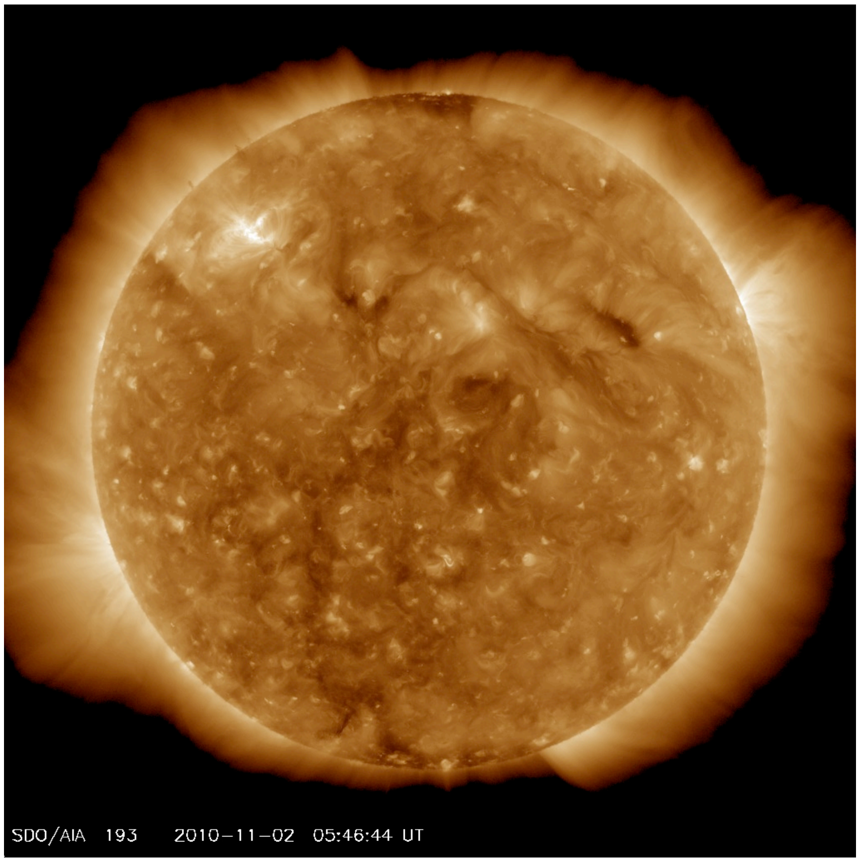
Is there Dark Matter in the Sun?



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Dark Matter is predicted from cosmological models

- Dark matter accounts for 23% of matter in the universe (dark energy 72%, baryonic matter only 5%)

- Various types of weakly interacting massive particles (WIMPs) have been proposed as the dark matter candidate

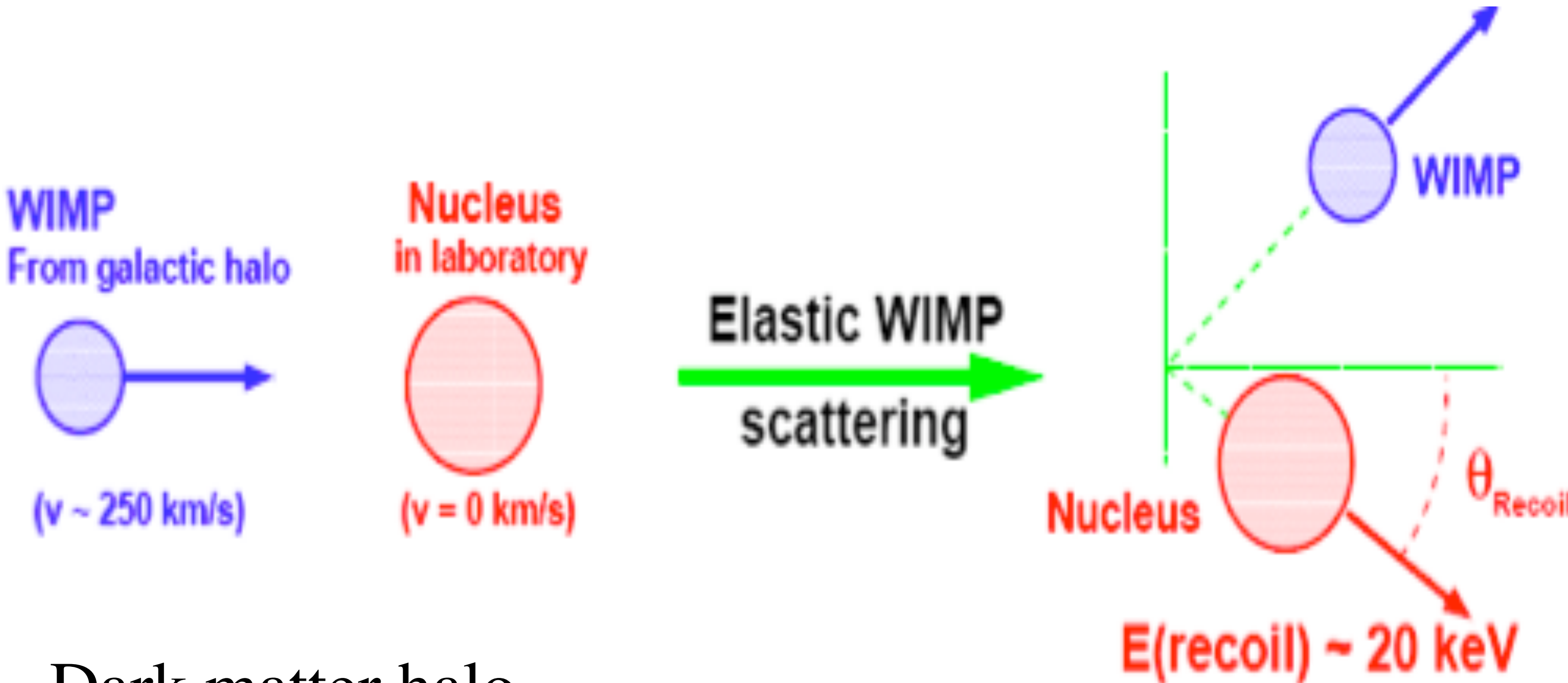
- Since WIMPs weakly interact with regular matter, if they have a large enough cross section they could be detected by scattering experiments

- If WIMPs have small enough mass, they could be produced in accelerator experiments (e.g. Large Hadron Collider)

- WIMPs of mass ~100 GeV would solve problems in particle physics, and also account for the dark matter of cosmological models (the "WIMP miracle").

Could WIMPs have accumulated in the Sun, and would they have observable effects on solar structure?

WIMPs arriving at Earth from the Galactic halo can be directly detected by scattering from nucleons



