Indirect Detection: Principles and Techniques

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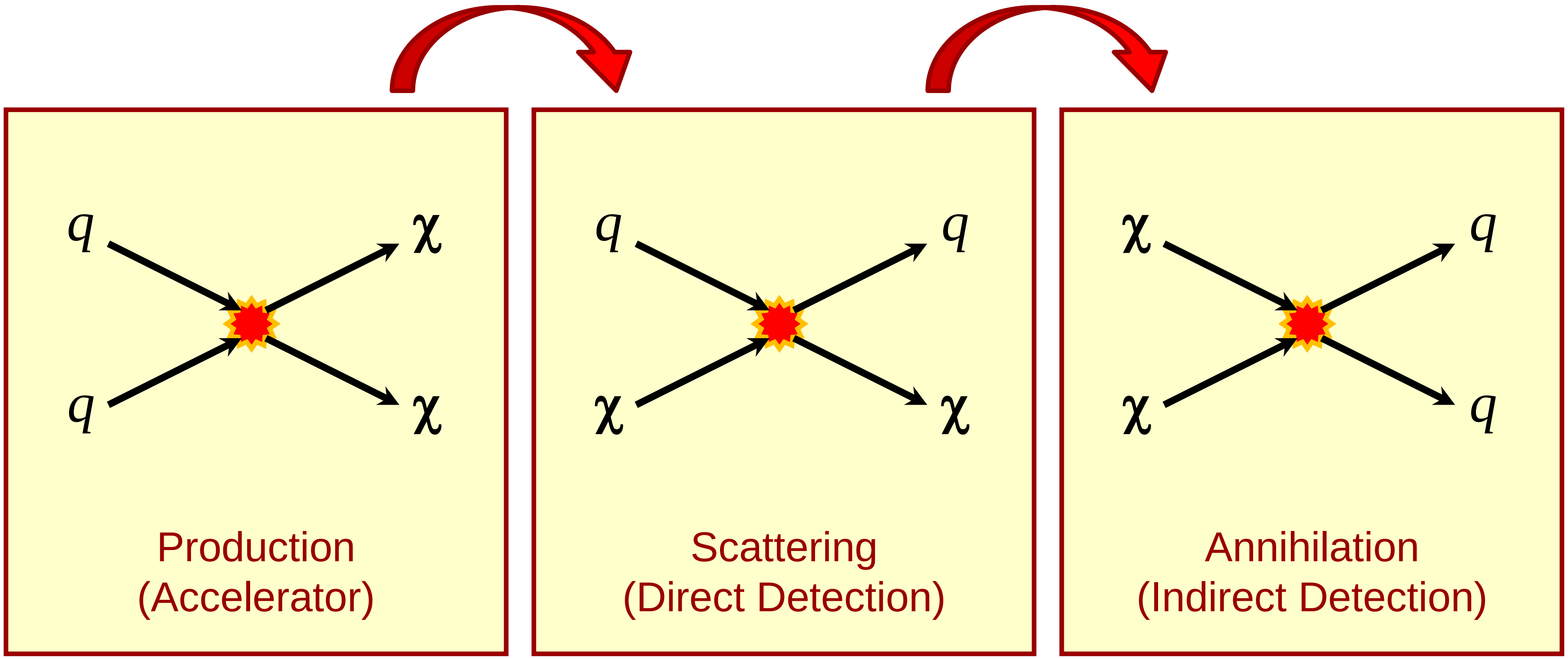
WIMP dark matter



Overview

Signals from relic dark matter interactions outside the laboratory

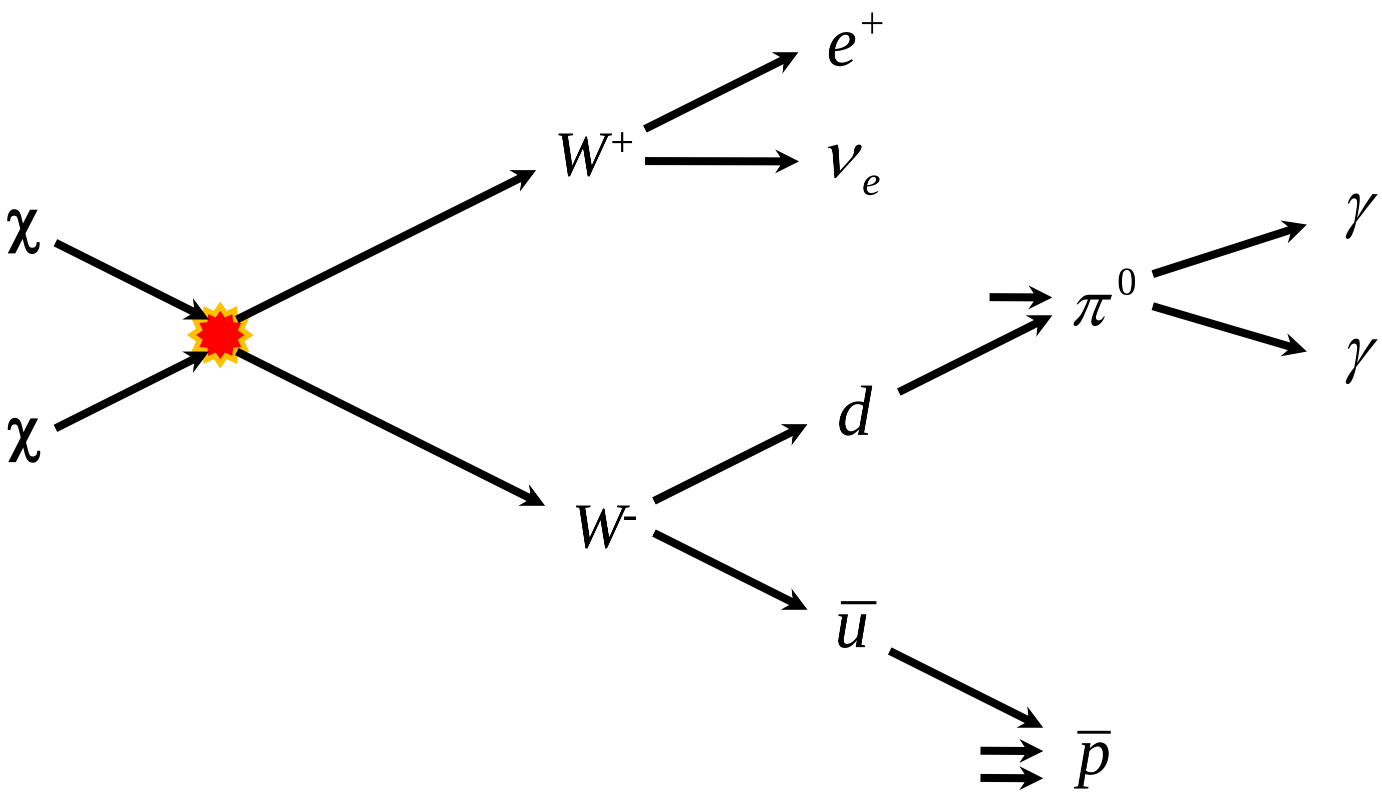
- Annihilation in galactic halos
  - Cosmic rays:
    positrons, anti-protons, γ-rays
- Capture/annihilation in massive bodies
  - Neutrinos
  - Stellar evolution
  - Stellar abundances
- Results: see later talks

