Astroparticle Physics

(Lecture 3)

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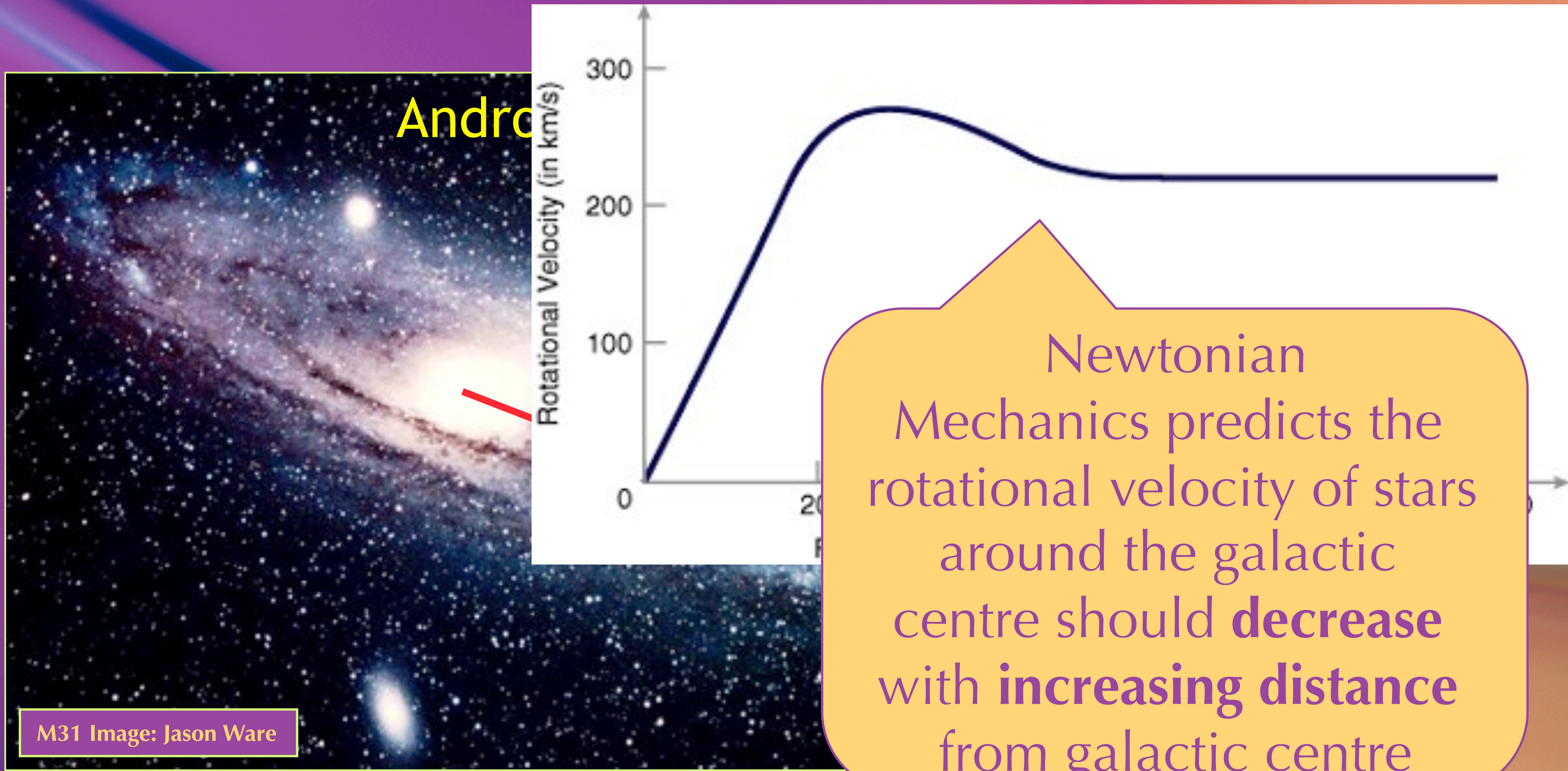
Why do we need dark matter?

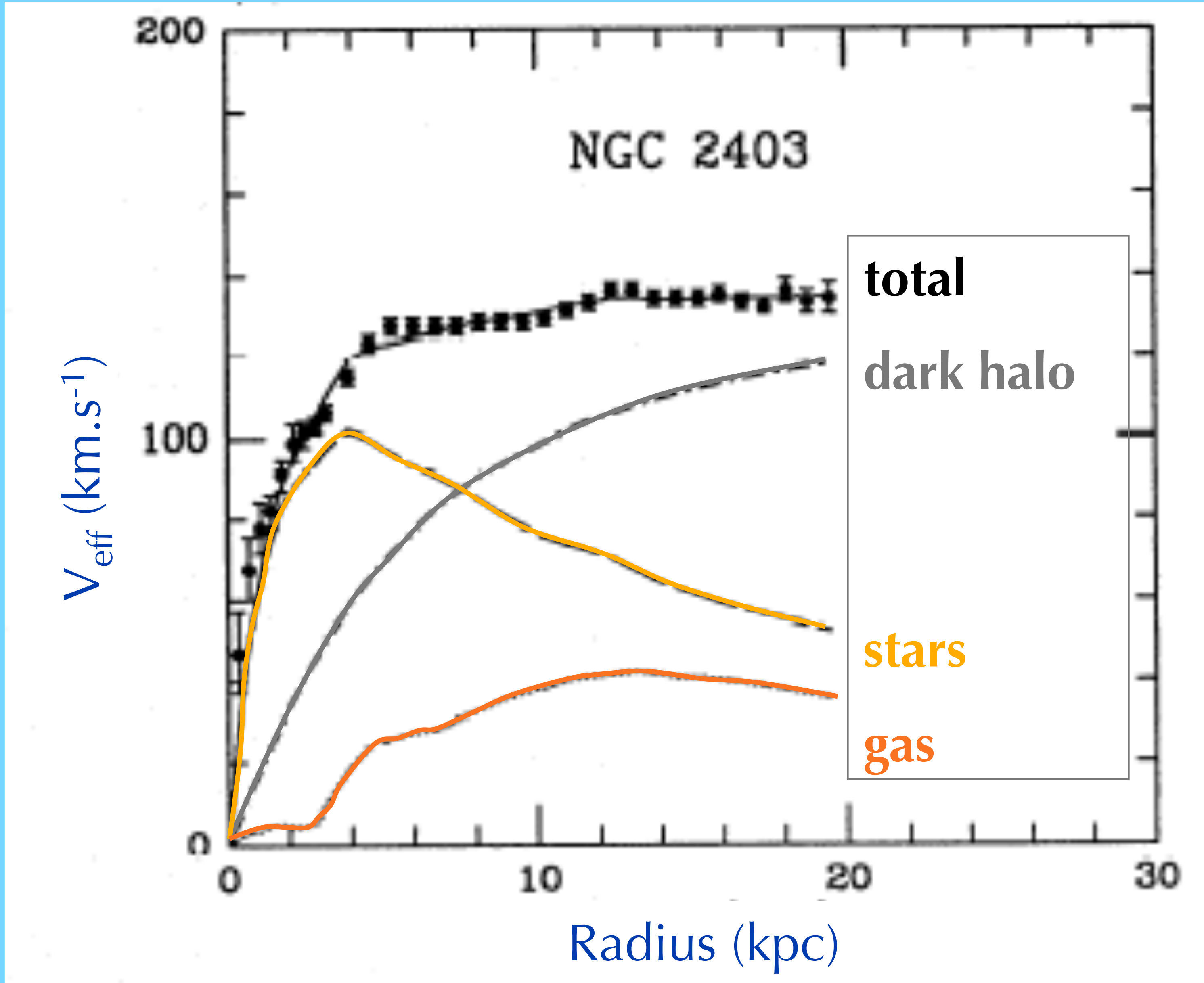


Newtonian Mechanics predicts the rotational velocity of stars around the galactic centre should **decrease** with **increasing distance** from galactic centre

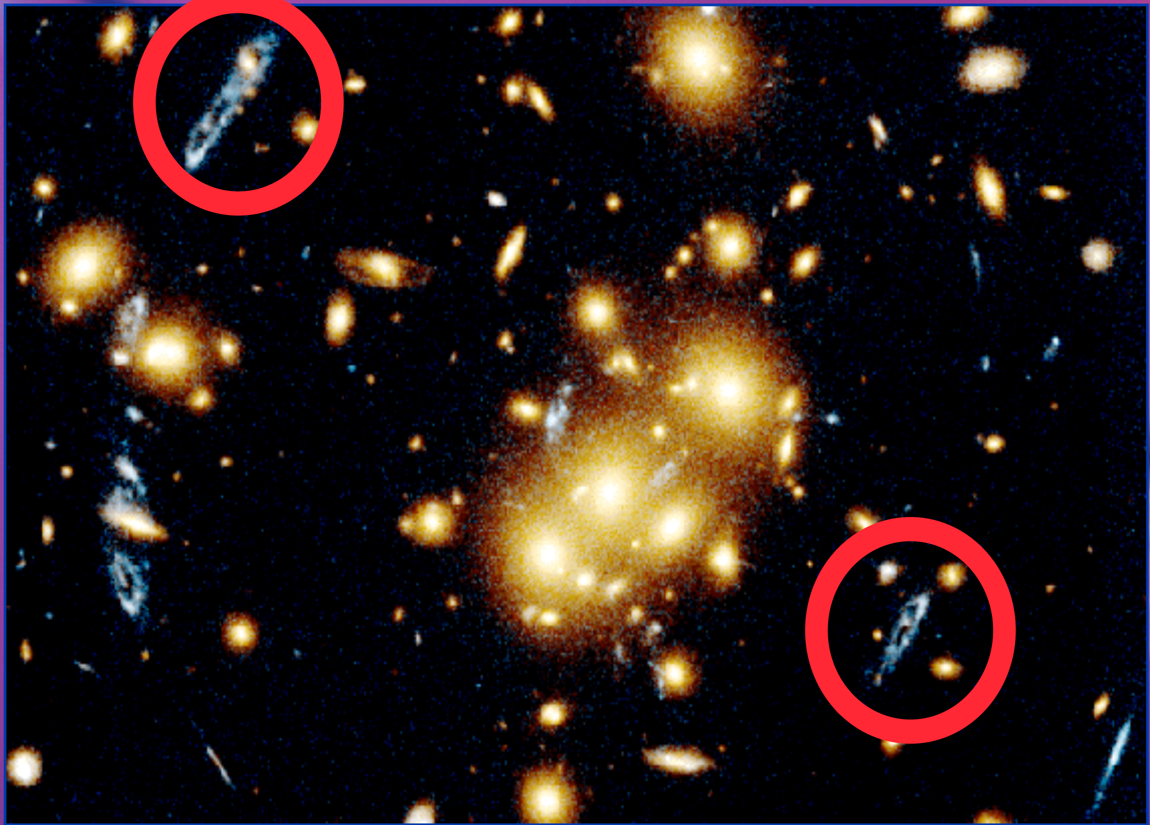
- **Measurements of the rotation curves of our own galaxy and many other galaxies tell us that the luminous matter alone is <u>not sufficient</u> to explain the observed dynamics**

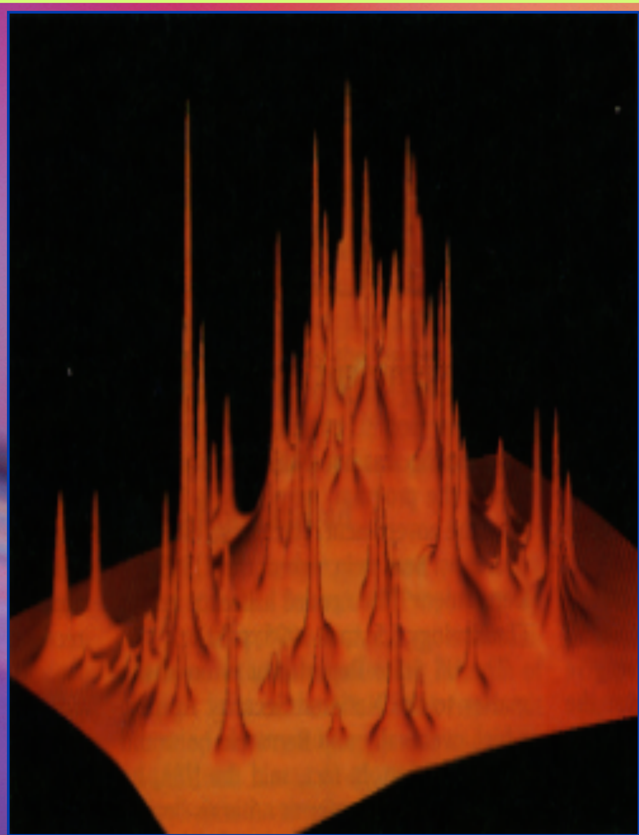
Why do we need dark matter?

