DARK MATTER IN THE UNIVERSE
and the ssDNA Tracker

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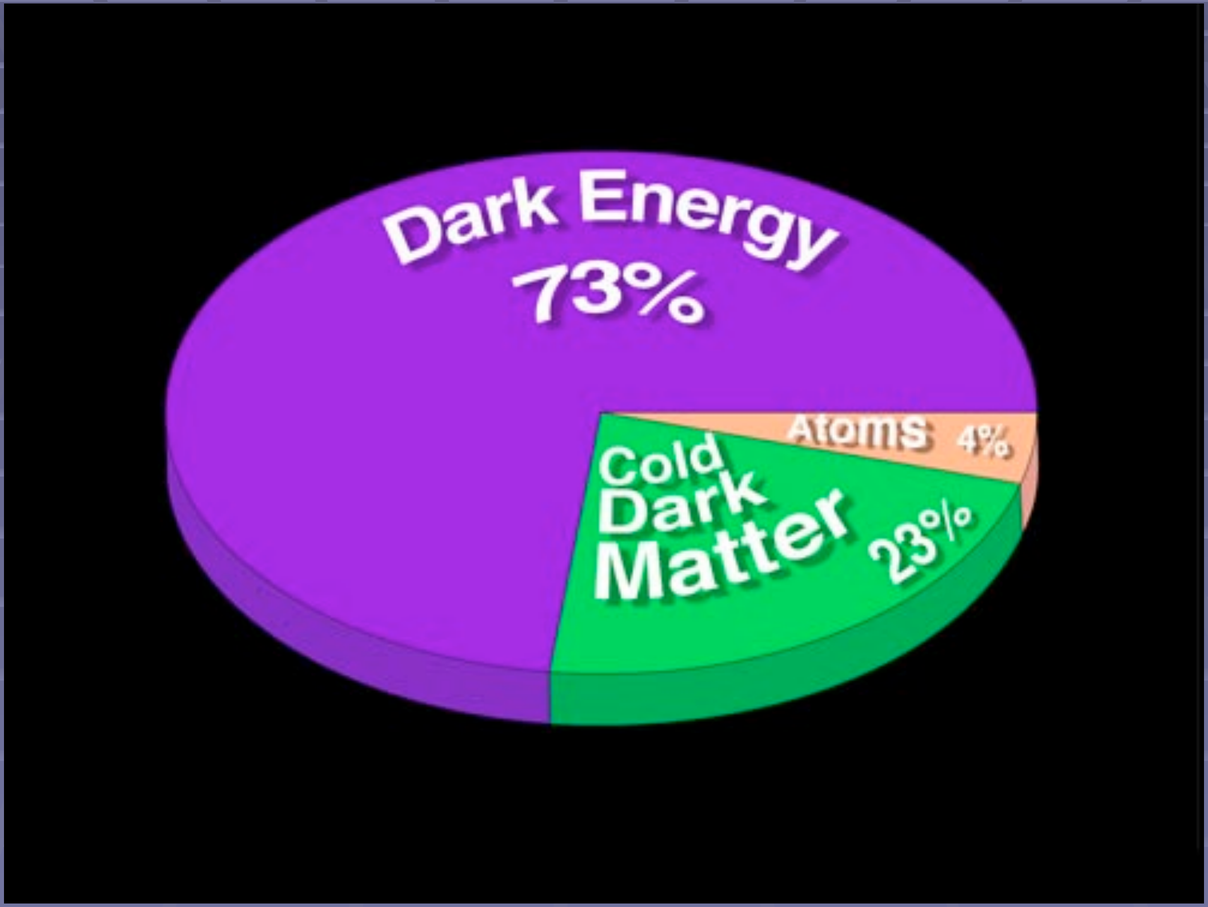
SUCCESS STORY OF PAST FIFTEEN YEARS

- Holy Grail of 1920's: what is geometry and total mass density of the Universe?
- Answered by Cosmic Microwave Background measurements
- What is the breakdown of the contents of the Universe?
- Answered by BBN, CMB, Type IA SN, large scale structure

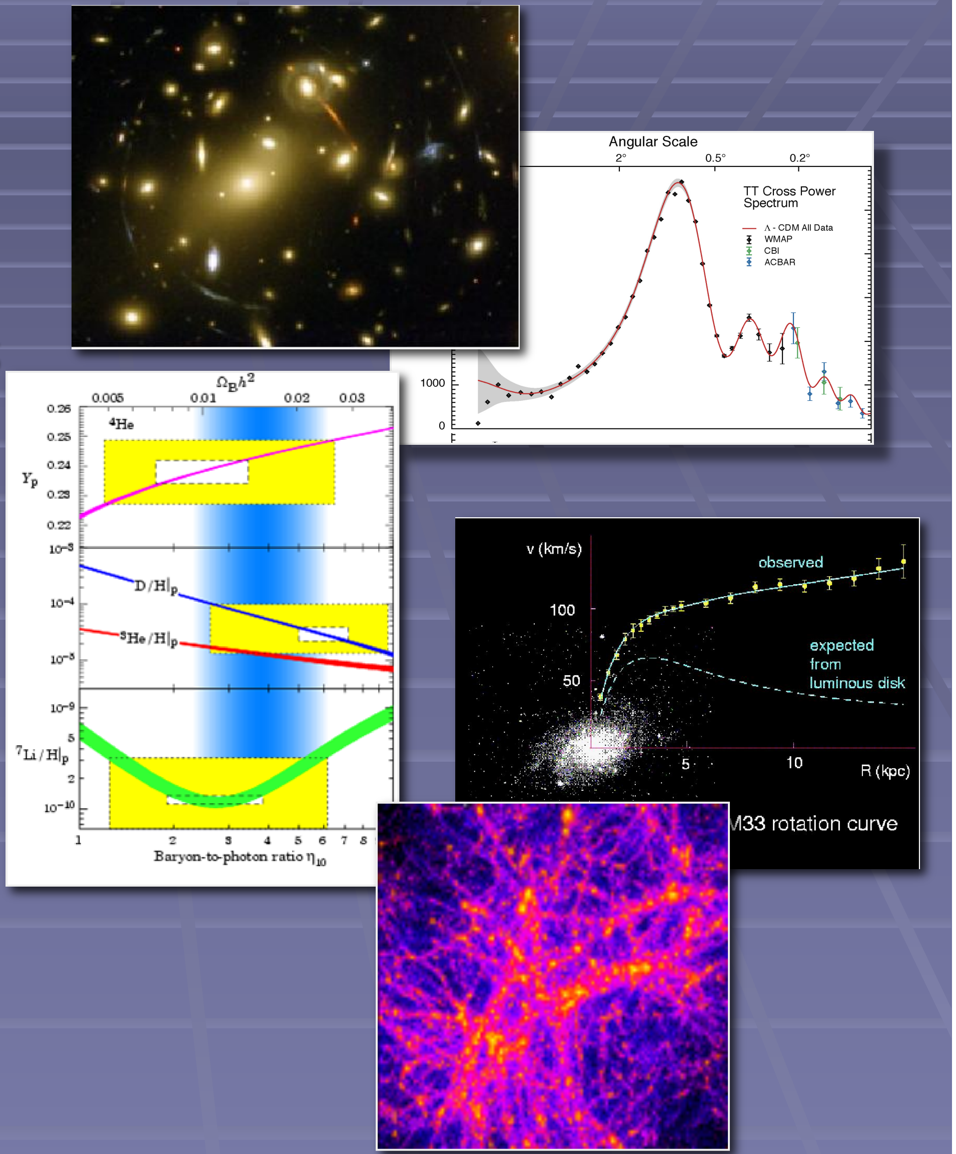
Pie Chart of The Universe



BUT WHAT ARE THE PIECES???

Evidence for Dark Matter Redux

- We have seen that there exists a wide variety of independent indications that dark matter exists
- Each of these observations infer dark matter’s presencethrough its gravitational influence
- Still no observations of dark matter’s electroweak interactions (or other non-gravitational interactions)



III. What is the Dark Matter? Candidates:

- MACHOs (massive compact halo objects)
- WIMPs (SUSY or Kaluza Klein)
- Axions
- Neutrinos (too light, ruin galaxy formation)
- Primordial black holes
- WIMPzillas
- Mirror matter
- Sterile Neutrinos: no Standard Model interaction: 4 neutrino types in CMB?

Baryonic Dark Matter is NOT enough

Death of stellar baryonic dark matter **candidates**
(Fields, Freese, and Graff, astro-ph/0007444)

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

I. The believers in MACHOs (Massive Compact Halo Objects)

II. 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, we have found that THESE CANNOT EXPLAIN ALL THE DARK MATTER IN GALAXIES

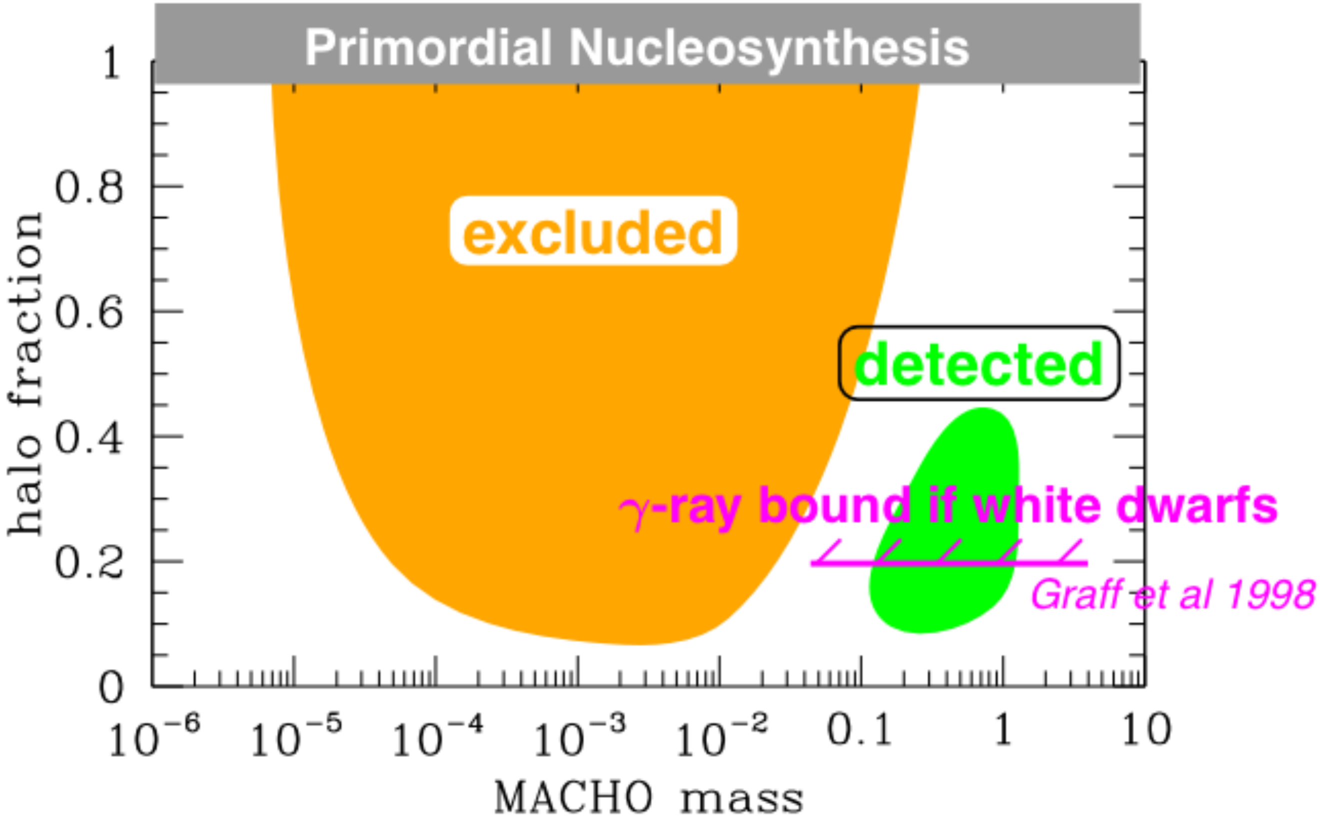
Is Dark Matter Made of Stars? NO

- Faint Stars: Hubble Space Telescope
- Planetary Objects:
  - parallax data
  - microlensing experiments

Together, these objects make up less than 3% of the mass of the Milky Way.

(Graff and Freese 96)

MACHOs!



MACHO & EROS 1996-2000

Is Dark Matter made of Stellar Remnants (white dwarfs, neutron stars, black holes)? partly

- Their progenitors overproduce infrared radiation.
- Their progenitors overproduce element abundances (C, N, He)
- Enormous mass budget.
- Requires extreme properties to make them.
- NONE of the expected signatures of a stellar remnant population is found.
- AT MOST 20% OF THE HALO CAN BE MADE OF STELLAR REMNANTS

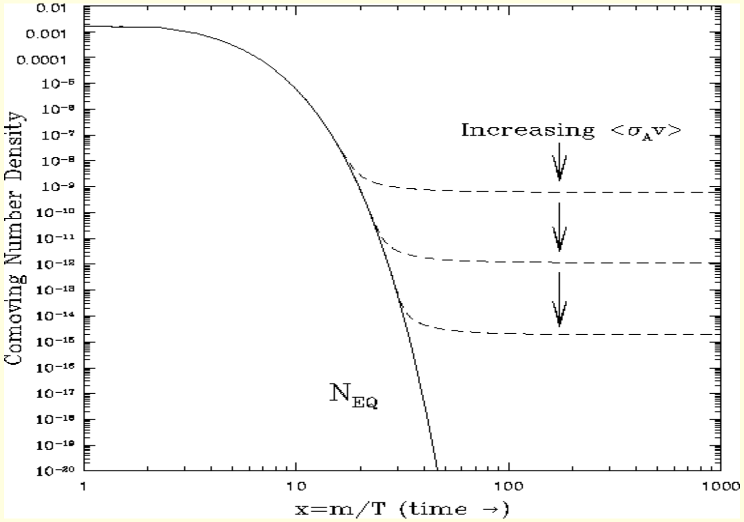
[Fields, Freese, and Graff (ApJ 2000, New Astron. 1998); Graff, KF, Walker and Pinsonneault (ApJ Lett. 1999)]

I HATE MACHOS!

DESPERATELY
LOOKING FOR **WIMPS**!

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

arises in Peccei-Quinn solution to strong-CP problem

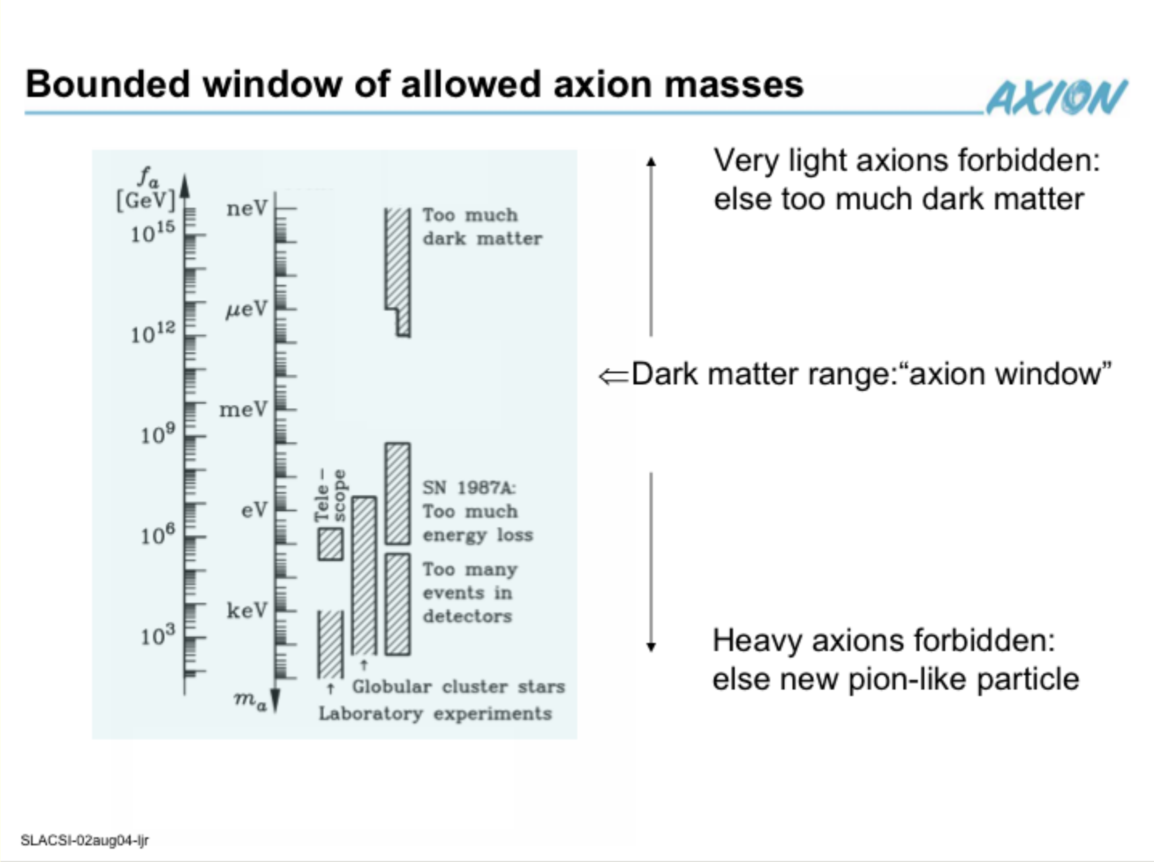
S. Weinberg
F. Wilczek

- THE BEGINNINGS OF DARK MATTER PARTICLE PHENOMENOLOGY

Axion detector (axion to photon conversion)

Pierre Sikivie
PRL 51 (1983) p. 1415

Axion masses



Bounded window of allowed axion masses

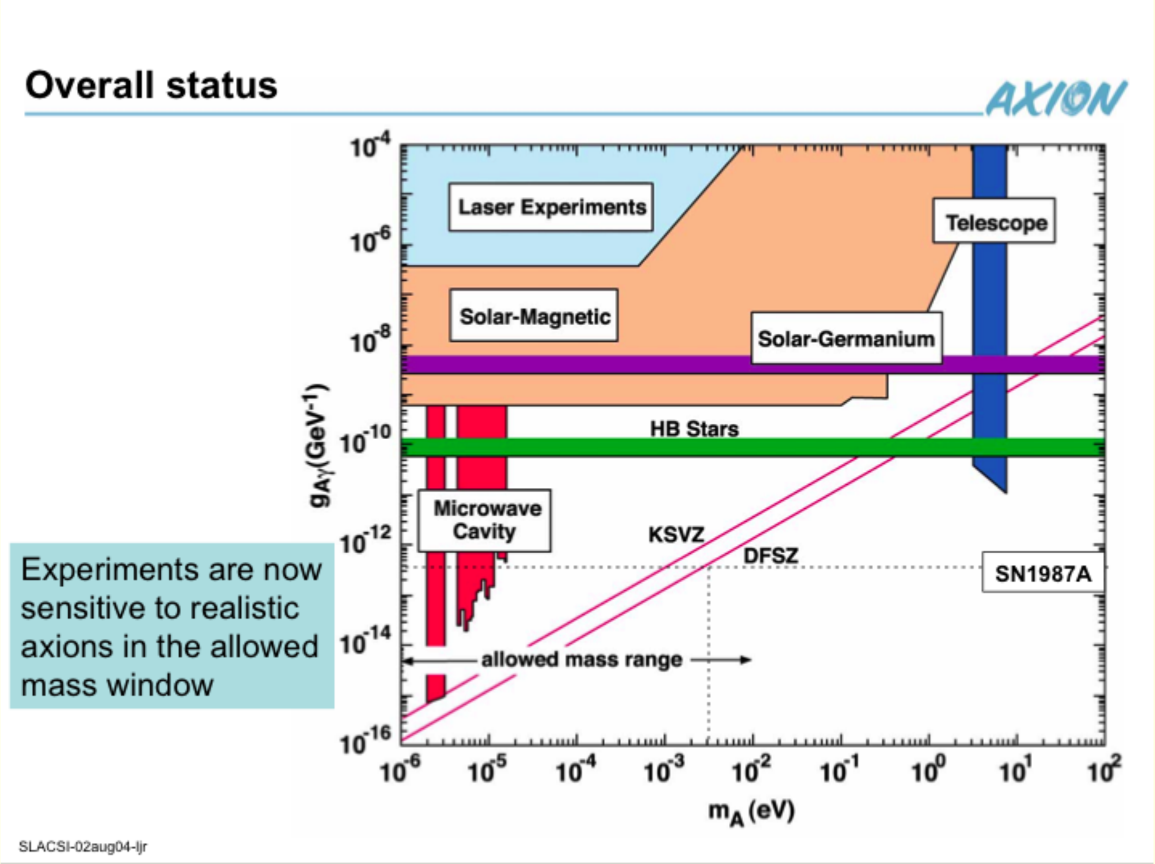
Very light axions forbidden: else too much dark matter

⇐Dark matter range:“axion window”

Heavy axions forbidden: else new pion-like particle

SLACSI-02aug04-ljr

Overall status of axion bounds



Overall status

SLACSI-02aug04-ljr

Experiments are now sensitive to realistic axions in the allowed mass window

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! LEE-WEINBERG BOUND.

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

More accurately, there is a small mass dependence

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

- Particle theory designed to keep particle masses at the right values
- Every particle we know has a partner:

photon	photino
quark	squark
electron	selectron

- The lightest supersymmetric partner is a dark matter candidate.

Lightest Supersymmetric Particle: Weakly interacting DM

- Sets Mass 1Gev-10TeV (take 100GeV)
- Sets annihilation cross section (WIMPS):

$$<\sigma v>_{ann} = 3x10^{-26} cm^3 /\sec$$

WIMP Dark Matter Phenomenology: History

- Looking for neutrinos (Drukier and Stodolsky)
- First paper suggesting direct detection: Goodman and Witten 1986
- Second paper on direct detection: we
- (I) took into account WIMP distribution in galaxy and (ii) suggested annual modulation (Drukier, Freese, and Spergel 1986).
- A followup paper (Freese, Frieman, Gould 1988) suggested using annual modulation to pull out signal from background. This is how the only current claim for direct detection was done (DAMA experiment).

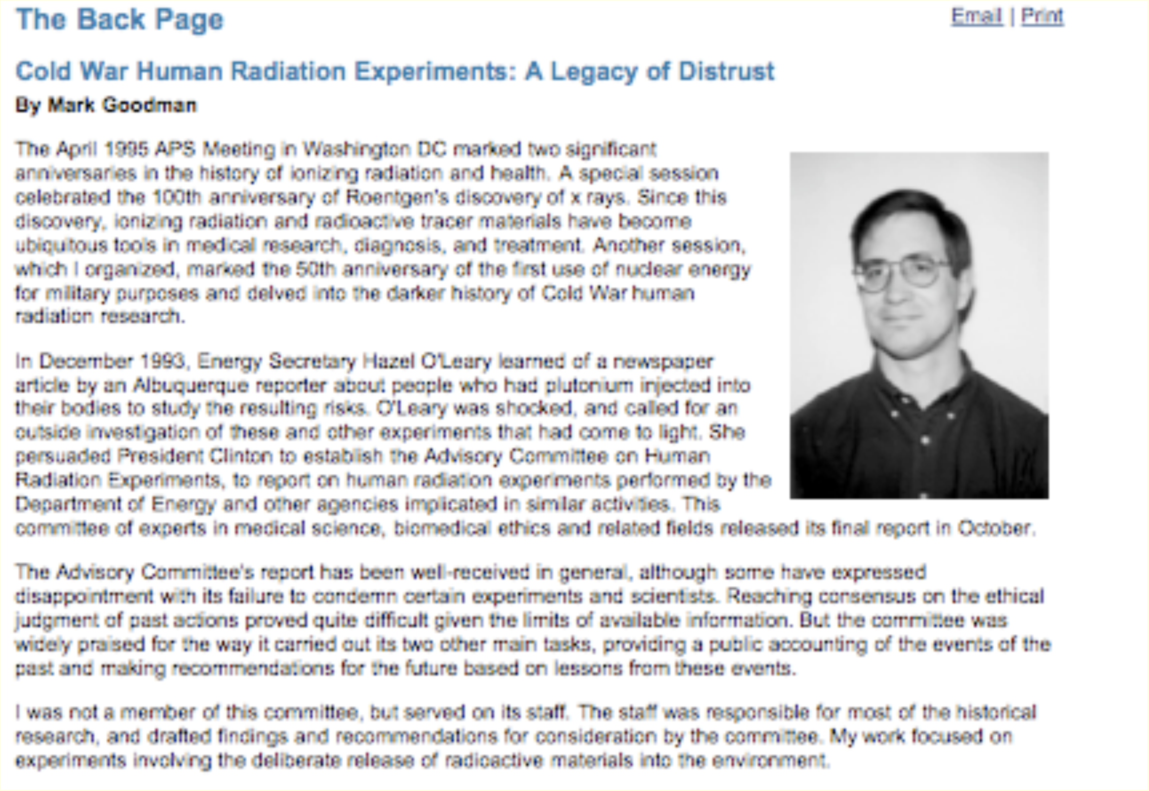
Drukier and Stodolsky (1984)

proposed MeV neutrino detection via elastic scattering off nuclei with 100 eV recoil energy

Andrzej Drukier

Leo Stodolsky

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



The Back Page

Cold War Human Radiation Experiments: A Legacy of Distrust

By Mark Goodman

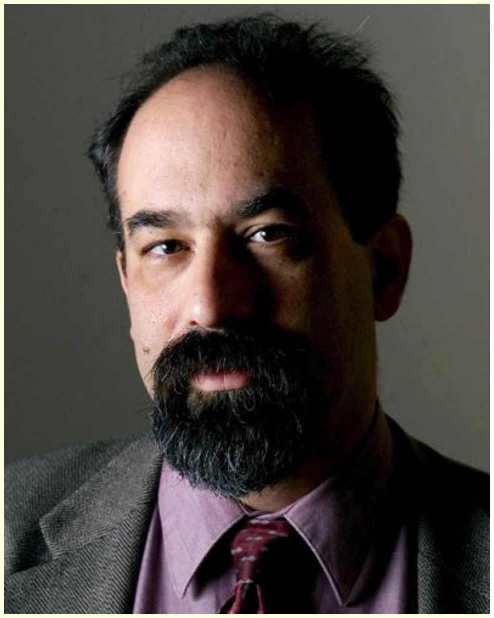
The April 1995 APS Meeting in Washington DC marked two significant anniversaries in the history of ionizing radiation and health. A special session celebrated the 100th anniversary of Roentgen's discovery of x rays. Since this discovery, ionizing radiation and radioactive tracer materials have become 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) i) included model for galactic halo, ii) proposed annual modulation, iii) SI/SD for various detector elements



detection

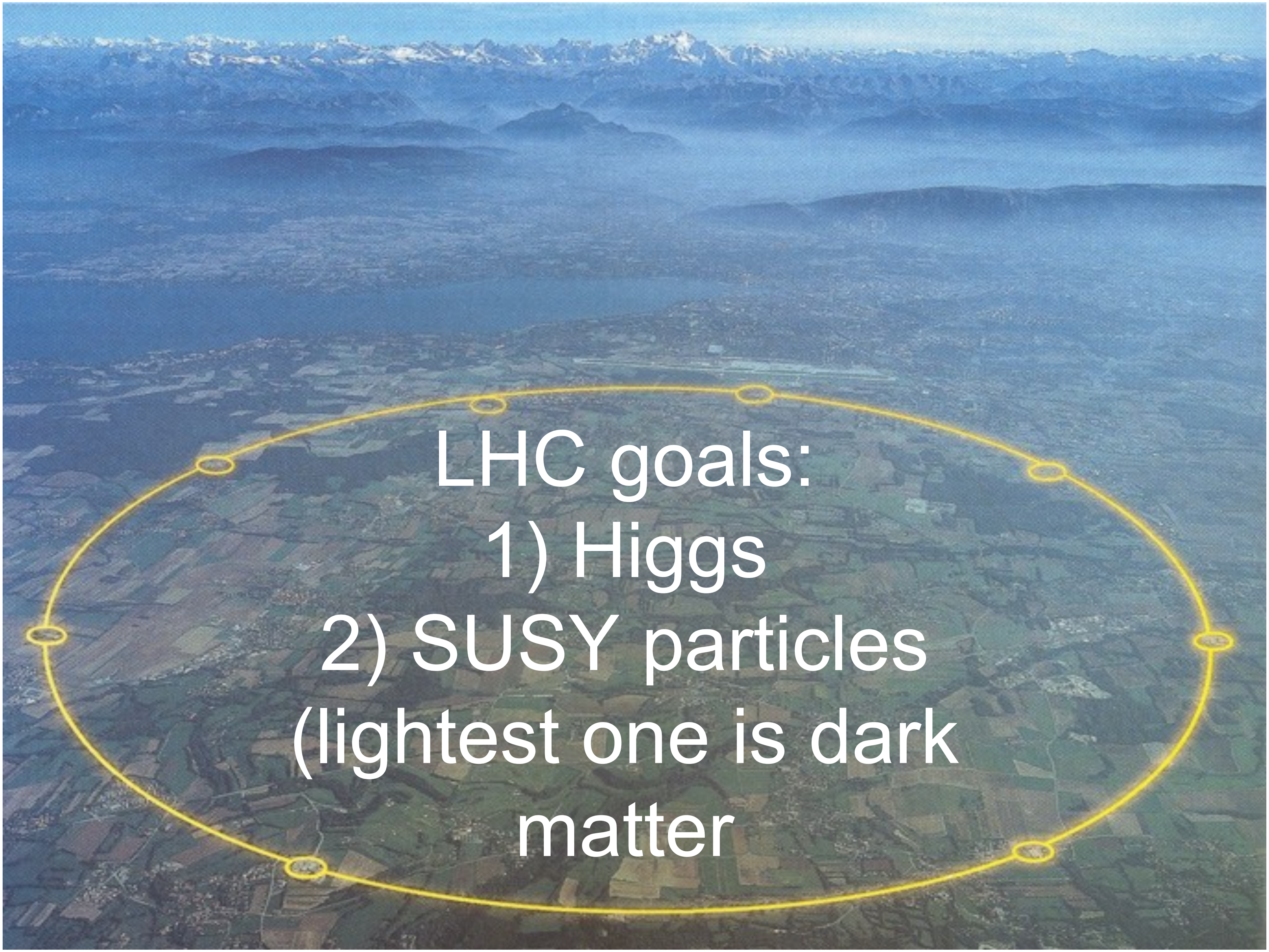
- Colliders: produce WIMPs directly at LHC (missing energy signature)
- Direct detection: observe WIMPs through collisions with matter in terrestrial detectors
- Indirect detection: observe products of WIMP annihilation/decay in terrestrial or space-based detectors

EXCITING TIMES

- We made WIMP proposals twenty years ago:
- It is coming to fruition!
- My personal prediction: one of the anomalous results is right and we will know very soon.