Dark matter halo
density 0.3 GeV/cm^3

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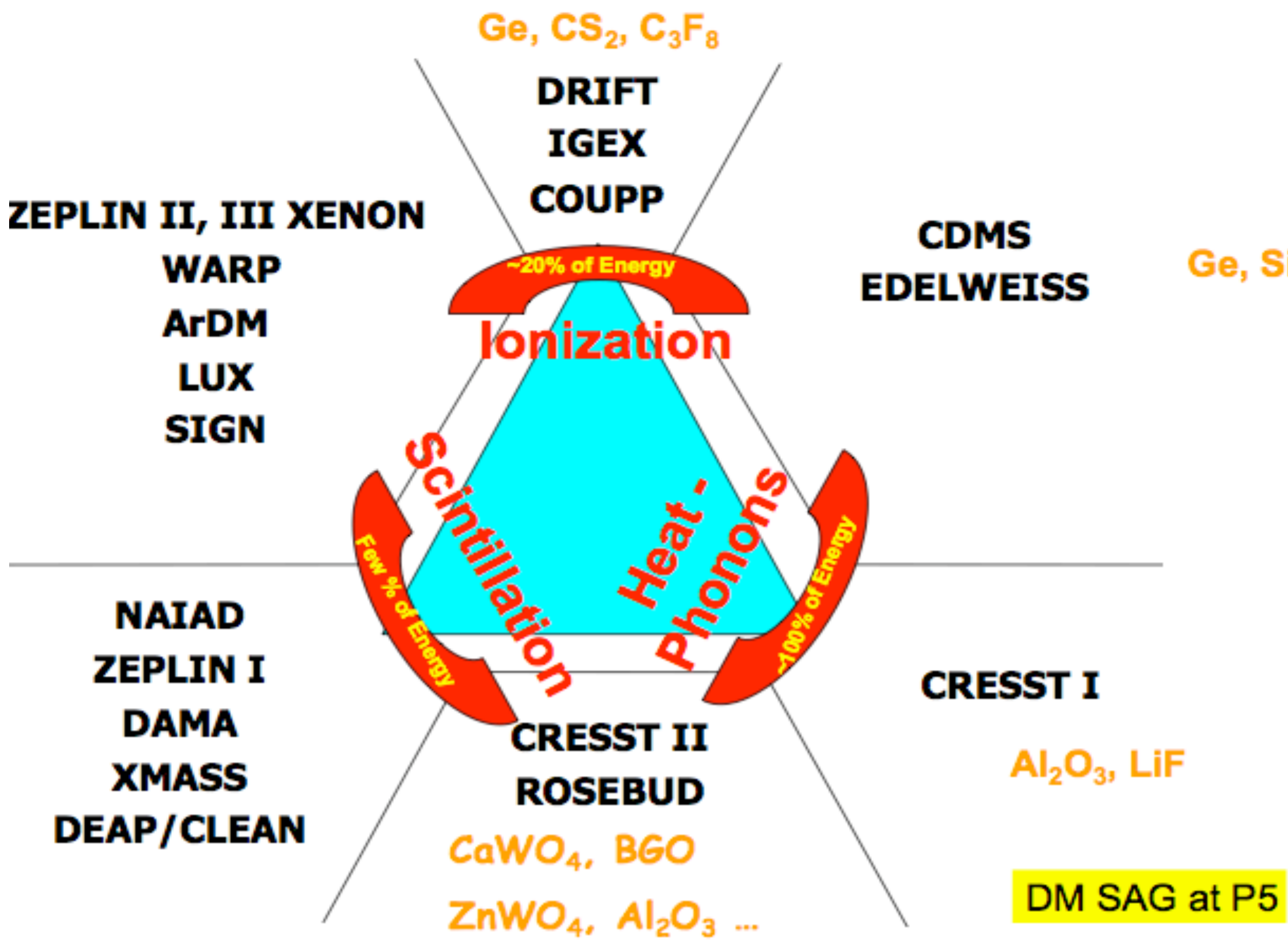
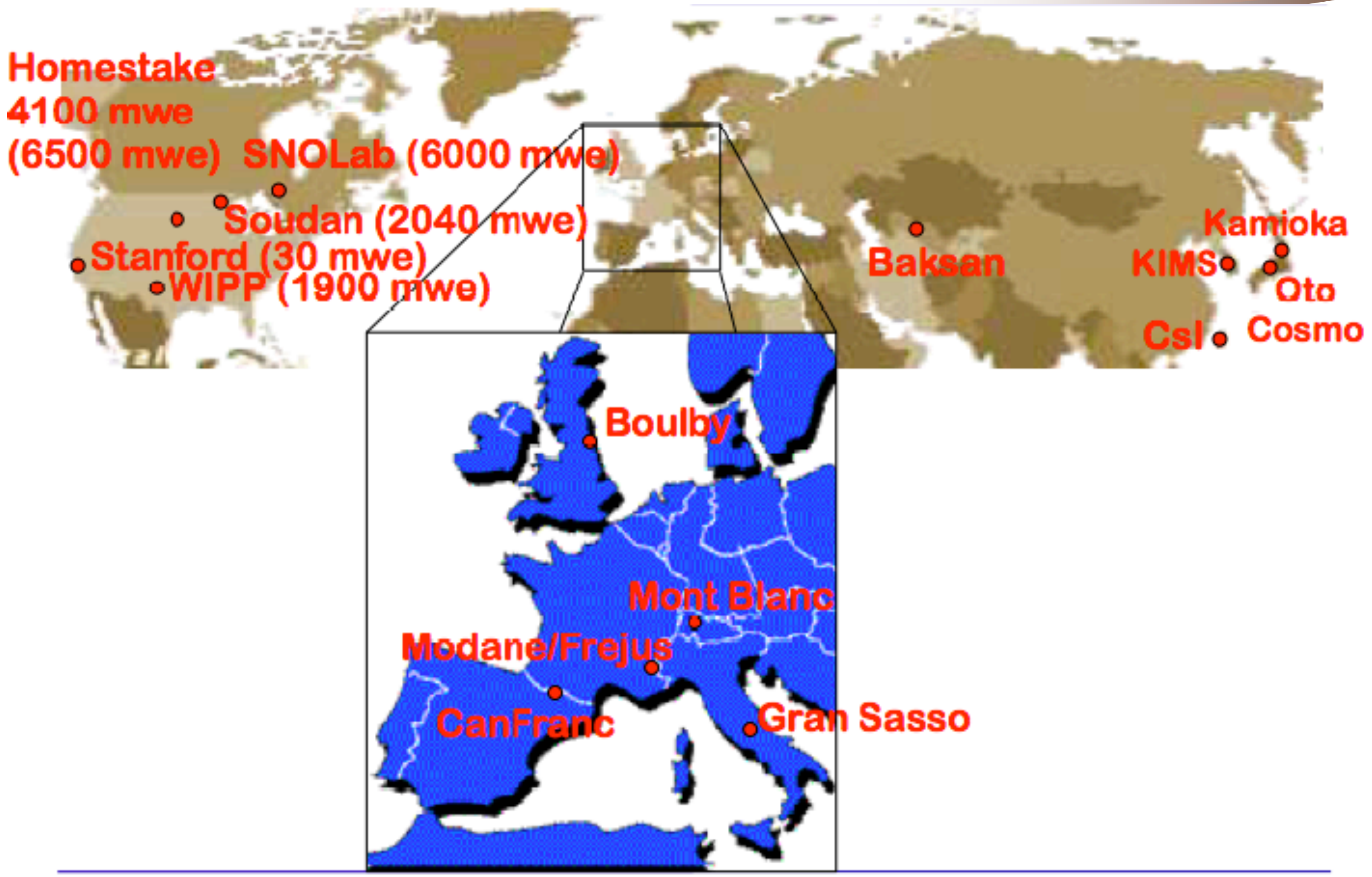
Experiments detect WIMP elastic scattering events by heat (phonons), light (scintillation), or ionization (current)



Chen 2010

Locations of Dark Matter detection experiments



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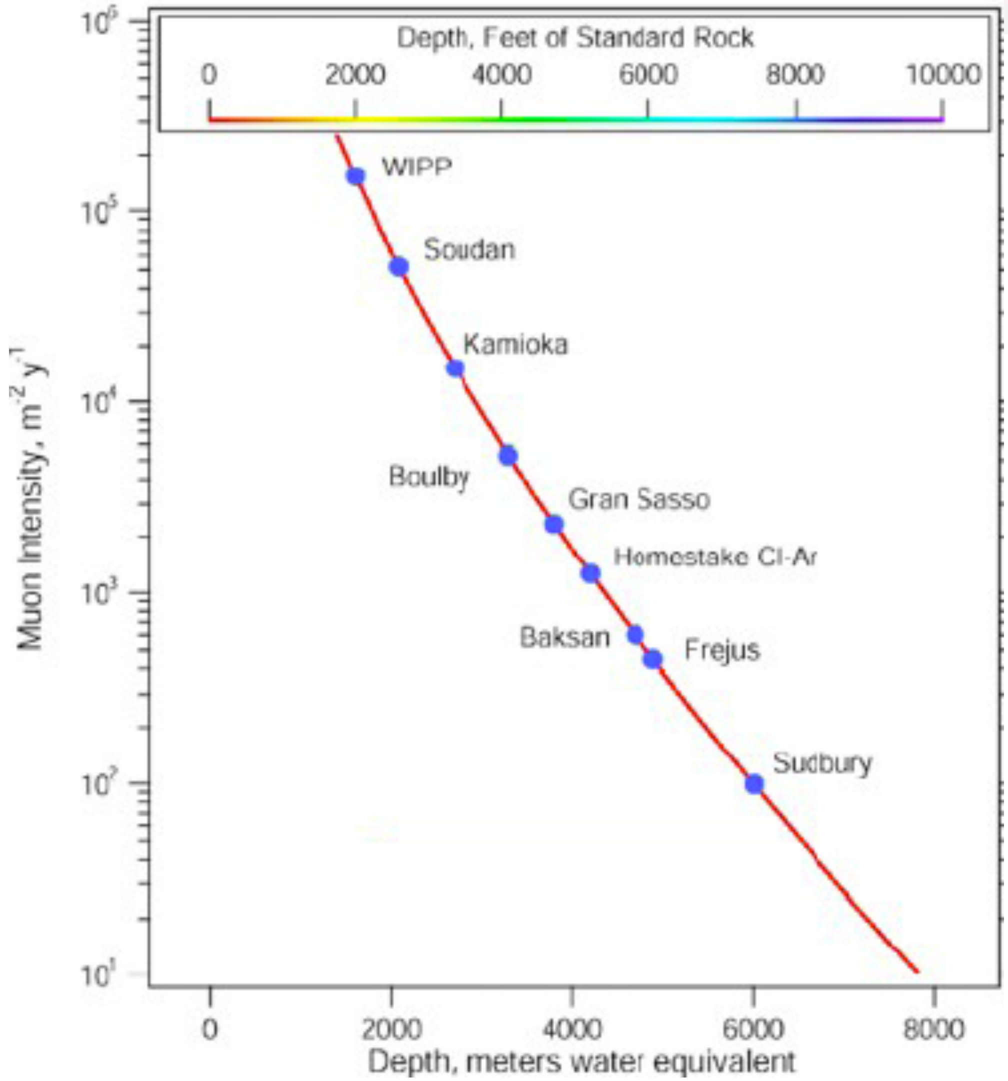
The scattering experiments are located deep underground and heavily shielded to reduce cosmic ray background