Assuming Newtonian Mechanics (no reason not to) then this implies that there is large quantities of invisible mass situated in the halos of spiral galaxies. Dark Matter



Why do we need dark matter?





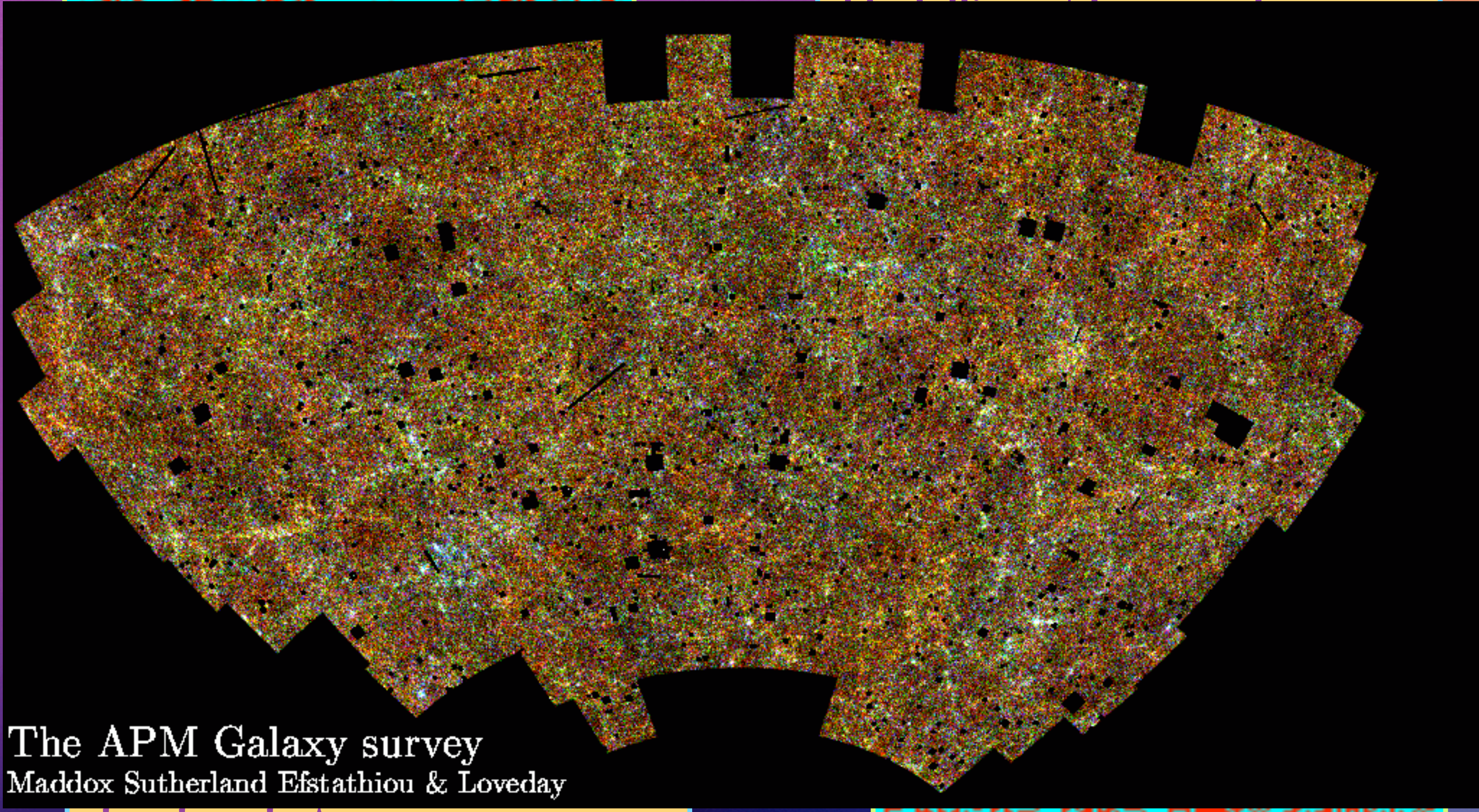
- Gravitational lensing, predicted by Einstein
- Here multiple images of a background object can be seen in the galaxy cluster CL0024+1654
- Light from this object is bent and focused by the matter in the cluster
- Analysis of these distortions enable the matter profile of the cluster to tbe mapped

Types of dark matter: Hot or Cold?

- Hot dark matter or Cold dark matter?
  - *Hot = fast moving or relativistic*
  - *Cold = slow moving*
- Hot dark matter would be some particle left over from the Big Bang that is light, fast moving and weakly interacting. Suitable candidates include a massive neutrino. A neutrino with a mass of just 92eV (1/5000 x $M_{electron}$!) could account for all the missing mass in the Universe!
- Cold dark matter (CDM) would be a slow moving, possibly massive particle
- How can we tell them apart?

  Look at large scale structure in the Universe.

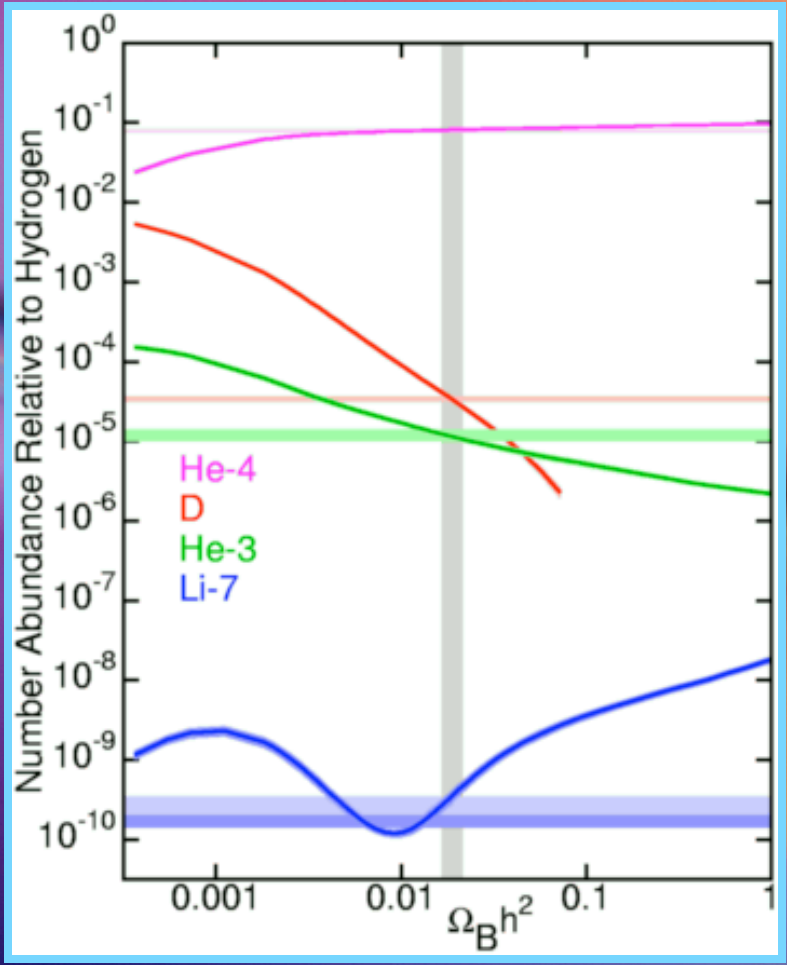
Types of dark matter: Hot or Cold?



structure to form

Types of dark matter: (non)baryonic

- Baryons, like protons and neutrons could contribute to the dark matter problem in the form of non-luminous objects.
- The amount of baryonic matter in the Universe is related to abundances of elements such as ^2H, ^3He, ^4He and ^7Li produced at the start of the Universe.
- Current measurements indicate only a small fraction of the matter in the Universe is baryonic.
- So, there is a more exotic, non-baryonic component

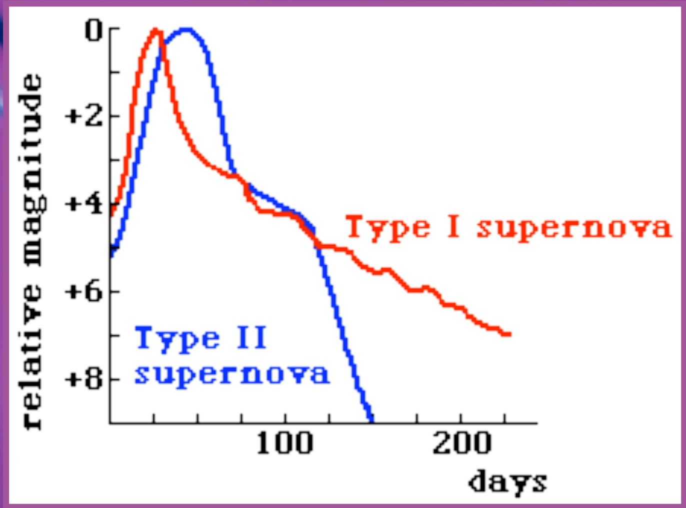


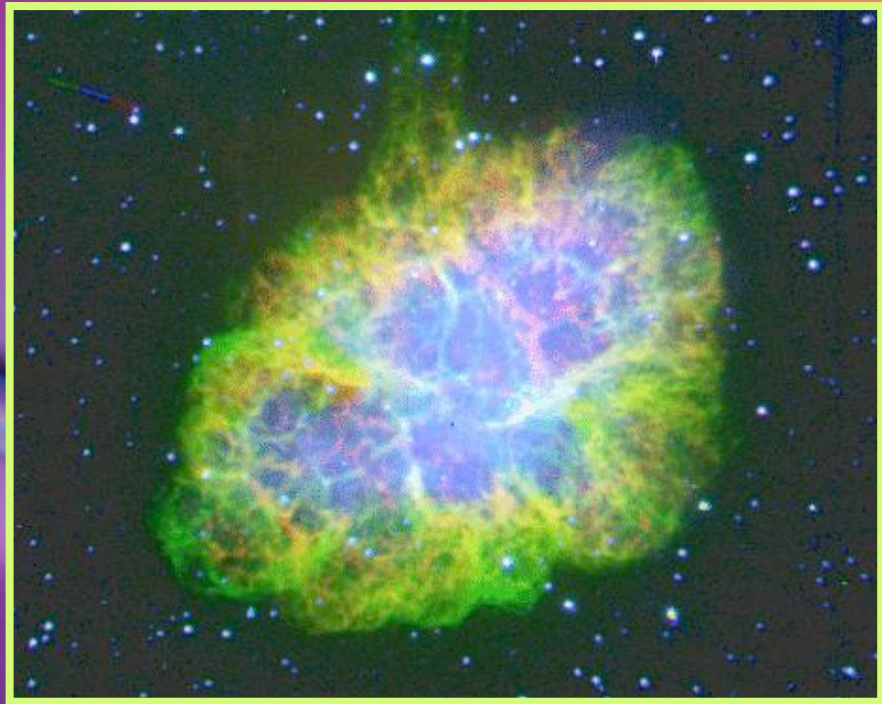
Summary so far …

- A lot of dark matter is needed to explain astrophysical observations
- Large scale structure prefers a cold (non-relativistic) dominated Universe
- Some (small amounts) of hot dark matter is allowed
- Dark matter appears to be predominantly non-baryonic
- Can we determine exactly how much dark matter there is?

