Dark Matter in the Universe

Katherine Freese

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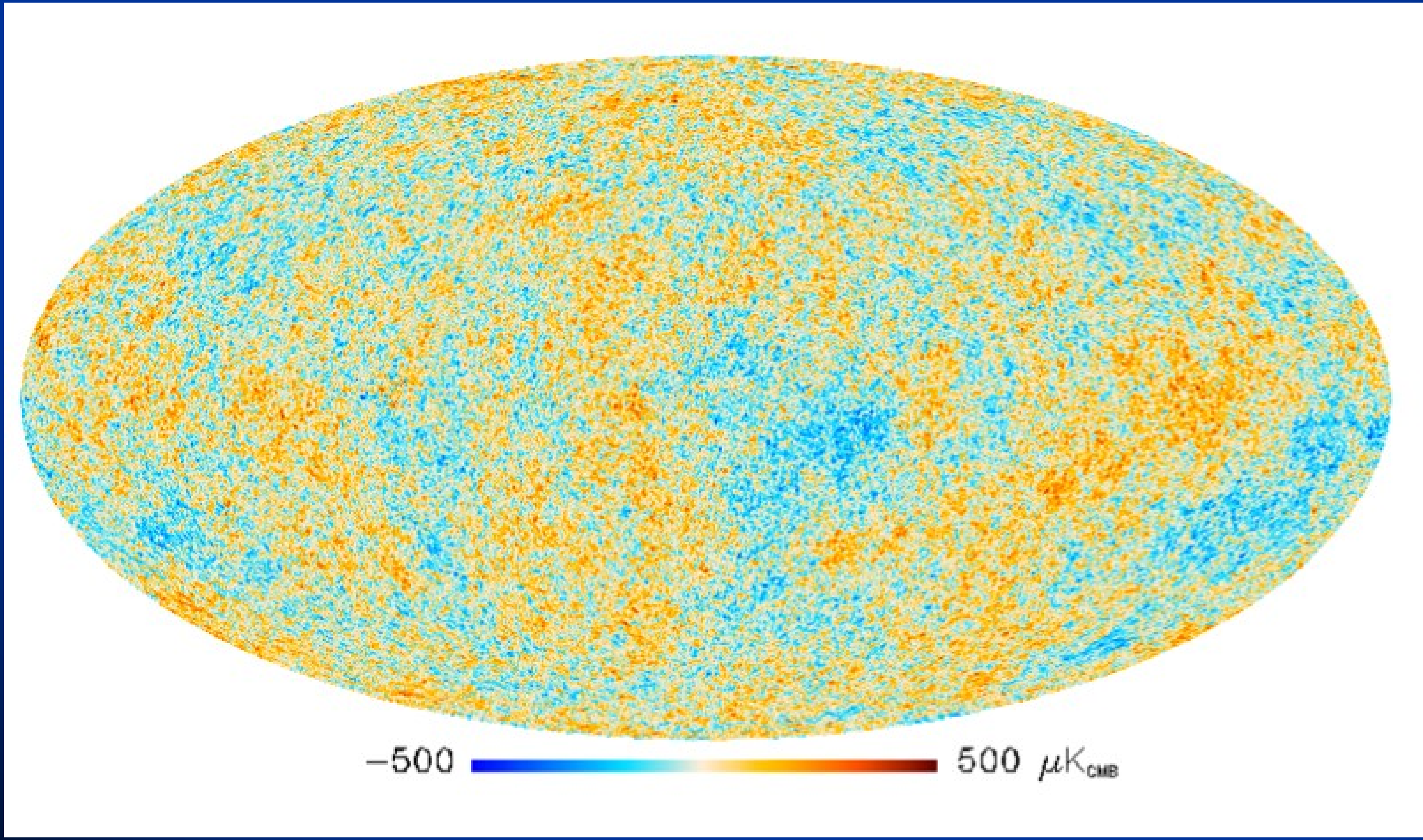
- Director Emerita, Nordita (Nordic Institute for Theoretical Physics, in Stockholm)

ENORMOUS PROGRESS OVER THE LAST CENTURY

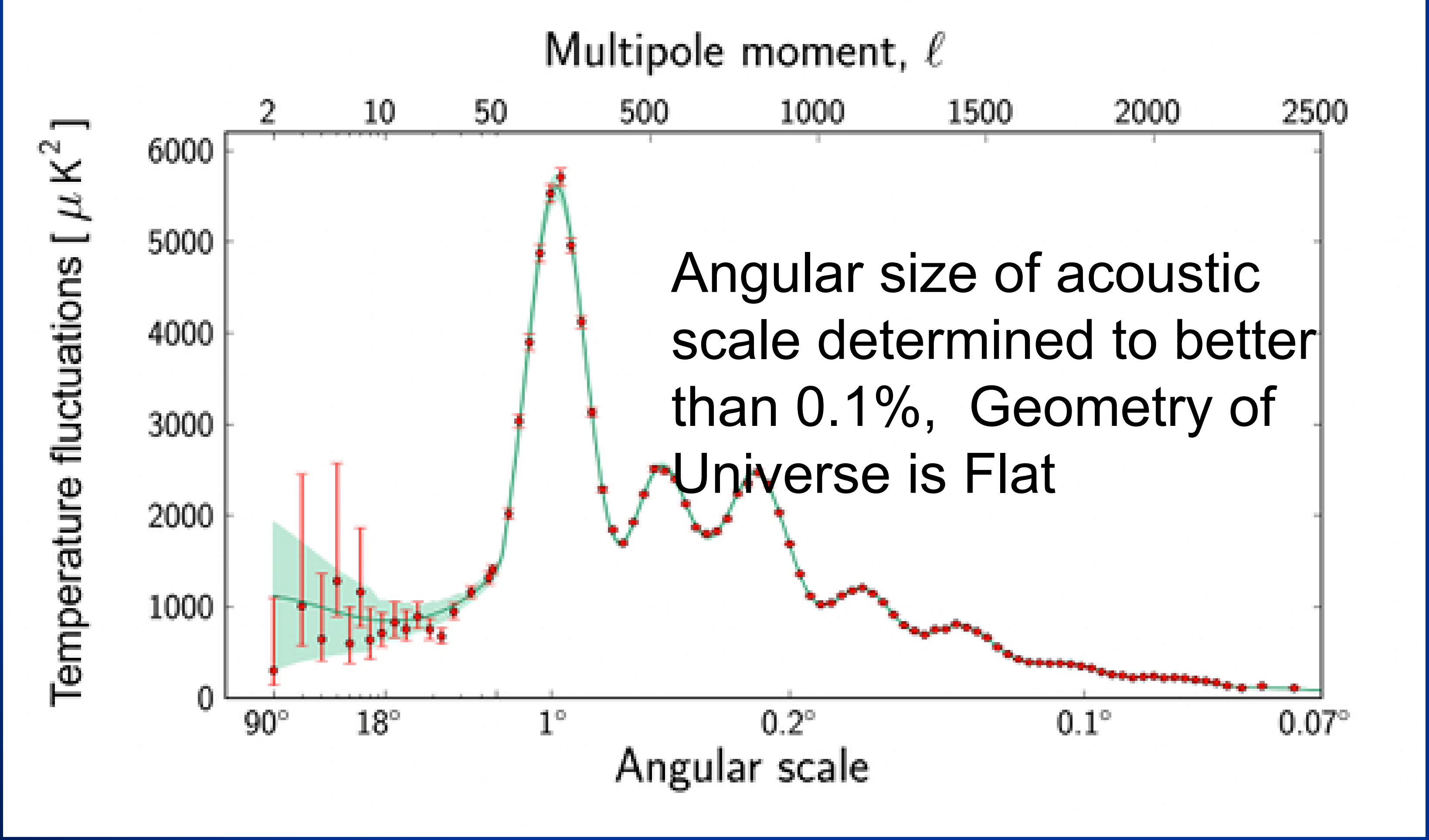
At the turn of the Millenium, recent experiments answered BIG QUESTIONS:

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

The Universe according to ESA's Planck Space Telescope



Planck Satellite (7 acoustic peaks)



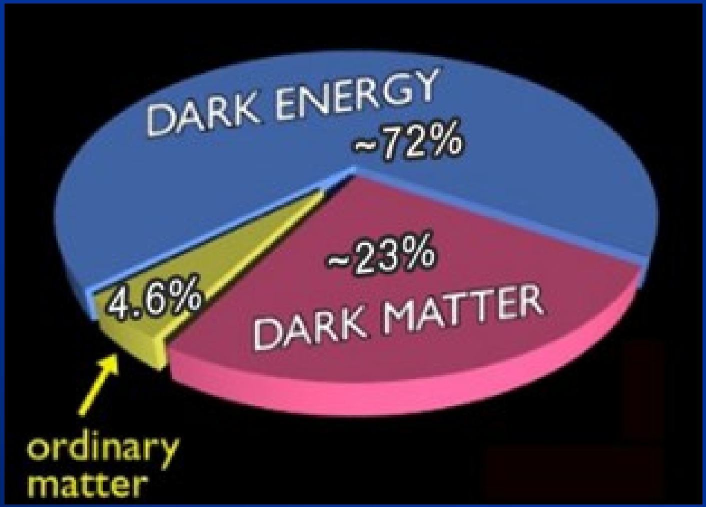
Implies energy density of the Universe is $\rho = \rho_c = 10^{-29}\ \mathrm{gm/cm^3}$

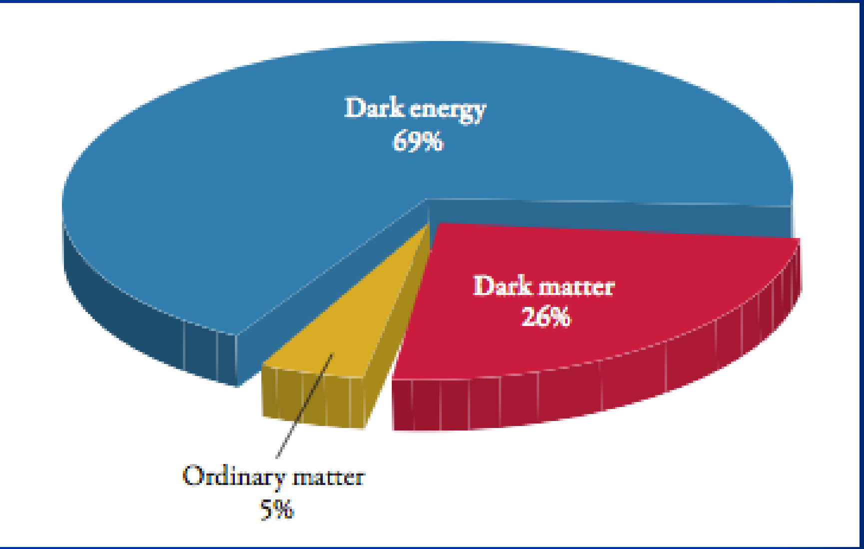
Cosmological Parameters from Planck

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

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.

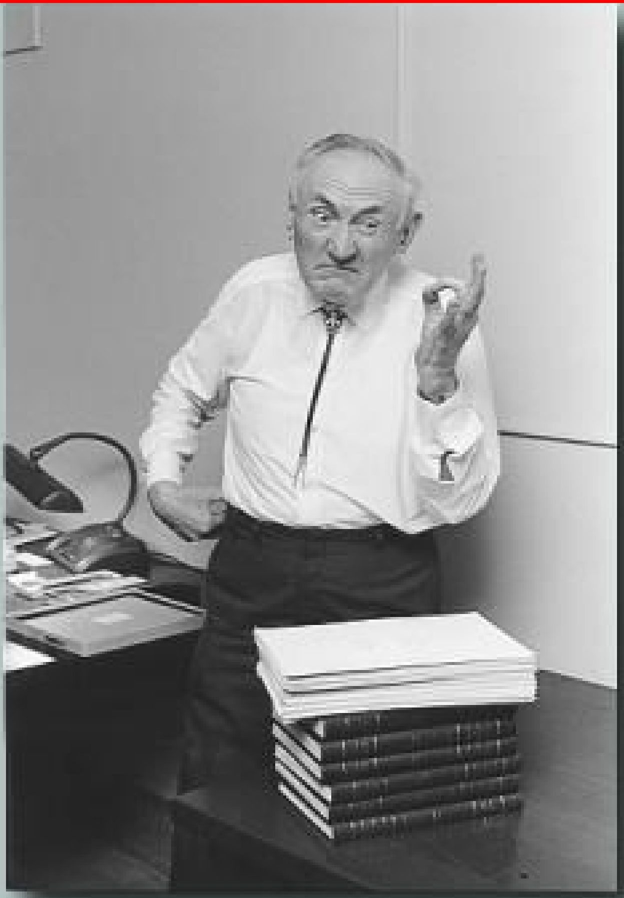
What is the dark matter? What is the dark energy?

The Dark Matter Problem is 80 years old: Dates back to Knut Lundmark in 1930 and Fritz Zwicky in 1933

Galaxies in the Coma cluster were moving too rapidly.

Proposed "Dunkle Materie" as the explanation.

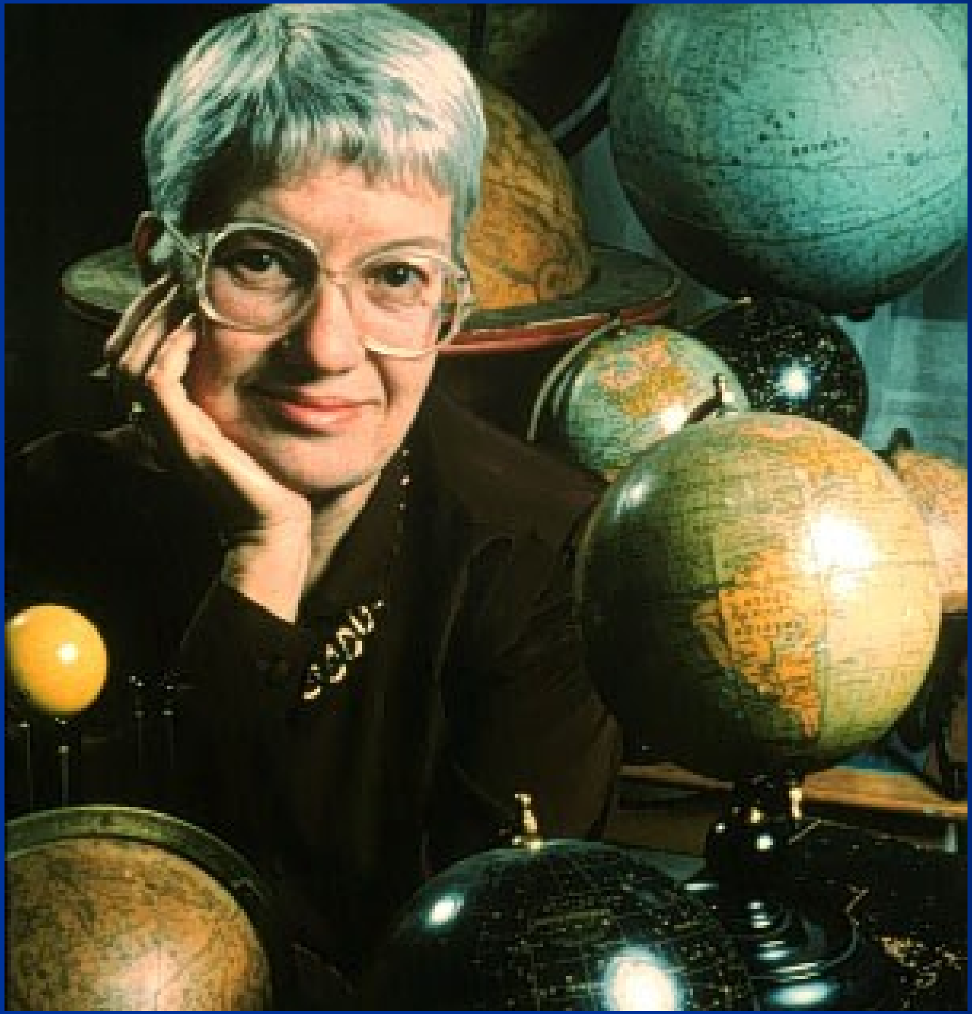
It's not stars, it doesn't shine.
It's DARK.



Vera Rubin and Kent Ford in 1970s

Studied rotation curves of galaxies, and found that they are all FLAT.

This work led to scientific consensus that the DM problem is ubiquitous.



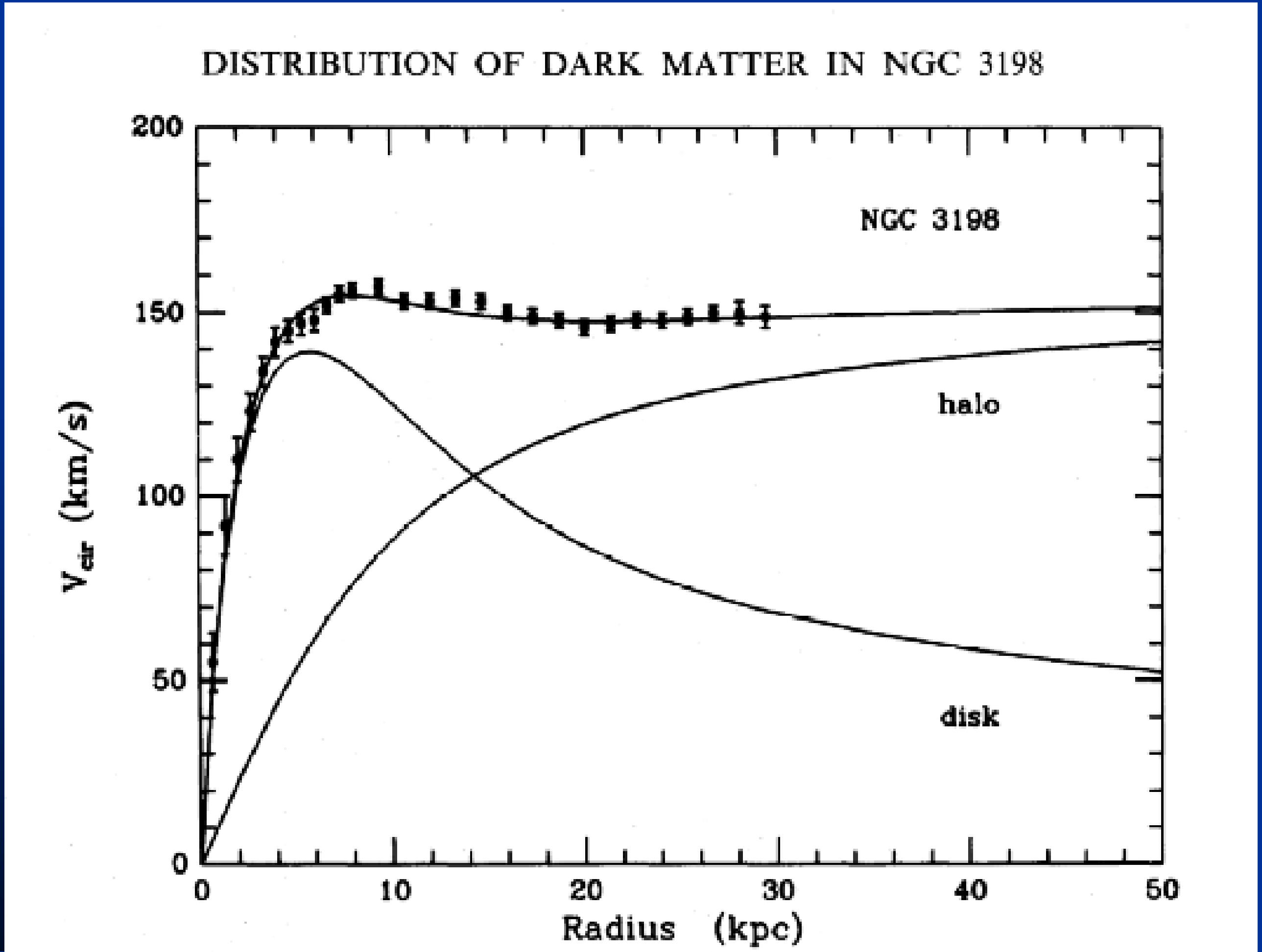
Rotation Curves of Galaxies

Orbit of a star in a Galaxy: speed is Determined by Mass. Larger mass causes faster orbits.

$$\frac{GM(r)m}{r^2} = \frac{mv^2}{r}$$

95% of the matter in galaxies is unknown dark matter

- Rotation Curves of Galaxies:



OBSERVED: FLAT ROTATION CURVE

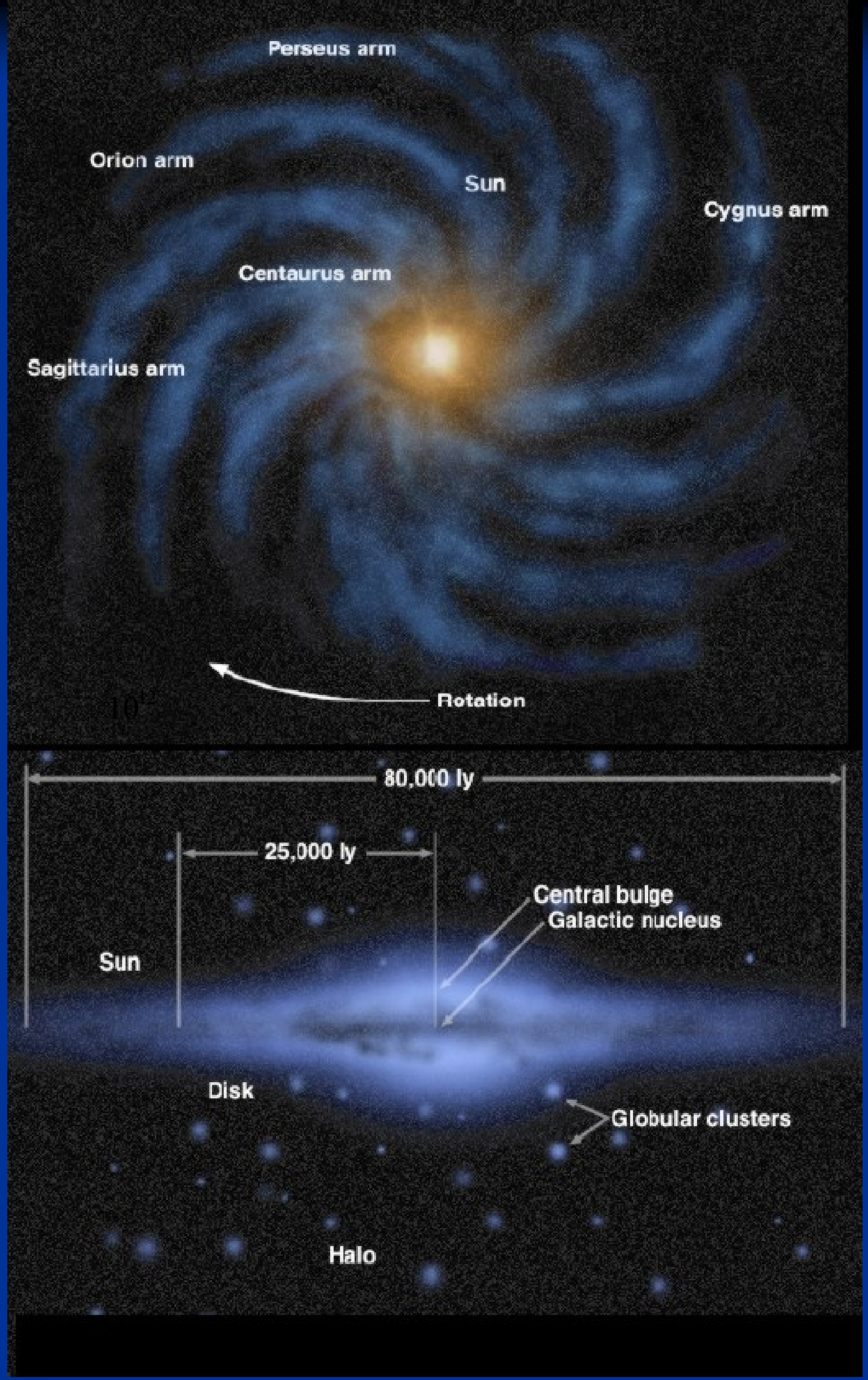
EXPECTED FROM STARS

Albert Bosma 1978

Our Galaxy: The Milky Way

The mass of the galaxy:

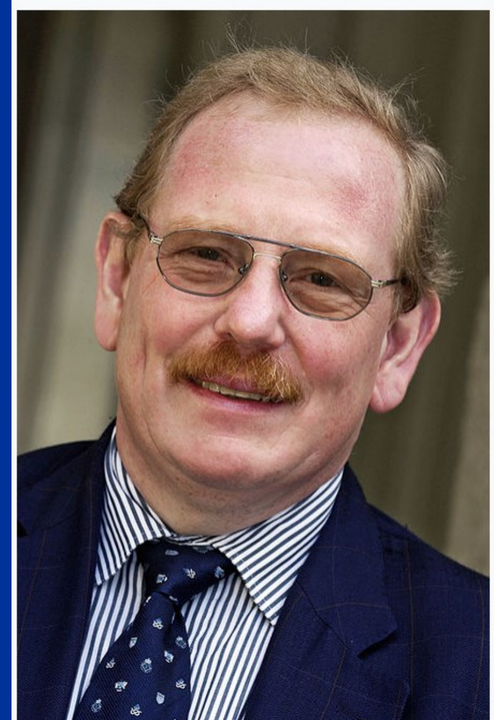
10^{12} solar masses



2020 Nobel Prize in Physics

(half) for the discovery of the supermassive black hole at the center of our Galaxy

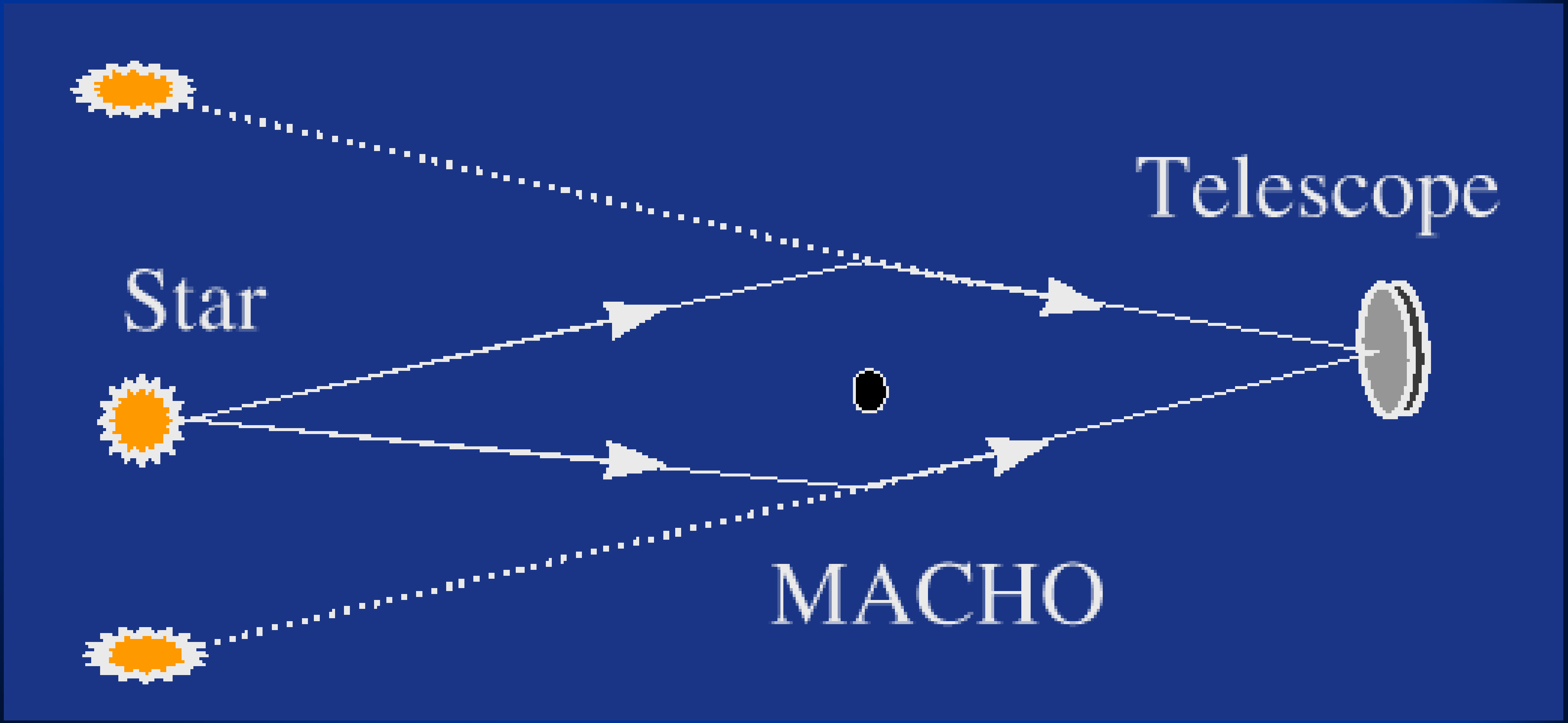

Andrea M. Ghez


Reinhard Genzel

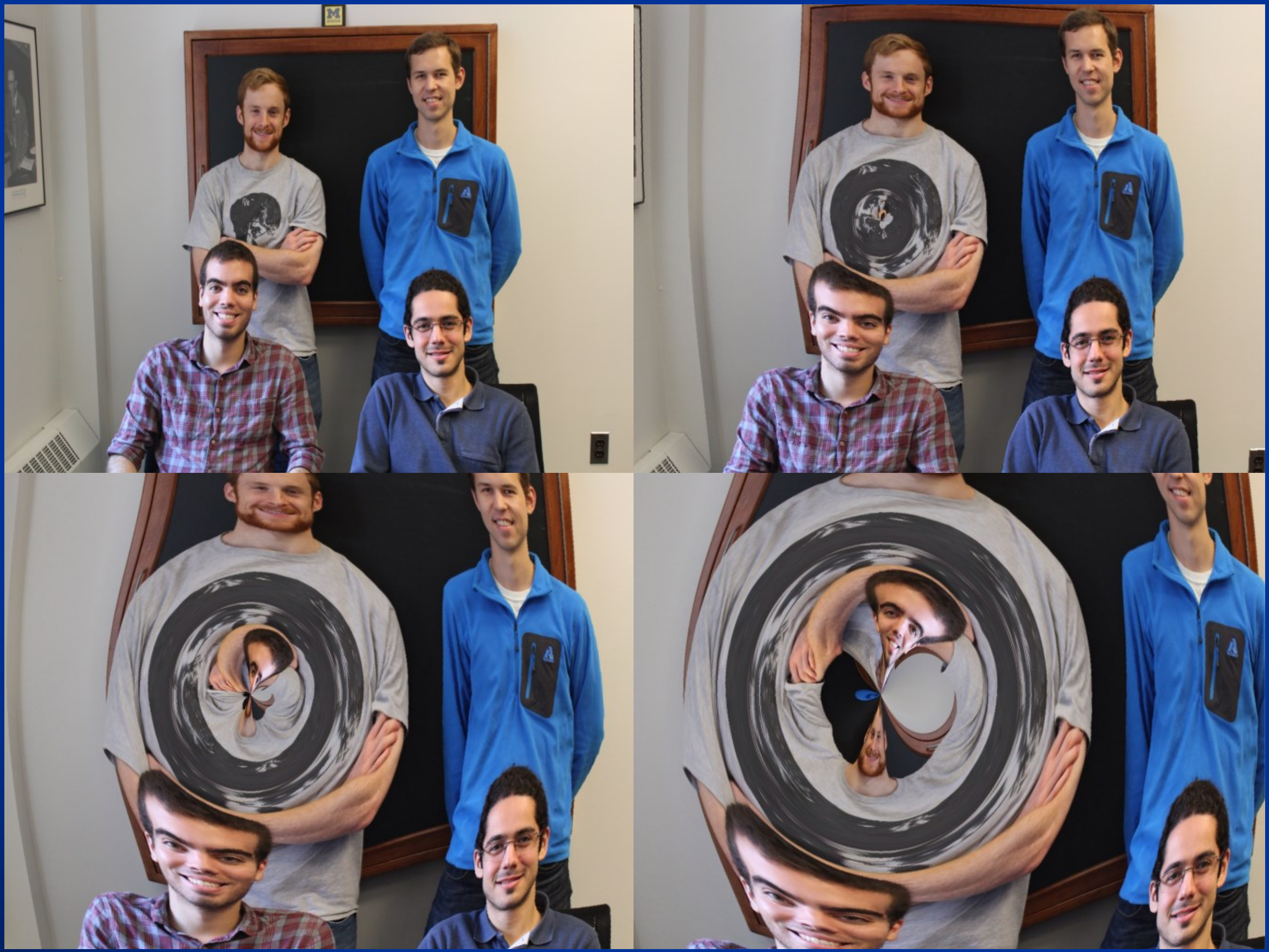
The BH weighs 4 million Suns

Galaxies have Dark Matter Haloes

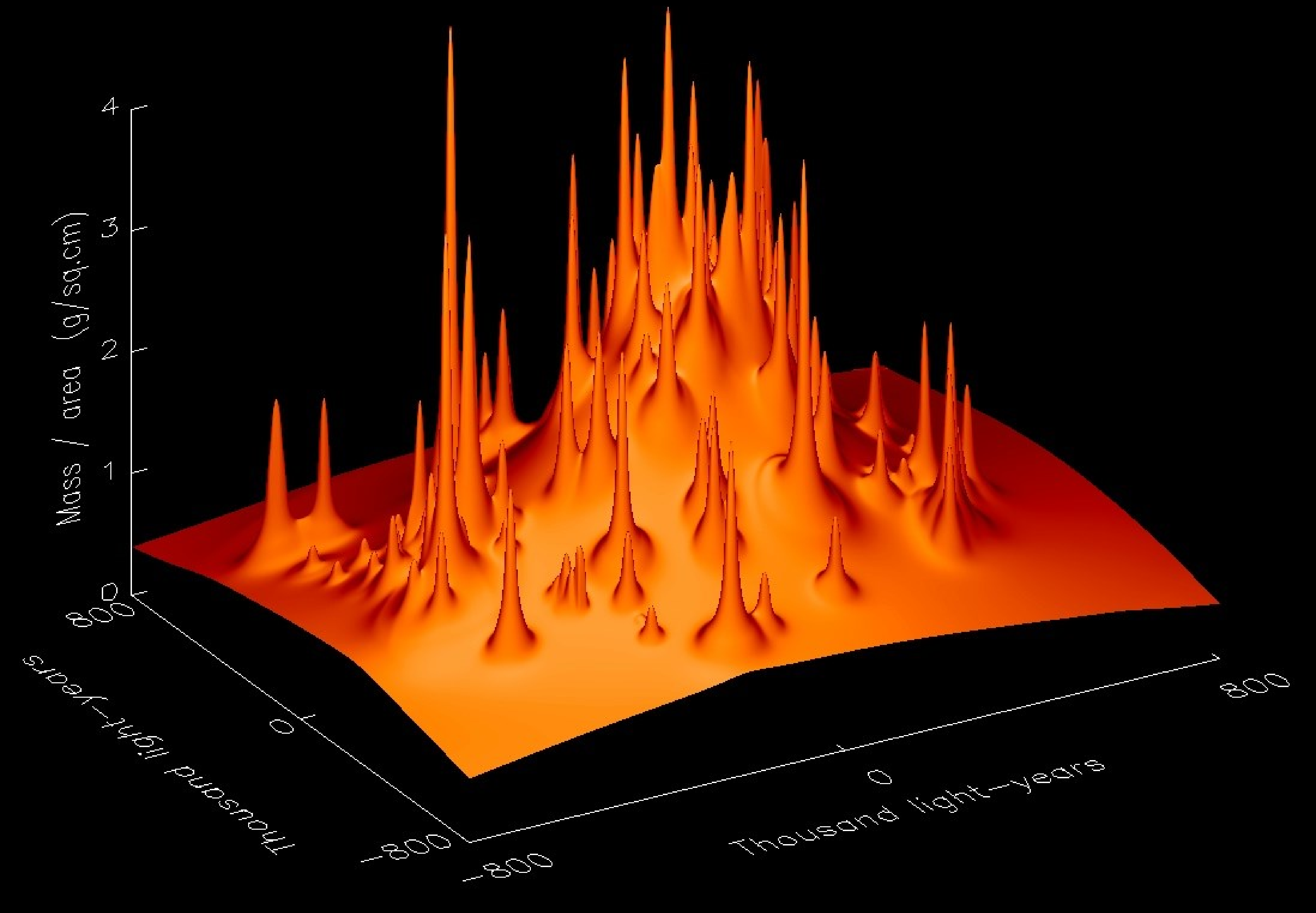
Einstein's Lensing: Another way to detect dark matter: it makes light bend