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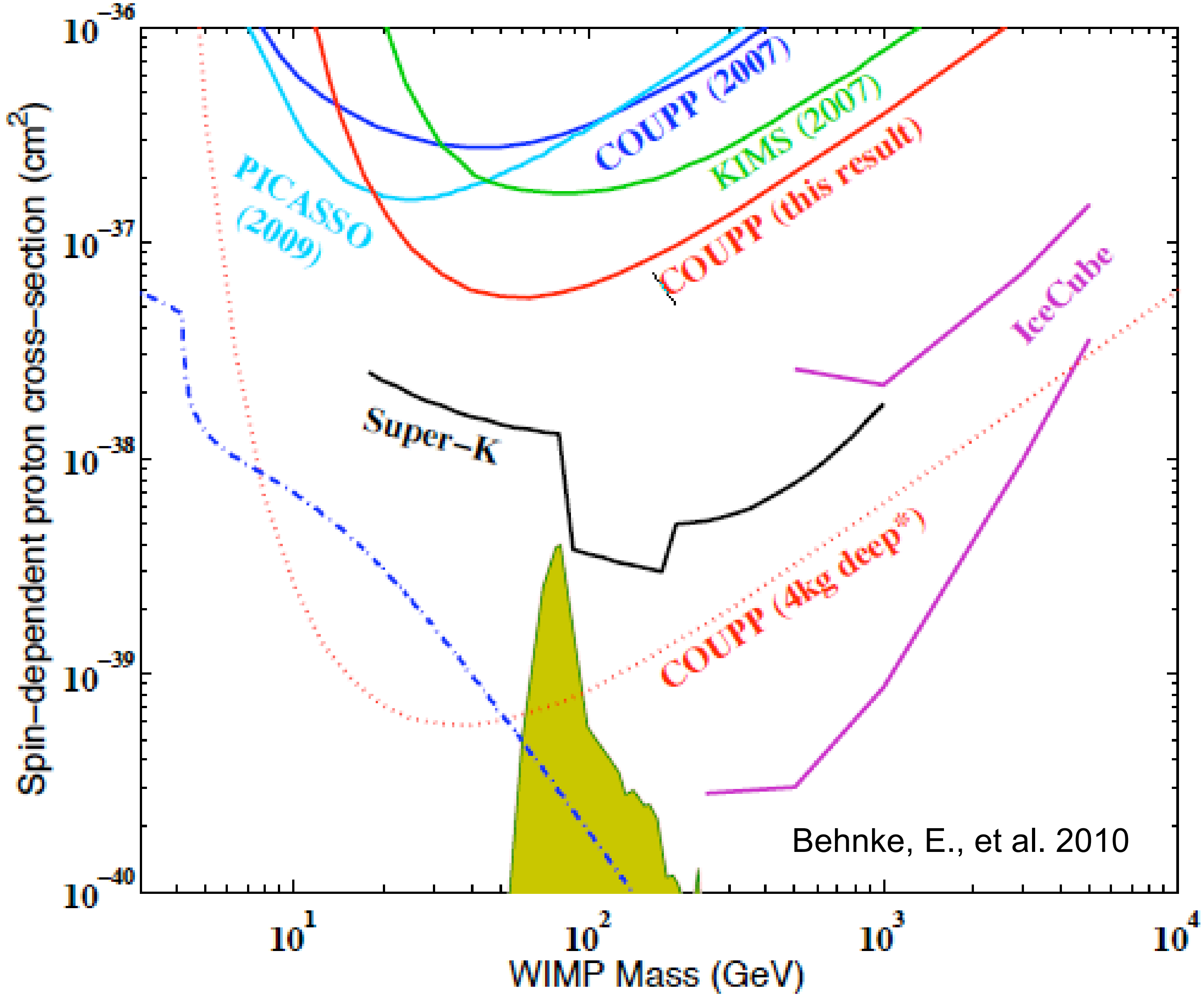
Experiments constrain upper limits on WIMP spin-dependent cross sections



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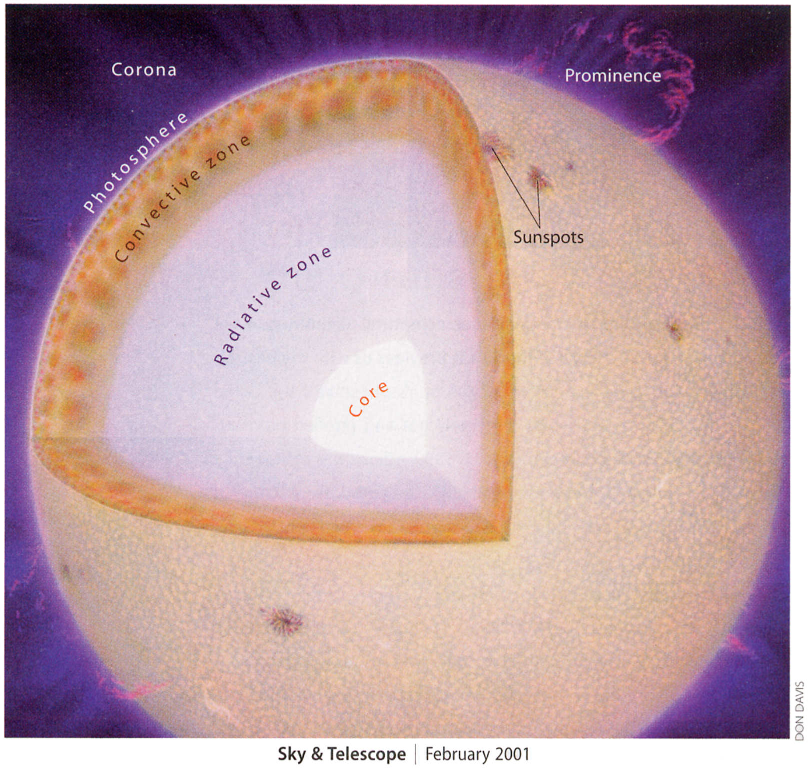
WIMPs of 5-10 GeV are about the right mass to fill the inner ~10% of the Sun

- WIMPs from the Galactic halo are captured as they scatter within the Sun
- If WIMP mass is too small (< 5 GeV), WIMPs can pick up energy from the core and gradually evaporate from the Sun
- With increasing mass, WIMPS orbit within a smaller volume in the center of the Sun



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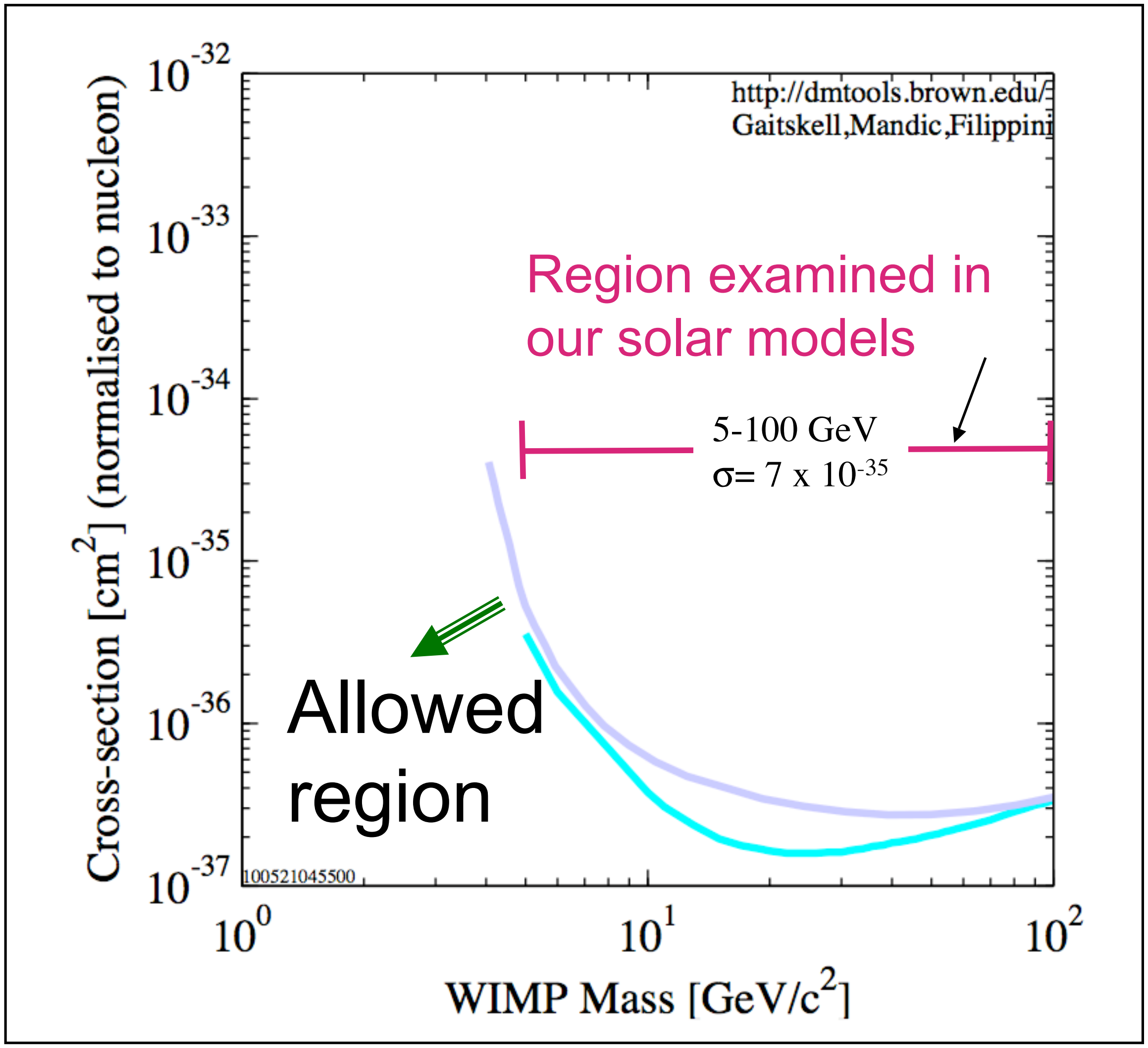
We explored solar models with WIMP masses low enough and cross sections high enough to influence solar structure



