Indirect Dark Matter Detection

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this is a simple lecture: outline

- Candidates

- Sources

- Detection techniques

based on a simple fact...

or maybe not so simple

DEN SOM INTE SYNS, FINNS INTE

(what you don't see does not exist)

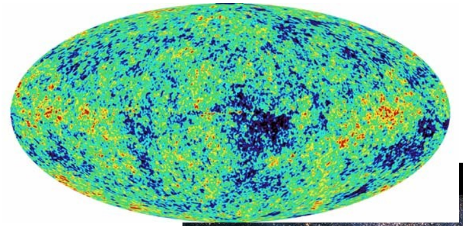
Använd lanternorna under mörker.

SJÖFARTSVERKET
Sjösäkerhetsrådet
www.sjosakert.nu

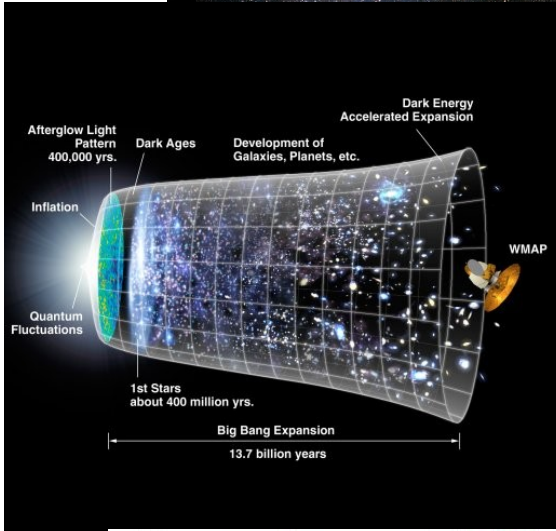
There are models with no dark matter (Modified Newtonian Dynamics for example)

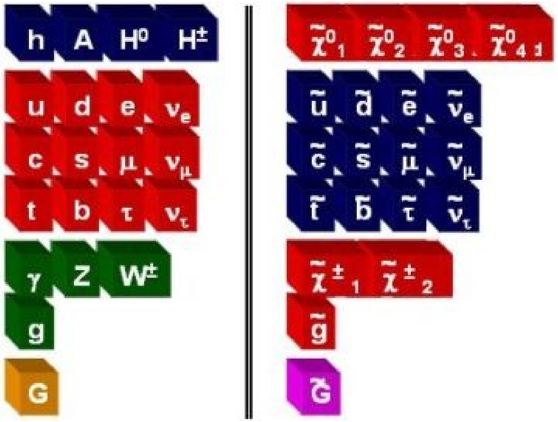
But have difficulties explaining all the signatures we will discuss

the cosmo-astroparticle connection



Models to explain the elementary particles and their interactions as studied in laboratory experiments can not spoil the understanding we have of the early universe and its evolution towards what we observe today.

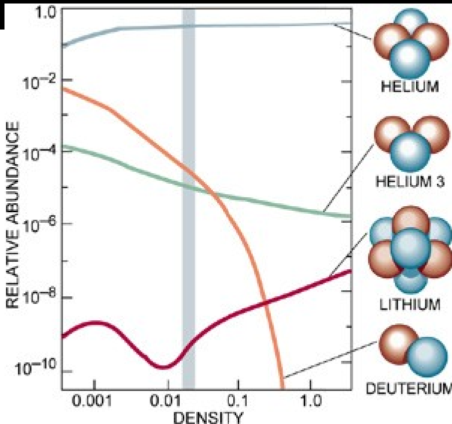




This provides a strong link between particle physics and astrophysics/cosmology

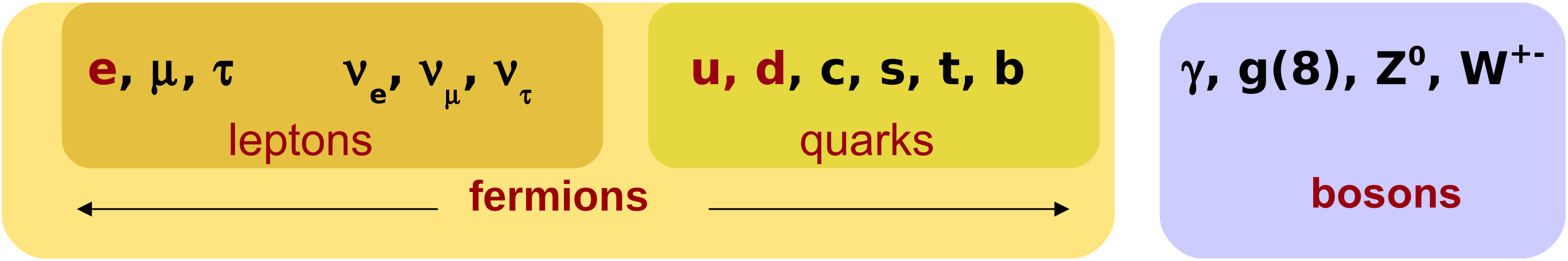
Cosmology limits the possible models of particle physics

Particle Physics ‘decides’ what is possible in the Universe



the Standard Model in two transparencies: I

- The Standard Model of particle physics is a Quantum Field Theory.
- Quantum field theories are used to describe relativistic, many-particle systems. They are an extension of QM (second quantization).
- A field is defined at every point in space-time with a continuous function of the space-time coordinates, $\Phi(x_\mu) \quad \mu=1,\ldots,4$
- Particles are understood as field excitations, ie. quanta, at a given space-time point where the field has non-zero value.
- There are several types of fields according to their behaviour under a Lorentz transformation: scalar, vector, tensor and spinor.
- The SM contains 24 elementary particles (plus antiparticles)



e, μ, τ **ν_e, ν_μ, ν_τ**

leptons

u, d, c, s, t, b

quarks

fermions

γ, g(8), Z^0, W^{+-}

bosons

all “normal” matter made of **u, d** and **e-**.

the Standard Model in two transparencies: II

- The dynamics and interactions of particles are described by a Lagrangian
- The equations of motion are derived from the Lagrangian
- The SM describes correctly the interactions of particles under three of the four fundamental forces:
  - **electromagnetic, nuclear strong, nuclear weak** (gravitation not included) which are "mediated" by the bosons γ, g, Z^0, $W^{+ -}$.
- Is Lorentz invariant (invariant under space-time translations)
- Is gauge invariant under U(1)EM x SU(2)weak x SU(3)strong
- 'Lepton number' (number of leptons-antileptons) is conserved in any interaction (for particles L=1, for antiparticles L= -1, for non-leptons L=0), as well as 'charge', spin and energy.
- Mass is not explained. It is added ad-hoc through the ''Higgs mechanism", which requires the existence of an additional particle, the Higgs boson, that has not been observed yet.

reminder: CM and Lab energies

Reminder:

In modern particle accelerators we collide counter-rotating particles, ie, $p_{beam} = - p_{target}$. That is, the CM system

(b=beam,

$$\mathbf{P}_b = (E_b, \vec{p}_b)$$

t=target)

$$\mathbf{P}_t = (E_t, p_t)$$

$$s = (\mathbf{P}_b + \mathbf{P}_t)^2 = (E_b + E_t, \underbrace{\vec{p}_b + \vec{p}_t}_{\vec{p}_b = -\vec{p}_t})^2 = (E_b + E_t)^2 = E_{cm}{}^2$$

In the lab frame (rest frame of the target particle), most usual case in detection of astrophysical processes:

$$\mathbf{P}_b = (E_b, p_b)$$

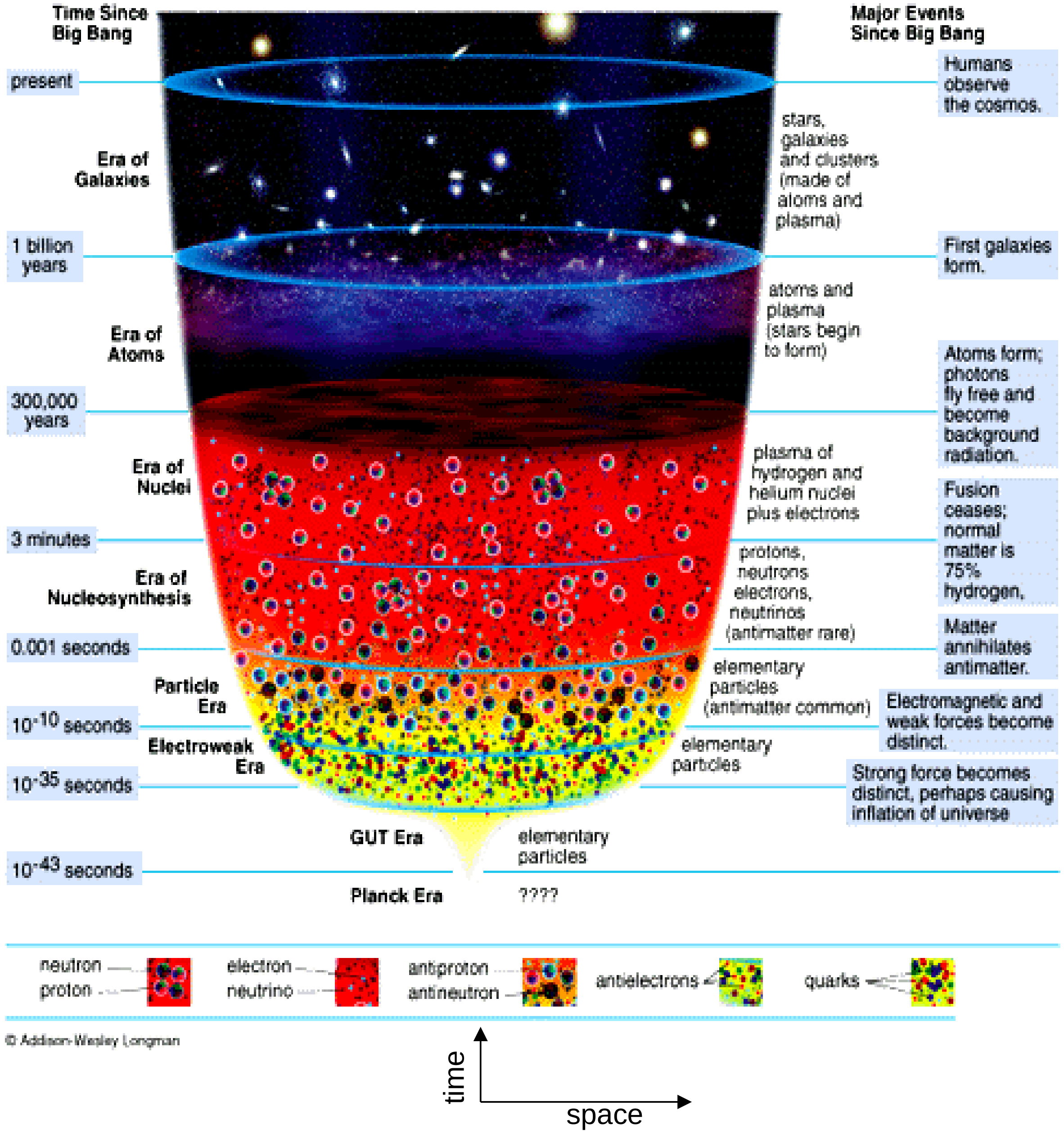
$$\mathbf{P}_t = (m_t, 0)$$

$$s = (\mathbf{P}_b + \mathbf{P}_t)^2 = (E_b + m_t, \vec{p}_b)^2 = (E_b + m_t)^2 - p_b{}^2 =$$

$$= E_b{}^2 + m_t{}^2 + 2E_b m_t - p_b{}^2 = m_b{}^2 + m_t{}^2 + 2E_b m_t \equiv E_{cm}{}^2$$

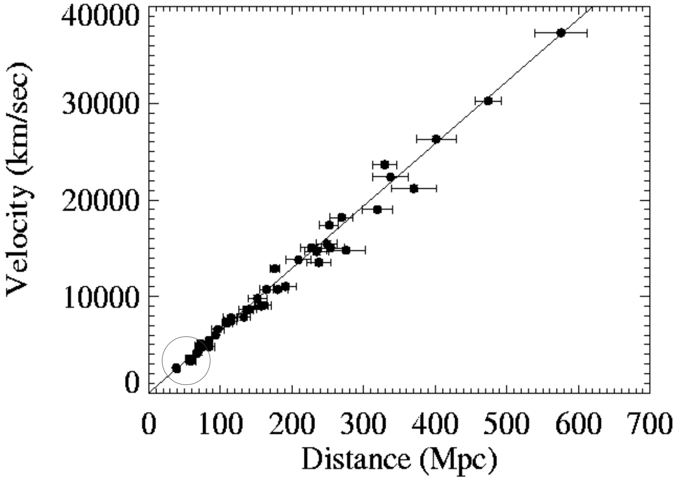
$$\boxed{\rightarrow E_{cm} \propto \sqrt{E_b}}$$

the Big Bang model in one transparency



- In the beginning there was nothing, which exploded (T. Pratchett)
- Inflation=exponential expansion
- Soup of q's, e's, ν's and γ's (at least)
- Quarks (+gluons) --> p and n
- Soup of p, n and e
- p and n + e --> light elements
- Universe becomes transparent
- Structures forms

Hubble diagram.
(first studies from 1920s)



features of the Big Bang model

- It has a singularity: ugly
- Inflationary period added ‘’ad hoc’’ to explain smoothness of matter distribution and flatness of space

But:

- It correctly predicts the cosmic microwave background (black-body radiation from the time the universe was in thermal equilibrium). Now measured and studied in detail by COBE, Boomerang and WMAP experiments
- It correctly predicts the abundances of light elements, H, He, Li.
- It predicts the number of light neutrino types, $N_\nu<3.3$, ie, no other light neutrinos apart from e, μ and τ-type

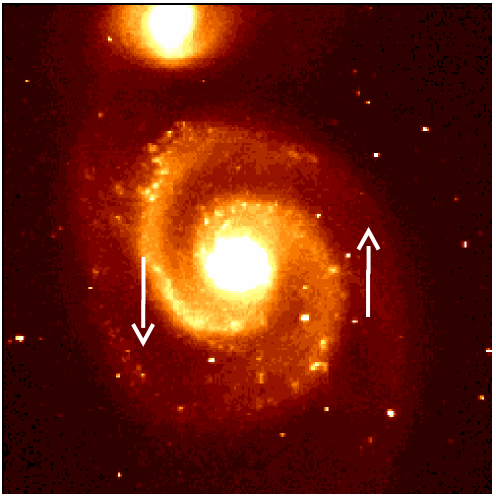
Evidence for non baryonic dark matter

how does dark matter fit in all this?

- Rotation curves of stars in galaxies
- Movement of galaxies in clusters
- Cosmic microwave background
- Gravitational lensing

- … and the result is:
    - The Universe is 23% dark, ie, composed of matter that does not emit electromagnetic radiation
    - It has to be non-baryonic, ie, not 'normal'

dark matter: rotational curve evidence



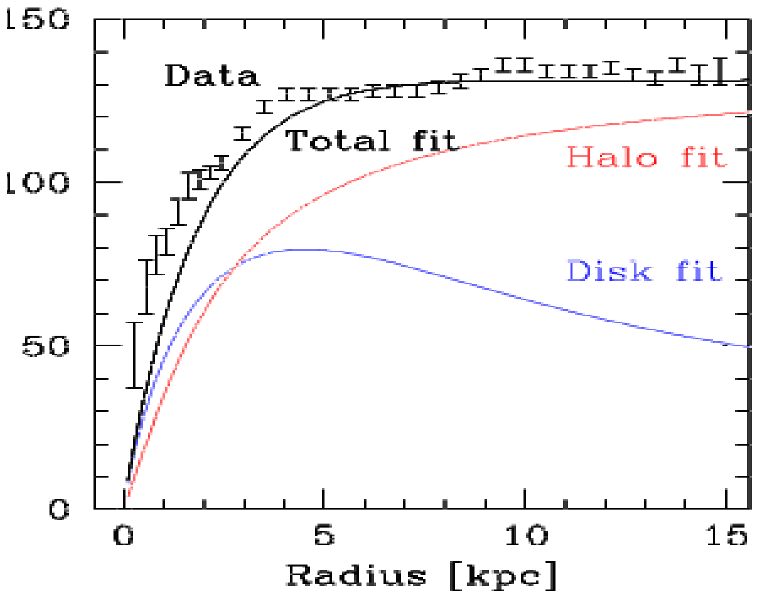
Doppler shift of spectral lines gives velocity:

$$\lambda(v)=\sqrt{\frac{1-v/c}{1+v/c}}\,\lambda_o$$

Velocity of an object moving in a $1/r^2$ potential:

$$v(r)=\sqrt{G\frac{m(r)}{r}} \qquad m(r) \text{ from } M/L$$

- M/L=mass to light ratio
- Measure M and L of stars
- Measure L from a galaxy
- Estimate total M

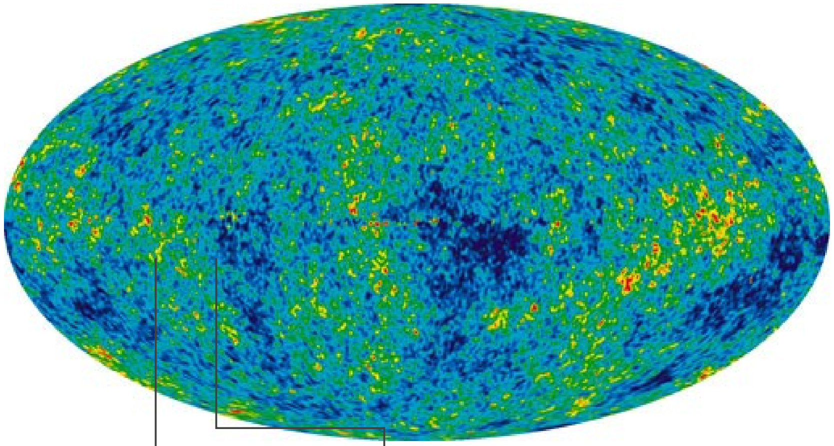


$$\frac{L}{L_\oplus}=\left(\frac{M}{M_\oplus}\right)^{4.0} \qquad \mathit{for}\ M>0.43M_\oplus$$

$$\frac{L}{L_\oplus}=0.23\left(\frac{M}{M_\oplus}\right)^{2.3} \qquad \mathit{for}\ M<0.43M_\oplus$$

this evidence is with us since the 1930's. Same if one uses the movement of galaxies in galaxy clusters, and it holds for all galaxies measured.

matter content of the universe from CMB



Things that do not shine?

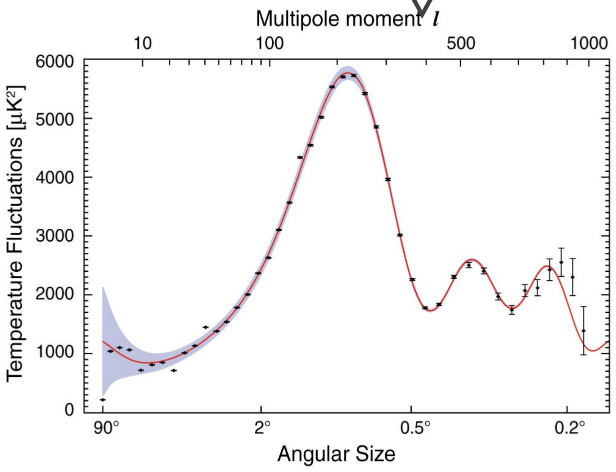
(‘MACHOs’ , Massive Compact Halo Objects)

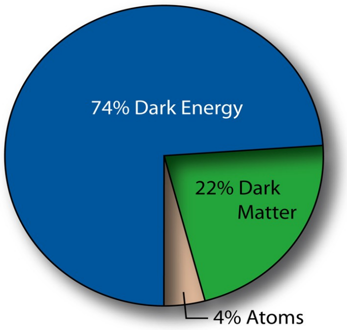
dead stars, unobserved planets, cold gas clouds…

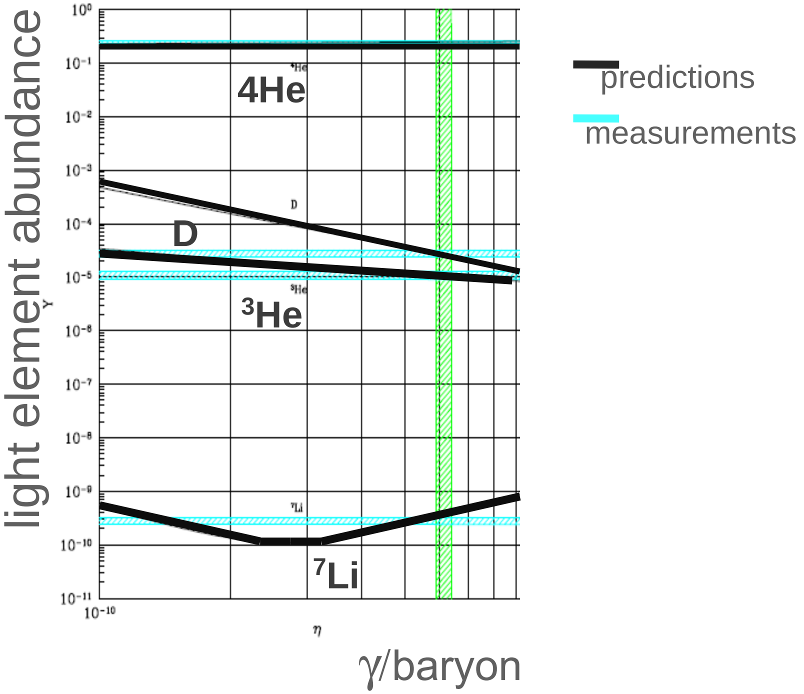
baryonic matter (made of usual stuff: p’s and n’s)

Not enough: big bang nucleosynthesis and CMB data put a very precise limit on how many baryons there are in the Universe. Otherwise the amount of observed primordial light elements (D, He, Li) can not be explained

$$\Delta T, \Theta$$







http://map.gsfc.nasa.gov/resources/camb_tool/index.html

standard dark matter candidates

Neutrinos: They exist! And we know they have mass, not much, but there are many of them. However, not enough to explain the missing mass:

experimental limits on the neutrino mass:

$$m_\nu < 2\, eV$$

The cosmic mass density of neutrinos calculated from Big-Bang theory

$$\Omega_\nu h^2 = \sum_{i=1}^{3} \frac{m_i}{93 eV}$$

$$\Omega_\nu h^2 \leq 0.07 << 1 \qquad \left(h = H_o / 100 \;\; km\, s^{-1}\; Mpc^{-1}\right)$$

ie, neutrinos are not abundant enough to be **the dominant** dark matter

Besides, the Pauli exclusion principle limits the number of neutrino states that can be accommodated in a galactic halo:

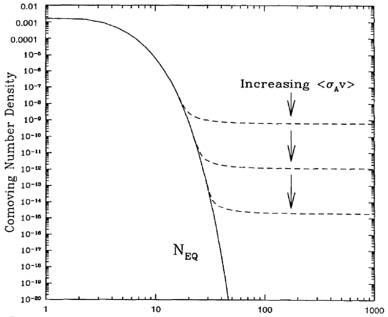
$$n_\nu(E) = g_\nu \frac{1}{e^{E/kT} + 1}$$

(gν=nb. of helicity states)

Need other candidates!

the particle physics connection: supersymmetry

- (x)MSSM: Minimal Supersymmetric extension of the Standard Model
- Extension(s) of the Standard Model
- Introduces (predicts) many new particles (one per existing elementary particle, differing in spin by 1/2)
- One has to be stable, with m>$\mathcal{O}$(10) GeV (from accelerator searches, model dependent) and m<300 TeV (from theoretical constraints)



- Is a good candidate for dark matter: neutralino,

$$\tilde{\chi}^0_1 = N_1\mathbf{B} + N_2\mathbf{W}^3 + N_3 H^0_1 + N_4\mathbf{H}^0_2$$

- It is produced in the big bang and a ‘gas’ of them remains as relics
- They interact only weakly and gravitationally

$$\Omega = \frac{3\text{x}10^{-27}\,cm^3\,s^{-1}}{\sigma\ v}$$

- Can be gravitationally bound in the halos of galaxies and be further trapped in heavy bodies: Sun, Earth, Galactic Center
- Increased concentration → $\underbrace{\text{annihilation } \chi\chi \rightarrow \text{ SM particles} \rightarrow \nu\text{'s, e's, } \gamma\text{'s}}_{\text{Indirect detection!}}$

Standard Model particles and fields		Supersymmetric partners			
		Interaction eigenstates		Mass eigenstates	
Symbol	Name	Symbol	Name	Symbol	Name
$q = d, c, b, u, s, t$	quark	$\tilde{q}_L, \tilde{q}_R$	squark	$\tilde{q}_1, \tilde{q}_2$	squark
$l = e, \mu, \tau$	lepton	$\tilde{l}_L, \tilde{l}_R$	slepton	$\tilde{l}_1, \tilde{l}_2$	slepton
$\nu = \nu_e, \nu_\mu, \nu_\tau$	neutrino	$\tilde{\nu}$	sneutrino	$\tilde{\nu}$	sneutrino
g	gluon	$\tilde{g}$	gluino	$\tilde{g}$	gluino
$W^\pm$	W-boson	$\tilde{W}^\pm$	wino	$\tilde{\chi}^\pm_{1,2}$	chargino
H^-	Higgs boson	$\tilde{H}^-_1$	higgsino		
H^+	Higgs boson	$\tilde{H}^+_2$	higgsino		
B	B-field	$\tilde{B}$	bino	$\tilde{\chi}^0_{1,2,3,4}$	neutralino
W^3	W^3-field	$\tilde{W}^3$	wino		
H^0_1	Higgs boson	$\tilde{H}^0_1$	higgsino		
H^0_2	Higgs boson	$\tilde{H}^0_2$	higgsino		
H^0_3	Higgs boson				

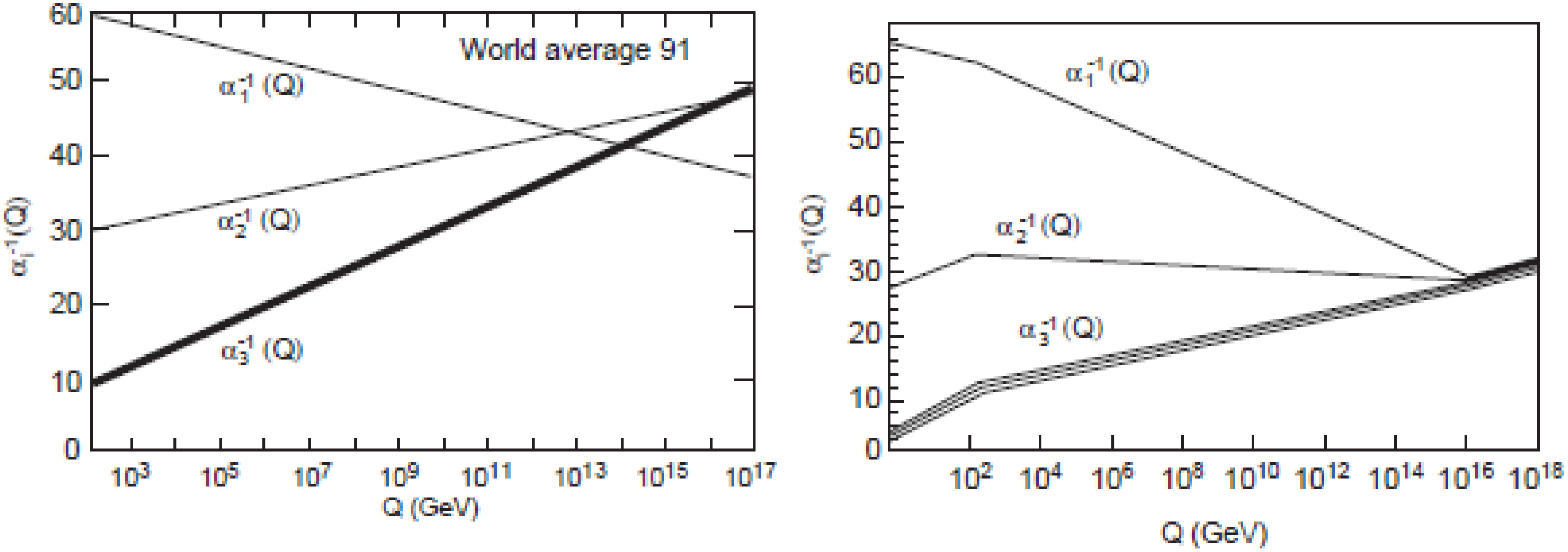
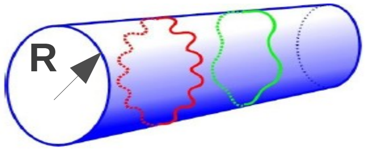


Fig. 10. The measurements of the gauge coupling strengths at LEP do not (left) evolve to a unified value if there is no supersymmetry but do (right) if supersymmetry is included [29,220].

other candidates

extra dimensions: models originally devised to unify gravity and electromagnetism. No experimental evidence again a space 3+δ+1 as long as the extra dimensions are ‘compactified’.



