Multimessenger Astroparticle Physics

Alessandro De Angelis
Univ. UD/PD, INFN/INAF Padova & LIP/IST Lisboa

4. The Budget of Energy and Matter in the Universe; Dark Matter

1

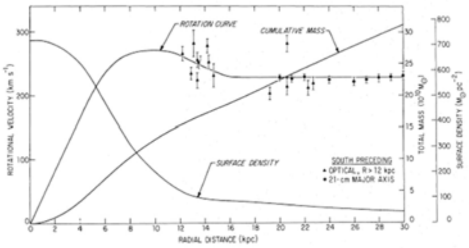
How can (V)HE photons be produced?

1. *Interaction of accelerated charged particles with radiation and matter fields*
   – *The particle is accelerated via the Fermi 1st order mechanism (collective shocks with a preferred direction)*
   – *It undergoes purely leptonic mechanisms (electrons), or hadronic collisions (protons) with subsequent π^0 decays*
2. Top-down mechanisms
   – The decay or the annihilation of a heavy particle produce unavoidably photons, either directly or in a q-qbar chain
   – Are there reservoirs of "TeV" particles around? Unlikely, unless there are new particles…

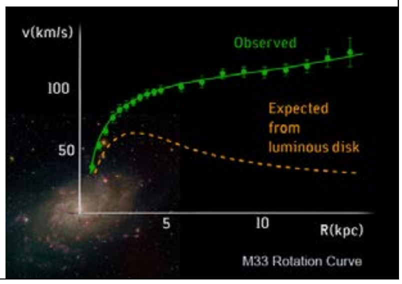
2

Top-down: are there new (heavy) particles which can produce HE photons?

- Rotation curves of spiral galaxies



  - flat at large radii: if light traced mass 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
    - Zwicky had already noted in 1933 that the velocities of galaxies in the Coma cluster were too high to be consistent with a bound system
    - Observed for many galaxies, including the Milky Way



A way out

To assume that in and around the Galaxies there is

Dark Matter

subject to gravitational interaction but no electromagnetic interaction

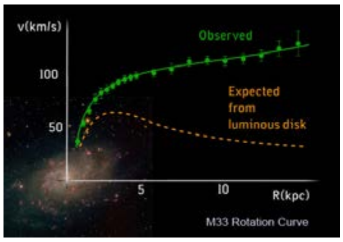
$$M(r) \propto r \Rightarrow v_{rot} = \sqrt{\frac{GM(r)}{r}} = const.$$

- Must be "cold", i.e., non-relativistic (it is trapped by the gravitational field)
- The hypothesis is not odd: remember that the existence of Neptune was suggested on the basis of the irregular motions of Uranus
- How much DM do we need? results to be 5 times more than luminous matter (astrophysics, evolution of the Universe)

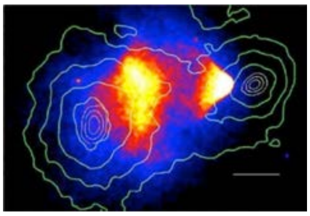
4

Evidence and features of Dark Matter

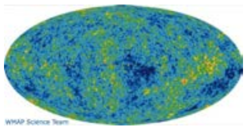
*Comprises **majority** of **mass** in Galaxies*
Missing mass on Galaxy Cluster scale
Zwicky (1937)

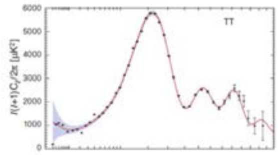


*Large **halos** around Galaxies*
Rotation Curves
Rubin+(1980)



Low cross section
Bullet Cluster
Clowe+(2006)

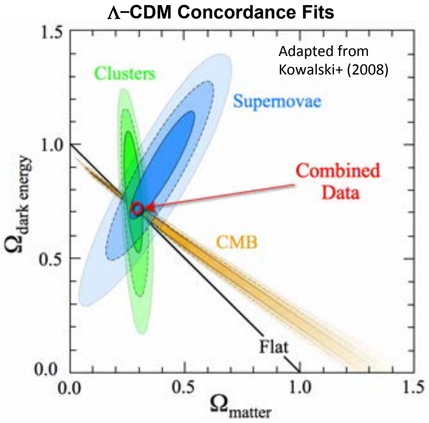




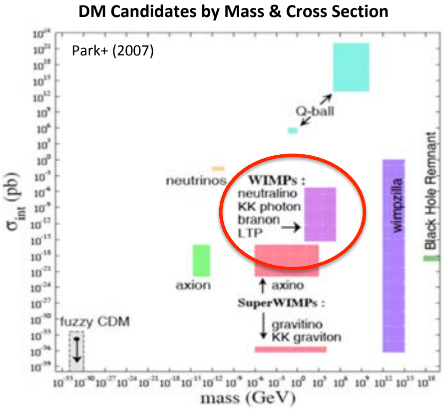
Non-Baryonic
Big-Bang Nucleosynthesis,
CMB Acoustic Oscillations
WMAP (2010), *Planck* (2015)

Constraints on Dark Matter

Λ–CDM Concordance Fits



DM Candidates by Mass & Cross Section



- No SM particle matches the required properties of dark matter
- Many candidate particles have been proposed and have implications in multimessenger astrophysics:
  - WIMPs
  - WISPs (axion-like particles, etc.)
  - Super-heavy particles

Average density $\rho_{DM} \sim 5\rho_B$ (1.5 GeV/m^3)
Near the Sun, $\rho_{DM} \sim 0.4$ GeV/cm^3

H and the energy density determine the fate of a Newtonian expanding Universe

Velocity of recession

$$v = HR$$

Escape velocity

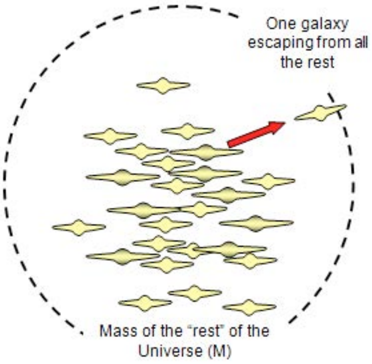
$$v_{esc} = \sqrt{\frac{2GM}{R}} = \sqrt{\frac{2G}{R}\cdot\frac{4}{3}\pi R^3\cdot\rho} = R\sqrt{\frac{8\pi G}{3}\cdot\rho}$$

Universe will recollapse if

$$v < v_{esc} \Rightarrow H < \sqrt{\frac{8\pi G}{3}\rho}$$

i.e., if

$$\rho > \rho_{crit} = \frac{3H^2}{8\pi G}$$



- Take H = 68 km s^{-1} Mpc^{-1} then:

  Critical density = $3H^2/8\pi G \sim 9.2 \times 10^{-27}$ kg m^{-3}
  The mass of a proton is ~ 1.66×10^{-27} kg => ~6 protons per cubic meter in average