COUPP 2007 (purple) and PICASSO 2009 (blue) upper limits

WIMPs are included in solar model by modifying the opacity

$$1/\kappa_{total} = 1/\kappa_{rad+cond} + 1/\kappa_{WIMP}$$

κ=opacity (cm^2/g)

$$\frac{dT}{dM} = -\frac{3}{4ac}\frac{\kappa_g}{T^3}\frac{L_r}{16\pi^2 r^4}$$

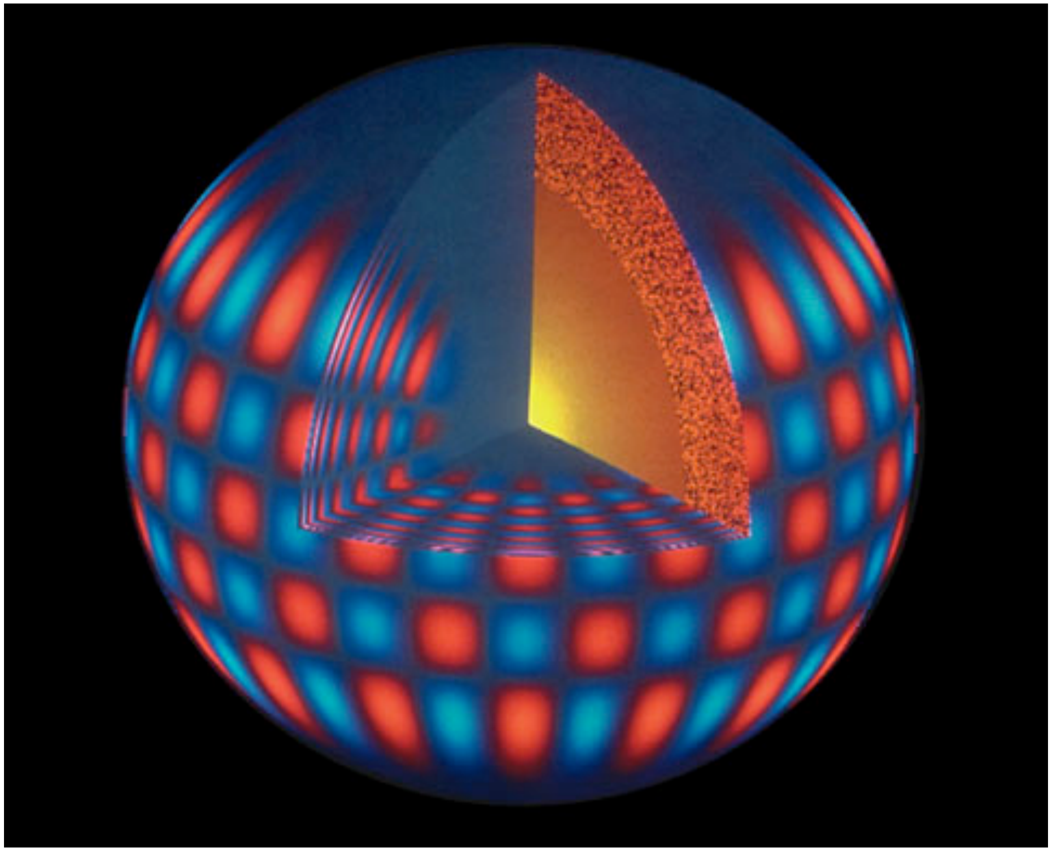
WIMP energy transport is essentially treated as a heat conduction process

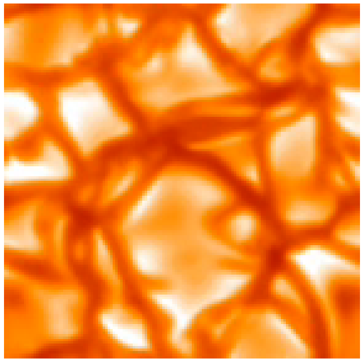
WIMPs orbiting through the center of the Sun and weakly interacting with protons transport energy from the inner to outer core

WIMP-WIMP annihilation assumed negligible

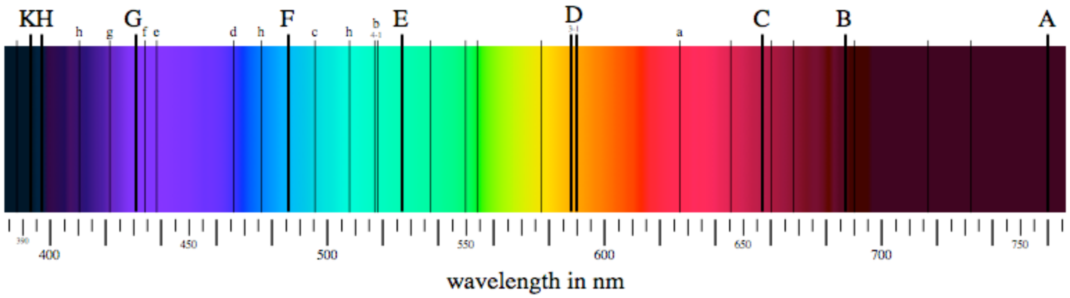
Solar oscillations help us see 'inside' the Sun to test our models

- Discovered in 1960
- Interpreted as acoustic (sound) oscillations in 1970
- Over 100,000 different modes observed
- Modes are initiated by turbulence in the Sun's convective layer