Lensing of students



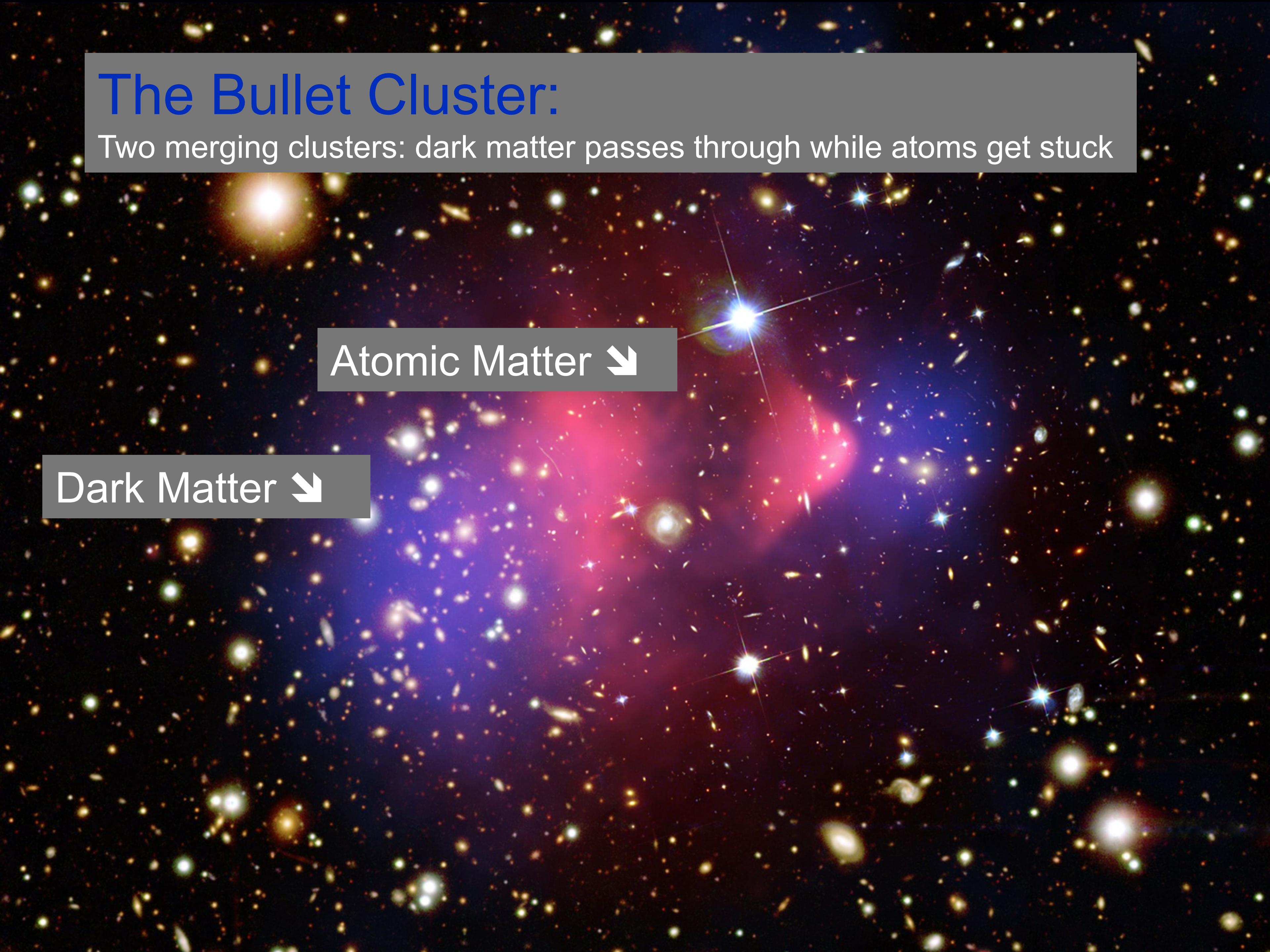
Strong lensing by dark matter



Mass / area (g/sq.cm)
4
3
2
1
0
800
0
−800
Thousand light−years
−800
0
800
Thousand light−years

The Bullet Cluster:

Two merging clusters: dark matter passes through while atoms get stuck



The Dark Matter Problem :

95% of the mass in galaxies and clusters of galaxies consists of an unknown dark matter component.

Known from:

rotation curves (out to tens kpc),

gravitational lensing (out to 200kpc),

Bullet Cluster.

Big Bang Nucleosynthesis

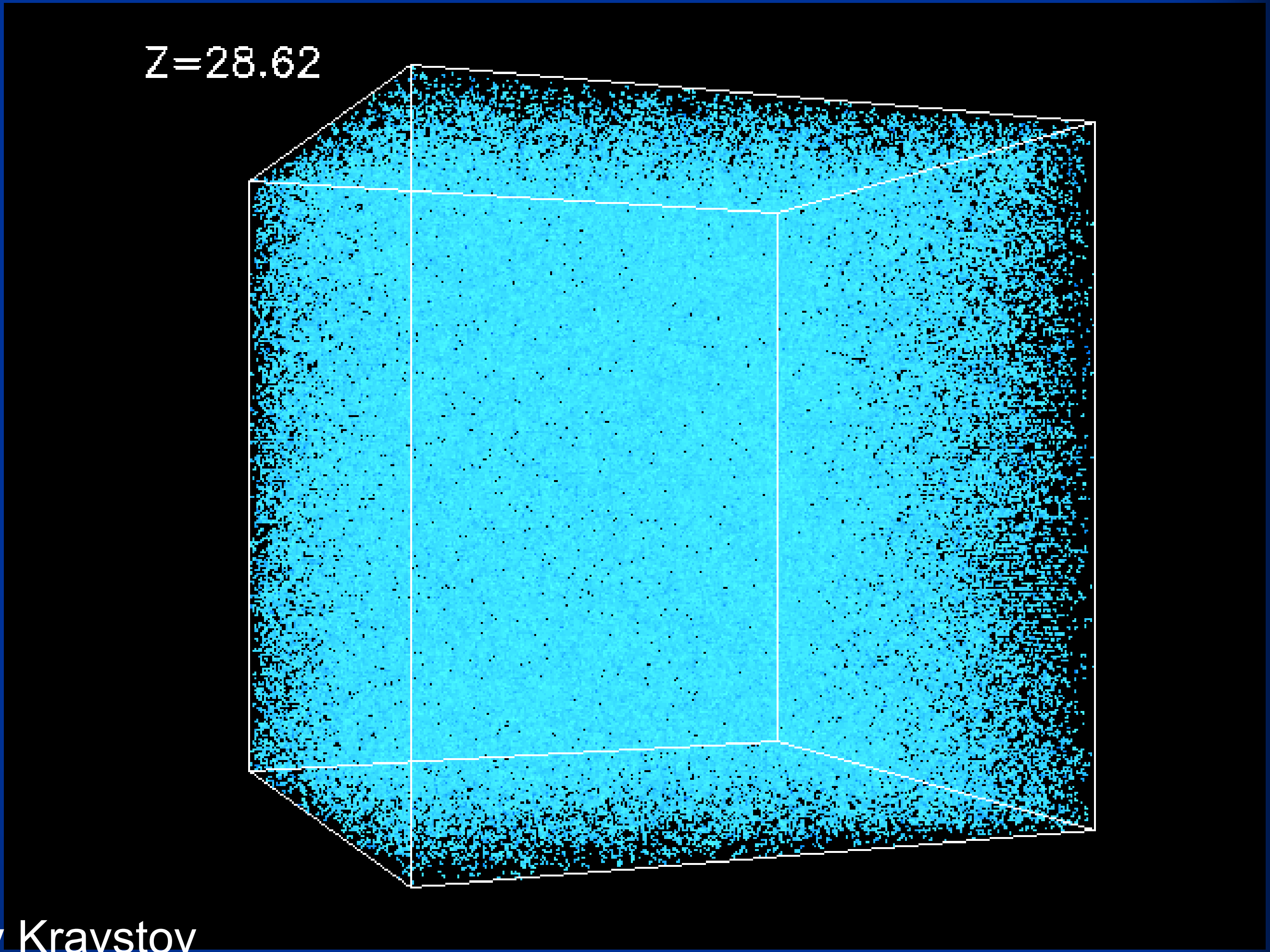
Peaks in the Cosmic Microwave Background.

Evidence for Dark Matter: Formation of Structure, Computer Simulations

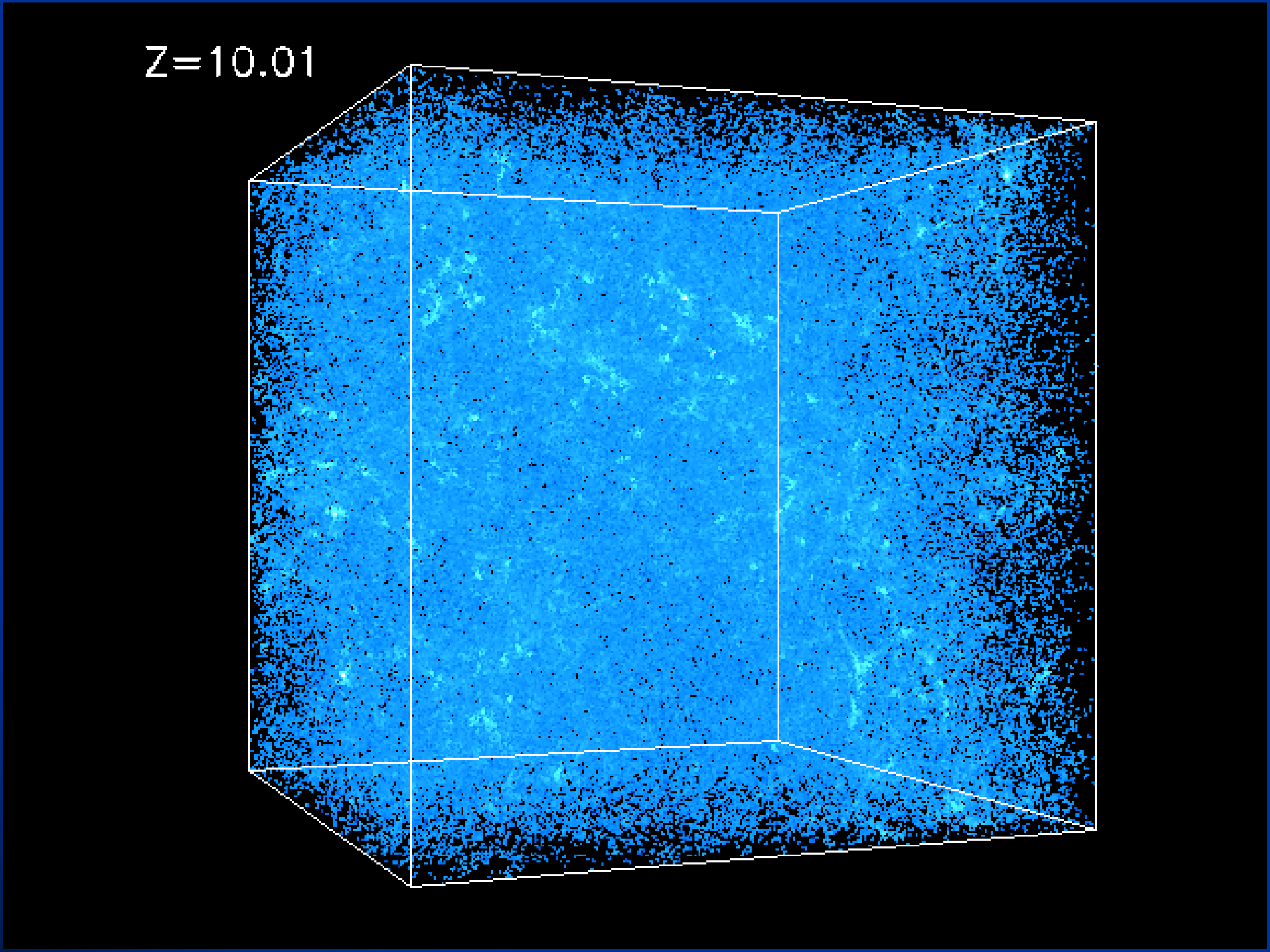
Initial conditions from inflation

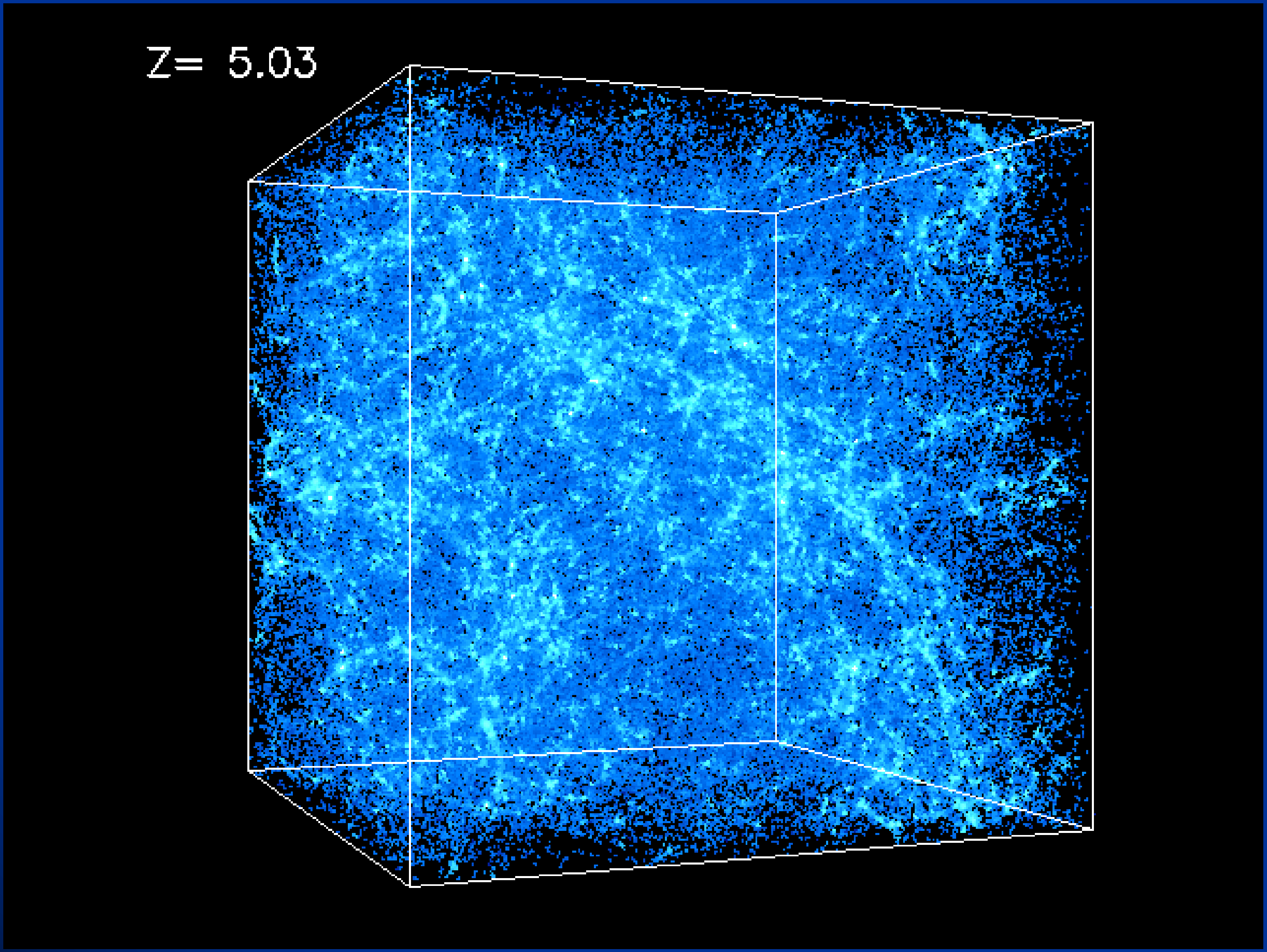
Dark Matter particles come together to make galaxies, clusters, and larger scale structures

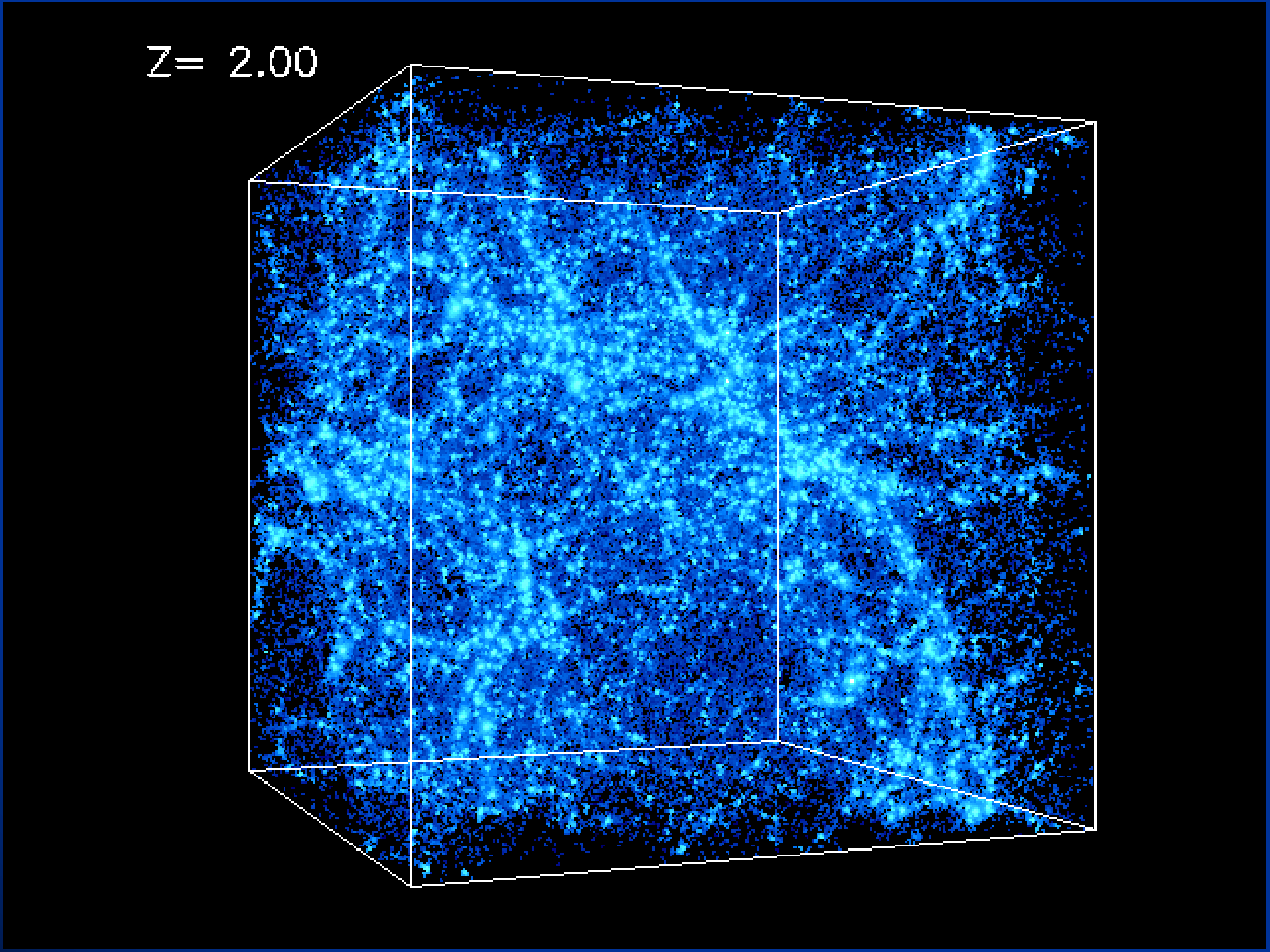
Computer simulations with dark matter match the data

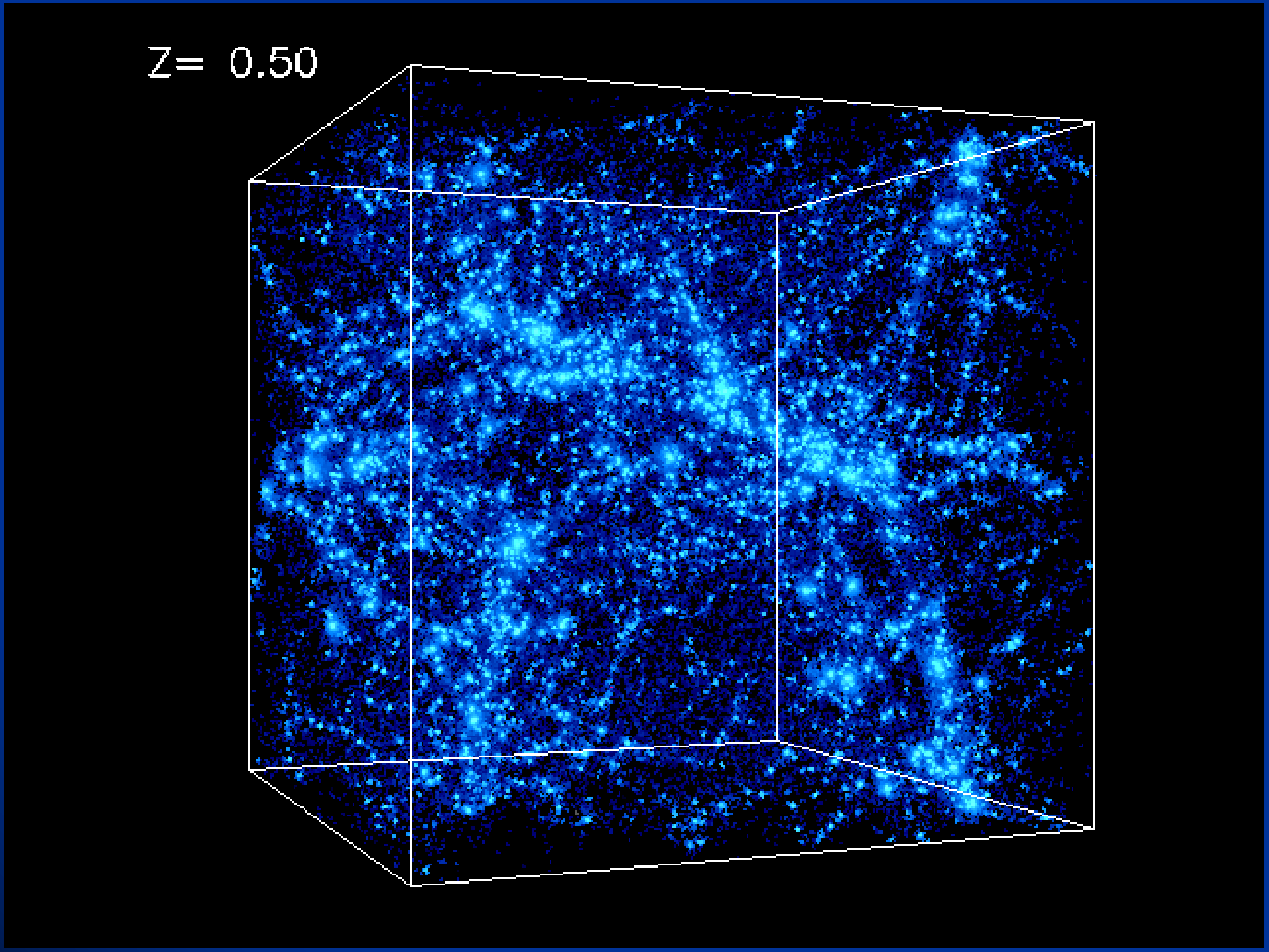


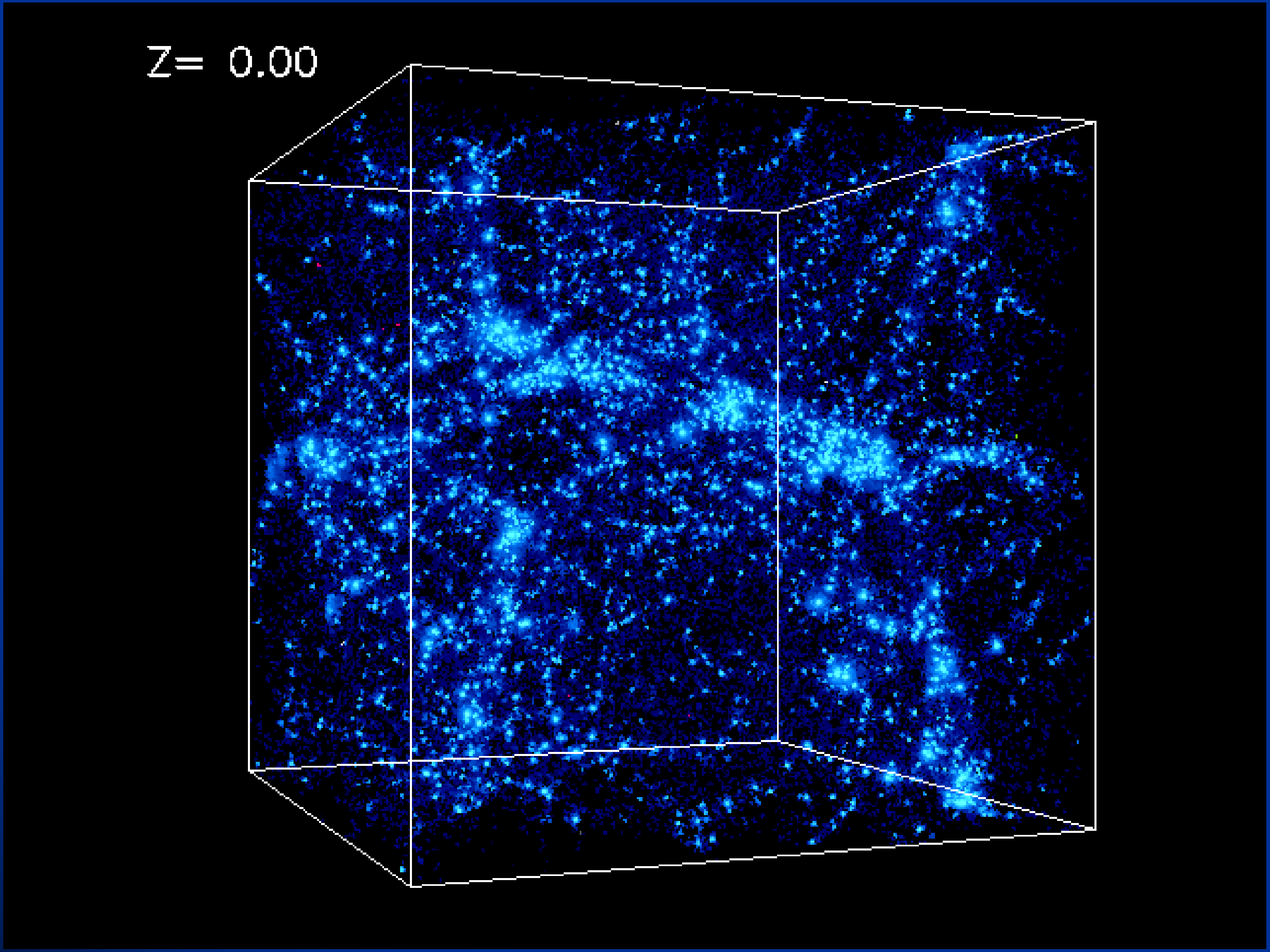
simulations by Kravstov


Z=10.01

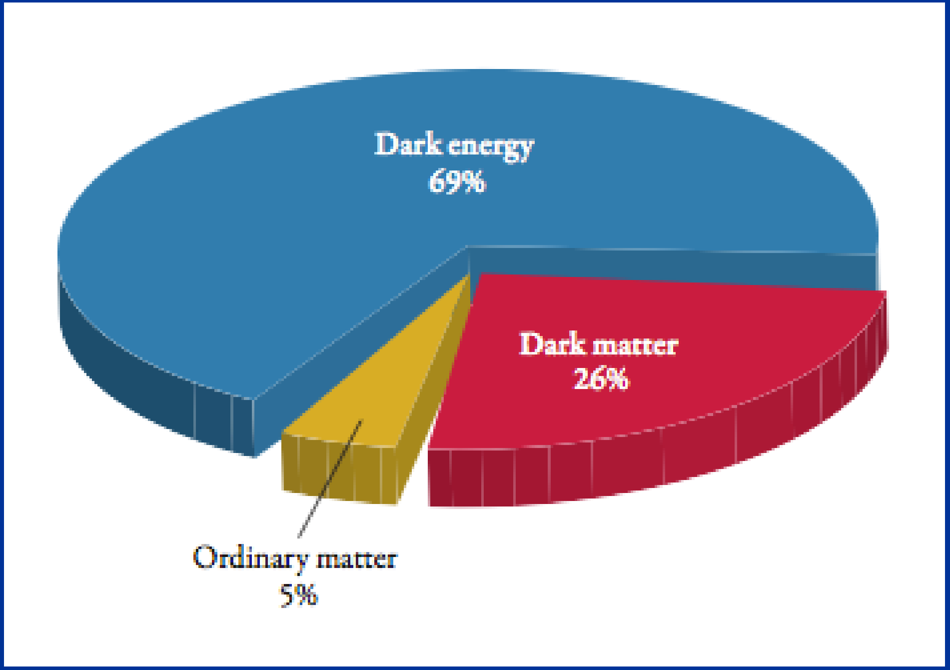

Z= 5.03


Z= 2.00


Z= 0.50


Z= 0.00

PIE CHART OF THE UNIVERSE



WHAT ARE THE PIECES OF THE PIE???