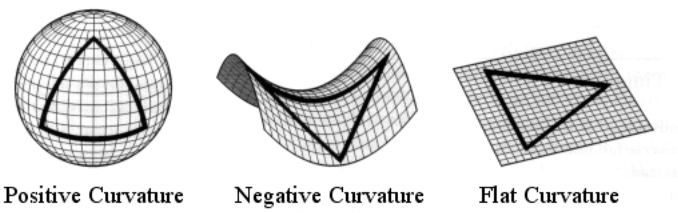
7

The geometry of a Friedmann-Robertson-Walker Universe

$$H^2 = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3} - \frac{K}{a^2}$$

- Define the "normalized density" $\Omega = \rho/\rho_{crit}$

- $\Omega < 1$: negative curvature
- $\Omega > 1$: positive curvature
- $\Omega = 1$: flat geometry (K=0)

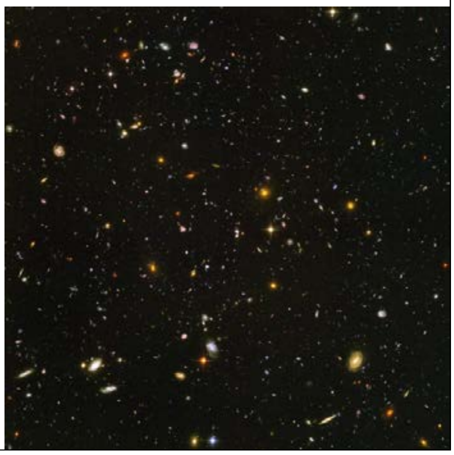


8

What is the matter density of the Universe?

- A simple technique to measure is just to count galaxies & dust!

Look into a dark spot with the HST for a long time, extrapolate to the full space, add some dust and some black holes…



$\Omega_b \sim 0.05 << 1$

- You can also use some cosmological models to confirm & increase the accuracy
- And how much Dark Matter? From the motions in the Galaxies, and astrophysics

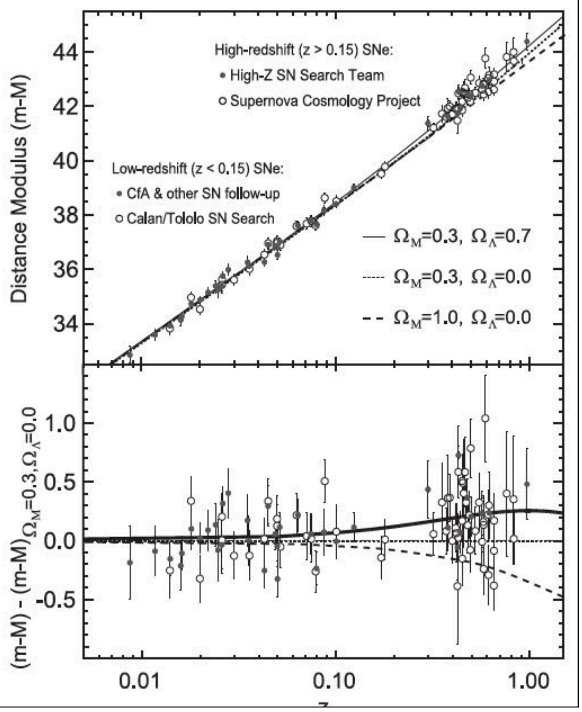
$\Omega_{CDM} \sim 0.26$

Experimental Observations

The luminosity-distance measurement of Type Ia supernovae (which can be reconducted to standard candles) proves that:

- The Universe is expanding
- The expansion is accelerating.

The Λ term in Friedmann's equation is different from 0, and $\Omega_m + \Omega_\Lambda \sim 1$



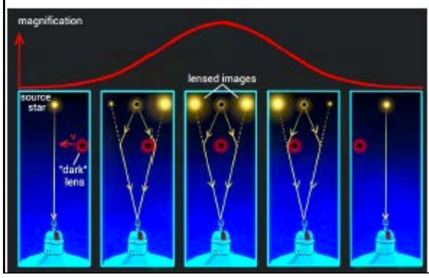
Summary of Experimental Observations

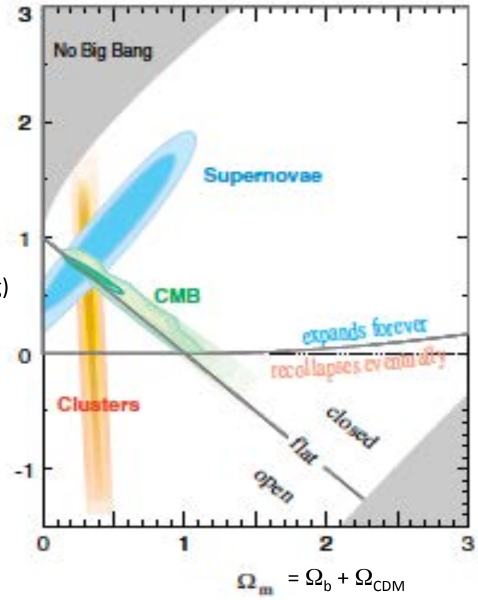
Energy density
consistent with the critical density

=> Flat space

Most energy is in the non-Newtonian term Λ

Barions ~5% (nucleosynthesis, microlensing)



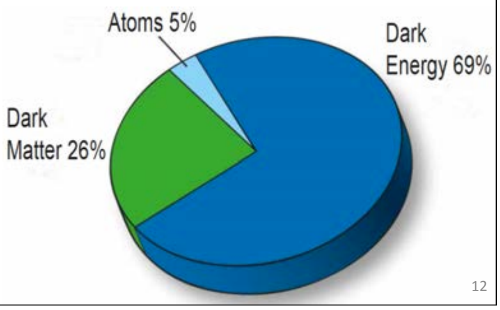


11

The ΛCDM model: $H^2 = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3}$

- The key CDM parameters are:
  - $H_0 = (68 \pm 2)$ km/s Mpc^{-1} $= 1/t_H \sim 1/t_0$
  - Ω_b, the baryonic matter density ~ 0.05 >> Ω_γ
  - Ω_{CDM}, the cold DM density = 0.258 ± 0.011
  - … (radiation, anisotropies)

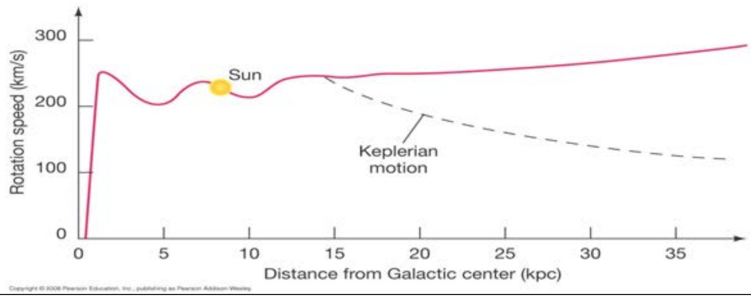
$\Omega_b + \Omega_{CDM} + \Omega_\gamma + \Omega_\Lambda = 1$
$\Rightarrow K = 0$
$\Rightarrow \Omega_{CDM} \sim 1.5$ GeV/m^3



12

But the density of DM is much larger nearby

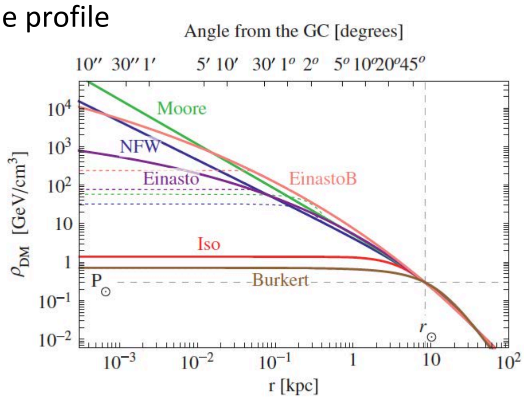
- 1.5 proton masses (~1.5 GeV) per cubic meter of dark matter in the Universe, so what?
- Well, there is a lot more near us…
- From the study of the rotation curve of the Milky Way, close to the solar system the density is 10^5 times larger than average: 4 10^5 proton masses/m^3
- The Earth moves in such a sea of dark matter. What is it?



