Physics Beyond the Standard Model with Electromagnetic Probes

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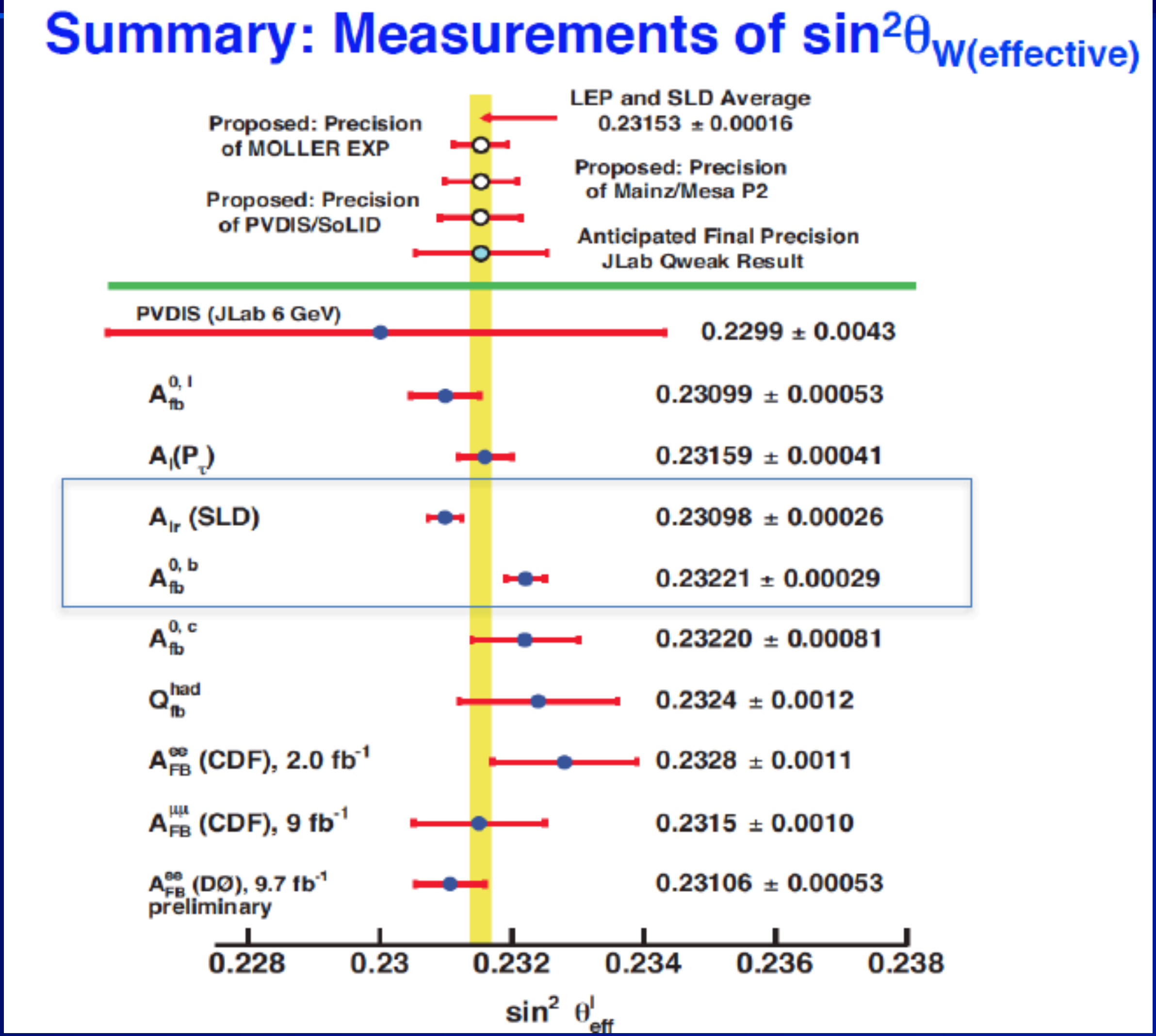
PRAE Workshop, Orsay,
9 Oct 2018

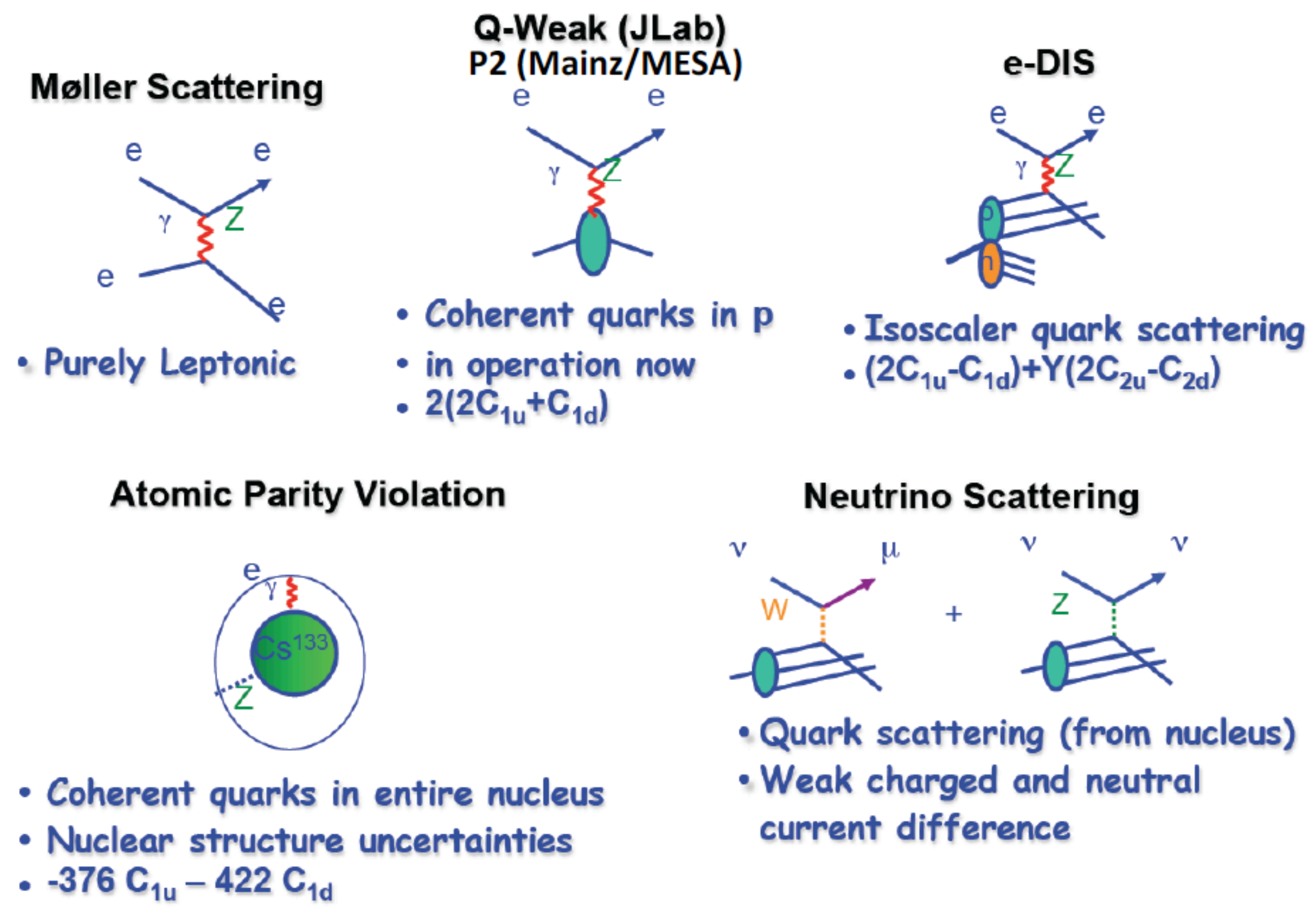
Beyond the Standard Model

- Low-energy high-precision measurements:
  - Parity-violating electron scattering (weak mixing angle)
  - Muon (g-2)
  - Neuton EDM
- Dark matter candidates and dark force mediators

Parity violating electron scattering



Precise measurements of electroweak interaction parameters



Møller Scattering

- Purely Leptonic

Q-Weak (JLab)
P2 (Mainz/MESA)

- Coherent quarks in p
- in operation now
- $2(2C_{1u}+C_{1d})$

e-DIS

- Isoscaler quark scattering
- $(2C_{1u}-C_{1d})+Y(2C_{2u}-C_{2d})$

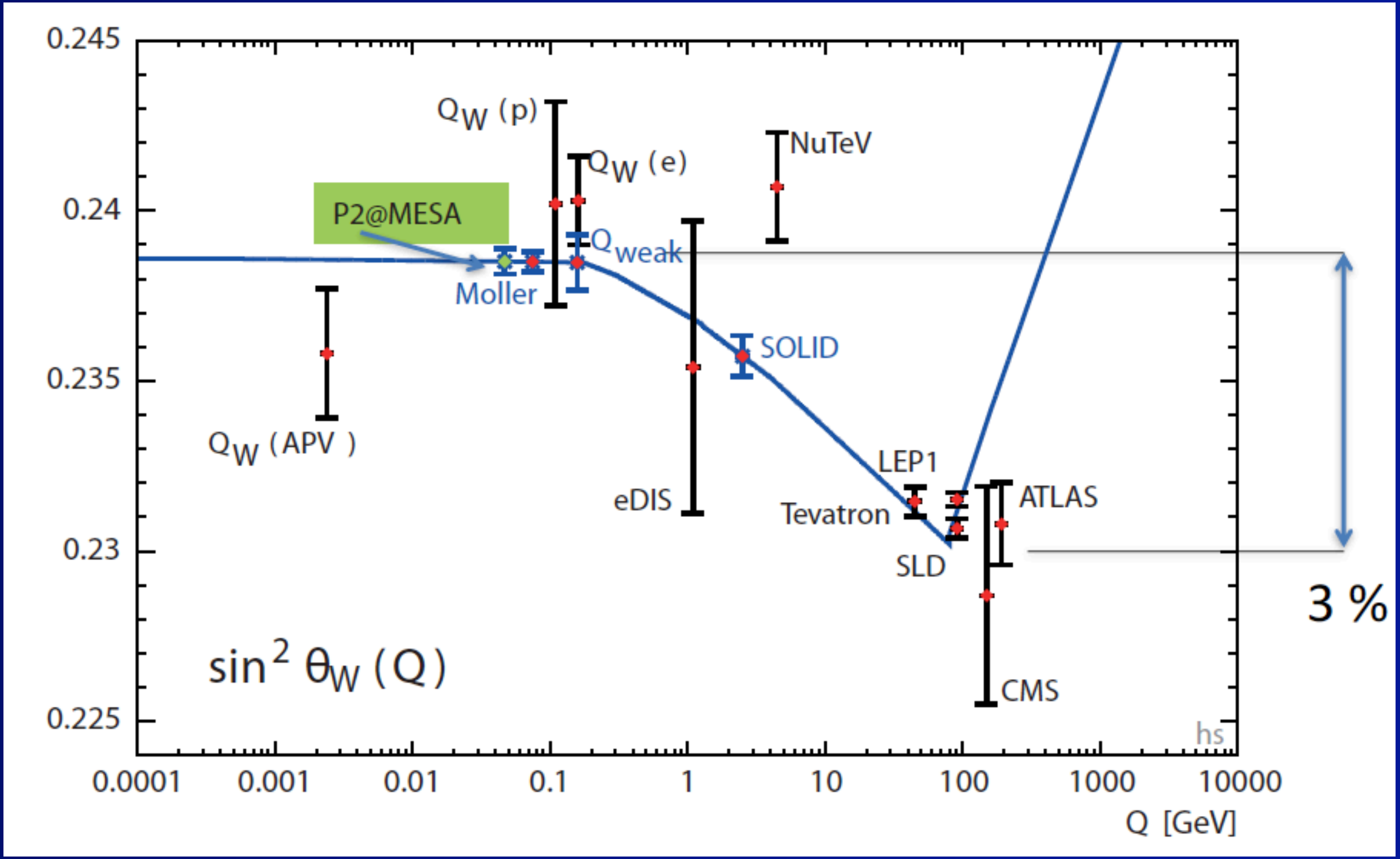
Atomic Parity Violation

- Coherent quarks in entire nucleus
- Nuclear structure uncertainties
- $-376\ C_{1u} - 422\ C_{1d}$

