Dark Matter Searches

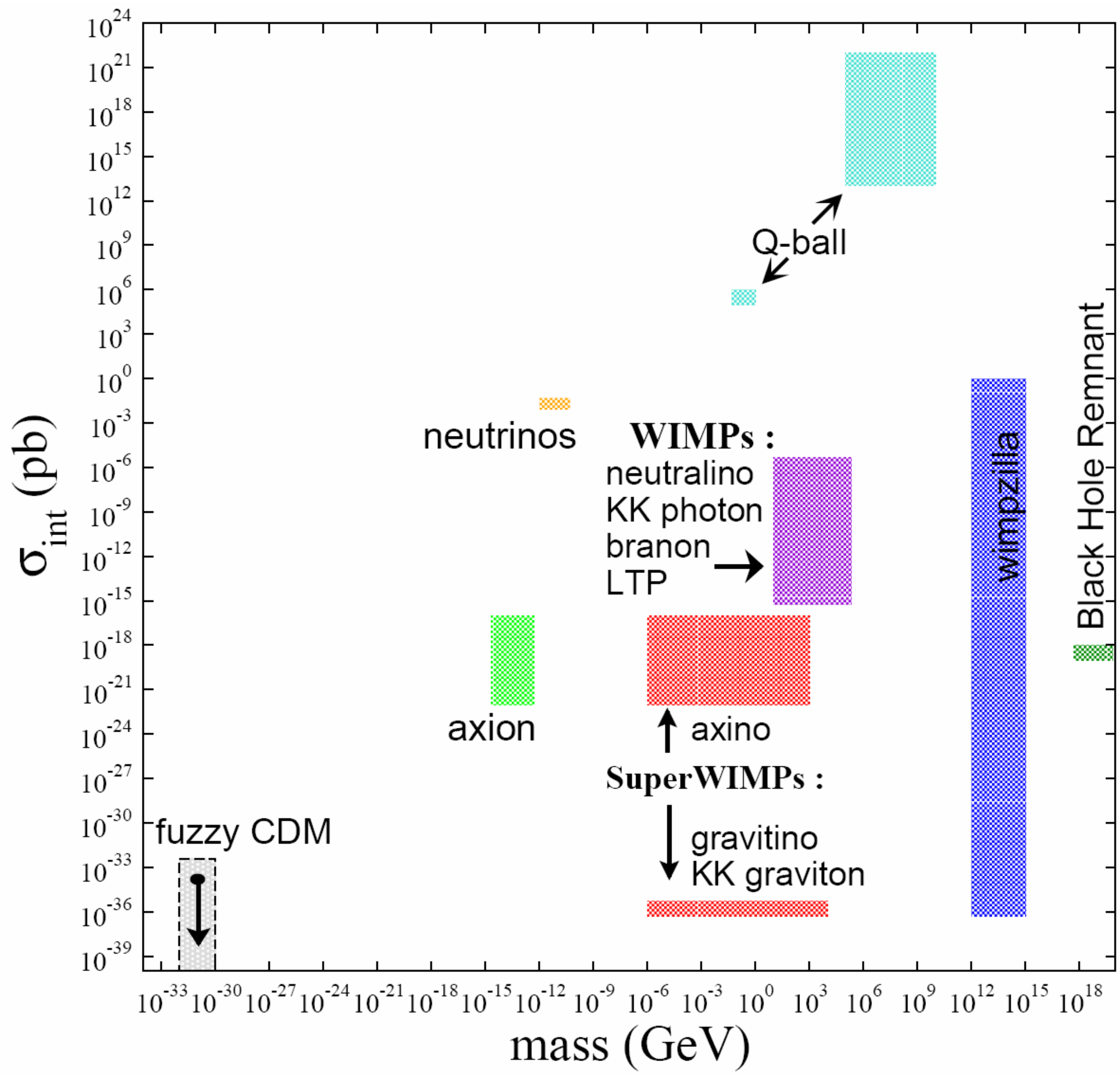
Christian Spiering
DESY, Zeuthen

Bad Honnef, 2.10.2007

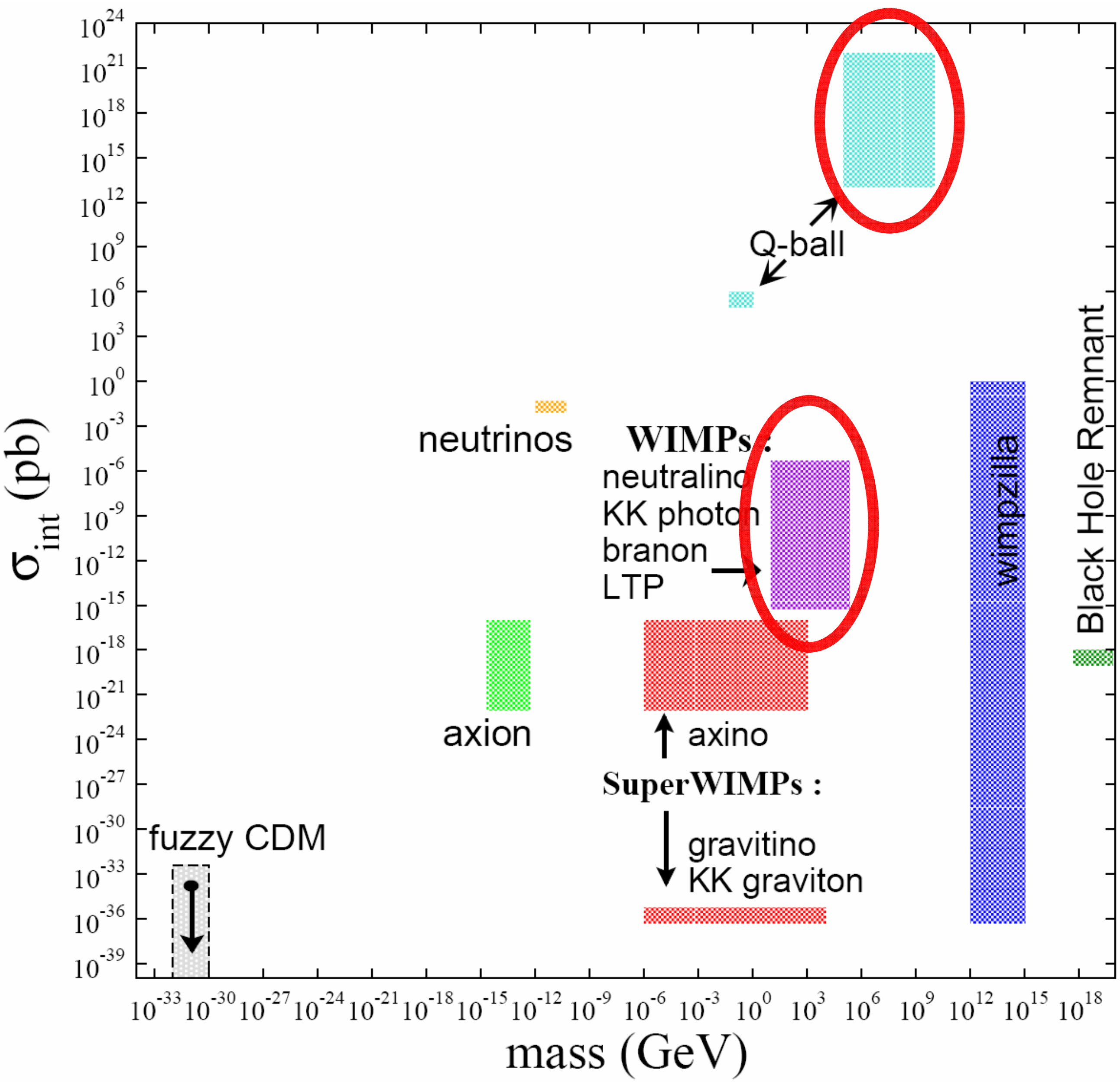
Outline

- CDM candidates
- WIMPs: direct and indirect detection
- Indirect detection with neutrino telescopes
- Search for Q-balls and other super-heavy exotics with neutrino telescopes

Dark Matter Candidates



Dark Matter Candidates



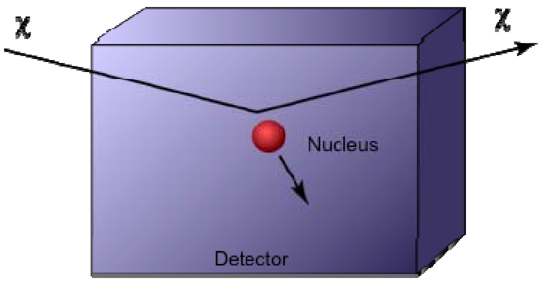
Neutralino WIMPs

$$\tilde{\chi}_1^0 = N_{11}\tilde{B} + N_{12}\tilde{W}^3 + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0$$

Detection methods

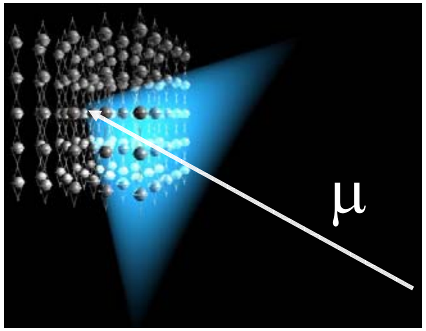
DIRECT DETECTION SEARCHES

Observe scattering of χ's off nuclei in low-background environments



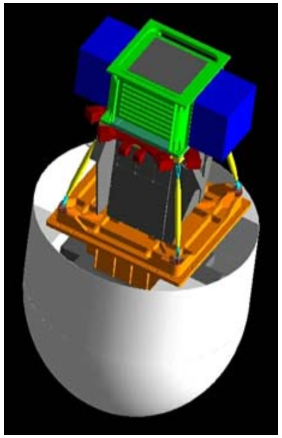
NEUTRINO INDIRECT SEARCHES

Search for neutrinos produced in $\chi\chi$ annihilations in the core of gravitational dips, e.g.the center of Sun or Earth, where χ's get "trapped"



ANTIMATTER INDIRECT SEARCHES

Disentangle antimatter produced in $\chi\chi$ annihilations in the galactic halo from standard antimatter Sources.



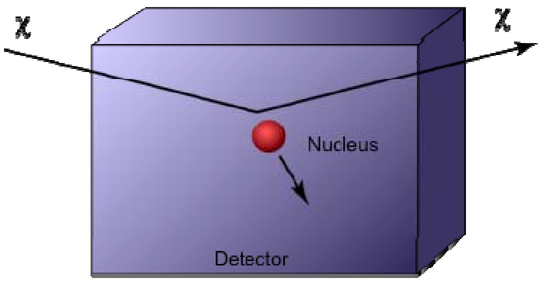
GAMMA RAY INDIRECT SEARCHES

Observe gamma rays produced by $\chi\chi$ annihilations regions of high DM density.

Detection methods

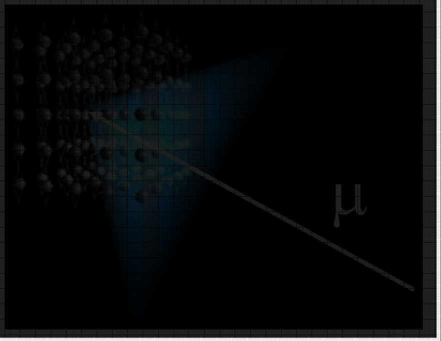
DIRECT DETECTION SEARCHES

Observe scattering of χ's off nuclei in low-background environments



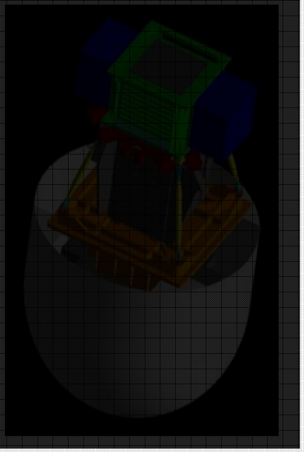
NEUTRINO INDIRECT SEARCHES

Search for neutrinos produced in $\chi\chi$ annihilations in the core of gravitational dips, e.g.the center of Sun or Earth, where χ's get "trapped"



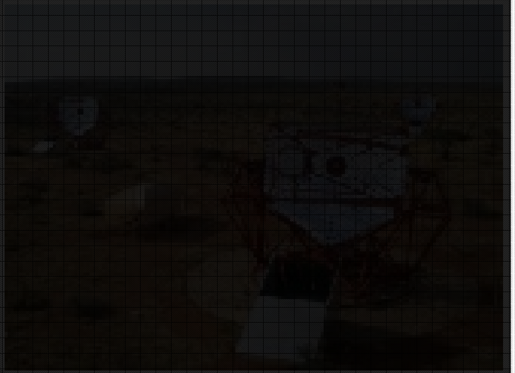
ANTIMATTER INDIRECT SEARCHES

Disentangle antimatter produced in $\chi\chi$ annihilations in the galactic halo from standard antimatter Sources.