13

How is it distributed in Galaxies?

- DM density is "measured" in the halo and extrapolated to cusps!
- Model dependence on the profile



Don't forget other reservoirs of DM

- Clusters of Galaxies
- Dwarf Spheroidals

14

What we know about Dark Matter

- Impossible to avoid if you believe that gravity is universal
  - Electrically neutral (dark, not observed in direct searches)
  - Non-baryonic (BBN, astrophysics)
  - Cold (astrophysics, structure formation)
  - "Weakly" interacting (bullet cluster, non-observation in direct searches)
  - If "weak"~ Weak at production => (very small m) or m > 45 GeV (LEP)
    Both ranges have important consequences in observational astrophysics
  - Ω_{CDM} = 0.258 ± 0.011 (WMAP, Planck) ~ 5 Ω_b
- No Standard Model candidate
  - neutrinos are too light, and they are "hot" (relativistic at decoupling)
    - hot dark matter does not reproduce observed large-scale structure

➔ Physics beyond the standard model

- WIMPs are particularly good candidates
  - well-motivated from particle physics [SUSY] (open a digression)

15

Beyond the Minimal SM of Particle Physics

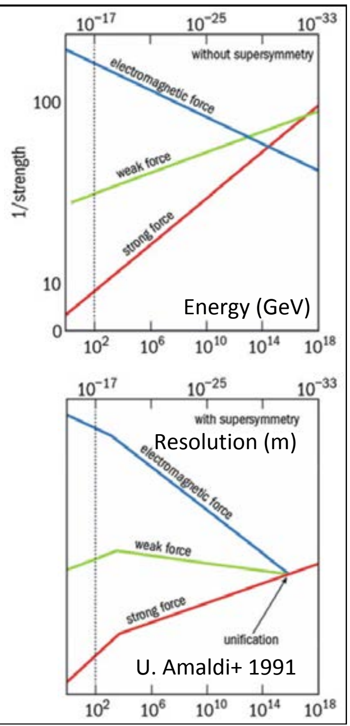
- The SM of PP has been incredibly successful. It looks however an ad-hoc model, and the SU(3)⊗ SU(2)⊗ U(1) looks like a low-energy symmetry which is part of a bigger picture.
  - The SM looks a bit too complicated to be the fundamental theory:
    - There are many particles, suggesting some higher symmetries (between families, between quarks and leptons, between fermions and bosons) grouping them in supermultiplets
      - Compositeness?
    - There are many free parameters
  - It does not describe gravity, which is the interaction driving the evolution of the Universe at large scale
  - It does not include dark matter
  - Interactions don't unify at high energy
  - The fundamental constants have values consistent with conditions for life as we know; this requires a fine tuning.
- Is there any physics beyond the SM we would need anyway and can provide "for free" DM candidates?

16

SUSY and the neutralino

- The most popular among non-minimal GUTs in particle physics is SUperSYmmetry.
- SUSY involves a symmetry between fermions and bosons: a SUSY transformation changes a boson into a fermion and vice-versa (each fermion & each boson have a superpartner)
- To each particle a quantum number is associated (R=1 for "our" particles and R=-1 for SUSY partners). If SUSY is not violated or if is mildly violated, R-parity is conserved, and the LSP is stable
- SUSY allows "for free" unification of forces at a scale below the Planck scale, provided

  25 GeV < m_{LSP} < 25 TeV (90% C.L.)
- The LSP is likely one of the neutralinos χ (a Majorana fermion!)
  - Warning: there are many "SUSYs" depending on parameters



WIMPs ast thermal relics

- If WIMPs are "standard" particles, must have been in thermal equilibrium in the early Universe, when the temperature T exceeded by far the mass of the particle, $k_BT >> m_\chi$.
- The equilibrium abundance was maintained by annihilation of the WIMP with its anti-WIMP χbar into lighter particles (χ χbar → f fbar) and vice versa (f fbar → χ χbar). If the WIMP is a gauge boson as the photon, or a Majorana particle, χ = χbar.
- When at a given time t* the Universe cooled to a temperature such that $k_BT << m_\chi$, the interaction length becomes larger than the radius of the Universe (or the rate Γ for the annihilation falls below the Universe expansion rate): decoupling

$$\lambda = 1/H \Rightarrow H(t^*) = \Gamma = \langle \sigma_\chi v \rangle n_\chi \quad [\mathrm{cm}^2][\mathrm{cm/s}][\mathrm{cm}^{-3}]$$

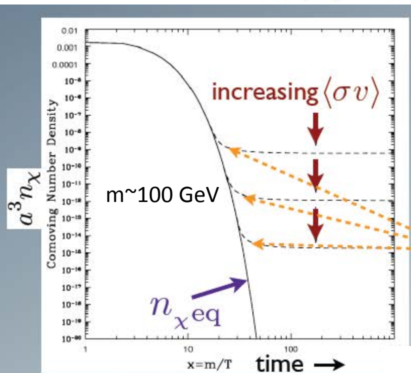


Fig.: Jungman, Kamionkowski & Griest, PR

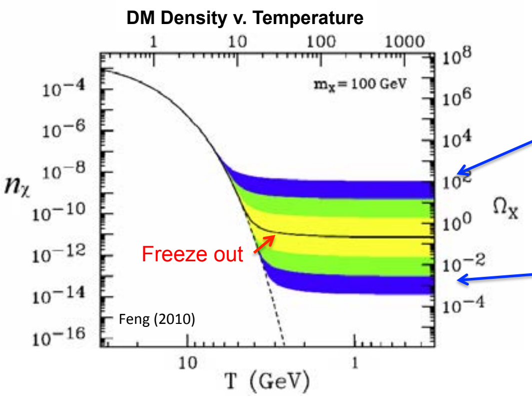
$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v \rangle \left(n_\chi^2 - n_{\chi \mathrm{eq}}^2 \right)$$

$\langle \sigma v \rangle$: $\chi\chi \to$ SM SM (thermal average)

"Freeze-out" when annihilation rate falls behind expansion rate ($\to a^3 n_\chi \sim$ const.)

$$\Omega_\chi \approx \frac{3\times 10^{-27}\ \mathrm{cm}^3/\mathrm{s}}{<\sigma v>} \approx 0.1\ ;\ k_B T \sim \frac{m_\chi c^2}{20} \Rightarrow v \sim \frac{c}{4}$$