Neutrino Scattering

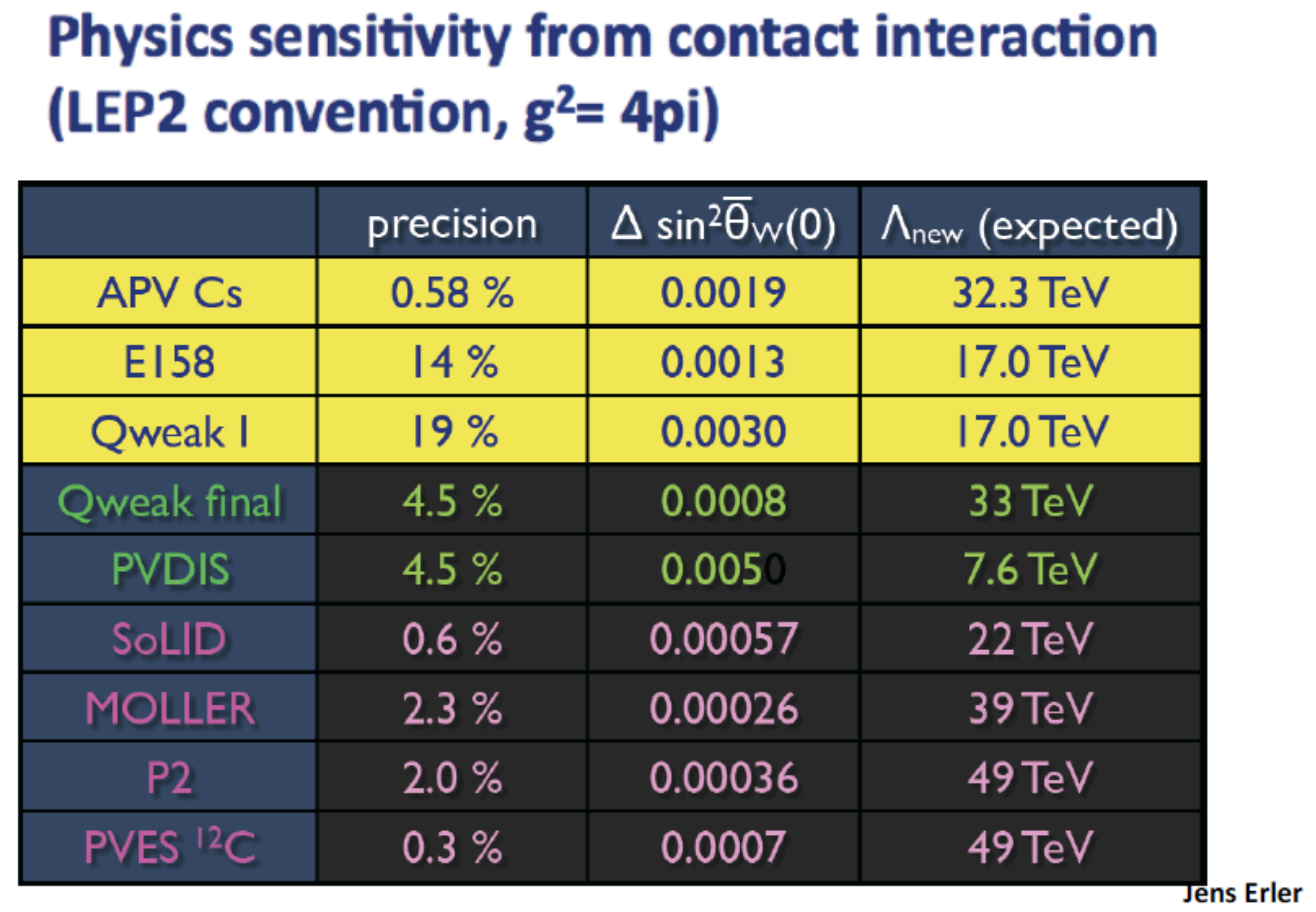
- Quark scattering (from nucleus)
- Weak charged and neutral current difference

Weak mixing angle



Slide from Frank Maas: High priority task for MESA

Implications for "new physics" mass scale



Physics sensitivity from contact interaction (LEP2 convention, $g^2 = 4pi$)

	precision	$\Delta \sin^2\bar{\theta}_W(0)$	Λ_{new} (expected)
APV Cs	0.58 %	0.0019	32.3 TeV
E158	14 %	0.0013	17.0 TeV
Qweak I	19 %	0.0030	17.0 TeV
Qweak final	4.5 %	0.0008	33 TeV
PVDIS	4.5 %	0.0050	7.6 TeV
SoLID	0.6 %	0.00057	22 TeV
MOLLER	2.3 %	0.00026	39 TeV
P2	2.0 %	0.00036	49 TeV
PVES ^{12}C	0.3 %	0.0007	49 TeV

Jens Erler

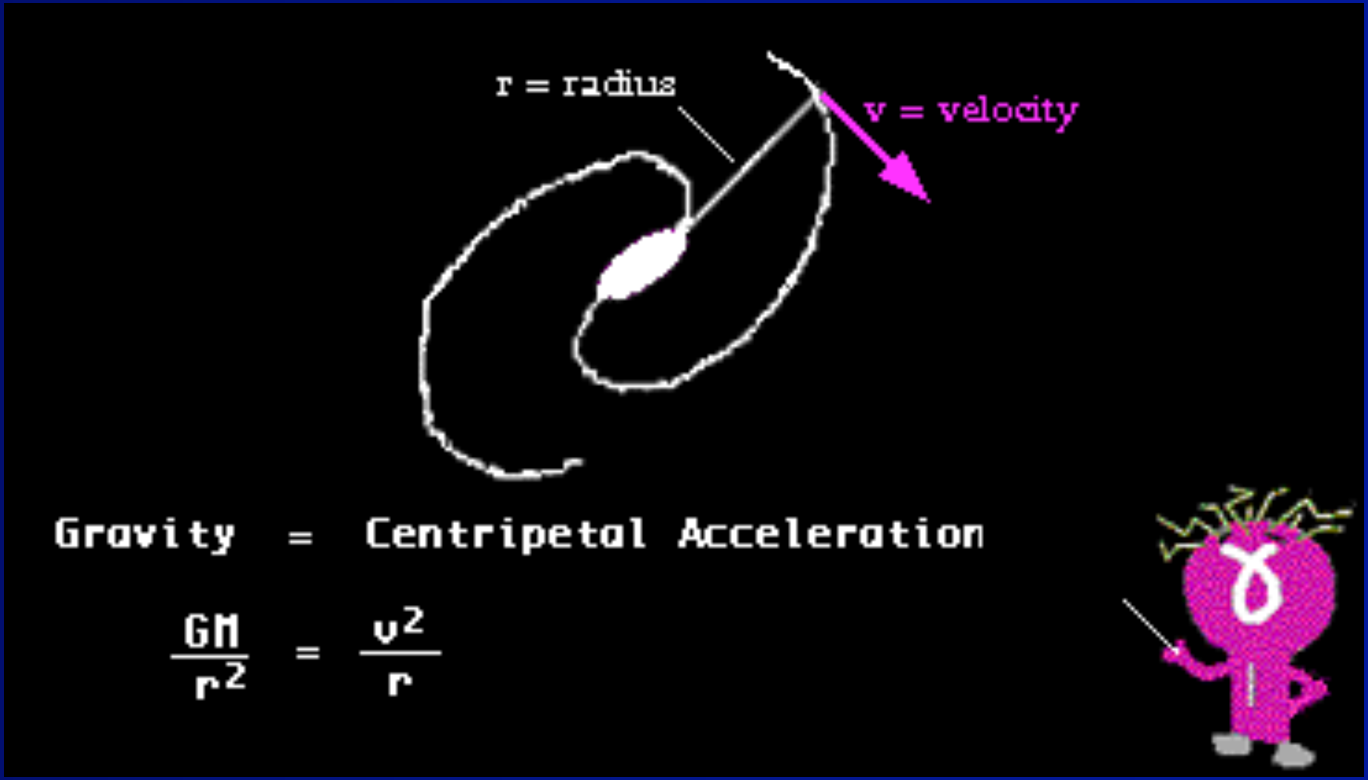
Dark matter and force mediators

- What is known?
- Astrophysical observations and implications for lab searches

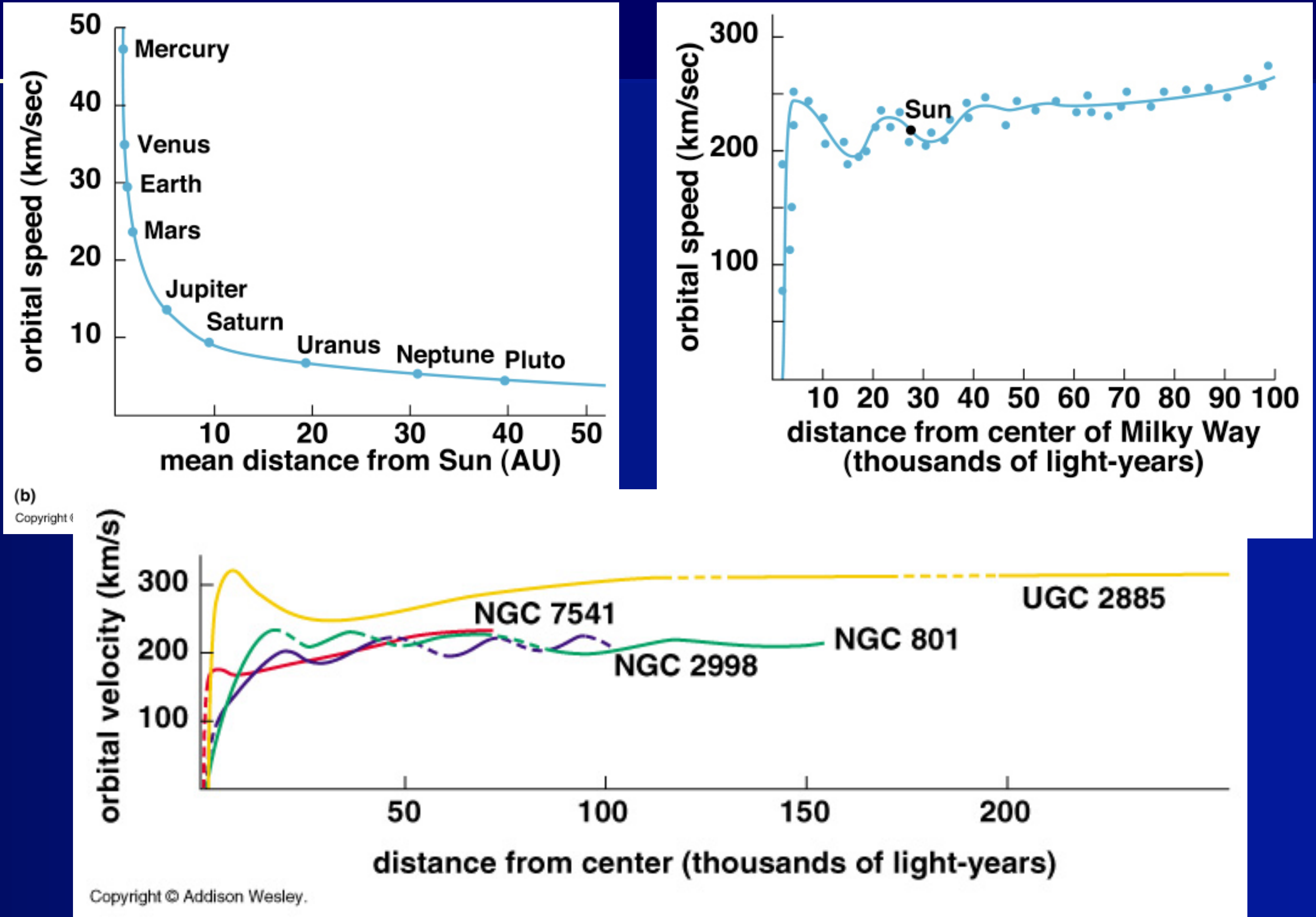
Galactic rotation

- Fritz Zwicky (1933); S. Smith (1936); Galaxy clusters
- Vera Rubin (1970): Measured rotation of spiral galaxies, discovered stars on the periphery revolve too fast around the galaxy center=> an invisible halo carries ~90% of galaxy mass

$v^2 \sim 1/r$?

