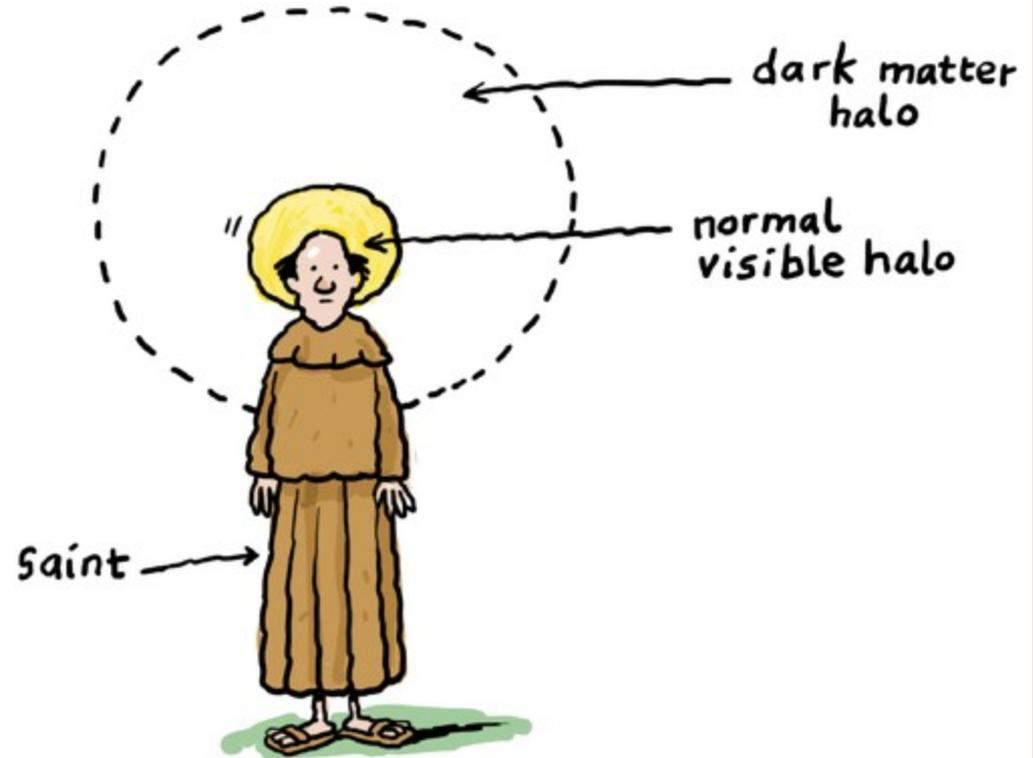




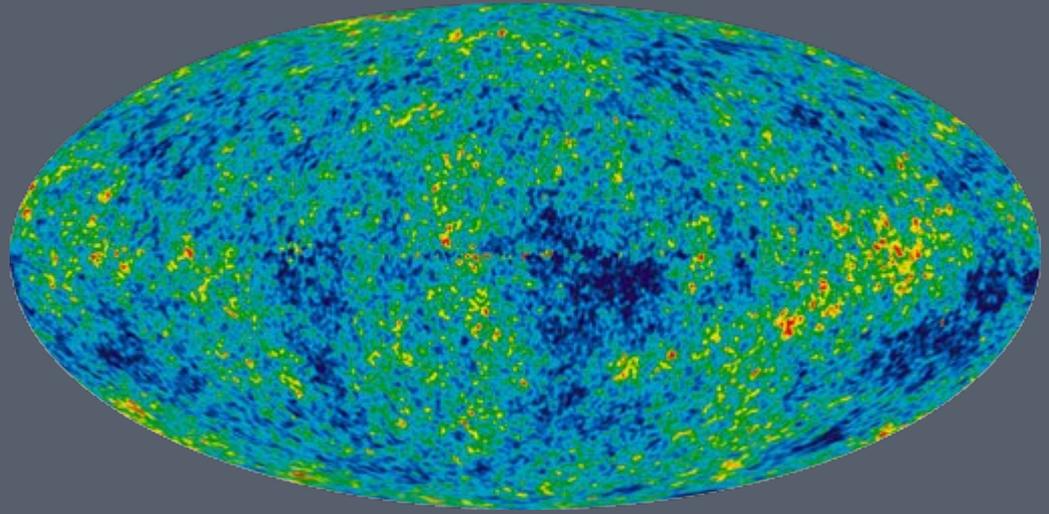
The  
University  
Of  
Sheffield.



# ASTROPARTICLE PHYSICS LECTURE 4

1

**Matthew Malek**  
University of Sheffield



# Dark Matter

Astrophysical Evidence  
Candidates  
Detection

2

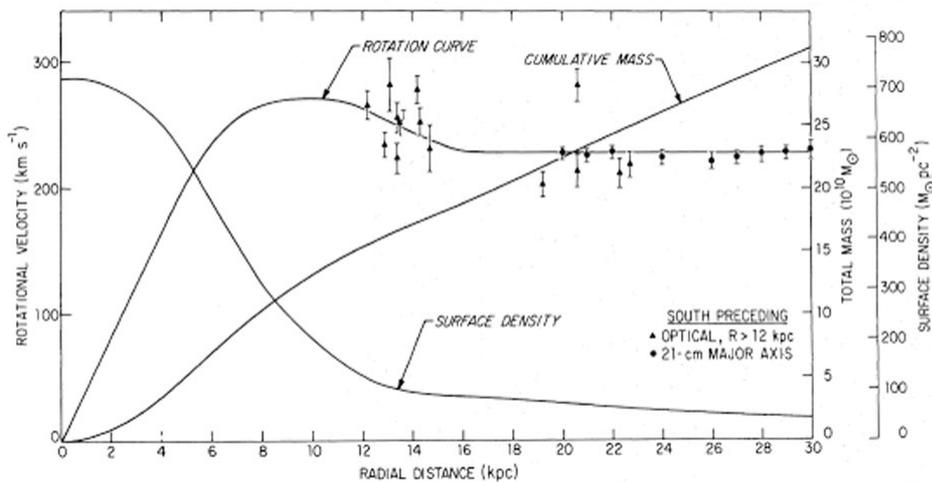
# The Astrophysical Evidence

- Dynamics of rich clusters
  - Zwicky (1933!) noted that the velocities of galaxies in the Coma cluster were too high to be consistent with a bound system



# The Astrophysical Evidence

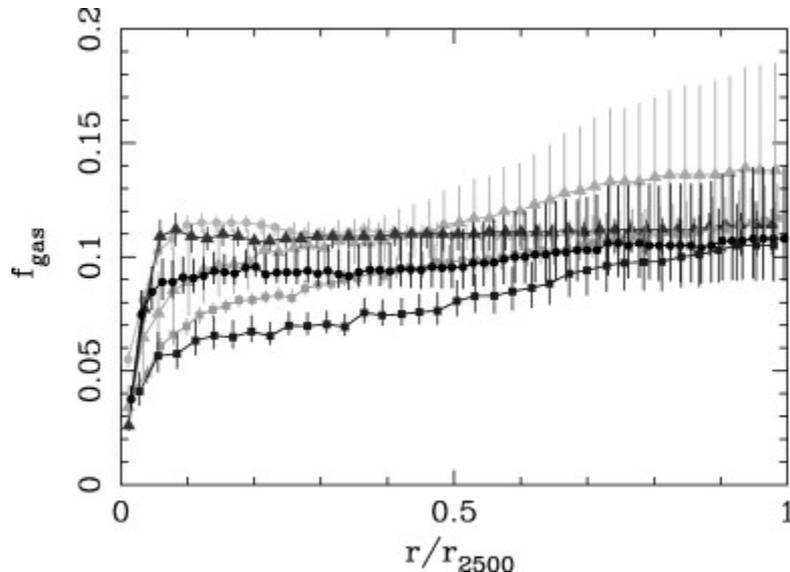
- Rotation curves of spiral galaxies  
Vera Rubin (R.I.P. Dec 2016) in the 1970s



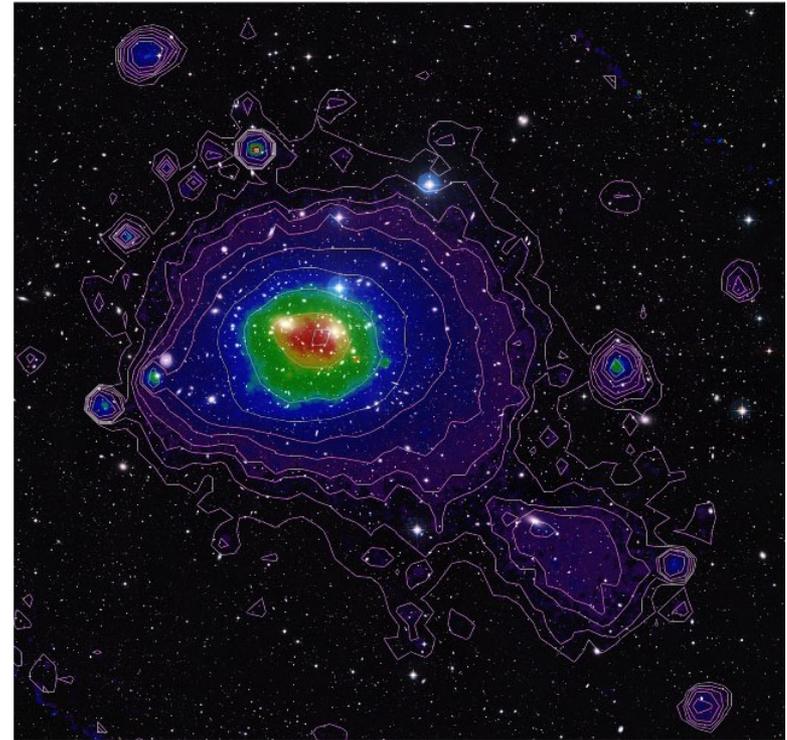
- flat at large radii: if mass traced light we would expect them to be Keplerian at large radii,  $v \propto r^{-1/2}$ , because the light is concentrated in the central bulge
- and disc light falls off exponentially, not  $\propto r^{-2}$ 
  - as required for flat rotation curve

# The Astrophysical Evidence

- Dynamics of rich clusters
  - mass of gas and gravitating mass can be extracted from X-ray emission from intracluster medium



Allen et al., *MNRAS* **334**  
(2002) L11

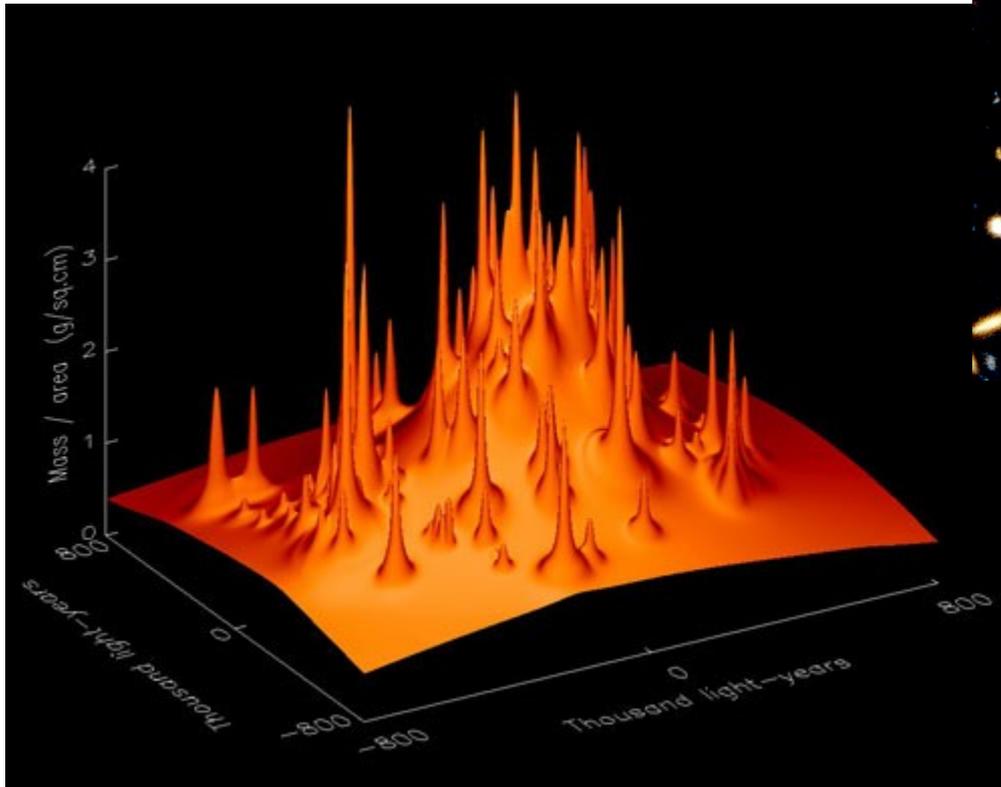


ROSAT X-ray image of  
Coma cluster overlaid on  
optical.