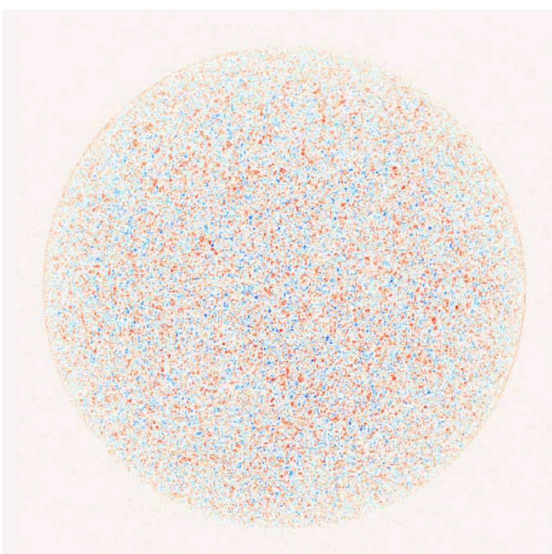


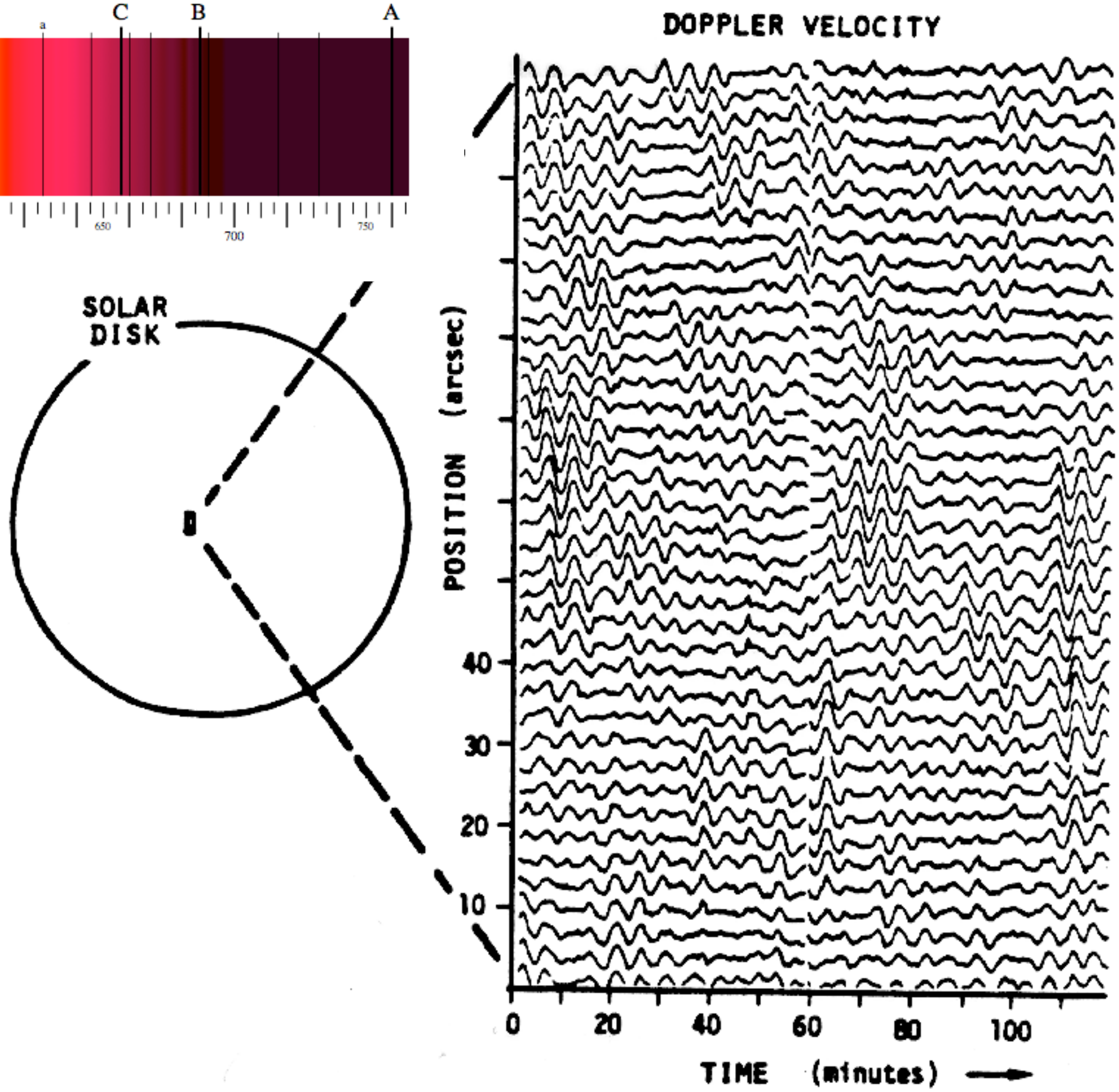


Velocities at surface of Sun are measured with spectra to detect oscillations

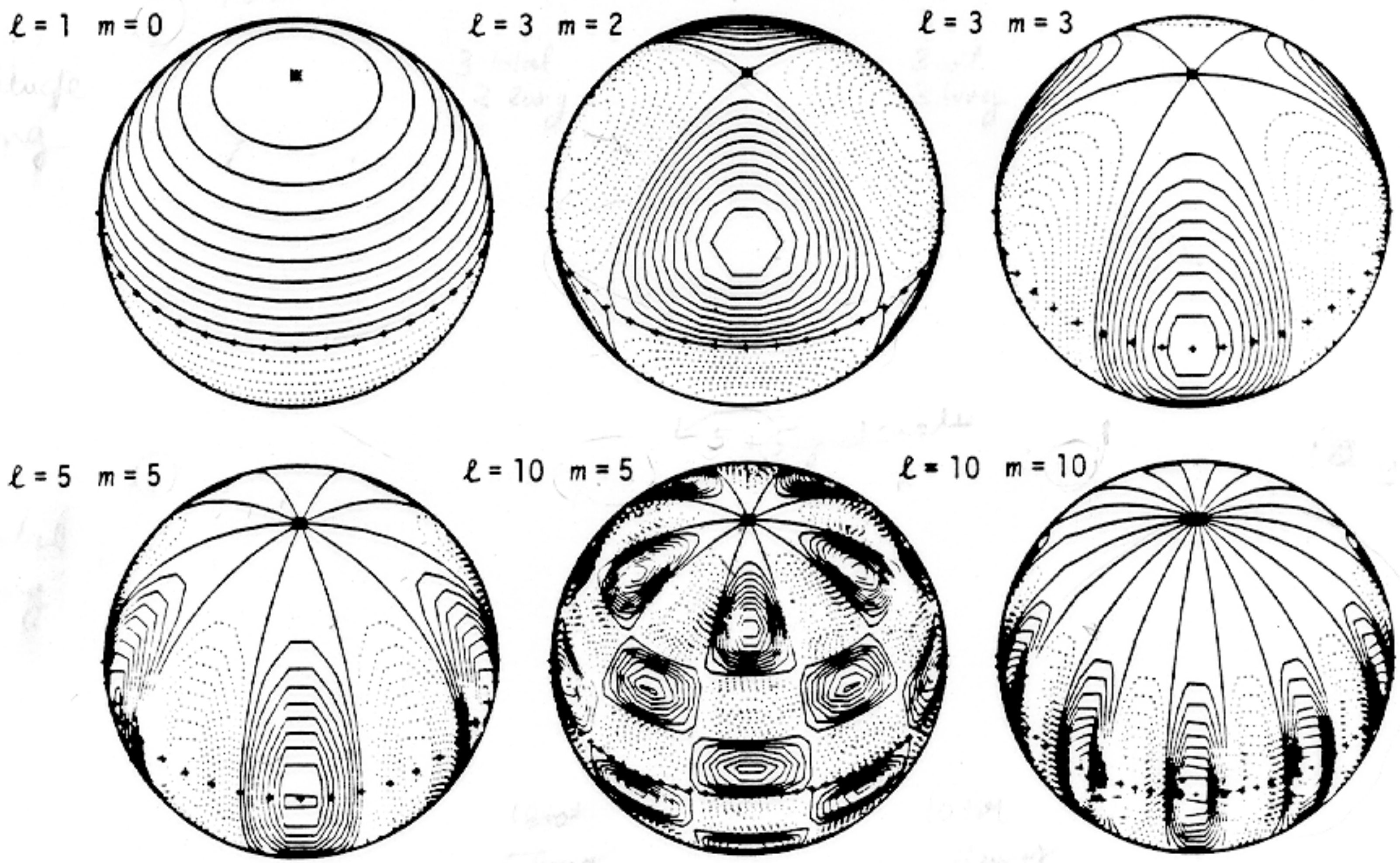


Dopplergram





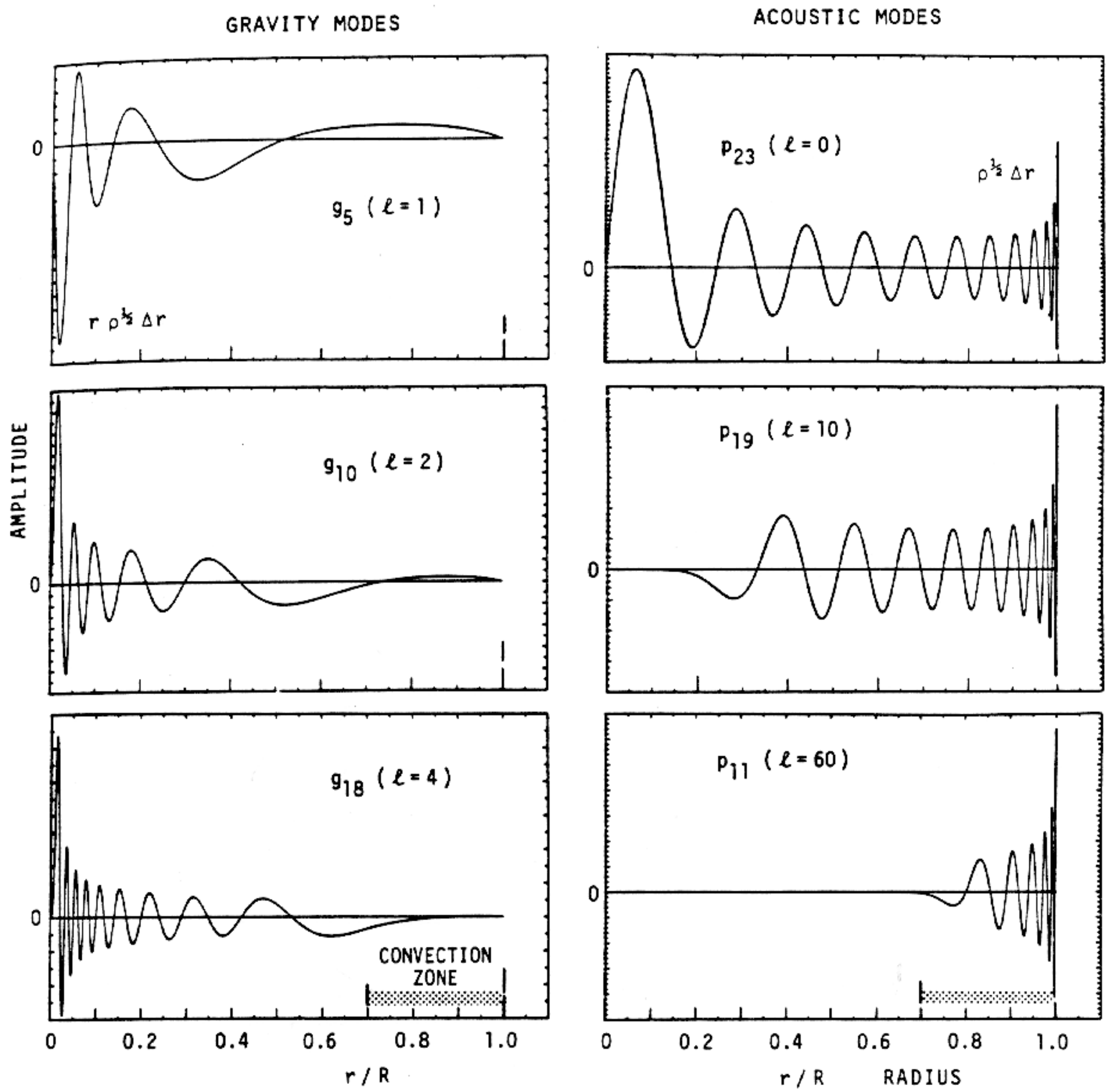
Angular dependence of modes are categorized by spherical harmonic indices



The lowest degree acoustic modes (and the gravity modes) are sensitive to solar center conditions