- Recent results from looking at the Cosmic Microwave Background (CMB) and type 1a supernovae combine to give stringent limits on the different components to the overall matter density of the Universe

How much dark matter is there?



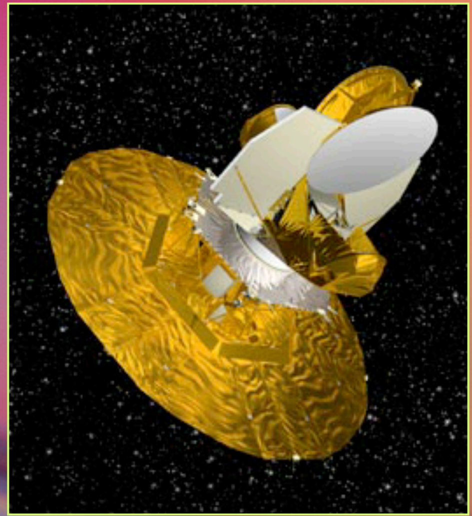


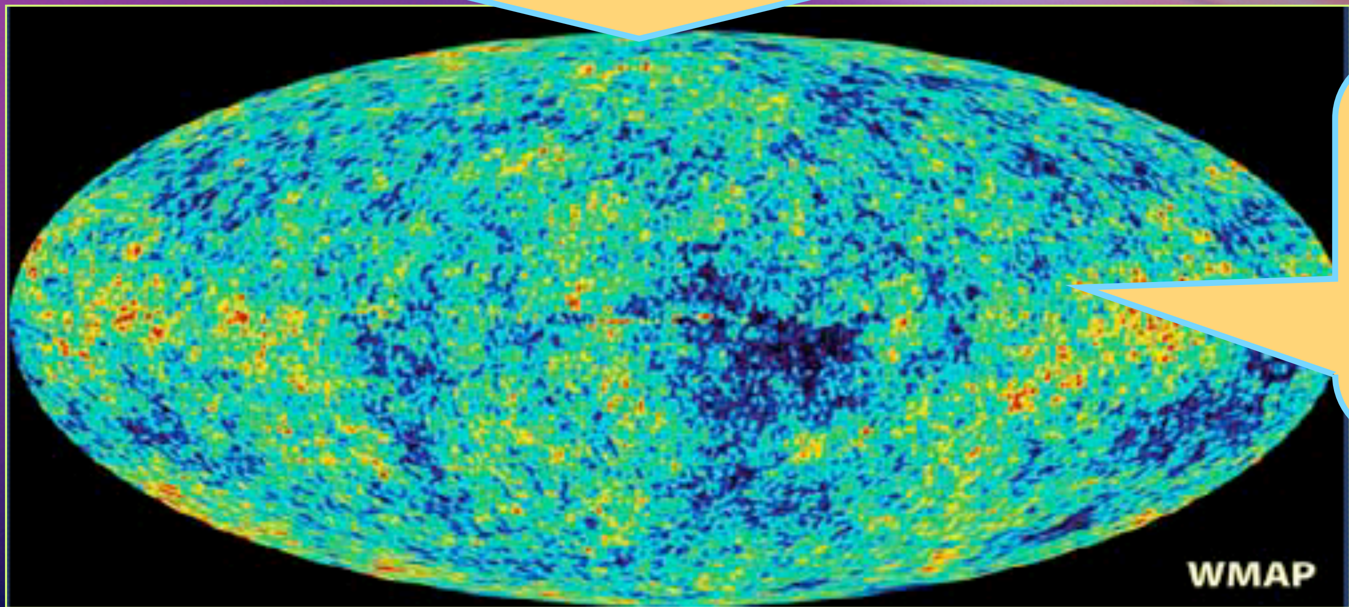
- SCP
  - *Type Ia supernova - death throes of a dying star*
  - *Briefly luminous as a complete galaxy! Huge energy release*
  - *Star always explodes with <u>same</u> brightness with <u>same</u> time profile (light curve)*
  - *Acts as a standard candle*

How much dark matter is there?

This is essentially a picture of the Universe 400,000 years ago. The minute temperature variations observed (10’s of micro-Kelvin) are very sensitive to the structure of the Universe at that time

400,000 ye ... ne Big Bang)



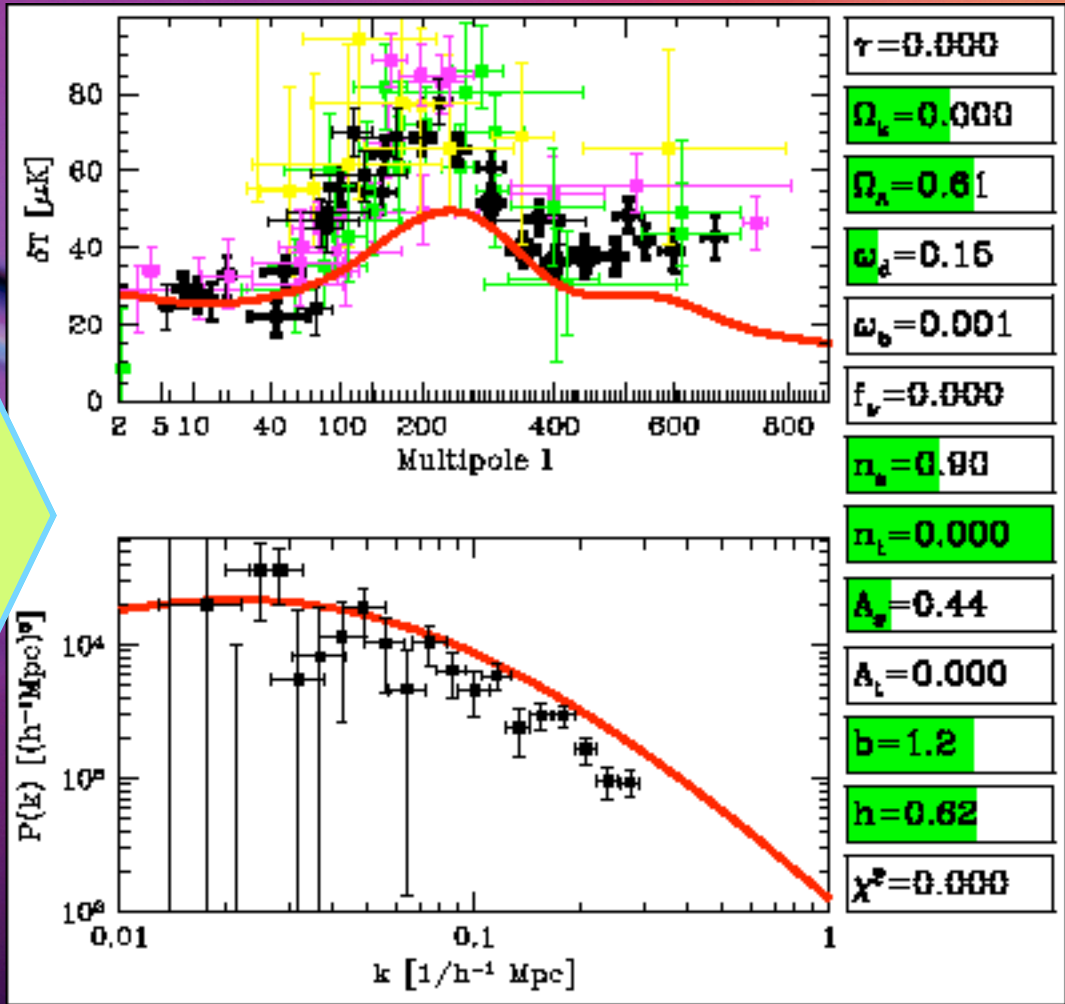


Anisotropies in the CMB measured at the 10^{-5} level

How much dark matter is there?

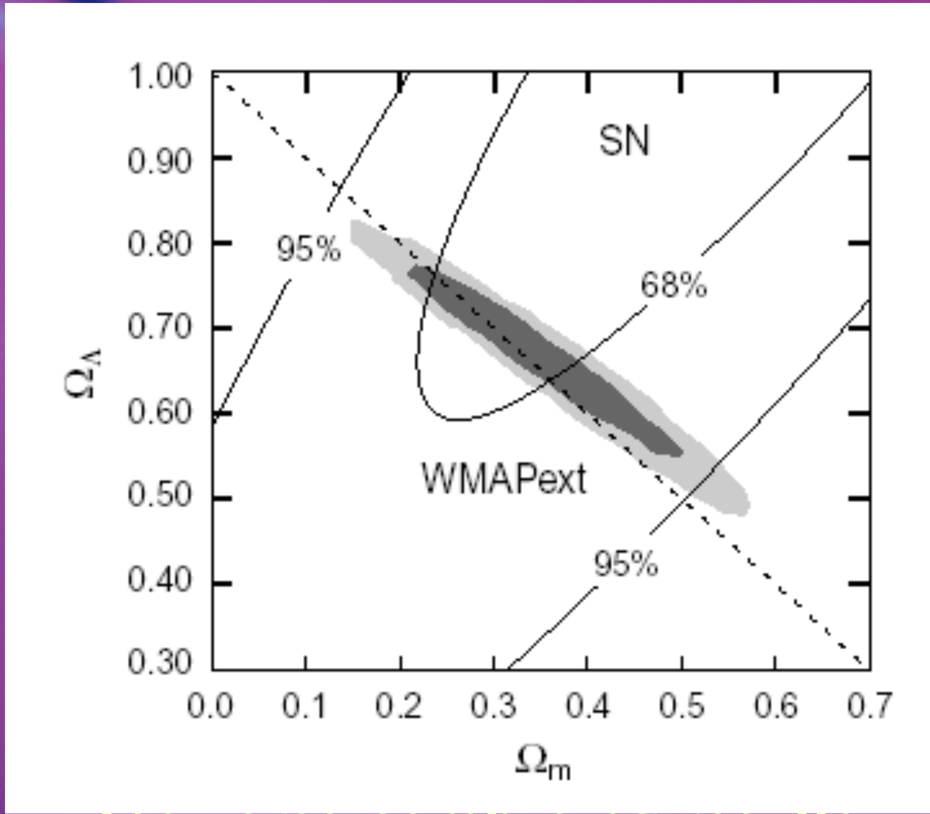
(top) CMB and (bottom) galaxy power spectra

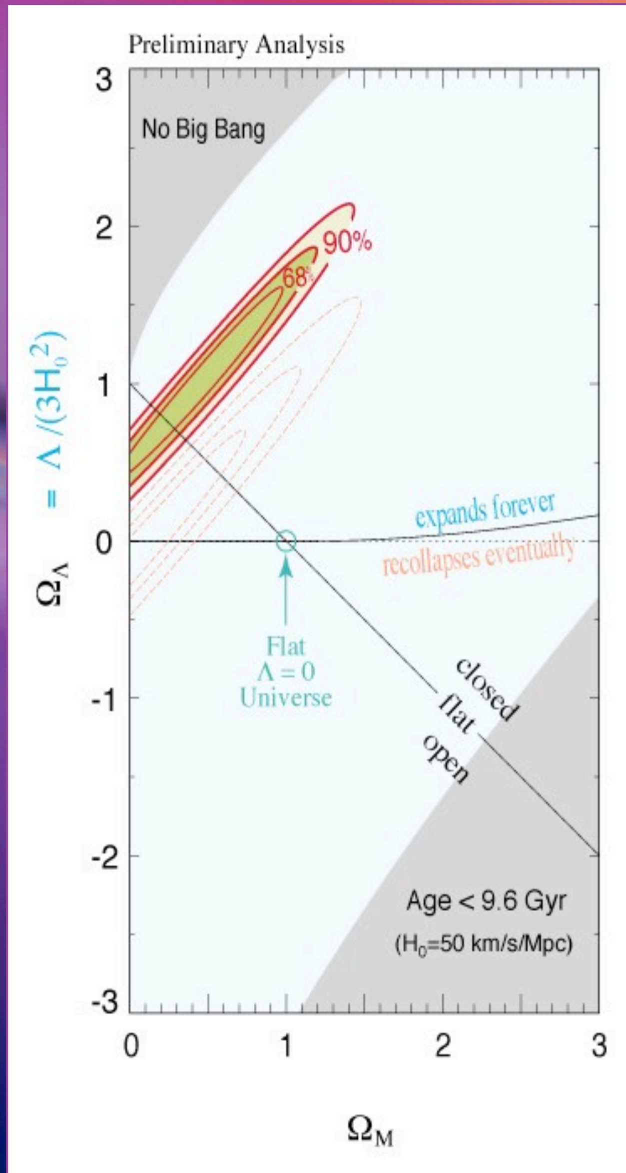
CMB acoustic peaks change due to a complicated relationship between dark matter and number of baryons



- Understanding how CMB data can determine cosmological parameters. From Max Tegmark's CMB website.