MPI (ROSAT image);  
NASA/ESA/DSS2 (visible  
image)

# The Astrophysical Evidence

- Dynamics of rich clusters
  - Gravitational lensing



Mass map of CL0024+1654 as determined from the observed gravitational lensing.

Tyson, Kochanski and Dell'Antonio, *ApJ* **498** (1998) L107

# The Astrophysical Evidence: The Bullet Cluster (2006)

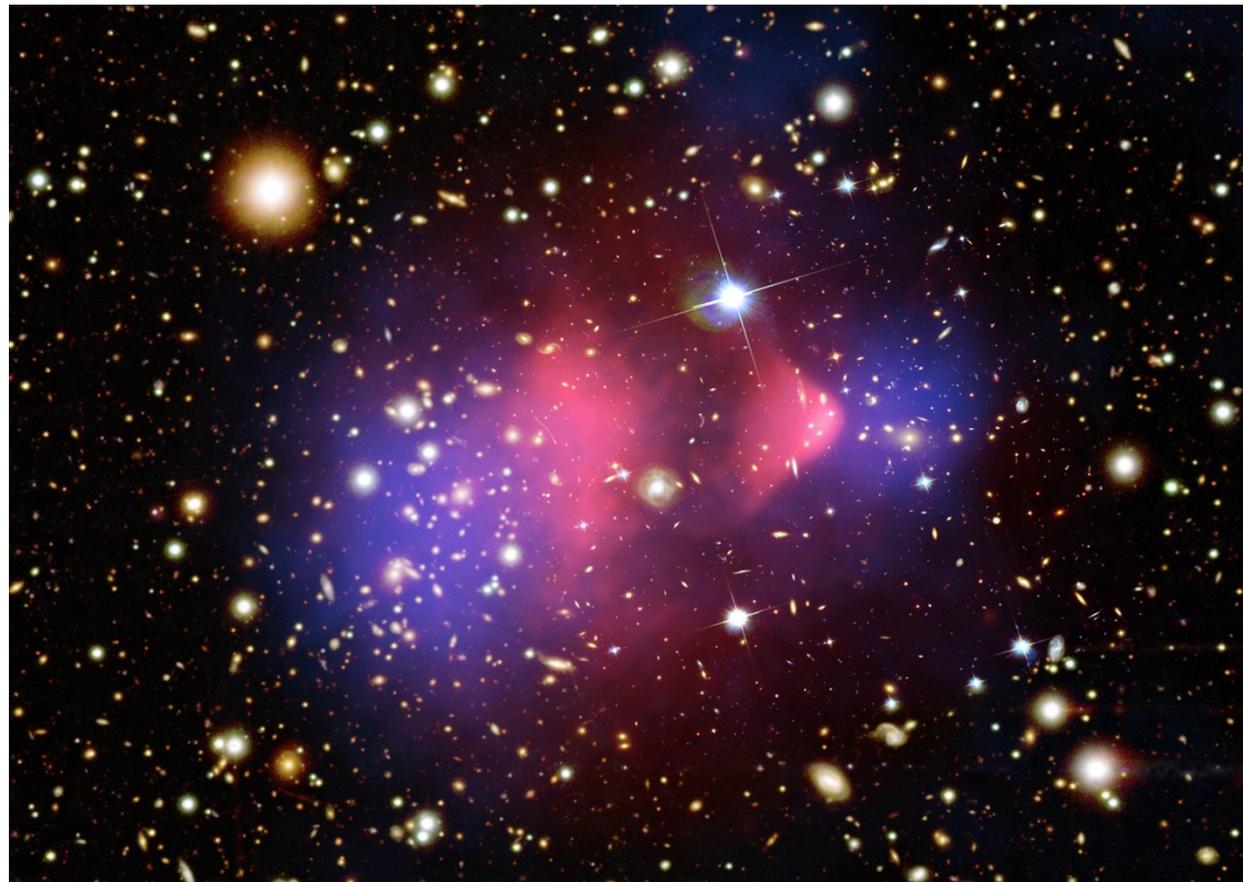
- Mass from lens mapping (blue) follows stars not gas (red)
  - ↳ dark matter is **collisionless**

## Composite Credit:

*X-ray:* NASA/CXC/  
CfA/  
M. Markevitch  
et al.;

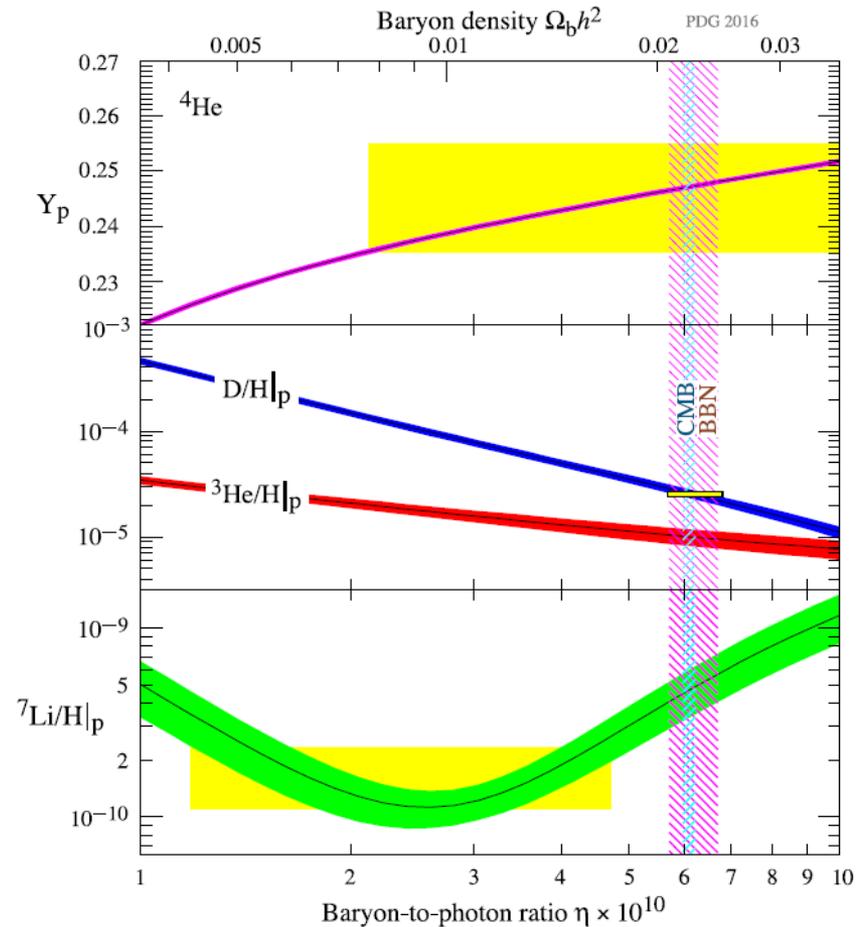
*Lensing Map:*  
NASA/STScI; ESO  
WFI; Magellan/  
U.Arizona/  
D.Clowe et al

*Optical:*  
NASA/STScI;  
Magellan/  
U.Arizona/  
D.Clowe et al.



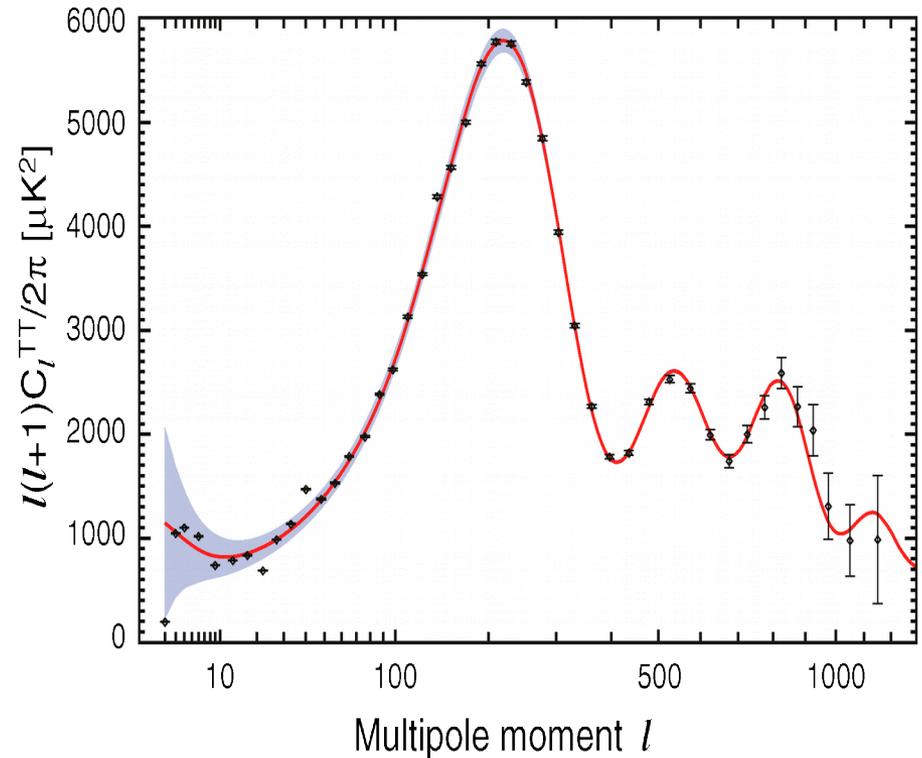
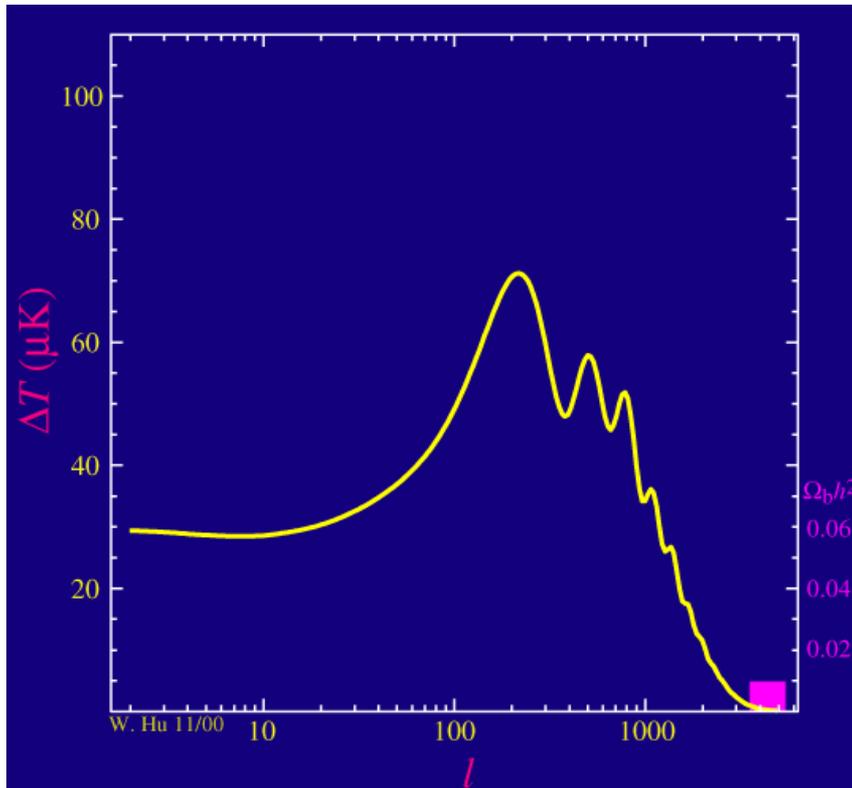
# Non-Baryonic Dark Matter

