Dark Matter in the Universe

Katherine Freese

- Director of Nordita
- George E. Uhlenbeck Professor of Physics, University of Michigan

NORDITA Activities

- 4 permanent faculty, 4 assistant profs, up to 20 postdoctoral fellows
- 6-8 one-month programs/yr
- 20 conferences/yr at Nordita or Nordic region
- 4 schools/yr
- KITP Santa Barbara was modeled after Nordita

NORDITA SCIENTIFIC PROGRAMS 2015

www.nordita.org/events

SCIENTIFIC PROGRAMS

Extended Theories of Gravity
2–20 March 2015
Coordinators: Kari Enqvist, Tomi Koivisto, David Fonseca Mota, Fawad Hassan, Lavinia Heisenberg, Justin Khoury, Claudia de Rham

Control of Ultrafast Quantum Phenomena
18 May – 12 June 2015
Coordinators: Esa Räsänen, Eva Lindroth, Jan Petter Hansen

Origin, Evolution, and Signatures of Cosmological Magnetic Fields
15 June – 10 July 2015
Coordinators: Tina Kahniashvili, Tanmay Vachaspati, Axel Brandenburg, Arthur Kosowsky

Magnetic Reconnection in Plasmas
27 July – 21 August 2015
Coordinators: Andris Vaivads, Stefano Markidis, Yuri Khotyaintsev, Åke Nordlund

Physics of Interfaces and Layered Structures
24 August – 11 September 2015
Coordinators: Alexander Balatsky, David Abergel, Philip Hofmann, Yoshihiro Iwasa, Annica Black-Schaffer

Stochastic Thermodynamics in Biology
21 September – 16 October 2015
Coordinators: Erik Aurell, Astrid de Wijn, Ralf Eichhorn

CONFERENCES

6th Nordic Workshop on Statistical Physics: Biological, Complex and Non-Equilibrium Systems
25–27 February 2015
Coordinators: Ralf Eichhorn, Alberto Imparato

Sunspot formation: theory, simulations and observations
9–13 March 2015
Coordinators: Illa R. Losada, Göran Scharmer, Nishant Singh, Axel Brandenburg

Probing the Fundamental Nature of Spacetime with the Renormalization Group
23–27 March 2015
Coordinators: Astrid Eichhorn, Dario Benedetti, Frank Saueressig

Further conferences and workshops may be organized during 2015. Please check www.nordita.org/events for updates.

SCHOOLS

Nordita Winter School 2015 on Theoretical Particle Physics
7–16 January 2015
Coordinators: Konstantin Zarembo, Paolo Di Vecchia

A Nordita scientific program is an extended workshop where a limited number of scientists work together on specific topics in theoretical physics for a period of 4 weeks.

More information about Nordita Scientific Programs can be found at

www.nordita.org/programs

Members of the scientific community in the Nordic countries and worldwide are invited to propose scientific programs for 2016.

Proposals should be submitted by 5 December 2014. Further information and submission instructions can be found at

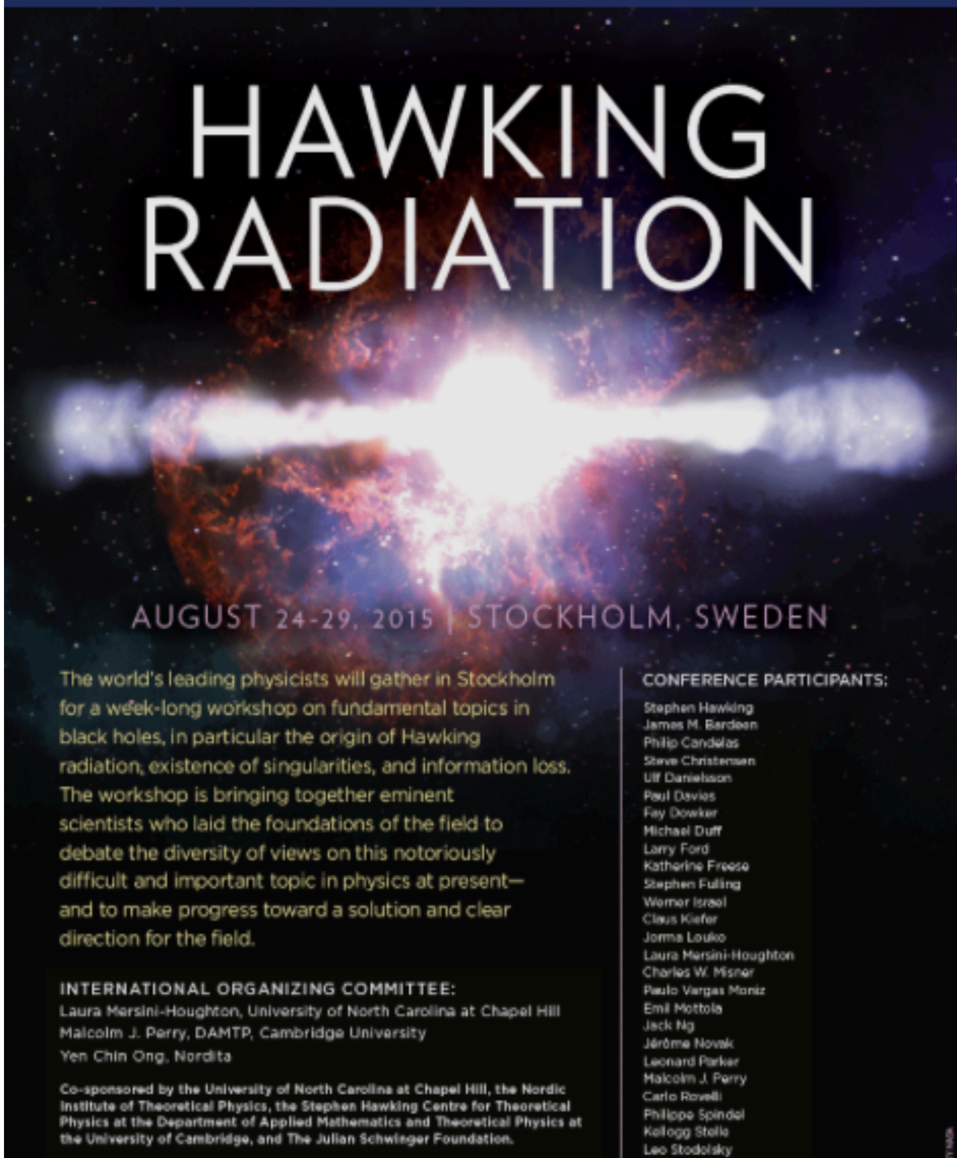
www.nordita.org/propose

Prof. Katherine Freese
Director of Nordita

Roslagstullsbacken 23
SE-106 91 Stockholm
Sweden
Tfn +46 8 5537 8436
Fax +46 8 5537 8404
info@nordita.org
www.nordita.org

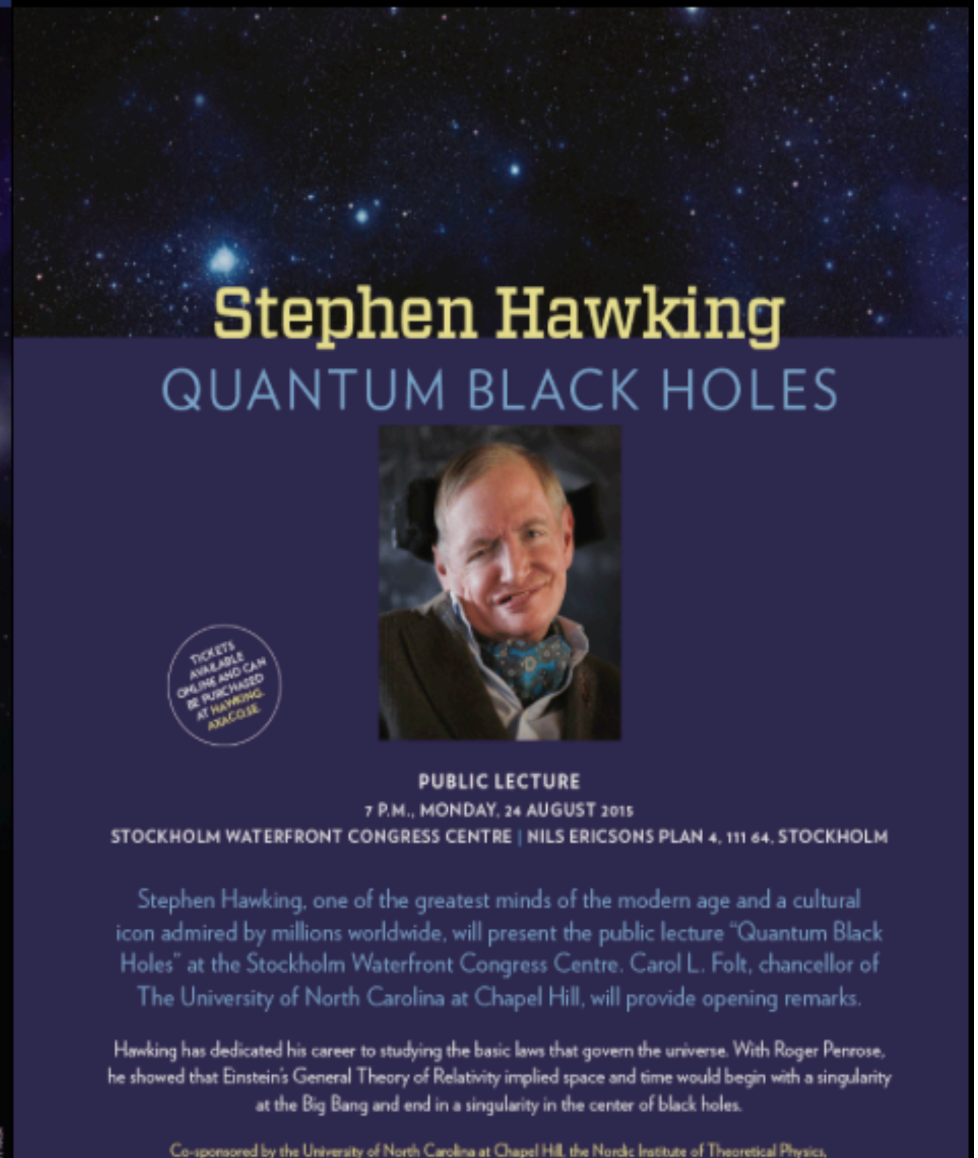
THE CONFERENCE

24—29 August 2015



THE PUBLIC LECTURE

24 August 2015

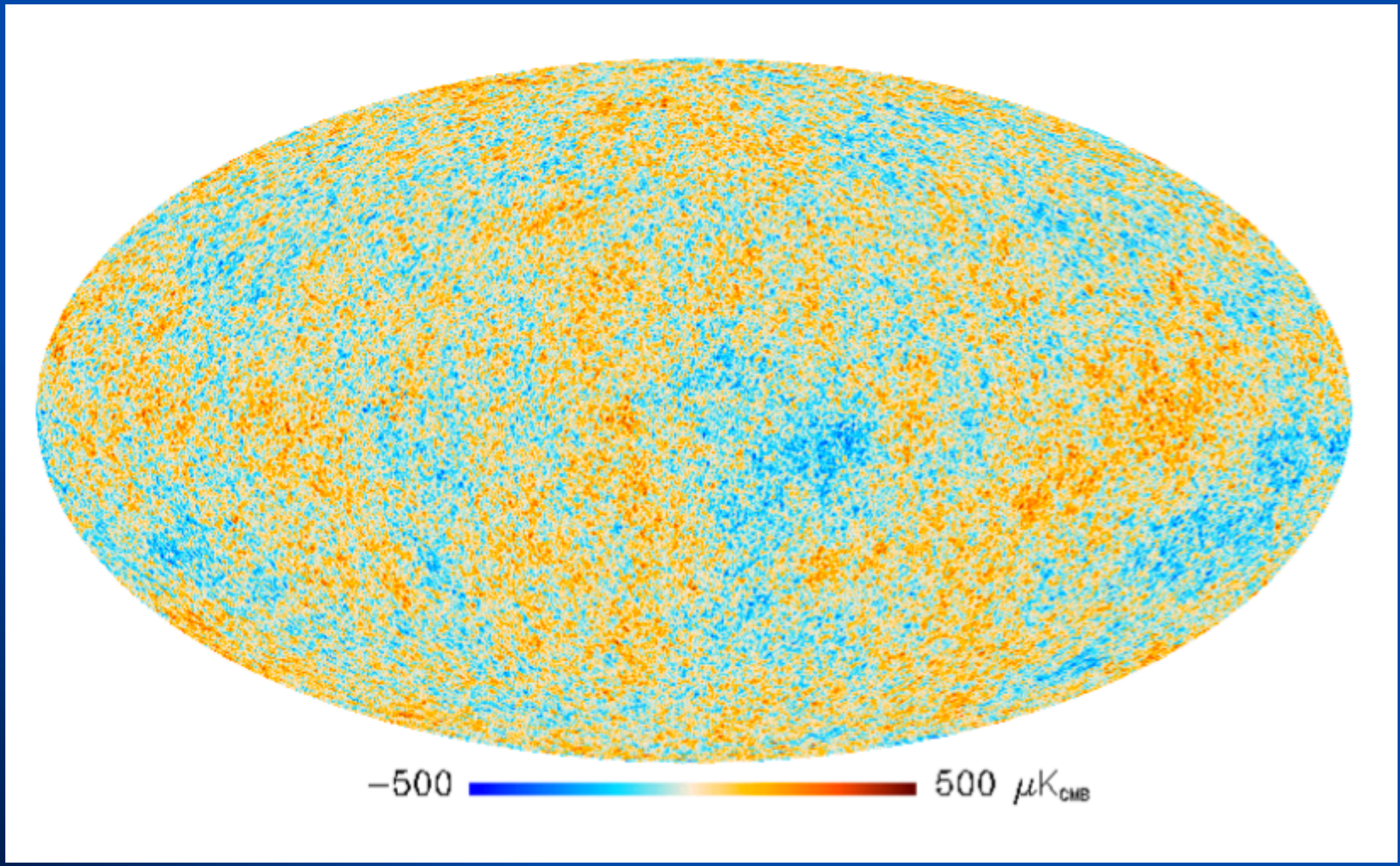


Where do we stand in Cosmology?

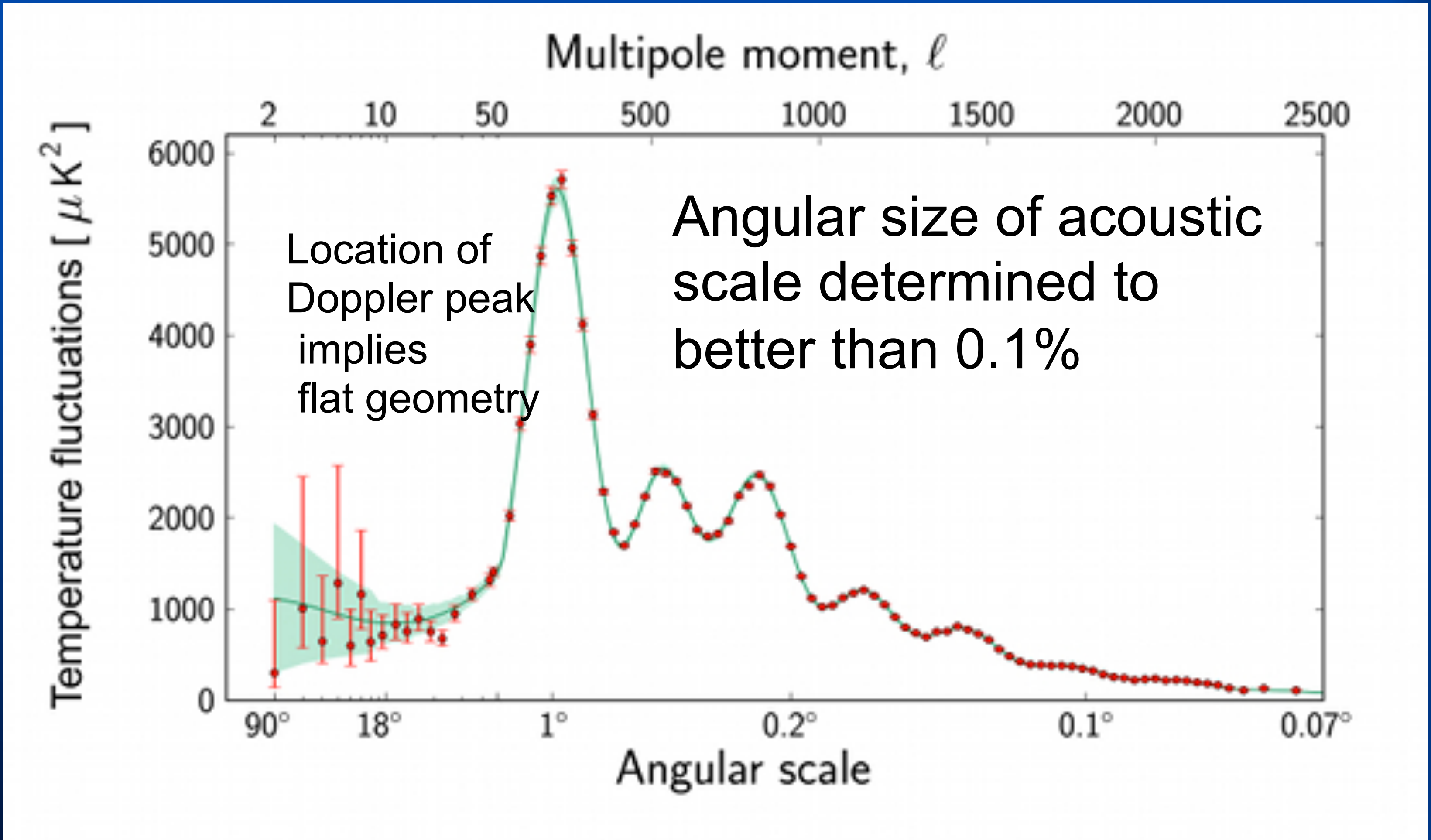
- Big questions answered at the turn of the millenium:
- What is the geometry of the Universe?
- What is the total mass/energy content of the Universe?
- How old is the Universe?
- Primordial density perturbations

- BUT questions remain:
- Quantum Gravity
- How did the Universe begin?
- What is the Universe made of? Dark matter, dark energy.

Data from ESA's Planck Space Telescope March 2013



Planck Data

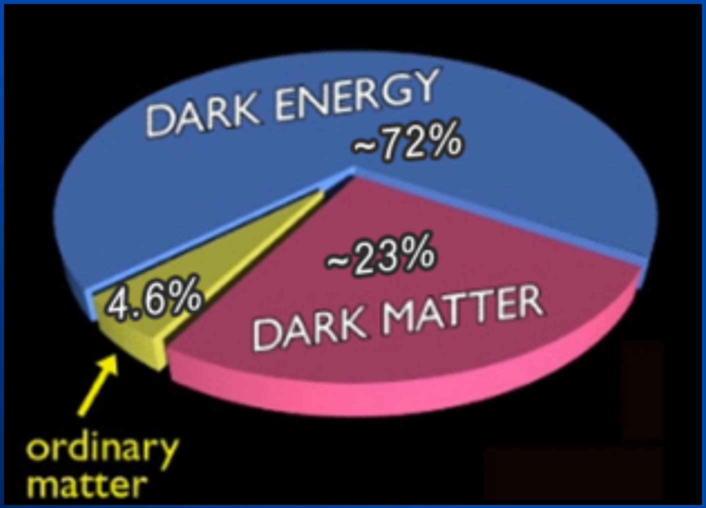


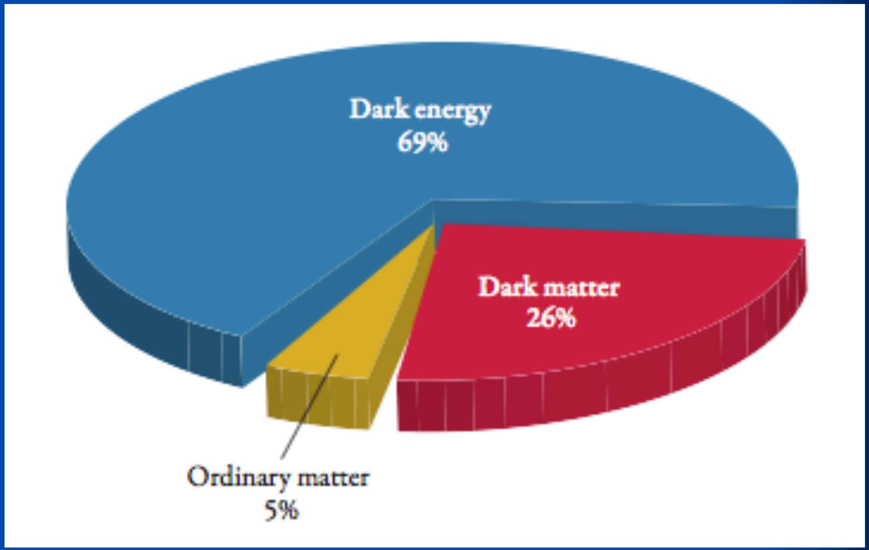
Seven acoustic peaks

LAMDA CDM FITS THE DATA

More Dark Matter (thanks to Planck)

- 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?

Cosmological Parameters from Planck

Parameter	*Planck* (CMB+lensing) Best fit	*Planck* (CMB+lensing) 68 % limits	*Planck*+WP+highL+BAO Best fit	*Planck*+WP+highL+BAO 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		

Inflation after Planck: only the simplest well-motivated models survive

- (plot from Planck paper, 2015)

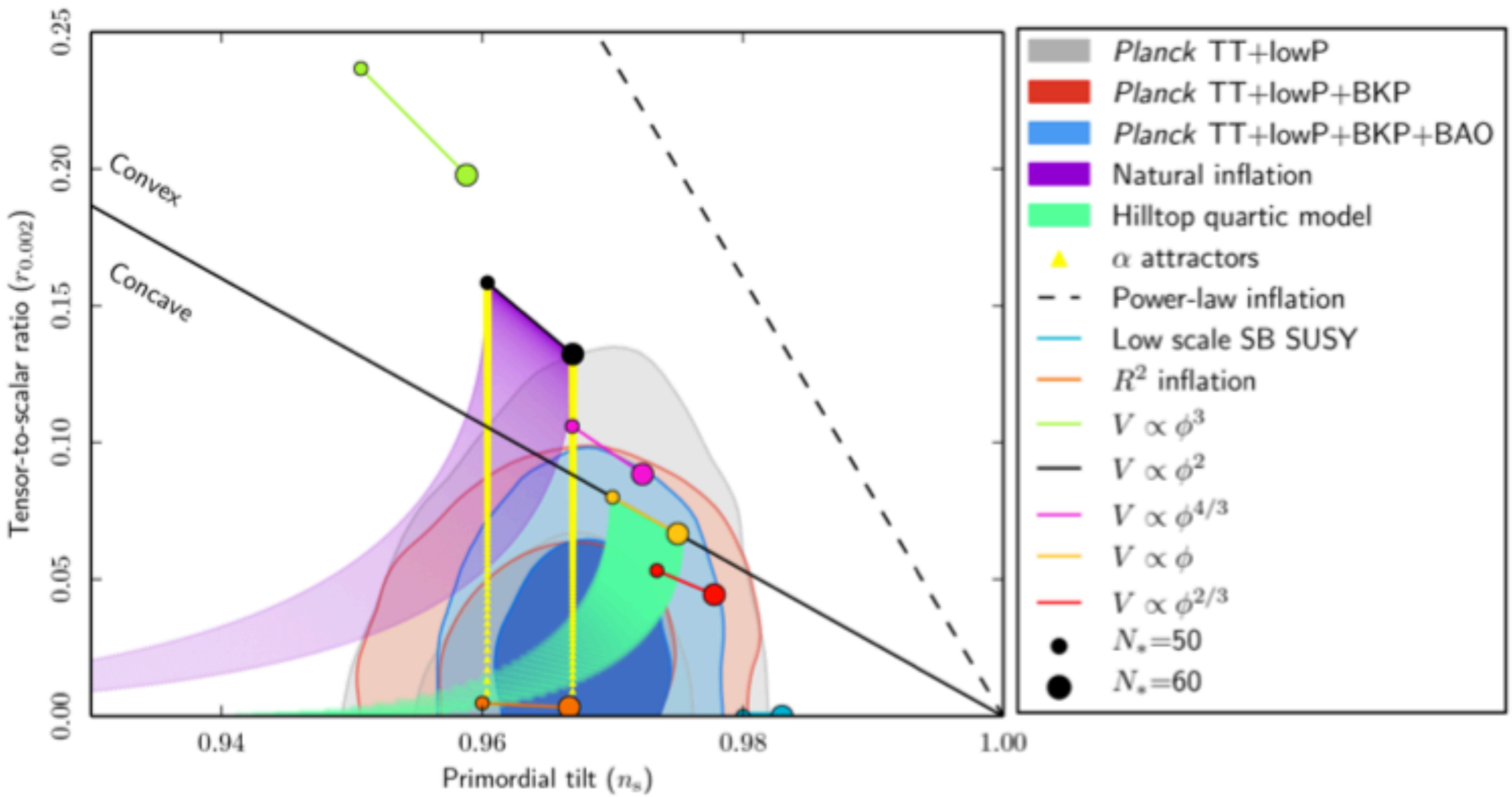


Fig. 54. Marginalized joint 68 % and 95 % CL regions for n_s and $r_{0.002}$ from *Planck* alone and in combination with its cross-

Planck had major impact on inflation models

- MOST MODELS ARE DEAD. THAT IS PROGRESS.
- MOST REMAINING MODELS ARE SIMPLE:
  SINGLE FIELD ROLLING DOWN A HILL

Minimal inflation:

- 1) a single weakly-coupled neutral scalar field, the inflaton, drives the inflation and generates the curvature perturbation
- 2) with canonical kinetic term
- 3) slowly rolling down featureless potential
- 4) initially lying in a Bunch-Davies vacuum state

- If any one of these conditions is violated, detectable amplitudes of nonGaussianity should have been seen.

$$\langle \Phi(\boldsymbol{k}_1)\Phi(\boldsymbol{k}_2)\Phi(\boldsymbol{k}_3)\rangle = (2\pi)^3\delta^{(3)}(\boldsymbol{k}_1+\boldsymbol{k}_2+\boldsymbol{k}_3)B_\Phi(k_1,k_2,k_3).$$

$$B_\Phi(k_1,k_2,k_3) = f_{\rm NL}F(k_1,k_2,k_3)\,.$$

No primordial nonGaussianities in Planck

- Single field models: so small as to be undetectable
- Other models: three shapes (configurations of triangles formed by the three wavevectors)
- Any detection of nonGaussianity would have thrown out all single field models
- Data show no evidence of nonGaussianity, implying single field models work

2013

f_{NL}		
Local	Equilateral	Orthogonal
2.7 ± 5.8	−42 ± 75	−25 ± 39

- Data bound the speed
- of sound cs>0.02

2015

Shape and method	f_{NL}(KSW) Independent	f_{NL}(KSW) ISW-lensing subtracted
SMICA (T)		
Local	10.2 ± 5.7	**2.5 ± 5.7**
Equilateral	−13 ± 70	**−16 ± 70**
Orthogonal	−56 ± 33	**−34 ± 33**
SMICA (T+E)		
Local	6.5 ± 5.0	**0.8 ± 5.0**
Equilateral	3 ± 43	**−4 ± 43**
Orthogonal	−36 ± 21	**−26 ± 21**

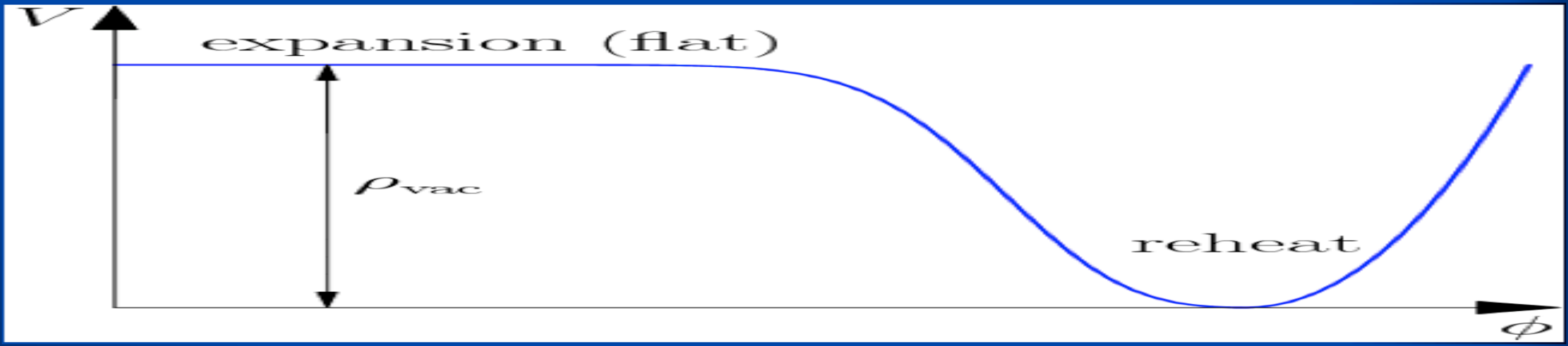
With polarization:

Philosophy and Progress

- Planck killed almost all models
- What is left? Simplest models
- Very few inflationary models are theoretically well motivated. Particle physics does NOT allow you to write down arbitrary garbage.
- Wonderful thing: the best motivated models in this sense are the ones that survive!
- Natural inflation
- Starobinsky inflation eg. As motivated by supergravity
- Higgs inflation

Fine Tuning in Rolling Models 1980-1990

- The potential must be very flat:



$$\frac{\Delta V}{(\Delta\Phi)^4} = \frac{\text{height}}{\text{width}^4} \le 10^{-8},$$
$$e.g. V(\phi) = \lambda\Phi^4, \lambda \le 10^{-12}$$

(Adams, Freese, and Guth 1990)

But particle physics typically gives this ratio = 1!