WHAT IS THE DARK MATTER?

The Dark Matter is NOT

- Diffuse Hot Gas (would produce x-rays)
- Cool Neutral Hydrogen (see in quasar absorption lines)
- Small lumps or snowballs of hydrogen (would evaporate)
- Rocks or Dust (high metallicity)

(Hegyi and Olive 1986)

Before 2000, there were two camps

The believers in MACHOs (Massive Compact Halo Objects)

vs.

The believers in WIMPs, axions and other exotic particle candidates

MACHOS (Massive Compact Halo Objects)

- Faint stars
- Substellar Objects Objects (Brown Dwarfs)
- Stellar Remnants:
- White Dwarfs
- Neutron Stars
- Black Holes

From a combination of observational and theoretical arguments, my student and I found that THESE CANNOT EXPLAIN ALL THE DARK MATTER IN GALAXIES. STILL A POSSIBILITY: 15% OF THE MASS IN THE GALAXY CAN BE MADE OF WHITE DWARFS.

Baryonic Dark Matter is NOT enough

Death of stellar baryonic dark matter **candidates (Fields, Freese, and Graff 2000)**

What is the Dark Matter? Candidates:

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

Neutrinos as Dark Matter? No

- 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.

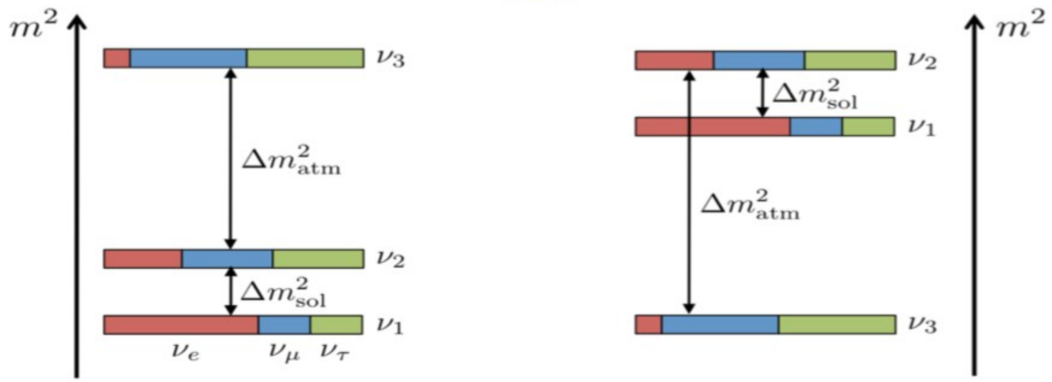
NEUTRINO MASS

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):

$$\Delta m^2_{21} = 7.6 \times 10^{-5}\ \mathrm{eV}^2 \qquad |\Delta m^2_{31}| = 2.5 \times 10^{-3}\ \mathrm{eV}^2\ \text{(NH)}, \quad 2.4 \times 10^{-3}\ \mathrm{eV}^2\ \text{(IH)}$$

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 $\qquad \Sigma m_\nu > 0.10$ eV

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

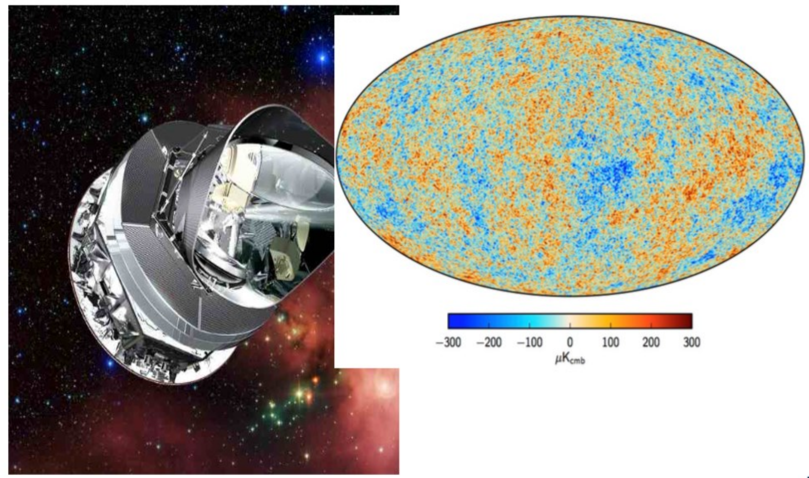
(depending on the hierarchy)

Figure credit: Juno Collaboration

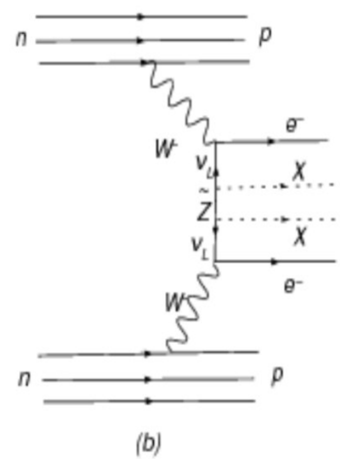
The tiny neutrino masses are a puzzle for the Standard Model of particle physics

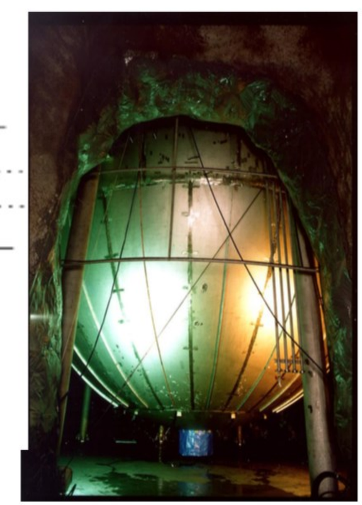
The absolute scale of neutrino masses can be measured in different ways

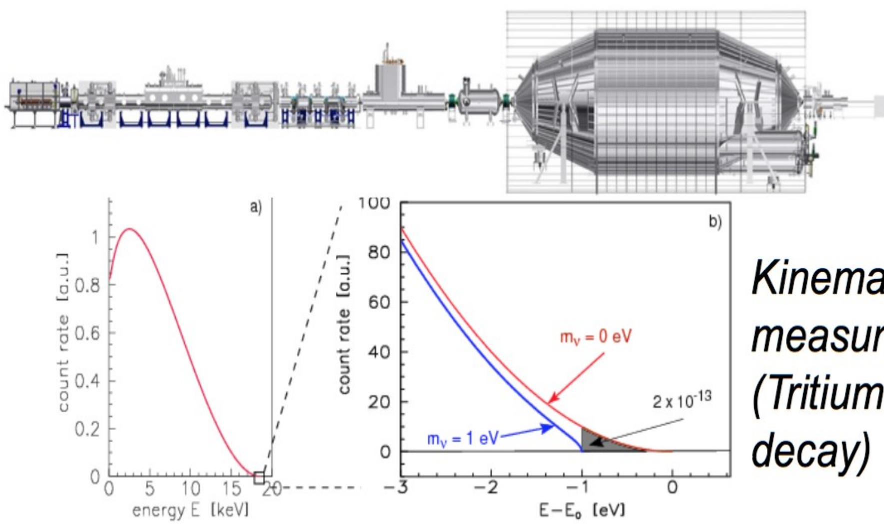
Cosmological observations (CMB, LSS)



Neutrinoless double β decay







Kinematic measuremets (Tritium β decay)

PHYSICAL REVIEW LETTERS

Editors' Suggestion

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

D. Q. Adams *et al.* (CUORE Collaboration)

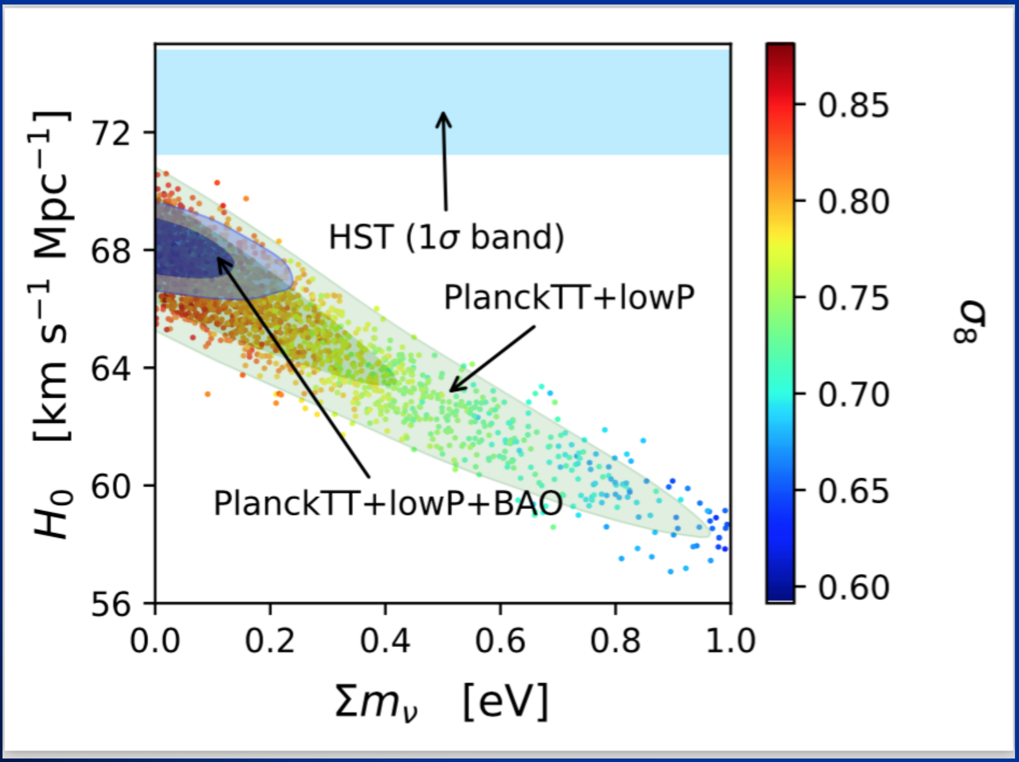
Phys. Rev. Lett. **124**, 122501 – Published 26 March 2020

Doug Adams

ABSTRACT

We report new results from the search for neutrinoless double-beta decay in $^{130}\mathrm{Te}$ 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 $^{130}\mathrm{Te}$ 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

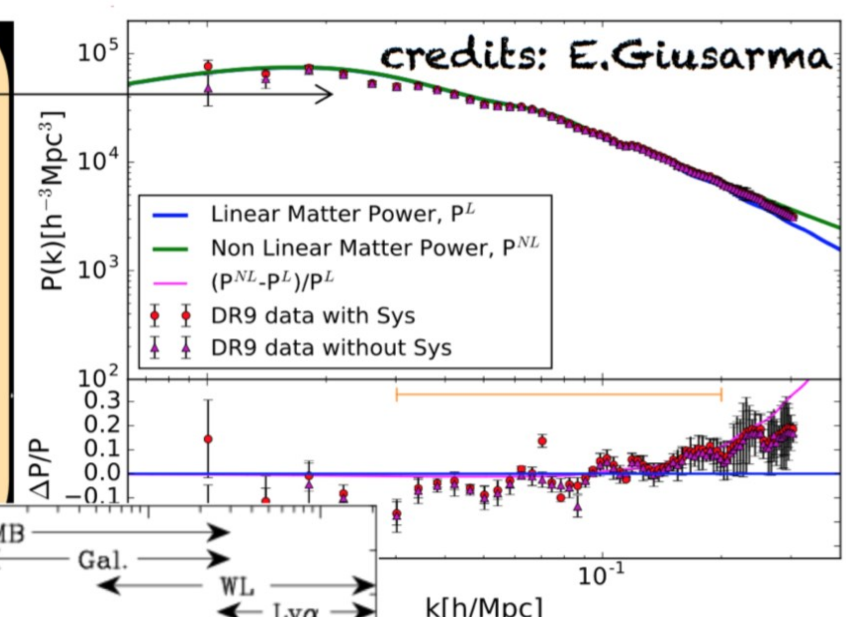
Assumes standard Lambda CDM
If w>-1, stronger bounds

From oscillations: >0.06 eV

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

LARGE SCALE STRUCTURES

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



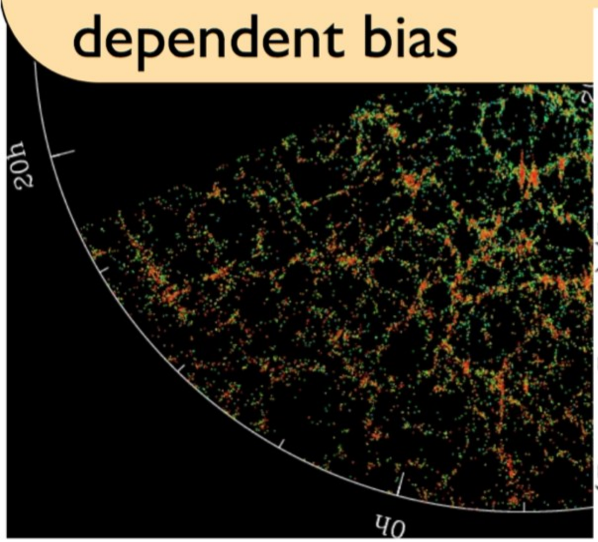
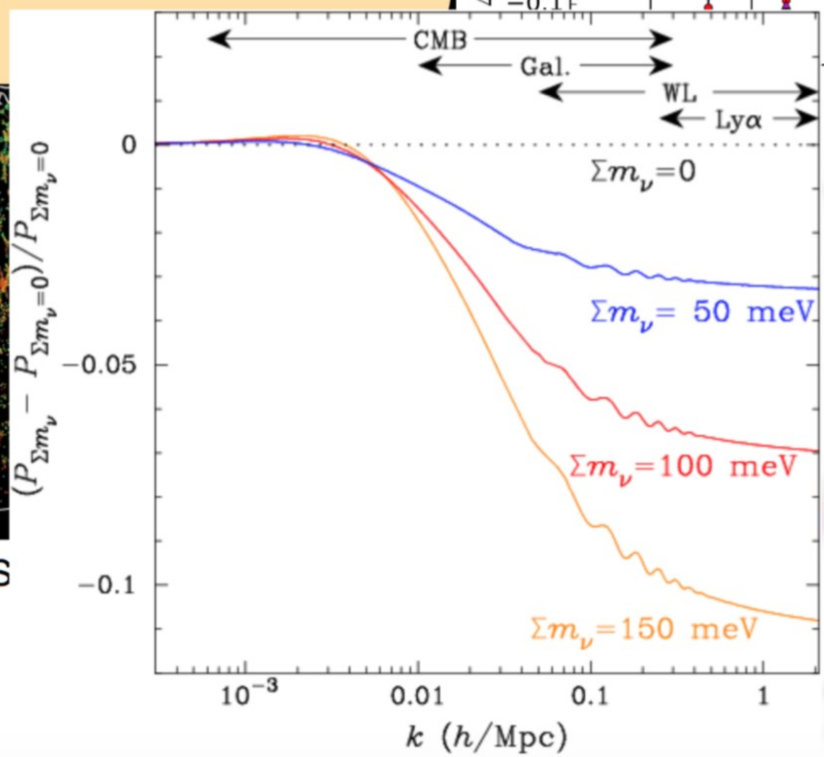
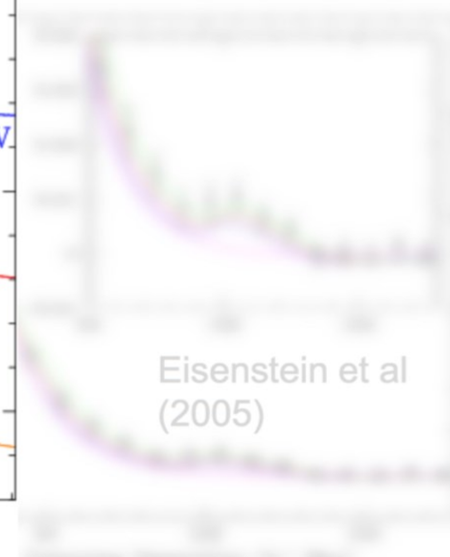


Image Credit: M. Blanton and the S



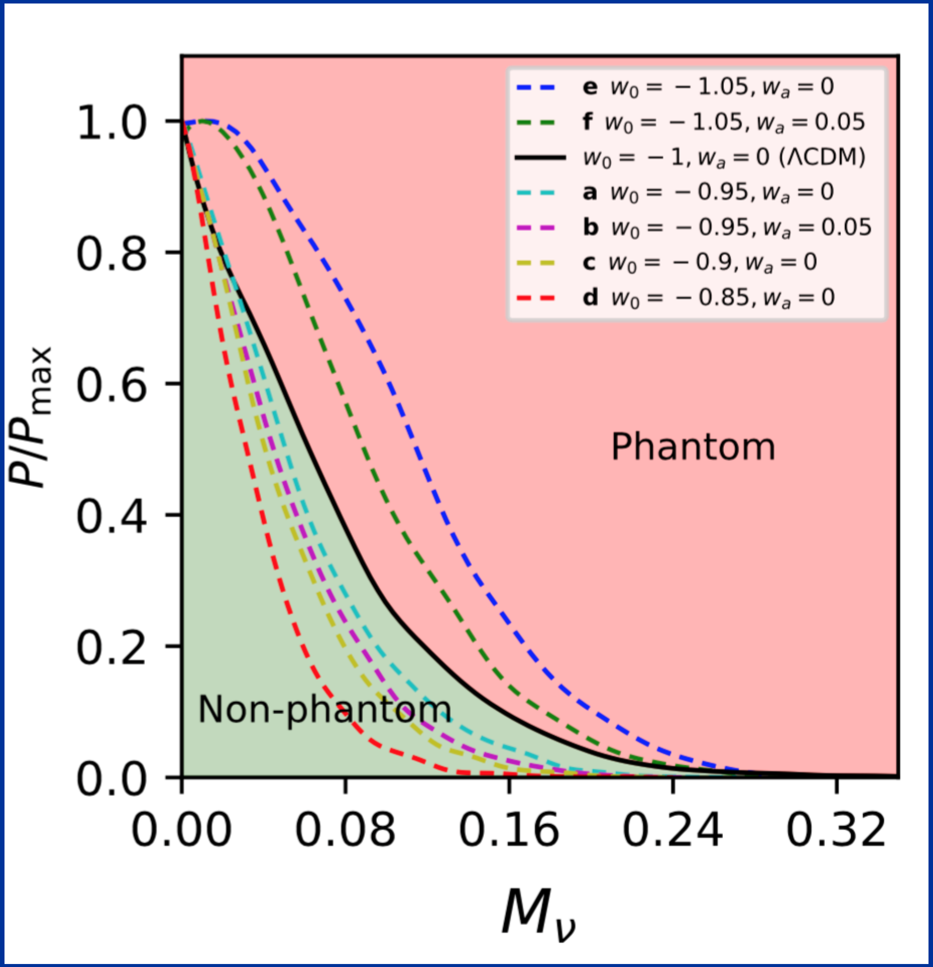


Eisenstein et al (2005)

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

MARTINA GERBINO

SUNNY VAGNOZZI

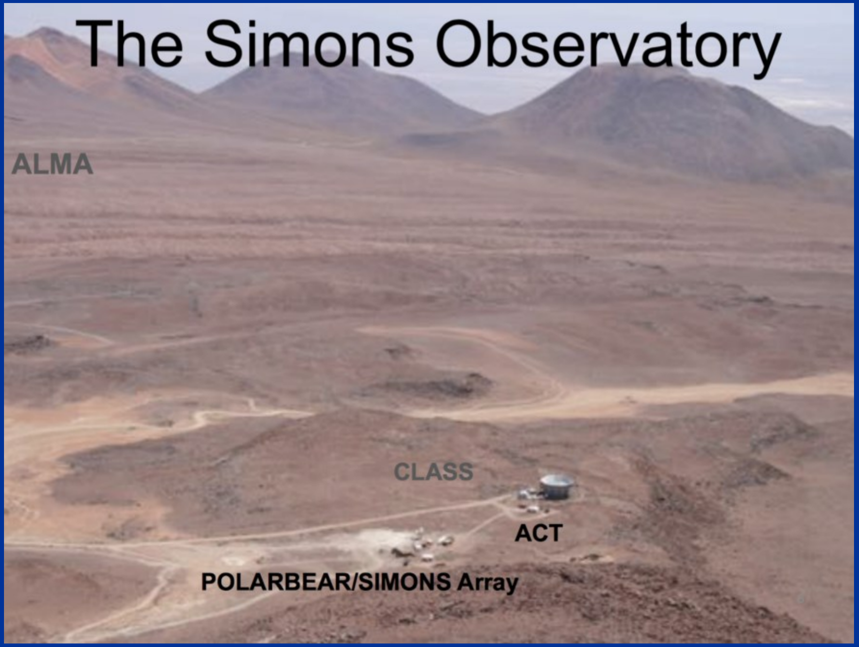


Vagnozzi, Gerbino, KF, etal http://lanl.arxiv.org/pdf/1801.08553

Upcoming Cosmic Microwave Background Experiments

SPIDER at South Pole

My group has joined these two experiments



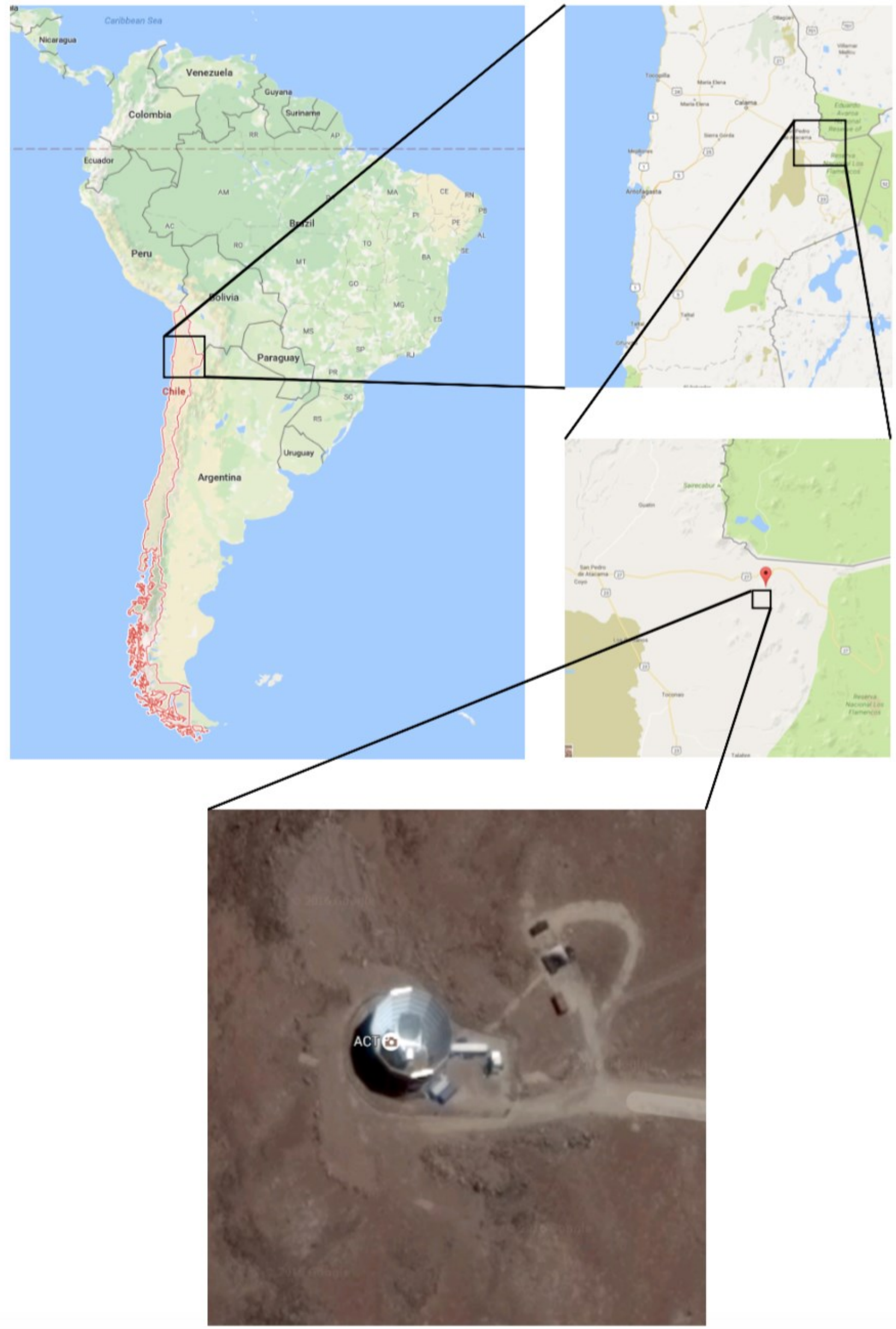
Jon Gudmundsson

Adri Duivenvoorden

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	$\kappa\kappa$ × 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 × 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 × 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

Pablo Fernandez de Salas

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:

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

Florian Kuhnel
Primordial
Black Holes

Primordial Black Holes in LIGO

Did LIGO detect dark matter?

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

[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

Explaining the newest LIGO black holes, which are in the mass gap and shouldn't exist

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[Submitted on 1 Oct 2020]

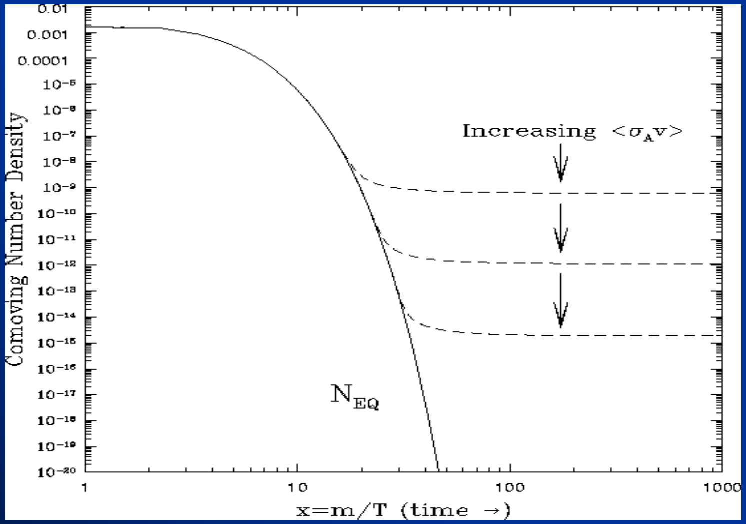
Filling the Black Hole Mass Gap: Avoiding Pair Instability in Massive Stars through Addition of Non-Nuclear Energy

Joshua Ziegler, Katherine Freese

In standard stellar evolution, stars with masses ranging from approximately 150 to $240 M_\odot$ are expected to evolve to a pair instability supernova with no black hole (BH) remnant. This evolutionary behavior leads to a predicted gap in the black hole mass function from approximately 50 to $140 M_\odot$. Yet the LIGO and Virgo Collaborations[1] recently discovered black holes of masses $66 M_\odot$ and $85 M_\odot$ in the gravitational wave event GW190521. We propose a new method to populate the BH mass gap. If an energy source is added throughout the star in addition to nuclear fusion, it is possible for the altered evolution to avoid the complete destruction of a pair instability supernova, and instead a BH remnant is left behind. An example of an extra energy source is dark matter annihilation within the star, but our results hold more generally. We show this phenomenon by exploring the effect of adding an energy source independent of temperature and density to a $180 M_\odot$ star, using the MESA one-dimensional stellar evolution software. If ~ 50\% of the star's energy is due to this new source, the star is capable of avoiding the pair instability entirely and evolving towards a core-collapse supernova and ultimately a BH remnant with mass $\sim 120 M_\odot$.