WIMP Dark Matter as a thermal relic: properties



Small cross-section: freeze out too early, too many WIMPs

Large cross-section: freeze out too late, too few WIMPs

$$\Omega_\chi h^2 \simeq \frac{3\times10^{-27}\text{cm}^3\text{s}^{-1}}{\langle\sigma_A v\rangle}$$

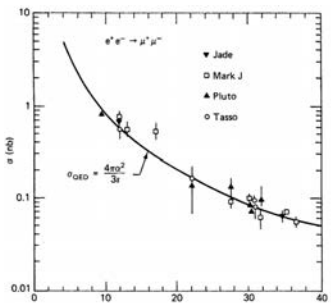
- The calculation of the thermal-averaged cross-section <σv> needed to obtain the relic density gives, for a single WIMP, <σv> ~ 3 10^{-26} cm^3s^{-1} at freeze-out

19

$$\Omega_\chi \approx \frac{3\times10^{-27}\ \text{cm}^3/\text{s}}{<\sigma v>} \approx 0.1 \Rightarrow <\sigma v> \sim 3\times10^{-26}\ \text{cm}^3/\text{s}$$

The WIMP "miracle"

- For electroweak interactions (see μμ production in ee collisions),



$$\sigma_W v \sim \frac{86.8\ \text{nb}}{(E/\text{GeV})^2}\frac{c}{4} \sim \frac{86.8\ \text{x}\ 10^{-33}\ \text{cm}^2}{(E/\text{GeV})^2} 3\ \text{x}\ 10^9 \frac{\text{cm}}{\text{s}} \sim \frac{3\ \text{x}\ 10^{-26}\ \text{cm}^3/\text{s}}{(E/100\ \text{GeV})^2}$$

=> Weak coupling gives for free the "right" density at m_χ~100 GeV

Holds between ~50 GeV and ~10 TeV

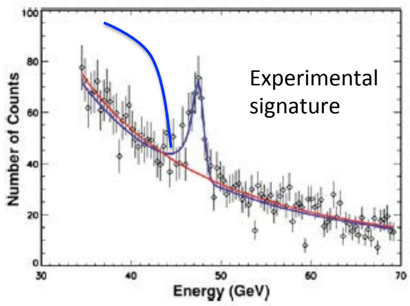
Particle must be stable on cosmological timescales

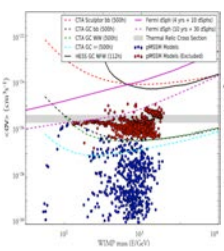
20

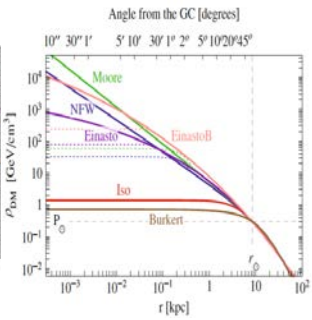
WIMP Dark Matter: production of SM partices

Particle Physics | **Astrophysics (*J*-Factor)**

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$





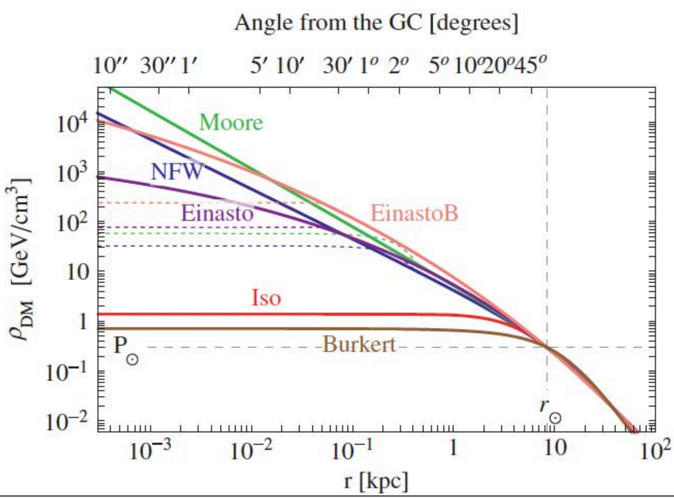


- *J*-factor includes distance, i.e., *J*-factor would decrease by four if a point-like source were twice as far away => look as close as possible
- The factor of $1/m_\chi^2$ is due to the fact we express the *J*-factor as a function of mass density (which we can measure), not number density
- We usually call χ the generic WIMP, like the SUSY neutralino, but it's more general

21

Large uncertainties on J-factors

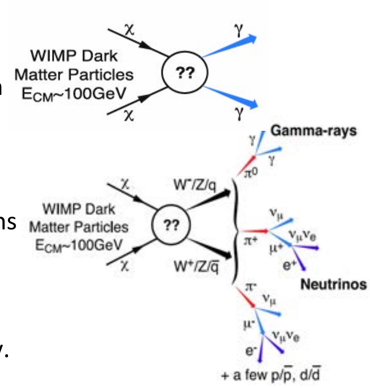
- DM density is "measured" in the halo and extrapolated to cusps!
- Model dependence on the profile

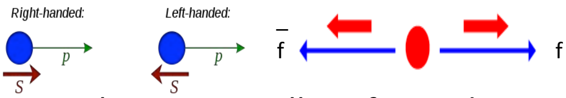


22

How do WIMPs produce photons?

- The energy "blob" from χχ annihilation might decay:
  – Directly into 2γ, or into Zγ if kinematically allowed. Clear experimental signature (photon line), but not very likely (requires one loop). In SUSY, the BR depends on what is the lightest neutralino composition.
  – Into a generic f-fbar pair, then generating a hadronic cascade with π^0 decaying into photons in the final state. Remind that flavors are left-handed and anti-flavors are right-handed with amplitude $[1+|p|/(E+m_f)]/2 \sim v/c$, and in this case for an s-wave you need to "force" one of the decay products to have the "wrong" elicity.



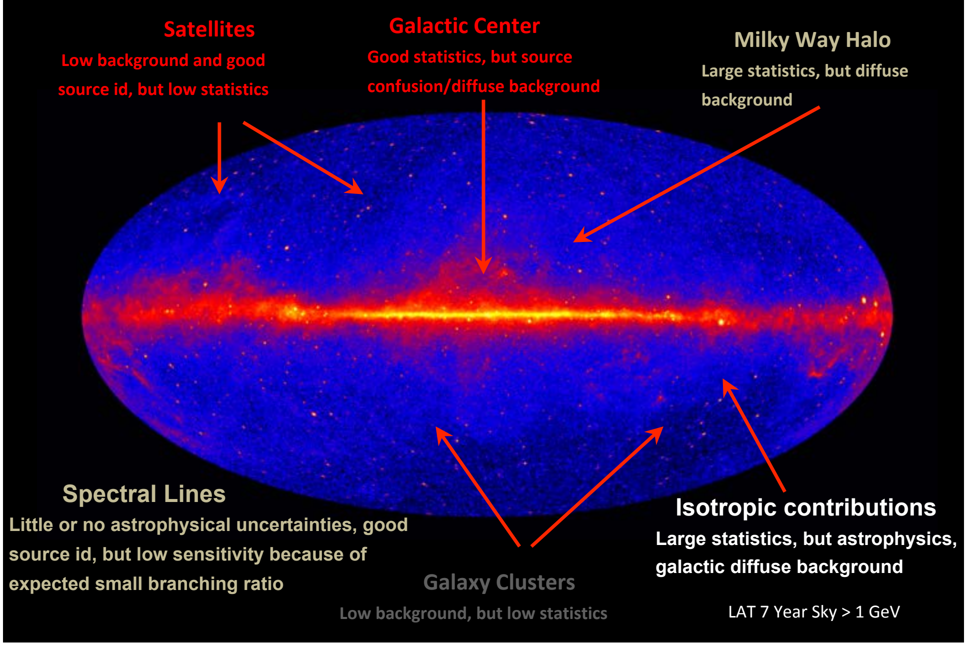


$$M_{fi} \propto \frac{1}{2}\left(1-\frac{|p|}{E+m_f}\right)=\frac{m_f}{2m_\chi+m_f}$$