I. FIRST WAY TO SEARCH FOR WIMPS

COLLIDERS:
Large Hadron Collider at CERN



LHC goals:
1) Higgs
2) SUSY particles
(lightest one is dark
matter

Higgs searches

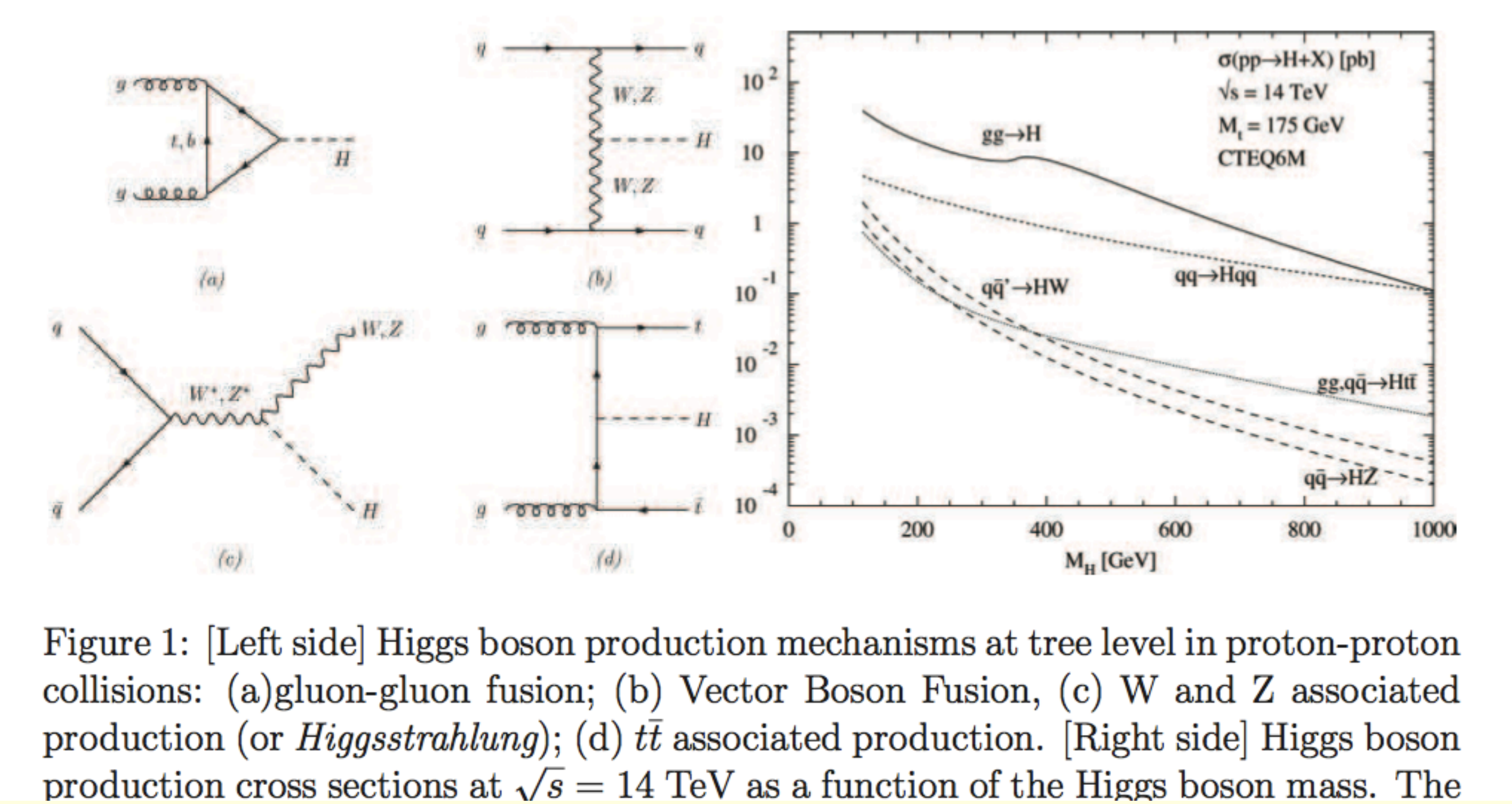


Figure 1: [Left side] Higgs boson production mechanisms at tree level in proton-proton collisions: (a)gluon-gluon fusion; (b) Vector Boson Fusion, (c) W and Z associated production (or *Higgsstrahlung*); (d) $t\bar{t}$ associated production. [Right side] Higgs boson production cross sections at $\sqrt{s} = 14$ TeV as a function of the Higgs boson mass. The

125 GeV Higgs boson discovery?

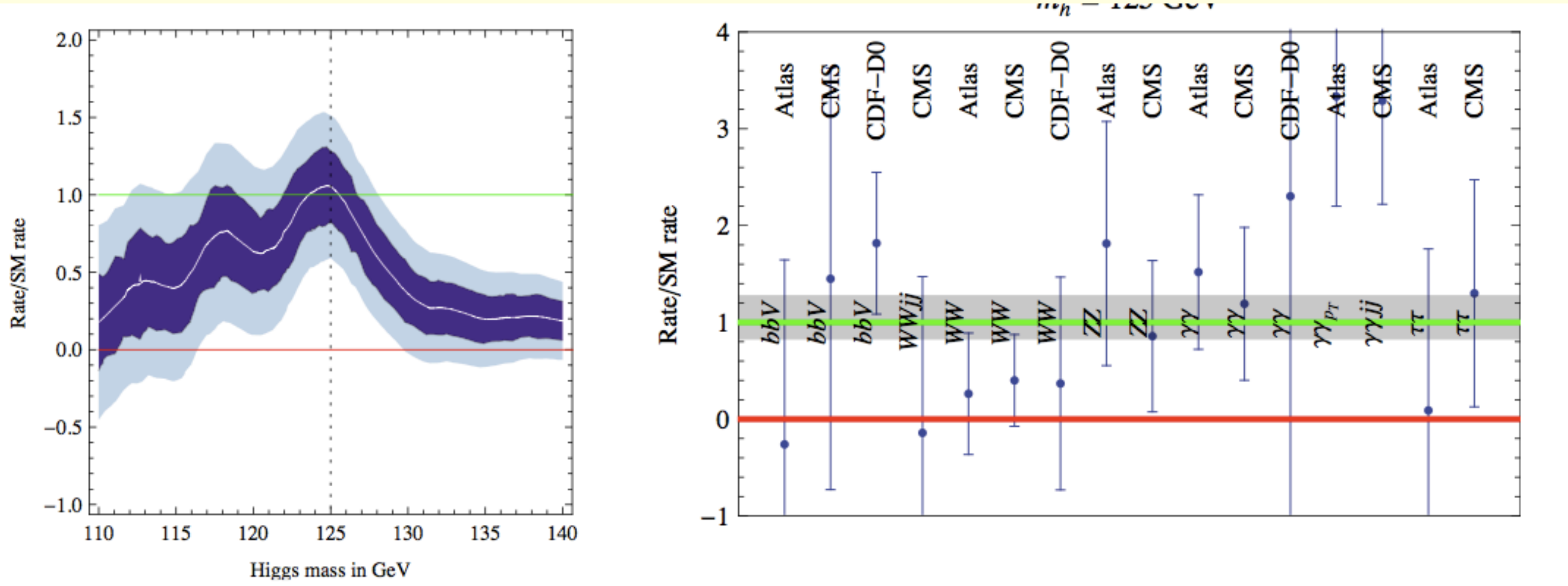
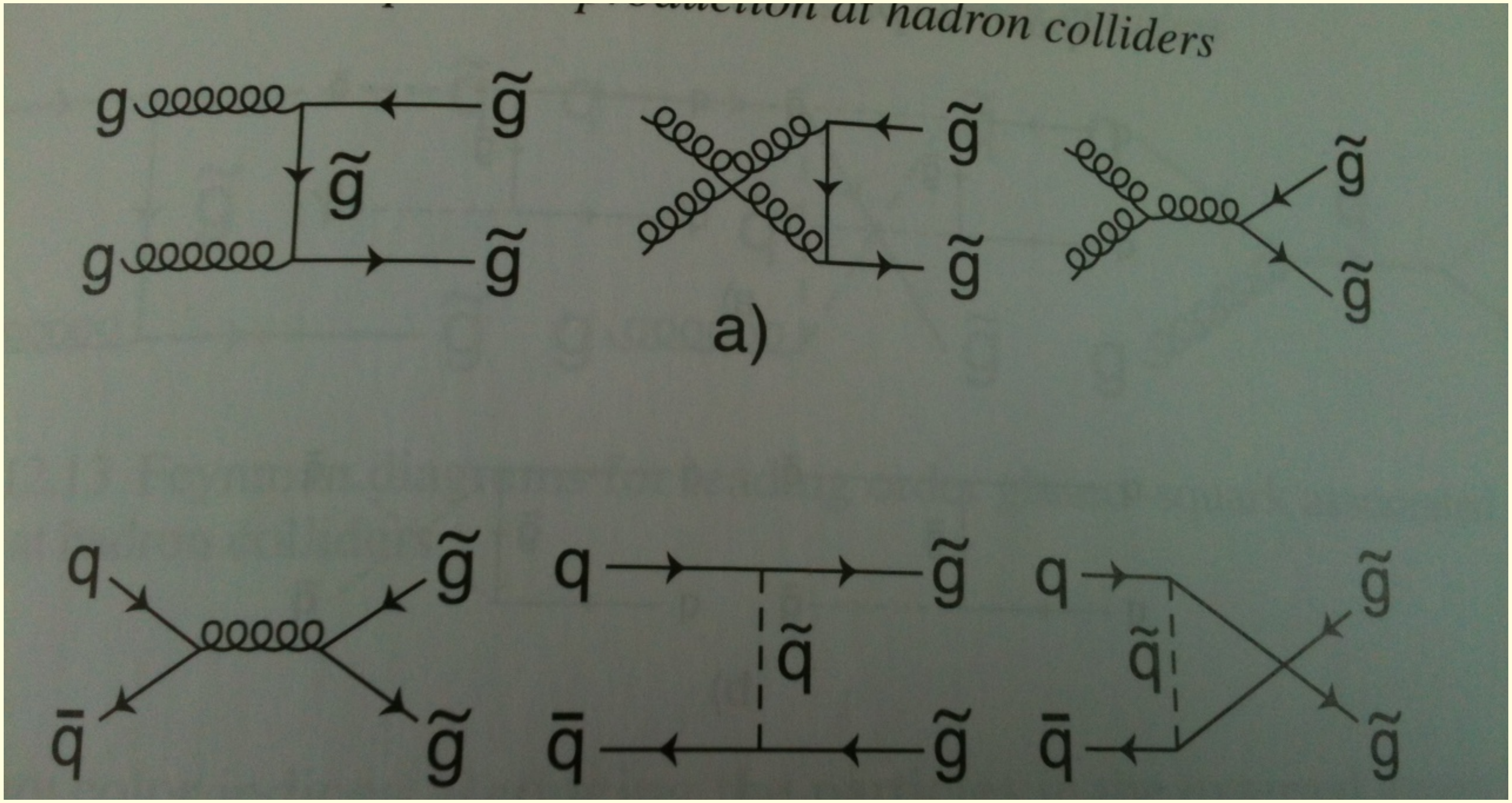


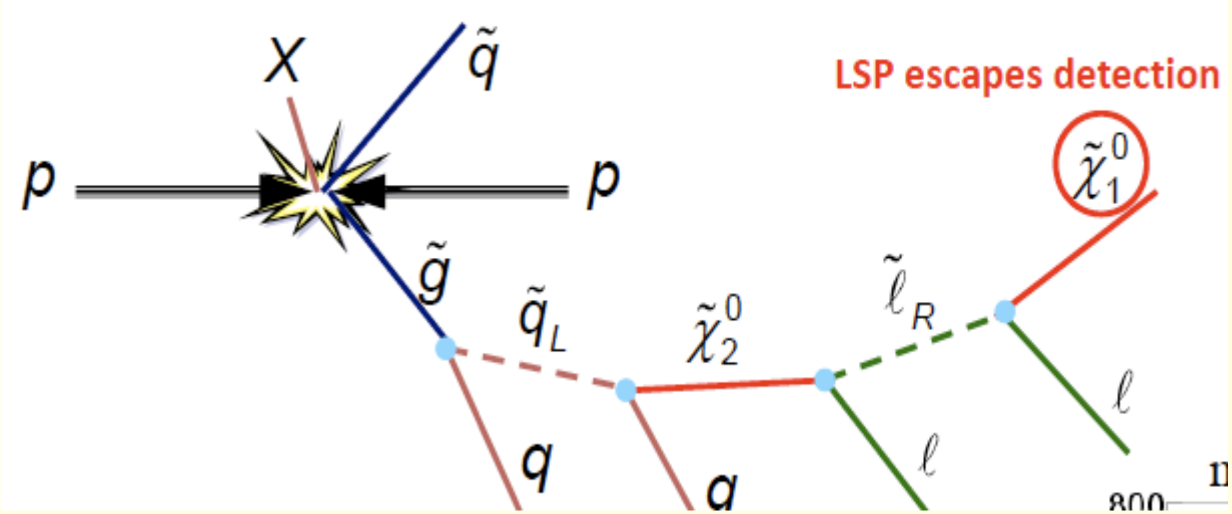
Figure 1: **Left**: *The Higgs boson rate favoured at* 1σ *(dark blue) and* 2σ *(light blue) in a global SM fit as function of the Higgs boson mass.* **Right**: *assuming* $m_h = 125\,\text{GeV}$, *we show the measured Higgs boson rates at ATLAS, CMS, CDF, D0 and their average (horizontal gray band at* $\pm 1\sigma$*). Here 0 (red line) corresponds to no Higgs boson, 1 (green line) to the SM Higgs boson.*

pp collisions into SUSY particles (squark/squark, gluino/gluino, or squark/gluino pairs)

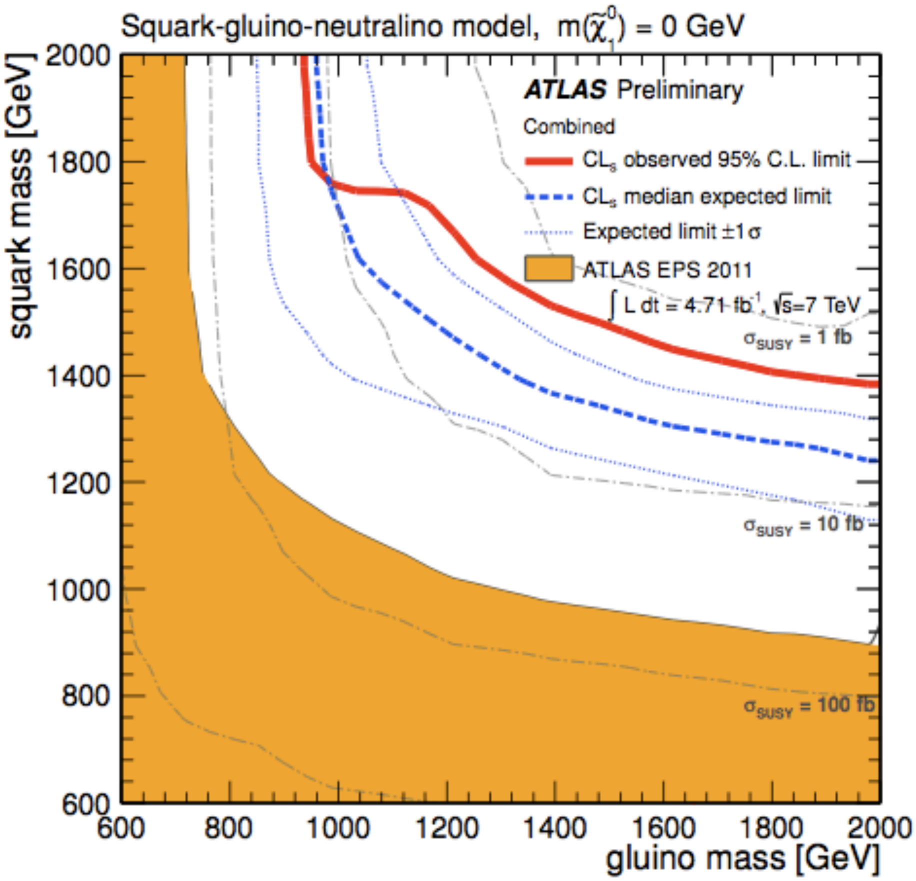


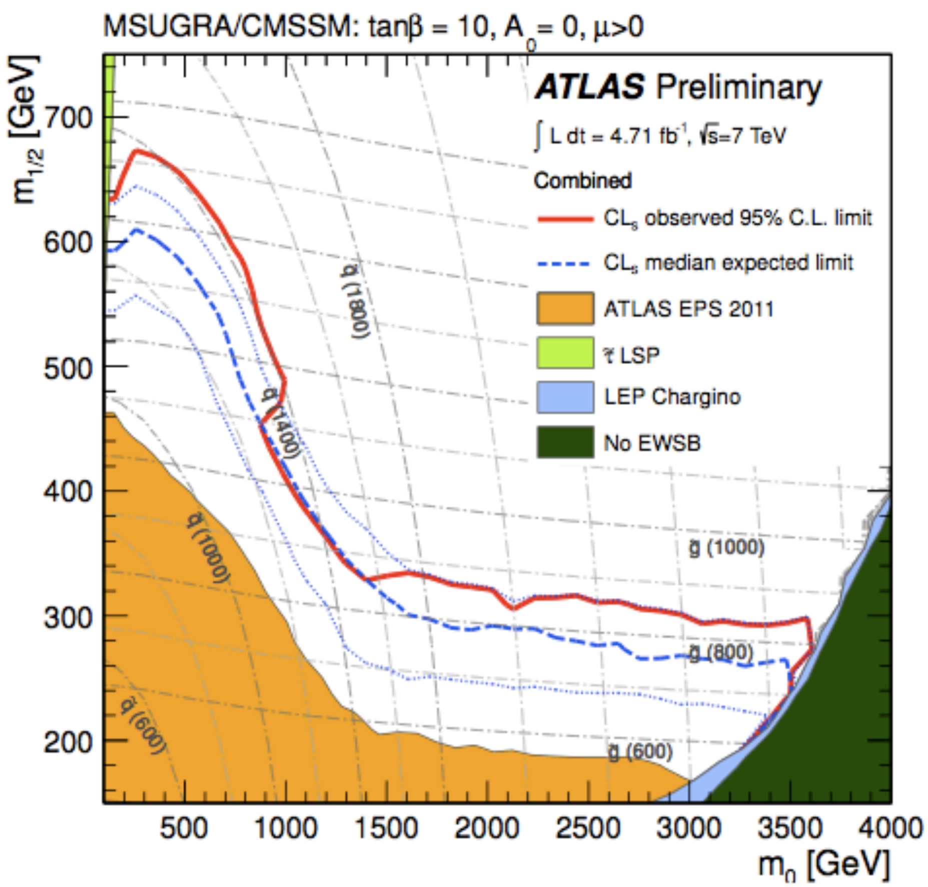
SUSY signatures in CMS and ATLAS

- Missing energy plus jets

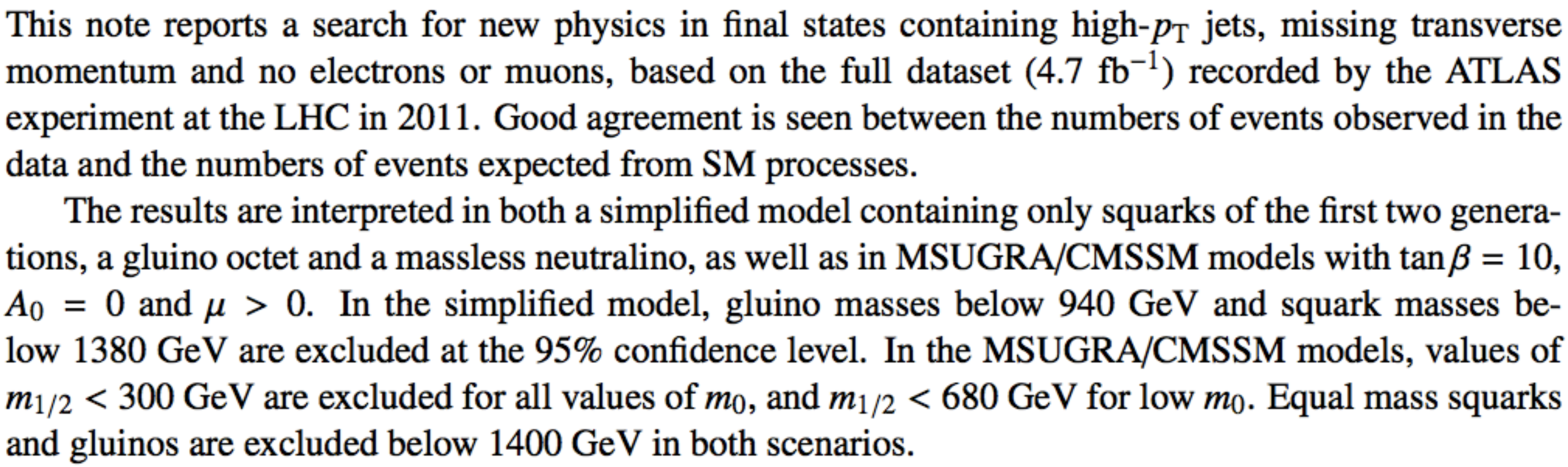


BOUNDS ON SUSY FROM LHC 2011



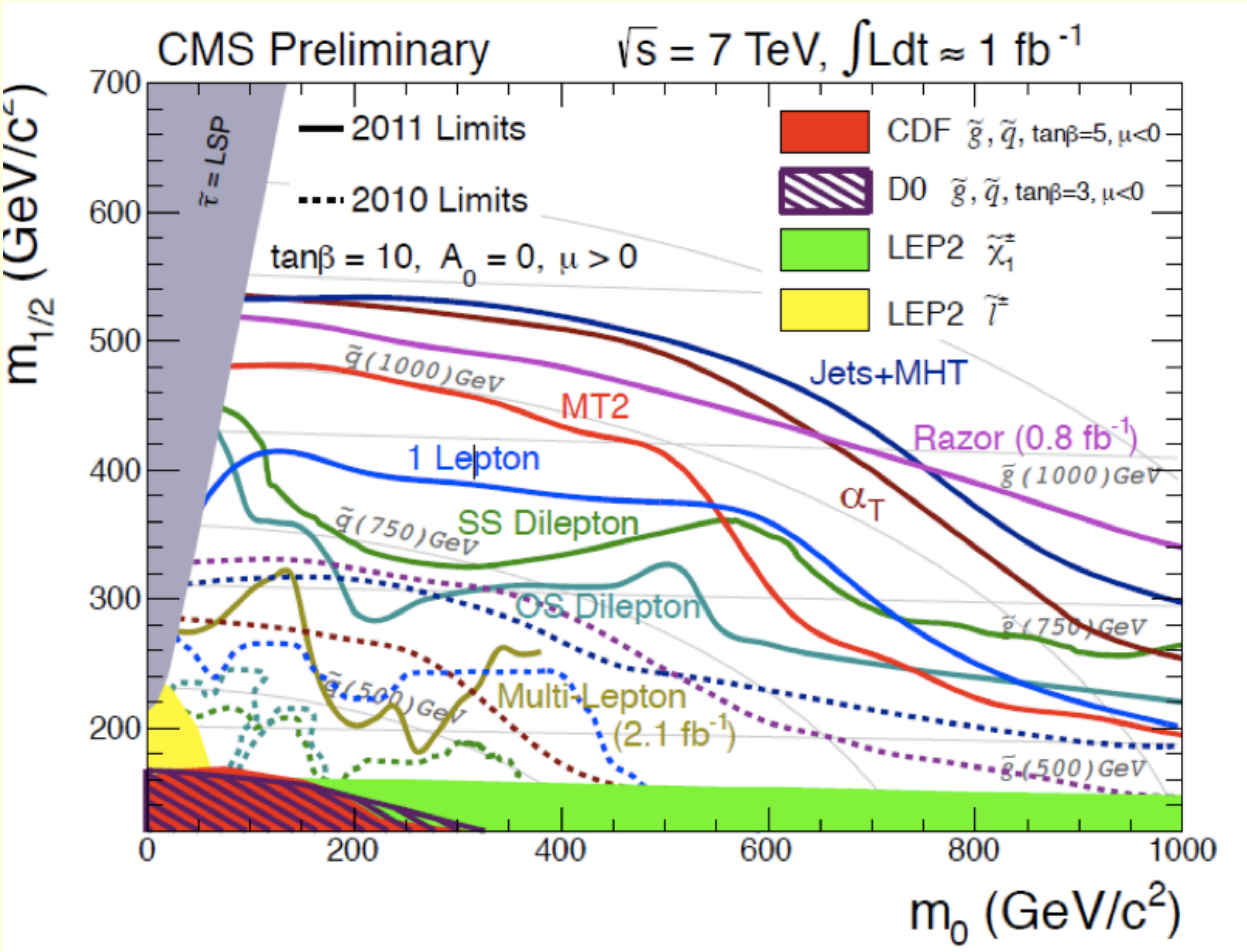


ATLAS results 2011



This note reports a search for new physics in final states containing high-p_T jets, missing transverse momentum and no electrons or muons, based on the full dataset (4.7 fb^{-1}) recorded by the ATLAS experiment at the LHC in 2011. Good agreement is seen between the numbers of events observed in the data and the numbers of events expected from SM processes.

The results are interpreted in both a simplified model containing only squarks of the first two generations, a gluino octet and a massless neutralino, as well as in MSUGRA/CMSSM models with $\tan\beta = 10$, $A_0 = 0$ and $\mu > 0$. In the simplified model, gluino masses below 940 GeV and squark masses below 1380 GeV are excluded at the 95% confidence level. In the MSUGRA/CMSSM models, values of $m_{1/2} < 300$ GeV are excluded for all values of m_0, and $m_{1/2} < 680$ GeV for low m_0. Equal mass squarks and gluinos are excluded below 1400 GeV in both scenarios.


CMS Preliminary
$\sqrt{s}$ = 7 TeV, $\int L dt \approx 1$ fb^{-1}
$\tilde{\tau}$ = LSP
2011 Limits
2010 Limits
tanβ = 10, A_0 = 0, μ > 0
🟥 CDF $\tilde{g}, \tilde{q}$, tanβ=5, μ<0
▨ D0 $\tilde{g}, \tilde{q}$, tanβ=3, μ<0
🟩 LEP2 $\tilde{\chi}_1^{\pm}$
🟨 LEP2 $\tilde{l}^{\pm}$
Jets+MHT
Razor (0.8 fb^{-1})
MT2
α_T
1 Lepton
SS Dilepton
OS Dilepton
Multi-Lepton (2.1 fb^{-1})
$\tilde{q}$(1000)GeV
$\tilde{g}$(1000)GeV
$\tilde{q}$(750)GeV
$\tilde{g}$(750)GeV
$\tilde{q}$(500)GeV
$\tilde{g}$(500)GeV
$m_{1/2}$ (GeV/c^2)
m_0 (GeV/c^2)
700
600
500
400
300
200
0
200
400
600
800
1000

Supersymmetric Particles in LHC

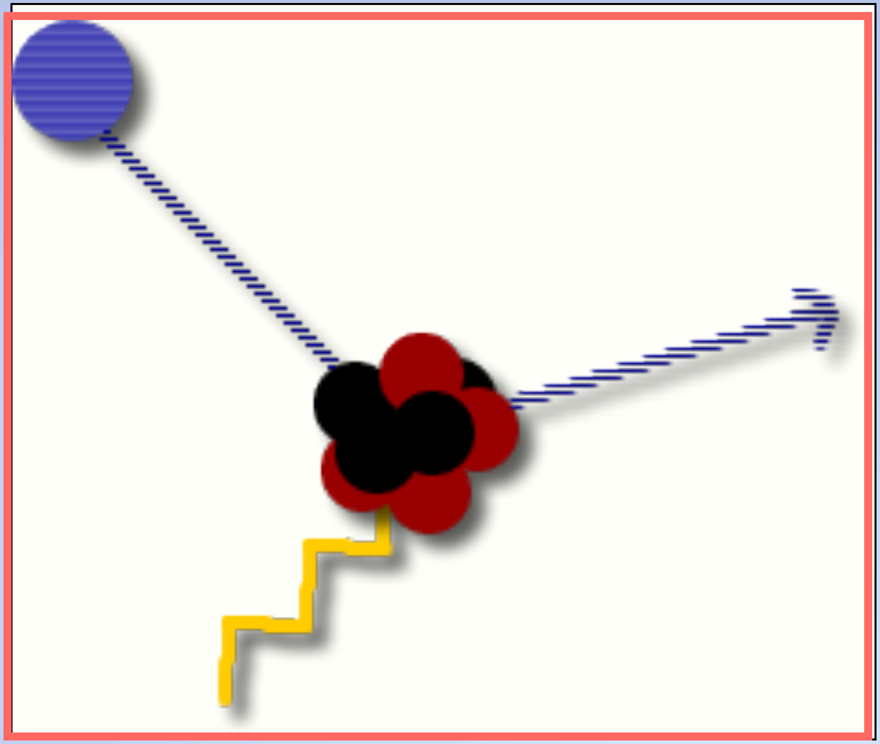
- Signature: missing energy when SUSY particle is created and some energy leaves the detector
- Problem with identification: degeneracy of interpretation
- SUSY can be found, but, you still don’t know how long the particle lives: fractions of a second to leave detector or the age of the universe if it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

Event rate

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

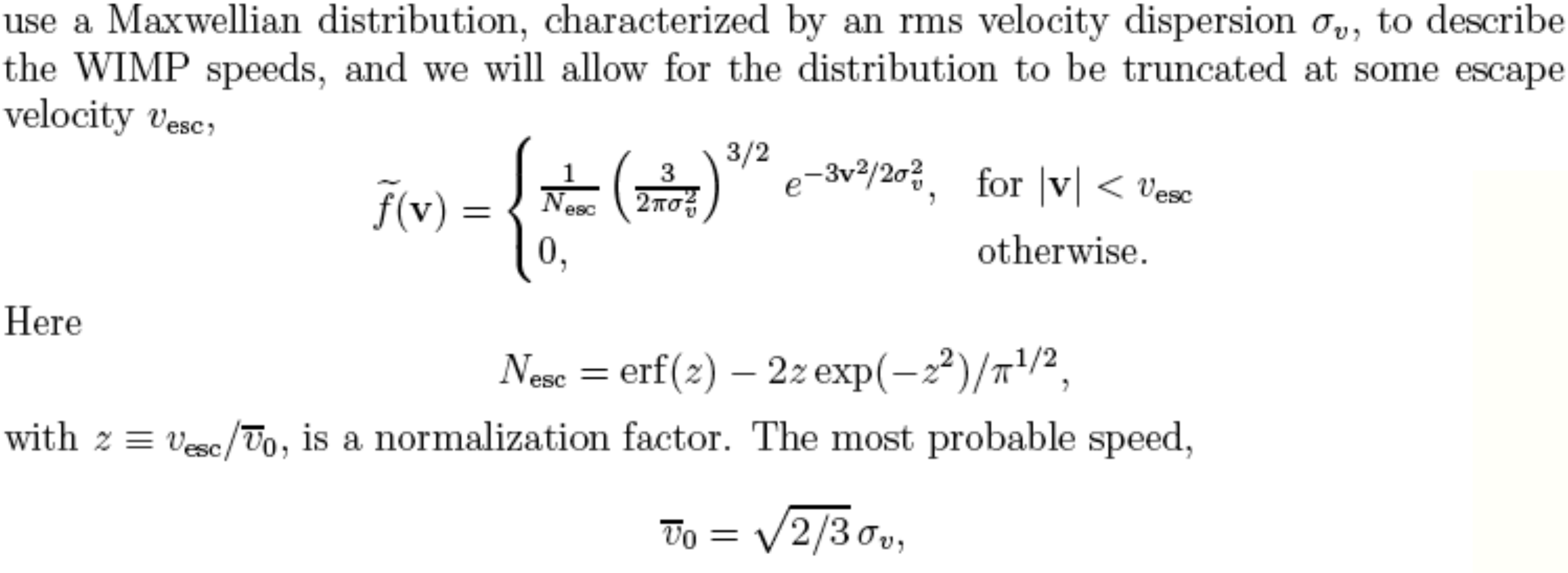
$$\frac{dR}{dE} = \int \frac{N_T}{M_T} \times \frac{d\sigma}{dE} \times nv\, f(v,t)\, d^3v$$

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

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_{esc},

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

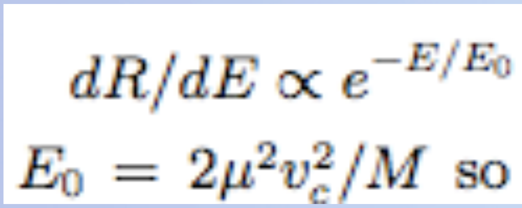
Here

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

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

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

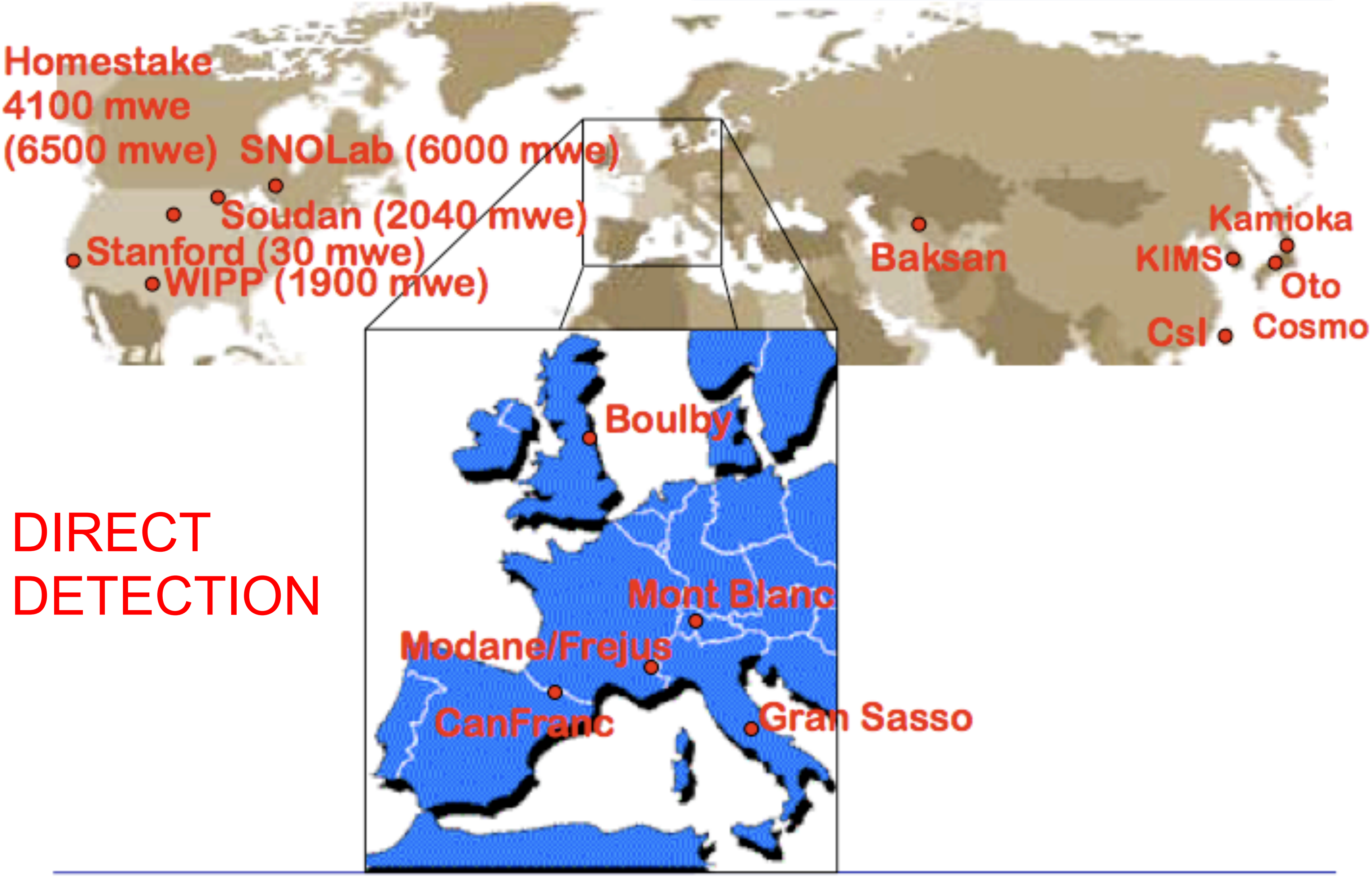
Typical particle speed is about 270 km/sec.