Inflation needs small ratio of mass scales

$$\frac{\Delta V}{(\Delta \Phi)^4} = \frac{\text{height}}{\text{width}^4} \leq 10^{-8},$$

Adams, KT, Guth 1990

- Two attitudes:

1) We know there is a heirarchy problem, wait until it’s explained

2) Two ways to get small masses in particles physics:

(i) supersymmetry (especially interesting: no-scale supergravity, Ellis, Nanopoulos, Olive)

(ii) “Axions” (shift symmetries)

1990 A solution to the Fine-Tuning Problem: Natural Inflation, which uses "Axions"

- We know of a particle with a small ratio of scales: the **axion**

$$\lambda_a \sim \left(\frac{\Lambda_{\mathrm{QCD}}}{f_{\mathrm{PQ}}} \right)^4 \sim 10^{-64}$$

- Due to shift symmetry, potential is invariant under

$$\Phi \rightarrow \Phi + \mathrm{constant}$$

protect flatness of inflaton potential

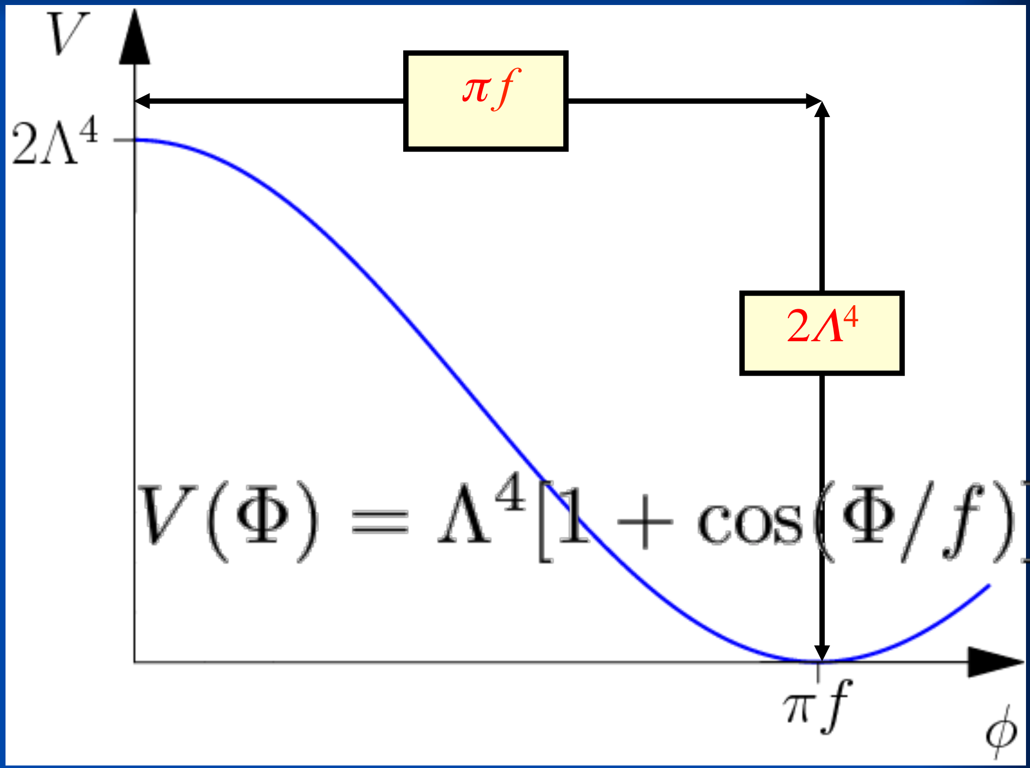
- IDEA: use a potential similar to that for axions in inflation
  - Here, we do *not* use the QCD axion. Instead, use a heavier particle with similar behavior. → "Natural Inflation"

Freese, Frieman & Olinto (1990)

Original Natural Inflation

For QCD axion:
$f \sim 10^{12}$ GeV
$\Lambda \sim 100$ MeV

For natural inflation:
$f \sim M_{Pl}$
$\Lambda \sim M_{GUT}$



- Width f :
  Scale of spontaneous symmetry breaking of some global symmetry
- Height Λ:
  Scale at which gauge group becomes strong

TODAY: MANY VARIANTS OF AXION INFLATION TAKE ADVANTAGE OF SHIFT SYMMETRY AS WE PROPOSED

Inflation after Planck: only the simplest well-motivated models survive

- (plot from Planck paper, 2015)

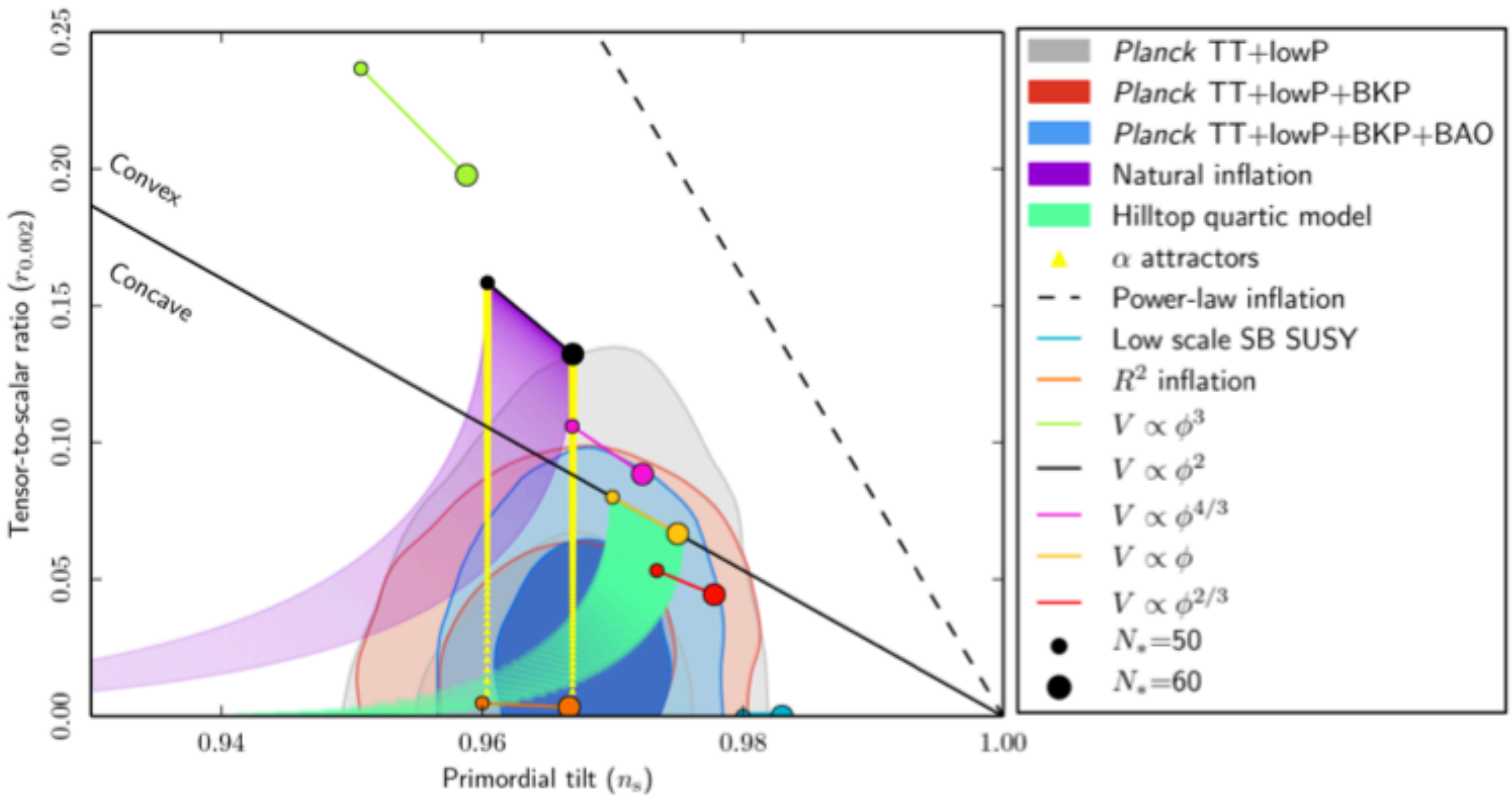


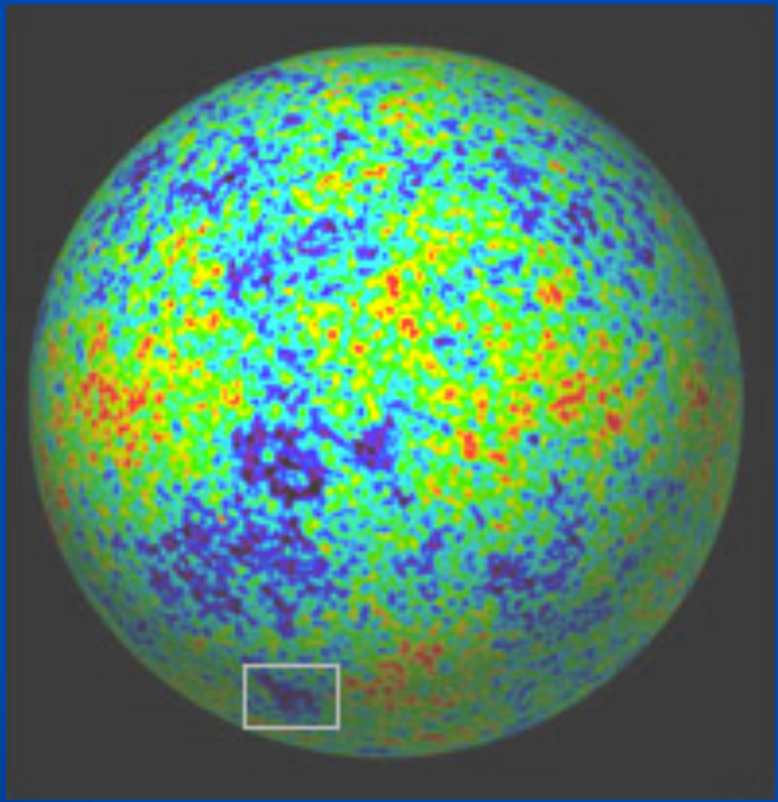
Fig. 54. Marginalized joint 68 % and 95 % CL regions for n_s and $r_{0.002}$ from *Planck* alone and in combination with its cross-

Weird Anomalies of WMAP hold up

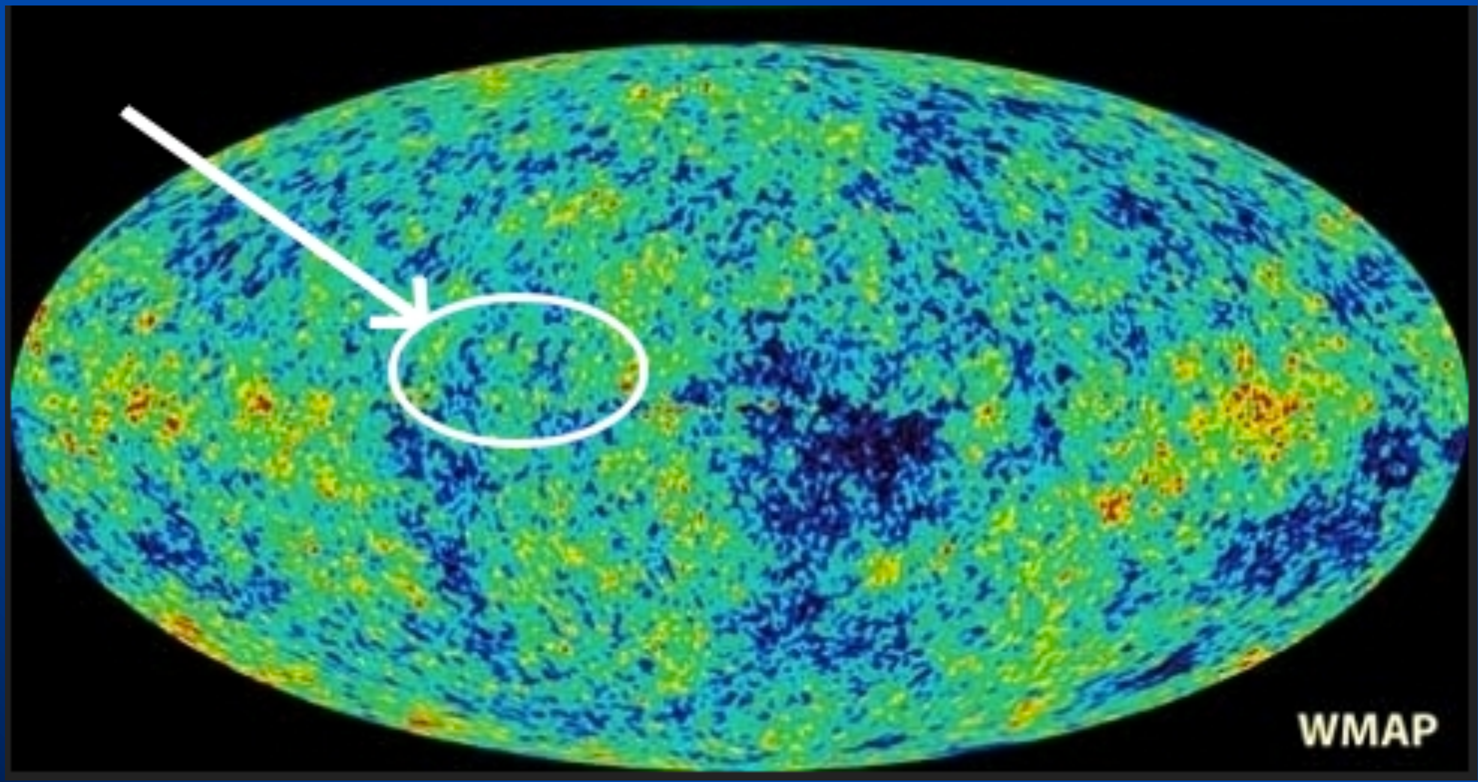
- Alignment between quadrupole and octopole moments (axis of evil)
- Asymmetry of power between two hemispheres
- The Cold Spot
- Deficit of power in low-l modes (below l=30)

- All confirmed to 3 sigma
- Cosmological origin favored (consistency between different CMB maps)

WMAP cold spot (also in Planck)



SH initials in WMAP satellite data



WHAT'S HOT IN DARK MATTER? Unexplained signals.

WIMPS:

- DAMA annual modulation (but XENON, LUX)
- Indirect Detection from DM annihilation:
  - The HEAT/PAMELA/FERMI positron excess
  - FERMI gamma ray excess near galactic center
- Theorists are working to reconcile data sets.

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7 keV Sterile neutrinos

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

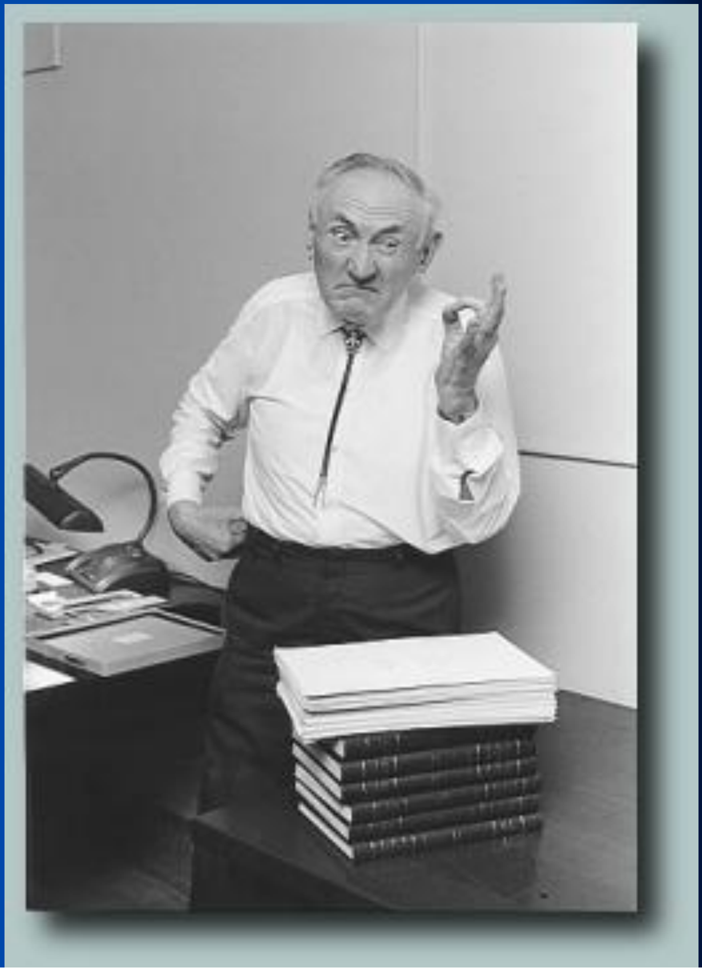
- MeV dark matter   511 keV line in INTEGRAL DATA

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

Galaxies in the Coma cluster were moving too rapidly.

He proposed "Dunkle Materie" as the explanation.

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



Rotation Curves of Galaxies

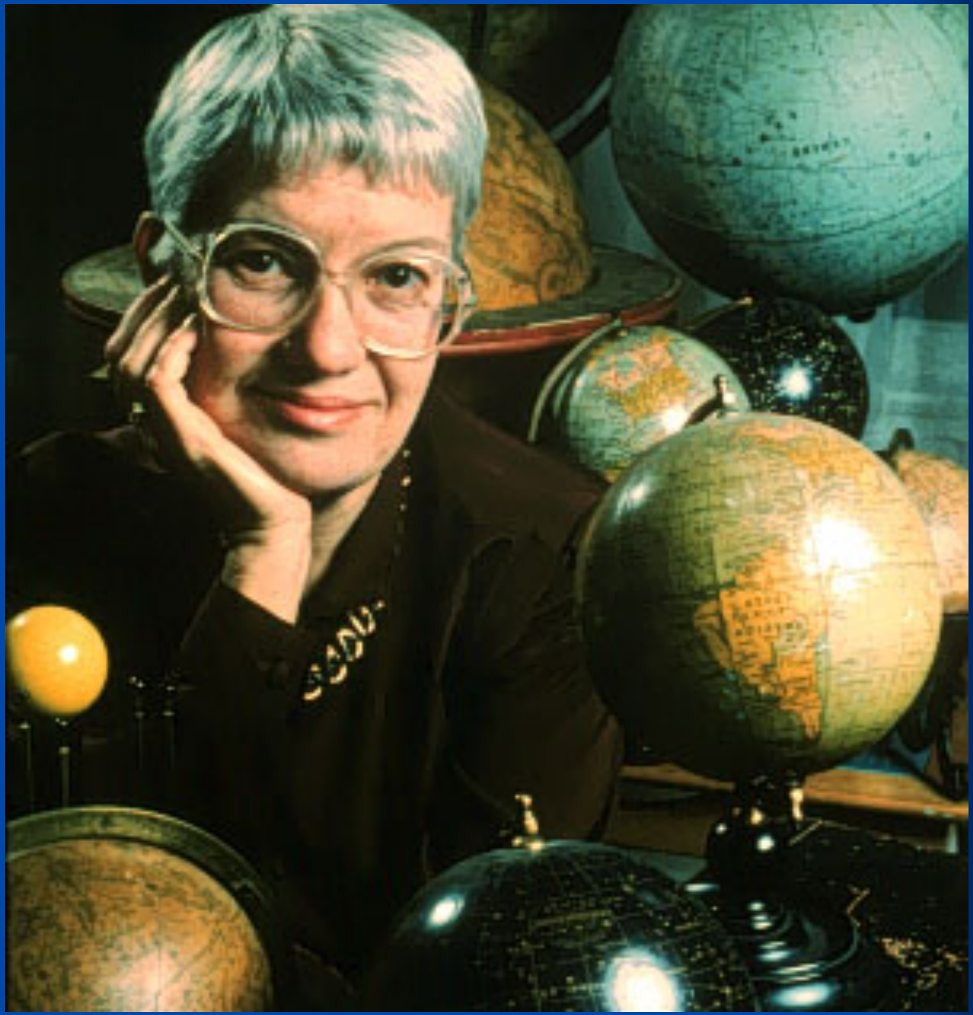
Orbit of a star in a Galaxy: speed is Determined by Mass. Larger mass causes faster orbits.

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

Vera Rubin and Kent Ford in 1970s

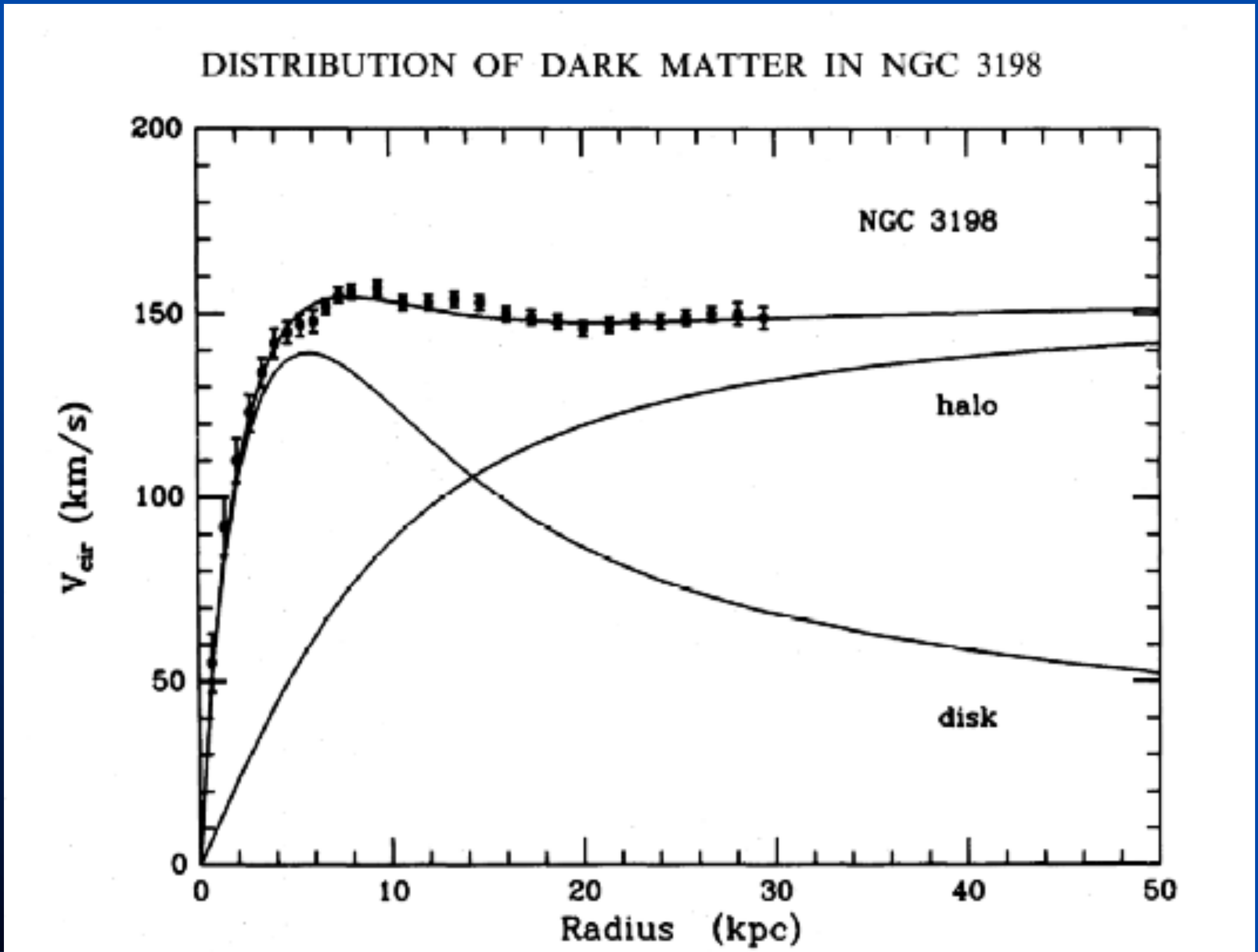
Studied rotation curves of galaxies, and found that they are all FLAT.

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



95% of the matter in galaxies is unknown dark matter

- Rotation Curves of Galaxies:

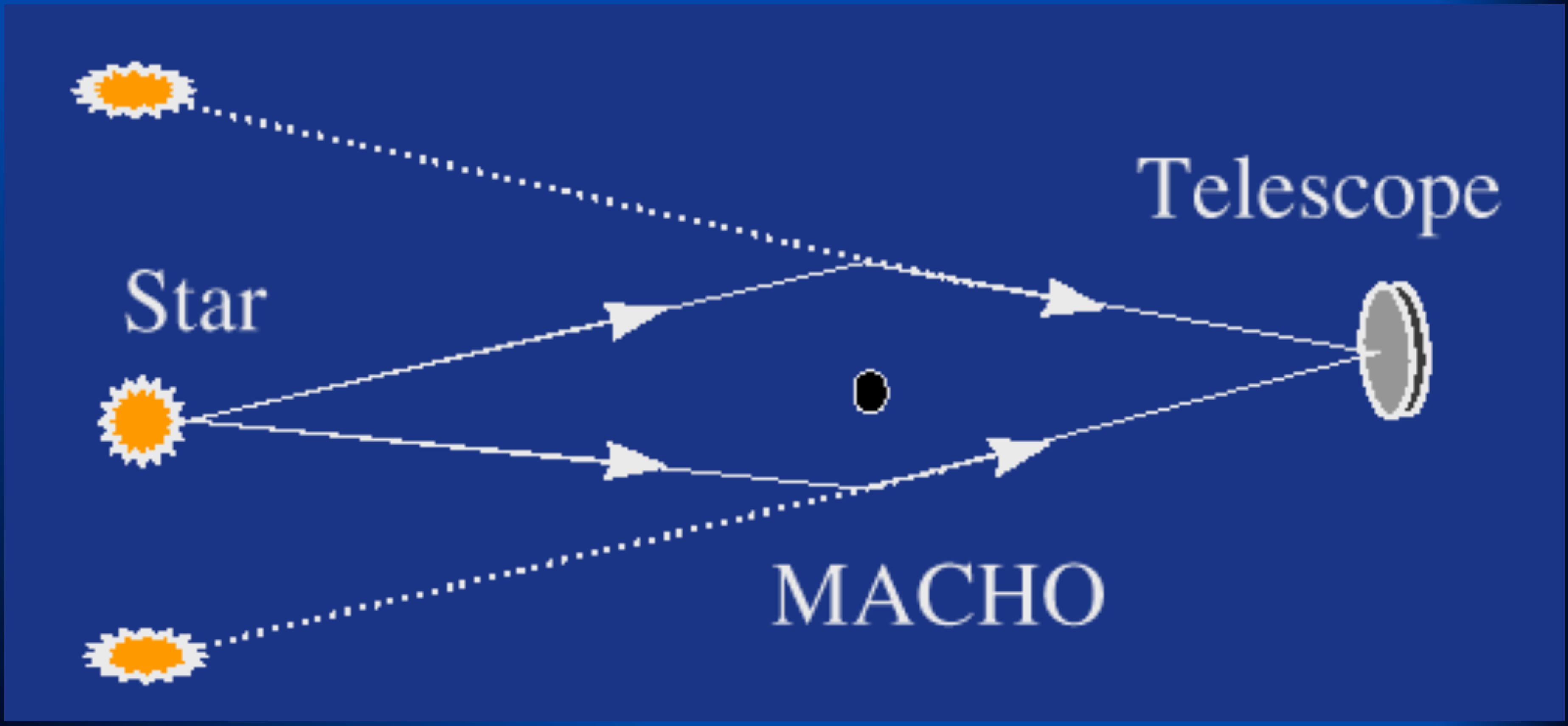


OBSERVED: FLAT ROTATION CURVE

EXPECTED FROM STARS

Galaxies have Dark Matter Haloes

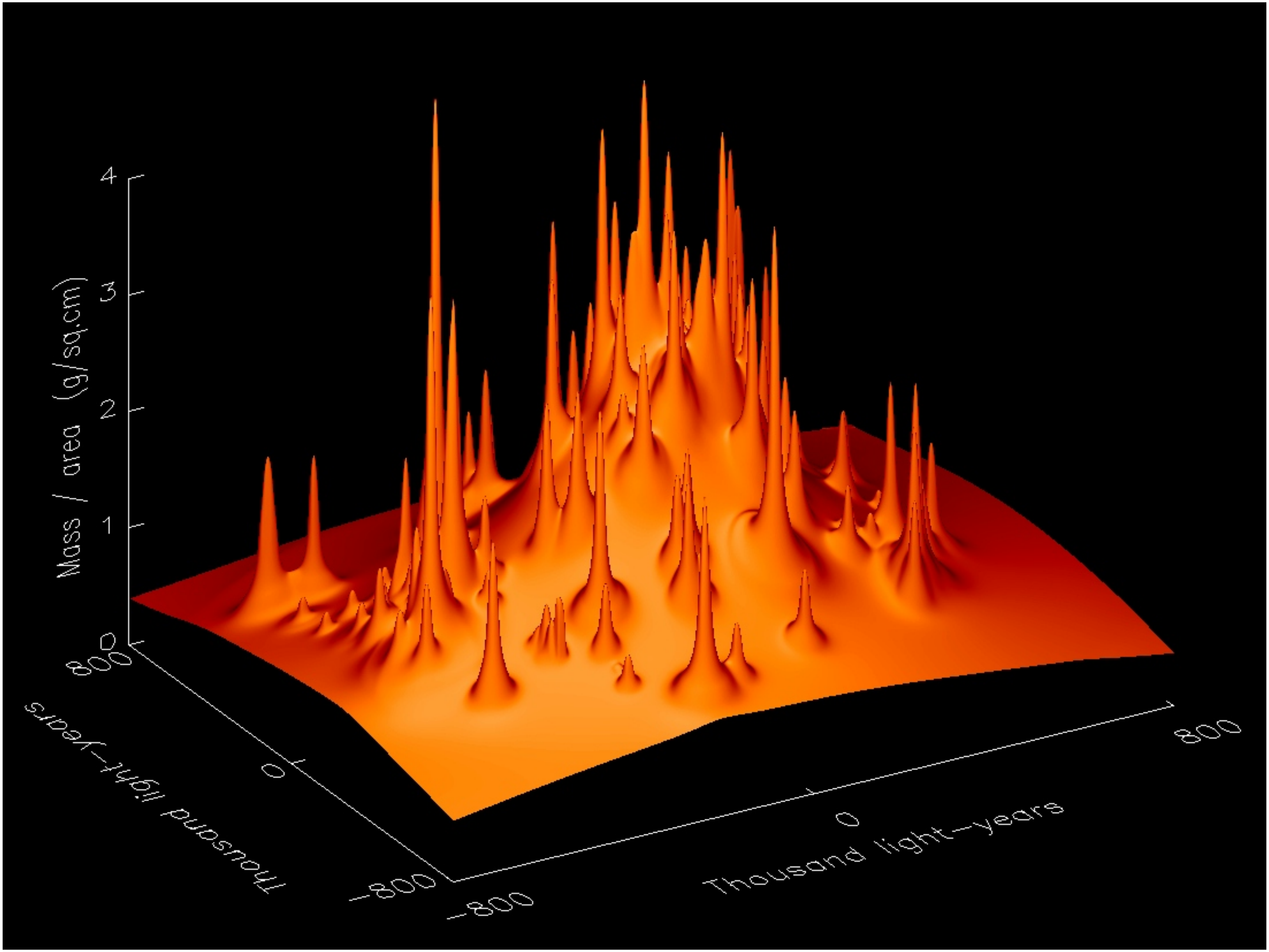
Einstein's Lensing: Another way to detect dark matter: it makes light bend