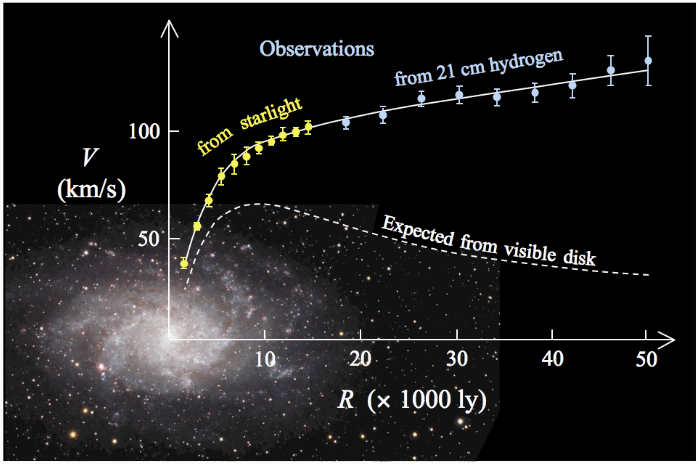


Galactic Rotational Curves



Recent news

The European Southern Observatory's
Very Large Telescope, based in Chile



- Dark matter less important 10 billion years ago *Nature* **543**, 397–401 (16 March 2017)

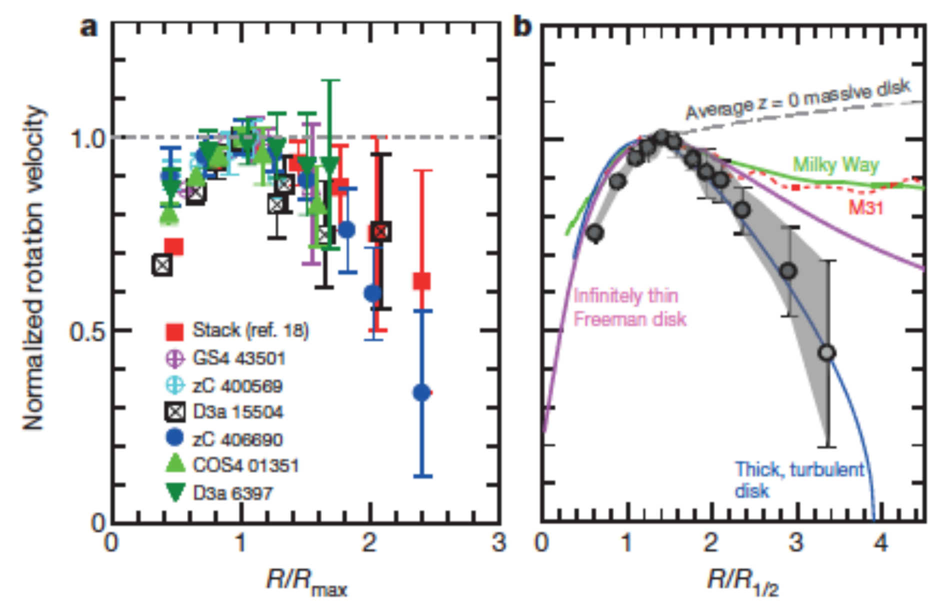
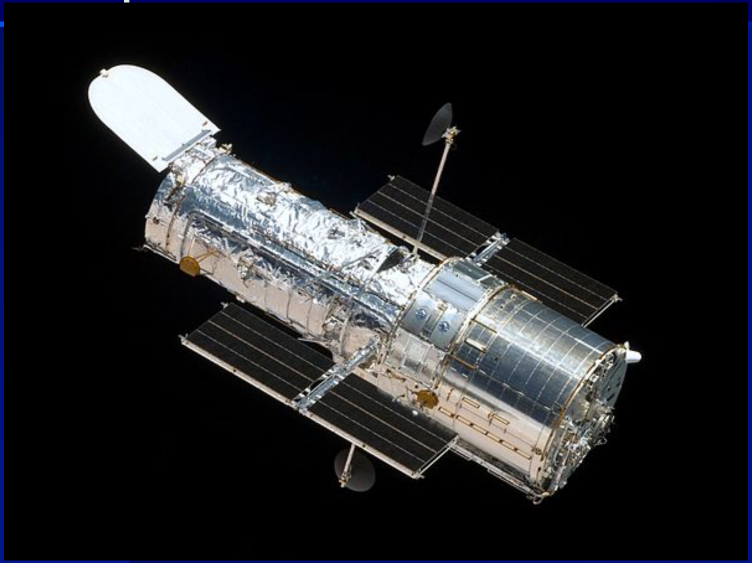
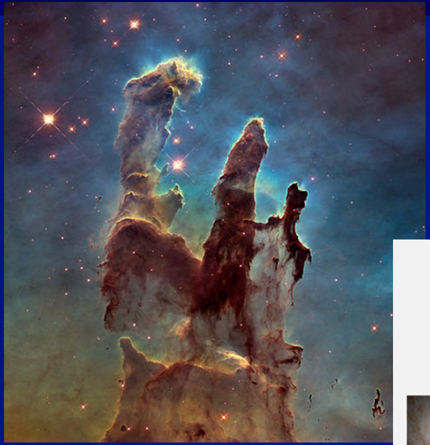


Figure 2 | Normalized rotation curves. a, The various symbols denote the folded and binned rotation curve data for the six galaxies in Fig. 1,

Tools of discovery: Hubble Space telescope





Star formation in
Eagle Nebula

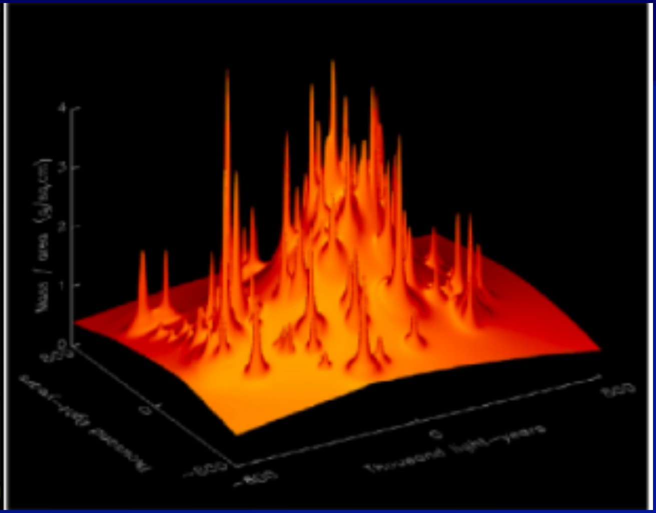
http://hubblesite.org

NASA's Hubble Finds Universe Is Expanding Faster Than Expected

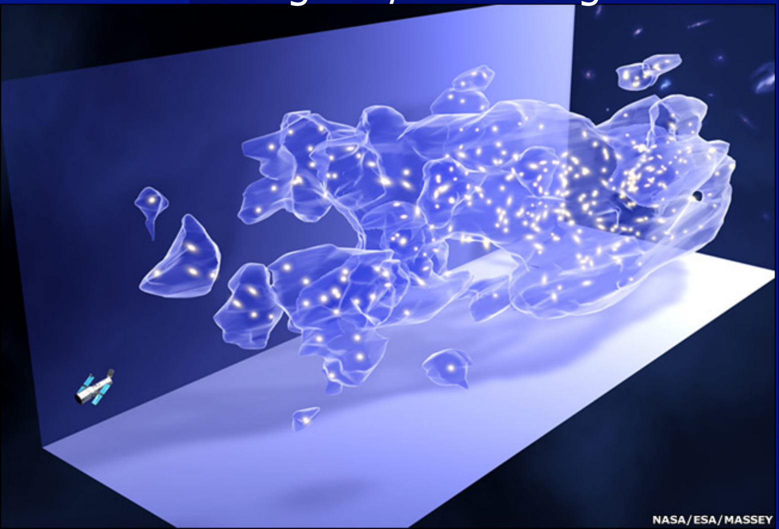
Release date: Jun 2, 2016 11:30 AM (EDT)

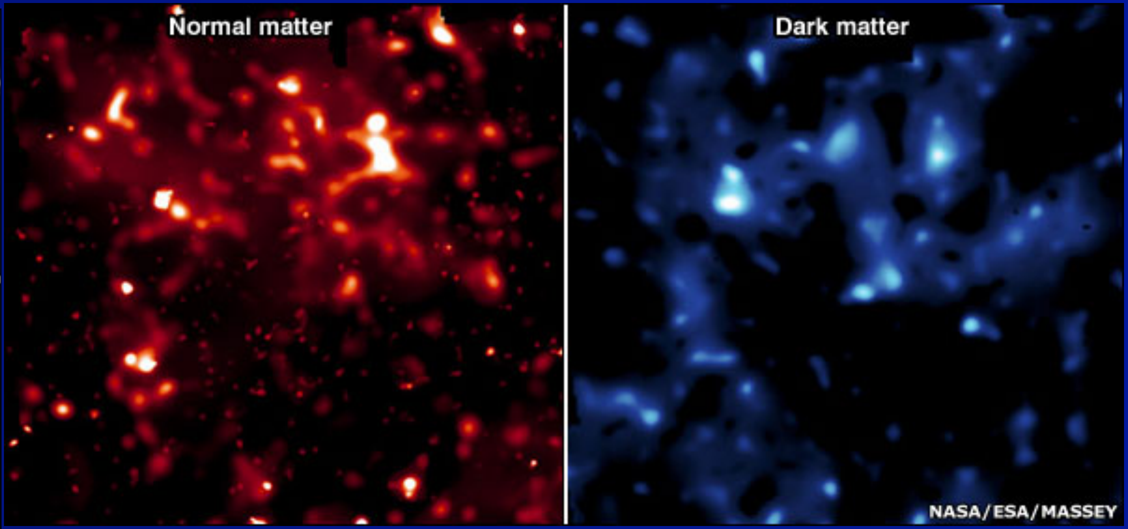
New James Webb Space Telescope to
Be launched by NASA in 2018,
6.5m mirror (vs 2.4m of Hubble)

Gravitational lensing: 3D map of observable Universe



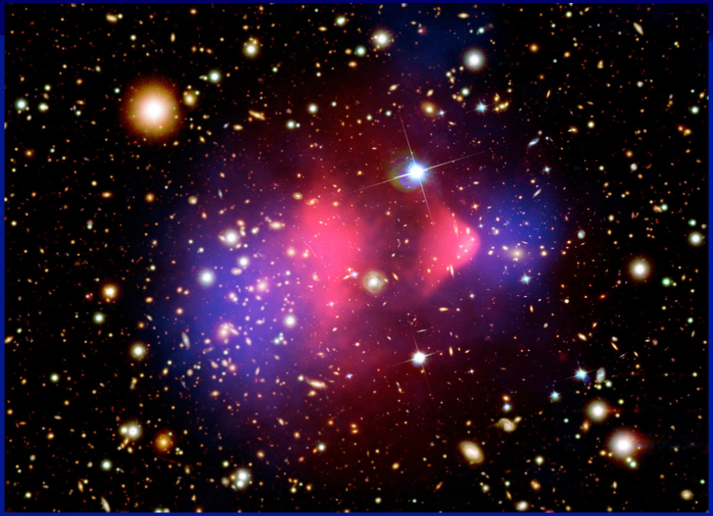
R. Massey et al, Nature 445, 286 (2007): Dark Matter Maps Reveal Cosmic Scaffolding
Area of 1.6 deg^2 ~1/2 million galaxies

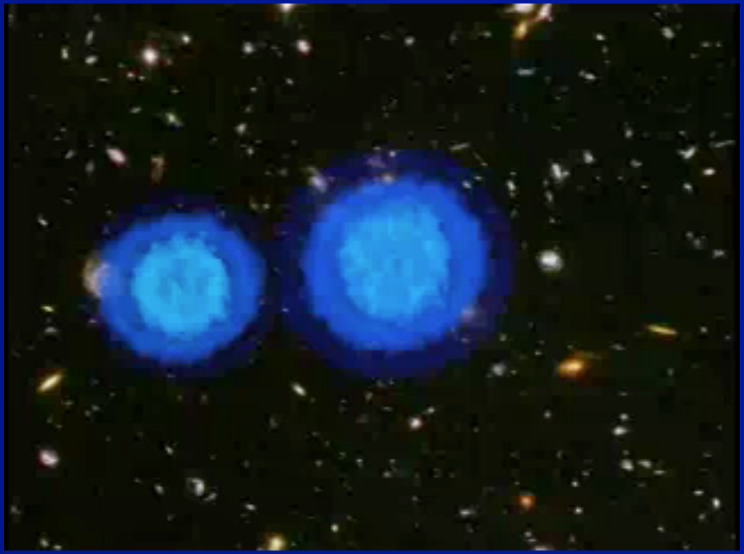




Chandra X-ray observatory data'06 (see chandra.harward.edu)