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

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

Underground Laboratories Worldwide



DIRECT
DETECTION

Many claims/hints of WIMP dark matter detection: how can we be sure?

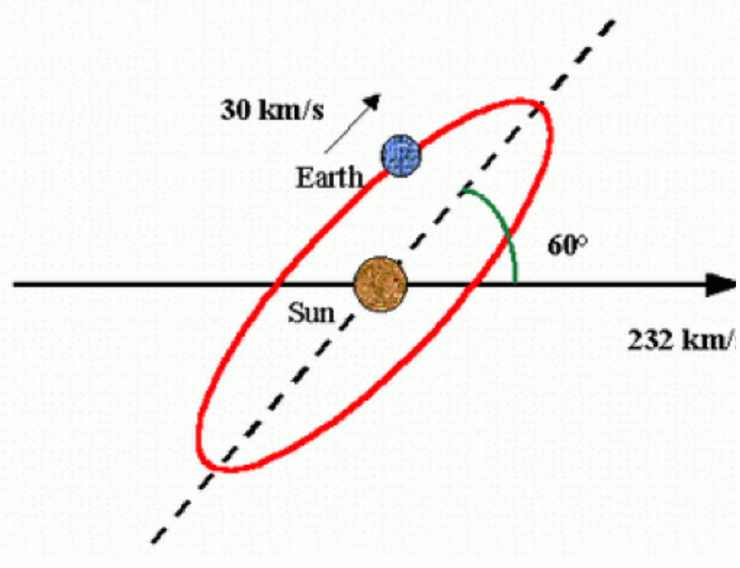
- 1) The DAMA annual modulation
- 2) The HEAT, PAMELA, and ATIC positron excess
- 3) Gamma-rays from Galactic Center (FERMI)
- 4) possible signal in COGENT and CRESST

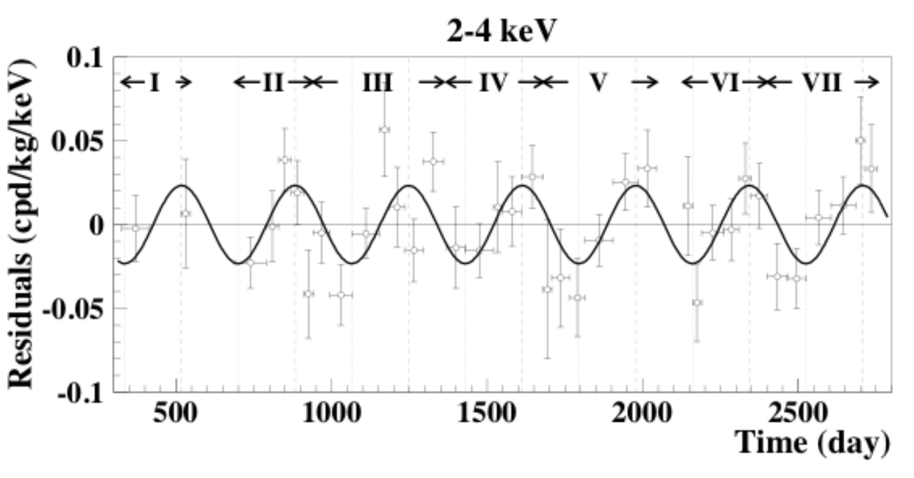
HAS DARK MATTER BEEN DISCOVERED?

DAMA annual modulation

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

Bernabei et al 2003





250 kg of NaI crystals in Gran Sasso Tunnel under the Apennine Mountains in Italy.

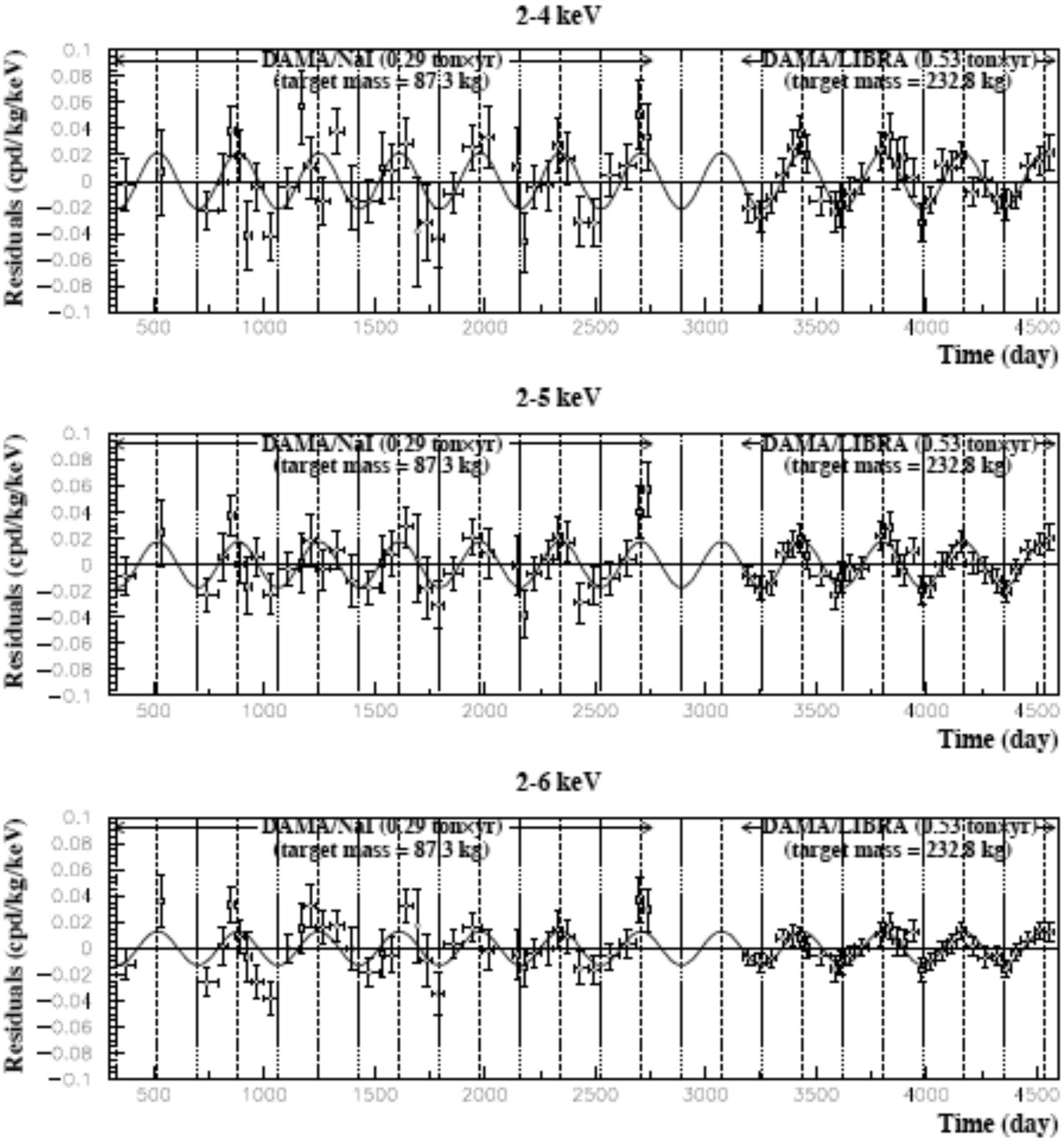
Data do show a 9σ modulation

WIMP interpretation is controversial

DAMA/LIBRA

9 sigma annual modulation consistent with dark matter signal

Peaks in June, Minimum in December



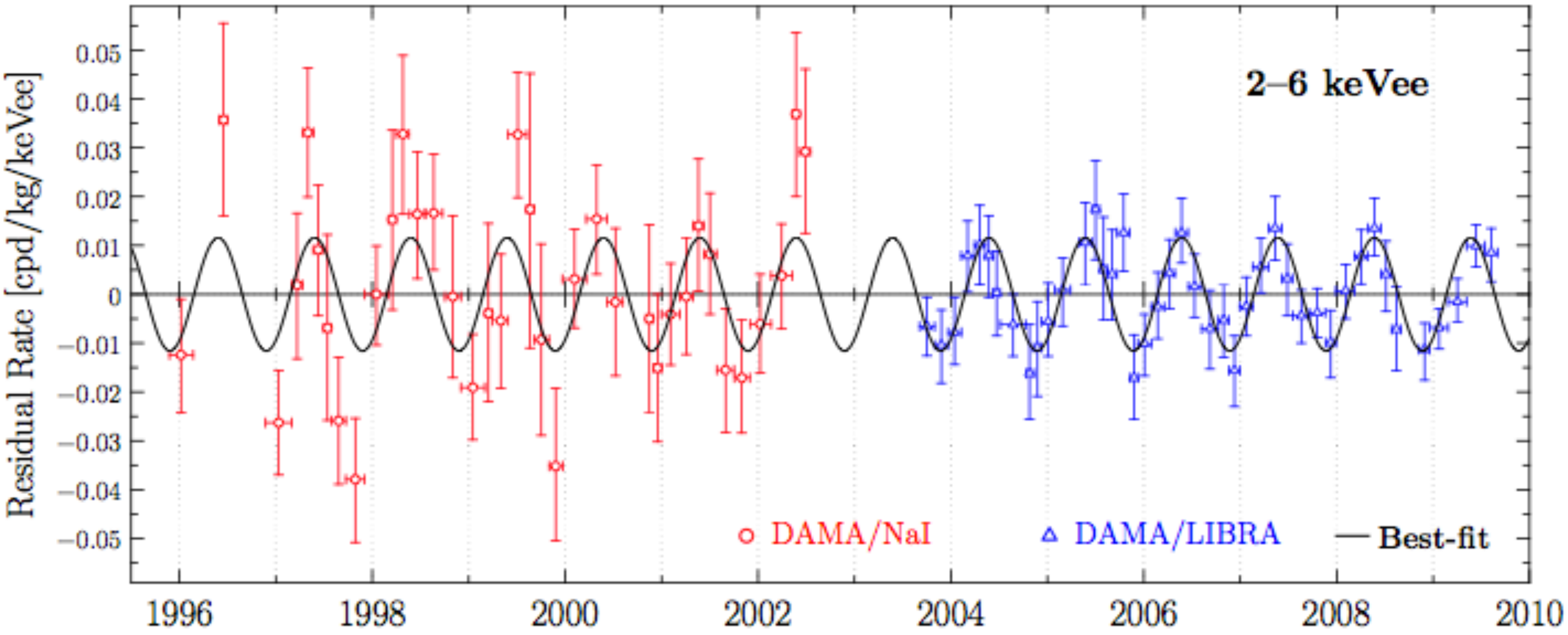


FIG. 5: The residual rate measured by DAMA/NaI (red circles, 0.29 ton-yr exposure over 1995–2002) and DAMA/LIBRA (blue triangles, 0.87 ton-yr exposure over 2003–2010) in the 2–6 keVee energy interval, as a function of time. Data is taken from Refs. [27, 29]. The solid black line is the best fit sinusoidal 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.

Is DAMA right?

- At first, 3 days of data in summer, a month in winter
- Everybody thought it must be wrong: temperature of Rome; radon; etc etc
- However, these issues were checked and spectrum is now reported
- Unexplained data have been there for ten years: 1 ton-year of exposure
- Burden of proof upon those who want to dismiss the results!

DAMA: spin independent?

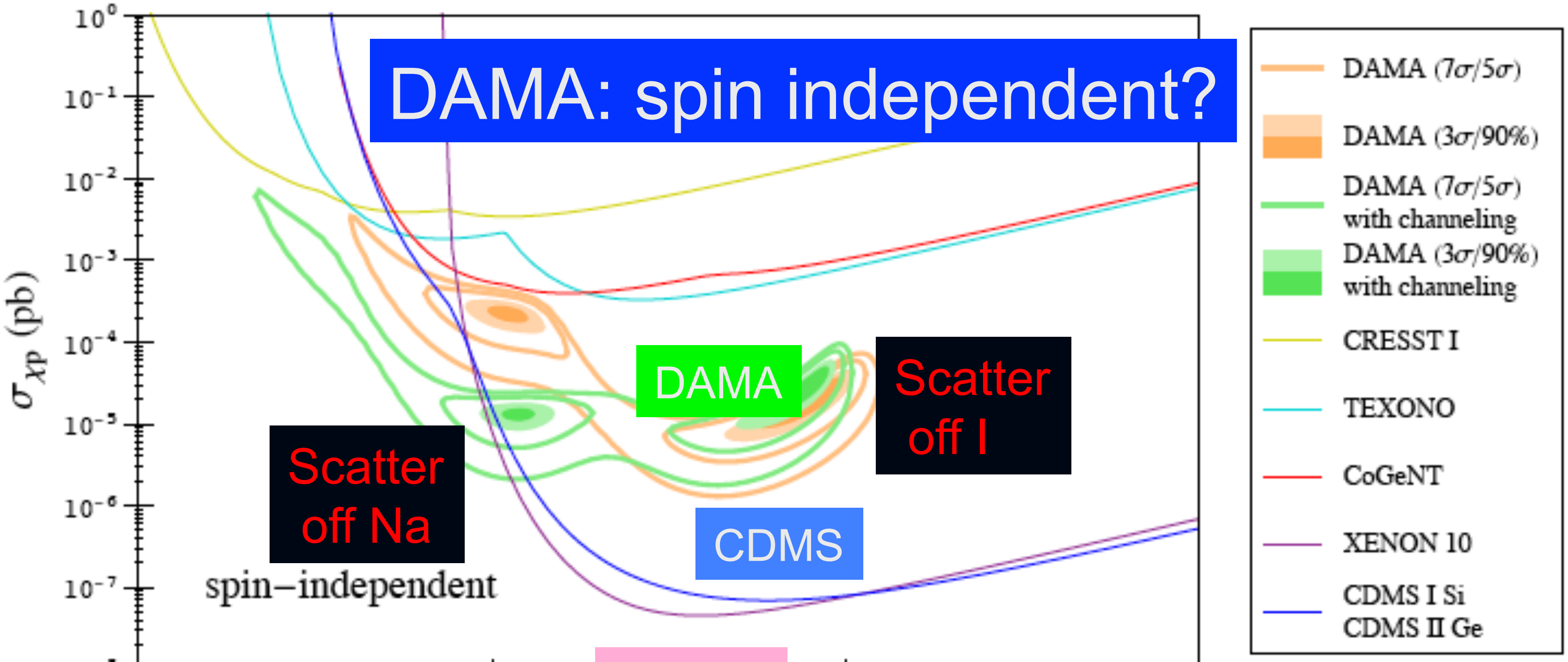
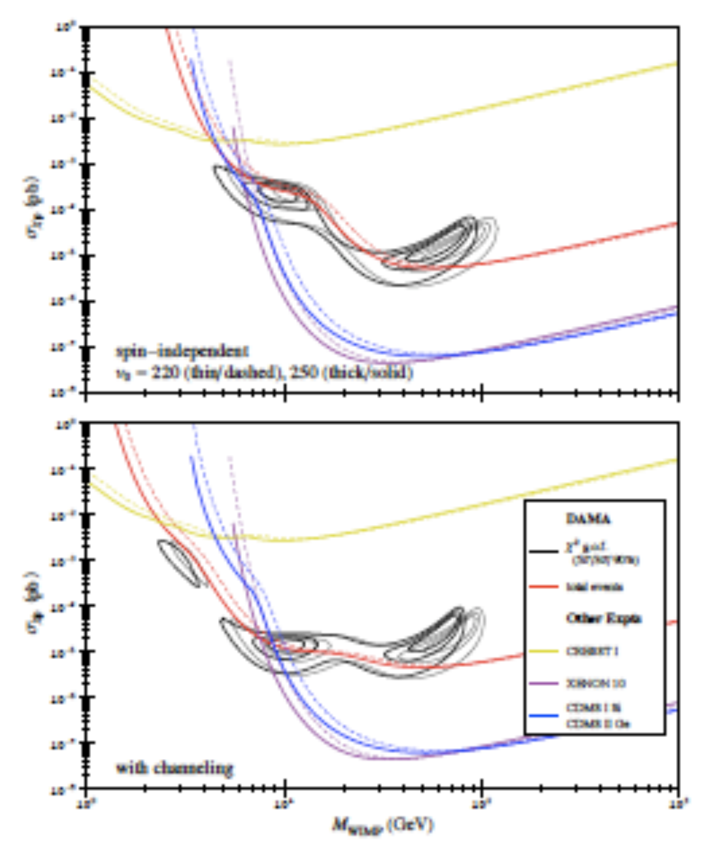


FIG. 5: Experimental constraints and DAMA preferred parameters for SI onl
DAMA preferred regions are determined using the likelihood ratio method with (g
(orange) the channeling effect.

SMALL REGION AT 10 GeV WIMP MASS

Savage, Gelmini, Gondolo, KF (series of pap

New measurements of Sun’s velocity relative to Halo: 250 km/sec (not 220 km/sec)



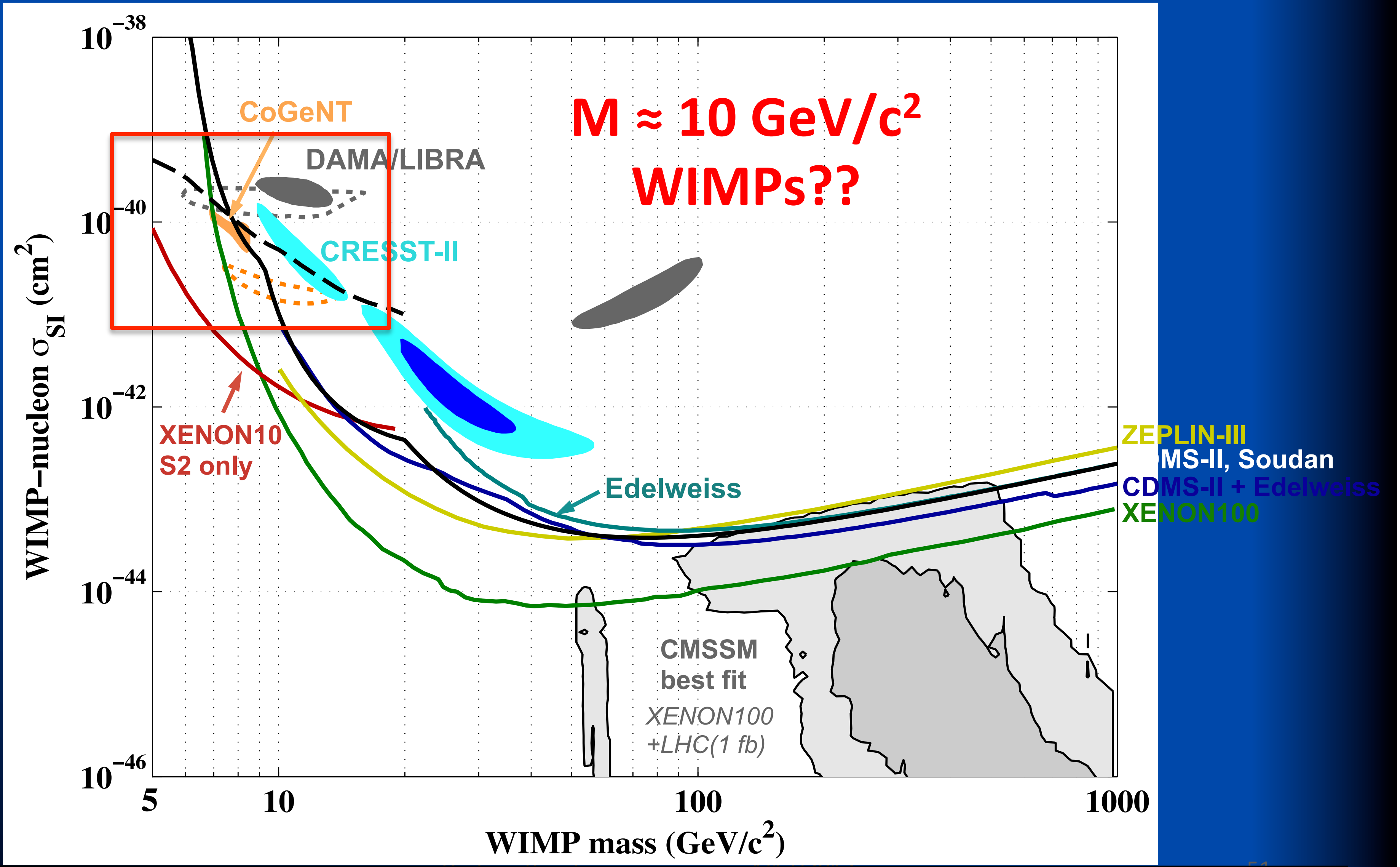
- All curves move to the left:
- Remaining window moves to 7-8 GeV at 3 sigma (5-15 for SD)

Savage, Freese, Gondolo, Spolyar 2009

Low Mass WIMPs in 2012

- Excitement about experimental evidence for 5-10 GeV WIMPs:
- 1) DAMA (Gelmini, Gondolo)
- 2) COGENT: low threshold germanium (Fermilab): one event at low WIMP mass, Claims annual modulation (n.b. their two results seem incompatible)
- 3) CRESST: uncertainty about backgrounds
- --
- What are they? Not MSSM. Historically, we studied 10 GeV WIMPs in the 80s, then LEP ruled them out as MSSM so detectors aimed for higher masses!
- Current status: XENON-10 and CDMS data reanalysis seem to rule them out for spin-independent cross sections

Direct Detection



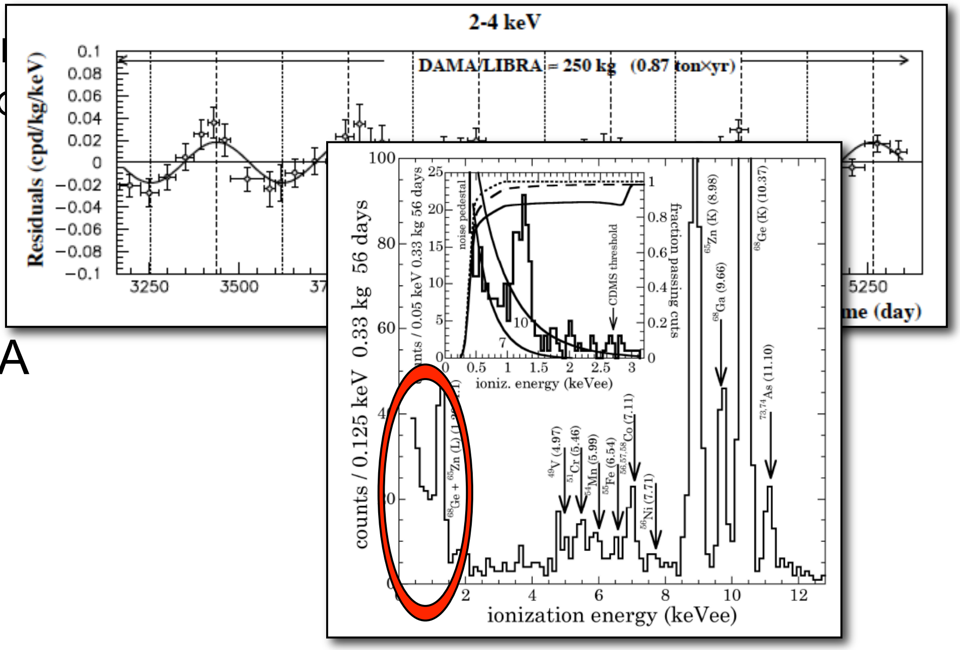
M ≈ 10 GeV/c^2 WIMPs??

Possible Signals From Direct Detection Experiments: 10 GeV WIMPs???

HAD TO STOP TAKING
DATA DUE TO FIRE
IN SOUDAN MINE.
NOW RESTARTED.

CoGeNT

- The CoGeNT collaboration has also reported an excess of low energy events, and has recently reported an annual modulation consistent with DAMA's (at 2.8σ)
- Although it has less exposure than other di detection experiments, CoGeNT is particul suited to look for low energy event (low mass WIMPs)



Controversy: are COGENT and DAMA compatible?

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

Rita Bernabei, DAMA

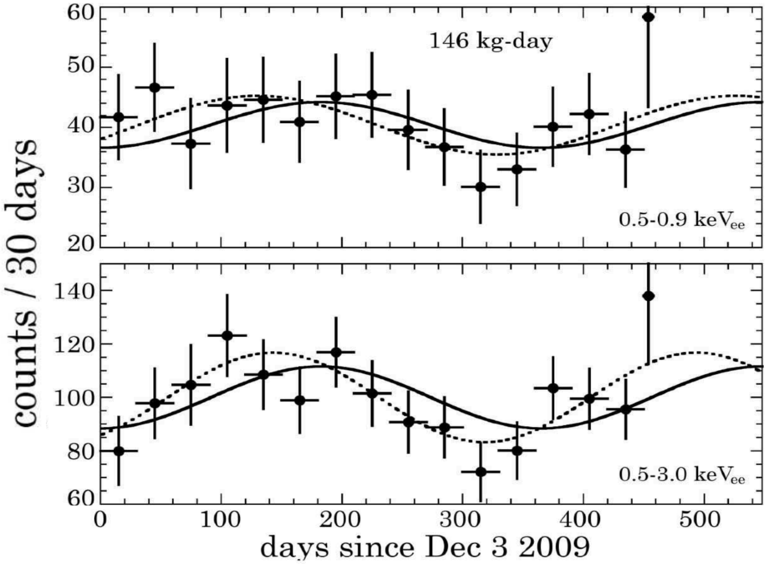
Juan Collar, COGENT

Elena Aprile, XENON

CoGeNT

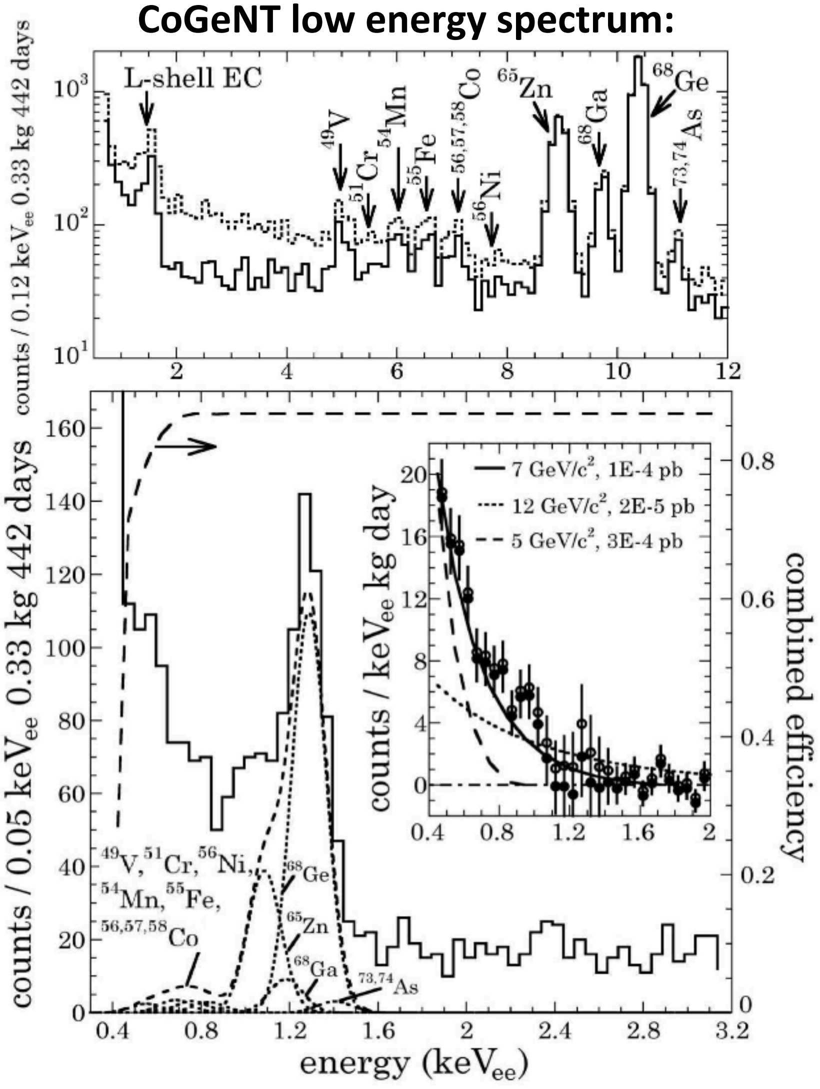
- 440 g PPC Ge detector with ~0.4 keVee threshold
- No electron recoil discrimination
- Low-energy excess above known backgrounds
- 2.8σ annual modulation in rate

CoGeNT rate vs. time:



Aalseth et al., Phys. Rev. Lett. **107**, 141301 (2011), arXiv:1106.0650v3
Aalseth et al., Phys. Rev. Lett. **106**, 131301 (2011), arXiv:1002.4703v2

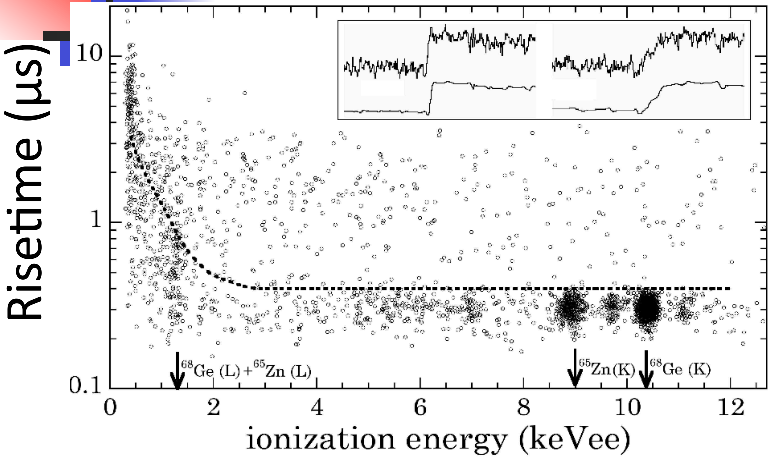
CoGeNT low energy spectrum:



CoGeNT

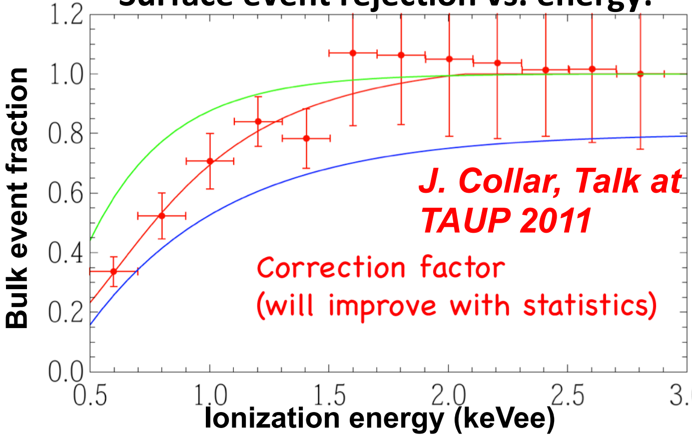
- Recent estimates suggest significant surface event contamination

