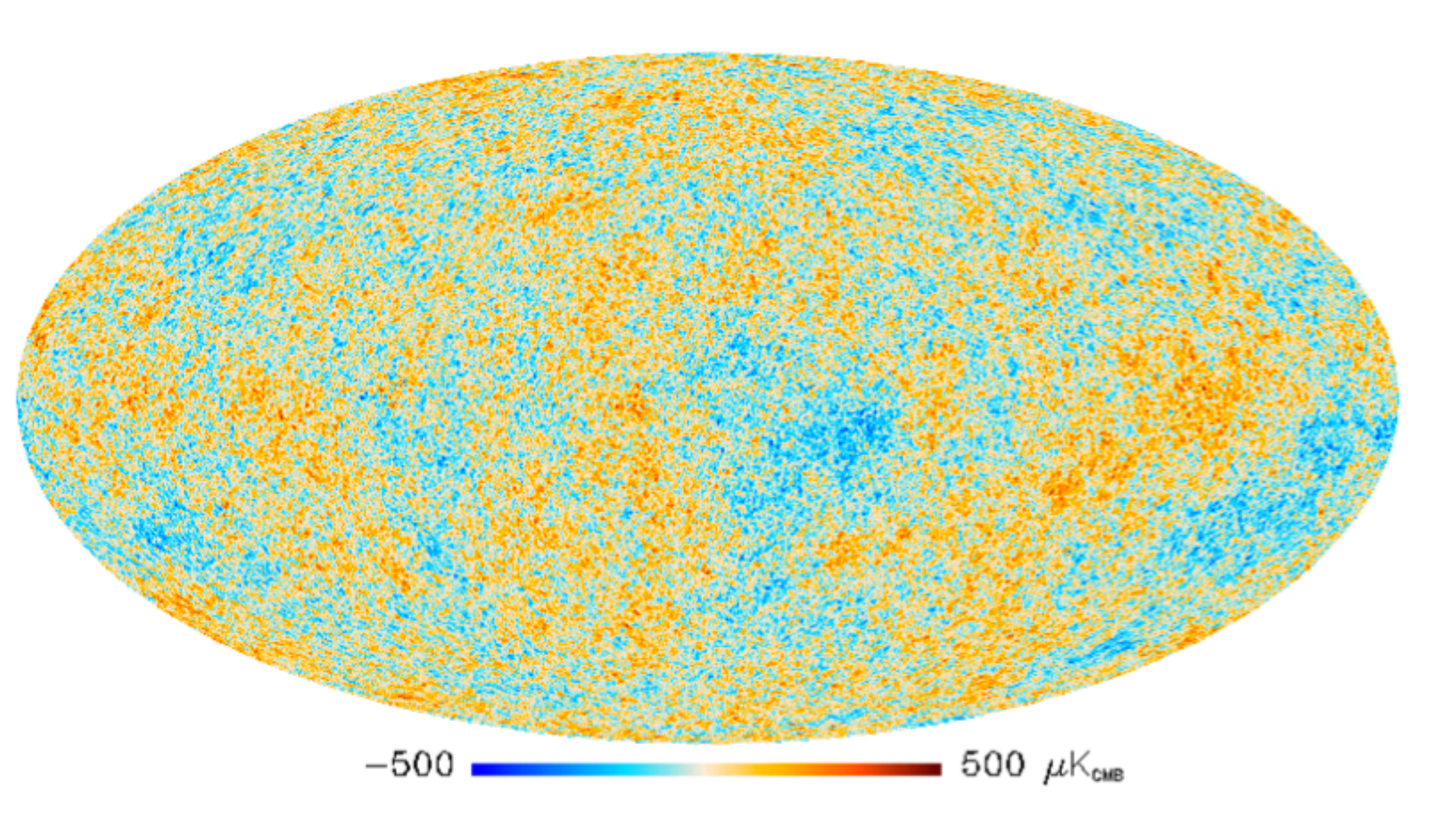
Particle Astrophysics and Cosmology

- Where are we now?
- Intriguing Hints of Discovery
- Inflation: Theory and Observation
- What are the missing pieces? Dark matter and dark energy

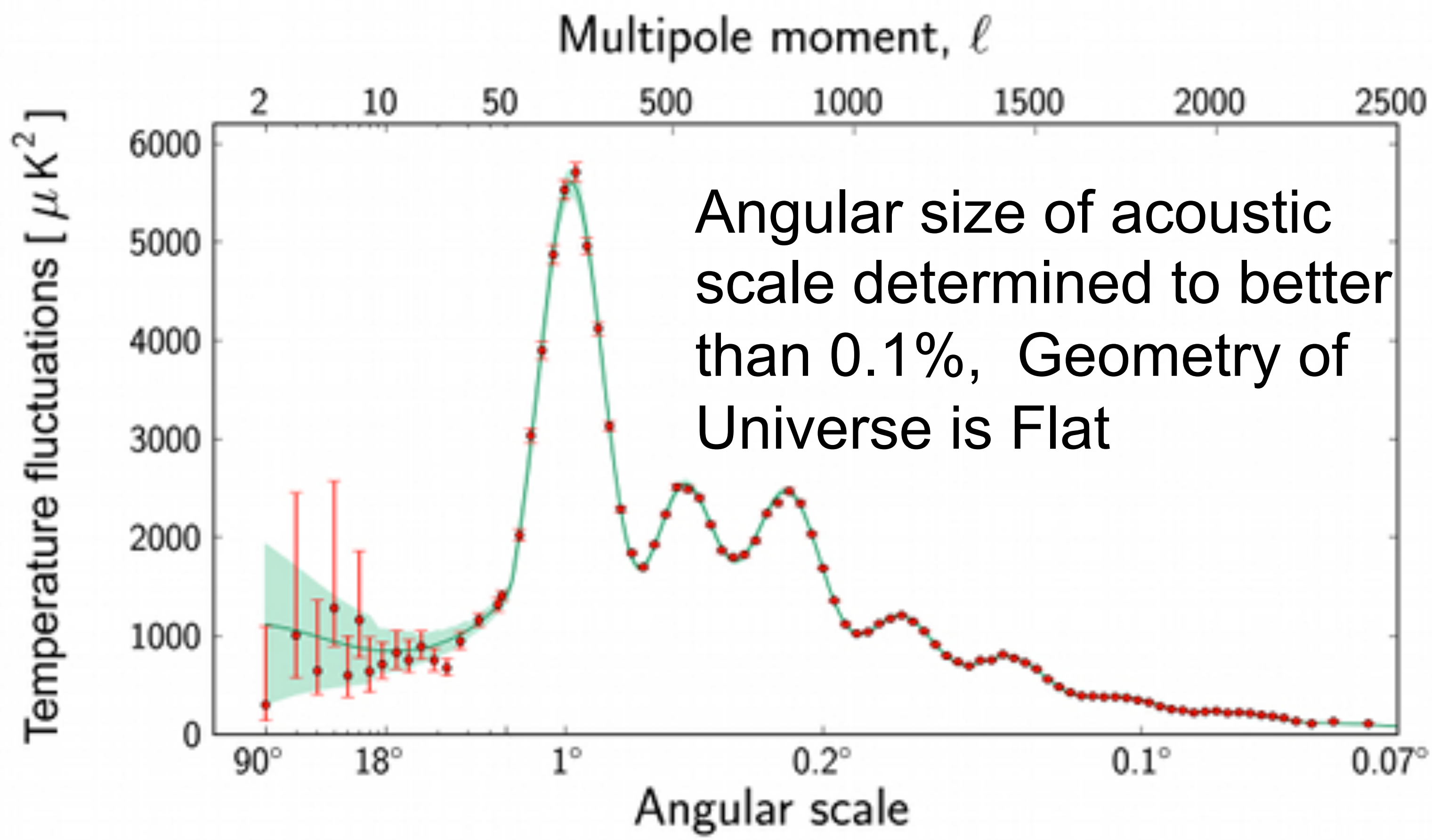
Katherine Freese, Director of Nordita and Professor at University of Michigan

The Universe according to ESA's Planck Space Telescope, March 2013



Planck Data

$$\Omega = 1$$



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

Seven acoustic peaks

LAMDA CDM FITS THE DATA

Cosmological Parameters from Planck

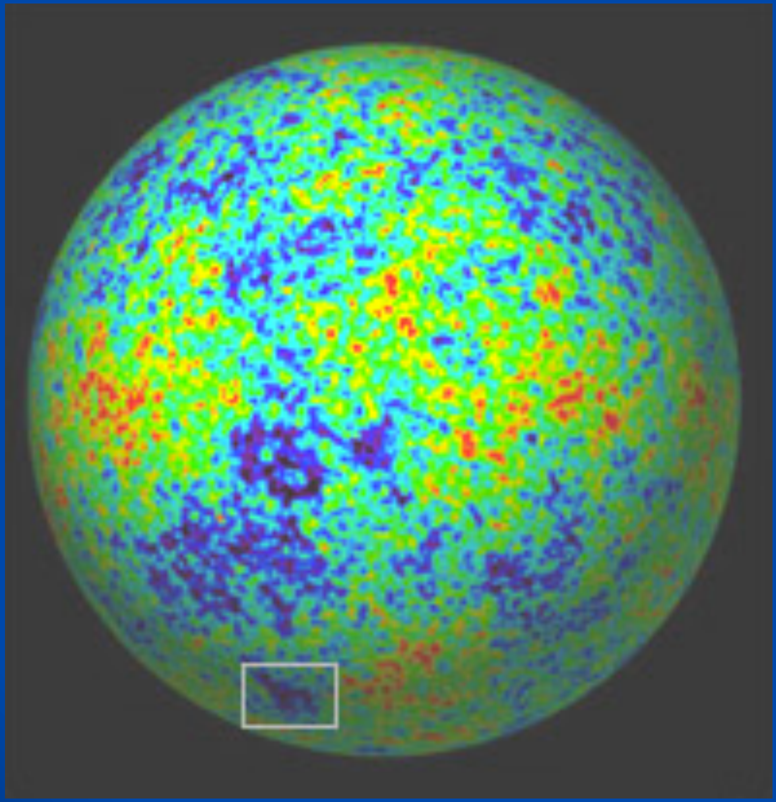
Parameter	*Planck* (CMB+lensing) Best fit	*Planck* (CMB+lensing) 68 % limits	*Planck*+WP+highL+BAO Best fit	*Planck*+WP+highL+BAO 68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04150	1.04141 ± 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		

Weird Anomalies of WMAP hold up

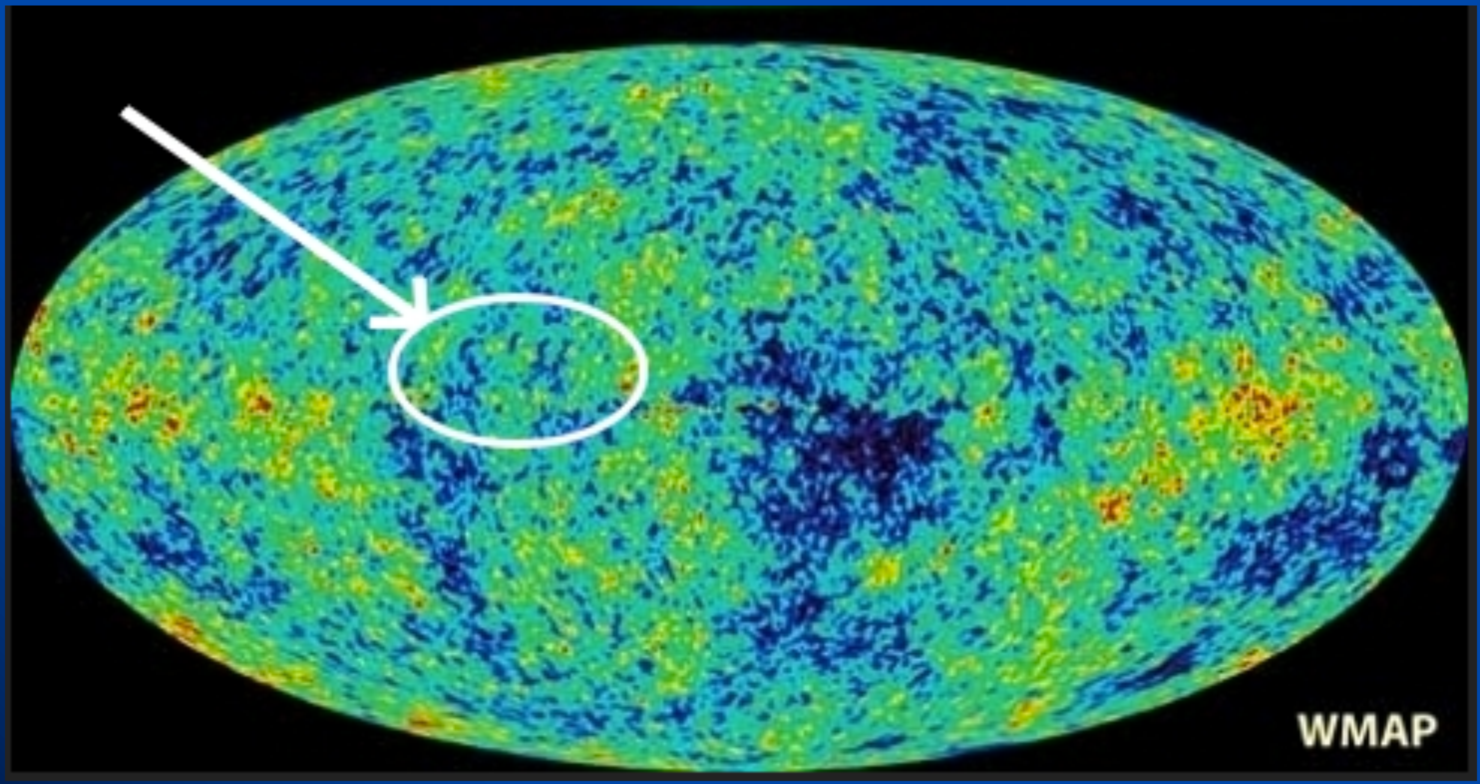
- Alignment between quadrupole and octopole moments (axis of evil)
- Asymmetry of power between two hemispheres
- The Cold Spot
- Deficit of power in low-l modes (below l=30)

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

WMAP cold spot (also in Planck)

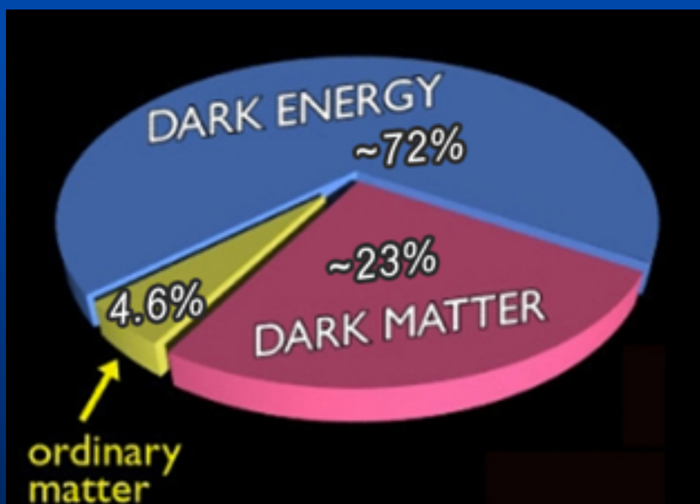


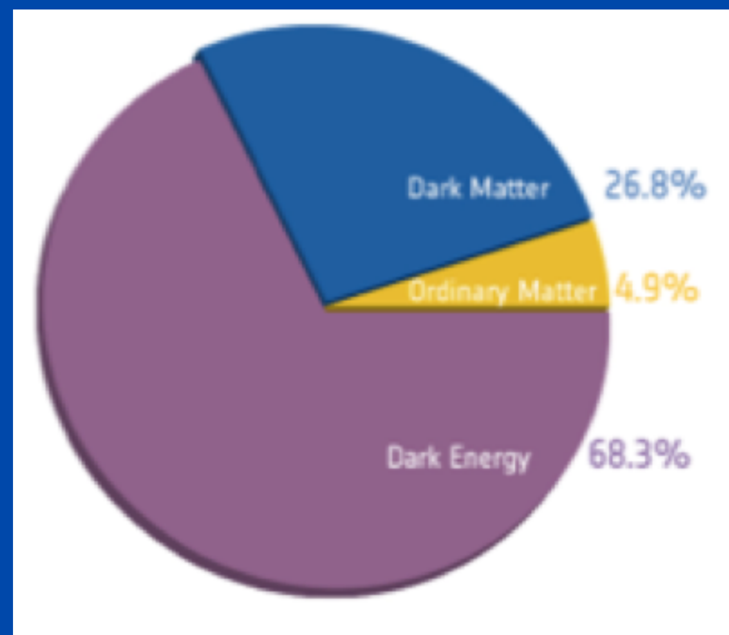
SH initials in WMAP satellite data



More dark matter

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





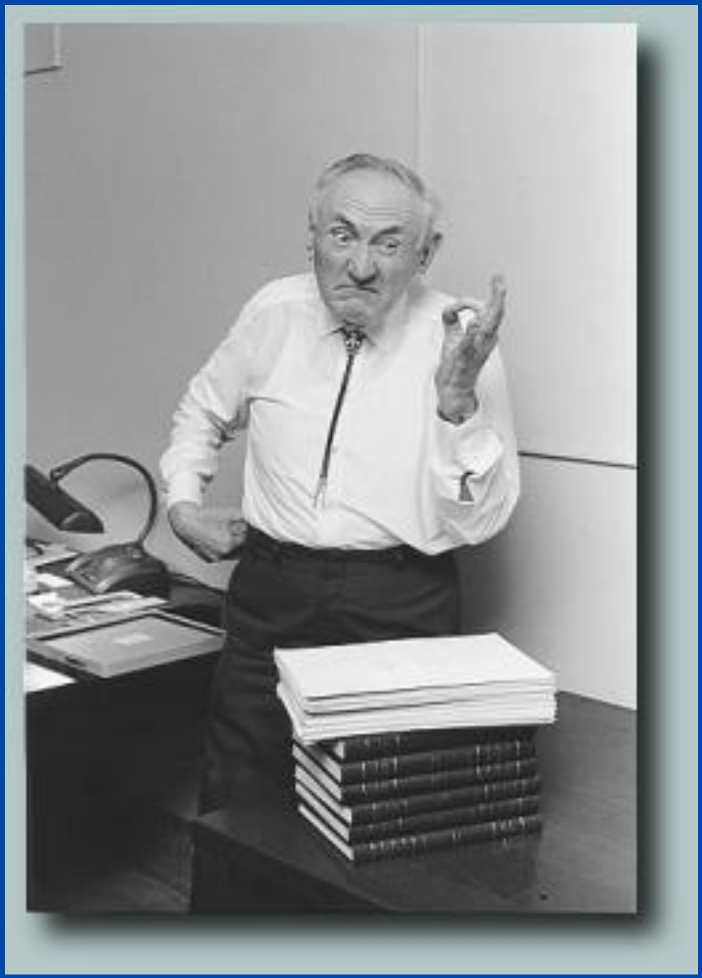
For discussion: is the difference due to instrumental effects? Is it due to 217 X 217 GHz spectra?

Fritz Zwicky in 1933

Galaxies in the Coma cluster were moving too rapidly.

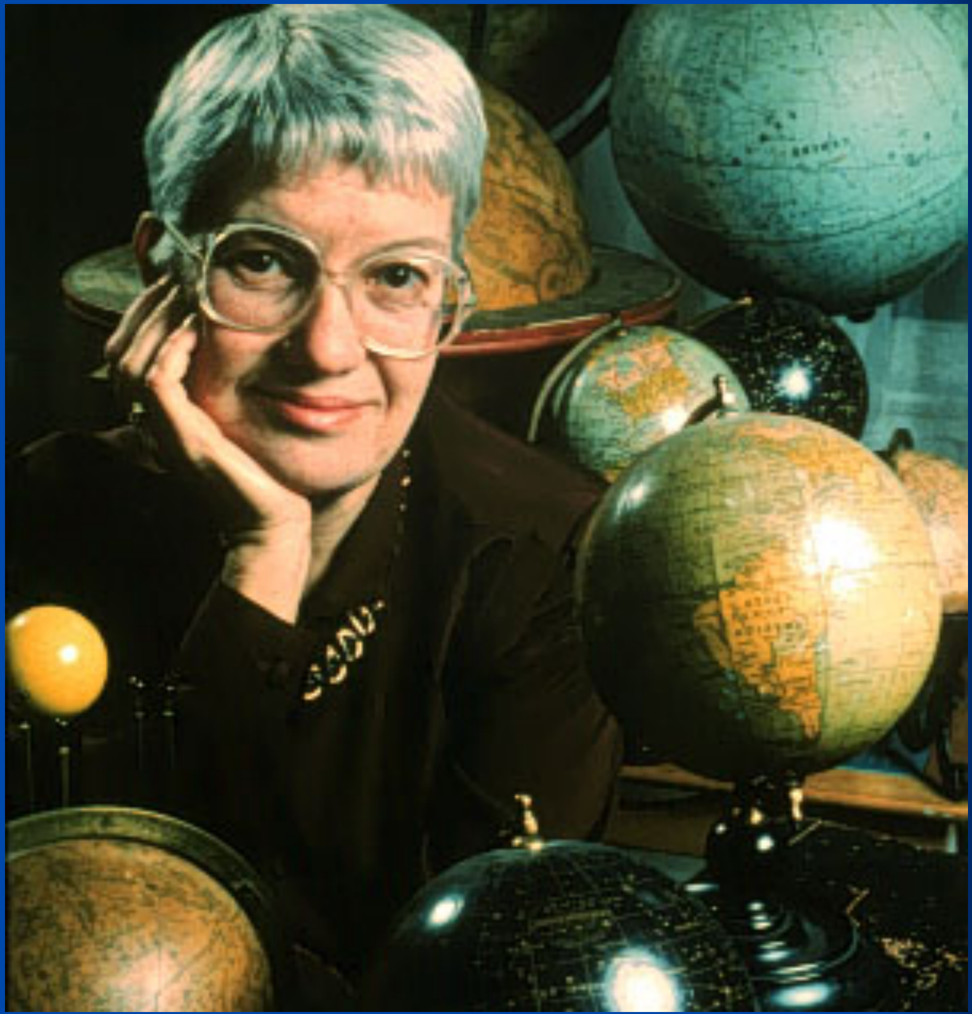
He proposed "Dunkle Materie" as the explanation.