- Simple quantum mechanics argument:
- Lightest Kaluza-Klein mode (n=1)
- m≈1/R~ 400 -1500 GeV

$$n\frac{\lambda}{2} = 2\pi R, \qquad n\frac{h}{2p} = 2\pi R \Rightarrow p = n\frac{h}{4\pi R}$$

$$E^2 = p^2c^2 + m_o{}^2c^4 = n^2\frac{1}{R^2}c^2 + m_o{}^2c^4 = m_n{}^2c^4$$

$$m_n^2 = \frac{n^2}{c^2R^2} + m_o^2$$

Superheavy dark matter (Simpzillas)

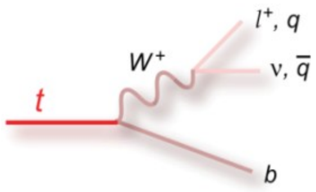
Produced **non-thermally** at the end of inflation through vacuum quantum fluctuations

strong Xsection (= not-weak)

m from **~10^4 GeV to 10^{18} GeV**

$$\frac{dN}{dE_\nu} \propto \frac{E_\nu + \mathrm{m_W}}{\sqrt{(E_\nu + \mathrm{m}_t)[(E_\nu + \mathrm{m}_t)^2 - \mathrm{m}_t^2][(E_\nu + \mathrm{m_W})^2 - \mathrm{m_W^2}]}}$$

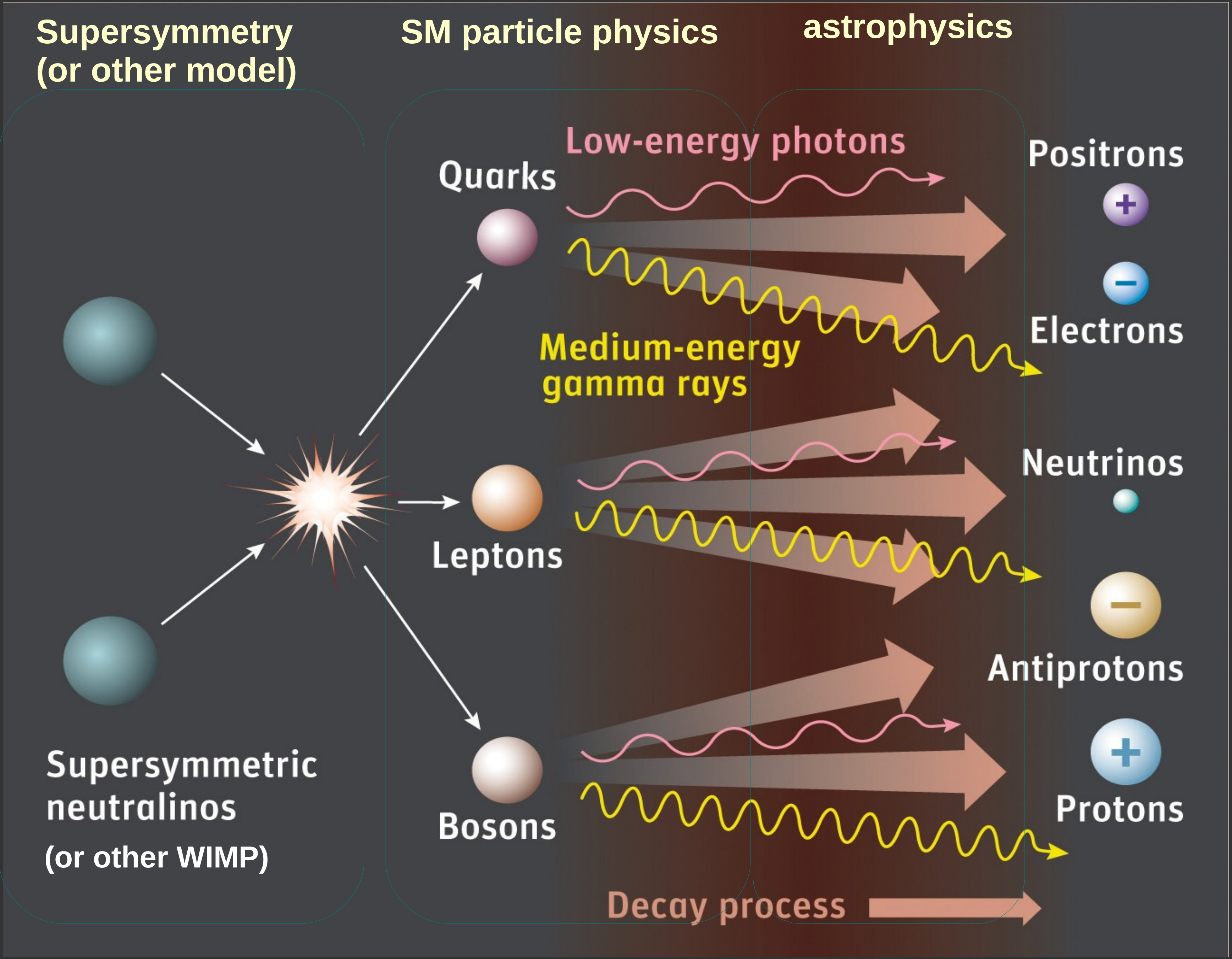
Can be accommodated in supersymmetric or UED models



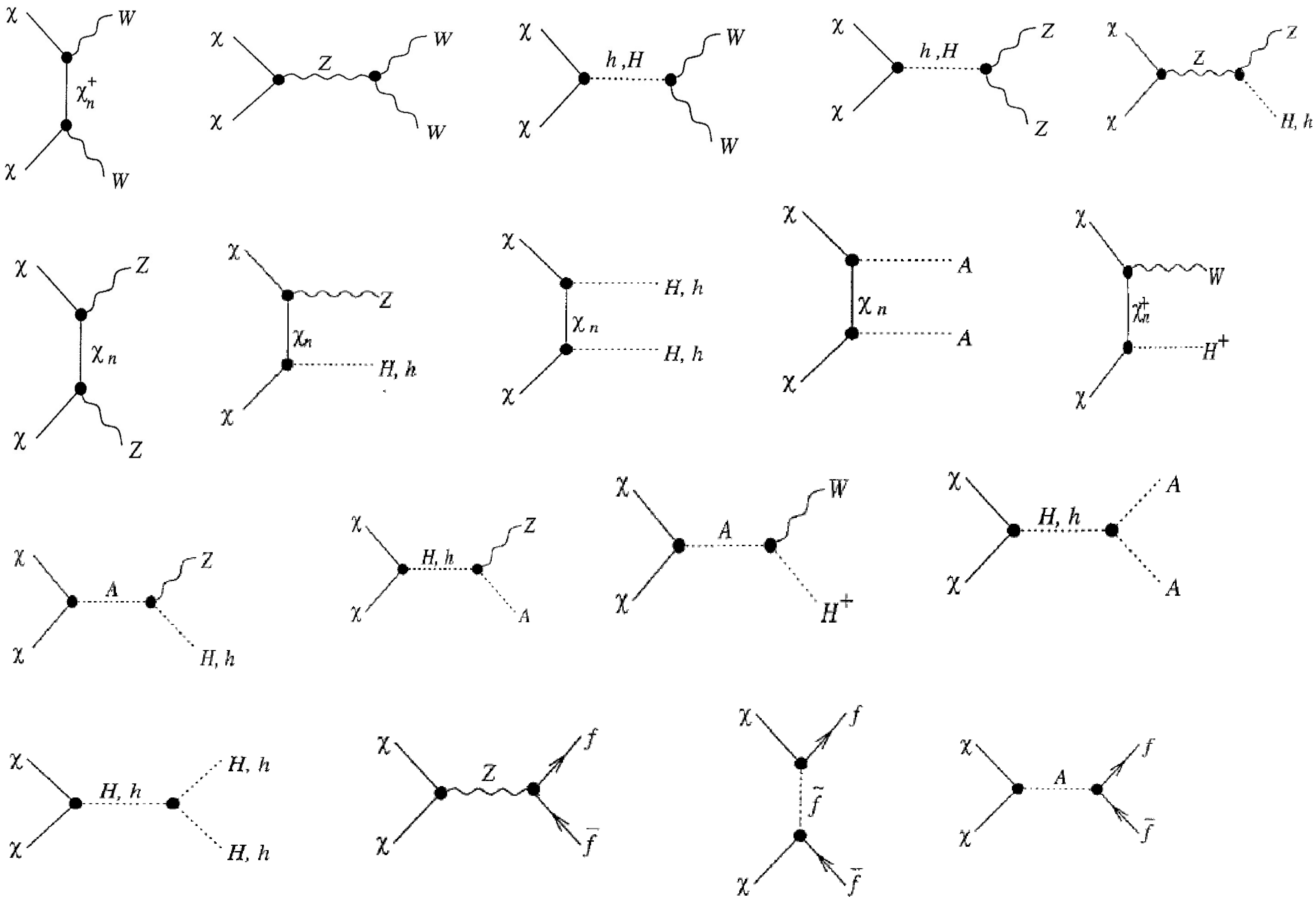
- S+S → t $\bar{t}$, ~3×10^5 sqr($m_S/10^{12}$GeV) tops per annihilation

indirect signatures from dark matter annihilation

the artist point of view...



… and the physicist point of view



…

indirect searches for dark matter

DM-induced SM particles:

$$\kappa\kappa,\ \chi\chi, SS \rightarrow \left\{ \begin{array}{c} q\bar{q} \\ \ell^+\ell^- \\ W, Z, H \\ \ldots \end{array} \right\} \rightarrow \nu, \gamma, e^+e^-, \bar{p}$$

Kaluza-Klein modes an additional useful channel:

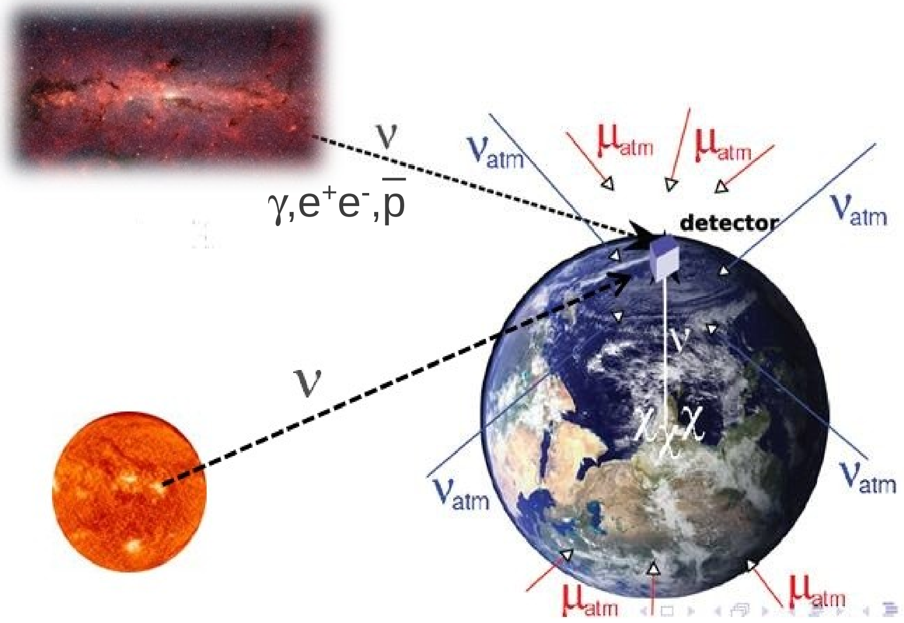
$$\kappa\kappa \rightarrow \nu\nu$$

signature:
excess over background from
Sun/Earth/Galactic Halo/nearby galaxies

A lot of physics uncertainties involved:
- relic density calculations
- DM distribution in the halo
- velocity distribution
- χ,K,S properties (MSSM/UED...)
- interaction of χ,K,S with matter (capture)
- self interaction (annihilation)

Look at objects where dark matter can have accumulated gravitationally over the evolution of the Universe

Sun, Earth, Galactic Halo/Center, Nearby galaxies



1 billion particle simulation of dark matter structure formation
during the evolution of the universe. The dark matter are the bright spots!
(note the scale)

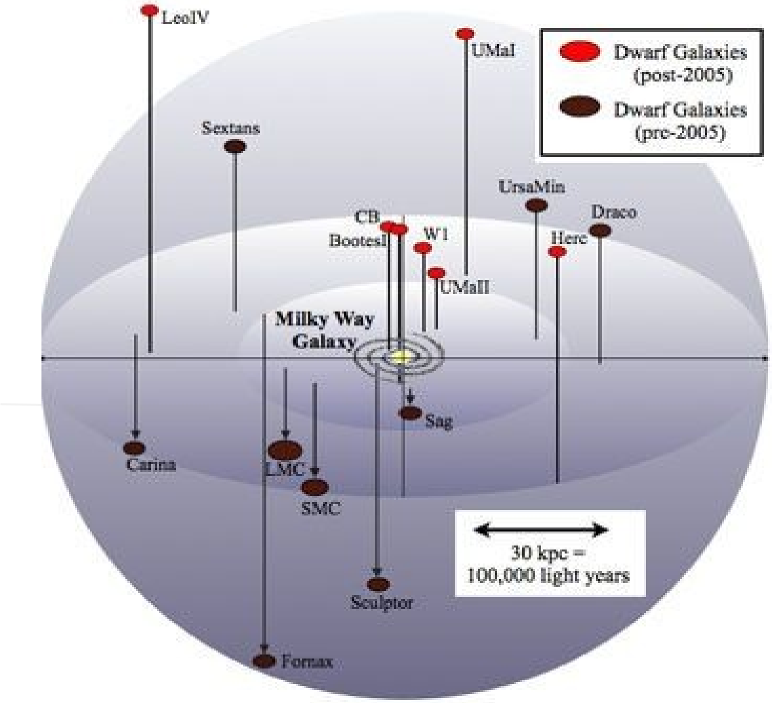
dark matter searches from nearby dwarf galaxies

- dwarf galaxies: high mass/light ratio → high concentration of DM in the halos

- known location. Distributed both in the north and southern sky.
    - Point-like search techniques: stacking
    - known distance -> determination of absolute annihilation rate if a signal is detected

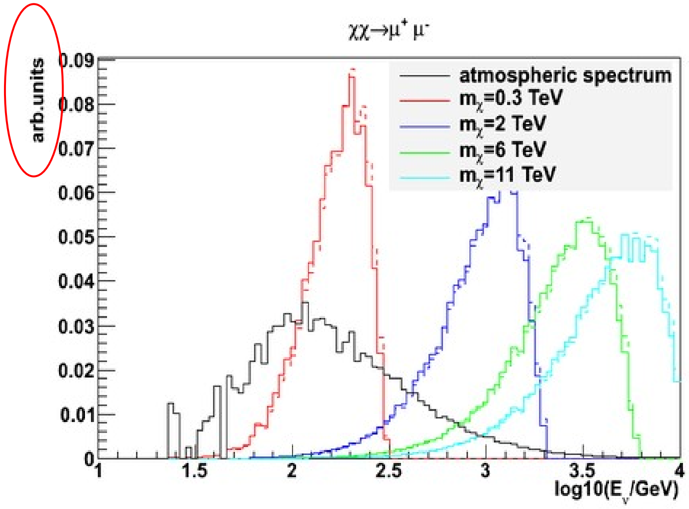
- close by: closer than 100 kpc to the galactic center

- same expected gamma/neutrino spectra as for the galactic center/halo, but less background from structure or point sources



Same strategy as in the galactic halo analysis:

$$\frac{d\Phi_j(\Delta\Omega, E_j)}{dE_j} = \frac{\langle\sigma v\rangle}{2m_\chi^2}\frac{dN_j}{dE_j}J(\Delta\Omega)$$



advantage for neutrino telescopes if DM is leptophilic, as suggested by PAMELA results (see below)

indirect searches for dark matter

The prediction of signals from dark matter annihilation is complex and involves many subjects of physics

- relic density calculations (cosmology)
- dark matter distribution in the halo (astrophysics)
- velocity distribution of the dark matter in the halo (astrophysics)
- physical properties of the dark matter candidate (particle physics)
- interaction of the dark matter candidate with normal matter (for capture) (nuclear physics/particle physics)
- self interactions of the dark matter particles (annihilation) (particle physics)
- transport of the annihilation products to the detector (astrophysics/particle physics)

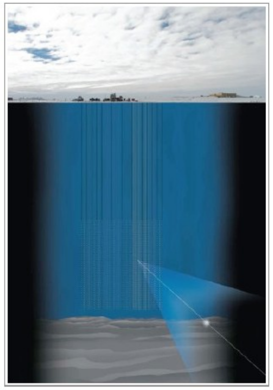
signatures and detection techniques

Indirect dark matter searches through these three ‘signatures’:
e+e- and $\bar{p}$, photons and neutrinos:

- e’s charged –> deflected by (inter)galactic magnetic fields
- γ’s easily absorbed by intervening matter
- ν’s extremely difficult to detect (only weak, and gravitational, interaction)

Detectors:

- γ’s: Cherenkov telescopes (surface), satellites (space)
- e+e-: satellites (space)
- ν’s: neutrino ‘telescopes’ (underground/underwater)



a daunting task to cover all indirect dark matter detection efforts

future exp.

TRACER

PEBS

GVD

BAIKAL

KM3NET

MILAGRO

ANTARES

AGILE

VERITAS

MAGIC

NEMO

AGIS

AMS

NESTOR

HAWC

Fermi

PAMELA

HESS

CTA

CANGAROO

VLA, HEAO-3, WMAP, Bonn, Parkes ,
COBE, FIRAS, Planck, Alma,Chandra

BESS-polar ICECUBE

CREAM

PPB-Bets

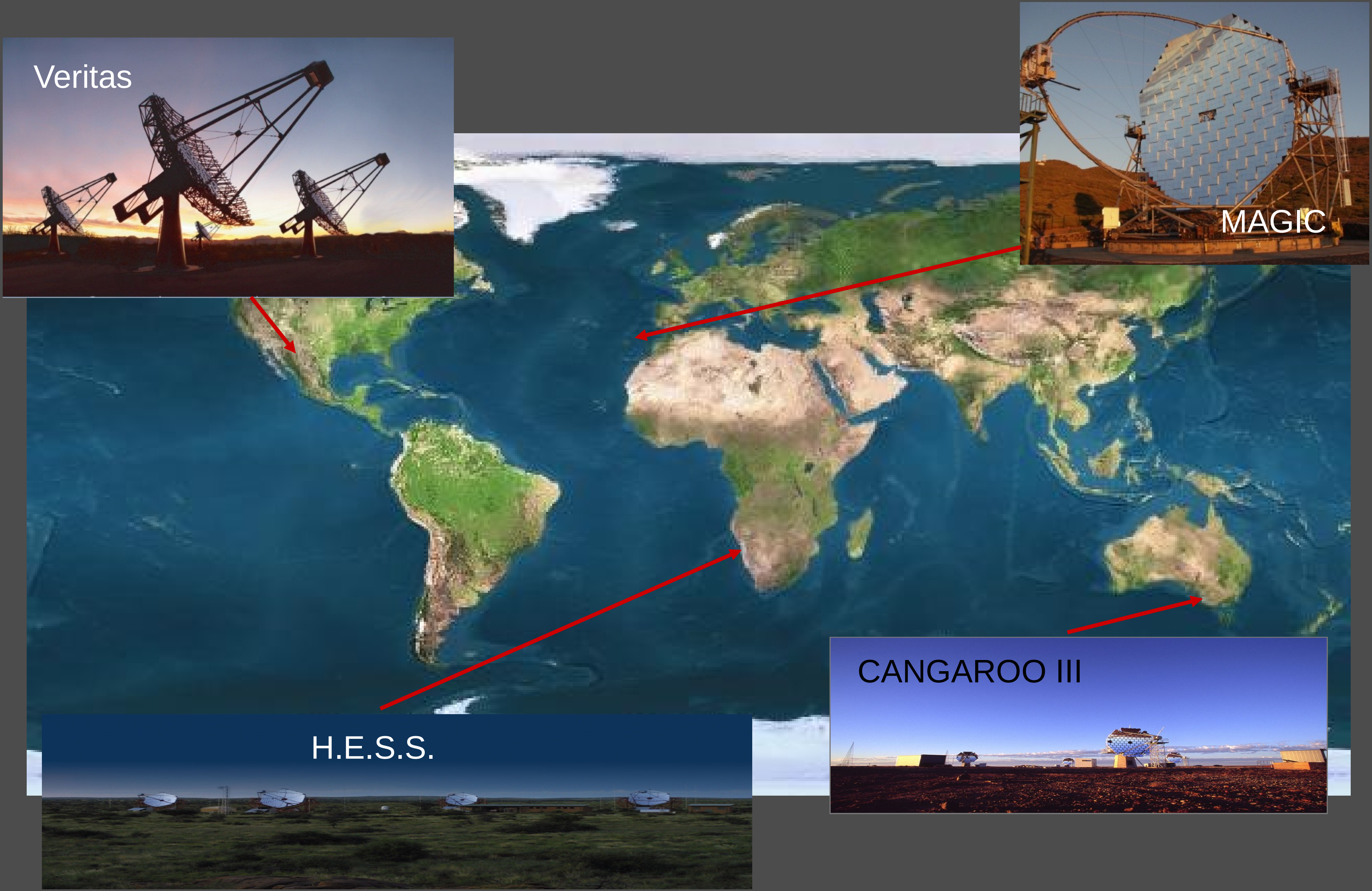
ATIC

GAPS

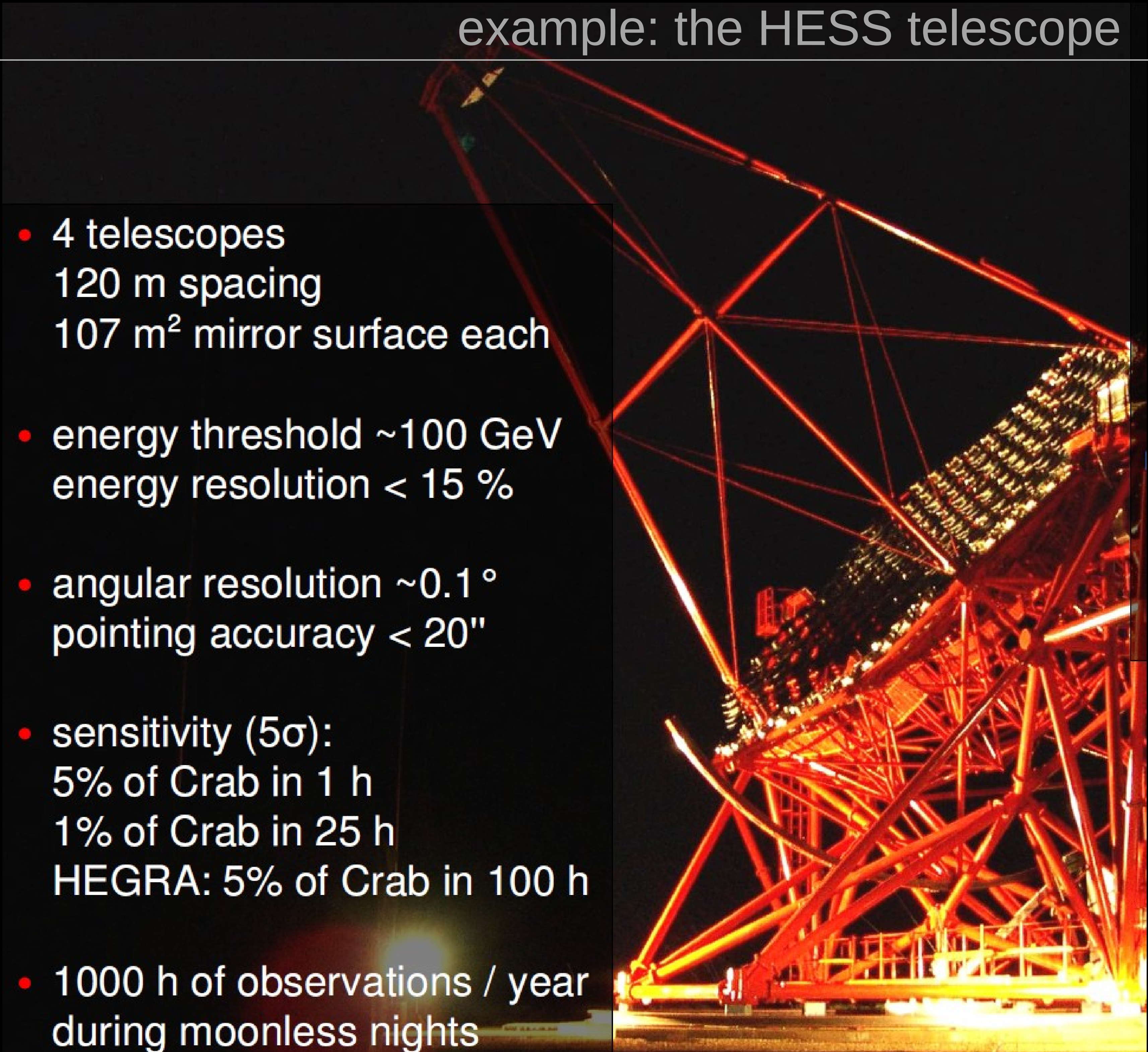
CALET

(stolen from J. Conrad)