WIMP annihilation

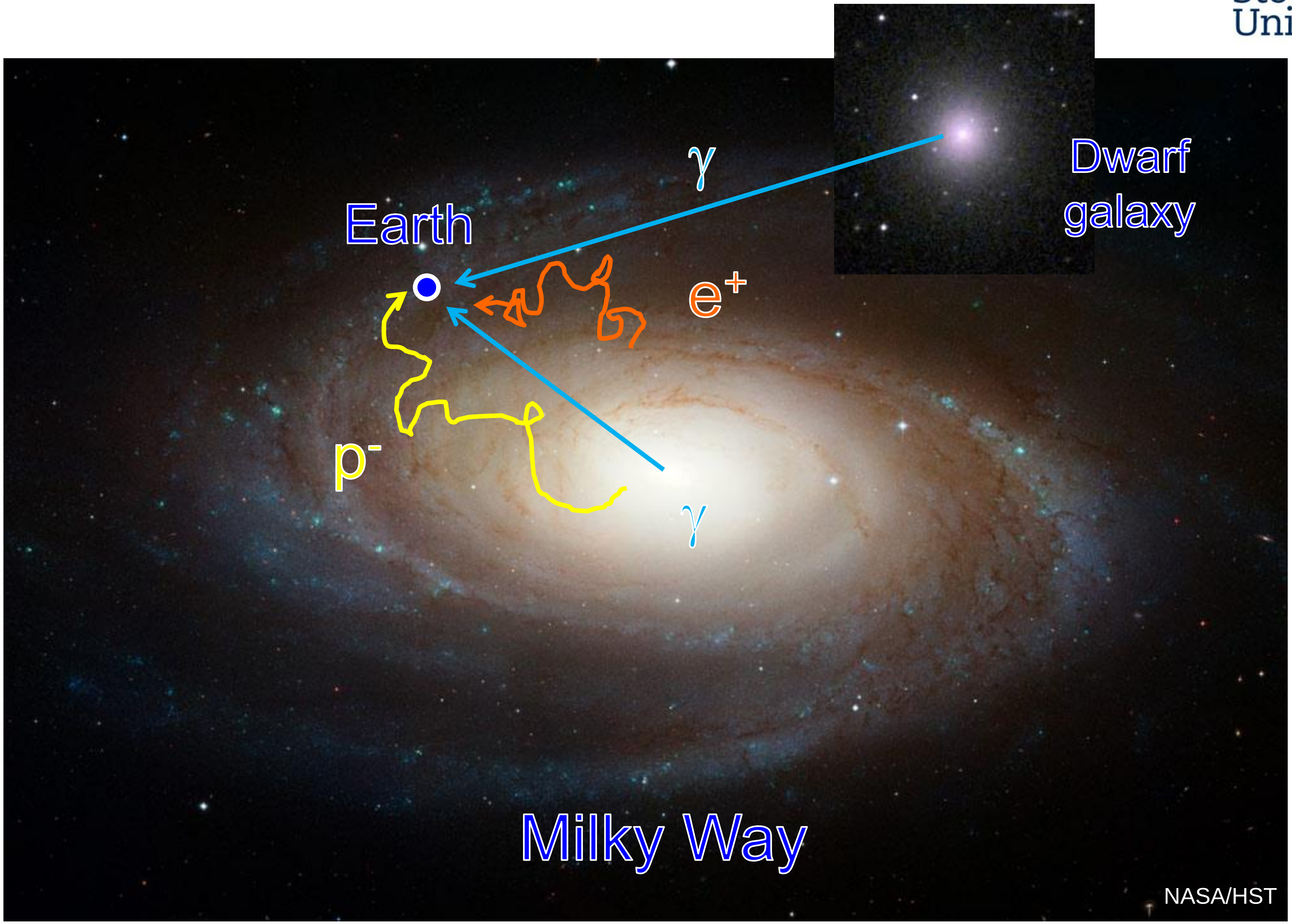
- Annihilation rate ~ ρ^2:
  Look for signal from high density regions
  - Galactic center
  - Clumps
  - Populations collected at centers of massive bodies

- Annihilation products:
  Positrons, γ-rays, neutrinos typically suppressed at tree level
  - Secondaries
  - 1-loop contributions (γ-rays)

WIMP annihilation



Cosmic rays



Cosmic rays

Silk & Srednicki (1984); Ellis et al. (1988)
Gondolo & Silk (1999)

- Charged cosmic rays
  - Positrons
  - Anti-protons
  - Anti-deuterons
  - Energy spectrum only
    No spatial resolution (magnetic fields)
- Gamma-rays
  - Both energy spectrum and spatial distribution available

Astrophysical modeling

- Dark matter halo density profile (rate ~ ρ^2)
  - Cuspy vs. cored center

$$\text{NFW}: \quad \rho(r) = \rho_0 \frac{r_0}{r}\left(\frac{1+(r_0/r_s)}{1+(r/r_s)}\right)^2$$

$$\text{isothermal}: \quad \rho(r) = \rho_0 \frac{1+(r_0/r_s)^2}{1+(r/r_s)^2}$$

  - Clumping → "boost factor"
- Cosmic ray propagation
  - Magnetic fields, interactions
  - Diffusion, convection, energy loss, reaccelereation

$$\frac{\partial \psi}{\partial t} = q(\vec{r}, p) + \vec{\nabla} \cdot (D_{xx} \vec{\nabla} \psi - \vec{V} \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi - \frac{\partial}{\partial p} \left[\dot{p} \psi - \frac{p}{3} (\vec{\nabla} \cdot \vec{V}) \psi \right] - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi$$

Strong & Moskalenko (1998)

- Cosmic ray backgrounds: supernova, pulsars, etc.

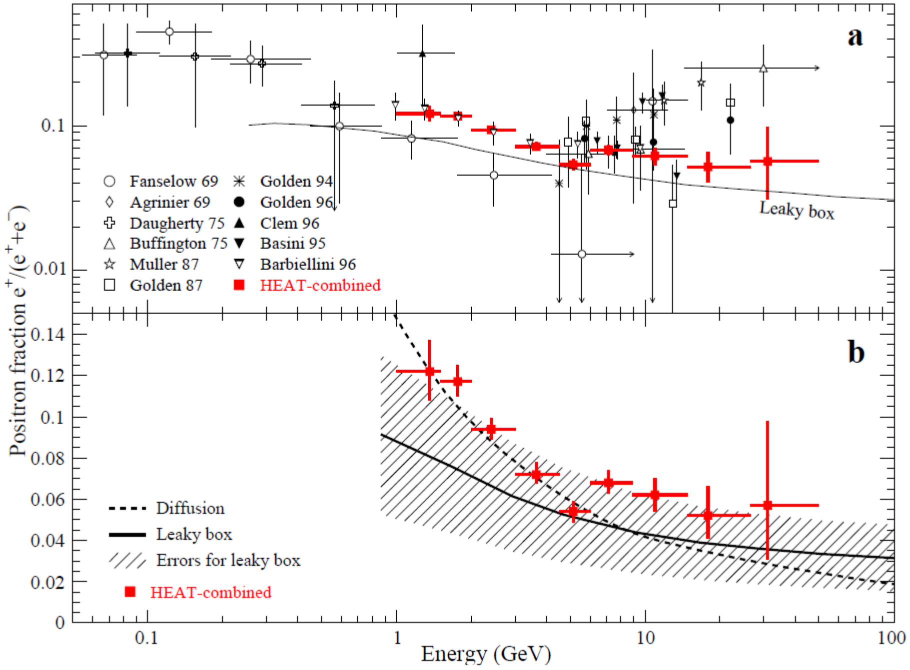
Positrons

- Spectrum
  - Annihilate directly to $e^{\pm}$
    - Mono-energetic ($E = m_\chi$)
    - Broadened by propagation effects
    - Channel suppressed in many models
  - Annihilate to $W^{\pm}$, W decays leptonically
    - Broad peak (centered ~ $m_\chi/2$)
  - Other channels
    - Continuum
- Background
  - Mainly secondaries from collisions with interstellar matter
  - Difficult to model, but continuum expected