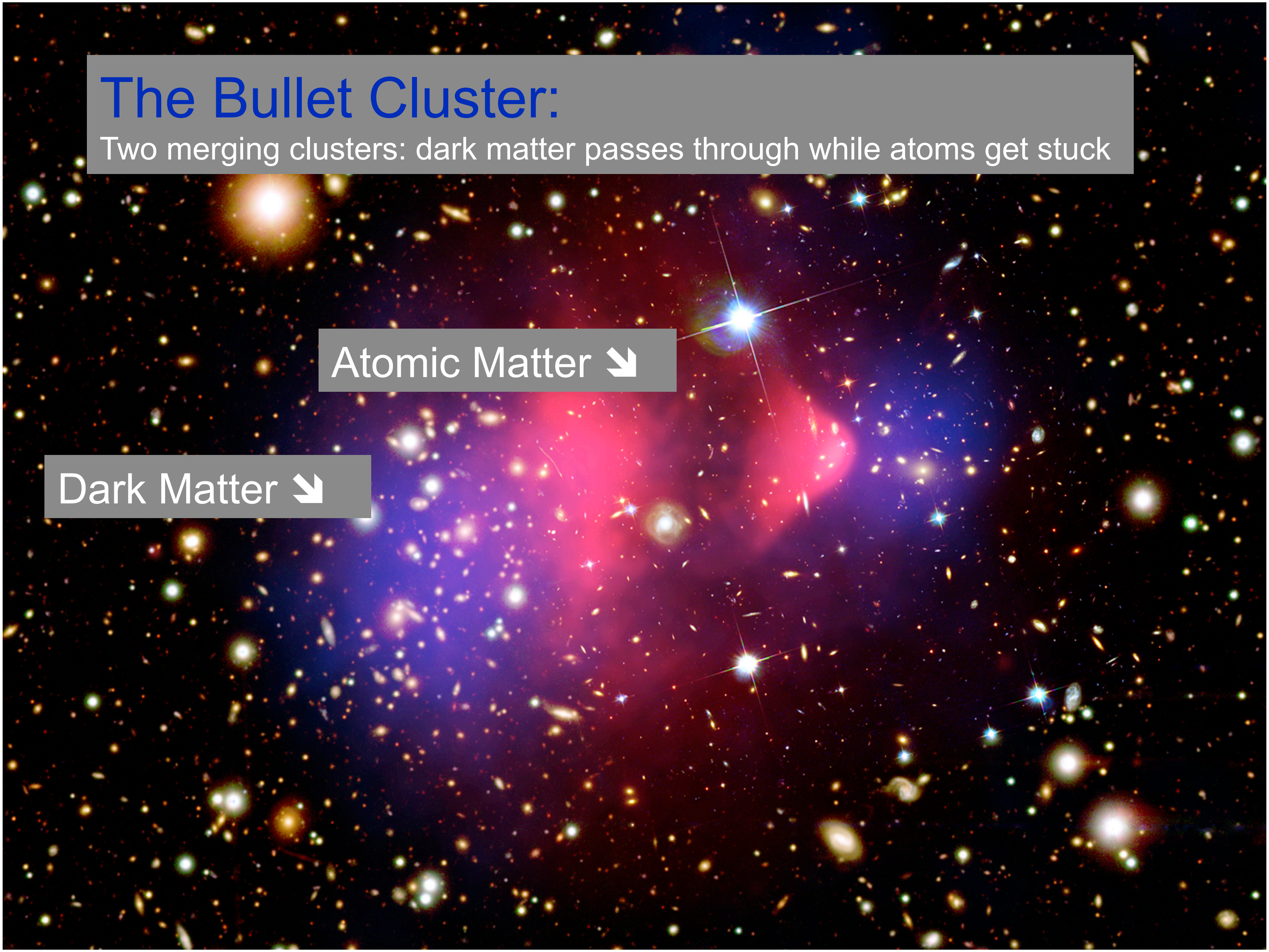
THE BEGINNING OF THE DARK MATTER PROBLEM



Vera Rubin in 1970s

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




The Bullet Cluster:
Two merging clusters: dark matter passes through while atoms get stuck
Atomic Matter ➘
Dark Matter ➘

What is the Dark Matter? Candidates:

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

The WIMP Miracle

Weakly Interacting Massive Particles are the best motivated dark matter candidates, e.g.: Lightest Supersymmetric Particles (such as neutralino) are their own antipartners. Annihilation rate in the early universe determines the density today.

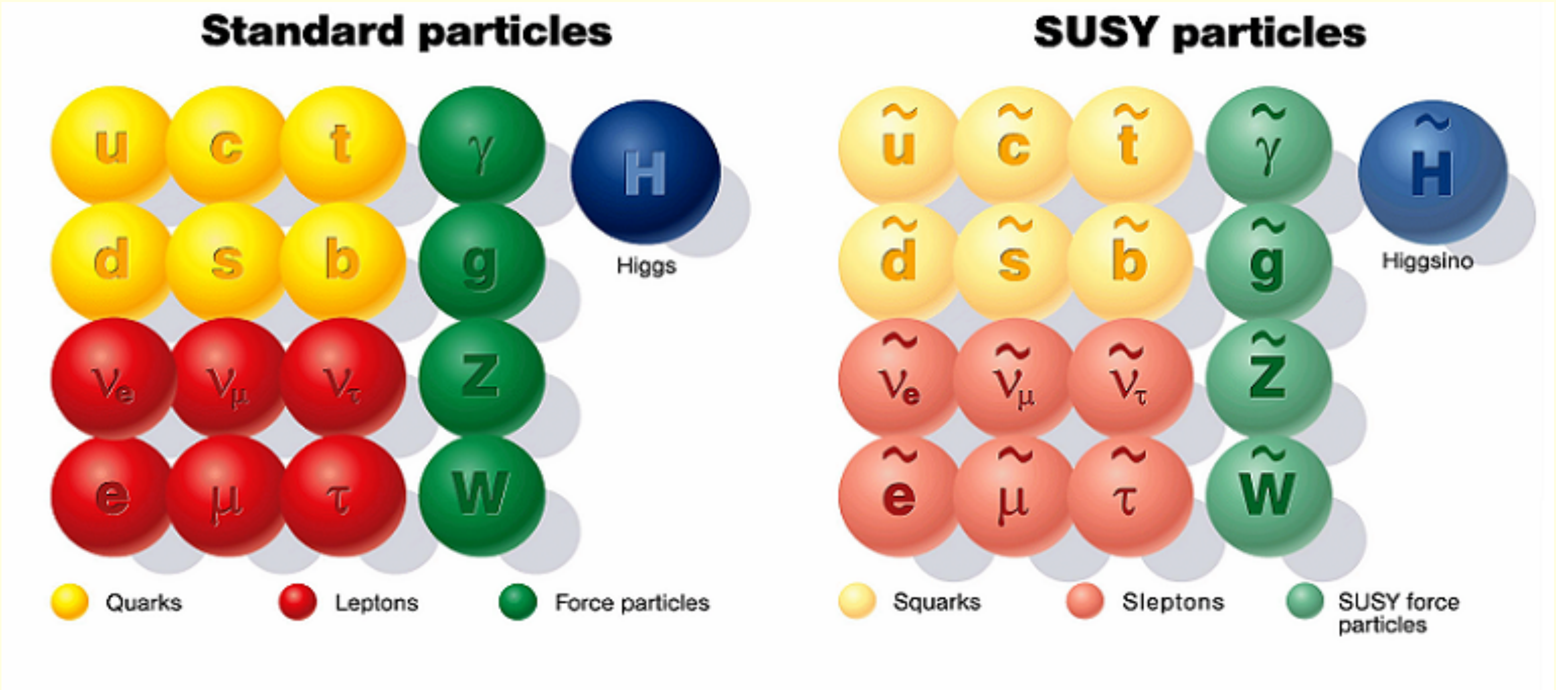
- The annihilation rate comes purely from particle physics and automatically gives the right answer for the relic density!

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

This is the mass fraction of WIMPs today, and gives the right answer (23%) if the dark matter is weakly interacting

WIMP mass: GeV – 10 TeV

Supersymmetry



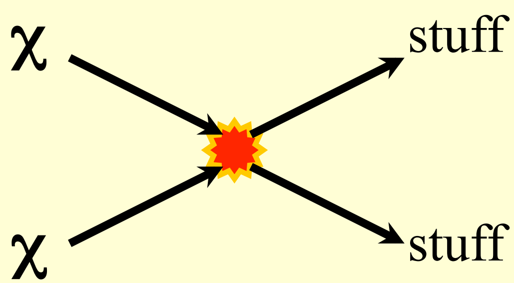
- The lightest supersymmetric particle may be the dark matter.

Another type of WIMP from Universal Extra Dimensions

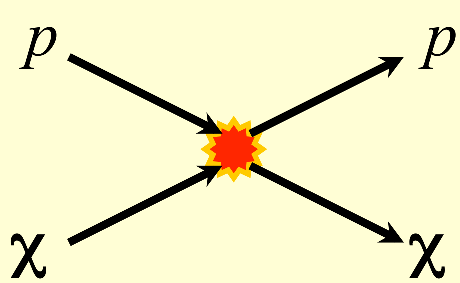
- All standard model fields propagate in a higher dimensional bulk that is compactified on a space TeV^-1
- Higher Dimensional momentum conservation in bulk translates in 4D to KK number (w/ b.c. to KK parity)
- Lightest KK particle (LKP) does not decay and is dark matter candidate

THREE PRONGED APPROACH TO WIMP DETECTION

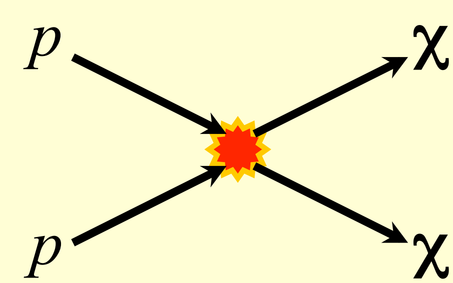
Interactions with Standard Model particles



Annihilation



Scattering



Production

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

Direct Detection:
Look for scattering events in detector

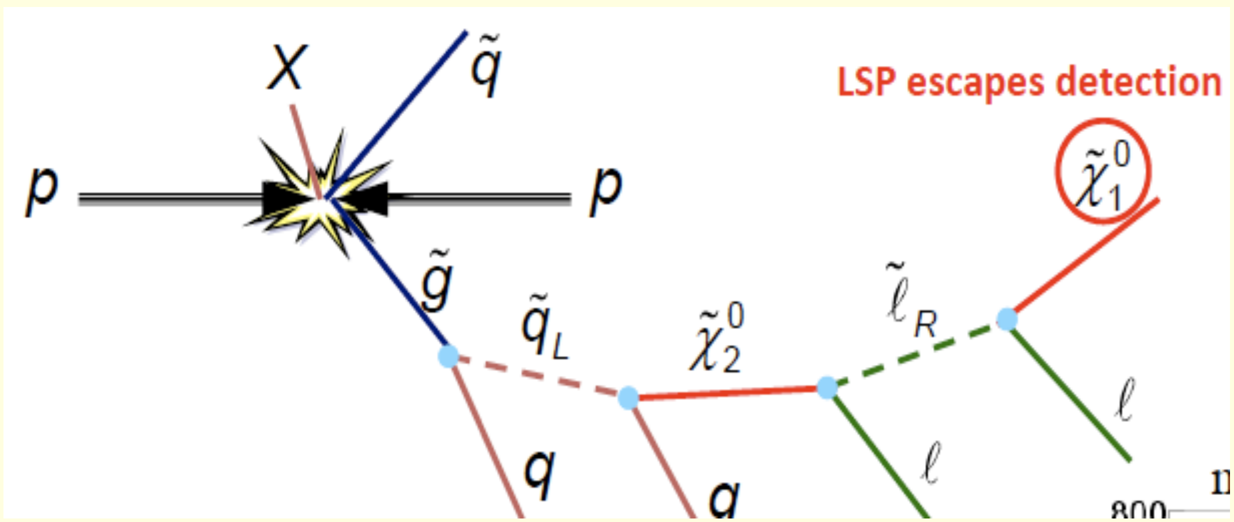
Accelerators:
LHC

(i) FIRST WAY TO SEARCH FOR WIMPS

COLLIDERS:
Large Hadron Collider at CERN

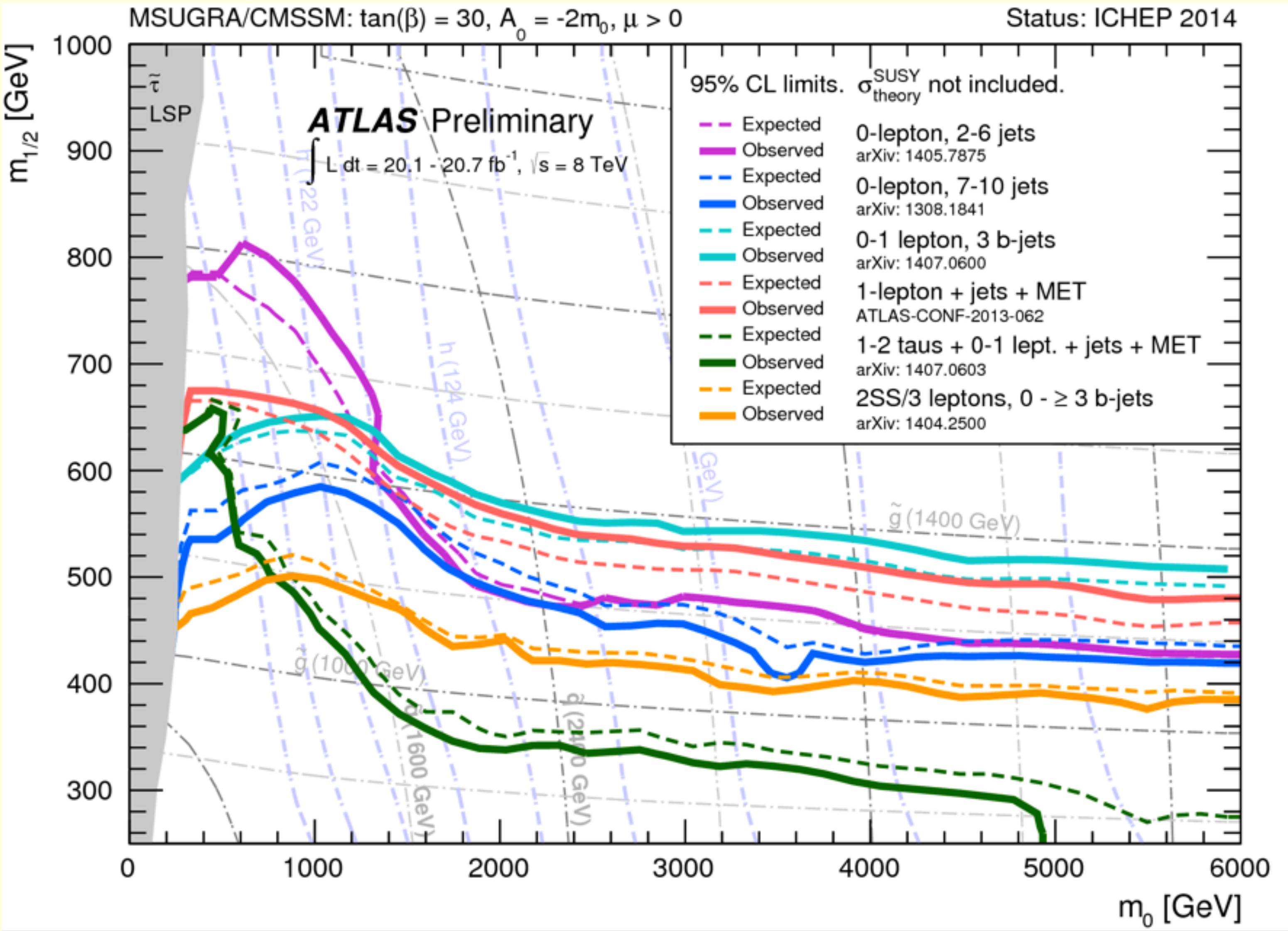
Signatures of Supersymmetric particles at CERN

- Missing energy plus jets



- Nothing seen yet: particle masses pushed up

ATLAS bounds on CMSSM



- Even in the MSSM, 25 GeV neutralino WIMPs can survive for now
- 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

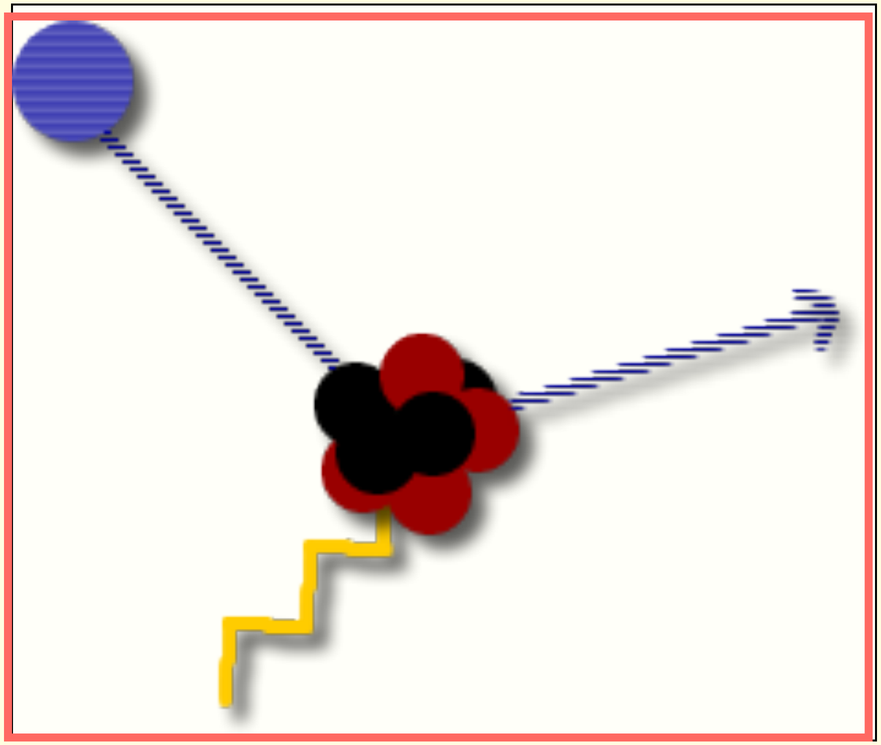
- Signature: missing energy when SUSY particle is created and some energy leaves the detector
- Problem with identification: degeneracy of interpretation
- SUSY can be found, but, you still don’t know how long the particle lives: fractions of a second to leave detector or the age of the universe if it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

(ii) SECOND WAY TO SEARCH FOR WIMPS

DIRECT DETECTION
Laboratory EXPERIMENTS

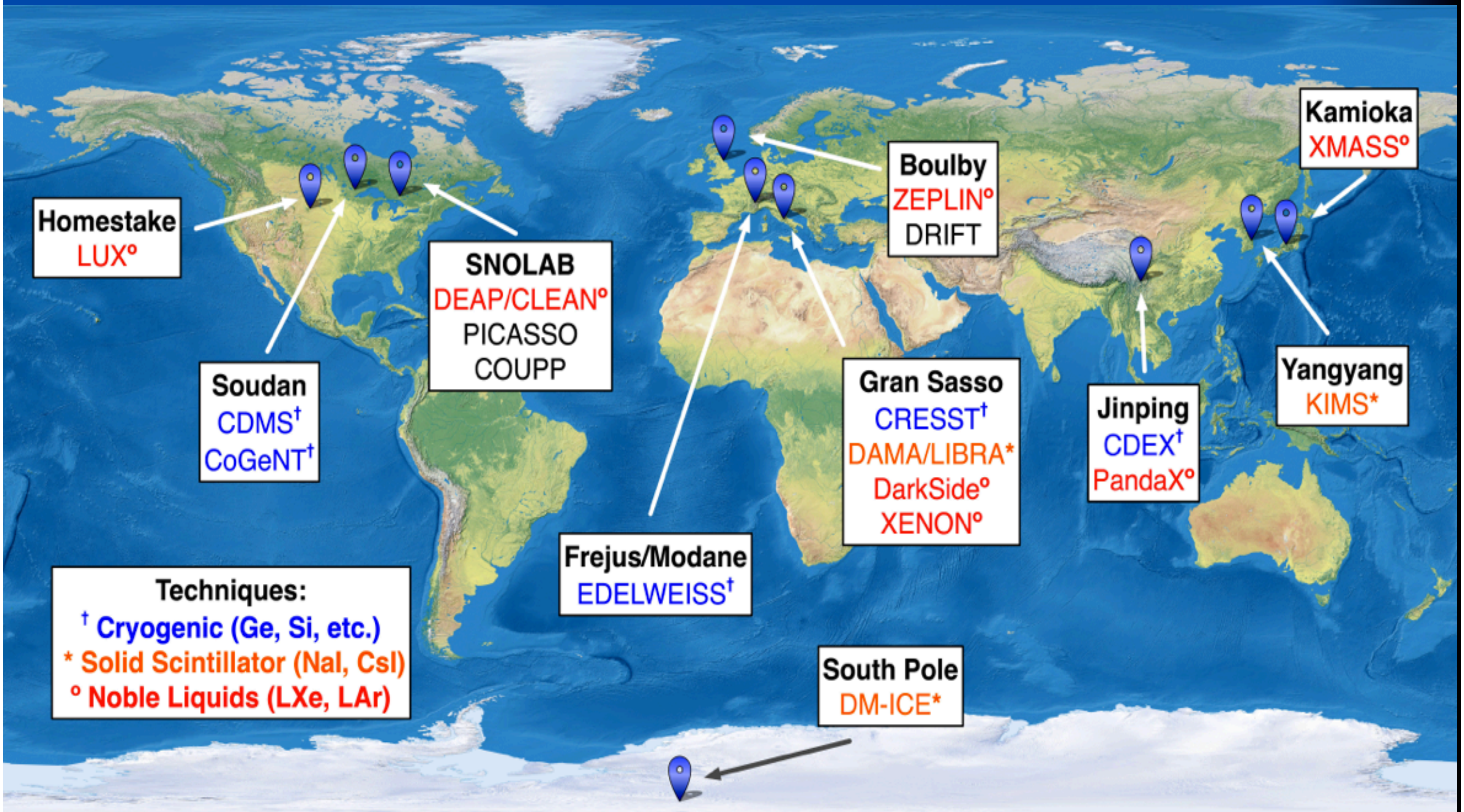
Direct Detection of WIMP dark matter

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.