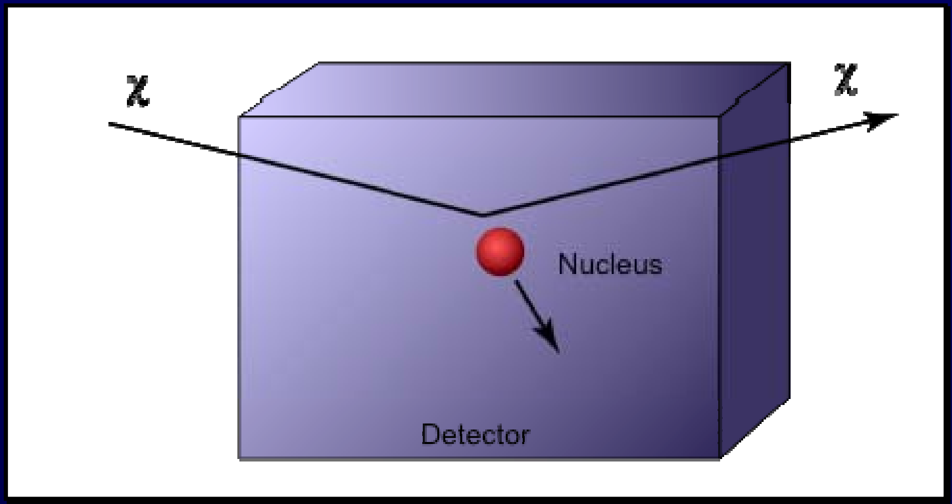


GAMMA RAY INDIRECT SEARCHES

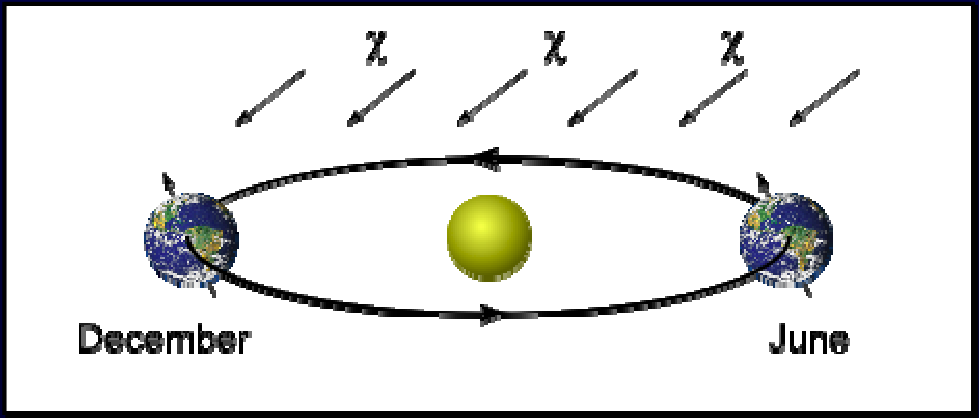
Observe gamma rays produced by $\chi\chi$ annihilations regions of high DM density.



Direct detection



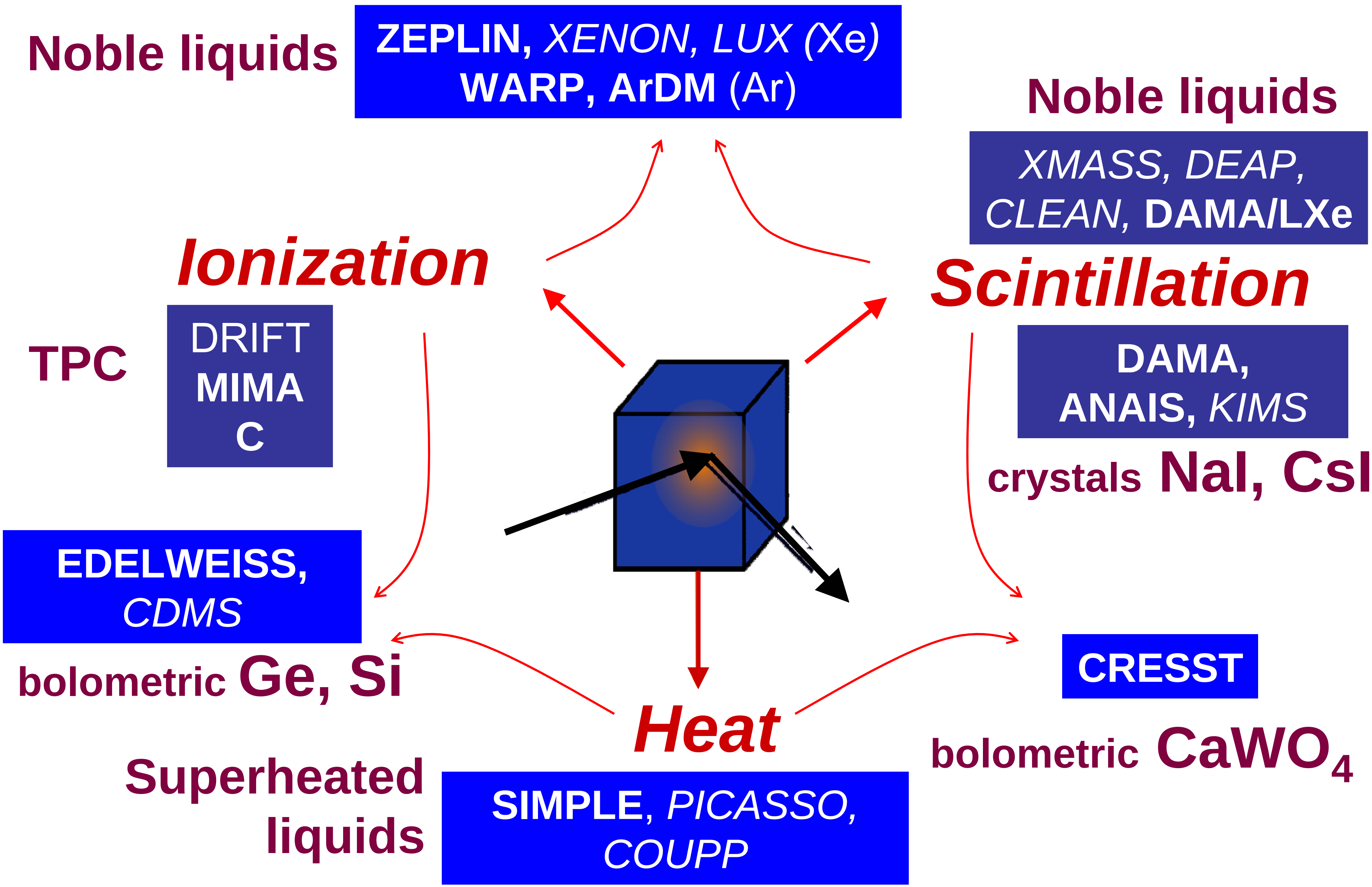
- WIMP + nucleus → WIMP + nucleus
- Measure recoil energy
- Suppress background enough to be sensitive to a signal (if possible zero)



Smoking gun signatures due to motion of Earth through halo:

- Search for annual modulation of rate
- Search for directional signature

Direct detection: experiments



Direct detection: experiments

Noble liquids

ZEPLIN, *XENON*, *LUX* (Xe)
WARP, **ArDM** (Ar)