- Density of baryonic matter strongly constrained by early-universe nucleosynthesis (BBN)
- density parameter of order 0.3 as required by data from, e.g., galaxy clusters is completely inconsistent with best fit



# Non-Baryonic Dark Matter: Cosmology

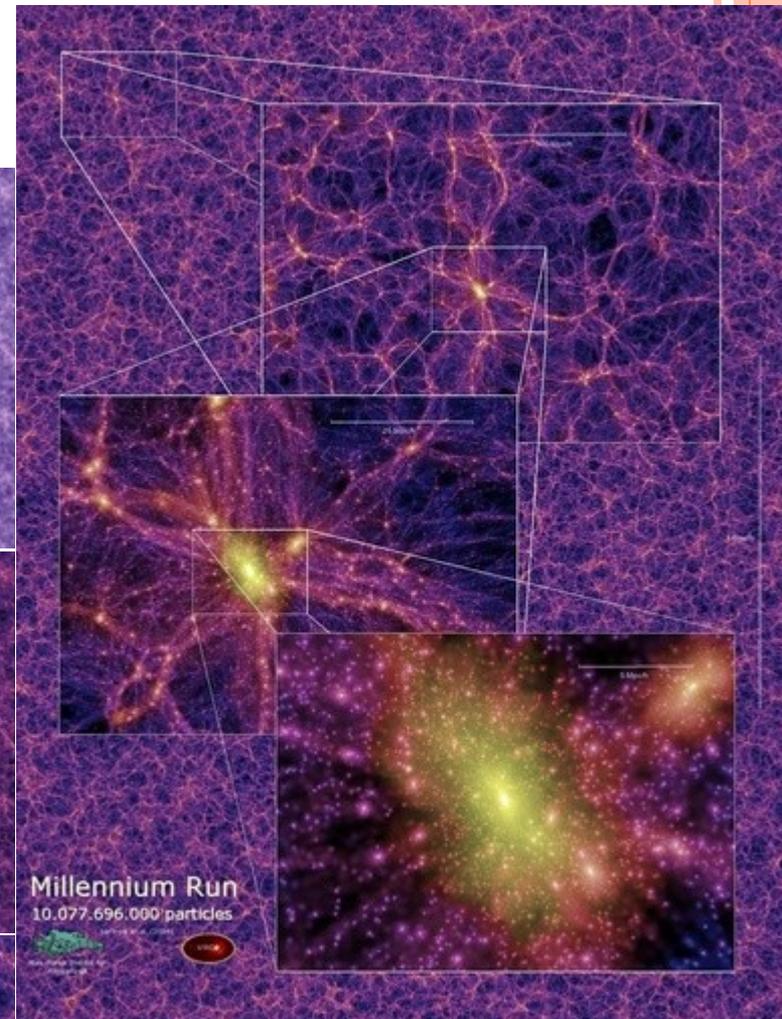
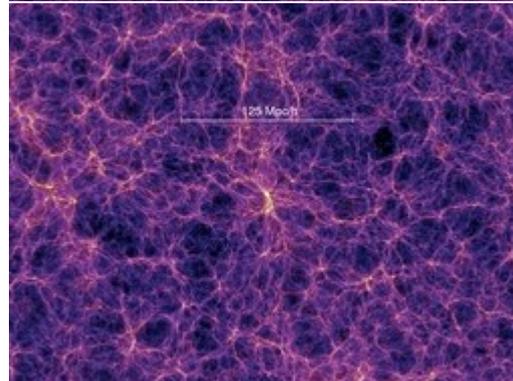
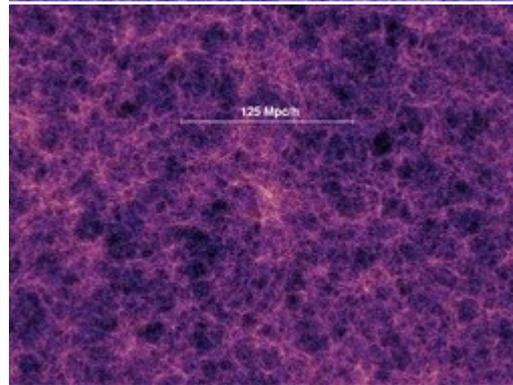
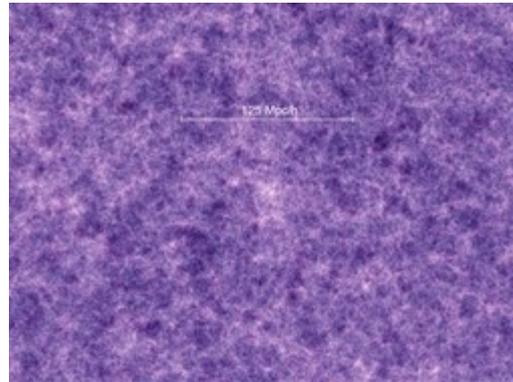
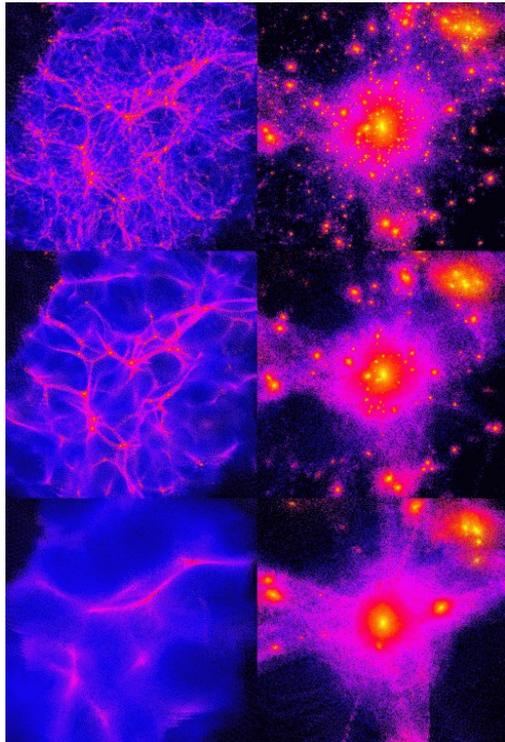
Ratio of odd/even peaks  
depends on  $\Omega_b$



Wayne Hu

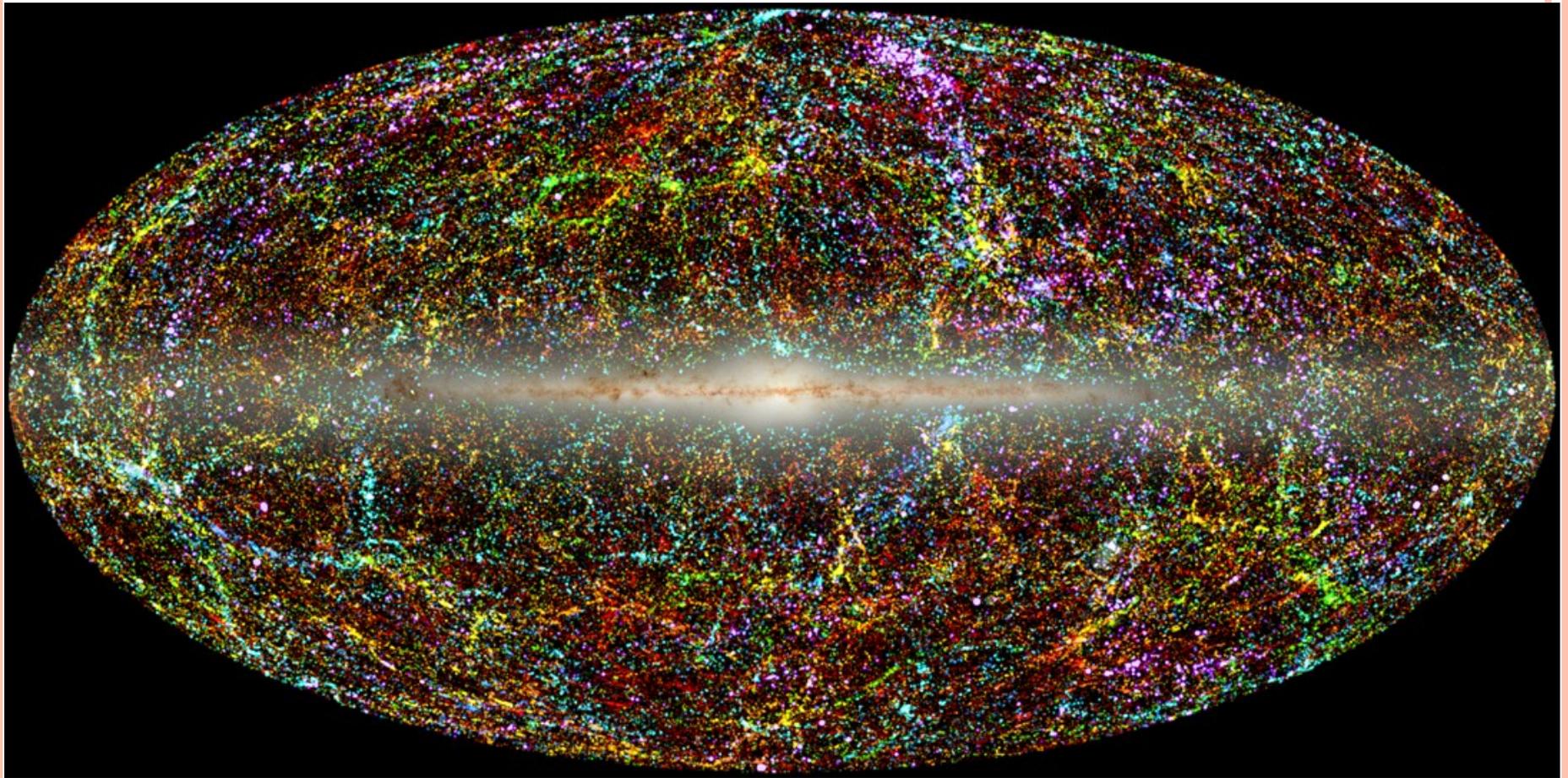
# Large Scale Structure

Relativistic (**hot**) dark matter makes structure top-down—  
non-relativistic (**cold**) bottom-up.  
Real world looks like **cold** dark matter.