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

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



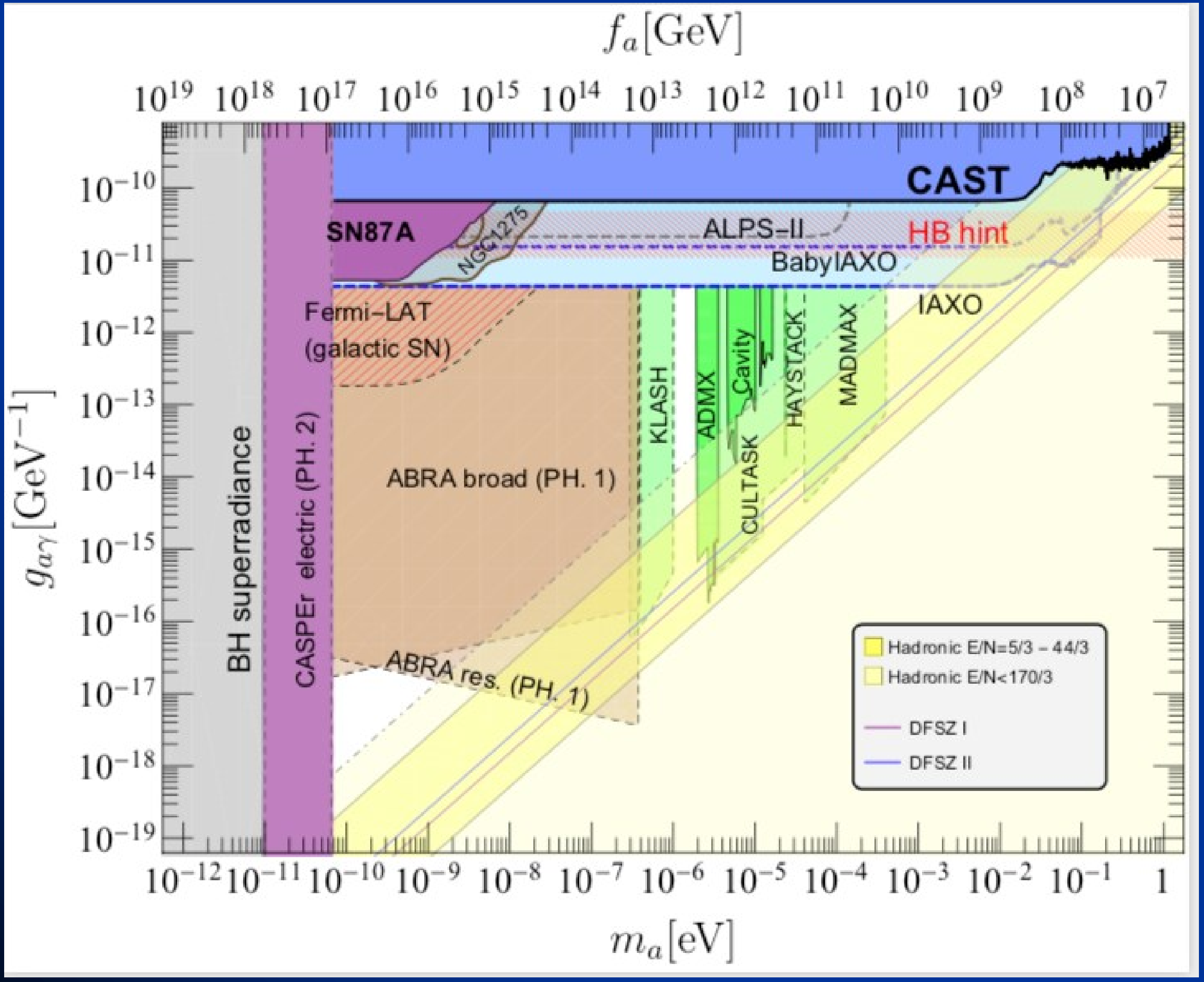
- Axions

  m_a~$10^{-(3-6)}$ eV

arise in Peccei-Quinn solution to strong-CP problem

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

Bounds on Axions and ALPs



From review by Luca Visinelli 2003.01100

Among theTop candidates for Dark Matter : WIMPs

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

Two reasons we favor WIMPs: First, the relic abundance

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

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

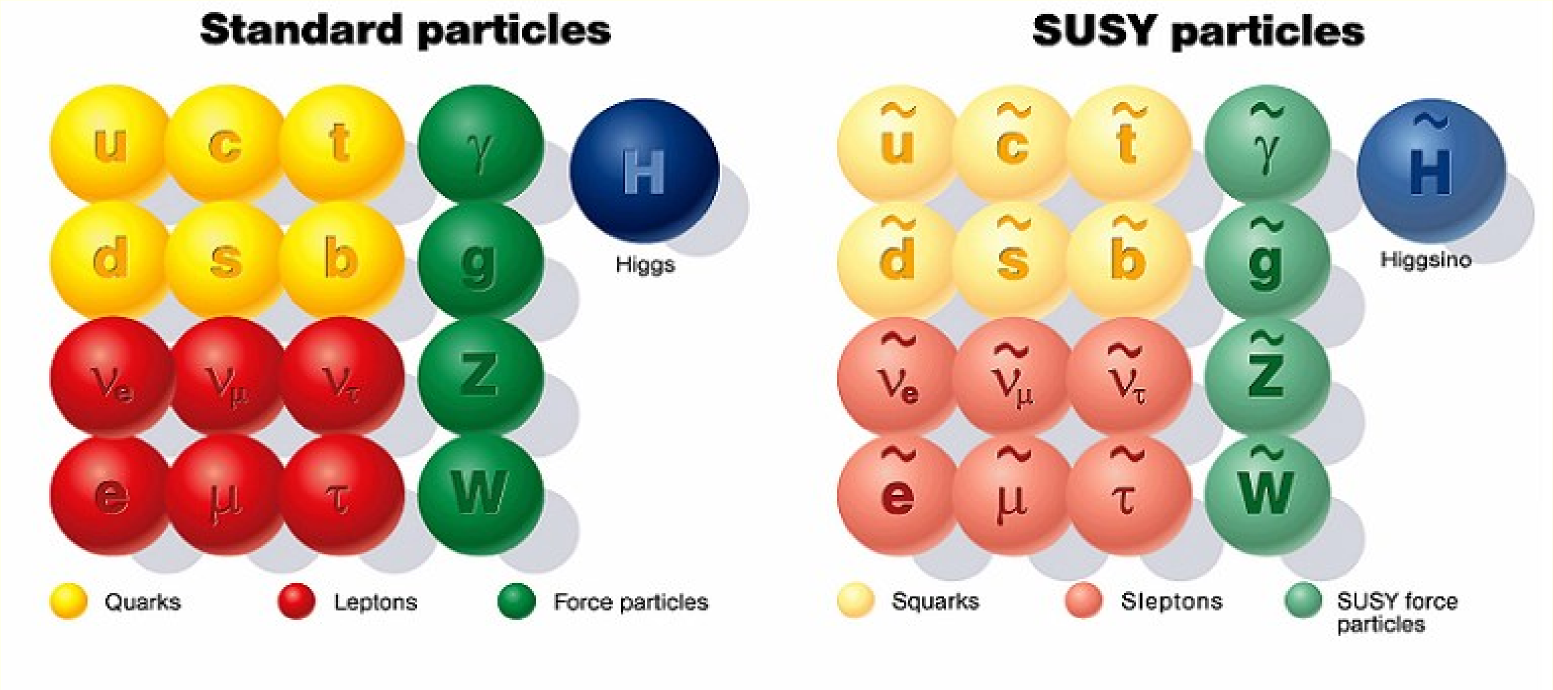
n.b. thermal WIMPs

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

WIMP mass: GeV – 10 TeV

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

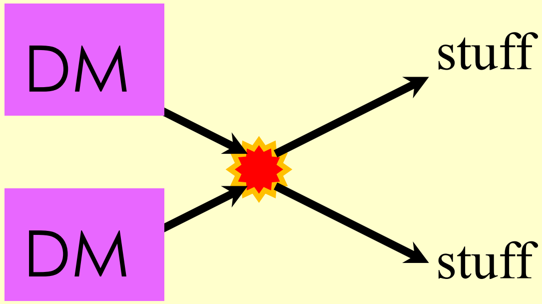
- Every particle we know has a partner



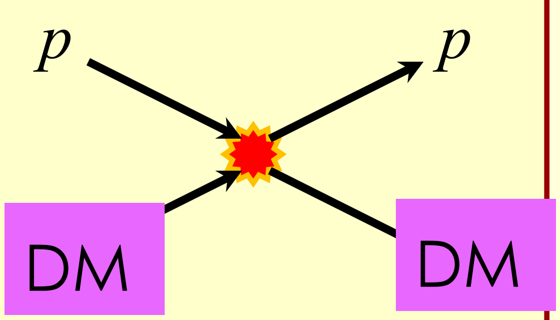
- The lightest supersymmetric particle may be the dark matter.

THREE PRONGED APPROACH TO WIMP DETECTION

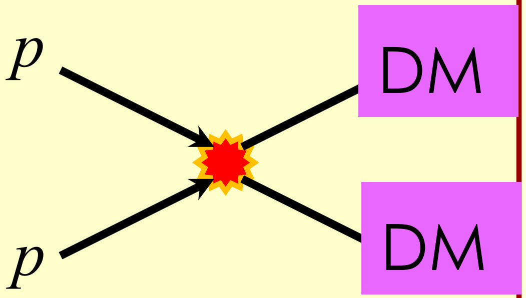
Interactions with Standard Model particles



Annihilation



Scattering



Production

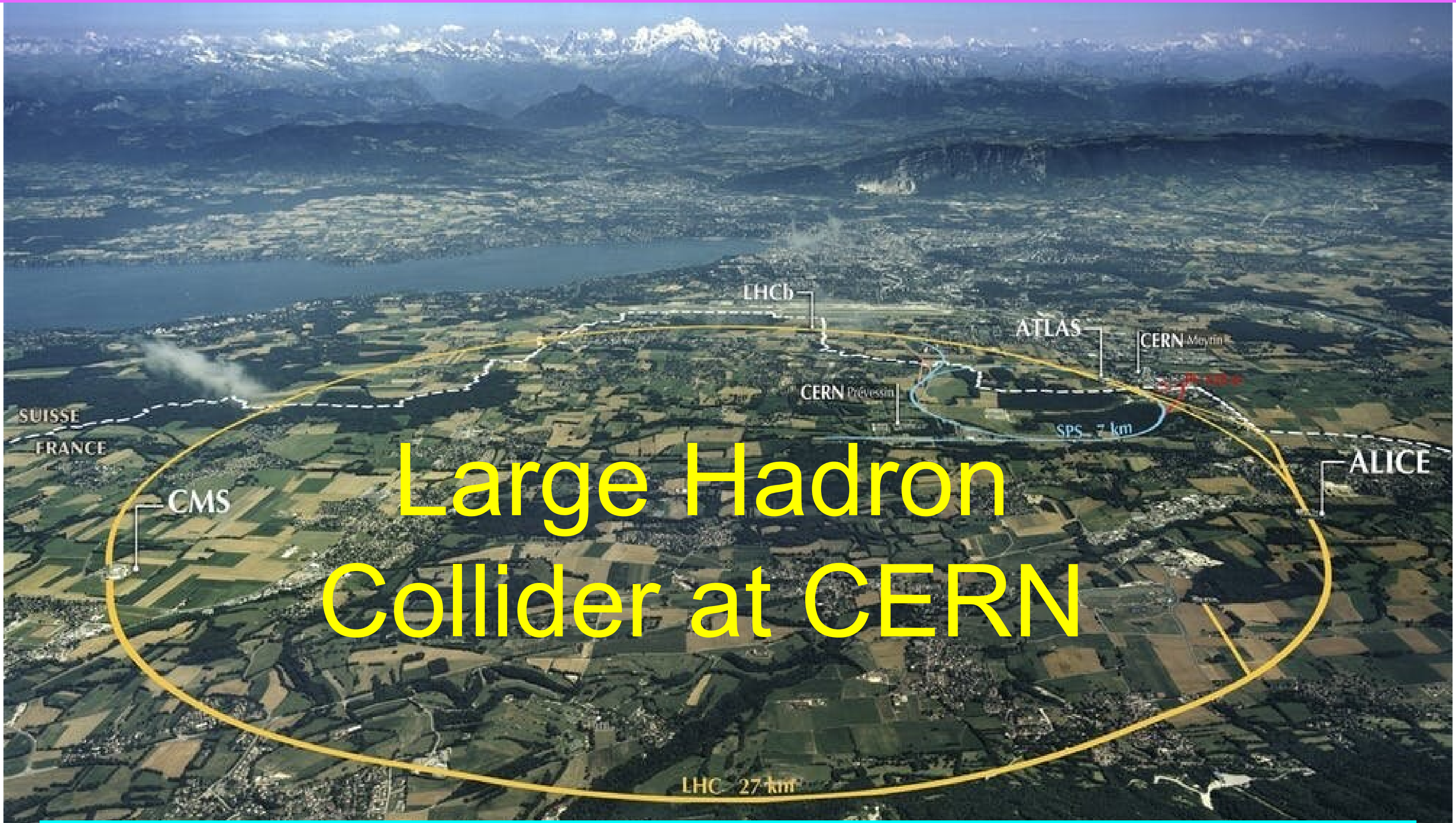
Indirect Detection:
Halo (cosmic-rays), capture in Sun (ν's)

Direct Detection:
Look for scattering events in detector

Accelerators:
LHC

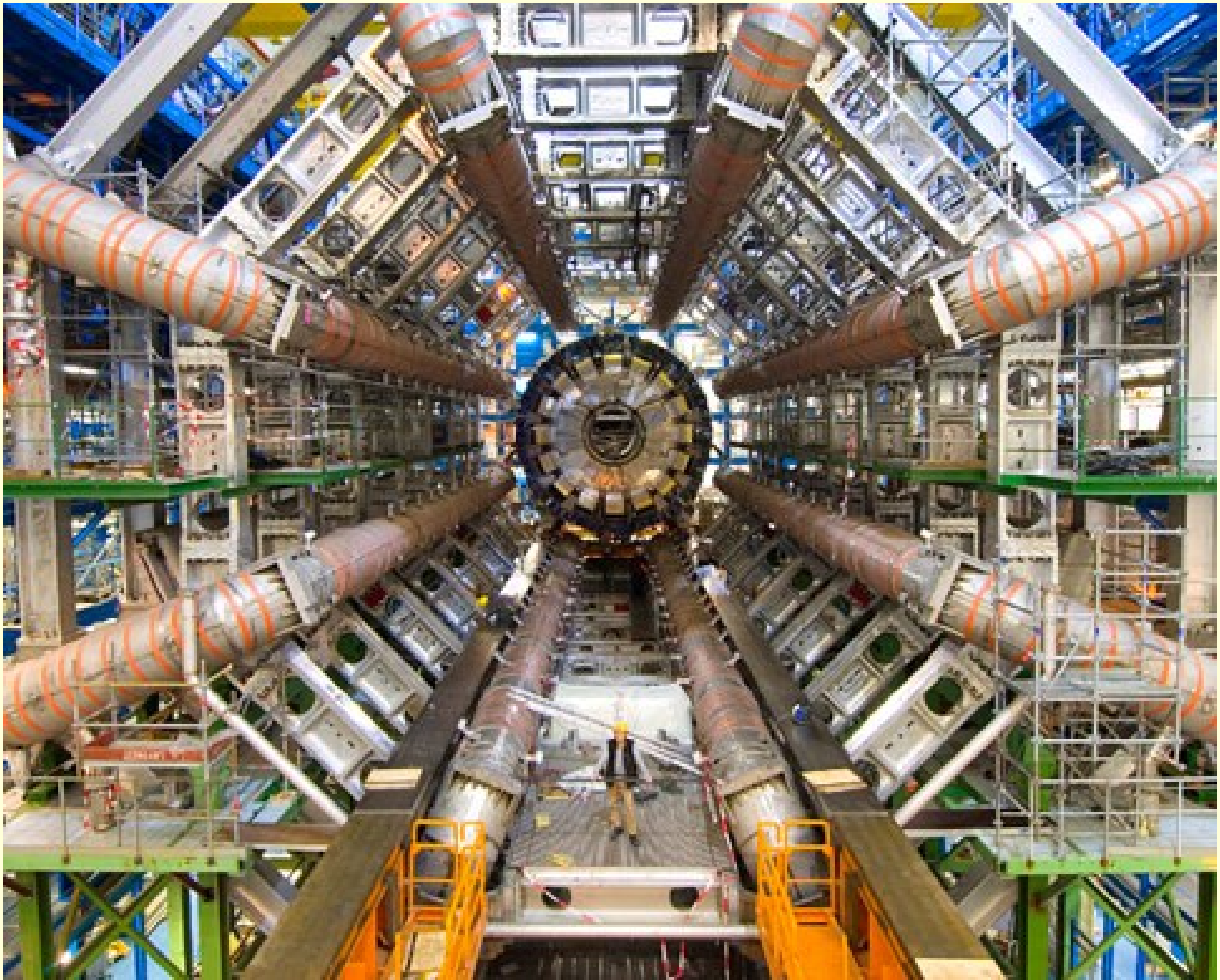
FOURTH PRONG: DARK STARS

FIRST WAY TO SEARCH FOR WIMPS

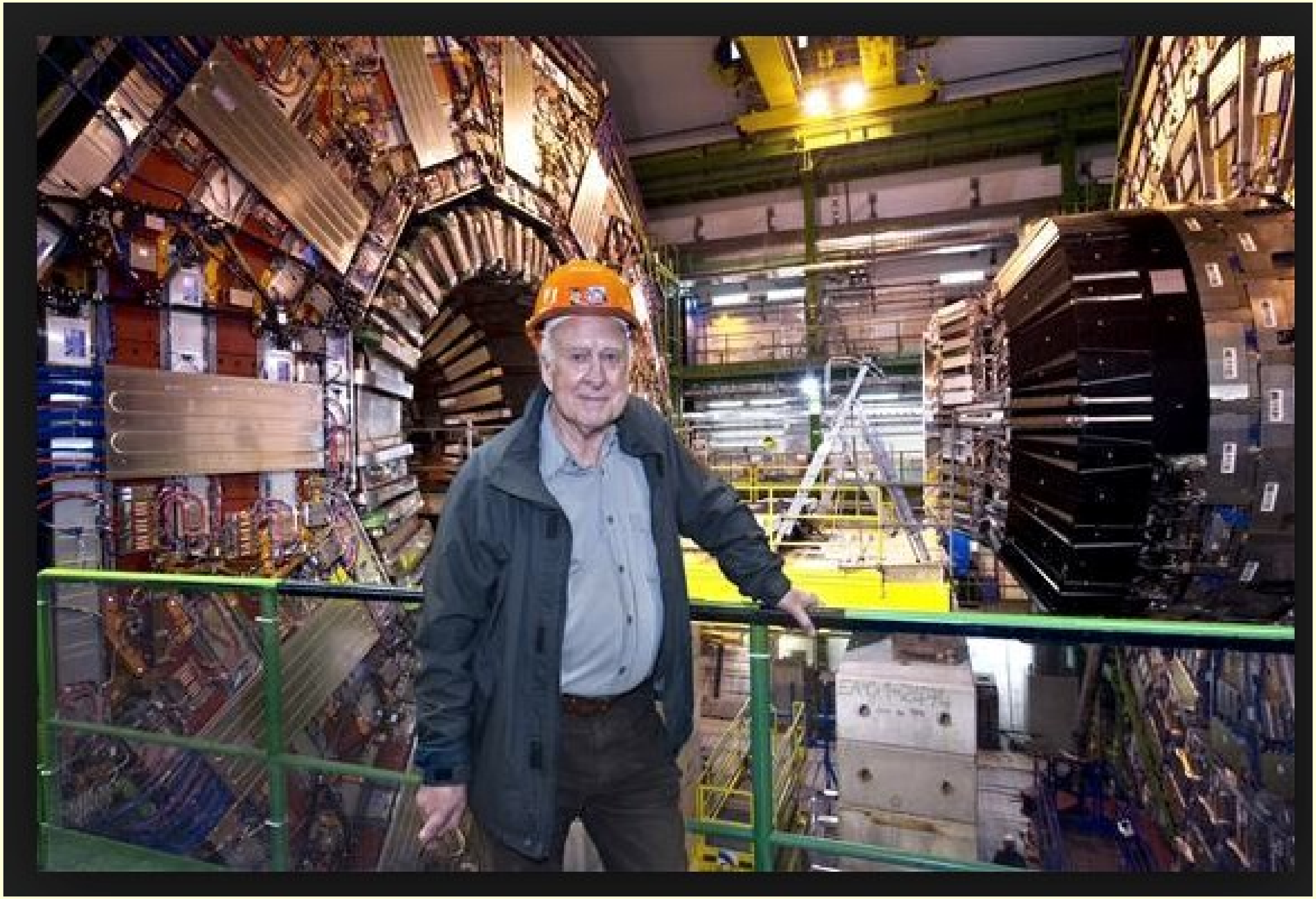


Ring that is 17 miles around.
Two proton beams traveling underground in opposite directions collide at the locations of the detectors

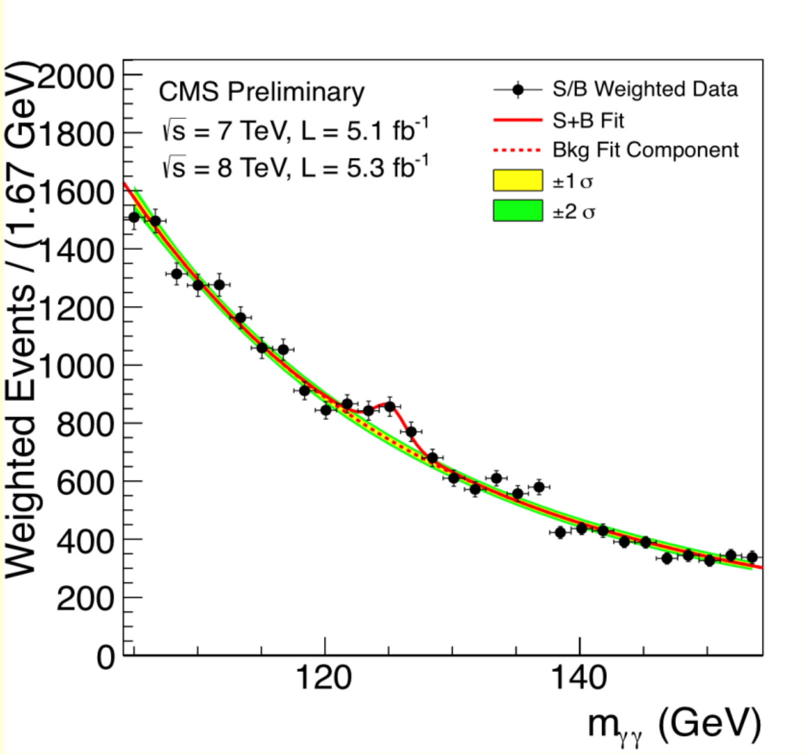
ATLAS Detector at CERN



Peter Higgs and CMS detector



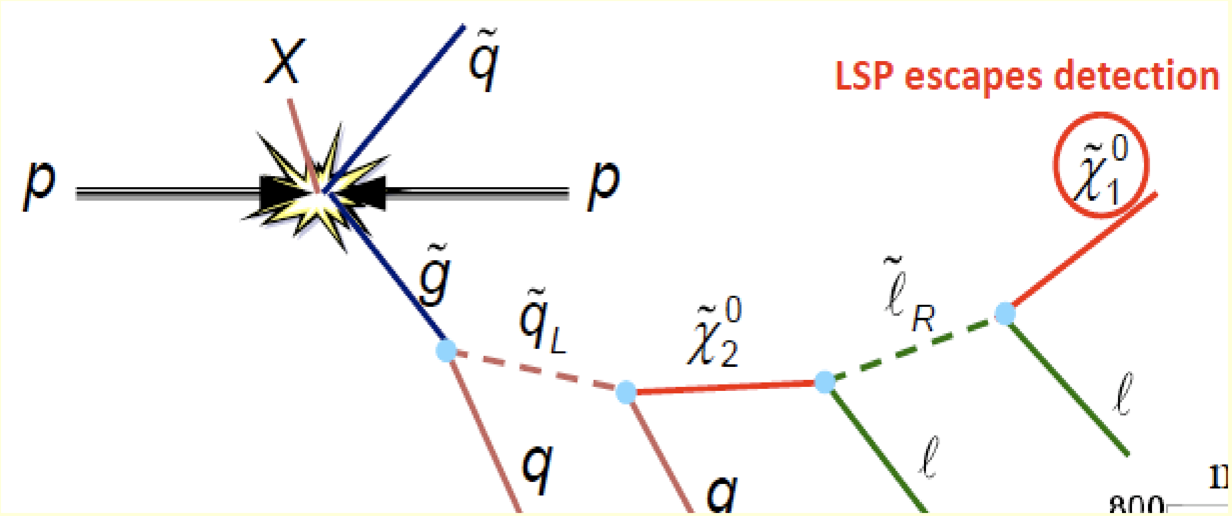
LHC's first success
Discovery of Higgs boson
weighing 125 GeV



Key role of Higgs:
imparts mass
to other particles

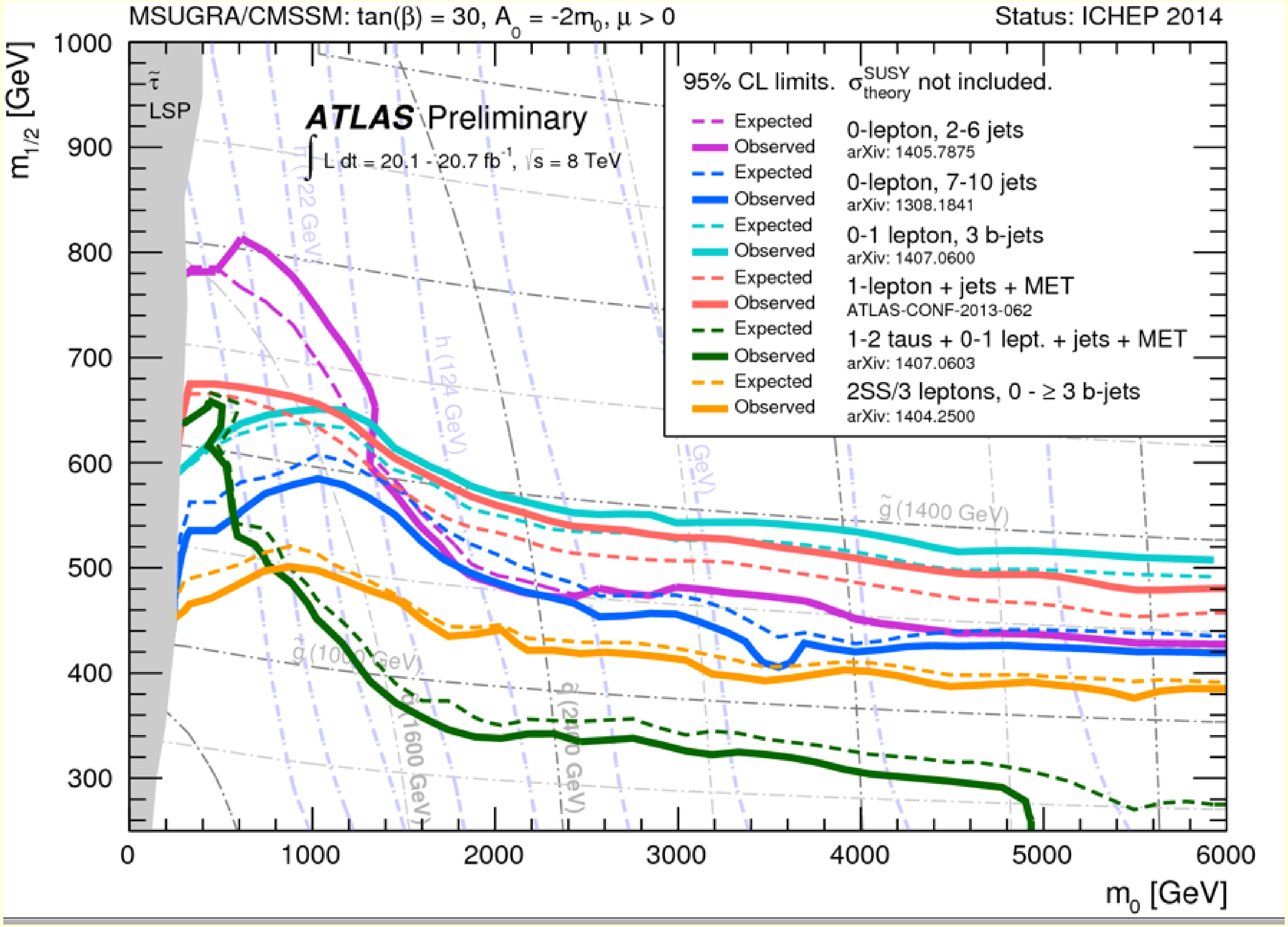
Second major goal of LHC: search for SUSY and dark matter

- Two signatures: Missing energy plus jets



- Nothing seen yet: particle masses pushed to higher masses

ATLAS bounds on CMSSM



Comments on DM at LHC

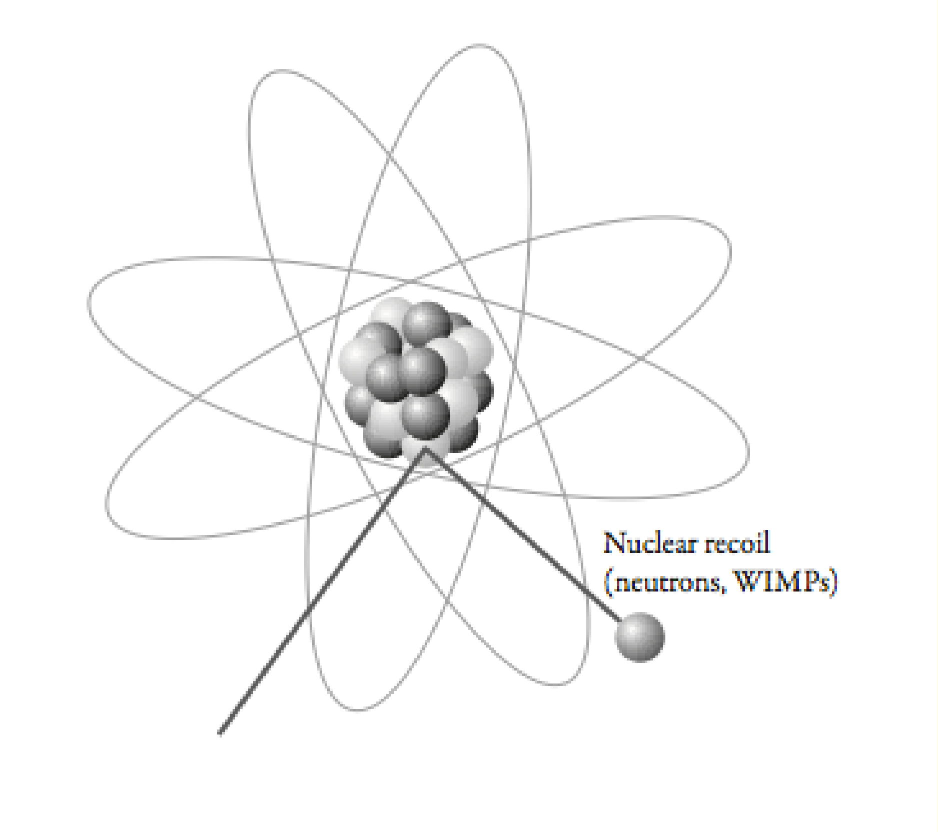
- If the LHC sees nothing, can SUSY survive? Yes.
- It may be at high scale,
- It may be less simple than all scalars and all fermions at one scale, e.g. NUHM (Pearl Sandick)
- Even is SUSY is found at LHC, we still won't know if particles are long-lived; to see if it's dark matter, need other approaches

SECOND WAY TO SEARCH FOR WIMPS

DIRECT DETECTION
Laboratory EXPERIMENTS

DIRECT DETECTION OF WIMP DARK MATTER

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



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

How did I get into Dark Matter?

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

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)

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

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

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

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

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.

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

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

WIMP detectors must be in underground laboratories

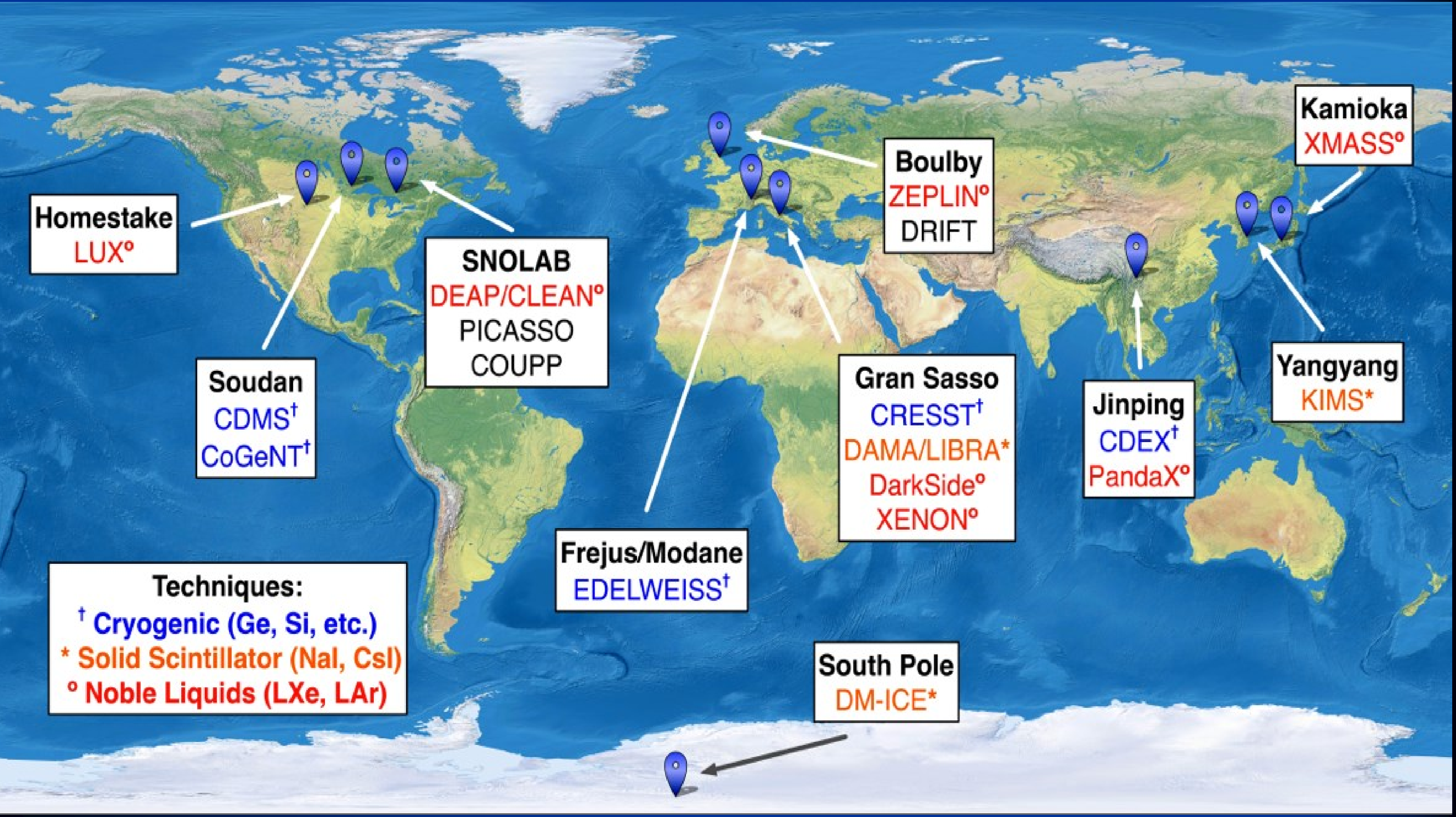
Need to shield from Cosmic Rays

XENON experiment in Gran Sasso Tunnel

WIMP detectors must be in underground laboratories

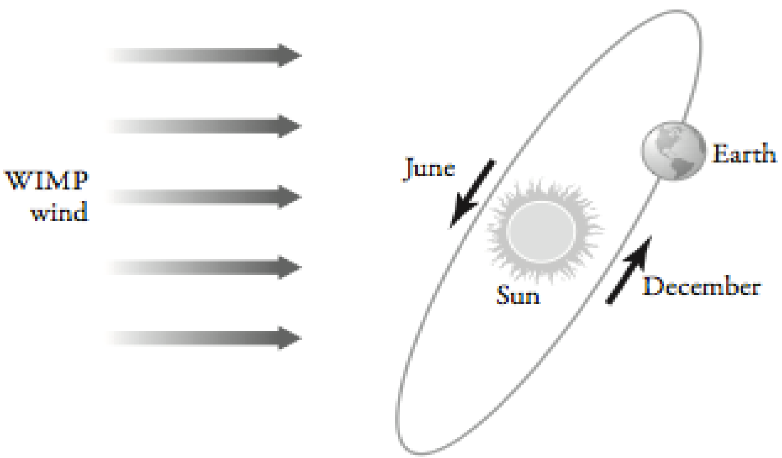
SNOLAB in a mine in Canada, 2 km below ground,
reduces cosmic rays that would overwhelm the detector
by a factor of 50 million. Location of SUPERCDMS experiment.