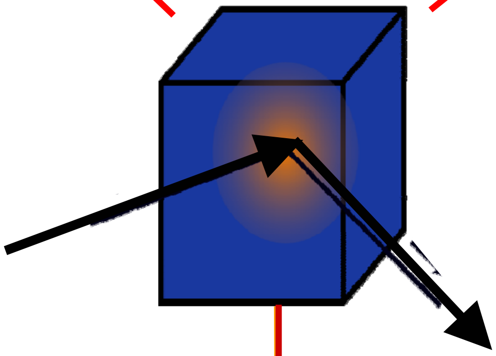
Noble liquids

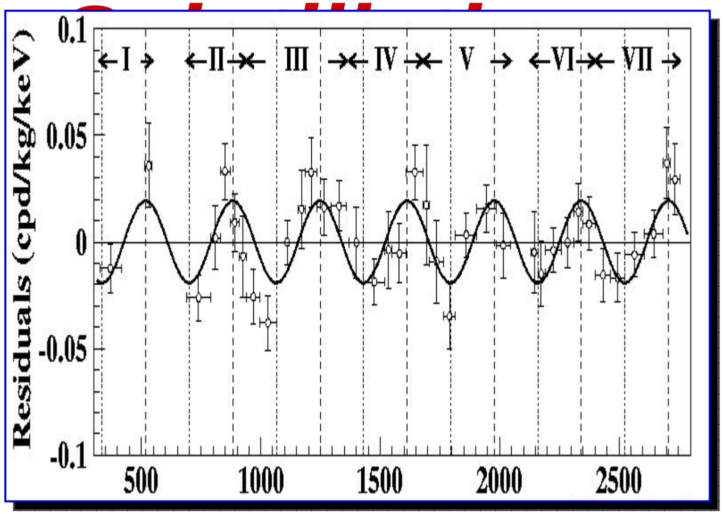
XMASS, *DEAP*,
CLEAN, **DAMA/LXe**

Ionization

TPC

DRIFT
MIMA
C





EDELWEISS,
CDMS

bolometric **Ge, Si**

Heat

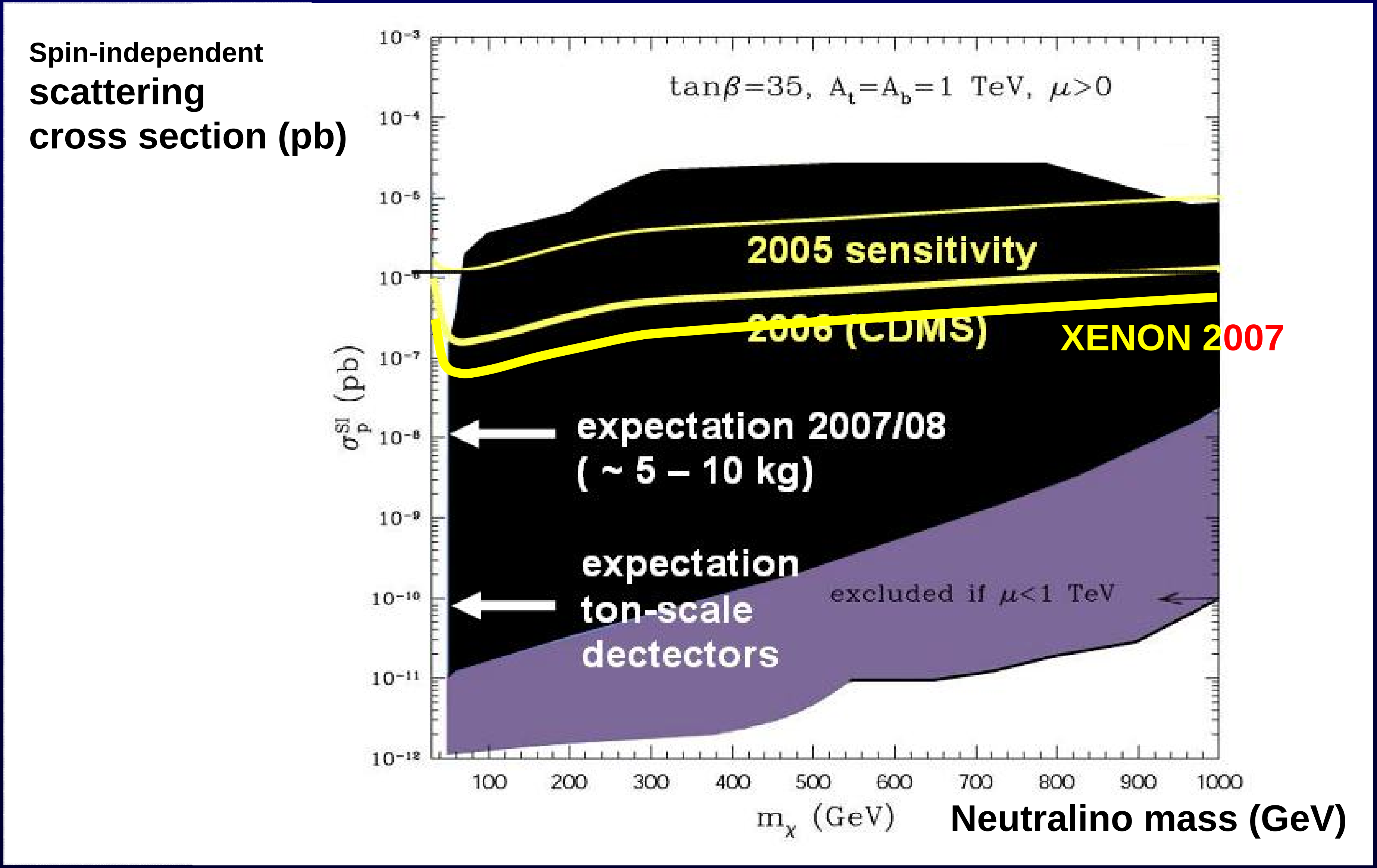
CRESST

bolometric $CaWO_4$

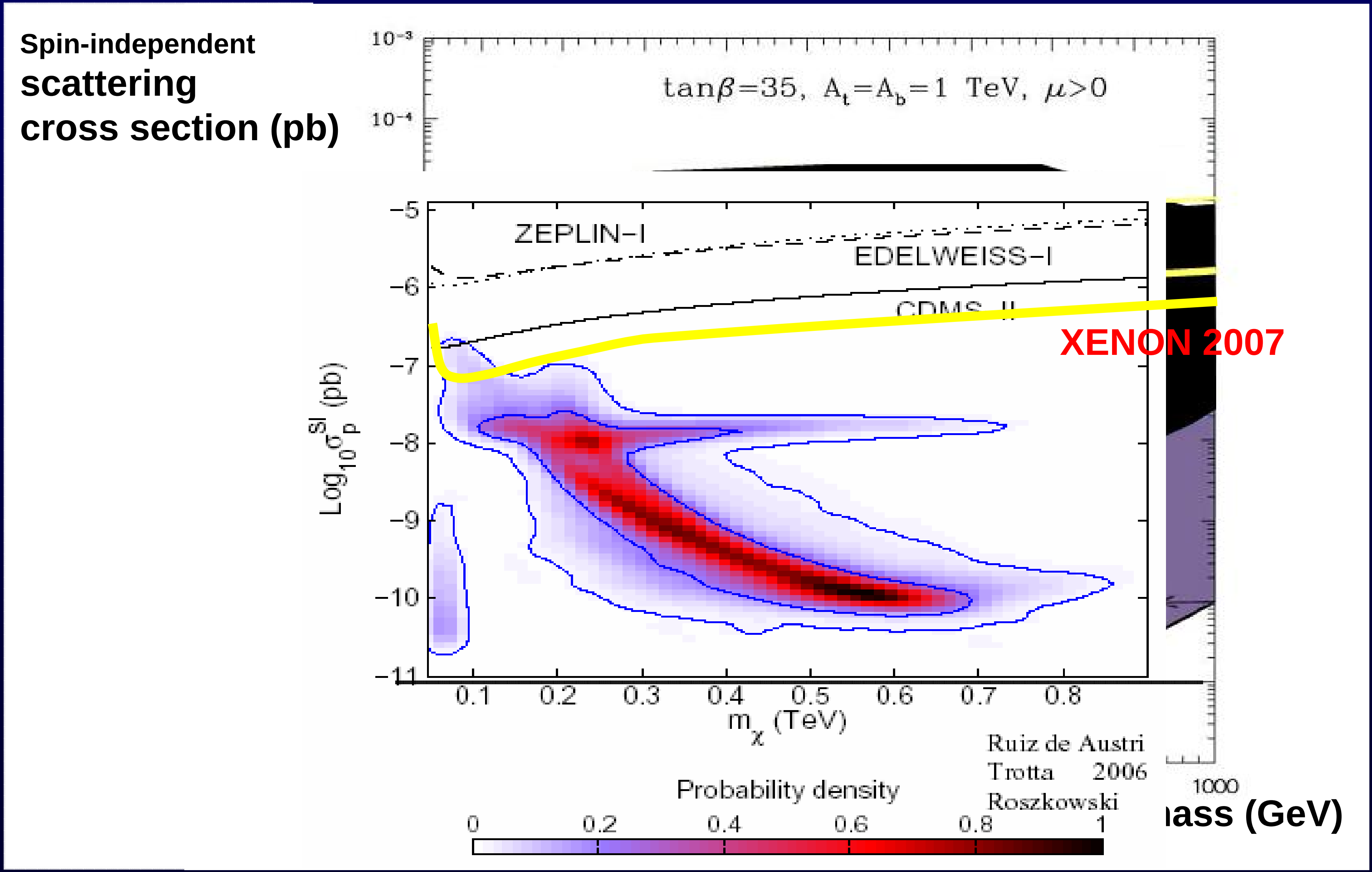
Superheated liquids

SIMPLE, *PICASSO*,
COUPP

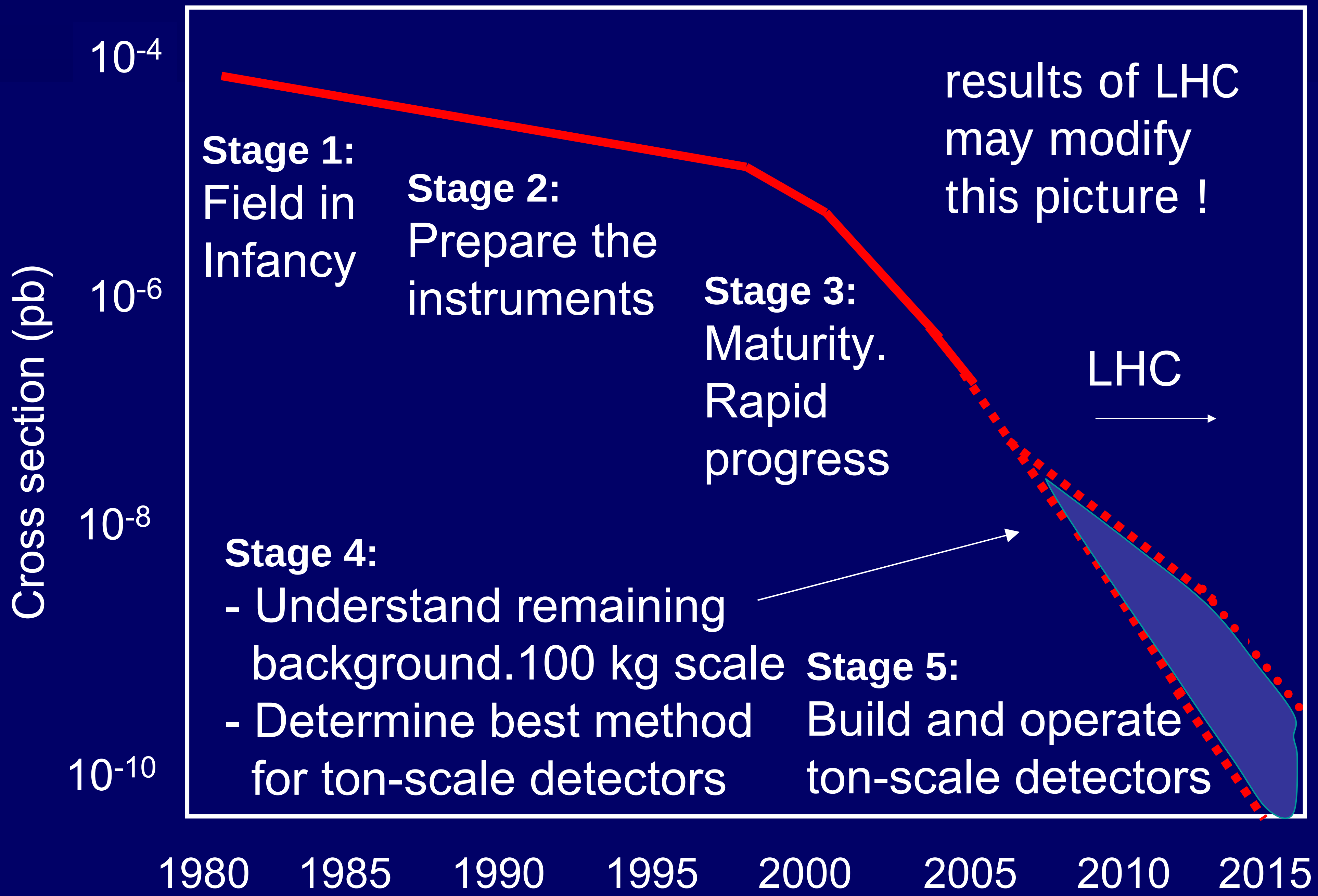
Limits vs. MSSM Model 2007



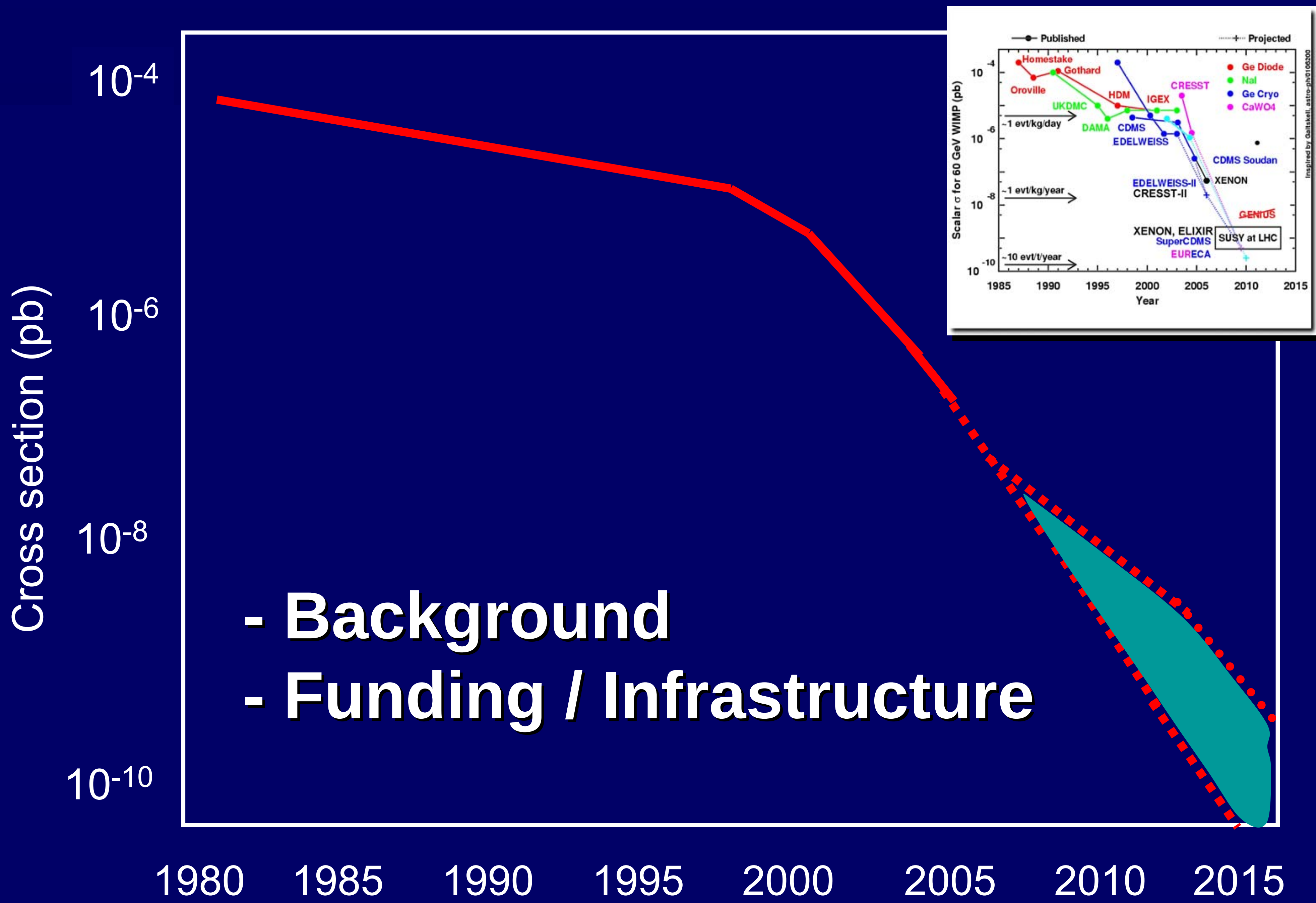
Limits vs. constrained MSSM Model 2007



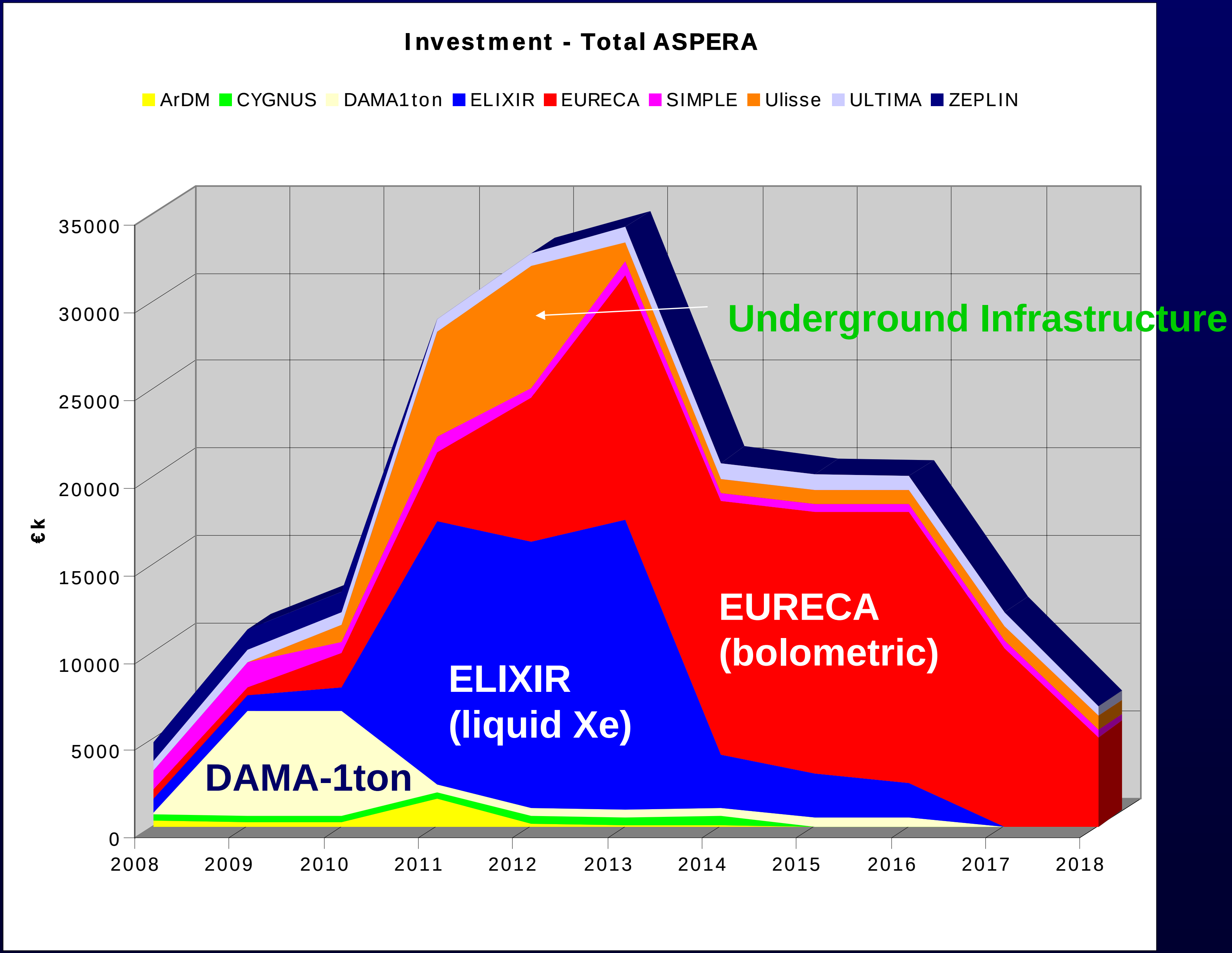
From infancy to technological maturity



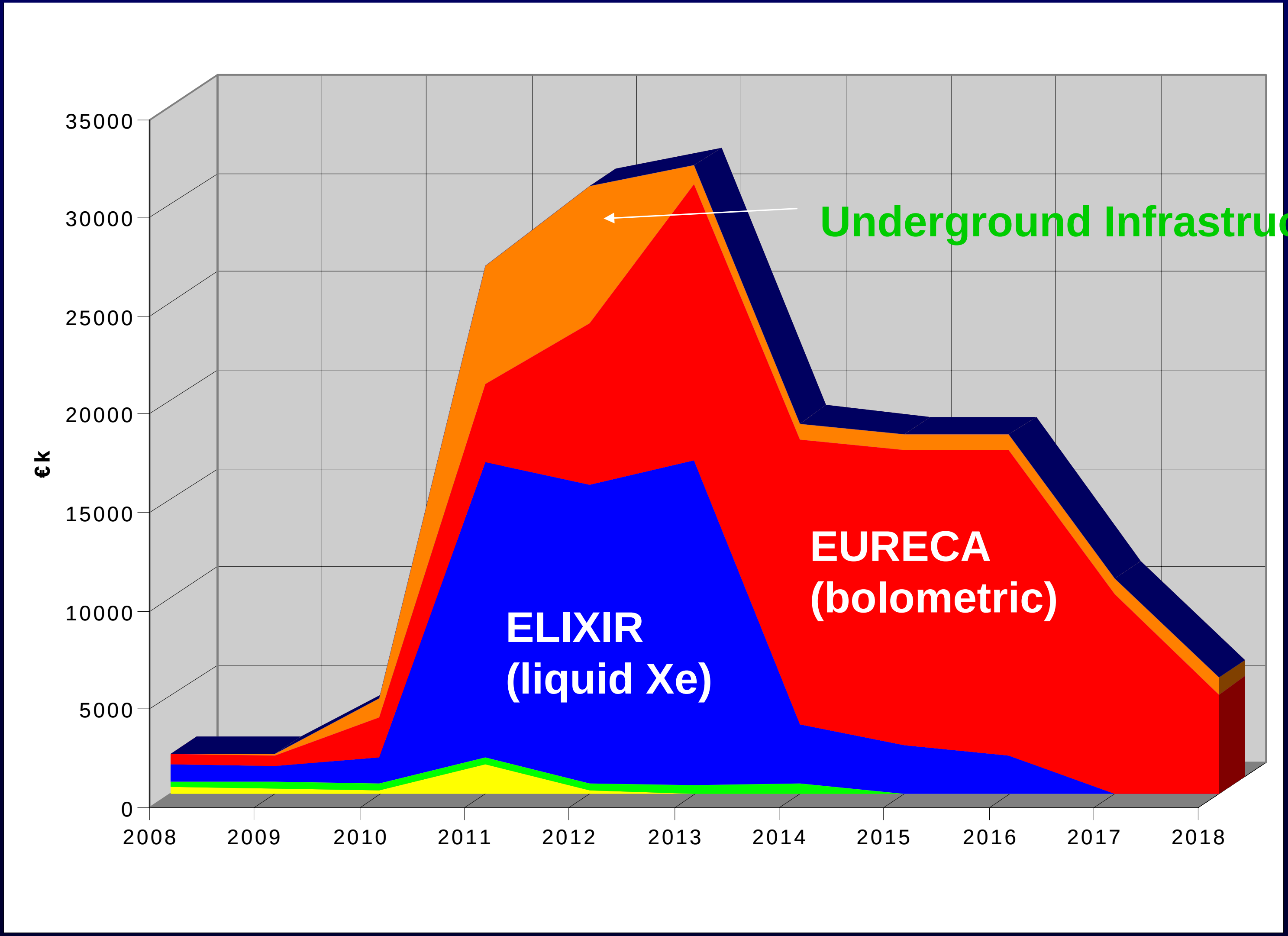
From infancy to technological maturity



WG *requests* for European Dark Matter projects



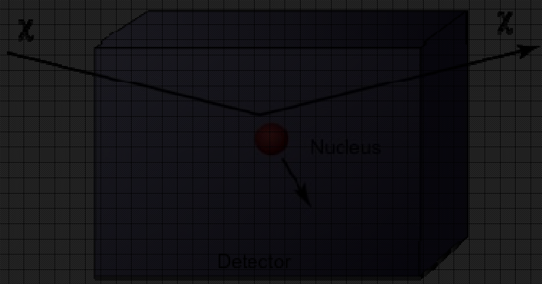
WG ***recommendations*** for European Dark Matter projects



Detection methods

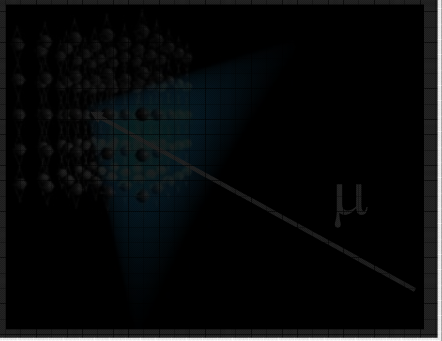
DIRECT DETECTION SEARCHES