How much dark matter is there?

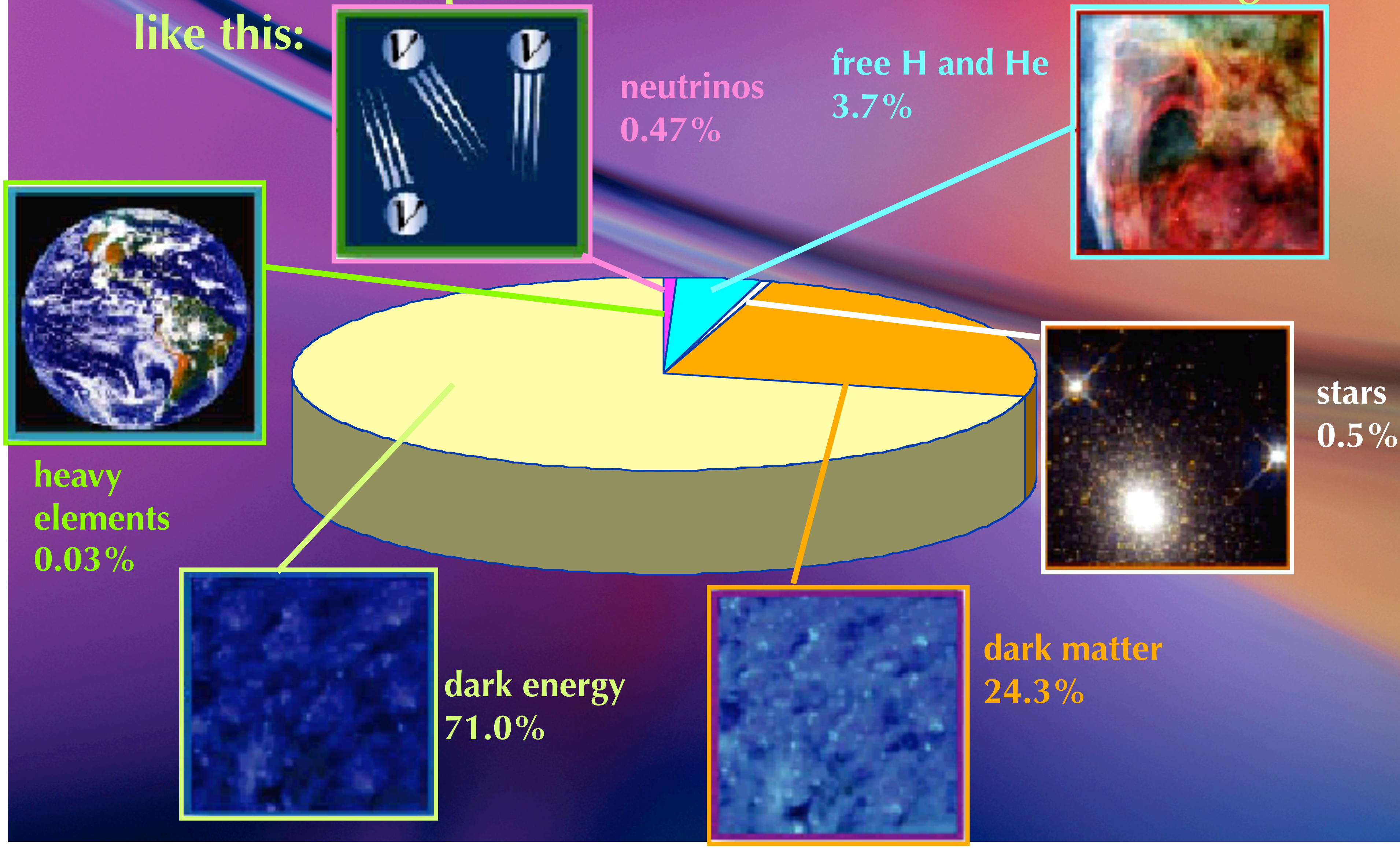




Universe combining results from the two experiments provides strong constraints

How much dark matter is there?

- So our current picture of the Universe looks something like this:



Structure formation

Simulations of structure formation (from Ben Moore and collaborators).

These “virtual Universes” look very similar as the real universe as seen from Cosmic Microwave Background studies, comprehensive galaxy surveys, etc. if DM is added

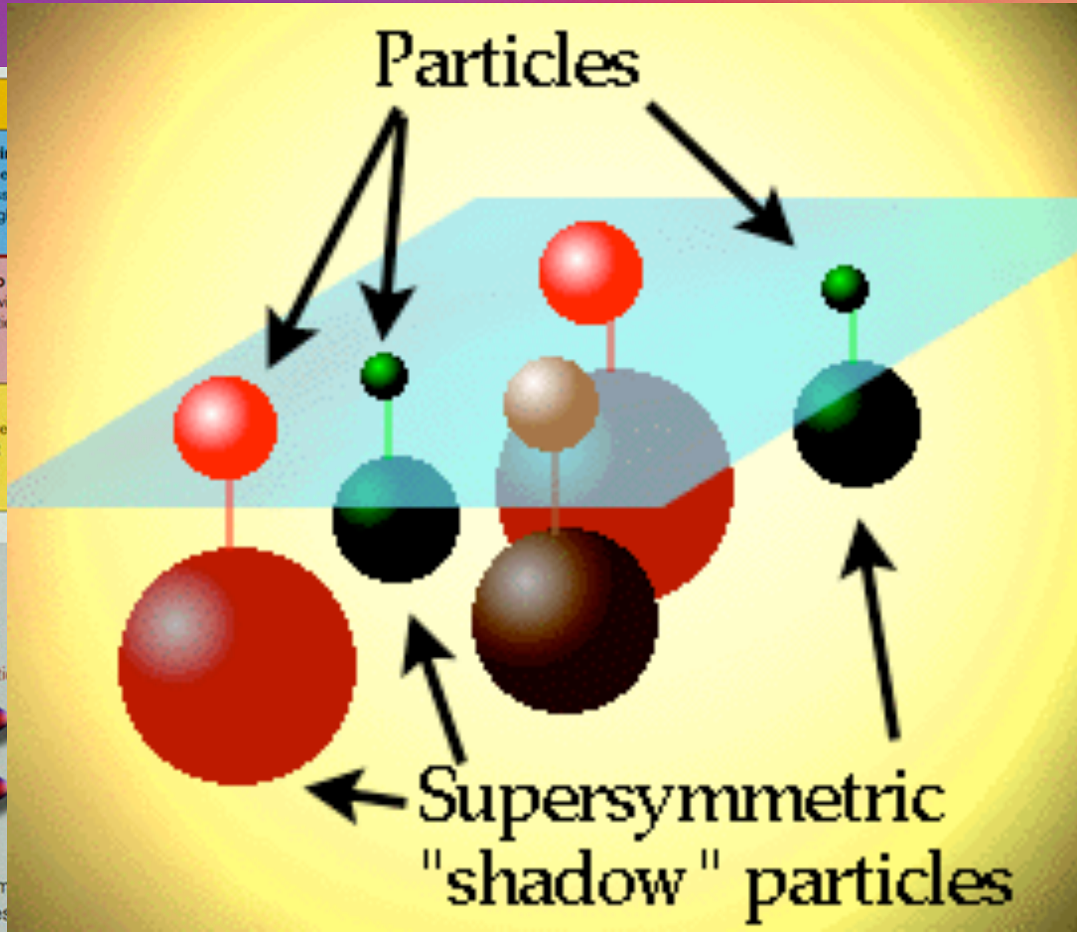
What might this dark matter be?

- Recall:
  - *Non-baryonic*
  - *Massive*
  - *Weakly interacting*

  ⟶ *WIMP (Weakly Interacting Massive Particle)*
- What are the candidates?
  - *Axions*
    - (super light ($M_a \geq 10^{-15}$GeV) particles that couple to photons
  - *Neutralinos - see next slides*
  - *Superheavy dark matter*
    - Particles with $M \geq 10^{14\pm5}$GeV, relics of the early Universe - may explain UHECR

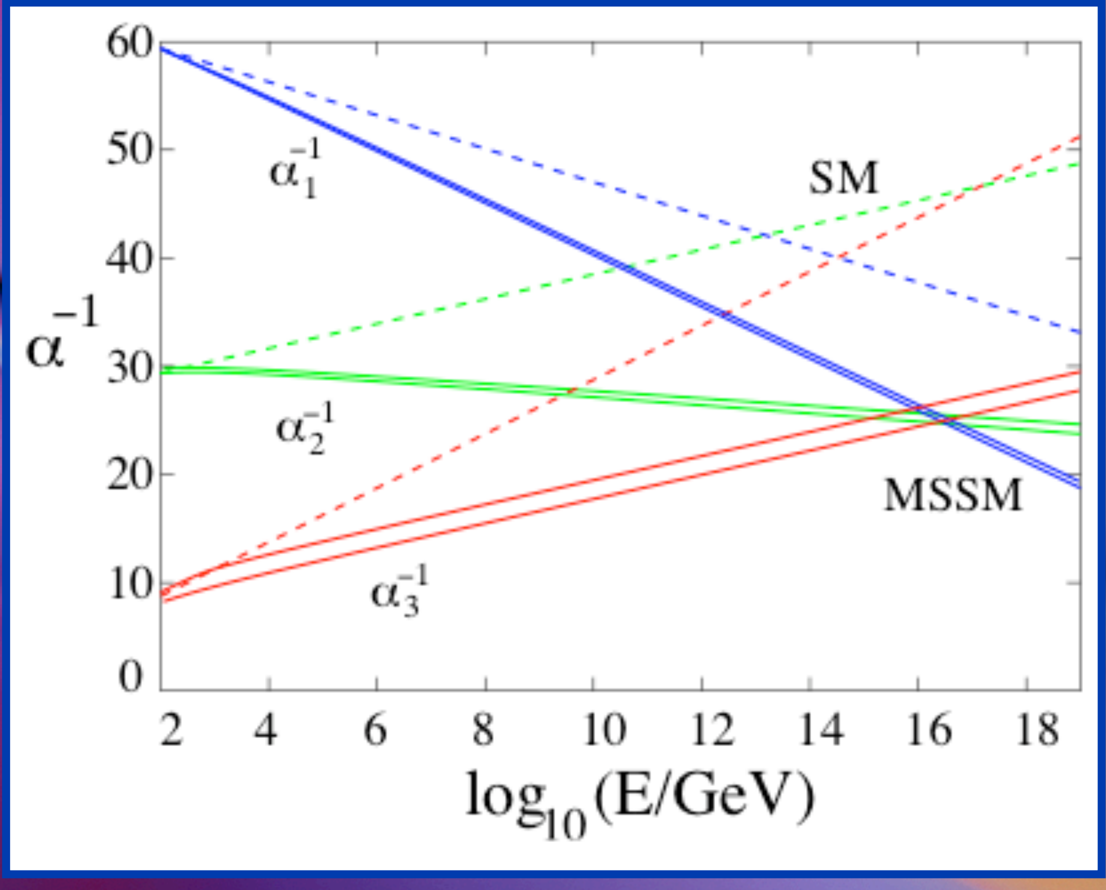
What might this dark matter be?