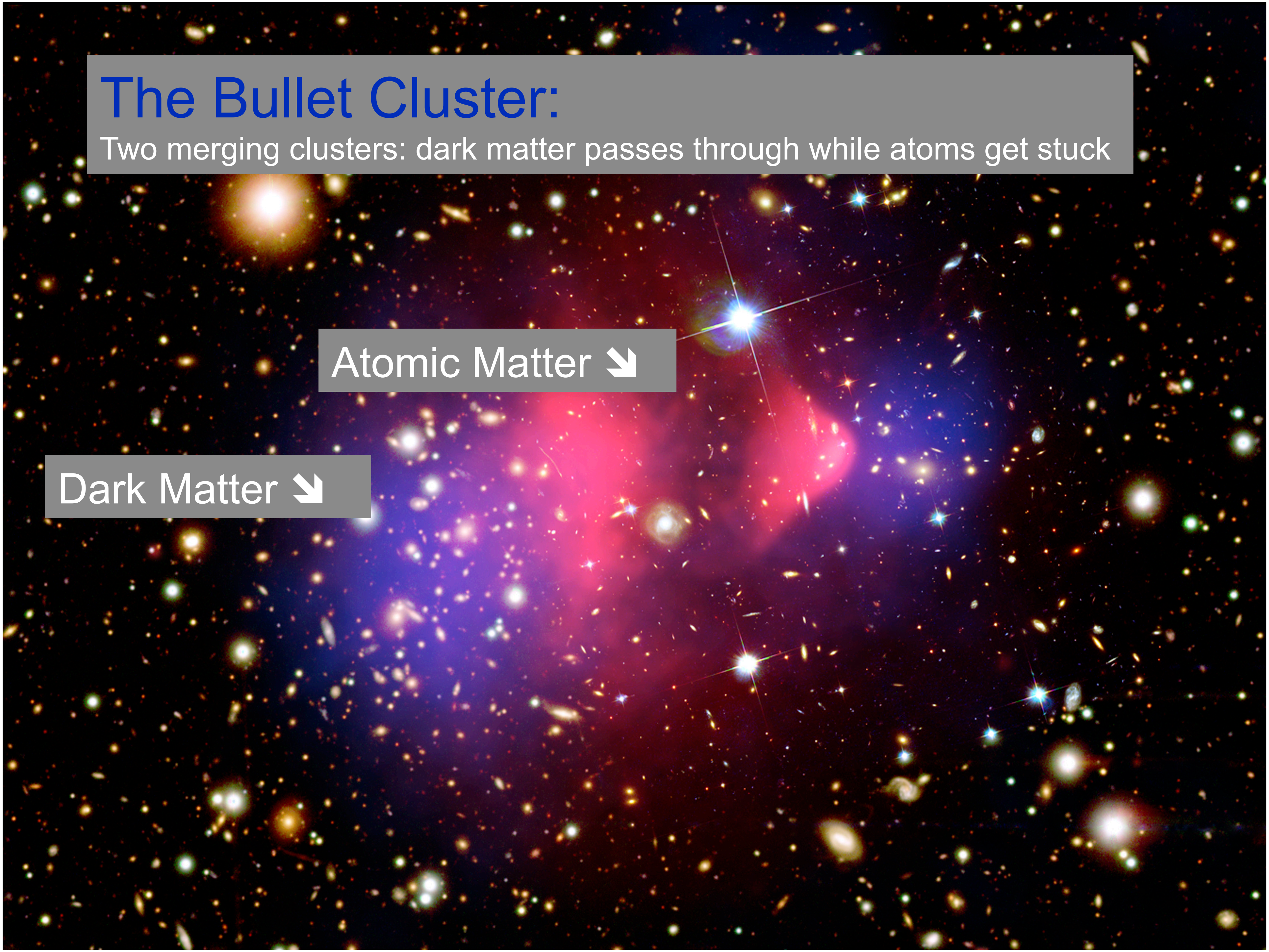
Strong lensing by dark matter

Gravitational Lens in Abell 2218 HST • WFPC2

PF95-14 • ST ScI OPO • April 5, 1995 • W. Couch (UNSW), NASA



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
Atomic Matter ➘
Dark Matter ➘

The Dark Matter Problem :

More than 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),

hot gas in clusters.

Bullet Cluster.

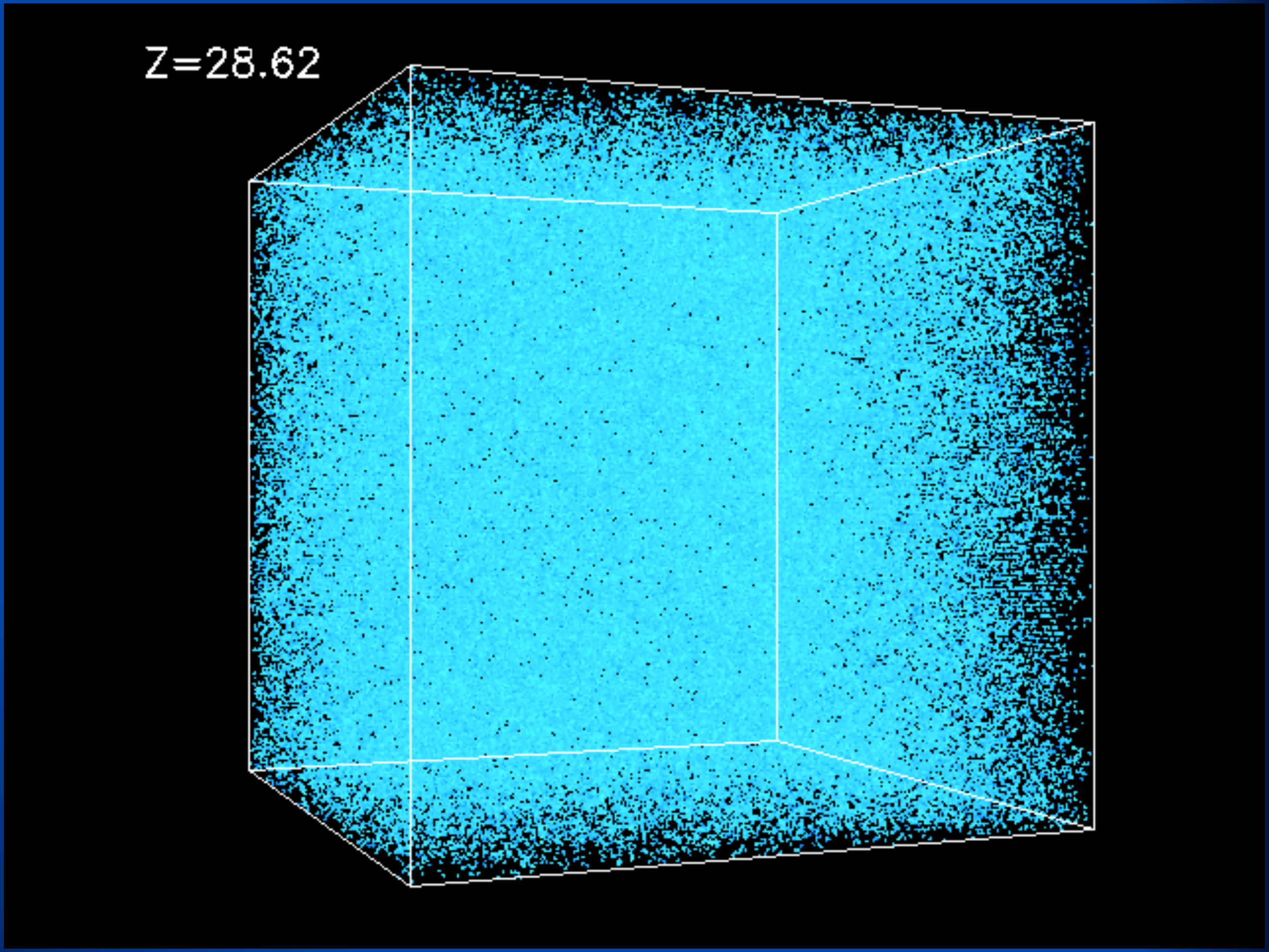
Needed for structure formation.

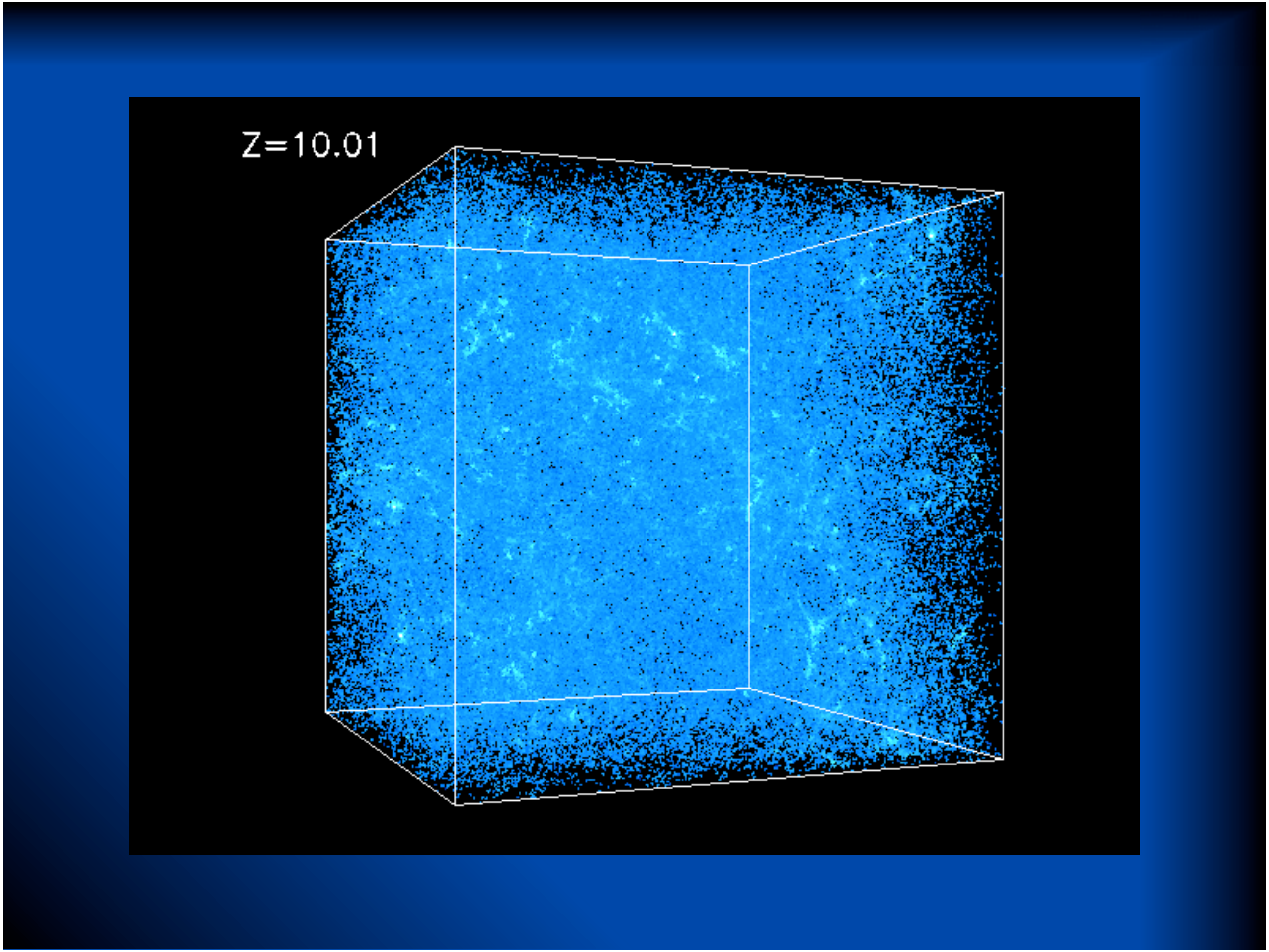
Evidence for Dark Matter: Formation of Structure, Computer Simulations

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

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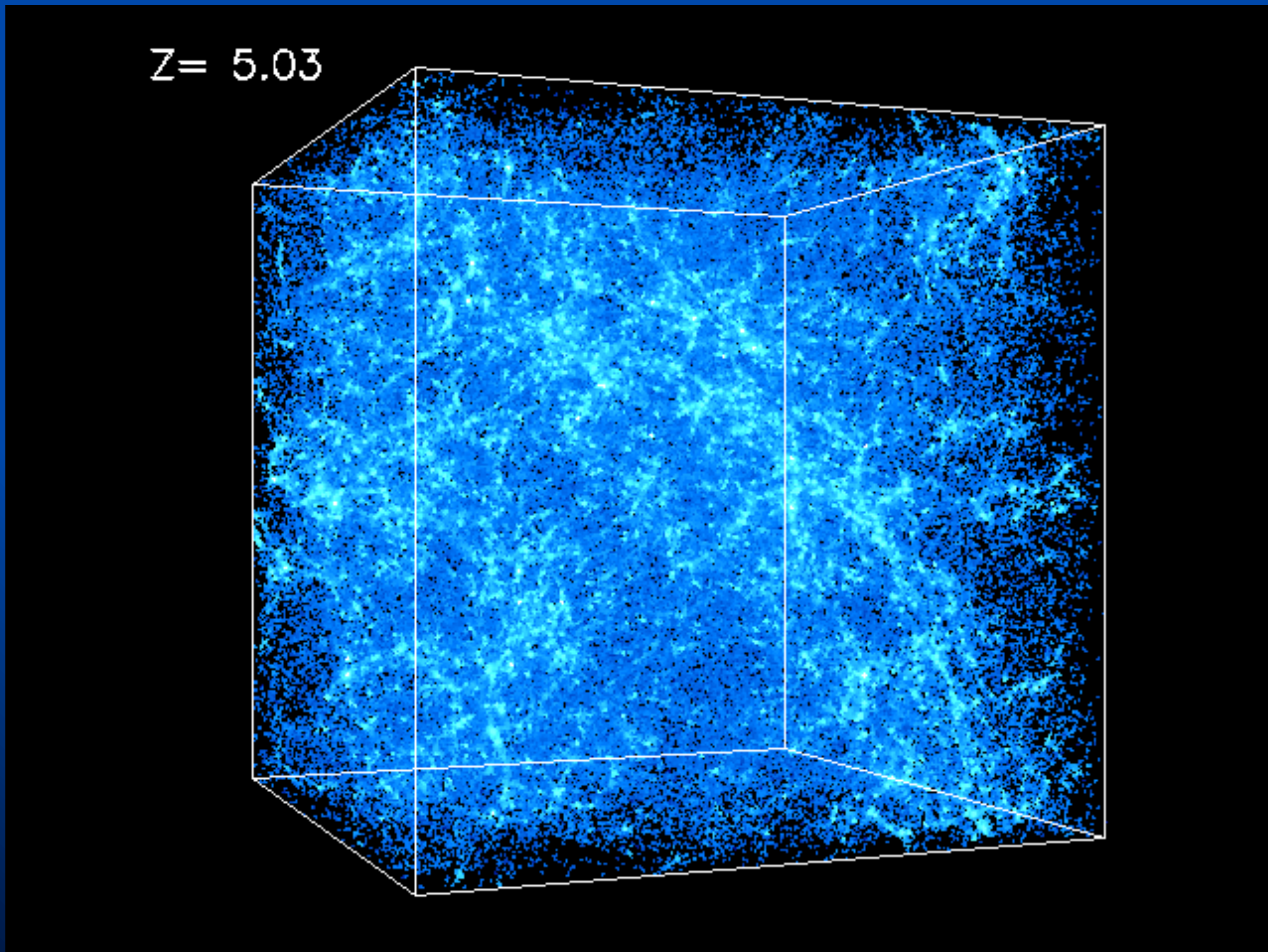
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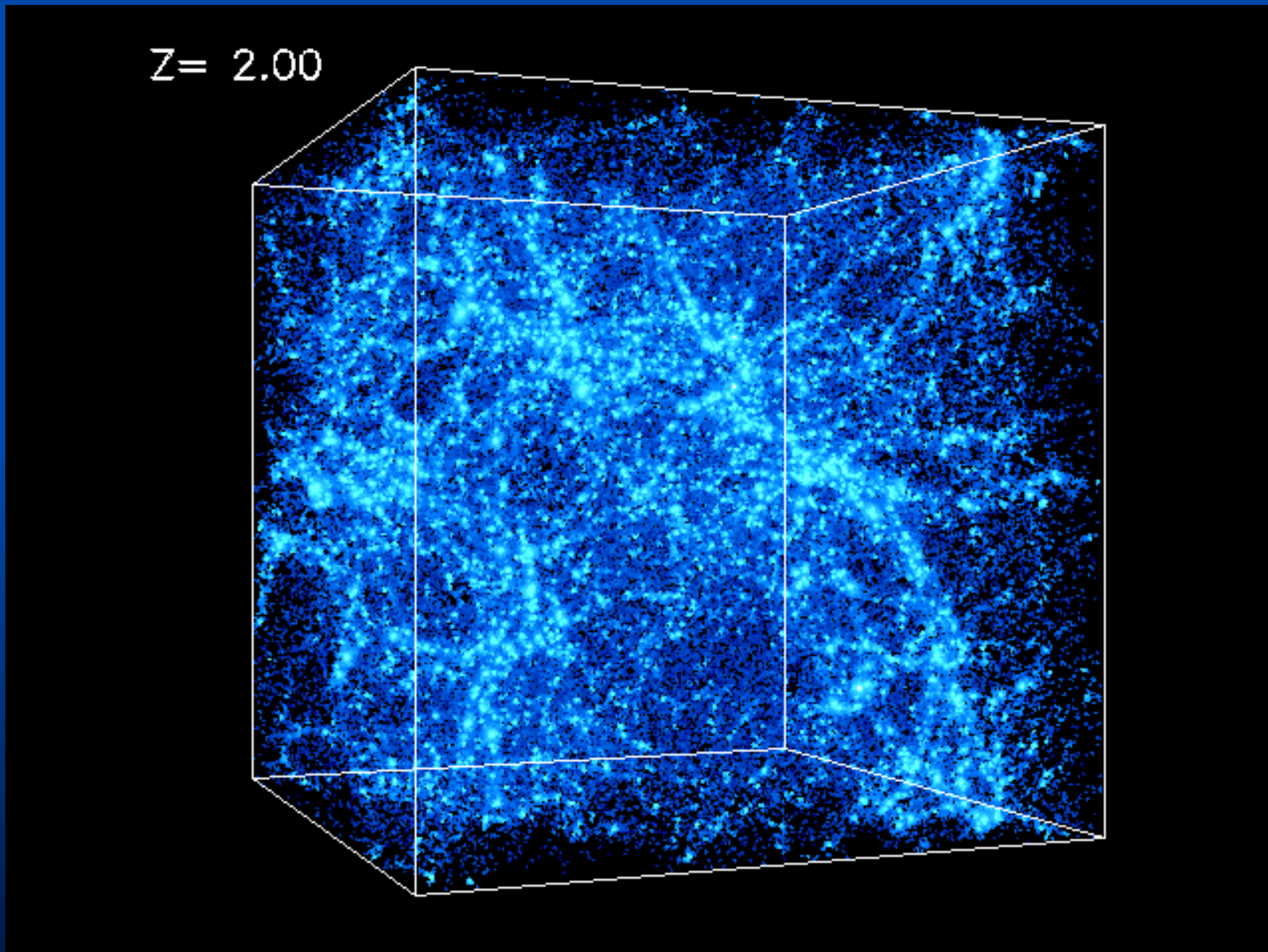
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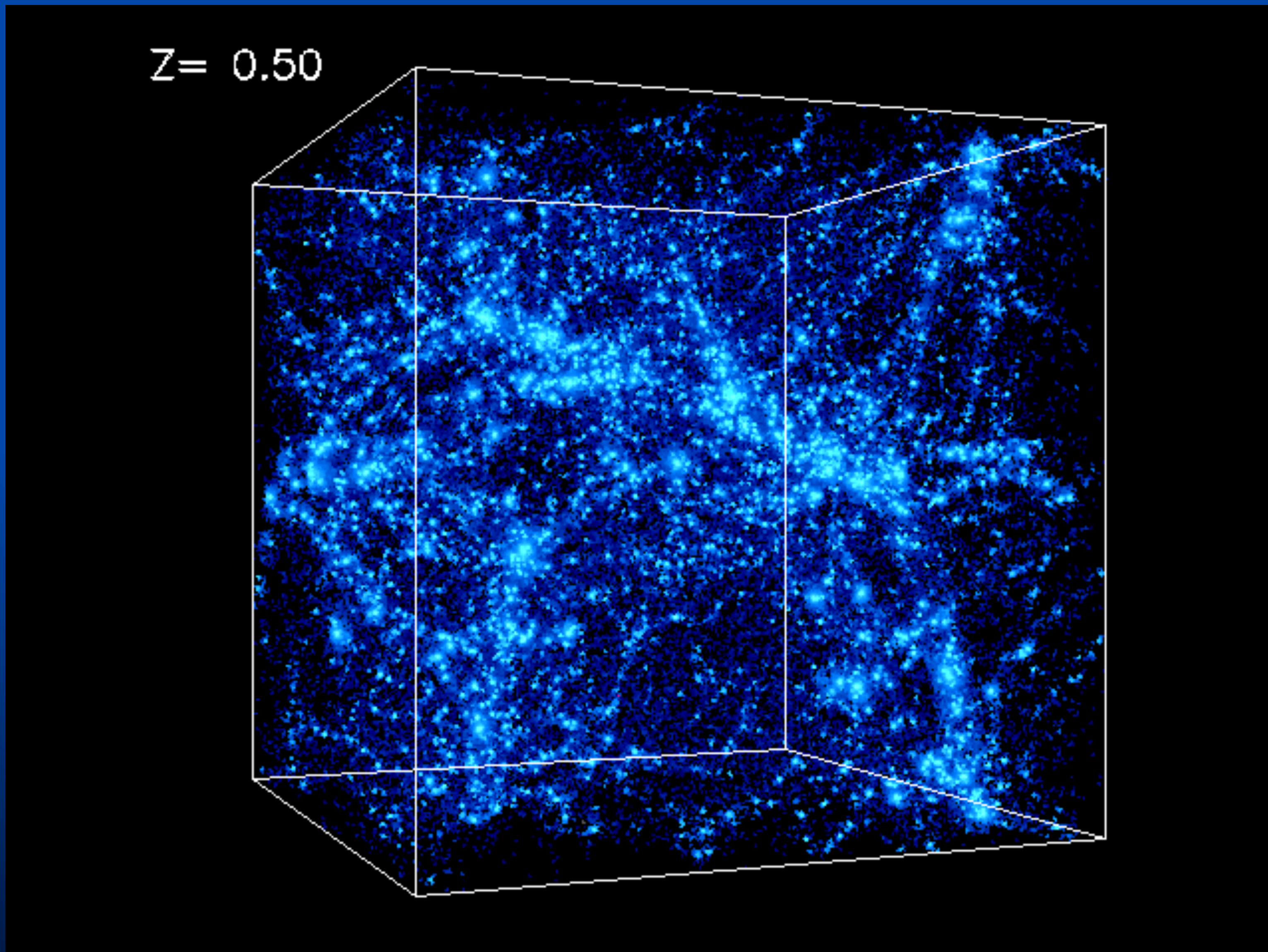
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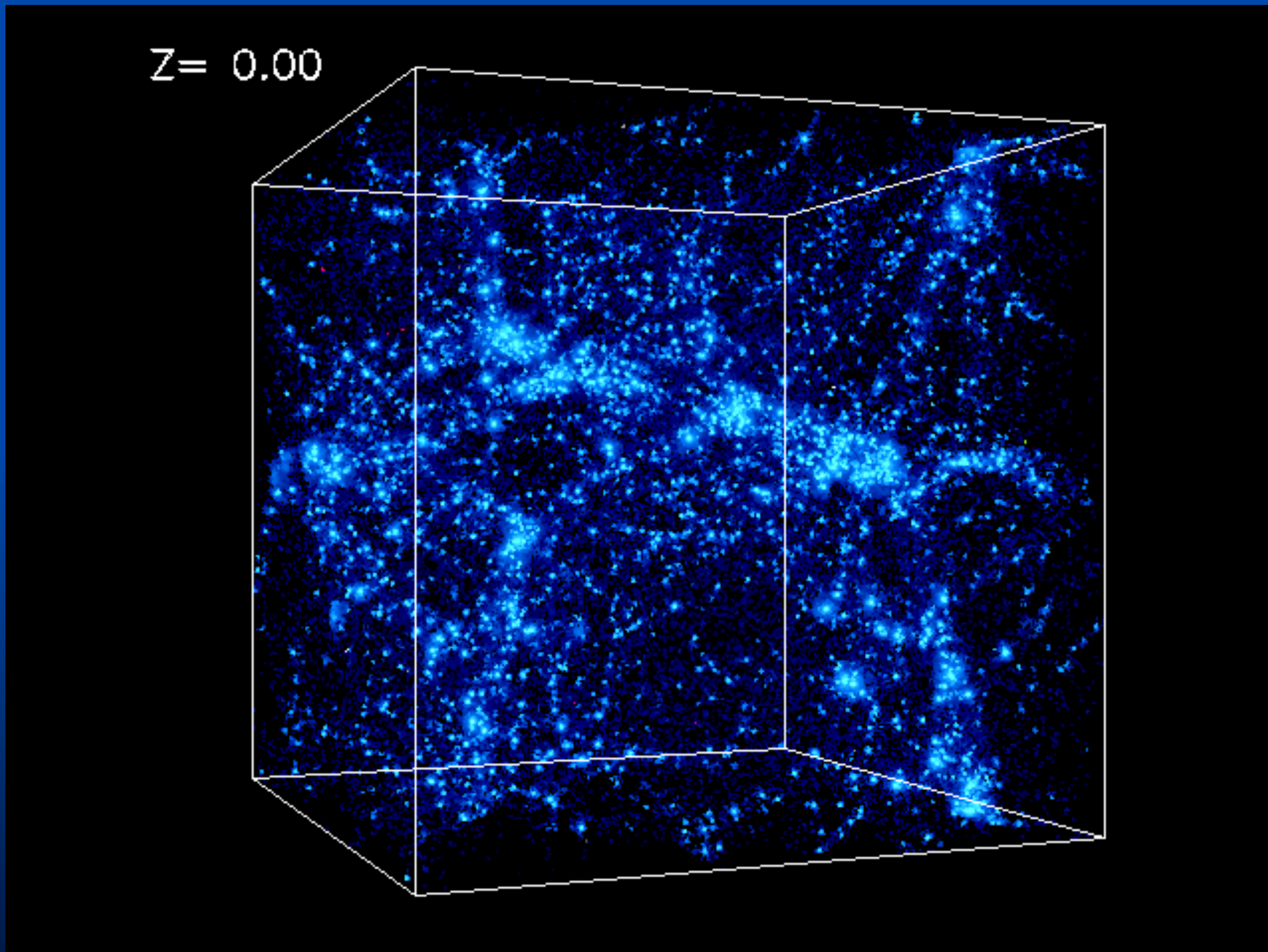