VIRGO Consortium  
Millennium Simulation  
<http://www.mpa-garching.mpg.de/galform/millennium/>

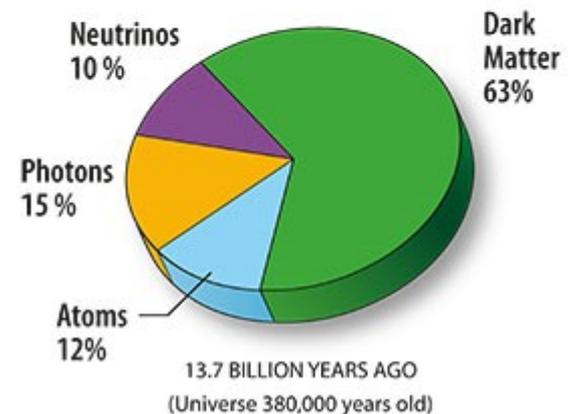
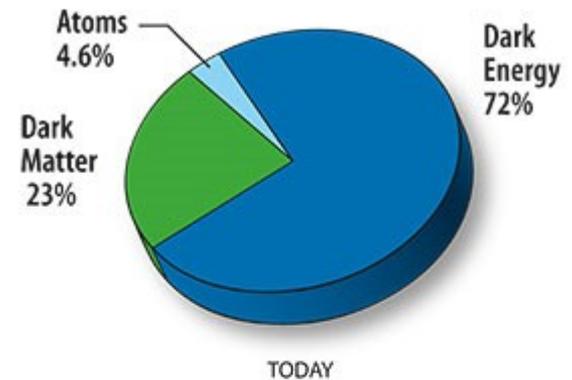
# 2MASS Galaxy Survey



Local galaxies ( $z < 0.1$ ; distance coded by colour, from blue to red)  
Statistical studies, e.g. correlation functions, confirm visual  
impression that this looks much more like cold than hot dark matter

# Brief Summary of Astrophysical Evidence

- Many observables concur that  $\Omega_{m0} \approx 0.3$
- Most of this must be non-baryonic
- BBN and CMB concur that baryonic
  - matter contributes  $\Omega_{b0} \approx 0.05$
  - Bullet Cluster mass distribution
  - indicates that dark matter is
  - collisionless
- No Standard Model candidate
- neutrinos are too light, and are
  - “hot” (relativistic at decoupling)
  - hot dark matter does not reproduce
    - observed large-scale structure
- *BSM physics*





# Dark Matter

Astrophysical Evidence  
Candidates  
Detection

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# Dark Matter Candidates

	WIMPs	SuperWIMPs	Light $\tilde{G}$	Hidden DM	Sterile $\nu$	Axions
Motivation	GHP	GHP	GHP/NPFP	GHP/NPFP	$\nu$ Mass	Strong CP
Naturally Correct $\Omega$	Yes	Yes	No	Possible	No	No
Production Mechanism	Freeze Out	Decay	Thermal	Various	Various	Various
Mass Range	GeV-TeV	GeV-TeV	eV-keV	GeV-TeV	keV	$\mu\text{eV}$ -meV
Temperature	Cold	Cold/Warm	Cold/Warm	Cold/Warm	Warm	Cold
Collisional				✓		
Early Universe		✓✓		✓		
Direct Detection	✓✓			✓		✓✓
Indirect Detection	✓✓	✓		✓	✓✓	
Particle Colliders	✓✓	✓✓	✓✓	✓		

GHP = Gauge Hierarchy Problem

NPFP = New Physics Flavour Problem

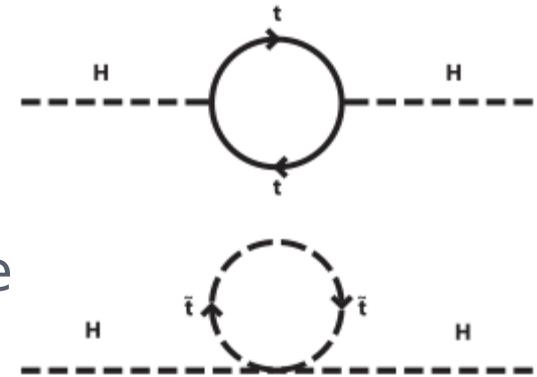
✓ = possible signal; ✓✓ = expected signal

Jonathan Feng, *ARAA* **48** (2010) 495 (highly recommended)

# Particle Physics Motivations

- Gauge Hierarchy Problem  
in SM, loop corrections to Higgs mass give

$$\Delta m_h^2 \approx \frac{\lambda^2}{16\pi^2} \int^\Lambda \frac{d^4 p}{p^2} \approx \frac{\lambda^2}{16\pi^2} \Lambda^2$$

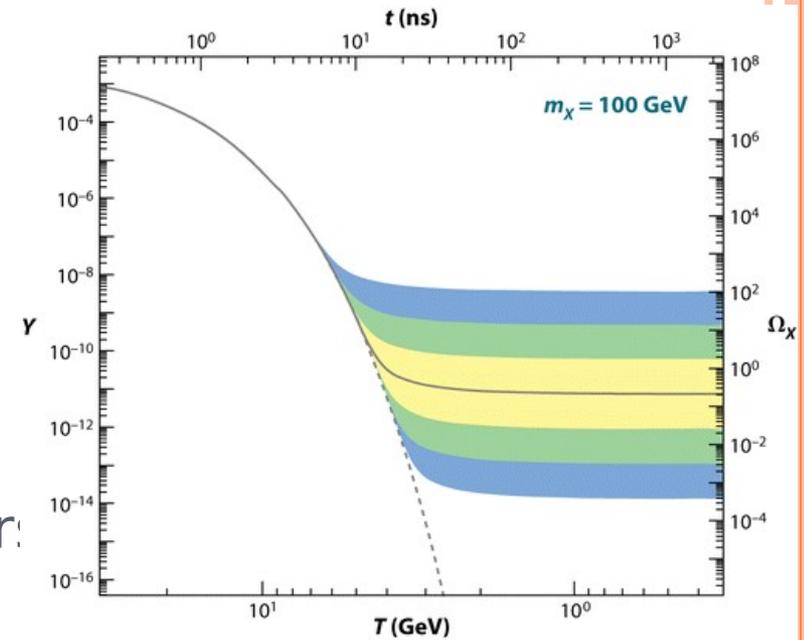


- and there is no obvious reason why  $\Lambda \neq M_{\text{Pl}}$ 
  - supersymmetry fixes this by introducing a new set of loop corrections that cancel those from the SM
  - new physics at TeV scale will also fix it (can set  $\Lambda \sim 1 \text{ TeV}$ )
- New Physics Flavour Problem
  - we observe conservation or near-conservation of B, L, CP
    - and do not observe flavour-changing neutral currents
  - new physics has a nasty tendency to violate these
    - can require fine-tuning or new discrete symmetries, e.g.  $R$ -parity

# WIMPs

## Weakly Interacting Massive Particles

- Produced thermally in early universe
- annihilate as universe cools, but “freeze out” when density drops so low that annihilation no longer occurs with meaningful rate
- freeze-out occurs when  $H \approx nf\langle\sigma_{AV}\rangle$ , and in radiation era we have  $H \propto T^2/M_{Pl}$ 
  - (because  $\rho \propto T^4$  and  $G \propto 1/M_{Pl}^2$ )
- can estimate relic density by considering freeze-out



 Feng JL. 2010.  
Annu. Rev. Astron. Astrophys. 48:495–545

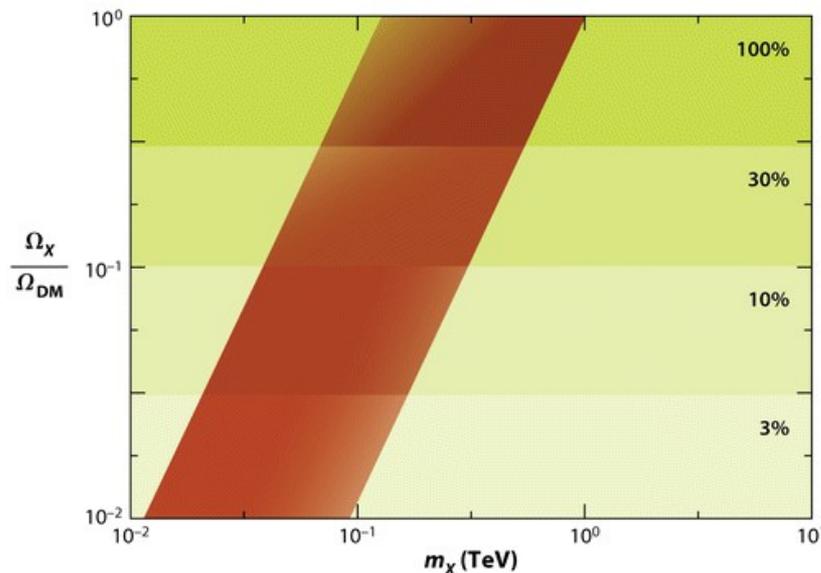
# WIMP Relic Density

Converting to  $\Omega$  gives: 
$$\Omega_X = \frac{m_X n_0}{\rho_c} \approx \frac{m_X T_0^3}{\rho_c} \frac{n_f}{T_f^3} \approx \frac{x_f T_0^3}{\rho_c M_{Pl}} \langle \sigma_{AV} \rangle^{-1}$$

• where  $x_f = m_X/T_f$

- and typically  $\langle \sigma_{AV} \rangle \propto 1/m_X^2$  or  $v^2/m_X^2$  (S or P wave respectively)
- Consequence: weakly interacting massive particles with electroweak-scale masses

“naturally” have reasonable relic densities



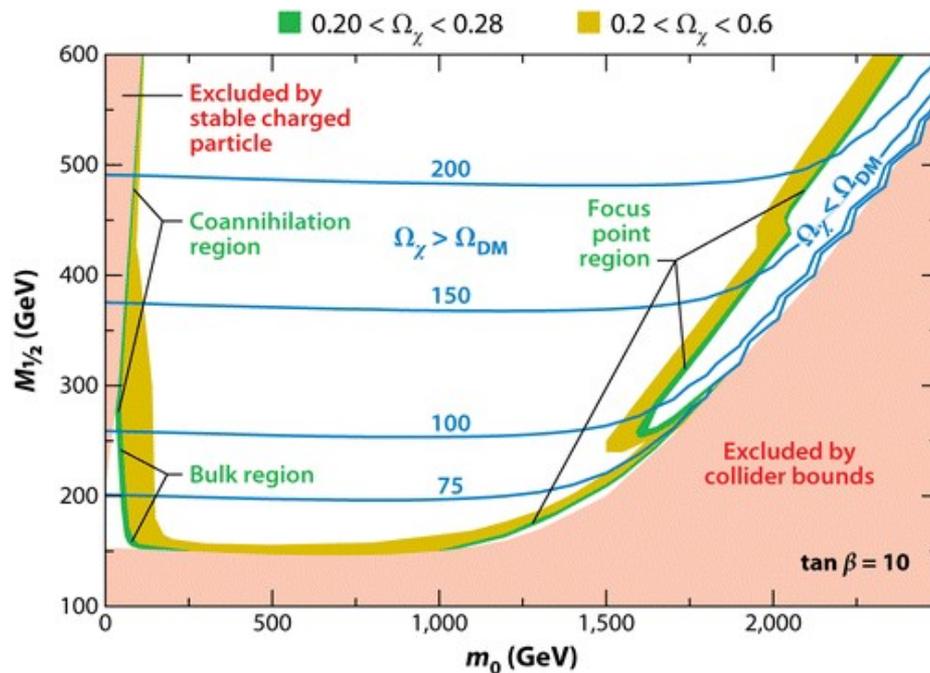
- (and therefore make excellent dark matter candidates )

# Supersymmetric WIMPs

- Supersymmetry solves the GHP by introducing cancelling corrections
  - predicts a complete set of new particles
  - NFP often solved by introducing  $R$ -parity—new discrete quantum number
    - then lightest supersymmetric particle is stable
    - best DM candidate is lightest neutralino (mixed spartner of  $W^0$ ,  $B$ ,  $H$ ,  $h$ )
  - far too many free parameters in most general supersymmetric models
    - so usually consider constrained models with simplifying assumptions
    - most common constrained model: mSUGRA
      - parameters  $m^0$ ,  $M_{1/2}$ ,  $A^0$ ,  $\tan \beta$ ,  $\text{sign}(\mu)$
    - mSUGRA neutralino is probably the best studied DM candidate