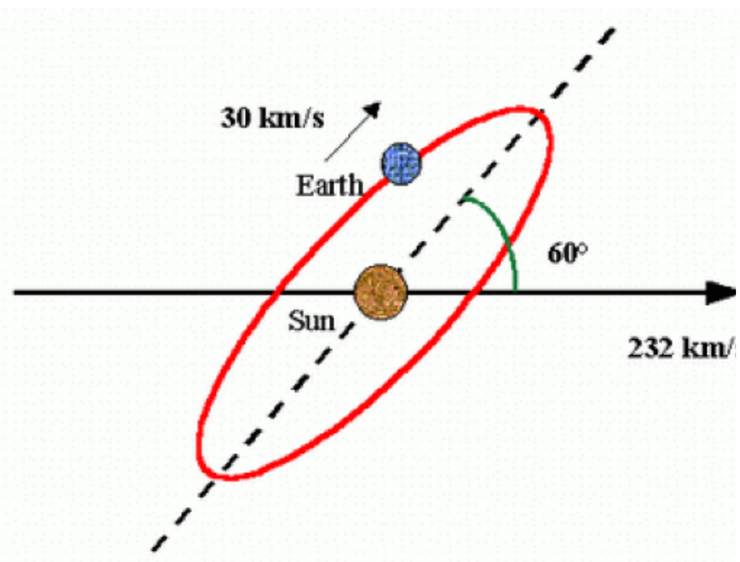
Expected Rate: less than one count/kg/day!

UNDERGROUND DARK MATTER LABORATORIES WORLDWIDE



DAMA annual modulation

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



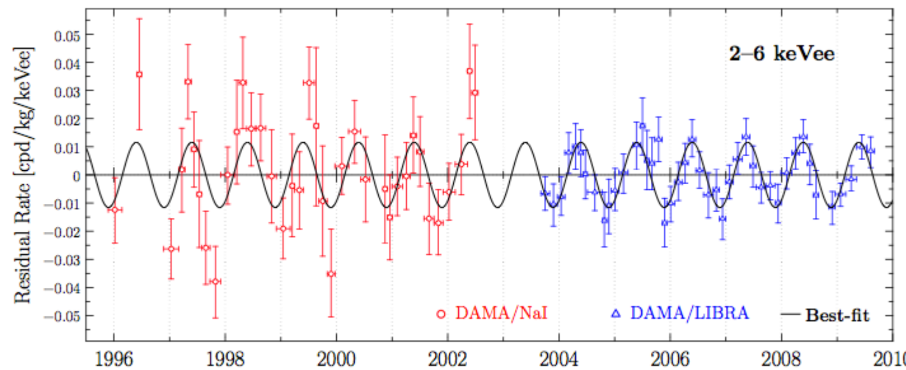


FIG. 5: The residual rate measured by DAMA/NaI (red circles, 0.29 ton-yr exposure over 1995–2002) and DAMA/LIBRA (blue triangles, 0.87 ton-yr exposure over 2003–2010) in the 2–6 keVee energy interval, as a function of time. Data is taken from Refs. [27, 29]. The solid black line is the best fit sinusoidal modulation $A\cos[\frac{2\pi}{T}(t-t_0)]$ with an amplitude $A = 0.0116 \pm 0.0013$ cpd/kg/keV, a phase $t_0 = 0.400 \pm 0.019$ yr (May 26 ± 7 days), and a period $T = 0.999 \pm 0.002$ yr [29]. The data are consistent with the SHM expected phase of June 1.

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

Data do show modulation! Peak in June, minimum in December (as predicted). WIMP interpretation???

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

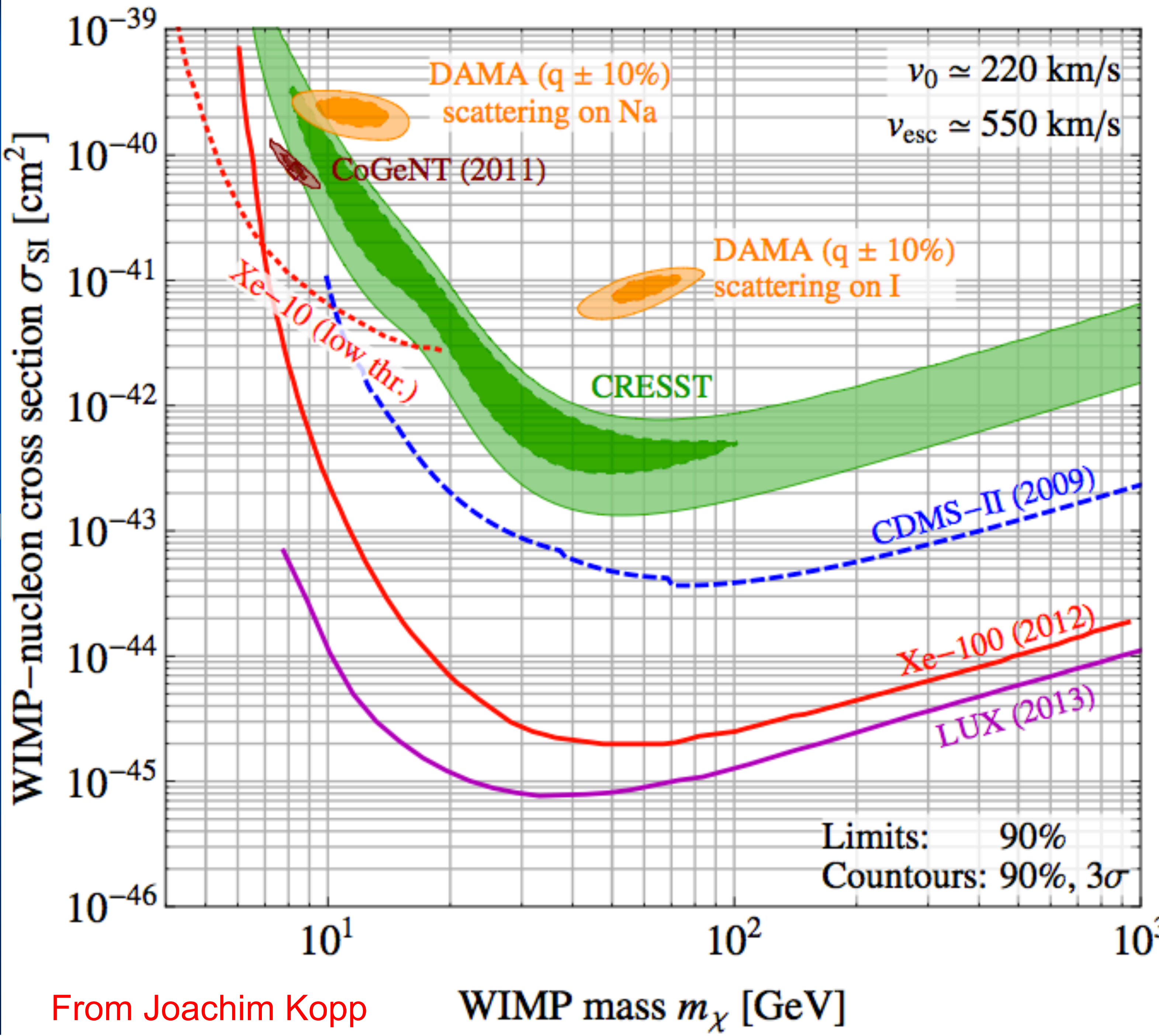
"I' m a Spaniard caught between two Italian women"

Rita Bernabei, DAMA

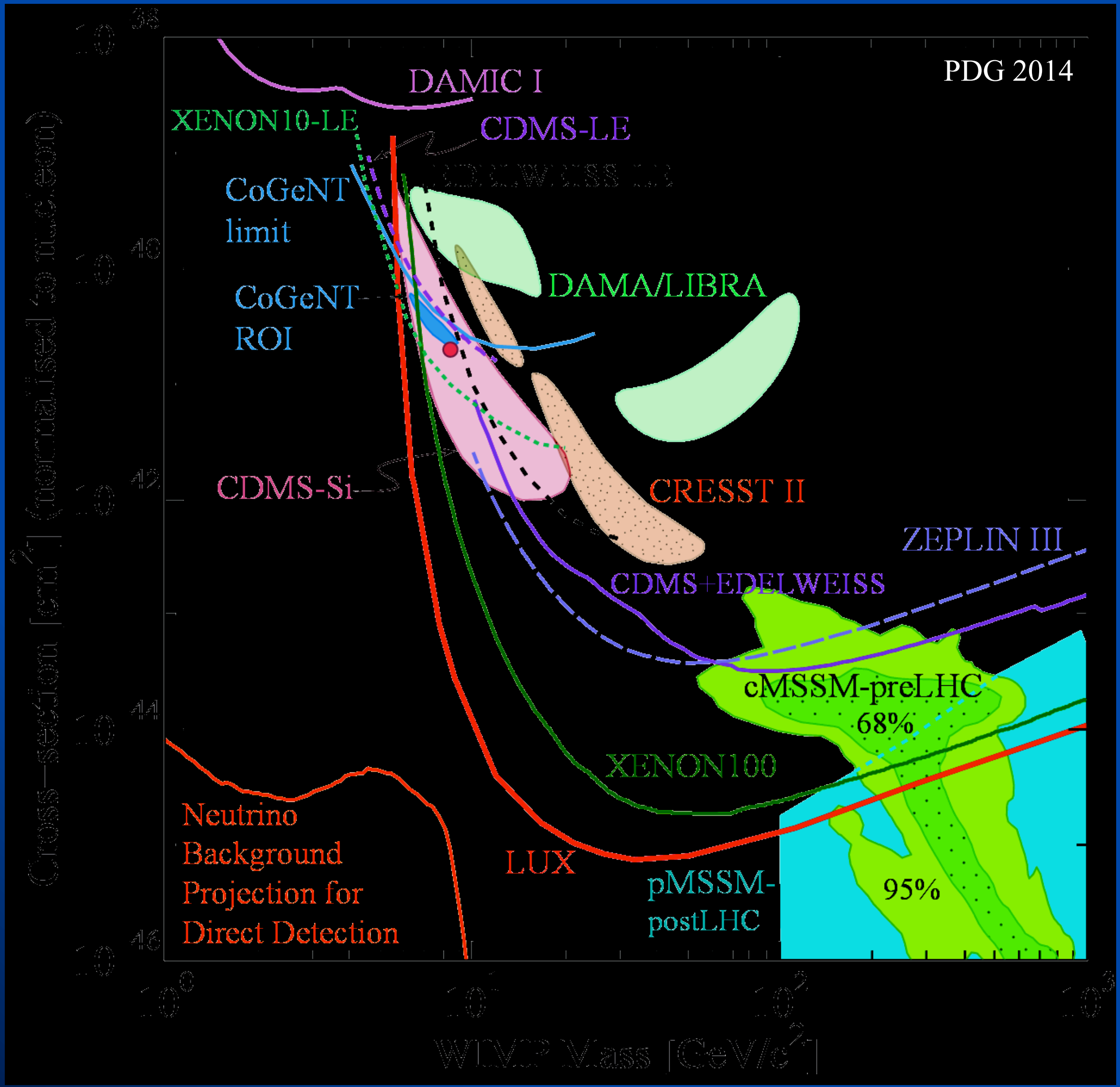
Juan Collar, COGENT

Elena Aprile, XENON

Assumes Spin-Independend. Scattering i.e. scales as A^2



From Joachim Kopp


PDG 2014
DAMIC I
XENON10-LE
CDMS-LE
EDELWEISS-LE
CoGeNT
limit
CoGeNT
ROI
DAMA/LIBRA
CDMS-Si
CRESST II
ZEPLIN III
CDMS+EDELWEISS
cMSSM-preLHC
68%
XENON100
Neutrino
Background
Projection for
Direct Detection
LUX
pMSSM-
postLHC
95%
WIMP Mass [GeV/c^2]
Cross−section [cm^2] (normalised to nucleon)

Status of DM searches

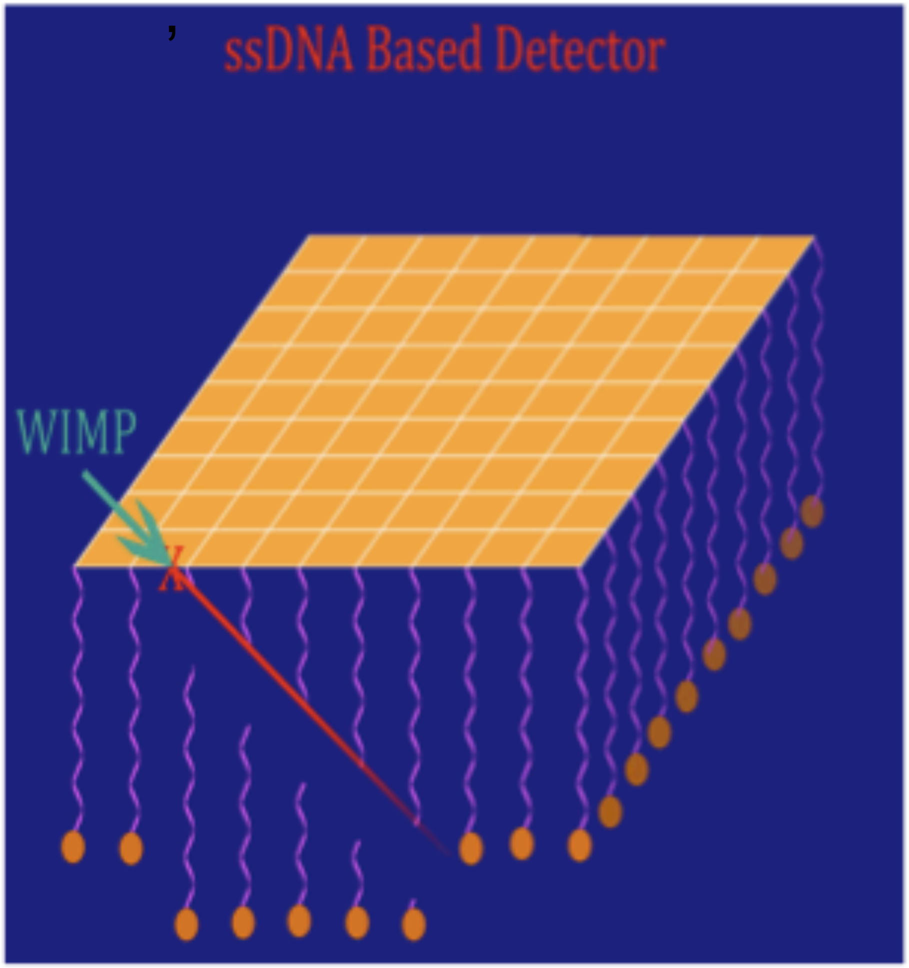
- See talk of Harry Nelson
- Difficulty: comparing apples and oranges, since detectors are made of different materials.
- Theory comes in: Spin independent scattering, Spin dependent, try all possible operators, mediators, dark sector, etc.
- Interesting avenue: nuclear physics. Wick Haxton finds DAMA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

A major Step Forward: Directional Capability

- 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 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, Freese, Spergel, Lopez, Cantor, Church, Sano

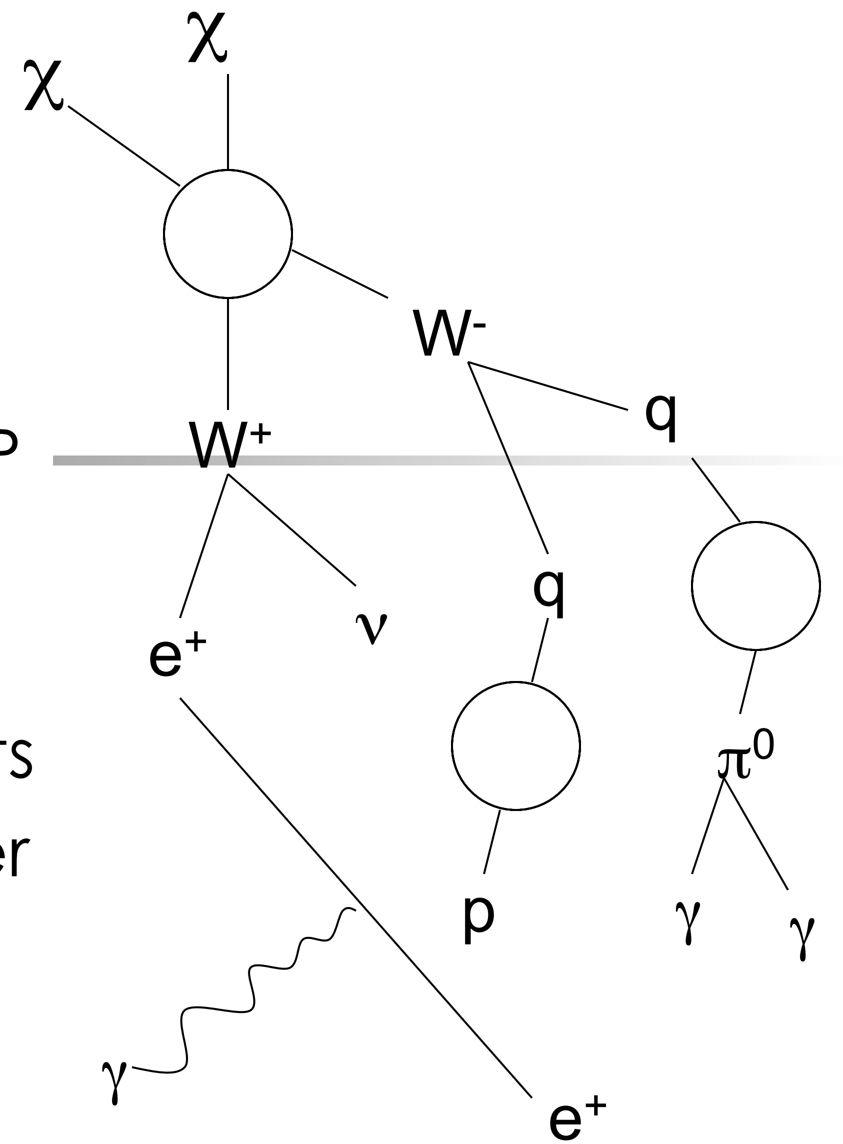
(iii) THIRD WAY TO SEARCH FOR WIMPS

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)

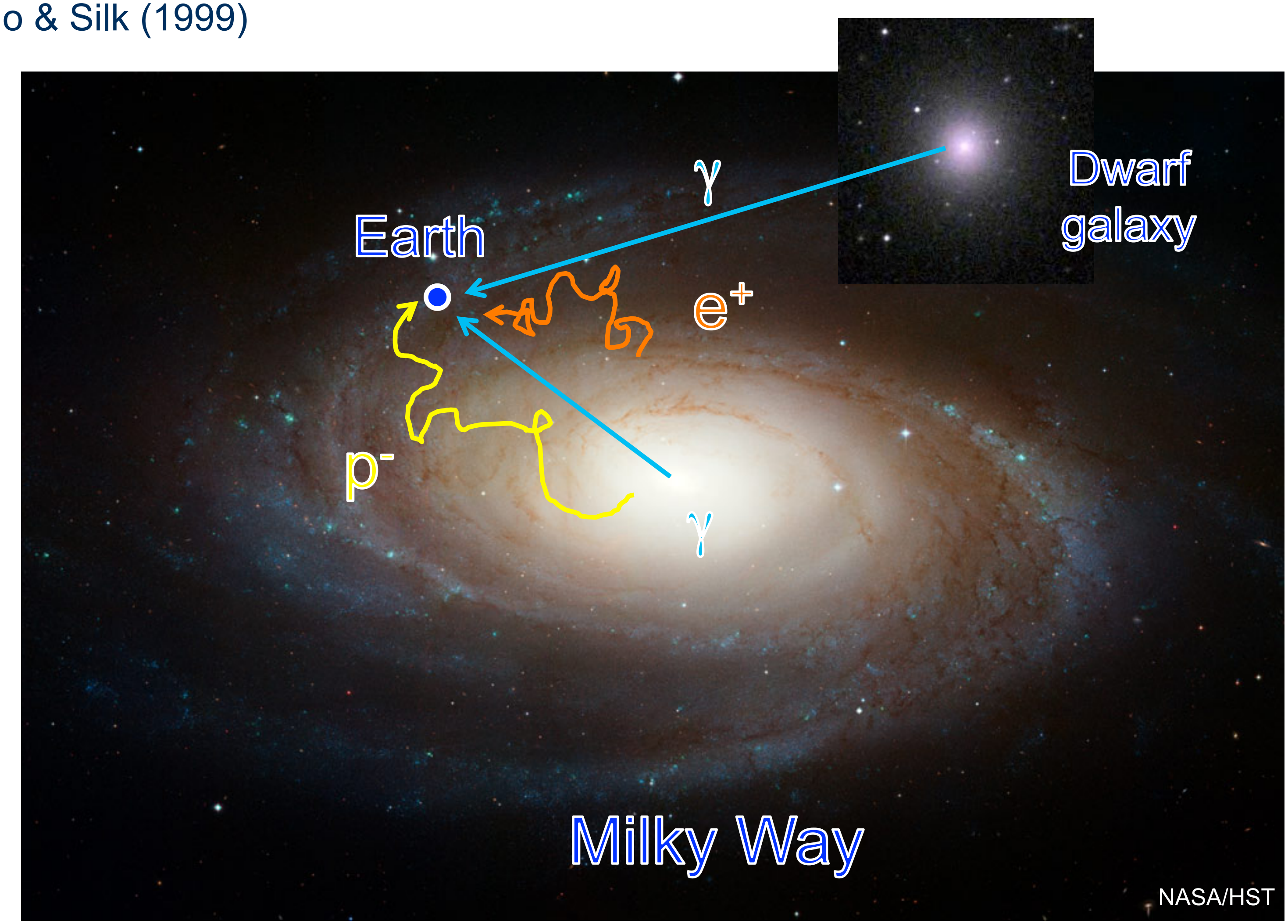


Annihilation Products

- 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

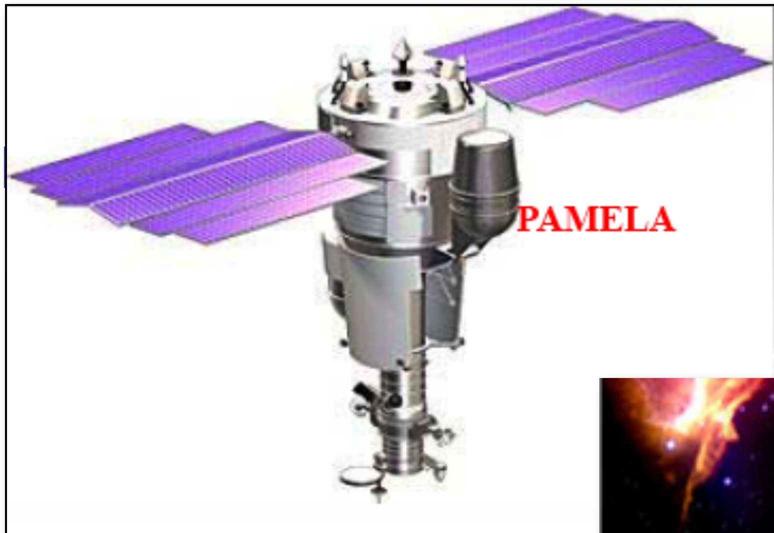
Silk & Srednicki (1984); Ellis et al. (1988)
Gondolo & Silk (1999)



