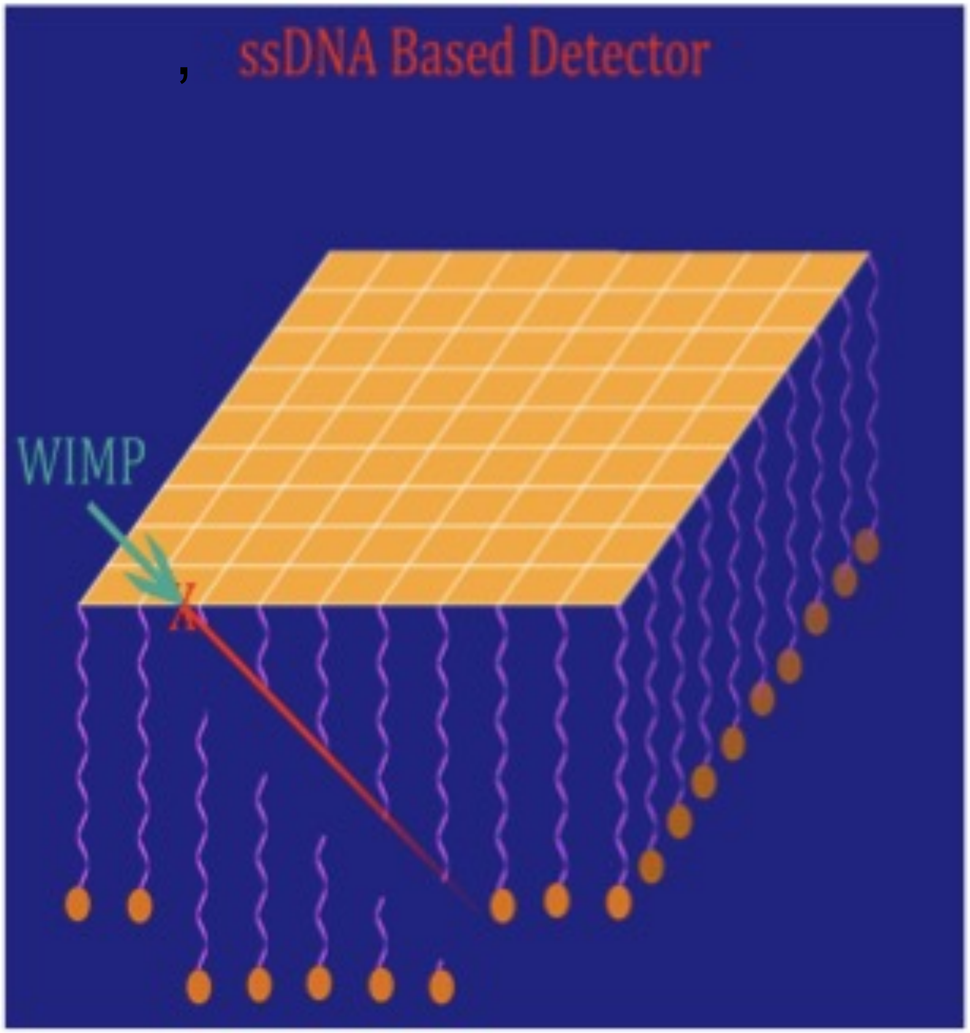
A major Step Forward: Directional Capability

to figure out what direction the WIMP came from

- Nuclei typically get kicked forward by WIMP collision
- Goal: identify the track of the recoiling nucleus i.e. the direction the WIMP came from
- Expect ten times as many into the WIMP wind vs. opposite direction.
- This allows dark matter discovery with much lower statistics (10-100 events).
- This allows for background rejection using annual and diurnal modulation.

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

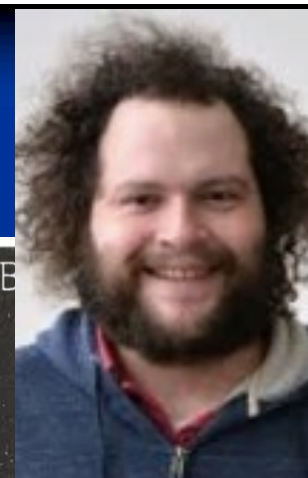
WIMPs leave tracks in ancient minerals from 10km below the surface of the Earth.

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)

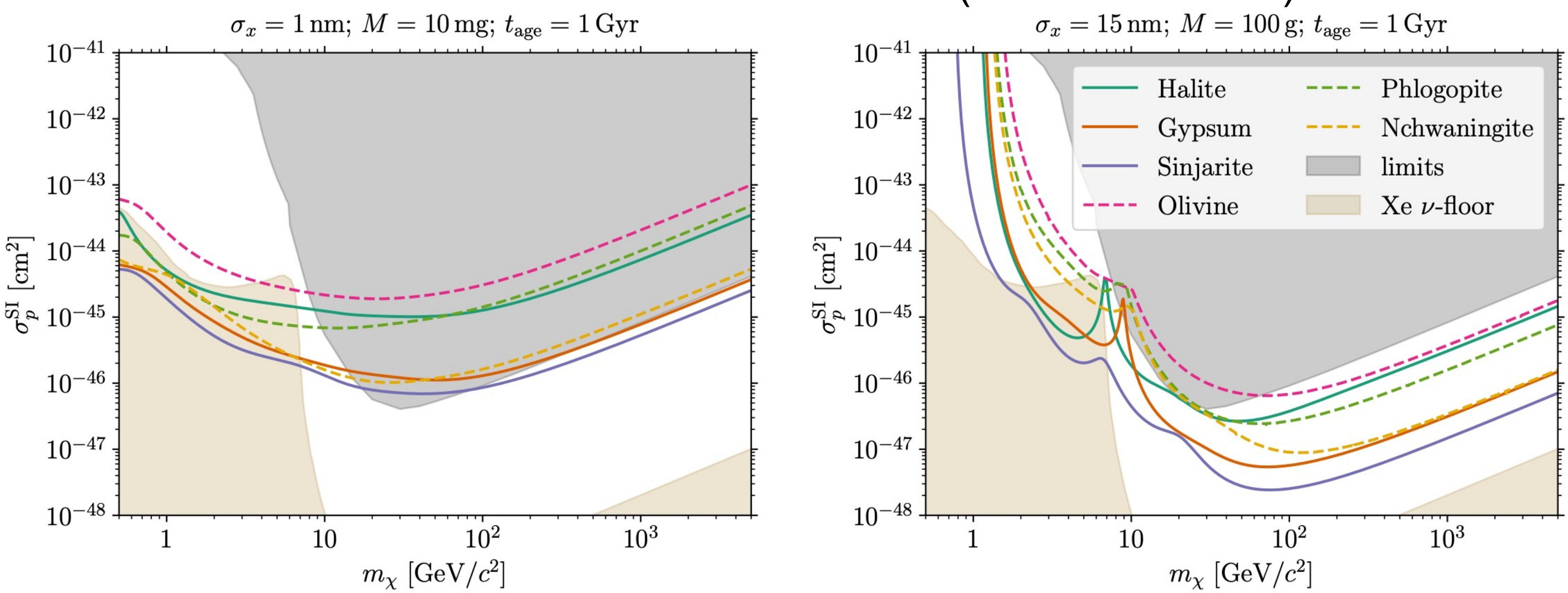
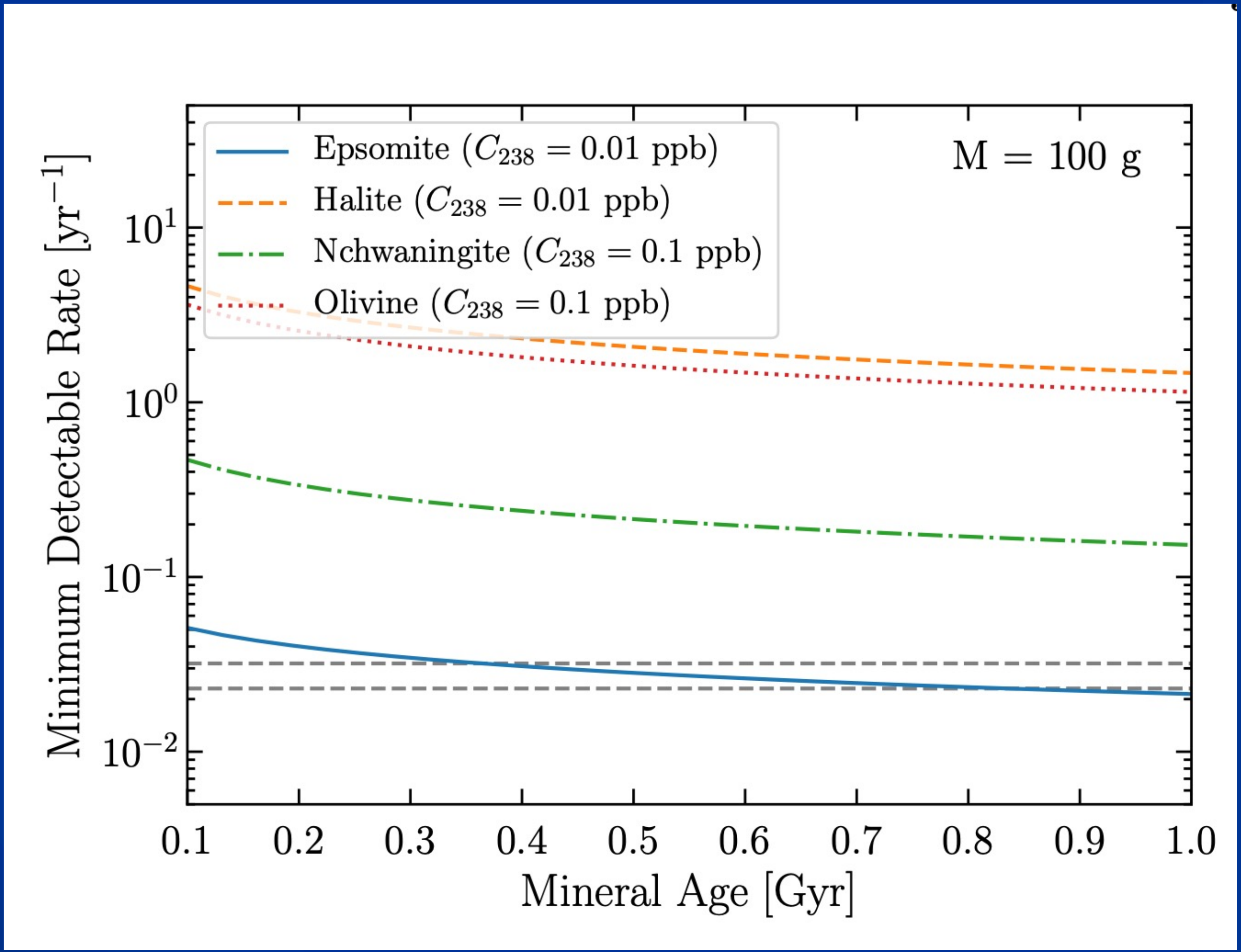


Figure 3. Projected 90 % confidence level upper limits in the WIMP mass (m_χ) – spin-independent WIMP-nucleus scattering cross section (σ_p^{SI}) plane in the high-resolution (sample mass $M = 10\,\mathrm{mg}$, track length resolution $\sigma_x = 1\,\mathrm{nm}$; left panel) and high-exposure ($M = 100\,\mathrm{g}$, $\sigma_x = 15\,\mathrm{nm}$; 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.

Paleodetectors for Galactic Supernova Neutrinos

Tom Edwards



Smallest galactic CC SN rate detectable at 3 sigma vs. mineral age

Baum, Edwards, Kavanagh, Stengel, Drukier, Freese, Ǵorski, Weniger, arxiv: 1906.05800

Time Dependence of local SN rate

- Paleodetectors would also contain information about the time-dependence of the local supernova rate over the past ~ 1 Gyr. Since the supernova rate is thought to be directly proportional to the star formation rate, such a measurement would provide a determination of the local star formation history.
- Eg we studied ten samples weighing M = 100g each, which have been recording events for different times {0.1, 0.2, 0.3, . . . , 1.0} Gyr.

Dominant Backgrounds

- The two dominant sources of (fast) radiogenic neutrons are spontaneous fission of heavy radioactive elements such as uranium-238 and neutrons produced by (α,n)-reactions of α-particles from radioactive decays with the nuclei in the target sample. Neutrons lose their energy predominantly via elastic scattering off nuclei, giving rise to nuclear recoils that are indistinguishable from those induced by neutrinos or WIMPs.
- Solution: add a little hydrogen to the detector as moderator.
- Since neutrons and hydrogen nuclei (protons) have approximately the same mass, neutrons lose a large fraction of their energy in a single collision with a hydrogen nucleus.

Conference in Trieste: Mineral Detection of Dark Matter and Neutrinos (Oct 17-21, 2022)

- The aim of MDDMv is to bring together astroparticle theorists who have been making the scientific case for mineral detection and experimentalists who have initiated preliminary studies of their feasibility. As these searches incorporate various aspects of geology, materials science and astroparticle physics, the participants in MDDMv are a diverse group with expertise encompassing these fields.