Observe scattering of χ's off nuclei in low-background environments



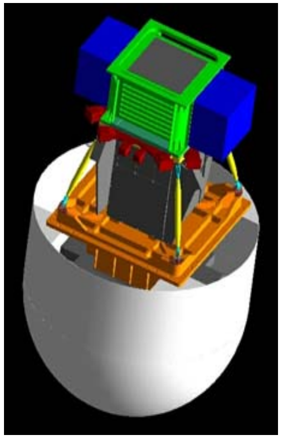
NEUTRINO INDIRECT SEARCHES

Search for neutrinos produced in χχ annihilations in the core of gravitational dips, e.g.the center of Sun or Earth, where χ's get "trapped"



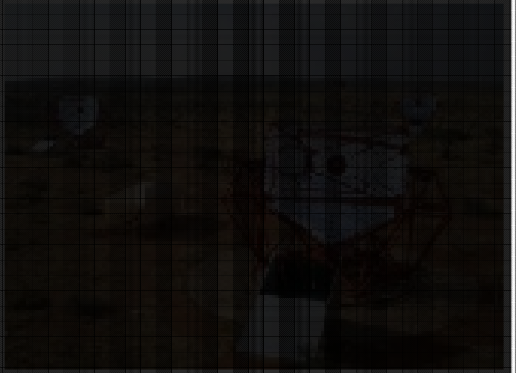
ANTIMATTER INDIRECT SEARCHES

Disentangle antimatter produced in χχ annihilations in the galactic halo from standard antimatter Sources.



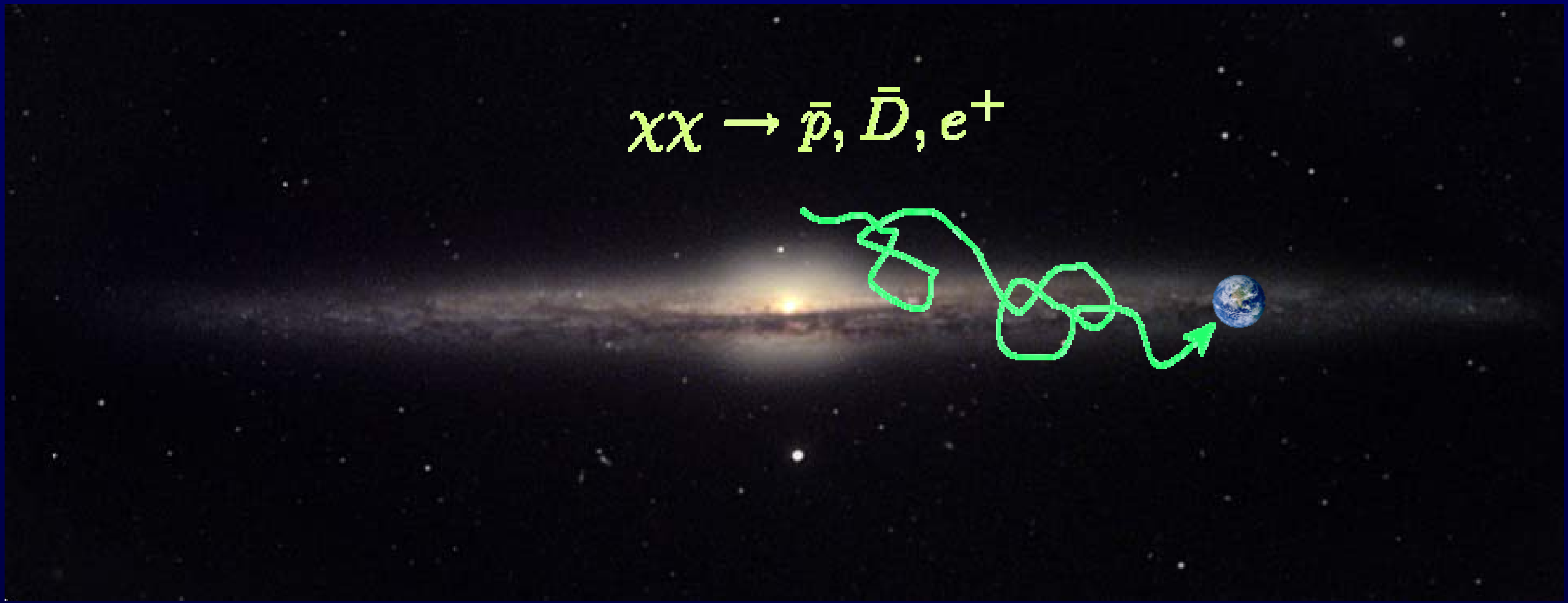
GAMMA RAY INDIRECT SEARCHES

Observe gamma rays produced by χχ annihilations regions of high DM density.



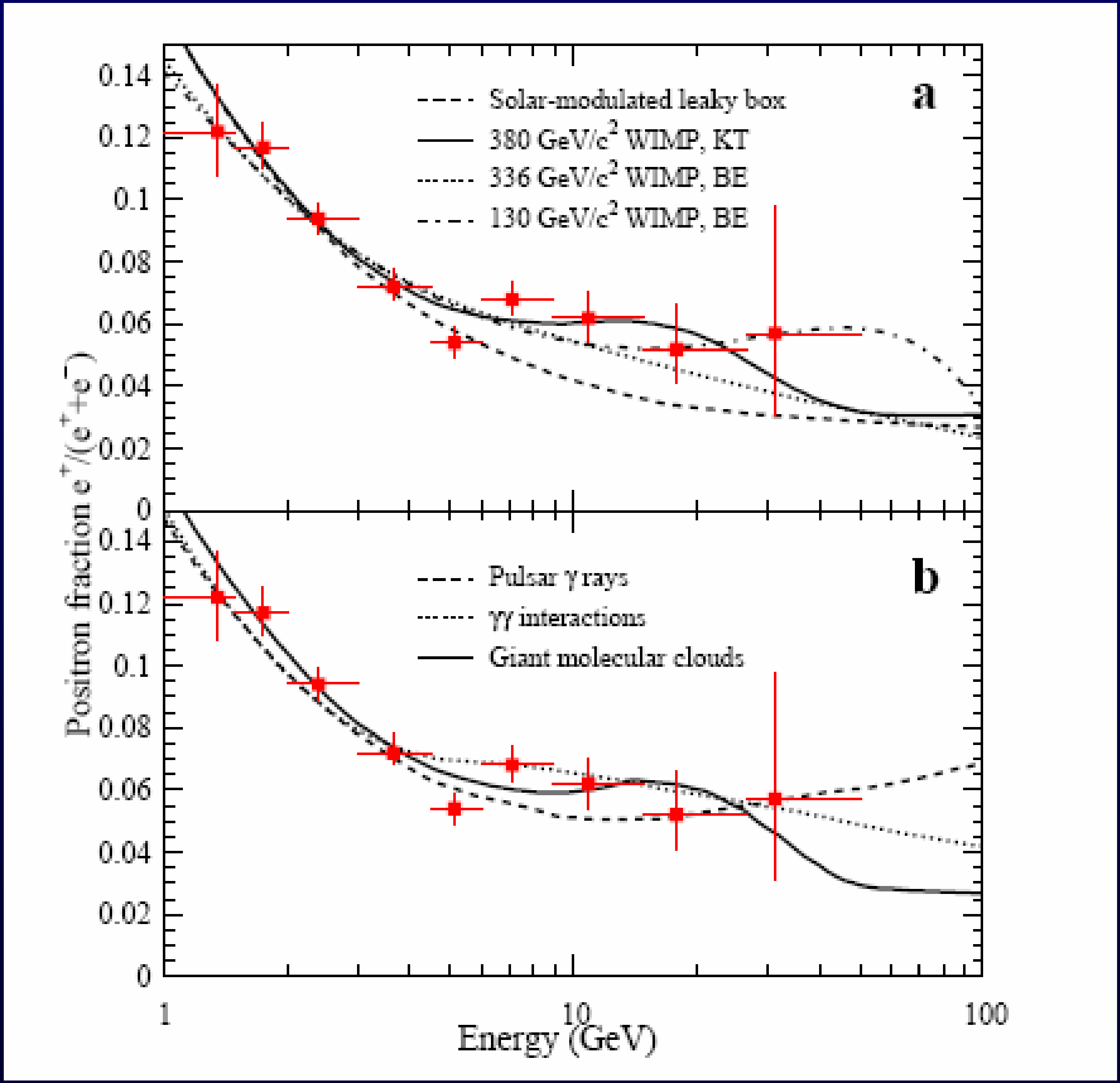
Annihilation in the halo

Charged annihilation products



- Diffusion of charged particles. Looking for excess of antiparticles.
- Best current detector is Pamela. Next big step would be AMS.

Example: the „HEAT Positron Excess“



Better data mandatory.

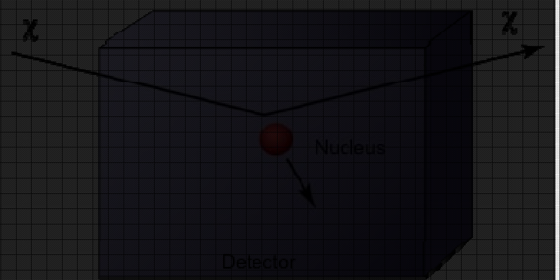
Wait first PAMELA data.

Then AMS !!