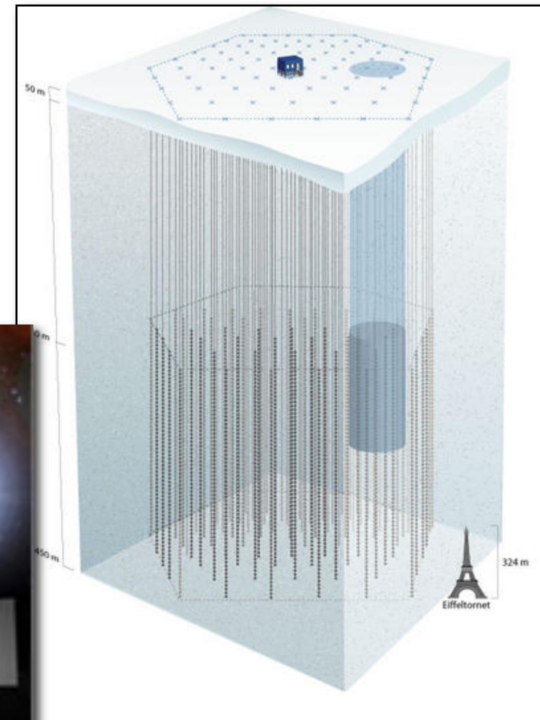
AMS, Fermi/LAT, HESS, …

New Indirect Detection Results

Pamela and AMS



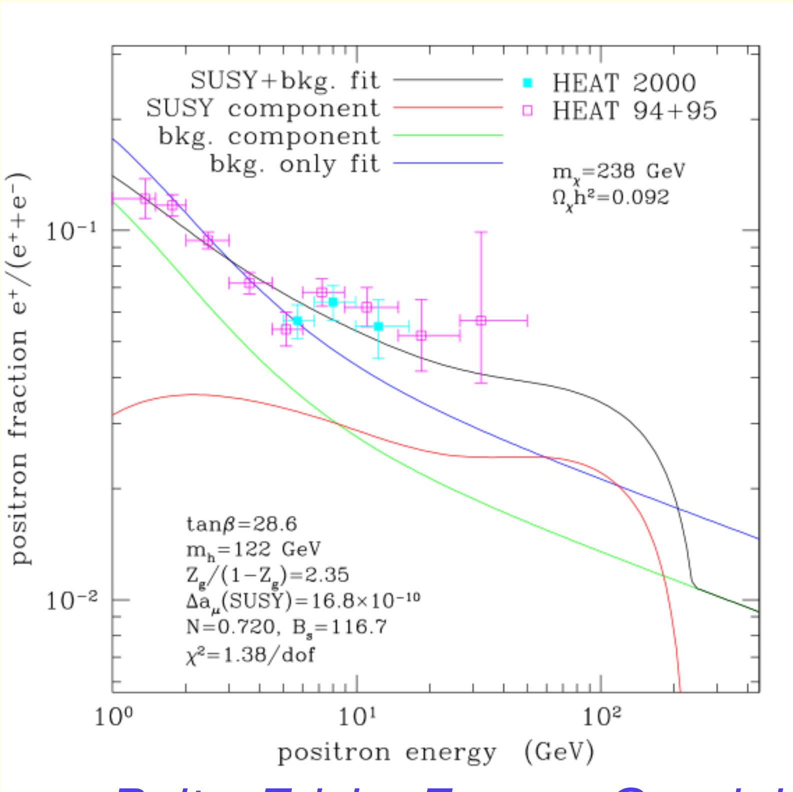
IceCube/DeepCore



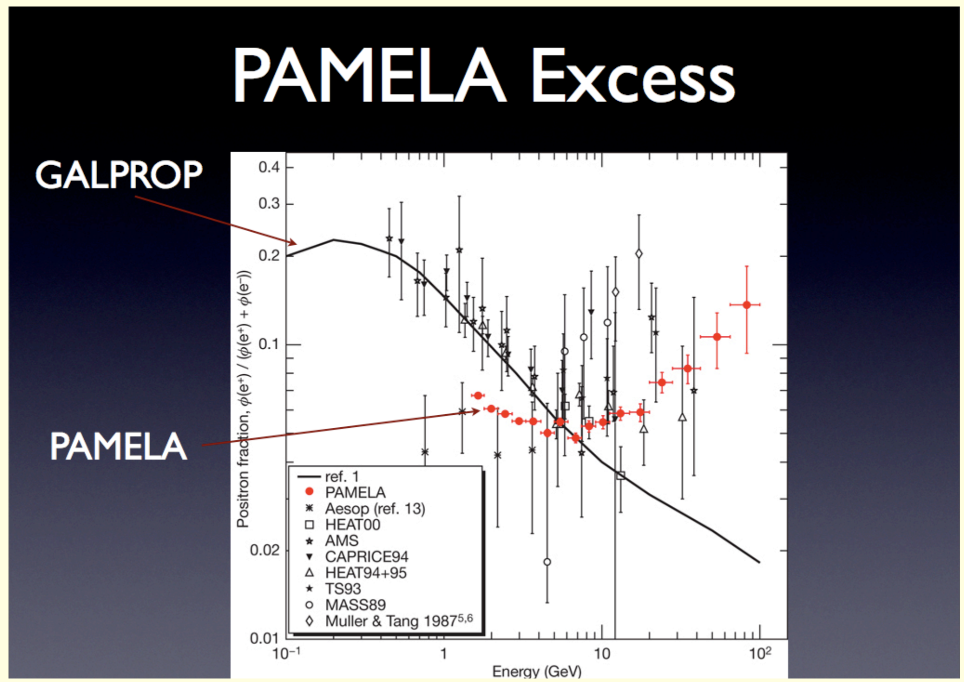
FERMI

Positron excess

- HEAT balloon found anomaly in cosmic ray positron flux
- Is it from dark matter annihilation

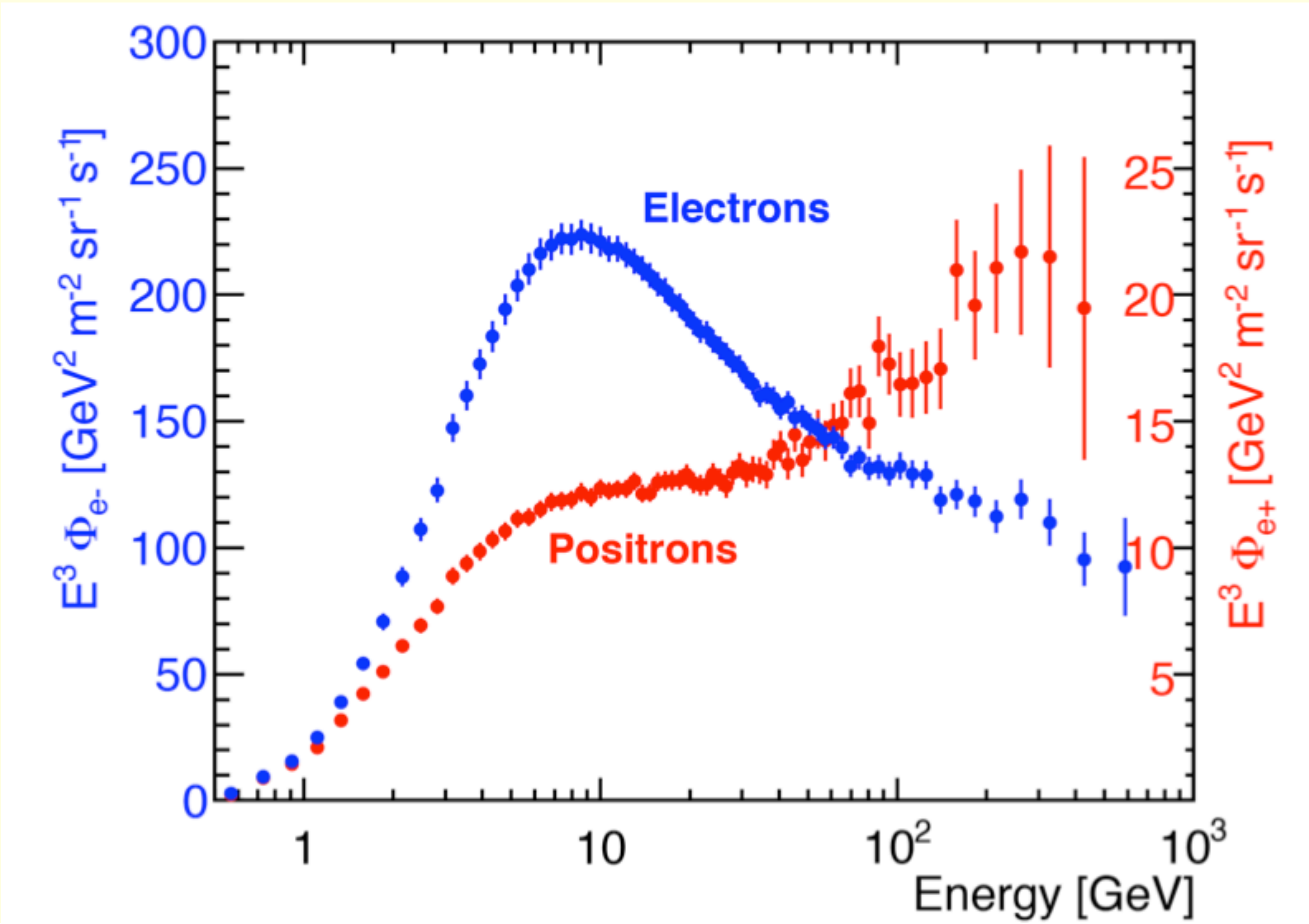


Baltz, Edsjo, Freese, Gondolo 2001



SEE TALK OF SAM TING

AMS Positron Excess



How to understand positron excess?

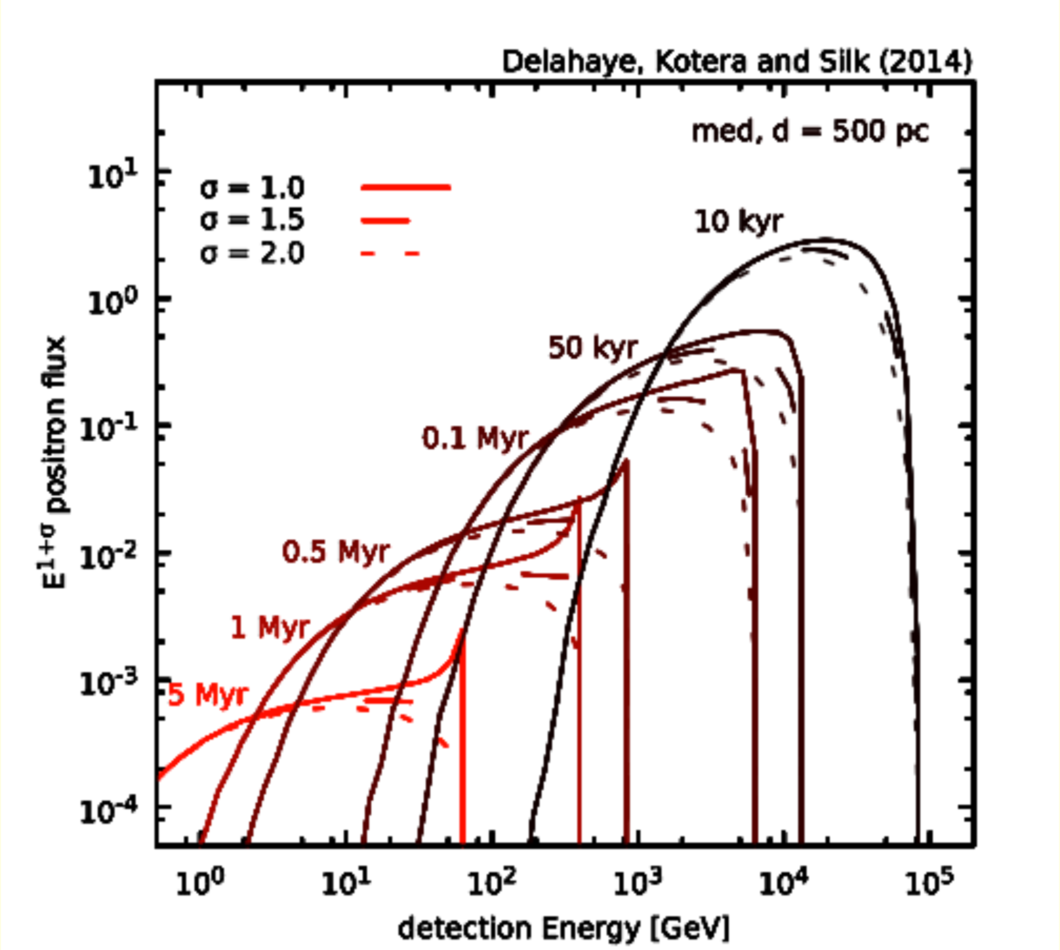
- The problem: positrons change directions in transit in magnetic fields, can't determine their origins

- 1) Pulsars: an equally good fit as DM
- 2) Dark matter annihilation requires:

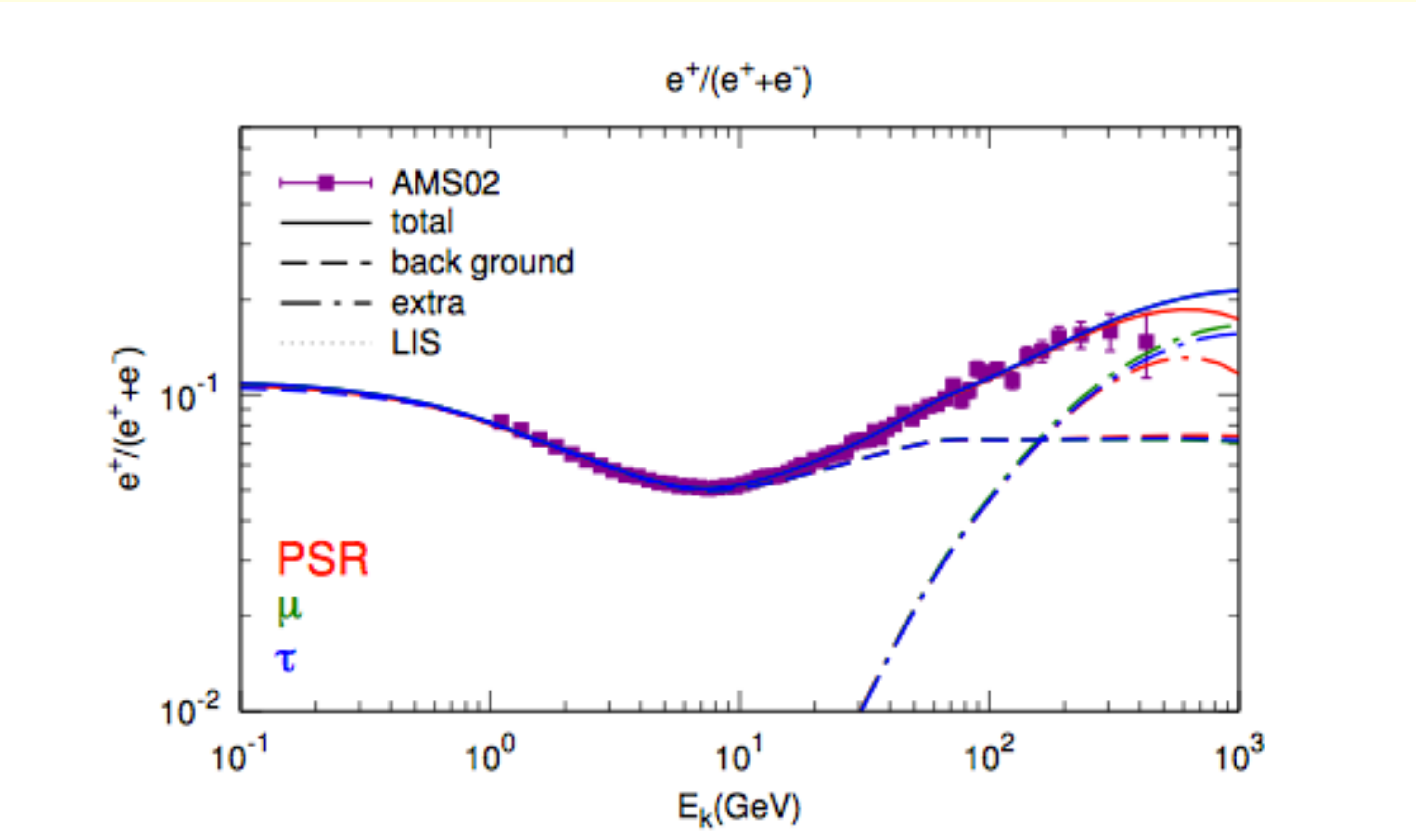
(i) we happen to live in a hot spot of high dark matter density (boosted by at least factor 10): unlikely

(ii) leptophilic WIMPs: must annihilate only to to electrons, positrons, and neutrinos (to avoid overproducing antiprotons)