- There exists an extention to the Standard model of Particle Physics where every particle has a "superpartner" (non of which have, to date, been observed). This is the theory called Supersymmetry (SUSY)



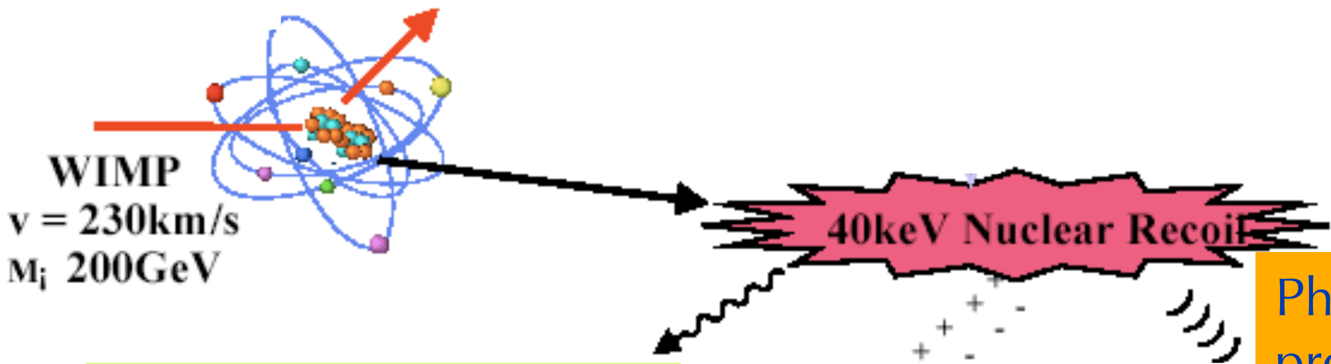
What might this dark matter be?

- SUSY is motivated by some underlying problems with the standard model, unifies couplings at high energy
- Supersymmetry requires there to be an LSP - a lightest supersymmetric particle that is stable, massive, and weakly interacting (sounds familiar!)



- A good candidate for the LSP is the neutralino which is also electrically neutral
- If the neutralino (χ) has mass less than ~ 1 TeV its "relic abundance" can account for the CDM deficit required in the Universe

How can we look for dark matter?



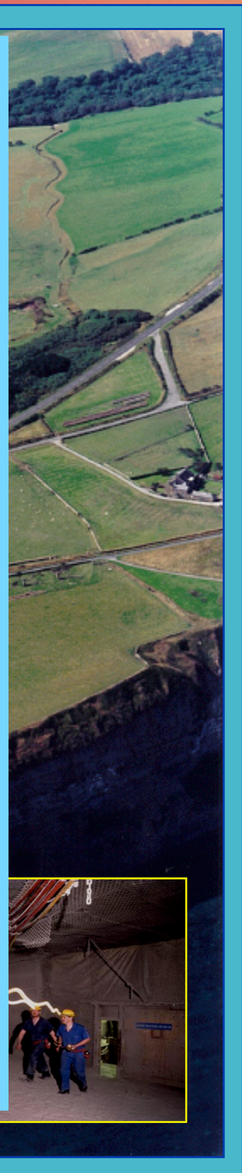
Scintillators give off a flash of light after nuclear recoil, e.g: NaI, CsI

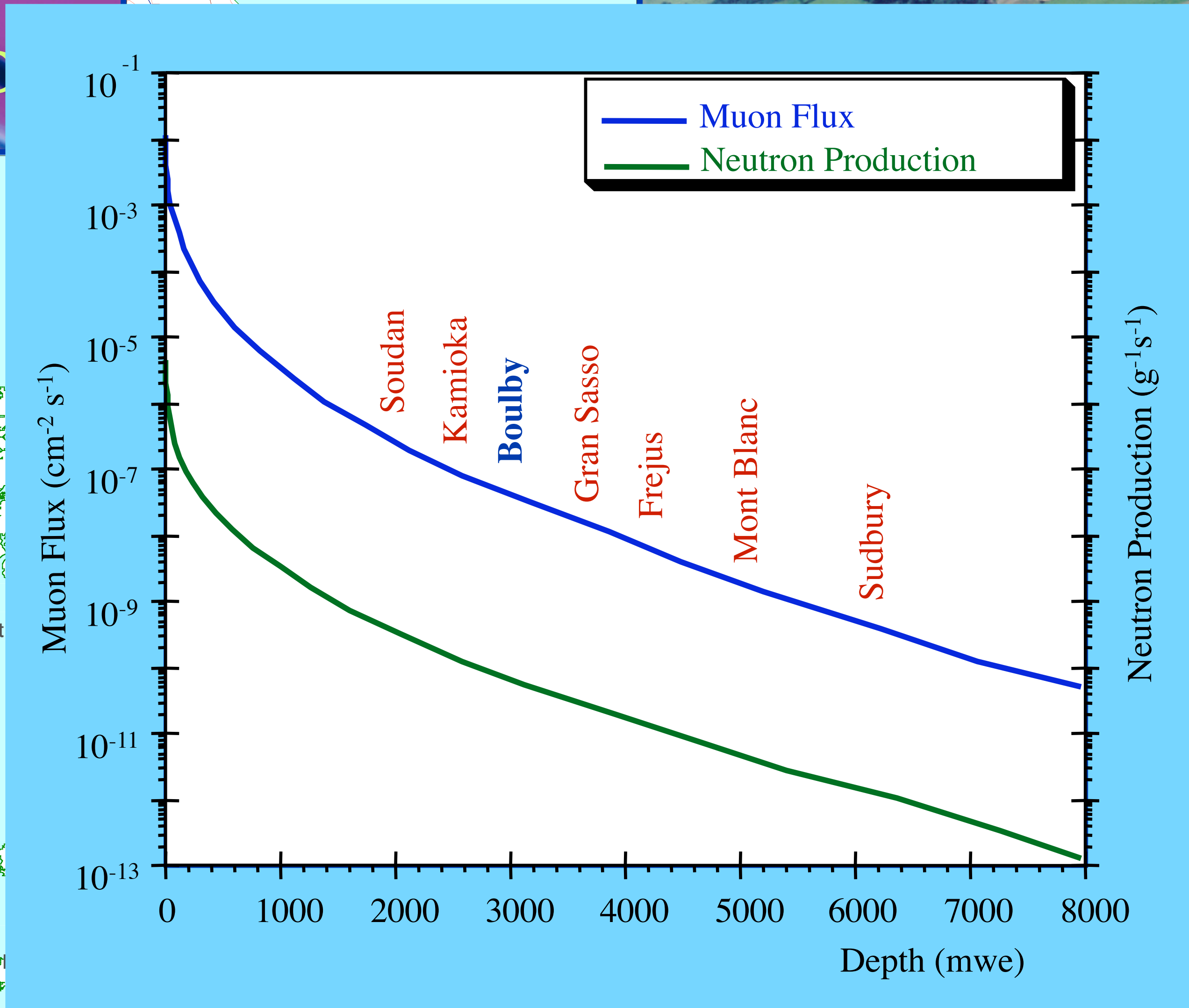
Ionization (free electrons, ions) can be drifted in a electric field and detected on an electrode

Phonons are produced in e.g: a crystal lattice and can be detected via a small temperature increase (requires cryogenics)

How can we look for dark matter?

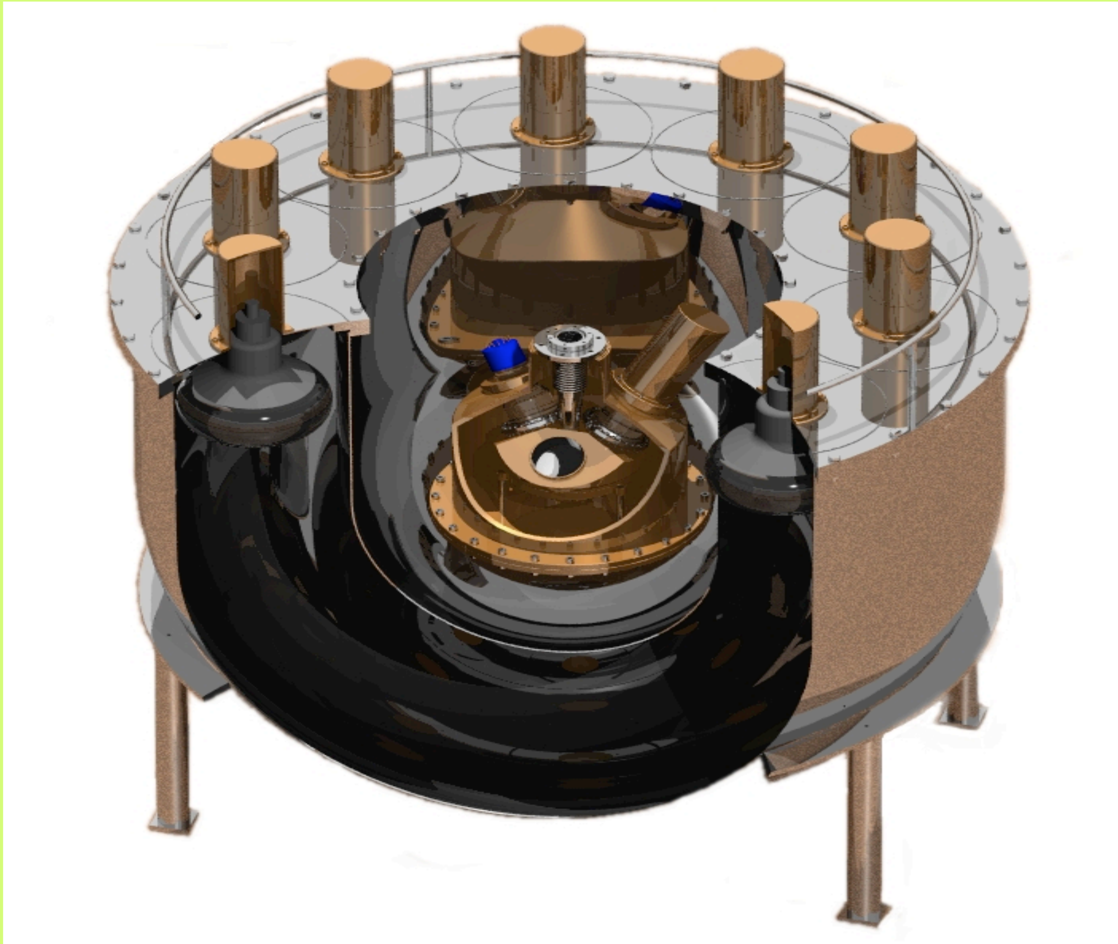
- DIREC

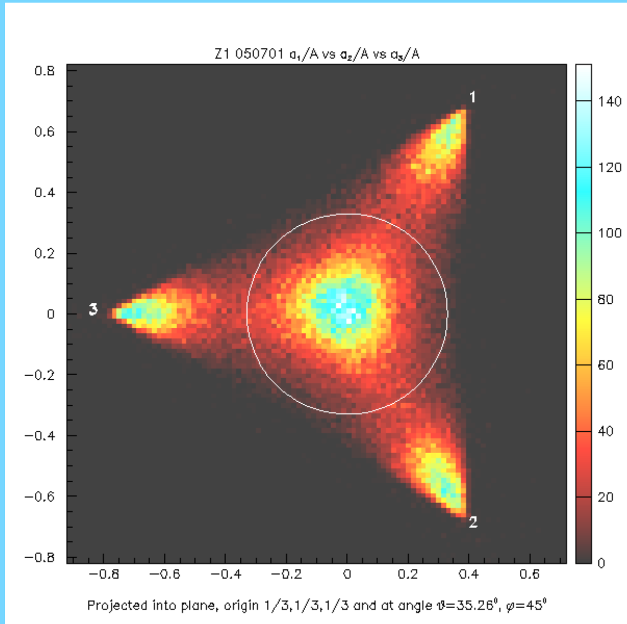




How can we look for dark matter?