Mineral Detection of Neutrinos and Dark Matter. A Whitepaper

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

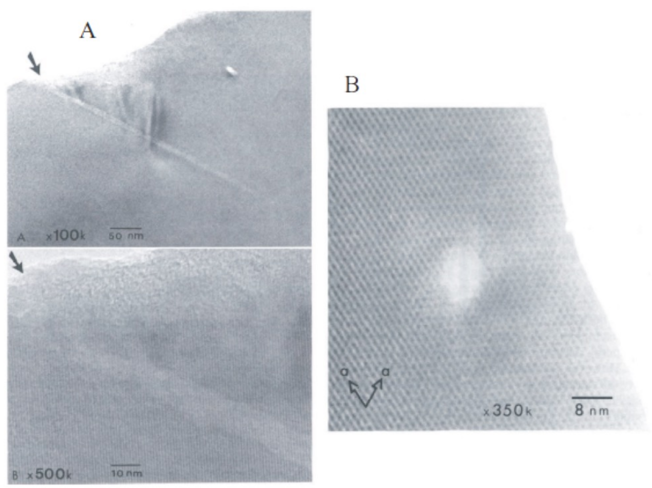


Figure 1: TEM-images of latent fission-tracks in apatite. *Left (A)*: Images taken parallel to the flight trajectory (light grey). *Right (B)*: Image taken perpendicular to the flight trajectory. Core of a fission-track is visible in the central part of the image. Figure taken from Ref. [90].

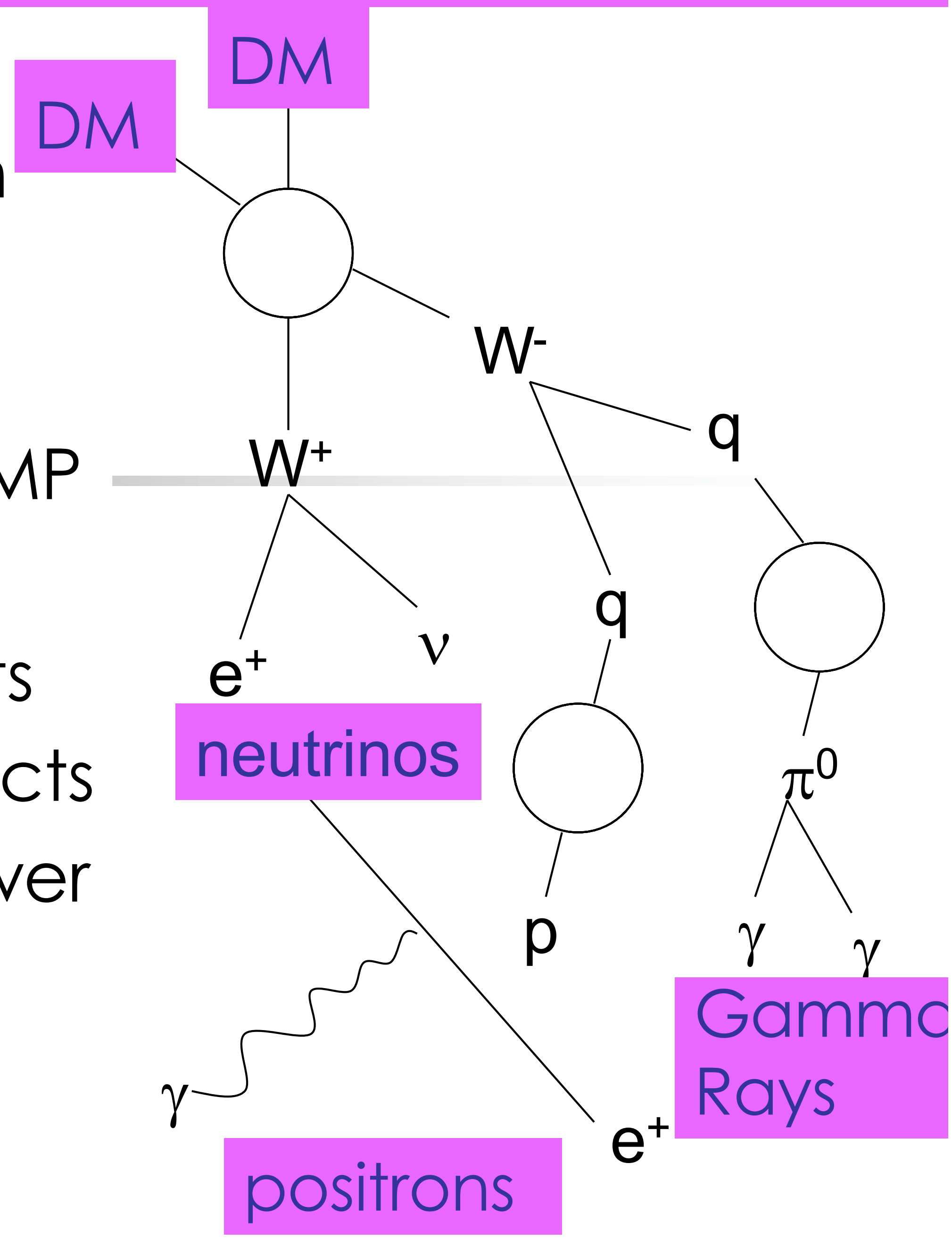
Color Centers:
Vacancies in crystal lattice,
e pairs fill in, get excited and fluoresce,
the crystal changes color

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

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

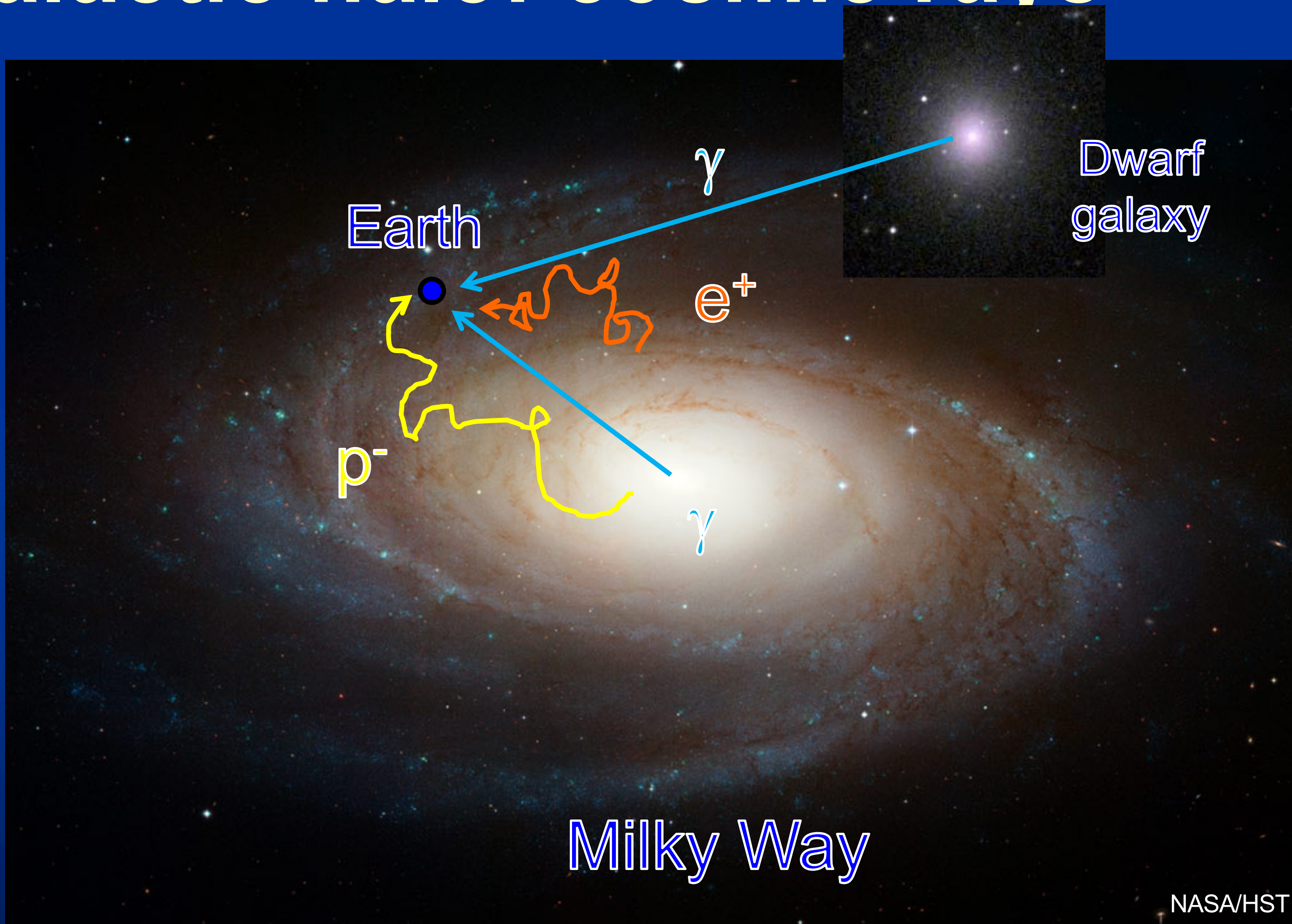
Many WIMPs are their own antiparticles, annihilate among themselves:

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



Silk & Srednicki (1984); Ellis, KF et al. (1988)
Gondolo & Silk (1999)

Galactic halo: cosmic rays



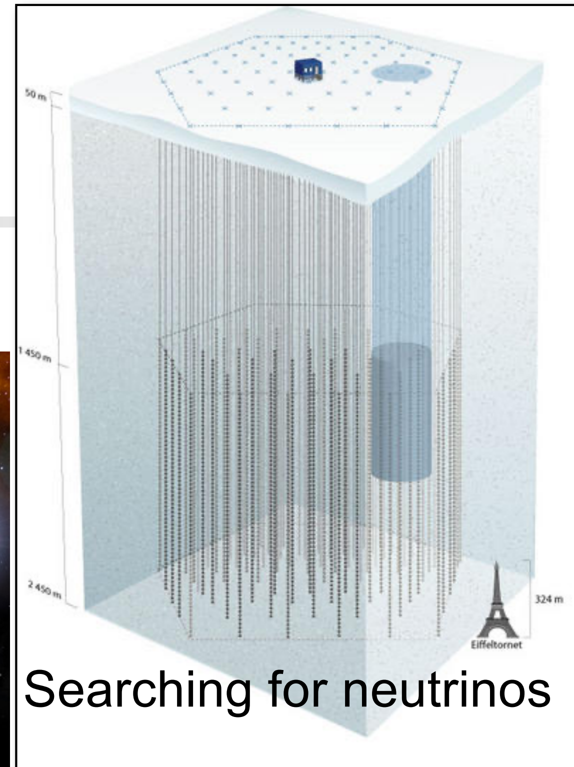
AMS, Fermi/LAT, HESS, …

Indirect Detection: looking for DM annihilation signals

AMS aboard the International Space Station

Found excess e+

IceCube
At the South Pole



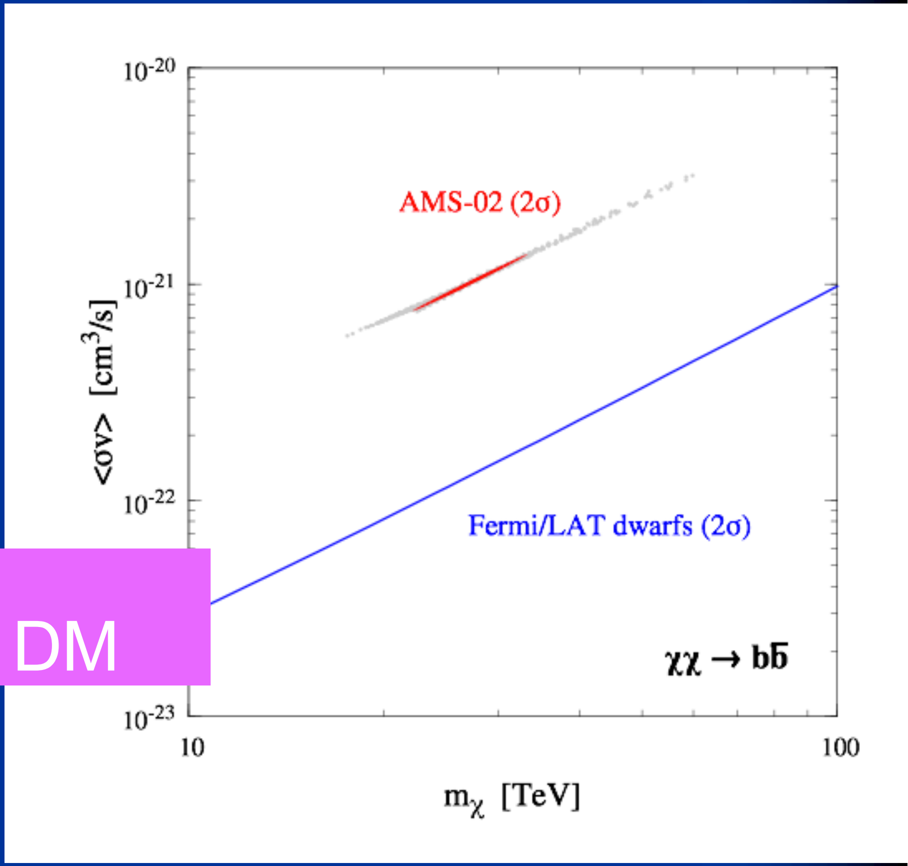
FERMI

FERMI bounds rule out most channels of dark matter interpretation of AMS positron excess