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

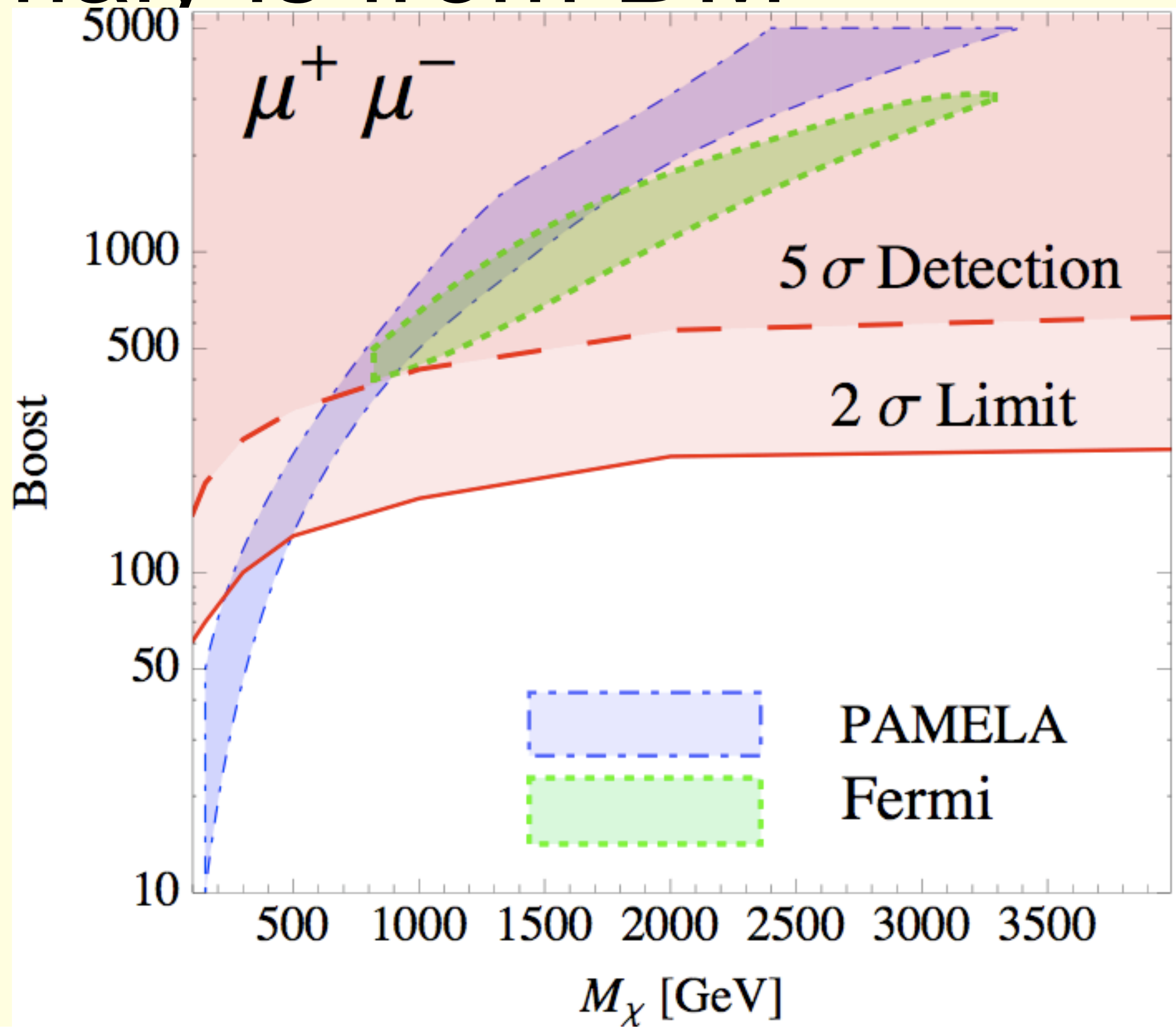


Lin, Yuan, Bi
1409.6248



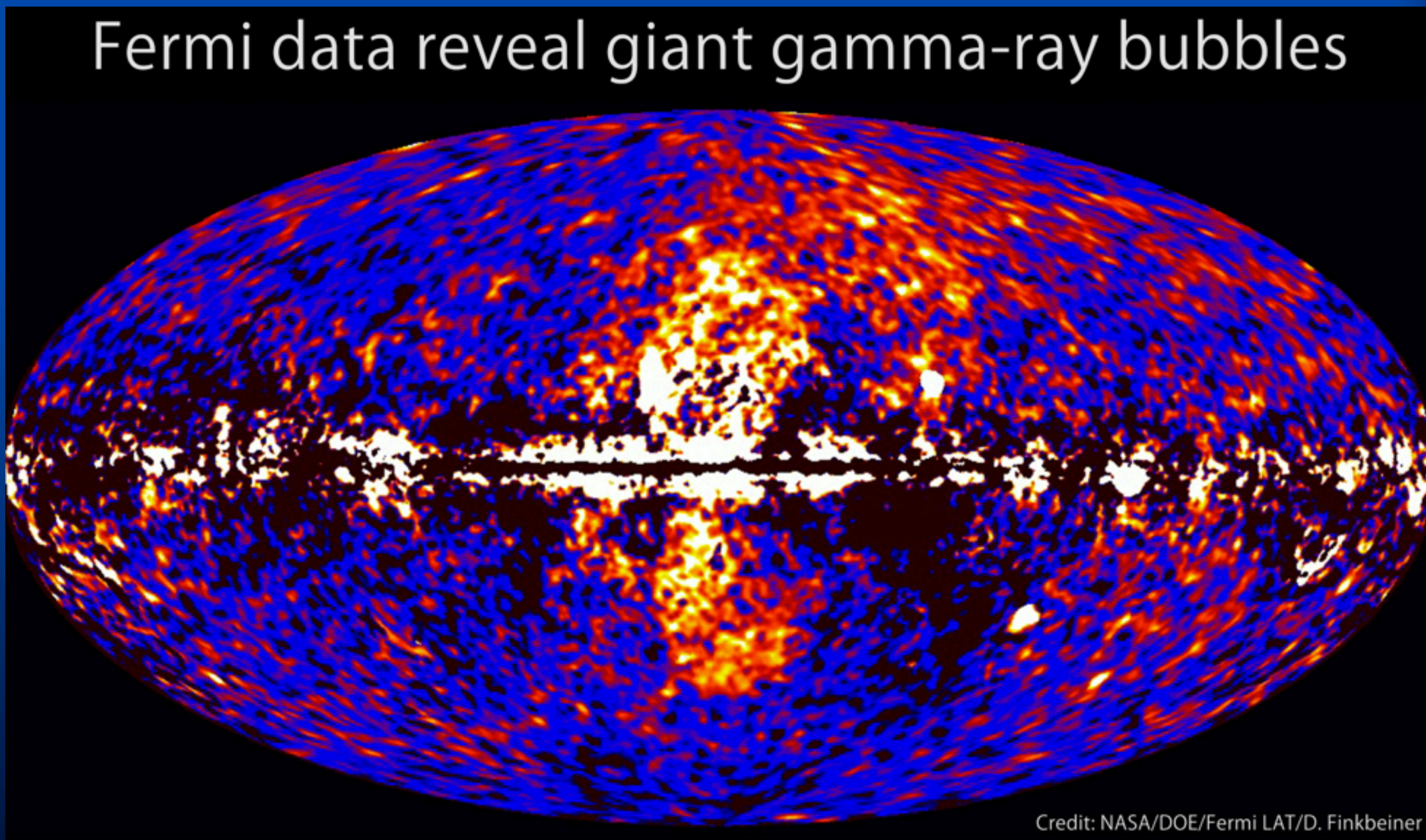
ICECUBE/DEEPCORE will see neutrinos if positron anomaly is from DM

Spolyar,
Buckley,
Freese,
Hooper,
Murayama
2009

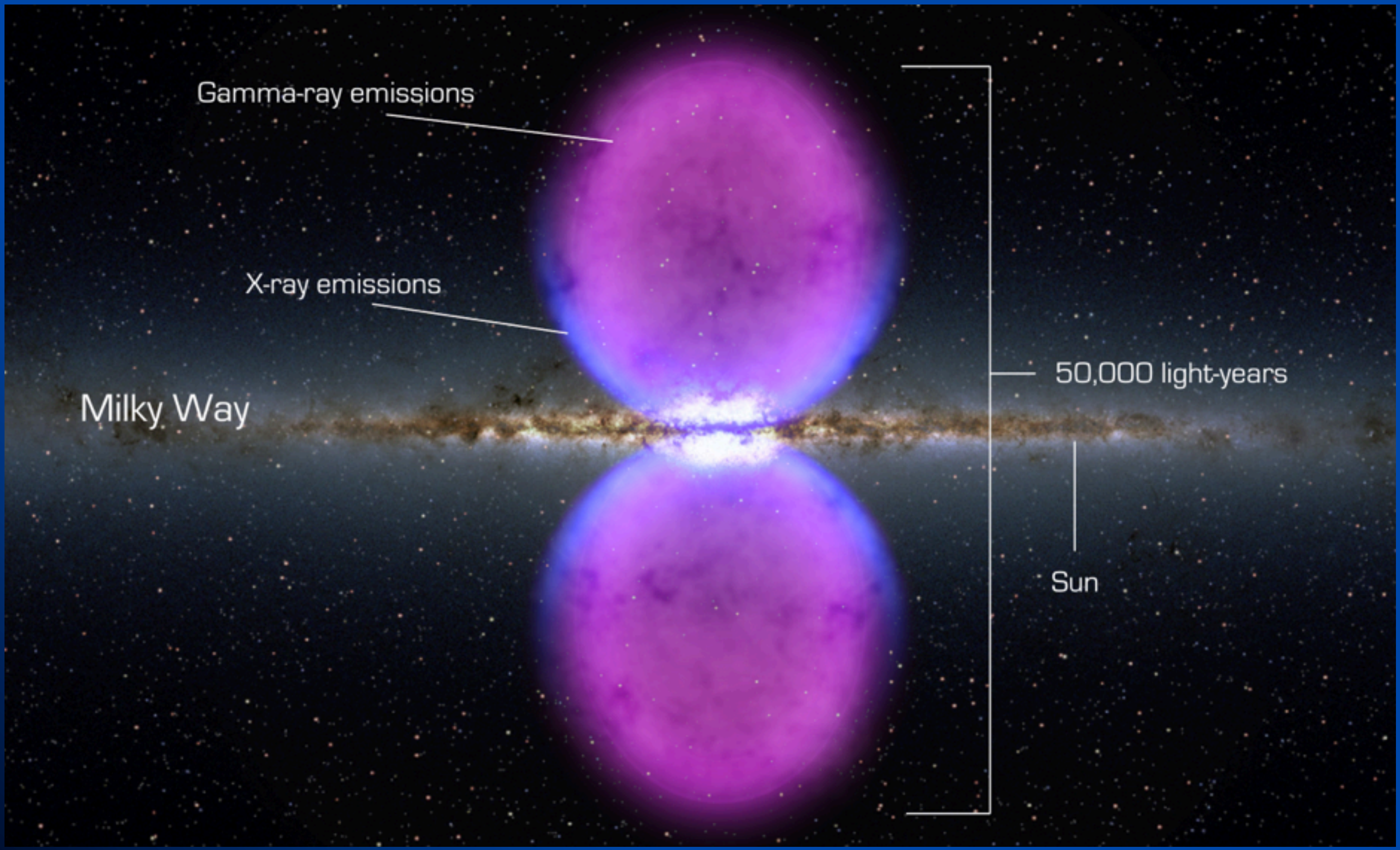


String of phototubes in ice at South Pole

THE FERMI SATELLITE: SEARCHING FOR GAMMA-RAYS, E.G. FROM DM ANNIHILATION


Fermi data reveal giant gamma-ray bubbles
Credit: NASA/DOE/Fermi LAT/D. Finkbeiner e

Fermi Bubble



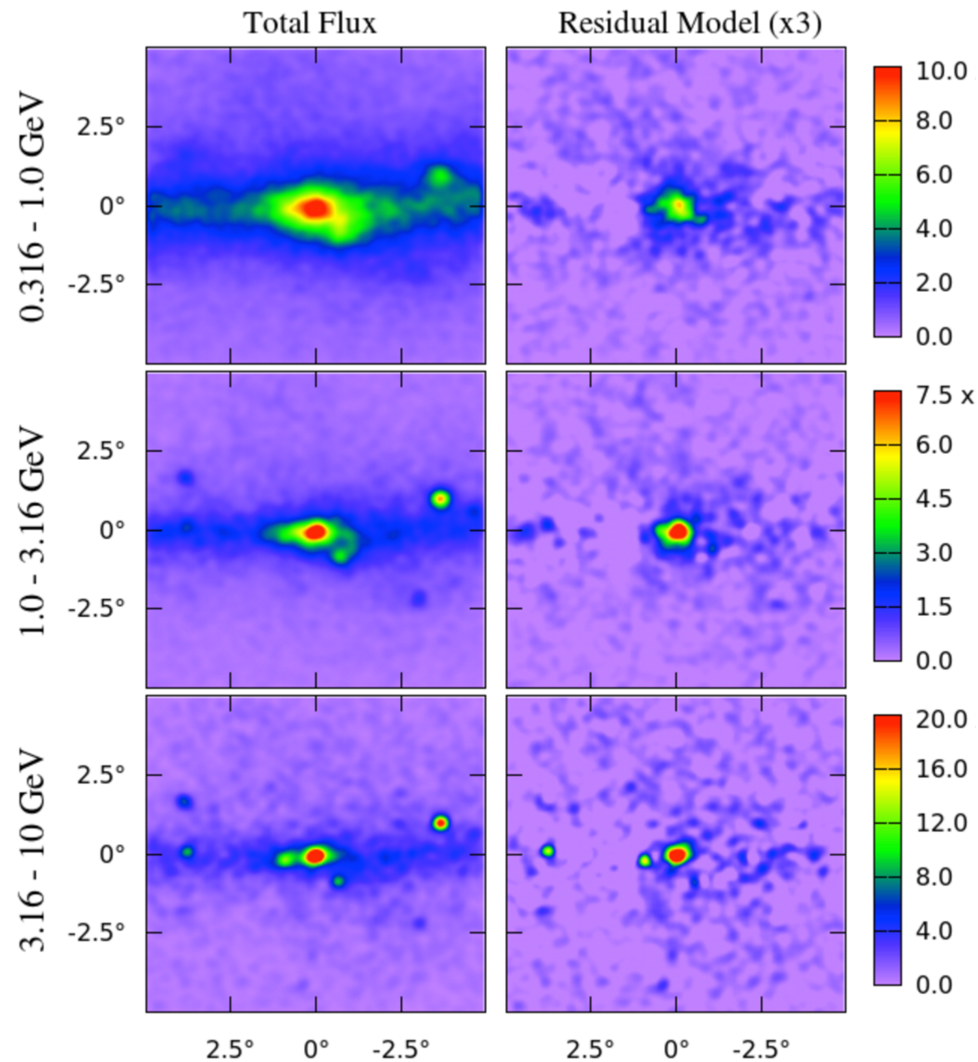
Fermi/LAT gamma-ray excess

Goodenough & Hooper (2009)

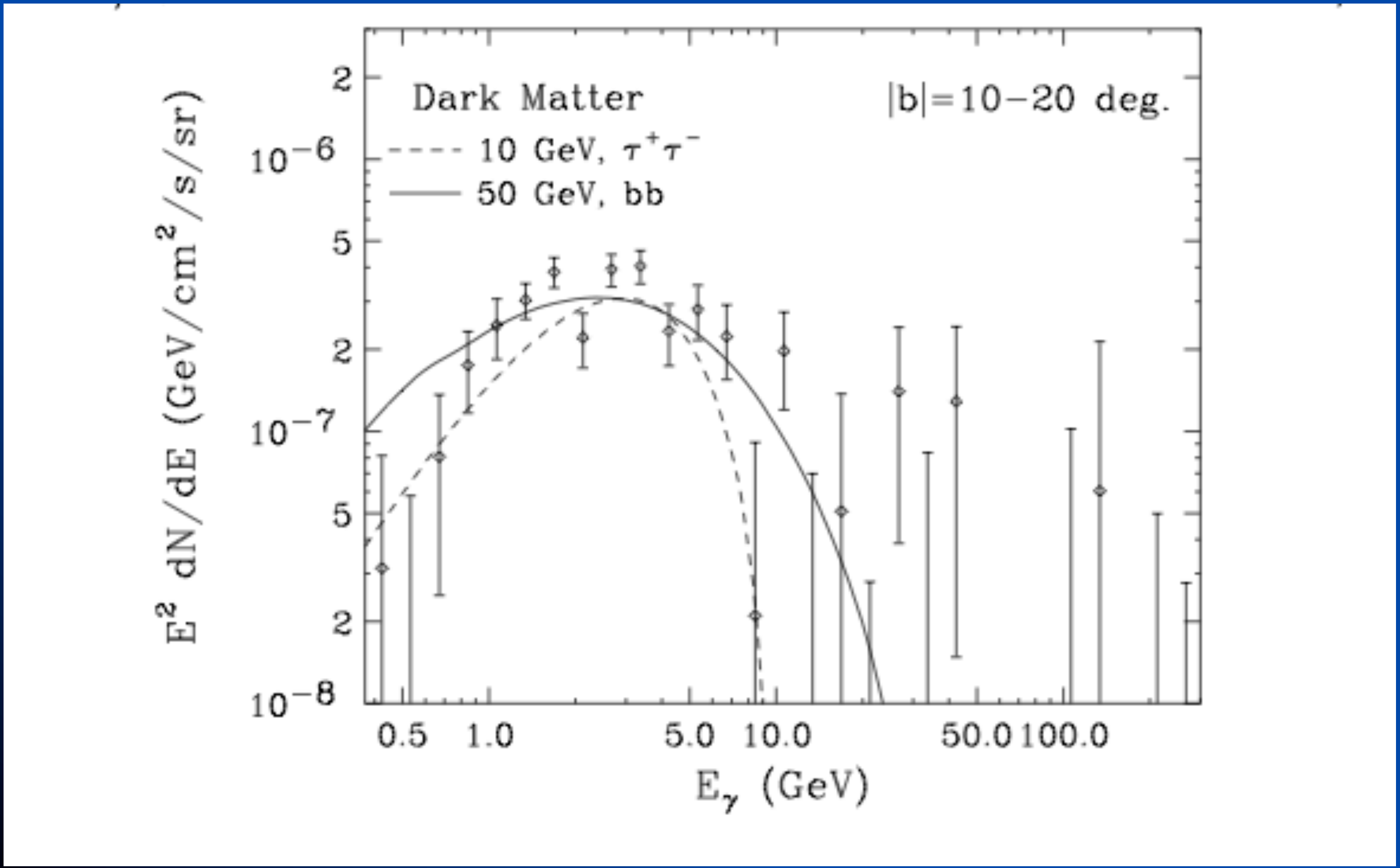
Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd, Slatyer (2014)

Towards galactic center:

- Model and subtract astrophysical sources
- Excess remains
- Spectrum consistent with DM (30 GeV, χχ → b-bbar)

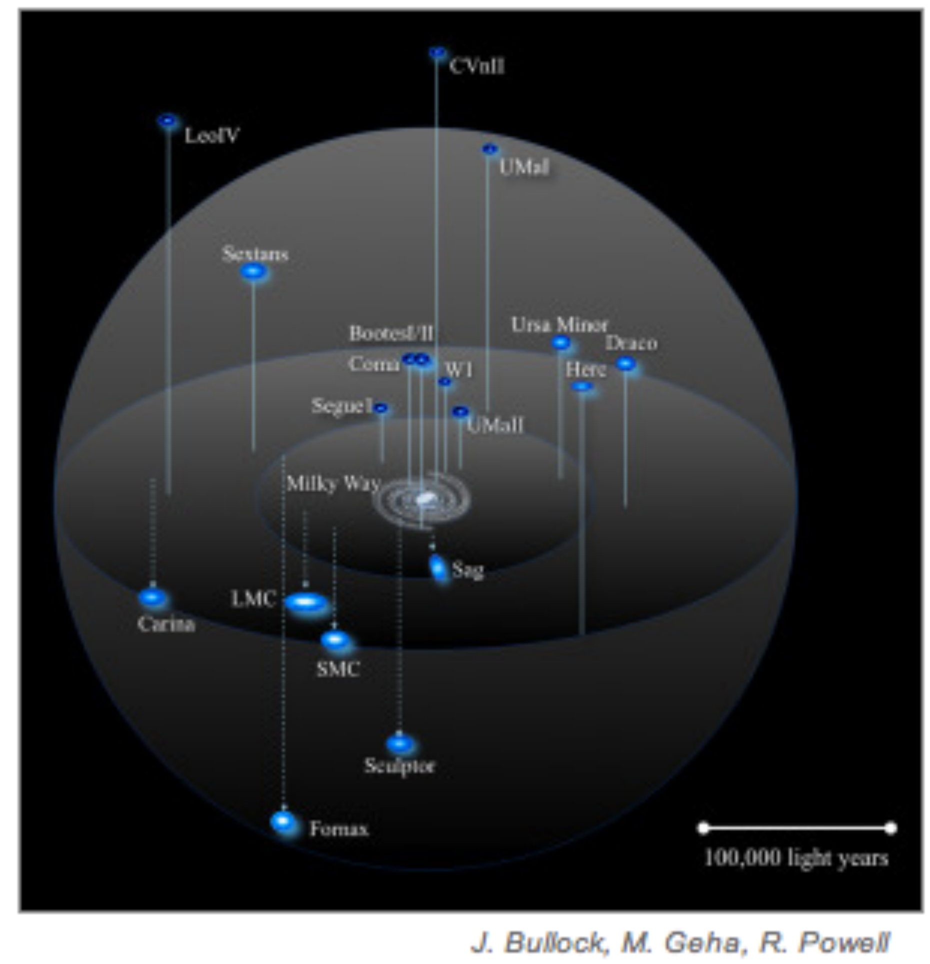


Dark Matter at Galactic Center annihilating to Gamma Rays?