- The ZEPLIN project
- Uses Liquid Xenon as a target
- Target sits inside a "Compton veto" - a tank of mineral oil that helps to discriminate against background gamma ray events

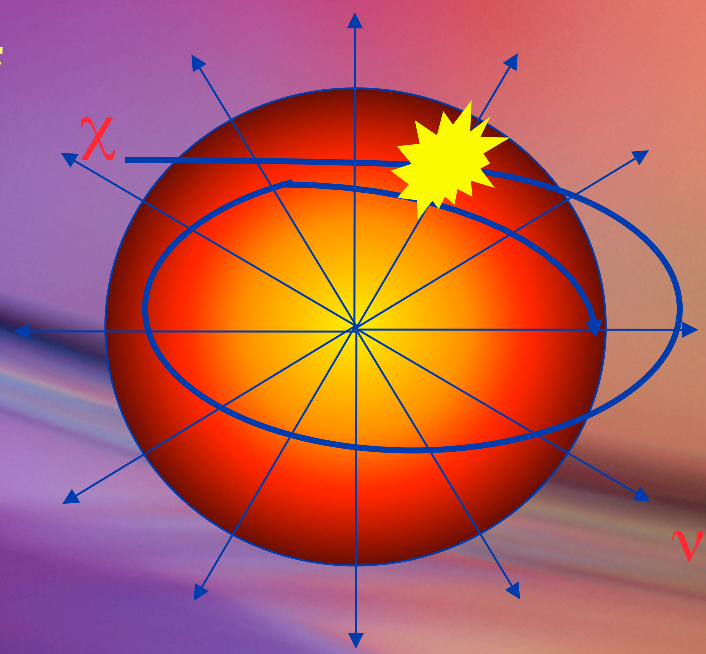




- Visualisation of events seen in the detector. "Arms" correspond to 3 PMTs

How can we look for dark matter?

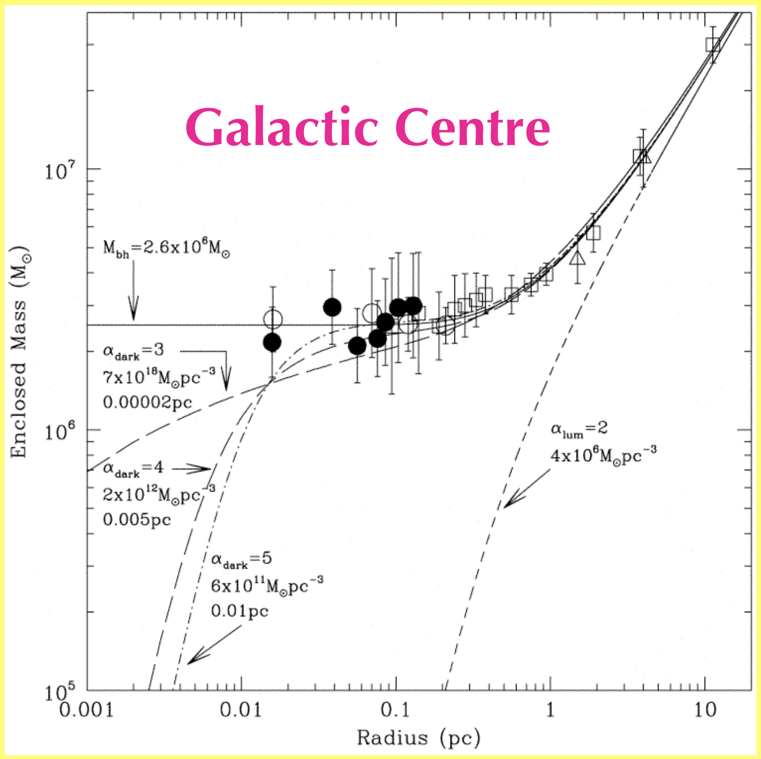
- WIMPs (Neutralinos) become gravitationally trapped in the cores of massive astrophysical objects
- Neutralinos are their own anti-particle (Majorana particles)
- Neutralinos self-annihilate into fermions or combinations of gauge and Higgs bosons
- Subsequent decays of c,b and t quarks, τ leptons and Z, W and Higgs bosons can produce a significant flux of high-energy neutrinos.

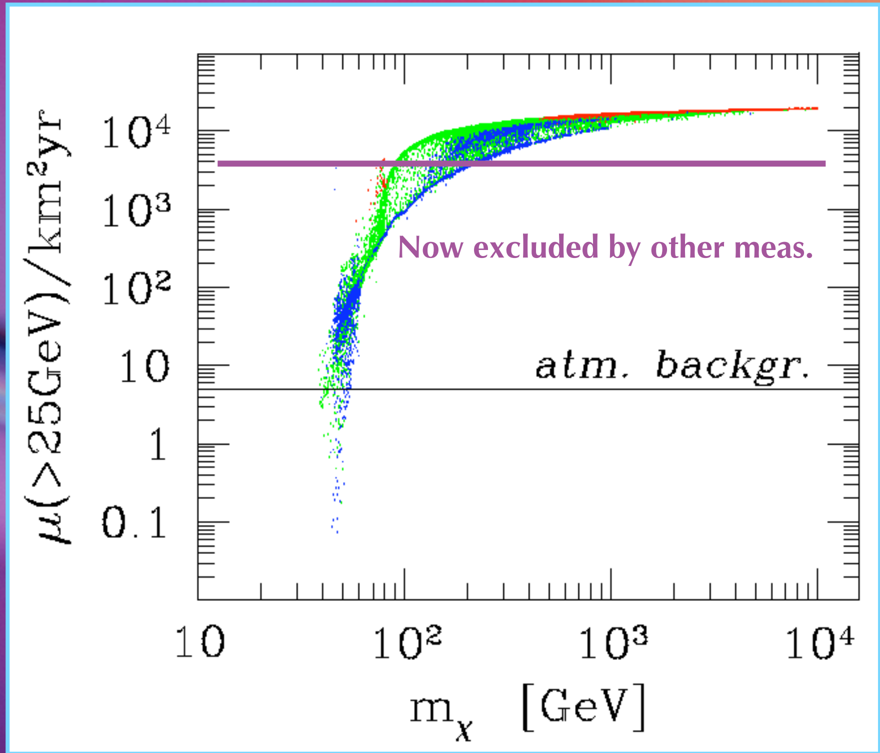


In the Sun: over time the neutralino population builds up at the core to an equilibrium value

Can also look for decay products other than neutrinos (positrons, photons, etc.)

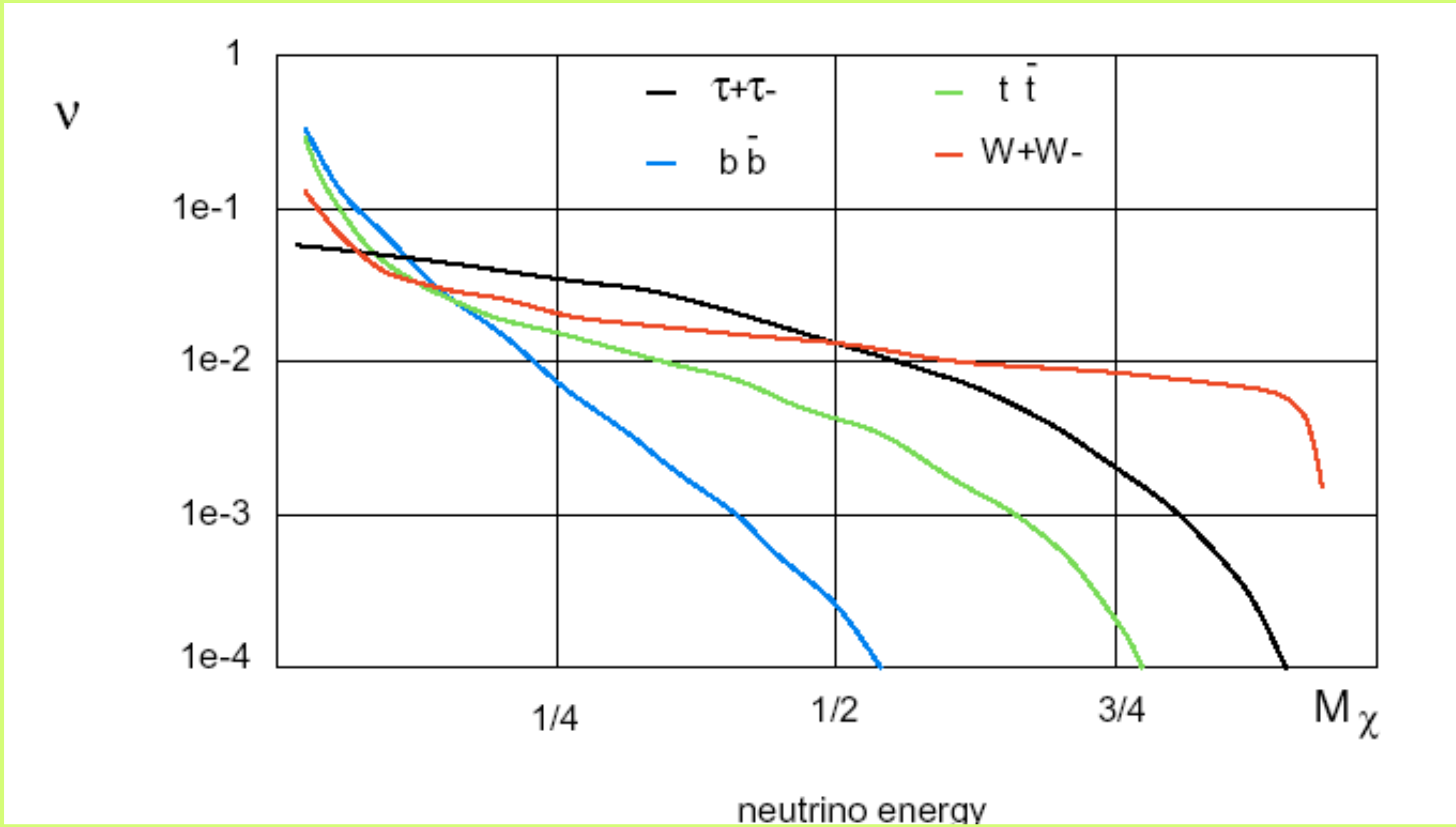
How can we look for dark matter?