searches with gamma rays: Cherenkov telescopes

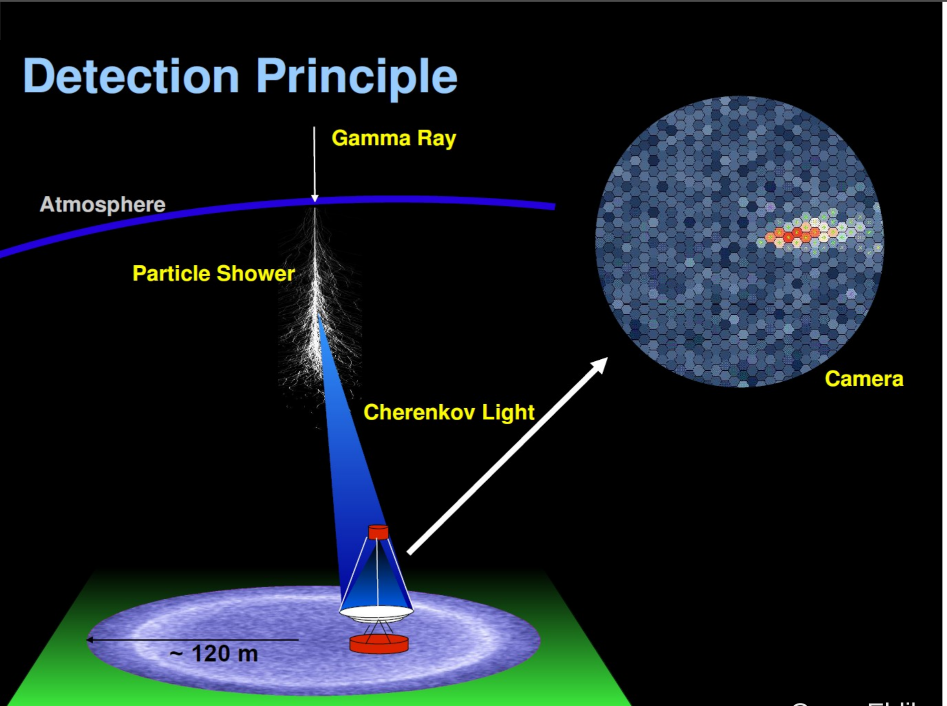


example: the HESS telescope

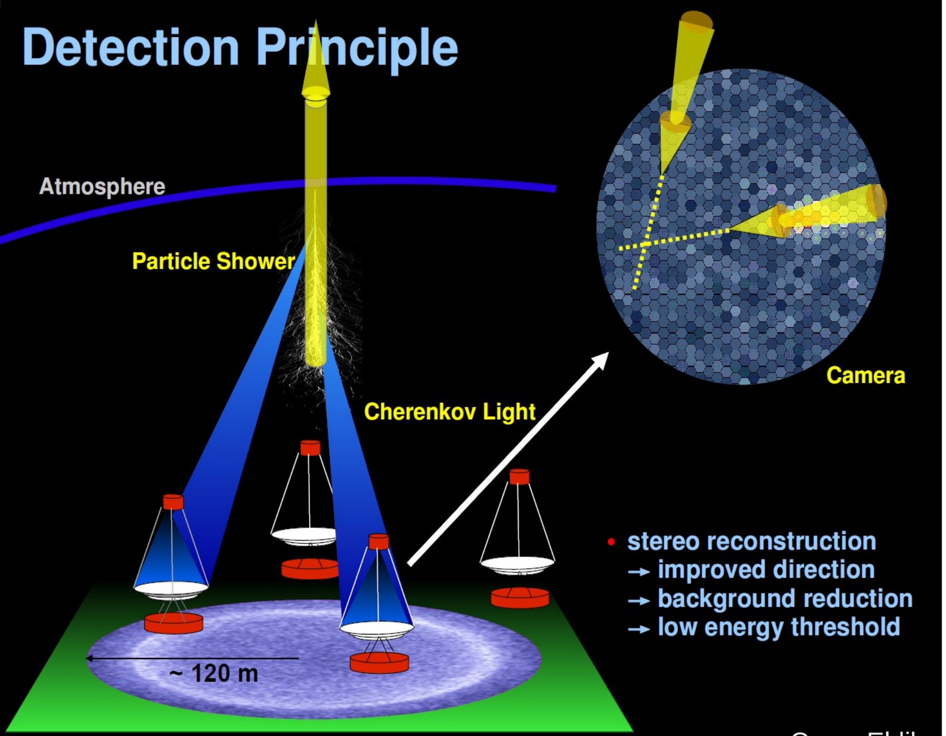


- 4 telescopes
  120 m spacing
  107 m^2 mirror surface each
- energy threshold ~100 GeV
  energy resolution < 15 %
- angular resolution ~0.1 °
  pointing accuracy < 20''
- sensitivity (5σ):
  5% of Crab in 1 h
  1% of Crab in 25 h
  HEGRA: 5% of Crab in 100 h
- 1000 h of observations / year
  during moonless nights

Cherenkov telescopes: principle of operation



C. vanEldik



C. vanEldik

- Aim: detect gamma rays ($E \gtrsim$ few GeV) with good angular resolution (0.1°)

- High energy gamma rays (or p/nuclei) create electromagnetic shower in the atmosphere:

  e^+e^- production+bremmstrahlung

-particle velocities > speed of light in air

→ Cherenkov light

-can be detected by telescopes with large mirrors focusing the light on highly pixelized cameras

image intensity → energy

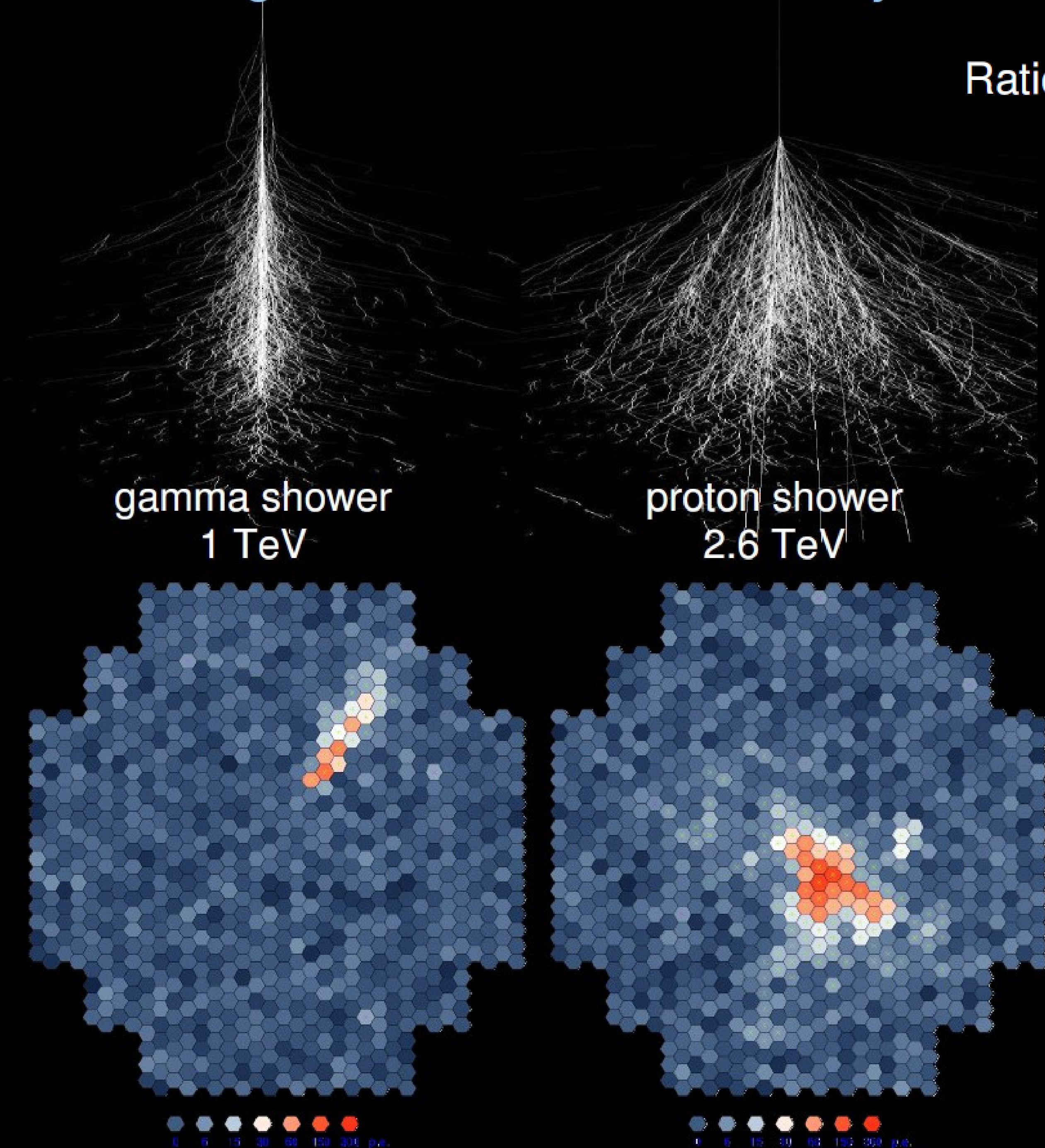
image orientation → direction

image shape → type of particle

Cosmic Rays...

...main background for Cherenkov astronomy

Ratio γ/hadron ≈ 1/1000

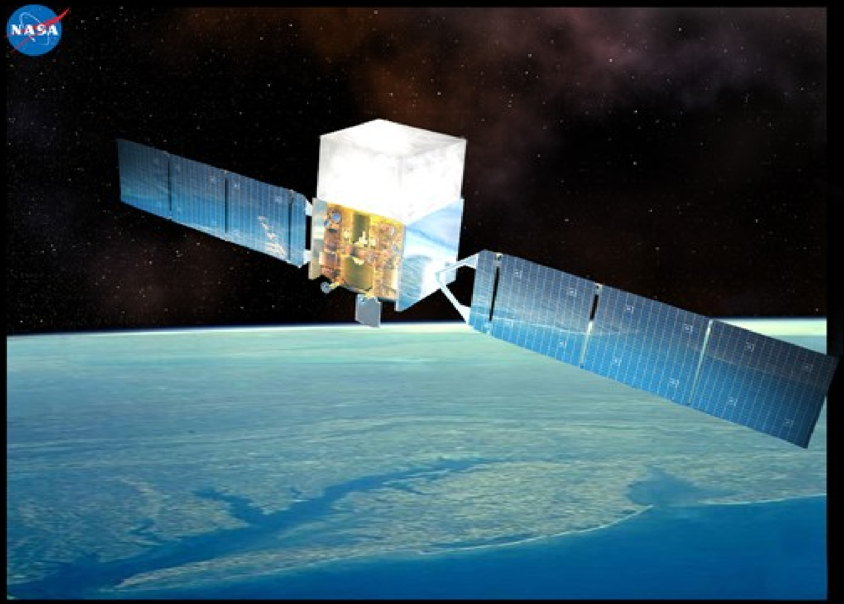


K. Bernlöhr

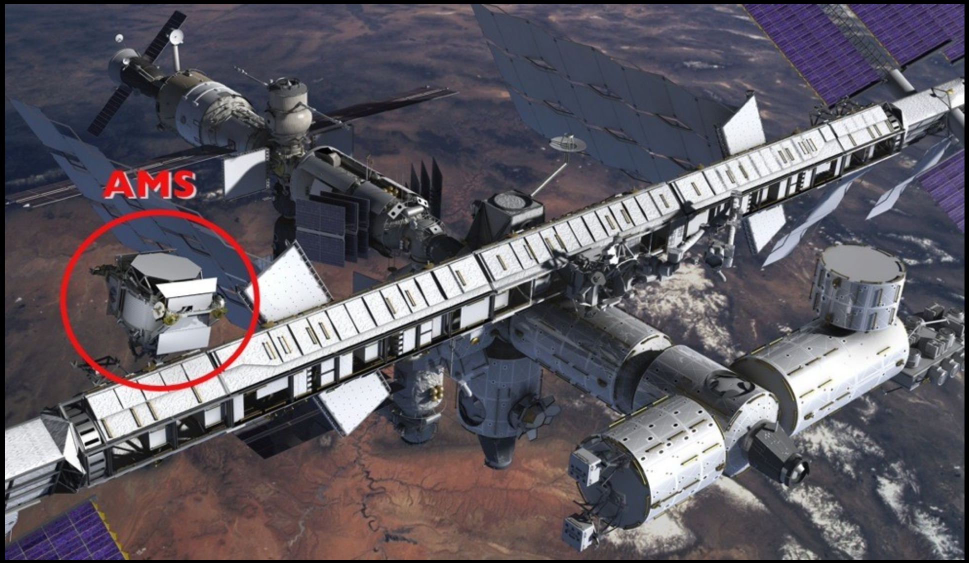
C. vanEldik

searches with cosmic rays: satellites

Fermi

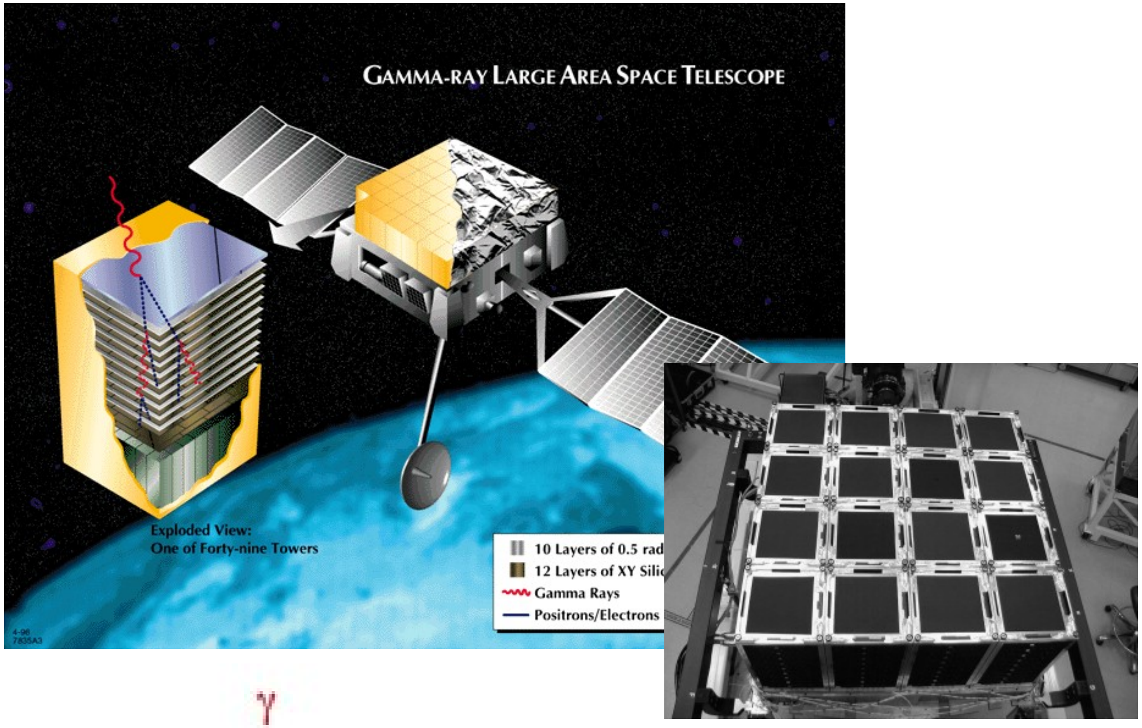


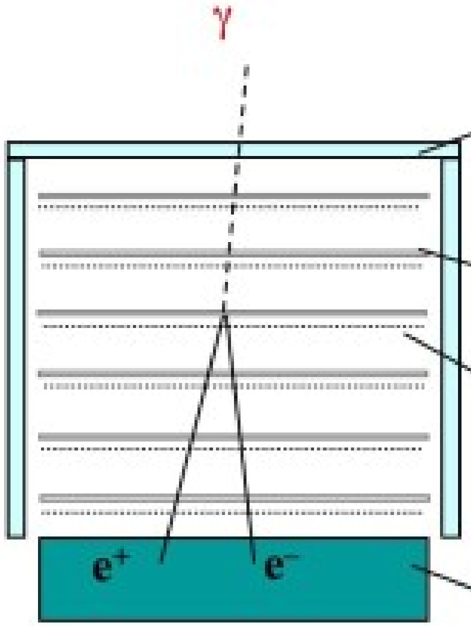
Pamela



AMS

the Fermi gamma ray satellite





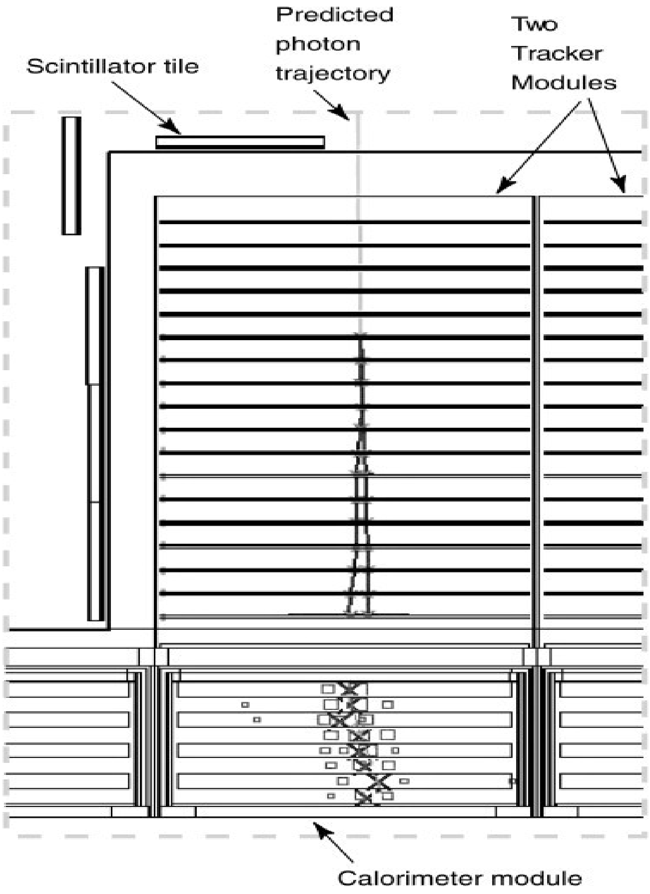
Anticoincidence Detector (background rejection)

Conversion Foil (tungsten)

Particle Tracking Detectors (x-y position)

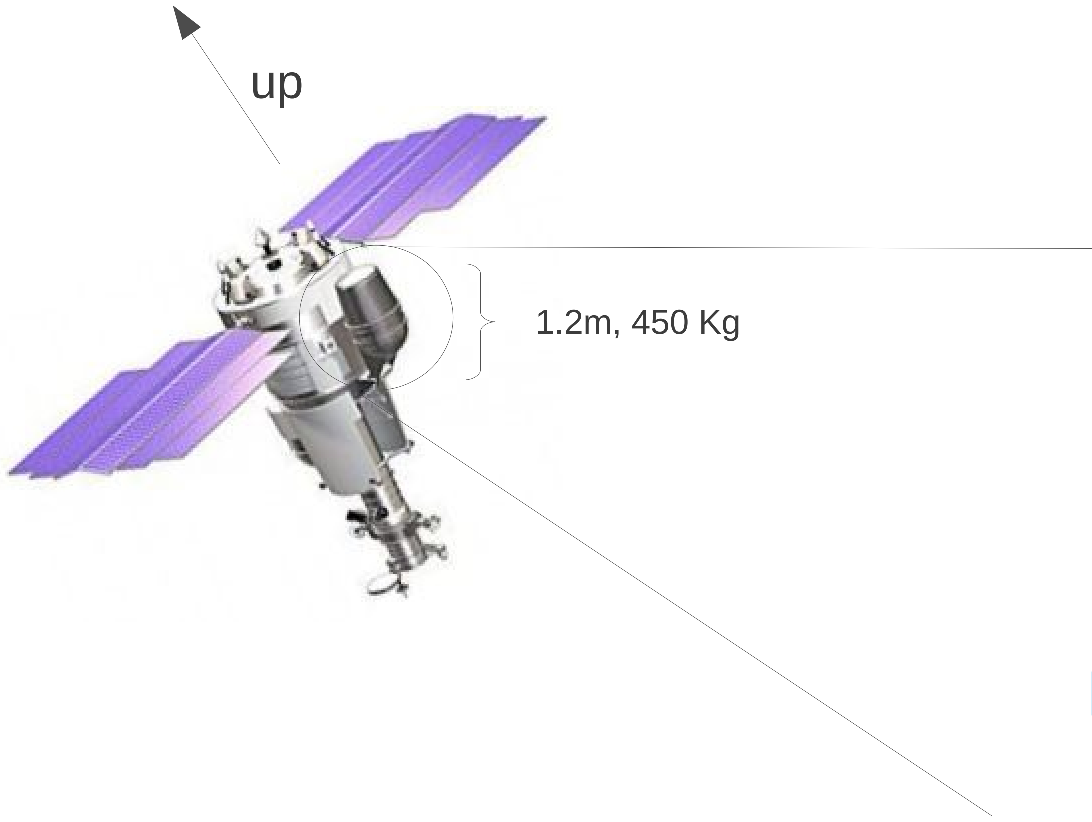
Calorimeter (energy measurement)