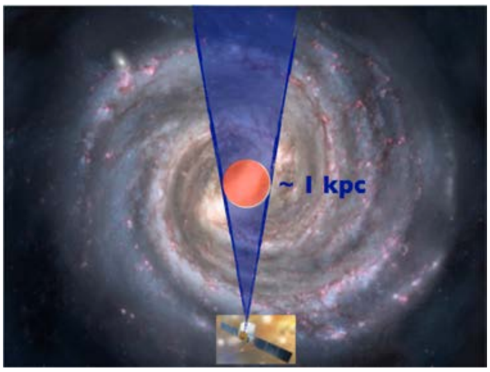
=> The χχ pair will prefer to decay into the heaviest available pair – i.e., if 20 GeV < m_χ < 80 GeV, into b-bbar

23

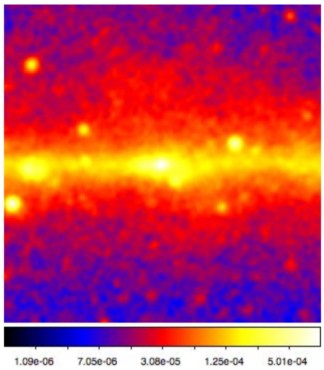
Search in the γ channel (waiting for neutrinos)



Observing the Inner Galaxy



LAT Intensity: 7 years, > 1 GeV, 15°x15°

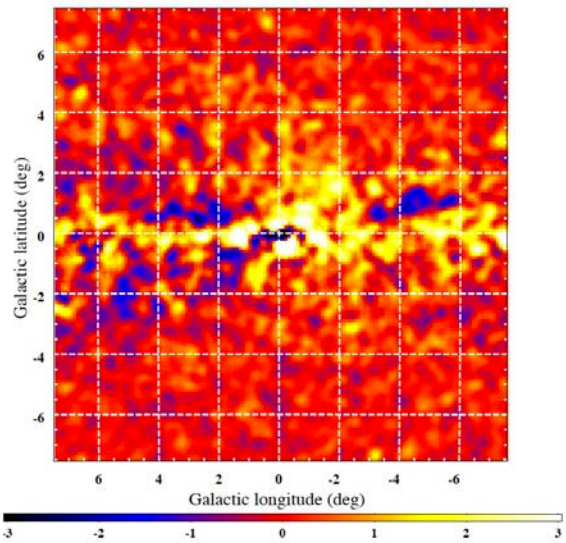


- Observations of the inner Galaxy include strong astrophysical foreground and backgrounds along the line of sight
- Because of the large astrophysical foregrounds, we must first understand the γ-ray emission from the Galaxy and from known source classes
  - In the 1-100 GeV energy band these account for ~85% of the γ-rays in a 15°x15° box around the Galactic center

Galactic Center GeV Excess?

- Modeling the diffuse γ-ray emission from cosmic ray interactions with matter and radiation fields in the galaxy is challenging (see extra slides)
- Spatially extended excess around the Galactic center at a few GeV has been report in several papers

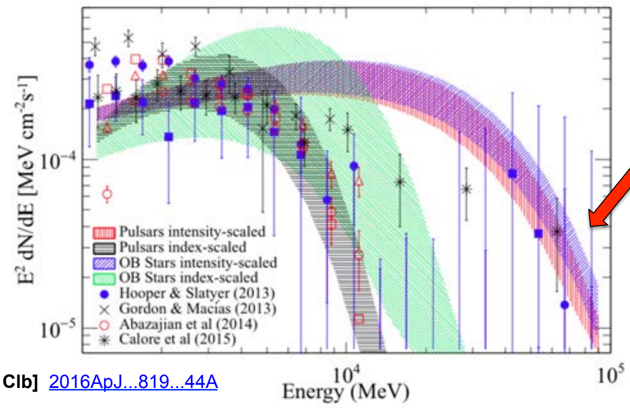
LAT Residuals (counts): 5 years, > 1.6-10 GeV, 15°x15°



Ajello+ [LAT Clb] 2016ApJ...819...44A

Spectrum of the Galactic Center Excess

Spectral Energy Density for Galactic Center Excess Compared to Several Models



Emission above 50 GeV not from 50 GeV dark matter

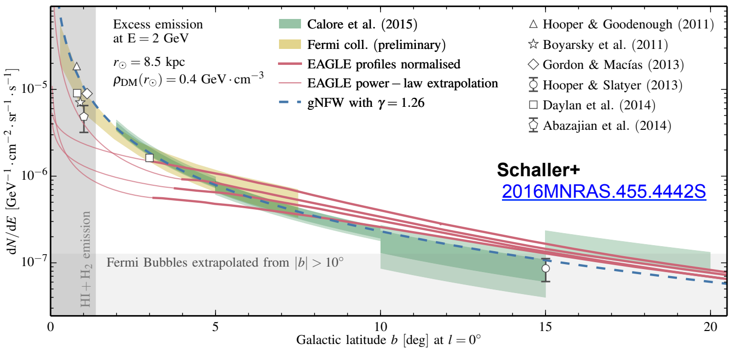
Ajello+ [LAT CIb] 2016ApJ...819...44A

- The presence for an γ-ray excess with respect to the modeled diffuse emission at the Galactic center at a few GeV is well established
- However, the details (and the interpretation) of the excess depend on the modeling of the astrophysical fore/background

27

Radial Profile of Galactic Center Excess

Radial profile of GC Excess (at 2 GeV) Compared to Predictions From N-Body Simulations