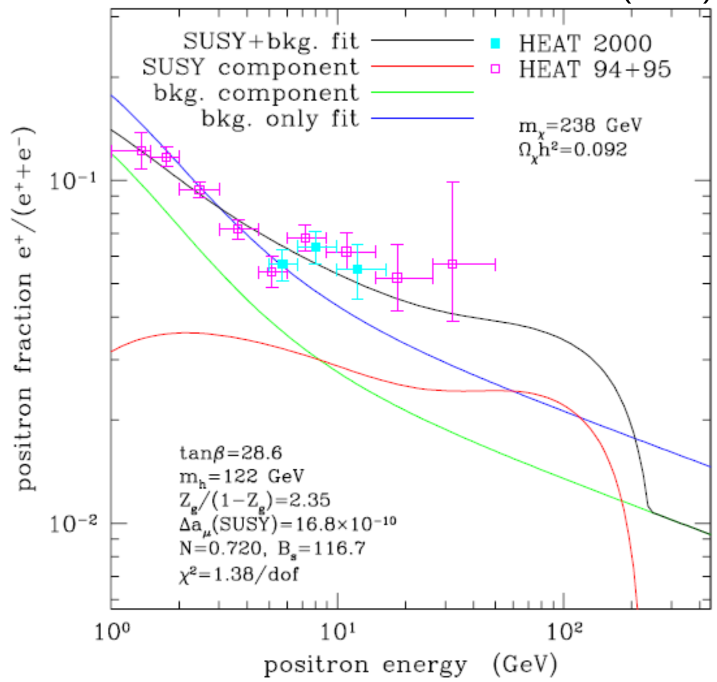
Positrons

- HEAT excess (...also PAMELA)

Coutu et al. (1999)



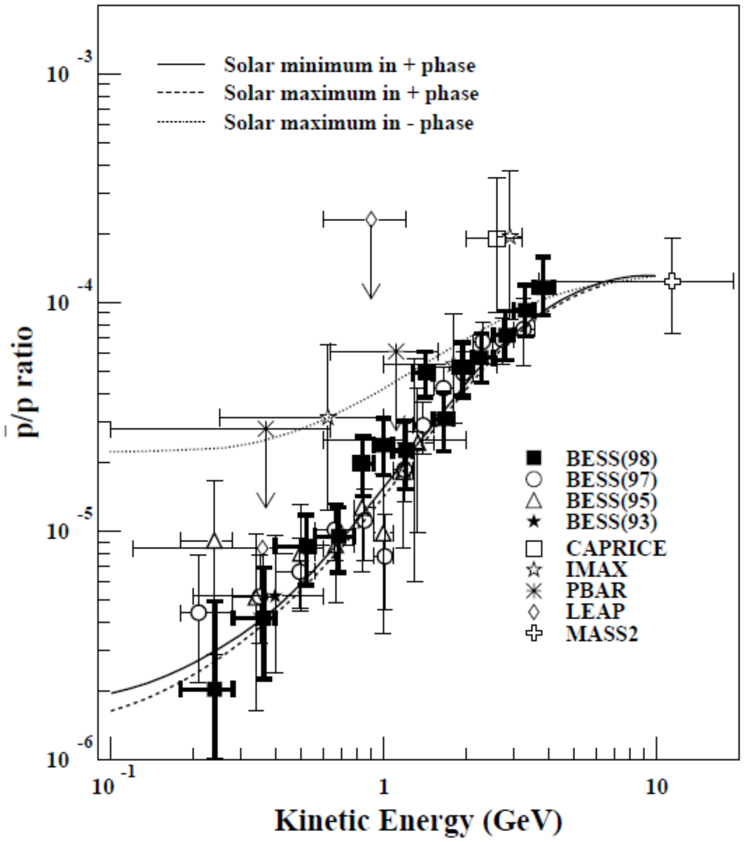
Baltz et al. (2002)



Anti-protons

- Spectrum
  - Hadronization: continuum only
- Background
  - Mainly secondaries from collisions with interstellar matter
  - Continuum, but decreases at low energies

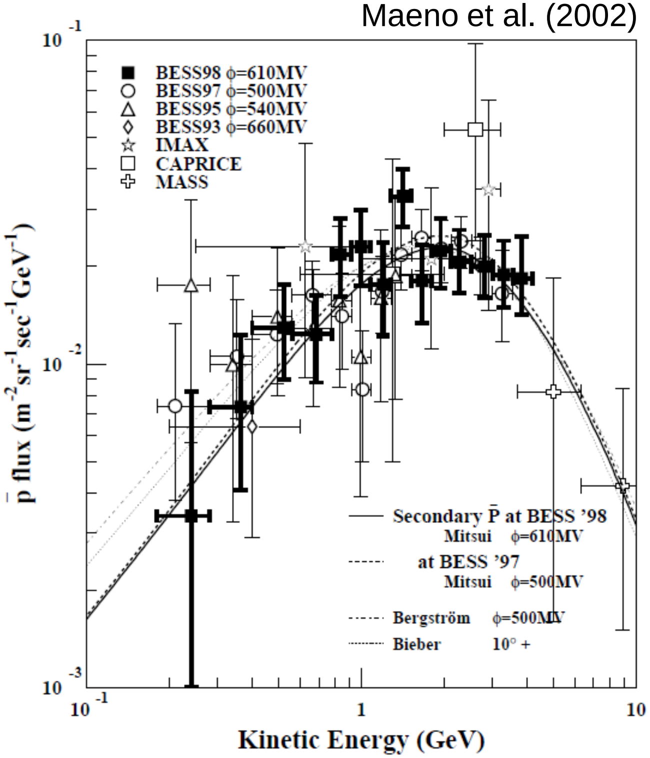
Maeno et al. (2002)

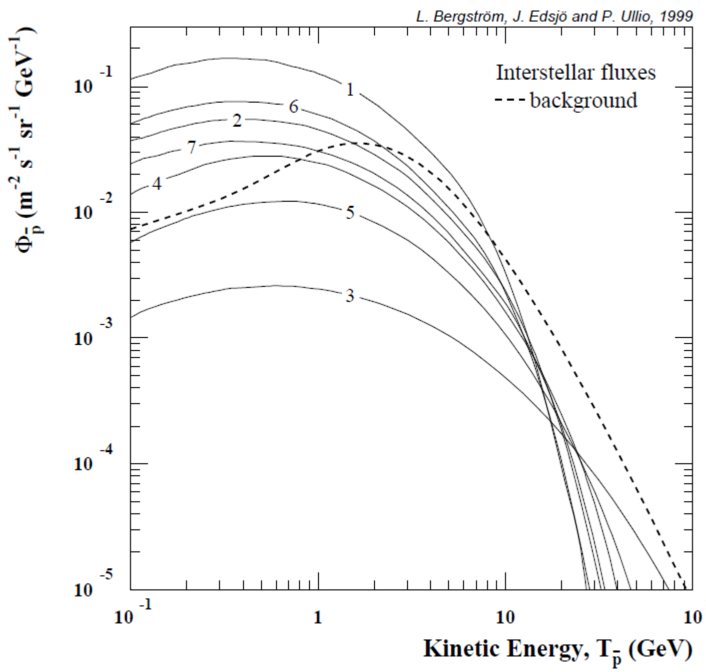


Anti-protons

- BESS

Maeno et al. (2002)