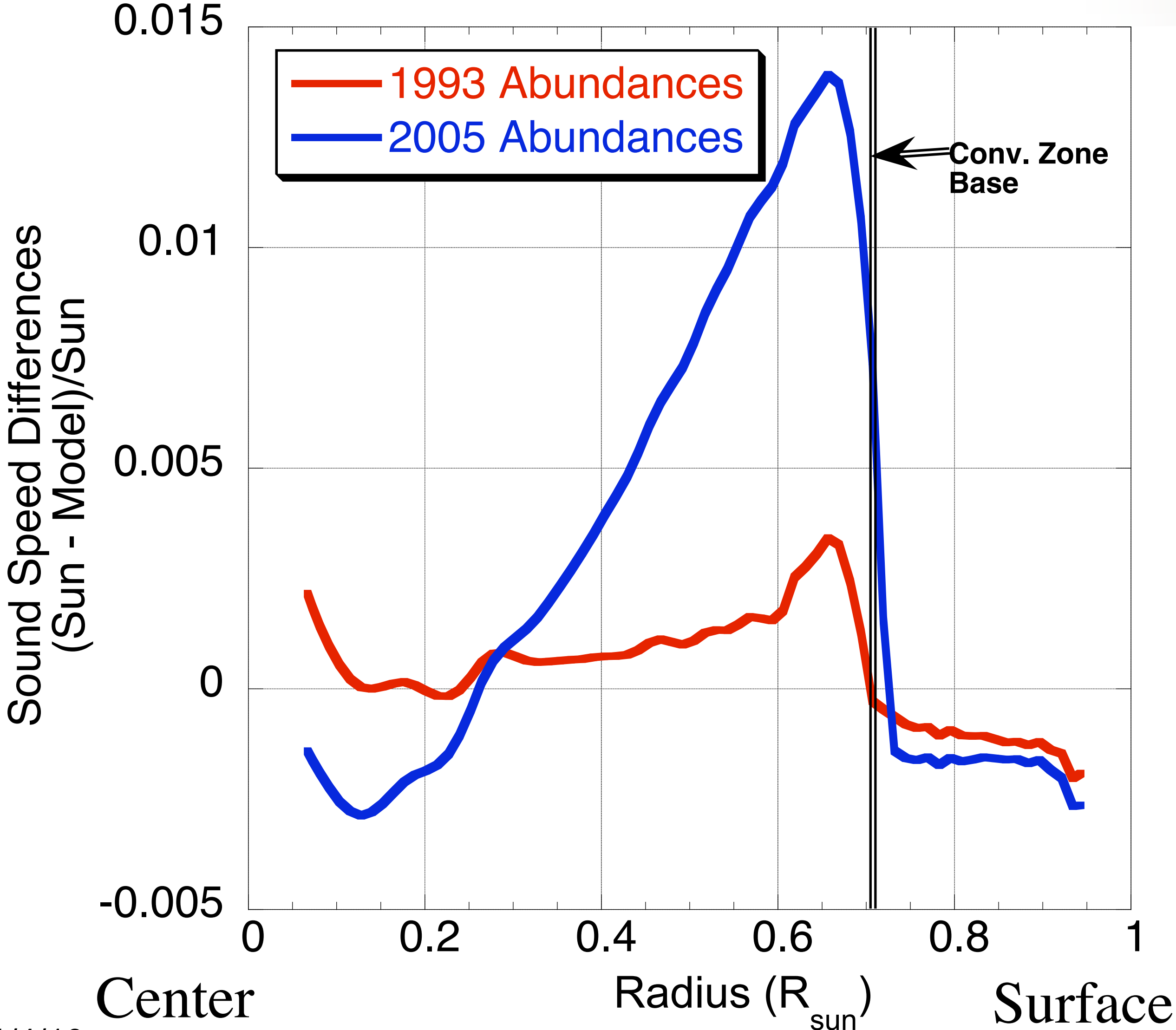
Mode Amplitude

Center



Surface

Sound speed profile inferred from solar oscillations does not match models using latest element abundances ("The solar abundance problem")



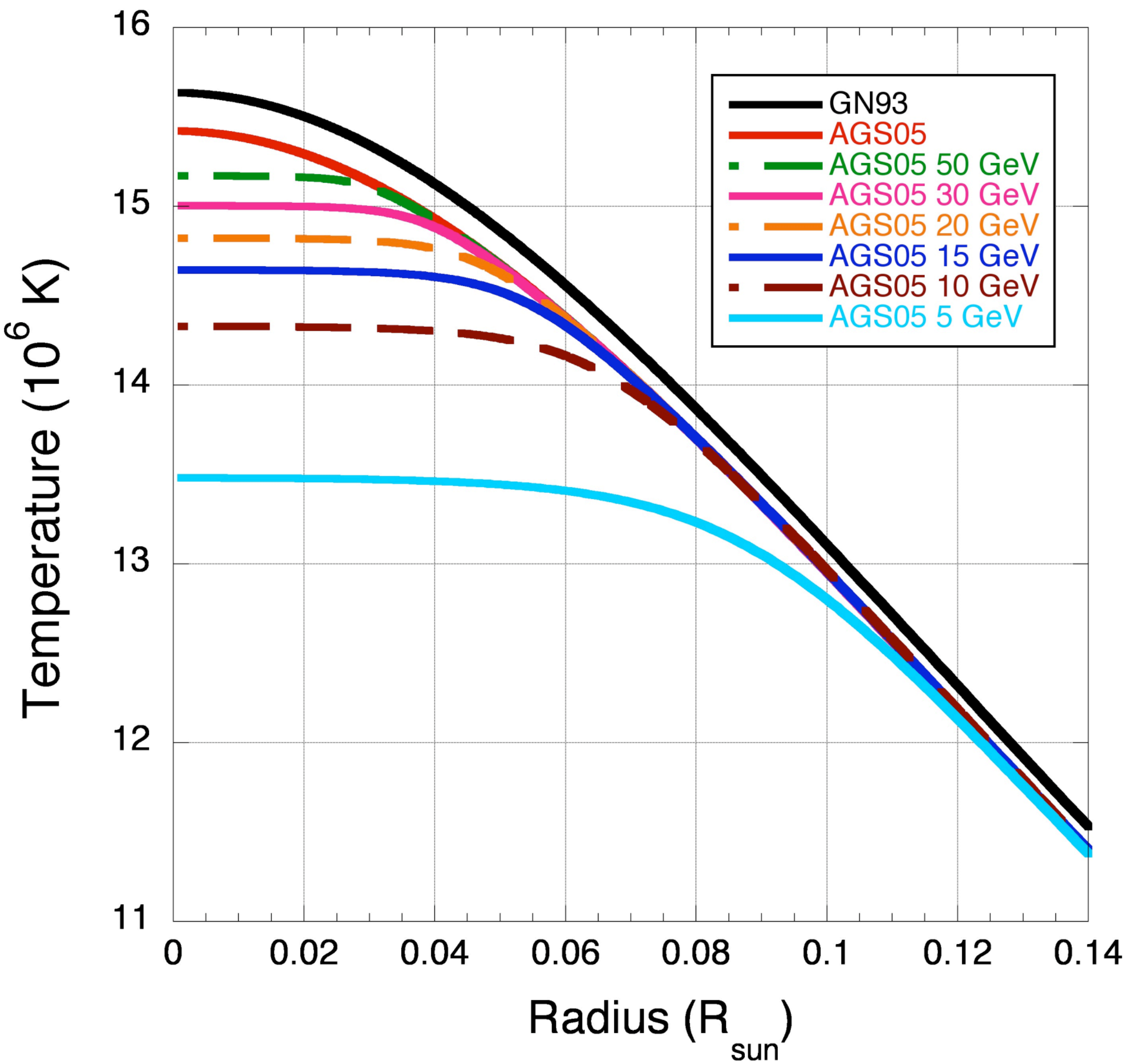
2005 element abundances

1.2% heavy elements

1993 element abundances

1.8% heavy elements

WIMP energy transport produces a cooler isothermal core



Lower-mass WIMPs have larger effect as they have larger orbits

Lower core temperature reduces ^8B solar neutrino output

Would change in temperature profile be detectable by pressure or gravity mode frequencies?

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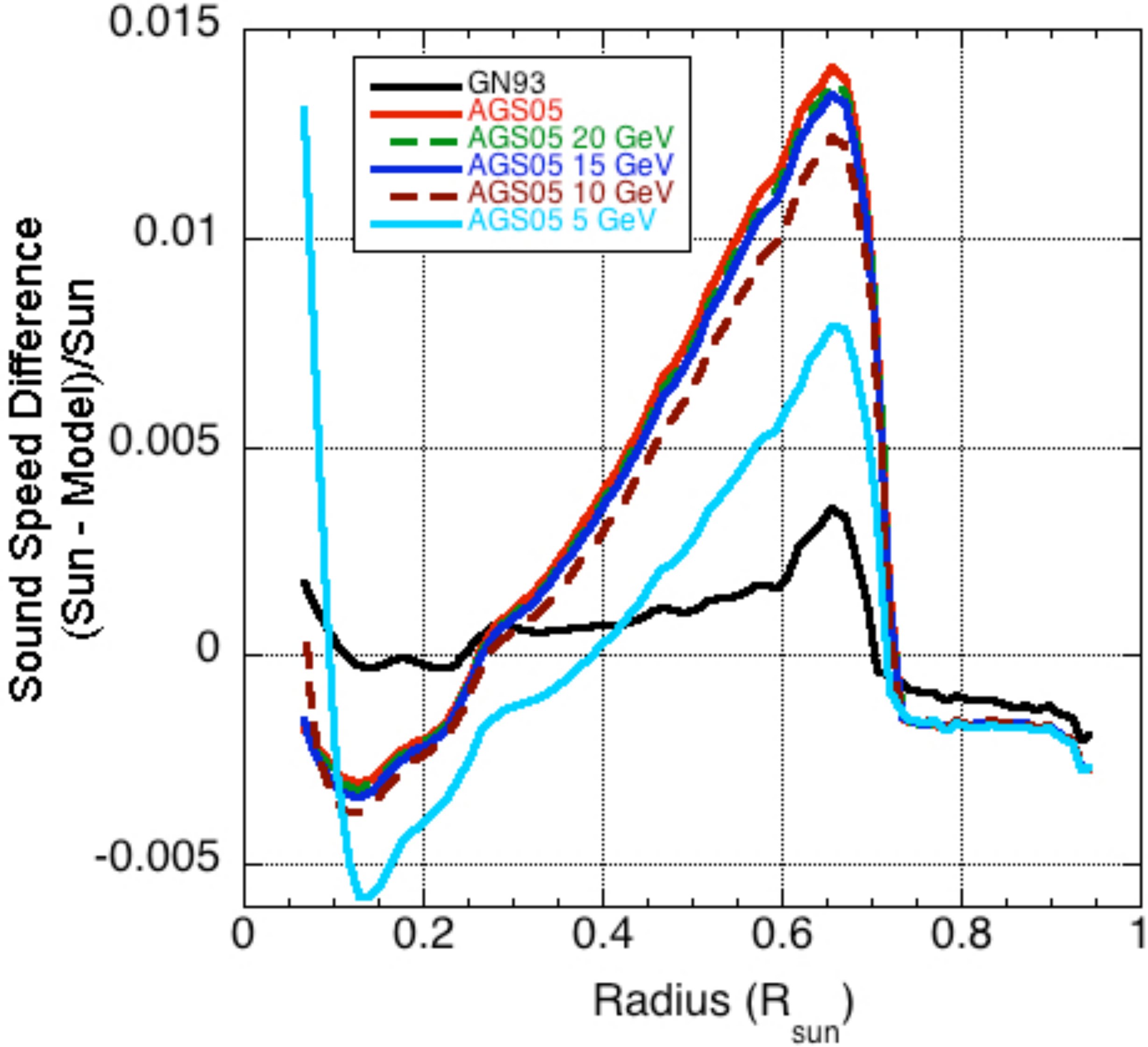
Comparisons with inferred sound speed appear to rule out 5-10 GeV WIMP masses