- Galaxy cluster 1E 0657-56 (`bullet cluster', ~1Gpc away)
- Dark matter (blue) not slowed by the impact; while hot gas (red) is slowed/distorted by drag force
- Separation during collision





Hot Gas in Galaxy Clusters

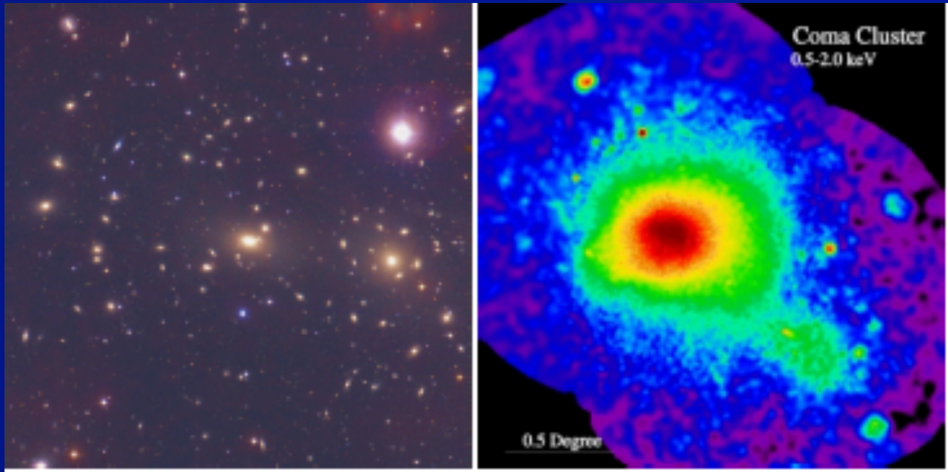
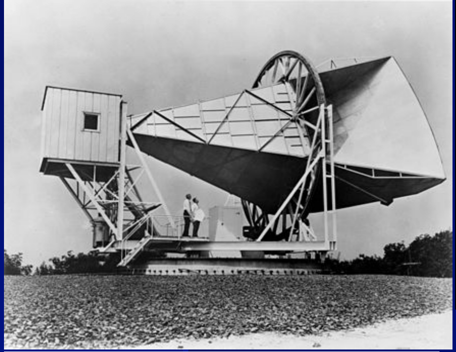


Fig. 3. COMA Cluster: without dark matter, the hot gas would evaporate. Left panel: optica image. Right panel: X-ray image from ROSAT satellite.

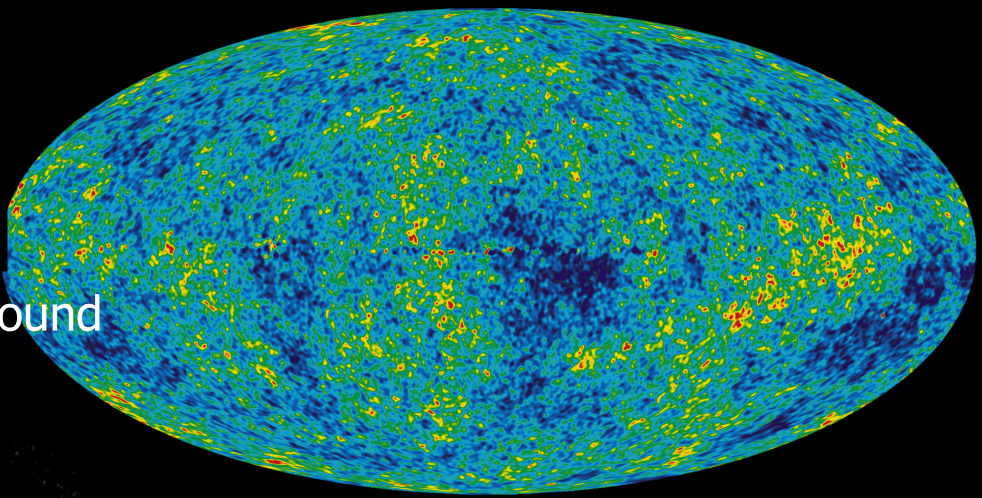
Dark Energy: Universe Expansion gets faster

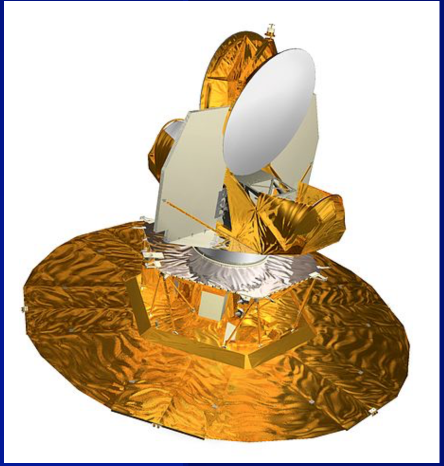
Cosmic Microwave Background

Holmdel Horn Antenna used
for discovery of CMB (1964)

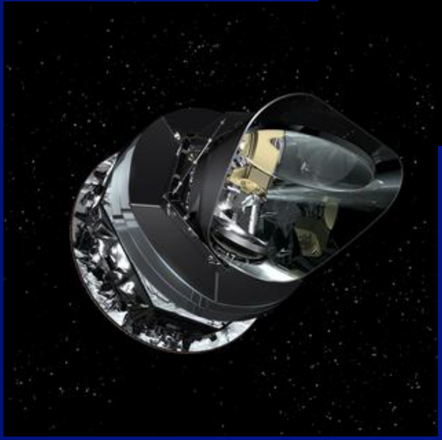


NASA Cosmic Background
Explorer (1989)





Wilkinson Microwave
Anisotropy Probe
(2001-2010)



Planck (2009-2013)

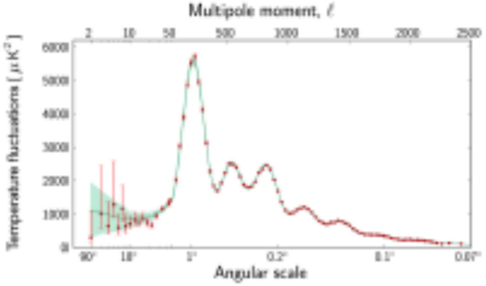
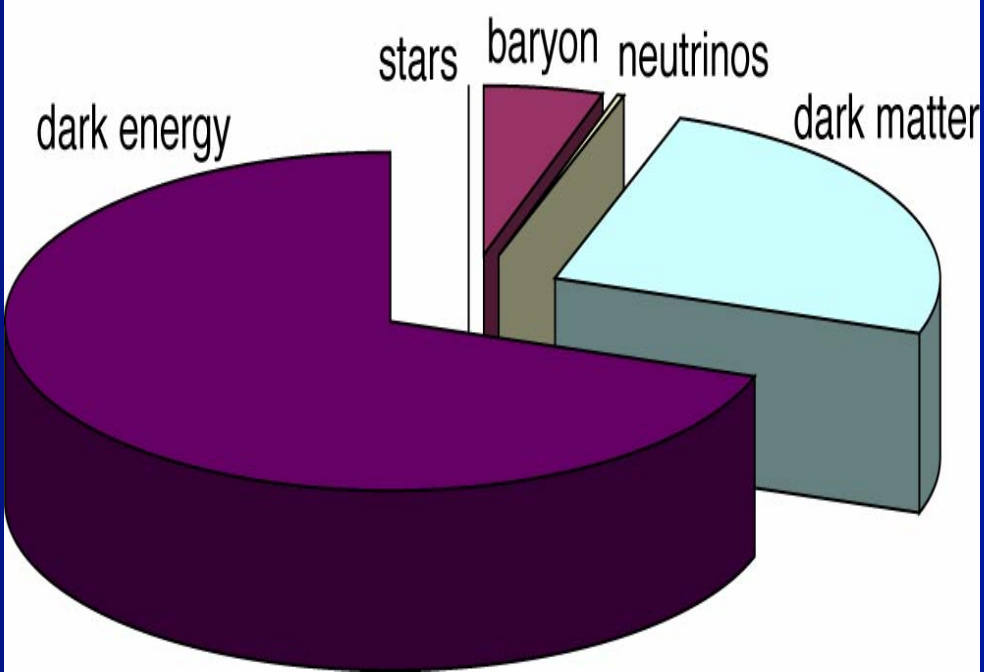


Fig. 5. Planck's power spectrum of temperature fluctuations in the cosmic microwave background. The fluctuations are shown at different angular scales on the sky. Red dots with error bars are the Planck data. The green curve represents the standard model of cosmology, ΛCDM. The peak at 1 degree is consistent with a flat geometry of the universe, the height of the second peak with 5%, and the second and third peaks with 26% dark matter.

matter/energy budget of universe

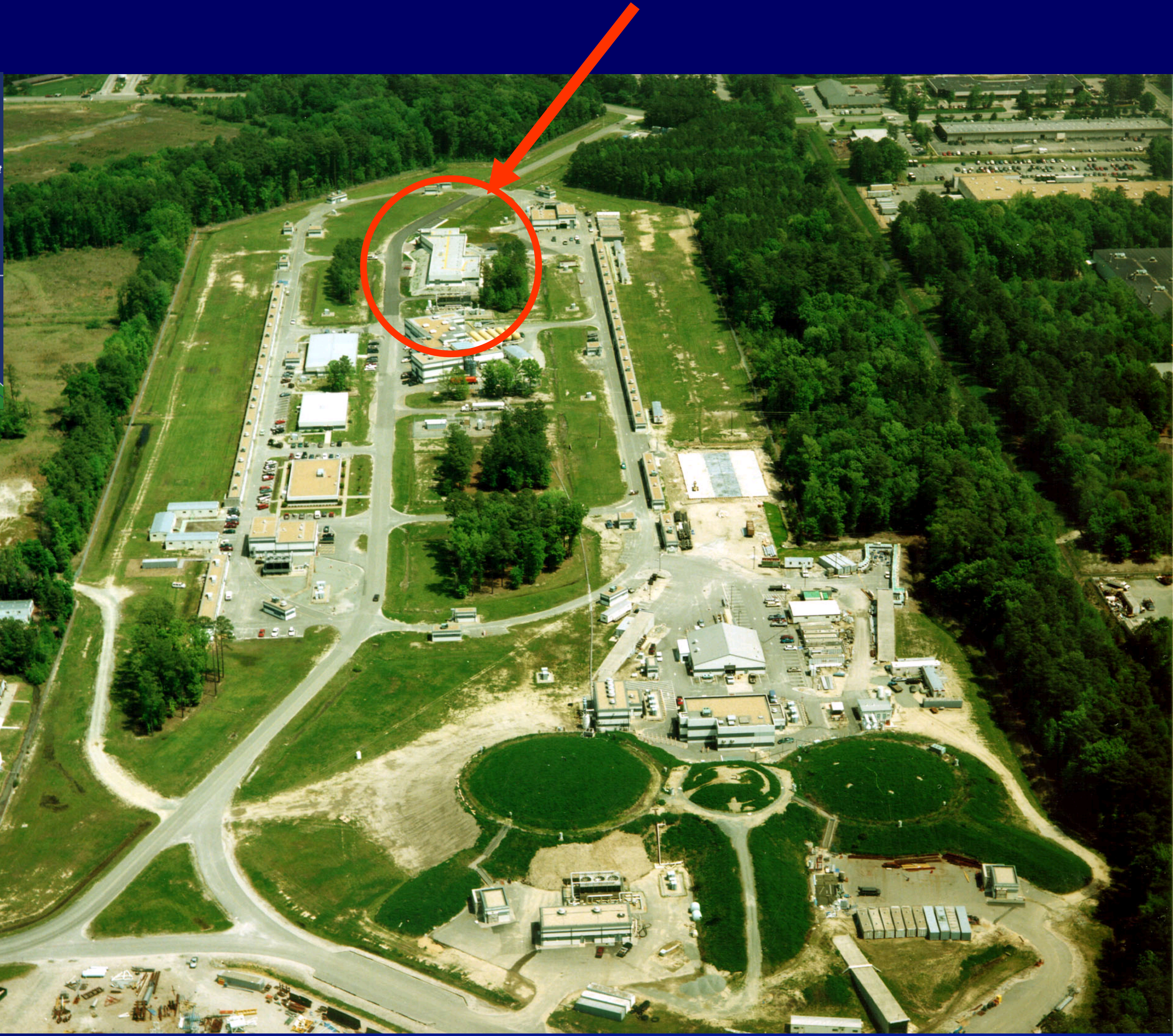
- Stars and galaxies are only ~0.5%
- Neutrinos are ~0.3–10%
- Rest of ordinary matter (electrons and protons) are ~5%
- Dark Matter ~30%
- Dark Energy ~65%
- Anti-Matter 0%

axion a dark matter candidate



Axions at the Institute for Advanced Study (Princeton, NJ, Oct.'06)