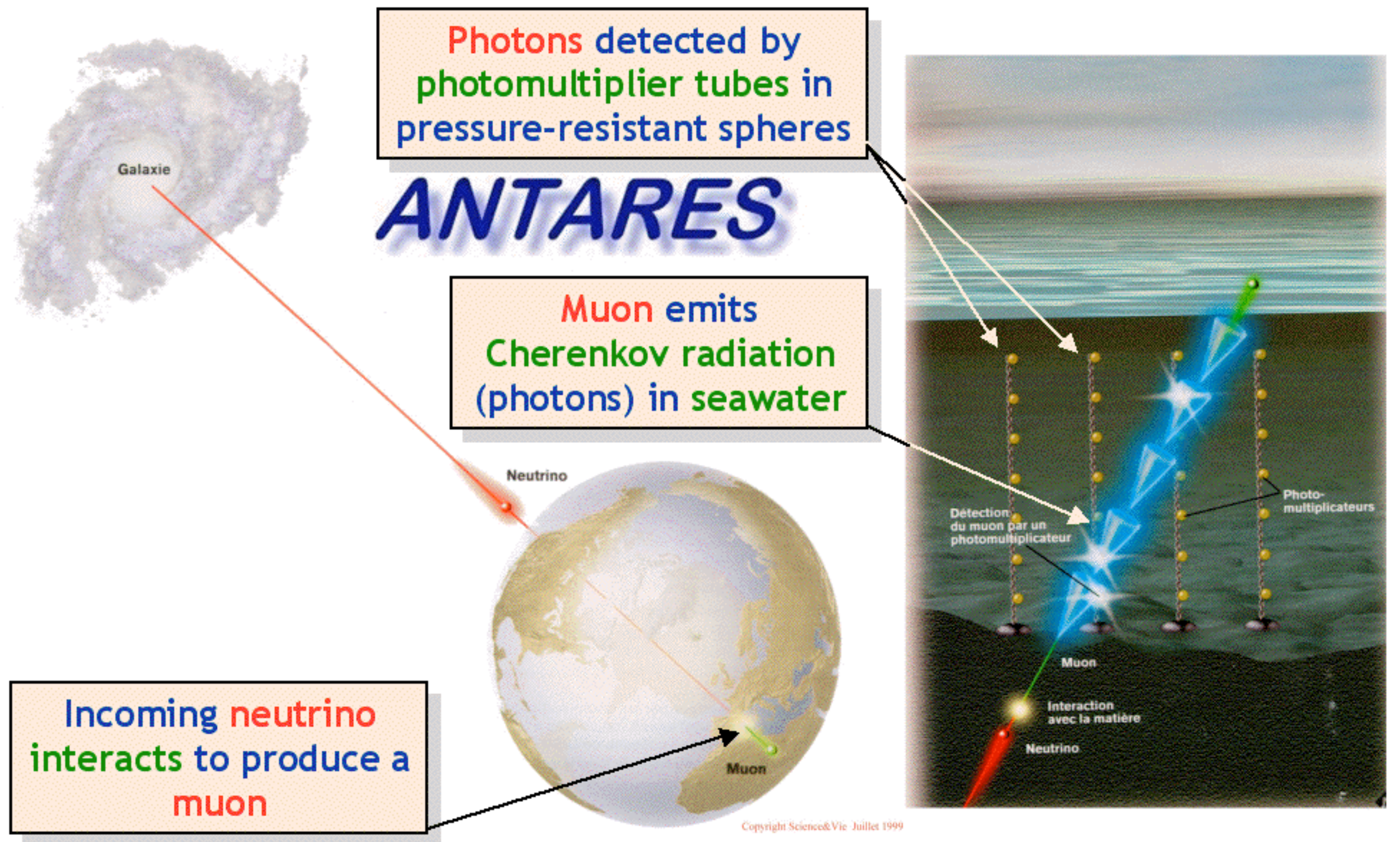
- Another possibility:
- There is significant evidence for a 3.0 x10^6 Solar mass black hole at the centre of the galaxy
- Some speculation that we will observe enhancements of neutrinos from neutralino annihilations
- Different BH formation models to be investigated

How can we look for dark matter?



- Energy spectrum of neutrinos (and hence muons seen in a neutrino telescope) is related to neutralino mass

Detecting high-energy neutrinos



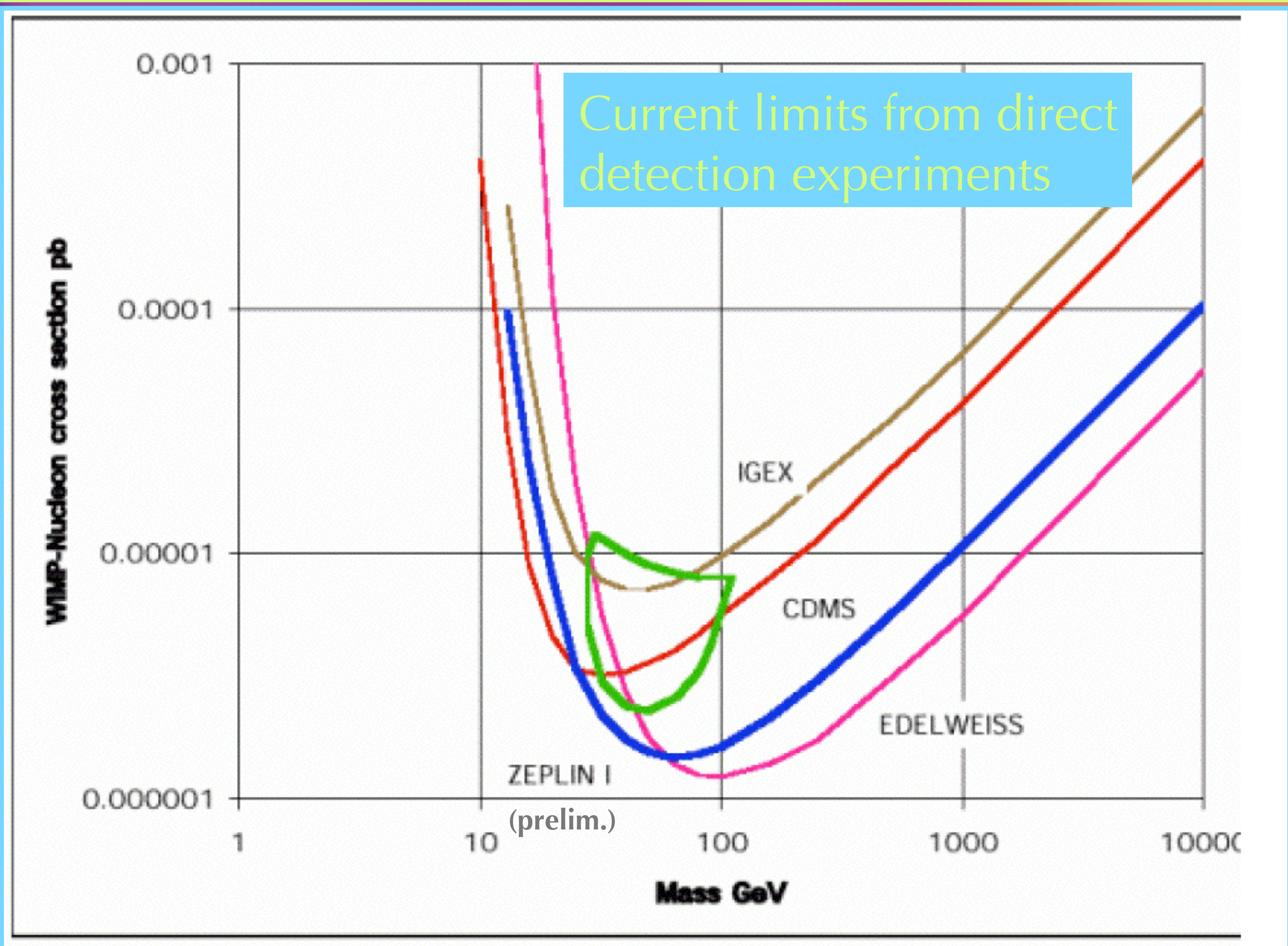
Sensitivities to dark matter

- **DIRECT DETECTION EXPERIMENTS**
  - *Sensitive to the WIMP-nucleon cross section*
  - *Can be spin-dependent or spin-independent according to the choice of target*
  - *Traditionally presented as a curve in cross-section vs. WIMP mass parameter space*

- **INDIRECT DETECTION EXPERIMENTS**
  - *Sensitive to a flux of secondary particles (in the case of ANTARES this is neutrinos, but could be other type)*
  - *Presented as a curve in flux vs. neutralino mass*

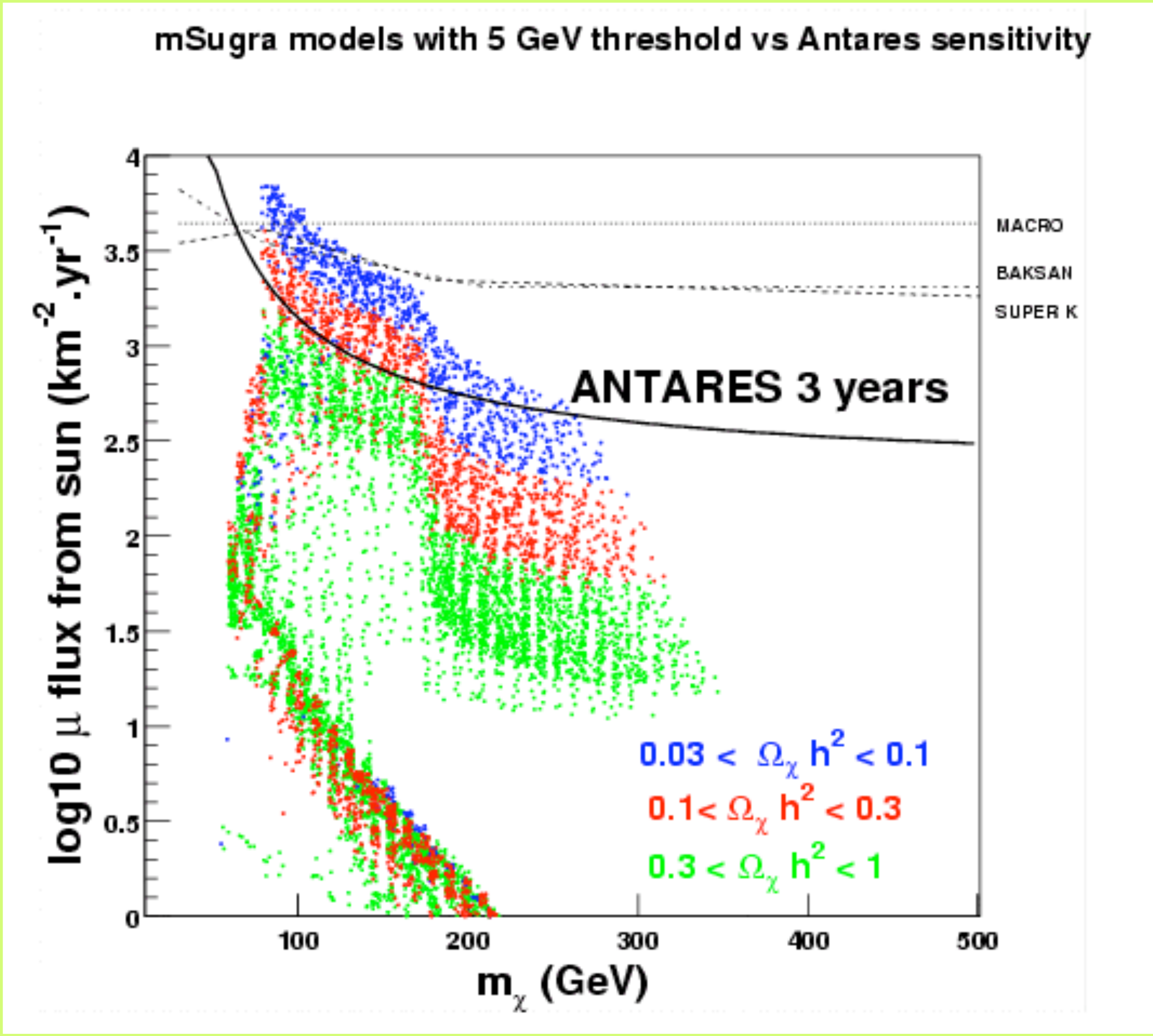
- **COMPARISON DIFFICULT (NOT IMPOSSIBLE)**
- **IN BOTH CASES MAY SUPERIMPOSE SUSY MODEL PREDICTIONS**