Surface event cut:



Aalseth et al., Phys. Rev. Lett. ***106****, 131301 (2011), arXiv:1002.4703v2*

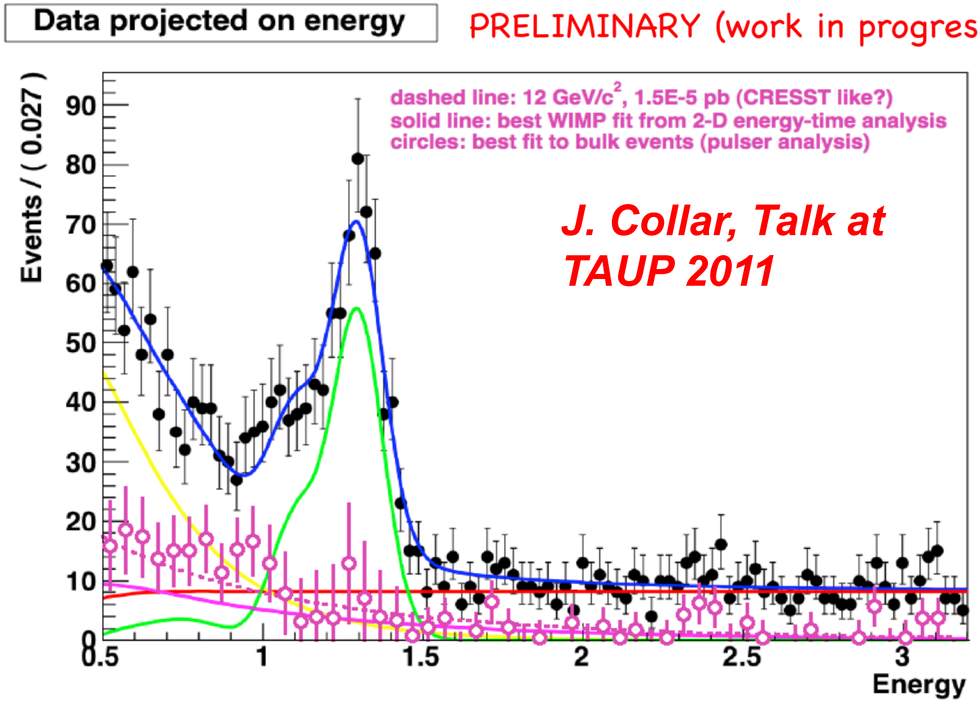
Surface event rejection vs. energy:



J. Collar, Talk at TAUP 2011

Correction factor (will improve with statistics)

Spectrum with background estimate:



PRELIMINARY (work in progress)

dashed line: 12 GeV/c^2, 1.5E-5 pb (CRESST like?)
solid line: best WIMP fit from 2-D energy-time analysis
circles: best fit to bulk events (pulser analysis)

J. Collar, Talk at TAUP 2011

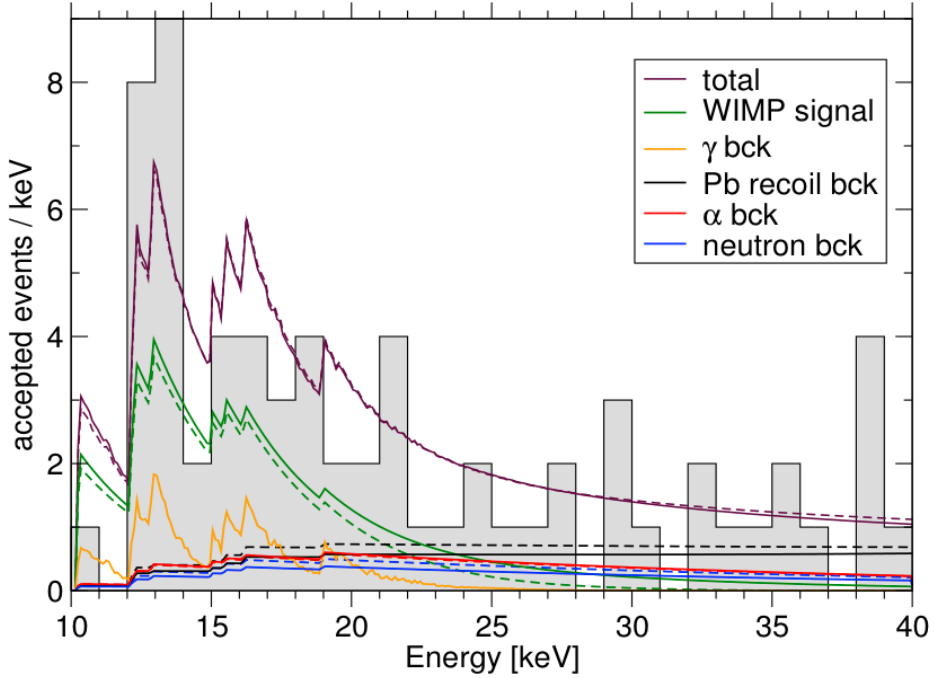
http://taup2011.mpp.mpg.de/?pg=Agenda&topic=9

Implies higher modulation fraction and harder spectrum than expected for standard halo

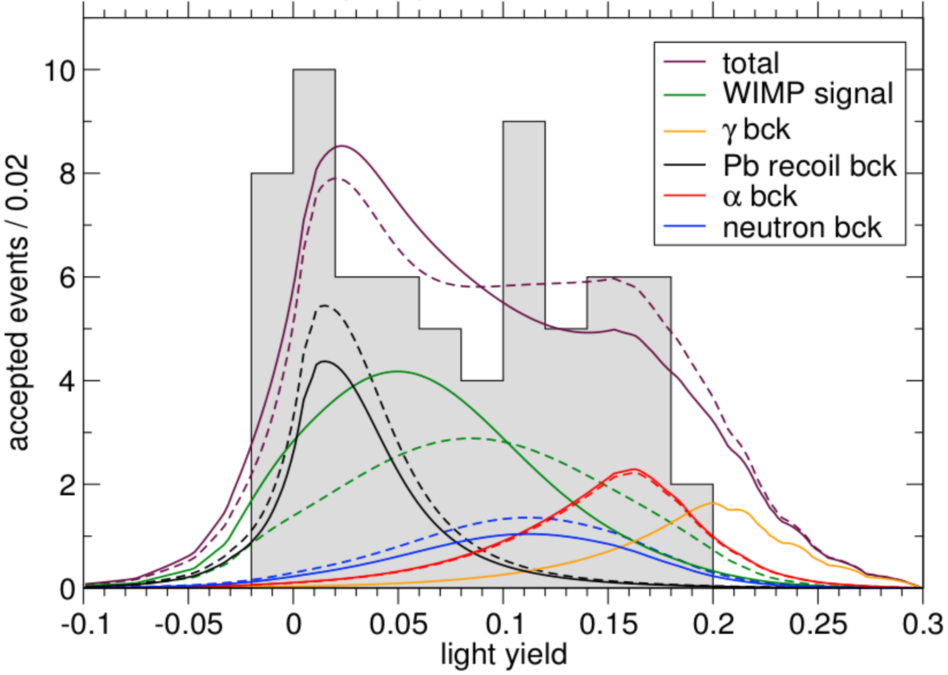
CRESST-II

- 730 kg-days exposure with $CaWO_4$ scintillator
- Measure both light and heat to reject electron recoils
- >4σ excess of low-energy events with low-light yield

Energy spectrum:



Light-yield spectrum:

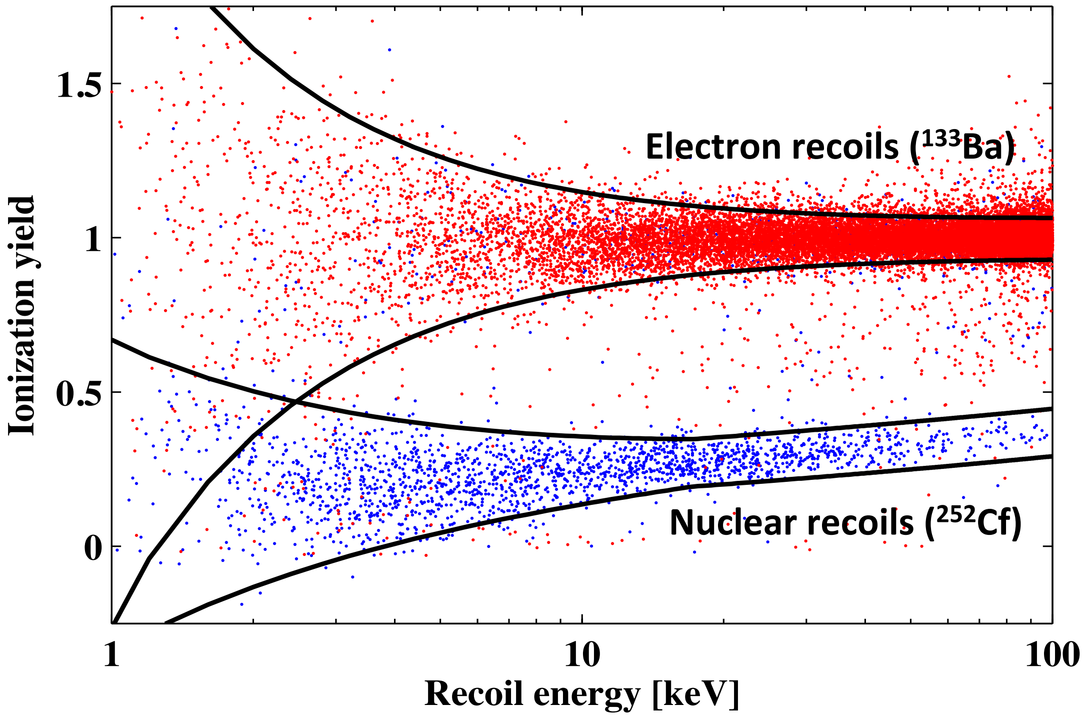


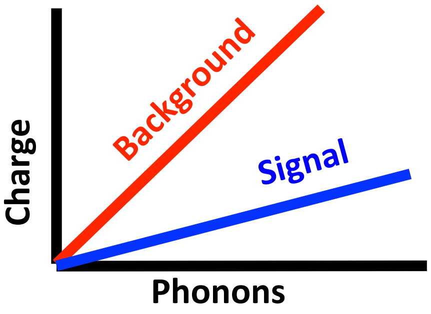
Angloher et al., arXiv:1109.0702v1

PROBLEM: HARD TO IDENTIFY BACKGROUNDS

CDMS experiment

- Electron-recoil backgrounds can be eliminated on an event-by-event basis
- Reduced ionization for nuclear recoils (Ionization yield = charge/phonons)





Rejection of calibration gammas:

> 10^4:1 above 10 keV

> 10:1 at 2 keV (T1Z5, T3Z4)

Germanium detector: same material and same location as COGENT

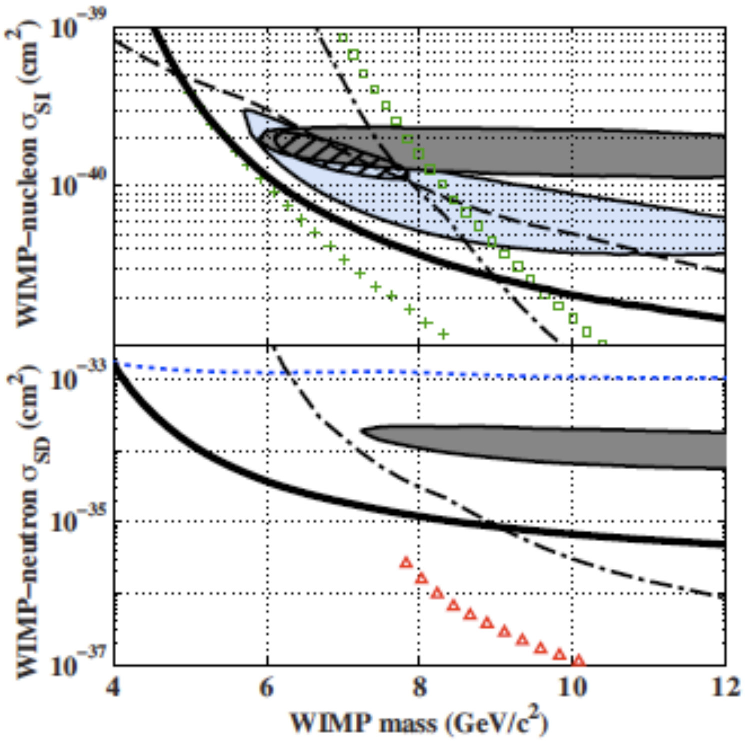


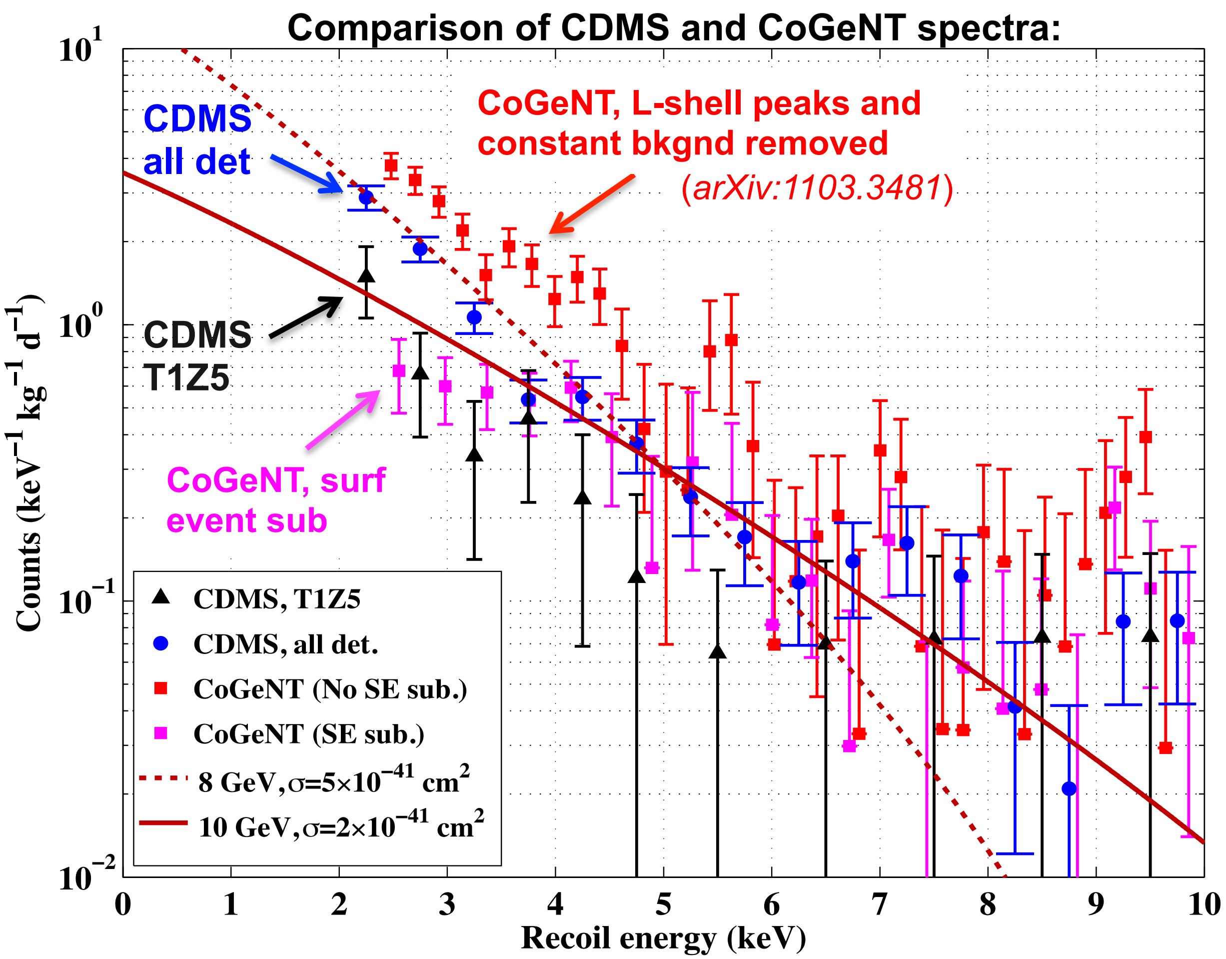
FIG. 3. (color online). Top: comparison of the spin-independent (SI) exclusion limits from these data (solid) to previous results in the same mass range (all at 90% C.L.). Limits from a low-threshold analysis of the CDMS shallow-site data [16] (dashed), CDMS II Ge results with a 10 keV threshold [13] (dash-dotted), recalculated for lower WIMP masses, and XENON100 with constant (+) or decreasing (□) scintillation-efficiency extrapolations at low energy [17] are also shown. The filled regions indicate possible signal regions from DAMA/LIBRA [6, 8] (dark), CoGeNT (light) [7, 8], and a combined fit to the DAMA/LIBRA and CoGeNT data [8] (hatched). Bottom: comparison of the WIMP-neutron spin-dependent (SD) exclusion limits from these data (solid), CDMS II Ge results with a 10 keV threshold (dash-dotted), XENON10 [18] (△), and CRESST [19] (dotted). The filled region denotes the 99.7% C.L. DAMA/LIBRA allowed region for neutron-only scattering [20]. An escape velocity of 544 km/s was used for the CDMS and XENON100 exclusion limits, whereas the other results assume an escape velocity from 600–650 km/s.

Reanalysis of CDMS data down to 2keV energy threshold claims to rule out anything below the solid black curves; this rules out COGENT low mass (10 GeV) region for spin-independent scattering (conservatively assumes all signal is WIMPs, no bkgnd)

N.b. red triangles are XENON-10 bounds

Comparison with CoGeNT

- Can directly compare rates for CDMSII and CoGeNT since both use Ge
- Both observe exponential spectrum above threshold
- Rate in T1Z5, T3Z4 inconsistent with CoGeNT excess
- Compatibility if only ≈25% of CoGeNT rate due to WIMPs, and backgrounds in CDMS smaller than expected
- No background subtraction for CDMS

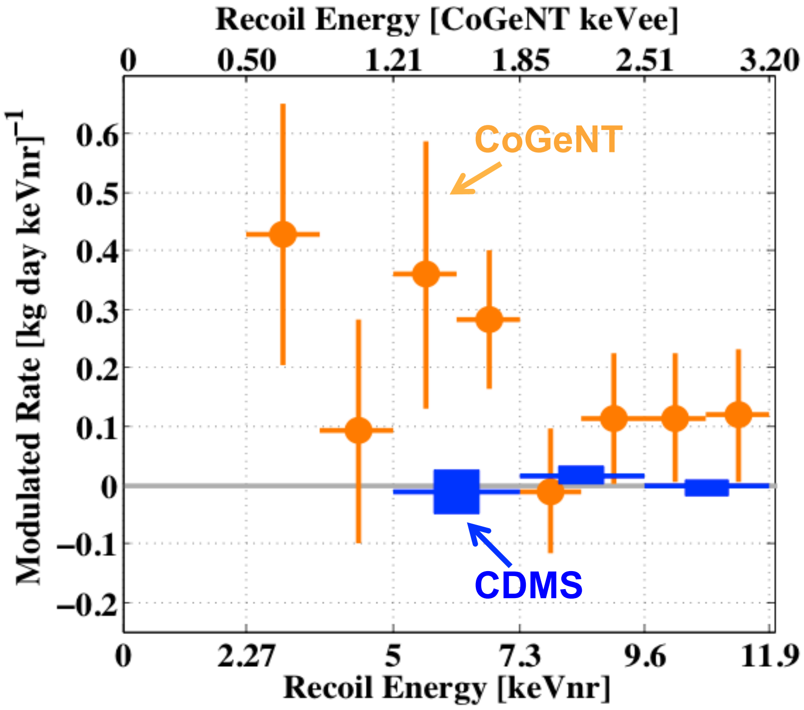


CDMS saw no Annual Modulation (down to 5keV)

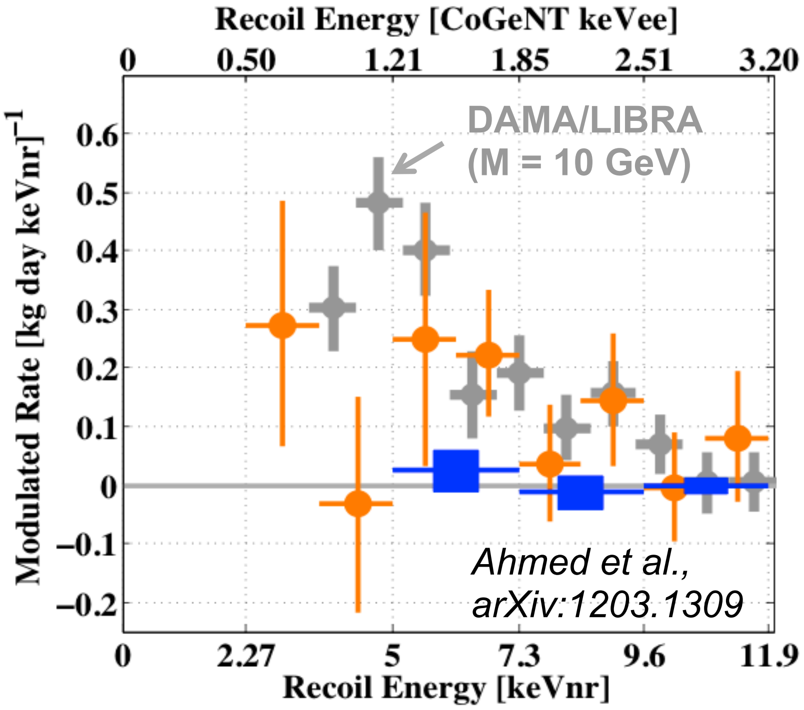
- Energy spectrum of modulation determined from maximum likelihood fits to CDMS and CoGeNT data
- DAMA/LIBRA spectrum converted to Ge expected rate assuming spin-independent elastic scattering from Na ($q_{Na} = 0.3$)

Fox et al., Phys Rev ***D*** *83, 103514 (2011), arXiv:1011.1915*

CoGeNT best fit phase (Apr. 16th):



Standard halo (max June 2nd):

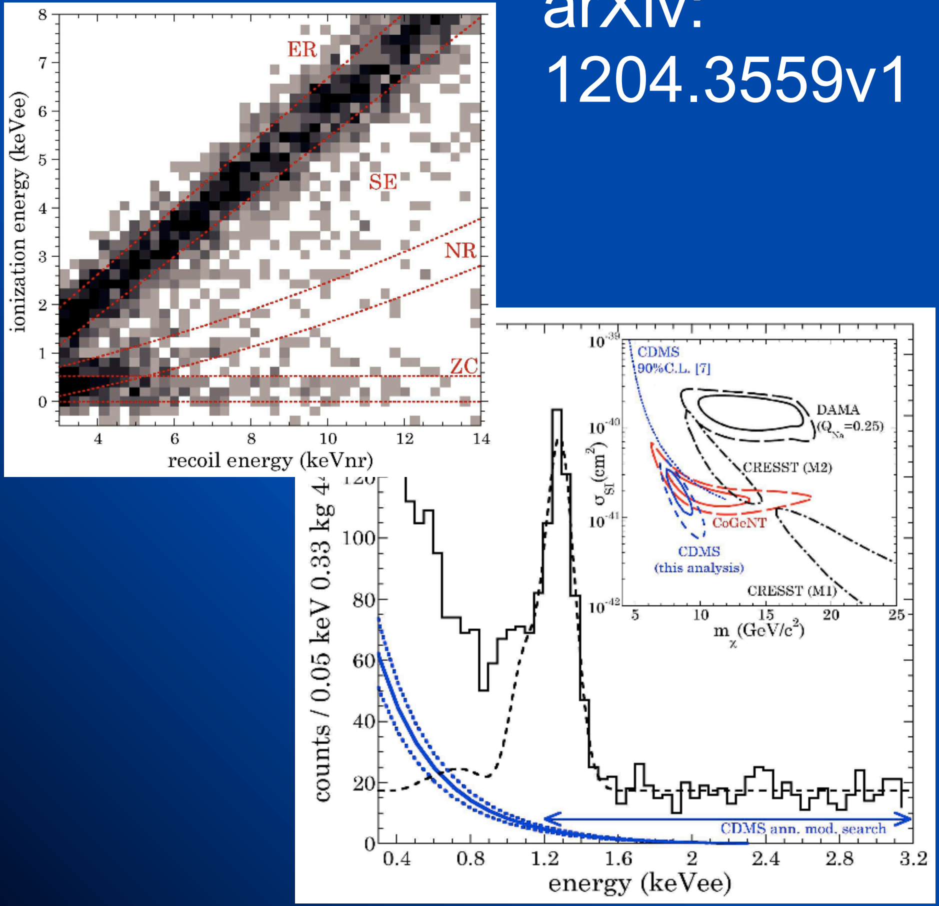


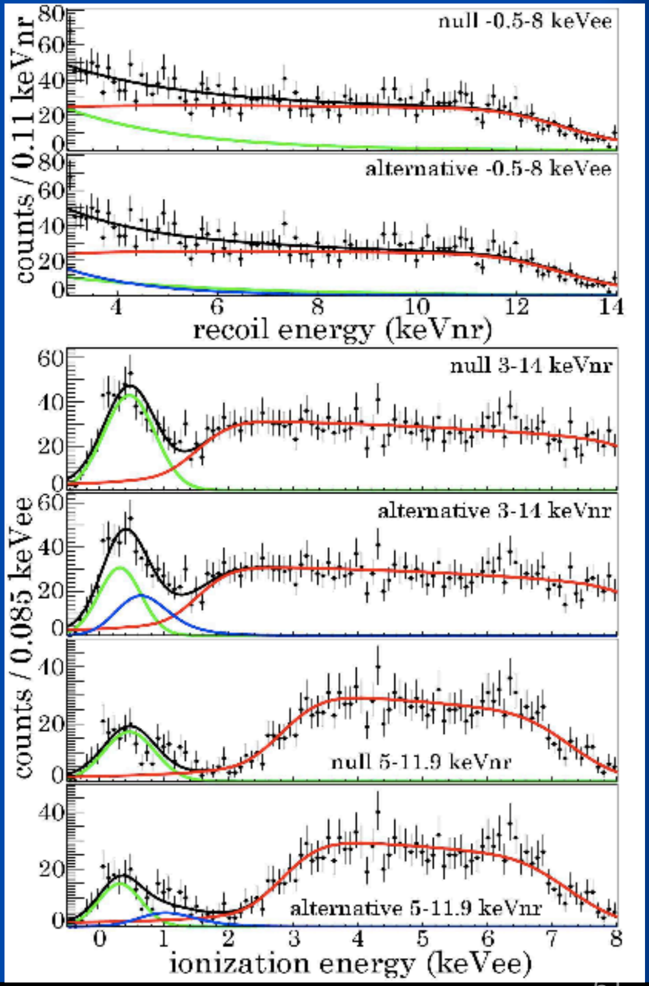
Ahmed et al., arXiv:1203.1309

Claims that CDMS saw the Dark Matter and missed it.   Not very likely!

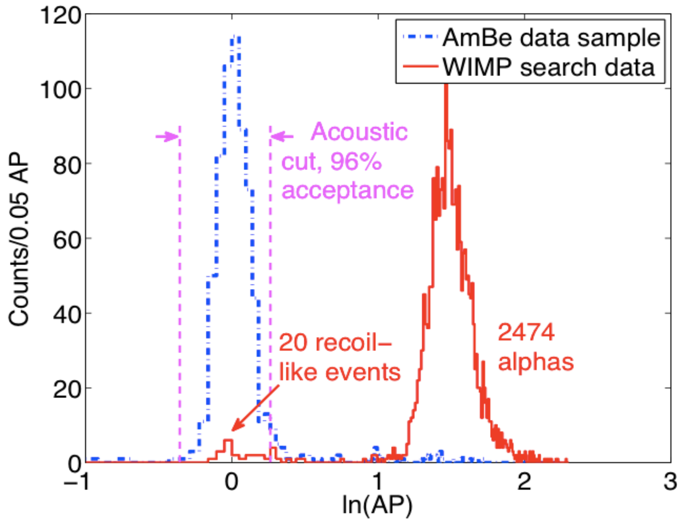
- J. Collar and N. Fields claim >5σ evidence for WIMP signal in CDMS

arXiv: 1204.3559v1



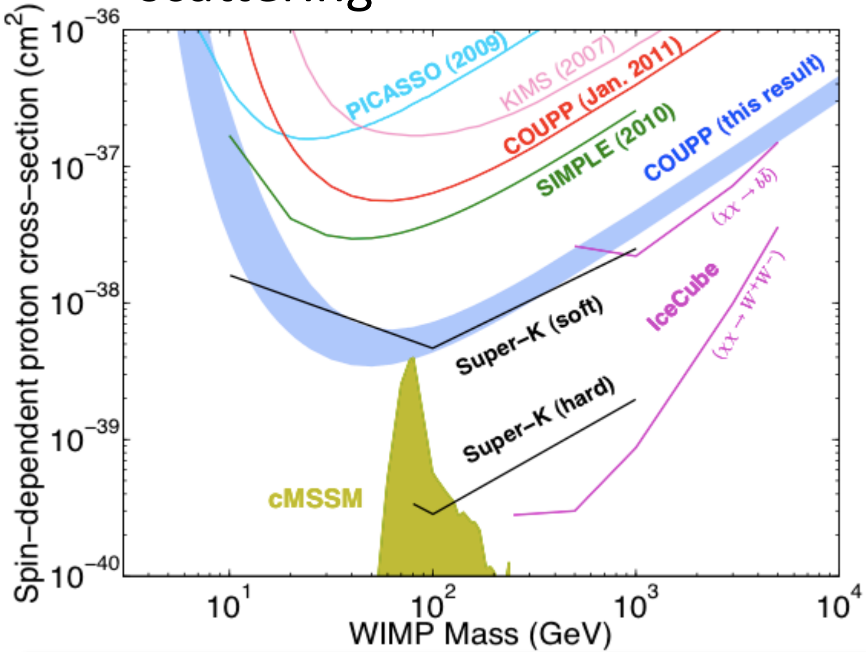


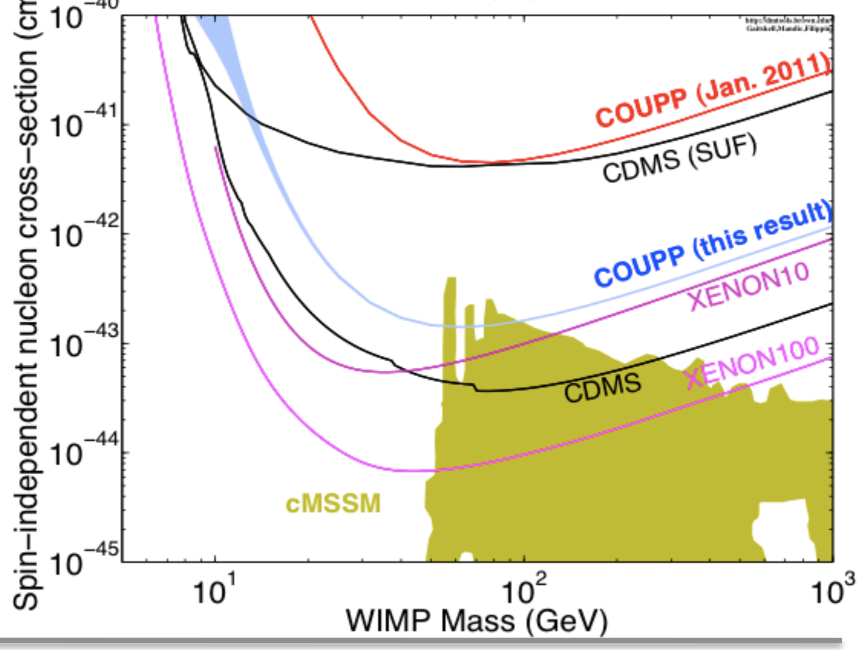
arXiv:1204.3094v1



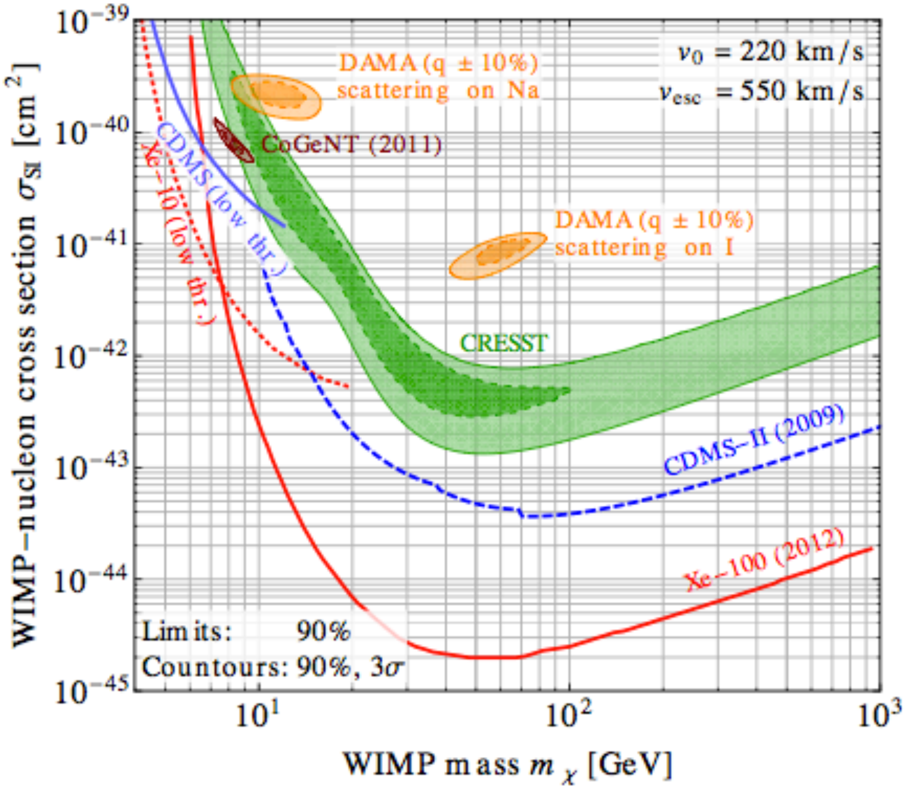
20 single bubble events in COUPP:

Tightest bound on Spin Dependent scattering





Data from Multiple Experiments for SI scattering



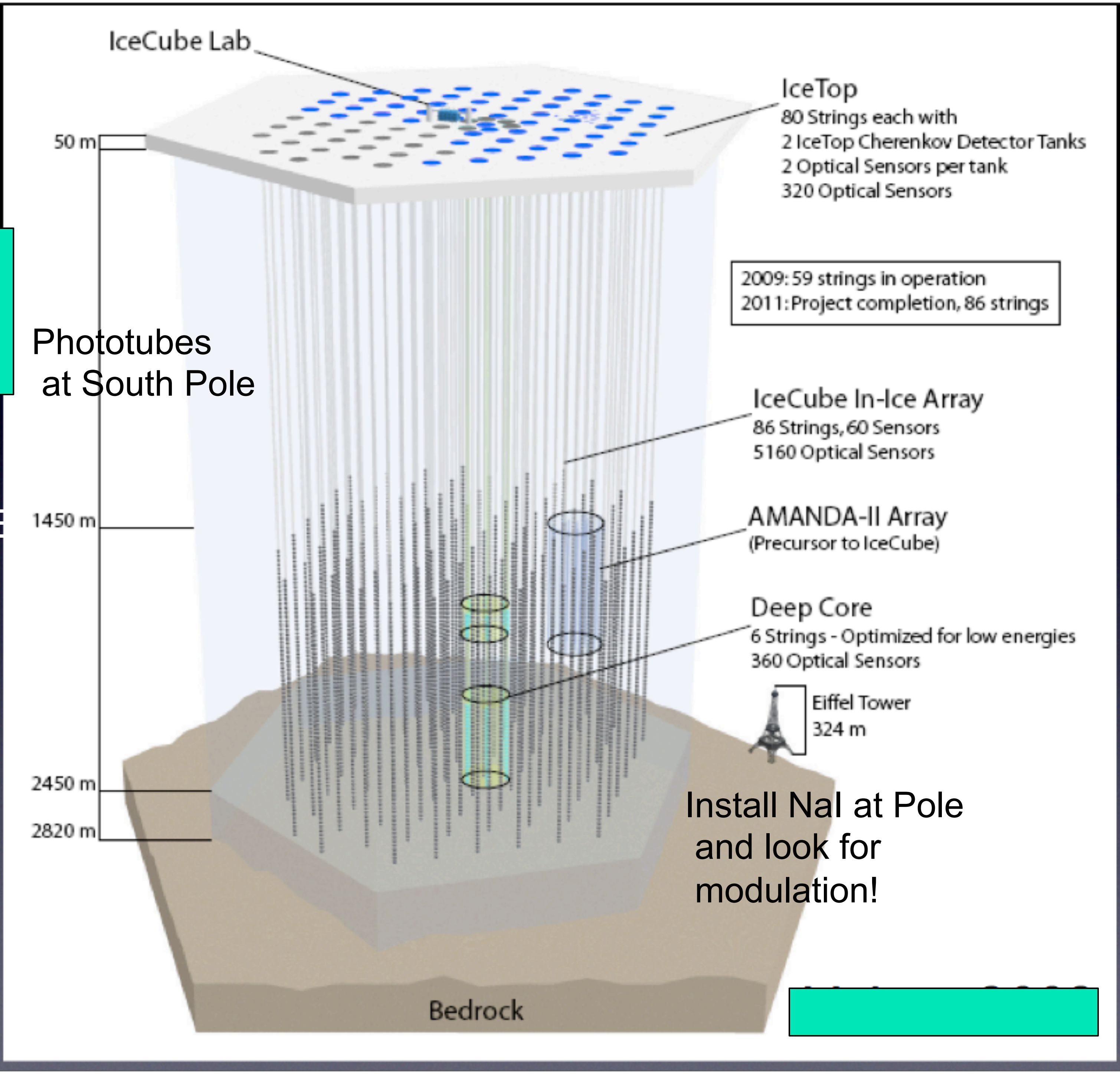
Joachim Kopp

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



Phototubes at South Pole

Install NaI at Pole and look for modulation!

[redacted]

More data soon!

- CoGeNT still running to increase statistics on modulation, more detectors proposed
- CRESST-II working to reduce Pb-210 backgrounds
- NaI experiment in southern hemisphere at IceCube (DMIce)
- XENON100, SuperCDMS, COUPP, LUX should improve sensitivity to low mass signal while probing high-mass region

To explain low mass DM: Non-Minimal?

Limited imagination or good taste?

- Dipole Dark Matter
- Inelastic Dark Matter (ruled out by XENON)
- Form Factor Dark Matter
- Electronic Interactions
- Asymmetric Dark Matter (tied to baryon asymmetry)

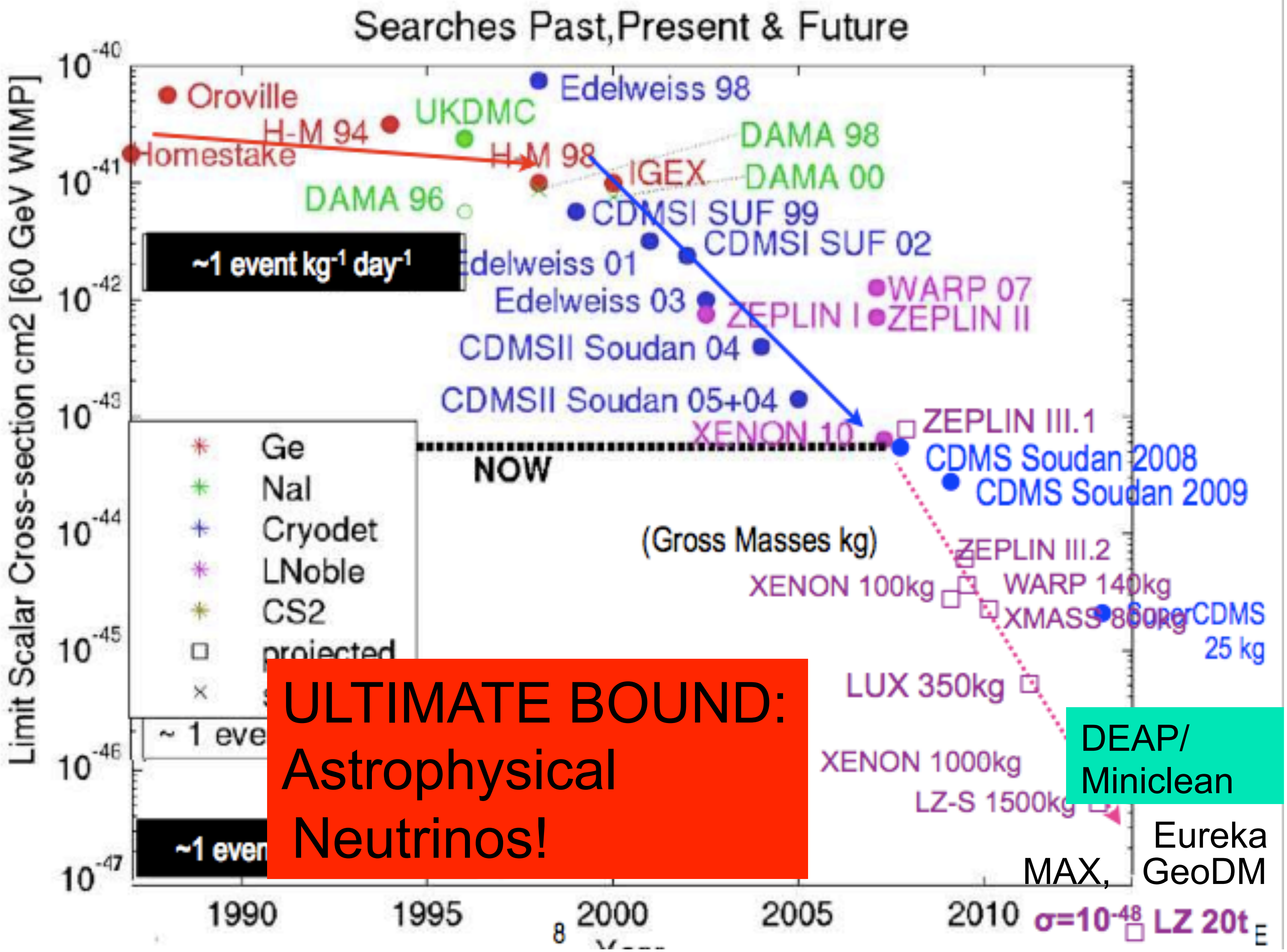
Non-minimal Dark Matter Interactions

$$\begin{aligned}
\mathcal{O}_{SI} &= (\bar{\chi}\chi)(\bar{q}q), \\
\mathcal{O}_{SD} &= (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q),
\end{aligned}$$

$$\begin{aligned}
\mathcal{O}_1 &= (\bar{\chi}\gamma_5\chi)(\bar{q}q), \\
\mathcal{O}_2 &= (\bar{\chi}\chi)(\bar{q}\gamma_5 q), \\
\mathcal{O}_3 &= (\bar{\chi}\gamma_5\chi)(\bar{q}\gamma_5 q), \\
\mathcal{O}_4 &= (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu q).
\end{aligned}$$

S. Chang, APierce, and N. Weiner JCAP 1001 (2010) 006
Also P. Fox

DM Direct Search Progress Over Time



ULTIMATE BOUND: Astrophysical Neutrinos!

DEAP/ Miniclean

Eureka

MAX, GeoDM

Dark Matt

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
- First, head/tail asymmetry: WIMP flux is peaked in direction of motion of Sun (towards constellation Cygnus). Recoil spectrum should be peaked in opposite direction with 10 times the event rate. Compare count rates 180 degrees apart. Only need 10-100 WIMPs to get statistical significance.

Diurnal Modulation (due to Earth's rotation)

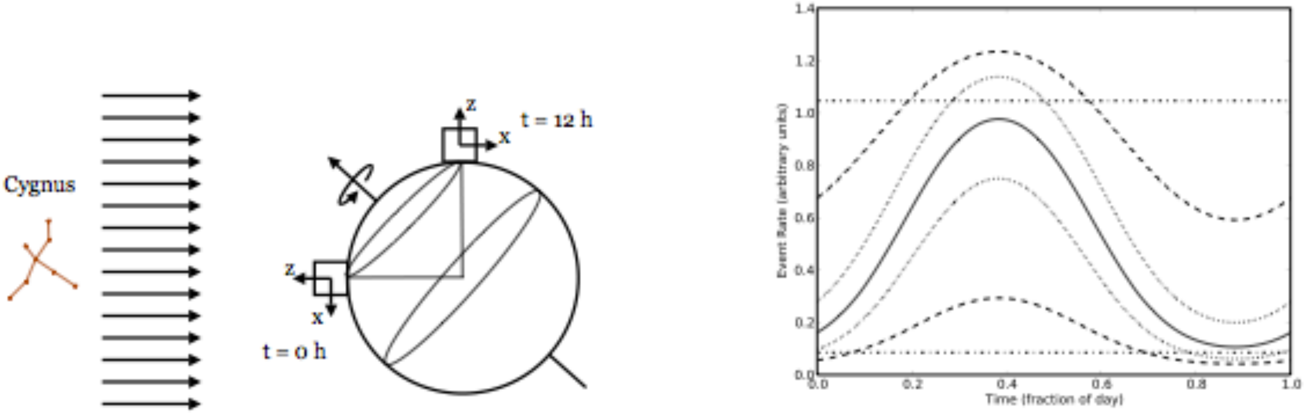


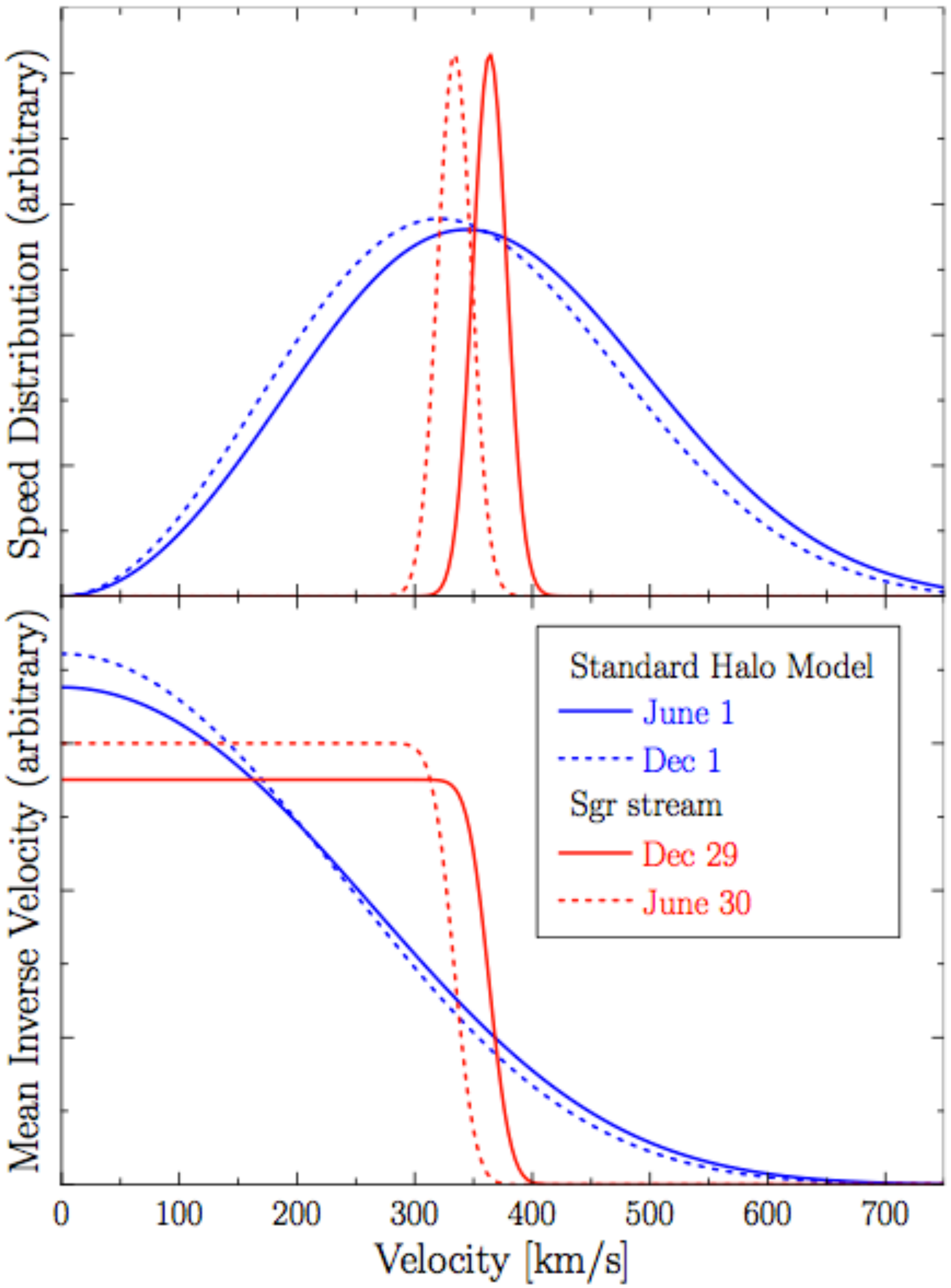
Fig. 2. (left) The daily rotation of the Earth introduces a modulation in recoil angle, as measured in the laboratory frame. (right) Magnitude of this daily modulation for seven lab-fixed directions, specified as angles with respect to the Earth's equatorial plane. The solid line corresponds to zero degrees, and the dotted, dashed, and dash-dot lines correspond to $\pm 18^\circ$, $\pm 54^\circ$ and $\pm 90^\circ$, with negative angles falling above the zero degree line and positive angles below. The $\pm 90^\circ$ directions are co-aligned with the Earth's rotation axis and therefore exhibit no daily modulation. This calculation assumes a WIMP mass of 100 GeV and CS_2 target gas. (from Ref. [13]).

Powerful tools for DM searches

- Measure of annual plus diurnal modulation would be smoking gun for WIMPs
- Plus, any galactic substructure such as streams would show up as spikes in a directional detector

Streams of WIMPs

- For example, leading tidal stream of Sagittarius dwarf galaxy may pass through Solar System
  Majewski et al 2003, Newberg et al 2003
- Dark matter density in stream $\sim 0.01^{+0.20}_{-0.01}\ \rho_{local}$
  Freese, Gondolo, Newberg 2003
- New annual modulation of rate *and* endpoint energy; difficult to mimic with lab effects
  Freese, Gondolo, Newberg, Lewis 2003

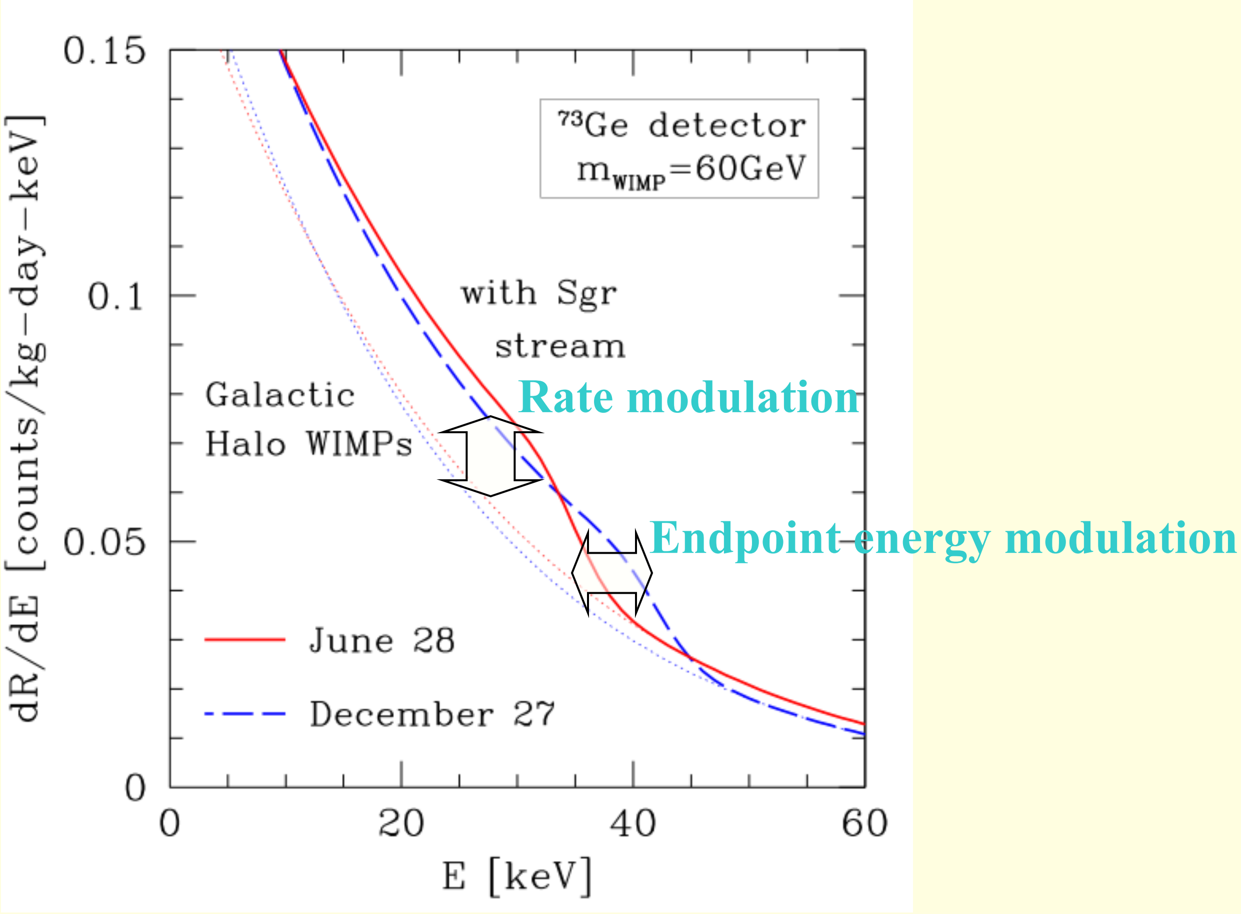


Freese
Lisanti
Savage

Annual Modulation
of Dark Matter:
A Review

(for Reviews of
Modern Physics)

Sagittarius stream

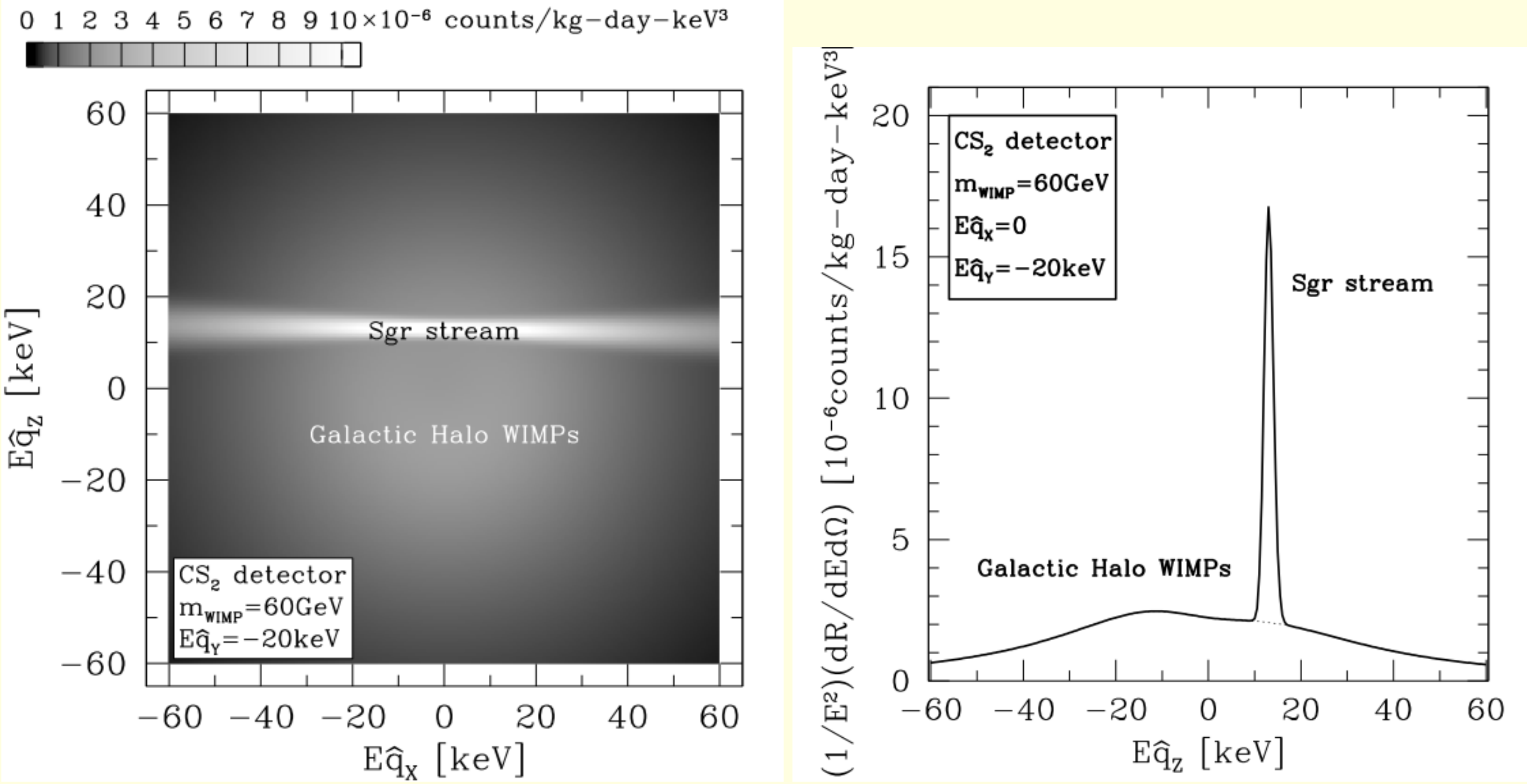


Plot for 20% Sgr stream density (to make effect visible); $\sigma_{\chi p}$=2.7x10^{-42}cm^{2}

Sagittarius stream

Freese, Gondolo, Newberg 2003

Directional detection with DRIFT-II

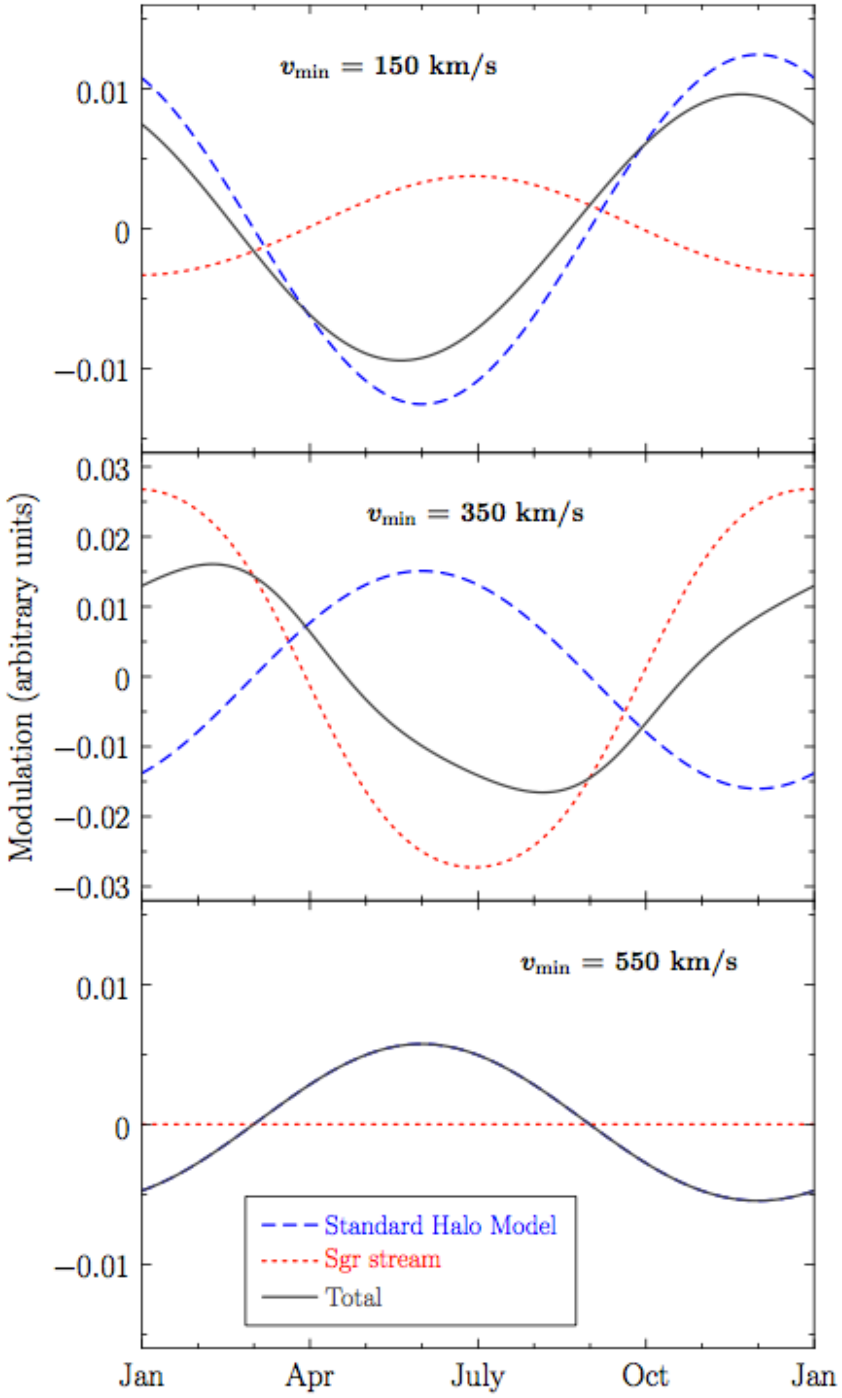


STREAM PLUS HALO

For 60 GeV WIMP and Ge target, 7 keV recoil energy

40 keV recoil energy

100 keV recoil energy



Shifts peak date of modulation.

Also, note phase reversal at different energy recoils: Can be used to determine WIMP mass (Freese and Lewis)

Chris Savage

Sagittarius stream

- Increases countrate in detectors up to cutoff in energy spectrum
- Cutoff location moves in time
- Sticks out like a sore thumb in directional detectors
- Changes date of peak in annual modulation
- Smoking gun for WIMP detection

Heirarchical Phase Space Structure of dark matter haloes

- Important for DM detection
- E.g. caustics with enhanced DM annihilation
- Afshordi, Mohayaee, Bertschinger 09

Limitations of Existing Detectors

- Track length of the recoiling nucleus (below 10 nm) is shorter than spatial resolution of the detector (microns).
- Approach: get detector to lower density to allow for longer recoil tracks, e.g. use CF4 gas pumped to 0.1 Atmosphere.. Required volume 10^4 m^3, one ton, $150 million.
- Existing prototypes: DRIFT 30gm(1m^3), DMTPC 3gm. Need to be scaled up.