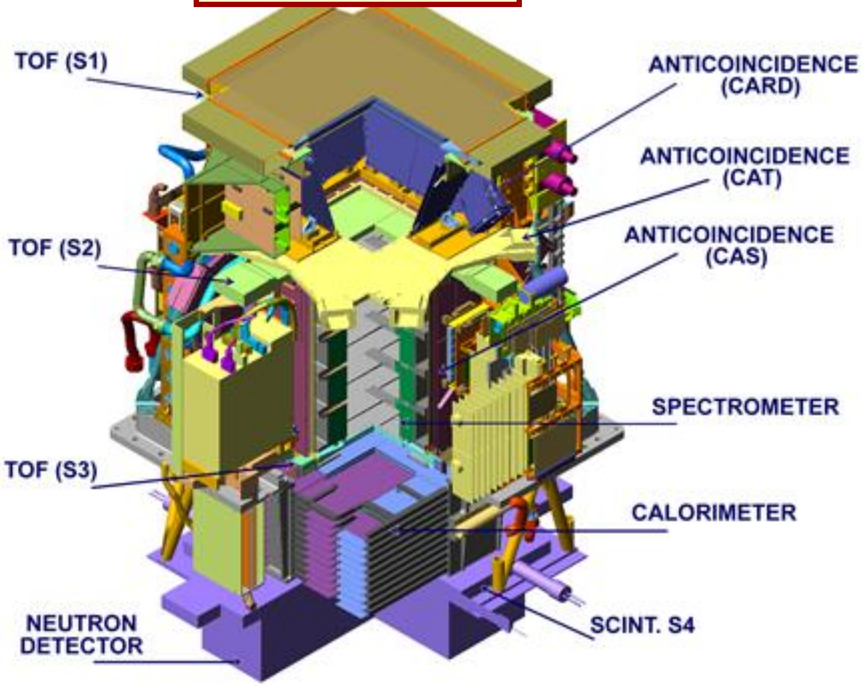




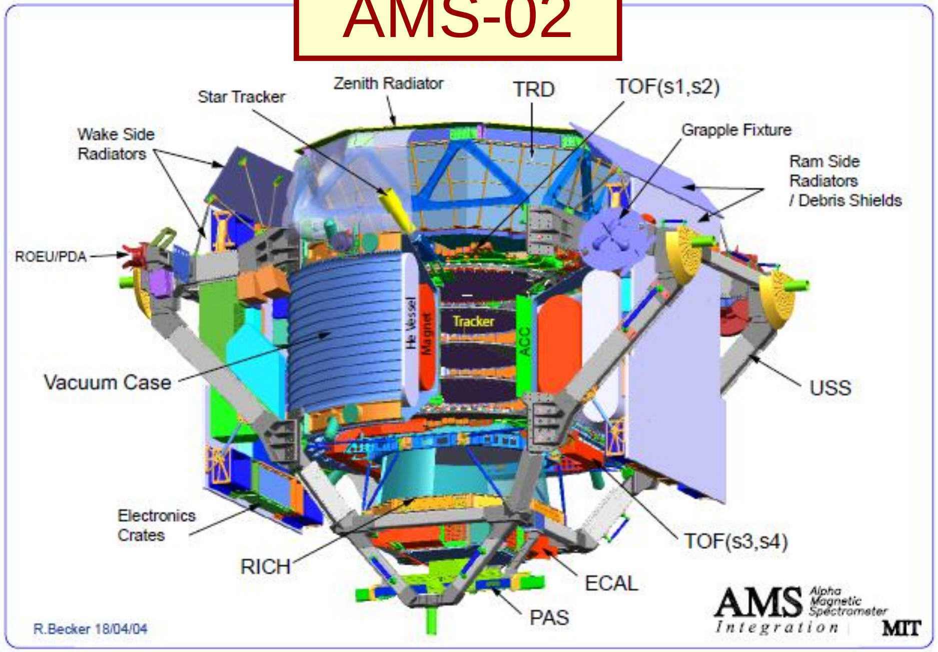
Charged cosmic ray experiments

HEAT, BESS, CAPRICE, ATIC,…

PAMELA



AMS-02

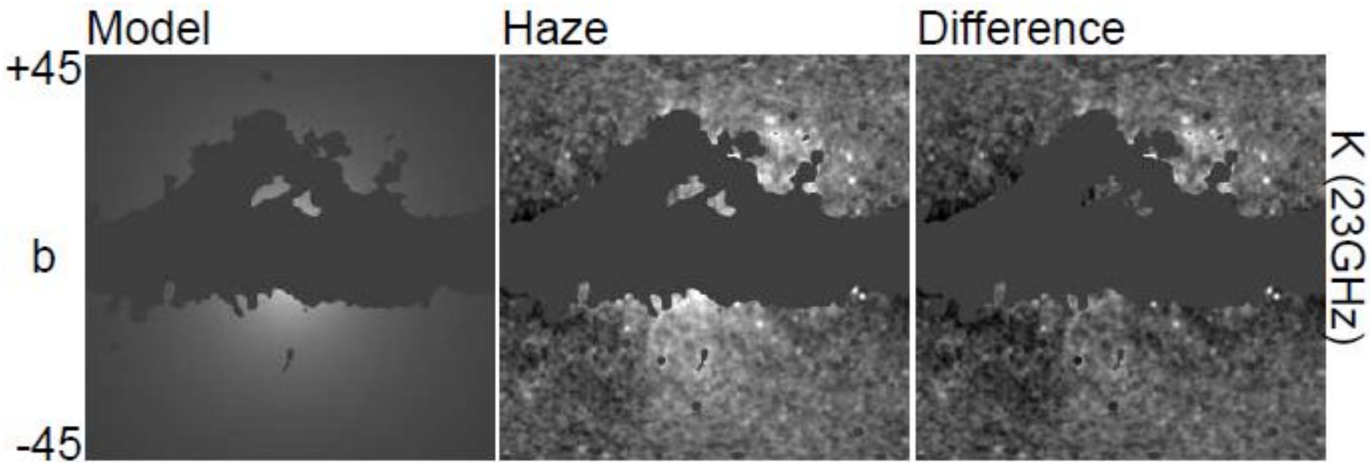


Synchrotron radiation

Finkbeiner (2004)
Hooper, Finkbeiner & Dobler (2007)

- Excess synchrotron radiation found when subtracting foregrounds from WMAP maps
- WIMP annihilations can provide the necessary electrons/positrons to explain the excess

Controversial!



Finkbeiner (2004)

Gamma-rays

- Spectrum
  - Annihilate directly to γ's
    - Mono-energetic ($E = m_\chi$)
    - Loop suppressed in most models
  - Annihilate to $Z + \gamma$
    - Mono-energetic peak ($E < m_\chi$) + continuum (Z decay)
    - Loop suppressed in most models
  - Internal bremsstrahlung
    - Hard spectrum
  - Other channels
    - Continuum (mainly from $\pi^0 \rightarrow \gamma\,\gamma$)

- Background
  - Continuum only
  - Peak is "smoking gun"

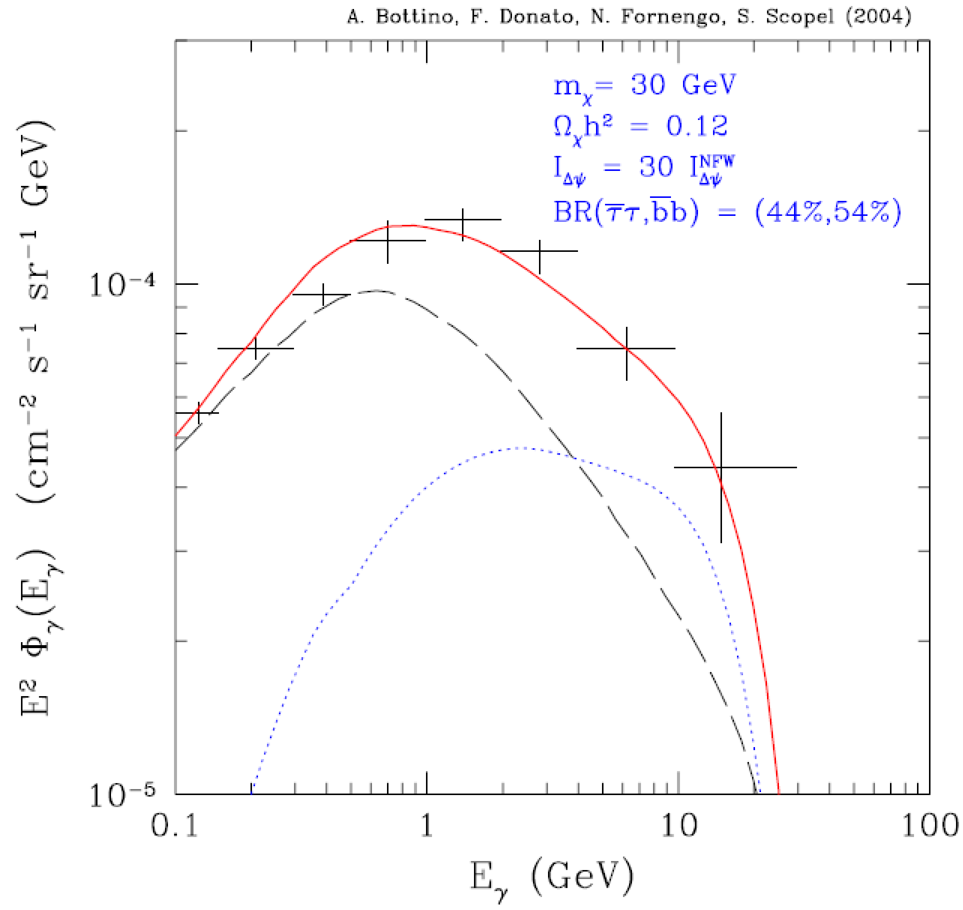
Gamma-rays

Background depends on observational target

- Galactic center
  - High signal
  - High background
- Dwarf galaxies, subhalos
  - Low signal
  - Low background
- Wide regions (diffuse)