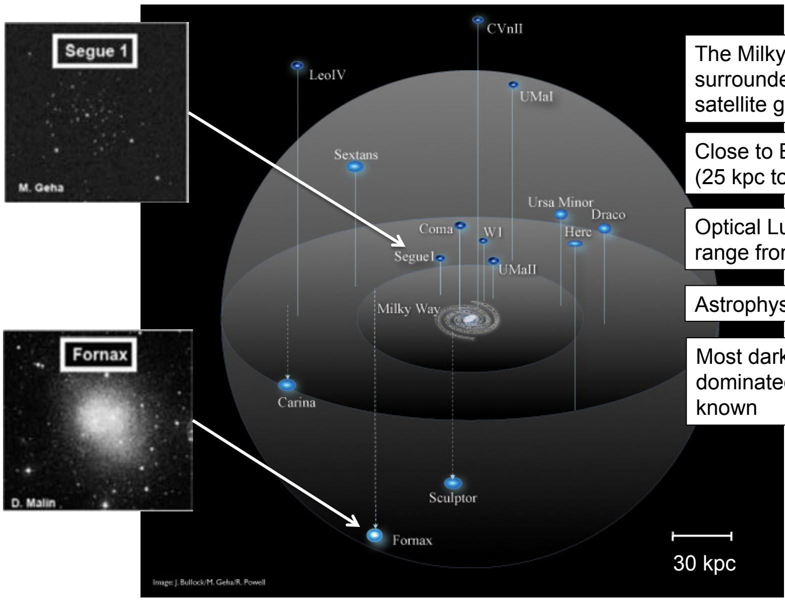


Schaller+
2016MNRAS.455.4442S

- The interpretation of the excess is unclear (similar size excesses attributed to local sources of cosmic rays are present elsewhere)
- The radial profile is of the GC excess is broadly consistent with dark matter expectations for N-body (red lines above)
  - N-body simulations of Milky-Way like galaxies tend to show less DM signal in the inner few degrees than observations of the Galactic center (grey shaded region)

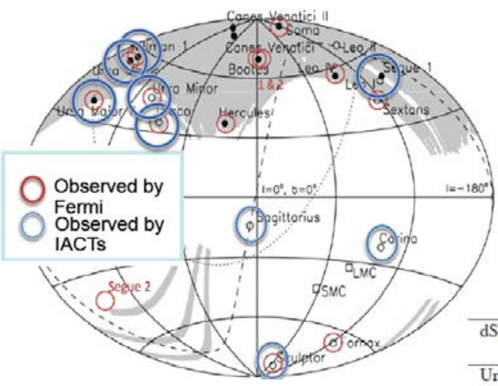
28

Dwarf Spheroidal Satellites of the Milky Way



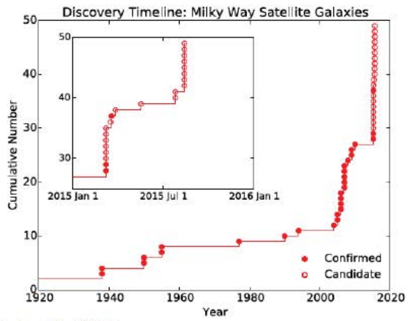
- The Milky Way is surrounded by small satellite galaxies
- Close to Earth (25 kpc to 250 kpc)
- Optical Luminosities range from 10^3 to 10^7 $L_\odot$
- Astrophysically inactive
- Most dark matter dominated objects known

Dwarf Spheroidal Satellites of the Milky Way



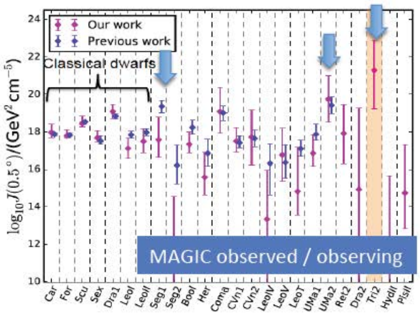
dSph	Dec. [deg]	D [kpc]	$\bar{J}$ [$GeV^2\,cm^{-5}$]	Profile
Ursa Minor	+44.8	66	2.2×10^{18}	NFW
Draco	+34.7	87	7.1×10^{17}	NFW
Sculptor	−83.2	79	8.9×10^{17}	NFW
			2.7×10^{17}	ISO
Carina	−22.2	101	2.8×10^{17}	NFW
Segue 1	+16.1	23	1.7×10^{19}	Einasto
Willman 1	+51.1	38	8.4×10^{18}	NFW
Coma Berenices	+23.6	44	3.9×10^{18}	NFW

You don't expect gamma emission, unless from DM



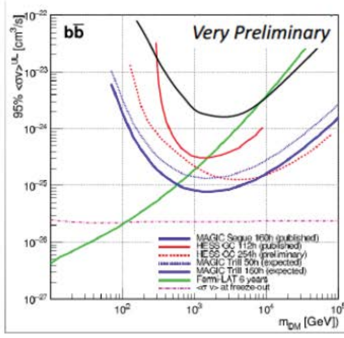
k. bechtol 2015

J-factors – K. Hayashi et al 2015



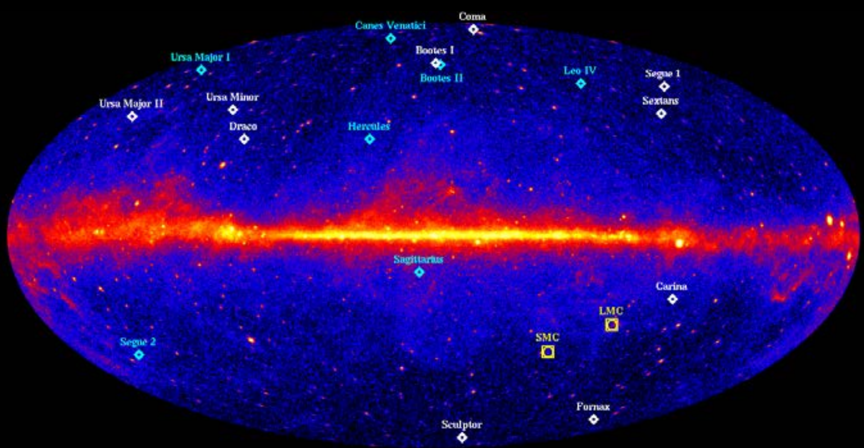
- The framework for particle dark matter particles is still very open, given the scarce guidelines from cosmology or accelerator physics

Be careful with uncertainties in J-factor estimates



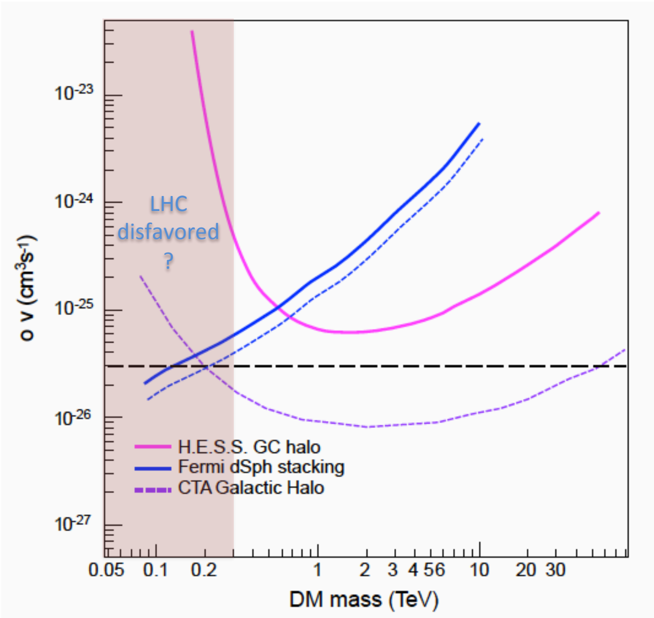
31

Searches for DM in satellite galaxies



- Roughly two dozen Dwarf spheroidal (dSph) satellite galaxies of the Milky Way known up to the DES era
- Negligible astrophysical γ-ray production expected