- Lopez, Savage, Spolyar, Adams (arxiv:1501.01618)
- Almost all channels ruled out,

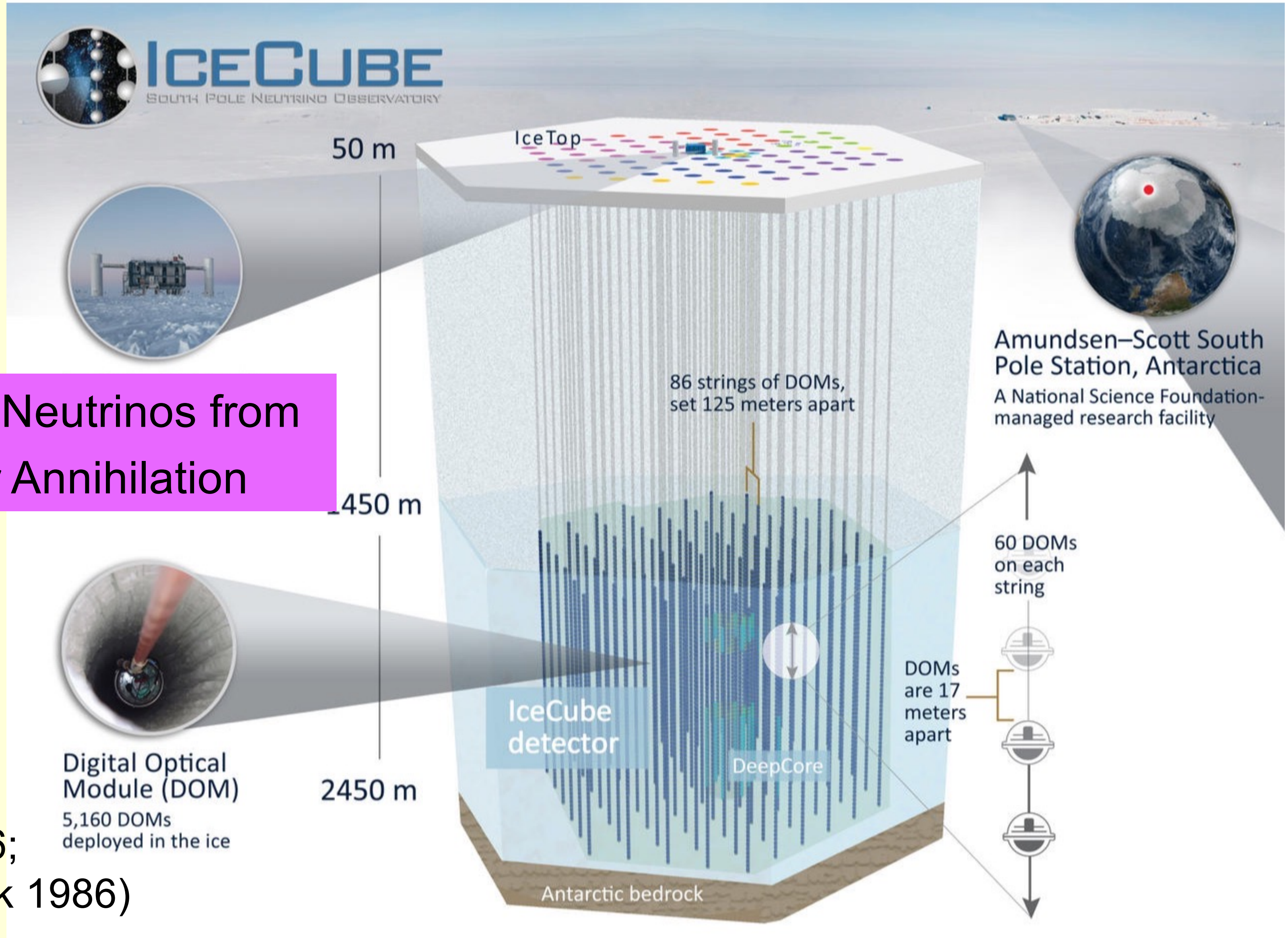
Including all leptophilic channels

(e.g. b bar channel in plot)



AMS positron excess is not from DM

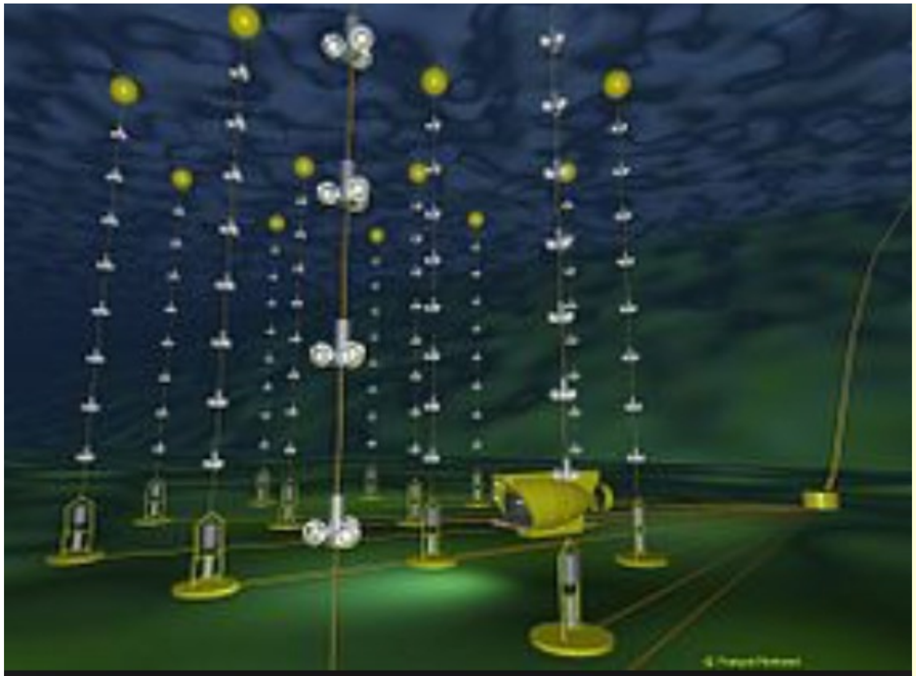
Indirect Detection of Neutrinos
IceCube at the South Pole



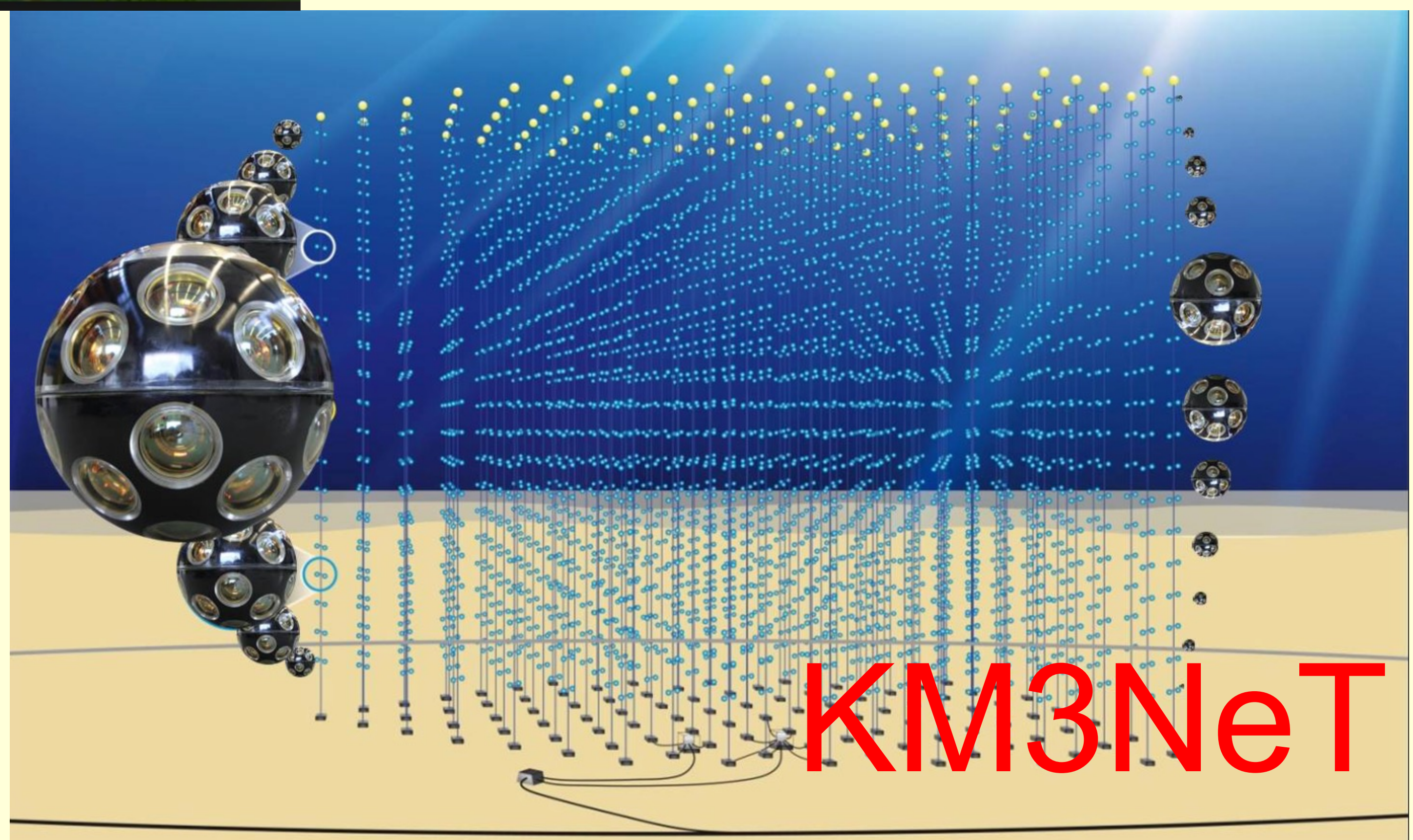
Looking for Neutrinos from Dark Matter Annihilation

Sun (Silk, Olive, Srednicki 80s)

Earth (Freese 1986; Krauss and Wilczek 1986)



ANTARES in the Mediterranean

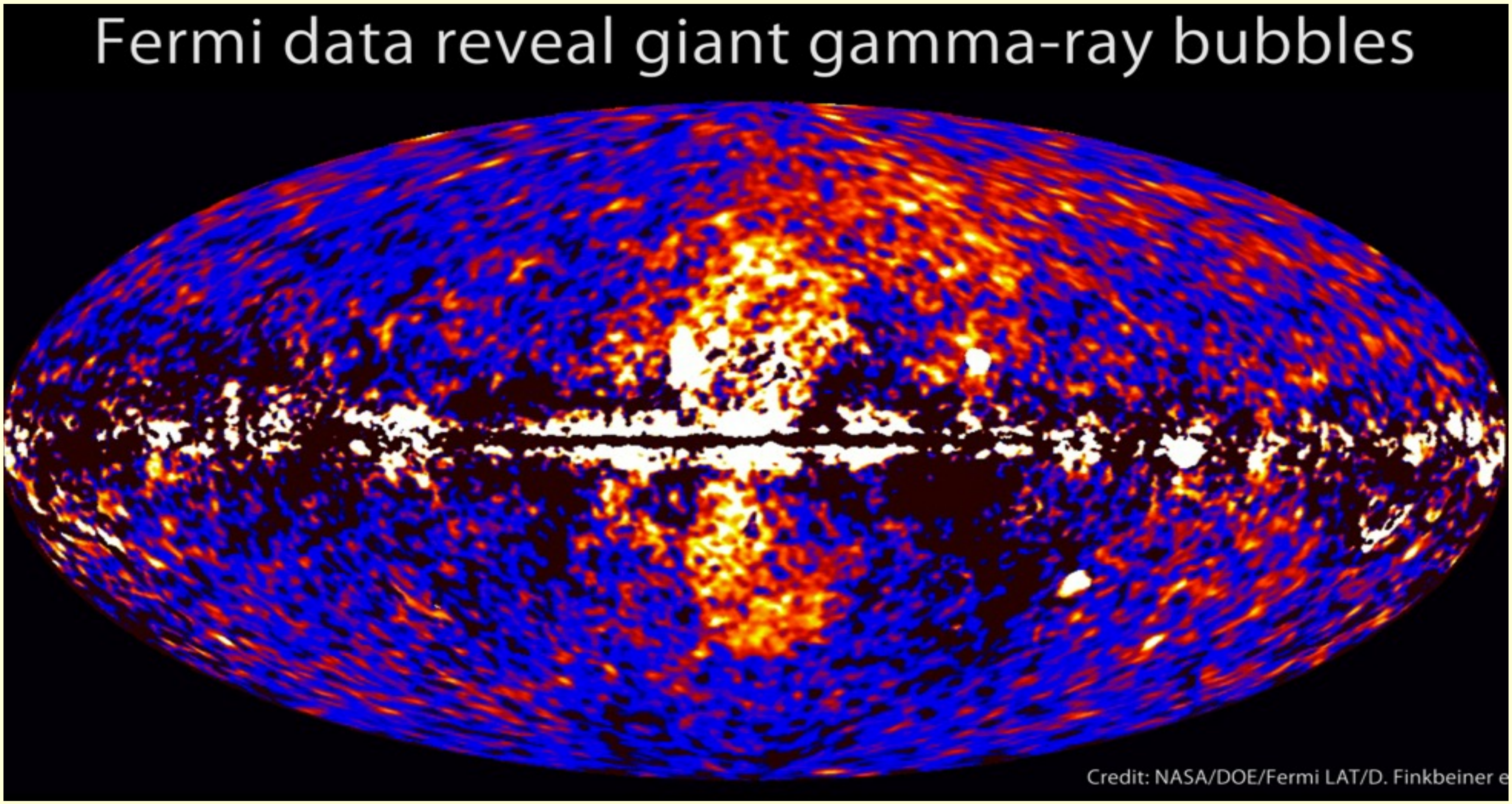


INDIRECT DETECTION of HIGH ENERGY PHOTONS (GAMMA-RAYS)

Are they from DM annihilation?