Jefferson Lab and the Free Electron Laser



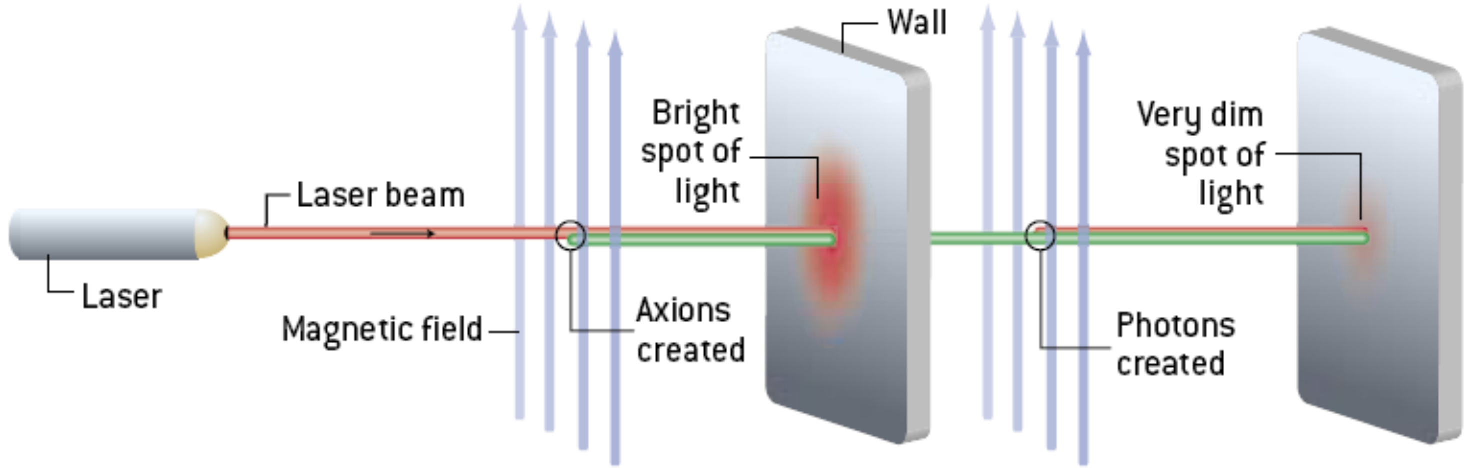
SCIENTIFIC AMERICAN

July 2006

PHYSICS

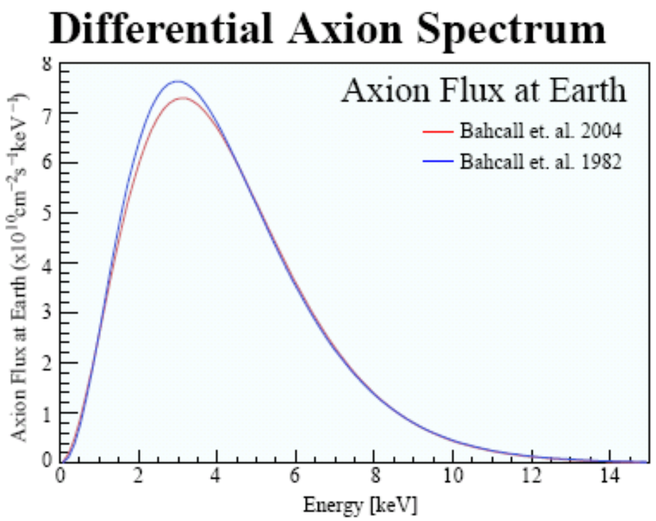
A Hint of Axions

AN EXPERIMENT MAY HAVE SEEN AN ELUSIVE NEW PARTICLE **BY GRAHAM P. COLLINS**



LIGHT BEAM experiment that would confirm the existence of axions passes a laser beam through a strong magnetic field, converting some photons to axions (*green beam*). The axions penetrate a wall before passing through another magnetic field that converts some of the particles back to photons, which form an extremely faint spot on the far wall.

CAST experiment



Mean energy: $\langle E \rangle = 4.2\,\mathrm{keV}$

Axion Luminosity:

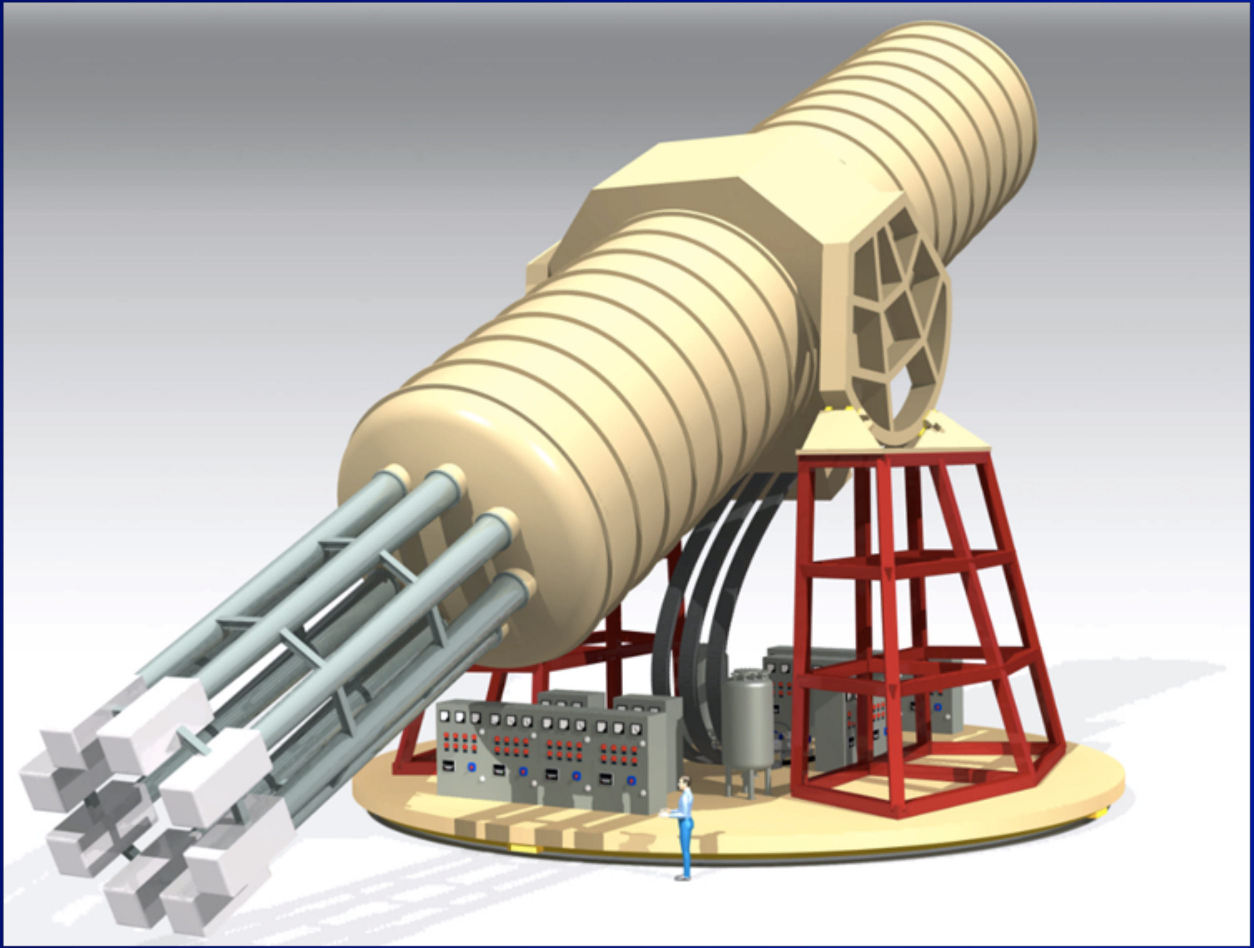
$$L_a = 1.9 \times 10^{-3} L_\odot$$

Axion flux: $\Phi_a = 3.8 \times 10^{11}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

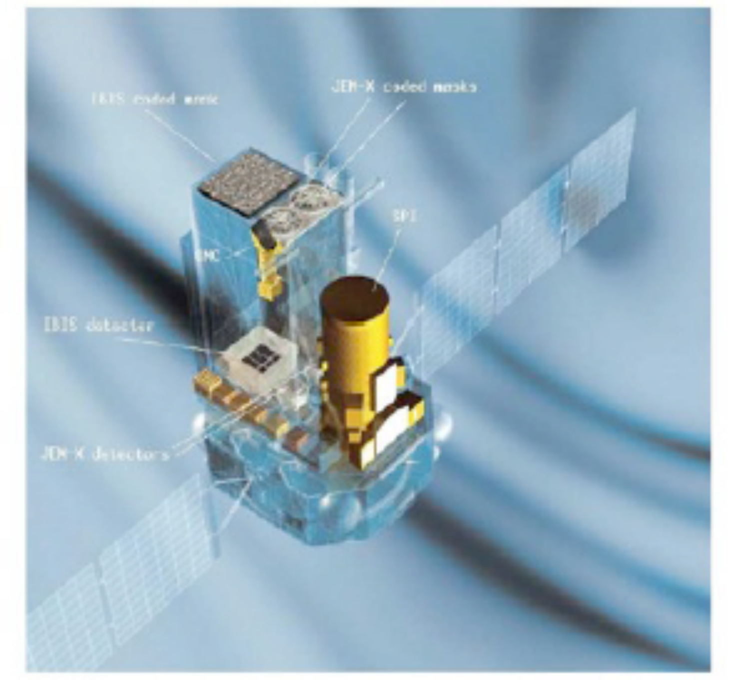
Uses LHC prototype dipole, looks for axions from the sun regenerating photons in the x-ray region. K. Zioutas *et al*., PRL 94, 121301 (2005)

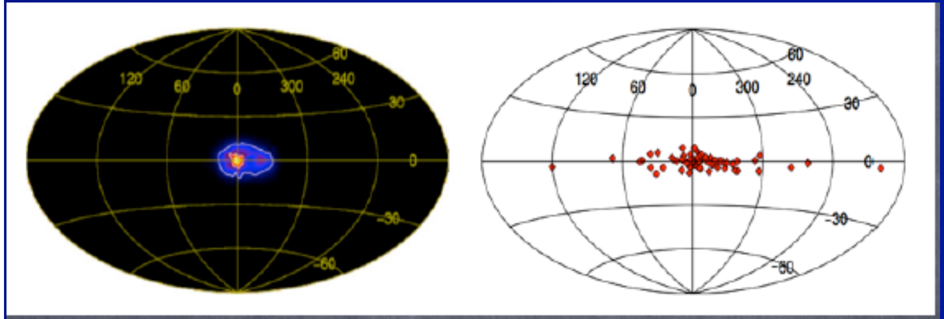
Has seen no effect

Helioscope of the future: IAXO



Galactic Center Positrons

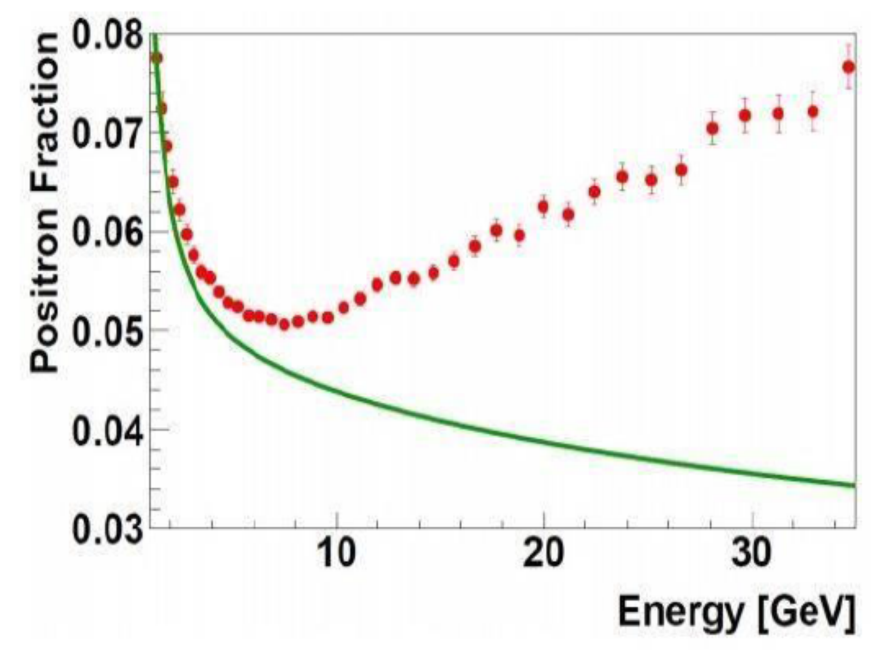




The SPI sky map in the 511 keV electron-positron annihilation line and the sky distribution of the hard X (E > 20 keV) LMXBs detected by IBIS (Weidenspointner et al., 2008)