Solar sound-speed inversion from Basu et al. (2000)

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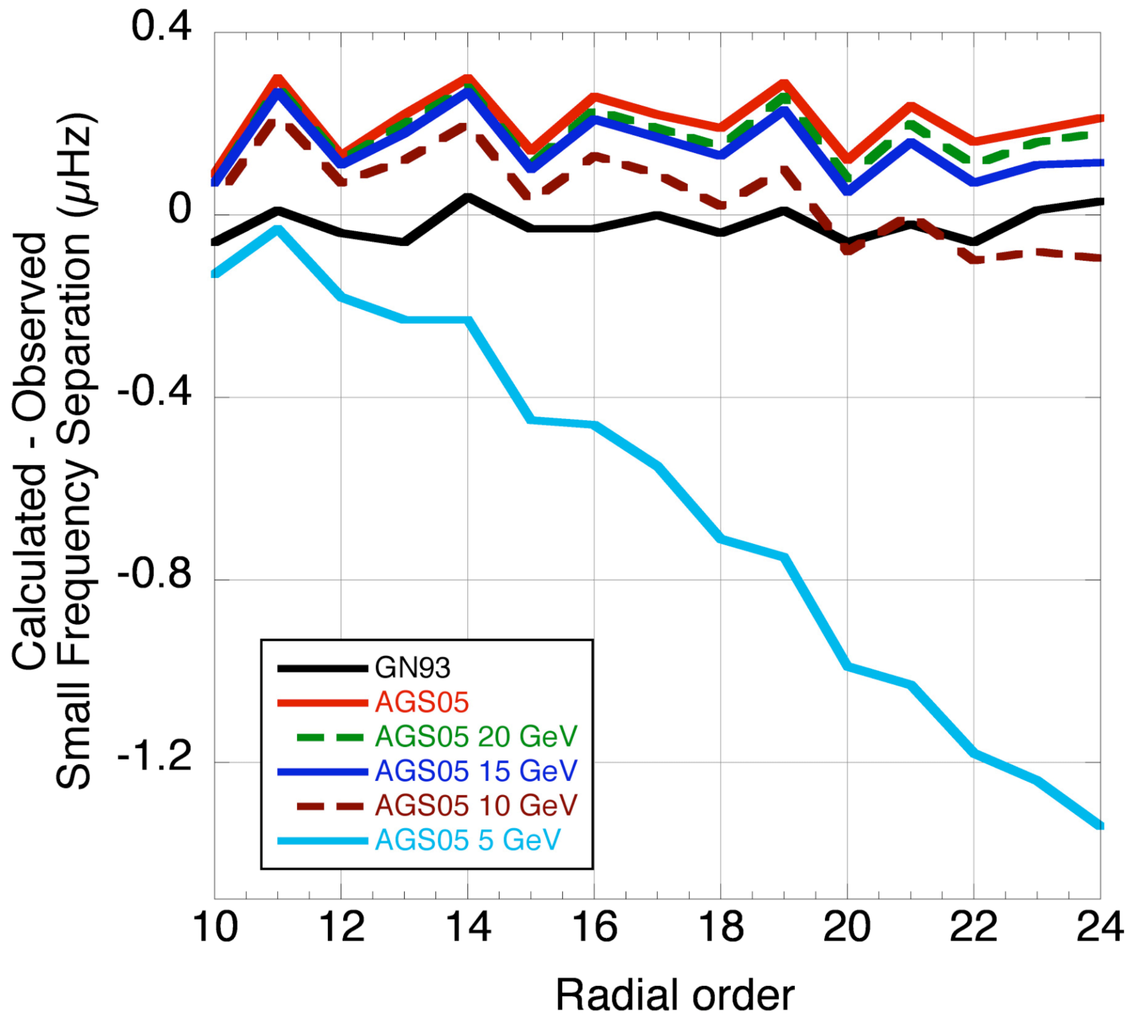
Small frequency separations rule out 5 GeV and possibly even 10 GeV WIMP masses



$\ell = 0, 2$

Solar-cycle corrected frequency observations from BiSON (Chaplin et al. 2007)

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Models calibrated including low-mass WIMPs affect predicted gravity modes, neutrino flux

	Standard model AGS05 abund.	**10 GeV WIMPs**	**5 GeV WIMPs**
^{8}B flux (SNUs)	6.32	2.96	1.18
ℓ =2 g-mode (μHz)	256	266	288
$\mathrm{He}_{\mathrm{conv.\ zone}}$	0.2273	0.2274	0.2227
$R_{\mathrm{CZ\ Base}}$ (R_{sun})	0.7294	0.7275	0.7220

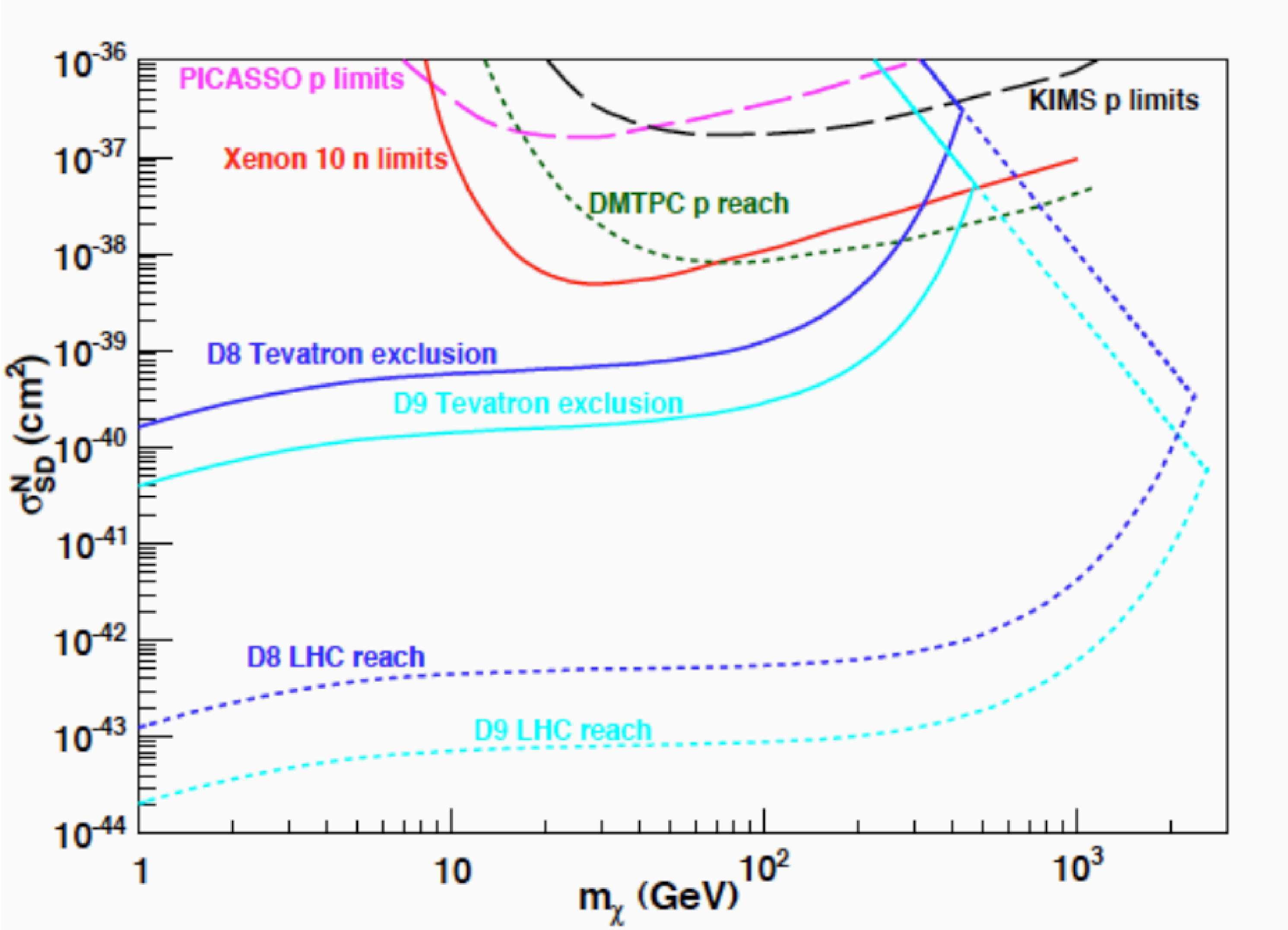
Conclusions

- Helioseismology can complement detection experiments to rule out some parameter space for Dark Matter (WIMP) candidate masses and interaction cross sections.
- In particular, helioseismology appears to rule out WIMPs with masses of <10 GeV, and spin-dependent interaction cross sections of greater than $\sim 10^{-34}$ cm^2. [exact #s TBD]
- There is a lot of WIMP parameter space that is not ruled out by helioseismology. Detection of solar g-modes would place stronger constraints.
- WIMPs also lower the expected solar neutrino output, and may be constrained by current and future neutrino detection experiments
- Including dark matter appears to worsen agreement with helioseismology for either the old or new element abundances, and does not offer a solution to the solar abundance problem.
- WIMPs, if present in stars, may have a much larger effect at later stages of stellar evolution.