THE FERMI SATELLITE

The gamma ray sky



Doug Finkbeiner (Fermi Bubbles)

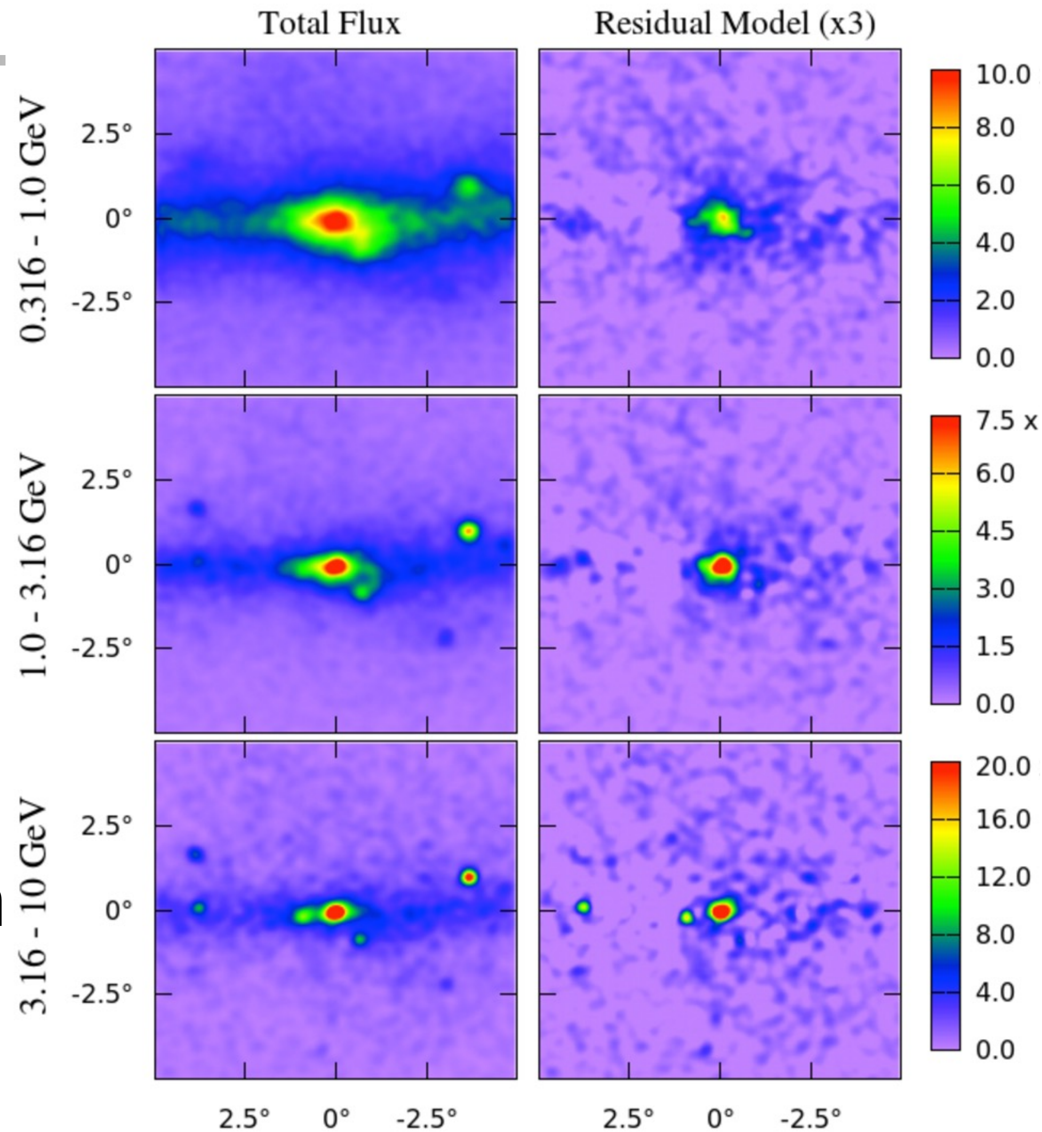
Fermi/LAT gamma-ray excess

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, χχ → b-bbar)



BUT also consistent with astrophysical point sources. Status unclear.

Possible evidence for Dark Matter detection already now:

- Direct Detection:
  - DAMA annual modulation
  - (but no signal in other experiments)
  - Other NaI detectors are now testing it
- Indirect Detection:
  - FERMI gamma ray excess near galactic center
- Theorists are looking for models in which some of these results are consistent with one another (given an interpretation in terms of WIMPs)

FOURTH WAY TO SEARCH FOR WIMPS

Dark Stars:
Dark Matter annihilation can power the first stars

Has JWST discovered Dark 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

This work

Cosmin Ilie

Colgate University

Jillian Paulin

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 has found ~ 700 high redshift objects with z > 10. They assume these are "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.

The role of WIMPs

Mass 1Gev-10TeV (canonical 100GeV)

Annihilation cross section (WIMPS):

$$<\sigma v>_{ann} = 3\times 10^{-26} cm^3/\sec$$

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 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.

Dark Matter Heating

Heating rate:

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

$$= \frac{\rho_\chi^2 < \sigma v >}{m_\chi}$$

Fraction of annihilation energy deposited in the gas:

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

f_Q:

1/3 electrons

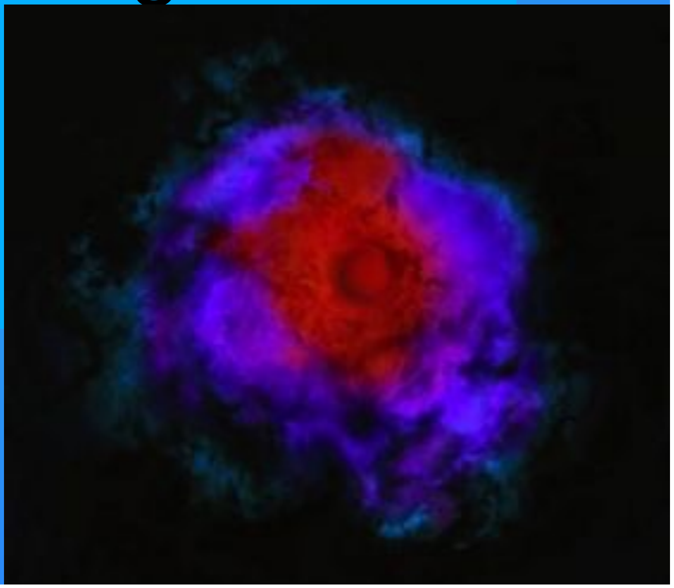
1/3 photons

1/3 neutrinos

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



First Condition: Large DM density

- DM annihilation rate scales as DM density squared, and happens wherever DM density is high. The first stars are good candidates: good timing since density scales as $(1+z)^3$ and good location at the center of DM halo
- Start from standard NFW profile in million solar mass DM halo.
- As star forms in the center of the halo, it gravitationally pulls in more DM. Treat via **adiabatic contraction**.
- If the scattering cross section is large, even more gets **captured** (treat this possibility later).

DS Basic Properties

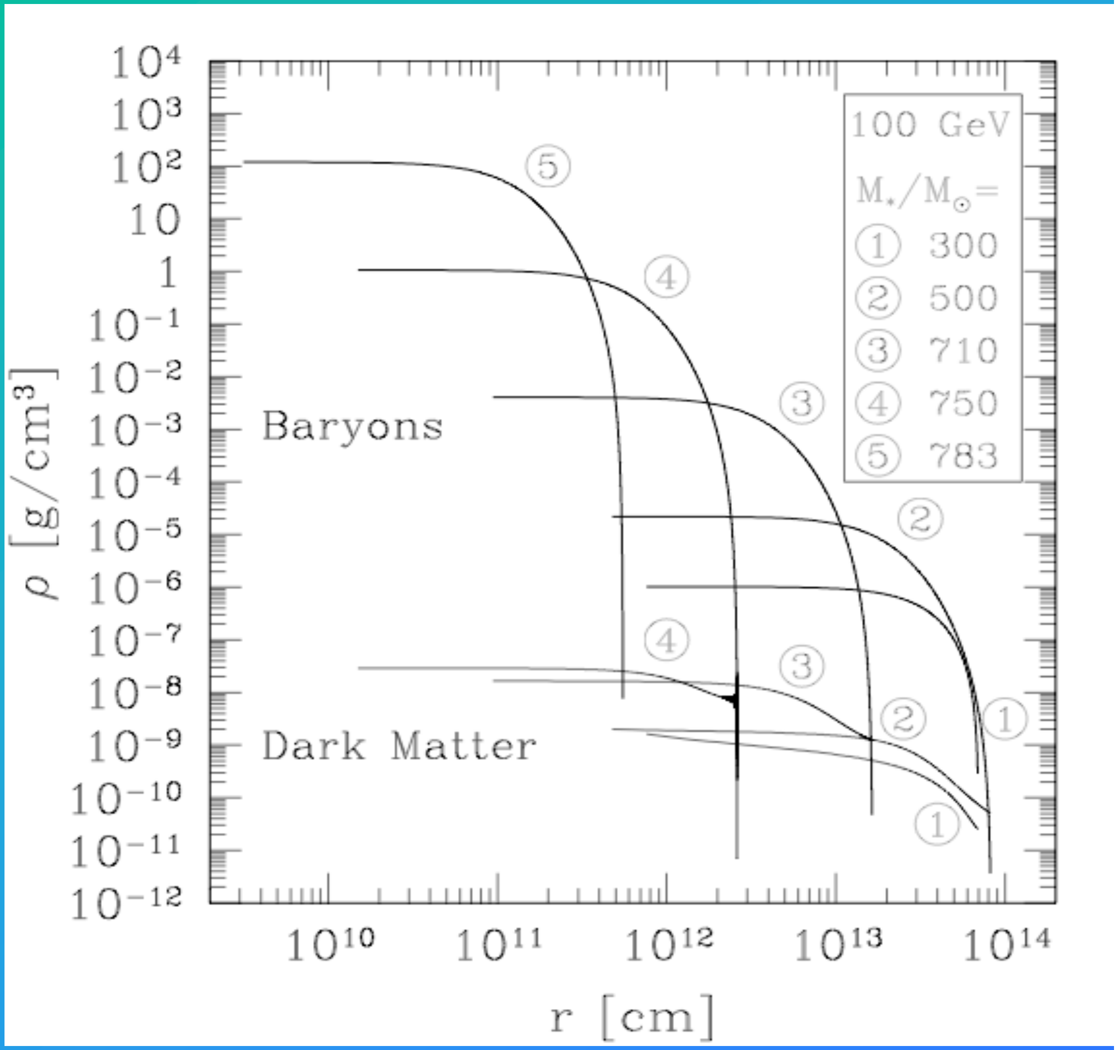
- We find that DS are big puffy objects:
  - Massive: can grow to 10^7 $M_\odot$
  - Large- 10 a.u. (radius of Earth's orbit around Sun)
  - Luminous: up to 10^{10} $L_\odot$
  - Cool: 10,000 K vs. 100,000 K plus
    - Will not reionize the universe.
  - Long lived: more than 10^6 years, even till today?.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