Gamma-rays

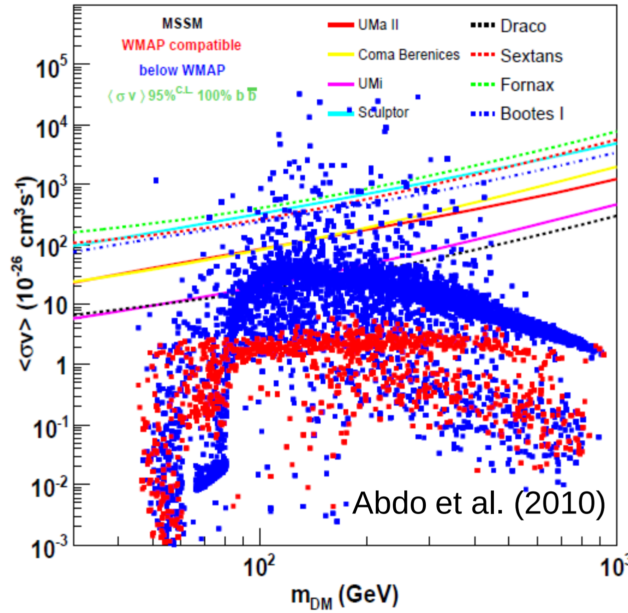
- EGRET Excess (galactic center)



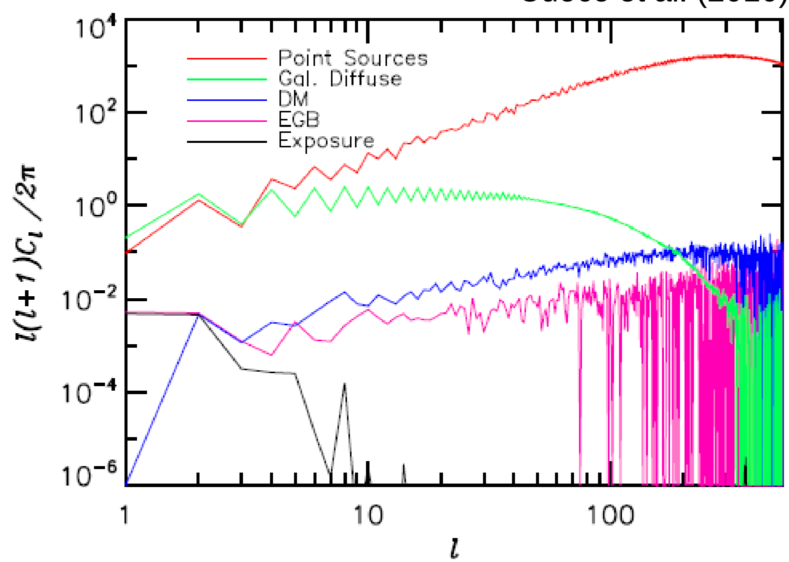
Gamma-rays

Prospects

- Dwarf galaxies
  - Dark matter dominated
  - Segue 1: nearby, high latitude



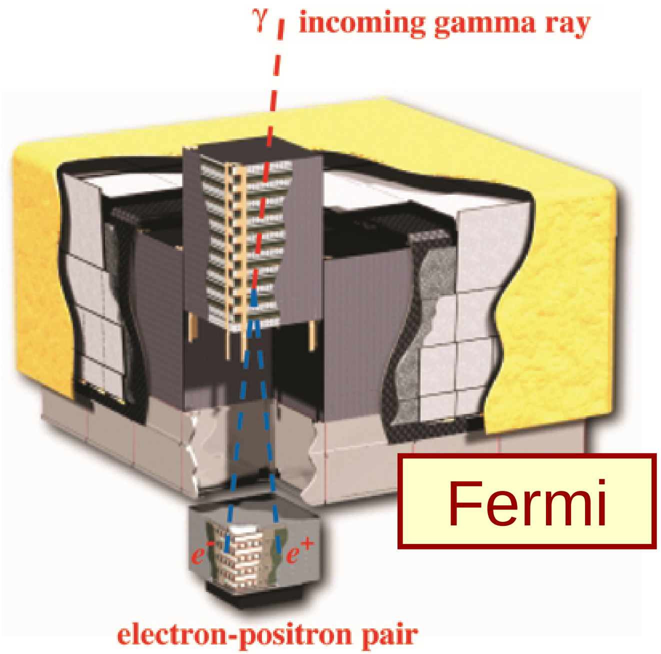
Cuoco et al. (2010)



- Diffuse
  - unresolved subhalos, extragalactic
  - Anisotropies (à la WMAP)

Gamma-ray experiments

- EGRET, CANGAROO, Whipple



Low energy gamma-rays

- INTEGRAL sees 511 keV line from galactic bulge

- Spherically shaped emission region
  - Consistent with expected DM distribution

- Light dark matter needed

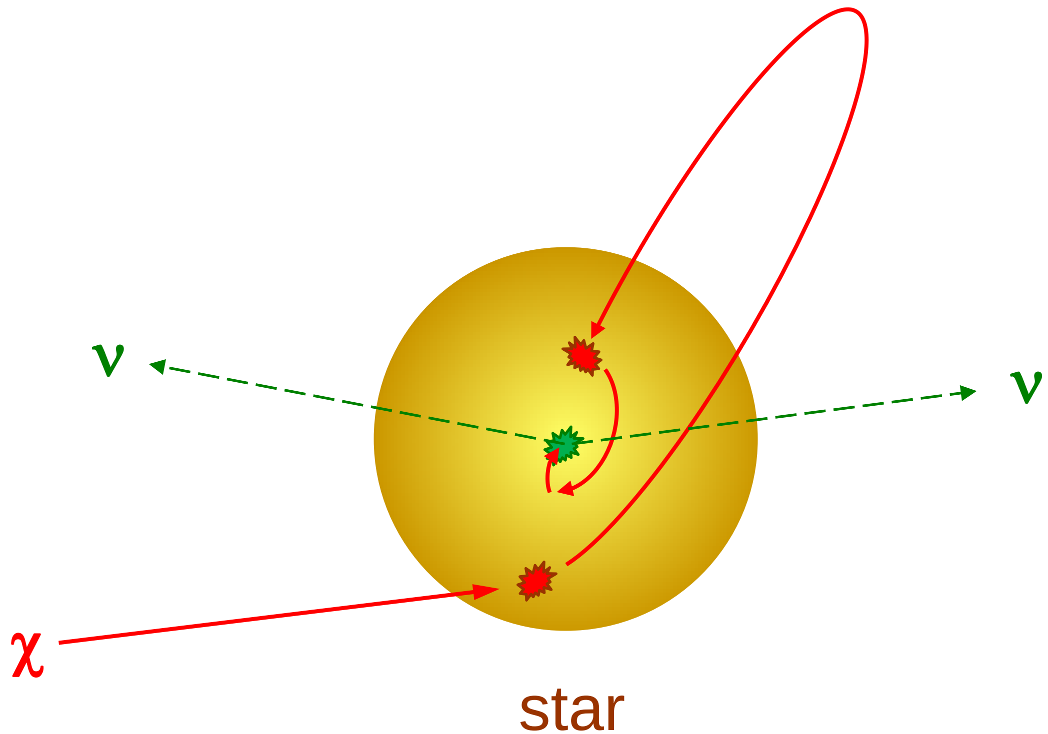
Cosmic rays: issues

- Some signals depend significantly on halo density profile (galactic center)

- Cosmic ray background models have significant uncertainties
  - Peaks in spectrum are clear WIMP signature
  - Non-matching continuum spectrum: not so clear