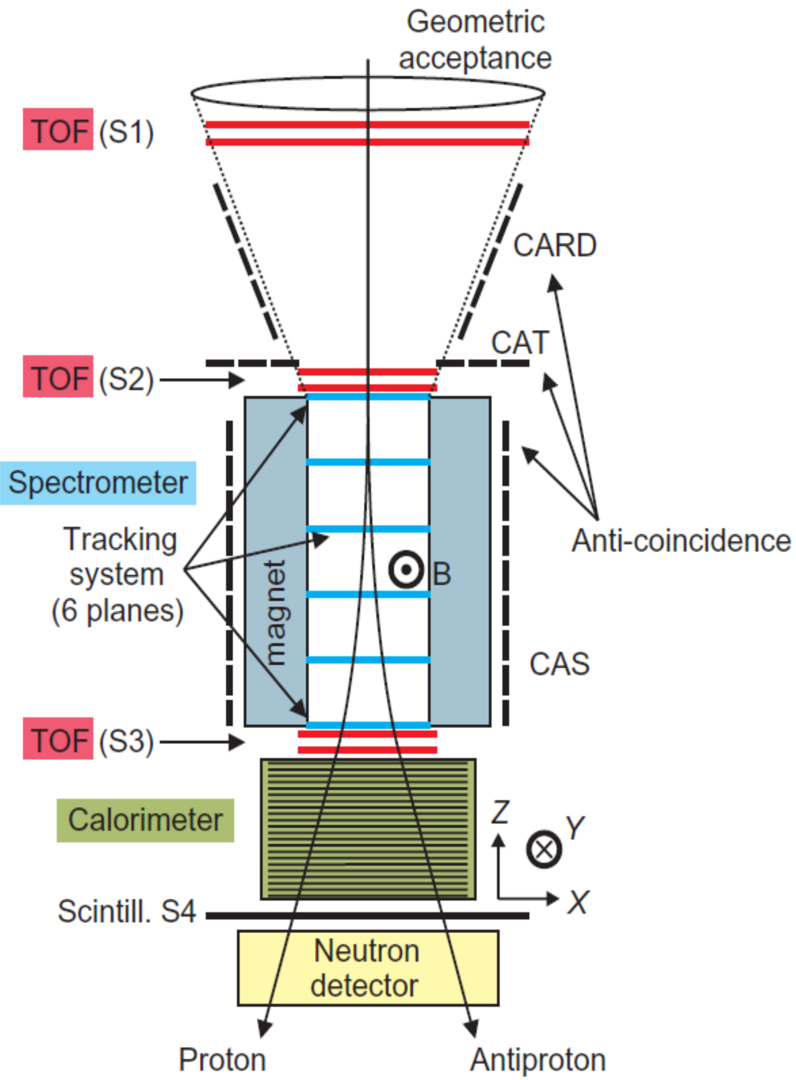
8-layer scintillator cristal



Parameter	Value or Range
Energy range	20 MeV – 300 GeV
Effective area at normal incidence[a]	9,500 cm^2
Energy resolution (equivalent Gaussian 1σ):	
100 MeV – 1 GeV (on axis)	9%–15%
1 GeV – 10 GeV (on axis)	8%–9%
10 GeV – 300 GeV (on-axis)	8.5%–18%
>10 GeV (>60° incidence)	$\leq$6%
Single photon angular resolution (space angle)	
on-axis, 68% containment radius:	
>10 GeV	$\leq$0.15°
1 GeV	0.6°
100 MeV	3.5°
on-axis, 95% containment radius	$< 3 \times \theta_{68\%}$
off-axis containment radius at 55°	< 1.7× on-axis value
Field of View (FoV)	2.4 sr
Timing accuracy	$< 10\ \mu$sec
Event readout time (dead time)	26.5 μsec

the PAMELA cosmic ray satellite



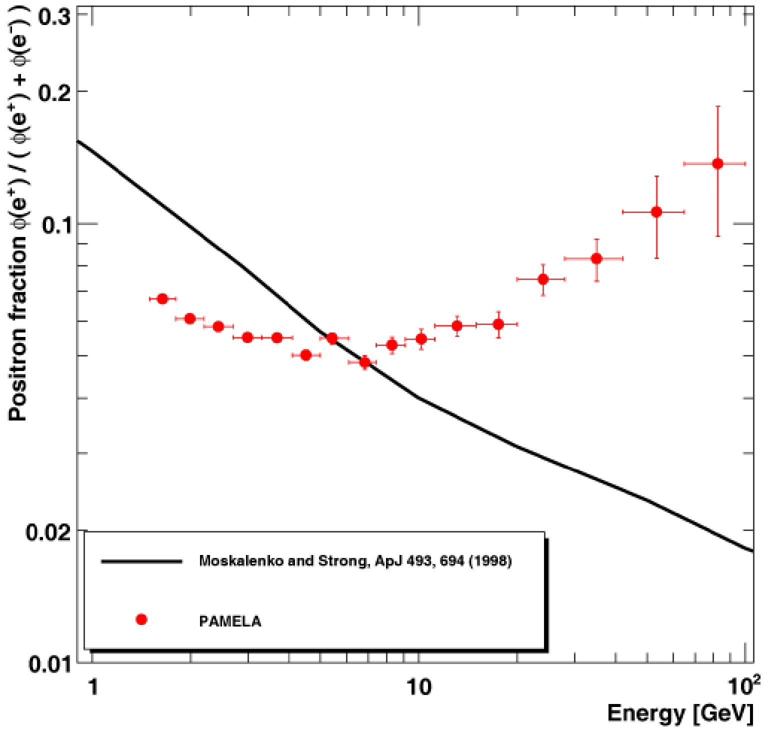


Particle	Energy range
Antiprotons	80 MeV–190 GeV
Positrons	50 MeV–300 GeV
Electrons	up to 500 GeV
Protons	up to 700 GeV
Electrons + positrons	up to ∼1 TeV (from calorimeter)
Light nuclei (He/Be/C)	up to 200 GeV nucleon $^{-1}$
Antinuclei search	sensitivity of 3×10^{-8} in anti-He/He

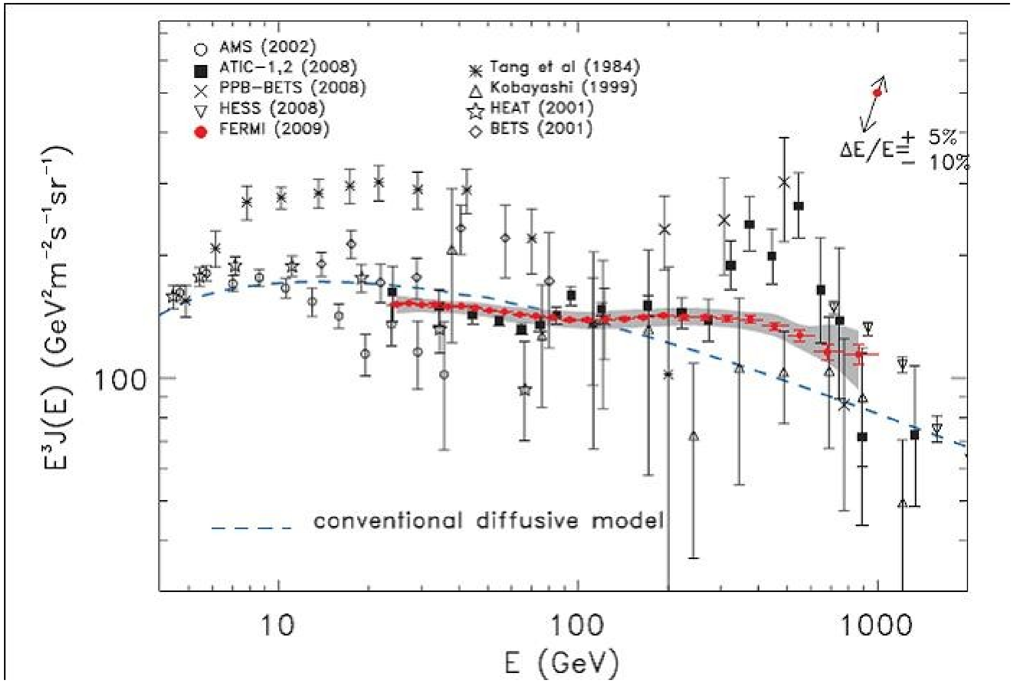
results from space: PAMELA and Fermi

What needs to be explained?

e^+/e^++e^- flux from Pamela



e^++e^- flux from Fermi



$$\frac{d\Phi}{dE} = \frac{\langle \sigma_A v \rangle}{2} J(\psi) \frac{R_{sc}\rho_{sc}^2}{4\pi m_\chi^2} \frac{dN}{dE}$$

Measure

Constrain

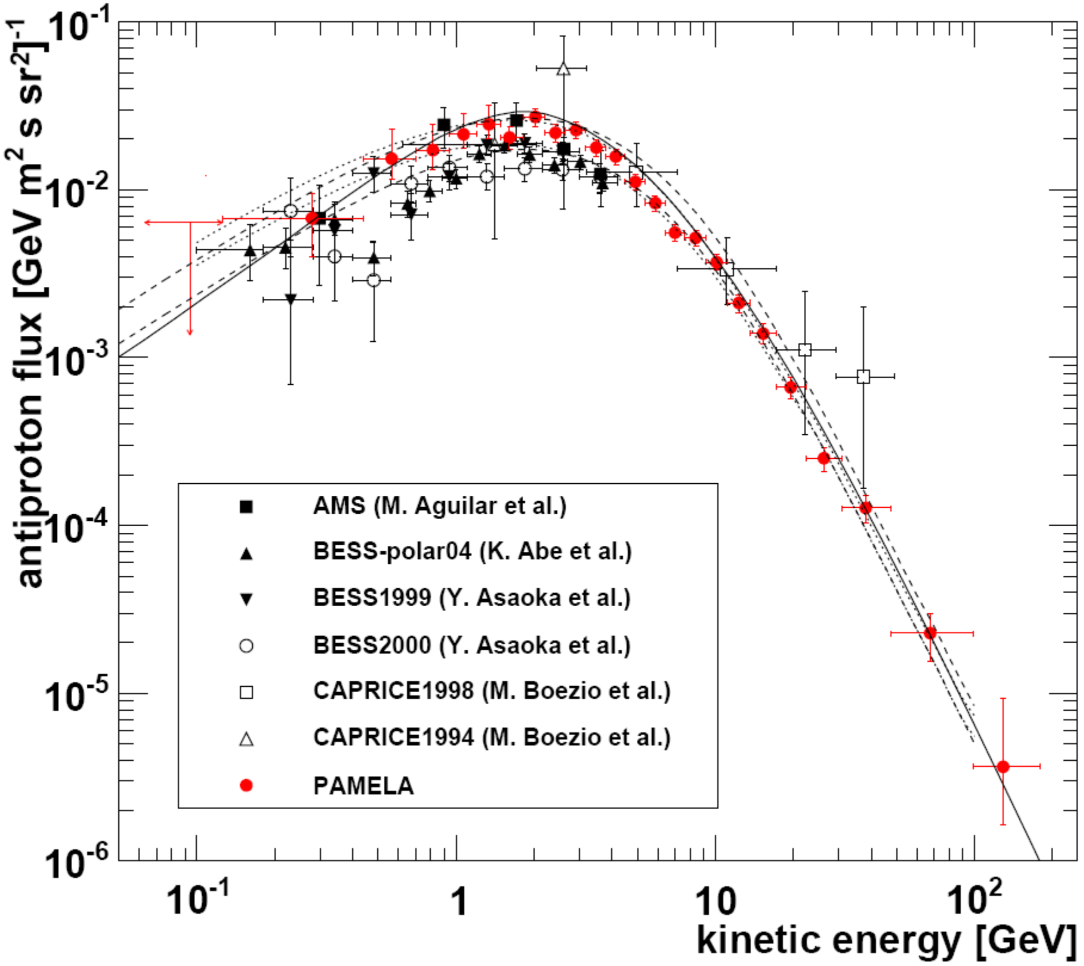
Halo

SUSY

photon or electron flux

results from space: PAMELA and Fermi

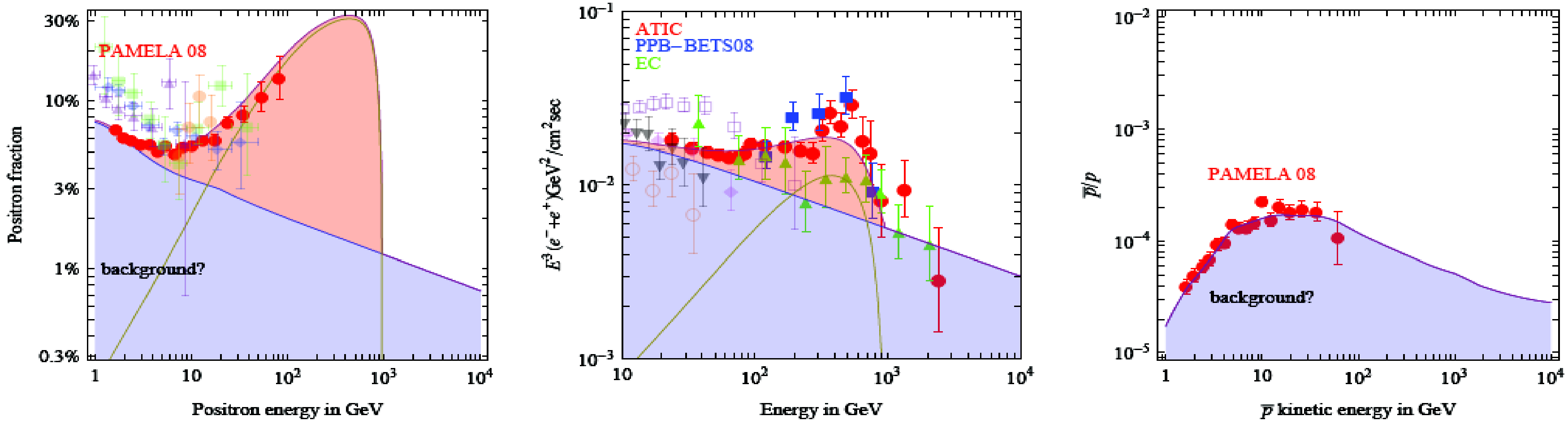
Remember: the $\bar{p}$ flux must not be spoiled



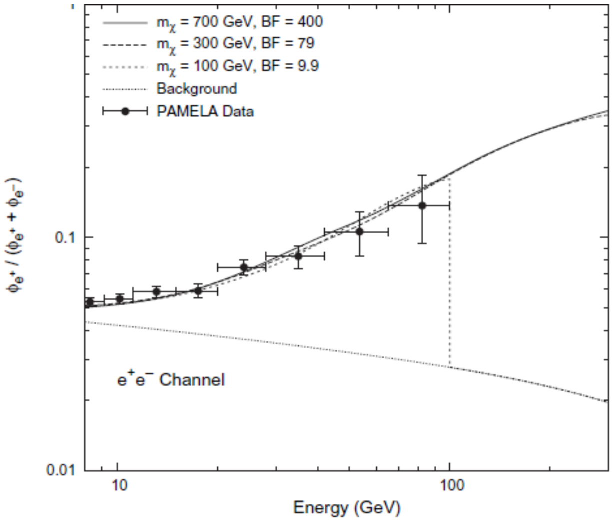
i.e., to explain the excess as dark matter we need models that produce electrons and positrons, but without producing too many photons and antiprotons

results from space: PAMELA and Fermi

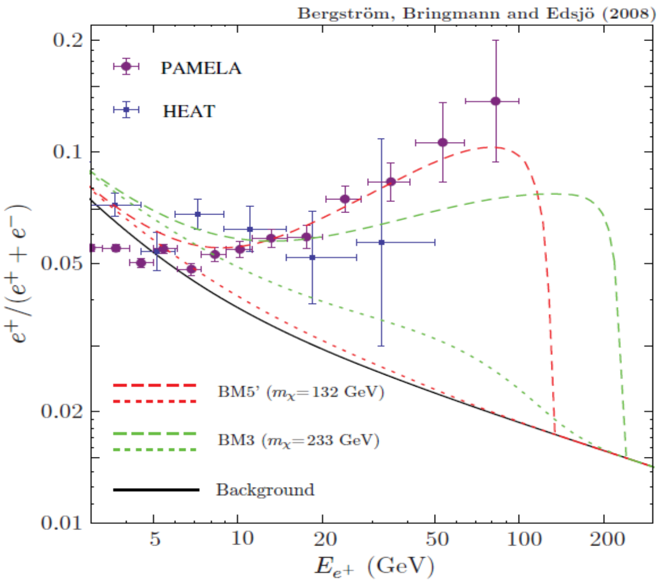
Plenty of dark matter explanations. Easy to fit due to the free parameters


Cirelli et al. arXiv:0809.2409

“leptophilic” DM: $\chi\chi \to \mu^+\mu^-$



new decay mode through
a new light boson, $\chi\chi \to \phi \to e^+e^-$


Bergström, Bringmann and Edsjö (2008)

“normal DM”

(then low masses favoured)

results from space: PAMELA and Fermi

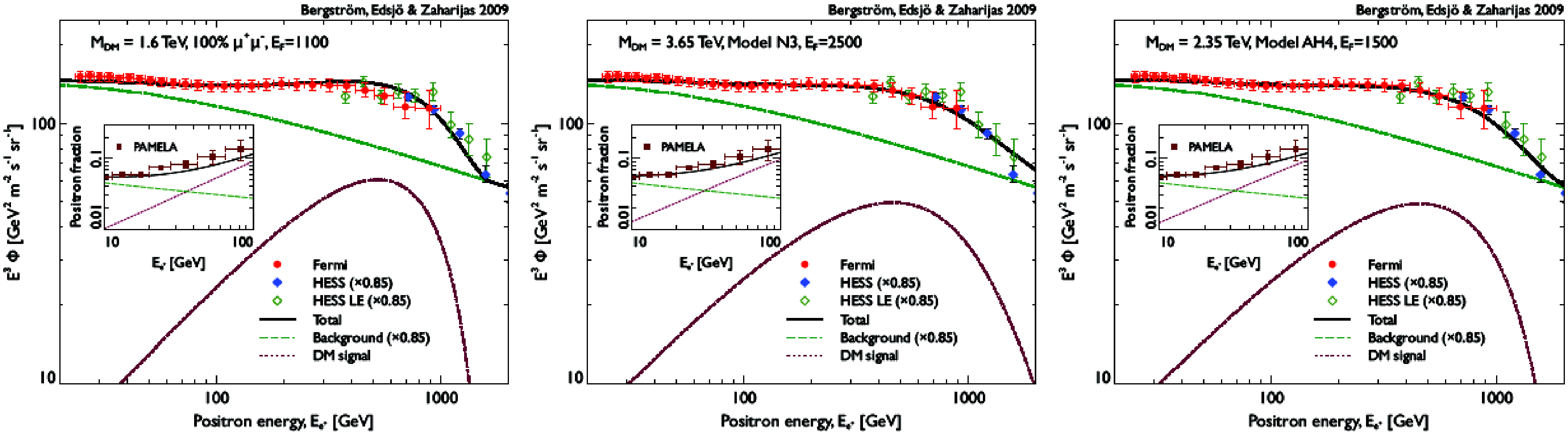
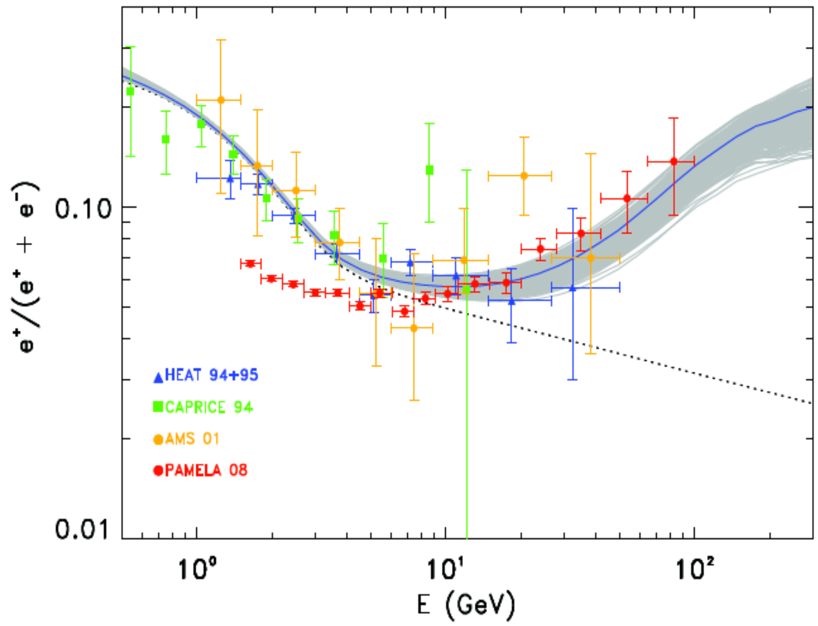


FIG. 2: Spectra for examples of good fit models in 1. The signal and background are shown for electrons $(e^+ + e^-)$ together with Fermi [9] and HESS data [11, 27]. The HESS data and the background model has been rescaled with a factor 0.85. In the inset, the positron fraction as measured with PAMELA is shown together with the predicted signal for the same model.

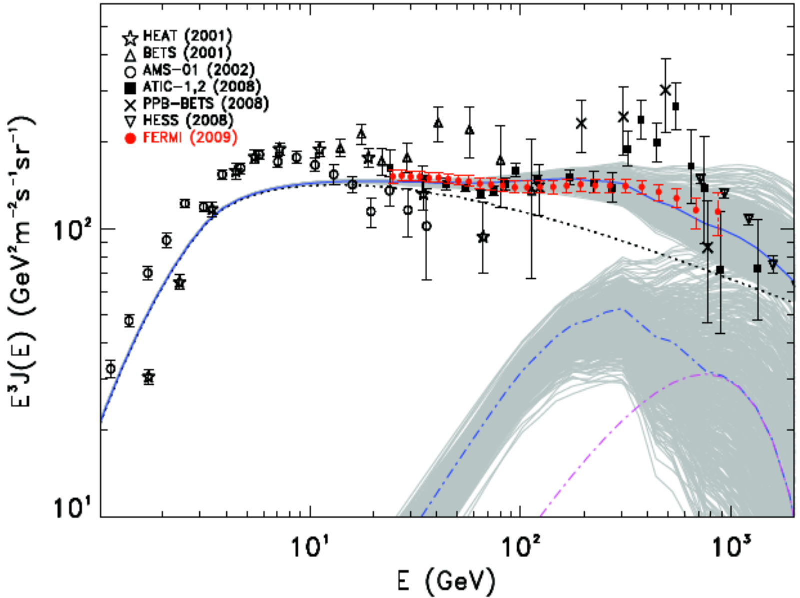
Bergström et al, arXiv:0905.0333

results from space: PAMELA and Fermi

e^+ fraction



e^++e^-



Grasso et al, arXiv:0905.0636

Conventional explanation possible:

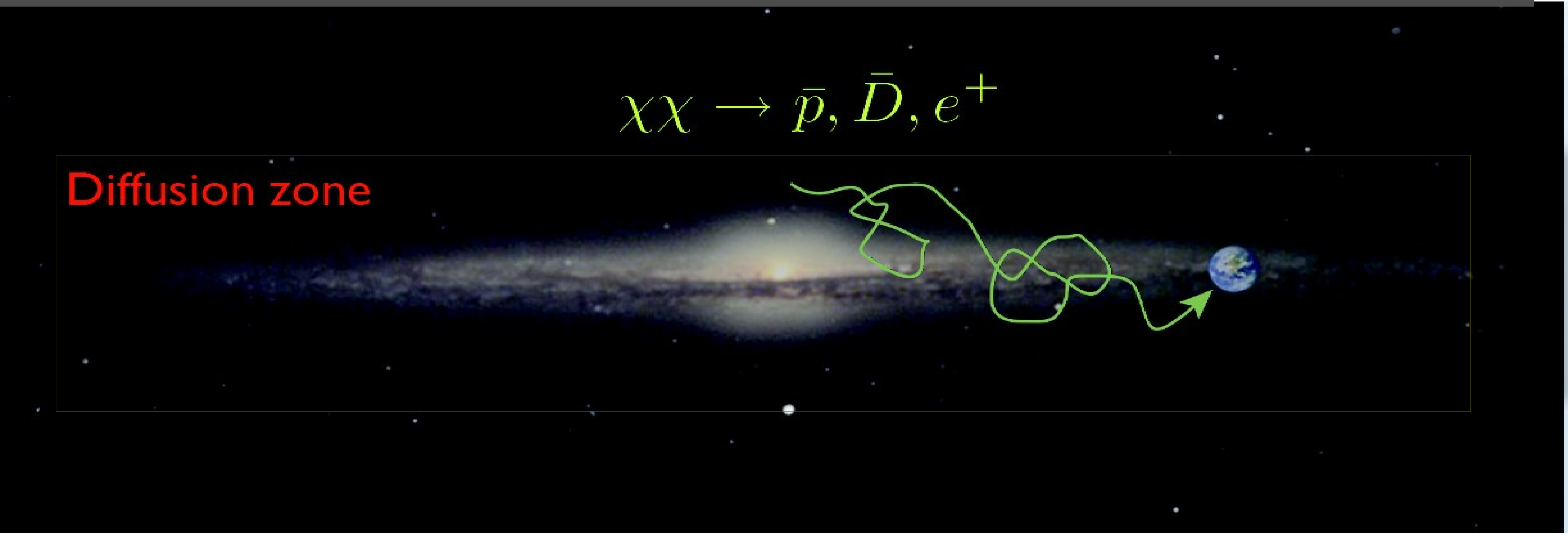
- Pulsars are known sources of e+e- pair production through the spinning magnetic field present: accelerated e- emit gammas than convert to e+e- pairs

The e+ and e- can scape at the Poles and contribute to the galactic flux, explaining the PAMELA e+ excess. The spectrum and intensity can be reproduced without much fine tuning

One needs to consider nearby pulsars, since e- suffer from synchrotron and inverse Compton energy losses. But there are sufficient known objects within a few kpc

If one or few pulsars dominate one can expect an anisotropy in the arrival direction, which can help to discriminate between the pulsar and dark matter origin of the excess

or... do we know our galaxy well enough?



Particles, emitted by whatever process, must reach the detector (Earth) travelling through a medium with structure (the galaxy): interstellar gas, magnetic field

We have a standard diffusion model (Galprop) which assumes the galaxy is a flat cylinder with free scape at the boundaries

$$\underbrace{\underset{\text{spatial diffusion}}{\partial_z\left(V_C\,\psi\right) - K\,\Delta\psi} + \partial_E\left\{\underset{\text{energy losses}}{b^{\text{loss}}(E)\,\psi} - \underset{\text{energy gain (reacceleration)}}{K_{EE}(E)\,\partial_E\overset{\text{particle density}}{\psi}}\right\}}_{\textbf{galactic model}} = \underbrace{\underset{\text{source}}{Q\left(\mathbf{x},E\right)}}_{\textbf{your model}}$$

is there really a positron excess?