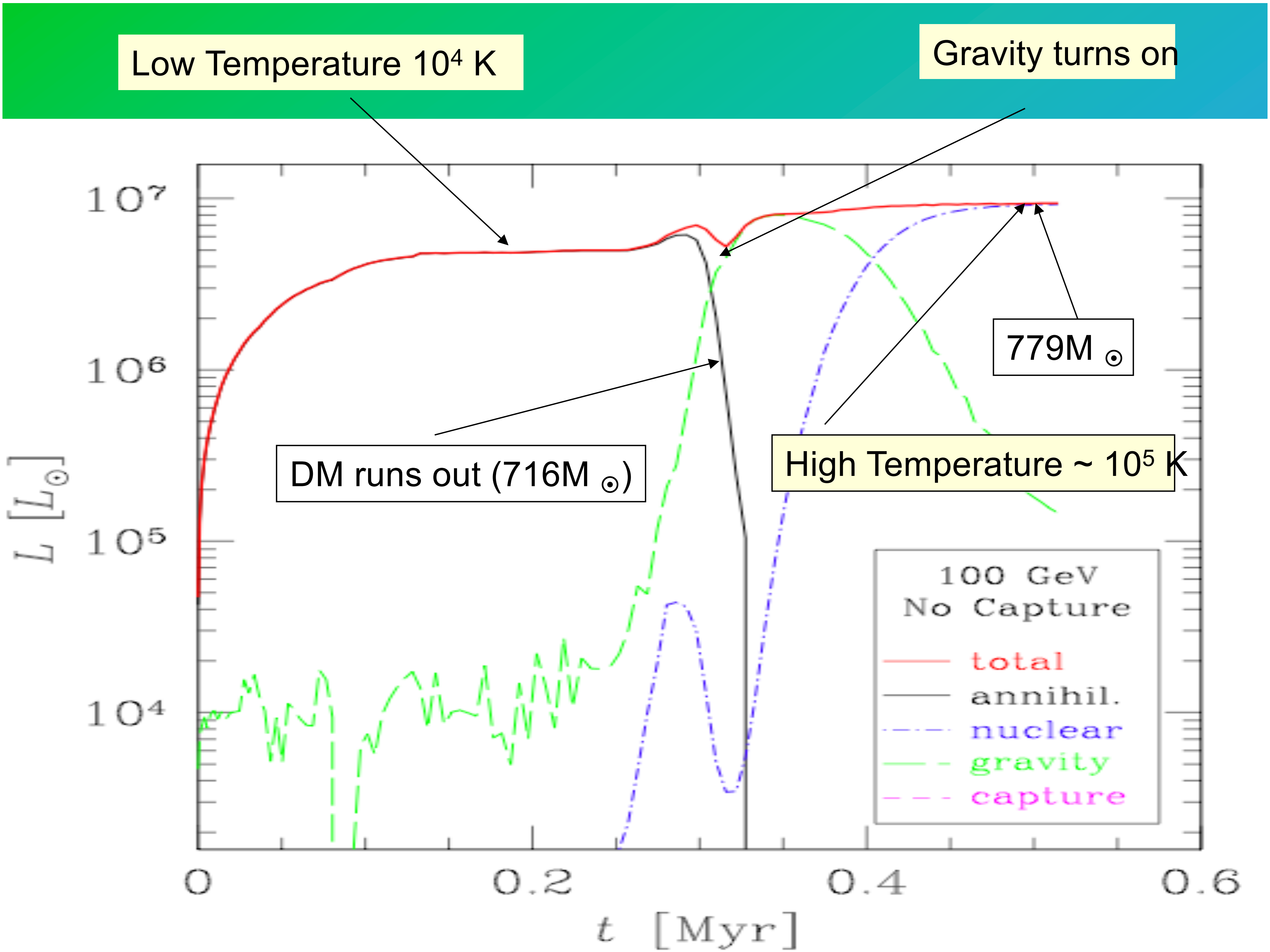
Building up the mass

- 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 giant black hole

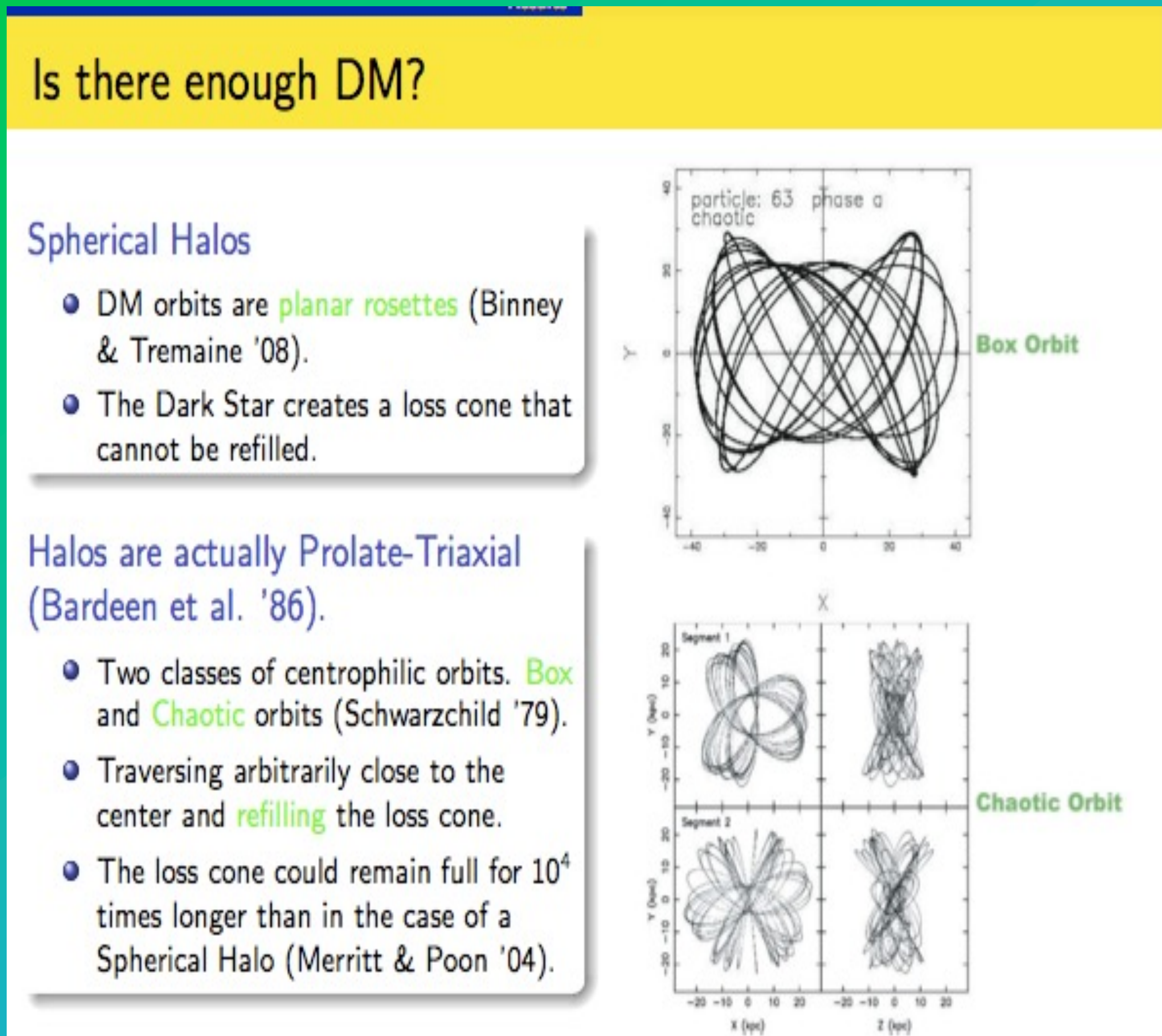
Following DS Evolution

- Gas Accretes onto molecular hydrogen Core, the system eventually forms a star.
- We then solve for stellar Structure by:
  - Self consistently solve for the DM density and Stellar structure
  - (Overly Conservative) DM in spherical halo. We later relax this condition





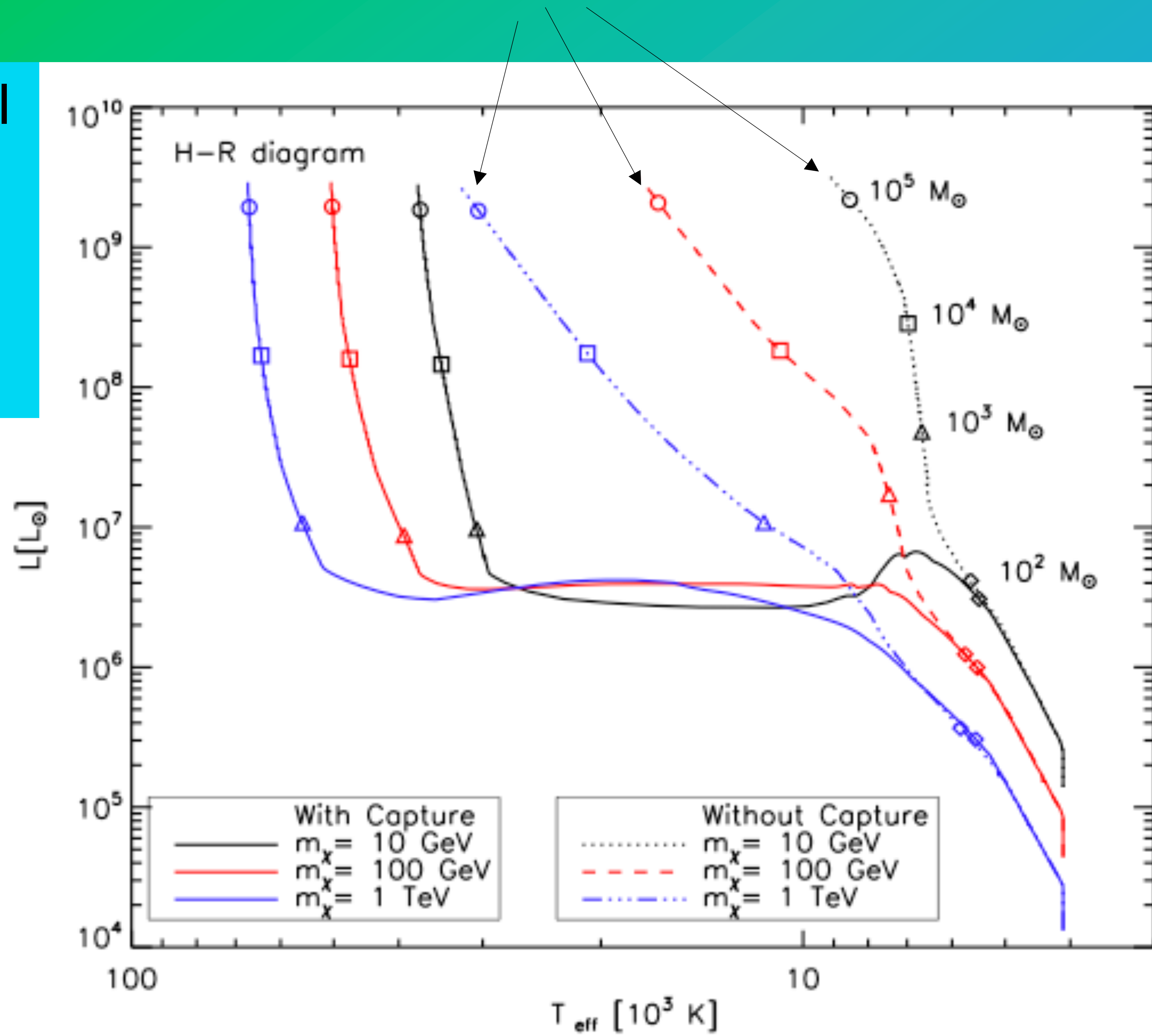
Low Temperature 10^4 K
Gravity turns on
10^7
10^6
10^5
10^4
$L\ [L_\odot]$
DM runs out (716M ⊙)
779M ⊙
High Temperature ~ 10^5 K
100 GeV
No Capture
total
annihil.
nuclear
gravity
capture
0
0.2
0.4
0.6
t [Myr]



A particle that comes through the center of the DS can be annihilated. However, that particle was not on an orbit that would pass through the center again anyway. The next particle will come in from a different orbit.

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



Additional possible source of DM fuel: capture

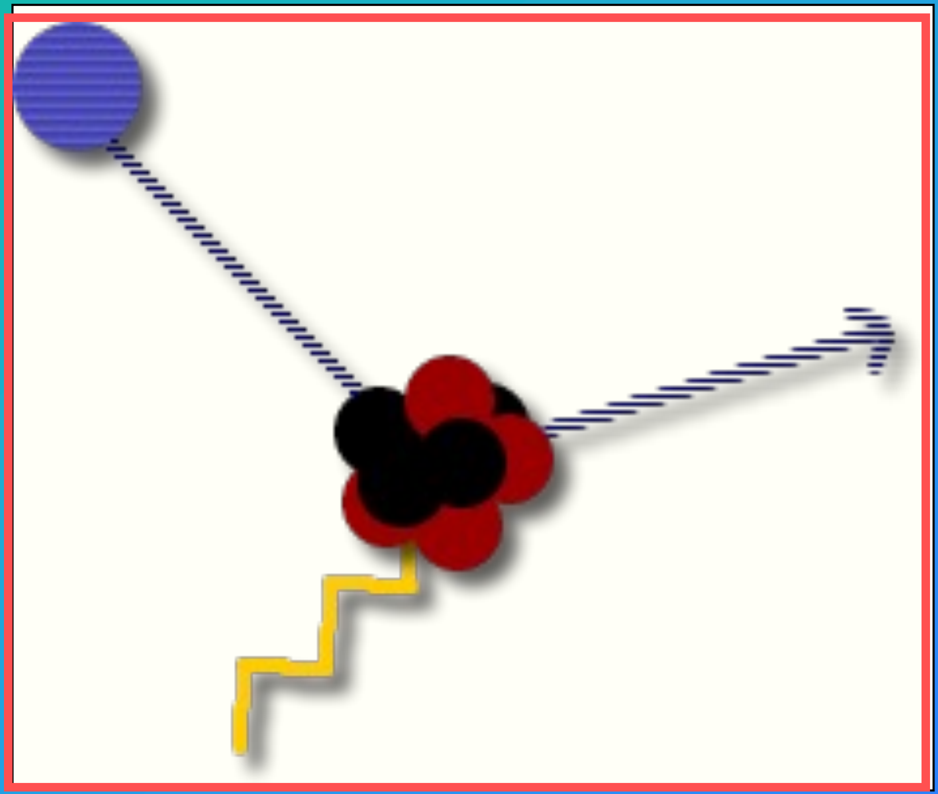
- Some DM particles bound to the halo pass through the star, scatter off of nuclei in the star, and are captured. (This it the origin of the indirect detection effect in the Earth and Sun).
- Two uncertainties:

  (I) ambient DM density (ii) scattering cross section must be high enough.
- Whereas the annihilation cross section is fixed by the relic density, the scattering cross section is a free parameter, set only by bounds from direct detection experiments.