Detection methods

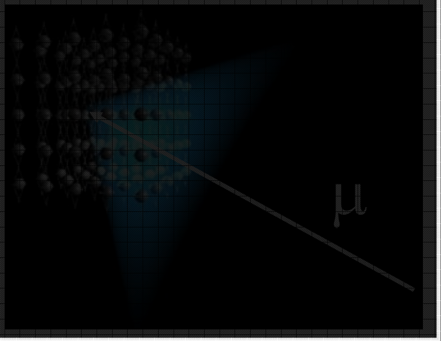
DIRECT DETECTION SEARCHES

Observe scattering of χ's off nuclei in low-background environments



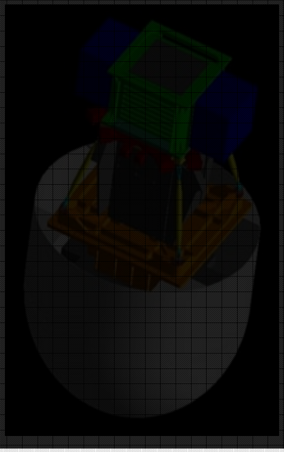
NEUTRINO INDIRECT SEARCHES

Search for neutrinos produced in $\chi\chi$ annihilations in the core of gravitational dips, e.g.the center of Sun or Earth, where χ's get "trapped"



ANTIMATTER INDIRECT SEARCHES

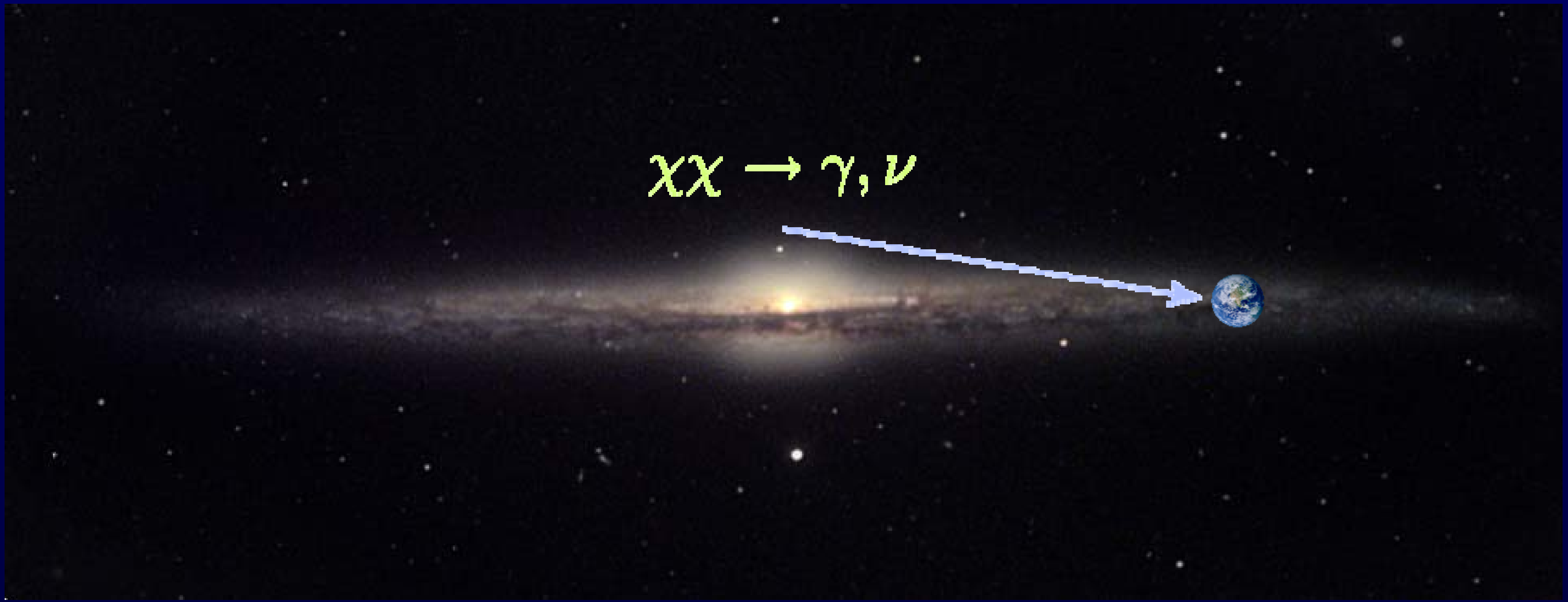
Disentangle antimatter produced in $\chi\chi$ annihilations in the galactic halo from standard antimatter Sources.



GAMMA RAY INDIRECT SEARCHES

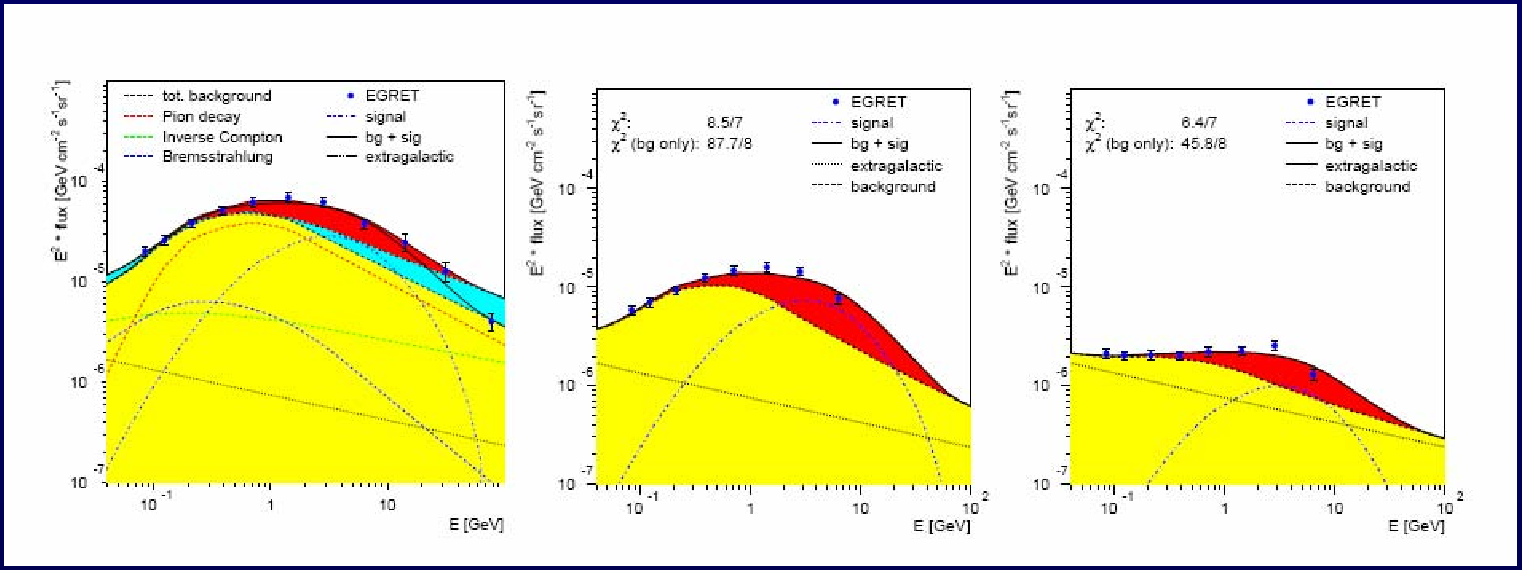
Observe gamma rays produced by $\chi\chi$ annihilations regions of high DM density.

Annihilation in the halo or certain regions

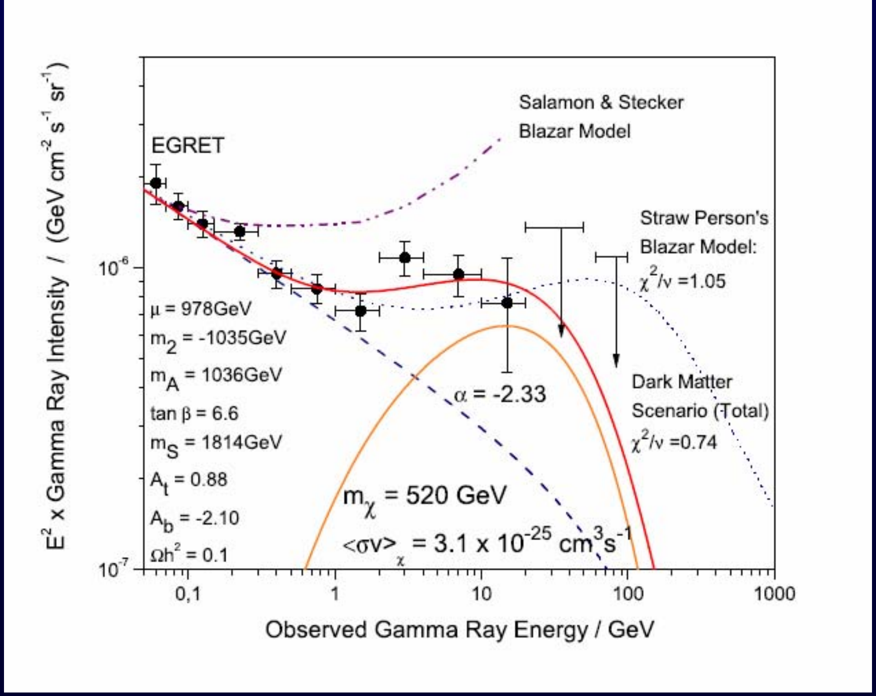


- Gamma rays can be searched for with Imaging Air Cherenkov Telescopes (IACTs) or GLAST.
- Signal depends strongly on the halo profile or local cluster factors

EGRET data



De Boer
halo origin
65 GeV

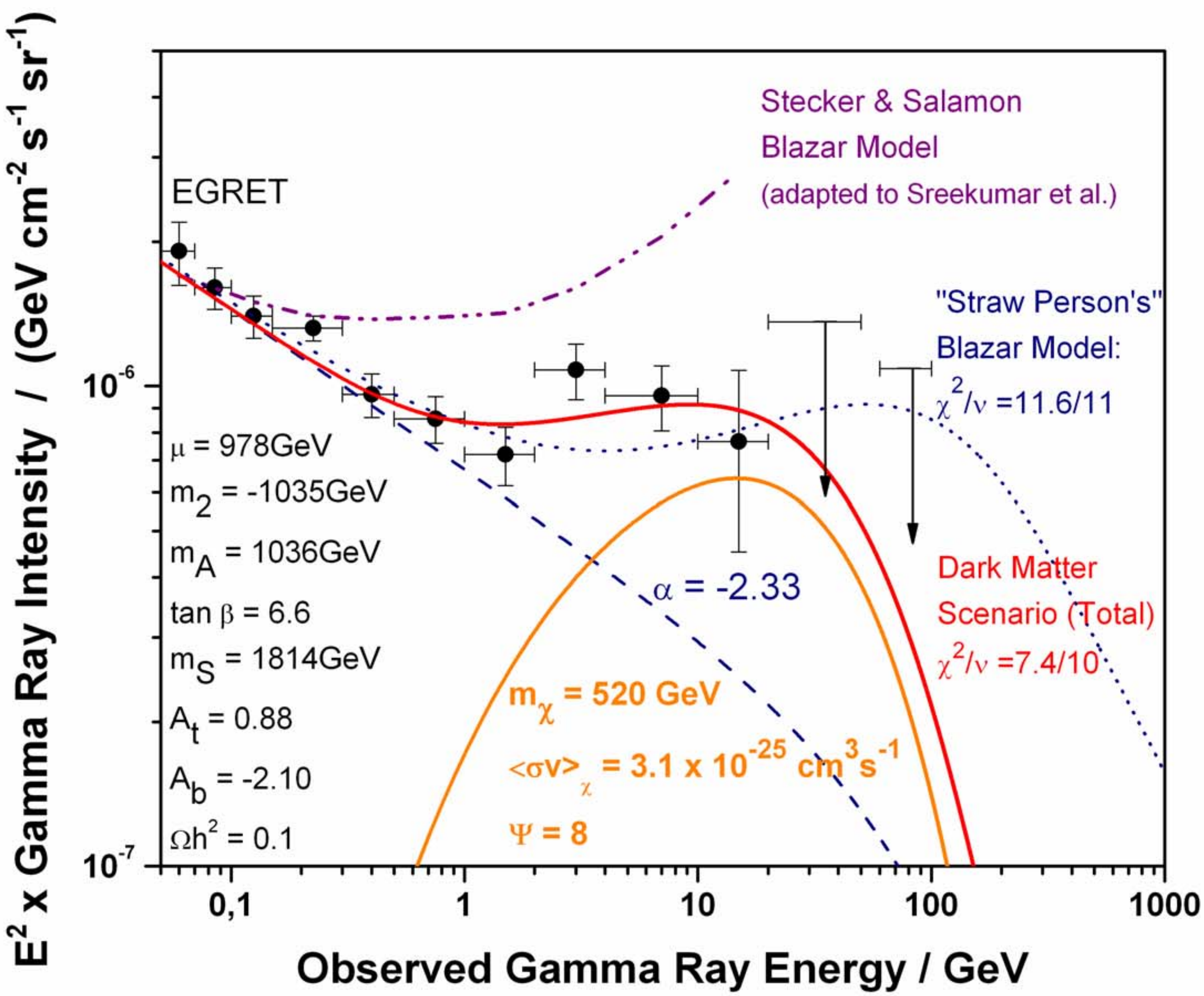


Mannheim & Elsässer
Subtract galactic/halo component
Extragalactic origin
520 GeV