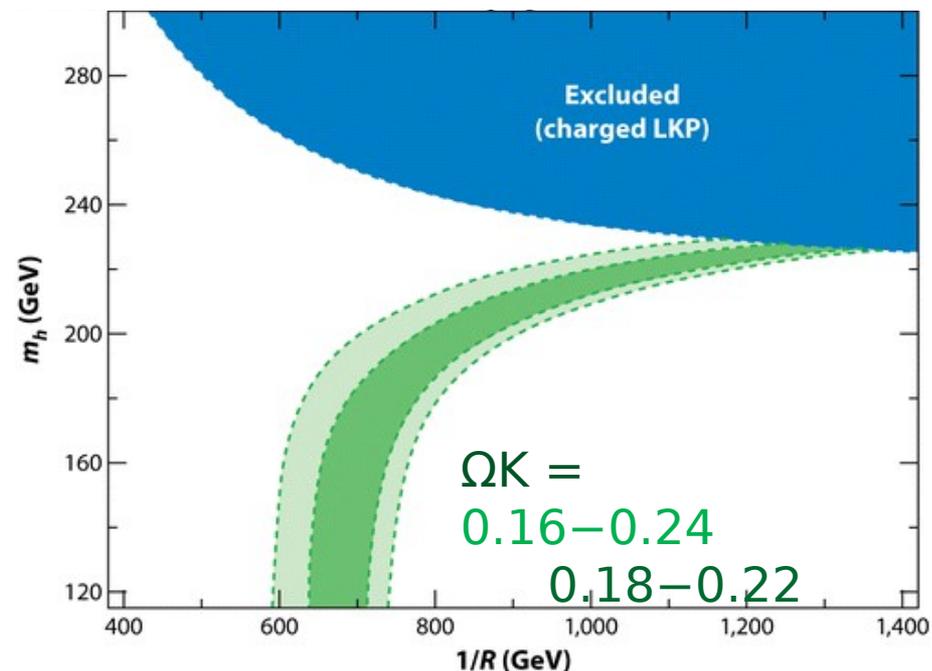
# SUSY WIMPs

- Neutralinos are Majorana fermions and therefore self-annihilate
  - Pauli exclusion principle implies that  $\chi_1\chi_1$  annihilation prefers to go to spin 0 final state
    - prefers spin 1
  - therefore annihilation cross-section is
    - suppressed
    - hence  $\Omega_\chi$  tends to be too high
    - parameter space **very** constrained by WMAP



# Kaluza-Klein WIMPs

- In extra-dimension models, SM particles have partners with the *same* spin
  - “tower” of masses separated by  $R-1$ , where  $R$  is size of compactified extra dimension
  - new discrete quantum number,  $K$ -parity, implies lightest KK particle is stable
  - this is the potential
    - WIMP candidate
    - usually  $B1$
    - annihilation not spin-suppressed
    - (it’s a boson), so
    - preferred mass higher
  - higher



# SuperWIMPs

Massive particles with

- superweak interactions
  - produced by decay of metastable WIMP
    - because this decay is superweak, lifetime is very long ( $10^3$ – $10^7$  s)
    - WIMP may be neutralino, but could be charged particle
      - dramatic signature at LHC (stable supermassive particle)
  - candidates:
    - weak-scale gravitino
    - axino
    - equivalent states in KK theories
- these particles cannot be directly detected, but indirect-detection searches and colliders may see them
  - they may also have detectable astrophysical signatures

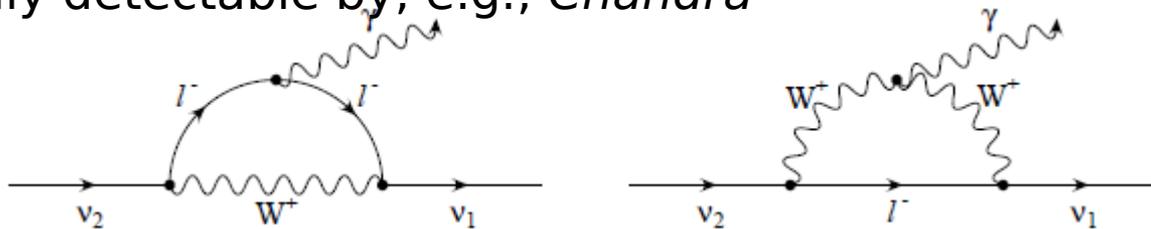
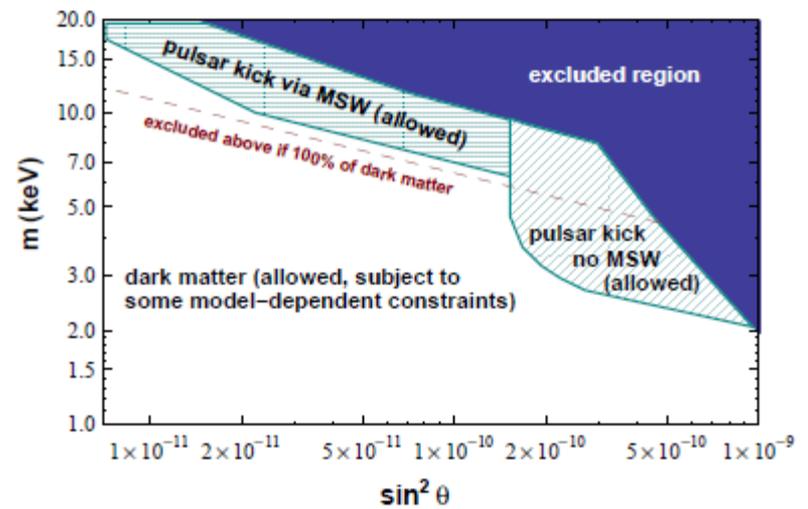
# Light Gravitinos

- Expected in gauge-mediated supersymmetry breaking
  - in these models gravitino has  $m < 1$  GeV
    - neutralinos decay through  $\gamma\tilde{G}$ , so cannot be dark matter
  - gravitinos themselves are possible DM candidates
    - but tend to be too light, i.e. too warm, or too abundant
    - relic density in minimal scenario is  $\Omega_{\tilde{G}} \approx 0.25 m_{\tilde{G}}/(100 \text{ eV})$ 
      - so require  $m_{\tilde{G}} < 100 \text{ eV}$  for appropriate relic density
      - but require  $m_{\tilde{G}} > 2 \text{ keV}$  for appropriate large-scale structure
  - models which avoid these problems look contrived

# Sterile Neutrinos

Seesaw mechanism for generating small  $\nu_L$  masses implies existence of

- massive right-handed sterile states
  - usually assumed that  $M_R \approx M_{GUT}$ , in which case sterile neutrinos are not viable dark matter candidates
  - but smaller Yukawa couplings can combine with smaller  $M_R$  to produce observed  $\nu_L$  properties together with sterile neutrino at keV mass scale—viable dark matter candidate
- such a sterile neutrino could also explain observed high velocities of pulsars (asymmetry in supernova explosion generating “kick”)
- these neutrinos are not entirely stable:  $\tau \gg 1/H^0$ , but they do decay and can generate X-rays via loop diagrams—therefore potentially detectable by, e.g., *Chandra*



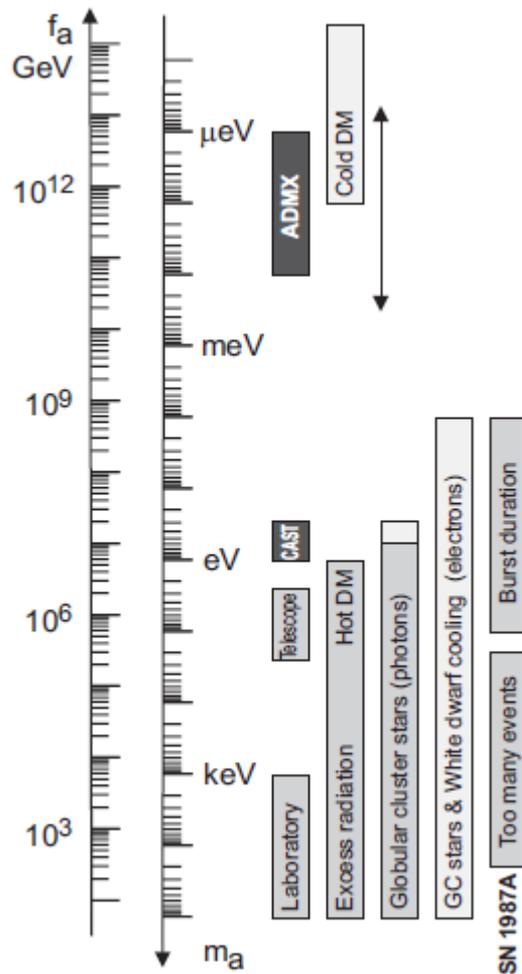
# Sterile Neutrinos

- Production mechanisms
  - oscillation at  $T \approx 100$  MeV
    - $\Omega\nu \propto \sin^2(2\theta) m^{1.8}$  from numerical studies
    - always present: requires small mass and very small mixing angle
      - not theoretically motivated: some fine tuning therefore required
  - resonant neutrino oscillations
    - if universe has significant lepton number asymmetry,  $L > 0$
  - decays of heavy particles
    - e.g. singlet Higgs driving sterile neutrino mass term
- Observational constraints
  - X-ray background
  - presence of small-scale structure
    - sterile neutrinos are “warm dark matter” with Mpc free-streaming

# Axions

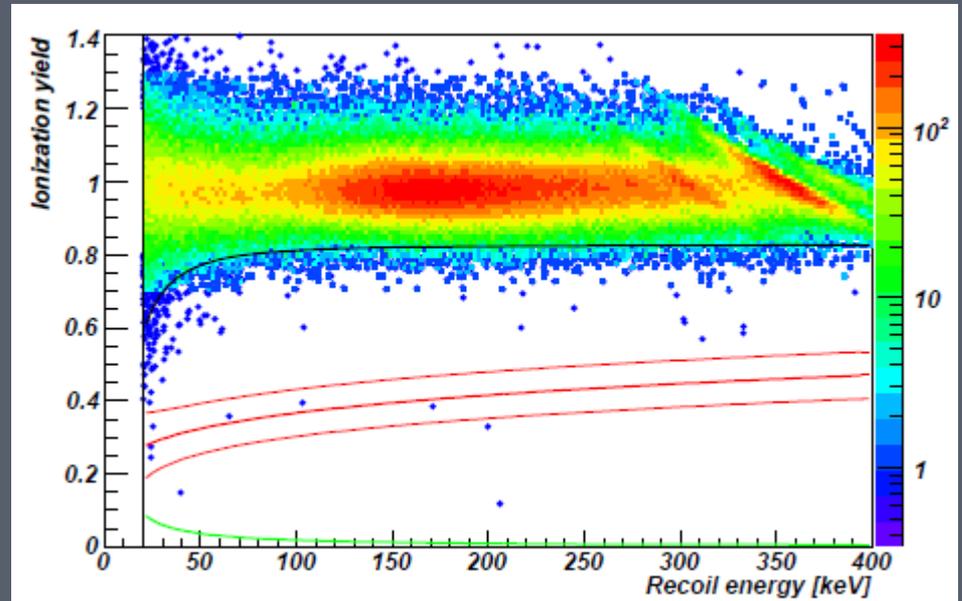
- Introduced to solve the “strong CP problem”
  - SM Lagrangian includes CP-violating term which should contribute to, e.g., neutron electric dipole moment
    - neutron doesn't appear to *have* an EDM ( $<3 \times 10^{-26}$  e cm, cf. naïve expectation of  $10^{-16}$ ) so this term is strongly suppressed
  - introduce new pseudoscalar field to kill this term (Peccei-Quinn mechanism)
    - result is an associated pseudoscalar boson, the axion
- Axions are extremely light ( $<10$  **meV**), but are cold dark matter
  - not produced thermally, but via phase transition in very early universe
    - if this occurs before inflation, visible universe is all in single domain
    - if after inflation, there are many domains, and topological defects such as axion domain walls and axionic strings may occur