Smaller, Cheaper Alternative: ssDNA Tracker

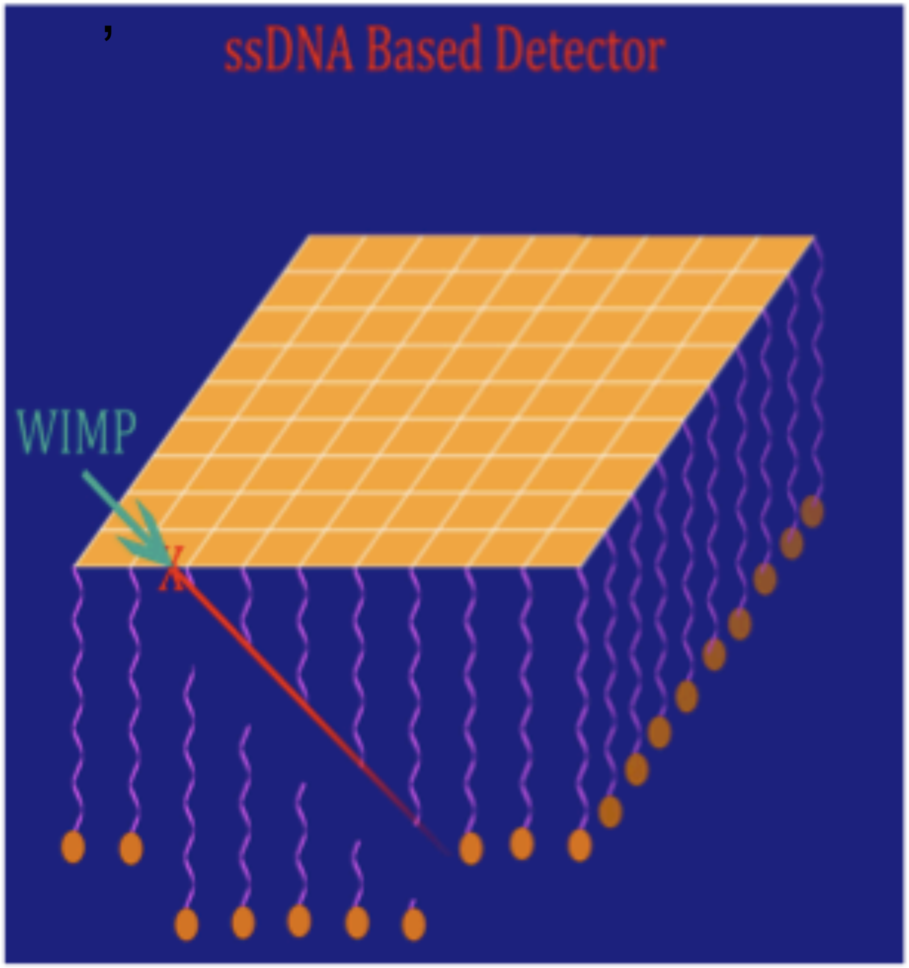
- Andrzej Drukier, Katherine Freese, David Spergel, Charles Cantor, George Church, Takeshi Sano

Use DNA as nanometer tracker

- WIMP hits nucleus (transducer)
- Recoiling nucleus travels through ssDNA with known sequence of base pairs (0.7 nm apart)
- Breaks ssDNA
- Location of break can be amplified and sequenced
- Track of nucleus known to nanometer accuracy

One implementation:

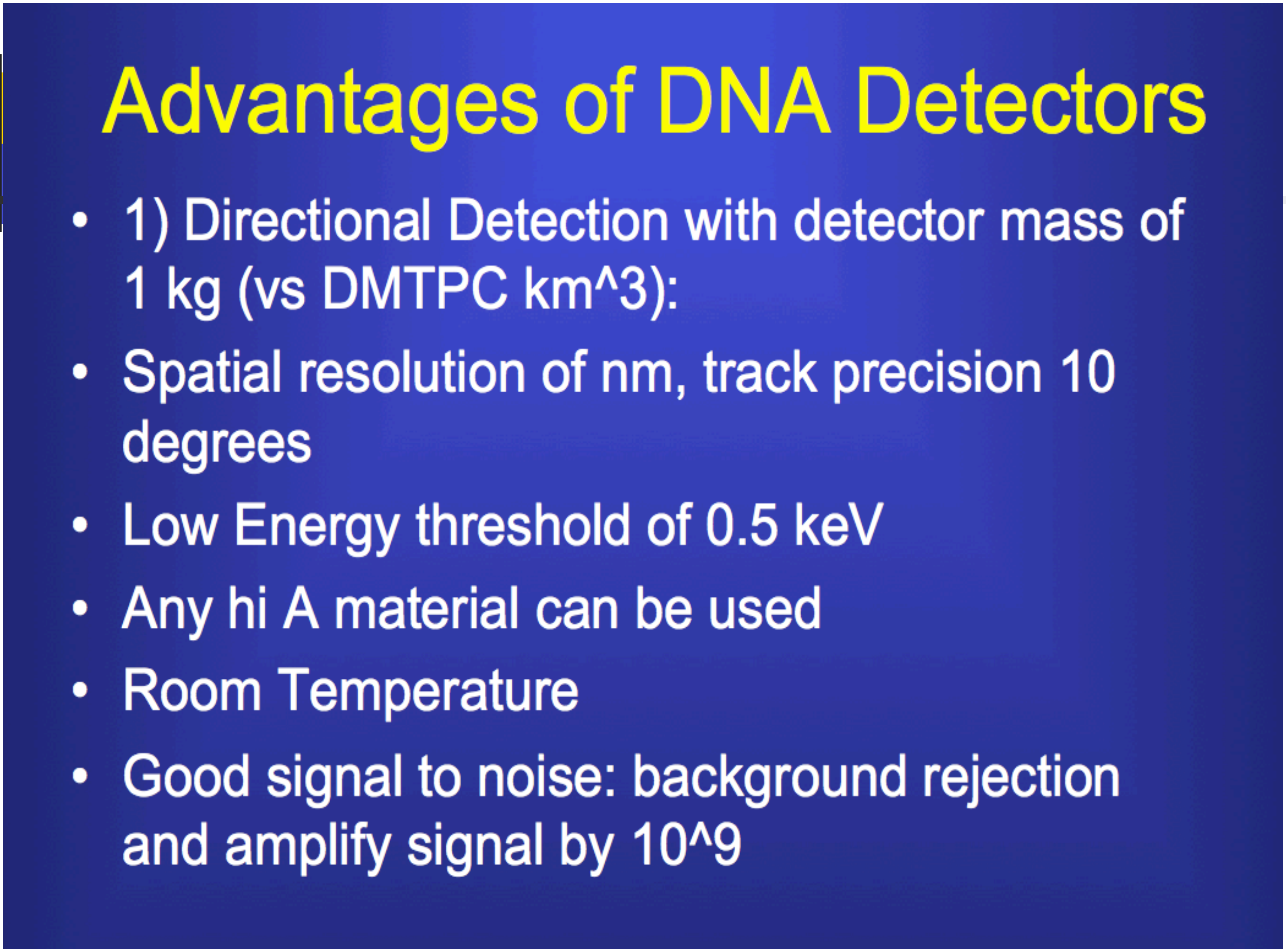
- 1 kg Gold, 1 kg ssDNA, identical sequences of bases with an order that is well known



BEADED CURTAIN OF ssDNA

WIMP from galaxy knocks out Au nucleus, which traverses DNA strings, severing the strand whenever it hits.

- Recoiling nucleus from WIMP interaction carries about 10 keV of energy.
- It takes about 10 eV to break ssDNA (will need experimental test).
- Cutoff segment of DNA falls down to a capture foil and is periodically removed.
- Errors in DNA are easy to replicate:
- Make copies of broken segment with PCR (amplify the signal a billion fold)
- DNA ladder: sequence with single base accuracy, i.e. nm precision



Advantages of DNA Detectors

- 1) Directional Detection with detector mass of 1 kg (vs DMTPC km^3):
- Spatial resolution of nm, track precision 10 degrees
- Low Energy threshold of 0.5 keV
- Any hi A material can be used
- Room Temperature
- Good signal to noise: background rejection and amplify signal by 10^9

Modular Detector

- Identical units stacked on top of each other (like a book): 5000 such units.
- On top: 1 micron layer of mylar (inactive)
- Next: 5-10 nm layer of gold (10 atoms thick); WIMP interacts with Au nuclei.
- ssDNA strands: 0.7nm per base when stretched, operate in helium or nitrogen gas
- Strands differ only in “terminus pattern” of say 20-100 bases at the bottom (actually members of a small bunch of DNA strands), like balls of different colors attached on the bottom.

Resolution of Detector

- In z direction, nm (distance between bases in DNA strand)
- In x-y direction, micron times micron (size of bunch of DNA strands with same base sequences).
- Location where DNA was severed is identified with nm resolution in z and micron resolution in x and y.
- Track of recoiling Au nucleus determined.

Head/Tail Asymmetry: use to discover dark matter with only 10-100 events.

- Expect WIMPs from direction of Cygnus to be 10 times that from opposite direction, since we are moving into Galactic wind of WIMPs.
- WIMPs coming first through mylar then through Au and ssDNA can be detected. Those going the other way will not (interaction with Au will produce nuclei that get stuck in mylar).

Next Generation

- Actually track the path of the recoiling particle
- Nanometer resolution in z-direction
- Micron resolution in x,y directions: polka dot pattern on Au produces periodic array of ssDNA

Backgrounds

- DNA is radioactive (i.e. you are too). Must eliminate C14 and K41. Also need clean thin films of Au or other elements.
- Must put detector underground (like all dark matter detectors)
- Gammas, alphas, e, cosmic rays: their range is 100 times longer (energy deposition scales as Z^2); they will traverse hundreds of foils (not just one)

More on backgrounds

- Backgrounds are isotropic, whereas signal comes from a preferred direction. Thus tracking capability is important.
- Biggest problem: fast neutrons. Do Monte Carlos. Put in Homestake mine, use water from LUX detector as shield.

Required Tests

- Test response of ssDNA to heavy ion hits e.g. 5,10,30 GeV Ga ions from an ion implementation machine. Best guess: it takes 10 eV to break a strand. Since nucleus carries about 10 keV energy from the WIMP, it takes 100s to 1000s of hits of Au on ssDNA to stop the Au.
- Currently off the shelf: arrays with 250 bases in length (Illumina Inc), 200 nm DNA strands
- Wanted: 1000 bases long, 0.7 micron

More experimental issues

- How to keep ssDNA strands straight? Electric field, weights along the strands?
- How to get severed strands to fall down: use electric or magnetic field?
- How to scoop the severed ssDNA (e.g. once per hour): use magentizable rod?

Goal: periodic array with 10 nm spacing

- Want single molecules attached to the Au plane on a well defined 2D “polka dot” pattern.
- DNA can be immobilized at one end, e.g. a Au-sulfur bond with DNA terminally labeled with a thiol group. OR Au coated with Streptavidin will hold DNA coated with biotin. OR simple positively charged dots.

Summary: ssDNA Tracker

- By identifying the track of the recoiling nucleus from a WIMP interaction, obtain directional sensitivity i.e. identify where the WIMP came from.
- This allows dark matter discovery with much lower statistics (10-100 events).
- This allows for background rejection using annual and diurnal modulation.

III. THIRD WAY TO SEARCH FOR WIMPS

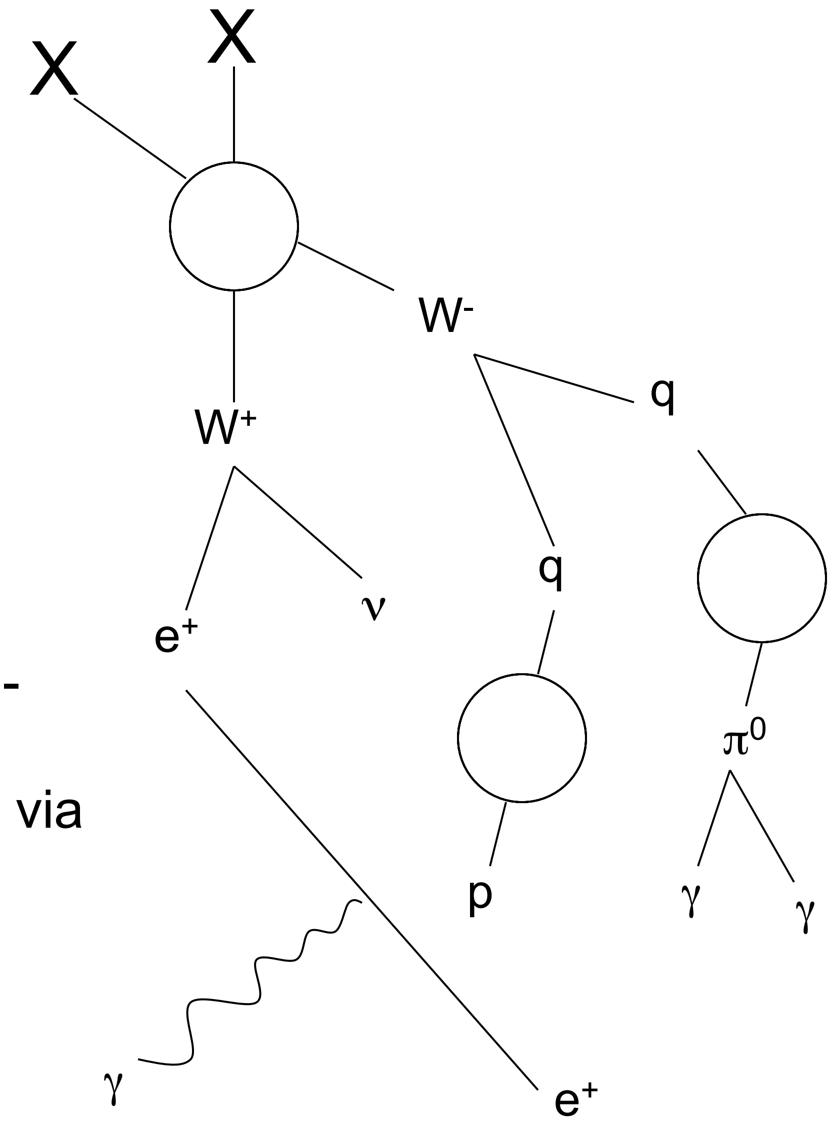
INDIRECT DETECTION:
searching for astrophysical WIMP annihilation products

Indirect Detection

1. **WIMP Annihilation** Depending on the model, annihilations can produce Standard Model fermions, gauge or Higgs bosons

2. **Fragmentation/Decay** Annihilation products decay and/or fragment into combinations of electrons, protons, deuterium, neutrinos and gamma-rays

3. **Synchrotron and Inverse Compton Scattering** Relativistic electrons up-scatter starlight/CMB to MeV-GeV energies, and emit synchrotron photons via interactions with magnetic fields



Annihilation Products

- 1/3 electron/positrons
- 1/3 gamma rays
- 1/3 neutrinos
- Typical particles have energies roughly 1/10 of the initial WIMP mass
- All of these are detectable!

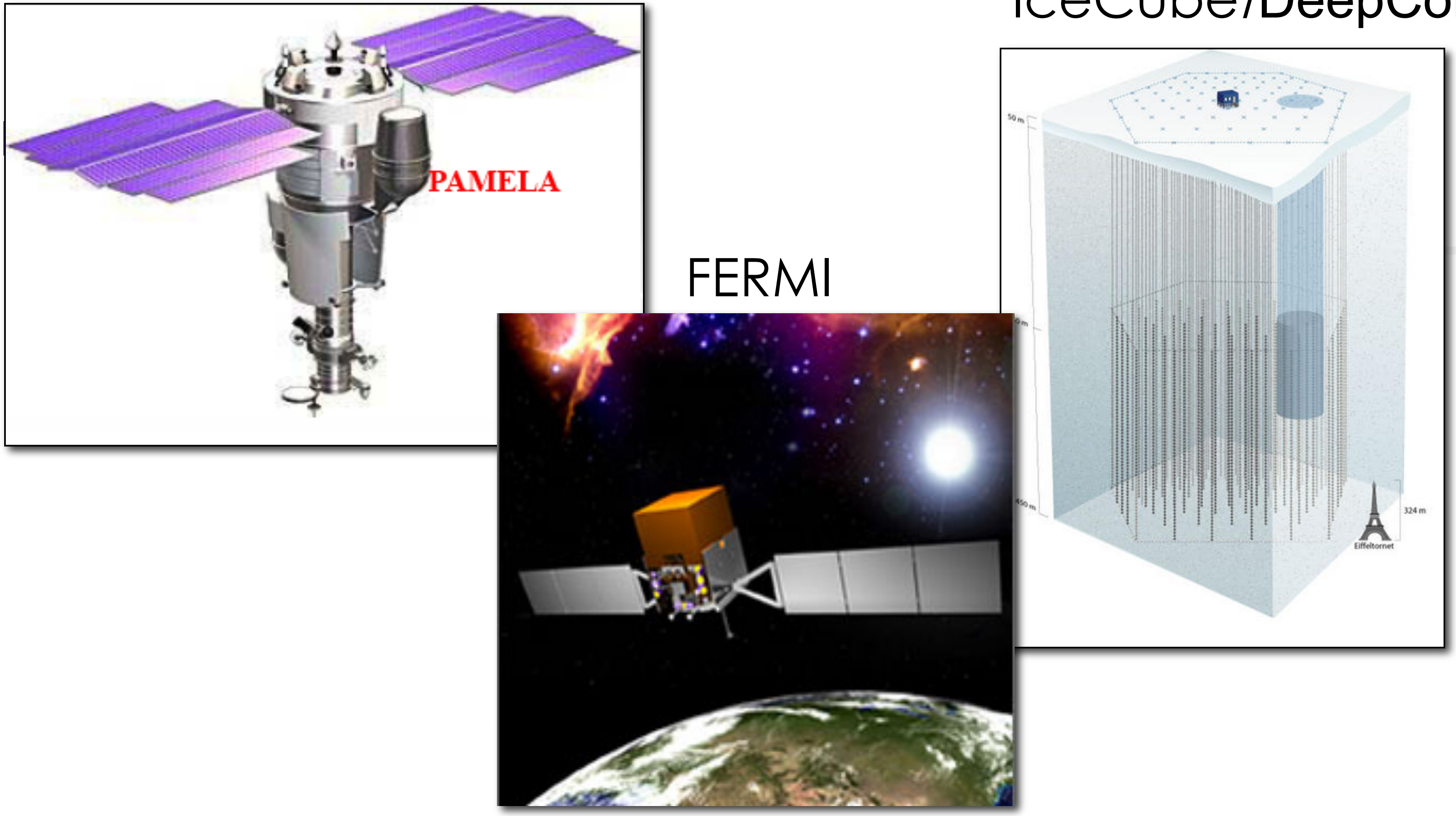
Indirect Detection History

- Indirect Detection (Neutrinos)
  - Sun (Silk,Olive,Srednicki '85)
  - Earth (Freese '86; Krauss, Srednicki, Wilczek '86)
- Indirect Detection (Gamma Rays, positrons)
  - Milky Way Halo (Ellis, KF et al '87)
  - Galactic Center (Gondolo and Silk 2000)
  - Anomalous signals seen in HEAT (e+), HESS, CANGAROO, WMAP, EGRET, PAMELA.

Indirect Detection in Sun

Silk, Olive, Srednicki
1985

New Indirect Detection Results

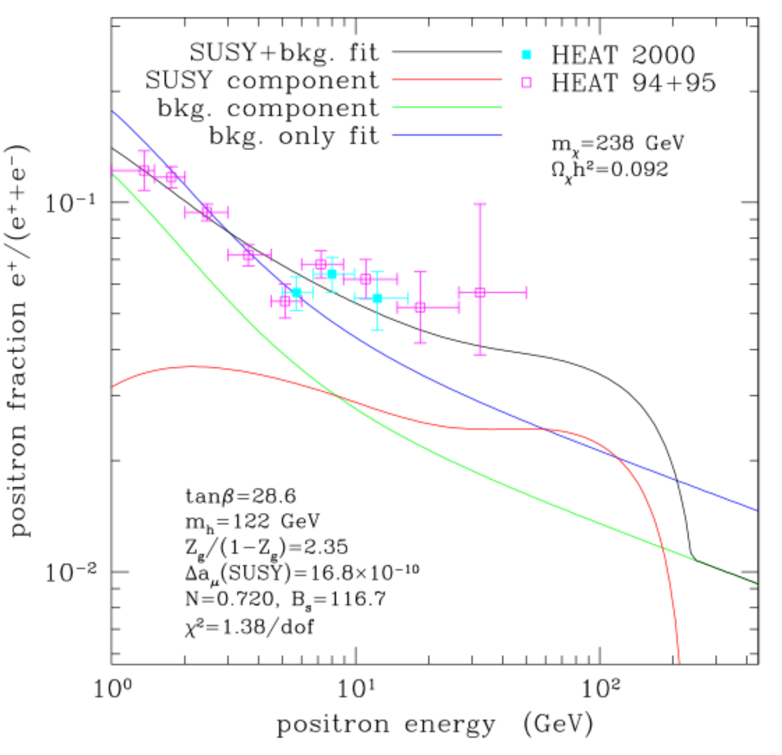


Pamela

FERMI

IceCube/DeepCore

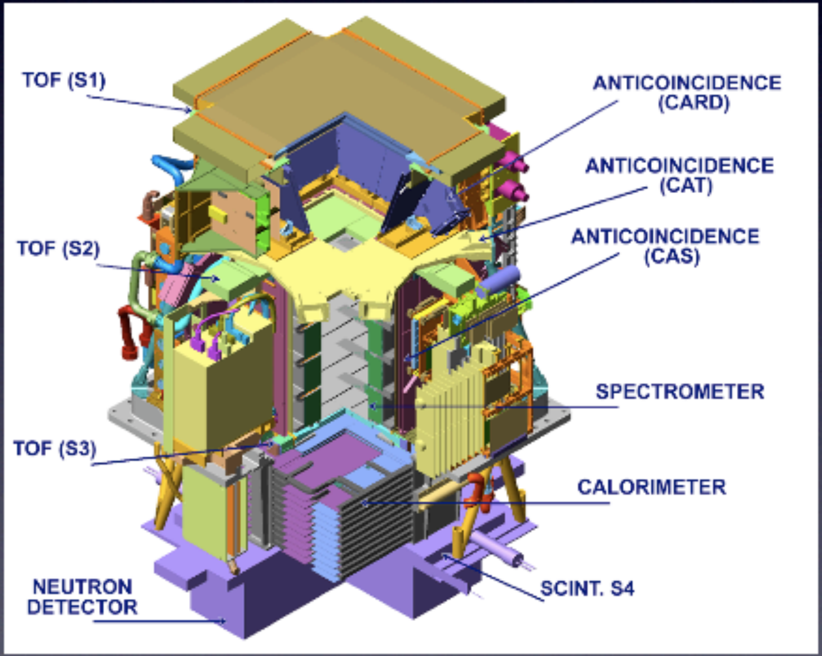
Positron excess

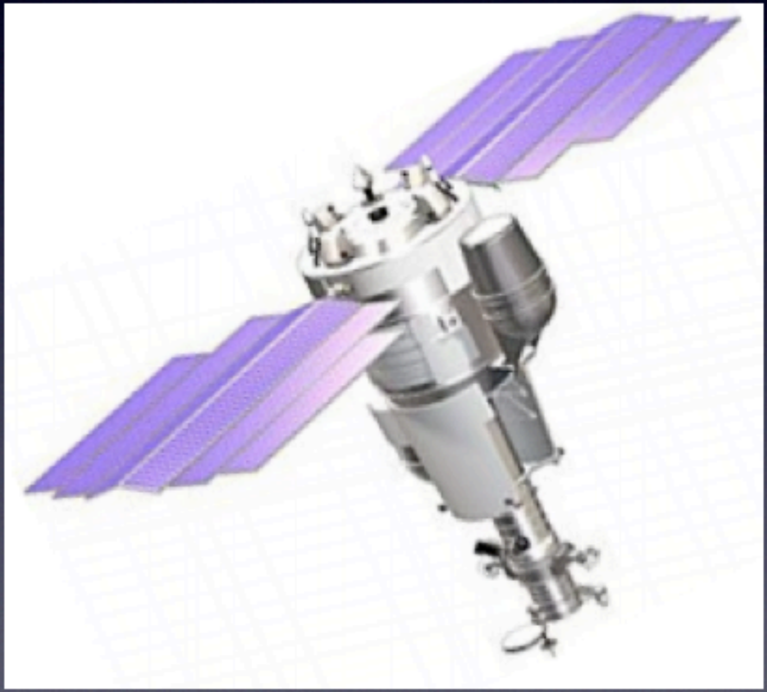


- HEAT balloon found anomaly in cosmic ray positron flux
- Explanation 1: dark matter annihilation
- Explanation 2: we do not understand cosmic ray propagation

Baltz, Edsjo, Freese, Gondolo 2001

PAMELA
Cosmic Ray Satellite

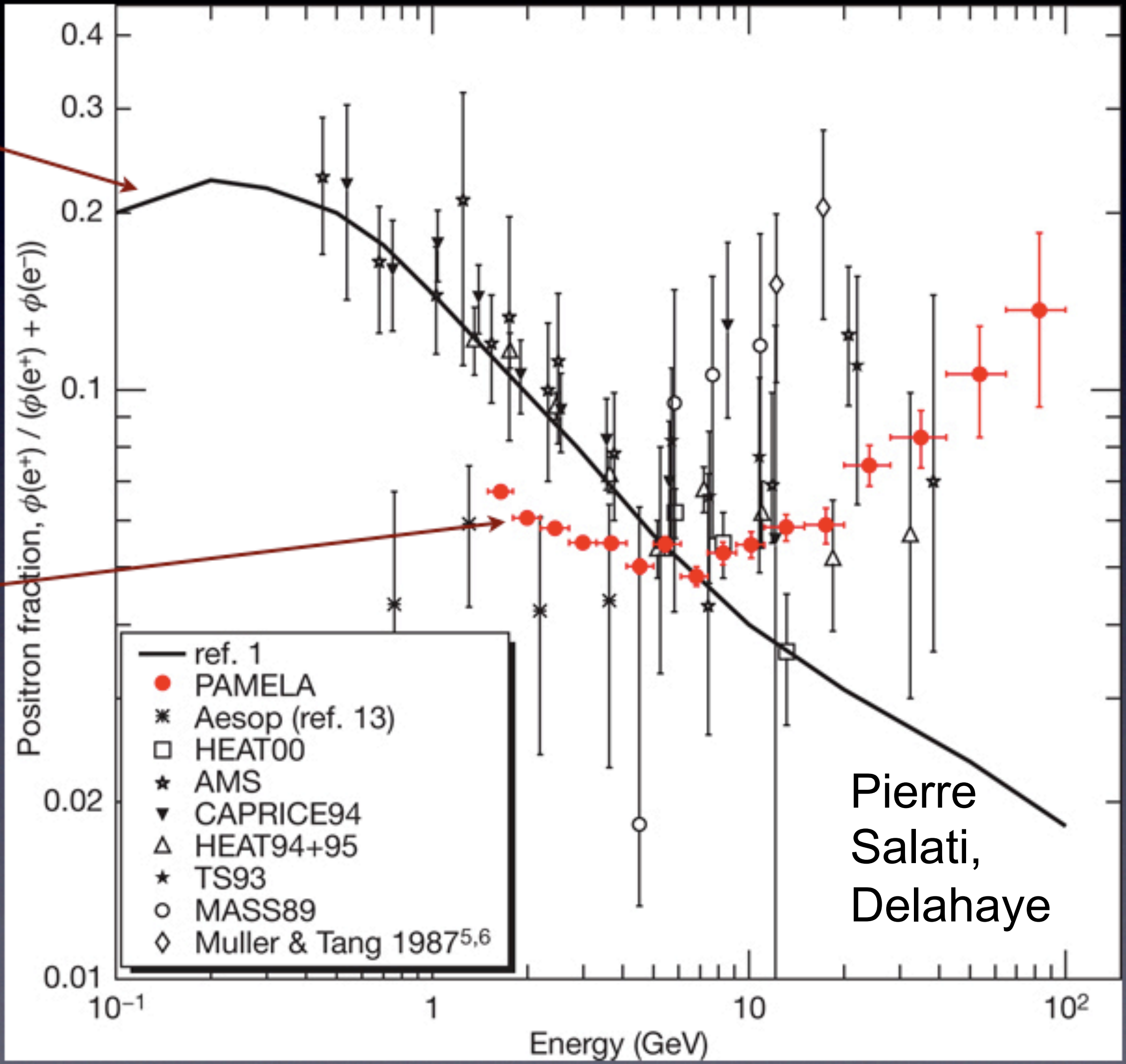




PAMELA Excess

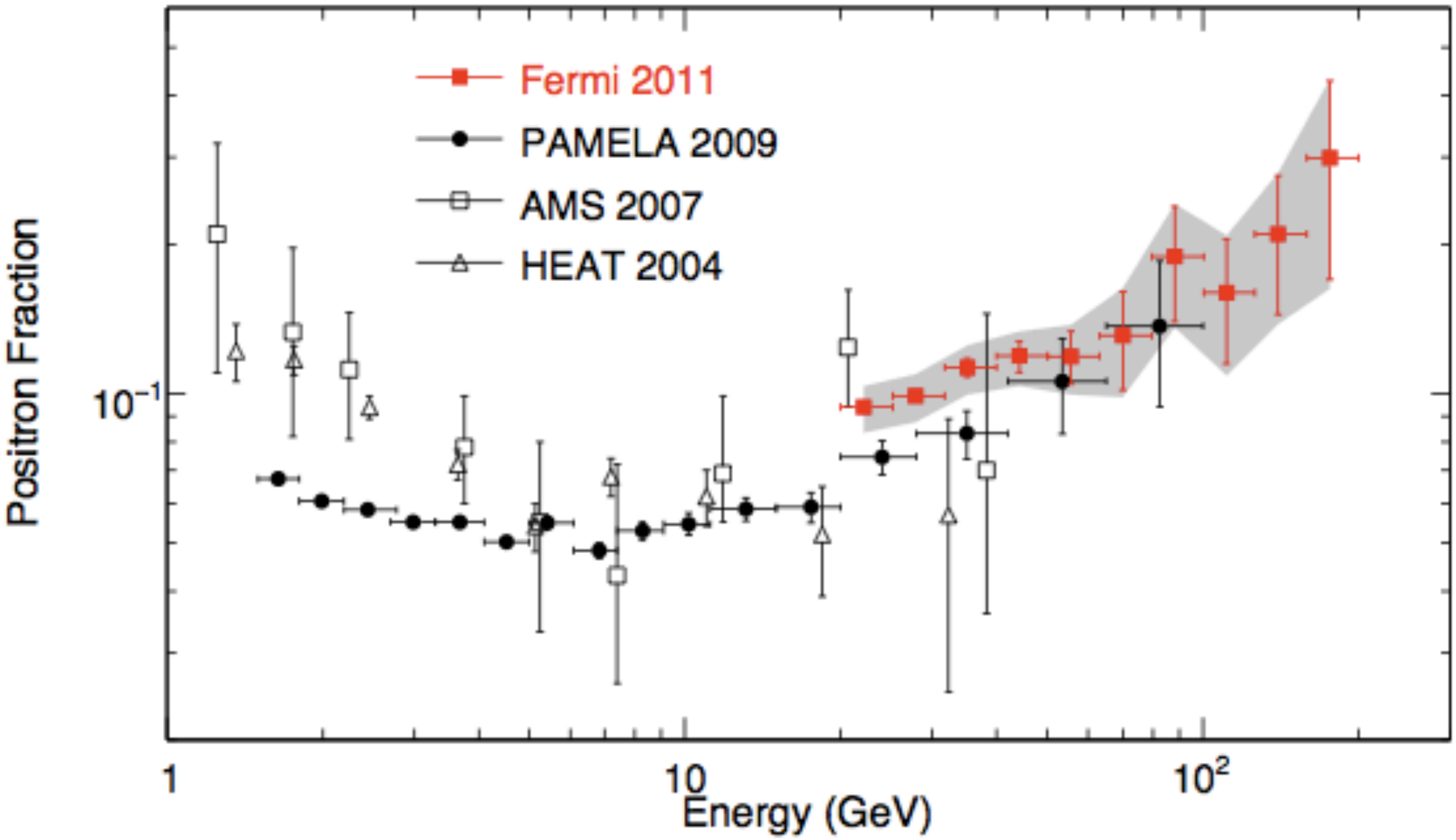
GALPROP

PAMELA



Pierre
Salati,
Delahaye

Fermi positron fraction



Ackermann et al. [Fermi LAT Collaboration] 2011

How to understand positron excess?

- 1) Pulsars: the best bet?