Indeed there are claims that there is no anomalous e^+e^- excess

(B. Katz et al, MNRS, 405, issue 3, 1458 (2010), T. Piran et al, arXiv:0905.0904)

if one parts with the standard model of cosmic ray propagation in the Galaxy (which, for example assumes a continuous distribution of CR sources. This is clearly not the case for high energies, ie, non-diffuse flux)

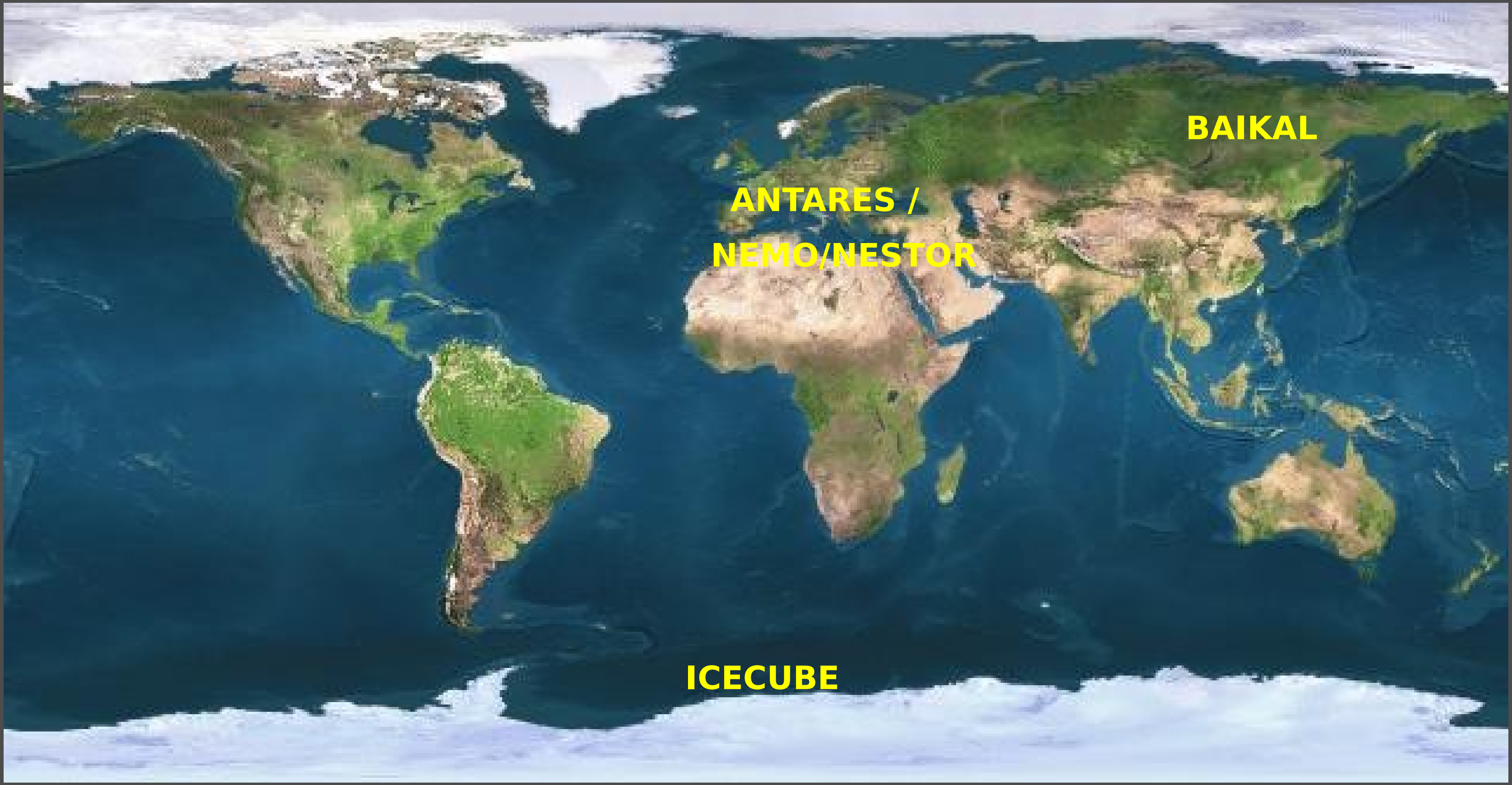
The galaxy has structure (spiral arms) which would suggest different diffusion processes in the galactic plane and in the perpendicular direction

→ cosmic ray diffusion in the galaxy needs updating

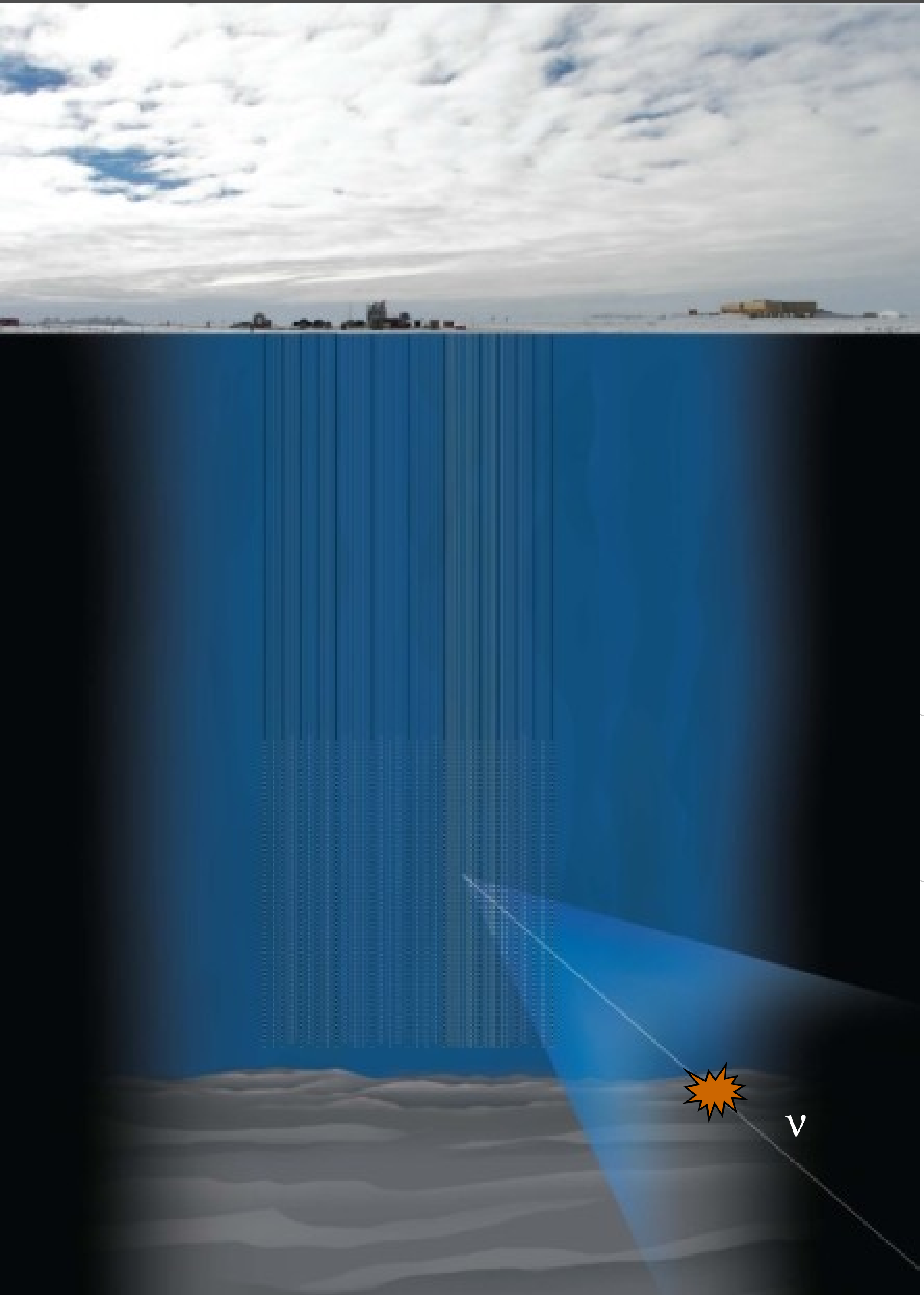
Remember Ockham's razor?

- *Pluralitas non est ponenda sine neccesitate* (original)
- *We are to admit no more causes of natural things than such as are both true and sufficient to explain their appearances* (Newton's version)
- *The procedure of induction consists in accepting as true the simplest law that can be reconciled with our experiences* (Wittgenstein)
- *Keep it simple!* (today's version)

searches with neutrino telescopes



neutrino detection principle



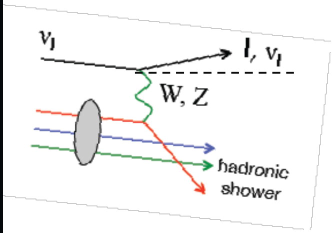
Array of optical modules in a transparent medium to detect the light emitted by relativistic secondaries produced in charged-current ν-nucleon interactions

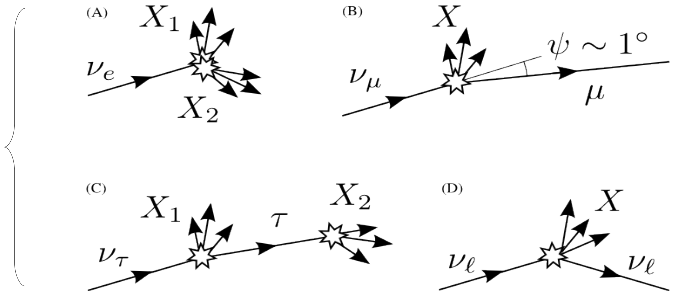
number of photons due to Cerenkov radiation: ~ 300 /cm in water/ice

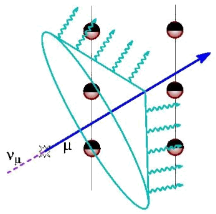
$\theta_{\nu\mu} \sim 0.7^{o}/E_{\nu}(\mathrm{TeV})^{0.6}$ => degree resolution

Need ns timing resolution

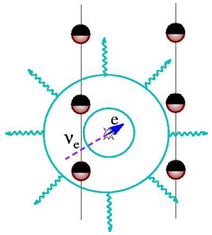
Need HUGE volumes (tiny Xsects & fluxes)







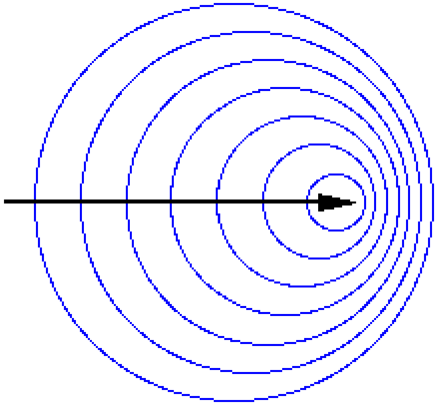
μ tracks >100m at E>100 GeV



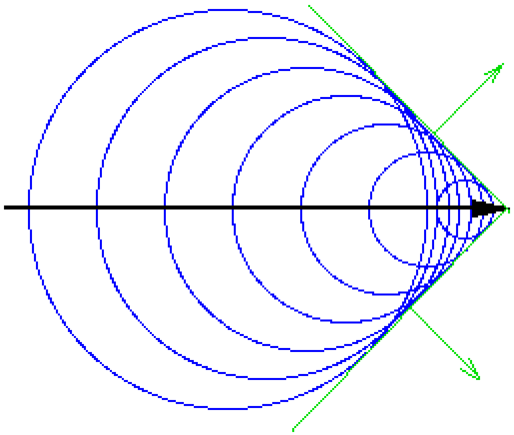
e^{+-} :electromagnetic shower

τ^{+-} : hadronic shower

the Cherenkov effect



$v<c/n$



$v>c/n$

Emission of light by relativistic charged particles traversing a medium at a higher speed than the speed of light in the medium, c/n. The radiation is emitted at a characteristic angle

$$\cos\theta = \frac{1}{\beta n}$$

and it appears above a critical velocity $\beta > 1/n$, ($\cos\theta$ must be ≤ 1) which depends on the medium. For the most common case of relativistic particles, $\beta \approx c$, $\cos\theta = 1/n$.

Atoms in the vicinity of the particle become polarized and emit coherent radiation when returning to the equilibrium state

The number of photons emitted per unit length and wavelength is (α is the EM constant)

$$\frac{dN^2}{dx d\lambda} = \frac{2\pi\alpha}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2}\right)$$

typical wavelengths of emission are ultraviolet-blue

$$\frac{dN}{dx} = 2\pi\alpha \sin^2\theta \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right) \text{ photons/cm}$$

~ 300 photons/cm in water for the relevant λ range.

Note that it is not the particle that emits the radiation, but the material. The particle does not loose energy through Cherenkov radiation and therefore the effect can be used over large distances

range/lifetime of a 1 TeV muon

$$E^2 = p^2c^2 + m^2c^4 \qquad (E = 1\,\text{TeV},\ m = 105\text{MeV}/c^2)$$

$$E \approx pc = mc\gamma v = mc\frac{v}{\sqrt{1-v^2/c^2}} = mc^2\frac{\beta}{\sqrt{1-\beta^2}}$$

$$\beta = \frac{E/mc^2}{\sqrt{1+E^2/m^2c^4}} \qquad \text{for } E = 10^6\text{ MeV},\quad \beta = 0.999999994$$

$$t' = \frac{t}{\sqrt{1-\beta^2}}$$

for $\beta = 0.999999994$, $t' = 10^4 t = 10^4 \text{x} 2.2\times10^{-6} s = 0.022 s$

$$v = 0.999999994c \Rightarrow v \approx 3\times10^8 m/s$$

$$L = v \text{ x } t \approx 10^3 km$$

no energy losses taken into account ! Just time dilation

range/lifetime of a 1 TeV tau

$$E^2 = p^2c^2 + m^2c^4 \qquad (E = 1\,\text{TeV},\ m = 1.78\,\text{GeV}/c^2)$$

$$E \approx pc = mc\gamma v = mc\frac{v}{\sqrt{1-v^2/c^2}} = mc^2\frac{\beta}{\sqrt{1-\beta^2}}$$

$$\beta = \frac{E/mc^2}{\sqrt{1+E^2/m^2c^4}} \qquad \text{for } E = 10^3\ \text{GeV},\quad \beta = 0.99999841$$

$$t' = \frac{t}{\sqrt{1-\beta^2}}$$

for $\beta = 0.999998$, $t' = 561t = 561\text{x}290\text{x}10^{-15}s = 1.63\text{x}10^{-10}s$

$$v = 0.999998c \Rightarrow v \approx 3\text{x}10^8 m/s$$

$$L = v\text{x}t \approx 0.05m$$

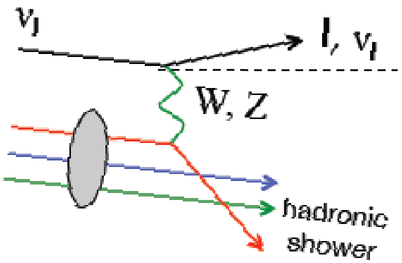
no energy losses taken into account ! Just time dilation

neutrino detection principle

muon range in ice/water with continuous energy losses:

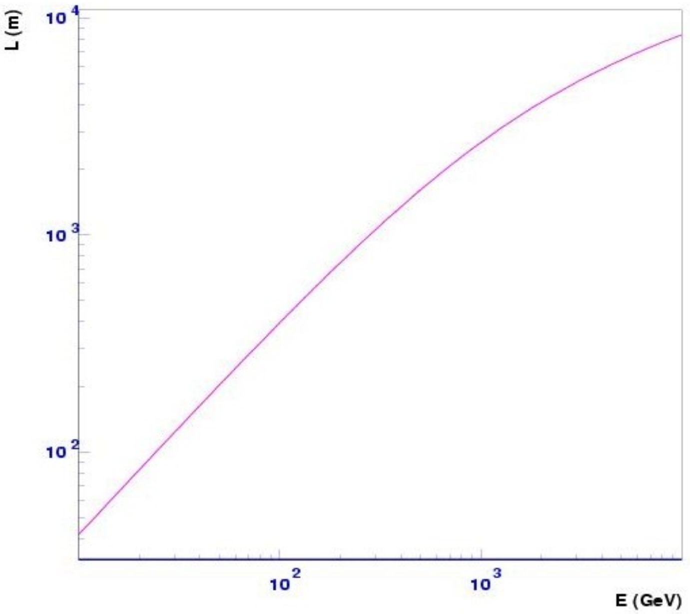
$$L_\mu = \frac{1}{b}\log\left(b\left(\frac{E_\mu}{a}\right)+1\right)$$

a, *b* material dependent constants



$$\sqrt{\left\langle \theta^2{}_{\nu\mu} \right\rangle} \propto \sqrt{m_p / E_\nu}$$ just kinematics

for Eν ≳ TeV, $\theta_{\nu\mu} \lesssim 1^\circ$



possible to point, ie,
possible to do astronomy

some operational characteristics of **current** neutrino telescopes:

- $E\nu$ threshold ~50 GeV (depends on inter-string and inter-module separation)

- background from downgoing atmospheric muons ~x10^6 atmospheric ν flux

- Large volume neutrino telescopes are three-flavour detectors

neutrino detection in ice/water

event reconstruction by Cherenkov light timing:

need array of PMTs with ~1ns resolution

→ optical properties of the medium of prime importance

	absorption length	scattering length
South Pole ice (IceCube)	**110 m** (@ 400nm)	**20 m** (@ 400nm)
Lake Baikal	25 m (@ 480nm)	59 m (@ 480nm)
Mediterranean (ANTARES/NESTOR)	~60 m (@ 470nm)	100-300 m (@ 470nm)

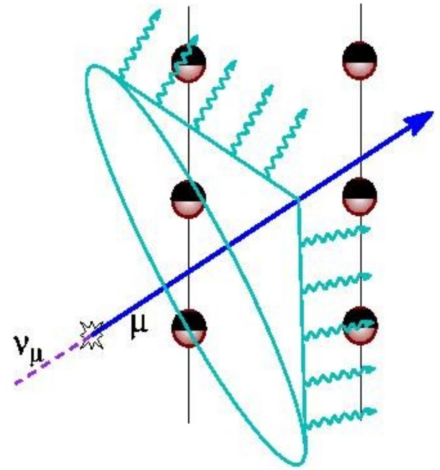
longer absorption length → larger effective volume

longer scattering length → better timing, (ie pointing resolution)

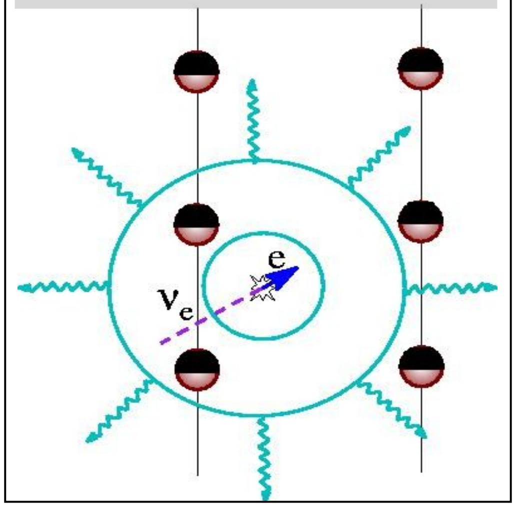
neutrino astronomy possible since $\Theta_{\mu\nu} \approx 0.7^\circ \cdot (E_\nu / \mathrm{TeV})^{-0.7}$

signatures

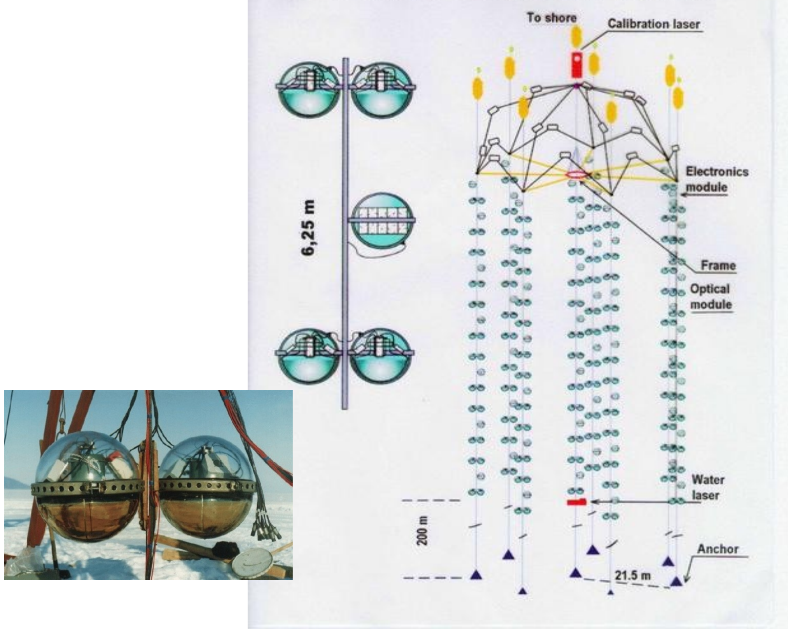
O(km) long muon tracks

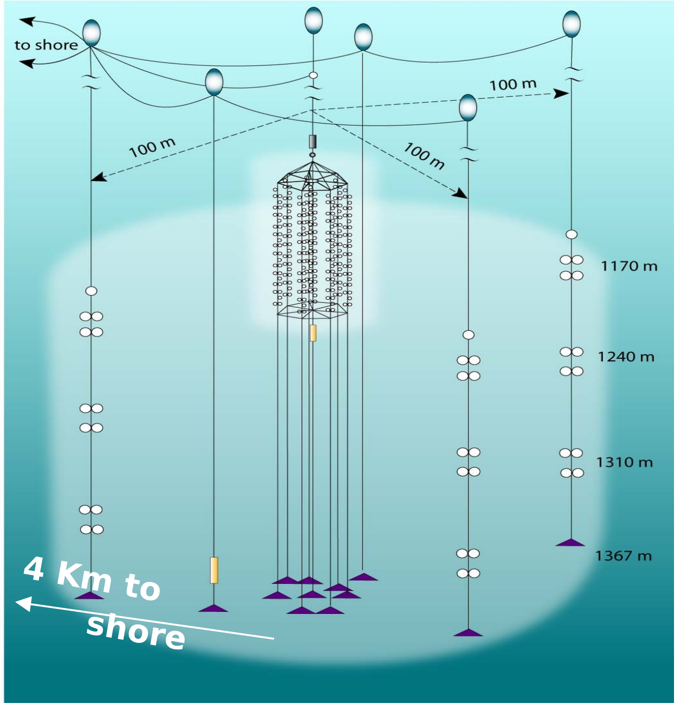


O(10m) cascades, ν_e ν_τ neutral current



the Baikal neutrino telescope





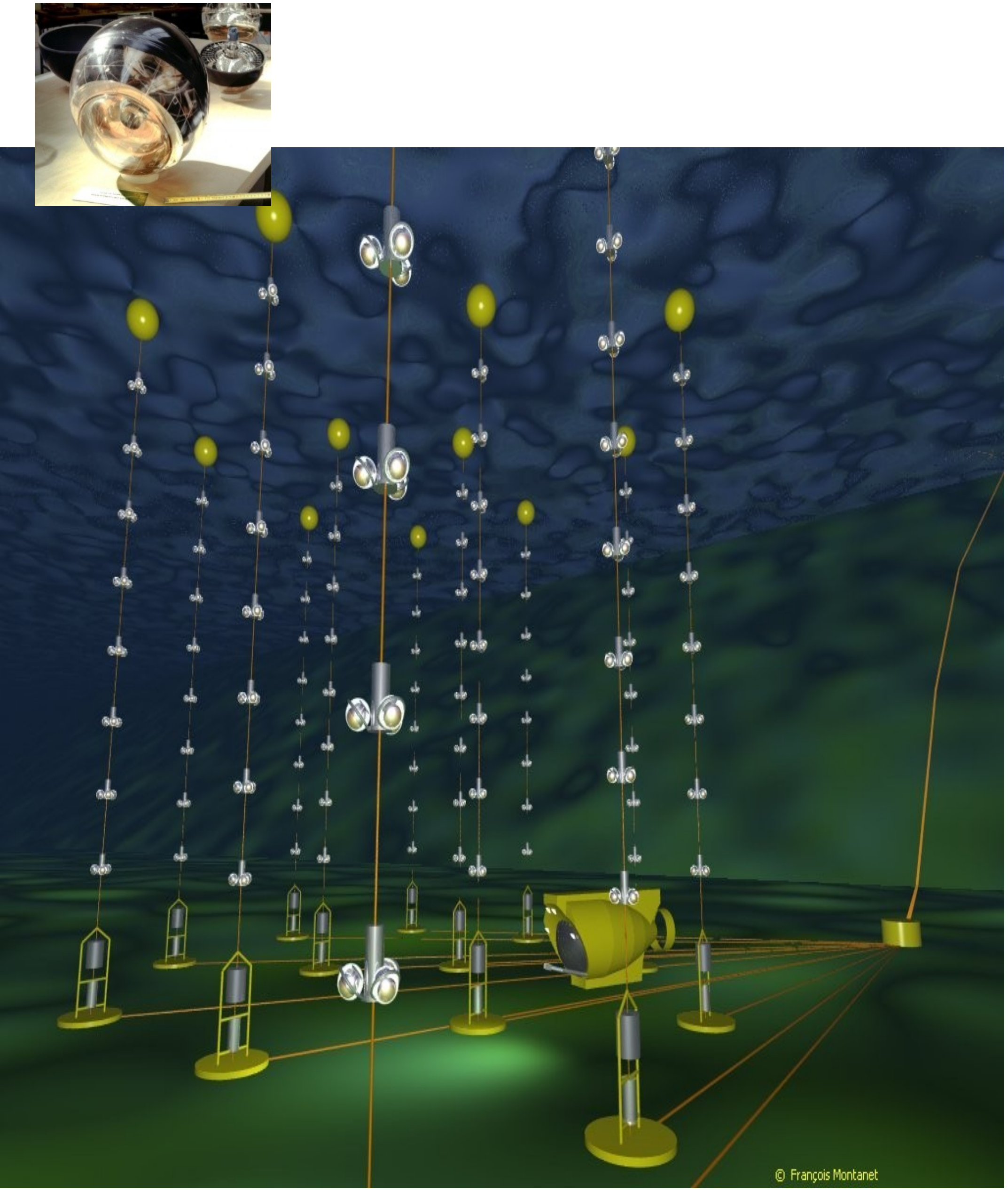
NT-200

- 8 strings with 192 optical modules
- 72 m height, 1070 m depth
- μ effective area >2000 m^2 (E_μ>1 TeV)
- Running since 1998