INTErnational Gamma-Ray Astrophysics Laboratory (**INTEGRAL**) is a currently operational space telescope for observing gamma rays. Launched by the European Space Agency into Earth orbit in 2002, designed to detect some of the most energetic radiation that comes from space. It was the most sensitive gamma ray observatory Launched before *Fermi.*

Cosmic Ray Positron Excess



The **Alpha Magnetic Spectrometer**, also designated **AMS-02**, is a particle physics experiment module that is mounted on the International Space Station (ISS). It is designed to measure antimatter in cosmic rays and search for evidence of dark matter. The launch of Space Shuttle *Endeavour flight STS-134 carrying AMS-02 took place on 16 May 2011, and the spectrometer was installed on 19 May 2011*

Weakly Interacting Massive Particles (WIMP)

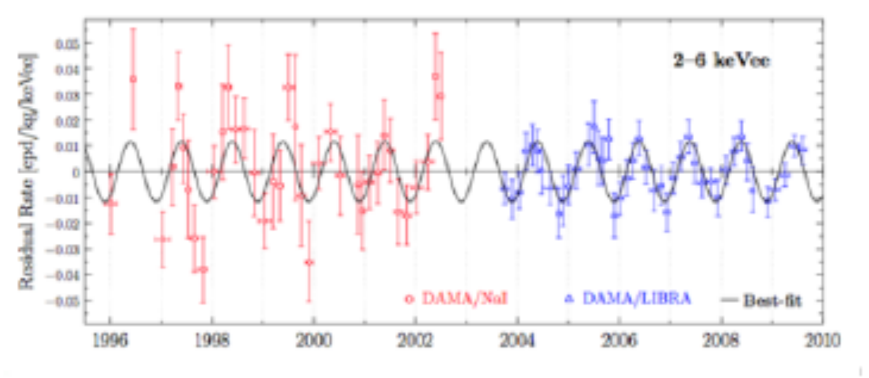


Fig. 8. DAMA data (including DAMA/LIBRA) has a 9 σ detection of annual modulation consistent with WIMPs.[66]

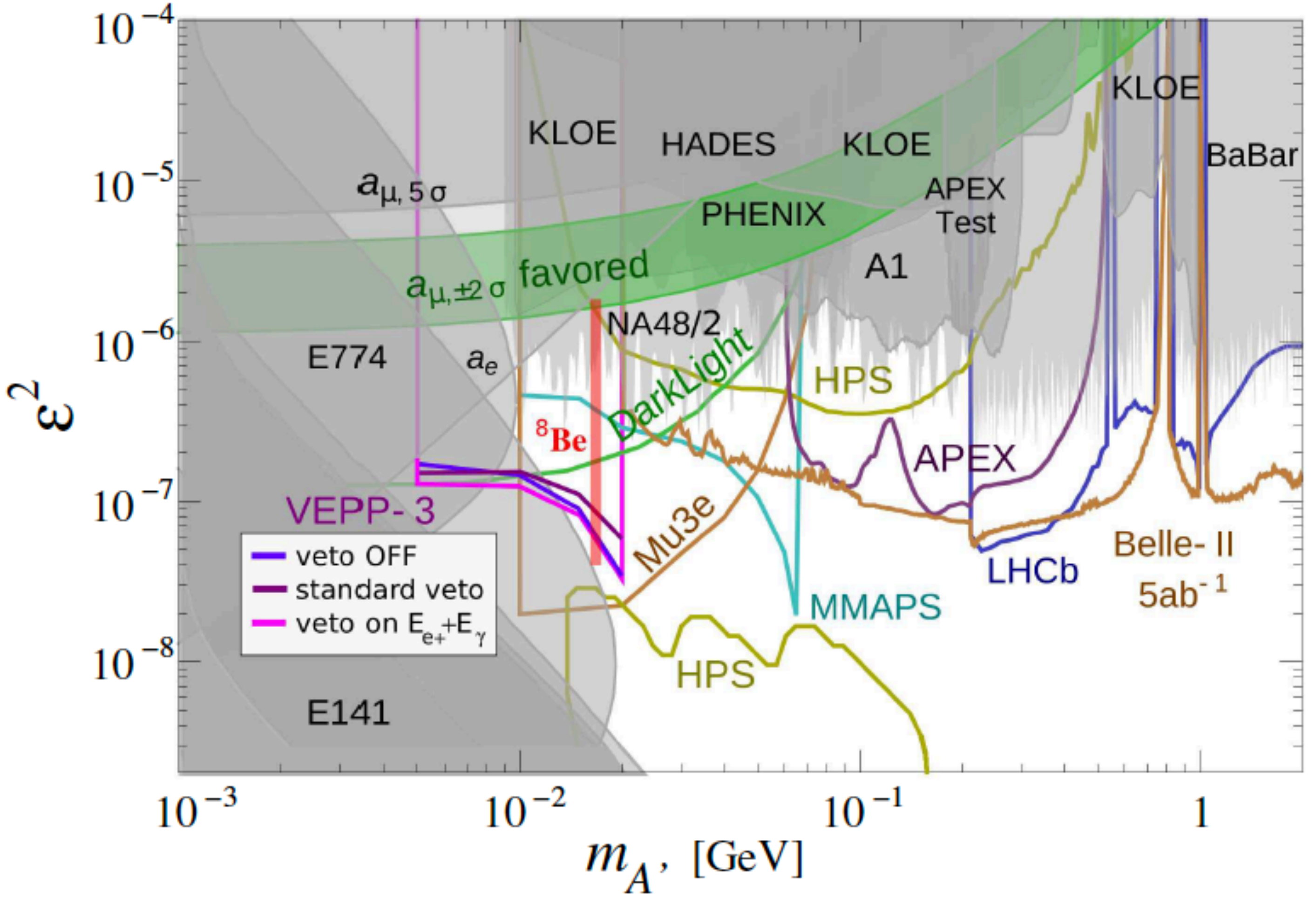
DAMA detector (Italy) observed a signal consistent with dark-matter (WIMP) scattering. However, not of other detectors confirmed the effect. Needs to be cross-checked with the same kind of detector material (NaI)

Jefferson Lab: experiments looking for BSM canditades and dark-force mediators

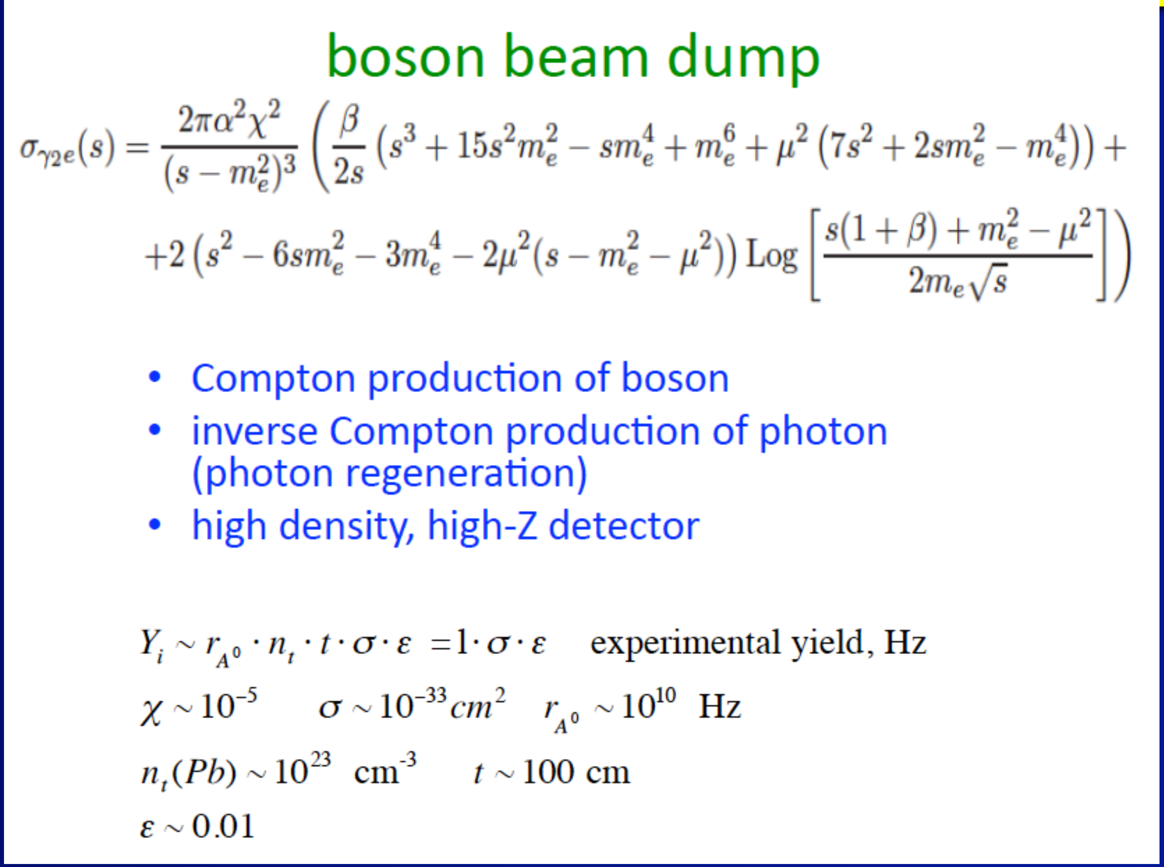
- LIPSS (axion-like particle and paraphoton searches, eV scales)
- APEX, HPS, DarkLight
- BDX (see Marco Battaglieri's talk)

Sensitivity of A’s searches

Phase space for all A’ searches



Light dark photons from Compton backscattering (AA, Baker for JLAB FEL)



boson beam dump

$$\sigma_{\gamma 2e}(s) = \frac{2\pi\alpha^2\chi^2}{(s-m_e^2)^3}\left(\frac{\beta}{2s}\left(s^3+15s^2m_e^2-sm_e^4+m_e^6+\mu^2\left(7s^2+2sm_e^2-m_e^4\right)\right)+\right.$$
$$\left.+2\left(s^2-6sm_e^2-3m_e^4-2\mu^2(s-m_e^2-\mu^2)\right)\mathrm{Log}\left[\frac{s(1+\beta)+m_e^2-\mu^2}{2m_e\sqrt{s}}\right]\right)$$

- Compton production of boson
- inverse Compton production of photon (photon regeneration)
- high density, high-Z detector

$Y_i \sim r_{A^0}\cdot n_t\cdot t\cdot\sigma\cdot\varepsilon\ = 1\cdot\sigma\cdot\varepsilon$ experimental yield, Hz

$\chi \sim 10^{-5}$ $\sigma \sim 10^{-33}cm^2$ $r_{A^0} \sim 10^{10}$ Hz

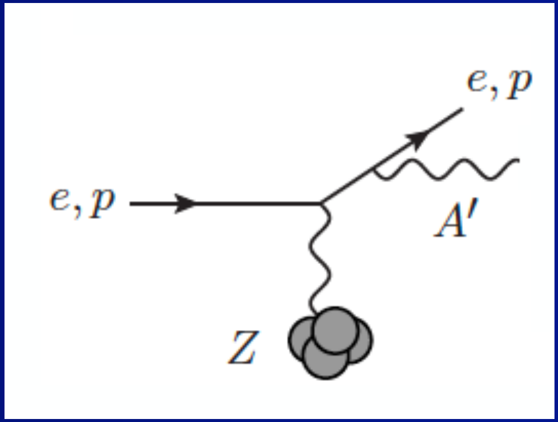
$n_t(Pb) \sim 10^{23}$ cm^{-3} $t \sim 100$ cm

$\varepsilon \sim 0.01$

Can be realized for PRAE with an “internal photon target”
= eg, Fabri-Perot cavity, similar to Compton polarimeter setup