- Some explanations for current excesses require boost factor

WIMP capture/annihilation in massive bodies



Signatures:

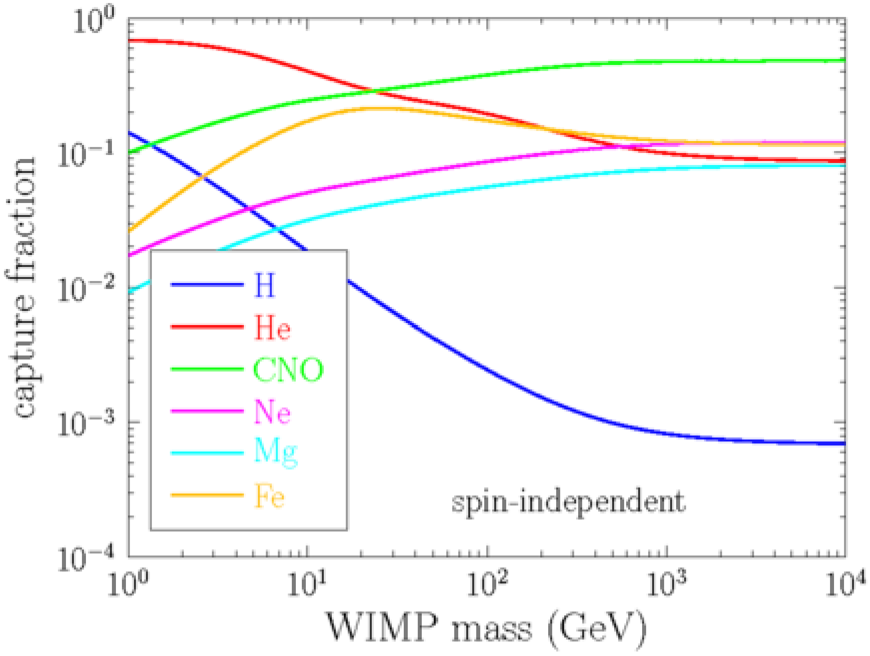
- Neutrinos (Sun, Earth)
- Heat: stellar evolution (WIMP burners/dark stars/pop III stars)

Neutrinos from the Sun

Silk, Olive & Srednicki (1985); Freese (1986)

Gravitational capture via WIMP-nucleus elastic scattering

- Solar abundances
  - Hydrogen ~ 74%
  - Helium ~ 25%
  - Metals ~ 1-2%
- Spin-dependent vs. spin-independent
- Metals significant
  - SI cross-section scales as A^2
  - Hydrogen/Helium inefficient at capturing
- Halo model
  - Local density
  - Velocity distribution



Neutrinos from the Sun

- Equilibrium between capture and annihilation?
  - Thermal relic ($<\sigma_{ann}\ v> \sim 10^{-26}$ cm³/s) -- probably
  - WIMP/anti-WIMP asymmetry

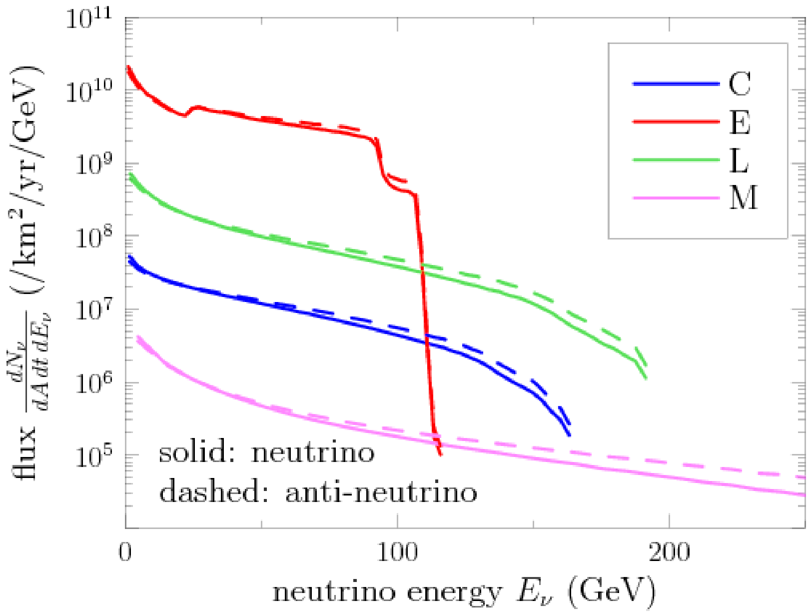
Talk by M Frandsen

- Annihilation channels
  - Directly to neutrinos
    - Mono-energetic, strong signature
  - W, Z, higgs, heavy quarks ← Majorana (neutralino)
    - Neutrinos from secondary decays
    - Continuous energy spectrum, ~ $^1/_3 – ^1/_2$ WIMP mass
  - Light quarks
    - Negligible neutrino energies

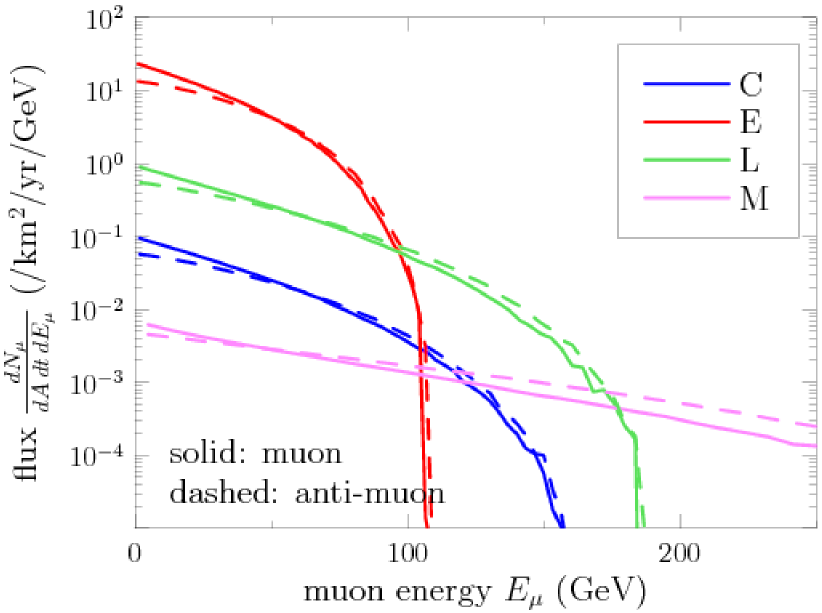
- Propagation: interactions, oscillations
  - Sun optically thick if E_ν > 200 GeV