Z= 0.00

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)

Fifteen Years ago, 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:

- WIMPs (SUSY or extra dimensions)
- Axions
- Neutrinos (too light, ruin galaxy formation)
- Sterile Neutrinos: no Standard Model interaction
- Asymmetric Dark Matter
- Self Interacting Dark Matter
- Primordial black holes
- WIMPzillas
- Axinos and gravitinos

Top candidates for the Dark Matter Particle: WIMPs

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

Two reasons we favor WIMPs: First, the relic abundance

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

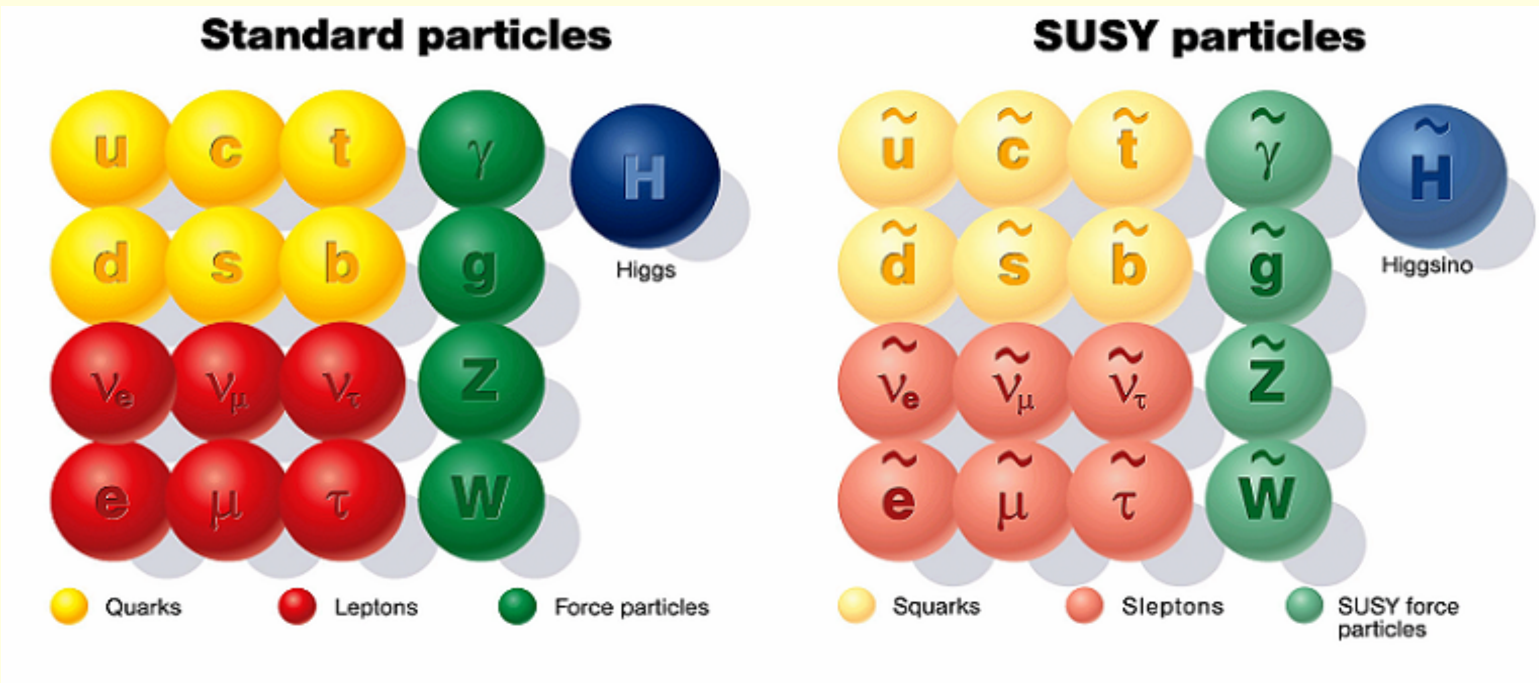
$$\Omega_\chi h^2 = \frac{3\times 10^{-27}\ cm^3/\sec}{<\sigma v>_{ann}}$$

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



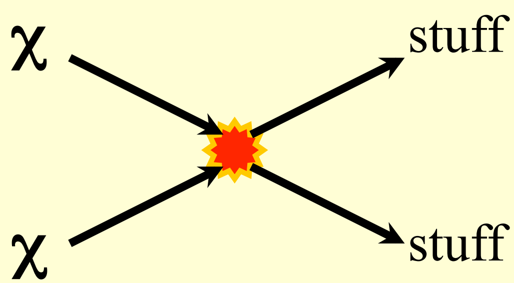
- The lightest supersymmetric particle may be the dark matter.

Another type of WIMP from Universal Extra Dimensions

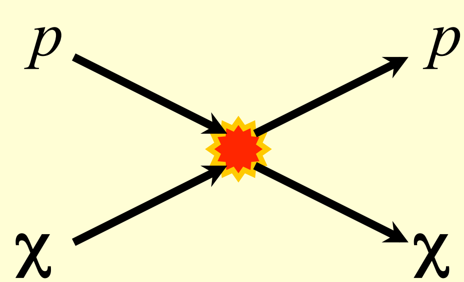
- All standard model fields propagate in a higher dimensional bulk that is compactified on a space TeV^-1
- Higher Dimensional momentum conservation in bulk translates in 4D to KK number (w/ b.c. to KK parity)
- Lightest KK particle (LKP) does not decay and is dark matter candidate

THREE PRONGED APPROACH TO WIMP DETECTION

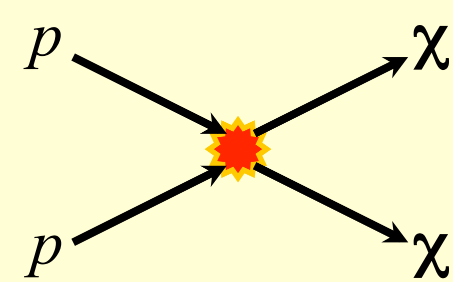
Interactions with Standard Model particles



Annihilation



Scattering



Production

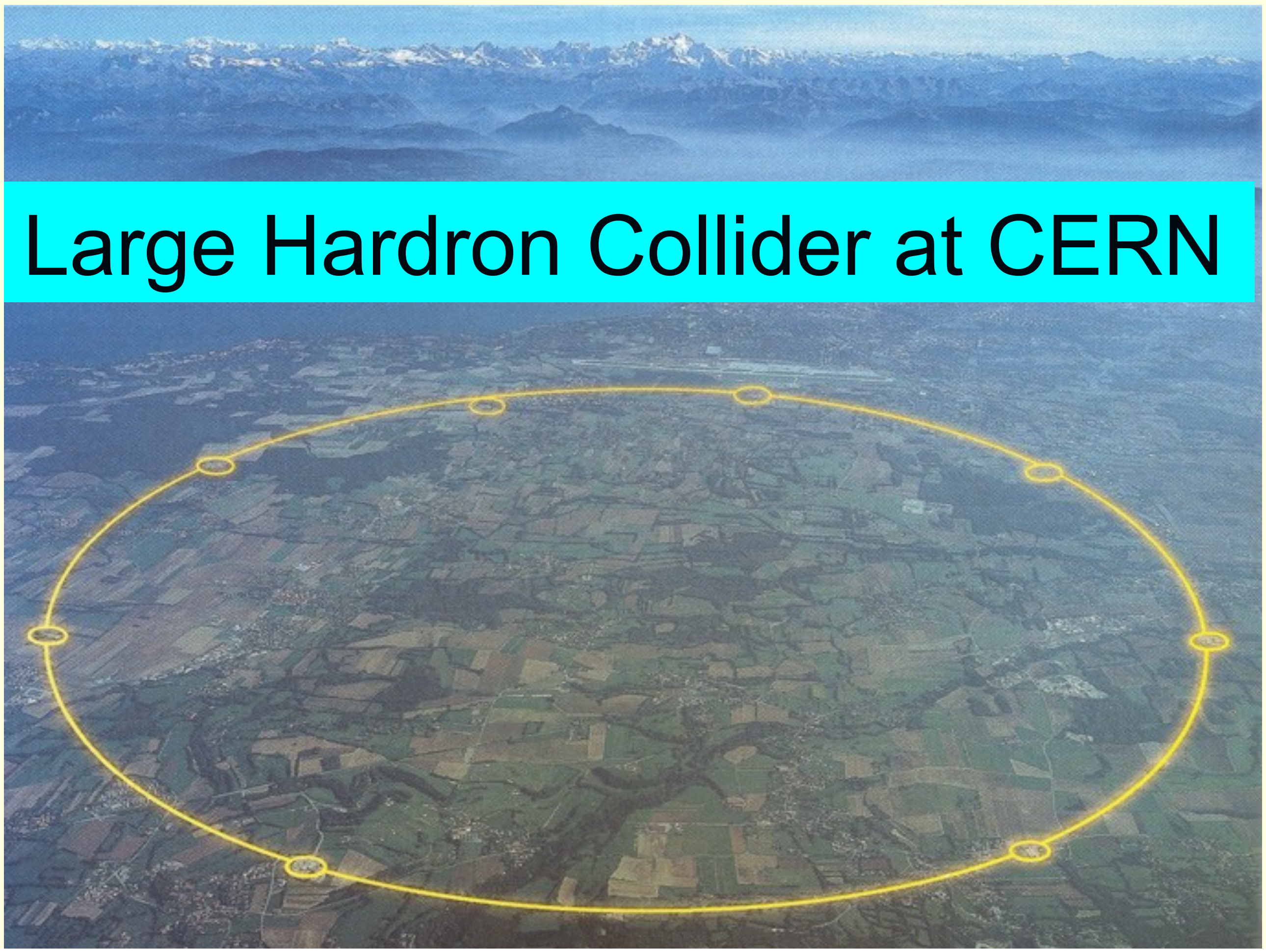
Indirect Detection:
Halo (cosmic-rays), capture in Sun (ν's)

Direct Detection:
Look for scattering events in detector

Accelerators:
LHC

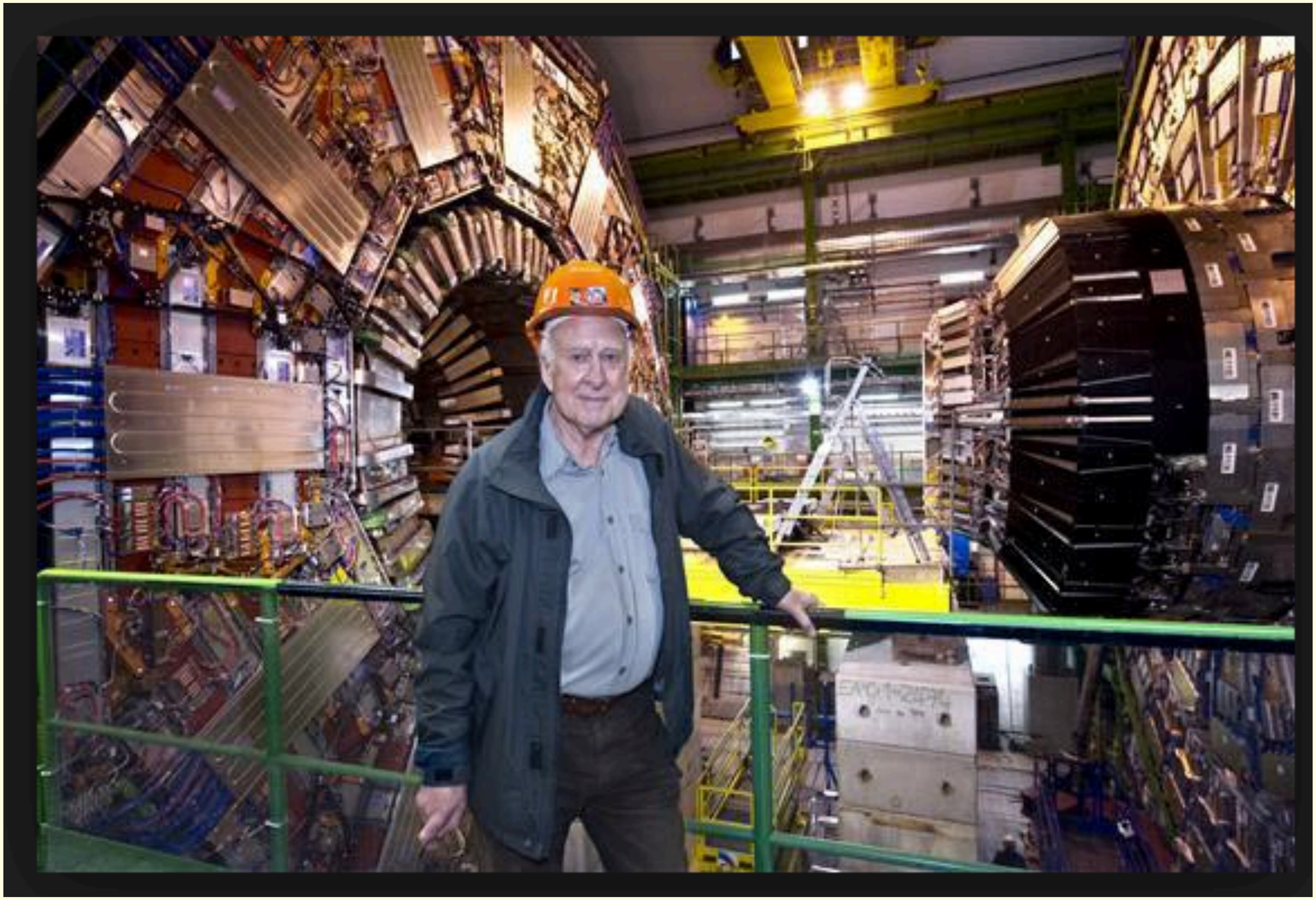
FOURTH PRONG: DARK STARS

(i) FIRST WAY TO SEARCH FOR WIMPS

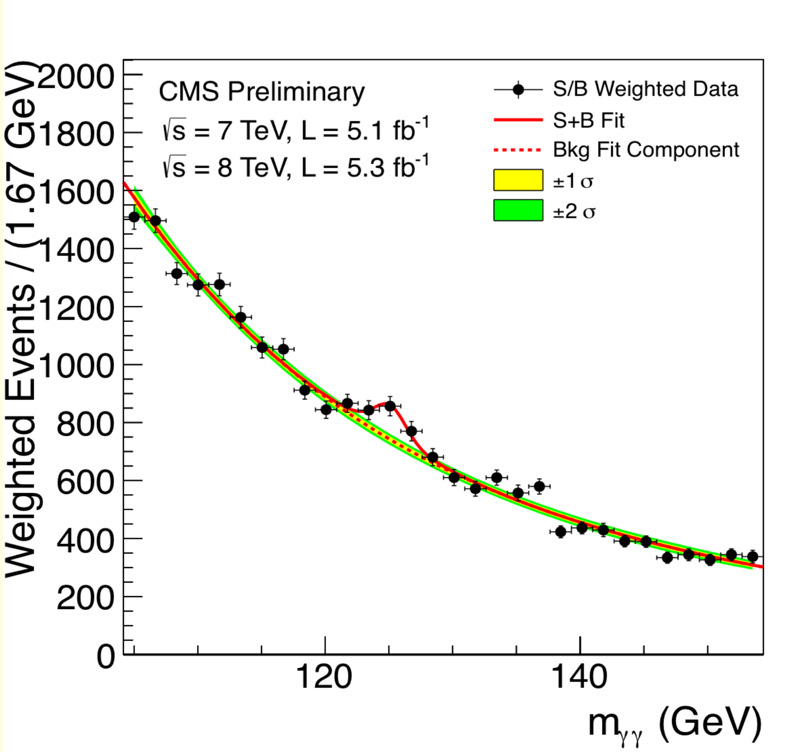


Fabiola Gianotti, spokesperson of ATLAS detector
Now Director General of CERN

Peter Higgs and CMS detector

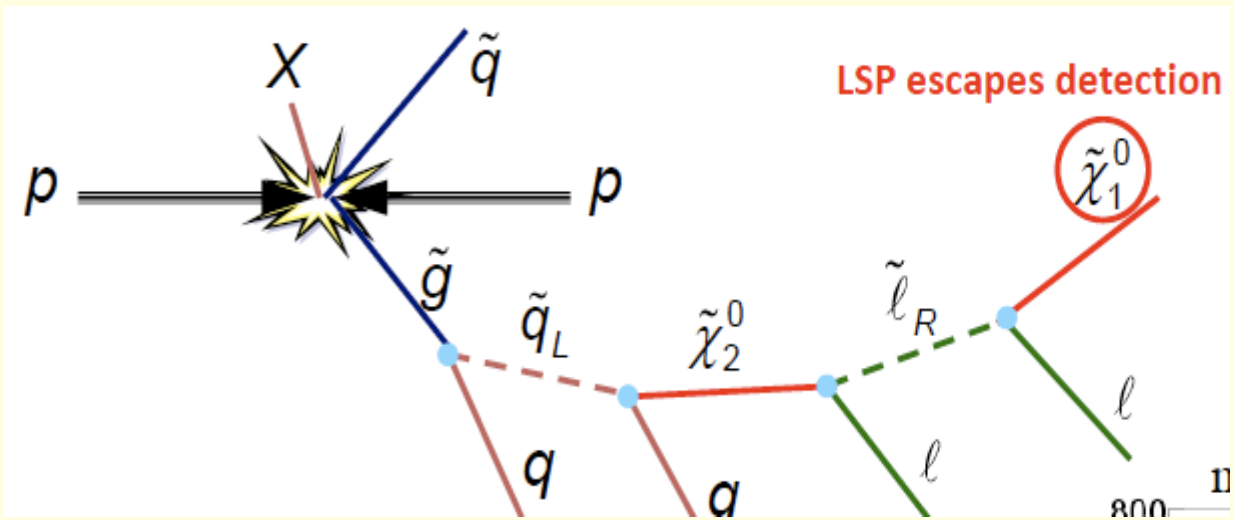


LHC's first success
Discovery of Higgs boson
weighing 125 GeV



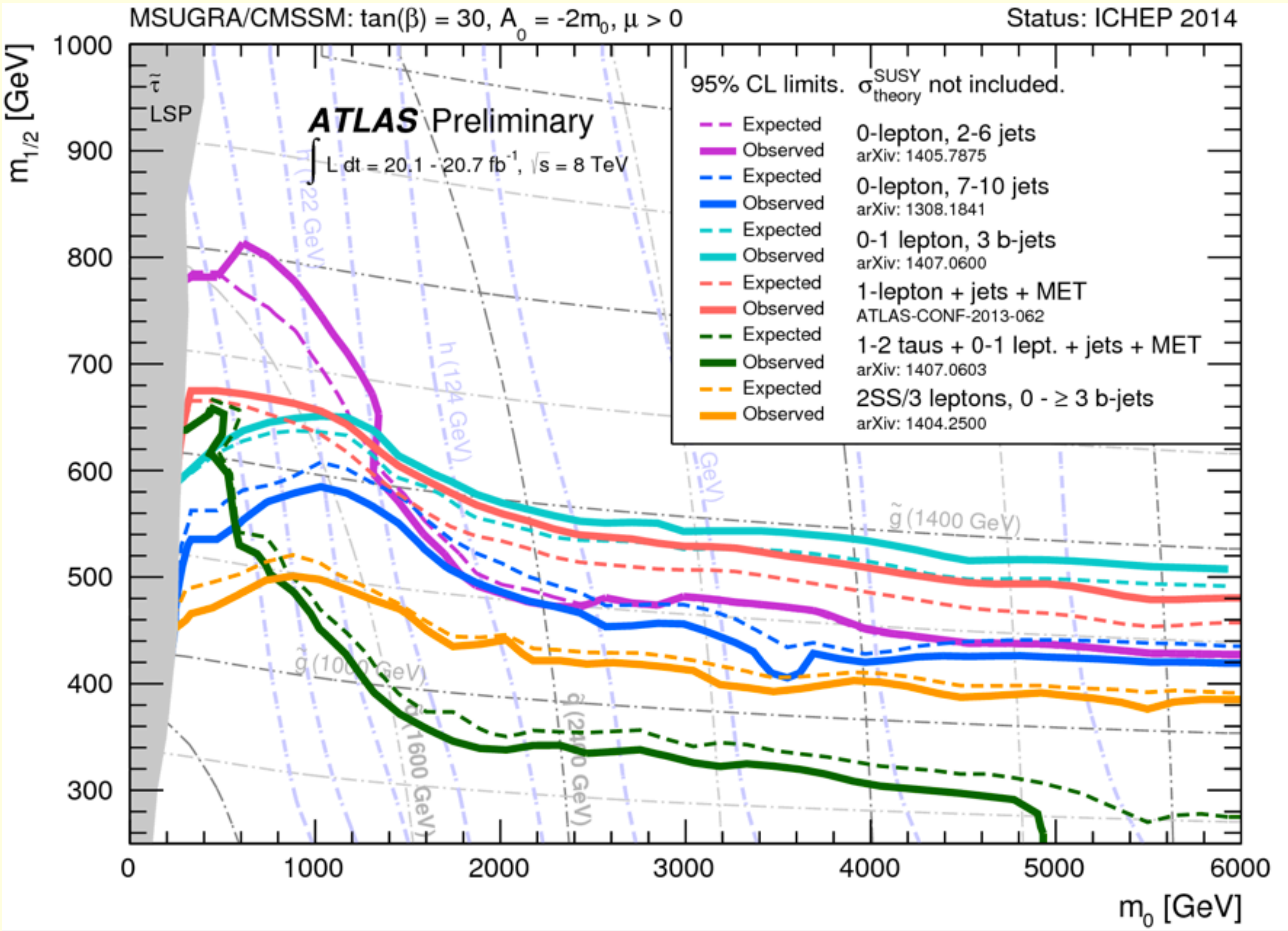
Second major goal of LHC: search for SUSY and dark matter

- Two signatures: Missing energy plus jets



- Nothing seen yet: particle masses pushed to higher masses

ATLAS bounds on CMSSM



Comments on DM at LHC

- Even in the MSSM, 25 GeV neutralino WIMPs can survive for now (Pierce, Shah, KF)
- The LHC has now reached energies where interesting new physics is within reach
- 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

Supersymmetric Particles in LHC

- Signature: missing energy when SUSY particle is created and some energy leaves the detector
- Problem with identification: degeneracy of interpretation
- SUSY can be found, but, you still don't know how long the particle lives: fractions of a second to leave detector or the age of the universe if it is dark matter
- Proof that the dark matter has been found requires astrophysical particles to be found

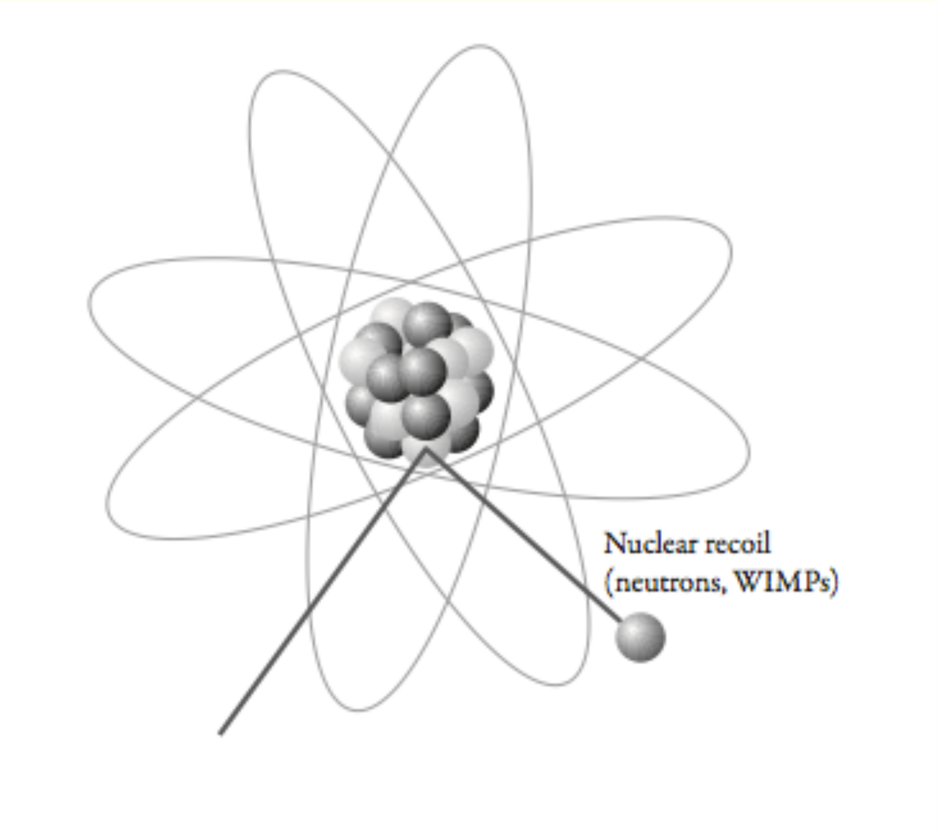
SECOND WAY TO SEARCH FOR WIMPS

DIRECT DETECTION

Laboratory EXPERIMENTS

DIRECT DETECTION OF WIMP DARK MATTER

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



Expected Rate: less than one count/kg/day

Drukier and Stodolsky (1984)

proposed neutrino detection via weak scattering off nuclei

Andrzej Drukier

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

The Back Page

Email | Print

Cold War Human Radiation Experiments: A Legacy of Distrust

By Mark Goodman

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

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

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

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

Drukier, Freese, & Spergel (1986)

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

Event rate

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

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

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

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

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

Canonical DM distribution in halo

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

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

Here

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

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

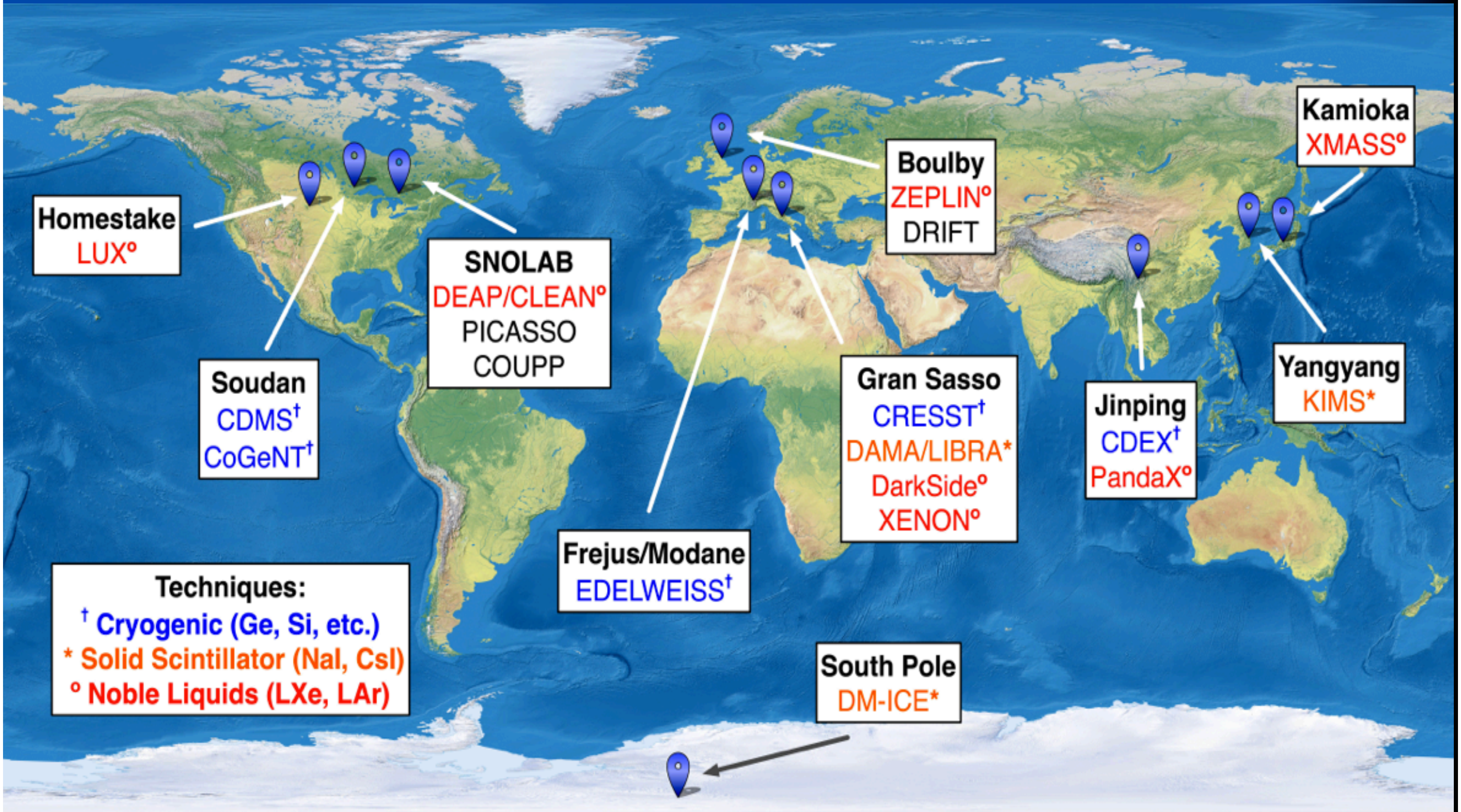
$$\overline{v}_0 = \sqrt{2/3}\,\sigma_v,$$

Typical particle speed is about 270 km/sec.