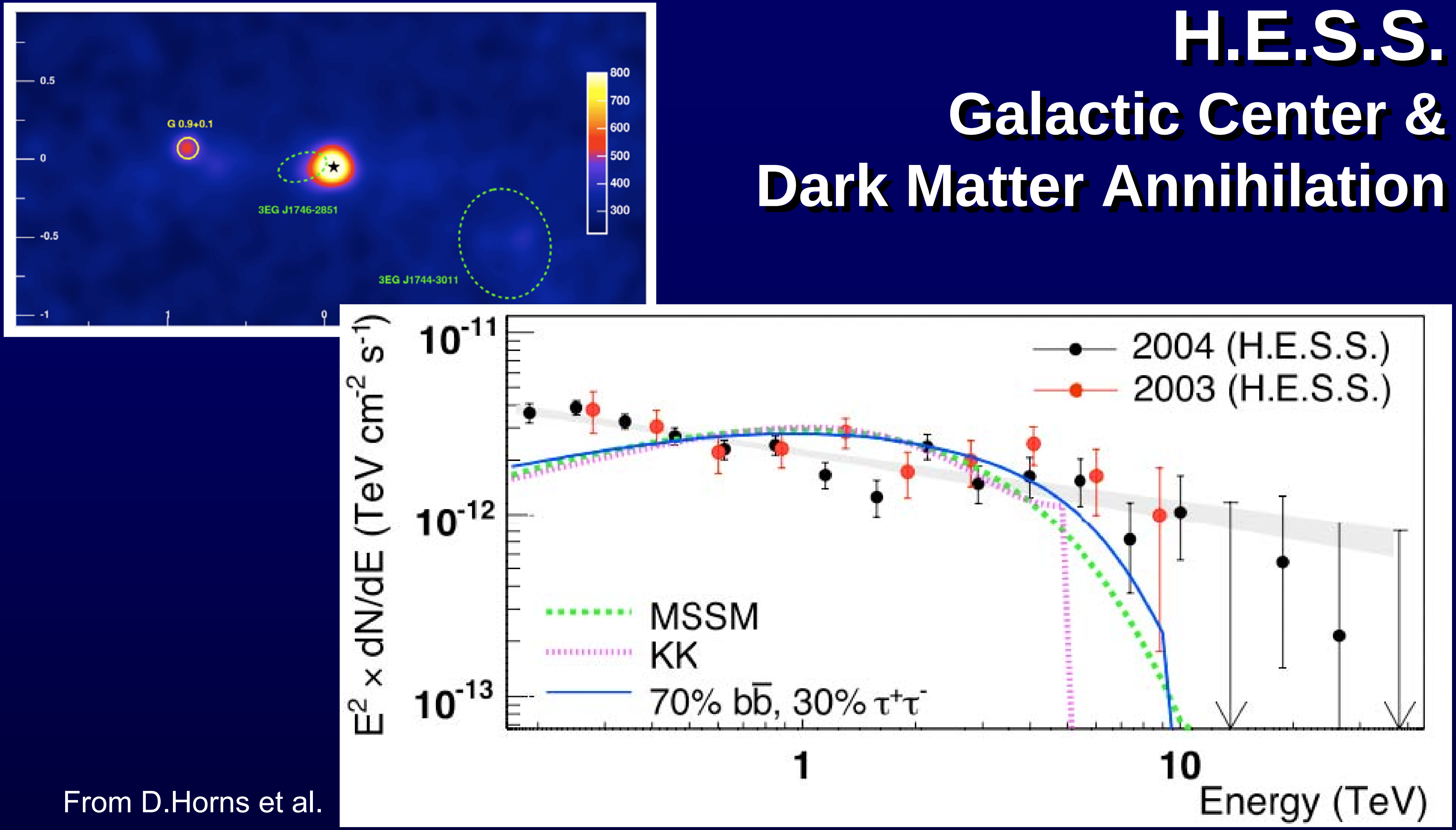
Now: Agile
Wait for GLAST !

Extragalactic gamma background

D. Elsässer & K. Mannheim, Phys.Rev.Lett. 94:171302, 2005



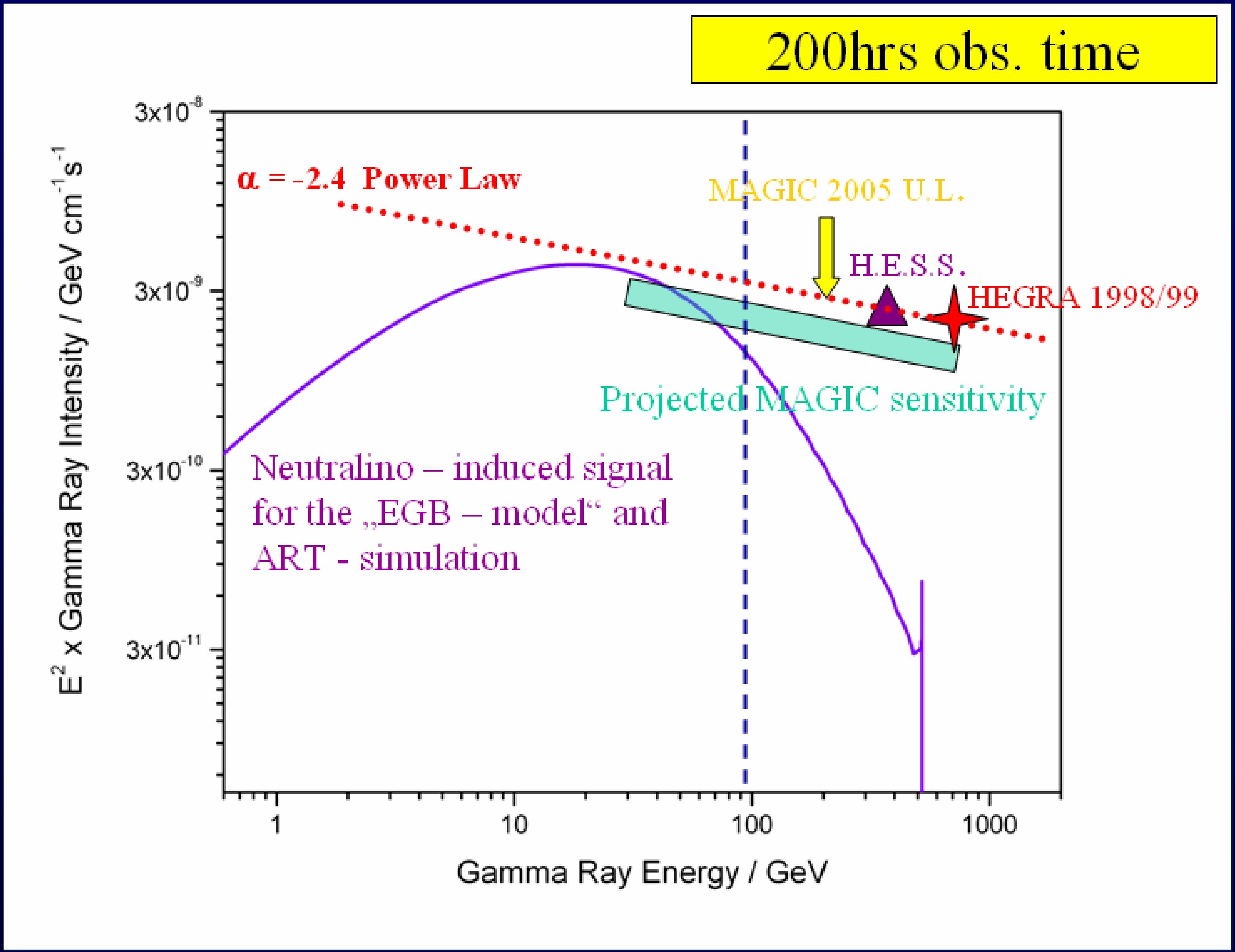
H.E.S.S.
Galactic Center &
Dark Matter Annihilation



From D.Horns et al.

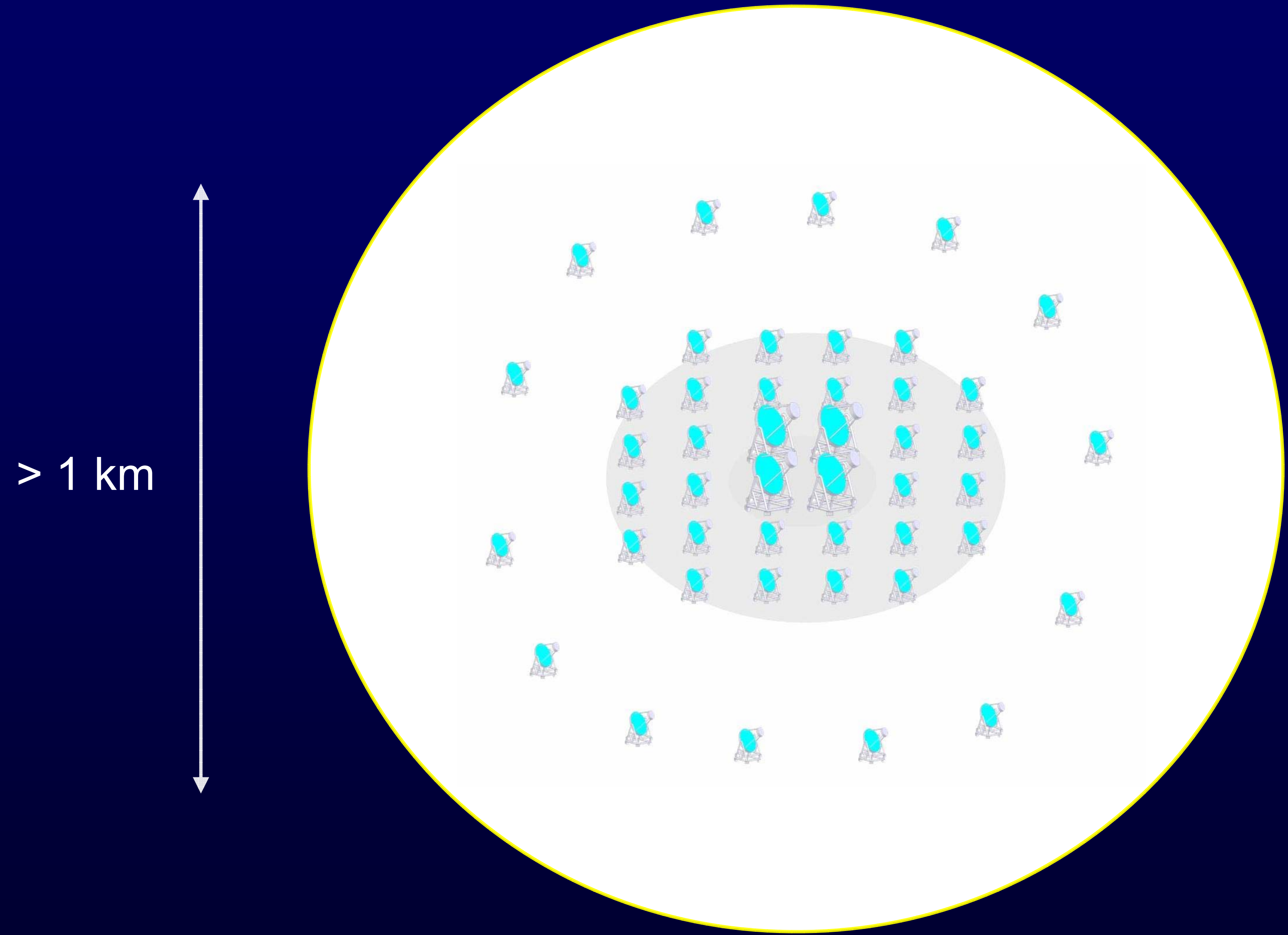
- Energy spectrum not well described by neutralino- or KK-annihilation (M_x =14 TeV, M_{KK}=5TeV)
- Sagittarus Dwarf Galaxy: astrophysical component small
  → set interesting limits on cross section (private comm. G. Heinzelmann)