Sensitivities to dark matter



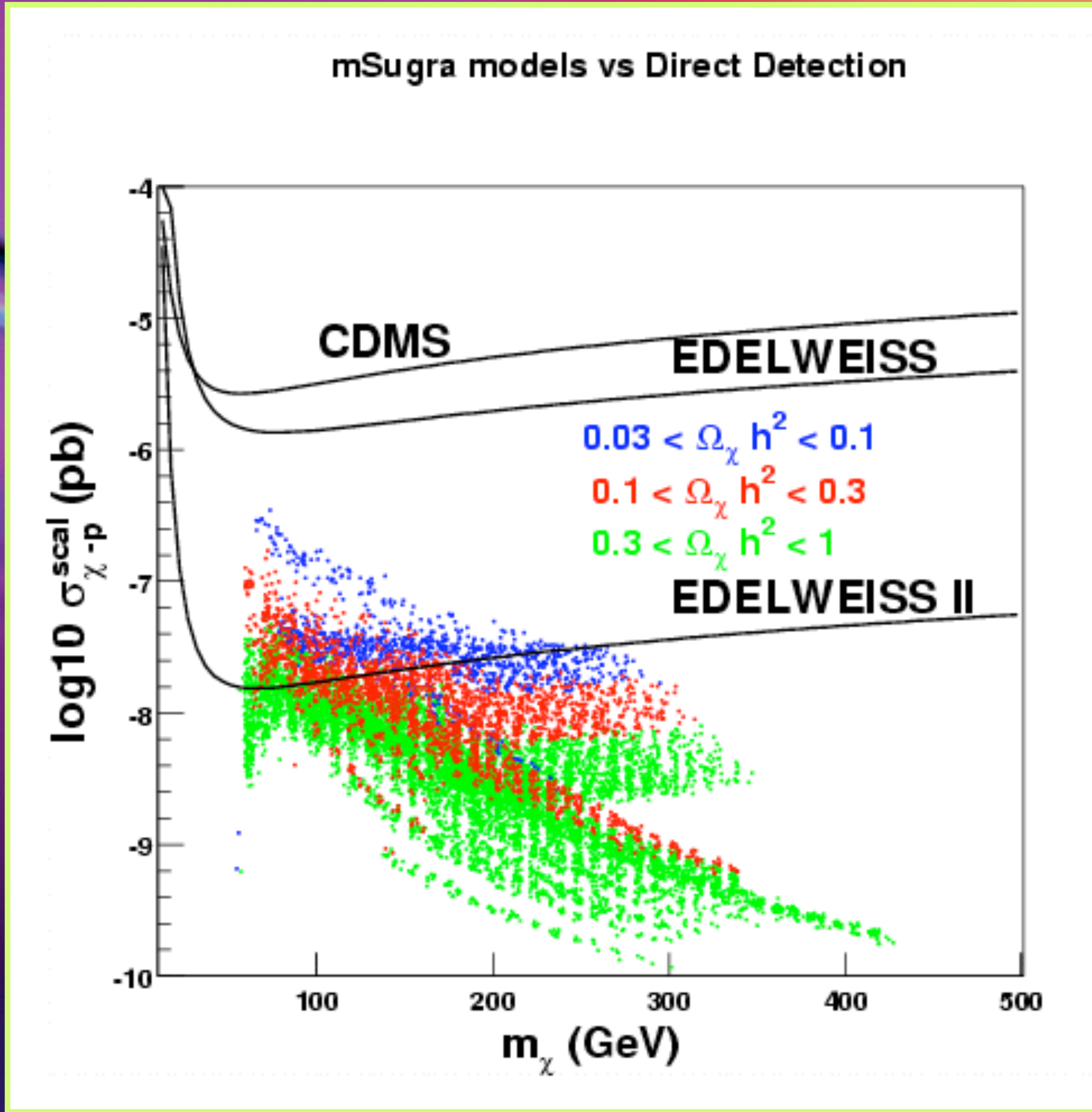
Sensitivities to dark matter

- ANTARES sensitivity to a muon flux from neutralino decay in the Sun
- Points correspond to individual SUSY models generated within a constrained SUSY framework



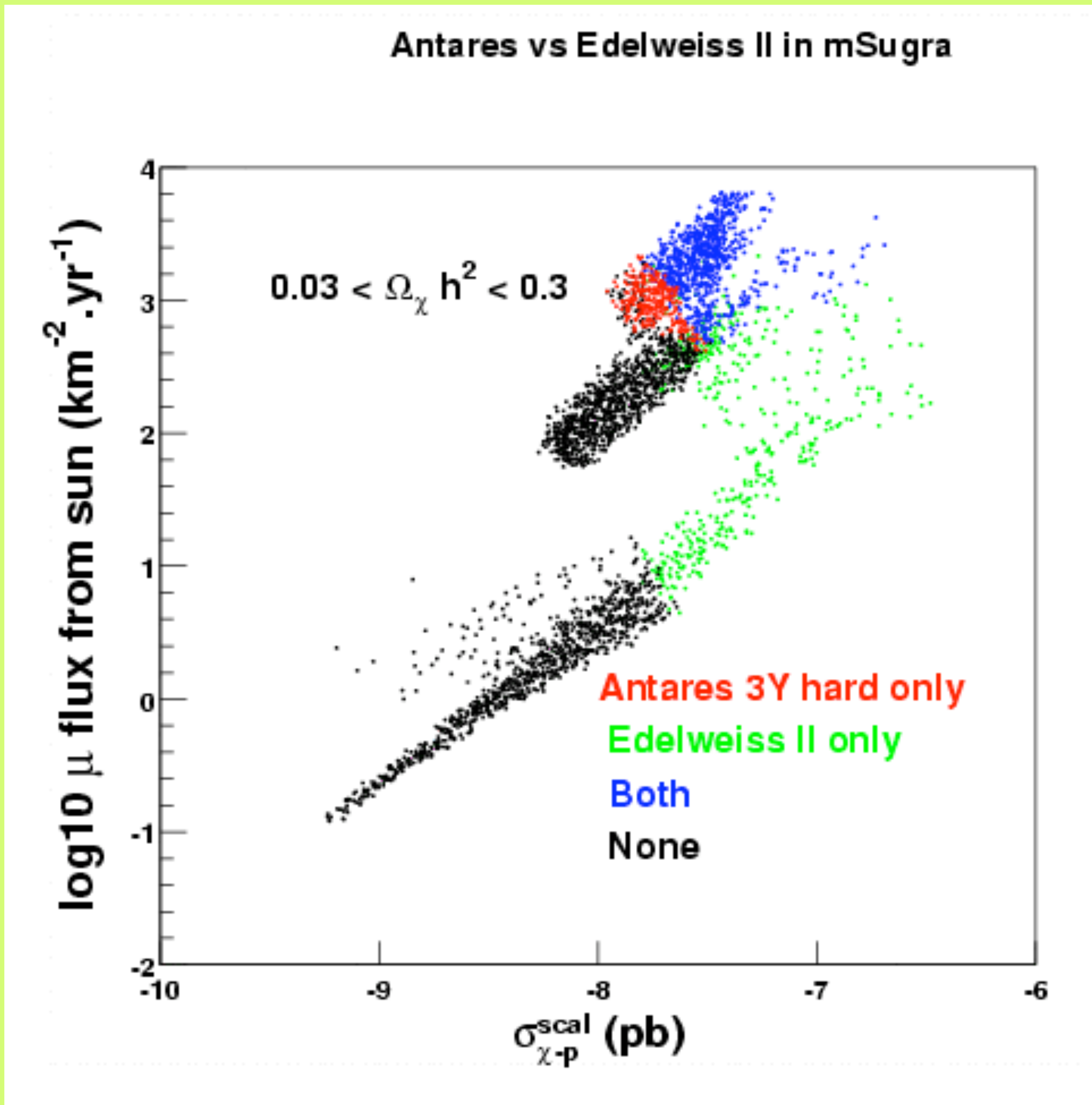
Sensitivities to dark matter

- For the same SUSY models in the previous plot sensitivity to scalar cross-section from established and proposed bolometric direct detection experiments



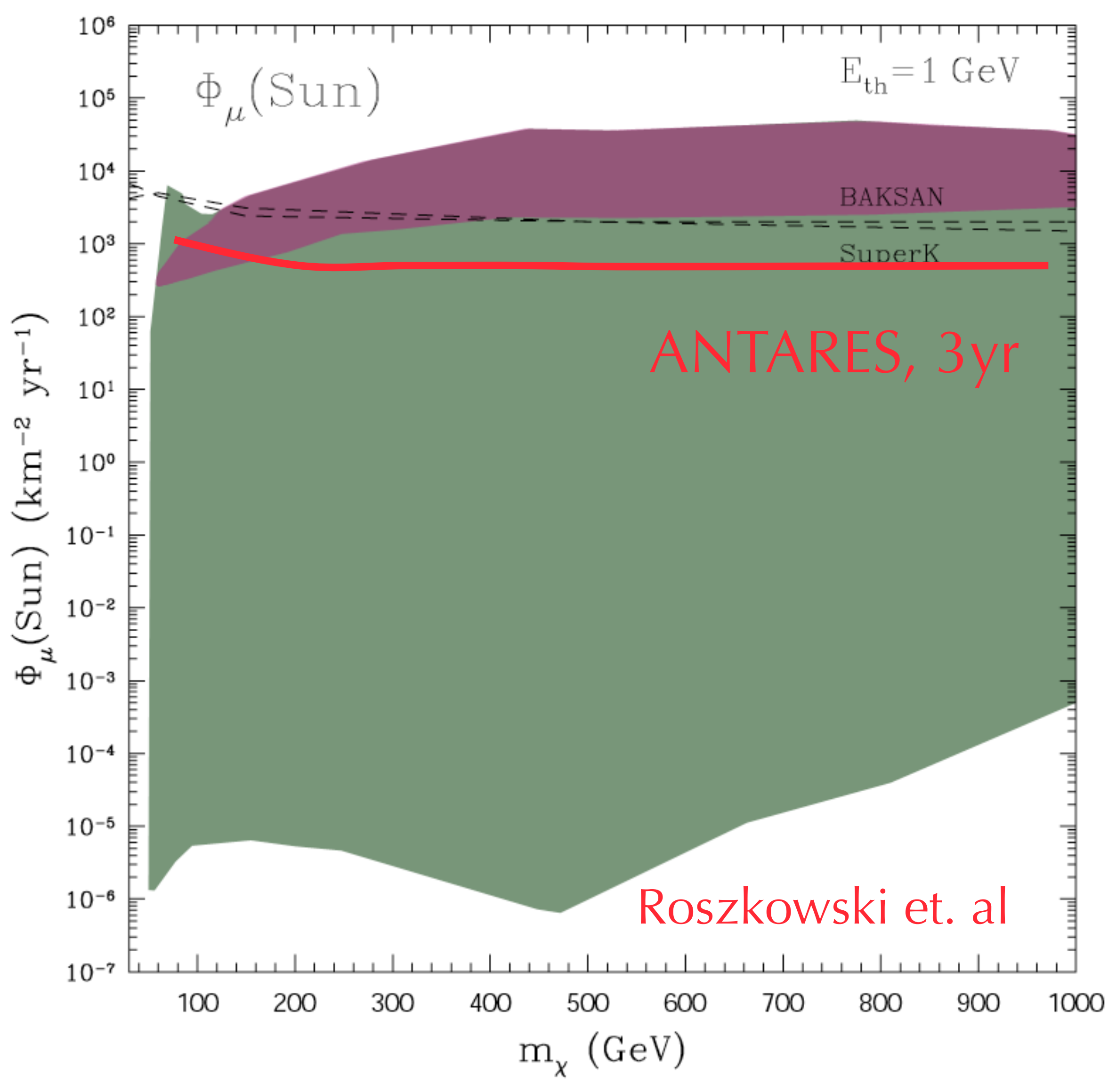
Sensitivities to dark matter

- Same constrained SUSY models
- Comparison of direct and indirect detection sensitivities
- Obvious complementarity between the two methods



Sensitivity to dark matter

- Range of parameter space that is relevant when relaxing requirements imposed by constrained MSSM
- Purple region is already ruled out by ZEPLIN and EDELWEISS



Conclusion

- Recent experiments such as WMAP and SCP have placed stringent constraints on the amount of dark matter in the Universe
- The supersymmetric extention to the Standard Model of particle physics provides a compelling candidate for a WIMP - the neutralino
- Searches for weakly-interacting non-baryonic dark matter is currently being done in a number of direct and indirect detection experiments
- Predicted experimental sensitivities tell us that significant tranches of SUSY parameter space will be excluded by these experiments in the coming years
- The next few years will be an exciting time for dark matter: if we "see" WIMPs and prove that they are supersymmetric particles we solve two major questions in science in one go (dark matter and supersymmetry)