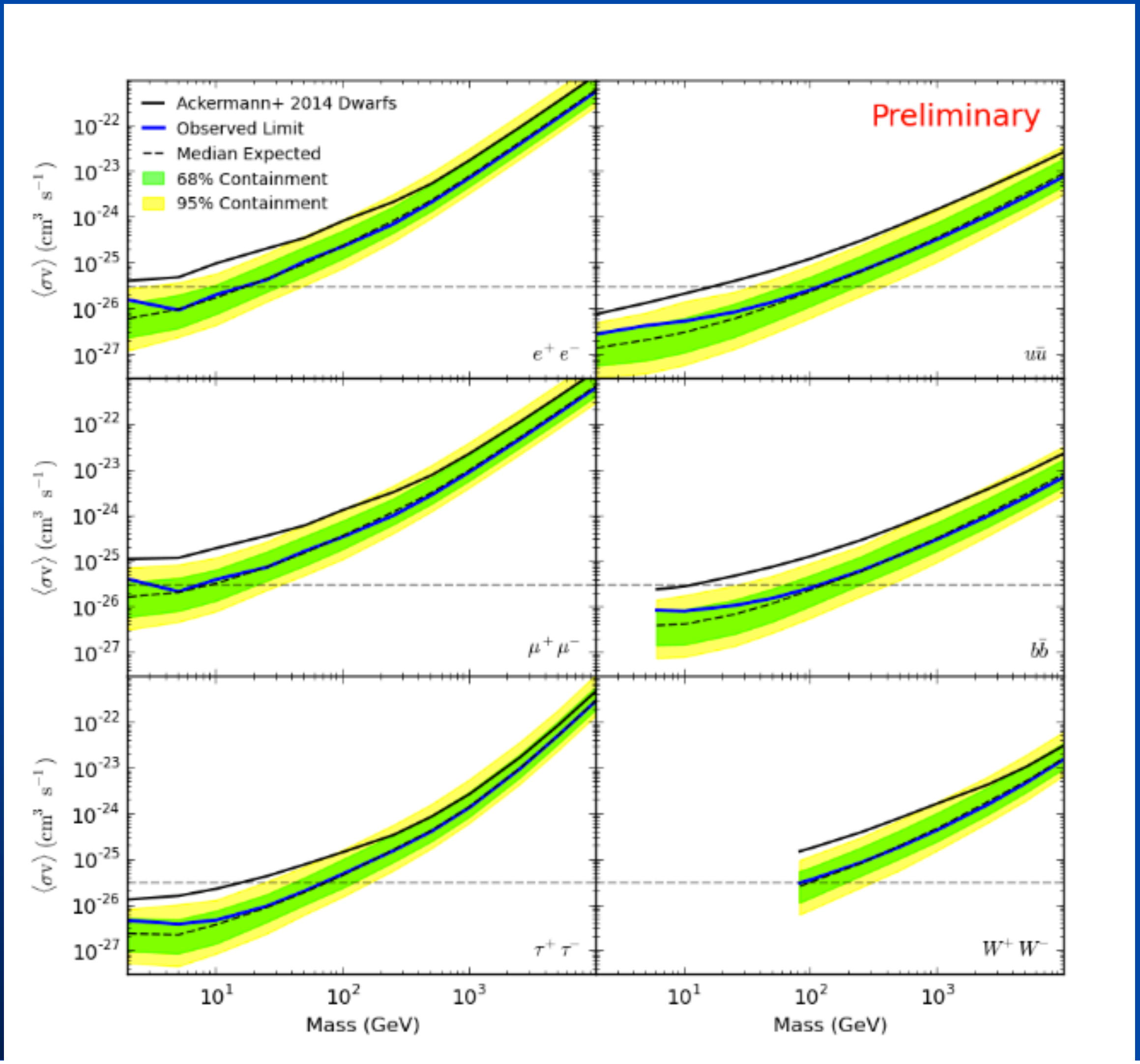
Hooper
Goodenough
Slatyer
Finkbeiner
Daylan etal

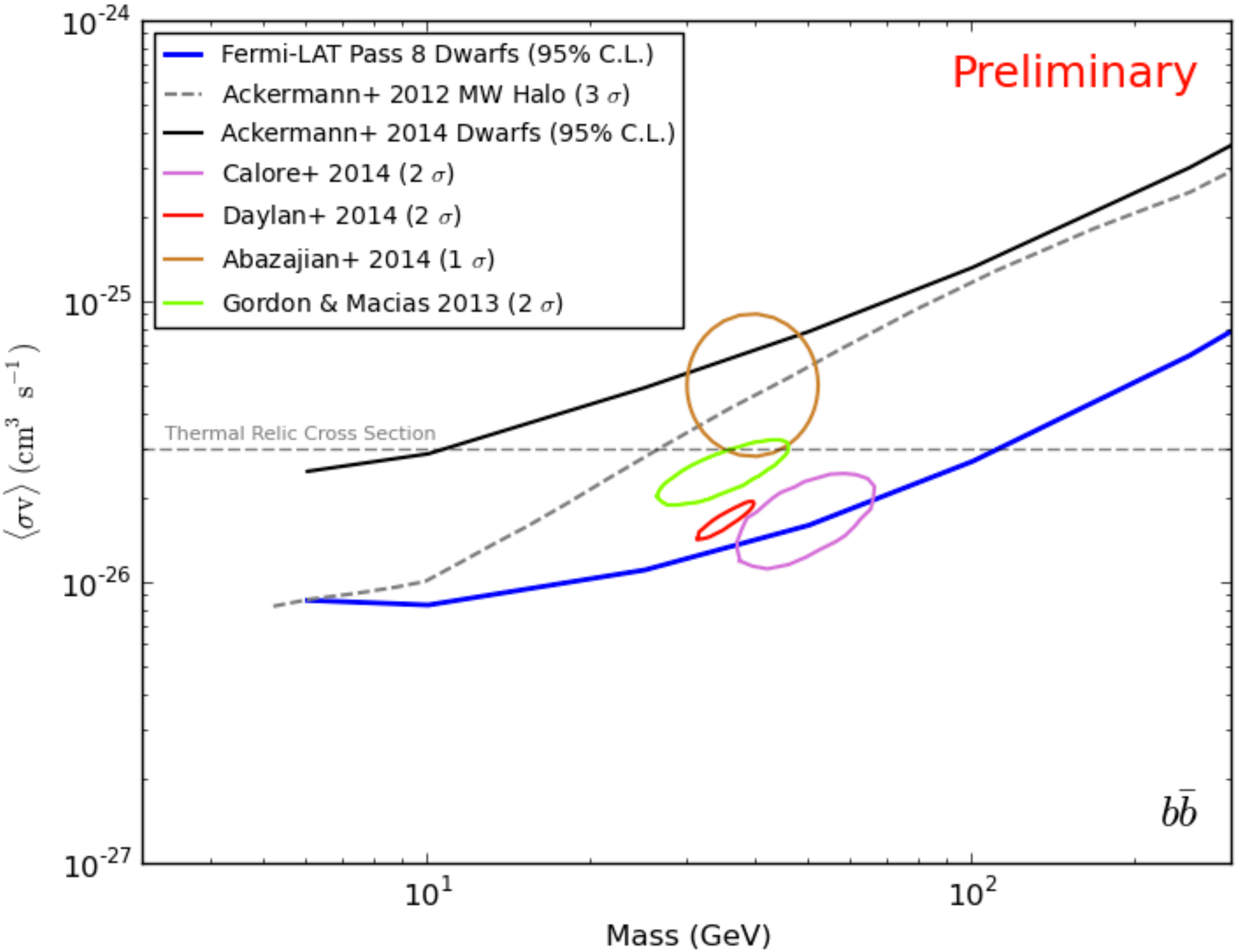
Test this 30 GeV DM model with dwarf galaxies (which are DM rich)



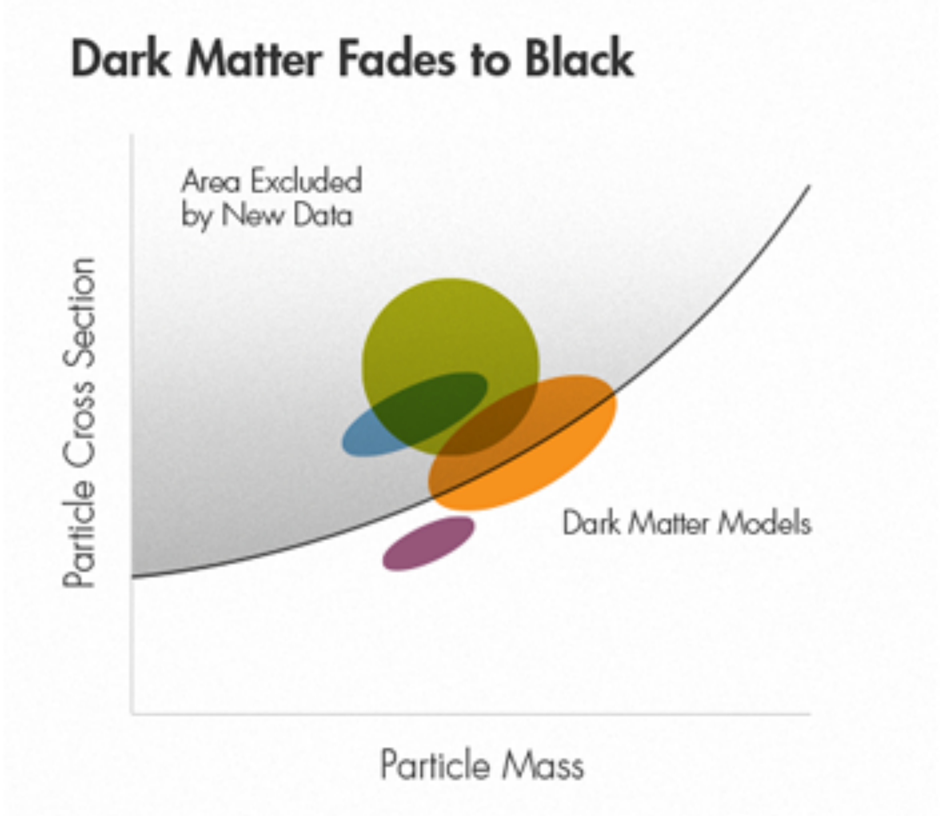
Look for
gamma-rays due to
DM annihilation
from dwarf galaxies
in FERMI data

From FERMI meeting in Japan last week, presented by Brandon Anderson





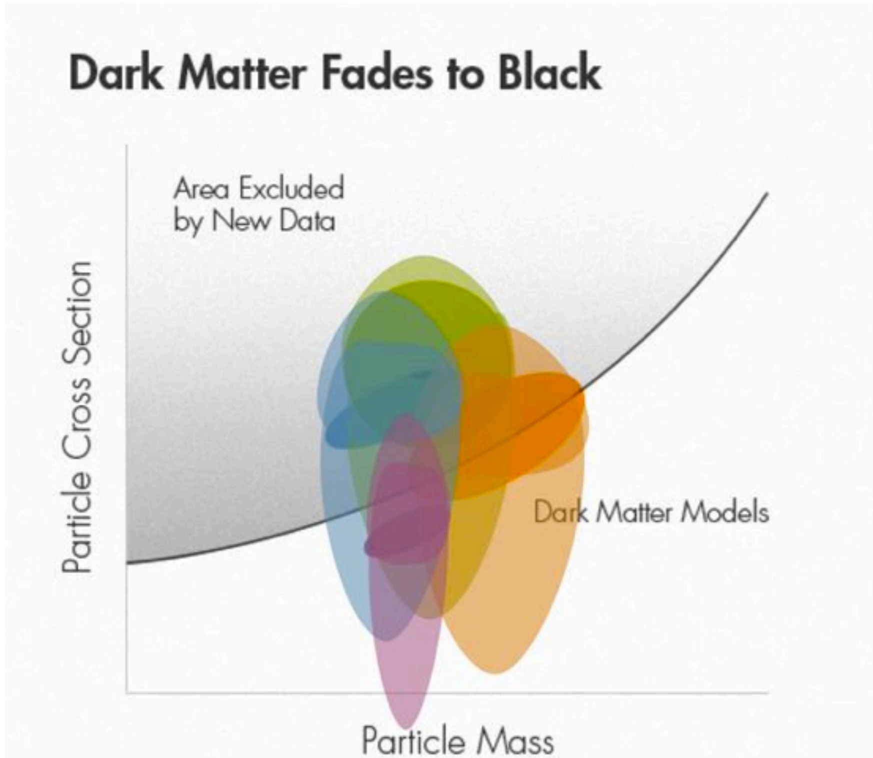
Fermi-LAT Pass 8 Dwarfs (95% C.L.)
Ackermann+ 2012 MW Halo (3 σ)
Ackermann+ 2014 Dwarfs (95% C.L.)
Calore+ 2014 (2 σ)
Daylan+ 2014 (2 σ)
Abazajian+ 2014 (1 σ)
Gordon & Macias 2013 (2 σ)
Preliminary
Thermal Relic Cross Section
$b\bar{b}$
10^{-24}
10^{-25}
10^{-26}
10^{-27}
$\langle \sigma v \rangle$ (cm^3 s^{-1})
10^1
10^2
Mass (GeV)



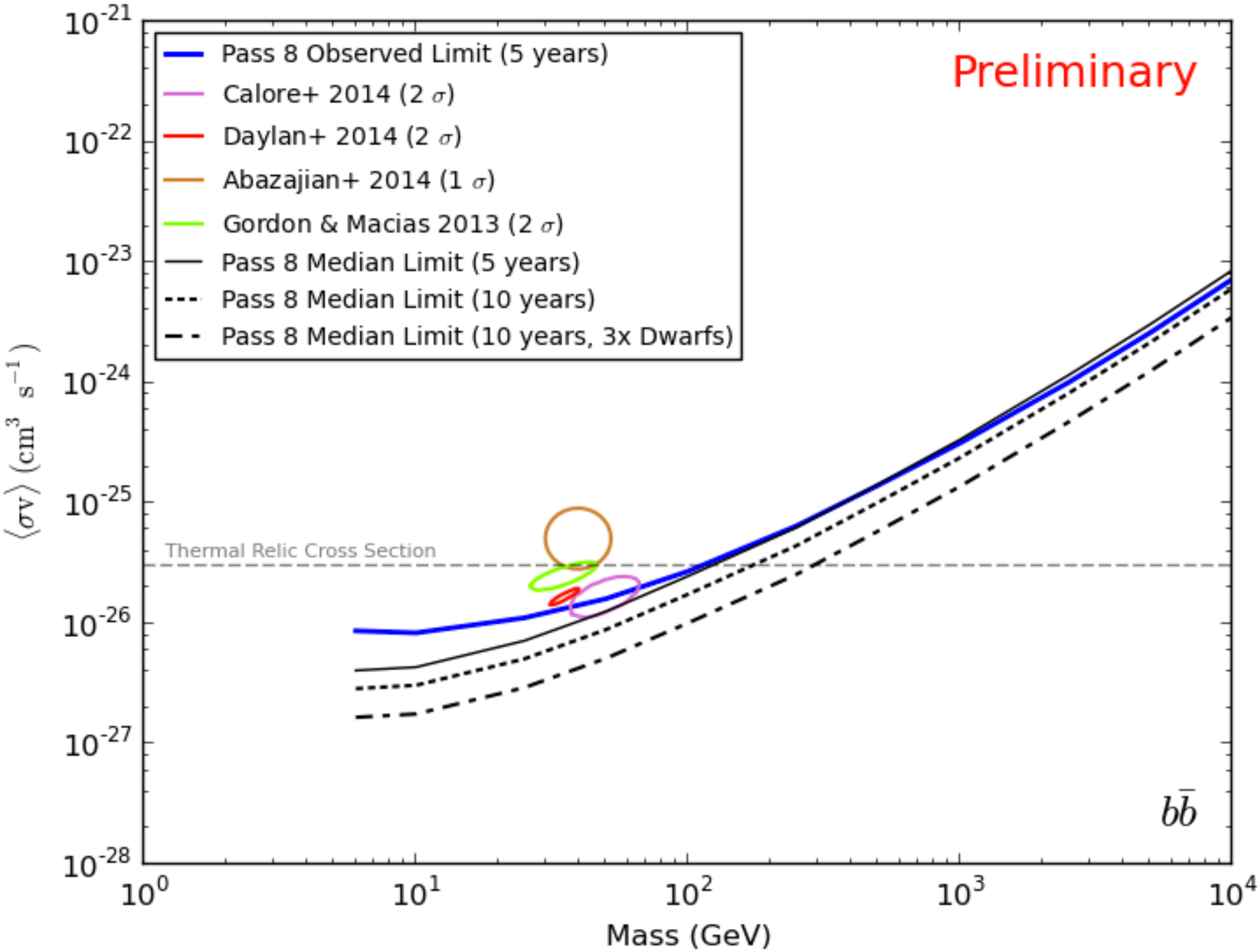
Olena Shmahalo/Quanta Magazine; data courtesy of Matthew Wood

Based on the analysis presented by the Fermi-LAT team, new observations of dwarf galaxies exclude some, but not all, models of dark-matter particles that could be producing a signal coming from the center of the Milky Way. The range of particle properties proposed in a 2014 paper by Dan Hooper and colleagues (purple) is still viable, while a model proposed by Francesca Calore et al. (orange), which experts consider the most comprehensive, predicts a range of properties that is cut exactly in half.

figure for the article to reflect the approx. halo density uncert to 2σ



From Quanta Magazine (Simons Foundation)
Right: corrected by Kev Abazajian



Pass 8 Observed Limit (5 years)
Calore+ 2014 (2 σ)
Daylan+ 2014 (2 σ)
Abazajian+ 2014 (1 σ)
Gordon & Macias 2013 (2 σ)
Pass 8 Median Limit (5 years)
Pass 8 Median Limit (10 years)
Pass 8 Median Limit (10 years, 3x Dwarfs)
Preliminary
Thermal Relic Cross Section
$b\bar{b}$
$\langle\sigma v\rangle$ (cm^3 s^{-1})
Mass (GeV)

Possible evidence for WIMP detection already now:

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

(iv) 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

Doug Spolyar

Paolo Gondolo

Pearl Sandick

Tanja Rindler-Daller

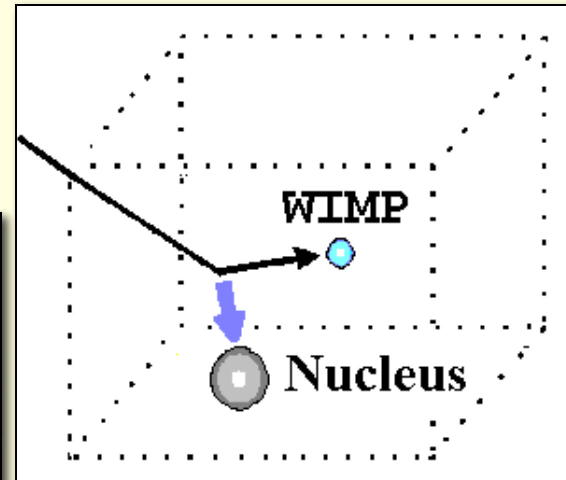
Peter Bodenheimer

Dark Stars

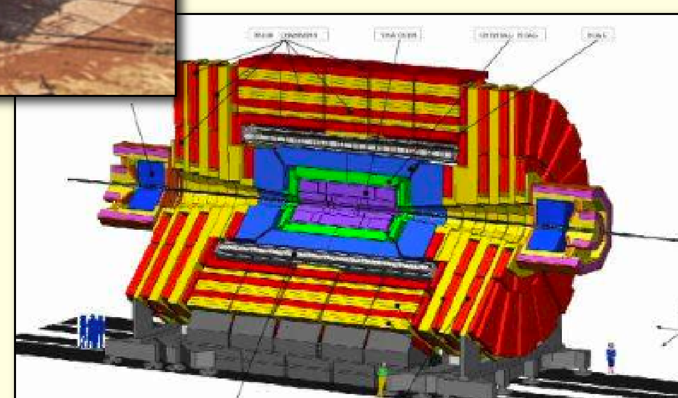
The first stars to form in the history of the universe may be powered by Dark Matter annihilation rather than by Fusion (even though the dark matter constitutes less than 0.1% of the mass of the star).

- This new phase of stellar evolution may last millions to billions of years
- Dark Stars can grow to be very large: thousands to millions of solar masses. Supermassive DS are very bright (millions to hundred billion solar luminosities) and can be seen in JWST or even HST
- 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?

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 $\sin^2 2\theta = (2 - 20) \times 10^{-11}$

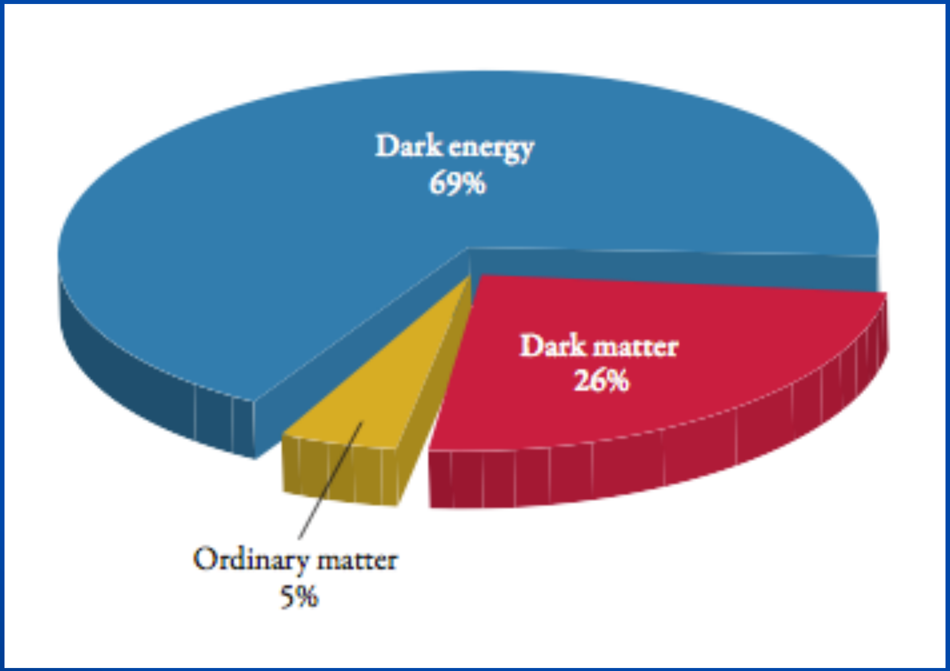
E. Bulbul, M. Markevitch, A. Foster, R. Smith, M. Lowenstein, S. Randall
"*Detection of an unidentified emission line in the stacked X-ray spectrum of Galaxy Clusters*" arXiv:1402.2301

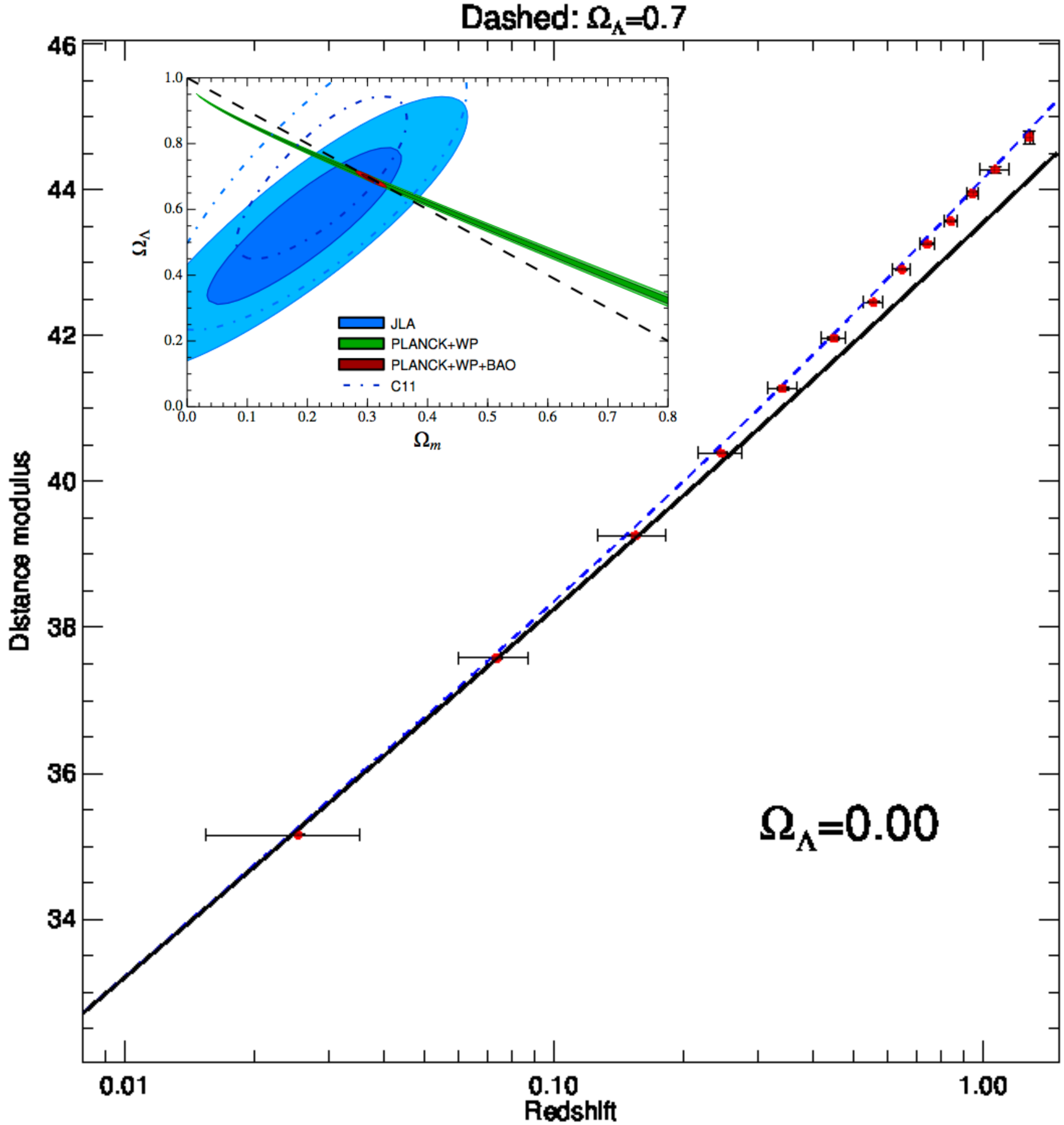
A. Boyarsky, O. Ruchayskiy, D. Iakubovskyi, J. Franse
"An unidentified line in the X-ray spectrum of the Andromeda galaxy and Perseus galaxy cluster" arXiv:1402.4119