NT-200+

- **commisioned April 9, 2005.**
- 3 new strings, 200 m height
- 1 new bright Laser for time calibration
  - imitation of 20TeV-10PeV cascades,
  - >10^12 photons/pulse w/ diffusor,
- new DAQ
- 2 new 4km cables to shore

the ANTARES neutrino telescope


© François Montanet

2.5 Km deep in the Mediterranean

12 lines

25 ‘storeys’ with 3 PMTs each

350 m long strings (active height)

~70 m inter-string separation

14.5 m vertical storey separation

0.04 km^3 instrumented volume

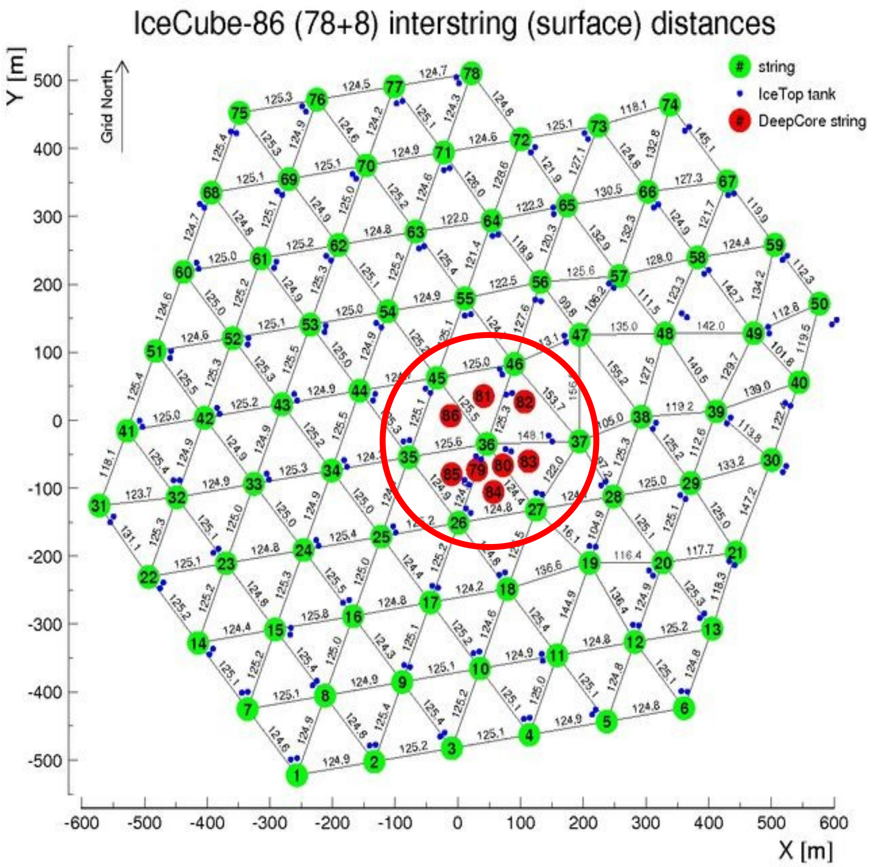
the IceCube neutrino telescope

86 strings, 5160 optical modules

86 ice tanks on the surface

~ 50 GeV energy threshold

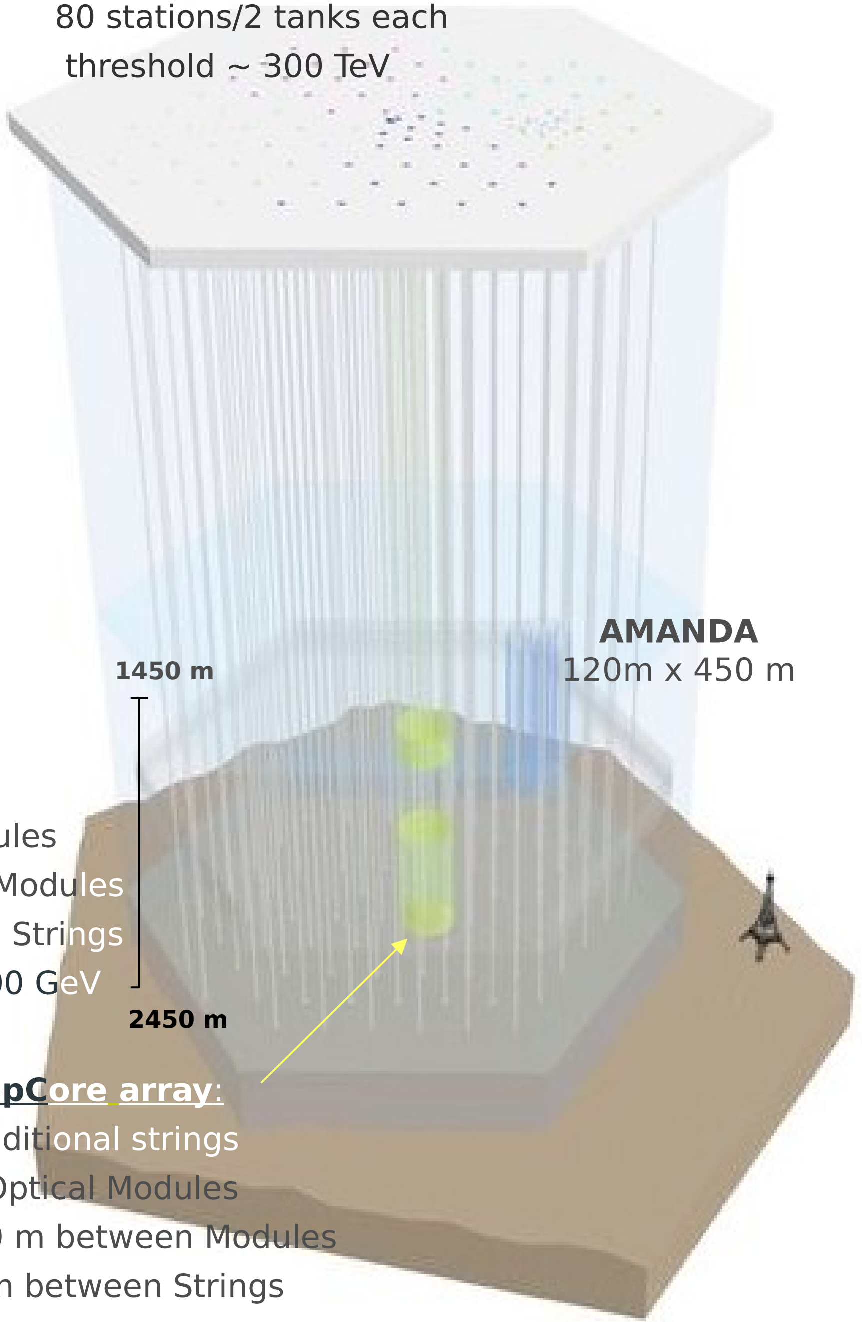
~ 1^{o} angular resolution



IceTop: Air shower detector

80 stations/2 tanks each

threshold ~ 300 TeV



InIce array:

80 Strings

60 Optical Modules

17 m between Modules

125 m between Strings

ν threshold ≲100 GeV

DeepCore array:

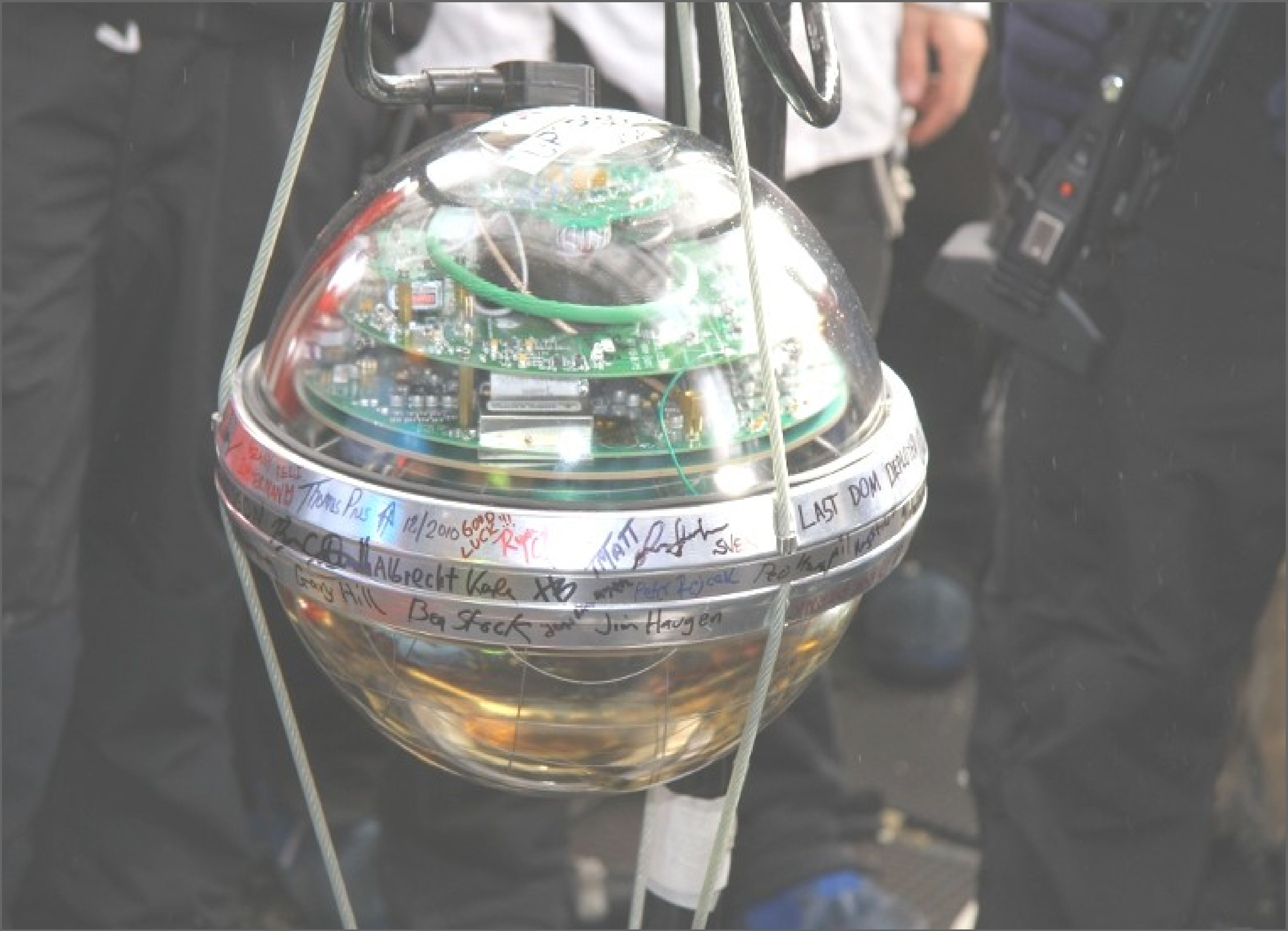
6 additional strings

60 Optical Modules

7/10 m between Modules

72 m between Strings

ν threshold ~10 GeV


Thomas Pas
12/2010
GOOD LUCK!!
RYC
MATT
SVE
LAST DOM DEPLO
Albrecht Karle
Peter Rojcak
Gary Hill
Ben Stock
Jim Haugen

example of track reconstruction in IceCube

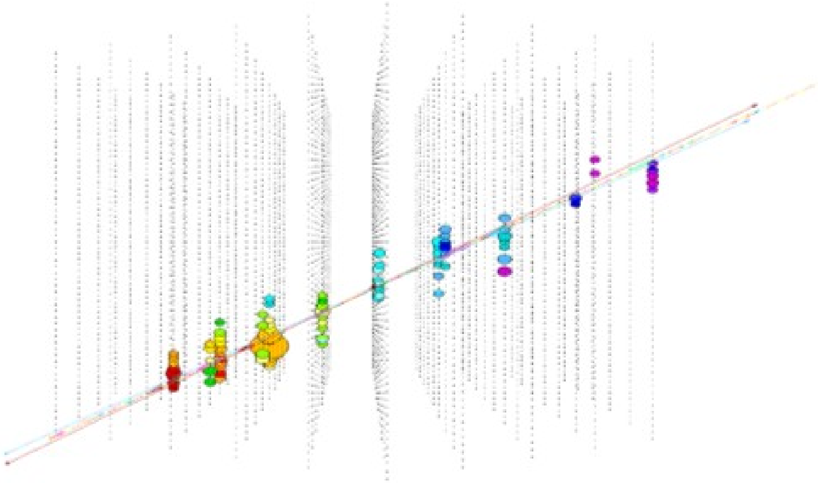


Figure 13: A 10-TeV muon track in IceCube.

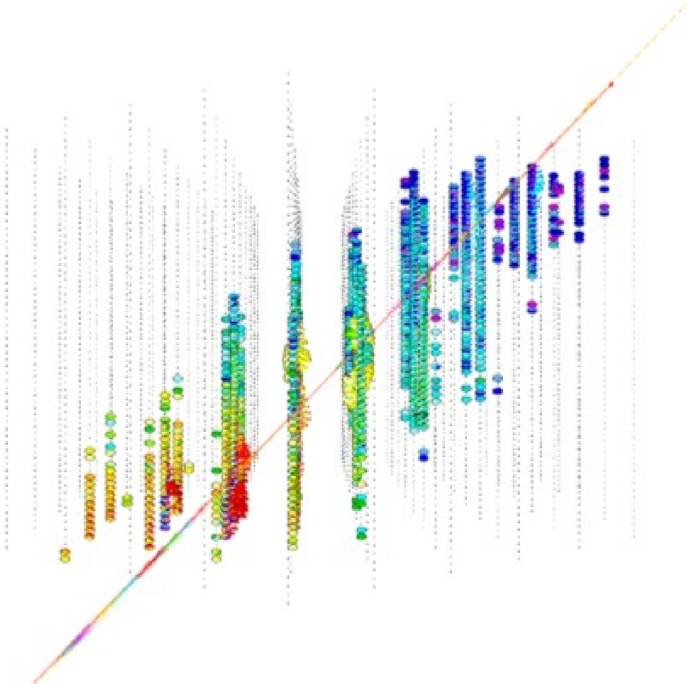


Figure 14: A 6-PeV muon track in IceCube.

detour: the concept of effective area

Neutrino telescopes do not have a fixed (hit or miss) collection area.

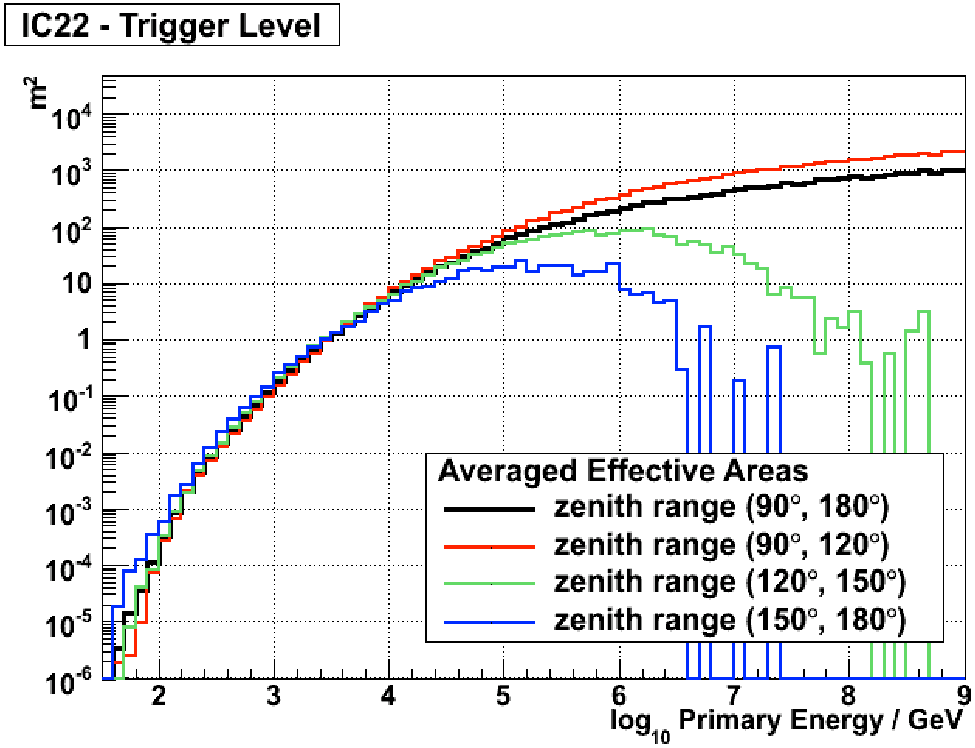
The efficiency to detect a neutrino of a given energy E_ν is characterized by the effective area of the detector

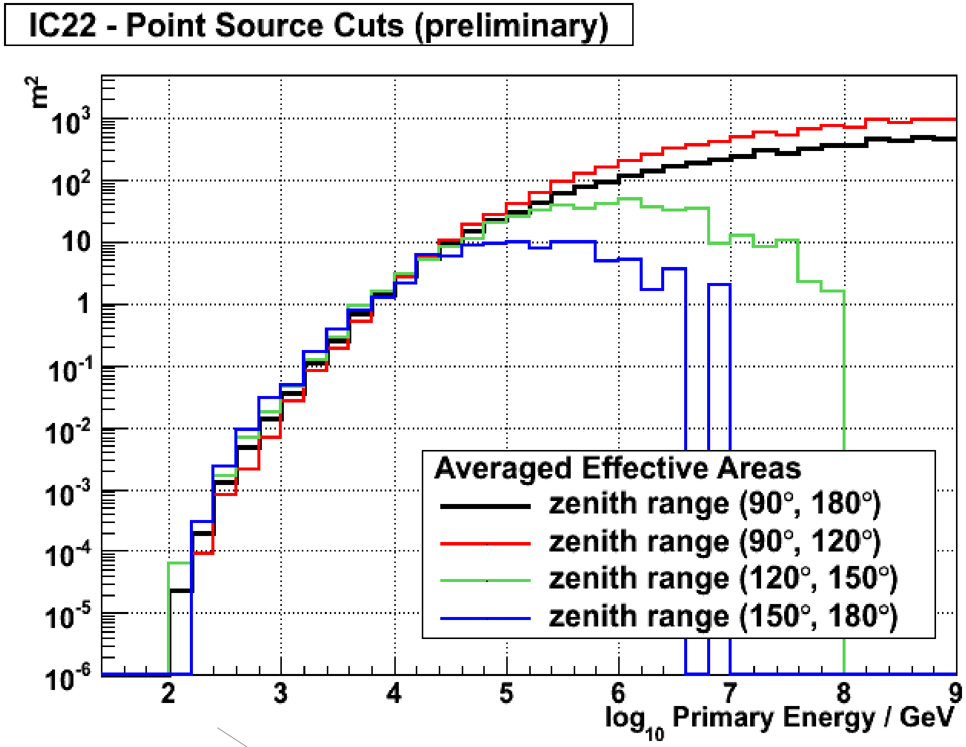
$$A_{eff}(E_\nu) = \frac{N_{det}}{N_{gen}} \times A_{gen}$$

which **can only be obtained by Monte Carlo simulations**. N_{gen} is the number of events generated in Monte Carlo, distributed over an area A_{gen}, which covers the detector geometrically, and N_{det} is the number of surviving events after a given analysis.

→ There is no a unique effective area of a neutrino telescope!
It depends on the analysis

the concept of effective area





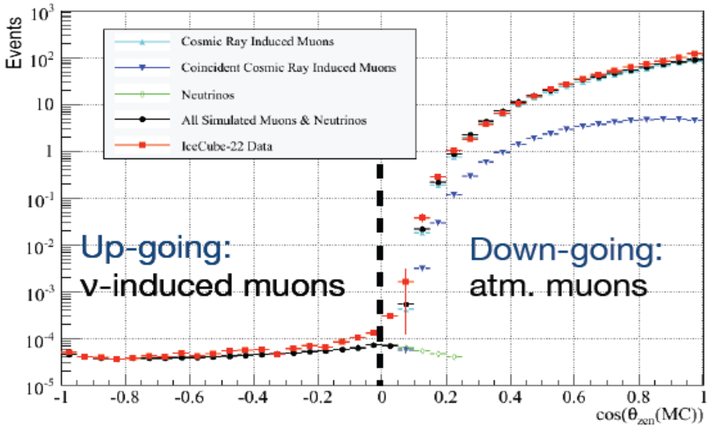
note the scale!

the measured atmospheric neutrino flux

$$CR + N \rightarrow \pi's + X$$

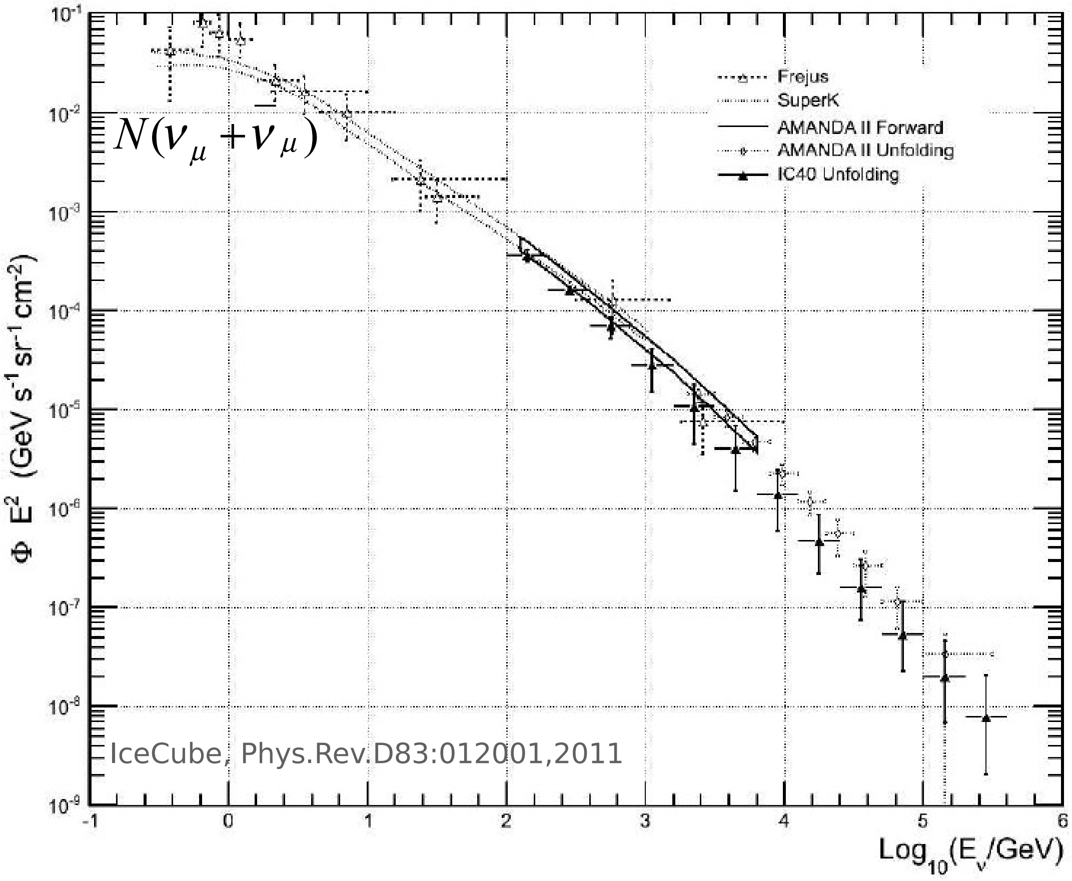
$$\pi^+ \rightarrow \mu^+ + \nu_\mu, \qquad \pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

$$\quad \hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu \qquad \quad \hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$$



expected flavour ratio:

$$\frac{N(\nu_\mu + \bar{\nu}_\mu)}{N(\nu_e + \bar{\nu}_e)} \approx 2$$



IceCube, Phys.Rev.D83:012001,2011

Interaction length of a neutrino in the Sun

Let's take 5000 GeV ν_e as an example:

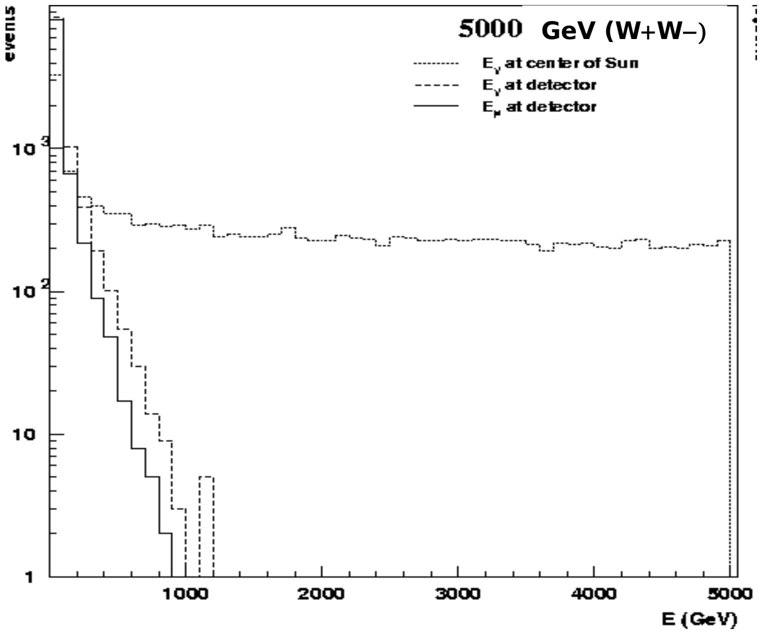
$\sigma^{NC}(\nu_e\, e^- \rightarrow \nu_e\, e^-) = 0.95\text{x}10^{-41}\, E_\nu/\text{GeV} \quad (\text{cm}^2)$