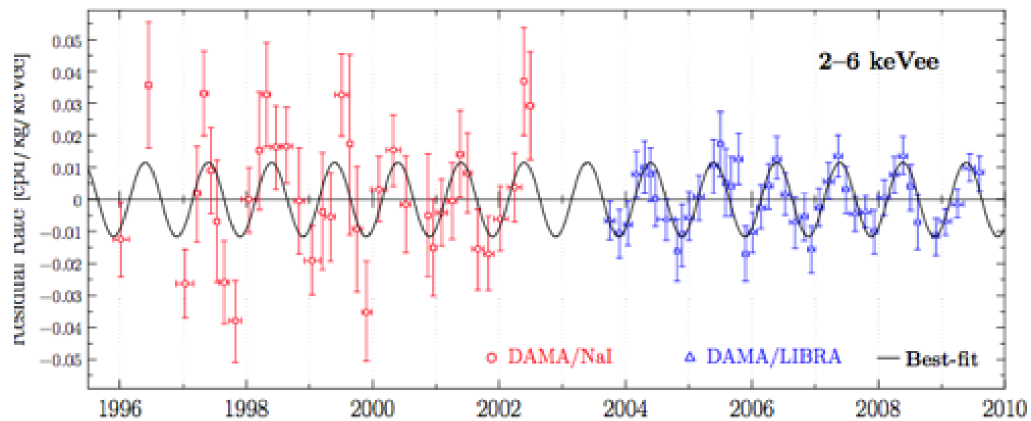
UNDERGROUND DARK MATTER LABORATORIES WORLDWIDE



DAMA annual modulation

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





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

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

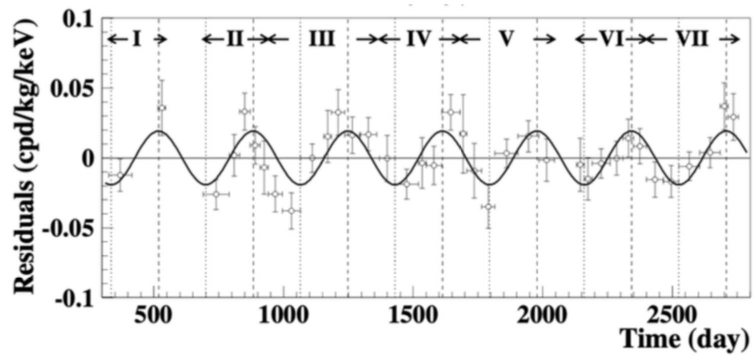


Figure 24: Experimental residual rate of the *single–hit* scintillation events measured by DAMA/NaI in the (2–6) keV energy interval as a function of the time (exposure of 0.29 ton $\times$ yr) . The superimposed curve is the cosinusoidal functional forms $A\cos\omega(t-t_0)$ with a period $T = \frac{2\pi}{\omega}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

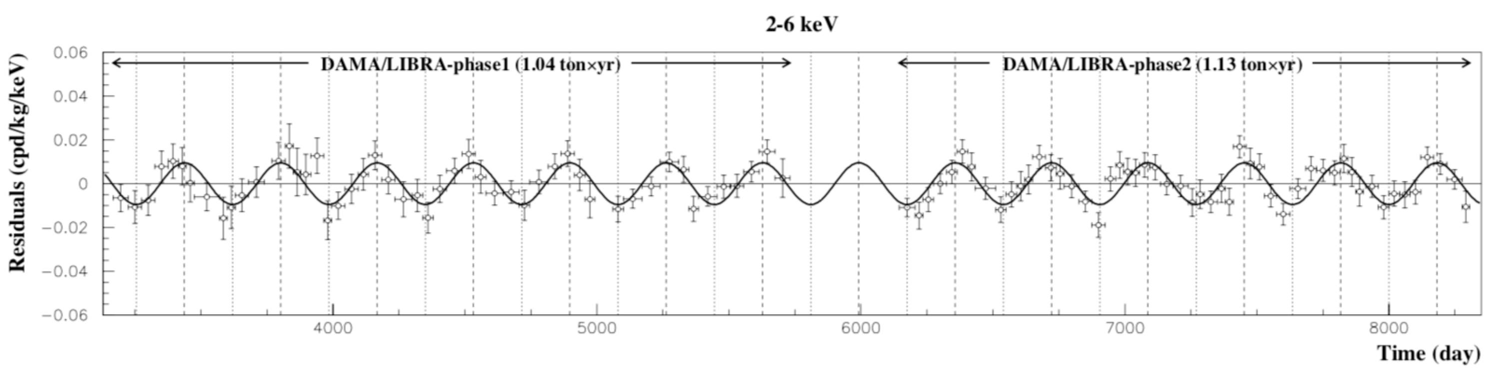


Figure 25: Experimental residual rate of the *single–hit* scintillation events measured by DAMA/LIBRA–phase1 and DAMA/LIBRA–phase2 in the (2–6) keV energy intervals as a function of the time. The superimposed curve is the cosinusoidal functional forms $A\cos\omega(t-t_0)$ with a period $T = \frac{2\pi}{\omega}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

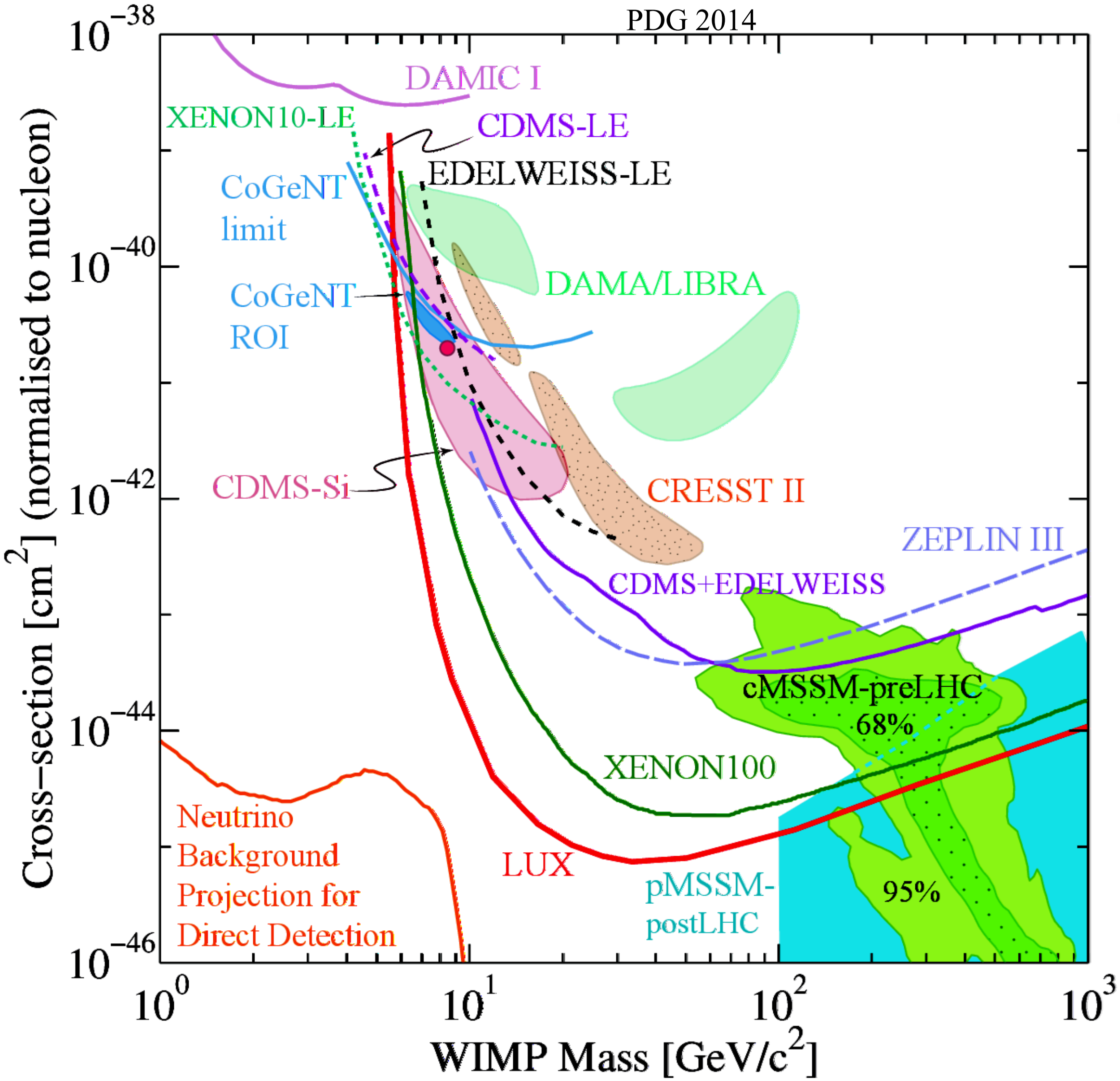
“I’ m a Spaniard caught between two Italian women”

Rita Bernabei, DAMA

Juan Collar, PICO

Elena Aprile, XENON

Bounds on Spin Independent WIMPs

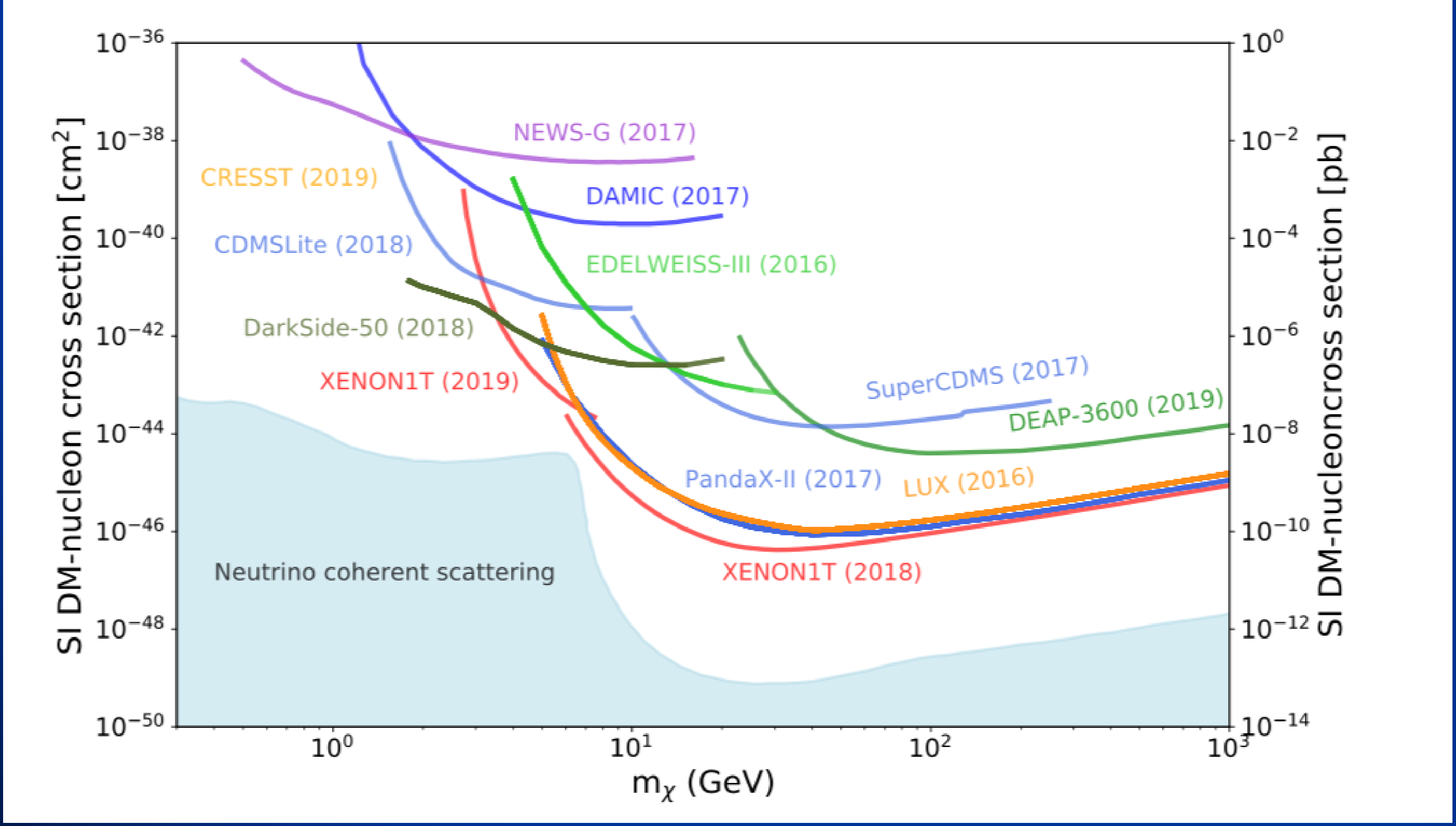


BUT:

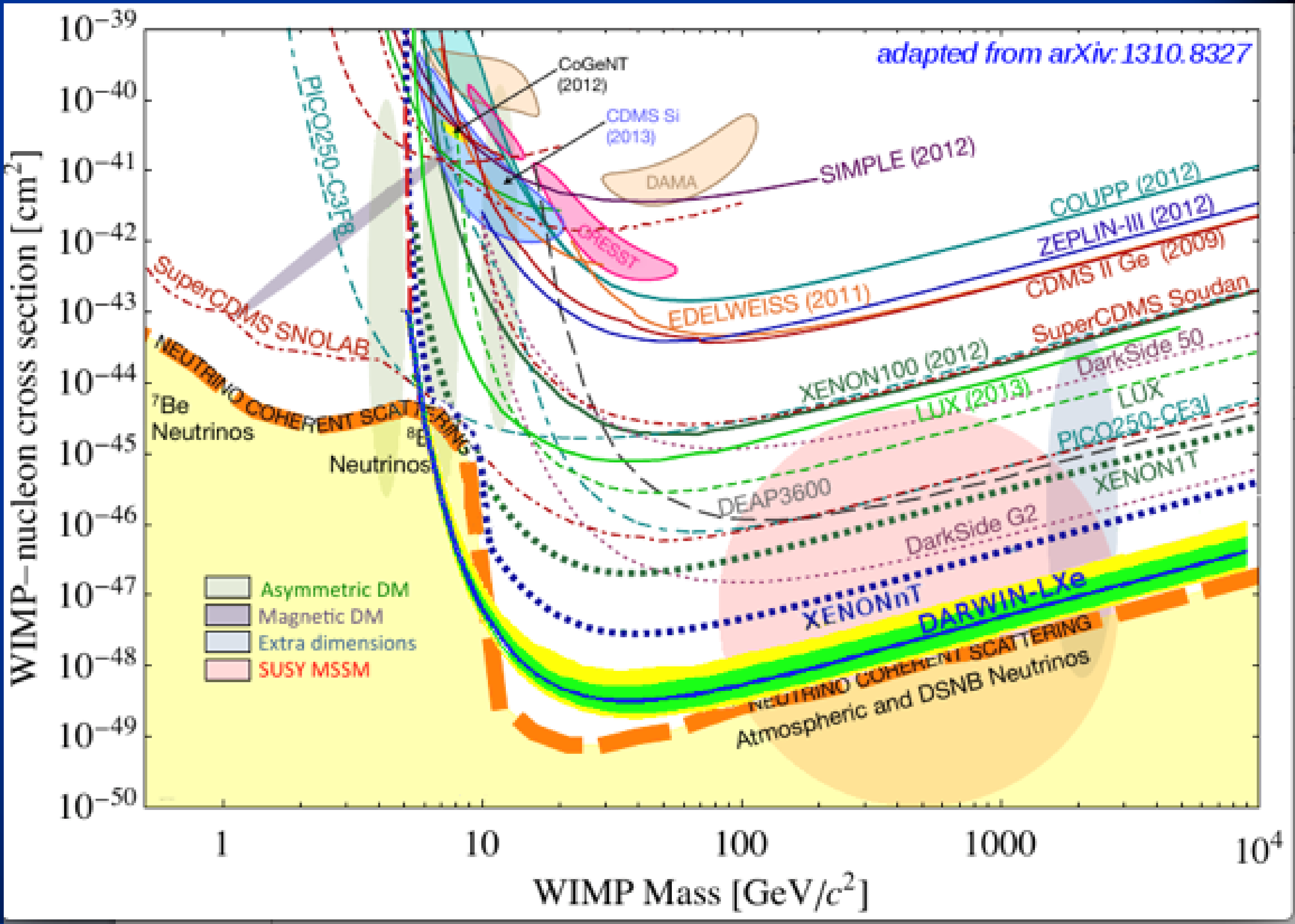
--- it's hard to compare results from different detector materials

--- can we trust results near threshold?

From PDG 2019

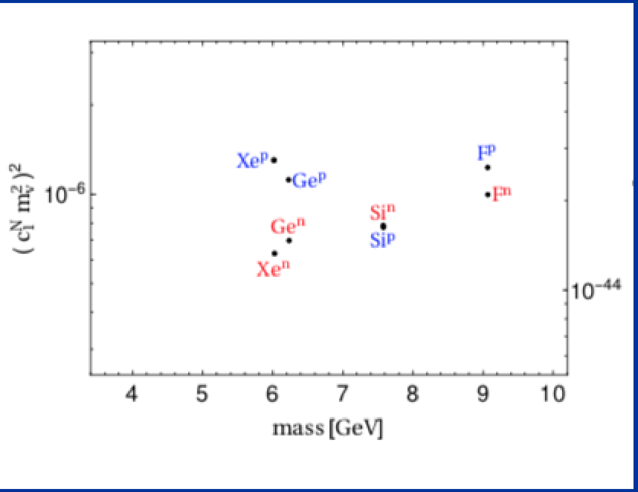


Future experiments

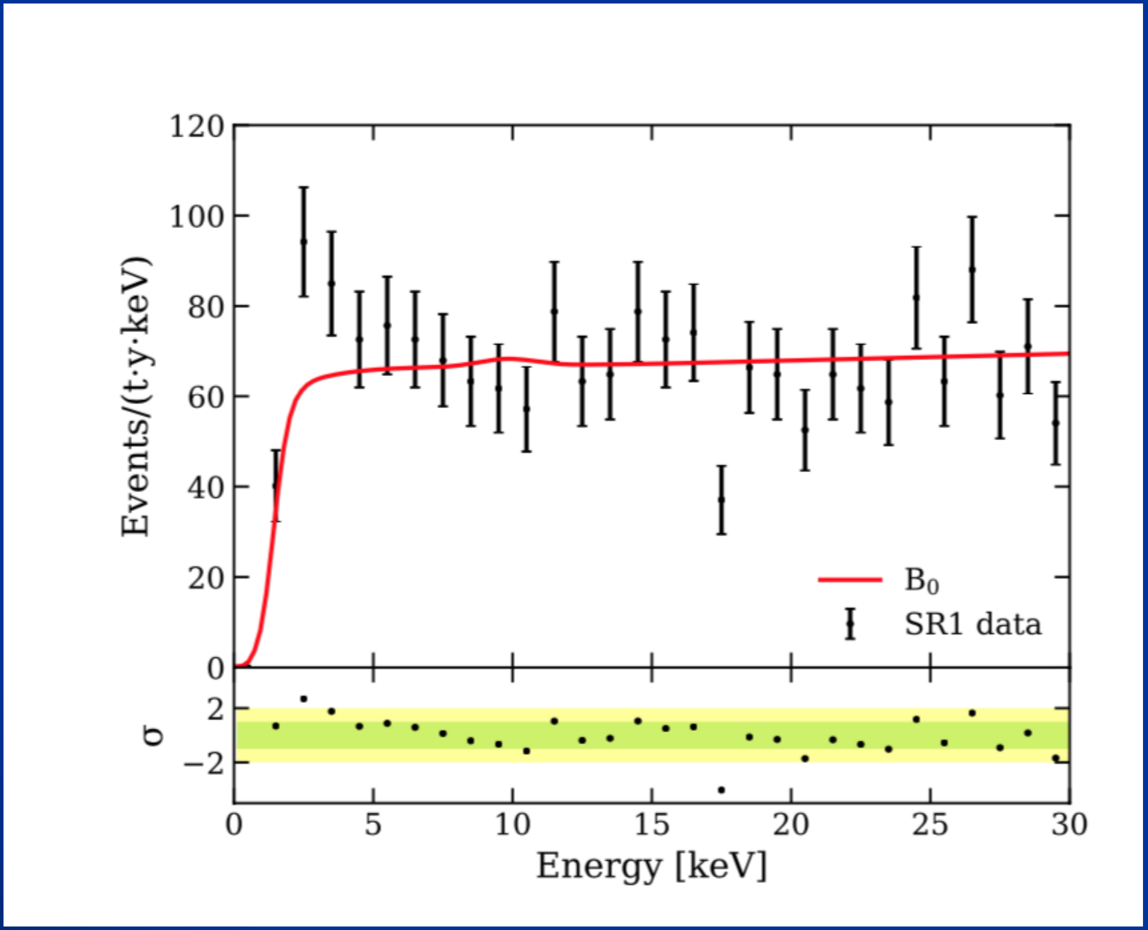


How to get below neutrino floor

- 1) Know neutrino backgrounds well so you can subtract them off
- 2) Directional Detection
- 2) Different energy spectra for WIMPs v.s neutrinos
- Except B8 neutrinos can have same spectra as 6 GeV WIMPs
- https://arxiv.org/pdf/1602.05300.pdf
- E.g. for SI WIMPs:

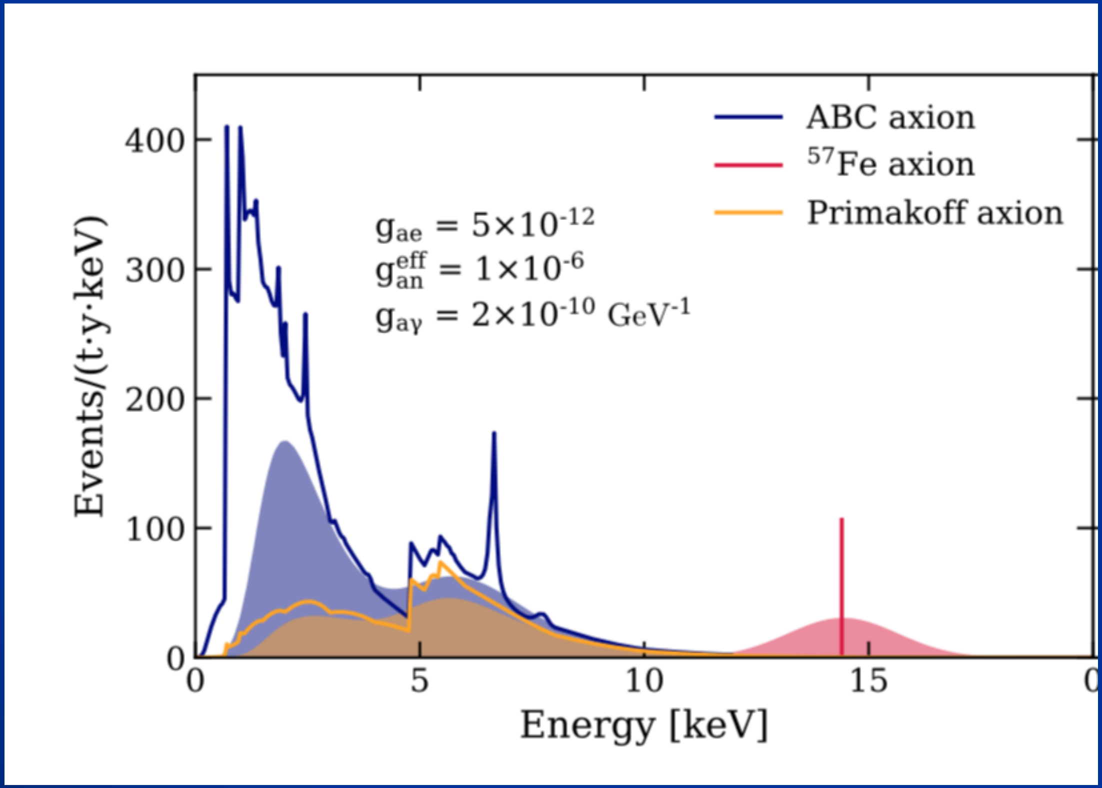


XENON 1T excess at 2-3 keV



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

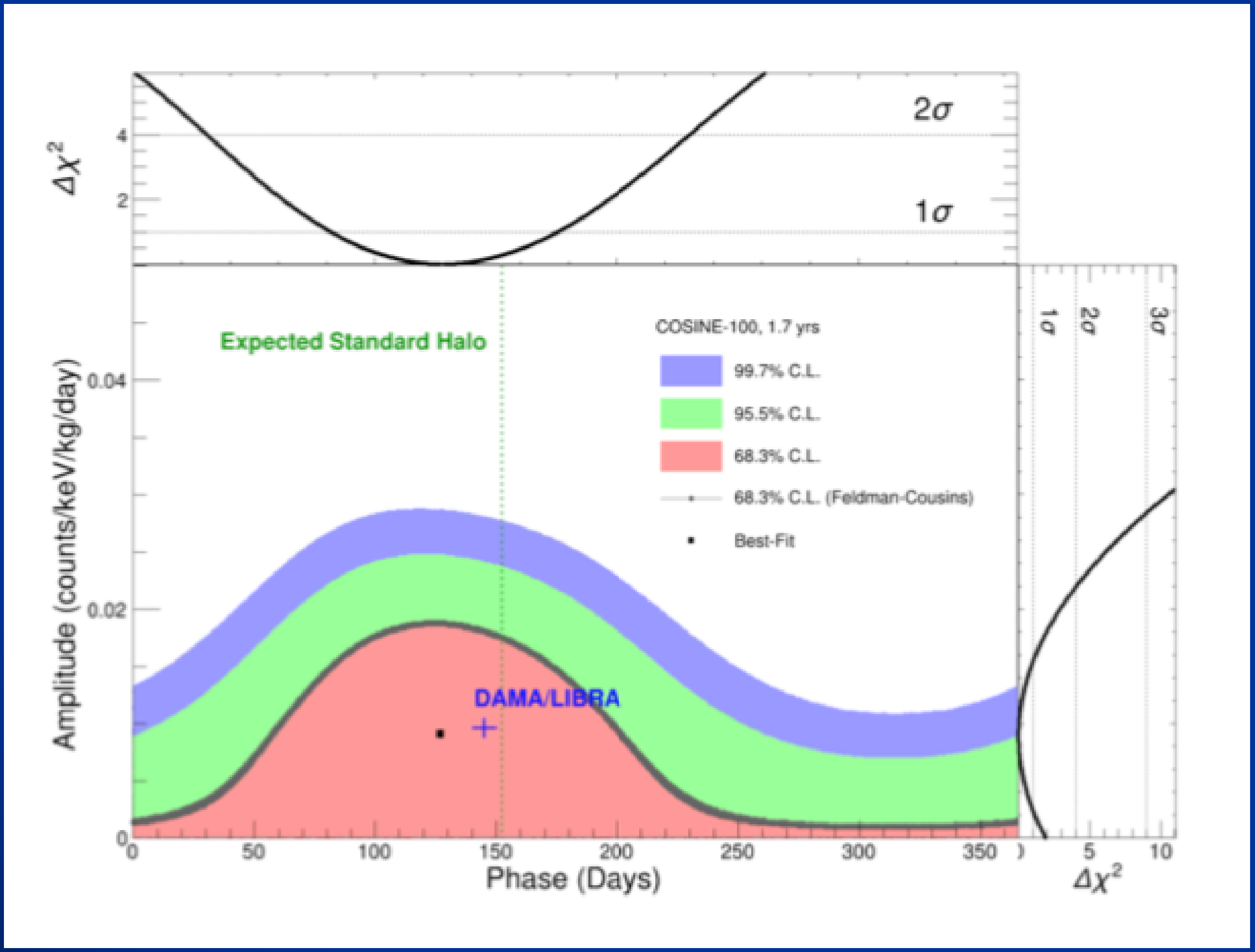
The one with the right spectrum is axions from the Sun, but this interpretation is ruled out by stellar cooling of white dwarfs and horizontal branch stars.