7 keV sterile neutrino: theoretically not well motivated

- Singlet under Standard Model
- Right handed neutrino
- Warm DM: this is OK since it might help with core/ cusp problem (if there is one) and missing satellites
- Thanks to x-ray constraints, cannot provide mass for SM neutrinos (Seesaw mechanism doesn't 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

PIE CHART OF THE UNIVERSE

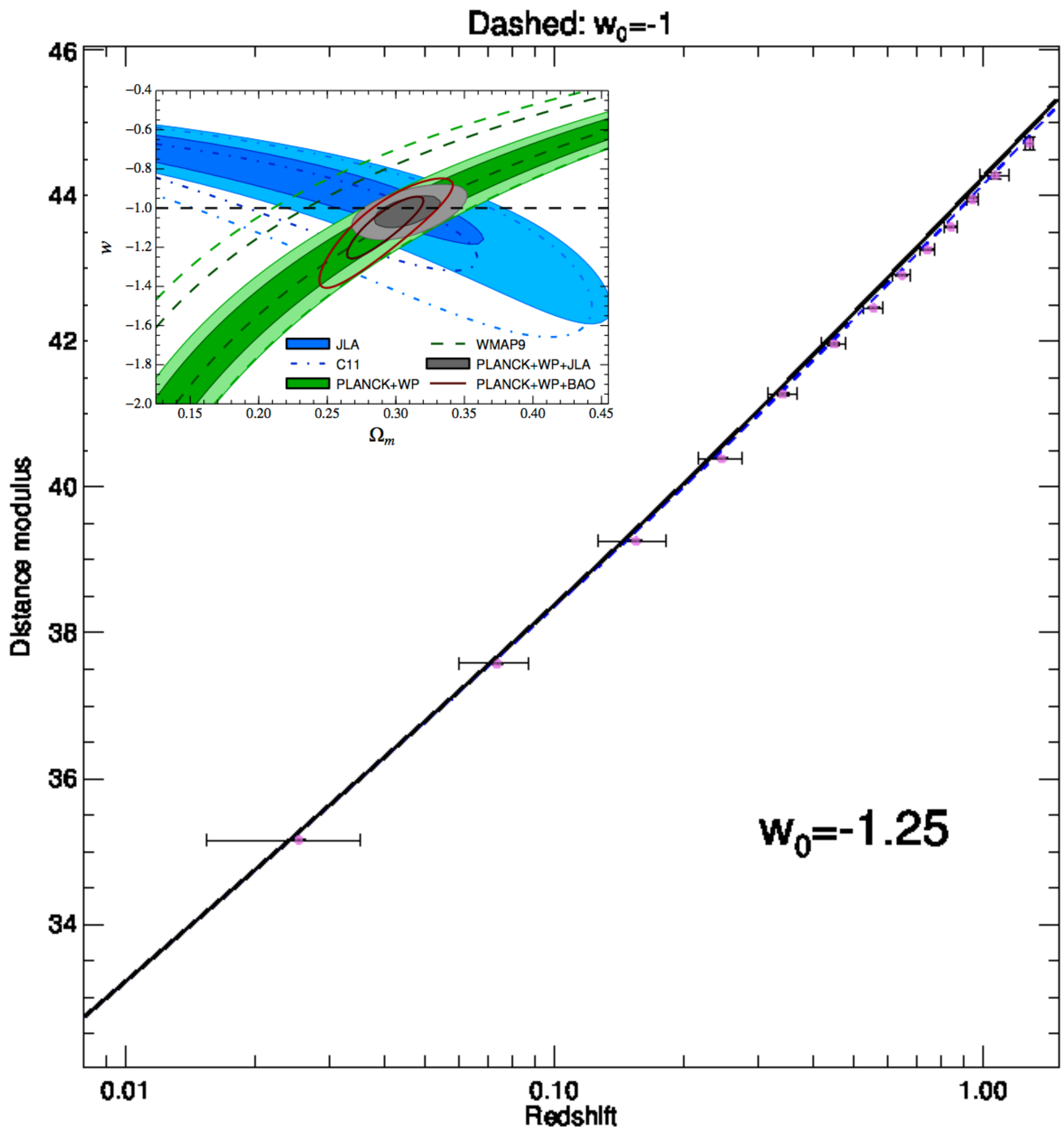




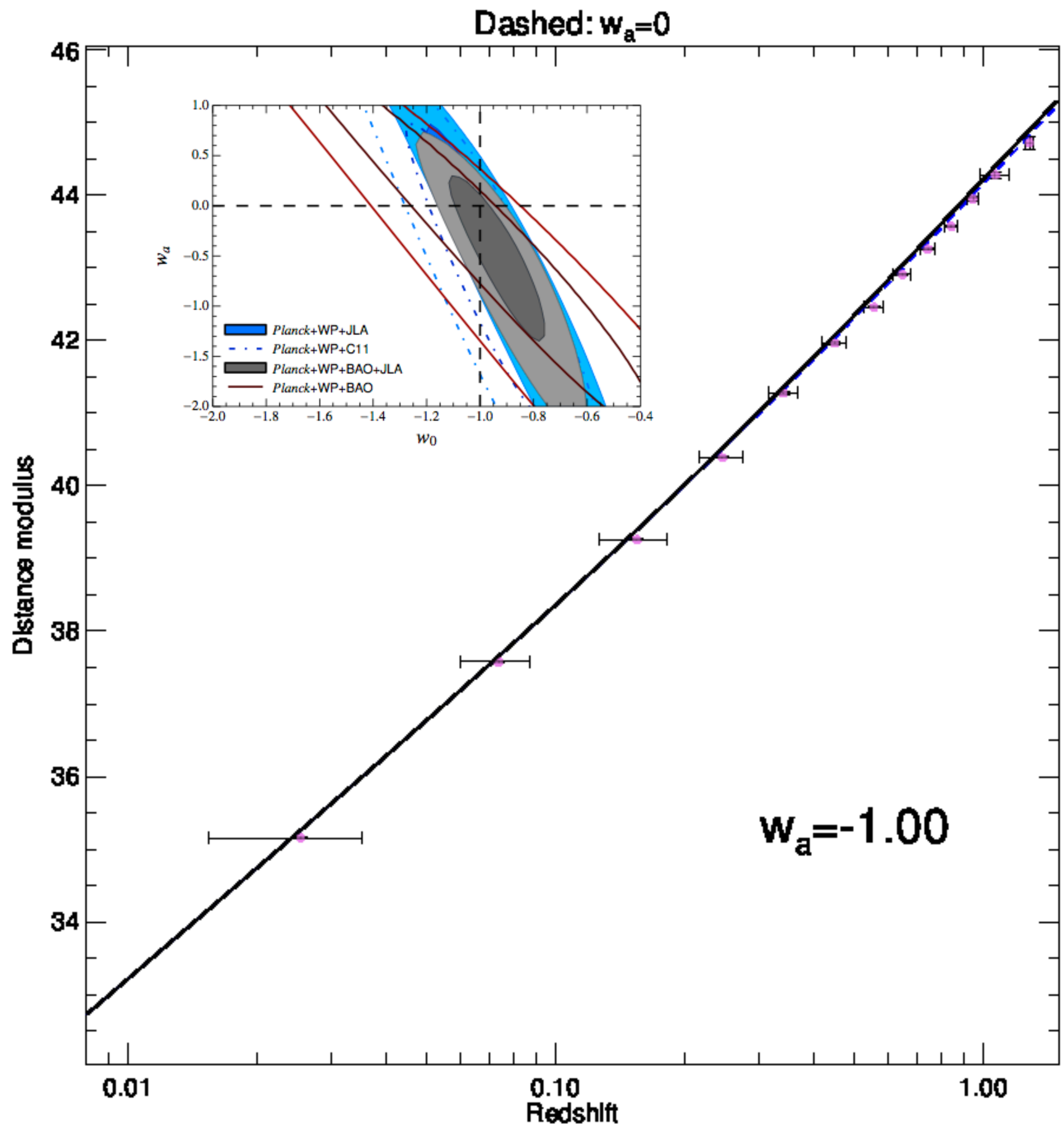
Slides from
Ariel Goobar,
Joint analysis
of SDSS-II and
SNLS supernovae
Arxiv:1401.4064

$$\rho = \rho_0 \left(\frac{a_0}{a} \right)^{3(1+w)} \quad ;$$

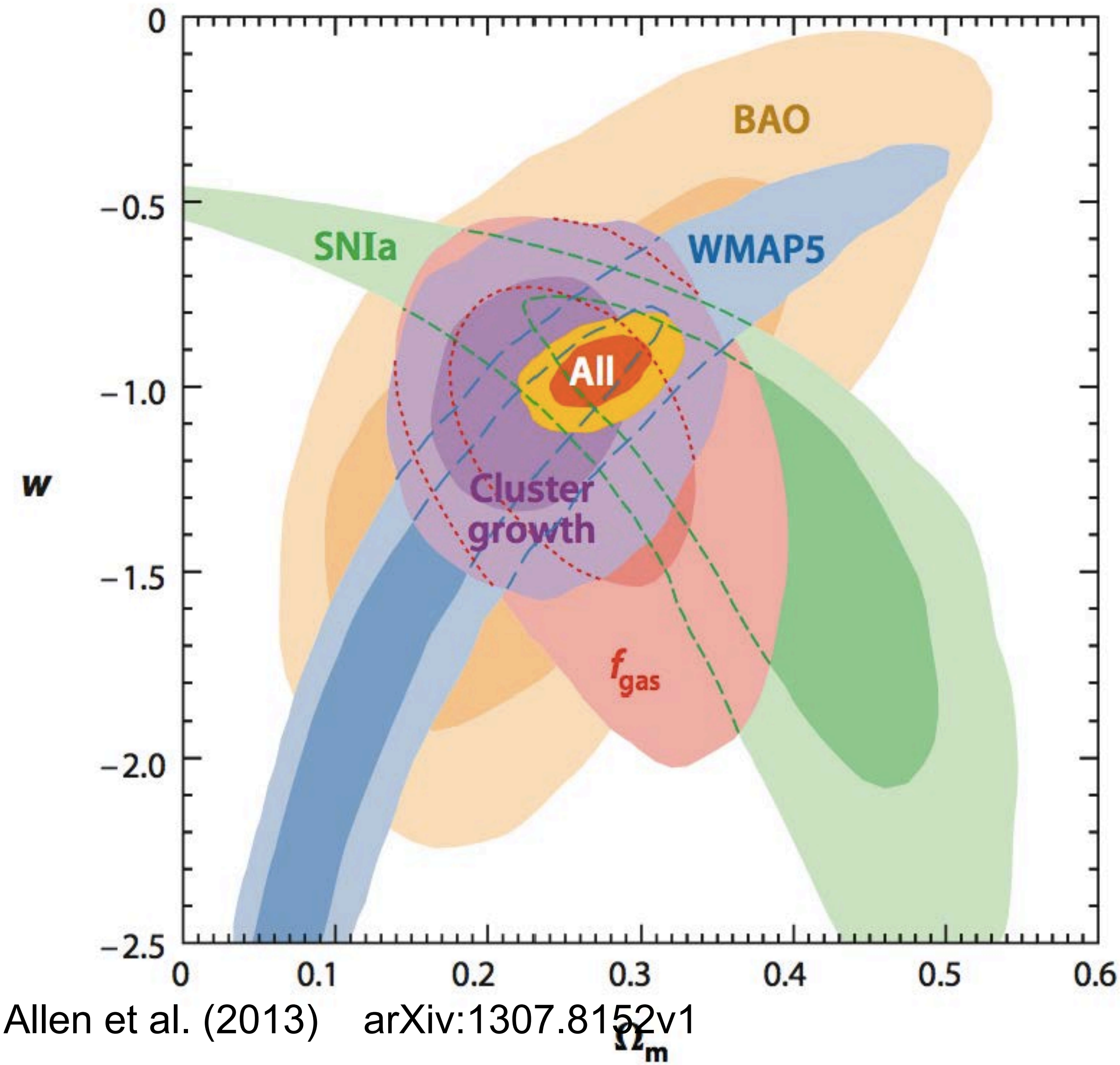
$$\frac{p}{c^2} = w \cdot \rho$$



$$w = w_0 + w_a(1-a)$$



Dashed: w_a=0
Distance modulus
Redshift
w_a=-1.00
Planck+WP+JLA
Planck+WP+C11
Planck+WP+BAO+JLA
Planck+WP+BAO
w_0
w_a



Allen et al. (2013) arXiv:1307.8152v1

Current and Future missions that will teach us about DE

- DES
- PANSTARRS
- RAISIN (use IR Camera on HST)
- JWST
- EUCLID
- LSST
- GMT
- AFTA/WFIRST

Optical Lensing Surveys

- Dark Energy Survey (5000 sq deg., 5 gal/arcmin^2) underway!
- HyperSuprime Camera (1200 sq. deg, 15 gal/arcmin^2) March 2014
- LSST (optical, 15000 sq deg., 20 gal/arcmin^2) 2021
- Euclid (optical, 12000 sq deg., 30 gal/arcmin^2) 2020
- WFIRST/AFTA (IR, 2000 sq deg., 70-250 gal/arcmin^2) 2023?

Theory of Dark Energy: Mystery

- Vacuum Energy
  - Cosmological Constant
  - Time Changing vacuum energy
    - E.g. quintessence with rolling scalar field
    - But, coincidence problem
- Modified Gravity, i.e. changes to Einstein's equations
  - Cardassian 2002
  - DGP 2002
  - f(R)
  - Disformal

SEE TALK OF SCOTT DODELSON

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!”

What is new in testing Inflation?

- Cosmological Puzzles unresolved by standard Hot Big Bang:
- 1) Large-scale ‘smoothness’ -- homogeneity and isotropy
- 2) flatness and oldness
- 3) GUT magnetic monopoles
- The idea of inflation was proposed to resolve these puzzles
- BONUS: causal generation of density fluctuations required for galaxy formation
- WHAT IS HOT NOW: Gravitational waves

Predictions of Inflation: Density Perturbations

- Power Spectrum $P_k = |\delta_k|^2 \sim k^n$

- During inflation, *H* and dϕ/d*t* vary slowly

$$\frac{\delta\rho}{\rho}\text{(when entering horizon)} = \frac{H^2}{\dot{\phi}}\text{(exiting horizon during inflation)}$$

  ~ same on all scales

- Predicts *n* ~ 1: CORRECT
- Precise predictions of *n* in different models leads to test of models. It's found that n<1 and the exact number is important.

Gravity Waves:

$$P_T^{1/2} = \frac{H}{2\pi}.$$

Perturbations

Field perturbations:

$$\phi = \phi_0 + \delta\phi$$

Metric perturbations:

$$g_{\mu\nu} = g_{\mu\nu}^{(0)} + \delta g_{\mu\nu}$$

Modes: scalar ~~vector~~ tensor

none in inflation
(no rotational velocity fields)

Status of Inflation in Light of Data

- I. The predictions of inflation are right:

  (i) the universe is flat with a critical density $\Omega = 1$

  (ii) superhorizon fluctuations

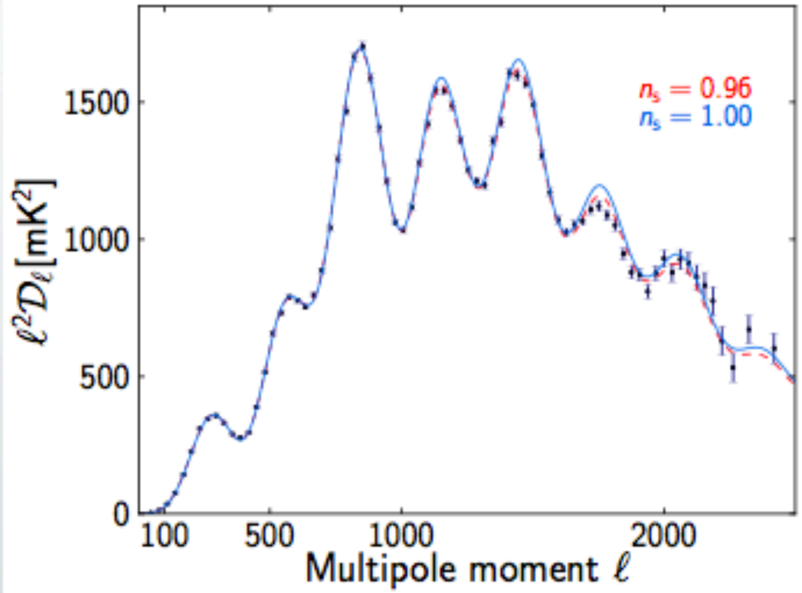
  (iii) density perturbation spectrum nearly scale invariant

  (iv) Single rolling field models vindicated: Gaussian perturbations, not much running of spectral index

- II. Data differentiate between models
- -- each model makes specific predictions for density perturbations and gravitational waves
- -- WMAP and Planck rule out many models

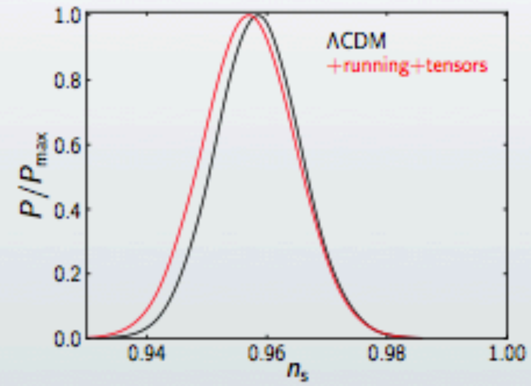
  -- **Natural Inflation** (shift symmetries) is best fit to data

Extensions to ΛCDM model
Early-Universe physics: ns, dn_s/dk and r



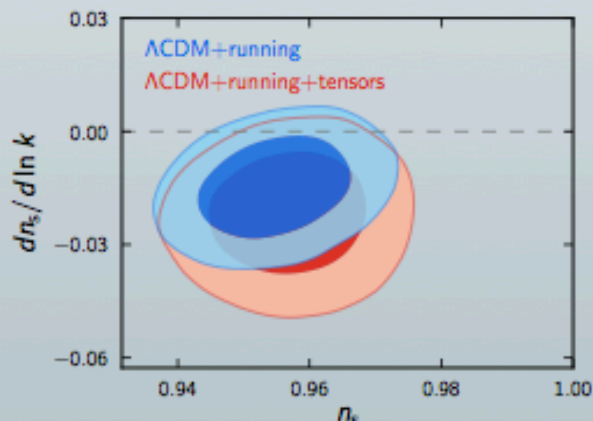
6σ departure from scale invariance

$$n_s = 0.9603 \pm 0.0073$$



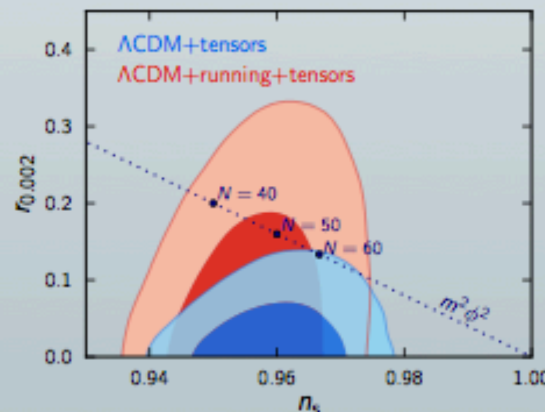
l<50

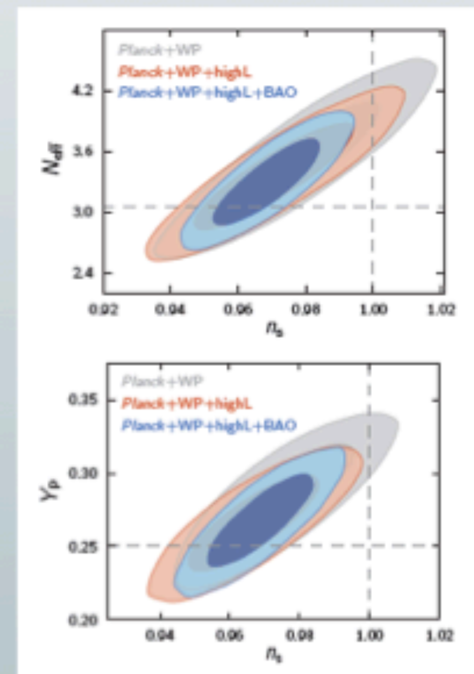
$$dn_s / d\ln k = -0.0134 \pm 0.0090$$



$$r < 0.11 \qquad V_*$$

$$V = (1.94 \times 10^{16}\,GeV)^4 (r_{0.02}/0.12)$$





3σ

Slide from Graca Rocha

Planck ruled out most inflation models! Thousands of models died.