# Axions



Georg Raffelt,  
hep-ph/0611350v1

- Axion mass is  $m_a \approx 6 \mu\text{eV} \times f_a / (10^{12} \text{ GeV})$  where  $f_a$  is the unknown mass scale of the PQ mechanism
- Calculated relic density is  $\Omega_a \approx 0.4 \theta^2 (f_a / 10^{12} \text{ GeV})^{1.18}$  where  $\theta$  is initial vacuum misalignment
  - so need  $f_a < 10^{12} \text{ GeV}$  to avoid overclosing universe
  - astrophysical constraints require
  - $f_a > 10^9 \text{ GeV}$
  - therefore  $6 \mu\text{eV} < m_a < 6 \text{ meV}$



# Dark Matter

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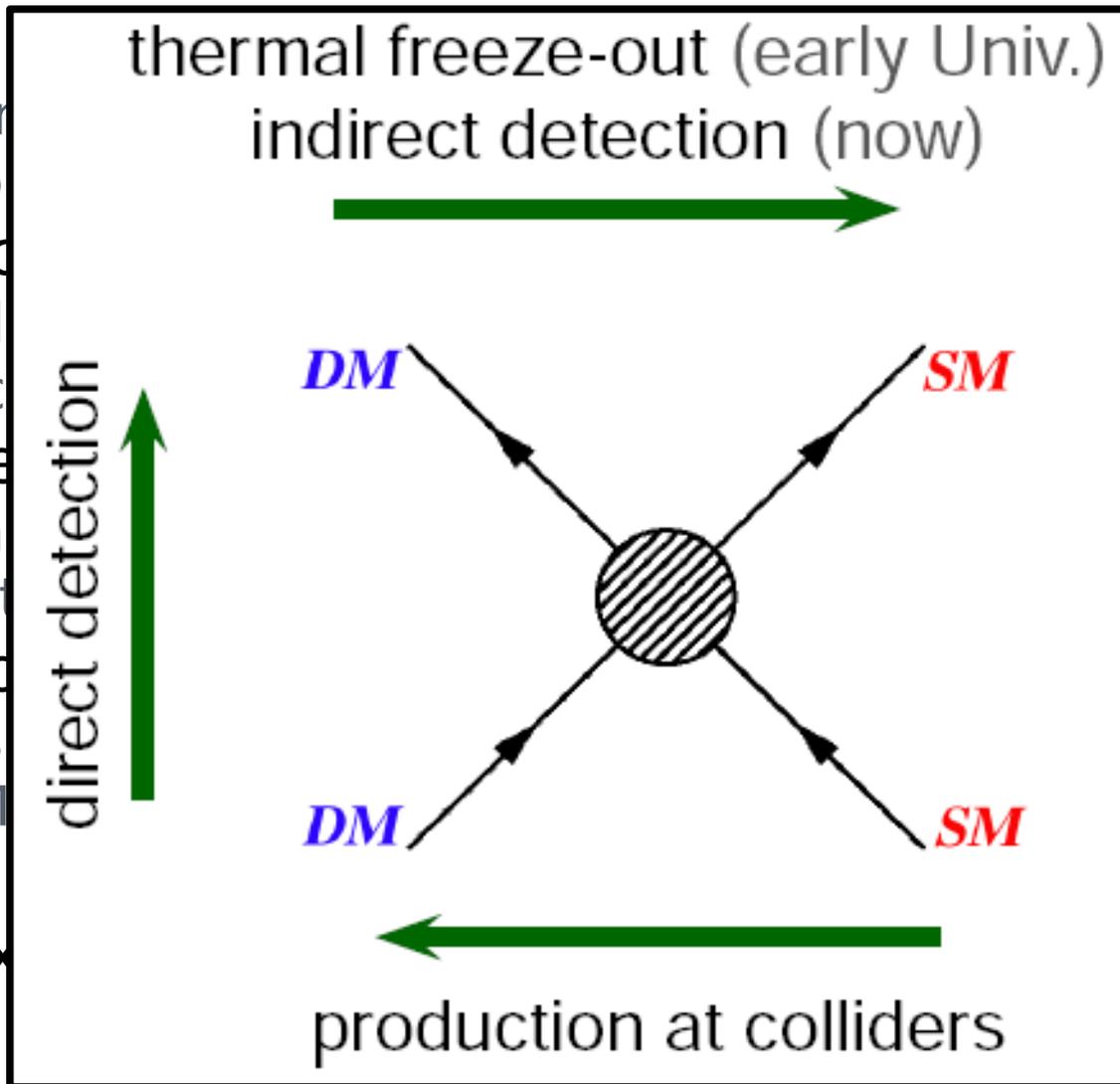
Astrophysical Evidence  
Candidates  
Detection

# Detection of Dark Matter Candidates

- **Direct detection**
  - dark matter particle interacts in your detector and you observe it
- **Indirect detection**
  - you detect its decay/annihilation products or other associated phenomena
- **Collider phenomenology**
  - it can be produced at, say, LHC and has a detectable signature
- **Cosmology**
  - it has a noticeable and characteristic impact on BBN or CMB
- **Focus here on best studied candidates—WIMPs and axions**

# Detection of Dark Matter Candidates

- Direct
  - dark matter
  - you observe
- Indirect
  - you detect
  - associated
- Collider
  - it can produce
  - signals
- Cosmological
  - it has
  - or CMB
- Focus
  - and axions



and  
other  
detectable  
on BBN  
WIMPs

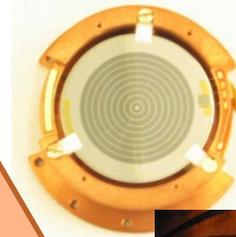
# Direct Detection of WIMPS

Basic principle: WIMP scatters elastically from nucleus; experiment detects nuclear recoil

CRESST-II



HEAT



EDELWEISS  
CDMS

DAMA/LIBRA



SCINT.

IONIS.

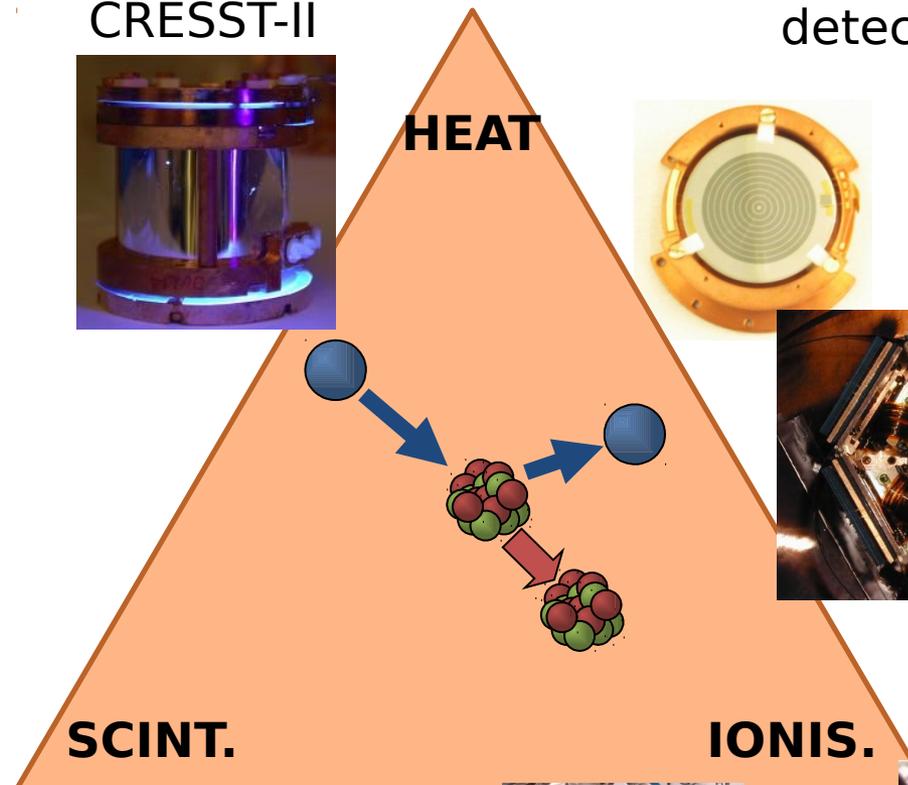
DRIFT



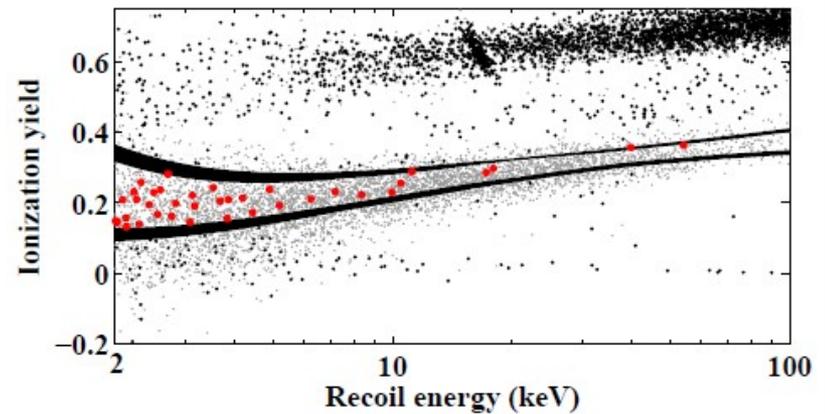
XMASS



ZEPLIN II



# Direct Detection of WIMPS



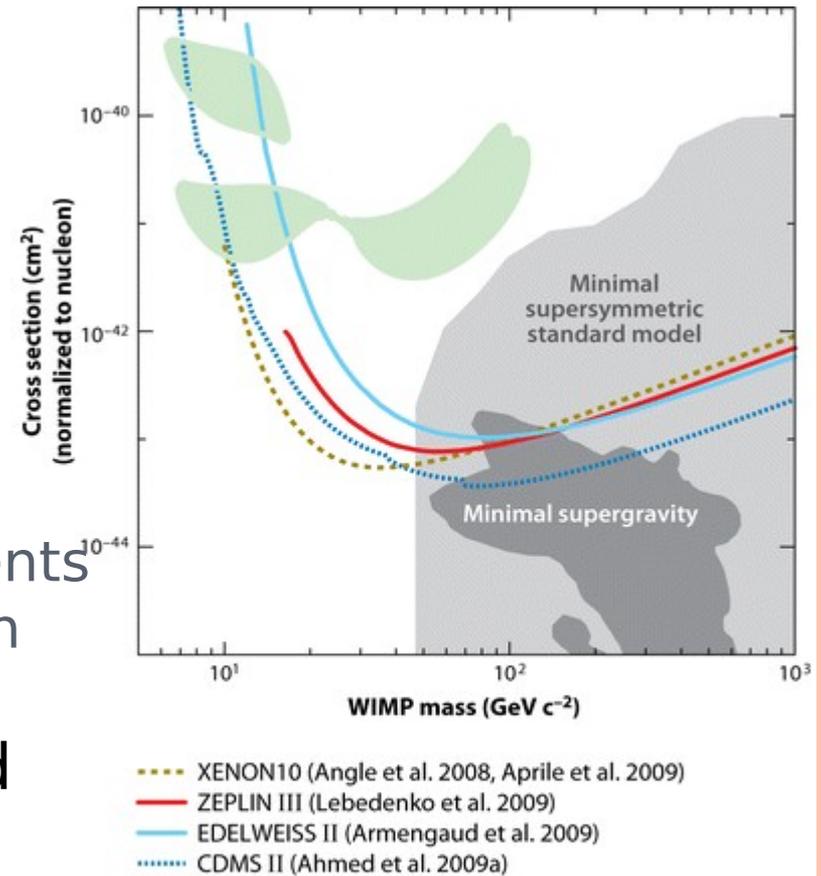
CDMS-II,  
*PRL* **106**  
(2011)  
131302