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

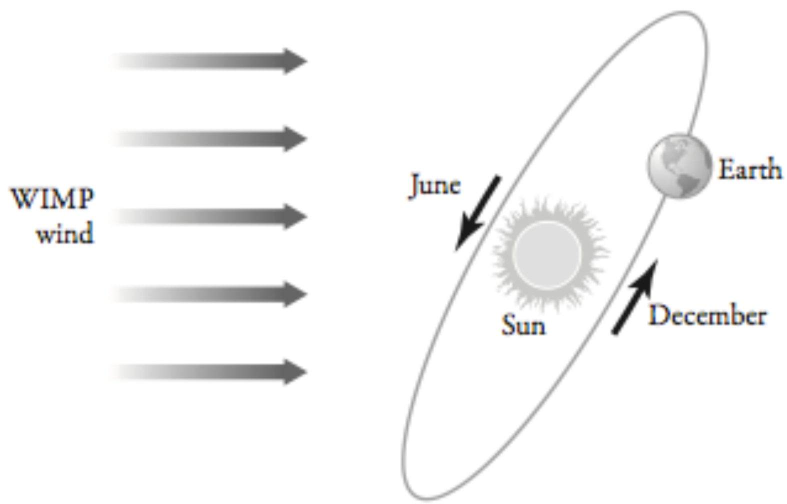
$E_0 = 2\mu^2 v_c^2/M$ so

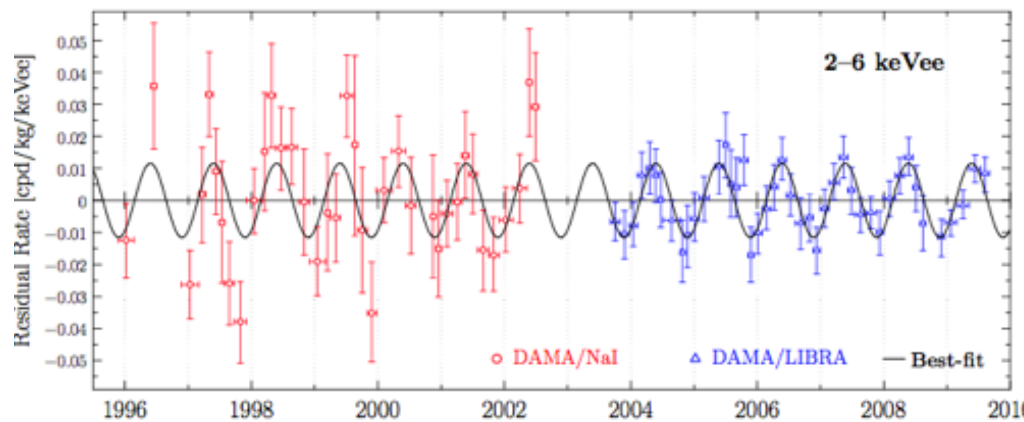
UNDERGROUND DARK MATTER LABORATORIES WORLDWIDE



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! Peak in June, minimum in December (as predicted). Are these WIMPs??

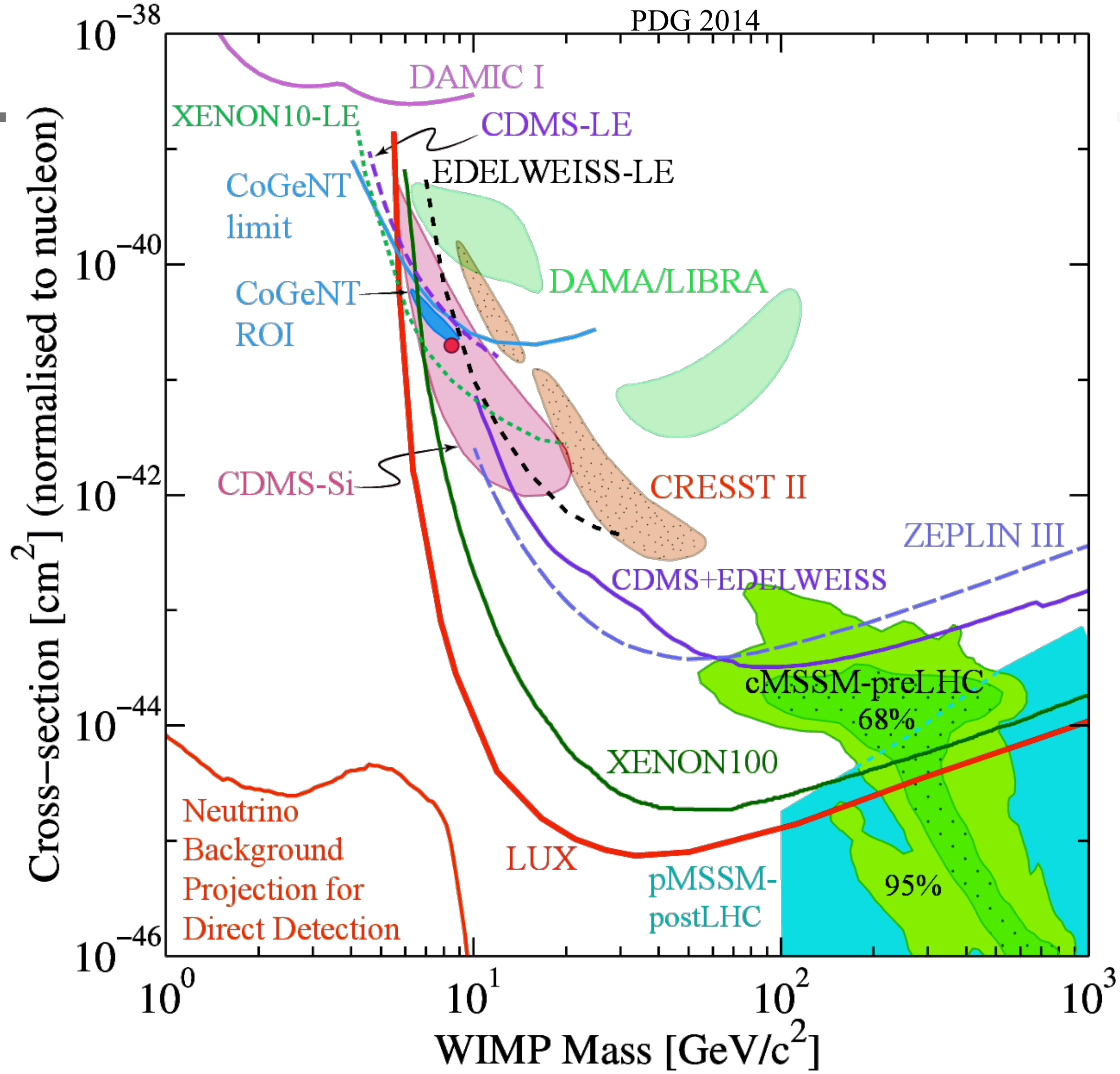
“I’ m a Spaniard caught between two Italian women”

Rita Bernabei, DAMA

Juan Collar, COGENT

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?

To test DAMA

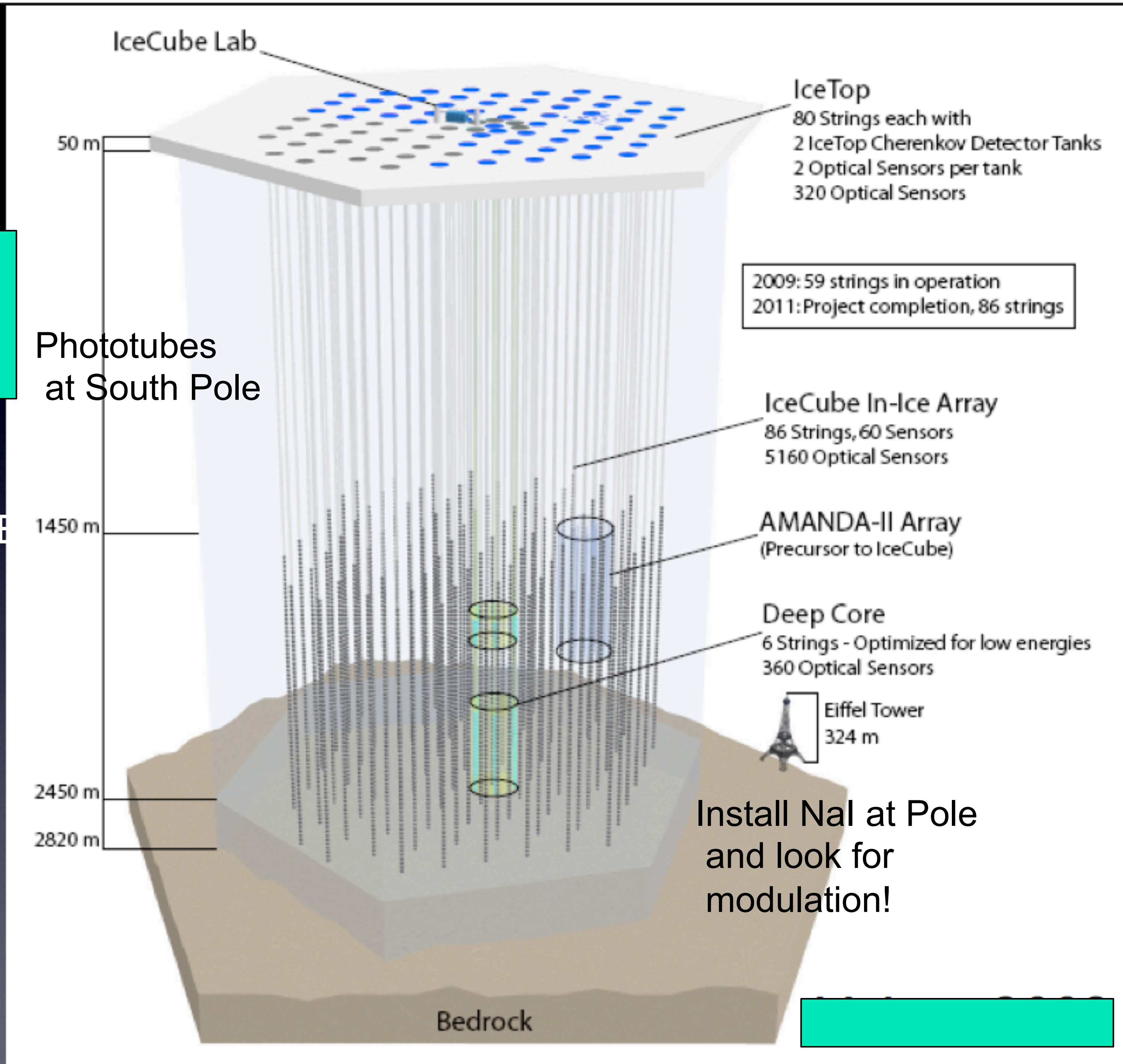
- The annual modulation in the data is still there after 13 years and still unexplained.
- Other groups are planning to use NaI crystals in the Southern Hemisphere:
- SABRE (Princeton) with Australia
- Also DM Ice at the South Pole

DM-ICE

TO TEST DAMA

IceCube

DEEPCORE experiment at South Pole has installed NaI xtals to look for annual modulation
1) no T variations
2) Southern Hemisphere



Status of DM searches

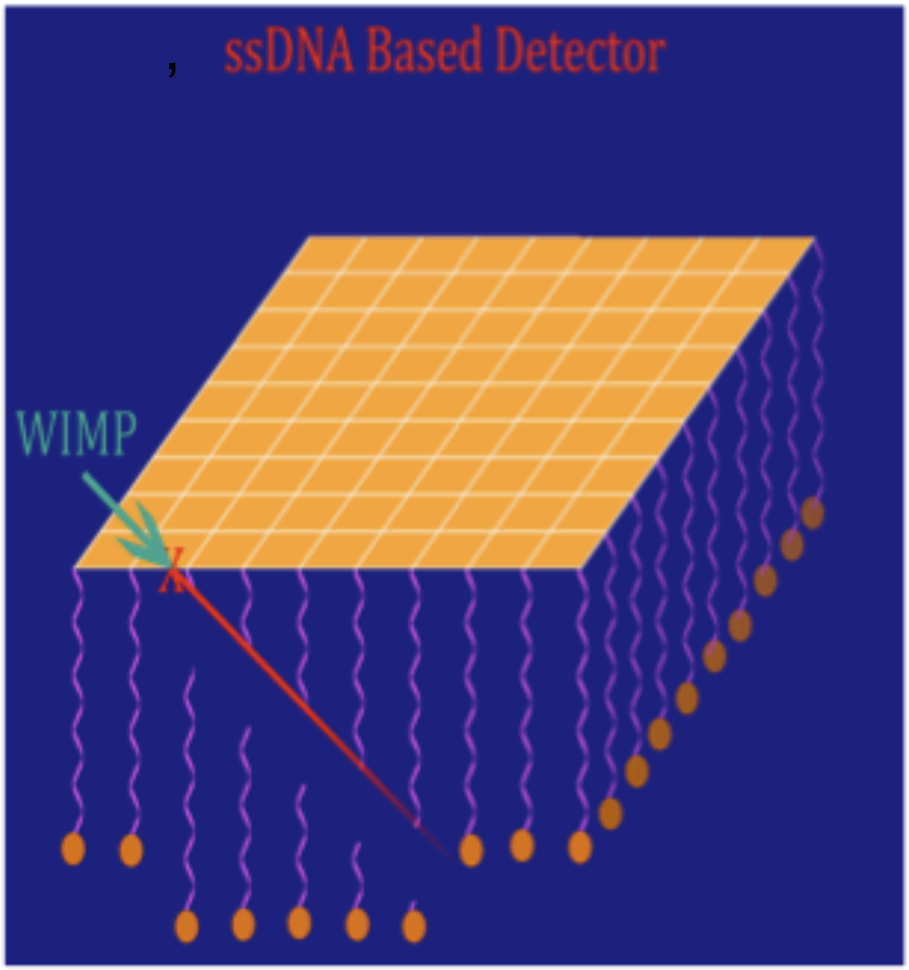
- Difficulty: comparing apples and oranges, since detectors are made of different materials.
- Theory comes in: Spin independent scattering, Spin dependent, try all possible operators, mediators, dark sector, etc.
- Interesting avenue: nuclear physics. Wick Haxton finds DAMA may be consistent with LUX

The Future of Direct Detection: 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: 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

Alternative DM detector:

NANOBOOMS

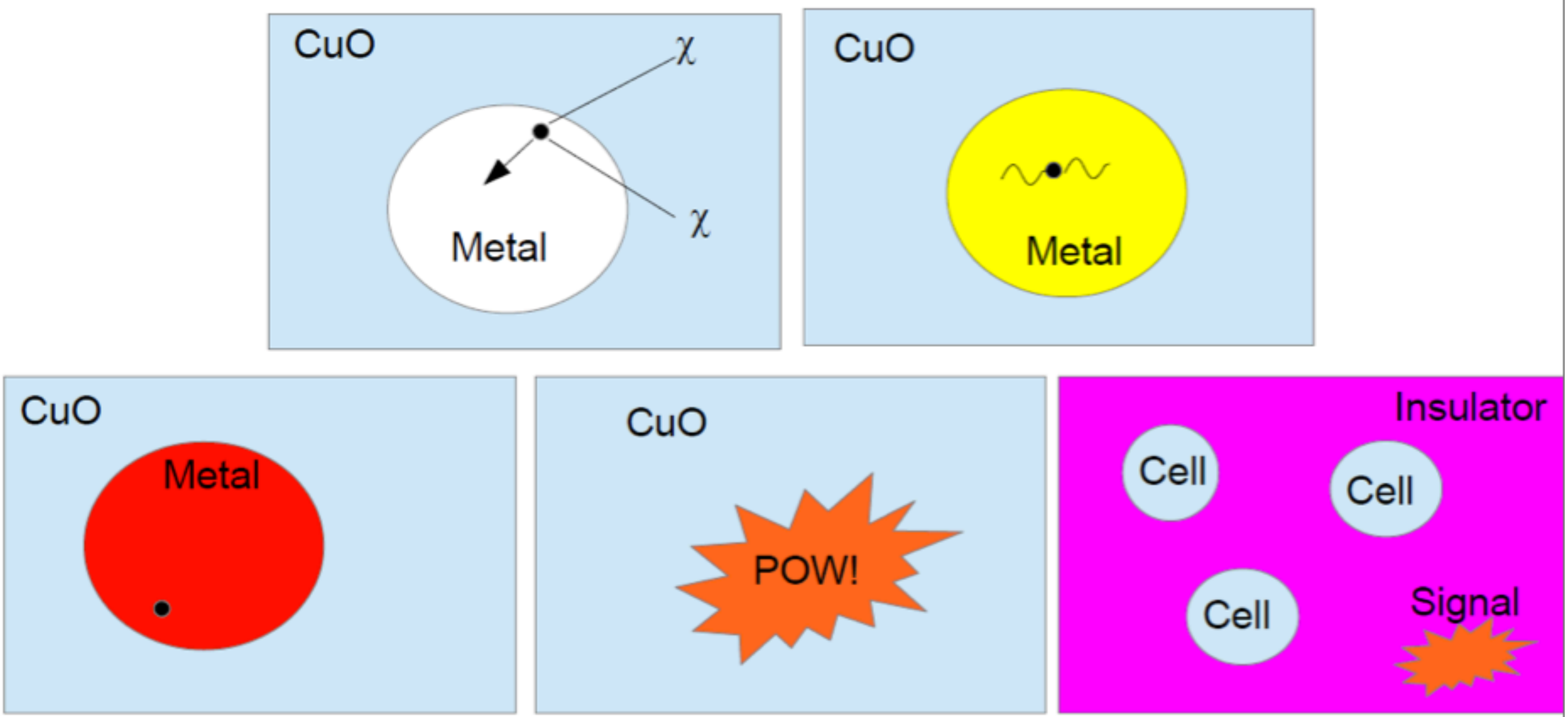
- Lopez, Drukier, Freese, Kurdak, Tarle, Budker

Nano-Thermite Detector: Thermites

- Thermite reaction is a chemical **exothermic** reaction between a metal fuel and a metal oxide.
- Metal fuel: Al, Zn, Mg and Si.
- Metal Oxide: Fe_2O_3, CuO and B_2O_3
- Common Ex:

$$2Al + Fe_2O_3 \longrightarrow Al_2O_3 + 2Fe + 852\ kJ/mol$$

Nano-Thermite Detector: Design



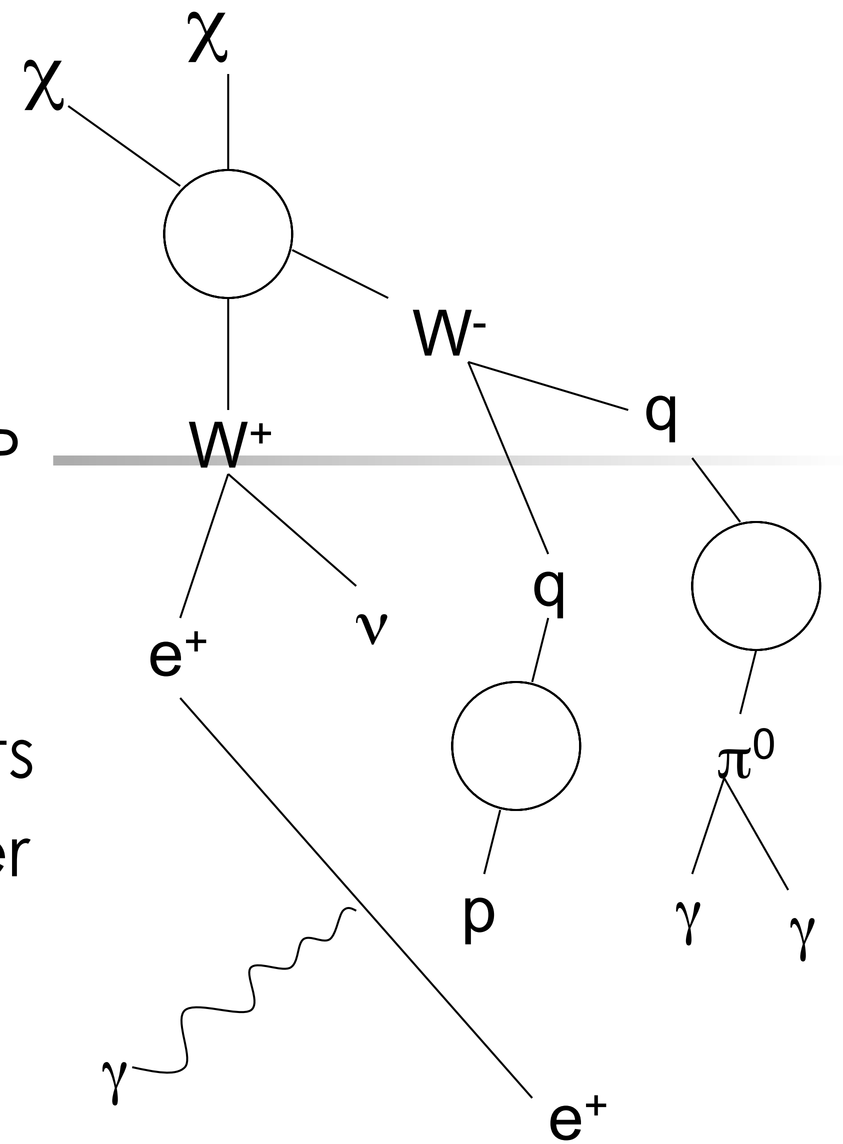
THIRD WAY TO SEARCH FOR WIMPS

INDIRECT DETECTION:
searching for astrophysical WIMP annihilation products

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)

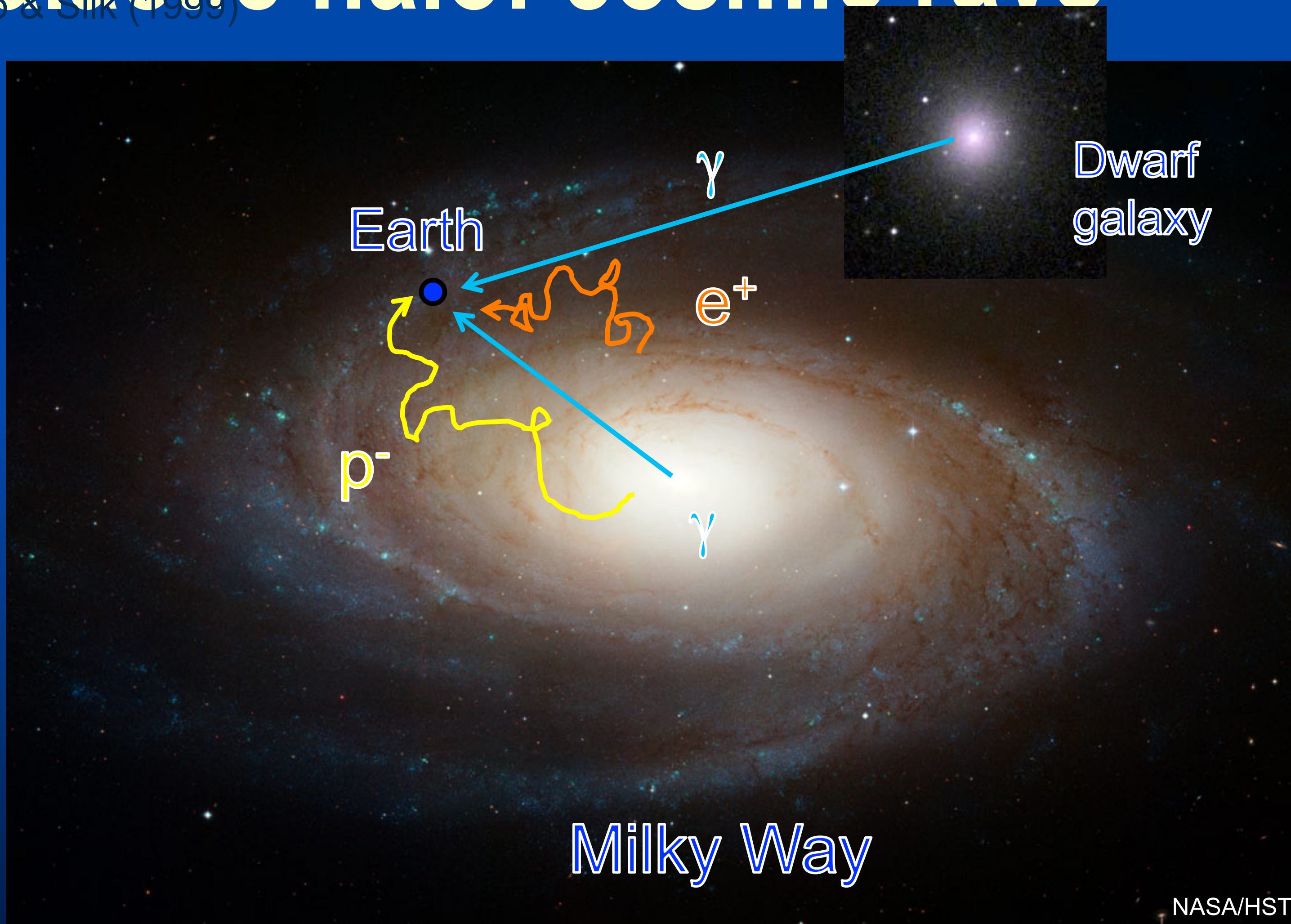


Annihilation Products

- 1/3 electron/positron pairs (positrons are antiparticles of electrons, so have same mass but opposite electric charge).
- 1/3 gamma rays (high energy photons)
- 1/3 neutrinos
- Typical particles have energies roughly 1/10 of the initial WIMP mass
- All of these are detectable

Galactic halo: cosmic rays

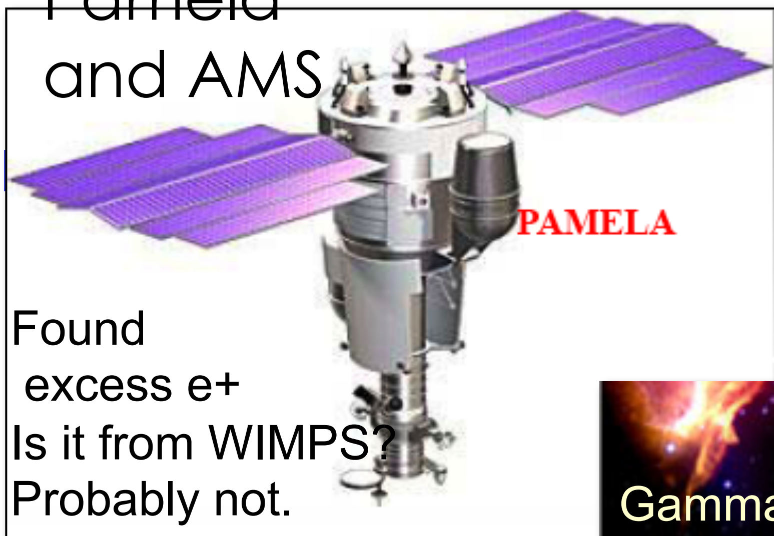
Silk & Srednicki (1984); Ellis et al. (1988)
Gondolo & Silk (1999)



AMS, Fermi/LAT, HESS, …

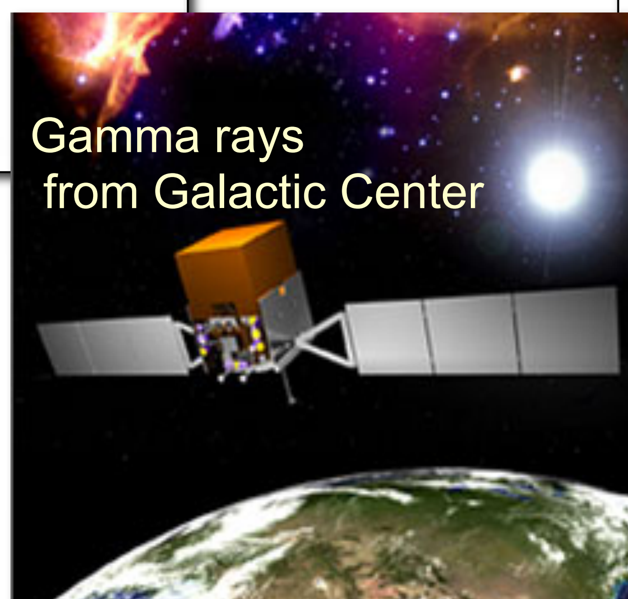
New Indirect Detection Results

HEAT, Pamela and AMS



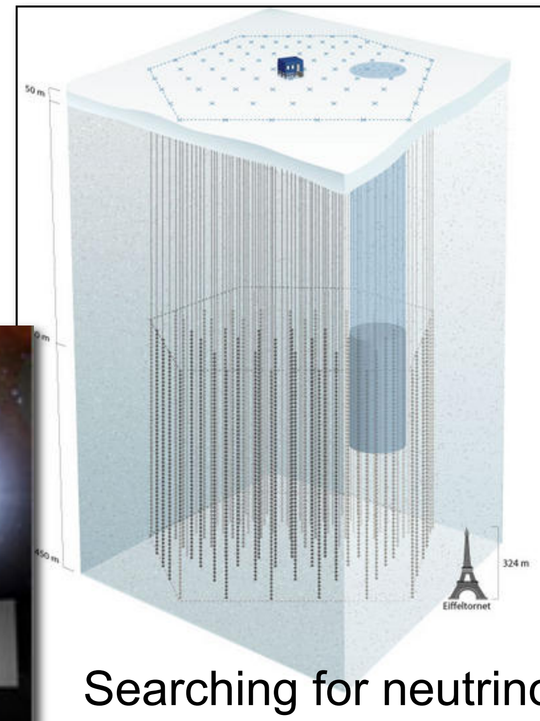
Found
excess e+
Is it from WIMPS?
Probably not.