Neutrinos from the Sun

- Point source
- Energy spectrum
  - WIMP mass, annihilation channel



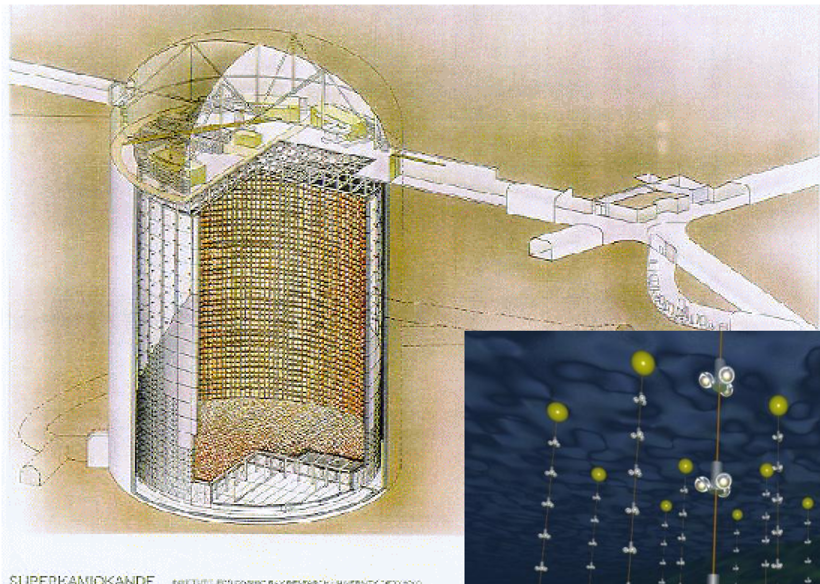
Neutrino spectra



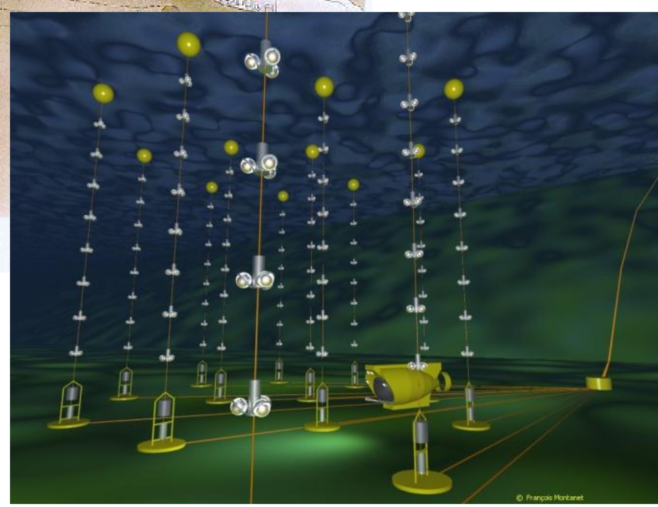
Neutrino induced muon spectra

Neutrinos from the Sun

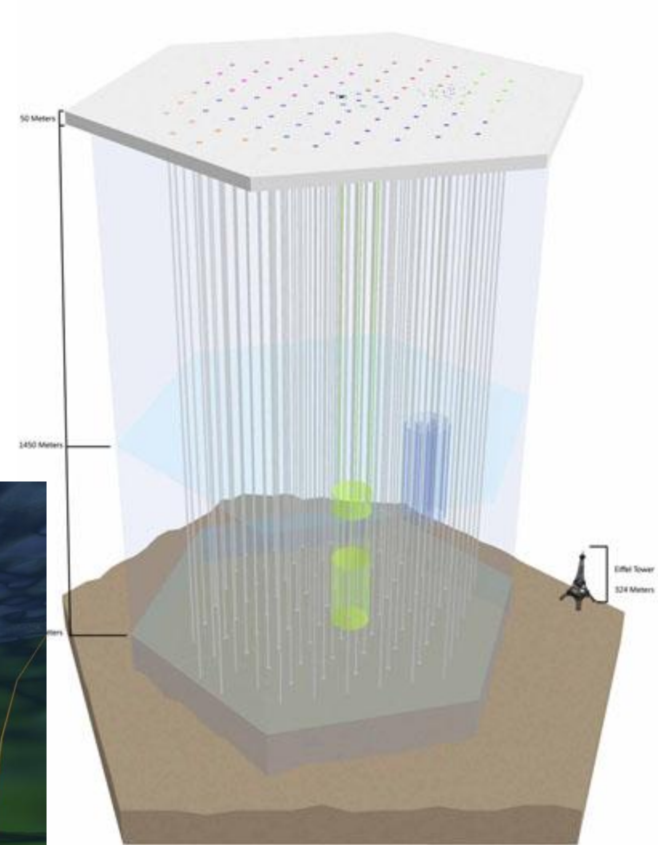
Super-K, IceCube/DeepCore, ANTARES



SuperKamiokande Collab.

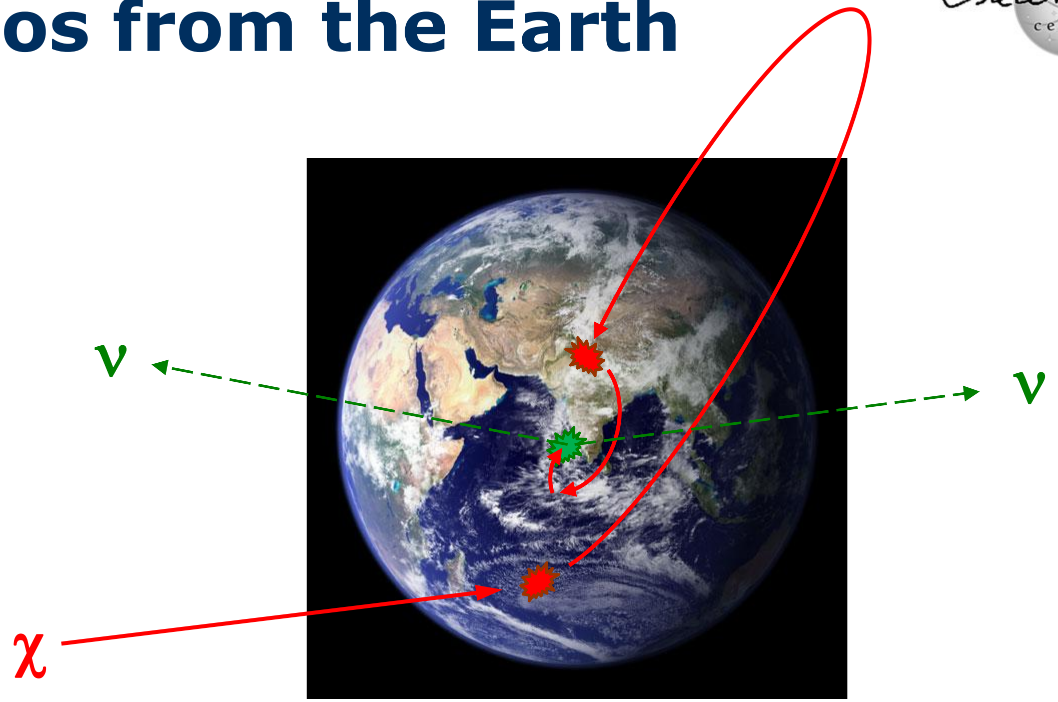


F.Montanet, CNRS/IN2P3 and UJF for Antares



NSF/IceCube

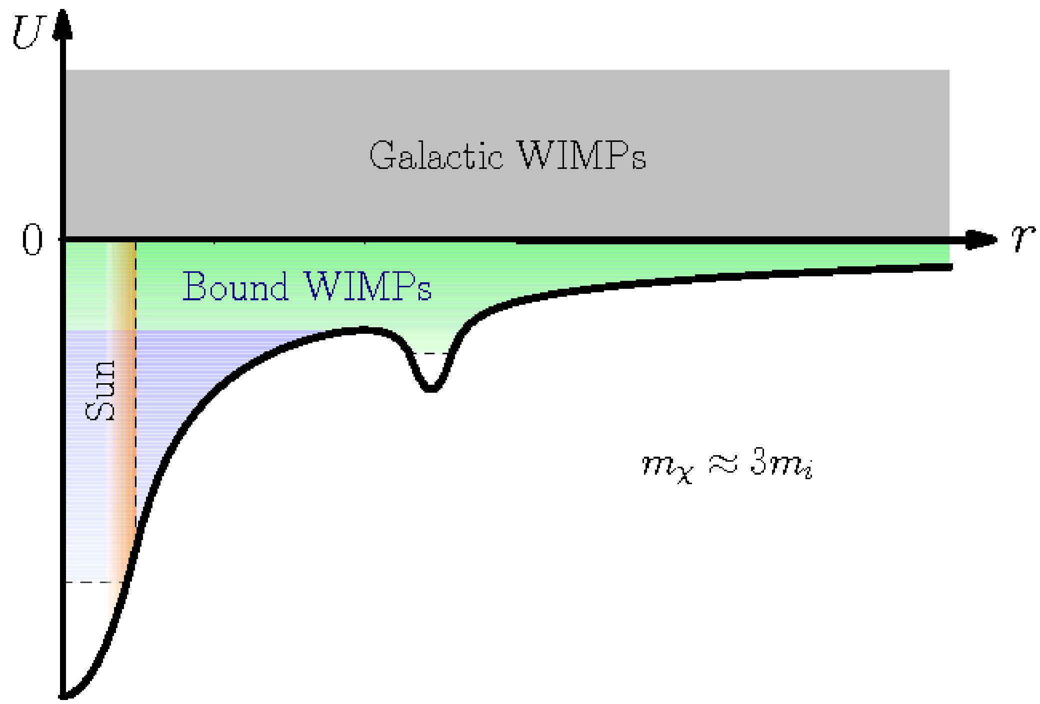
Neutrinos from the Earth



- Closer to annihilations (flux ~ $1/r^2$)
- Smaller body ⇒ smaller capture rate
  - Capture and annihilation: not in equilibrium
- Embedded within Sun's gravitational well