$\rho_{sun} = 1.6\text{x}10^5\ \text{gr/cm}^3$

$R_{sun} = 7\text{x}10^{10}\ \text{cm}$

mean free path between interactions:

$$\langle L\rangle = \frac{A_H}{N_A\,\rho\,\sigma} = \frac{1\,mol}{6.023\text{x}10^{23}\,mol/gr\;1.6\text{x}10^5\,gr/cm^3\;0.95\text{x}10^{-41}\,cm^2/GeV\;5000\text{GeV}} = 2.2\text{x}10^8\,cm, < 7\text{x}10^{10}\,cm = R_{sun}$$



Indirect dark matter searches from the **Sun** are a low-energy analysis in neutrino telescopes: even for the highest DM masses, we do not get muons above few 100 GeV

Not such effect for the Earth and Halo (no ν energy losses in dense medium)

analysis strategies in neutrino telescopes

Triggered data still dominated by atmospheric muons

Reject misreconstructed atmospheric muon background through event and track quality parameters

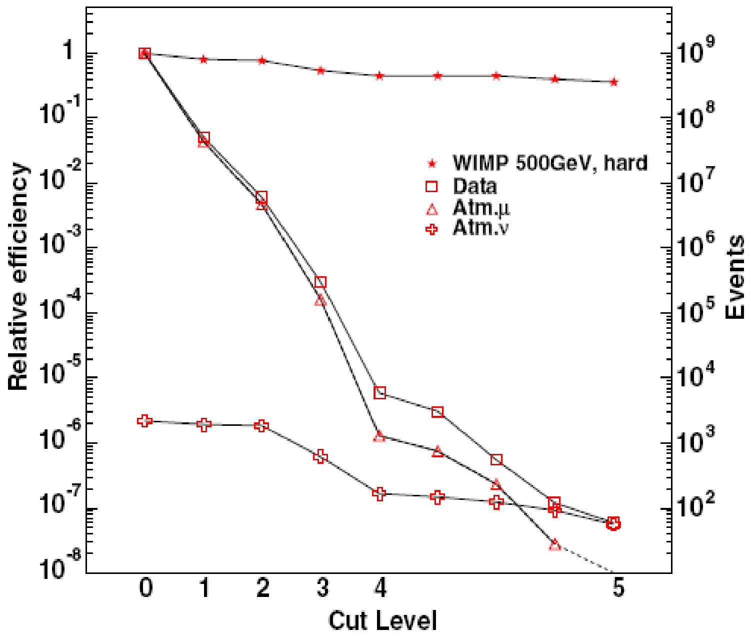
Use of **linear cuts** and/or multivariate methods to extract irreducible atmospheric neutrino background (Neural Nets, Support Vector Machines, Boosted Decision Trees)

DM searches directional: good additional handle on event selection

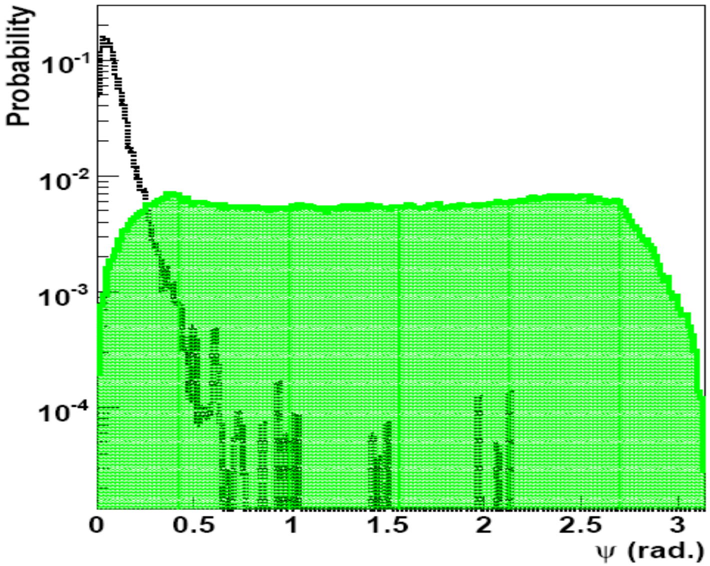
distribution-shape analysis

(allow for a higher background contamination)

sequential cuts



shape analysis



Solid angle to the Sun ψ (rad)

analysis strategies in neutrino telescopes

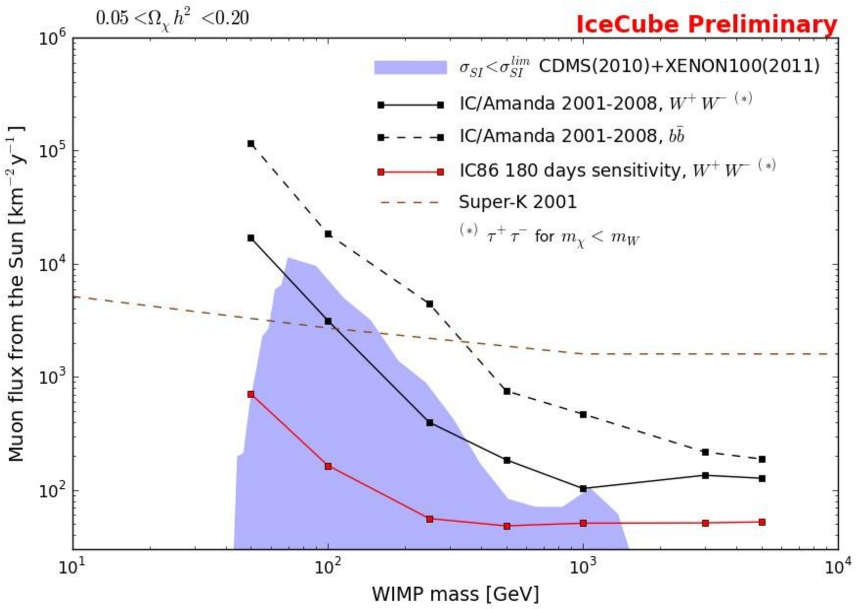
$$\left.\begin{array}{l} N_{data}, N_{bck} \\ \Psi_{data}, \Psi_{bck} \end{array}\right\} \rightarrow N_{90}$$

$$\Gamma_{\nu\mu} \leqslant \frac{N_{90}}{V_{eff} \cdot t}$$

Experimentally obtained quantity: allowed number of signal events still compatible with background, at 90% confidence level

Use model to convert to a muon flux

$$\left.\begin{array}{l} \Gamma_{\nu\mu}(m_\chi) = \Gamma_A \cdot \dfrac{1}{4\pi R_\oplus^2} \displaystyle\int_0^{m_\chi} \sum B_{\chi\bar{\chi}\rightarrow X} \left(\frac{dN_\nu}{dE_\nu}\right) \\ \times\, \sigma_{\nu+N\rightarrow\mu+\ldots}(E_\nu | E_\mu \geqslant E_{thr})\, \rho_N\, dE_\nu \end{array}\right\} \longrightarrow \phi_\mu(E_\mu \geqslant E_{thr}) = \frac{\Gamma_A}{4\pi D_\odot^2} \int_{E_{thr}}^{\infty} dE_\mu \frac{dN_\mu}{dE_\mu}$$

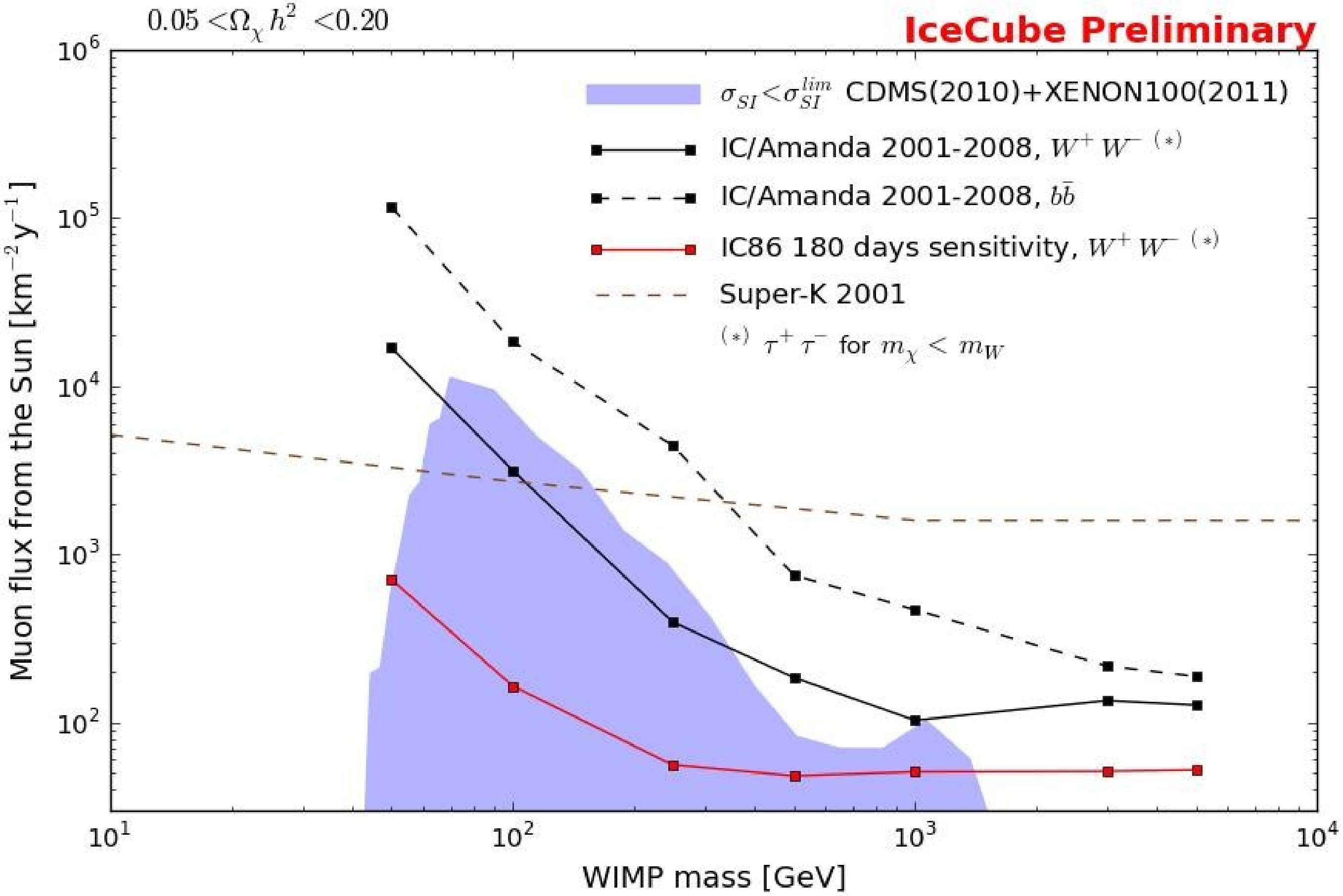


limits on the neutralino-induced muon flux from the Sun

- Look for an excess of neutrinos from the direction of the Sun
(excess over the measured atmospheric neutrino flux)

Non-detection so far → limits on the flux of muons (neutrinos)

90% CL **muon flux limits** from the Sun
(compared to MSSM scans)



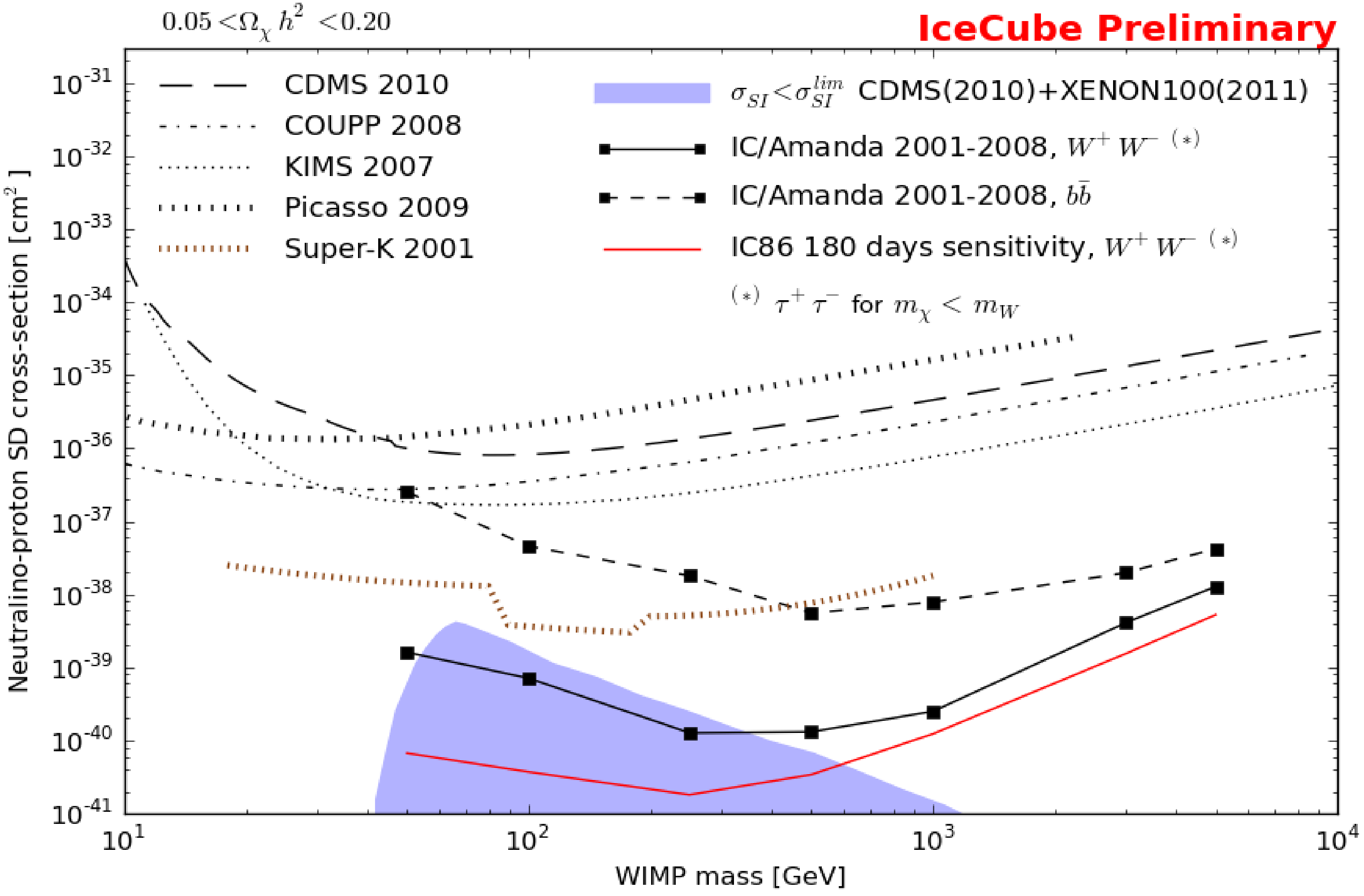
limits on the neutralino-proton cross section

Non-detection so far → limits on the WIMP-proton cross section

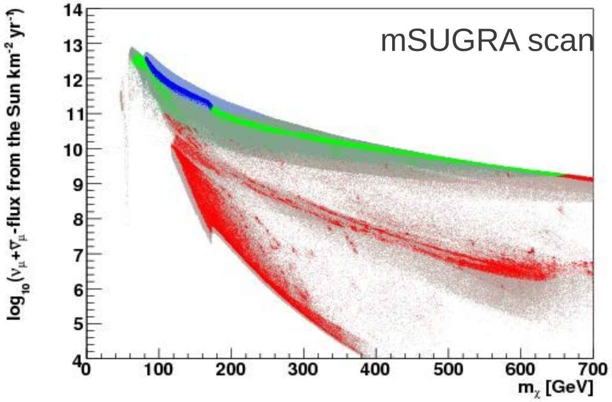
$$\Phi\mu \rightarrow \Gamma_A \rightarrow C_c \rightarrow \sigma_{Xp}$$

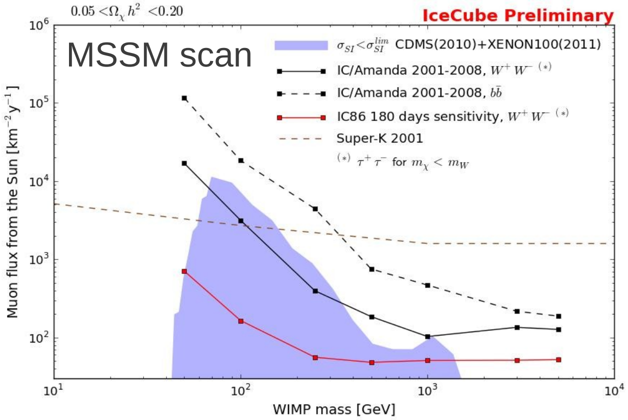
90% CL **neutralino-p Xsection limits**

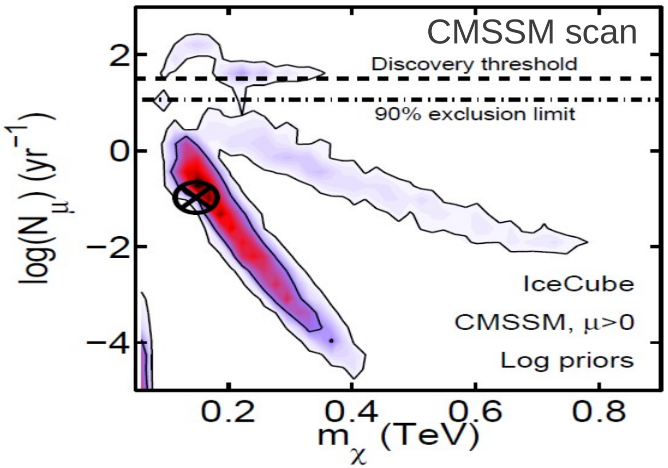
(compared to MSSM scans)



what are these kid of plots and what do they mean?







Supersymmetric models have a few free parameters (4, 5, 7, 21...). Let's take mSugra, with 5 free parameters

- *m0: universal sfermion mass at the GUT scale*
- *m1/2: universal gaugino mass at the GUT scale*
- *tanβ: ratio of Higgs vacuum expectation value*
- *A_0: universal trilinear coupling at the GUT scale*
- sign(μ): sign of the Higgsino mass parameter

All other quantities (masses, couplings...) can be derived from these 5 parameters using the theory.

Each 'model' (combination of the 5 parameters) predicts observables that can be compared with experiments

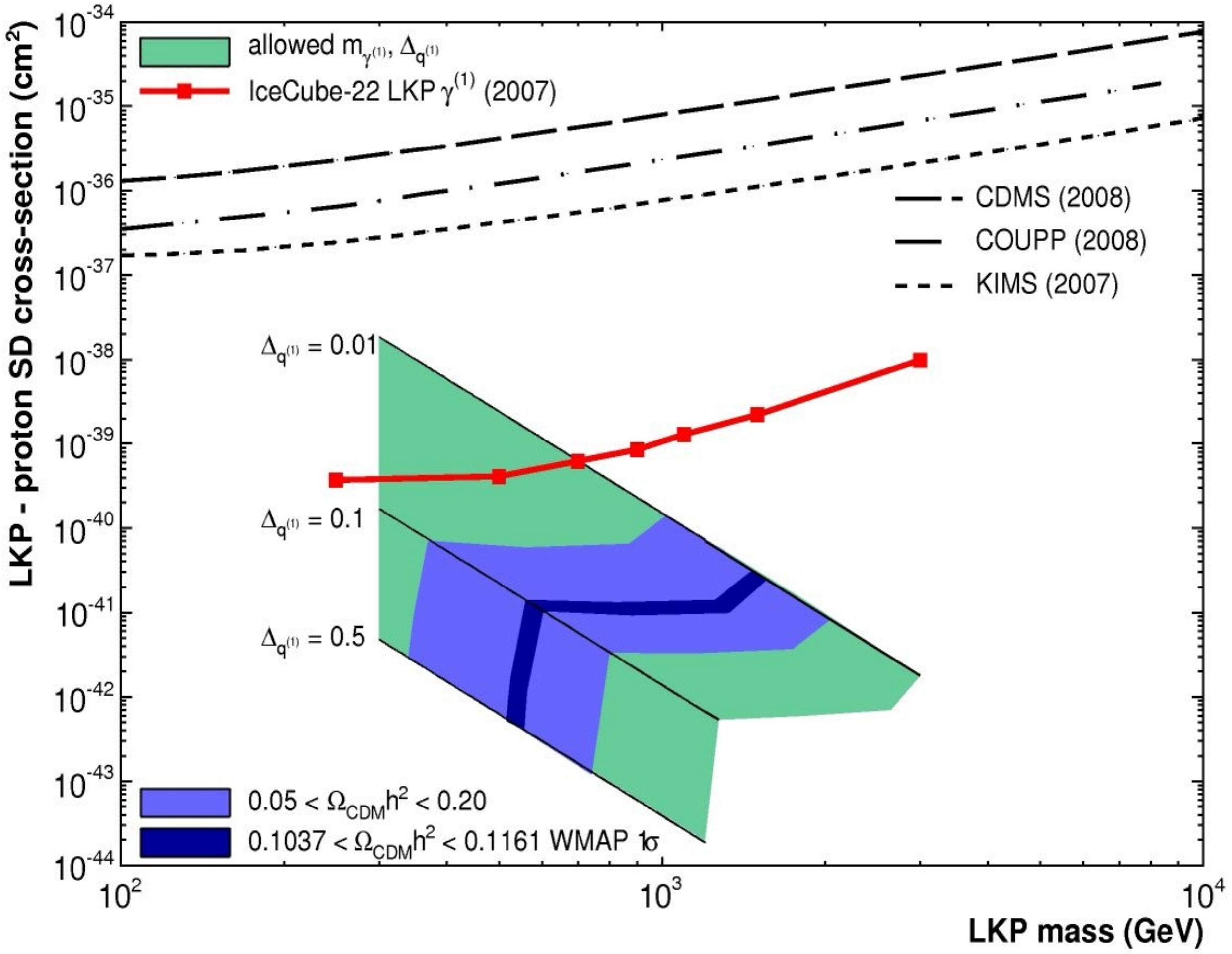
Random scans using high statistics are performed using different techniques (MCMC, simulated annealing, genetic algorithms...)