FERMI



Gamma rays
from Galactic Center

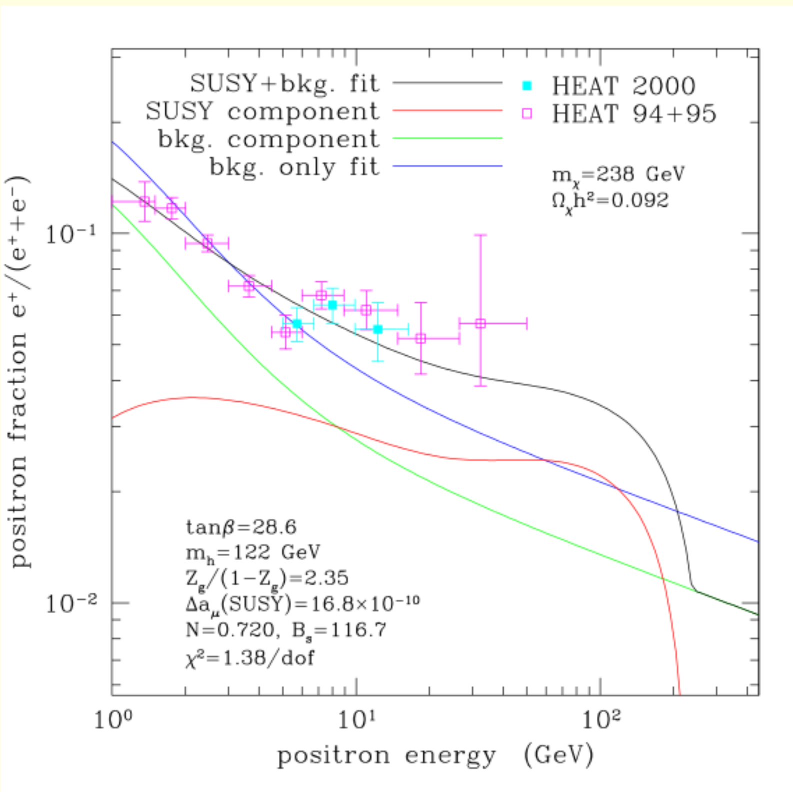
IceCube/DeepCore



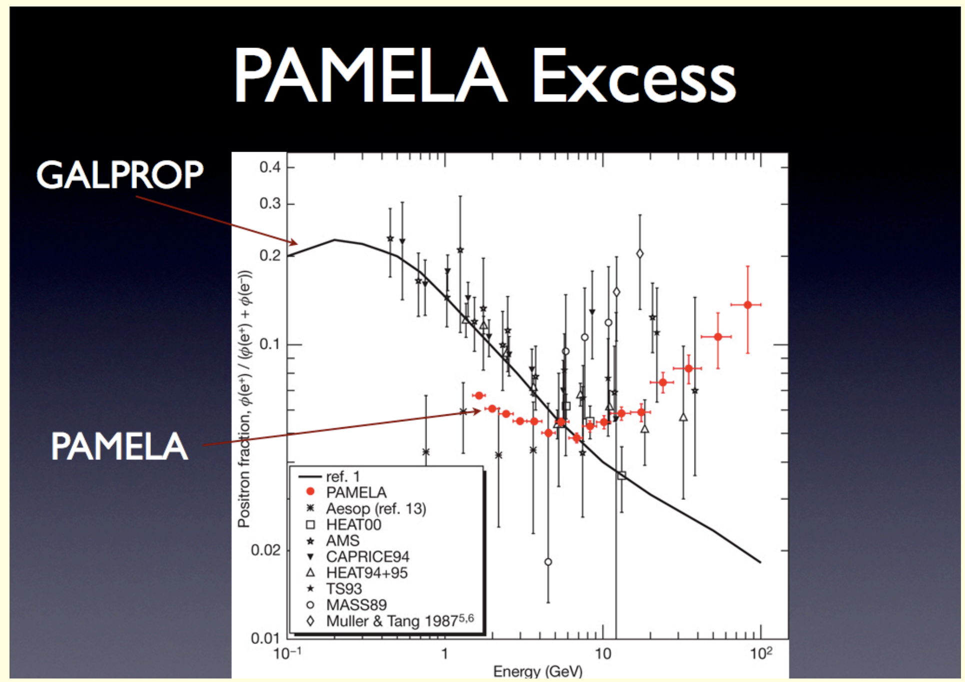
Searching for neutrinos

Indirect Detection:
(1) Is the positron excess from Dark Matter Annihilation?

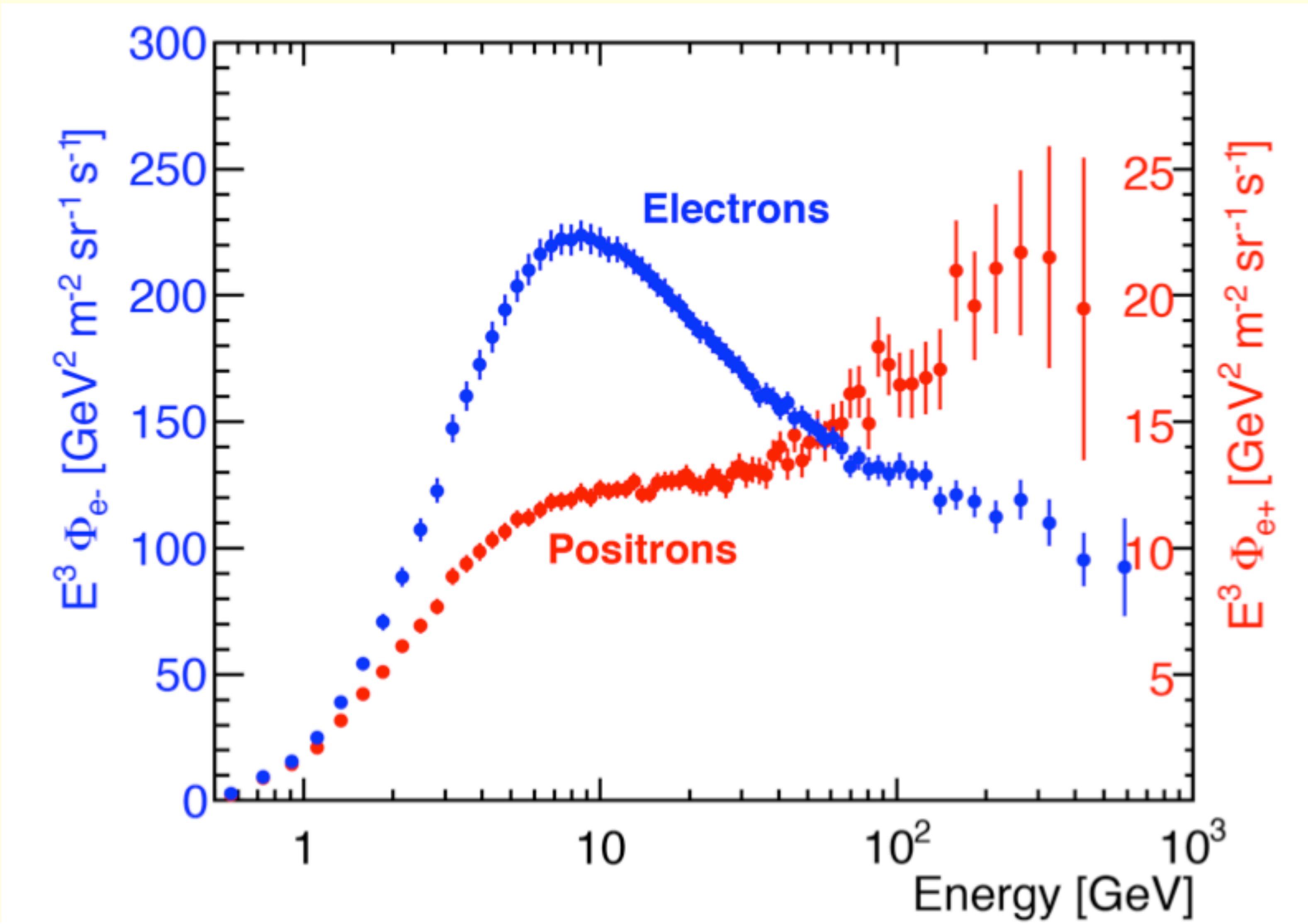
- HEAT balloon found excess in cosmic ray positron flux



Baltz, Edsjo, Freese, Gondolo 2001



AMS Positron Excess
(aboard International Space Station)



How to understand positron excess?

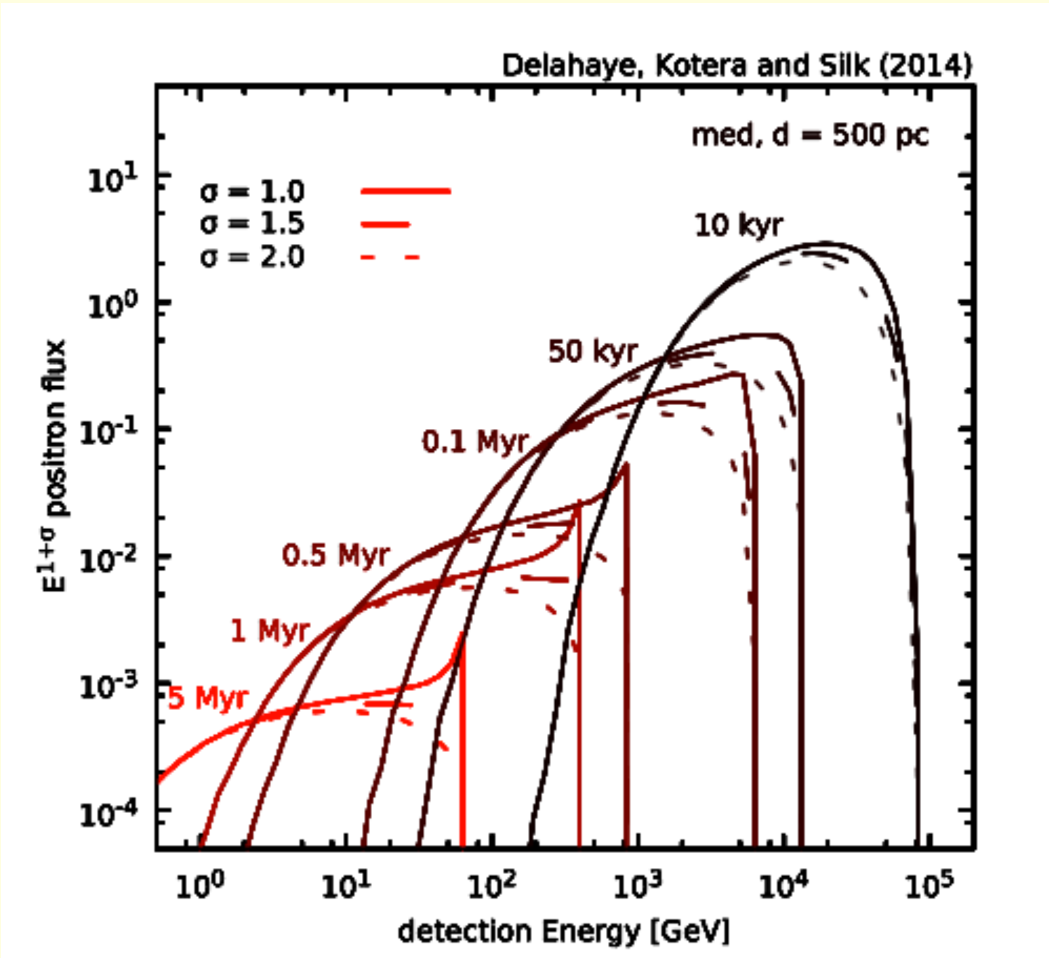
- The problem: positrons change directions in transit in magnetic fields, can't determine their origins

- 1) Pulsars: an equally good fit as DM (work of Timur Delahaye)
- 2) Cosmic Ray Propagation Models (Tarle)
- 2) Dark matter annihilation requires:

(i) we happen to live in a hot spot of high dark matter density (boosted by at least factor 10): unlikely. OR:

(ii) leptophilic WIMPs (must annihilate only to to electrons, positrons, and neutrinos) or WIMPs heavier than 10 TeV to avoid overproducing antiprotons

One pulsar at 1kpc from us could produce the observed positron flux with fit as good as DM



Timur Delahaye

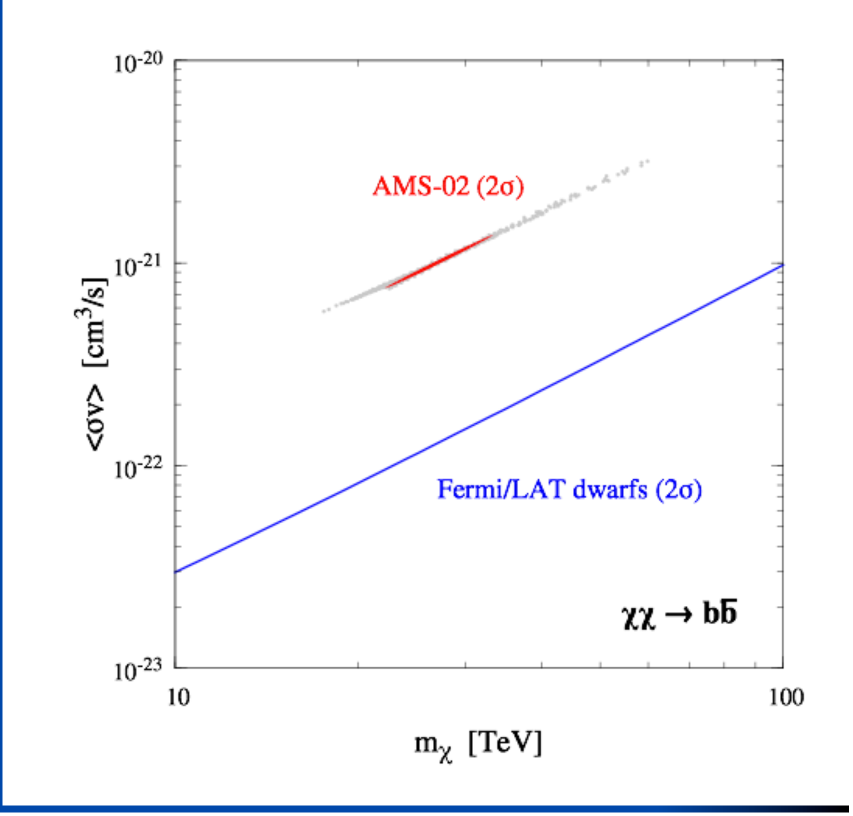
FERMI bounds (almost) rule out dark matter interpretation of AMS positron excess

- Lopez, Savage, Spolyar, Adams

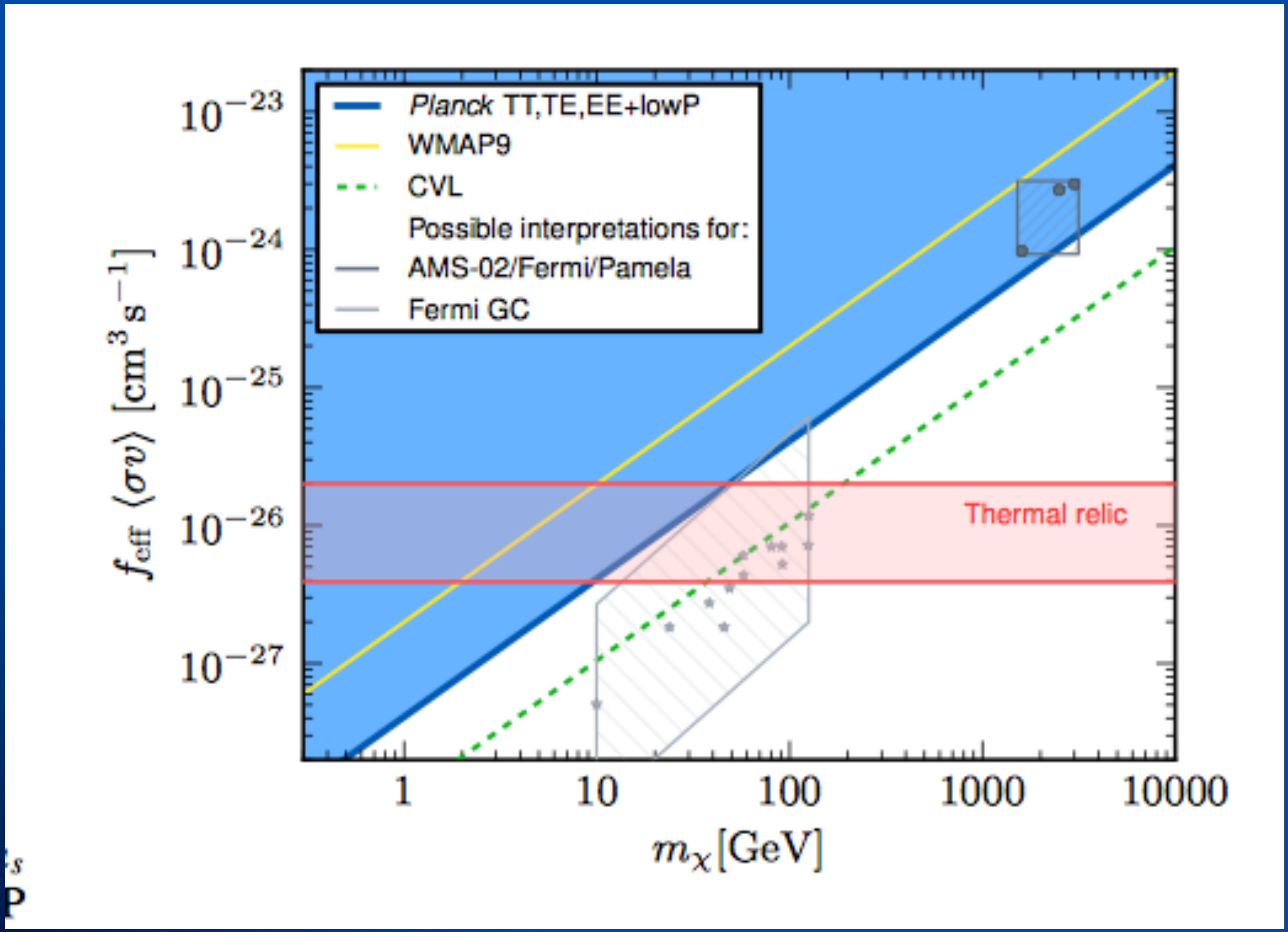
- Almost all channels ruled out,

Including all leptophilic channels
(e.g. b bar channel in plot)

What remains
DM annihilation
via mediator to four mus,
We are working on that now.

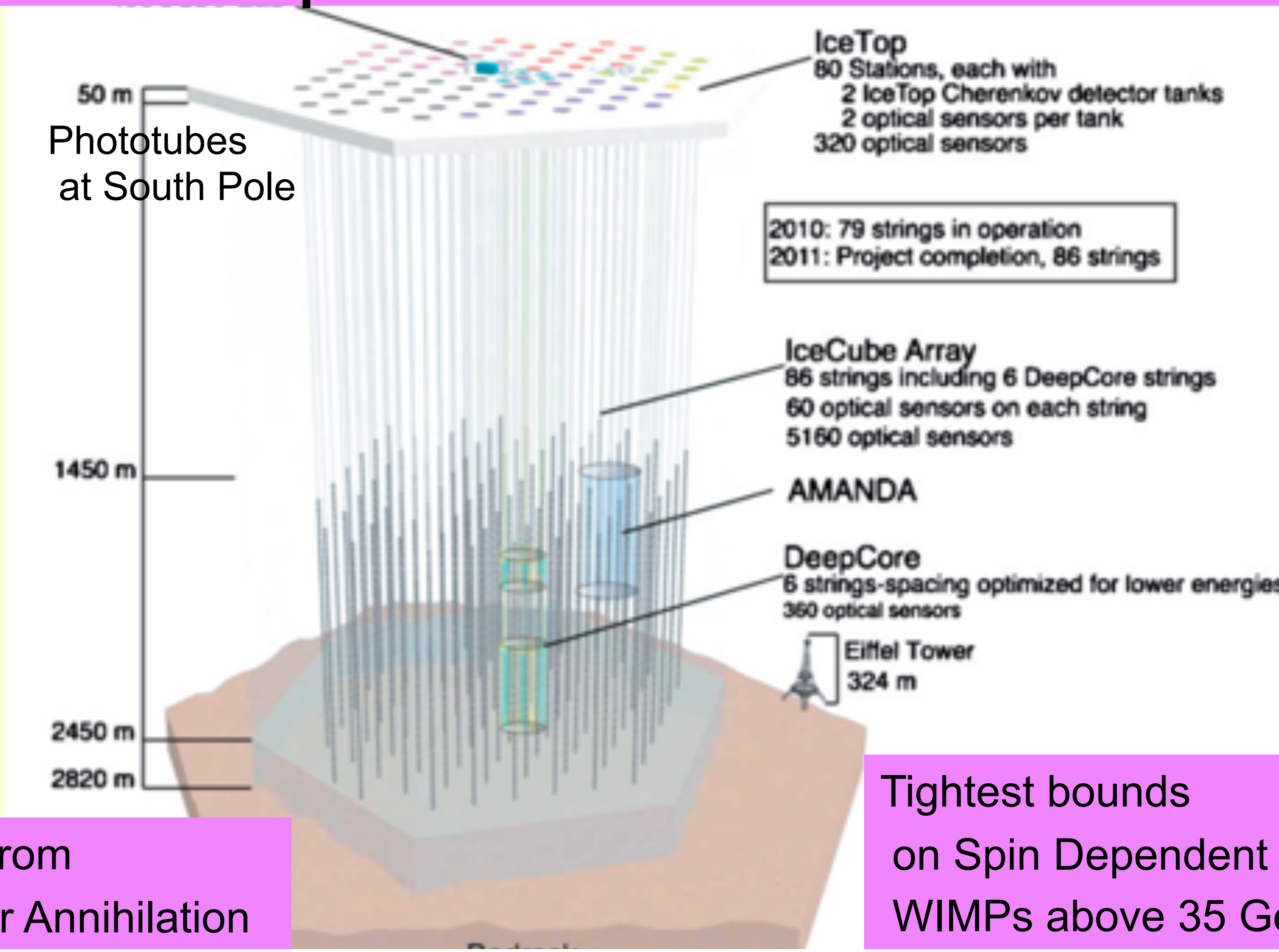


A month later, Planck placed further bounds



Must be below blue line

Indirect Detection II: Neutrinos
IceCube/DeepCore at the South Pole



Neutrinos from
Dark Matter Annihilation

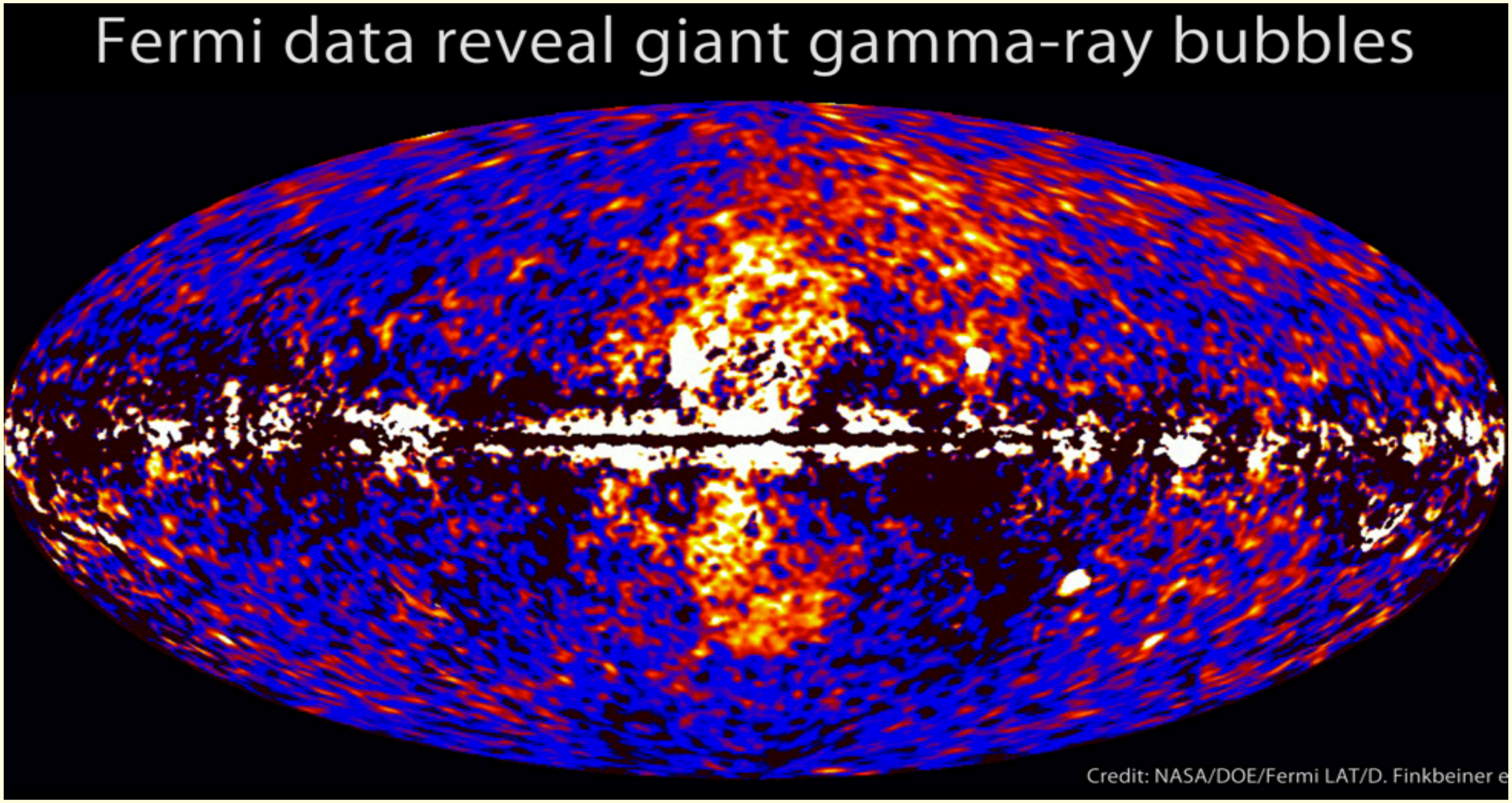
Tightest bounds
on Spin Dependent
WIMPs above 35 GeV

INDIRECT DETECTION III: HIGH ENERGY PHOTONS (GAMMA-RAYS)

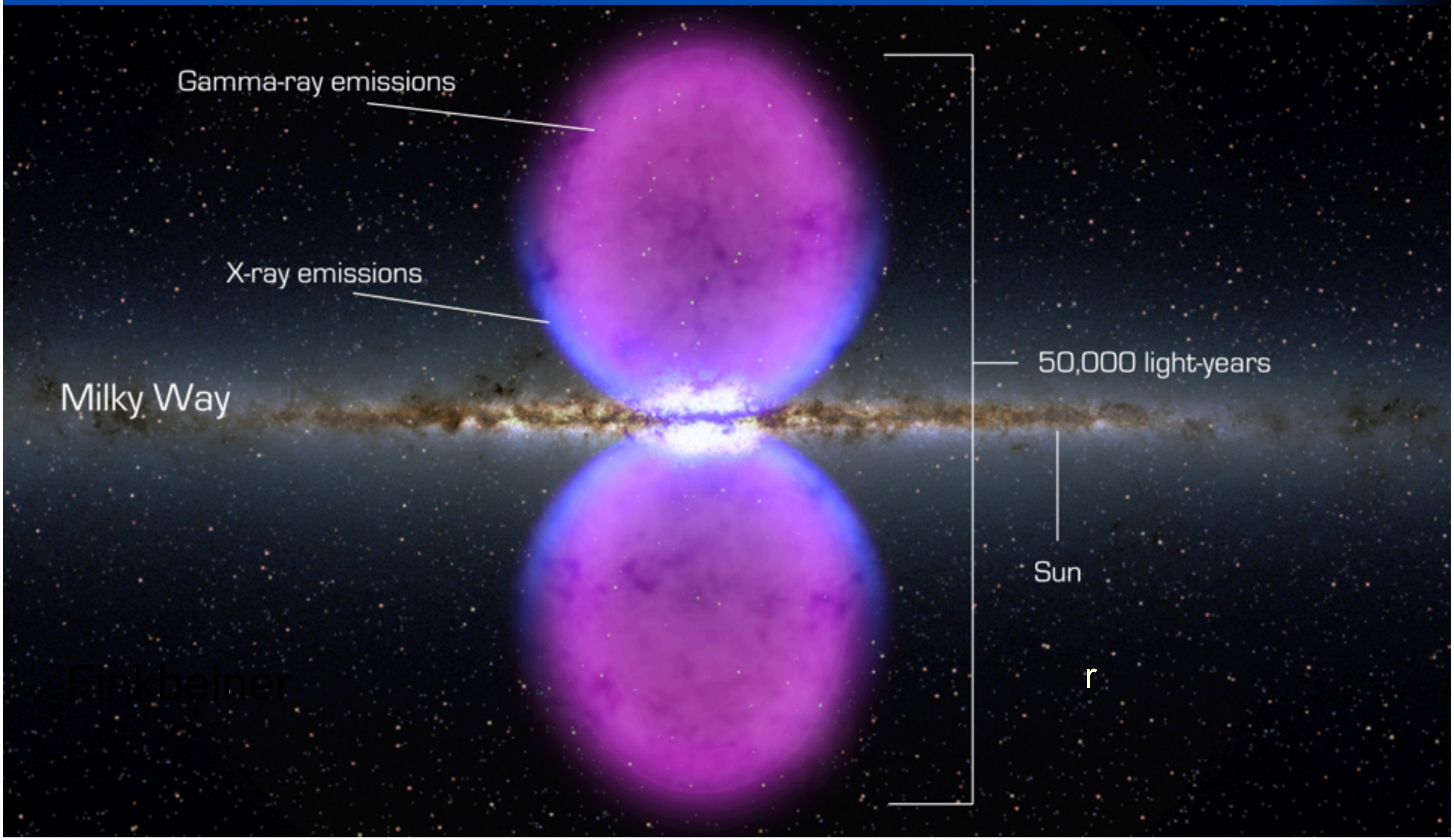
Are they from DM annihilation?