Further Reading

- Cumberbatch et al., *Light Wimps in the Sun: Constraints from Helioseismology*, Phys Rev D, 2010 (accepted Sept. 23), http://arxiv.org/pdf/1005.5102v2
- Jonathan L. Feng, *Dark Matter Candidates from Particle Physics and Methods of Detection*, Annual Reviews of Astronomy and Astrophysics, Vol. 48, September 2010
- Ron Cowen, *Mining for Missing Matter*, Science News, August 28, 2010

Direct and indirect detection experiments place limits on spin-dependent WIMP mass and interaction cross sections



Goodman et al. 2010, http://arxiv.org/abs/1008.1783

The solar abundance problem

- The Asplund et al. 2005 (AGS05) solar abundance determination revises *downward* the mass fraction of elements heavier than H and He (Z), particularly oxygen, carbon, and nitrogen.

- For the older (e.g. Grevesse & Sauval 1998) abundances, Z/X = 0.023, and Z ~*0.018.* For the new abundances, Z/X = 0.0165, and Z ~*0.0122.*

- Models evolved with the new abundances give worse agreement with helioseismic constraints
  - 1.4% discrepancy in sound speed
  - too-shallow convection zone
  - too-low surface helium abundance

How can this discrepancy be resolved?
Should we adopt the new abundances?

Abundances of all elements are decreased from previous Grevesse & Sauval (1998) determination

Oxygen	**48% decrease**	8.66±0.05 (*cf* GS98 8.83±0.06)
Carbon	**35% decrease**	8.39 ± 0.05 (*cf* GS98 8.52±0.06)
Nitrogen	**27.5% decrease**	7.78±0.06 (*cf* GS98 7.92±0.06)
Neon	**74% decrease**	7.84 ± 0.06 (*cf* GS98 8.08 ± 0.06)
Argon	**66% decrease**	6.18 ± 0.08 (*cf* GS98 6.40 ± 0.06)

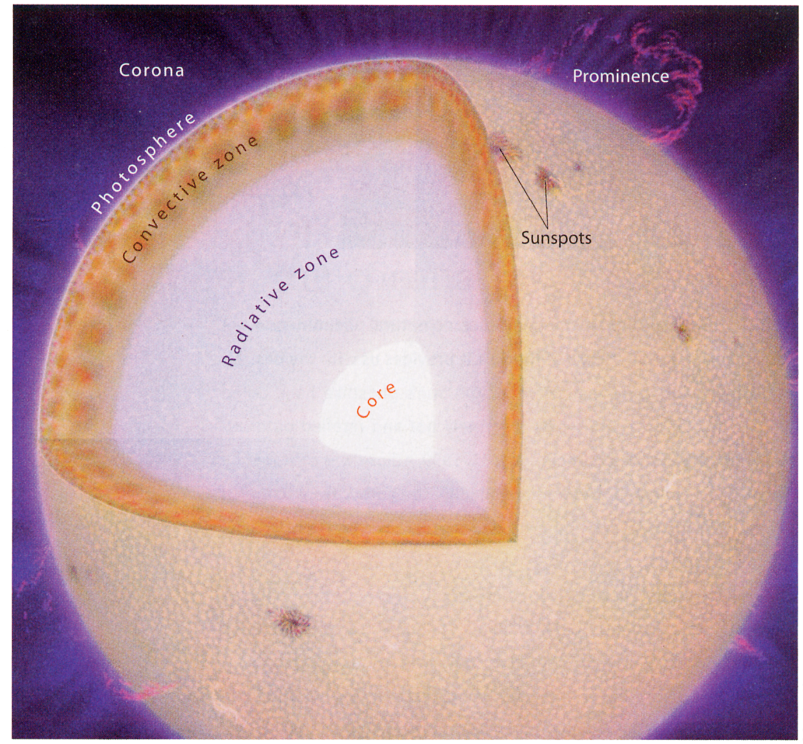
Na to Ca: lower by 0.05 to 0.1 dex (12 to 25%); smaller impact since basis is atomic transitions rather than molecular transitions. Only 1D NLTE corrections applied so far, so could change.

Fe: 7.45 ± 0.05 (*cf* GS98 7.50 ± 0.05) **12% decrease**

Revised mass fraction of 'metals' at Sun's surface (Z) is now only 0.0122 (instead of 0.018)

What did we learn from solar modeling?

- **The center is hot and dense**
  - **~27 million ^{o}F (15.6 million K)**
  - **150-160 times more dense than water**
- **Convection occurs in the outer layers**
- **Sun will run out of fuel in about 7.5 billion years**
- **Sun is growing in size and luminosity; it started at 70% current luminosity, and 86% current radius**



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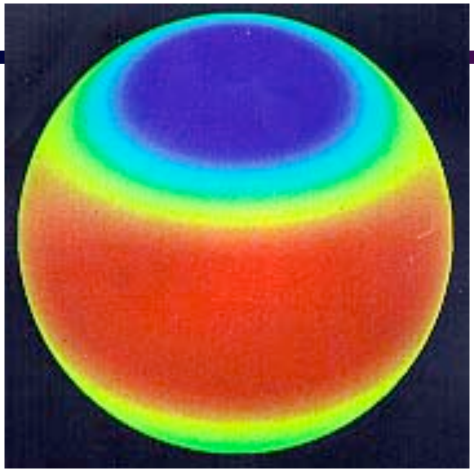
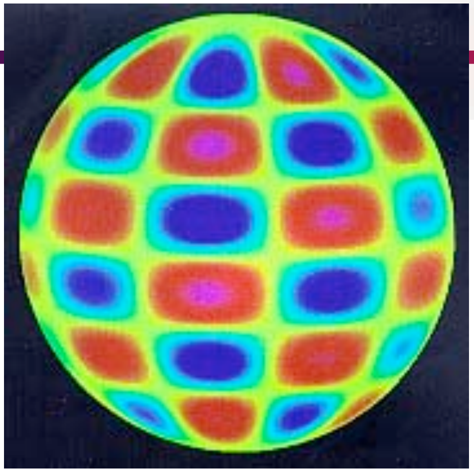
Helium abundance, initial Z, Y, and mixing length (α) are adjusted to calibrate L, R, and Z/X at present solar age

	Grevesse & Noels 1993 Mixture	Asplund, Grevesse & Sauval 2005 Mixture	
Y_o	0.2703	0.2570	
Z_o	0.0197	0.0135	
α	1.7698	1.9948	*Helioseismic inference* *(Basu & Antia 2004)*
$Y_{surface}$	0.2418	0.2273	0.248 ± 0.003
R_{czb} (R_{sun})	0.7133	0.7306	0.713 ± 0.001

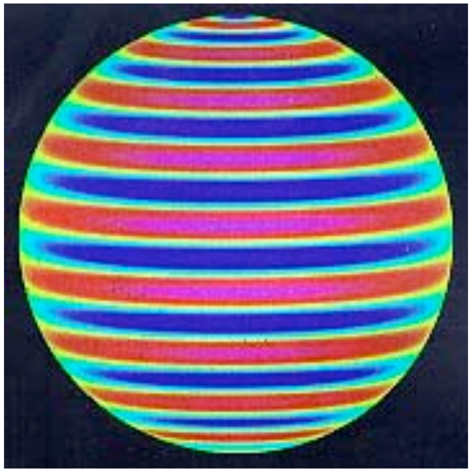
More example oscillation modes of the Sun



l=2 *m*=0



l=10 *m*=5



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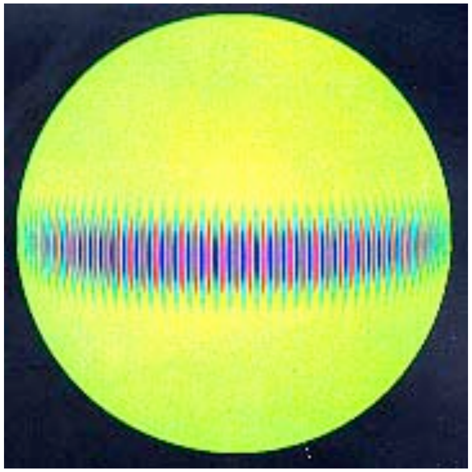

l=100 *m*=100