Dark-particle bremstrahhlung

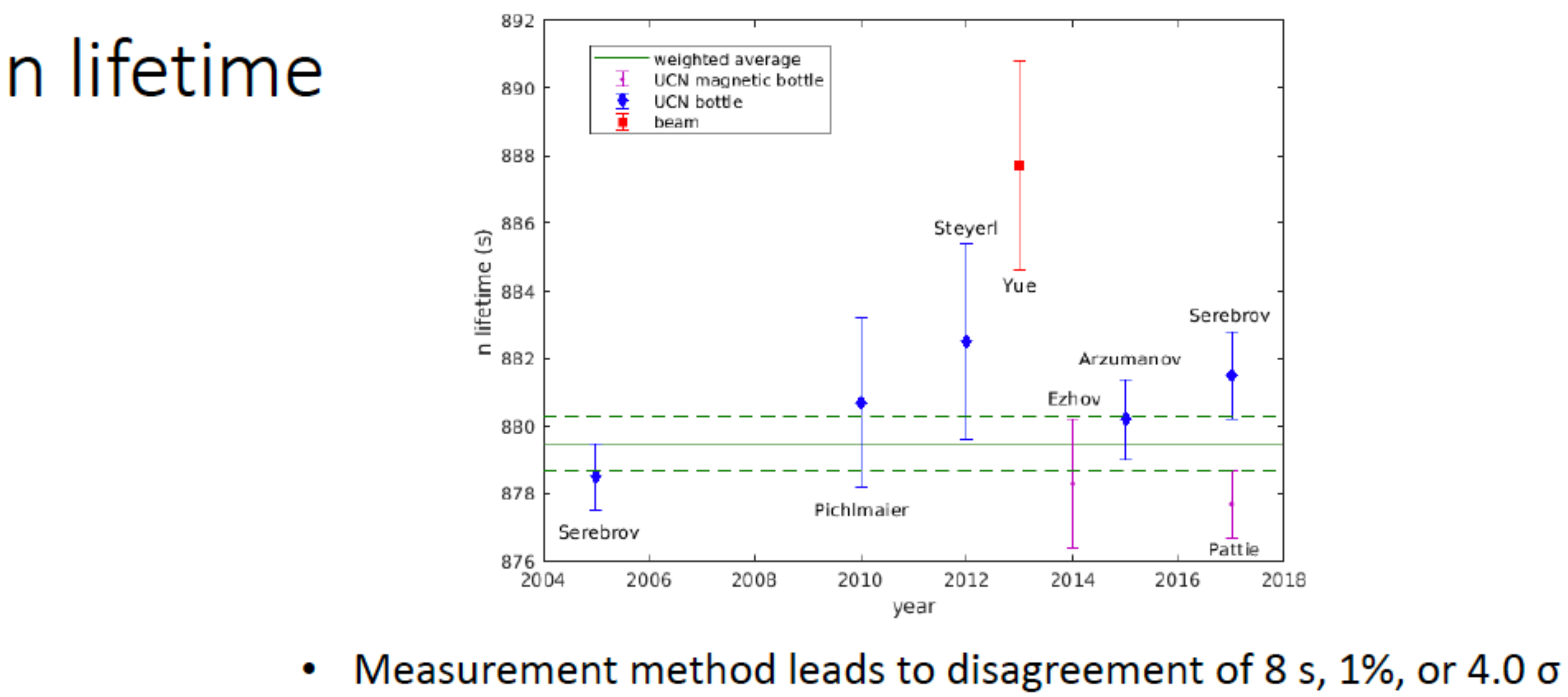
- All A'-search experiments consider total production rates and e-e+ decay channels
- Let us take advantage of PRAE low beam emittance and thin (internal) target and study
  - Spin structure of bremsstrahlung



Spin structure of bremsstrahlung

- Real-photon hard collinear bremsstrahlung flips helicity of a relativistic electron
  - As a result, zero-angle brem amplitude is suppressed by a factor m_e/E
  - However, scalar ALPs or non-zero mass A′ may have zero helicity, hence total helicity is conserved with no flipping of electron helicity
  - Also possible with collinear emission of "twisted photons" with l=1
- What to measure: angular distribution of bremsstrahlung near || to electrons

Neutron lifetime puzzle



n lifetime

- Measurement method leads to disagreement of 8 s, 1%, or 4.0 σ

Slide credit:

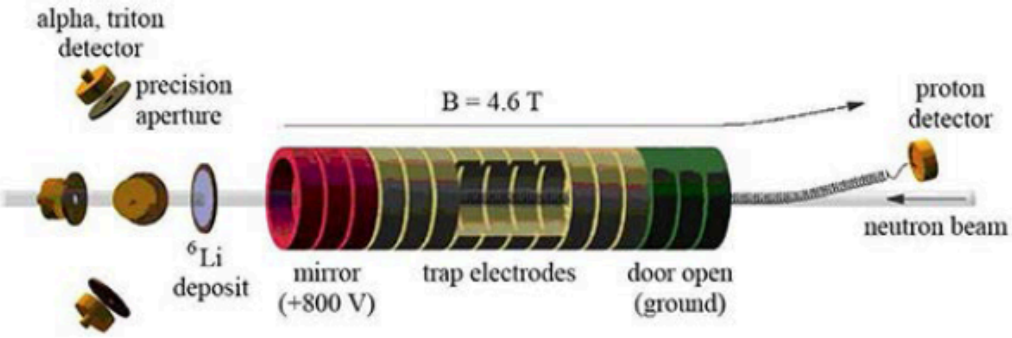
Neutron lifetime

n lifetime

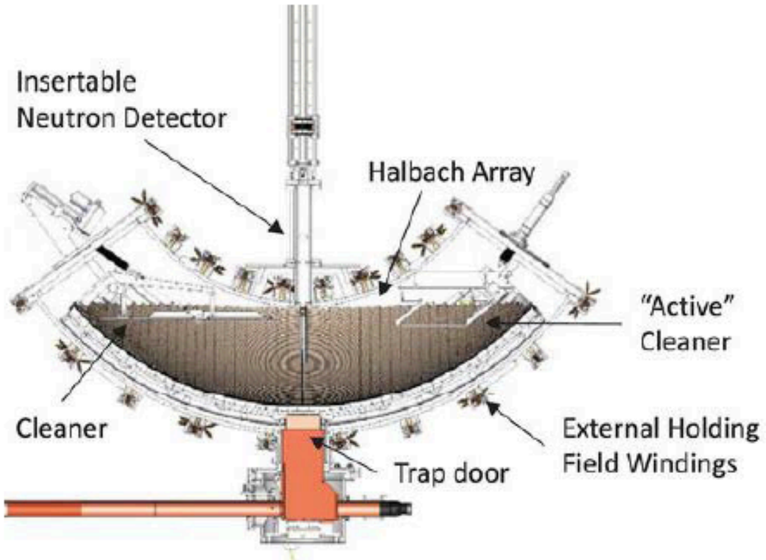
- Fundamental Measurement difference, Beam vs Bottle

Beam measures protons

Bottle measures surviving neutrons

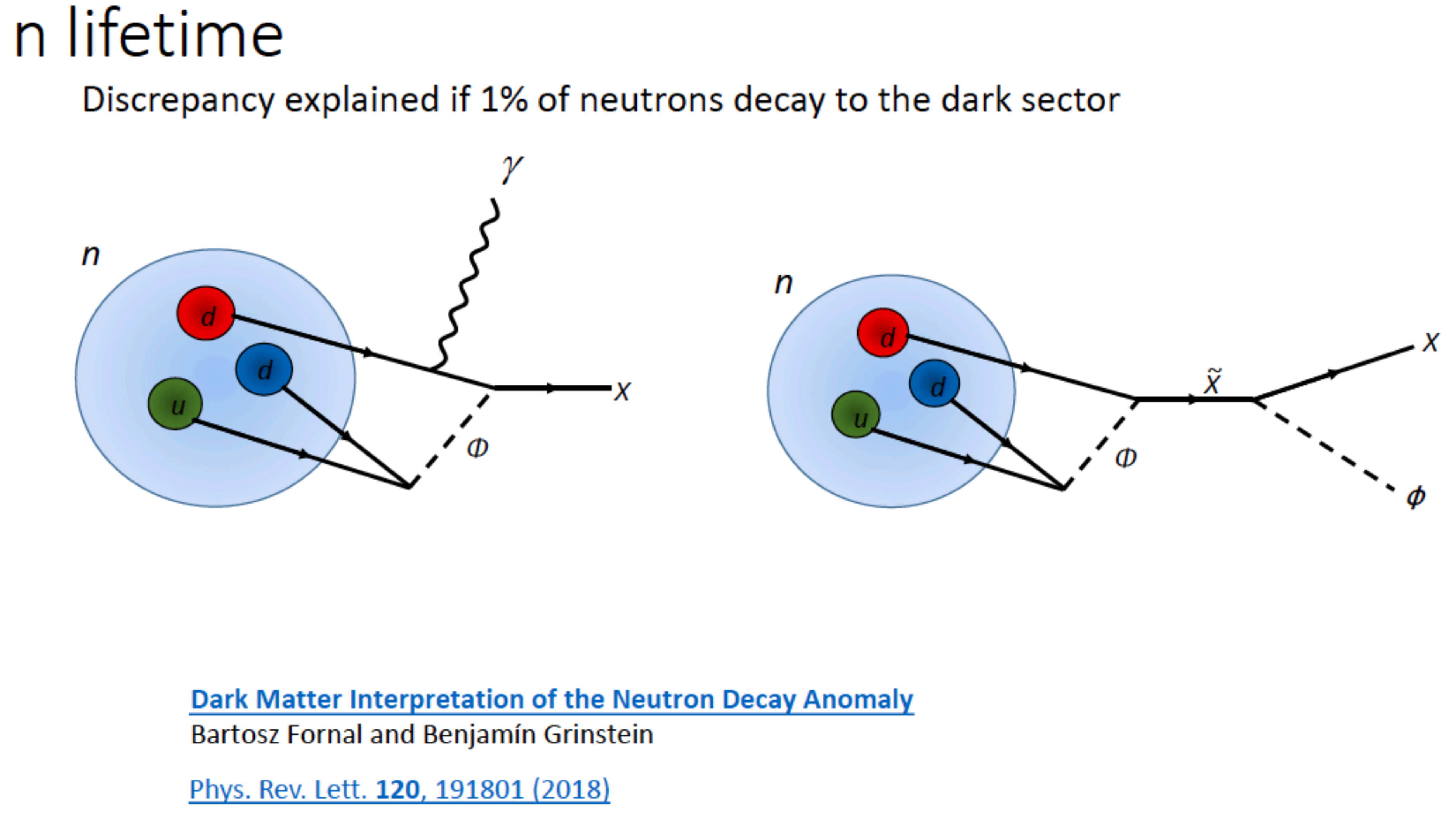


A. T. Yue, et al. DOI: 10.1103/PhysRevLett.111.222501



R.W. Pattie, et al. DOI: 10.1126/science.aan8895

Dark decays of a neutron



n lifetime

Discrepancy explained if 1% of neutrons decay to the dark sector

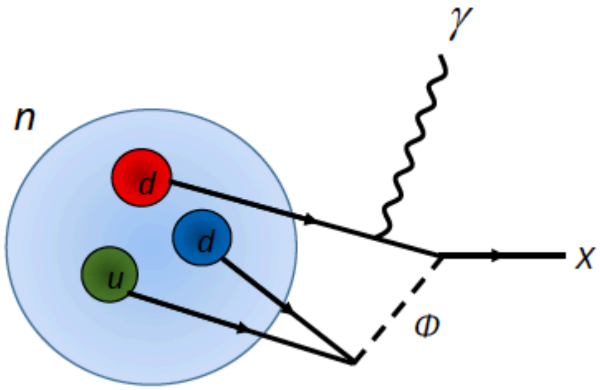
Dark Matter Interpretation of the Neutron Decay Anomaly
Bartosz Fornal and Benjamín Grinstein

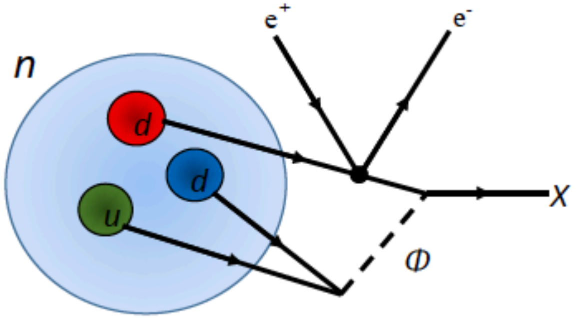
Phys. Rev. Lett. **120**, 191801 (2018)