- Prior to Planck, all models but the simplest ones with a single rolling scalar field predicted nonGaussianities.
- Any detection of nonGaussianity would have thrown out all single field models
- Planck found no evidence of nonGaussianity

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

- “With these results, the paradigm of standard single-field nflation has survived its most stringent tests to date”

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.

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

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

Four parameters from inflationary perturbations:

I. Scalar perturbations:

amplitude $(\delta\rho/\rho)|_s$ spectral index n_s

II. Tensor (gravitational wave) modes:

amplitude $(\delta\rho/\rho)|_T$ spectral index n_T

Expressed as $r \equiv \frac{P_T^{1/2}}{P_S^{1/2}}$

Inflationary consistency condition: $r = -8n_T$

Plot in r-n plane (two parameters)

Inflation after Planck (Planck paper XXII)

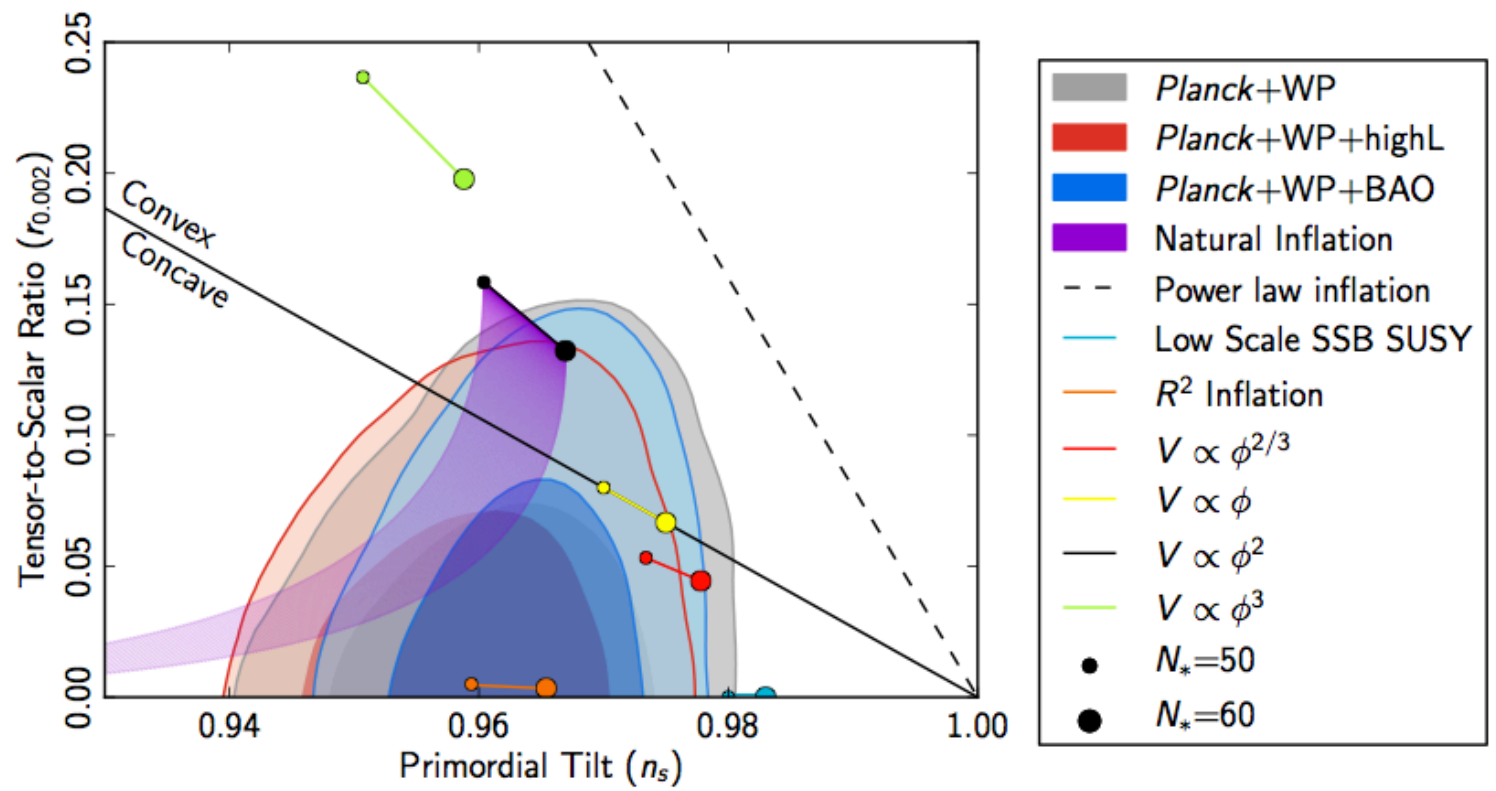


Fig. 1. Marginalized joint 68% and 95% CL regions for n_s and $r_{0.002}$ from *Planck* in combination with other data sets compared to the theoretical predictions of selected inflationary models.

Purple swath is natural inflation model of Freese, Frieman, and Olinto 1990

Natural Inflation: Shift Symmetries

- Shift symmetries protect flatness of inflaton potential

  $\Phi \rightarrow \Phi + \text{constant}$ (inflaton is Goldstone boson – an "axion")
- Additional explicit breaking allows field to roll.
- This mechanism, known as natural inflation, was first proposed in

Freese, Frieman, and Olinto 1990;
Adams, Bond, Freese, Frieman and Olinto 1993

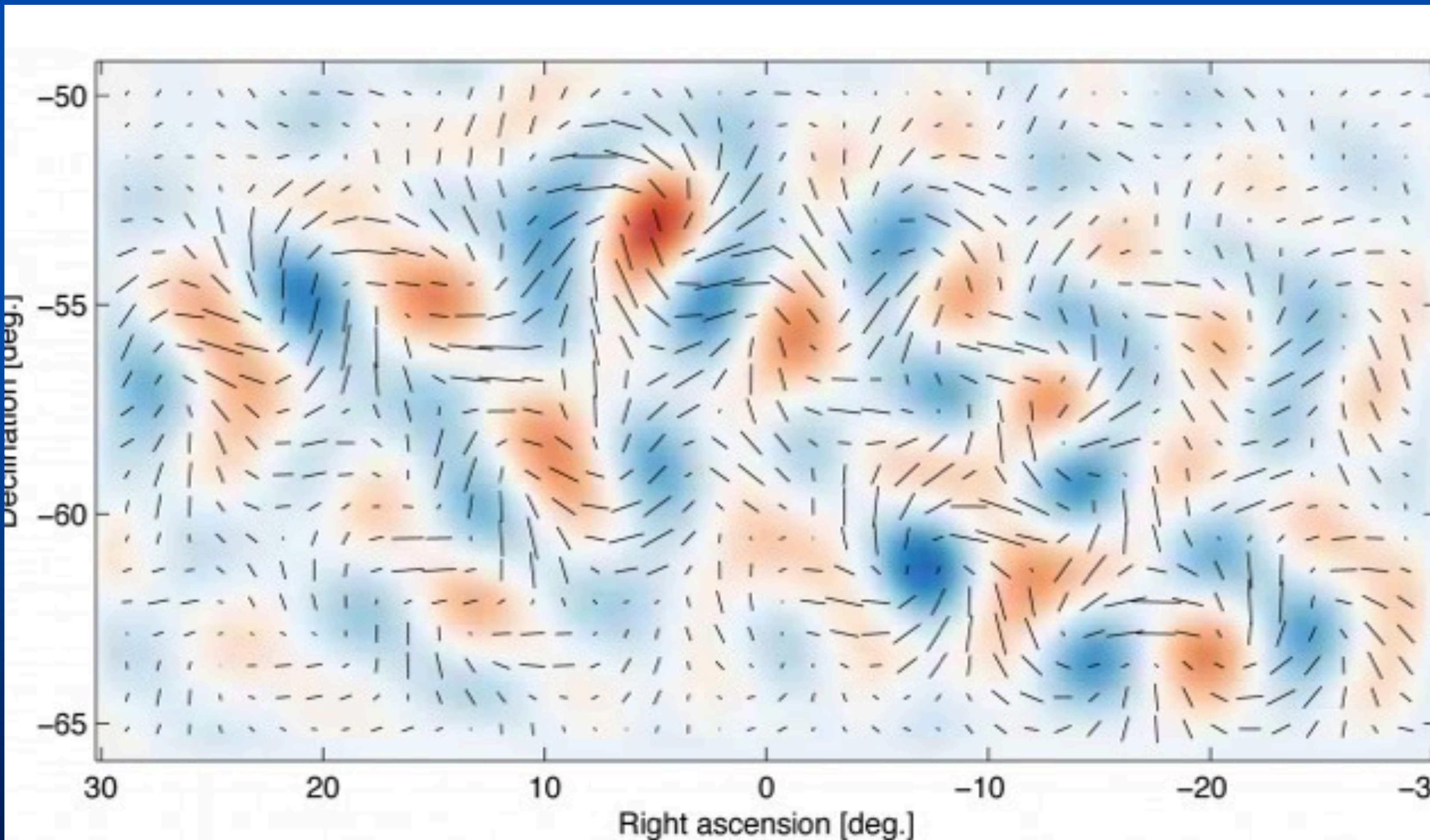
Recent Excitement: Claimed Detection of Gravity Waves from Inflation

See talk of Chao-Lin Kuo

BICEP2 at the South Pole

BICEP2 at the South Pole.

Polarization in BICEP2



BICEP2 revealed a faint but distinctive twist in the polarization pattern of the CMB. Here the lines represent polarization; the red and blue shading show the degree of the clockwise and counter-clockwise twist.

Right away, experimental tension between BICEP2 + Planck. Here, with running of ns

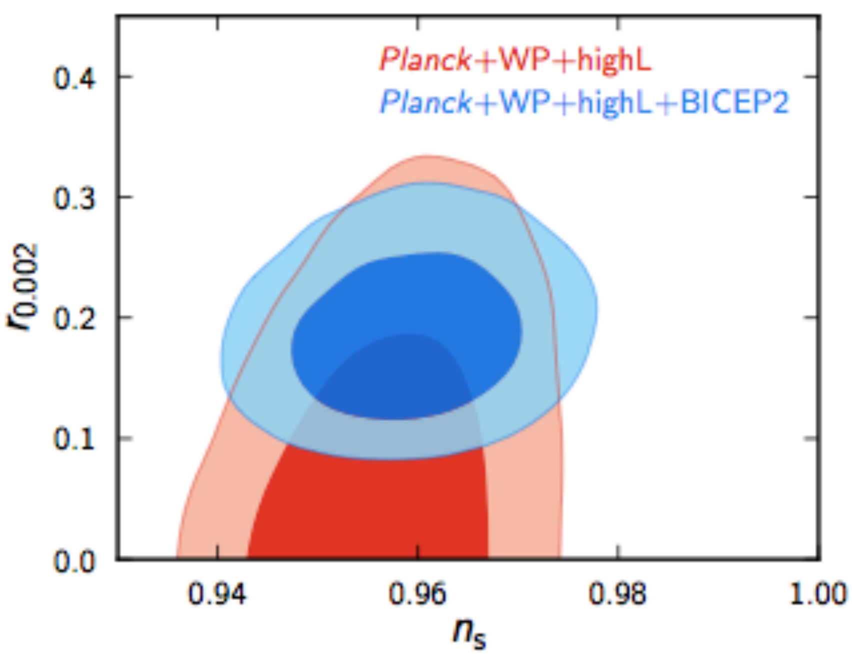


FIG. 13.— Indirect constraints on r from CMB temperature spectrum measurements relax in the context of various model extensions. Shown here is one example, following Planck Collaboration XVI (2013) Figure 23, where tensors and running of the scalar spectral index are added to the base ΛCDM model. The contours show the resulting 68% and 95% confidence regions for r and the scalar spectral index n_s when also allowing running. The red contours are for the "Planck+WP+highL" data combination, which for this model extension gives a 95% bound $r < 0.26$ (Planck Collaboration XVI 2013). The blue contours add the BICEP2 constraint on r shown in the center panel of Figure 10. See the text for further details.

PLANCK without BICEP2:

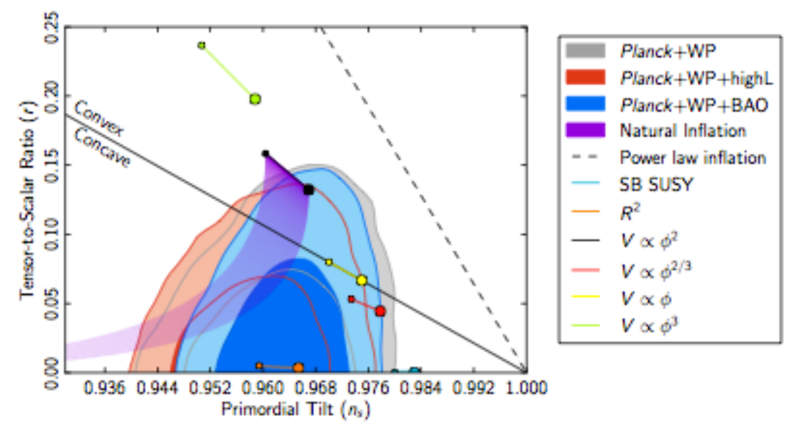
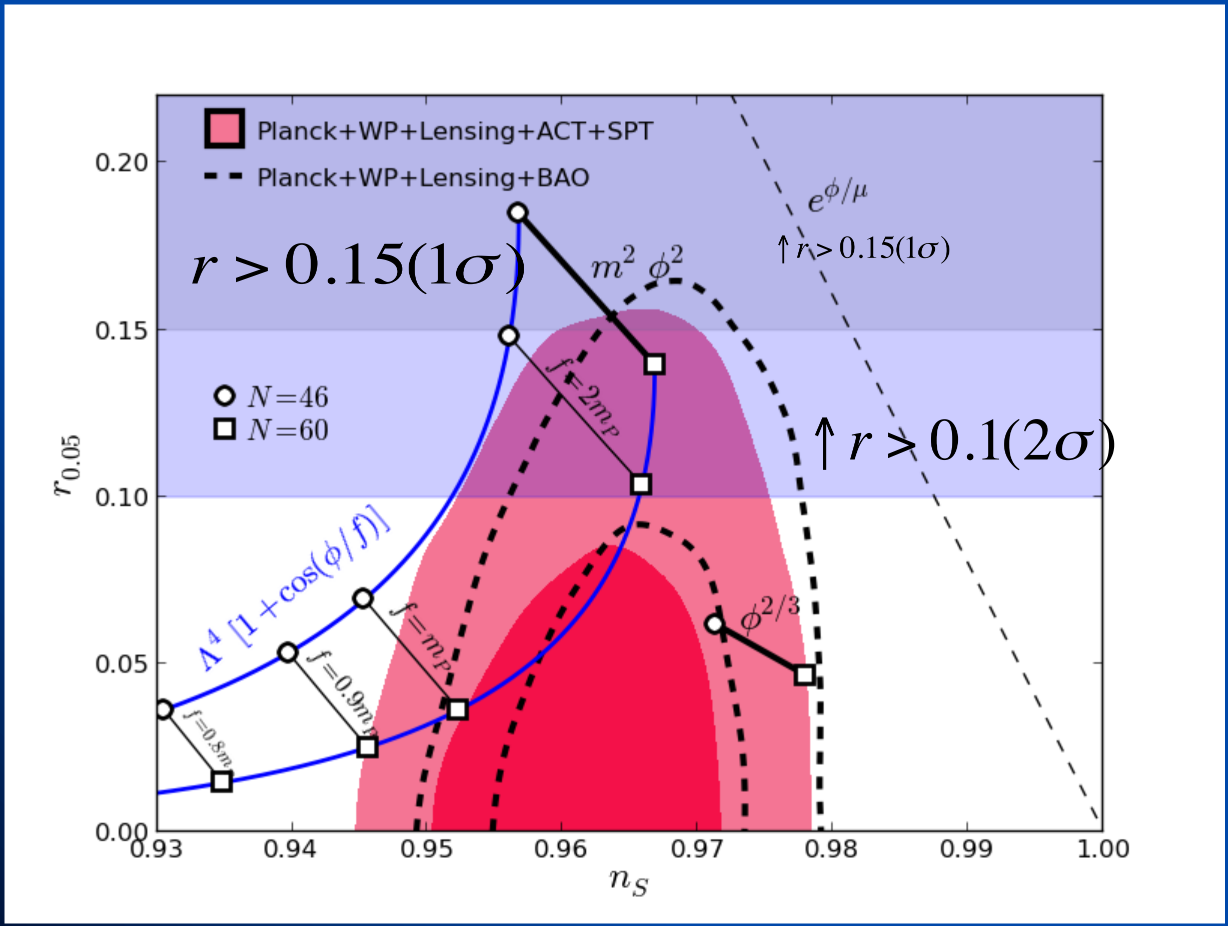


Fig. 26. Marginalized 68 % and 95 % confidence levels for n_s and r from Planck+WP and BAO data, compared to the theoretical predictions of selected inflationary models.

Cosine Natural Inflation after BICPE2: good fit for f>mpl

Freese and Kinney 2014



V=m^2 phi^2 is limiting case of cosine for large f

Axion monodromy with linear or phi^2/3 potentials are in tension with BICEP2 at sigma

Blue regions indicate BICEP2 data: r>0.15 (1 sigma) and r>0.1 (2 sigma)

Models that survive after Planck and BICEP2 data (if primordial GW):

- Of the thousands of models existing in 2013, most have been ruled out. Simple remaining potentials:

- 1) $m^2\phi^2$ Yet the flatness of the potential remains unexplained (unless motivated by shift symmetry)

- 2) Shift symmetries (natural inflation) are a winning mechanism for generating a flat inflationary potential

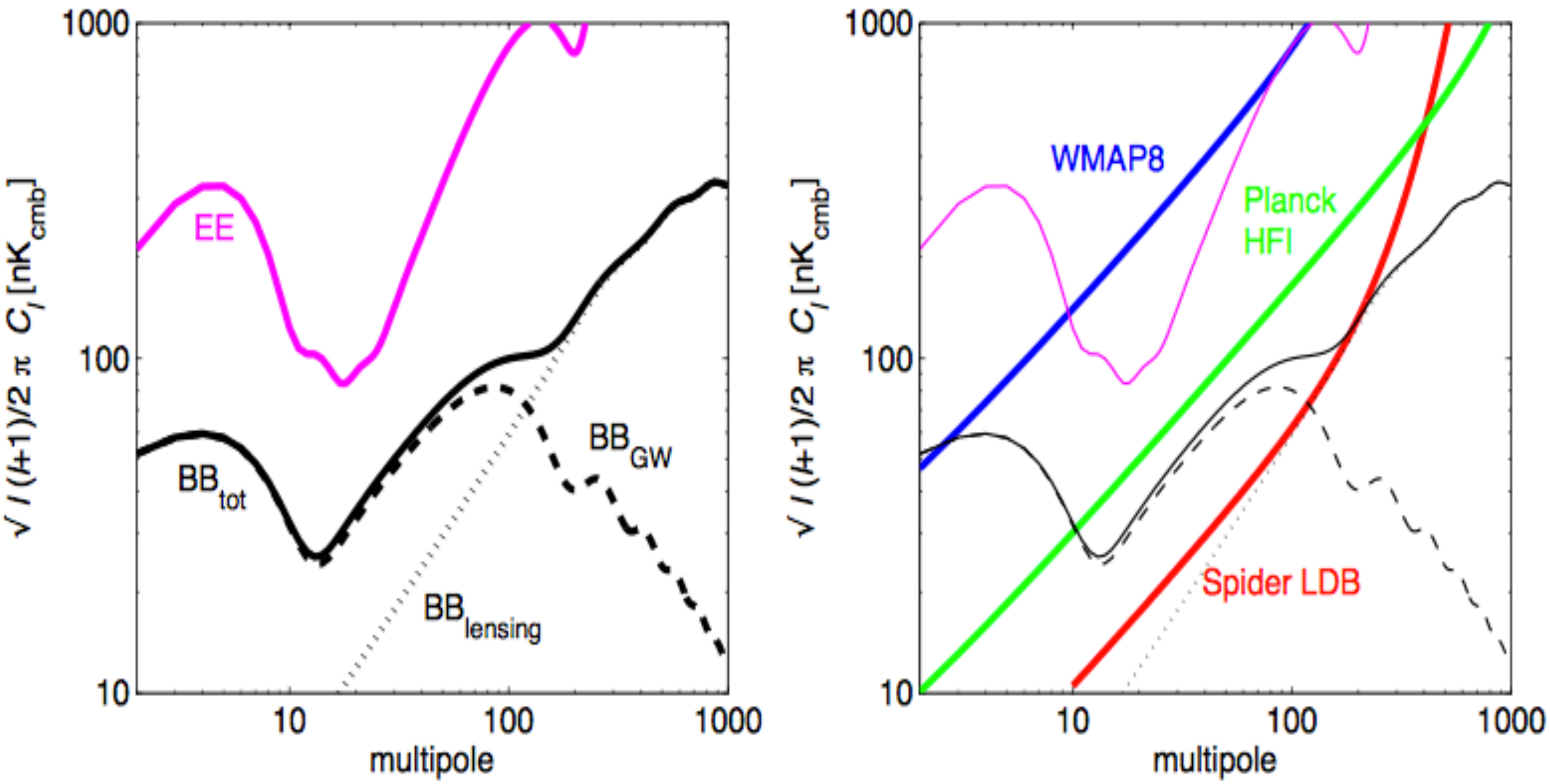
  Original model had cosine-shaped potential

  Today many variants exist

3) Higgs-type potentials at high scale

But Planck shows that all of BICEP2 data can be explained by dust! Back to the drawing board. Very disappointing.

What's next for inflation? Polarization: SPIDER (summer 2015 at South Pole), ACT, SPT



Particle Astrophysics and Cosmology

- Intriguing hints of discovery
- Inflation: Gravity waves?
- What are the missing pieces? Dark matter and dark energy
- DM annihilation in GC to gamma-rays seen in FERMI?
- DM annihilation to positrons seen in AMS?
- Sterile neutrinos seen in x-rays?