THE FERMI SATELLITE

The gamma ray sky



FERMI Bubbles discovered by Doug Finkbeiner



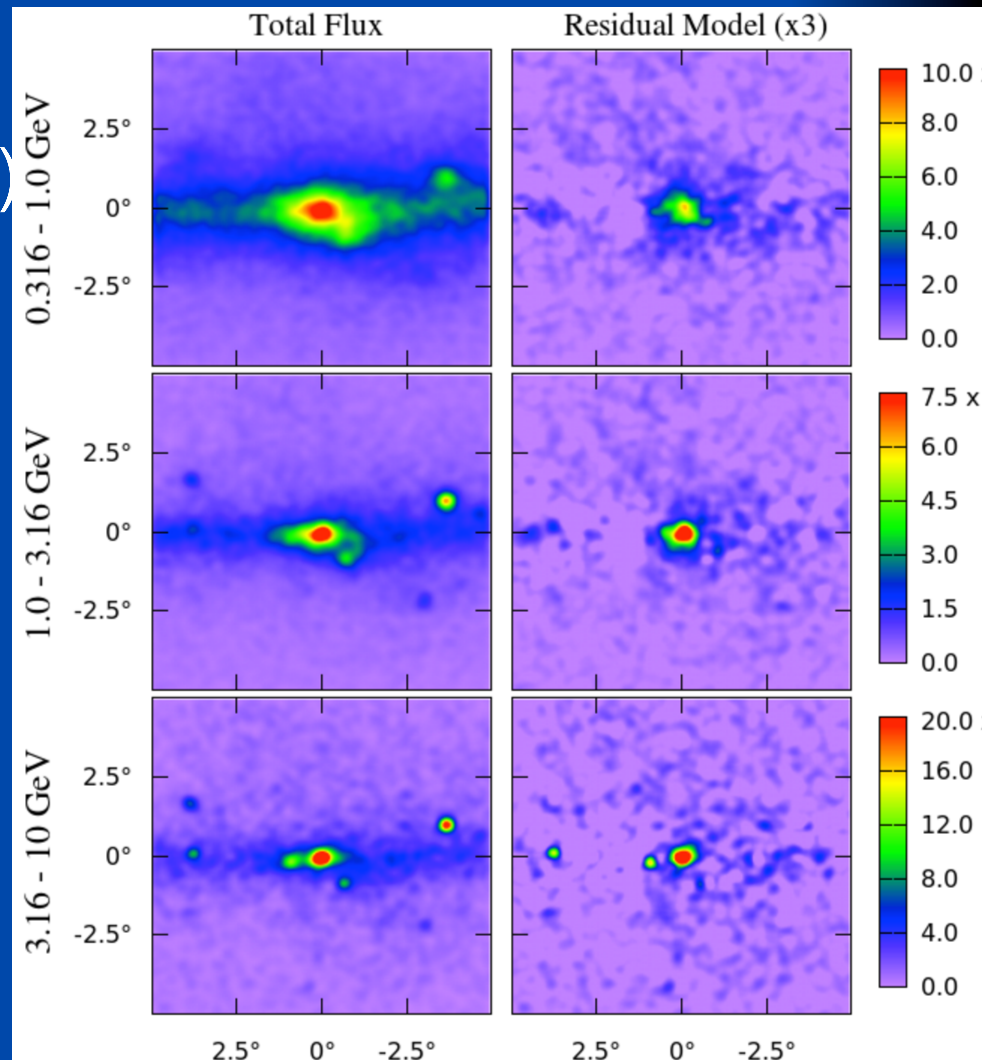
Fermi/LAT gamma-ray excess

Goodenough & Hooper (2009)

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

Towards galactic center:

- Model and subtract astrophysical sources
- Excess remains
- Spectrum consistent with DM DM annihilation

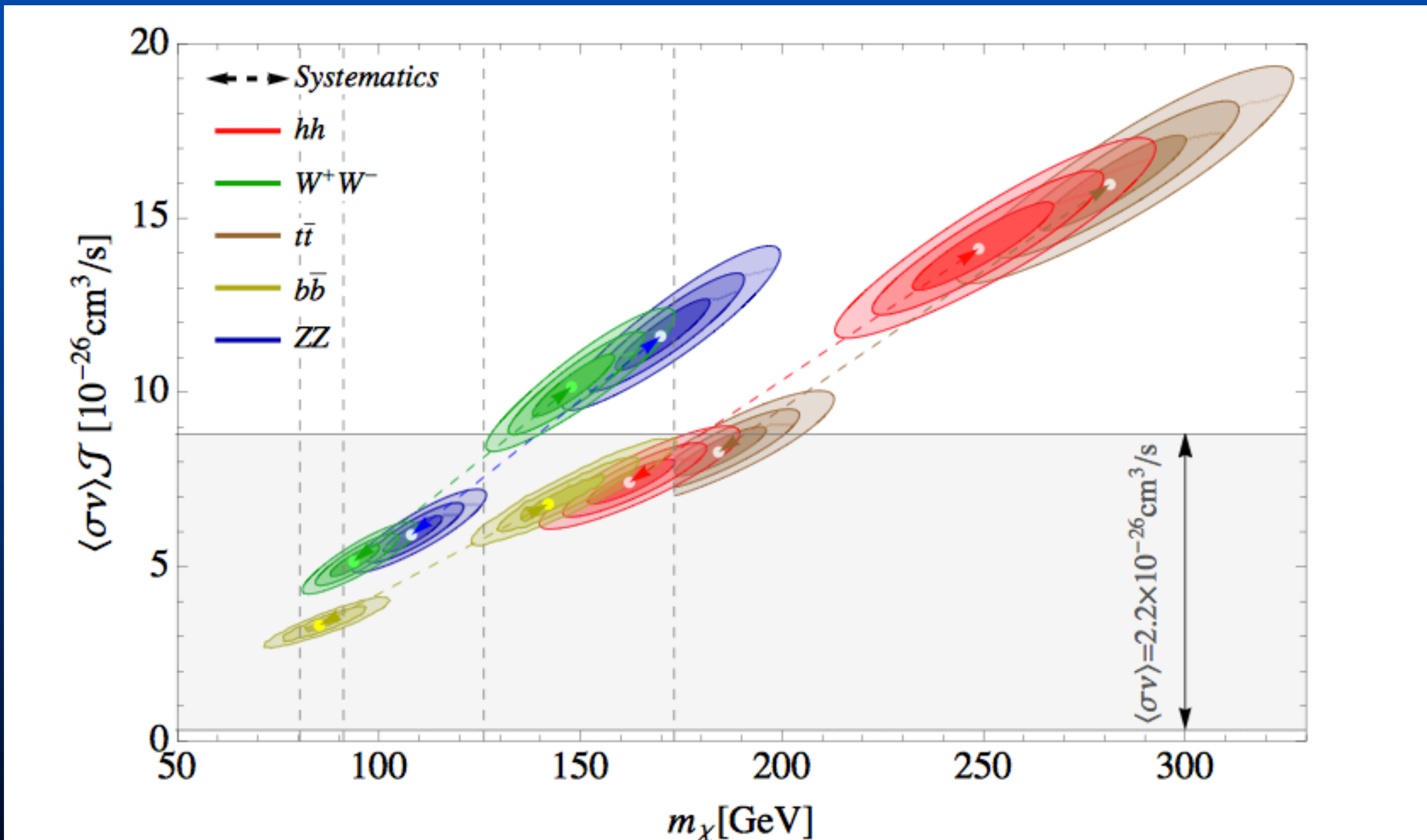


GC gamma-ray excess in FERMI: could be from DM annihilation

- At first people thought it had to be from 10-30 GeV WIMPs, based on subtraction of cosmic ray backgrounds, annihilating via b bbar. Could not be from MSSM.
- More information on CRs in galaxy imply heavier WIMPs, 50-400 GeV, via a variety of channels
- Now can come from MSSM.

- (With Lopez, Shah, Shakya investigating annihilation via pseudoscalar Higgs and predictions for LHC)

WIMPs compatible with FERMI gamma-ray excess toward GC



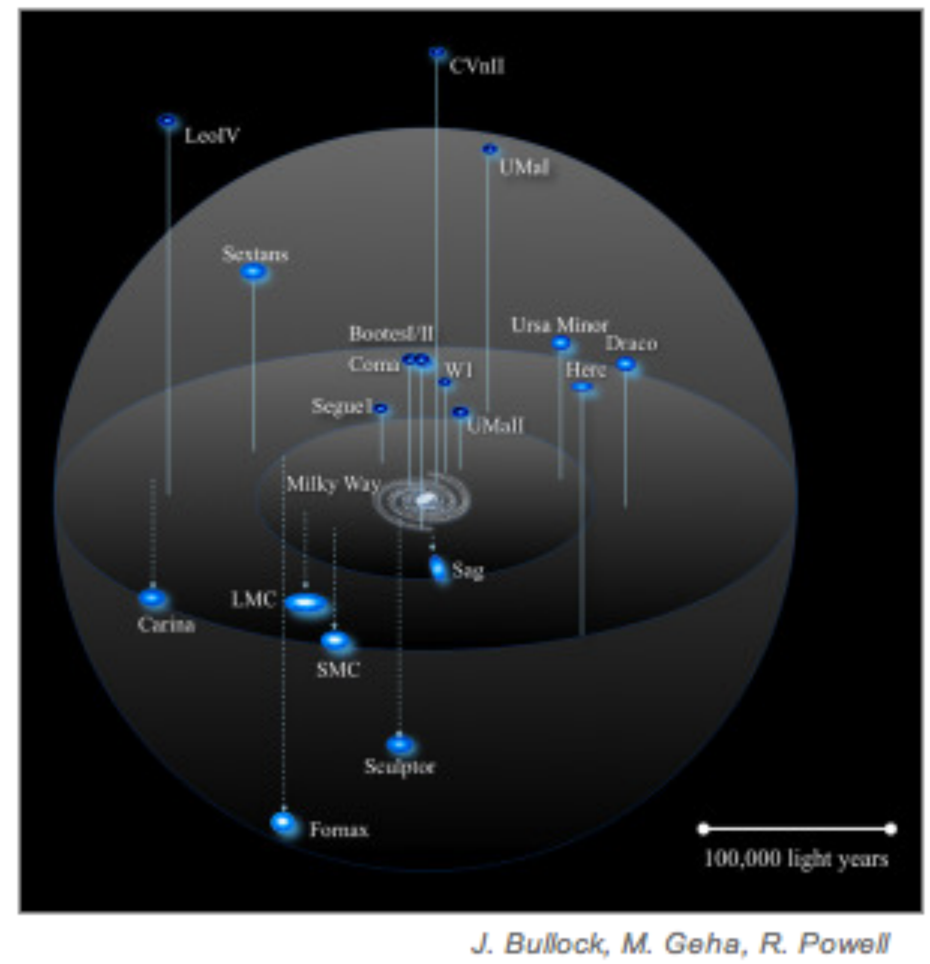
Agrawal, Batell, Fox, Harnik

Paper from a month ago

- Alternate explanation of Galactic Center gamma-ray excess (instead of DM):
- Unresolved point sources in Fermi data
- Extrapolating to future data (just below current threshold) may be source of excess. Detectable in the future

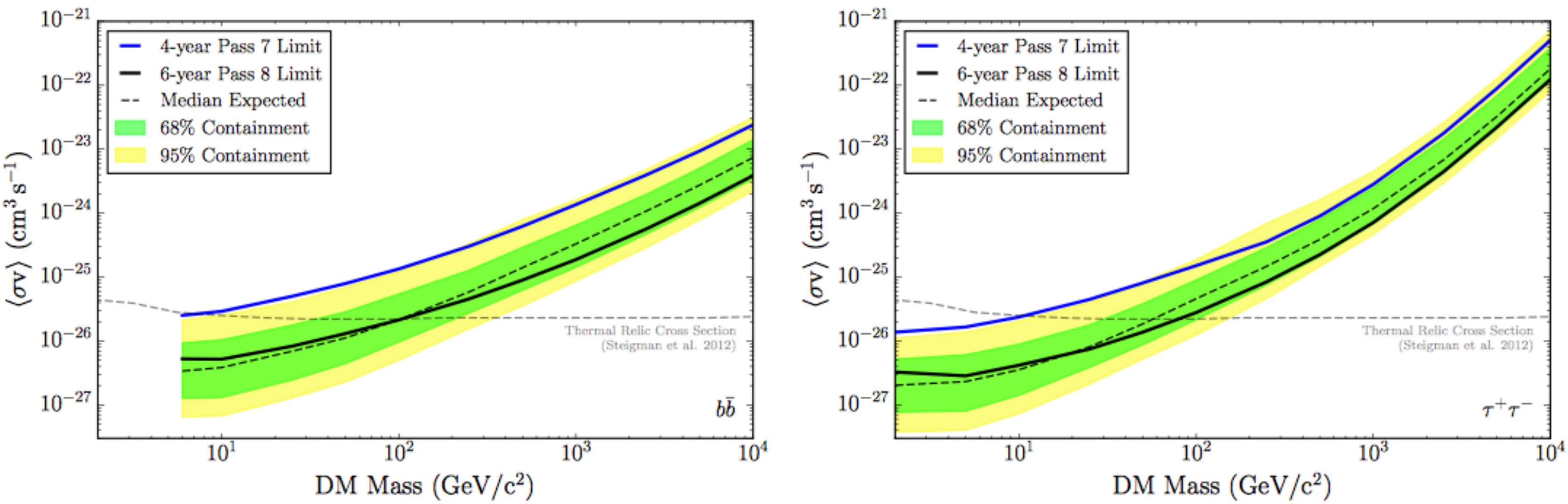
- (Lee, Lisanti, Safti, Slatyer, Xue)

Test this DM interpretation of GC excess with dwarf galaxies (which are DM rich)



Look for gamma-rays due to DM annihilation from dwarf galaxies in FERMI data

Gamma-rays from dwarf galaxies in FERMI give bounds on WIMP annihilation



Dashed line is thermal annihilation cross section

New dwarf satellite galaxies found: 9 in DES

- FERMI collaboration reports no significant γ-ray excess in any of them
- In Reticulum, a dwarf that is 30 kpc away:

Geringer-Sameth etal report 2.3 (3.7) sigma excess when they use model-independent background (Poisson process)

- We shall see.

Summary of Possible evidence for WIMP detection already now:

- Direct Detection:
  - DAMA annual modulation
  - (but XENON, LUX)
- Indirect Detection:
  - The HEAT/PAMELA/FERMI/AMS positron excess
  - 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)

What will it take for us to believe DM has been found?

- Compatible signals in a variety of experiments made of different detector materials, and all the parties agree

FOURTH WAY TO SEARCH FOR WIMPS

Dark Stars:
Dark Matter annihilation can power the first stars


DAVID GRANT presents
A JOHN CARPENTER film
From
ALAN DEAN FOSTER
FIRST
2001: A SPACE ODYSSEY
THEN
THE POSEIDON ADVENTURE
NOW
DARK STAR
A
DS-1
bombed out in space
with a spaced out bomb!
An OPPIDAN ENTERTAINMENTS Release of a JACK H. HARRIS Production Starring DAN O'BANNON and BRIAN NARELLE Produced & directed by JOHN CARPENTER

Collaborators

Paolo Gondolo

Pearl Sandick

Tanja Rindler-Daller

Peter Bodenheimer

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 hyrdogen and helium, with dark matter constituting less than 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.

Dark Matter Power vs. Fusion

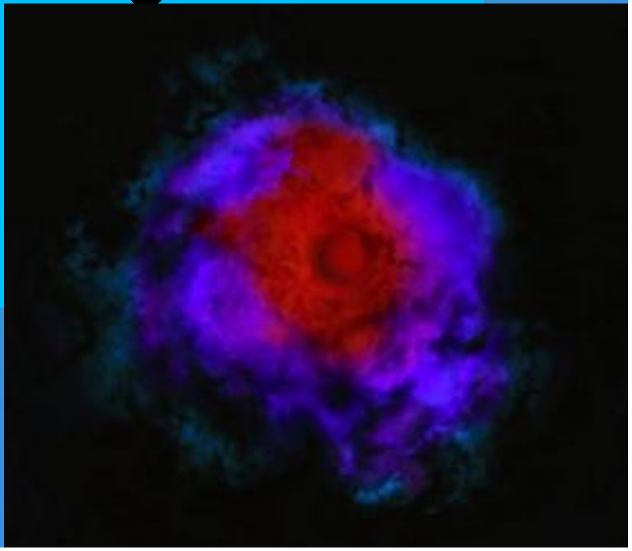
- DM annihilation is (roughly) 100% efficient in the sense that all of the particle mass is converted to heat energy for the star
- Fusion, on the other hand, is only 1% efficient (only a fraction of the nuclear mass is released as energy)
- Fusion only takes place at the center of the star where the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

Three Conditions for Dark Stars

(Spolyar, Freese, Gondolo 2007 aka Paper 1)

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

New Phase



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:

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

Previous work noted that at $n \leq 10^4 cm^{-3}$ annihilation products simply escape (Ripamonti,Mapelli,Ferrara 07)

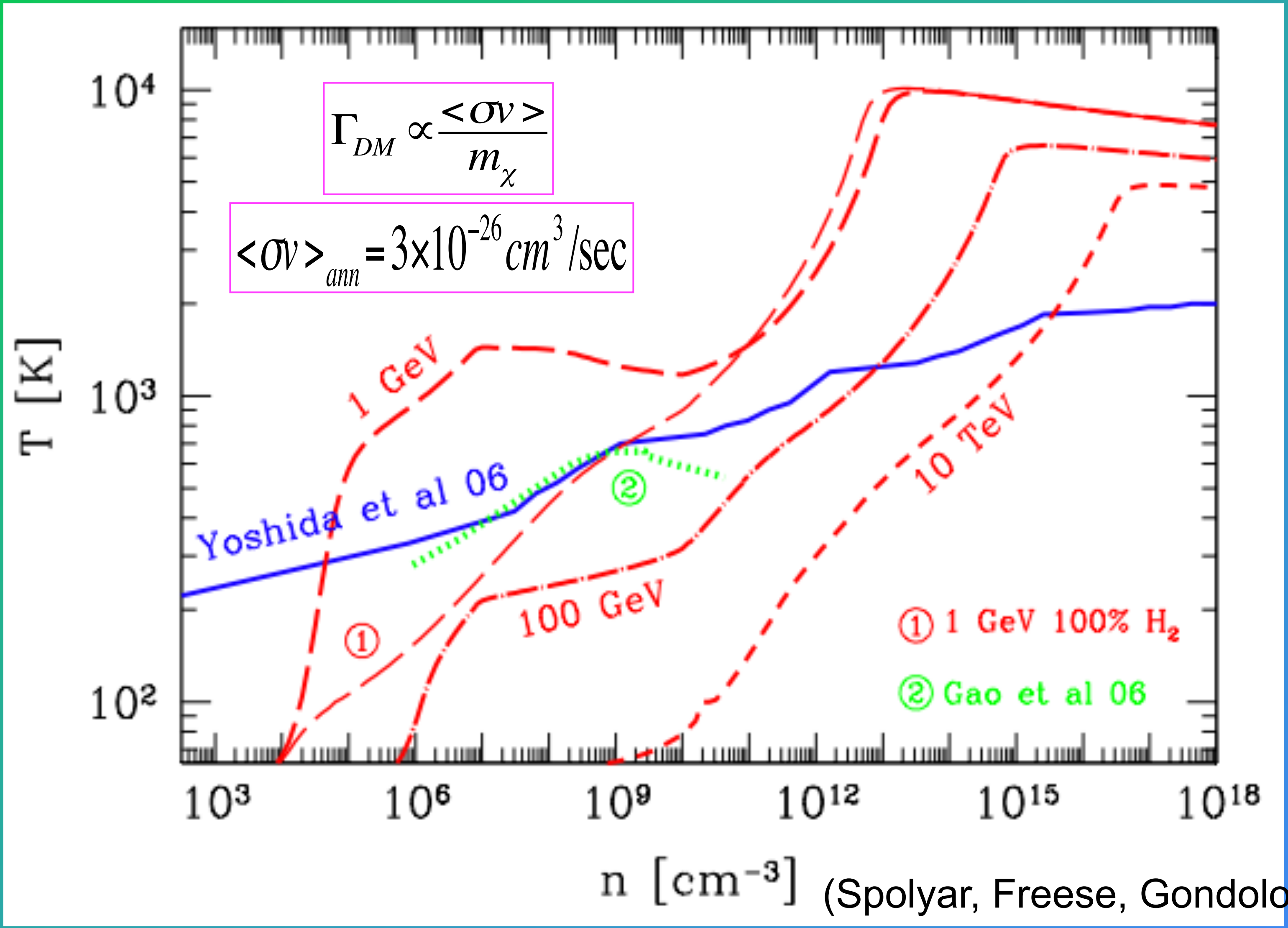
f_Q :

1/3 electrons

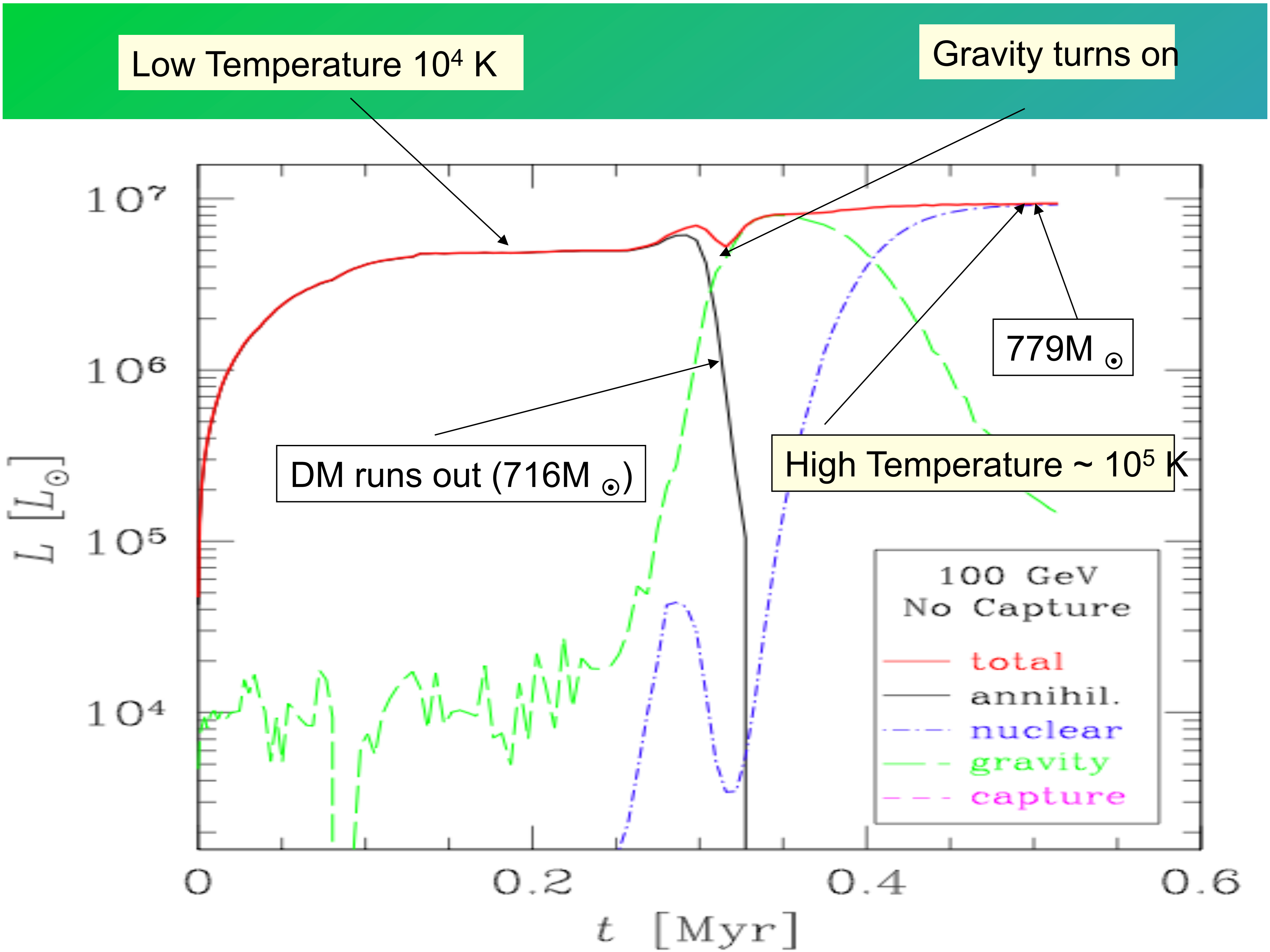
1/3 photons

1/3 neutrinos

DM Heating dominates over cooling when the red lines cross the blue/green lines (standard evolutionary tracks from simulations). Then heating impedes further collapse.