Neutrinos from the Earth

- Resonant capture:
  $m_\chi \sim m_{nuc}$
- Gravitational diffusion: 3-body interactions with Jupiter
  - Gould (1991)
- Orbital dynamics after first scatter in Sun
  - Damour & Krauss (1999)
  - Lundberg & Edsjo (2004)
  - Peter (2009)



- Dynamics also important for capture in Sun with heavy WIMPs (above TeV)

WIMP burners/dark stars

- Majority of annihilation energy deposited in stellar medium
  - Sun/Earth: negligible heat contribution
- Stars in higher dark matter density regions: non-negligible heat contribution?
  - Galactic center
  - Early universe

WIMP burners

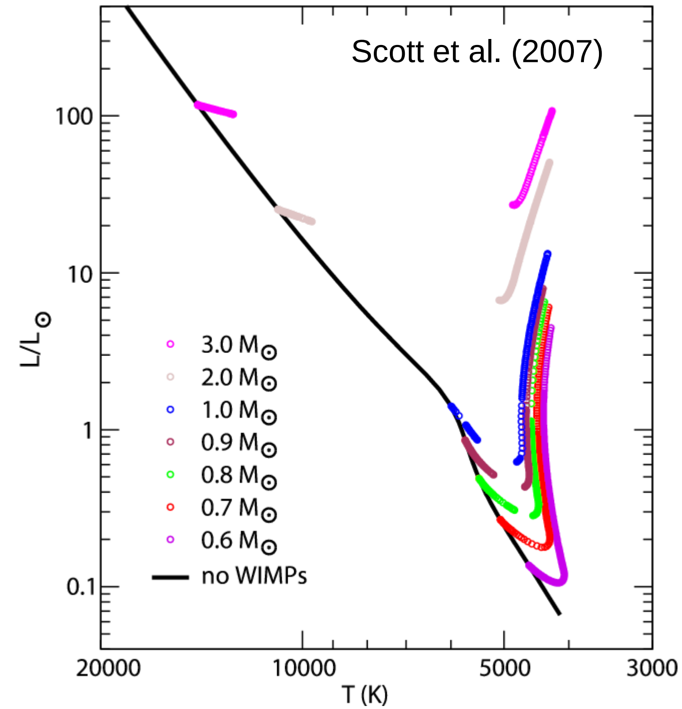
Salati & Silk (1989); Moskalenko & Wai (2007);
Scott, Edsjo & Fairbarn (2007)

Higher DM density at galactic center

- Spike around central black hole?

- White dwarfs
  - Large boost in luminosity
  - Eccentric orbits: varying luminosity?

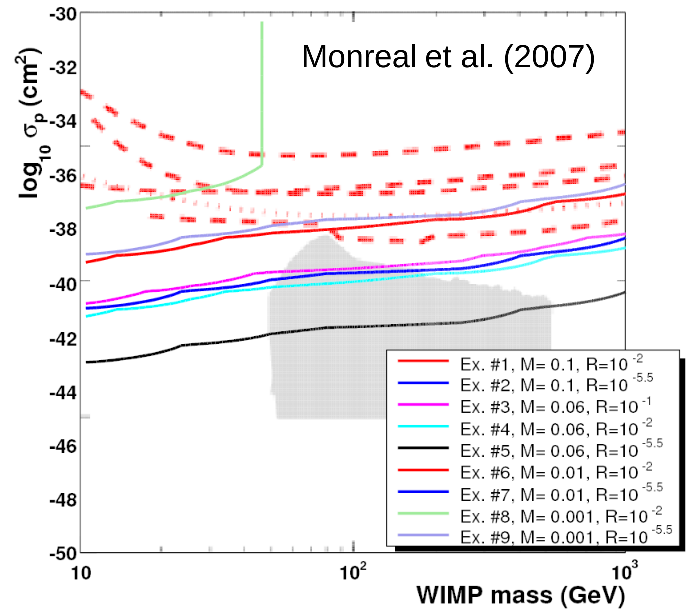
- Low mass main sequence stars
  - Longer lifetimes
  - Modified HR diagram track



Anomalous chemical abundances

Monreal, Nelson & Formaggio (2007)

- High energy annihilation products
  $\Rightarrow$ spallation reactions
- Low mass stars at galactic center: excess lithium, beryllium, boron
- Detection prospects
  - Spectral measurements difficult at galactic center.
  - Ejected stars?



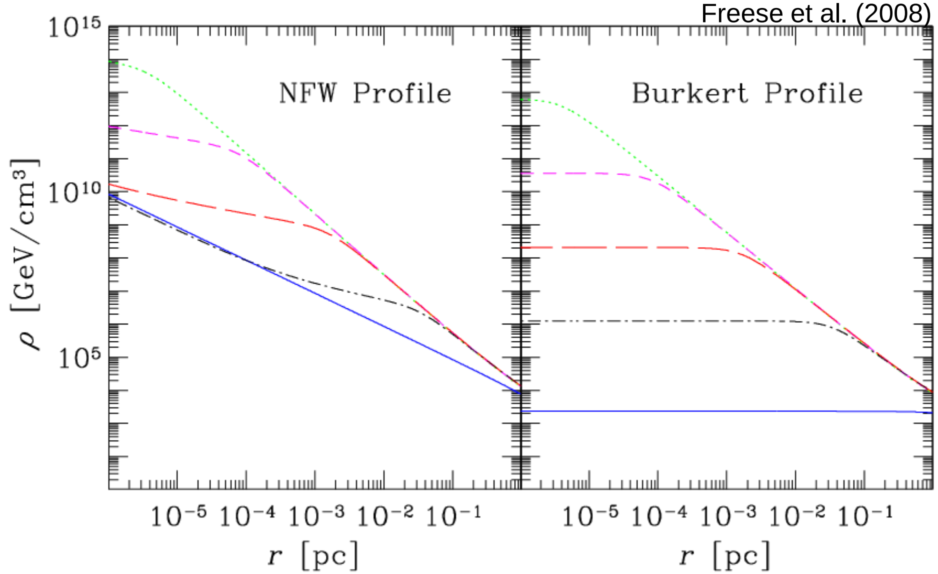
Parameters that yield Boron abundance > 10^{-8} for a variety of low mass stars/brown dwarfs.

Dark stars/Pop III stars

Spolyar, Freese & Gondolo (2008)

- First stars produced from $10^5 – 10^6$ solar mass protostellar halos
- Adiabatic contraction of DM with baryons leads to high DM densities
  $\Rightarrow$ WIMP annihilation
- Heat from annihilation stops collapse of baryons:
  stable body powered by WIMP annihilation instead of fusion

Freese et al. (2008)



Dark stars/Pop III stars

Iocco (2008); Freese, Spolyar & Aguirre (2008)

- Second phase: capture
  - As WIMPs depleted, further contraction of baryons
  - Higher baryon densities: WIMP-nuclear scattering
    $\Rightarrow$ WIMP capture
  - Star powered partly or wholly by annihilation
- Dark stars vs. traditional Pop III stars
  - Potentially more massive
  - Different luminosity vs. temperature
  - Potentially very long lived
- Detection prospects
  - HST, JWST

Summary

Wide range of potential indirect signals for relic dark matter

- Annihilation in galactic halos
  - Cosmic rays:
    positrons, anti-protons, γ-rays

HESS/MAGIC/CTA (D Horns)

PAMELA (R. Sparvoli)

FERMI (L Strigari)

- Capture/annihilation in massive bodies
  - Neutrinos
  - Stellar evolution
  - Stellar abundances

IceCube (T. Montaruli)

- Room for more techniques
  - Synchrotron radiation (WMAP excess)
  - low energy gammas (511 keV)