To test DAMA within next 5 years

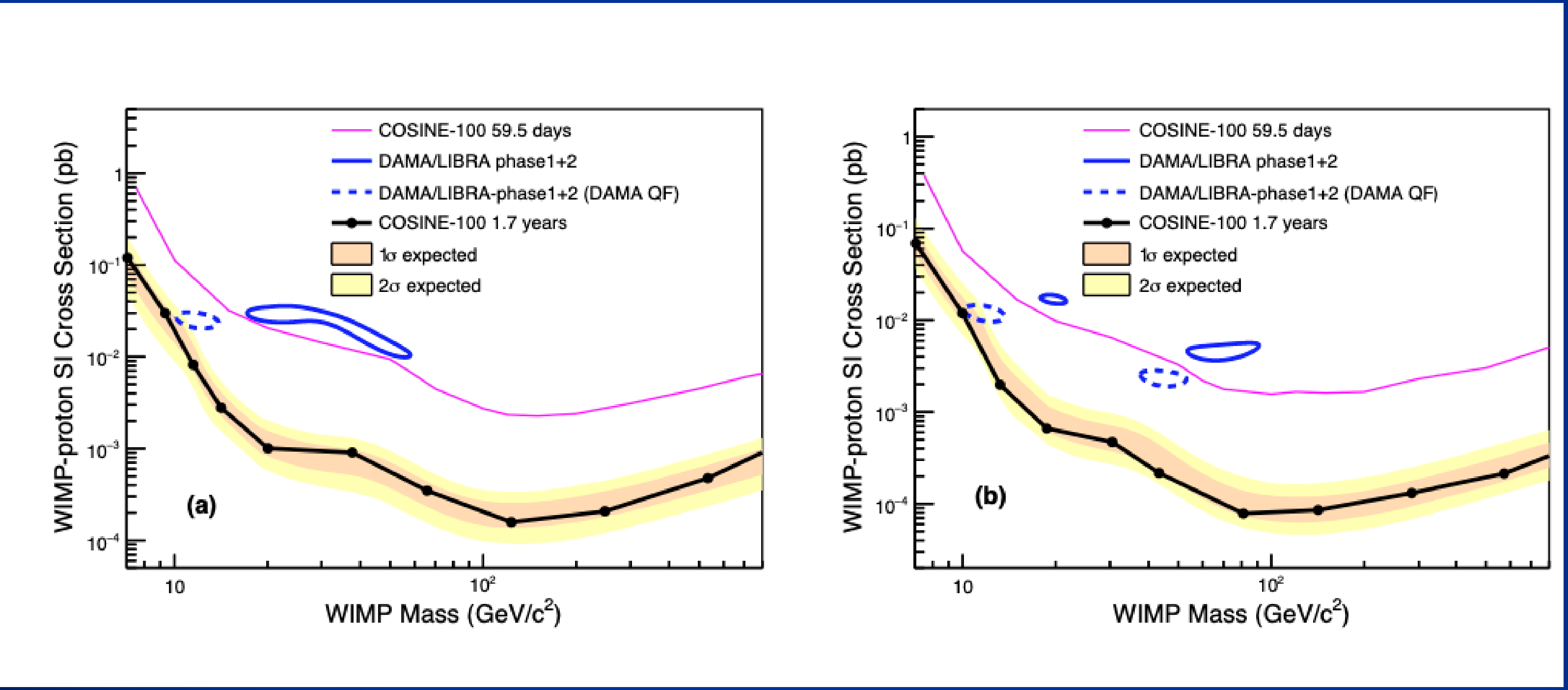
- The annual modulation in the data is still there after 13 years and still unexplained.
- New DAMA data down to keV still see modulation (DAMA all by itself is not compatible with SI scattering) Baum, Freese,Kelso 2018
- Other groups are using NaI crystals:
- COSINE-100 has 1.7 years of data release, will have an answer within 3-5 years
- SABRE (Princeton) with Australia
- ANAIS

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

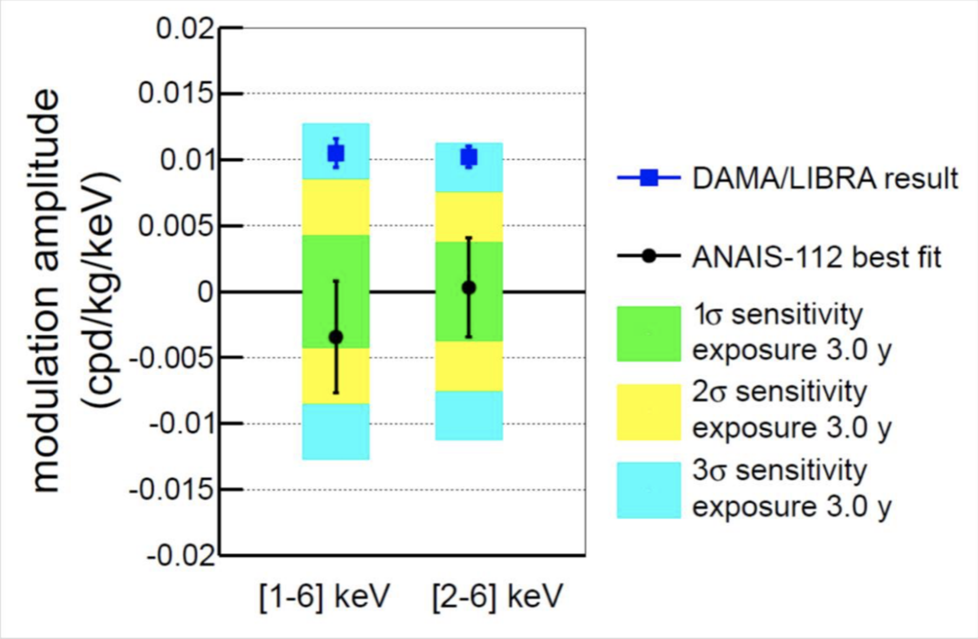
New ANAIS-112 results on annual modulation – three years exposure

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

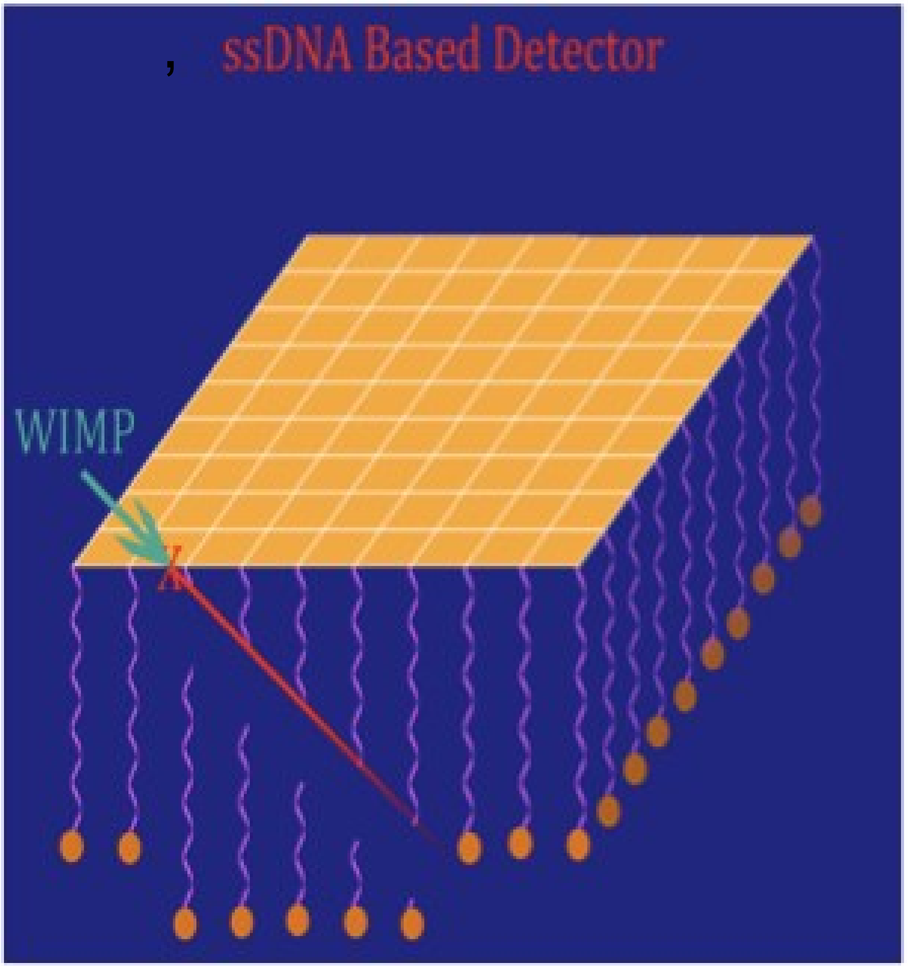
A major Step Forward: Directional Capability

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

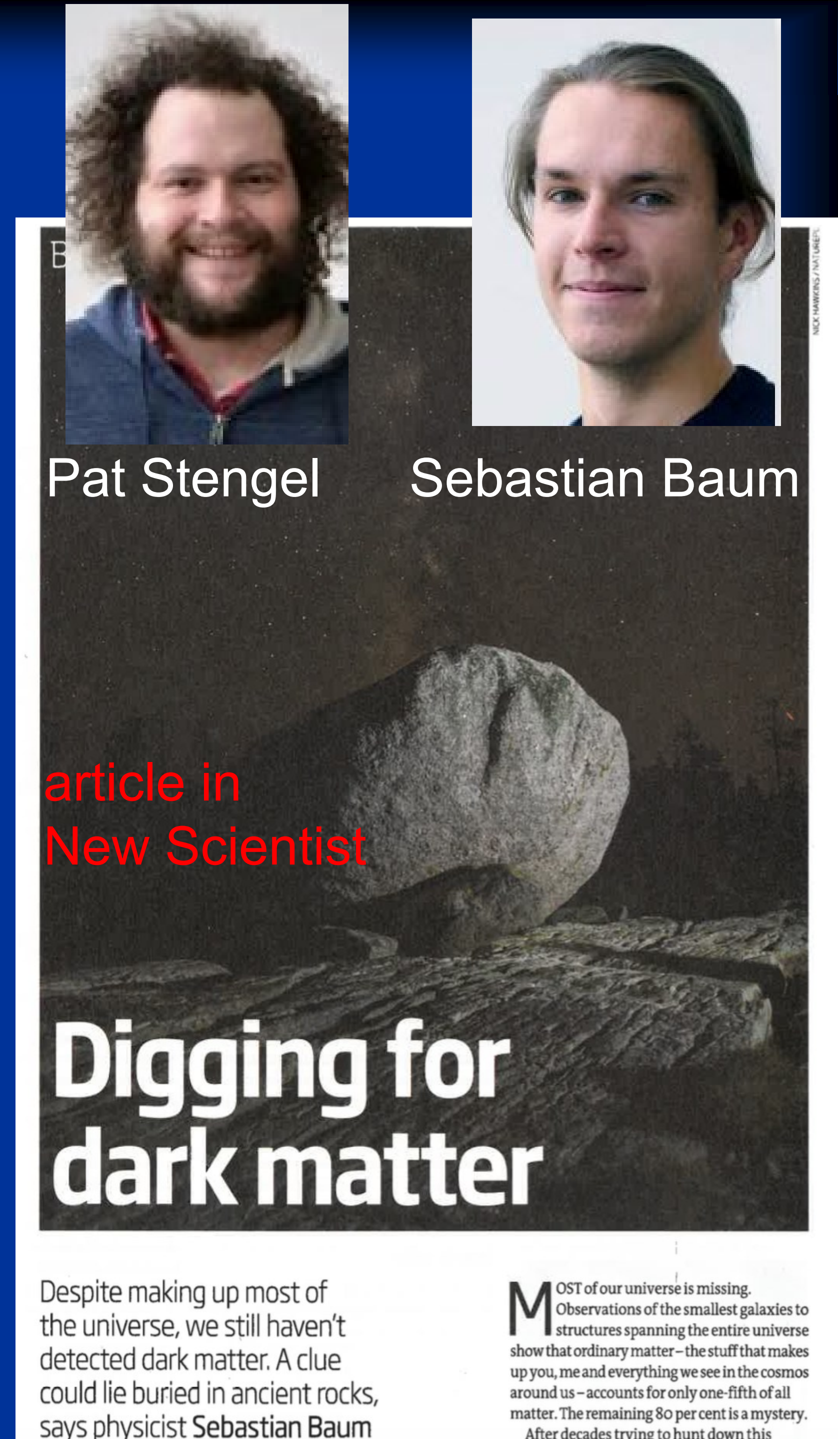
WIMPs leave tracks in ancient minerals from 10km below the surface of the Earth.

Collecting tracks for 500 Myr.

Backgrounds: Ur-238 decay and fission

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

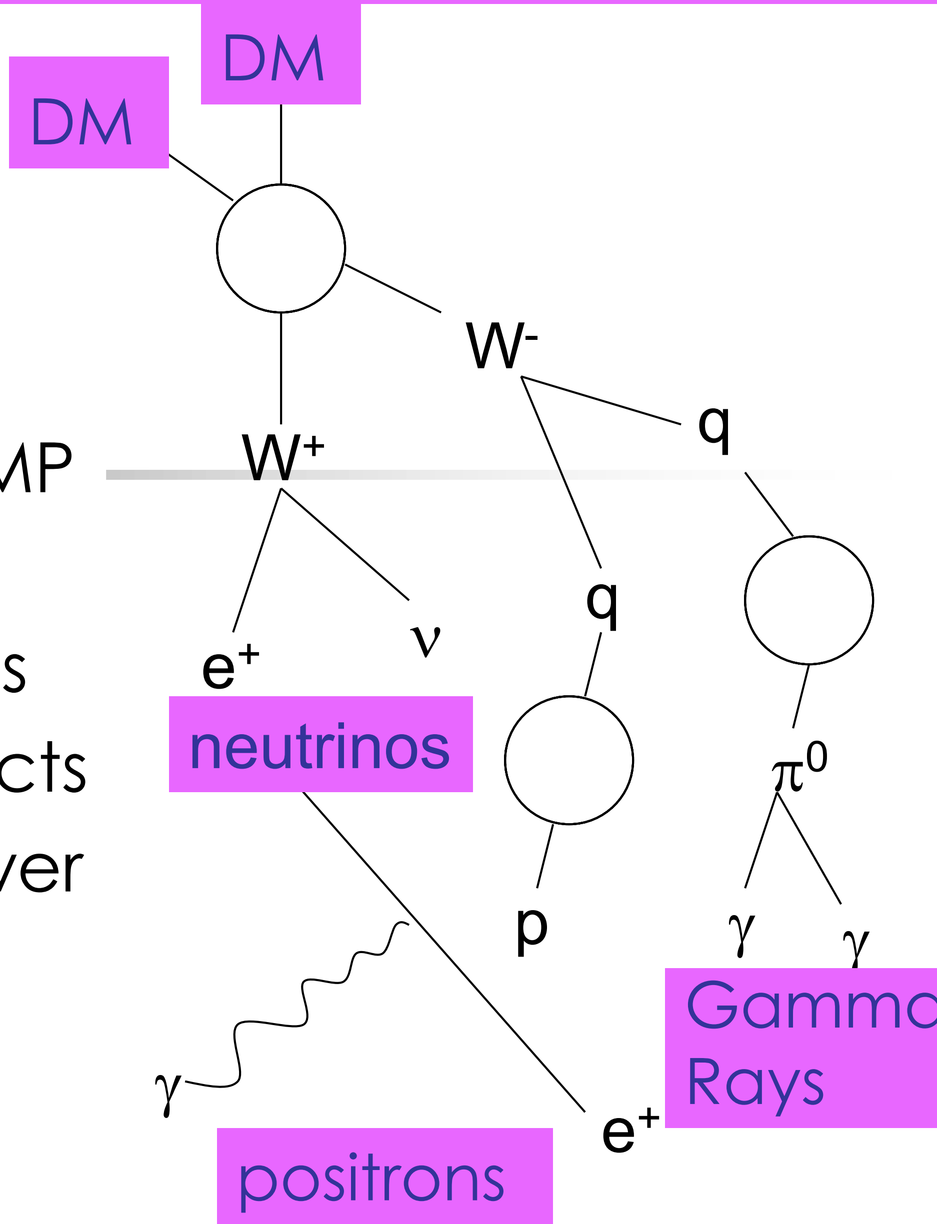
Baum, Drukier, Freese, Gorski, Stengel arXiv:1806.05991



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

Many WIMPs are their own antiparticles, annihilate among themselves:

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



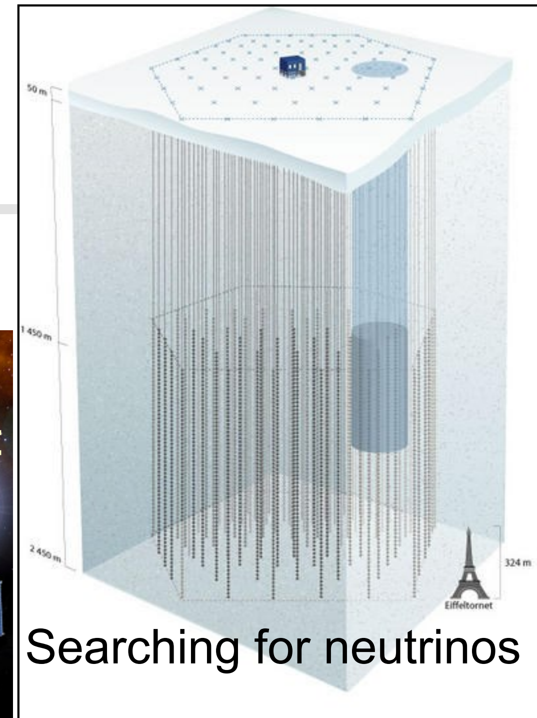
Indirect Detection: looking for DM annihilation signals

AMS aboard the International

Space Station

Found excess e+

IceCube
At the South Pole



FERMI

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

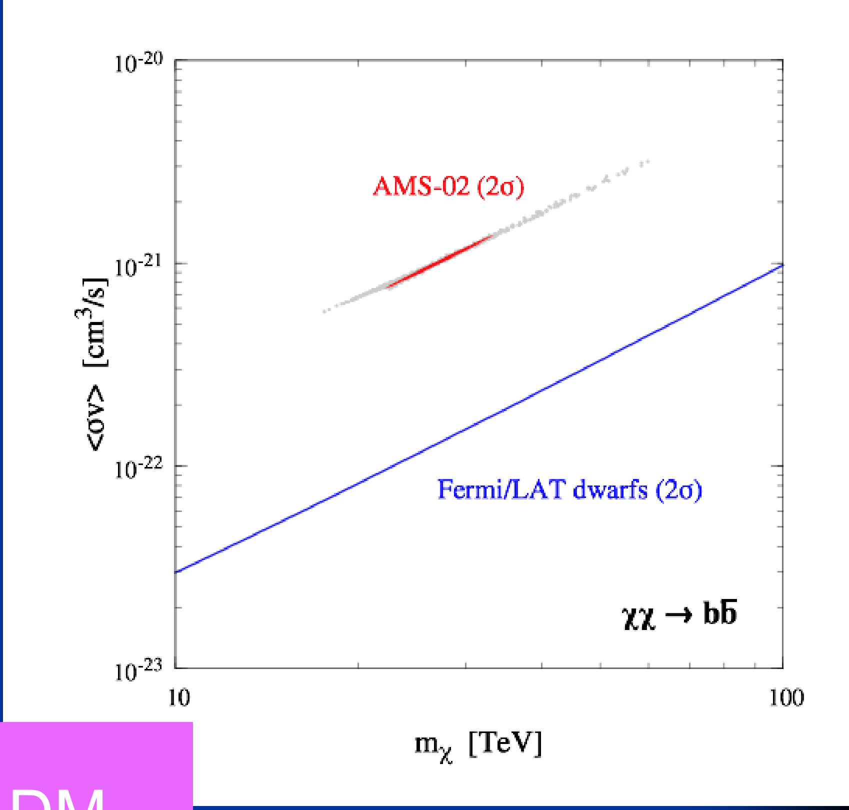
- Lopez, Savage, Spolyar, Adams (arxiv:1501.01618)
- Almost all channels ruled out,

Including all leptophilic channels

(e.g. b bar channel in plot)

What remains
DM annihilation

via mediator to four mus



AMS positron excess is not from DM

Potential Antihelium Excess seen by AMS

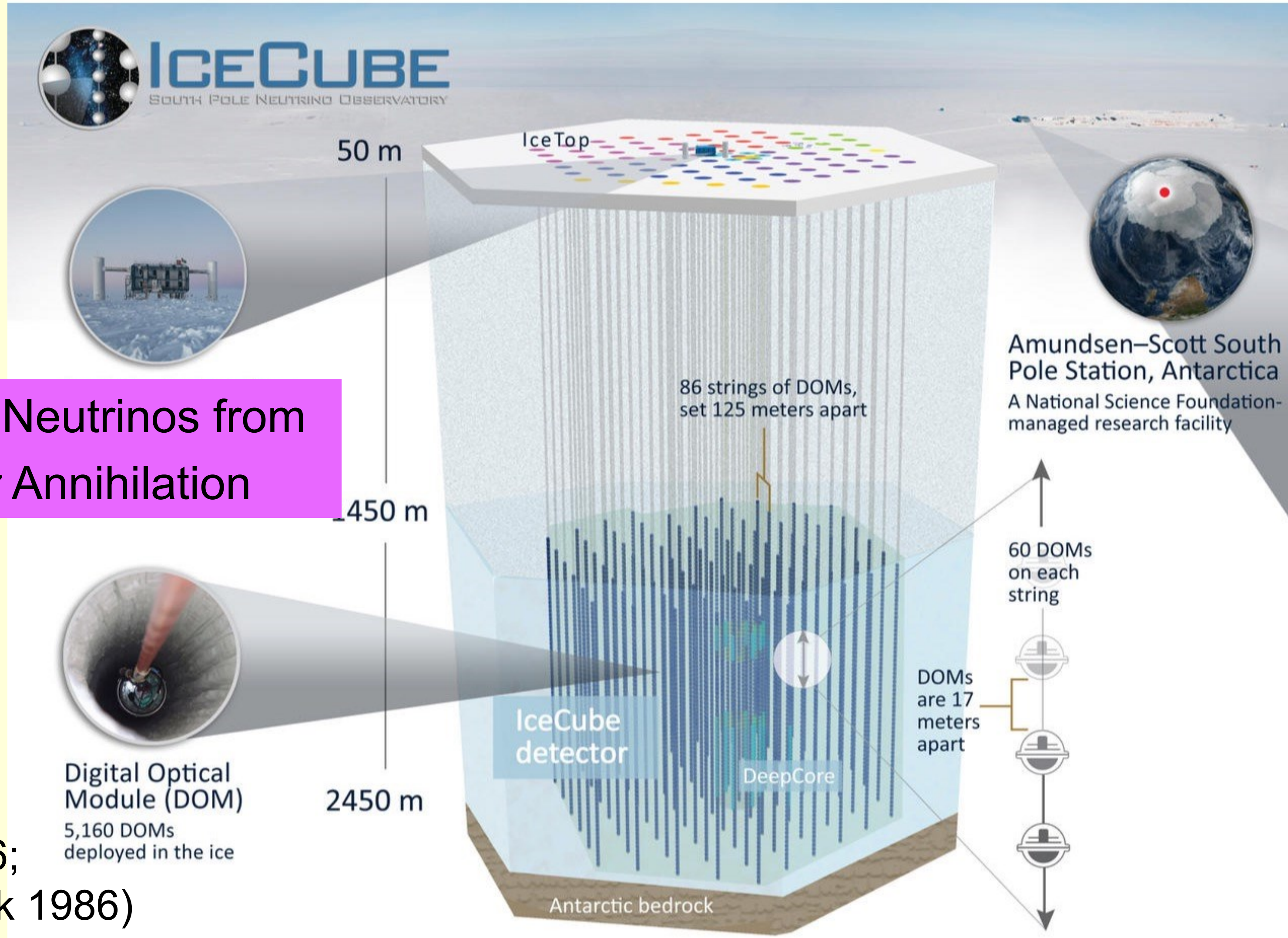
Dark Matter Annihilation Can Produce a Detectable Antihelium Flux through $\bar{\Lambda}_b$ Decays

Martin Wolfgang Winkler[1,*] and Tim Linden[1,†]

[1] *Stockholm University and The Oskar Klein Centre for Cosmoparticle Physics, Alba Nova, 10691 Stockholm, Sweden*

Recent observations by the Alpha Magnetic Spectrometer (AMS-02) have tentatively detected a handful of cosmic-ray antihelium events. Such events have long been considered as smoking-gun evidence for new physics, because astrophysical antihelium production is expected to be negligible. However, the dark-matter-induced antihelium flux is also expected to fall below current sensitivities, particularly in light of existing antiproton constraints. Here, we demonstrate that a previously neglected standard model process — the production of antihelium through the displaced-vertex decay of $\bar{\Lambda}_b$-baryons — can significantly boost the dark matter induced antihelium flux. This process can triple the standard prompt-production of antihelium, and more importantly, entirely dominate the production of the high-energy antihelium nuclei reported by AMS-02.

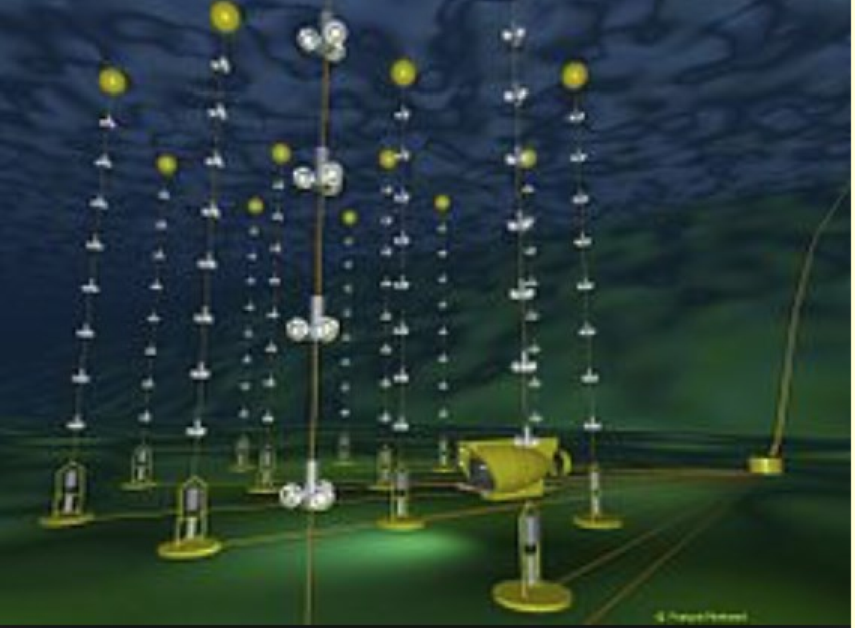
Indirect Detection of Neutrinos
IceCube at the South Pole



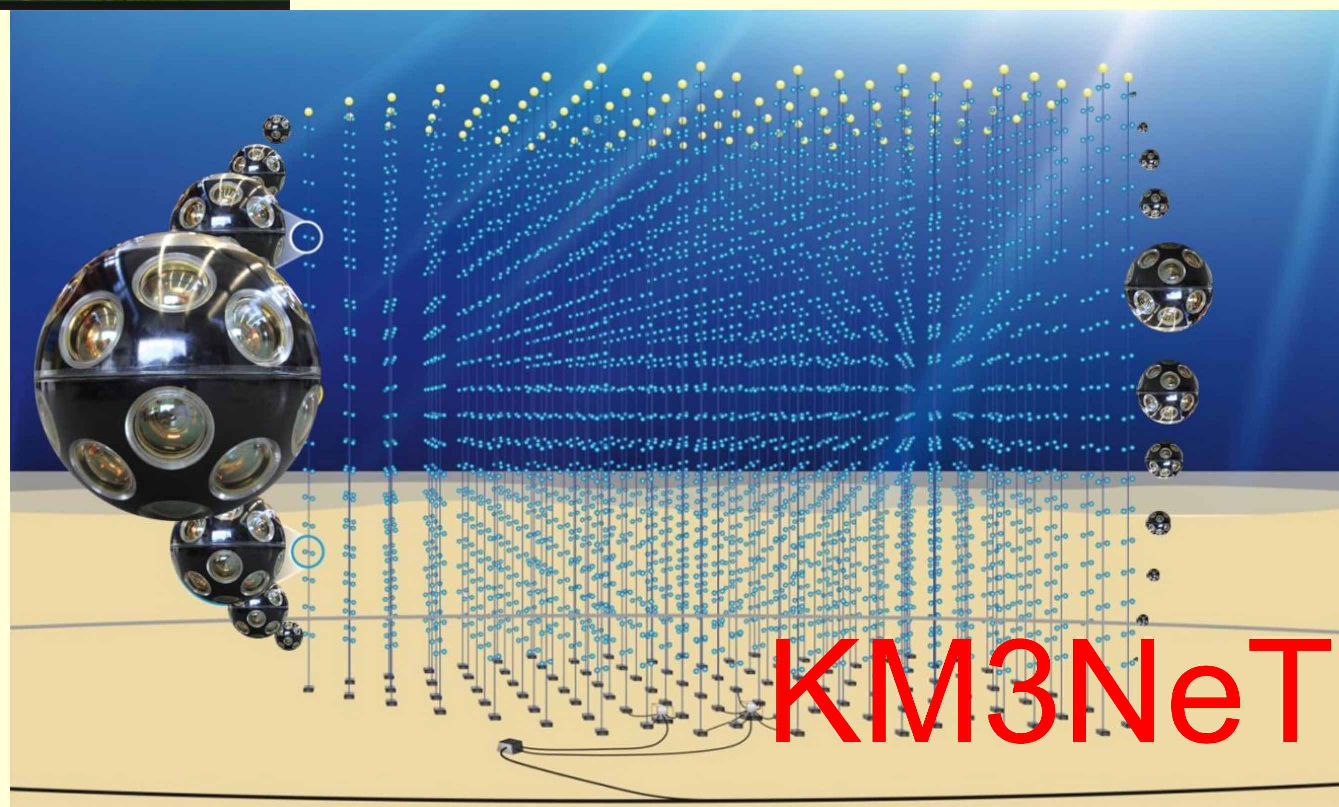
Looking for Neutrinos from Dark Matter Annihilation

Sun (Silk, Olive, Srednicki 80s)

Earth (Freese 1986; Krauss and Wilczek 1986)



ANTARES
in the Mediterranean

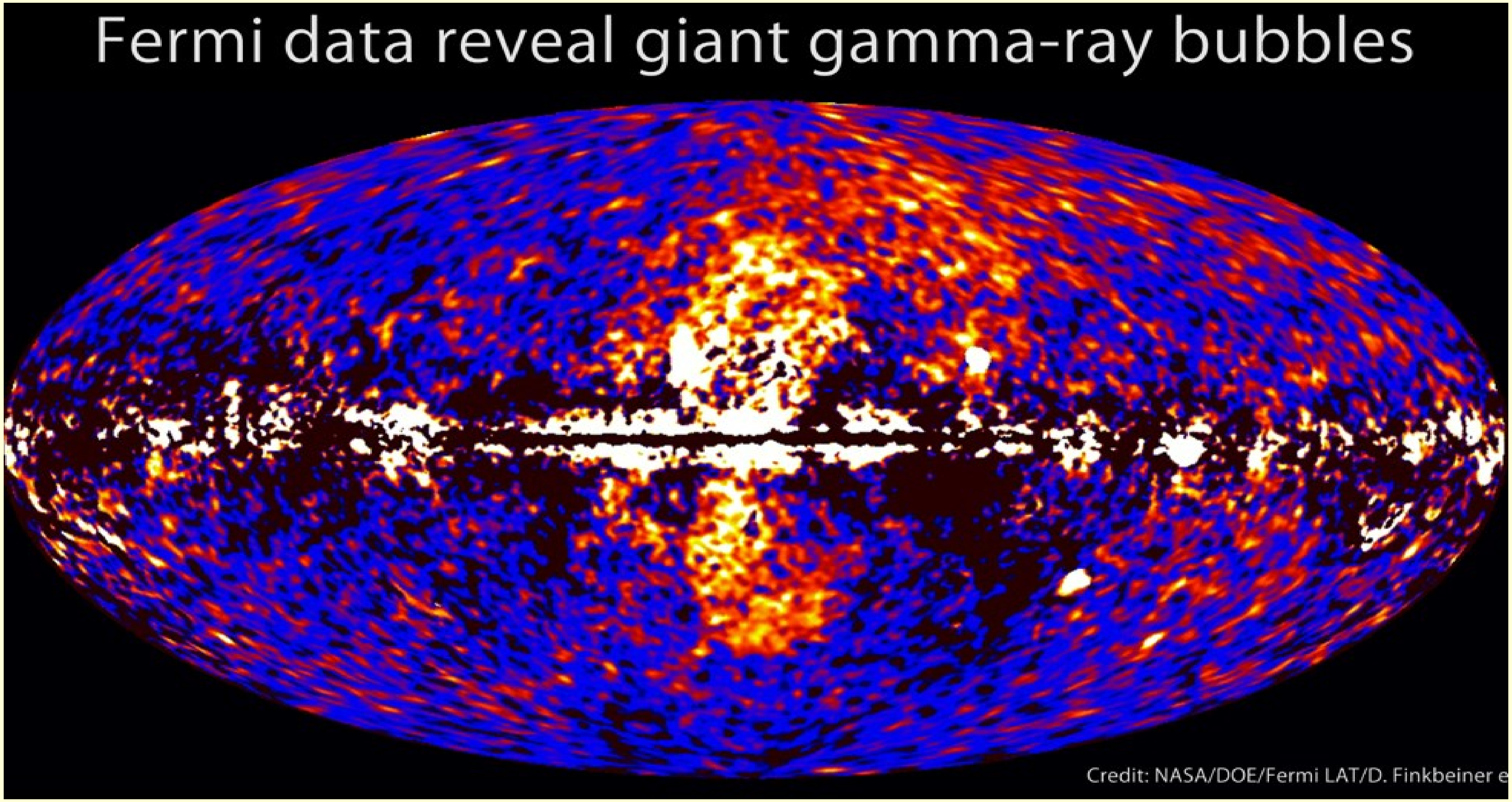


INDIRECT DETECTION of HIGH ENERGY PHOTONS (GAMMA-RAYS)

Are they from DM annihilation?