M87 spectrum for WIMP annihilation



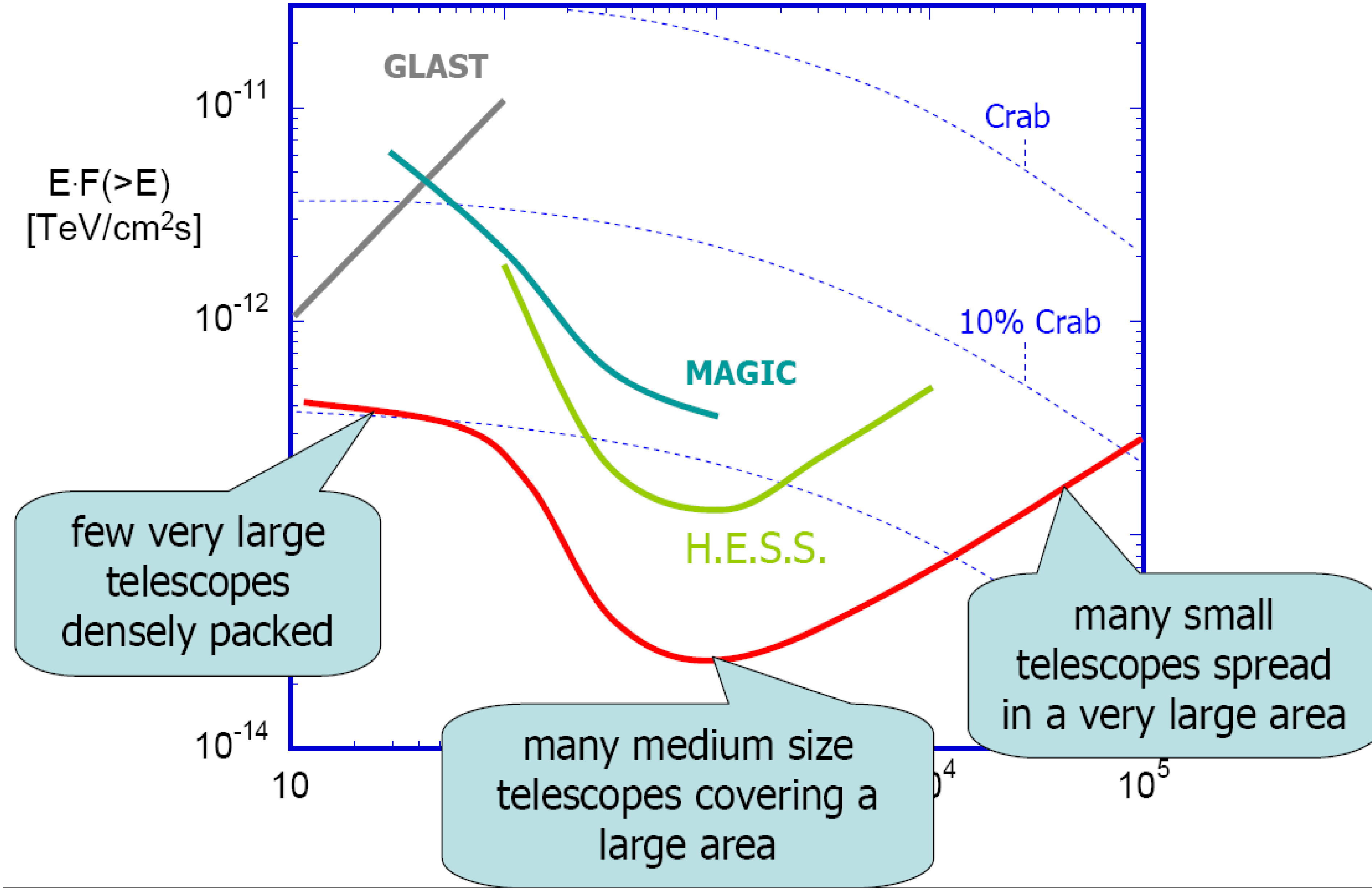
From D. Elsässer

CTA – Cherenkov Telescope Array



Large ~50 dish IACT array of 2-3 different sizes

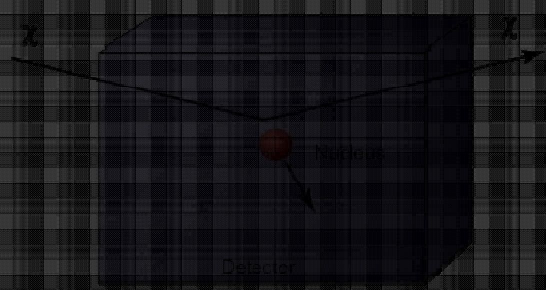
CTA


GLAST
10^{-11}
$E \cdot F(>E)$
[TeV/cm^{2}s]
Crab
10^{-12}
10% Crab
MAGIC
H.E.S.S.
10^{-14}
10
10^5
few very large telescopes densely packed
many medium size telescopes covering a large area
many small telescopes spread in a very large area

Detection methods

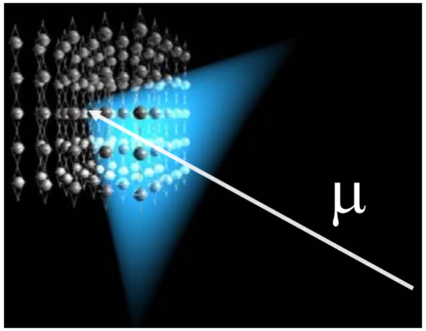
DIRECT DETECTION SEARCHES

Observe scattering of χ's off nuclei in low-background environments



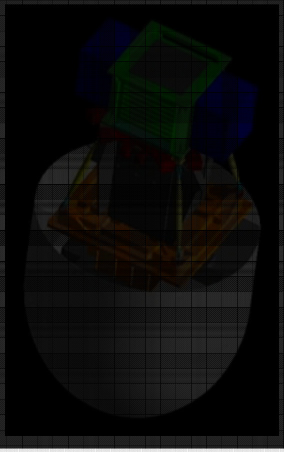
NEUTRINO INDIRECT SEARCHES

Search for neutrinos produced in $\chi\chi$ annihilations in the core of gravitational dips, e.g.the center of Sun or Earth, where χ's get "trapped"



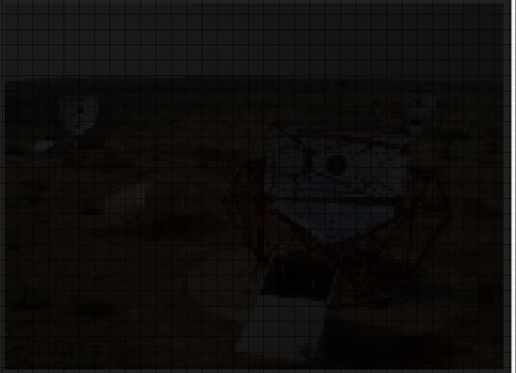
ANTIMATTER INDIRECT SEARCHES

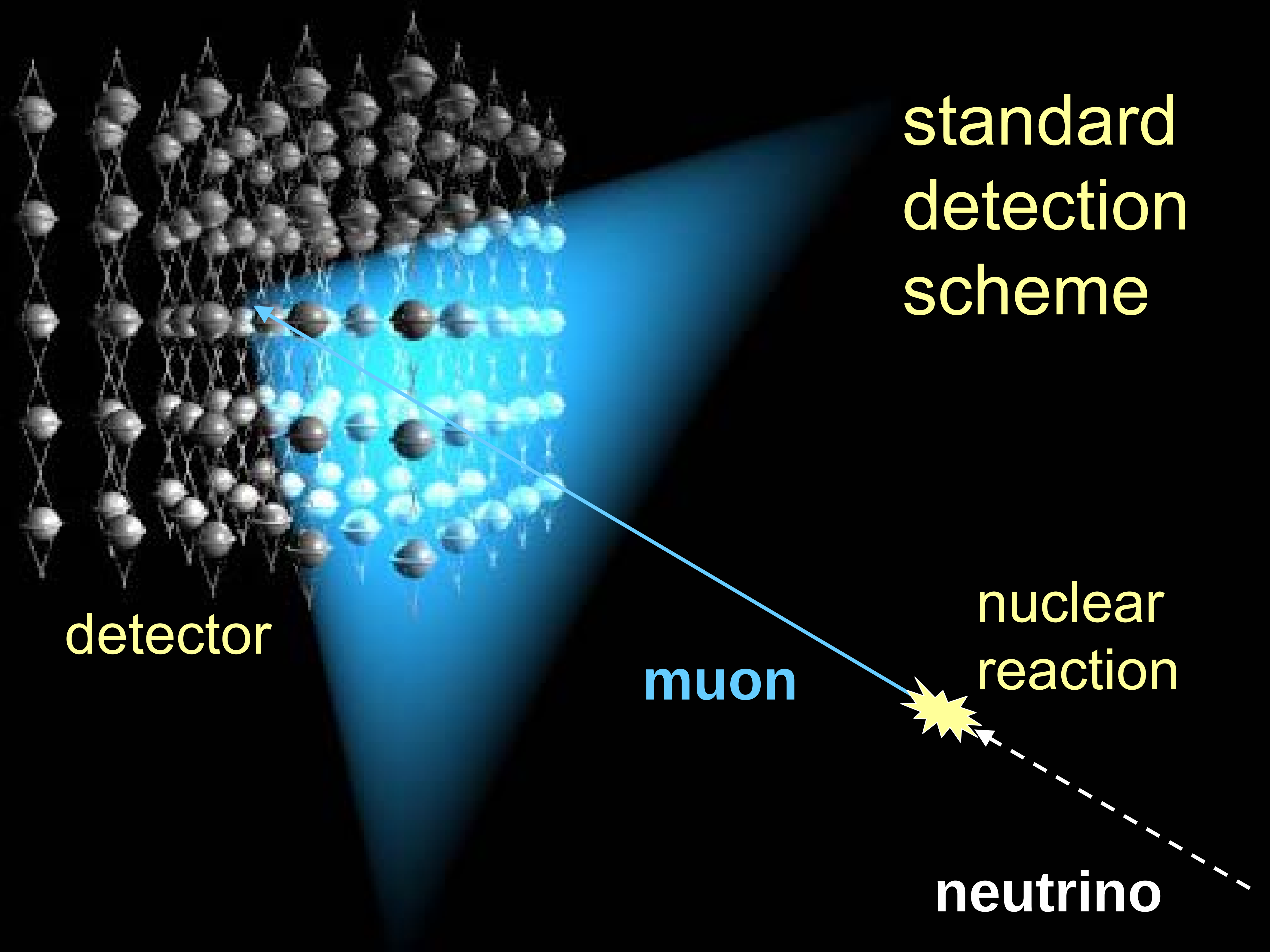
Disentangle antimatter produced in $\chi\chi$ annihilations in the galactic halo from standard antimatter Sources.



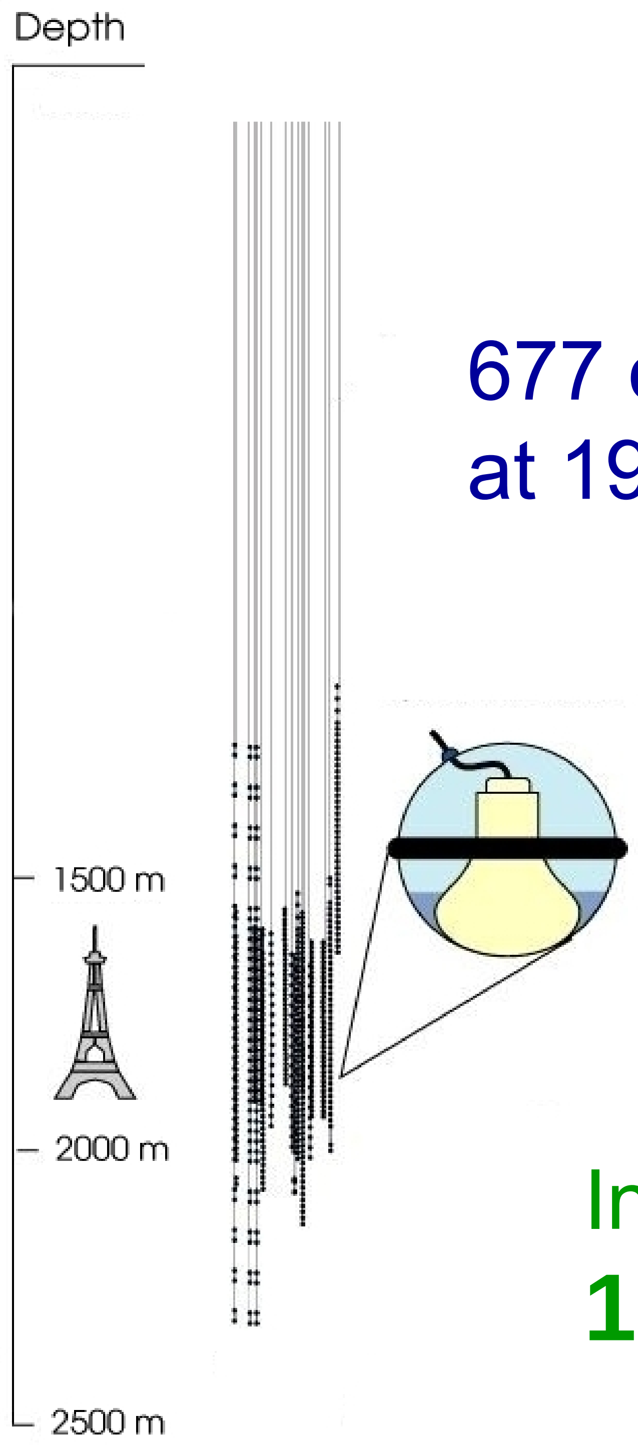
GAMMA RAY INDIRECT SEARCHES

Observe gamma rays produced by $\chi\chi$ annihilations regions of high DM density.