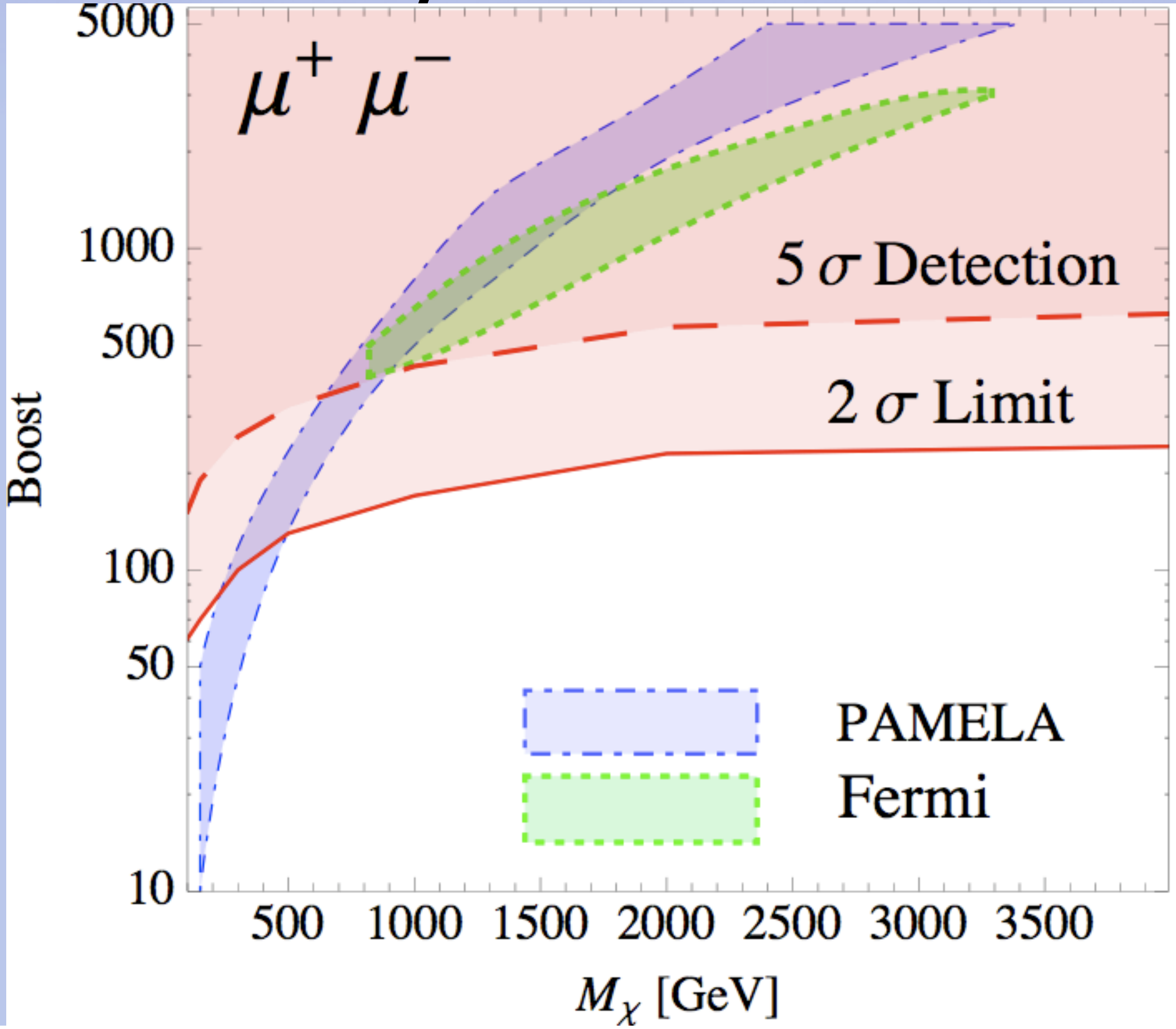
- 2) We happen to live in a hot spot of high dark matter density (boosted by at least factor 10): unlikely

- 3) nonstandard WIMPs: e.g., nonthermal WIMPs

MUST HAVE BOOSTED ANNIHILATION CROSS SECTION AND LEPTOPHILIC PRODUCTS

ICECUBE/DEEPCORE will see neutrinos in five years if PAMELA anomaly is from DM

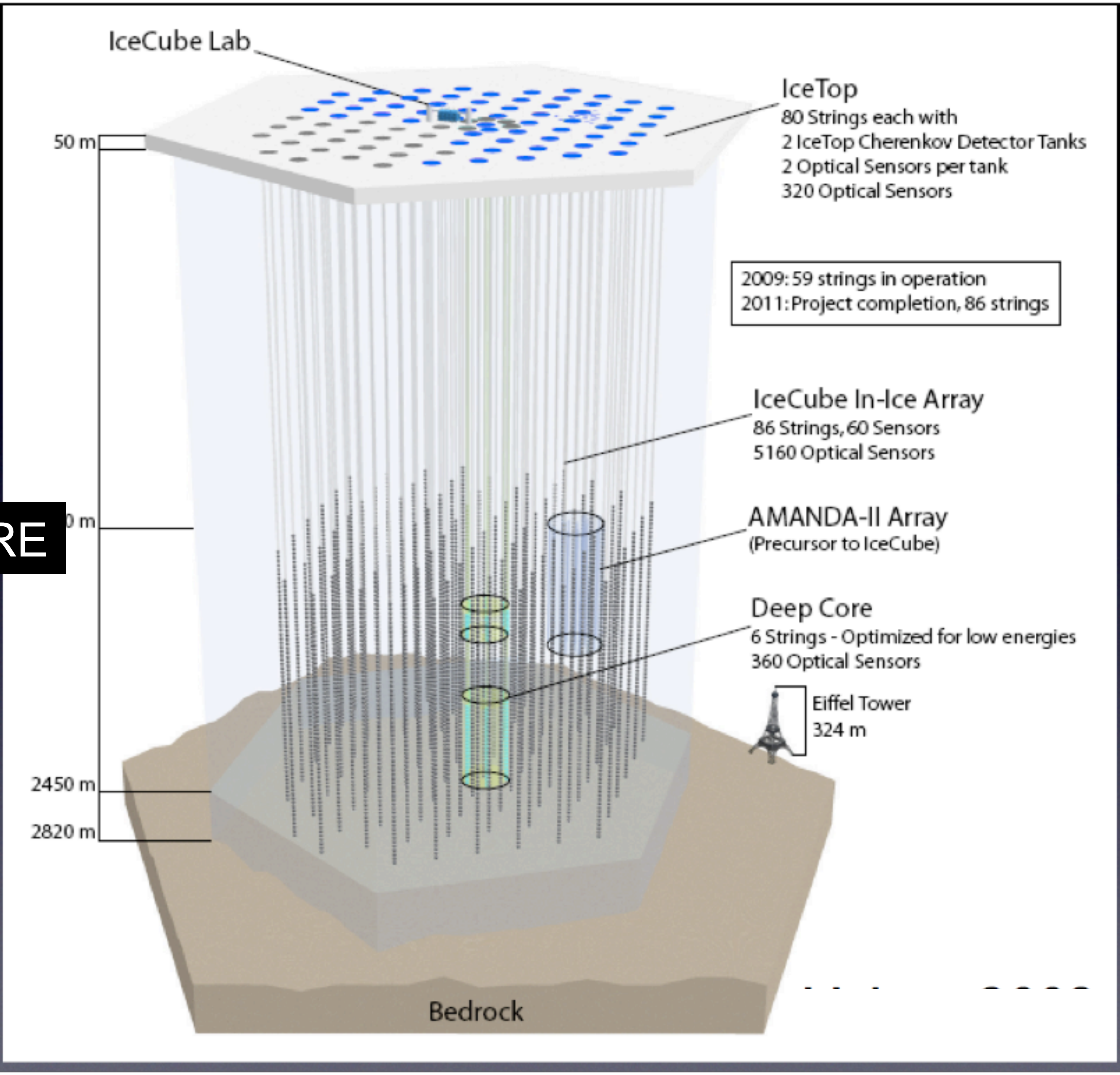
Spolyar,
Buckley,
Freese,
Hooper,
Murayama
2009



String of phototubes in ice at South Pole

IceCube

DEEPCORE



Test of boosted cross sections

- Streams in M31: DM annihilation to gamma rays testable in FERMI
- Sanderson Mohayaee, Silk 2011

Gamma-rays from the Galactic Center

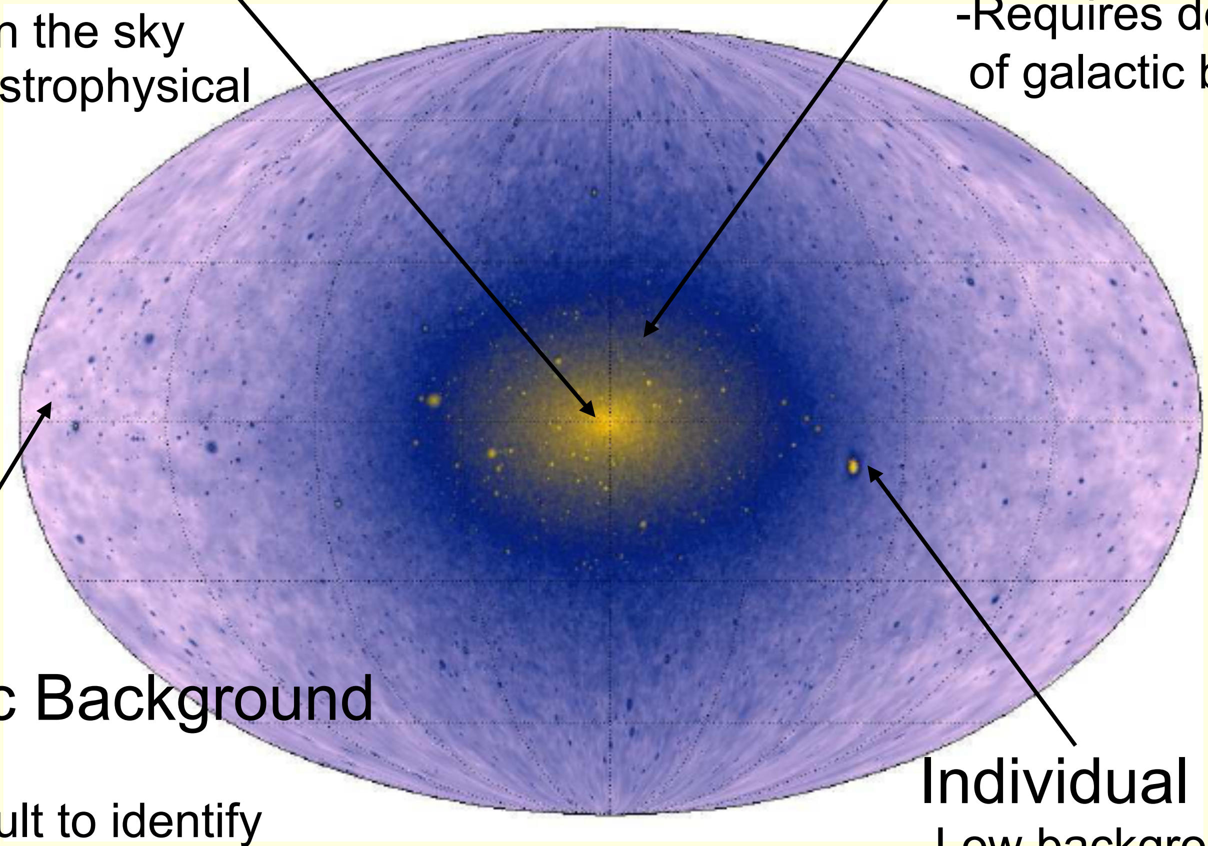
Searches For Gamma Rays From Dark Matter Annihilations With Fermi

- The Fermi Gamma Ray Space Telescope has been collecting data since June 2008

- Fermi's Large Area Telescope (LAT) possesses far superior effective area (~7000-8000 cm^2), angular resolution (sub-degree), and energy resolution (~10%) than its predecessor EGRET

- Unlike ground based gamma ray telescopes, Fermi observes the entire sky, and can study far lower energy emission (down to ~100 MeV)

Where To Look For Dark Matter With FERMI?



The Galactic Center

-Brightest spot in the sky

-Considerable astrophysical backgrounds

The Galactic Halo

-High statistics

-Requires detailed model of galactic backgrounds

Extragalactic Background

-High statistics

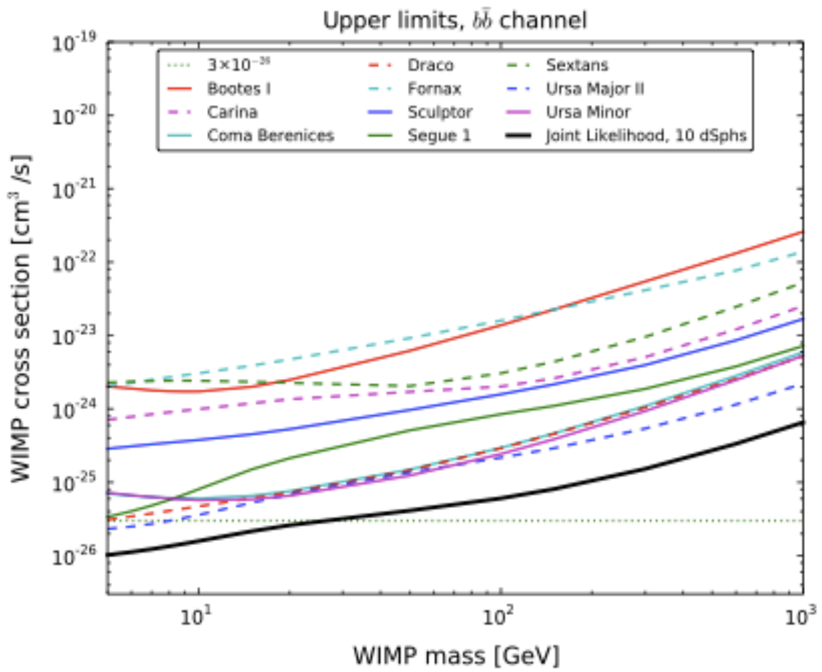
-potentially difficult to identify

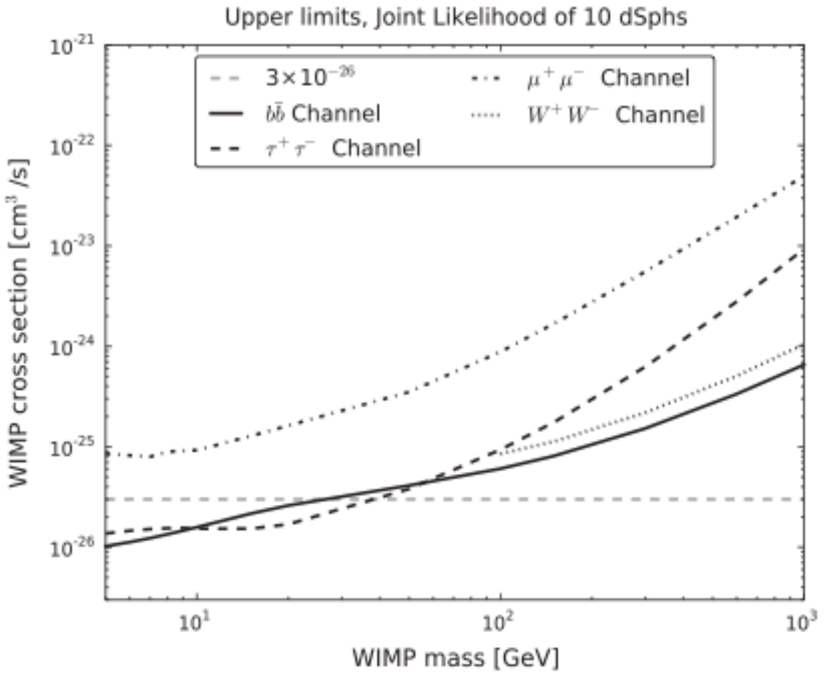
Individual Subhalos

-Low backgrounds

Diemand, Kuhlen, Madau, APJ, astro-ph/0611370

DM limits from combined analysis of dSphs





M. Ackermann et al. [Fermi LAT Collaboration], PRL 107, 241302 (2011)

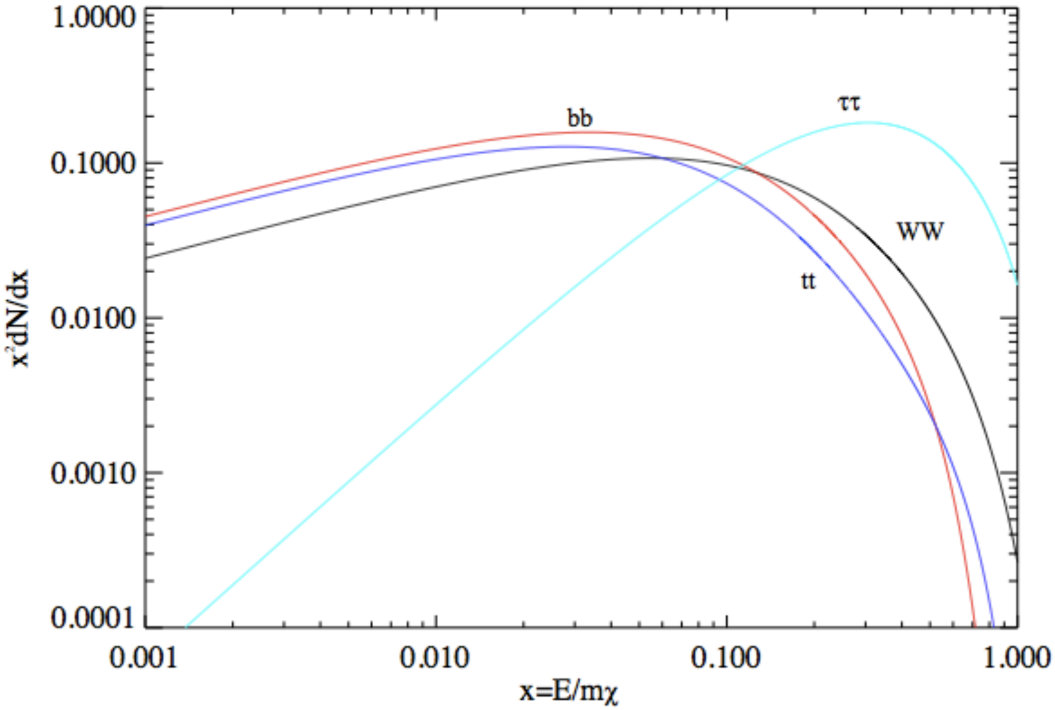
Joint likelihood analysis of Fermi LAT data:

- 10 dwarf galaxy targets
- 2 years data, energy range: 200 MeV - 100 GeV, P6_V3_diffuse
- 4 annihilation channels
- incorporates statistical uncertainties in the solid-angle-

results exclude the canonical WIMP thermal relic cross-section for annihilation to $b\bar{b}$ or $\tau^+\tau^-$ for masses below ~ 30 GeV

Dark matter photon spectra

- soft channels produce a continuum gamma-ray spectrum primarily from decay of neutral pions
- internal bremsstrahlung radiation from charged lepton final states (much harder)
- line emission (γγ, Zγ)

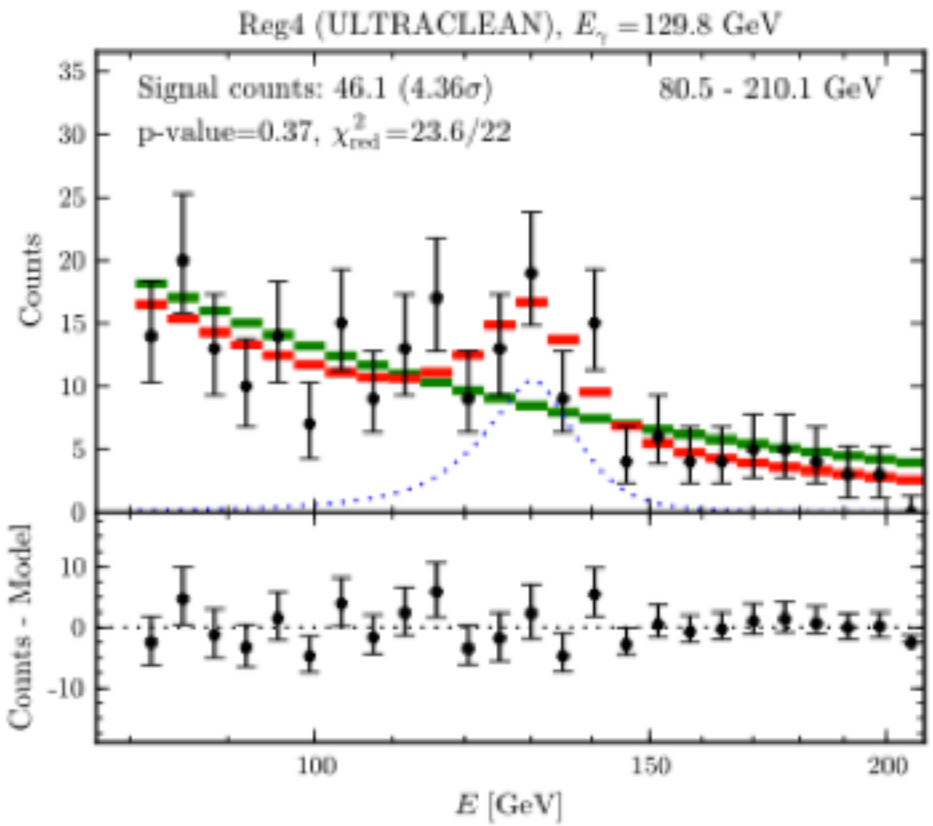


130 GeV gamma-ray line in FERMI?

Christoph Weniger, not yet vetted by the collaboration

Lars Bergstrom pioneered idea of line searches in 1980s

- From annihilation of 130 GeV WIMPs? 2 WIMPs to 2 gammas
- 3.2 sigma,
- From nearby the Galactic Center



Possible evidence for WIMP detection already now:

- Direct Detection:
  - DAMA annual modulation
  - COGENT, CRESST (but CDMS and XENON)
- Indirect Detection:
  - The HEAT/PAMELA/FERMI positron excess
  - 130 GeV gamma ray line in FERMI

- Theorists are looking for models in which these results are consistent with one another (given an interpretation in terms of WIMPs)

Upcoming Data: will the Dark Matter be found in 2013?

- LHC (find SUSY)

- Indirect Detection due to annihilation:
- FERMI (gamma rays)
- PAMELA (positrons)
- ICECUBE (neutrinos)
- GAPS (antideuterons)

- Direct Detection: XENON 100, COGENT, COUPP, and others are taking data
- Directional Detection

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

- I. Direct detection:

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

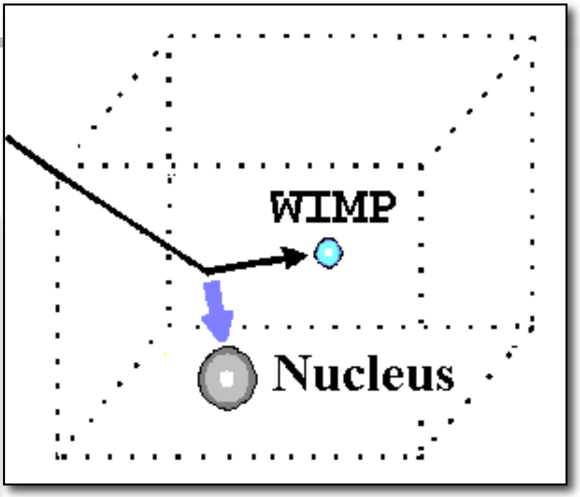
- 2. Indirect detection:

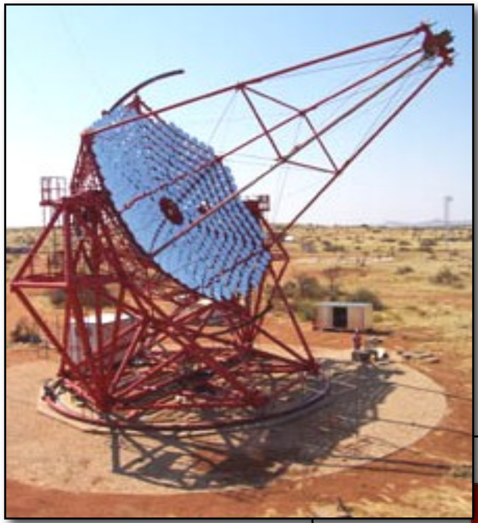
  annihilation signals in a variety of channels (neutrinos, gamma-rays, etc) all coming from the same source

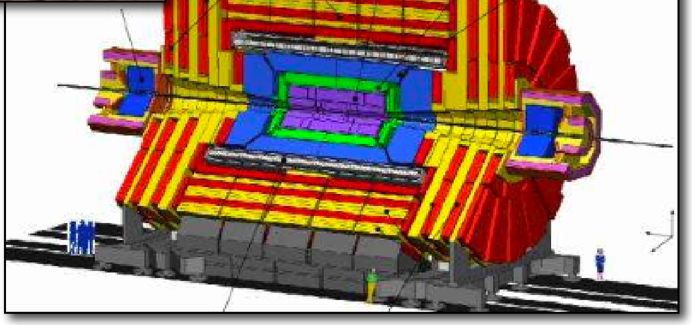
WIMP Hunting: Good chance of detection this decade

- Direct Detection
- Indirect Detection
- Collider Searches

Looking for Dark Stars

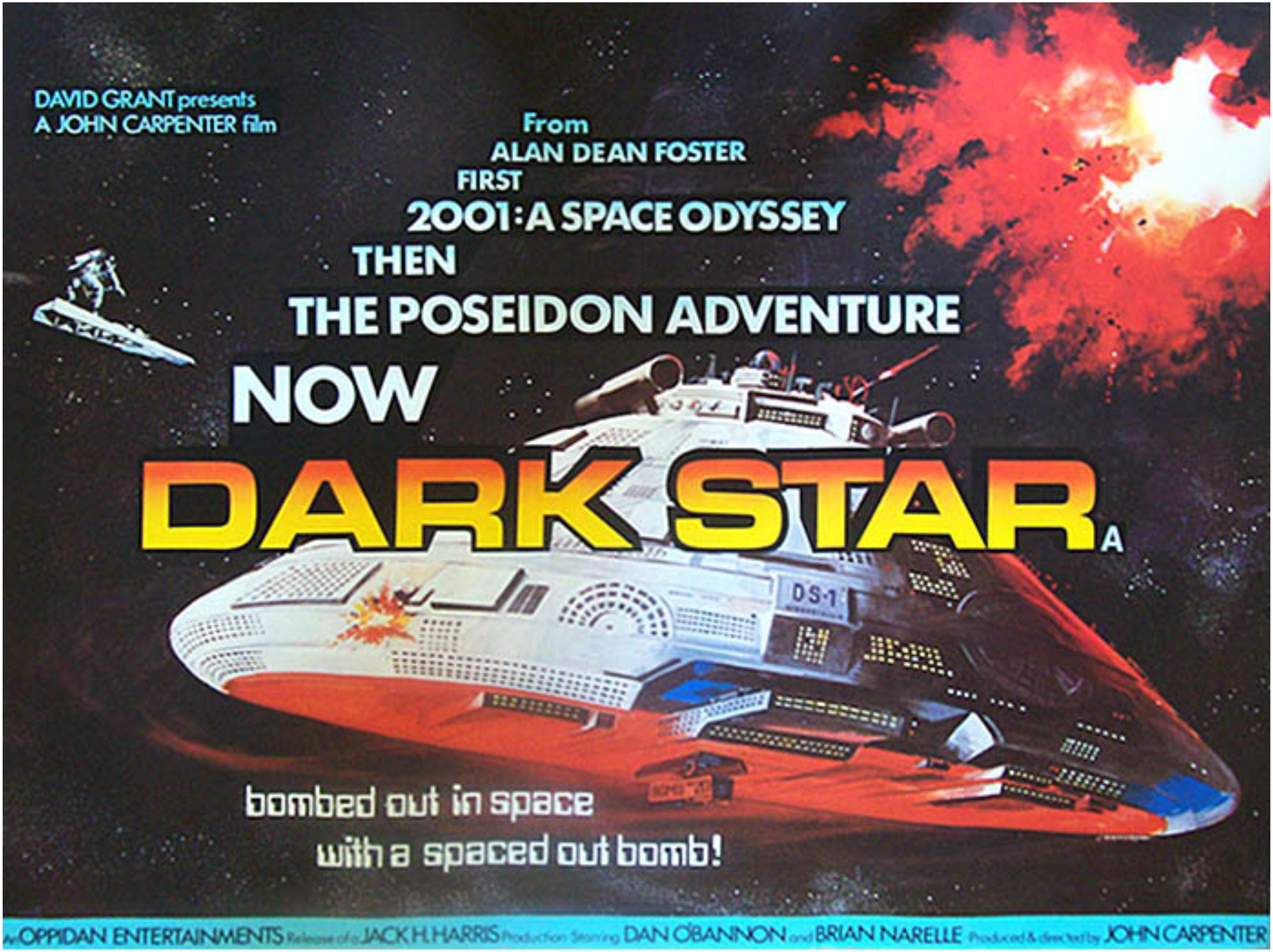




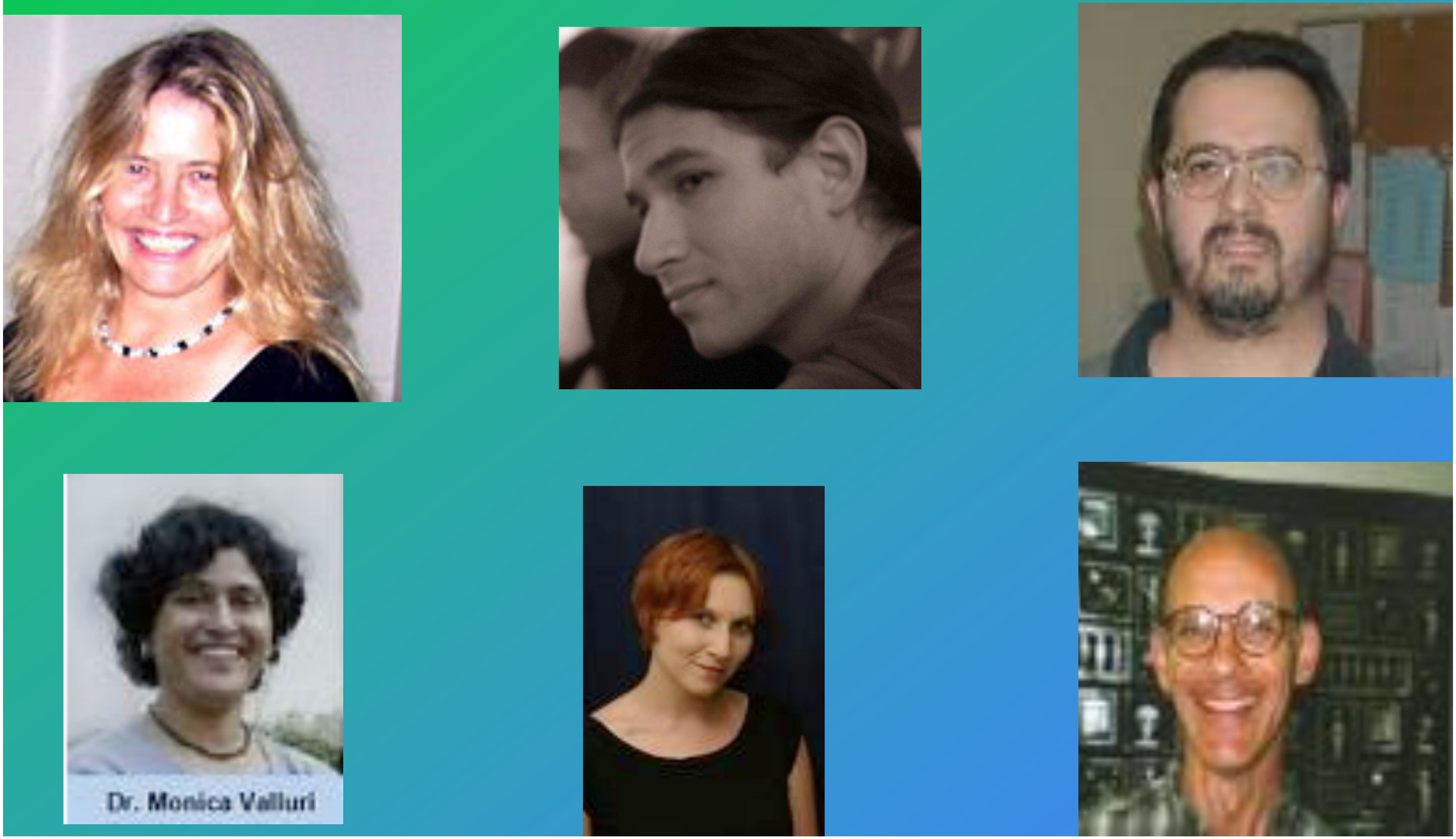


IV. FOURTH WAY TO SEARCH FOR WIMPS

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



Papers

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D. Spolyar , K .Freese, and P. Gondolo

JCAP,11,014F (2008) arXiv:0802.1724
K. Freese, D. Spolyar, and A. Aguirre

Astrophys.J.693:1563-1569,2009, arXiv:0805.3540
K. Freese, P. Gondolo, J.A. Sellwood, and D. Spolyar

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K. Freese, P. Bodenheimer, D. Spolyar, and P. Gondolo

Astrophys.J.705:1031-1042,2009**,** arXiv:0903.1724
D. Spolyar, P. Bodenheimer, K Freese, and P Gondolo

arXiv:1002.2233, K. Freese, C. Ilie, D. Spolyar, M. Valluri, and P. Bodenheimer
arXiv:1008.3552: P. Sandick, J. Diemand, K. Freese, and D. Spolyar
arXiv:1110.6202, C.Ilie, K. Freese, M. Valluri, I. Iliev, P. Shapiro

From Science et Vie: Mars 2010

fondamental > ASTROPHYSIQUE

REPÈRES

Faute de pouvoir être observées directement, les étoiles primitives demeurent une énigme pour les scientifiques. Aussi, le scénario de leur formation repose-t-il sur celui des étoiles connues, où la mystérieuse matière noire tient un faible rôle. Or, voilà qu'une astrophysicienne américaine émet une hypothèse audacieuse : la matière noire serait au cœur même de l'extraordinaire rayonnement de ces premiers astres titanesques.

Etoiles noires

Elles seraient les premiers astres

Par Mathieu Grousson

Imaginez le spectacle : il y a plus de 13 milliards d'années, notre Univers vit sa prime jeunesse, les futures galaxies ne sont encore que des nébuleuses de poussière et, en leur centre, voici que brillent des boules de gaz mille fois plus lourdes, deux mille fois plus grandes et un million de fois plus lumineuses que ne le sera jamais notre Soleil ! Titanesques, inouïs, ces astres sont comme les phares d'un monde en gestation : les seules sources de lumière d'un espace par ailleurs obscur et glacé.