THE FERMI SATELLITE

The gamma ray sky

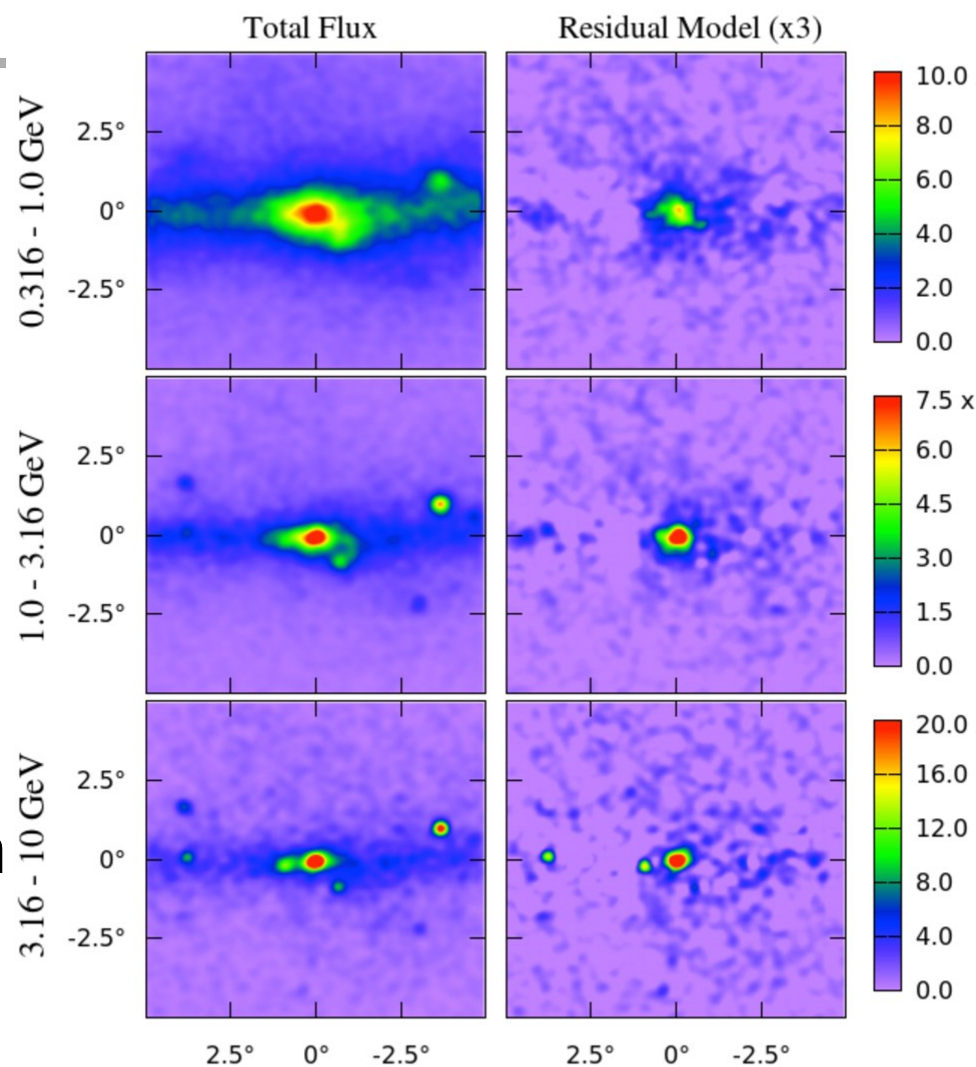


Doug Finkbeiner (Fermi Bubbles)

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, $\chi\chi \rightarrow$ b-bbar)

BUT also consistent with astrophysical point sources. Status unclear.

Possible evidence for WIMP detection :

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

FOURTH WAY TO SEARCH FOR WIMPS

Dark Stars:
Dark Matter annihilation can power the first stars

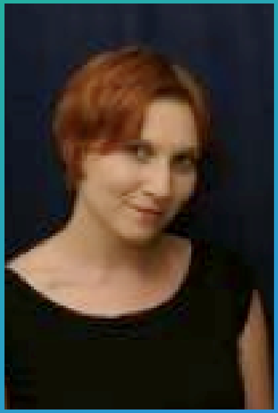
Fourth Way: Find Dark Stars (hydrogen stars powered by dark matter) in James Webb Space Telescope, sequel to Hubble Space Telescope

W Doug Spolyar, P. Gondolo

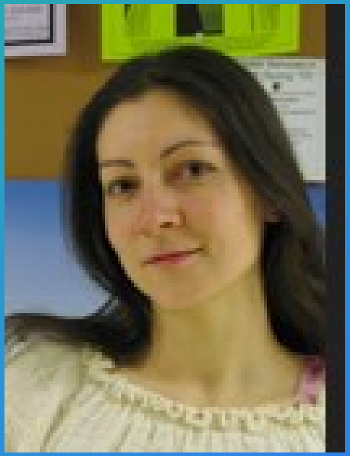
Collaborators

Doug Spolyar

Paolo Gondolo



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).

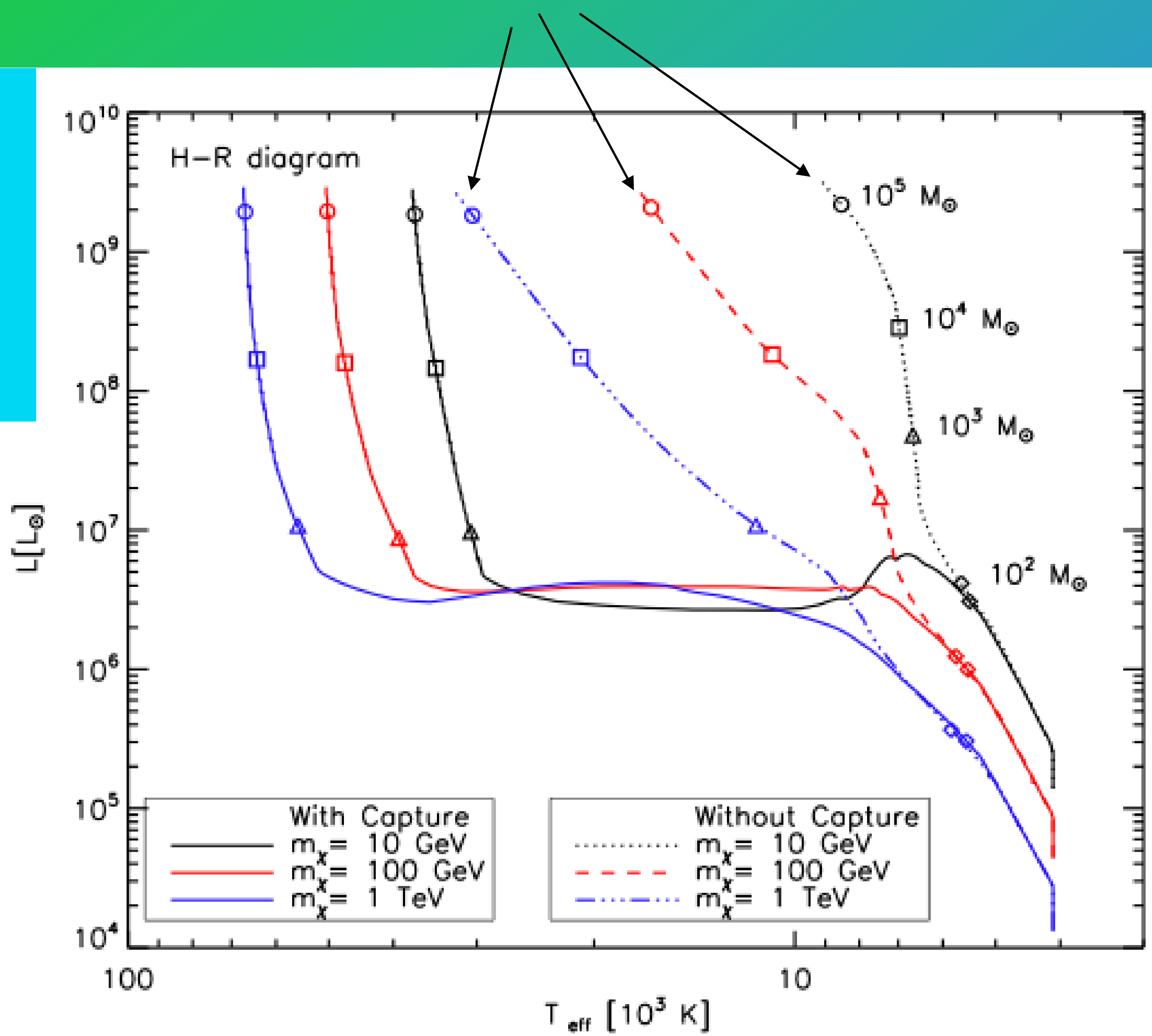
- This new phase of stellar evolution may last millions to billions of years
- Dark Stars can grow to be very large: up to ten million times the mass of the Sun. Supermassive DS are very bright, up to a billion times as bright as the Sun. **These can be seen in James Webb Space Telescope.**
- Once the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

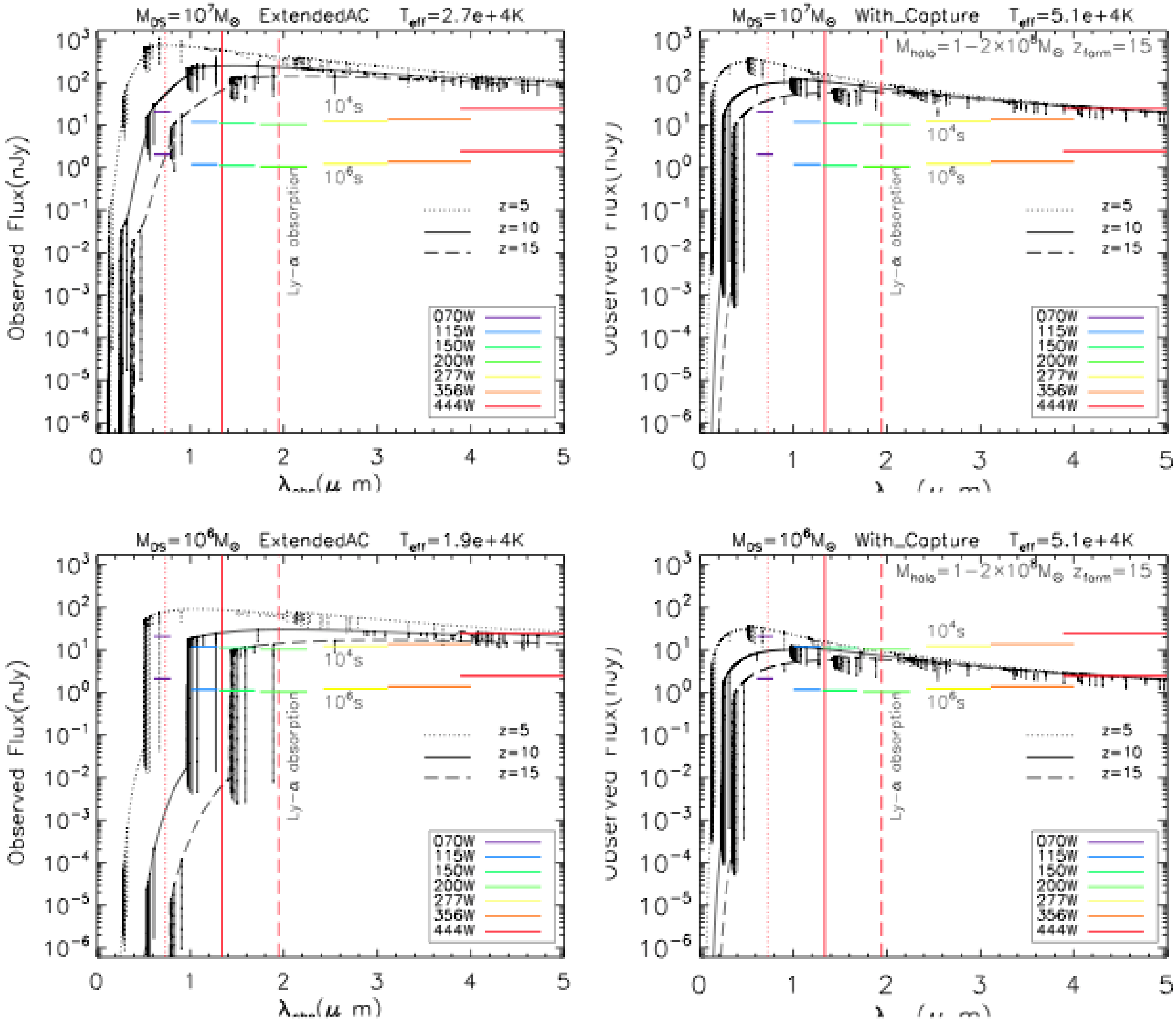
Basic Picture

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

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

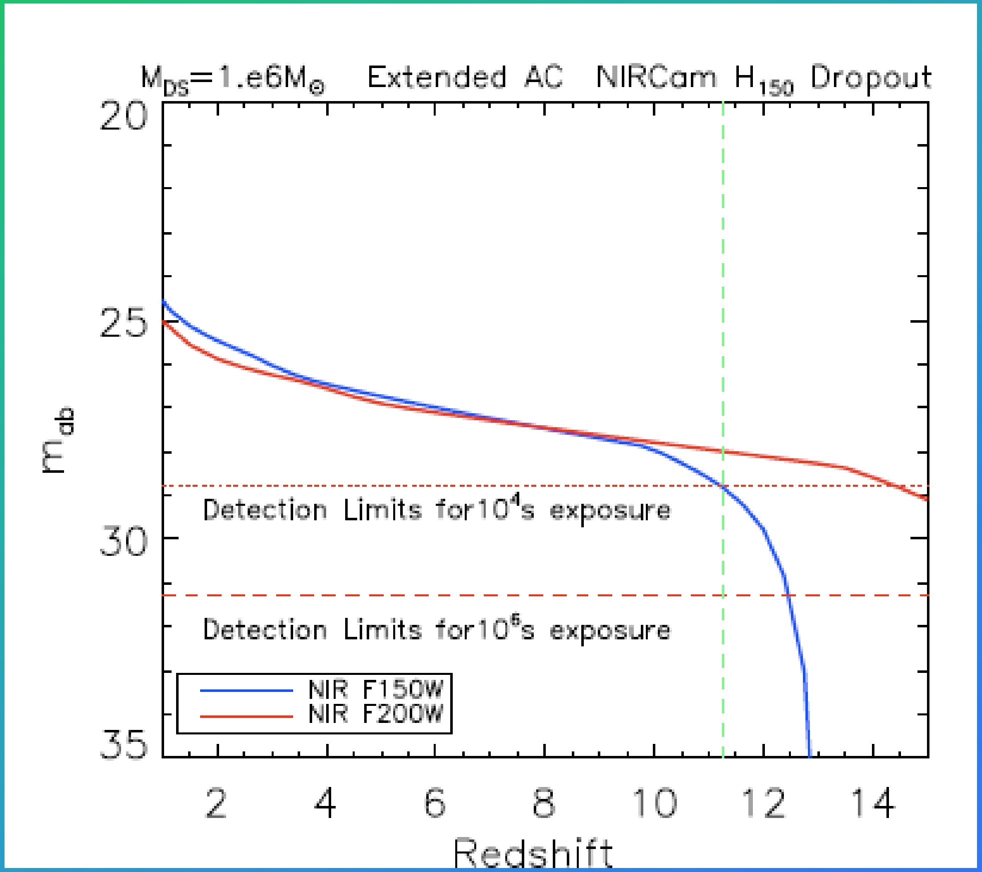




DS in JWST

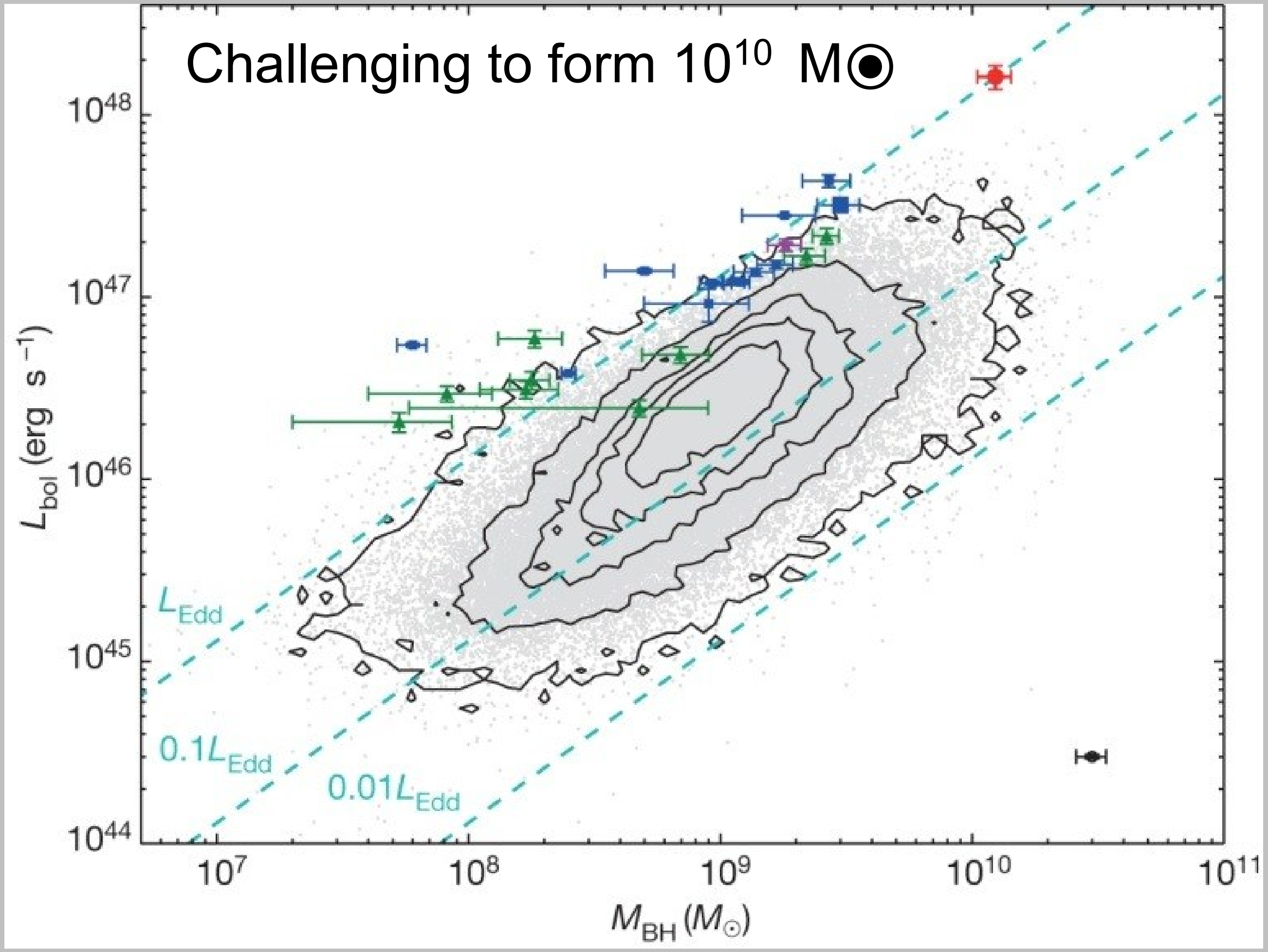
Figure 7. Spectra for supermassive DSs formed at $z_{\rm form} = 15$ (formation redshift)

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)

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



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

nature

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

Eduardo Bañados[1,*], Bram P. Venemans[2], Chiara Mazzucchelli[2], Emanuele P. Farina[2], Fabian Walter[2], Feige Wang[3,4], Roberto Decarli[2,5], Daniel Stern[6], Xiaohui Fan[7], Fred Davies[8], Joseph F. Hennawi[8], Rob Simcoe[9], Monica L. Turner[9,10], Hans-Walter Rix[2], Jinyi Yang[3,4], Daniel D. Kelson[1], Gwen Rudie[1], and Jan Martin Winters[11]

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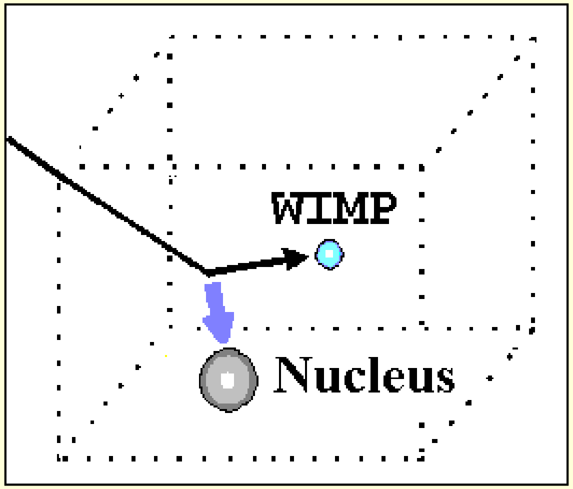
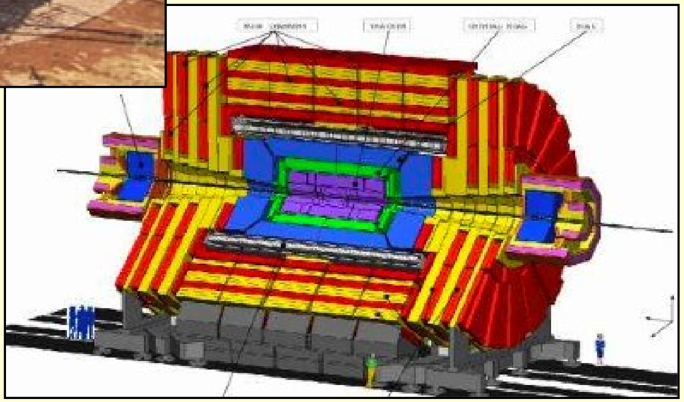
ABSTRACT

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 $\bar{x}_{HI} > 0.33$ ($\bar{x}_{HI} > 0.11$) at 68% (95%) probability, indicating that we are probing well within the reionization epoch.

WIMP Hunting: Good chance of detection this decade



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



Looking for Dark Stars

WHAT'S HOT IN DARK MATTER? Unexplained signals.

WIMPS:

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

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

FERMI gamma ray excess near galactic center

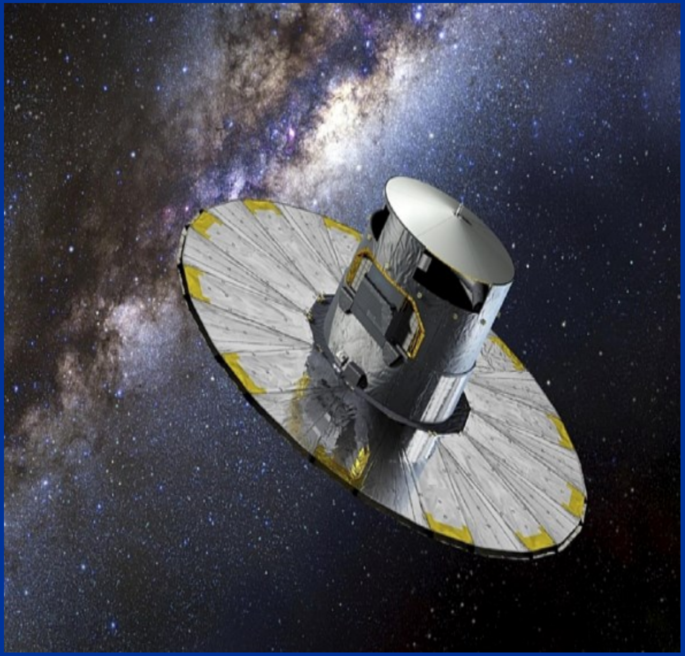
- --

7 keV Sterile neutrinos

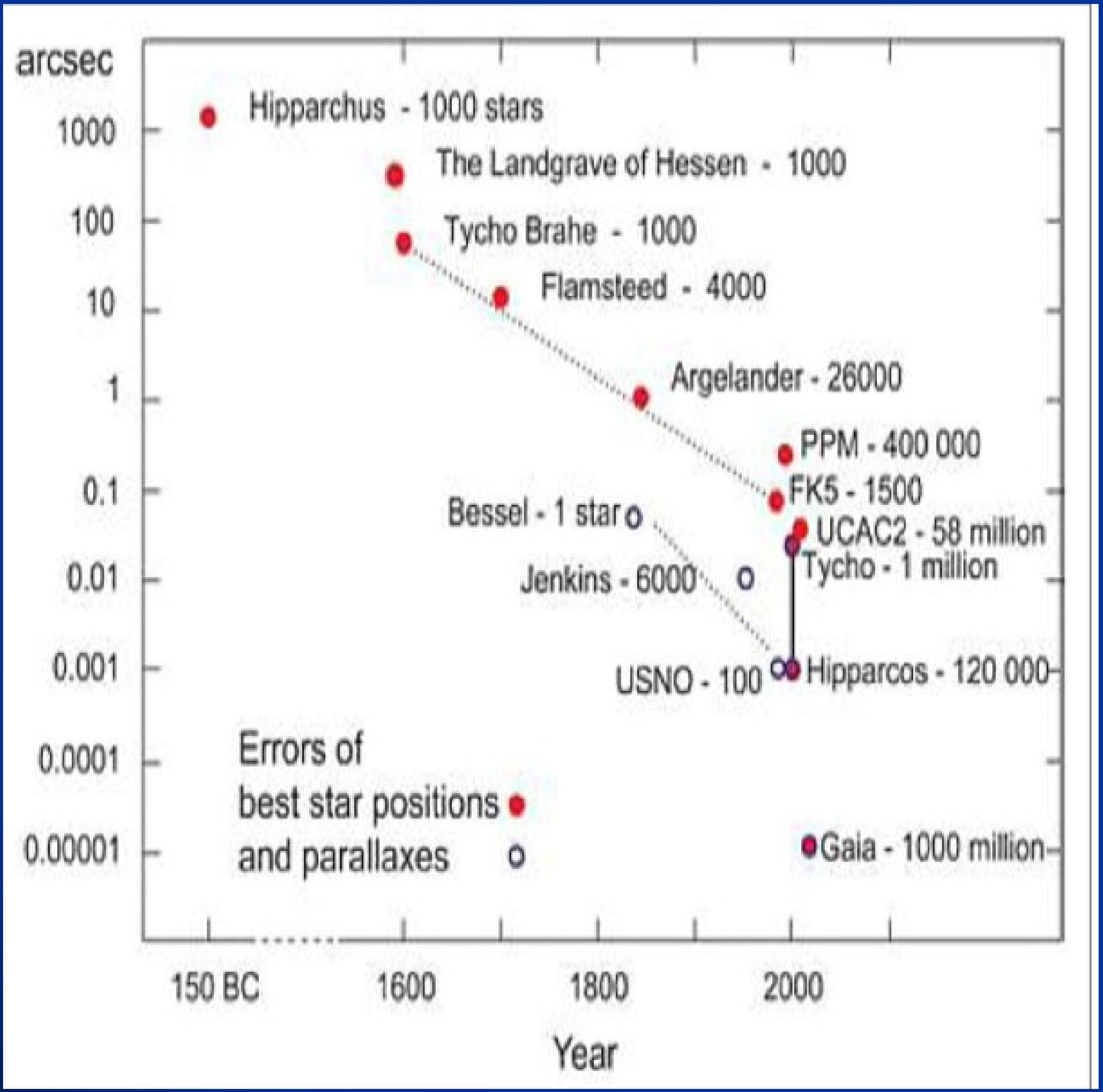
- 3.5 keV x-ray line in Perseus, M31, and GC

- MeV dark matter   511 keV line in INTEGRAL DATA

4) New ways to test nature of DM: use GAIA data



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


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

Small-scale observations are not quite consistent with CDM

<u>Small-scale</u>=> M_{halo} ~$\mathbf{10^{9\text{-}12}\,M_{\odot}}$, length scale ~ **1 kpc-1 Mpc**

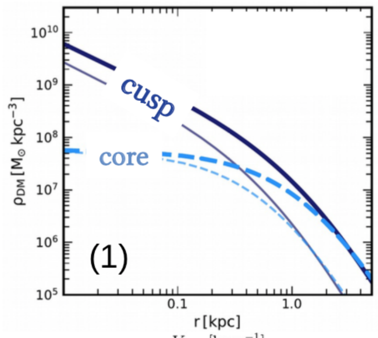
Problems

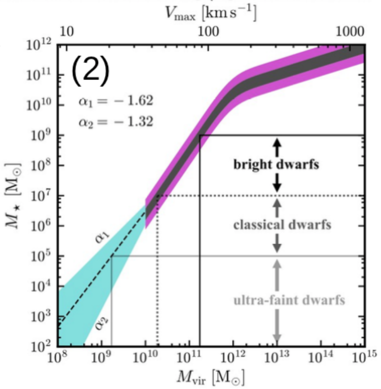
1. <u>Prediction</u>: The central-DM profiles of individual halos are steeply-rising and form high-density "cusps"
   <u>Observations</u>: Central-DM profiles are low-density "cores"

2. <u>Prediction:</u> >1000 subhalos (dwarf galaxies, physical size ~ 1-3 kpc) should orbit any Milky Way like galaxy
   <u>Observations</u>: only ~60-70 known galaxies with M_{halo}~$10^{8\text{-}9}\,M_{\odot}$ (M_* > 300M within 300 kpc of the Milky Way

3. <u>Prediction</u>: The local universe should have galaxies with M_{vir} ~ $10^{10}M_{\odot}$
   <u>Observations:</u> "Too-Big-to-Fail"

Bullock & Boylan-Kolchin (2017)



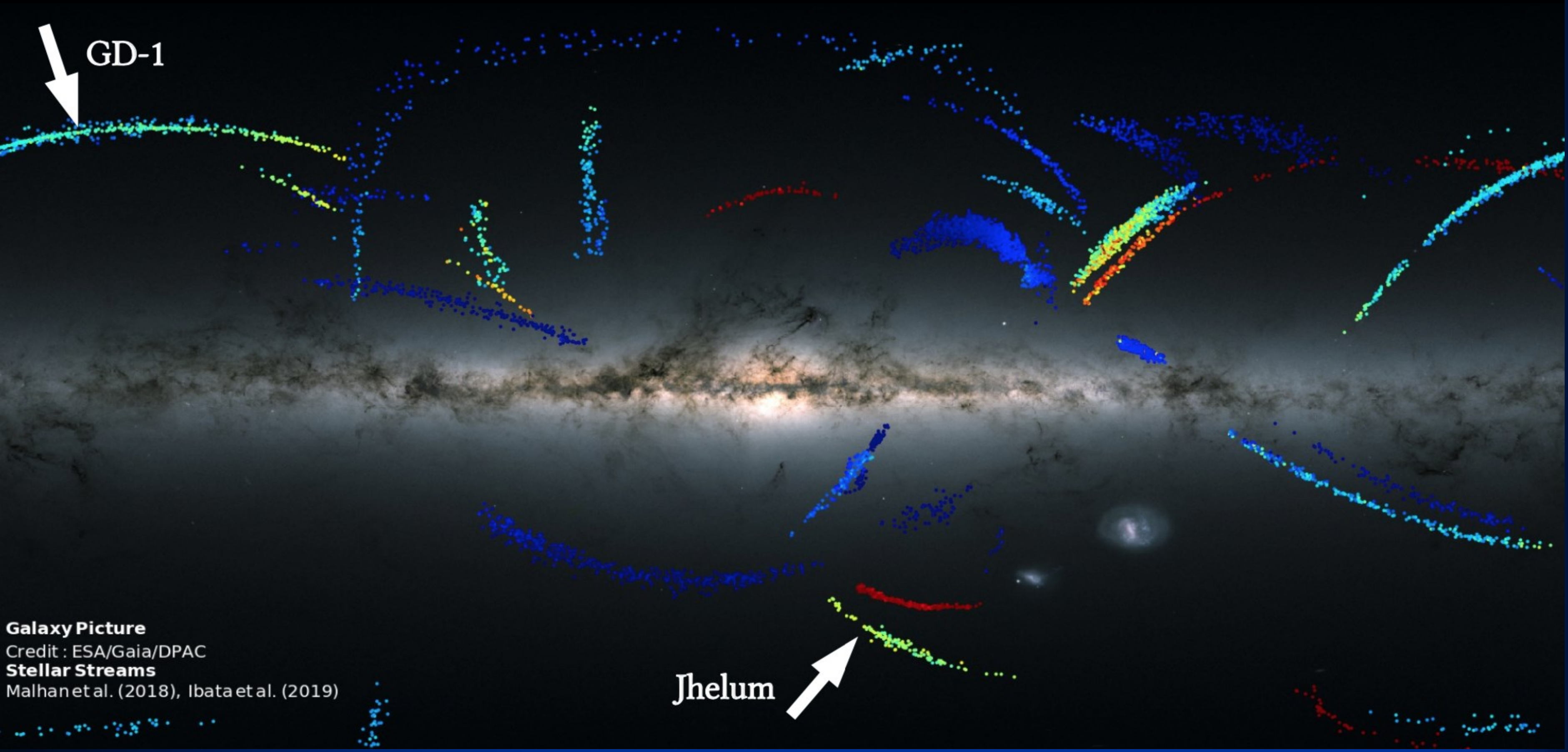


Probing Nature of DM with Streams in GAIA data

- We know of 70 stellar streams in the Milky Way. With GAIA data, more are being found, and their properties can tell us about the nature of DM.
- Streams form by tidal stripping of Dwarf Galaxies (e.g. the Sagittarius Stream) or by tidal stripping of Globular Clusters of stars inside halos
- GCs are dense and old star clusters (formed at redshifts $z \sim 2-4$) with $M \sim 10^5 M_\odot$ and a physical sizes of a few tens of pc that reside in the halos of galaxies.