Upper Limits



33

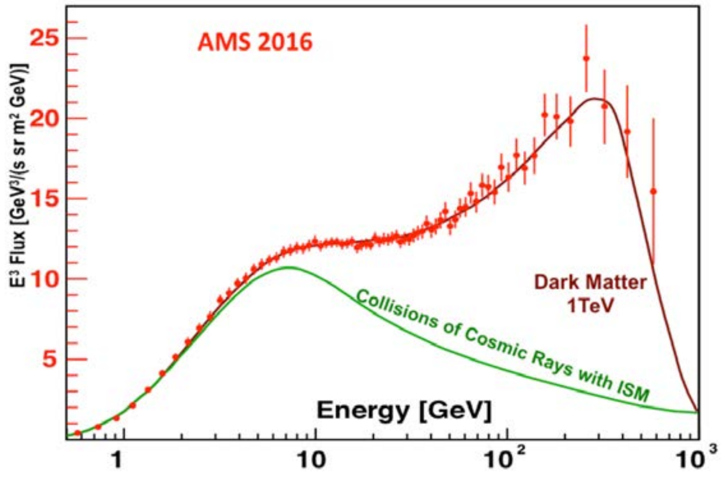
WIMPs can produce neutrinos…

Similar features with respect to photons, but:

- Smaller production cross section (no radiative return)
- Smaller detection cross section
- Cleaner events

34

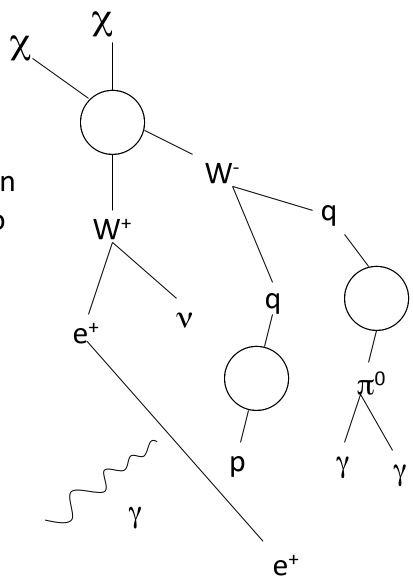
WIMPs produce antimatter, too…



35

Summary: the indirect detection of DM

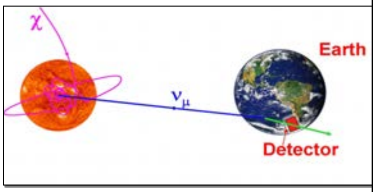
- **WIMP Annihilation** Typical final states include heavy fermions, gauge or Higgs bosons
- **Fragmentation/Decay** Annihilation products decay and/or fragment into combinations of electrons, protons, deuterium, (and their antiparticles), gamma-rays and neutrinos



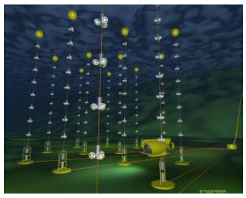
36

No conclusions from…

- **Gamma Rays** from annihilations in the galactic halo, near the galactic center, in dwarf galaxies, etc. Drawback: Unknown astrophysical background.



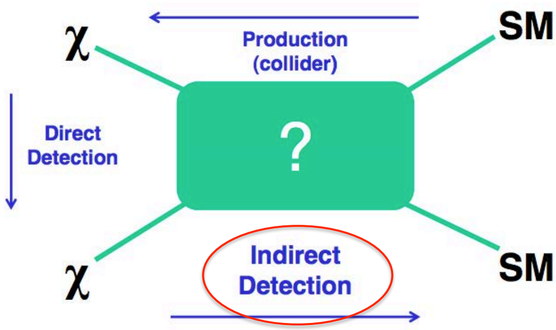
- **Neutrinos** from annihilations in the core of the Sun or in the sama sources as gamma rays (IceCube, Antares). Not the sensitivity, yet



- **Positrons/Antiprotons** from annihilations throughout the galactic halo. Drawback: Unknown astrophysical background.
  - Measured in space–based detectors: Fermi (gammas), PAMELA, AMS (antimatter) or in atmospheric Cherenkov telescopes: MAGIC

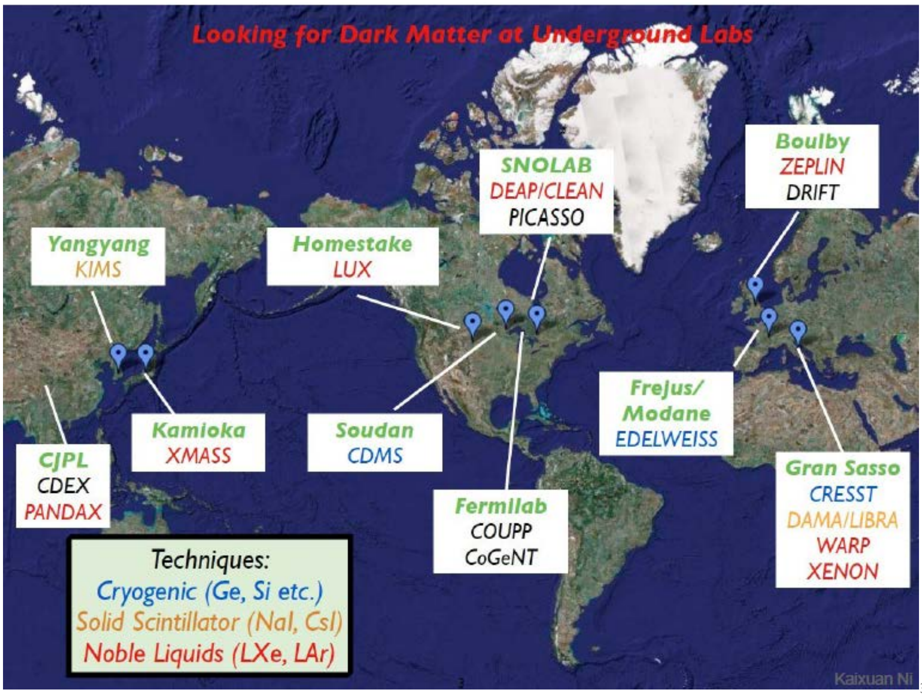
37

Indirect Dark Matter Searches in Context



- *Compared to collider searches*: indirect detection is sensitive to higher mass scales
  - *If "W" is electroweak, LEP excludes masses between few eV and 45 GeV*
- *Compared to direct detection*: indirect detection is sensitive to annihilation rather than scattering off of nuclei (i.e., more sensitive when χ couples more to heavy quarks and vector bosons than to light quarks and gluons)

38

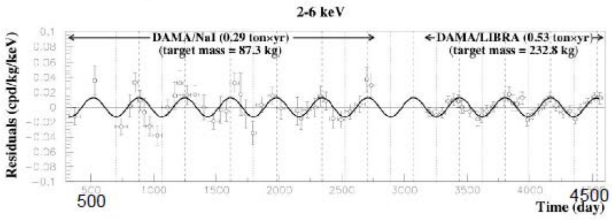


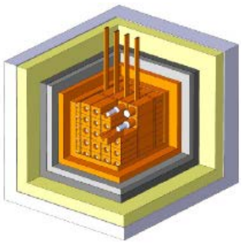
39

Signals?