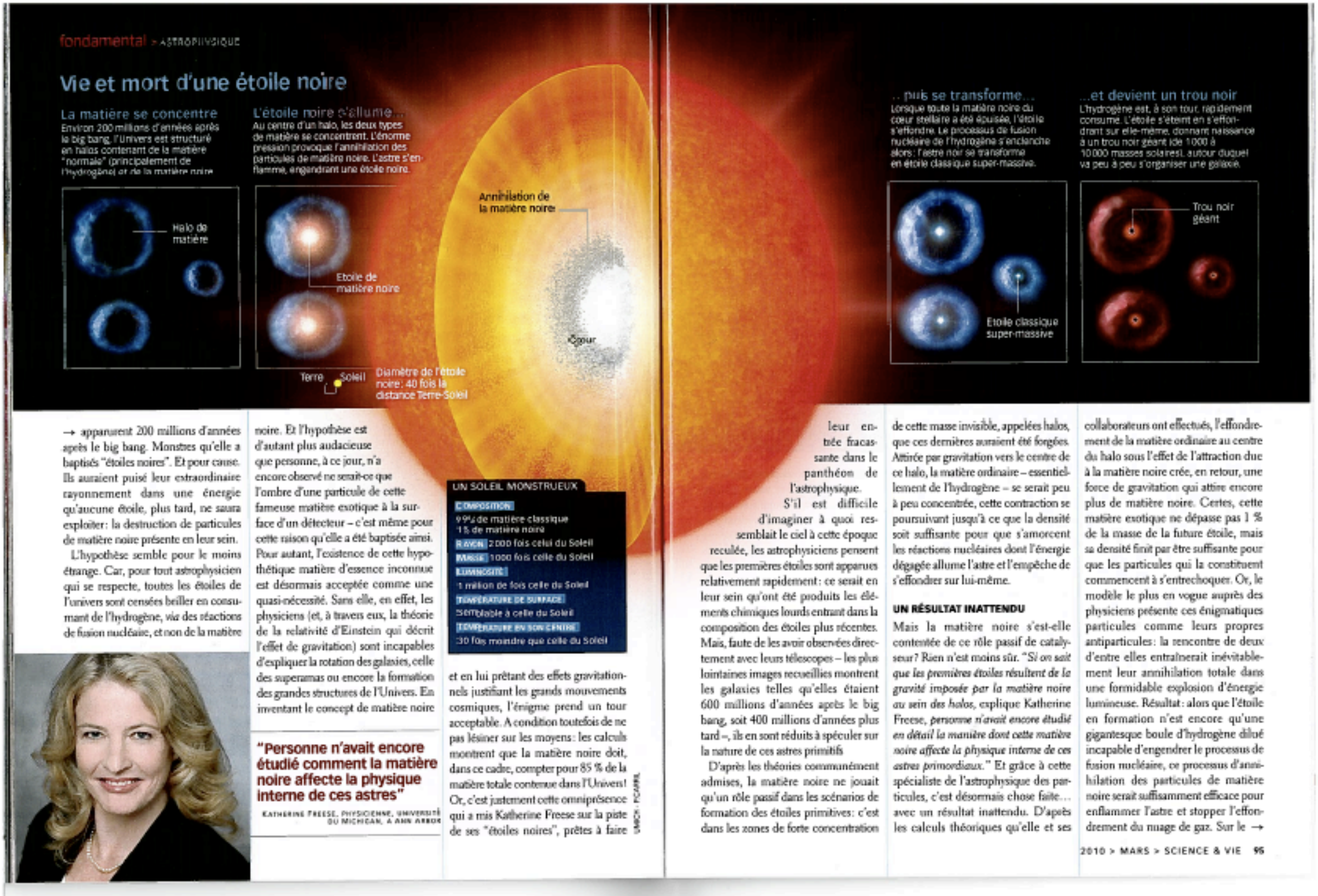
Ce spectacle sidéral de l'Univers primitif, on le doit à une physicienne américaine de l'université du Michigan, à Ann Arbor : à la lueur des équations tournant dans sa tête, Katherine Freese s'est aventurée dans les recoins sombres des premiers temps du cosmos pour en ramener une vision inédite, qui bouleverse l'image qu'en avaient jusqu'ici les astrophysiciens. Car la chercheuse en est revenue convaincue que les premiers astres qui ont illuminé l'Univers furent ces monstres stellaires nichés au cœur des nébuleuses de poussière, qui →

Au début de l'Univers...

▲ Extraordinairement massives et lumineuses, les étoiles noires auraient illuminé fugacement l'Univers 200 millions d'années après le big bang, avant de donner naissance aux étoiles classiques.

P. CARRIL

Vie et mort d'une étoile noire



La matière se concentre

Environ 200 millions d'années après le big bang, l'Univers est structuré en halos contenant de la matière "normale" (principalement de l'hydrogène) et de la matière noire

L'étoile noire s'allume…

Au centre d'un halo, les deux types de matière se concentrent. L'énorme pression provoque l'annihilation des particules de matière noire. L'astre s'enflamme, engendrant une étoile noire.

…puis se transforme…

Lorsque toute la matière noire du cœur stellaire a été épuisée, l'étoile s'effondre. Le processus de fusion nucléaire de l'hydrogène s'enclenche alors : l'astre noir se transforme en étoile classique super-massive.

…et devient un trou noir

L'hydrogène est, à son tour, rapidement consumé. L'étoile s'éteint en s'effondrant sur elle-même, donnant naissance à un trou noir géant (de 1000 à 10000 masses solaires), autour duquel va peu à peu s'organiser une galaxie.

→ apparurent 200 millions d'années après le big bang. Monstres qu'elle a baptisés "étoiles noires". Et pour cause. Ils auraient puisé leur extraordinaire rayonnement dans une énergie qu'aucune étoile, plus tard, ne saura exploiter : la destruction de particules de matière noire présente en leur sein.

L'hypothèse semble pour le moins étrange. Car, pour tout astrophysicien qui se respecte, toutes les étoiles de l'univers sont censées briller en consumant de l'hydrogène, via des réactions de fusion nucléaire, et non de la matière noire. Et l'hypothèse est d'autant plus audacieuse que personne, à ce jour, n'a encore observé ne serait-ce que l'ombre d'une particule de cette fameuse matière exotique à la surface d'un détecteur – c'est même pour cette raison qu'elle a été baptisée ainsi. Pour autant, l'existence de cette hypothétique matière d'essence inconnue est désormais acceptée comme une quasi-nécessité. Sans elle, en effet, les physiciens (et, à travers eux, la théorie de la relativité d'Einstein qui décrit l'effet de gravitation) sont incapables d'expliquer la rotation des galaxies, celle des superamas ou encore la formation des grandes structures de l'Univers. En inventant le concept de matière noire et en lui prêtant des effets gravitationnels justifiant les grands mouvements cosmiques, l'énigme prend un tour acceptable. A condition toutefois de ne pas lésiner sur les moyens : les calculs montrent que la matière noire doit, dans ce cadre, compter pour 85 % de la matière totale contenue dans l'Univers ! Or, c'est justement cette omniprésence qui a mis Katherine Freese sur la piste de ses "étoiles noires", prêtes à faire leur entrée fracassante dans le panthéon de l'astrophysique.

S'il est difficile d'imaginer à quoi ressemblait le ciel à cette époque reculée, les astrophysiciens pensent que les premières étoiles sont apparues relativement rapidement : ce serait en leur sein qu'ont été produits les éléments chimiques lourds entrant dans la composition des étoiles plus récentes. Mais, faute de les avoir observées directement avec leurs télescopes – les plus lointaines images recueillies montrent les galaxies telles qu'elles étaient 600 millions d'années après le big bang, soit 400 millions d'années plus tard –, ils en sont réduits à spéculer sur la nature de ces astres primitifs

D'après les théories communément admises, la matière noire ne jouait qu'un rôle passif dans les scénarios de formation des étoiles primitives : c'est dans les zones de forte concentration de cette masse invisible, appelées halos, que ces dernières auraient été forgées. Attirée par gravitation vers le centre de ce halo, la matière ordinaire – essentiellement de l'hydrogène – se serait peu à peu concentrée, cette contraction se poursuivant jusqu'à ce que la densité soit suffisante pour que s'amorcent les réactions nucléaires dont l'énergie dégagée allume l'astre et l'empêche de s'effondrer sur lui-même.

UN RÉSULTAT INATTENDU

Mais la matière noire s'est-elle contentée de ce rôle passif de catalyseur ? Rien n'est moins sûr. "*Si on sait que les premières étoiles résultent de la gravité imposée par la matière noire au sein des halos,* explique Katherine Freese, *personne n'avait encore étudié en détail la manière dont cette matière noire affecte la physique interne de ces astres primordiaux.*" Et grâce à cette spécialiste de l'astrophysique des particules, c'est désormais chose faite… avec un résultat inattendu. D'après les calculs théoriques qu'elle et ses collaborateurs ont effectués, l'effondrement de la matière ordinaire au centre du halo sous l'effet de l'attraction due à la matière noire crée, en retour, une force de gravitation qui attire encore plus de matière noire. Certes, cette matière exotique ne dépasse pas 1 % de la masse de la future étoile, mais sa densité finit par être suffisante pour que les particules qui la constituent commencent à s'entrechoquer. Or, le modèle le plus en vogue auprès des physiciens présente ces énigmatiques particules comme leurs propres antiparticules : la rencontre de deux d'entre elles entraînerait inévitablement leur annihilation totale dans une formidable explosion d'énergie lumineuse. Résultat : alors que l'étoile en formation n'est encore qu'une gigantesque boule d'hydrogène dilué incapable d'engendrer le processus de fusion nucléaire, ce processus d'annihilation des particules de matière noire serait suffisamment efficace pour enflammer l'astre et stopper l'effondrement du nuage de gaz. Sur le →

UN SOLEIL MONSTRUEUX

COMPOSITION
99 % de matière classique
1 % de matière noire
RAYON 2000 fois celui du Soleil
MASSE 1000 fois celle du Soleil
LUMINOSITÉ
1 million de fois celle du Soleil
TEMPÉRATURE DE SURFACE
Semblable à celle du Soleil
TEMPÉRATURE EN SON CENTRE
30 fois moindre que celle du Soleil

> "Personne n'avait encore étudié comment la matière noire affecte la physique interne de ces astres"
>
> KATHERINE FREESE, PHYSICIENNE, UNIVERSITÉ DU MICHIGAN, À ANN ARBOR

UMICH : PCARRIL

Dark Stars

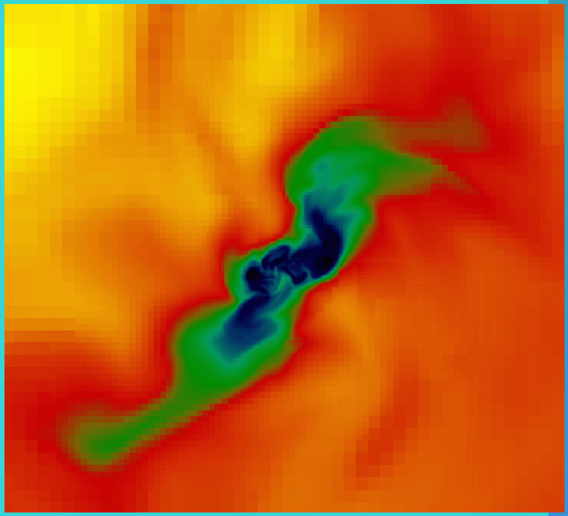
The first stars to form in the history of the universe may be powered by Dark Matter annihilation rather than by Fusion (even though the dark matter constitutes less than 1% of the mass of the star).

THESE REALLY ARE STARS: atomic matter that shines due to dark matter, possibly a billion times as bright as the Sun

- This new phase of stellar evolution lasts millions to billions of years (possibly even to today, see work of Fabio Iocco)

First Stars: Standard Picture

- Formation Basics:
  - First luminous objects ever.
  - At z = 10-50
  - Form inside DM haloes of ~10^6 $M_\odot$
  - Baryons initially only 15%
  - Formation is a gentle process



Made only of hydrogen and helium from the Big Bang.

Dominant cooling Mechanism is

H_2

Not a very good coolant

(Hollenbach and McKee ‘79)

Pioneers of First Stars Research: Abel, Bryan, Norman; Bromm, Greif, and Larson; McKee and Tan; Gao, Hernquist, Omukai, and Yoshida; Klessen; Nishii

Why DM annihilation in the first stars is more potent than in today’s stars: higher DM density

- **THE RIGHT PLACE**:

  one single star forms at the center of a million solar mass DM halo

- **THE RIGHT TIME:**

  the first stars form at high redshift,

  z = 10-50, and density scales as (1+z)^3

Basic Picture

- The first stars form in a DM rich environment
- As the gas cools and collapses to form the first stars, the cloud pulls DM in.
- DM particles are their own antipartners, and annihilate more and more rapidly as the density increases
- DM annihilates to e+/e- and photon endproducts of 100 GeV (or so) which 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

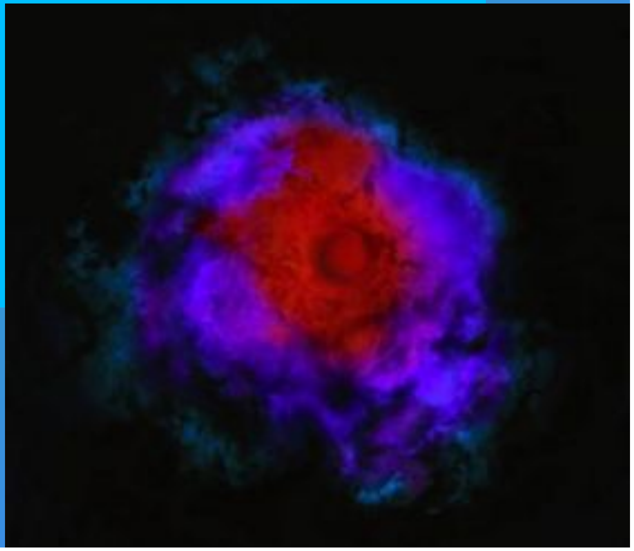
- DM annihilation is (roughly) 100% efficient in the sense that all of the particle mass is converted to heat energy for the star
- Fusion, on the other hand, is only 1% efficient (only a fraction of the nuclear mass is released as energy)
- Fusion only takes place at the center of the star where the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

SUPERMASSIVE dark stars (SMDS) from extended adiabatic contraction

- Previously we thought dark matter runs out in a million years with 800 $M_\odot$ stars: end up with a donut, i.e., big spherical halo of dark matter with hole in the middle
- But, triaxial haloes have all kinds of orbits (box orbits, chaotic orbits) so that much more dark matter is in there. Dark stars can grow much bigger and make supermassive stars, 10^5-10^7 $M_\odot$, last much longer, and reach 10^9-10^{11} $L_\odot$. Some may live to today
- Visible in James Webb Space Telescope.
- Leads to (as yet unexplained) big black Holes.

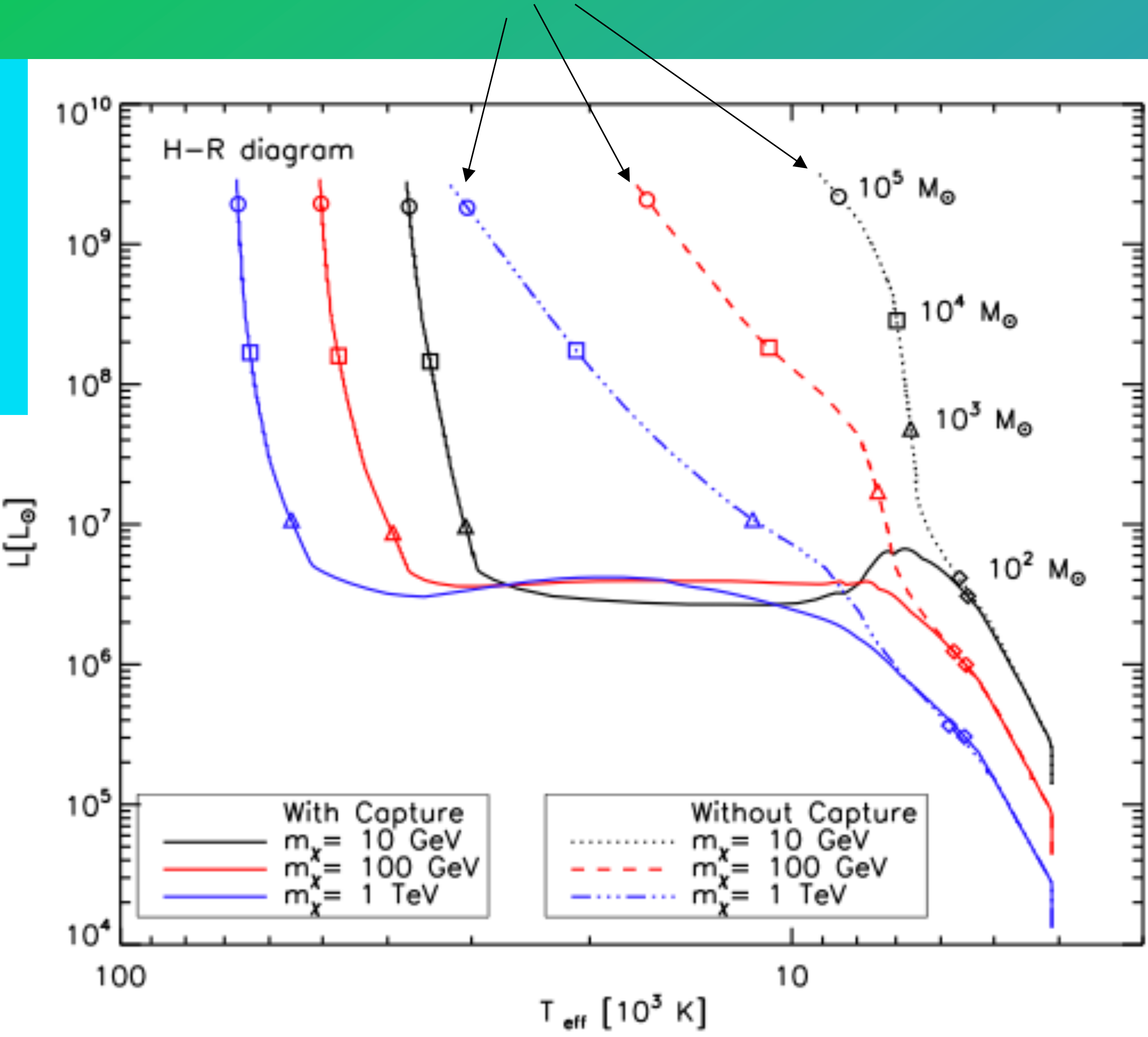
Additional mechanism: see Umeda etal (JCAP 2009)

Disagreement re success of WIMP capture

- Sivertsson and Gondolo
- vs. Valluri, Freese, Ilie

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



Lifetime of Dark Star

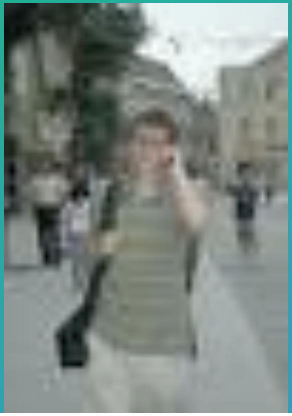
- The DS lives as long as DM orbits continue through the DS or it captures more Dark Matter fuel: millions to billions of years.
- The refueling can only persist as long as the DS resides in a DM rich environment, I.e. near the center of the DM halo. But the halo merges with other objects.
- You never know! They might exist today.
- Once the DM runs out, switches to fusion.

What happens next?
BIG BLACK HOLES

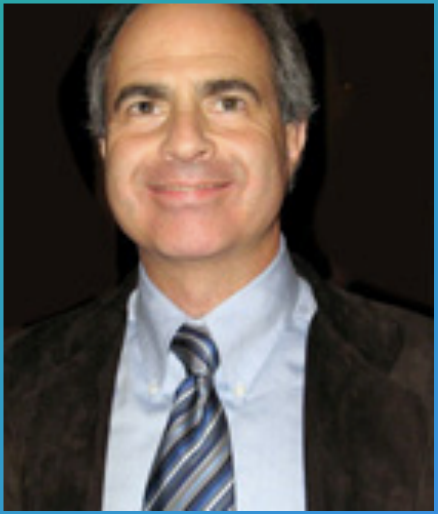
- Star reaches $T=10^7$K, fusion sets in.
- A. Heger finds that fusion powered stars heavier than 153,000 solar masses are unstable and collapse to BH
- Less massive Pop III star lives a million years, then becomes a Black Hole
- Helps explain observed black holes:
- (i) in centers of galaxies
- (ii)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

Observing Dark Stars

- Supermassive Dark Stars may be detected in upcoming James Webb Space Telescope
- One of JWST goals is to find first stars: only if they are dark stars is this goal realizable

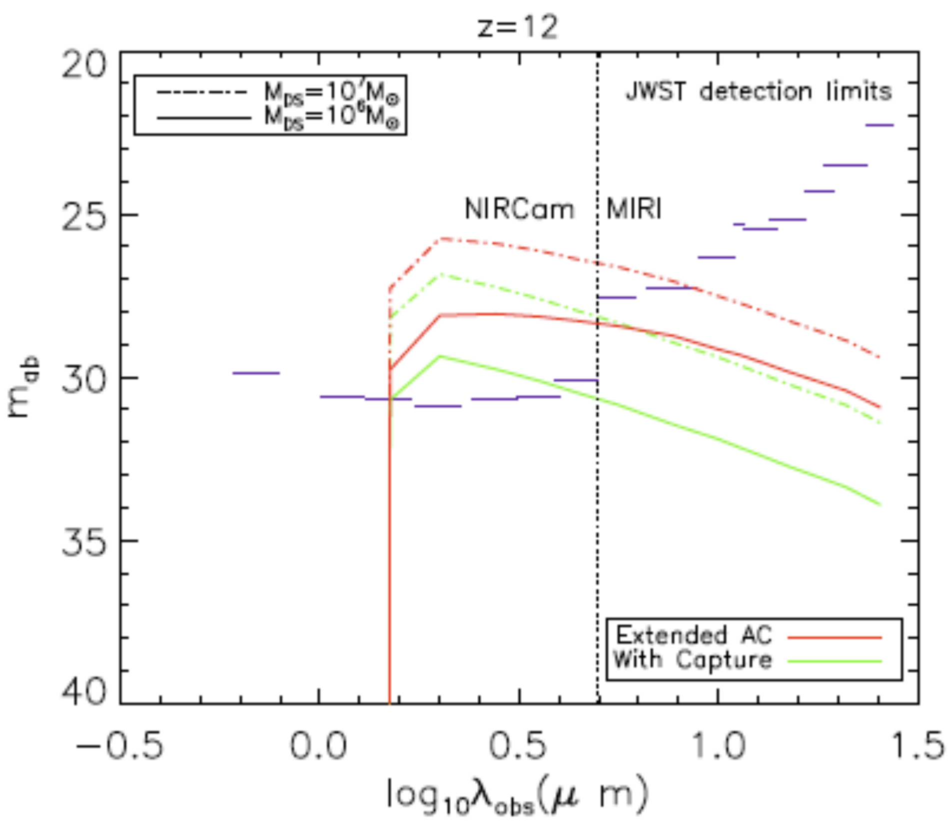


Cosmin
Ilie,
Paul
Shapiro

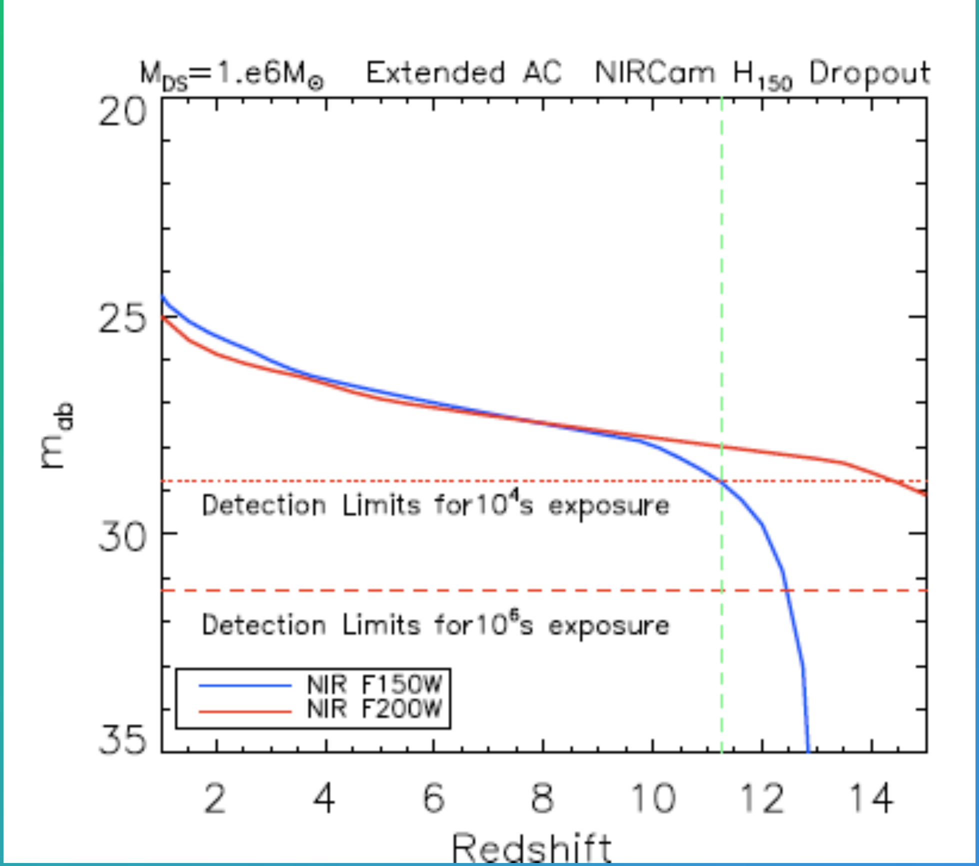


Pat
Scott

SMDS in JWST


z=12
M_DS=10^7 M_⊙
M_DS=10^6 M_⊙
JWST detection limits
NIRCam
MIRI
Extended AC
With Capture
m_ab
20
25
30
35
40
−0.5
0.0
0.5
1.0
1.5
log10λobs(μ m)

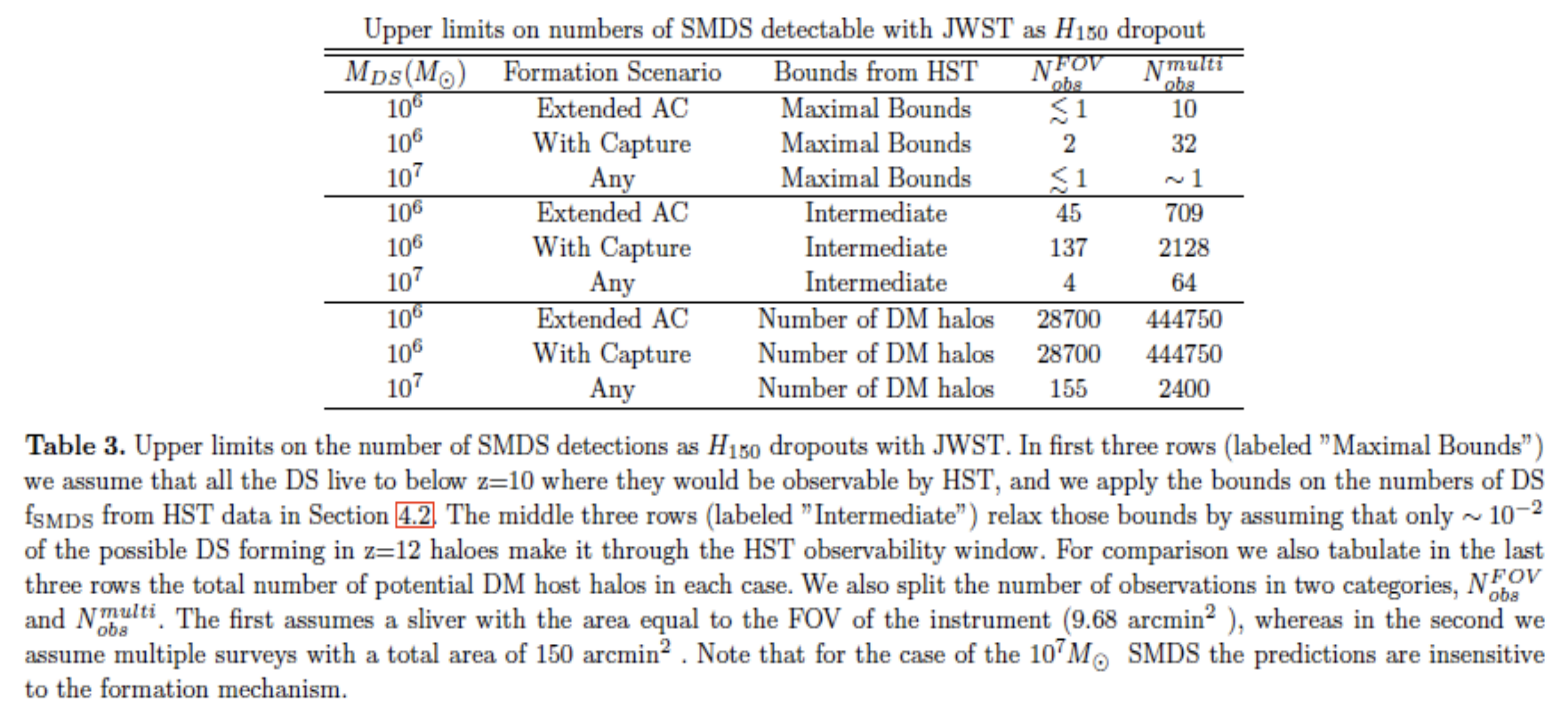
Million solar mass SMDS as H-band dropout



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

Numbers of SMDS detectable with JWST as H-band dropouts

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



Upper limits on numbers of SMDS detectable with JWST as H_{150} dropout

$M_{DS}(M_\odot)$	Formation Scenario	Bounds from HST	N_{obs}^{FOV}	N_{obs}^{multi}
10^6	Extended AC	Maximal Bounds	$\lesssim 1$	10
10^6	With Capture	Maximal Bounds	2	32
10^7	Any	Maximal Bounds	$\lesssim 1$	~ 1
10^6	Extended AC	Intermediate	45	709
10^6	With Capture	Intermediate	137	2128
10^7	Any	Intermediate	4	64
10^6	Extended AC	Number of DM halos	28700	444750
10^6	With Capture	Number of DM halos	28700	444750
10^7	Any	Number of DM halos	155	2400

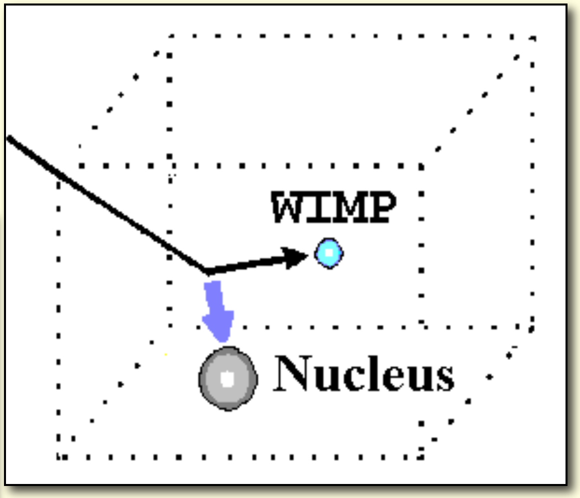
Table 3. Upper limits on the number of SMDS detections as H_{150} dropouts with JWST. In first three rows (labeled "Maximal Bounds") we assume that all the DS live to below z=10 where they would be observable by HST, and we apply the bounds on the numbers of DS $f_{\rm SMDS}$ from HST data in Section 4.2. The middle three rows (labeled "Intermediate") relax those bounds by assuming that only $\sim 10^{-2}$ of the possible DS forming in z=12 haloes make it through the HST observability window. For comparison we also tabulate in the last three rows the total number of potential DM host halos in each case. We also split the number of observations in two categories, N_{obs}^{FOV} and N_{obs}^{multi}. The first assumes a sliver with the area equal to the FOV of the instrument (9.68 arcmin^2), whereas in the second we assume multiple surveys with a total area of 150 arcmin^2 . Note that for the case of the $10^7 M_\odot$ SMDS the predictions are insensitive to the formation mechanism.

(following work of Zackrisson etal 2010)

Dark Stars (conclusion)

- The dark matter can play a crucial role in the first stars
- The first stars in the Universe may be powered by DM heating rather than fusion
- These stars may be very large (1000-100,000 solar masses) and bright (million to ten billion solar luminosities) and can be detected by JWST

WIMP Hunting: Good chance of detection this decade



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

Looking for Dark Stars