Freese, Aguirre, Spolyar 08; Iocco 08

WIMP scattering off nuclei leads to capture of more DM fuel

Some DM particles bound to the halo pass through the star, scatter off of nuclei in the star, and are captured.

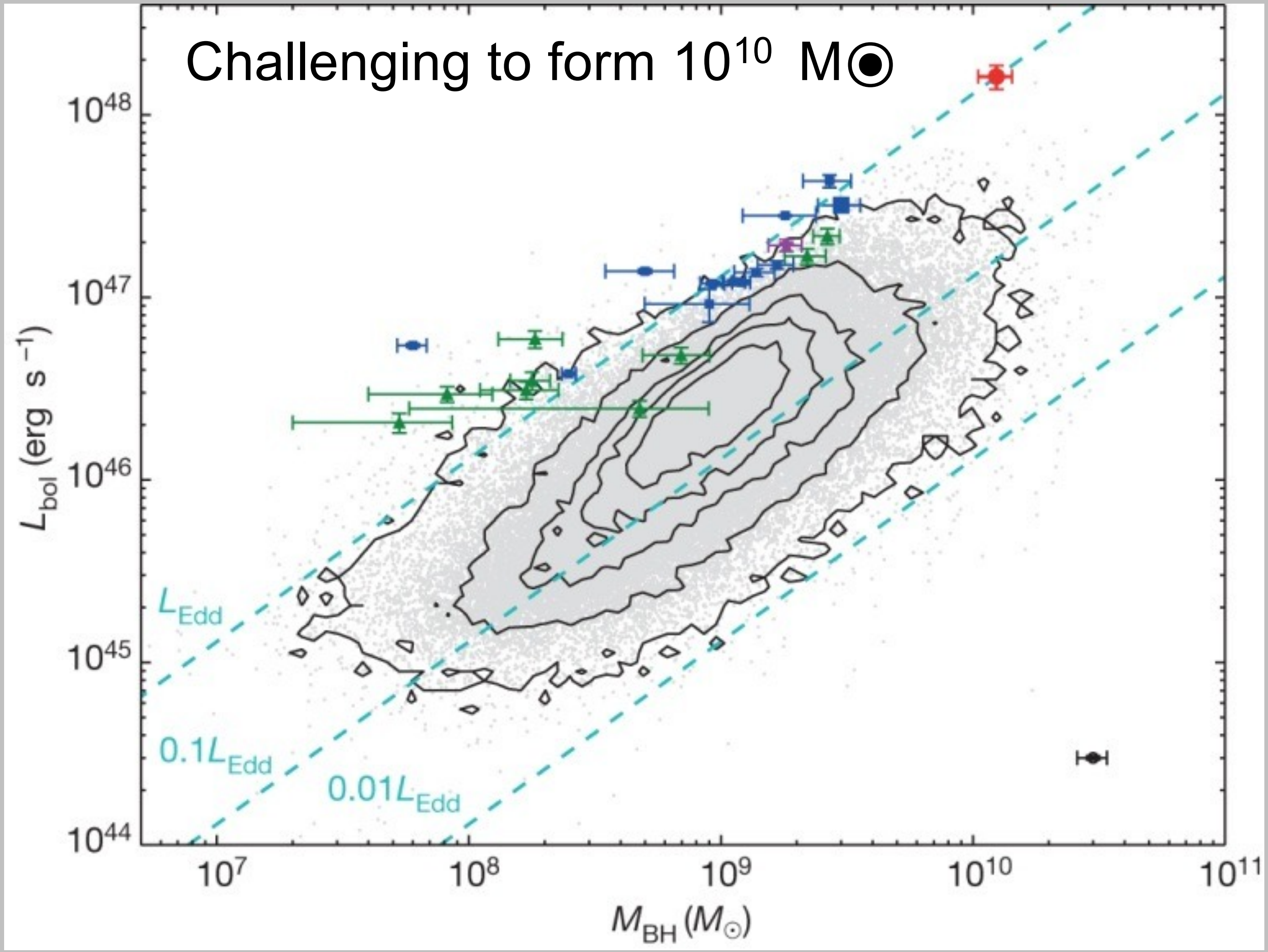


This is the same scattering that direct detection experiments are looking for

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
No other way to form supermassive BH this early z=6



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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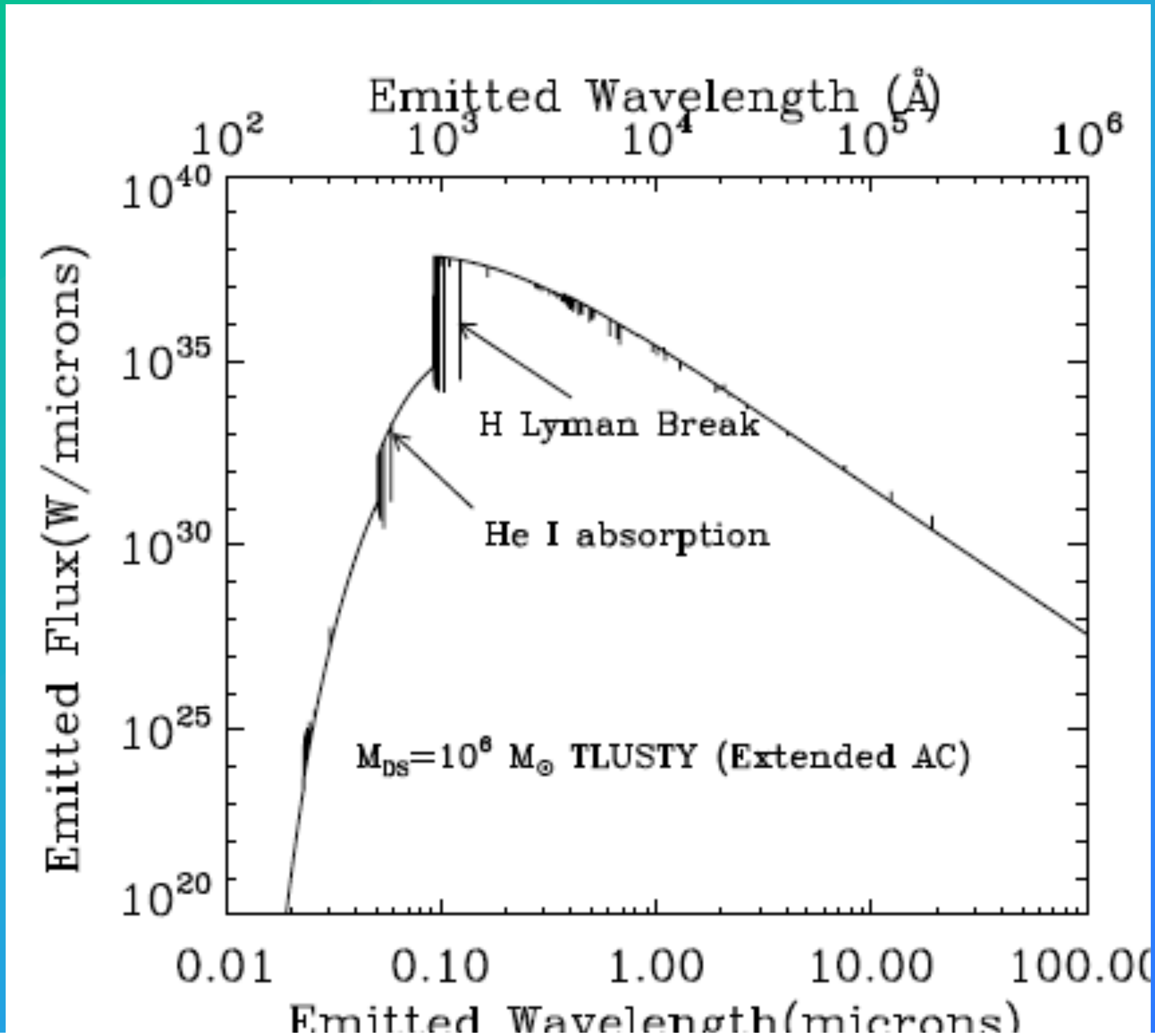
ABSTRACT

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.

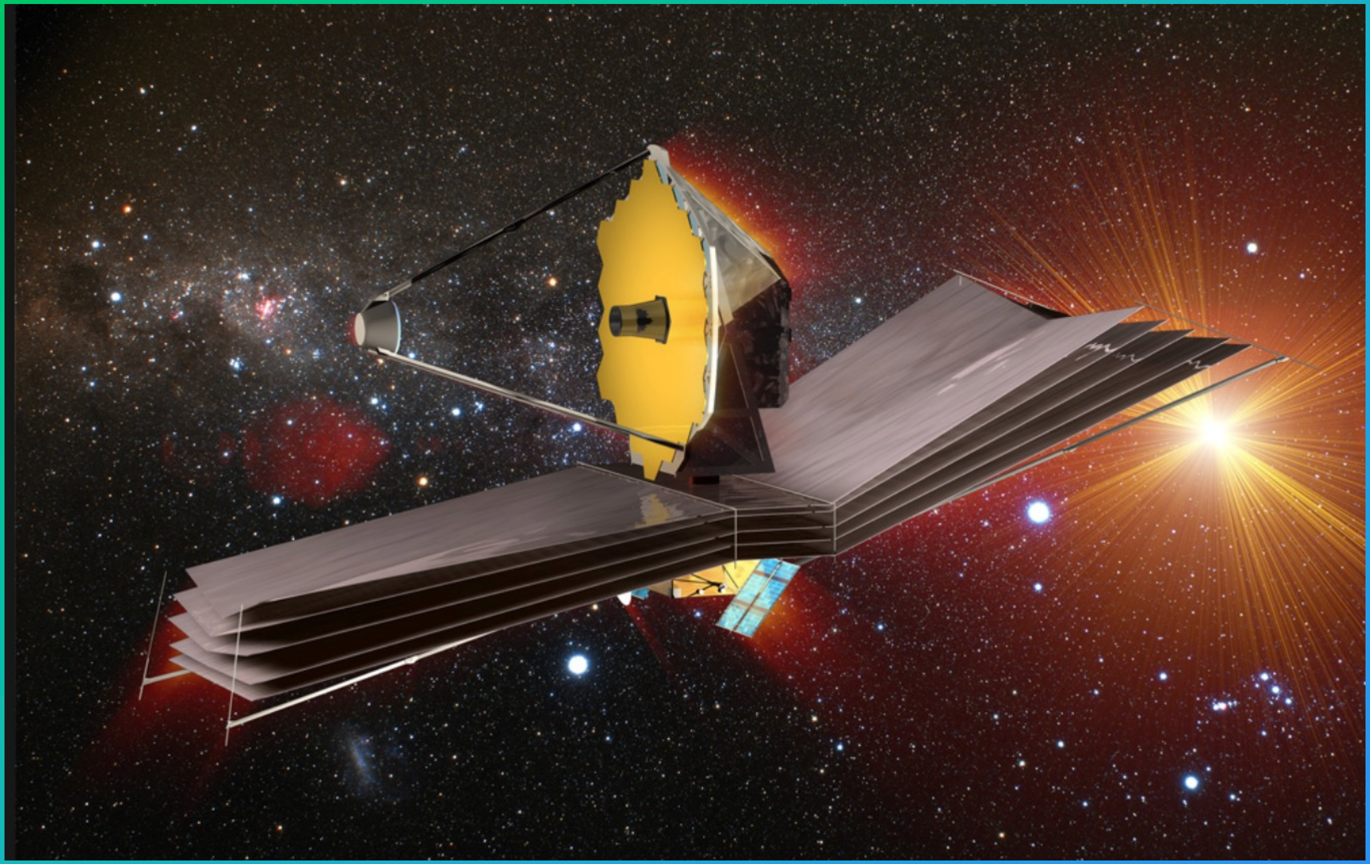
OBSERVING DARK STARS

DS Spectrum from TLUSTY (stellar atmospheres code)