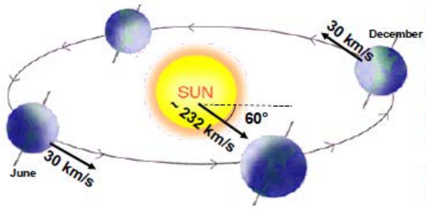
DAMA/LIBRA Annual Modulation

R. Bernabei et al. EPJ C 56, 333 (2008), arxiv:0804.2741
EPJ C 67, 39 (2010), arxiv:1002.1028





- ~250 kg of NaI counters
- 1.17 ton-year exposure (2010)

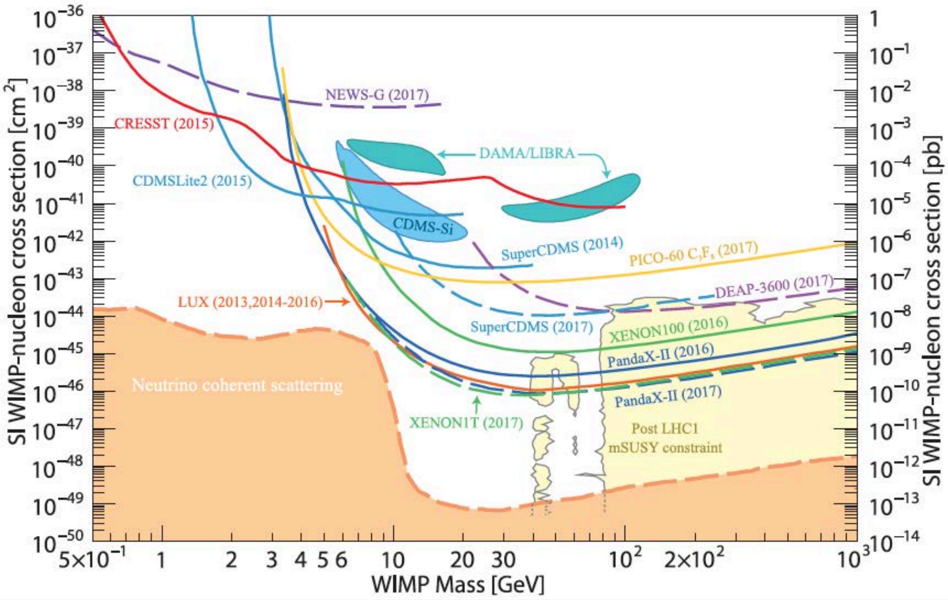


- Modulation in 2-6 keV single hits: 8.9 σ
- Mostly in 2-4 keV, ~0.02 cts/d/kg/keV
- Total single rate ~1 cts/d/kg/keV
- Standard DM distribution: < ~5% modulation
- Period & phase about right for DM.
- No annual modulation in 6-14 keV.
- No annual modulation in multiple hits. (which?)
- **DM detection?**
- Conflict with other experiments in standard scenarios that test the larger steady state effect.

Drukier, Freese, Spergel PRD 86
Freese et al. PRD 88

40

Exclusion/Signal region



WISPs and other DM candidates

- WIMPs in the form of SUSY LSP are not the only possible "cold" DM candidates theoretically motivated:
  - WISPs, or weakly interacting slim particles.
    - Axions. Hypothetical light pseudoscalar postulated to explain the strong CP problem (CP should not be a symmetry of the QCD Lagrangian; however, CP appears to be conserved in QCD). A SSB at a very-high-energy scale, giving rise to an associated boson called the axion, might explain it. Being pseudoscalar (like the π^0), the axion can decay into two photons.

$$g_{a\gamma\gamma} \approx \frac{1}{M} \; ; \; \frac{m_a}{1\ \text{eV}} \sim \frac{1}{M/(6\ \text{x}\ 10^6\ \text{GeV})}$$

      Some other consequences for cosmological photon propagation (see later in these lectures).
    - ALPs. An extension of axions, relaxing the above relation between mass and coupling.
    - Sterile Neutrinos. A neutrino which does not interact via weak interactions. Constraints form cosmology make it unlikely that they can be the main component of DM; sterile neutrinos with masses of ~ keV and above could be, with some difficulty, accommodated in the present theories.
    - Matter in parallel branes; Shadow or Mirror matter. Some theories postulate the presence of matter in parallel branes, interacting with our world only via gravity or a super-weak interaction. In theories popular in the 1960s, a "mirror matter" was postulated to form astronomical mirror objects; the cosmology in the mirror sector could be different from ours, possibly explaining the formation of dark halos. This mirror-matter cosmology has been claimed to explain a wide range of phenomena.
  - Other possible candidates:
    - Superheavy Particles. Particles above the GZK cutoff (WIMPzillas) and other gravitational monsters could have been produced in the early Universe; their presence could result in excess of CR at UHE.

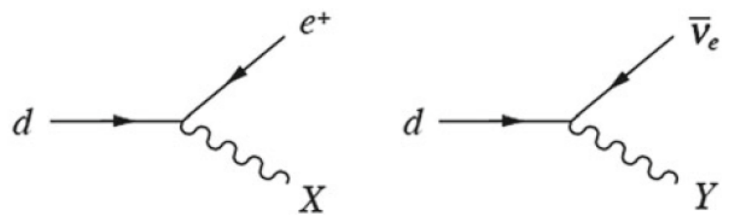
Heavier monsters

- In top-down scenarios, cosmic rays can come from the decays of heavier, exotic particles with masses ranging
  - from the typical 100 GeV - 1 TeV scale of supersymmetry
  - to the 10^{11} GeV scale of superheavy particles
  - to the GUT scale, $M_{GUT} \sim 10^{24}$ eV, and beyond - in this case the GZK cutoff can be avoided, since protons can be produced near Earth
- Some even believe that at the highest energy CRs are decay products of remnant particles or topological structures created in the early universe. A topological defect from a phase transition in GUTs with typical energy scale of 10^{24} eV could undergo a chain decay into GUT mediators X and Y that then decay to known particles; in the long term the number of neutral pions (decaying into photons) is two orders of magnitude larger than the number of protons => if the decay of topological defects is the source of the highest energy CRs, they must be photons and neutrinos.

43

GUT mediators X and Y

- SU(5) is the smallest special unitary group that can contain SU(3) x SU(2) x U(1)
- One has dimension 5 spinors $\psi = (d_R, d_G, d_B, e^+, \bar{\nu}_e)$



But don't forget, although unpopular, modifications of the theory of gravitation…

44

Summary of the Lecture

- If our understanding of gravity is correct, unknown "dark" "matter" populates the Universe with a density 5 times larger than ordinary matter. Its presence might manifest in a flux of cosmic gamma rays and an excess of neutrinos and anti-matter, or in any case affect the flux of cosmic gamma rays
- No firm experimental evidence of DM, yet
  - But in many scenarios we just are not sensitive enough to see dark matter, and maybe we'll never be

45