Each dot in the figure results from a choice of the parameters

Using Bayes theorem one can assign relative probabilities to models

limits on the lightest KaluzaKlein-proton cross section

90% CL LKP-p Xsection limit vs LKP mass



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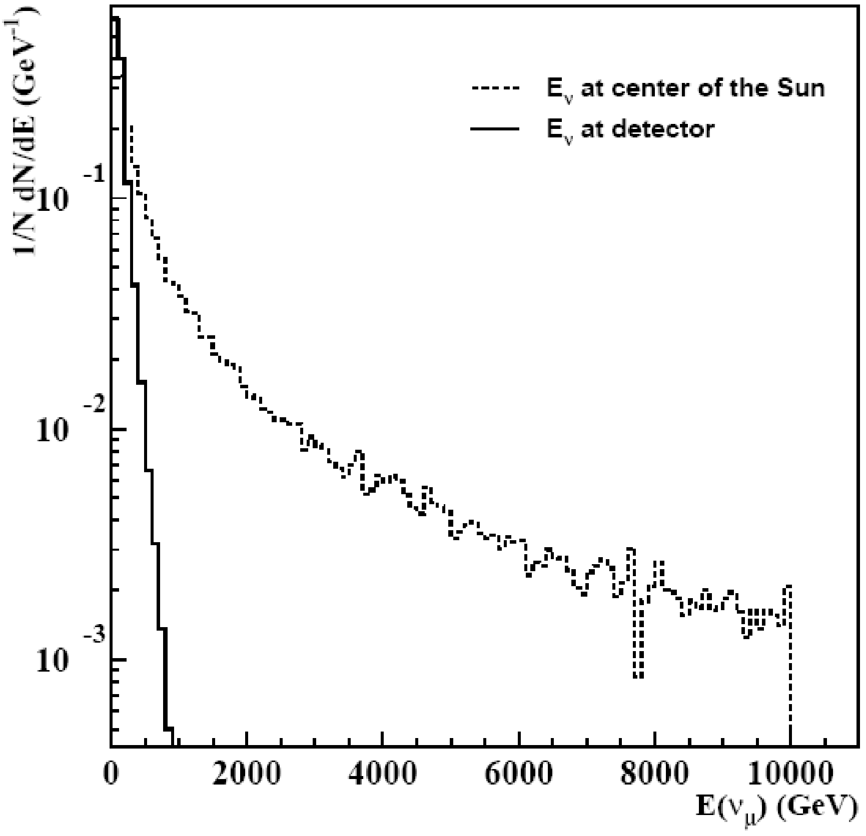
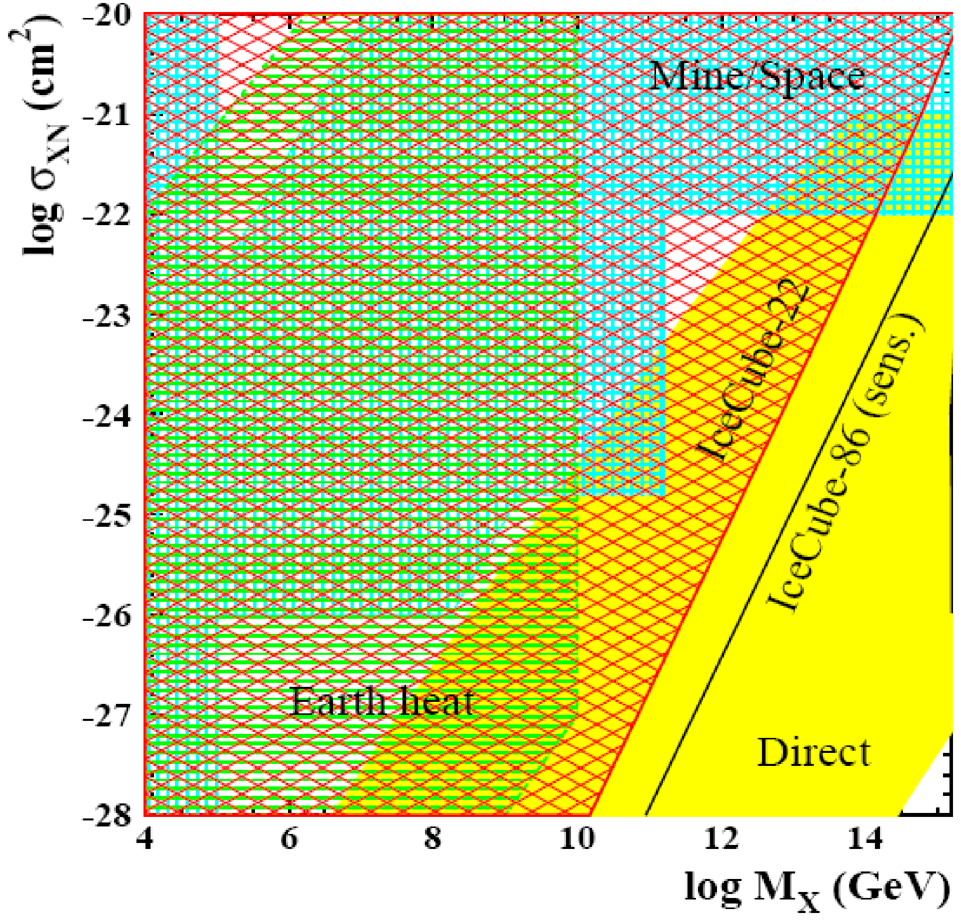
limits on the simpzilla-proton cross section

90% CL simpzilla-p Xsection limit *vs* simpzilla mass

$$\frac{dN}{dE_\nu} \propto \frac{E_\nu + \mathrm{m_w}}{\sqrt{(E_\nu + \mathrm{m}_t)[(E_\nu + \mathrm{m}_t)^2 - \mathrm{m}_t^2][(E_\nu + \mathrm{m_w})^2 - \mathrm{m_w^2}]}}$$

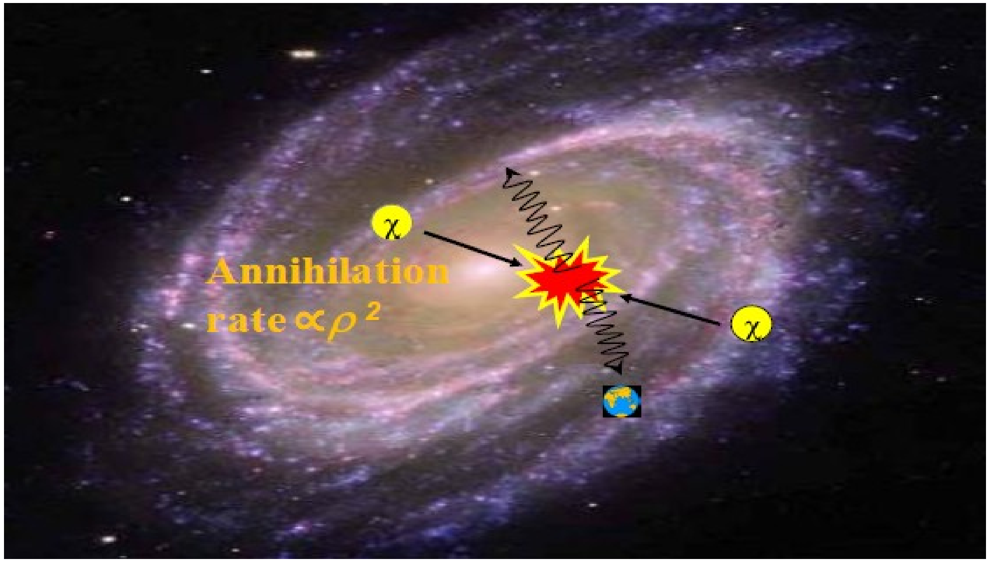




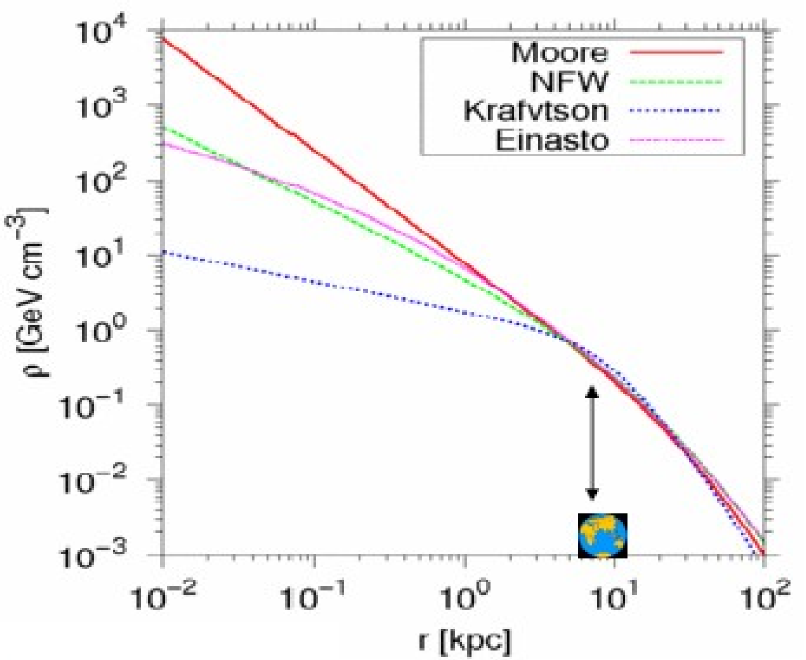
$$N_s(m_\mathrm{X}, \sigma_\mathrm{XN}) = N_t \cdot BR_\mathrm{W} \cdot \Gamma_A(m_\mathrm{X}, \sigma_\mathrm{XN}) \cdot T \cdot \int \frac{dN_\nu}{dE} A_{eff}\, dE$$

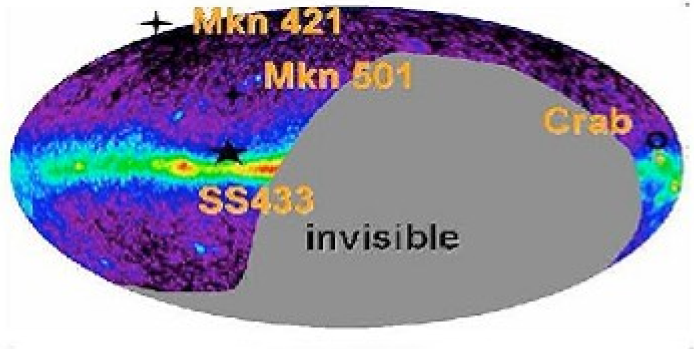
searches from the galactic center and halo

- Problem: strong dependence on the dark matter distribution in the galaxy
- We do not know how dark matter is distributed in the galaxy

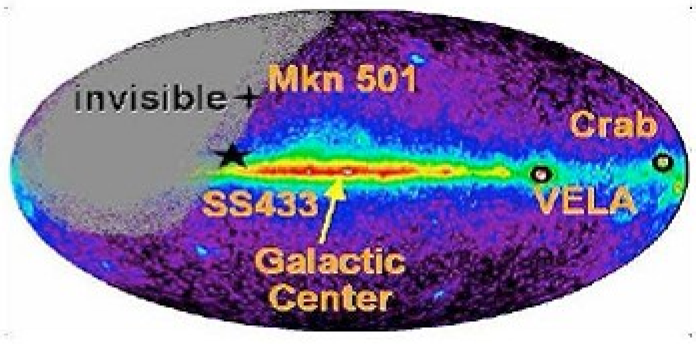


models of the dark matter density as a function of distance to the galactic center





IceCube



ANTARES

example on galactic halo analysis: IceCube

(see posters by H. Taavola and R. Ström)

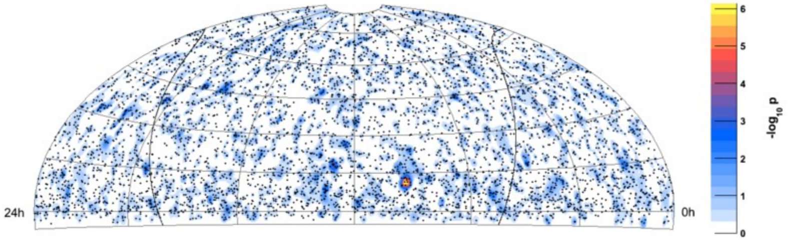
$$\frac{d\Phi}{dE} = \frac{<\sigma_A v>}{2} J(\psi) \frac{R_{sc}\rho_{sc}^2}{4\pi m_\chi^2} \frac{dN}{dE}$$

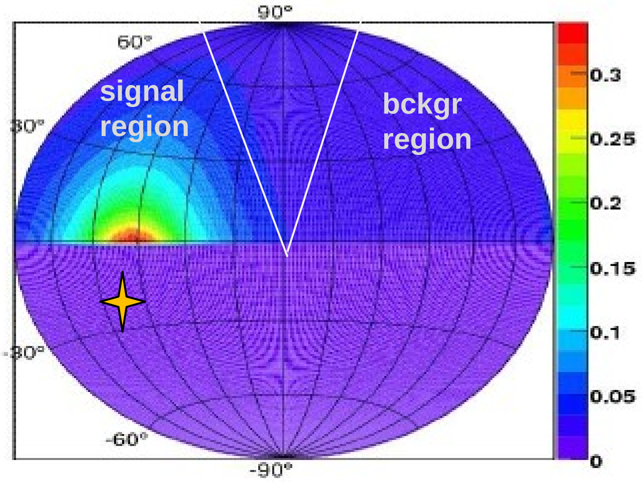
Measure

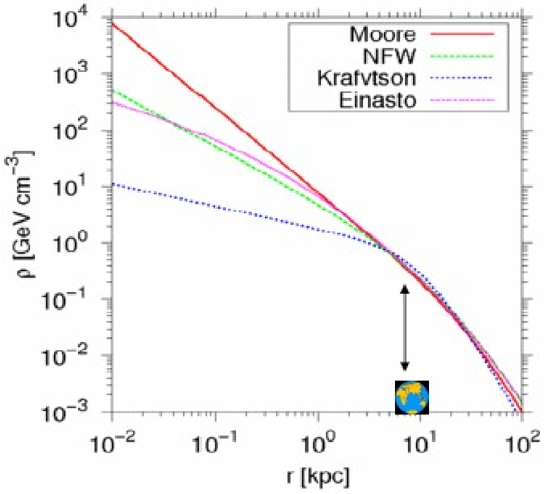
Constrain

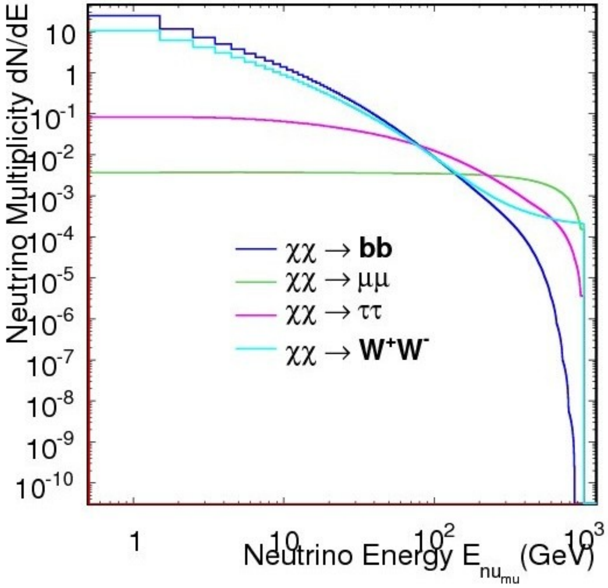
Halo

SUSY







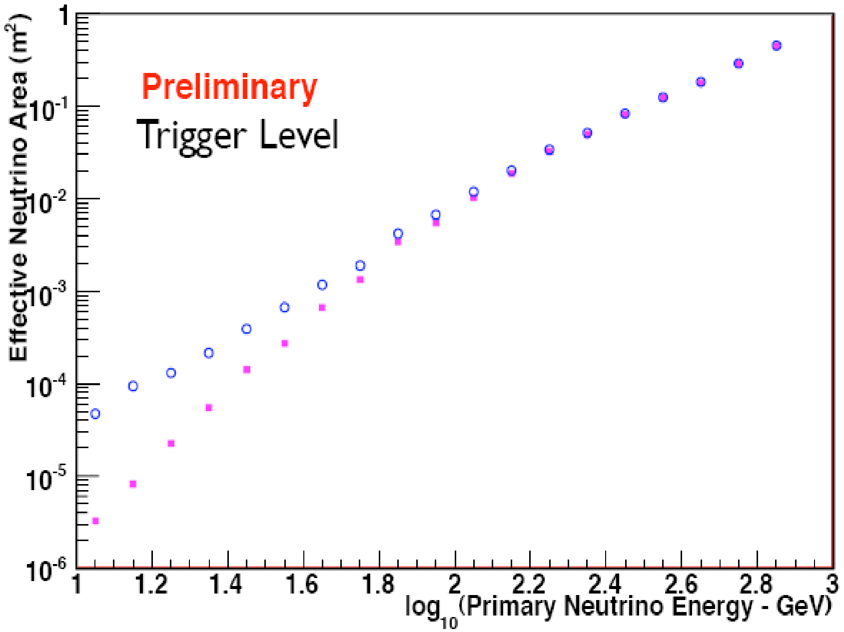


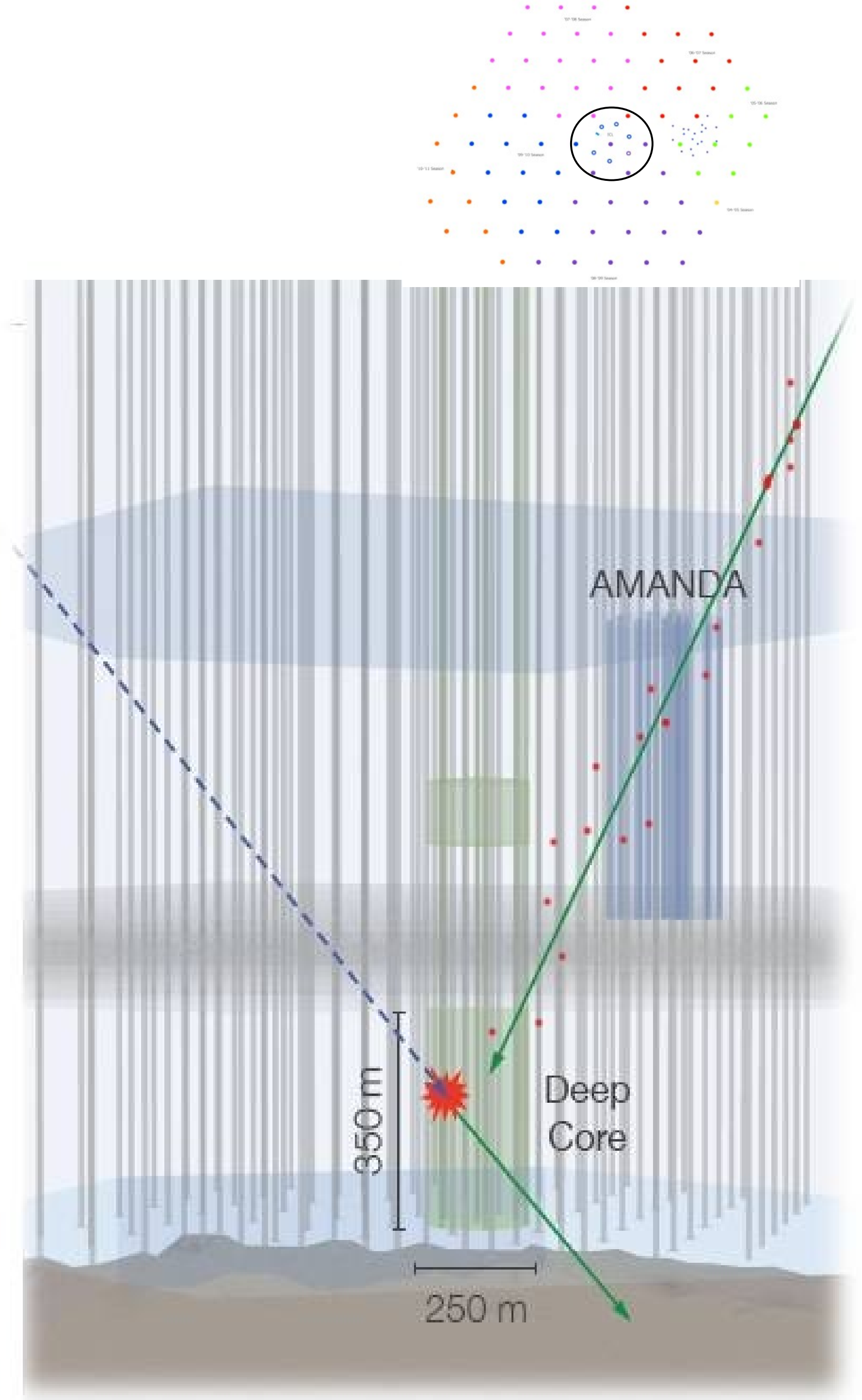
how to look at the southern sky/Galactic Center with IceCube

- **full sky sensitivity** using IceCube surrounding strings as a veto:

375m thick detector veto: three complete IceCube string layers surround DeepCore
→ access to southern hemisphere, galactic center and all-year Sun visibility

- preliminary studies show background rejection with 98% signal efficiency possible



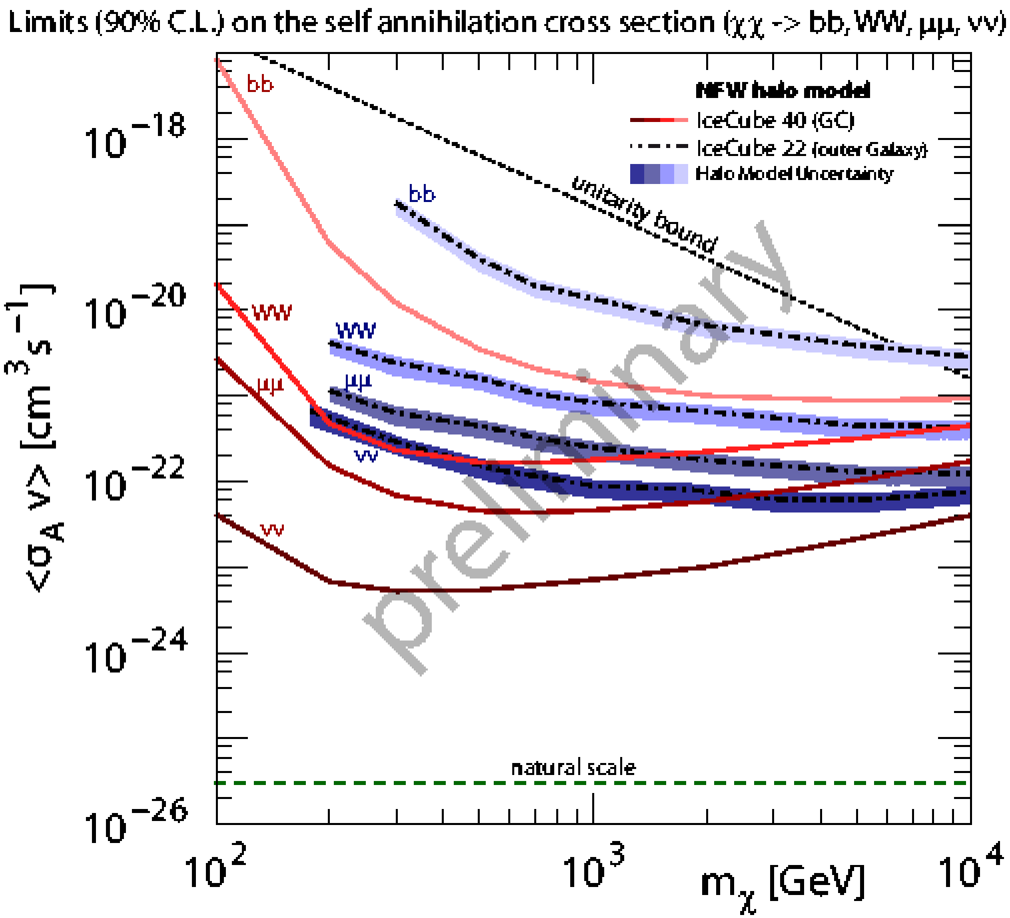


results from IceCube on DM searches from the galactic halo and center

- Look for an excess of neutrinos from the galactic halo and center

(excess over the measured atmospheric neutrino flux)

Non-detection so far → limits on the annihilation cross section

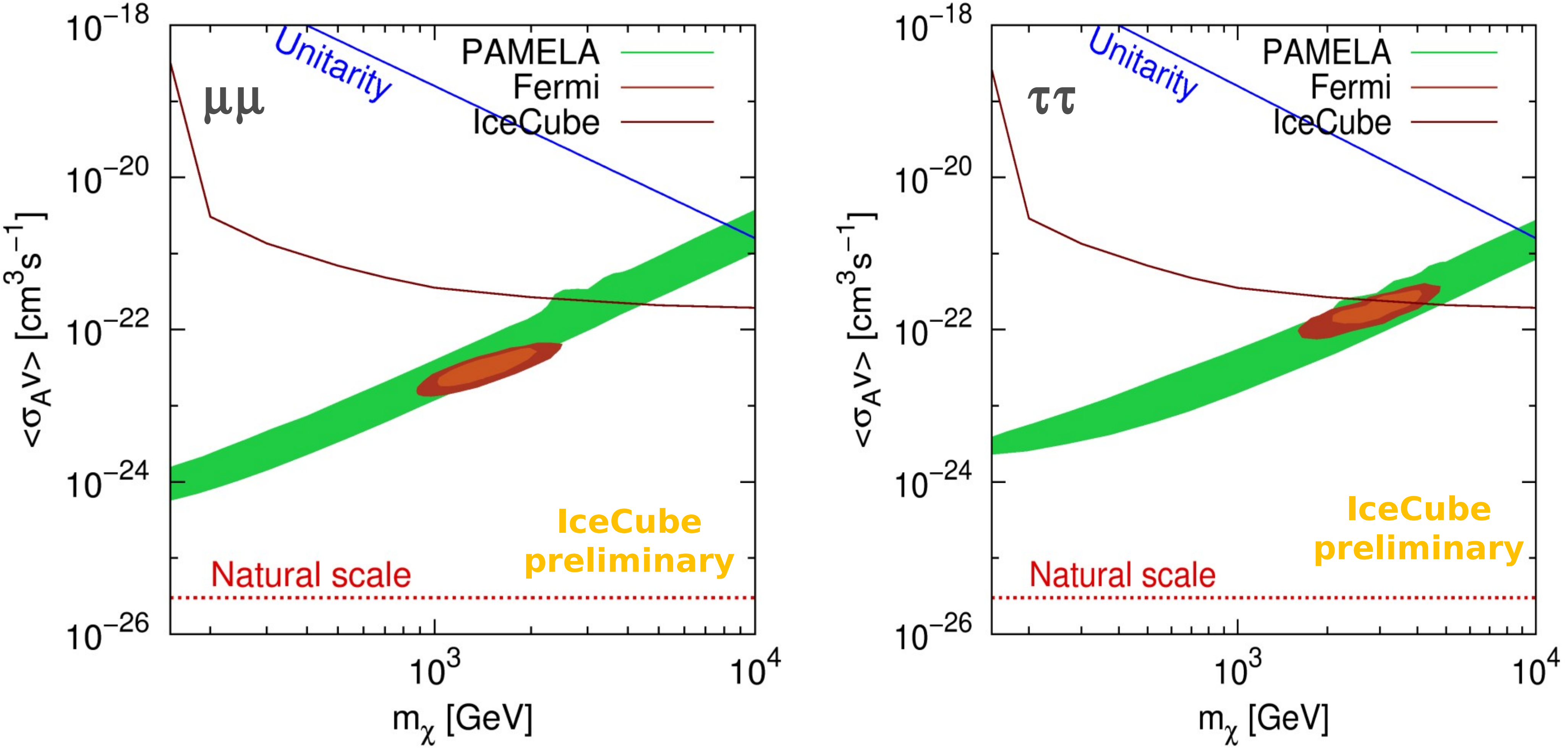


🟦 galactic halo
with 22 string detector

🟥 galactic center
with 40-string detector

- multi-wavelength approach to dark matter searches:

IceCube results in the context of Pamela and Fermi anomaly



conclusions/outlook

I hope I have convince you that searching for dark matter is a complex business

but also, that I have convinced you that it is fun!

(you can go to the South Pole, the Canary Islands, Namibia…, or launch satellites!)

There are plenty of approaches/experiments running or in R&D phase for indirect dark matter detection.

(and I have not mentioned the LHC and direct detection techniques!, covered in other lectures in this school)

The smoking gun for any claim is a coherent signal from indirect, direct and accelerator experiments. The complexity of the backgrounds can make single-detector claims controversial

“In order to make further progress, particularly in the field of cosmic rays, it will be necessary to apply all our resources and apparatus simultaneously and side-by-side”

(V. Hess. Nobel Lecture, 1936)

All these searches should be taken as a part in the grand scheme of efforts in searches of physics beyond the Standard Model using accelerators, underground detectors, space-based detectors, gamma-ray telescopes and air shower arrays