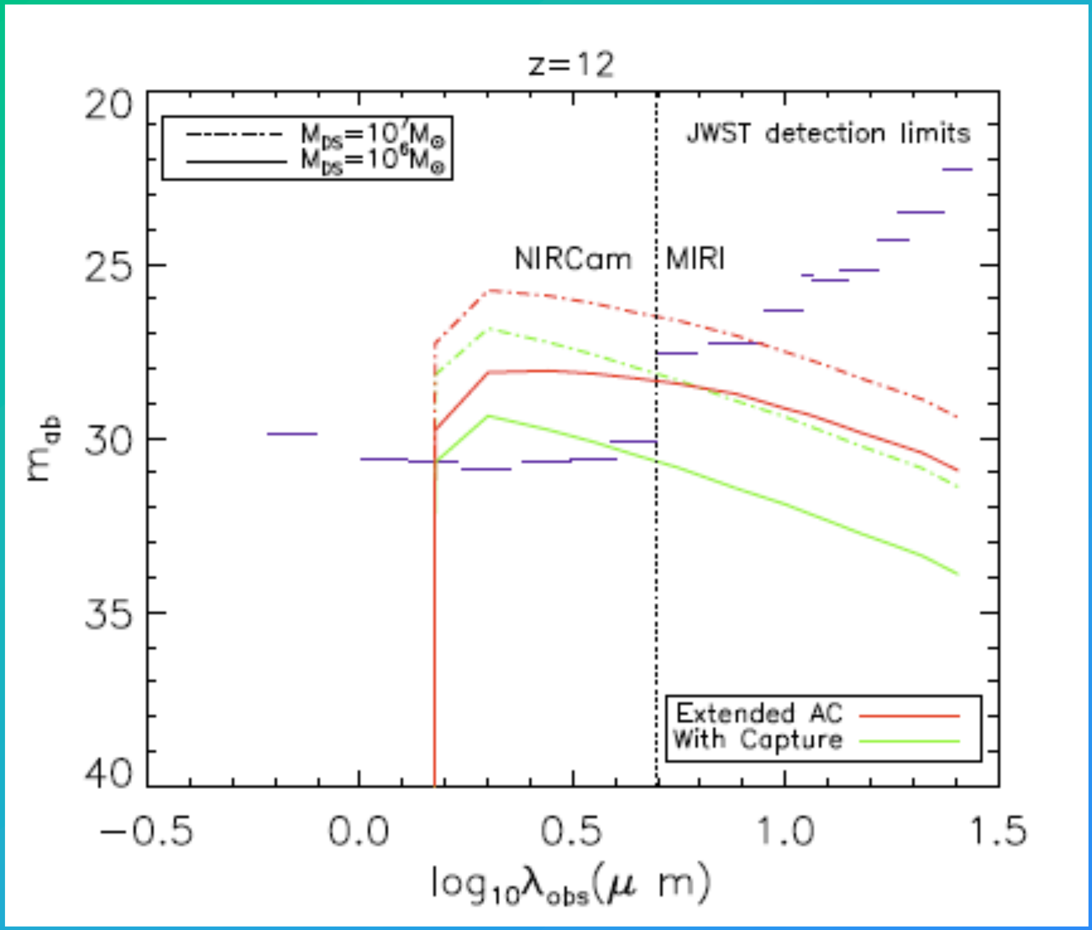
n.b. DS are made of hydrogen and helium only

James Webb Space Telescope

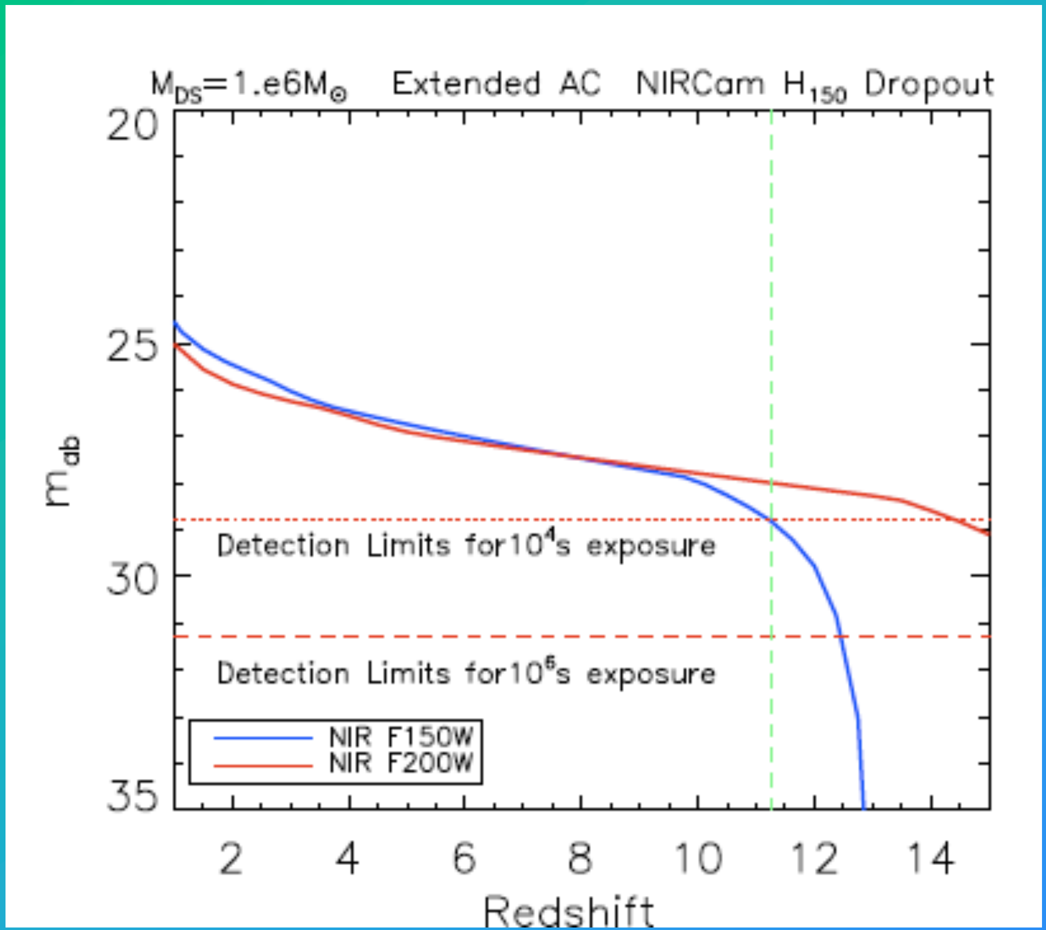


Supermassive Dark Stars:
They would be a billion times brighter than the Sun
But the same temperature as the Sun.

Dark Stars in JWST

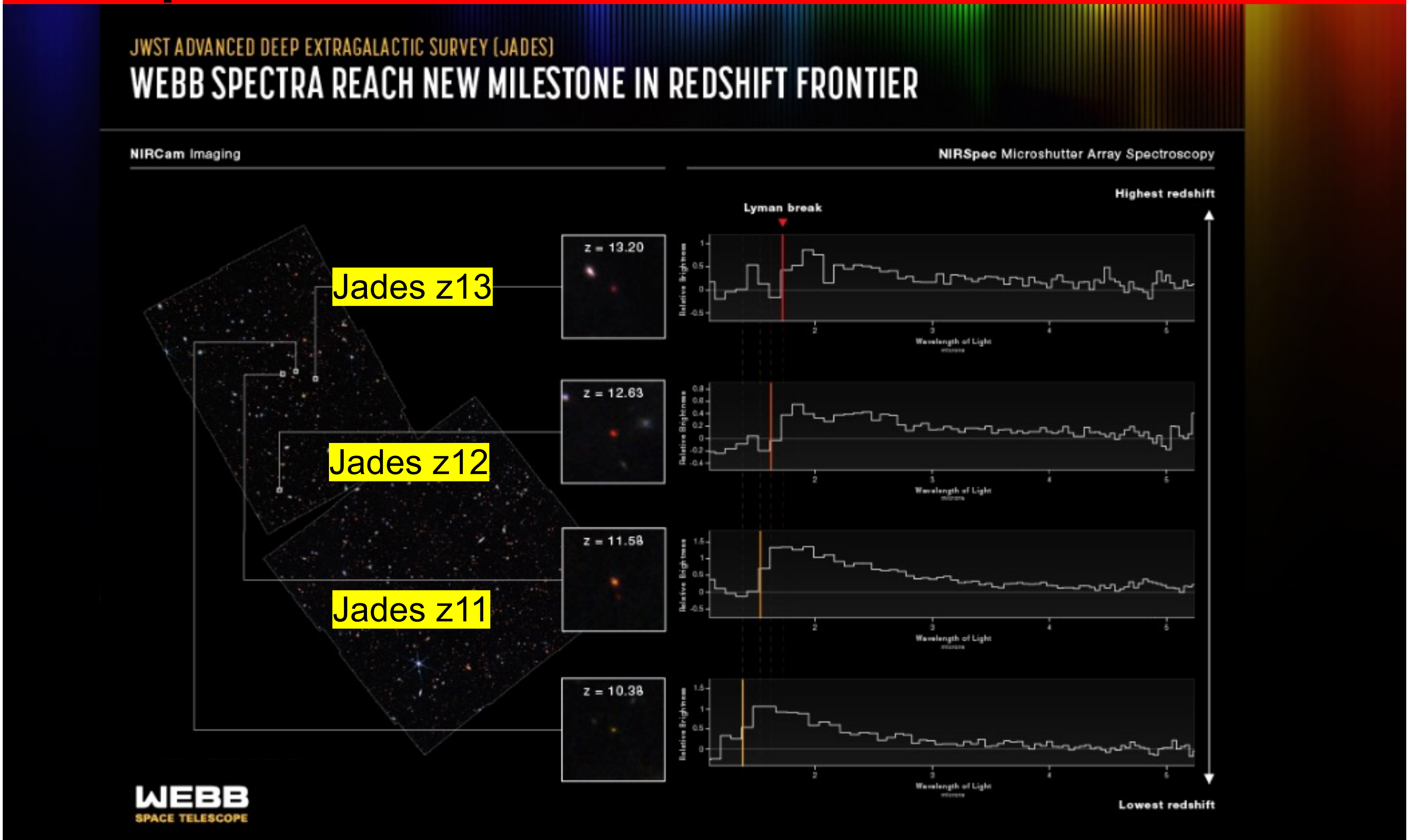


Million solar mass SMDS as H-band dropout



(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!



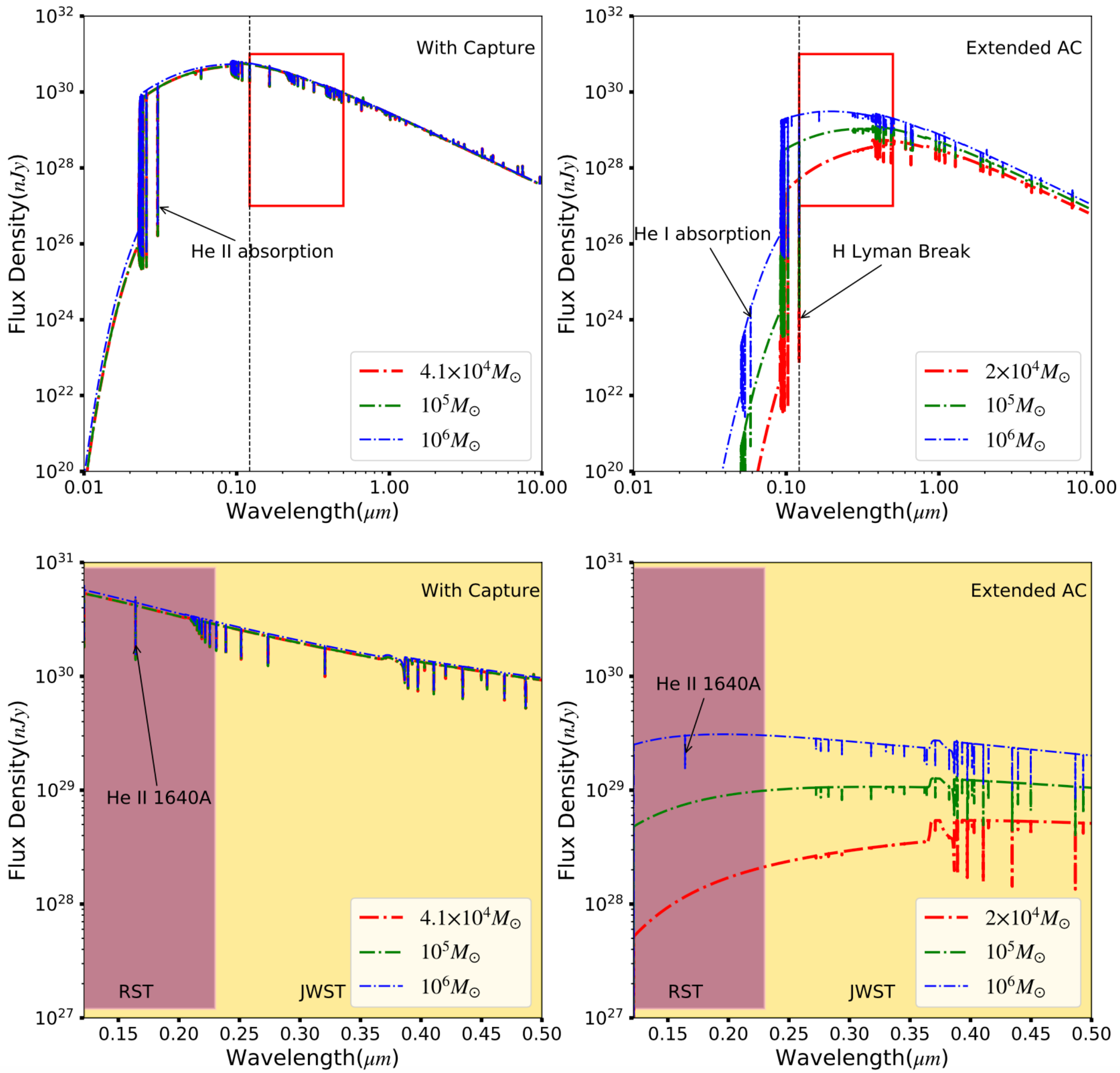
Criteria for hi-z objects to be Supermassive Dark Star candidates