- Backgrounds
  - cosmics and radioactive nuclei (especially radon)
    - use deep site and radiopure materials
    - use discriminators to separate signal and background
- Time variation
- expect annual variation caused by Earth's
  - and Sun's orbital motion
    - small effect,  $\sim 7\%$
    - basis of claimed signal by DAMA experiment
    - much stronger diurnal variation caused by
  - changing orientation of Earth
    - “smoking gun”, but requires directional detector
    - current directional detector, DRIFT, has rather small target mass (being gaseous)—hence not at leading edge of sensitivity

# Direct Detection of WIMPs

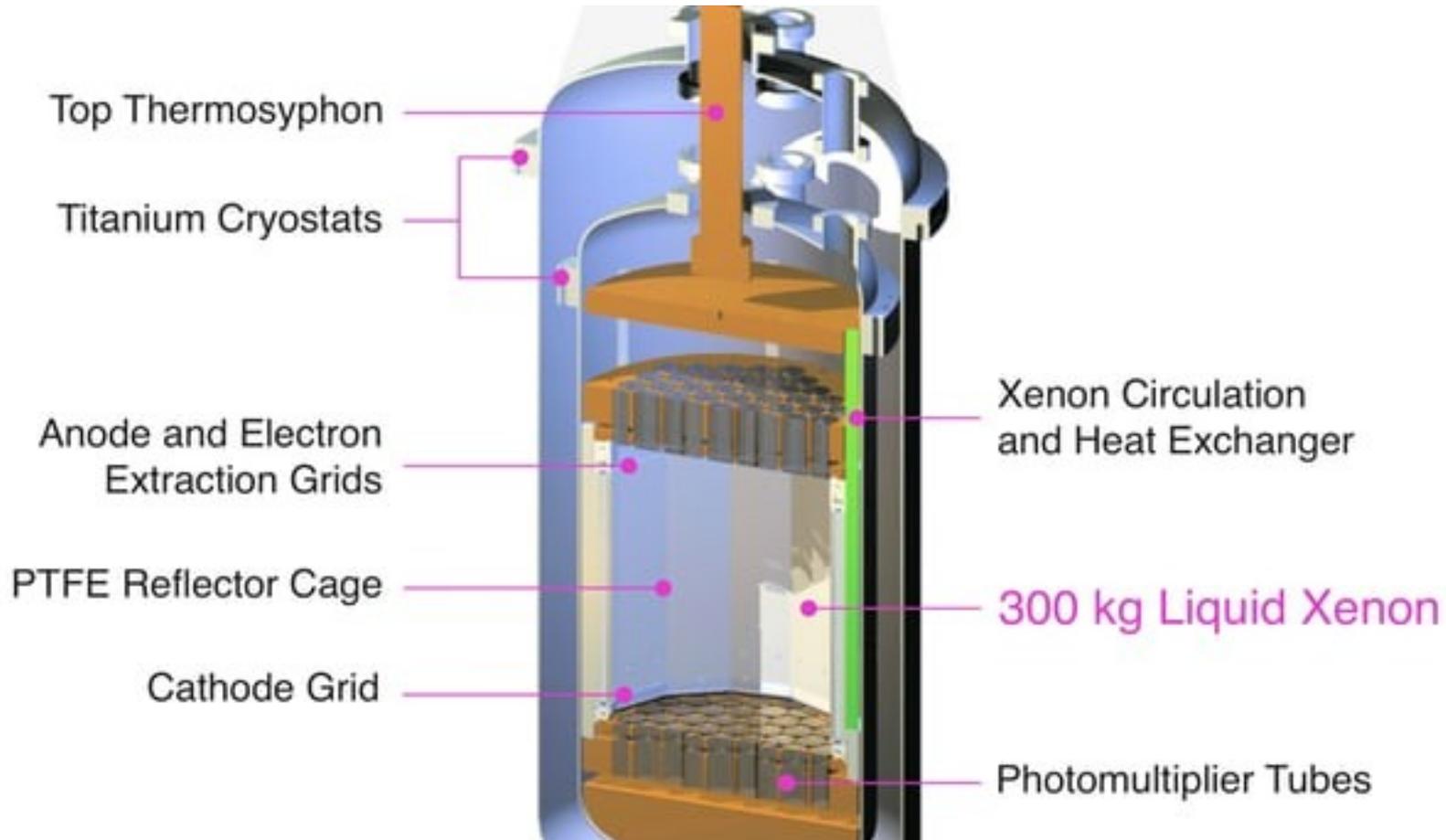
Interaction with nuclei can be spin-independent or

- spin-dependent
- spin-dependent interactions
  - require nucleus with net spin
  - most direct detection experiments focus on SI, and limits are much better in this case
  - Conflict between DAMA and others tricky to resolve
- requires very low mass and
  - high cross-section
    - if real, may point to a non-supersymmetric DM candidate

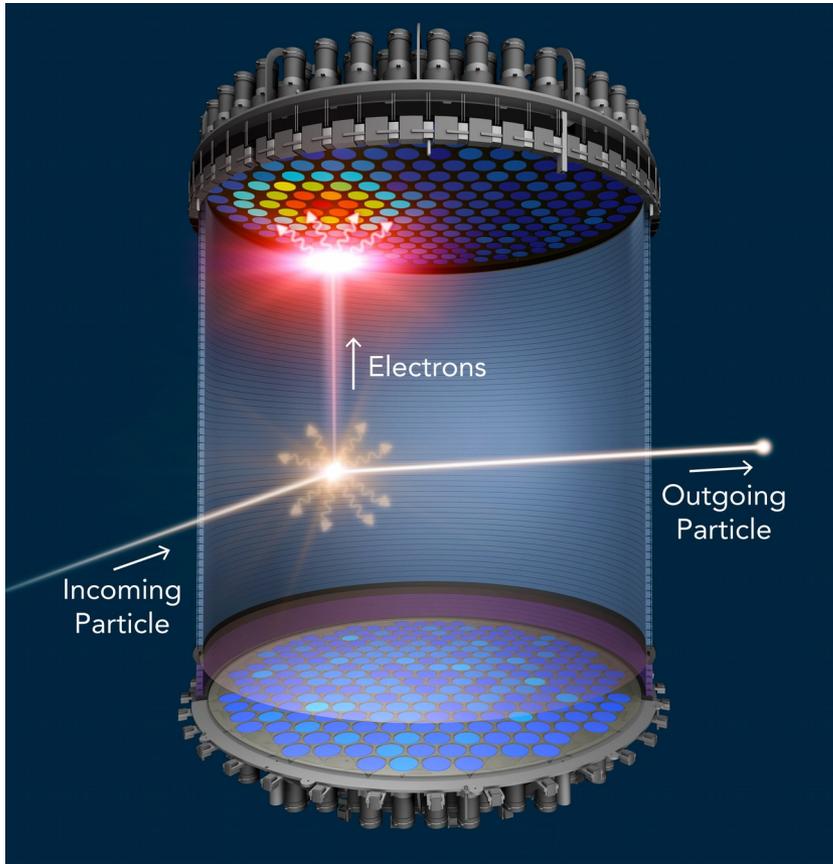


 Feng JL. 2010. DMTools (Butler/Desai)  
Annu. Rev. Astron. Astrophys. 48:495–545

# Direct Detection of WIMPs

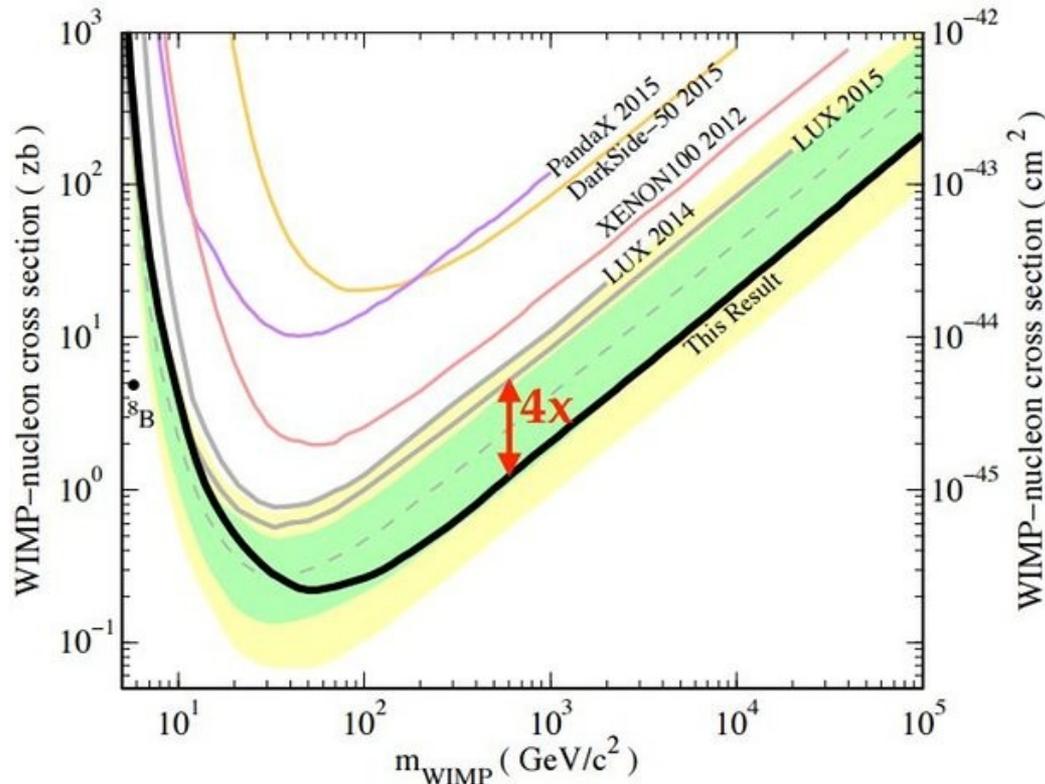


# Direct Detection of WIMPs



- Steps to detection:
  1. Collisions deposit energy in liquid Xe → flash of light
  - 
  1. Electromagnetic backgrounds produce electrons that drift to the gas phase Xe at the top
    - → second flash of light
  1. Nuclear recoils (like WIMPs) do not produce electrons, so only one flash is seen

# Direct Detection of WIMPs



- Currently, leading results at most WIMP masses come from LXe experiments (LUX, XENON, PandaX)
- Results shown here were presented in July 2016 in **Sheffield** at the Identification of Dark Matter 20th anniv. International conference
- No signal... but rules out false claims by other experiments
- LUX is now finished, and the next generation of experiments has just begun, for example:

(LUX-Zeplin) in South Dakota

→ **Stay tuned!**

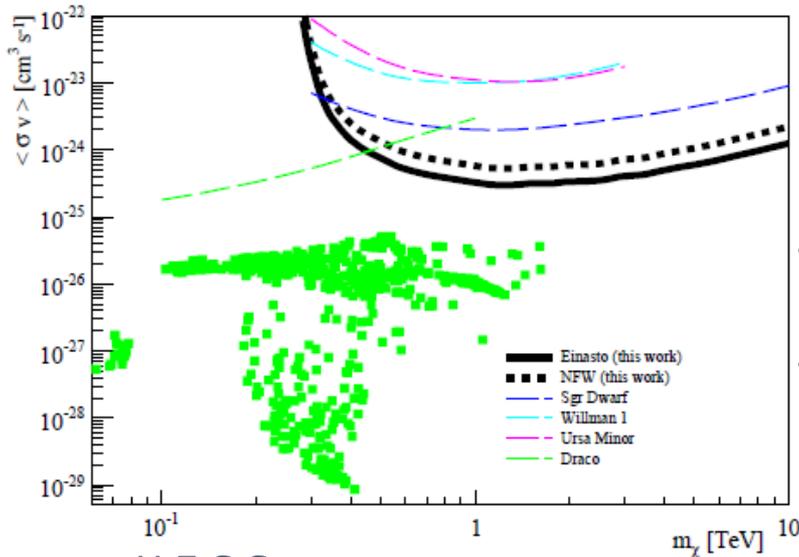
From IDM2016

# Indirect Detection of WIMPs

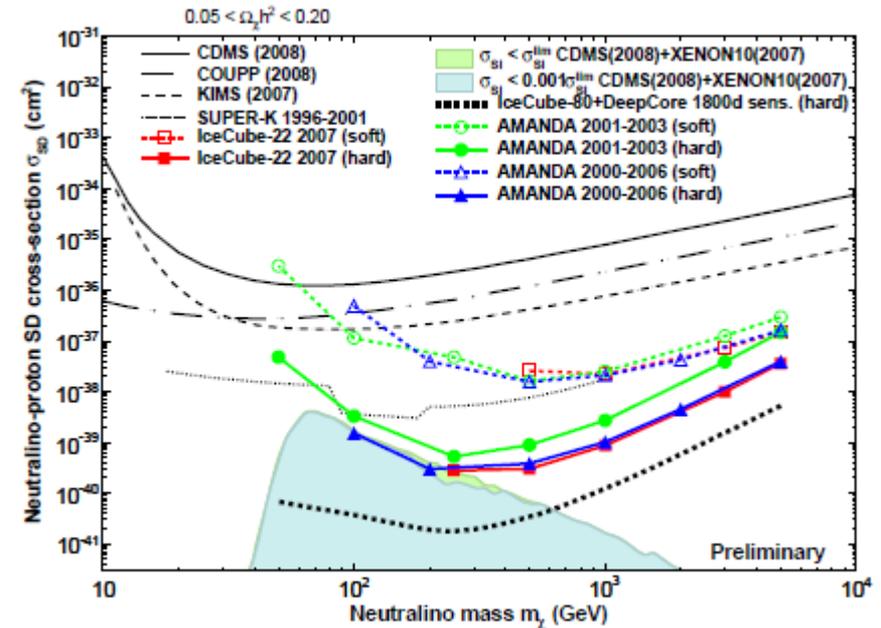
- After freeze-out, neutralino self-annihilation is negligible in universe at large
  - but neutralinos can be captured by repeated scattering in massive bodies, e.g. Sun, and this will produce a significant annihilation rate
    - number of captured neutralinos  $N = C - AN^2$  where  $C$  is capture rate and  $A$  is  $\langle \sigma Av \rangle$  per volume
    - if steady state reached, annihilation rate is just  $C/2$ , therefore determined by scattering cross-section
  - annihilation channels include  $W+W-$ ,  $b\bar{b}$ ,  $\tau+\tau-$ , etc. which produce secondary neutrinos
    - these escape the massive object and are detectable by neutrino telescopes

# Indirect Detection of WIMPs

- Relatively high threshold of neutrino telescopes implies greater sensitivity to “hard” neutrinos, e.g. from WW
- Also possible that neutralinos might collect near Galactic centre



H.E.S.S.,

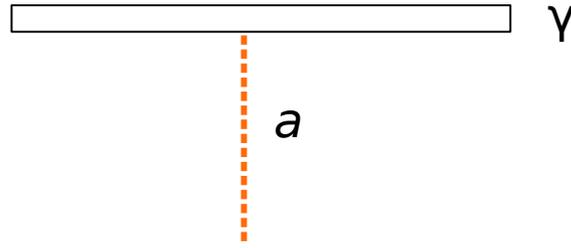


Braun & Hubert, 31st ICRC (2009): astro-ph/0906.1615

- search by H.E.S.S. found nothing
- signals at lower energies could be astrophysical not astroparticle

# LHC Detection of WIMPs and SWIMPs

- WIMPs show up at LHC through missing-energy signature
  - note: not immediate proof of dark-matter status
    - long-lived but not stable neutral particle would have this signature but would not be DM candidate
    - need to constrain properties enough to calculate expected relic density if particle *is* stable, then check consistency
- SuperWIMP parents could also be detected
  - if charged these would be spectacular, because of extremely long lifetime
    - very heavy particle exits detector without decaying
      - if seen, could in principle be trapped in external water tanks, or even dug out of cavern walls (Feng: “new meaning to the phrase ‘data mining’”)
  - if neutral, hard to tell from WIMP proper
    - but mismatch in relic density, or conflict with direct detection, possible clues



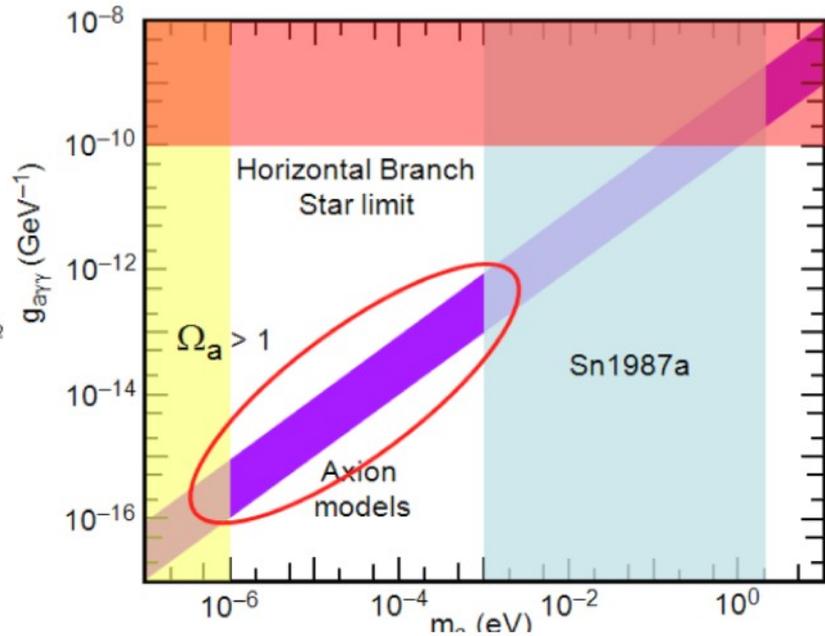
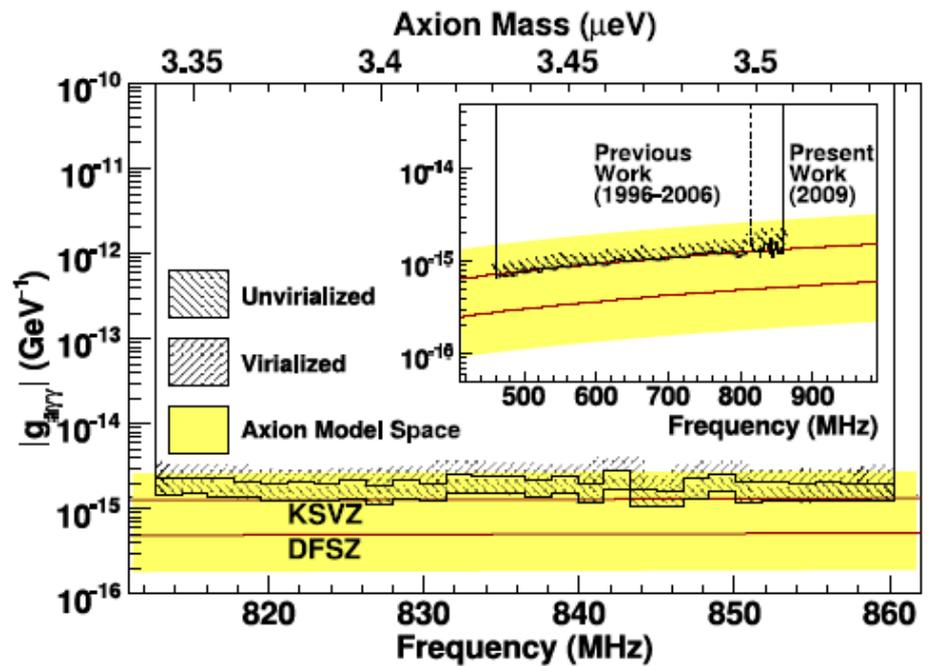
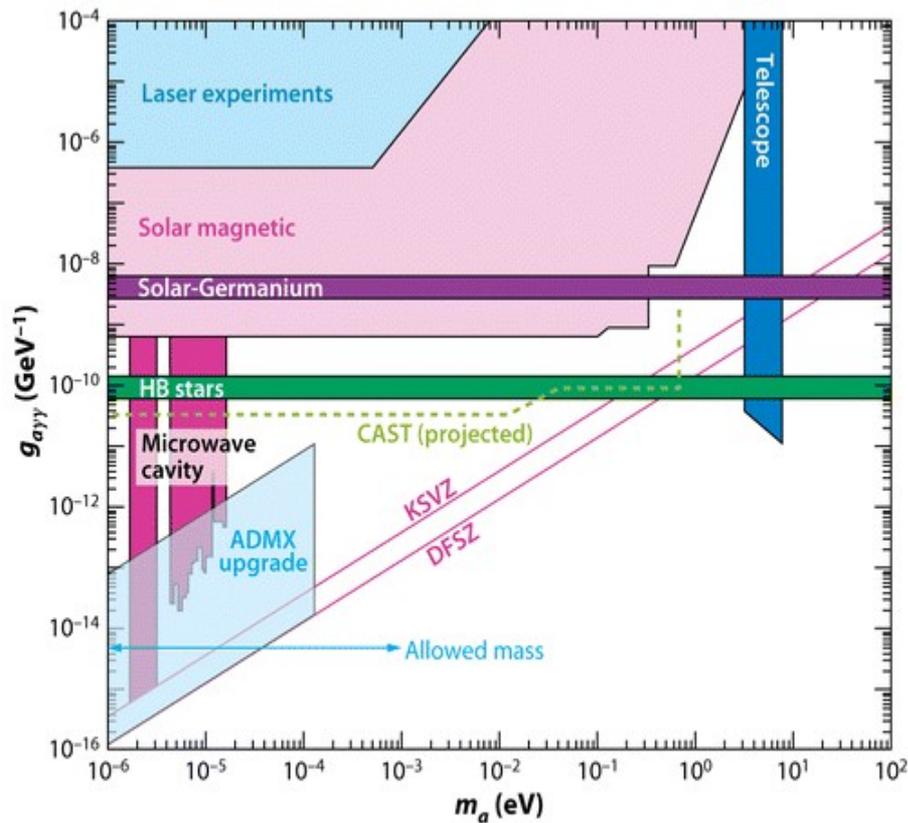
# Axion Detection

Axions couple (unenthusiastically) to photons via

- $\mathcal{L}_a \gamma\gamma = -g_a \gamma\gamma \mathbf{E} \cdot \mathbf{B}$
- they can therefore be detected using Primakoff effect
  - (resonant conversion of axion to photon in magnetic field)
  - ADMX experiment uses very high  $Q$  resonant cavity in
  - superconducting magnet to look for excess power
- this is a scanning experiment: need to adjust resonant frequency to “see” specific mass (very tedious)
- alternative: look for axions produced in Sun (CAST)
  - non-scanning, but less sensitive



# Axion Detection



 Feng JL. 2010.  
Annu. Rev. Astron. Astrophys. 48:495–545

# Dark Matter: Summary

- Astrophysical evidence for dark matter is consistent and compelling
  - not an unfalsifiable theory—for example, severe conflict between BBN and WMAP on  $\Omega_b$  might have scuppered it
- Particle physics candidates are many and varied
  - and in many cases are not *ad hoc* inventions, but have strong independent motivation from within particle physics
- Unambiguous detection is possible for several candidates, but will need careful confirmation
  - interdisciplinary approaches combining direct detection, indirect detection, conventional high-energy physics and astrophysics may well be required

THE END