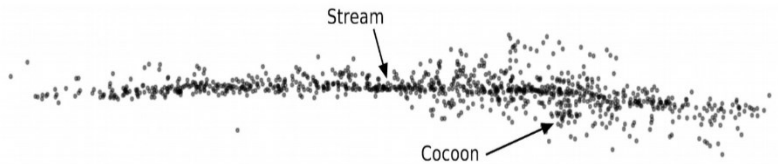
Stellar Streams in the Milky Way

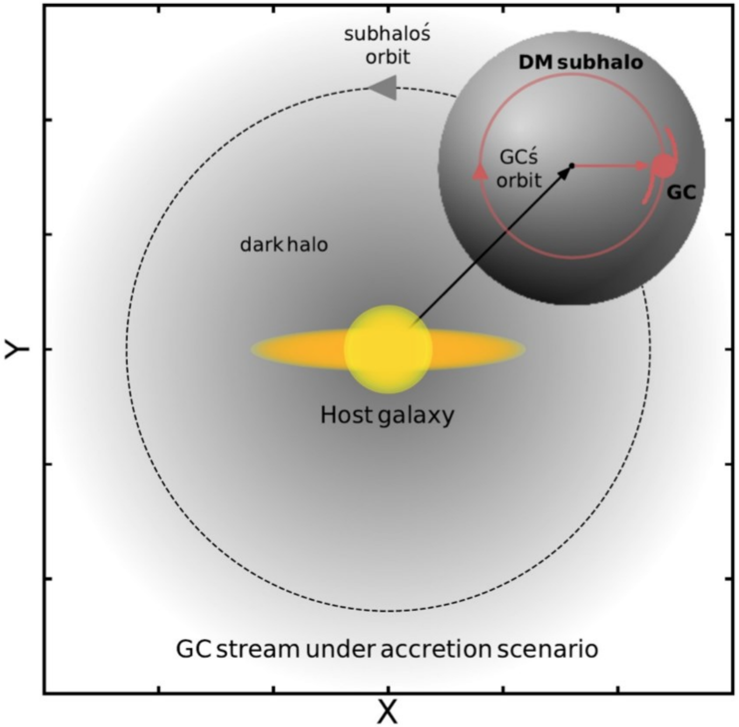
Question: Can the present day physical properties of such accreted GC streams provide information about the DM density of their parent subhalos?



Accreted GC streams as direct probes of dark matter

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



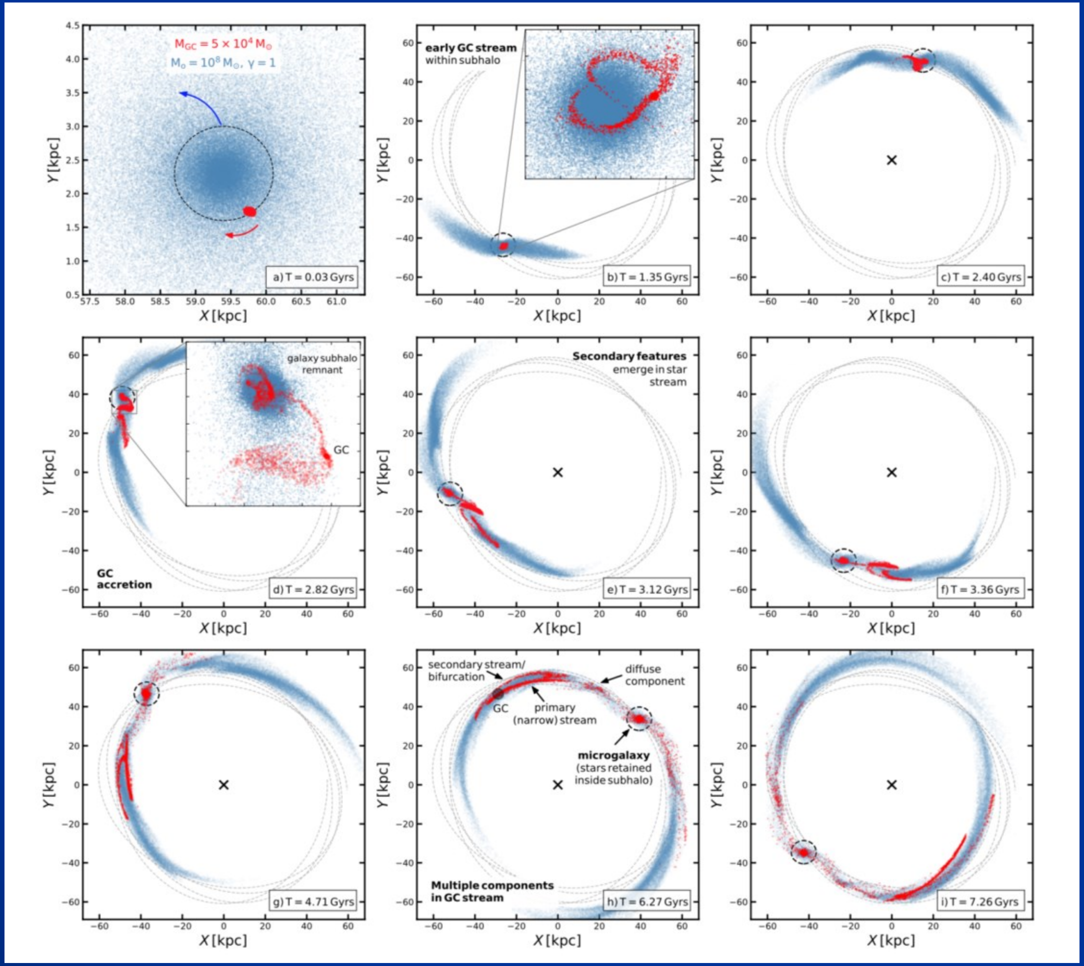


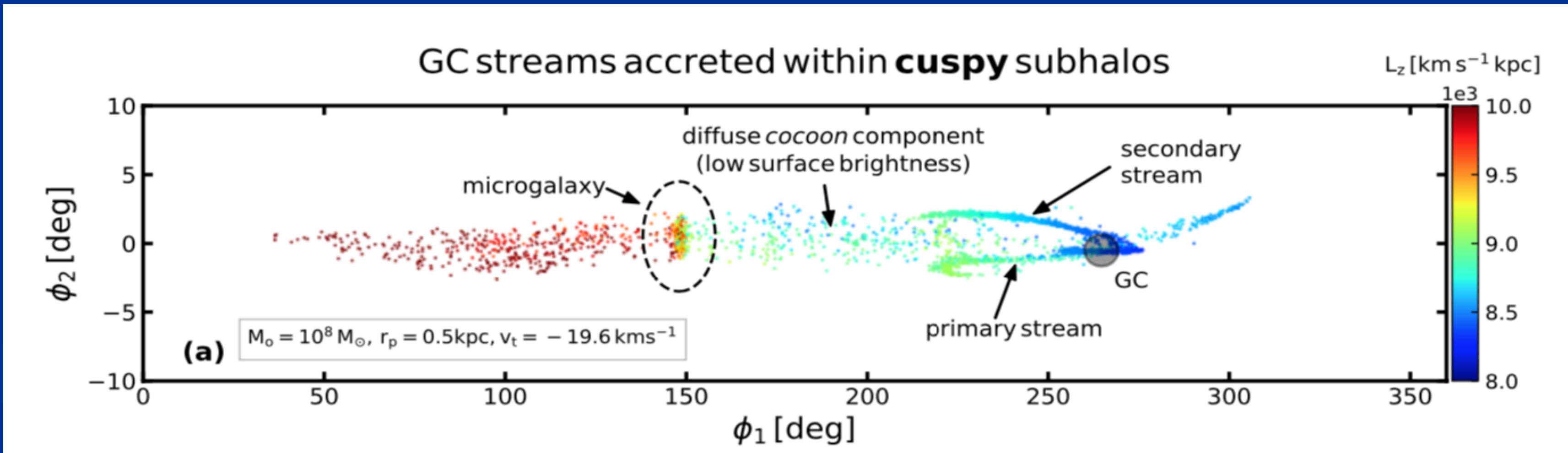
Khyati Malhan

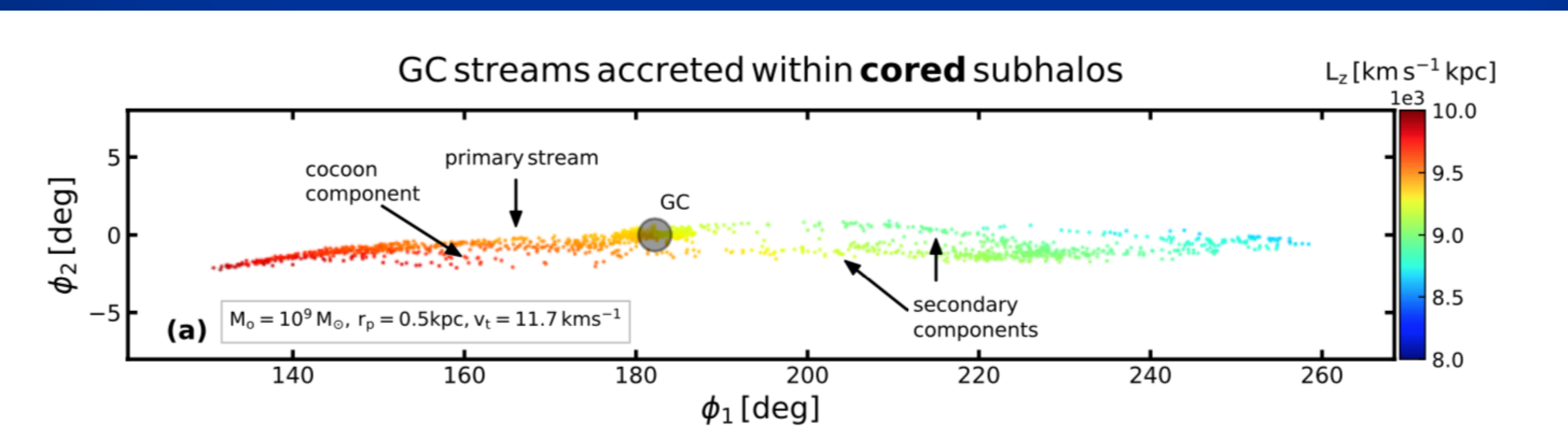
Monica Valluri

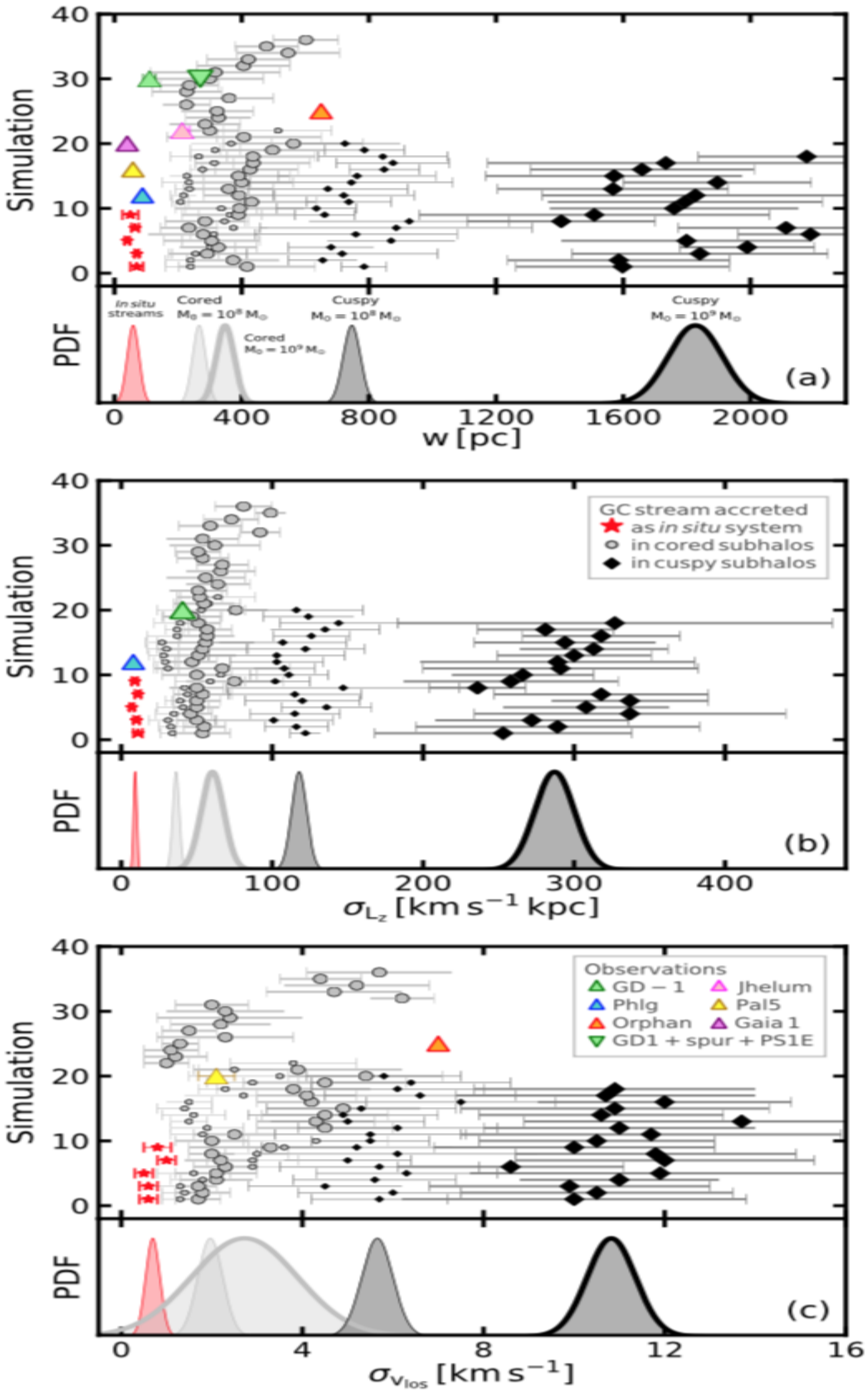
Malhan, Valluri, Freese 2020

Formation of stream by tidal stripping of accreted GC




GC streams accreted within **cuspy** subhalos
L_z [km s^{-1} kpc]
1e3
10.0
9.5
9.0
8.5
8.0
diffuse *cocoon* component
(low surface brightness)
secondary
stream
microgalaxy
GC
primary stream
(a)
$M_o = 10^8 M_\odot$, $r_p = 0.5$kpc, $v_t = -19.6$ kms^{-1}
ϕ_2 [deg]
ϕ_1 [deg]
10
5
0
−5
−10
0
50
100
150
200
250
300
350


GC streams accreted within **cored** subhalos
L_z [km s^{-1} kpc]
1e3
10.0
9.5
9.0
8.5
8.0
primary stream
cocoon
component
GC
secondary
components
(a)
$M_o = 10^9 M_\odot$, $r_p = 0.5$kpc, $v_t = 11.7$ kms^{-1}
ϕ_2 [deg]
ϕ_1 [deg]
5
0
−5
140
160
180
200
220
240
260



Streams coming from cuspy subhalos are wider physically and dynamically hotter than those from cored subhalos

First comparison with observed streams GD-1 and Jhelum indicates a preference for cored subhalos

If this result holds up, then either there was baryonic feedback or must go beyond CDM

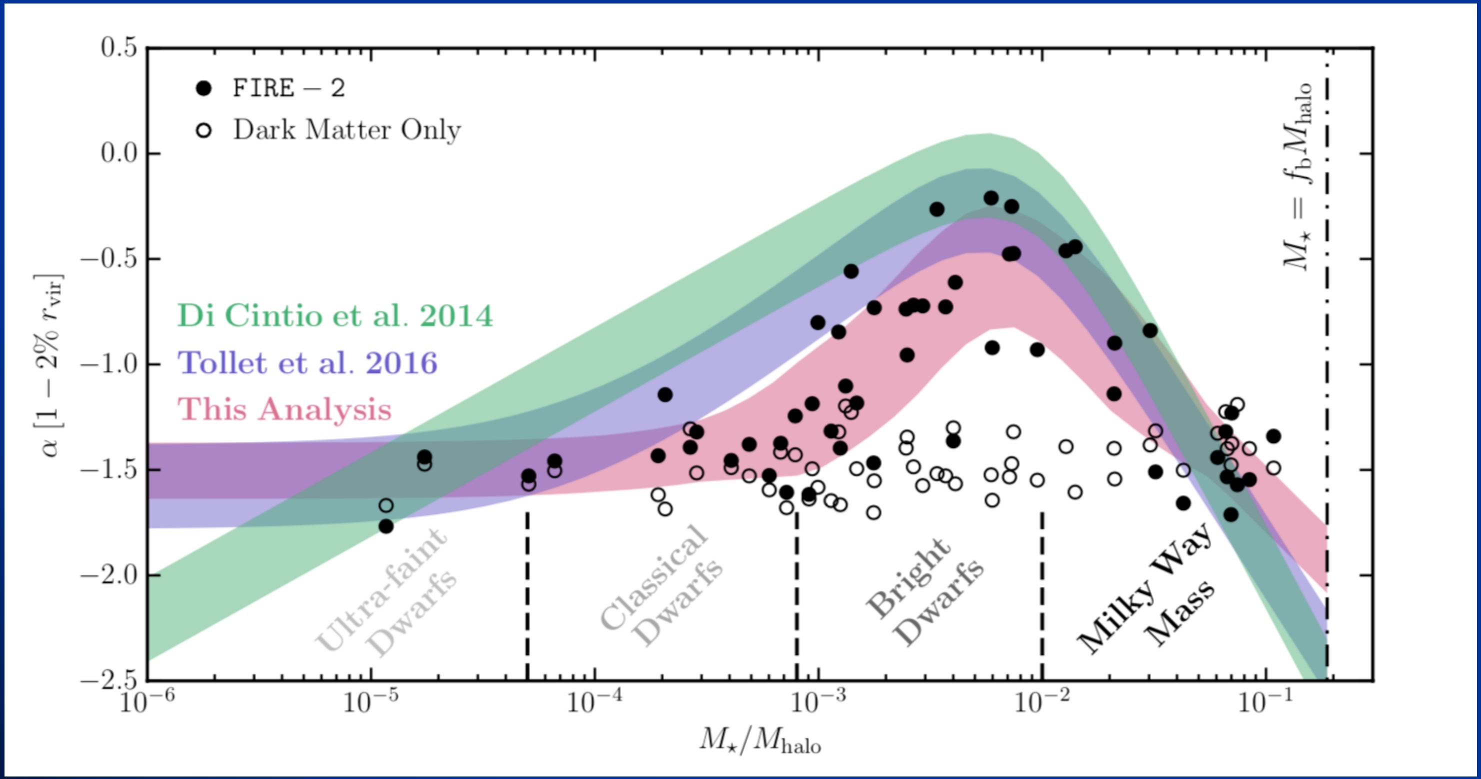
What's new In Cold Dark Matter Simulations:

- Impact of stellar feedback on core/cusp of inner DM density most effective at ~5 x 10^10 M☉

$$\rho(r) \propto r^{\alpha}$$

CORE
α ~ 0

CUSP
α ~ −1



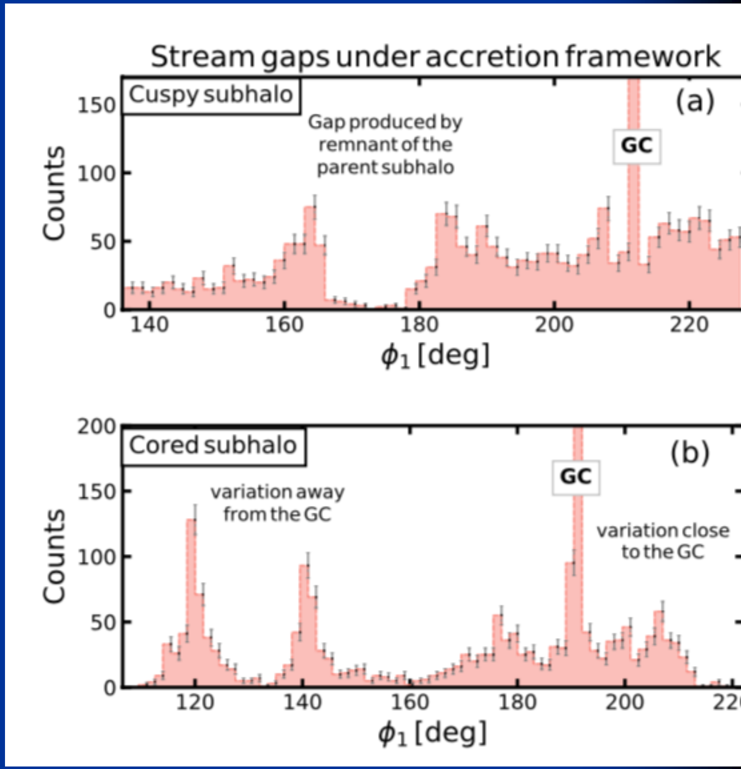
Lazar, Bullock, Boylan-Kolchin etal arXiv:2004.10817

Gaps in Stellar Streams as probes of DM

- When subhalos pass through stellar streams, they can create gaps. CDM predicts hundreds or thousands of subhalos.

Evidence of passage of subhalos ~ 10^7 M⨀ or less would strongly favor CDM over alternatives.

Our mechanism: longer, stronger interactions when microgalactic remnant of accreted subhalo passes through its own GC stream (they are on the same orbit).



(Bonaca etal for GD-1 stream, must be very compact million solar mass subhalo)

GAIA tests Cold Dark Matter hypothesis

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

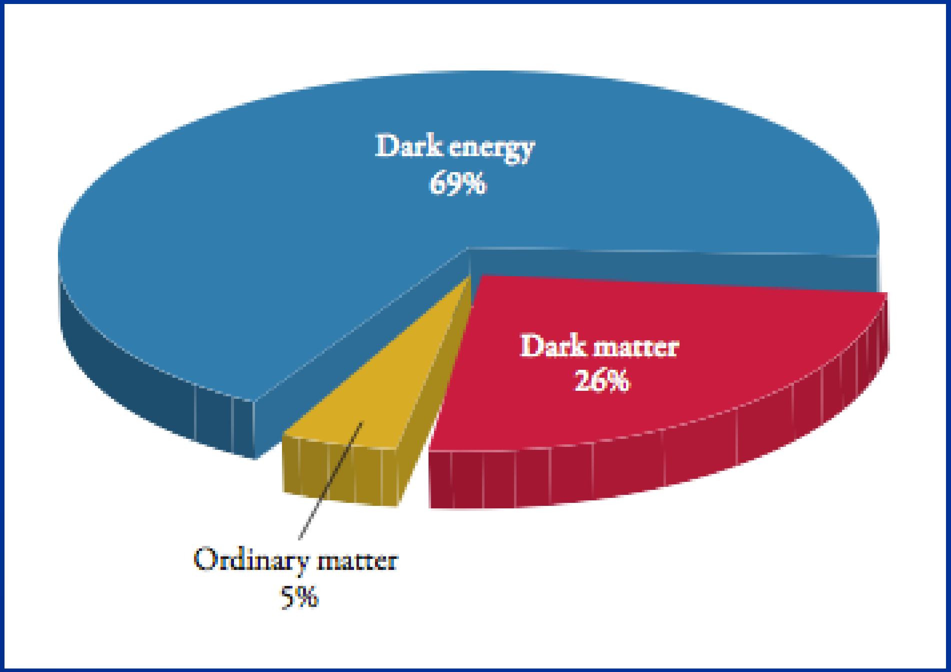
Summary

- 1) Neutrino mass ~ 0.1 eV. We are close to knowing the answer. Cosmology is very powerful.
- 2) WIMP searches: what is going on with DAMA? It is not Spin-Independent.

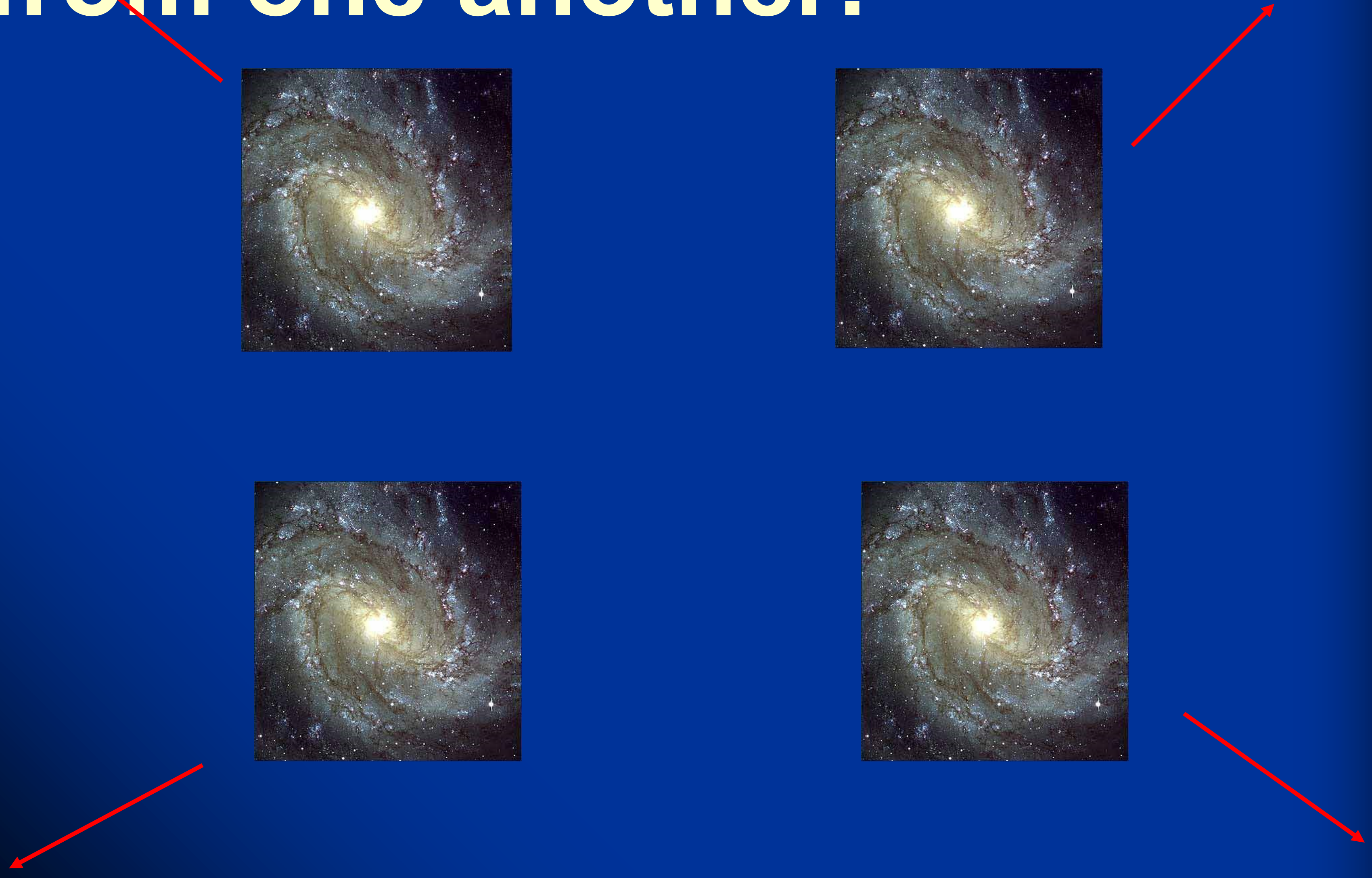
COSINE-100 and ANAIS are testing it (also consist of NaI crystals, same material as DAMA.

- 3) Dark Stars: the first stars could have been powered by Dark Matter rather than by fusion. Powered by WIMPs or SIDM or …
- 4) New ways to test nature of DM: GAIA satellite and stellar streams as a test of Cold Dark Matter

Even stranger: Dark Energy



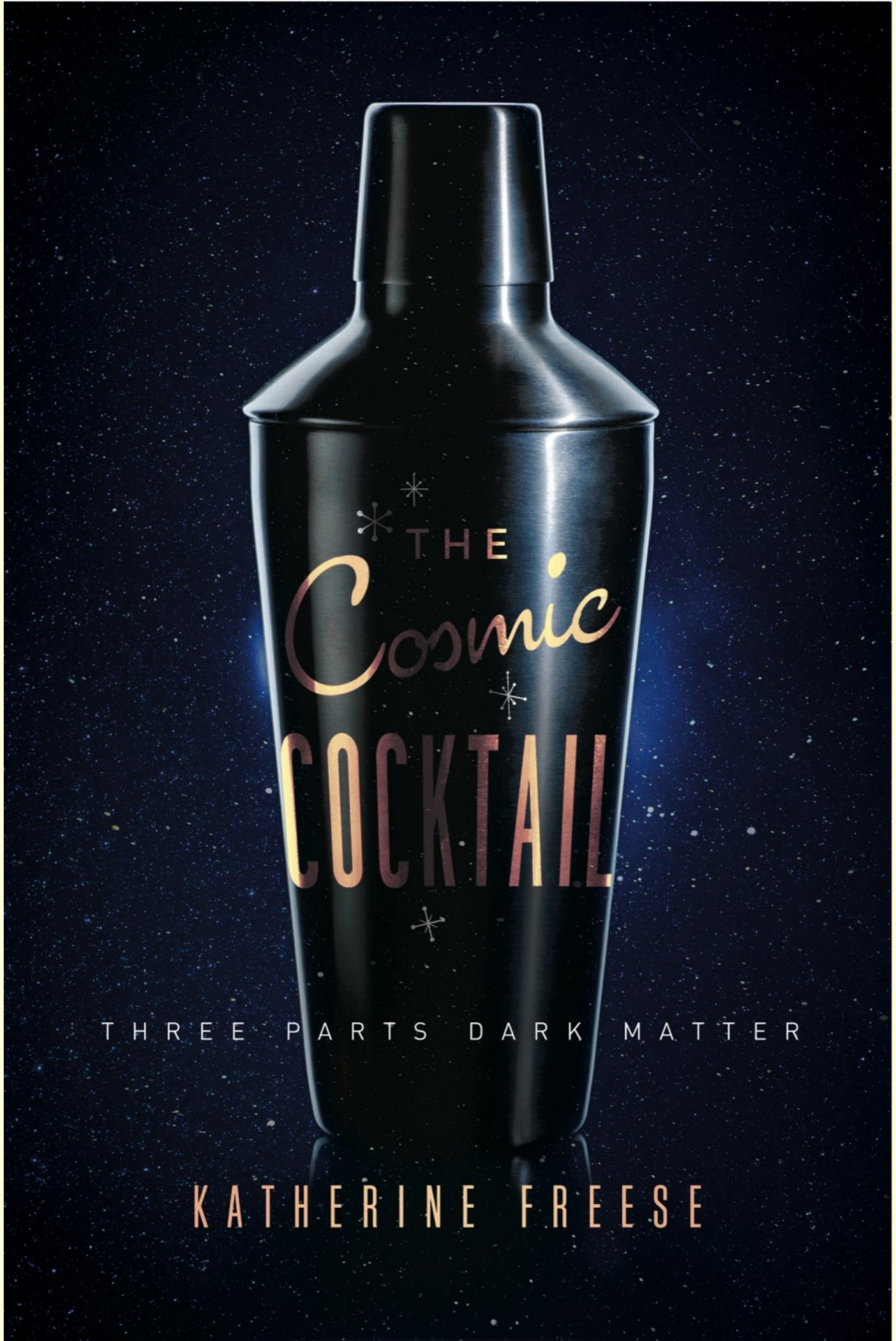
DARK ENERGY: Galaxies are accelerating apart from one another!



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

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

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


THE
Cosmic
COCKTAIL
THREE PARTS DARK MATTER
KATHERINE FREESE