- 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”

Dark Star spectra



Assumes z =10 object

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)

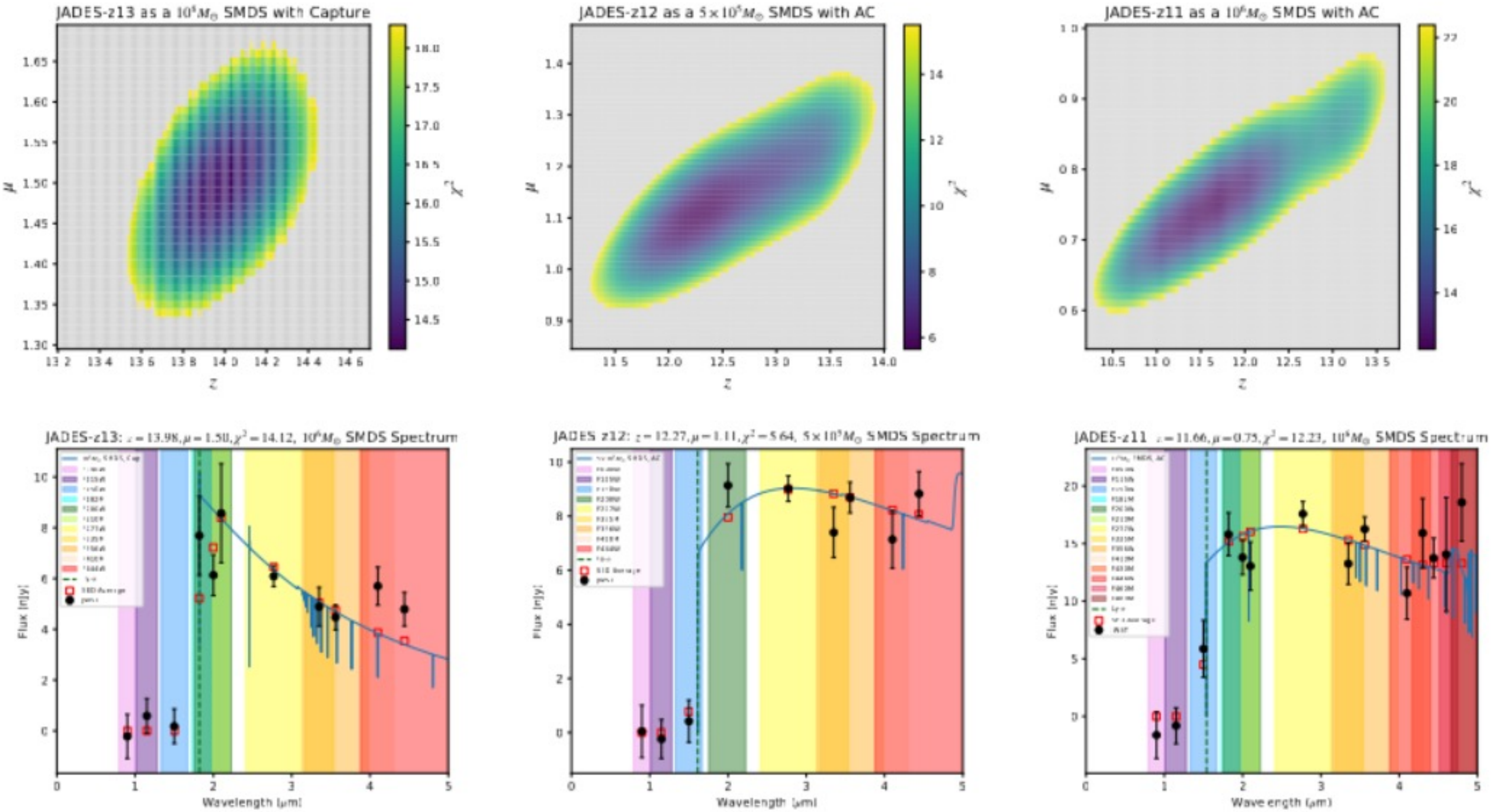
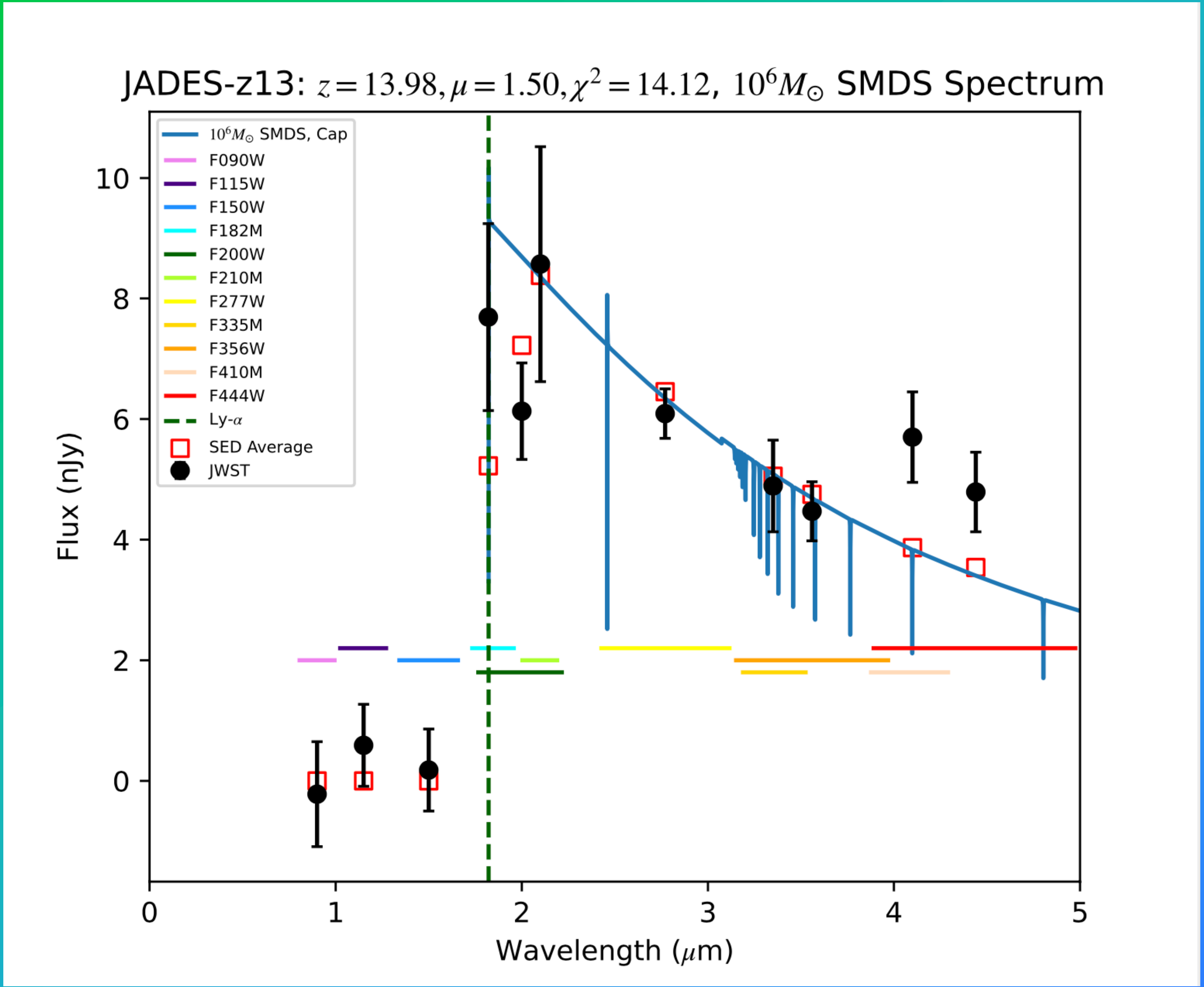


FIG. 1. (Top Row) Optimal fit regions in the z vs μ (magnification) parameter space for Supermassive Dark Star fits to JADES-GS-z11-0 , JADES-GS-z12-0 , and JADES-GS-z13-0 photometric data. The heatmap is color coded according to the value of the χ^2, and is cut off (grayed out) at the critical value 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
0
1
2
3
4
5

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GNz11: An object with beautiful spectrum: a galaxy

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

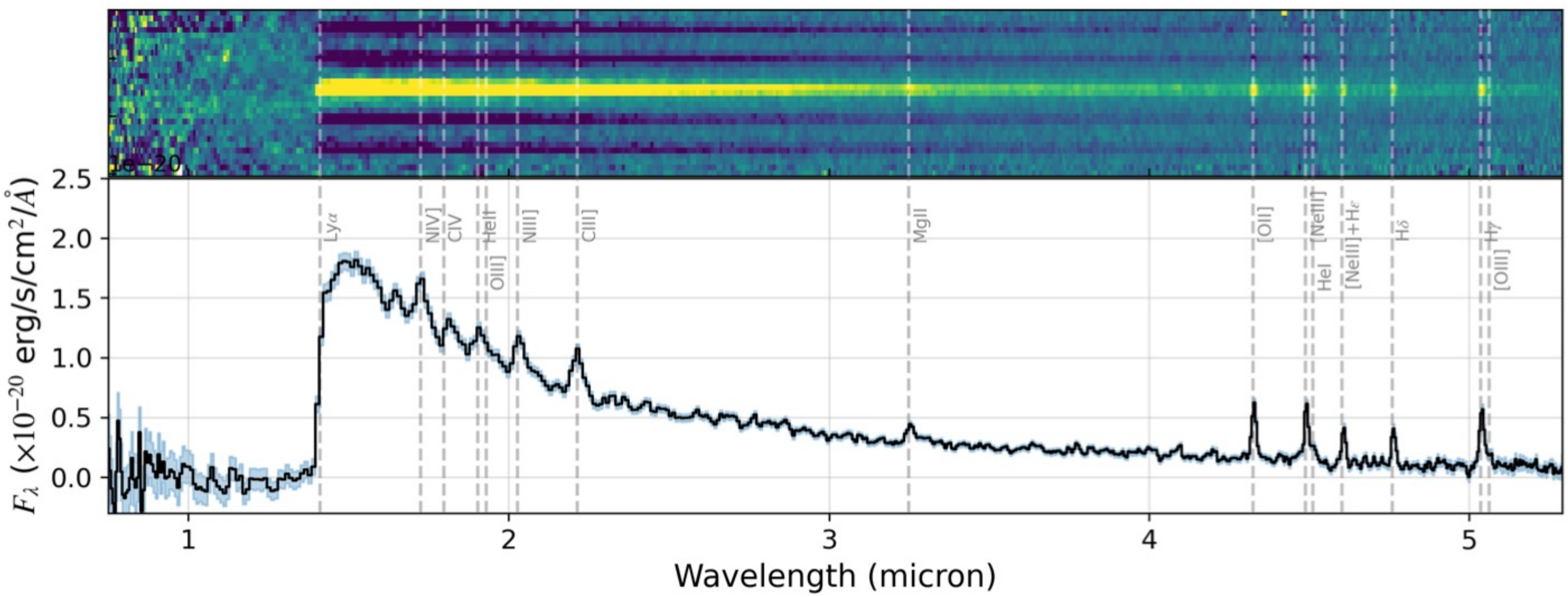

Fig. 1. 2D (top) and 1D (bottom) spectra of GN-z11 using PRISM/CLEAR configuration of NIRSpec. Prominent emission lines present in the spectra are marked. The signal to noise ratio (SNR) of the continuum is high and the emission lines are clearly seen in both the 1D and 2D spectra.

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 ~ 100 high redshift objects with z > 10. They assume these are "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. One is a galaxy.

(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 five hi-z JWST objects w published spectra are consistent with Dark Stars.

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) in progress

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

- Hot on the trail of neutrinos
- WIMP searches: DAMA? Galactic Center excess?
- Dark Stars:

first stars made of hydrogen and helium but powered by DM, big puffy massive and bright. Has JWST discovered them?


DARK MATTER SILVER JUBILEE
PACIFIC NORTHWEST NATIONAL LABS
SUMMER 2012, RICHLAND, WA
“I’m an old Seadog”

HAPPY BIRTHDAY FRANK!!!