Possible detection scenarios

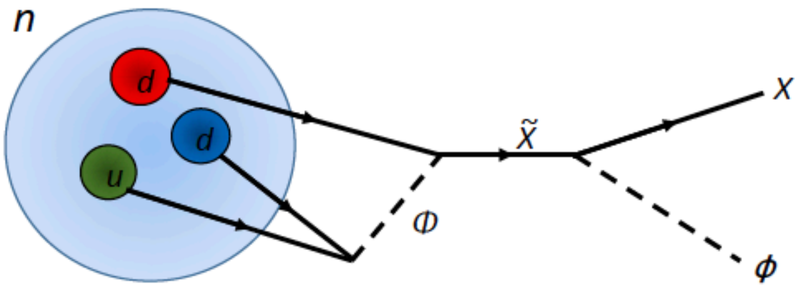
3 decays proposed by Fornal and Grinstein

2 are detectable (with modern technology)



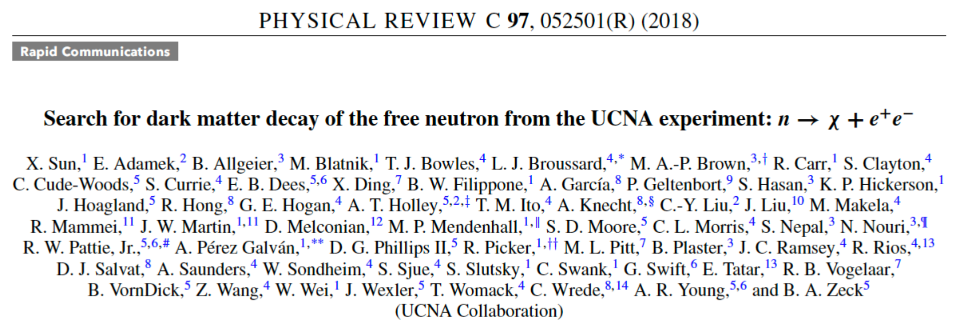


1 is a purely dark decay



To be studied, eg, by UCNA Collaboration

UCNA excluded e+e- mode

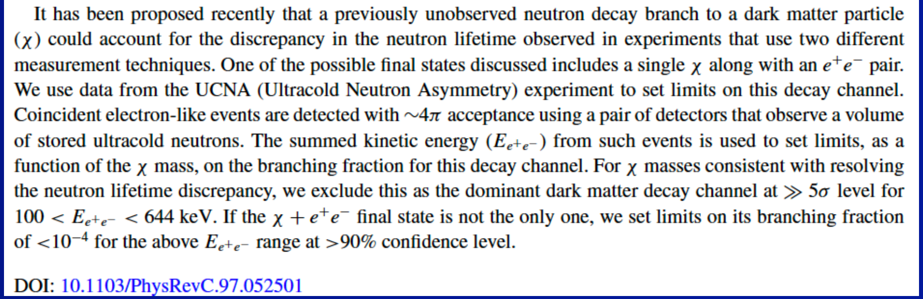


PHYSICAL REVIEW C **97**, 052501(R) (2018)

Rapid Communications

Search for dark matter decay of the free neutron from the UCNA experiment: $n \rightarrow \chi + e^+e^-$

X. Sun,[1] E. Adamek,[2] B. Allgeier,[3] M. Blatnik,[1] T. J. Bowles,[4] L. J. Broussard,[4,*] M. A.-P. Brown,[3,†] R. Carr,[1] S. Clayton,[4] C. Cude-Woods,[5] S. Currie,[4] E. B. Dees,[5,6] X. Ding,[7] B. W. Filippone,[1] A. García,[8] P. Geltenbort,[9] S. Hasan,[3] K. P. Hickerson,[1] J. Hoagland,[5] R. Hong,[8] G. E. Hogan,[4] A. T. Holley,[5,2,‡] T. M. Ito,[4] A. Knecht,[8,§] C.-Y. Liu,[2] J. Liu,[10] M. Makela,[4] R. Mammei,[11] J. W. Martin,[1,11] D. Melconian,[12] M. P. Mendenhall,[1,‖] S. D. Moore,[5] C. L. Morris,[4] S. Nepal,[3] N. Nouri,[3,¶] R. W. Pattie, Jr.,[5,6,#] A. Pérez Galván,[1,**] D. G. Phillips II,[5] R. Picker,[1,††] M. L. Pitt,[7] B. Plaster,[3] J. C. Ramsey,[4] R. Rios,[4,13] D. J. Salvat,[8] A. Saunders,[4] W. Sondheim,[4] S. Sjue,[4] S. Slutsky,[1] C. Swank,[1] G. Swift,[6] E. Tatar,[13] R. B. Vogelaar,[7] B. VornDick,[5] Z. Wang,[4] W. Wei,[1] J. Wexler,[5] T. Womack,[4] C. Wrede,[8,14] A. R. Young,[5,6] and B. A. Zeck[5]
(UCNA Collaboration)



It has been proposed recently that a previously unobserved neutron decay branch to a dark matter particle (χ) could account for the discrepancy in the neutron lifetime observed in experiments that use two different measurement techniques. One of the possible final states discussed includes a single χ along with an e^+e^- pair. We use data from the UCNA (Ultracold Neutron Asymmetry) experiment to set limits on this decay channel. Coincident electron-like events are detected with $\sim 4\pi$ acceptance using a pair of detectors that observe a volume of stored ultracold neutrons. The summed kinetic energy ($E_{e^+e^-}$) from such events is used to set limits, as a function of the χ mass, on the branching fraction for this decay channel. For χ masses consistent with resolving the neutron lifetime discrepancy, we exclude this as the dominant dark matter decay channel at $\gg 5\sigma$ level for $100 < E_{e^+e^-} < 644$ keV. If the $\chi + e^+e^-$ final state is not the only one, we set limits on its branching fraction of $<10^{-4}$ for the above $E_{e^+e^-}$ range at $>90\%$ confidence level.

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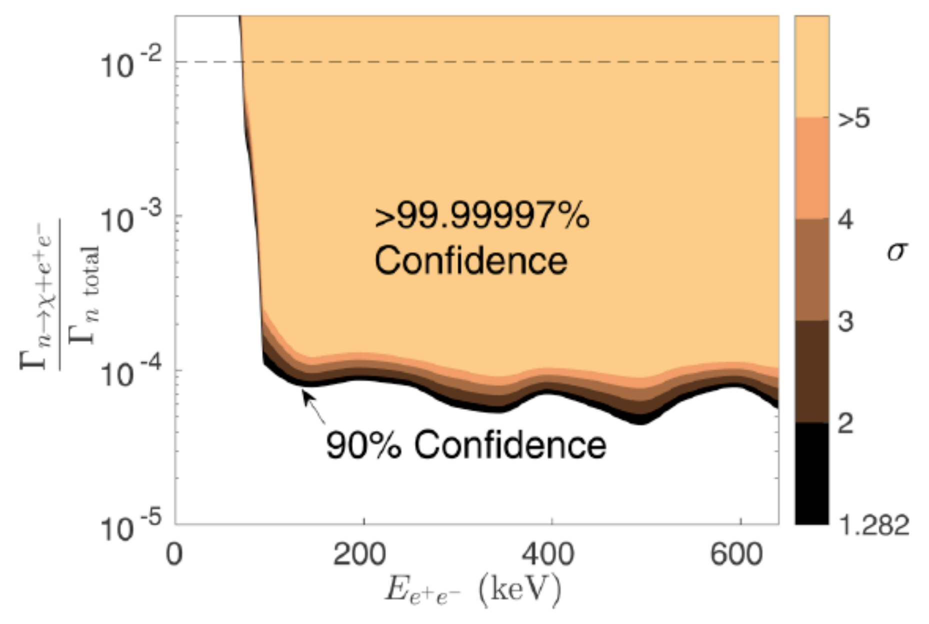


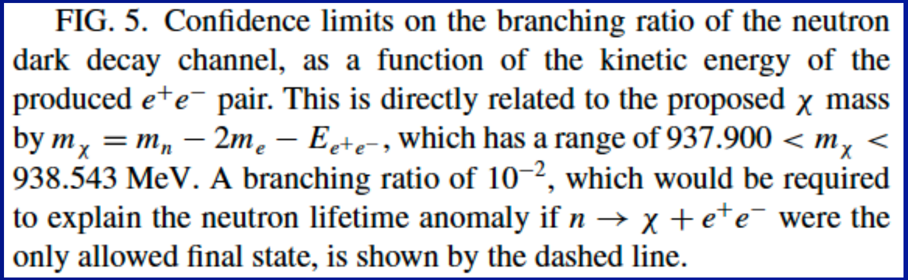
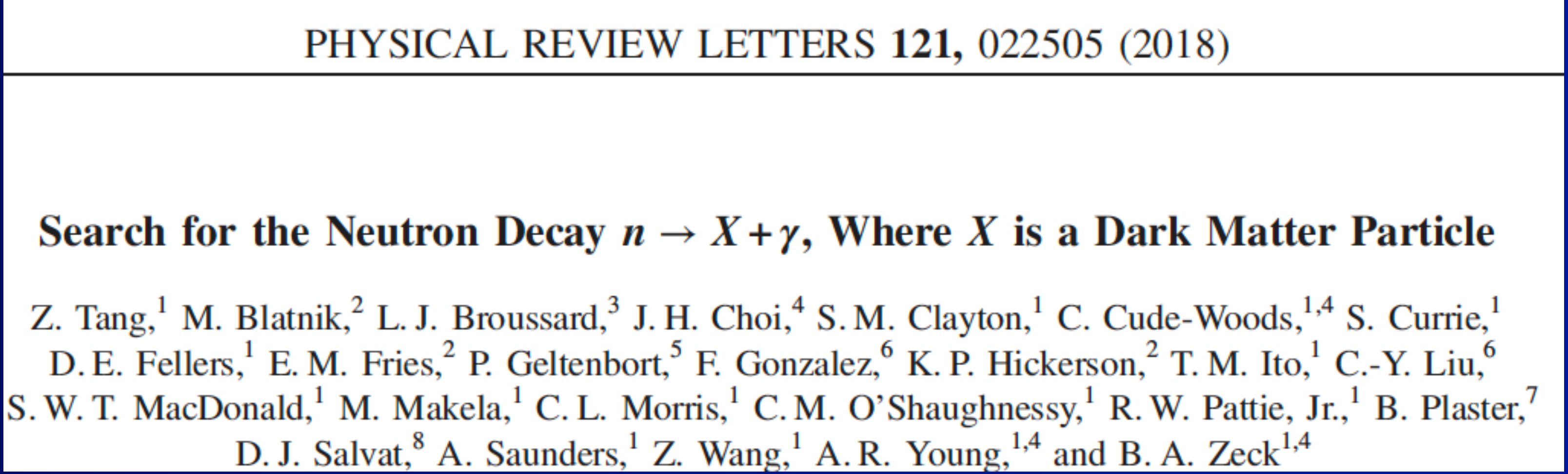


FIG. 5. Confidence limits on the branching ratio of the neutron dark decay channel, as a function of the kinetic energy of the produced e^+e^- pair. This is directly related to the proposed χ mass by $m_\chi = m_n - 2m_e - E_{e^+e^-}$, which has a range of $937.900 < m_\chi < 938.543$ MeV. A branching ratio of 10^{-2}, which would be required to explain the neutron lifetime anomaly if $n \rightarrow \chi + e^+e^-$ were the only allowed final state, is shown by the dashed line.

Gamma-decay mode

- excluded at $0.782\ \mathrm{MeV} < E\gamma < 1.664\ \mathrm{MeV}$.
- The case $E\gamma < 0.782\ \mathrm{MeV}$ remains unexplored.



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Search for the Neutron Decay $n \to X + \gamma$, Where X is a Dark Matter Particle

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Electrodisintegration of Deuteron into Dark Matter and Proton Close to Threshold

- Ivanov et al, arXiv:1807.04604
- Argue that $m_\chi > m_n - 2m_e$
- Look for triple-coincidence measurements of e^-+D->e^-+p+n

- **Accessible for PRAE**

Summary

- Several “puzzles”, both in astrophysics and in the lab allow interpretation in terms of dark matter coupling to visible matter
- Suggested for consideration in PRAE
  - Photon “beam dump” (light A’, paraphotons);
  - Helicity structrure of near-collinear bremsstrahlung (effect of A’ mass)
  - Deutron electrodisionegration near threshold (dark modes of neutron decay)