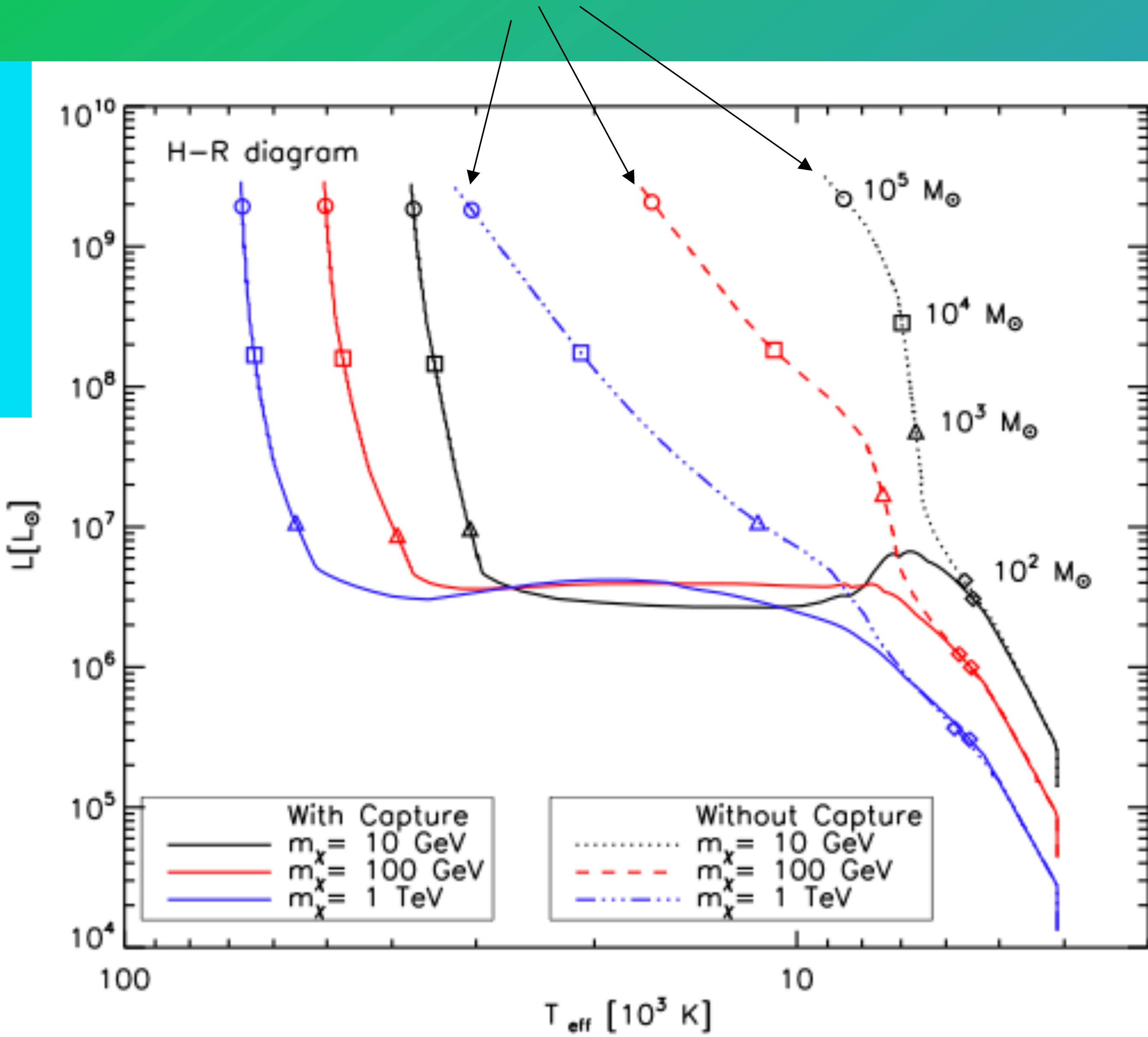
(Spolyar, Freese, Gondolo April 2007)



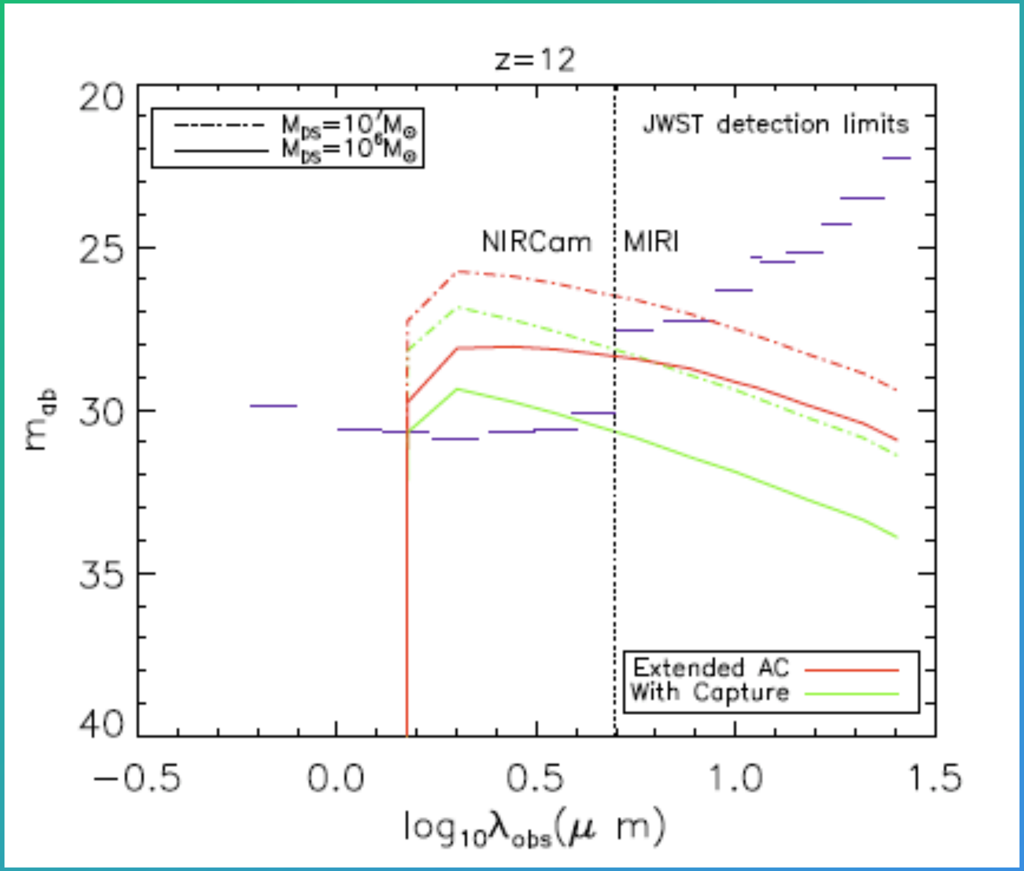
Low Temperature 10^4 K
Gravity turns on
779M ☉
DM runs out (716M ☉)
High Temperature ~ 10^5 K
10^7
10^6
10^5
10^4
$L\ [L_\odot]$
0
0.2
0.4
0.6
t [Myr]
100 GeV
No Capture
total
annihil.
nuclear
gravity
capture

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

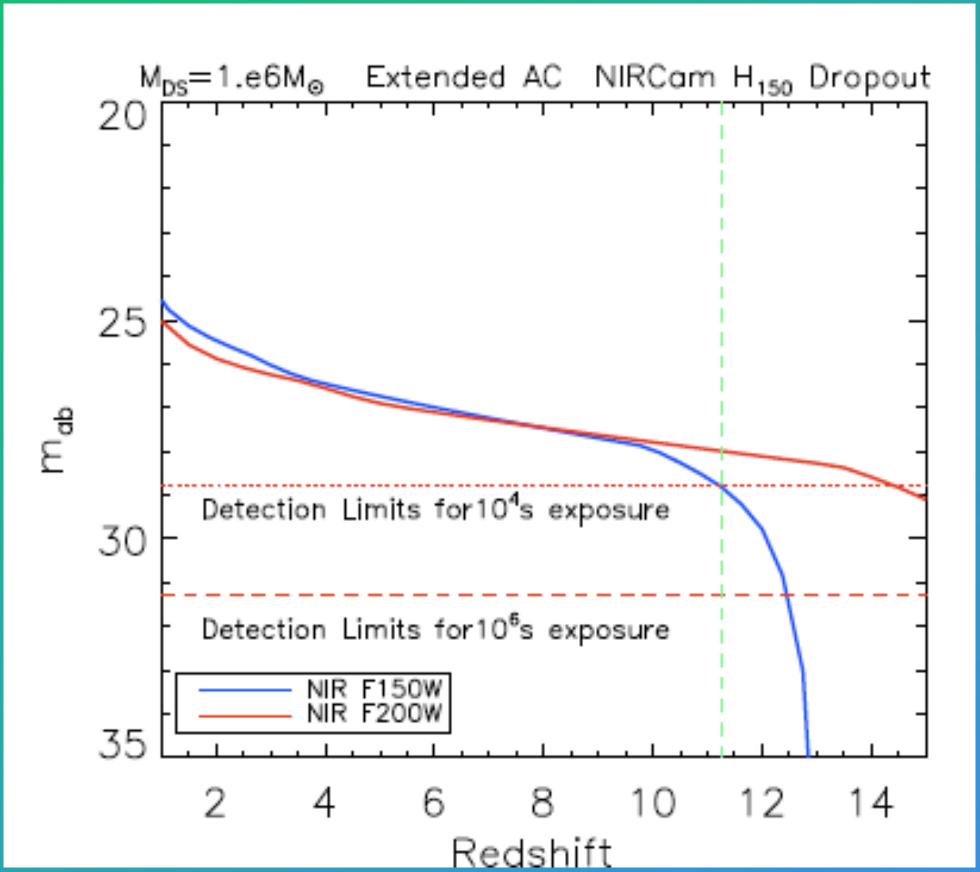
Assuming all of the baryons can accrete in a 10^6 $M_\odot$ halo



DS detectable in JWST, the upcoming sequel to HST



Million solar mass SMDS as H-band dropout

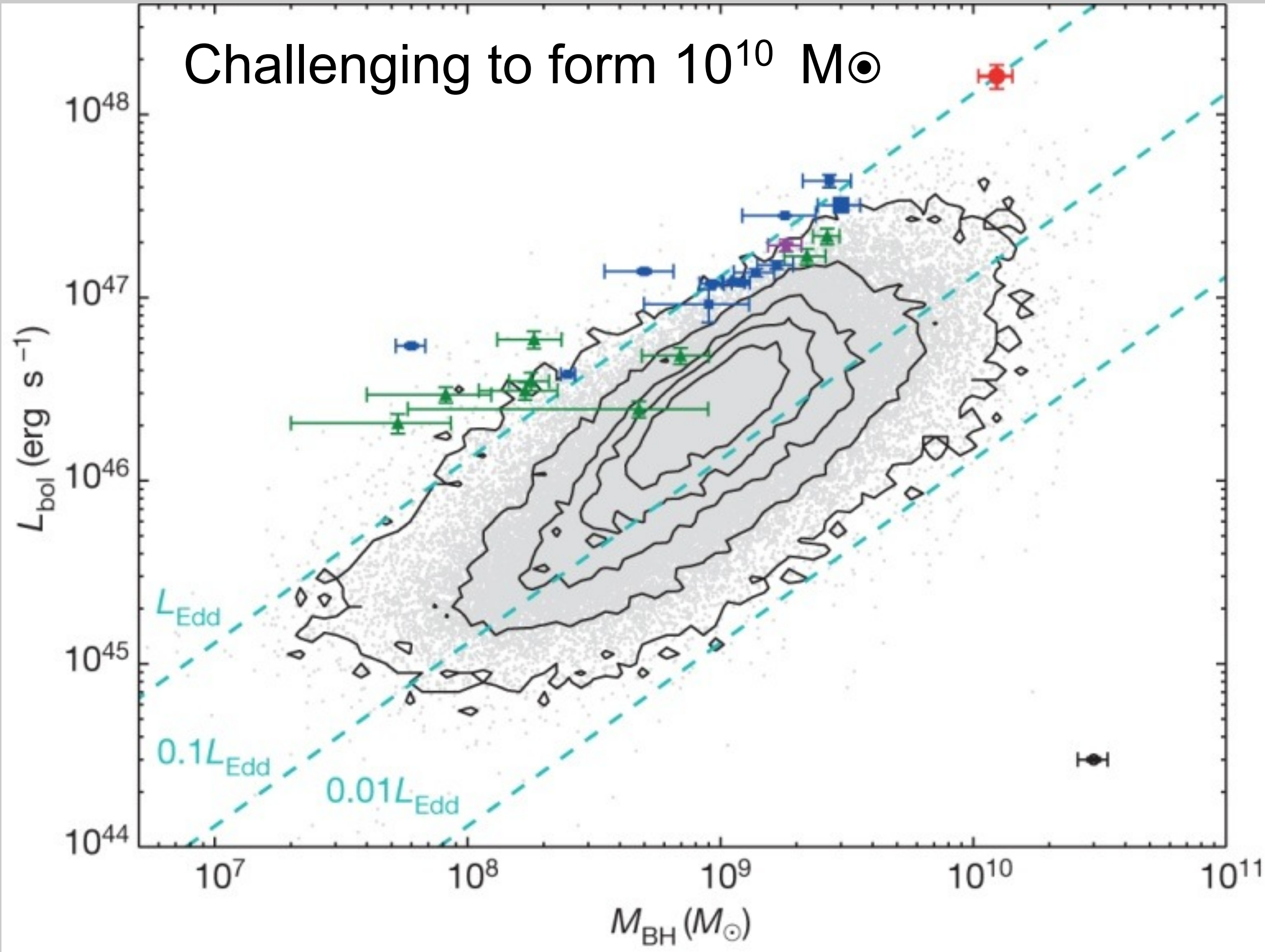


(see in 2.0 micron but not 1.5 micron filter, implying it's a z=12 object)

What happens next? BIG BLACK HOLES

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

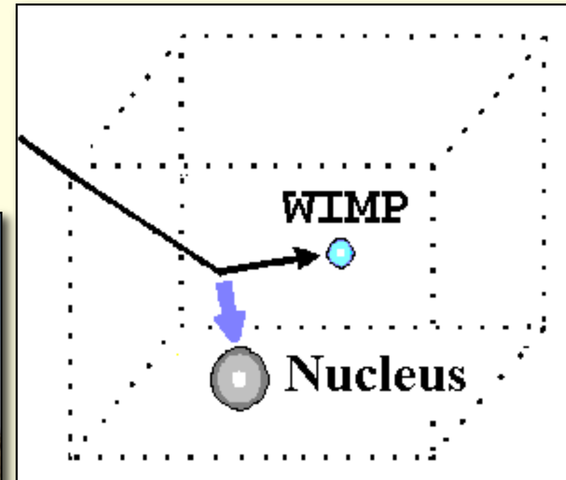
SupperMassive Black holes from Dark Stars
Very Massive progenitor Million Solar Masses at z=6
No other way to form supermassive BH this early



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

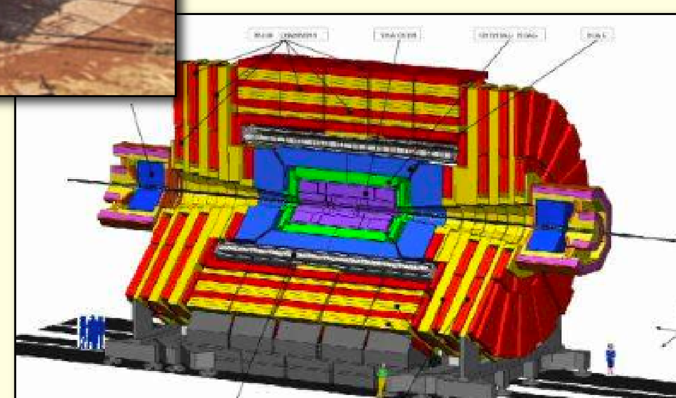
nature

WIMP Hunting: Good chance of detection this decade



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

Looking for Dark Stars



Another Intriguing Signal: 7 keV sterile neutrino?

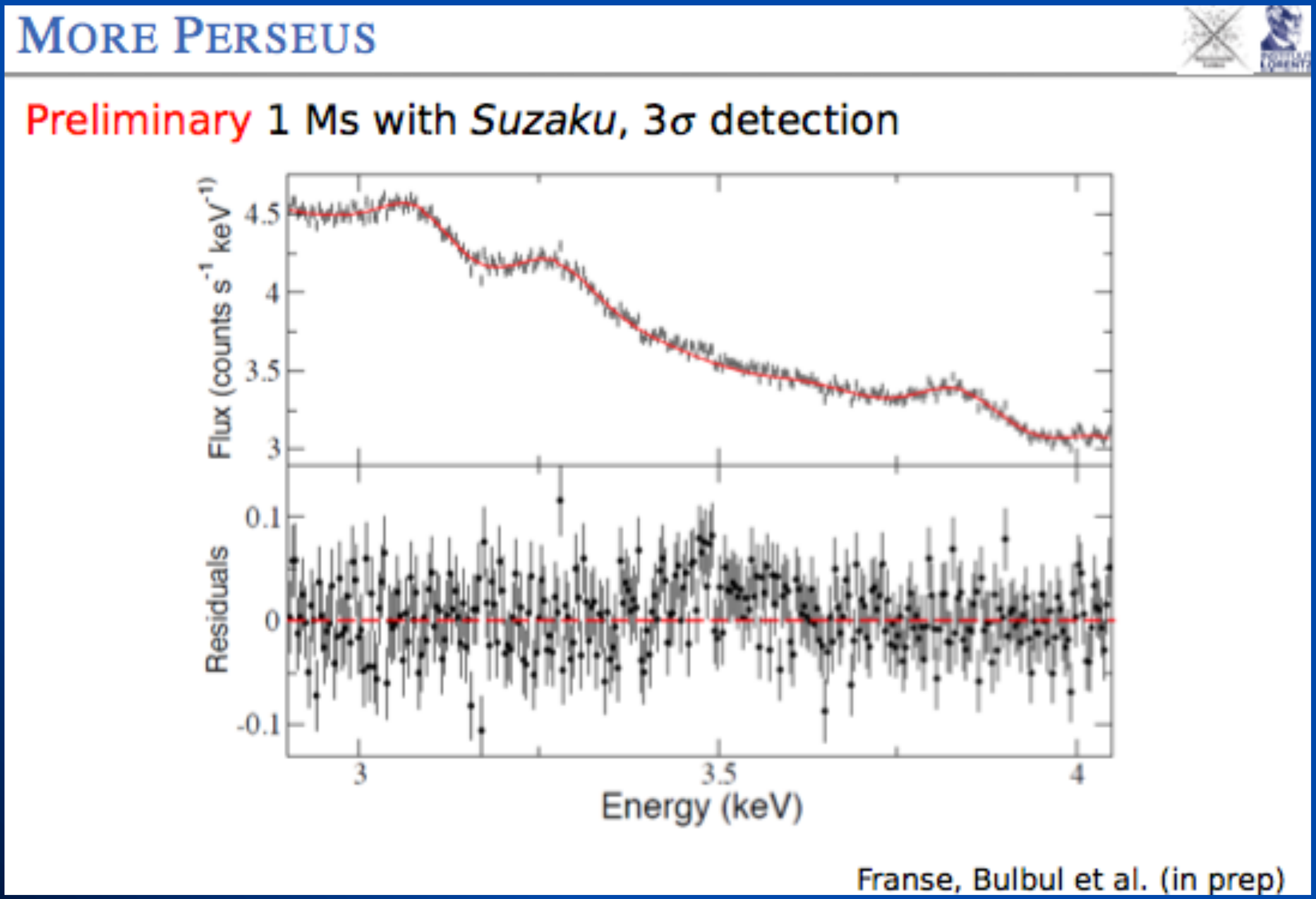
Possible Detections

two different X-ray astronomy groups see a **3.5 keV** line in **clusters of galaxies** and in M31, and this line is ***consistent with a dark matter decay origin***, corresponding to a **7 keV rest mass sterile neutrino** with vacuum mixing with active neutrinos $\sin^2 2\theta = (2-20)\ \times\ 10^{-11}$

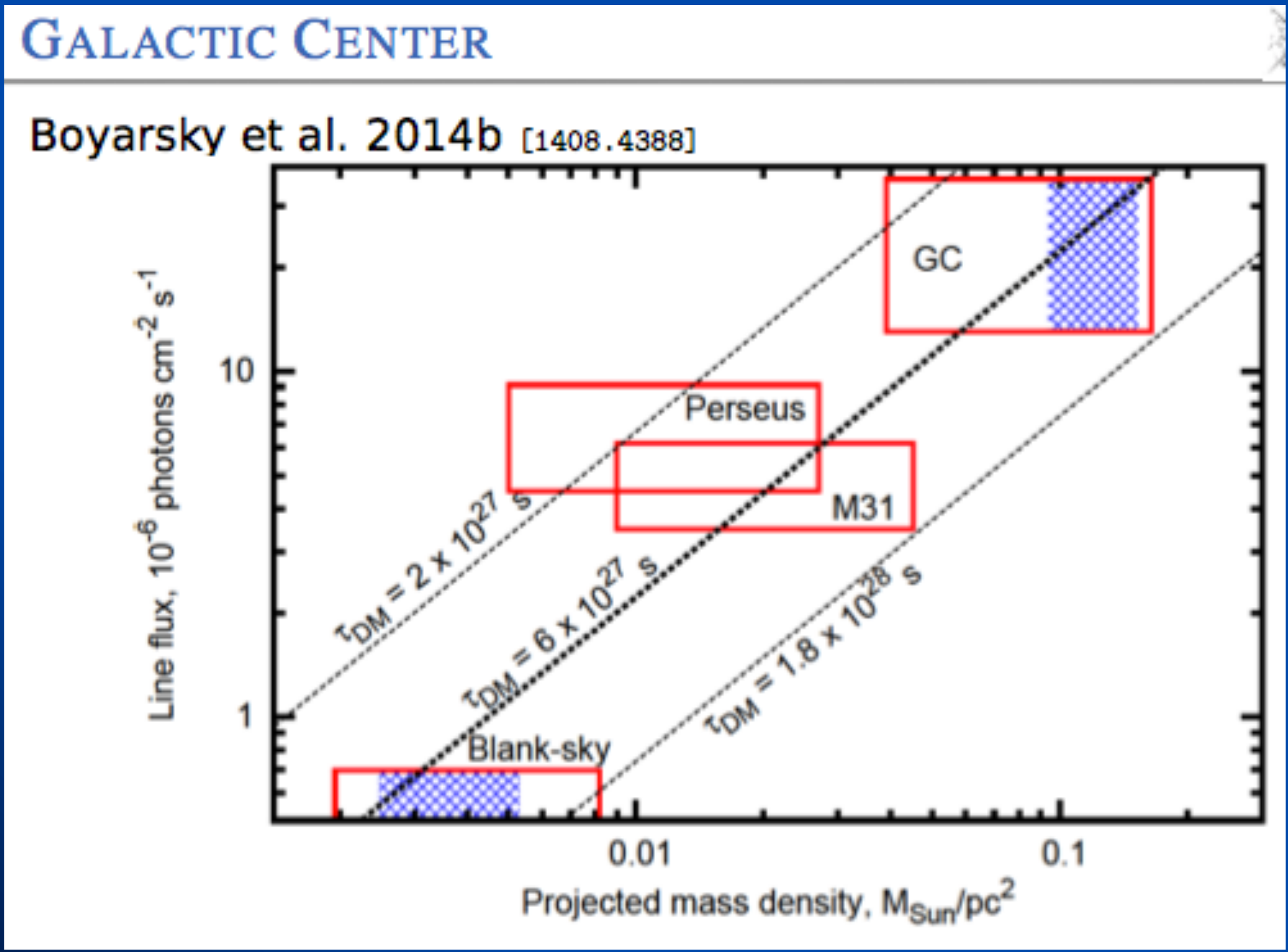
E. Bulbul, M. Markevitch, A. Foster, R. Smith, M. Lowenstein, S. Randall
"*Detection of an unidentified emission line in the stacked X-ray spectrum of Galaxy Clusters*" arXiv:1402.2301

A. Boyarsky, O. Ruchayskiy, D. Iakubovskyi, J. Franse
"An unidentified line in the X-ray spectrum of the Andromeda galaxy and Perseus galaxy cluster" arXiv:1402.4119

3.5 keV line. From sterile neutrino?



3.5 keV line



GALACTIC CENTER
Boyarsky et al. 2014b [1408.4388]
GC
Perseus
M31
Blank-sky
$\tau_{DM} = 2 \times 10^{27}$ s
$\tau_{DM} = 6 \times 10^{27}$ s
$\tau_{DM} = 1.8 \times 10^{28}$ s
Line flux, 10^{-6} photons cm^{-2} s^{-1}
10
1
0.01
0.1
Projected mass density, M_{Sun}/pc^2

Look for 3.5 keV line in DRACO

We have been ***awarded 1.4 Ms*** of XMM observations of the Draco dwarf galaxy this year

- Nearby, dark matter dominated object
- Highest expected signal of all dwarf galaxies (Geringer-Sameth+ 2014, Lovell+ 2014)
- Very gas-poor (***do not expect any atomic lines***)
- We will be able to **confirm or deny the DM origin** of the 3.5 keV line somewhere **in 2016**.

7 keV sterile neutrino: theory

- Singlet under Standard Model
- Right handed neutrino
- Warm DM: this might help with core/cusp problem (if there is one) and missing satellites
- Does Seesaw mechanism work?
- Production is hard to explain:
  - Cannot be thermal particles (would overclose the Universe)
  - Dodelson-Widrow mechanism via tiny interactions with hot early plasma with small mixing angle fails (due to x-ray constraints)
  - Could be via resonance using large lepton asymmetry, Shaposhnikov model requires 3 sterile neutrinos

Final Intriguing Signal: 511 keV line in INTEGRAL data

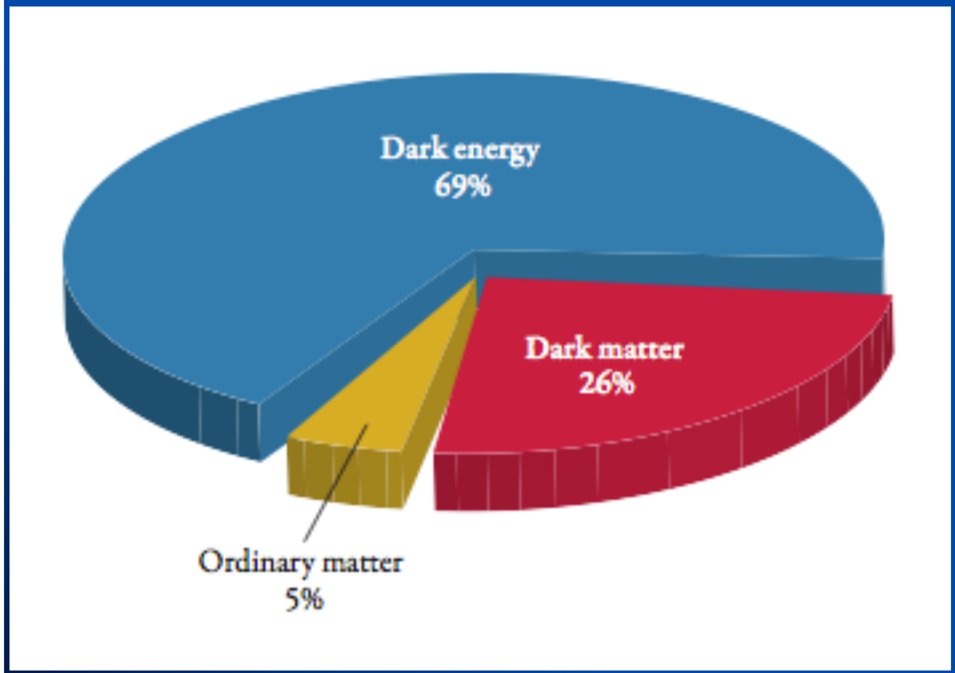
Seen in Galactic bulge, out to 6 degrees (3 kpc).

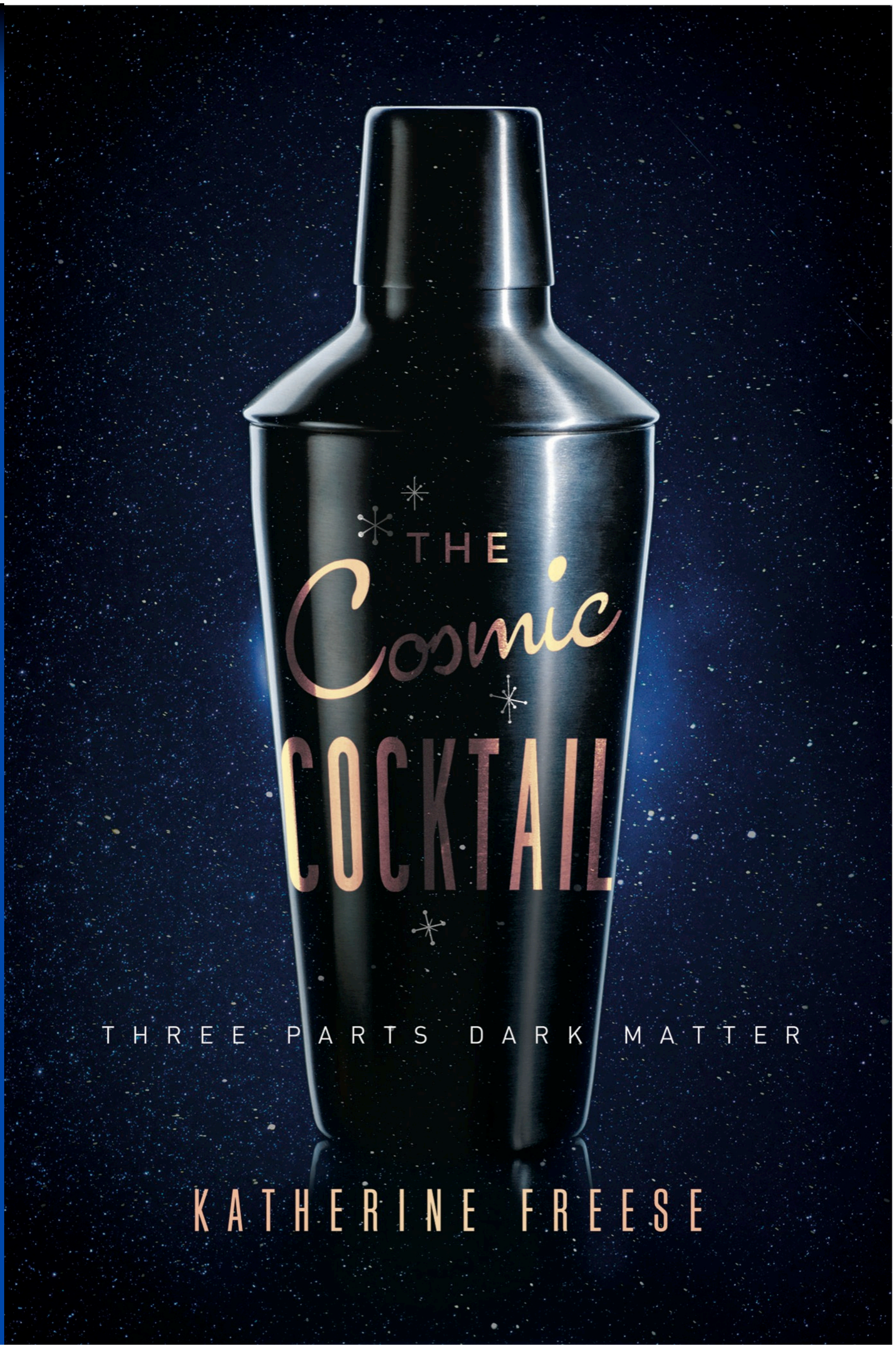
No clear astrophysical explanation. Low mass xray binaries were most compelling option but not looking good

Is it DM annihilation to e+e- pairs?

Would be MeV dark matter.

(Boehm, Hooper, Silk, Casse, Paul 2003)


Dark energy
69%
Dark matter
26%
Ordinary matter
5%


THE
Cosmic
COCKTAIL
THREE PARTS DARK MATTER
KATHERINE FREESE

WHAT'S HOT IN DARK MATTER? Unexplained signals.

WIMPS:

- DAMA annual modulation (but XENON, LUX)
- Indirect Detection from DM annihilation:
  - The HEAT/PAMELA/FERMI/AMS positron excess
  - FERMI gamma ray excess near galactic center
- Theorists are working to reconcile data sets.

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7 keV Sterile neutrinos

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

- MeV dark matter 511 keV line in INTEGRAL DATA

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!”