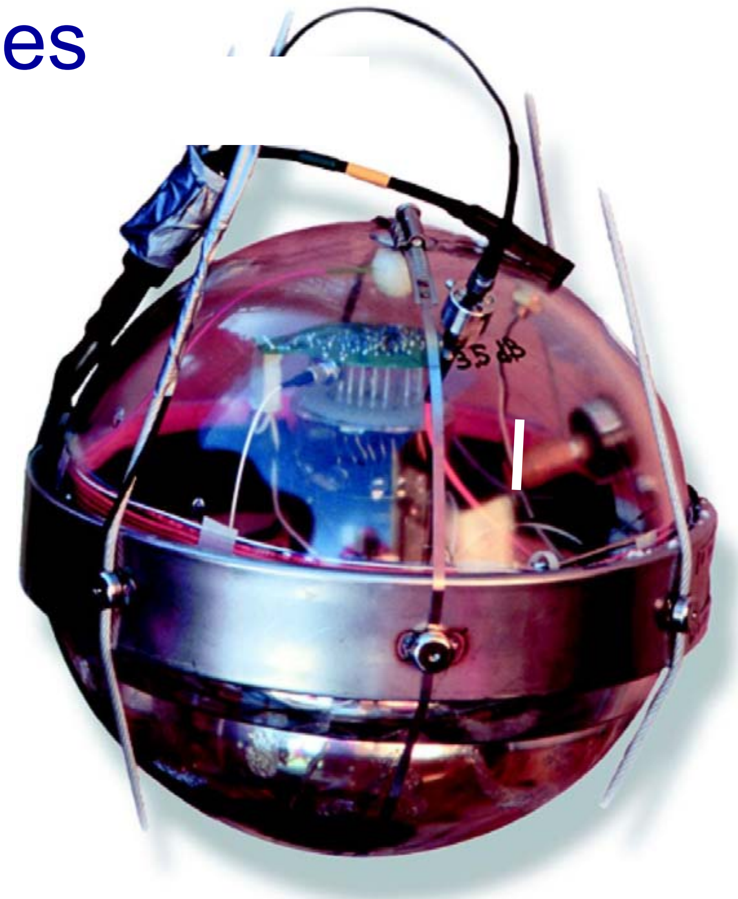



standard
detection
scheme
detector
muon
nuclear
reaction
neutrino

AMANDA



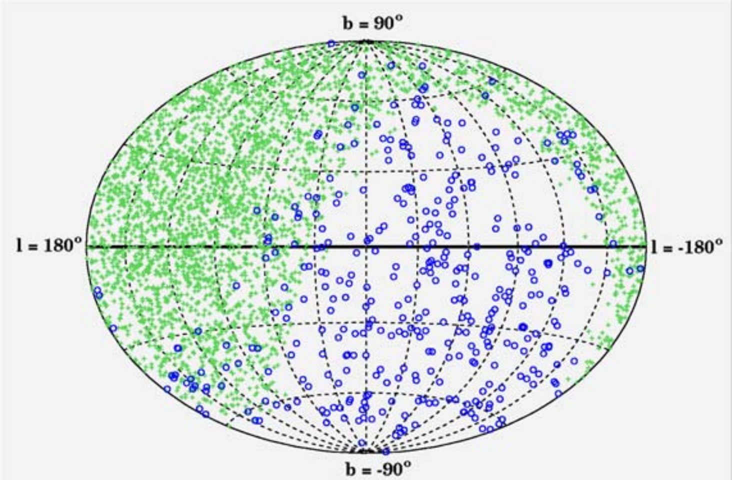
677 optical modules
at 19 strings



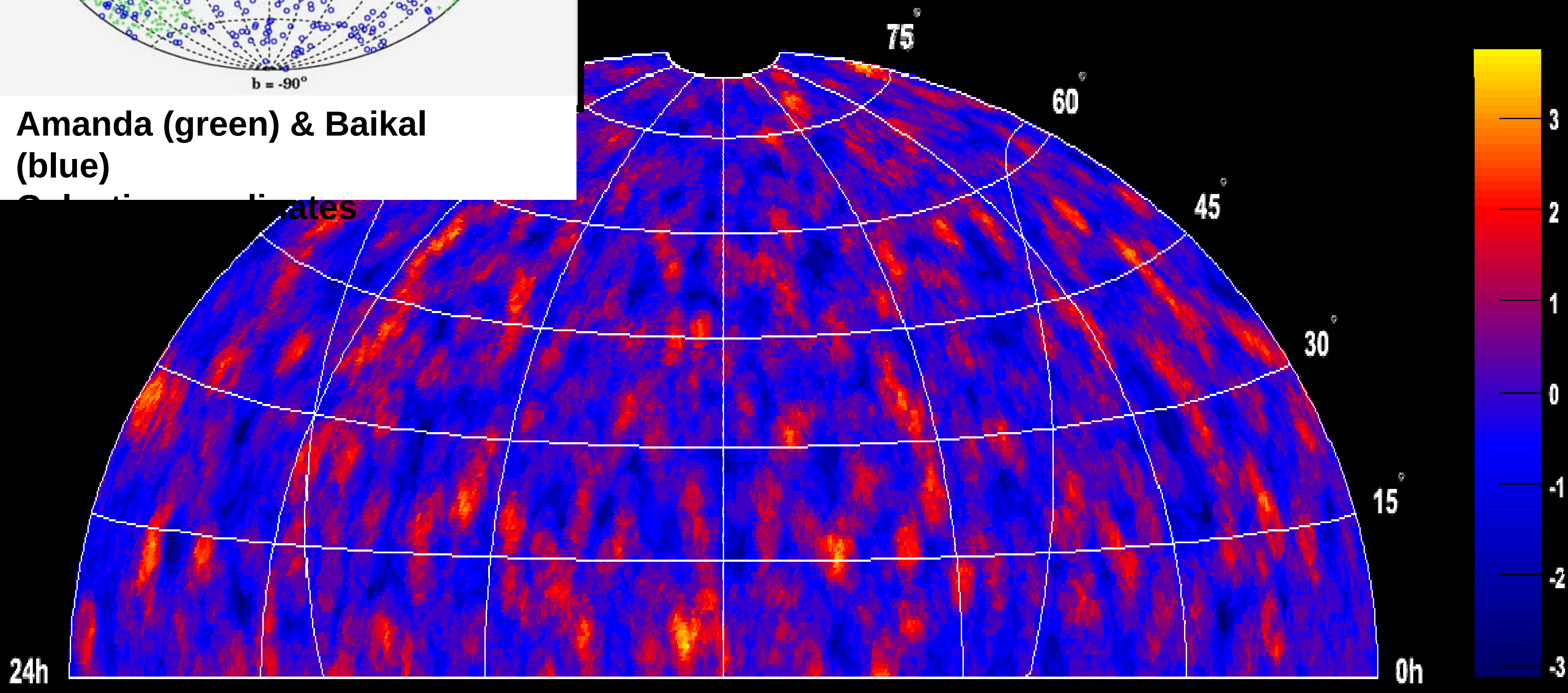
Installation
1996-2000

AMANDA

Neutrino Skymap



Amanda (green) & Baikal (blue)
Galactic coordinates

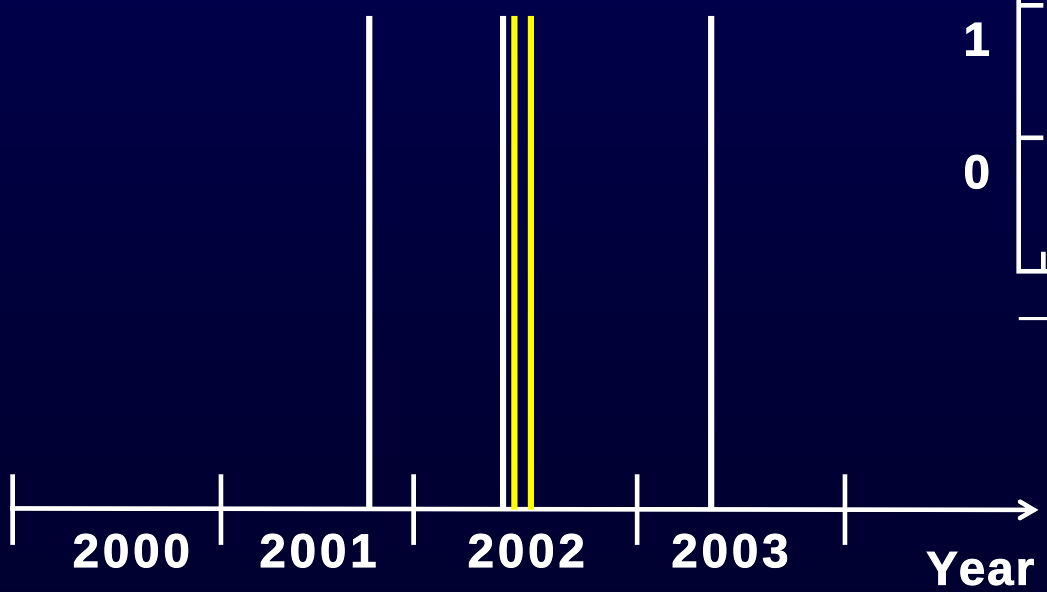


AMANDA-II: 2000-2004 (1001 live days) 4282 ν from Northern hemisphere

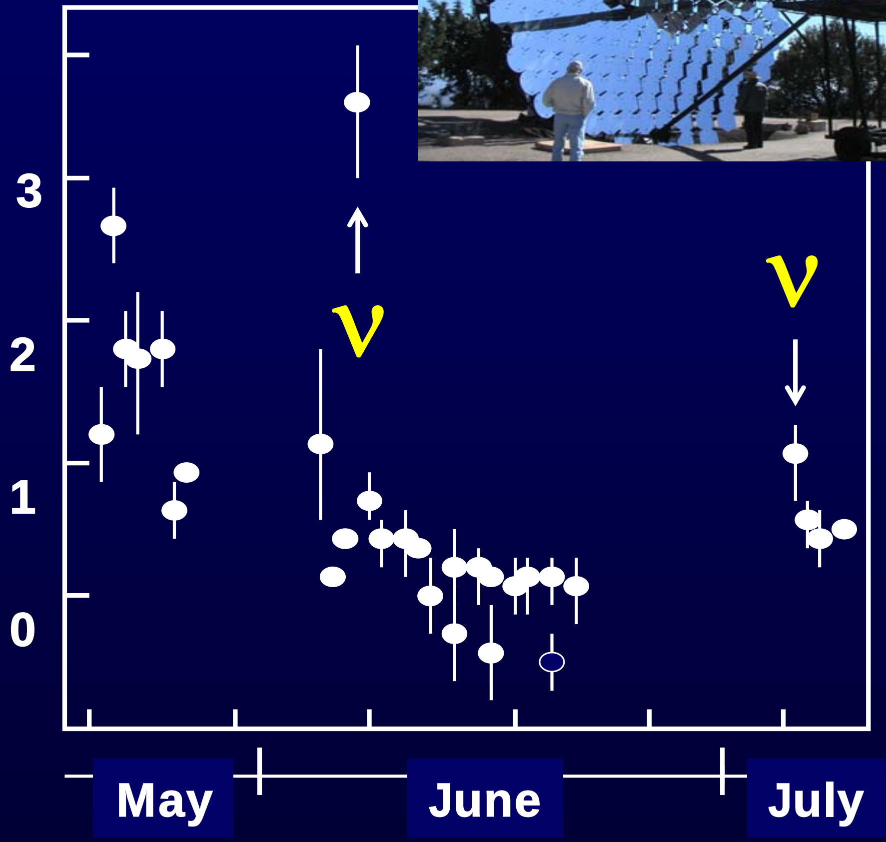
No significant excess found

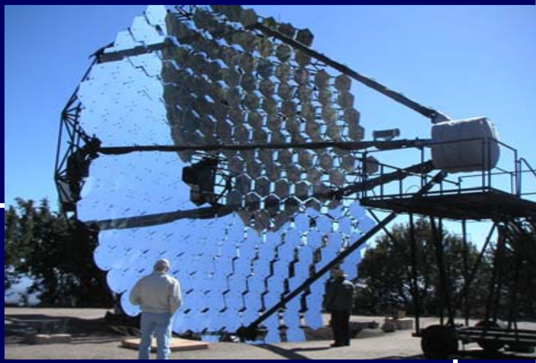
A curious coincidence

Arrival time of neutrinos from the direction of the AGN ES1959+650

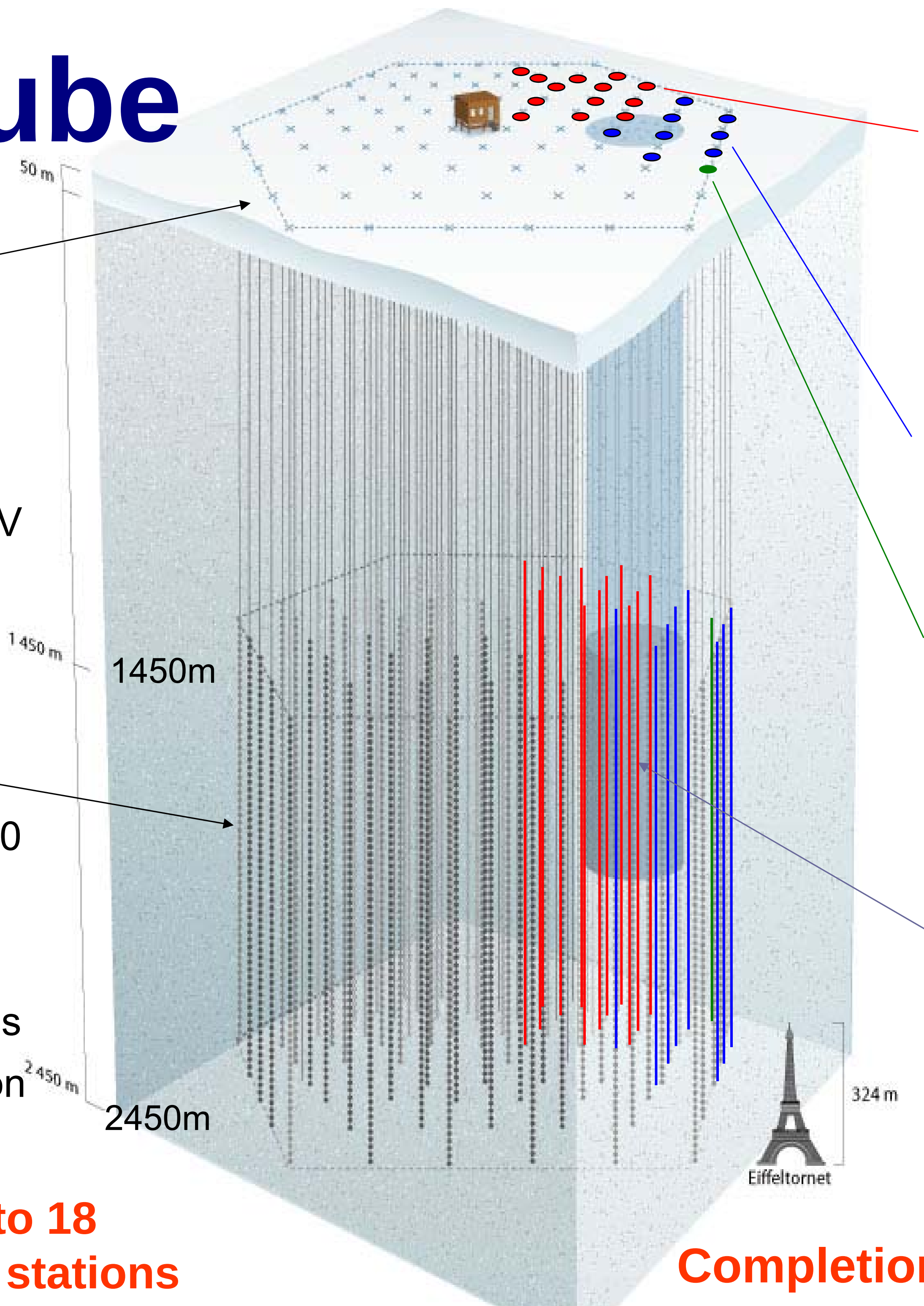


WHIPPLE





IceCube



IceTop

Air shower detector

80 pairs of ice

Cherenkov tanks

Threshold ~ 300 TeV

InIce

Goal of 80 strings of 60 optical modules each

17 m between modules

125 m string separation

2006-2007:

13 strings deployed

2005-2006: 8 strings

2004-2005 : 1 string

AMANDA-II

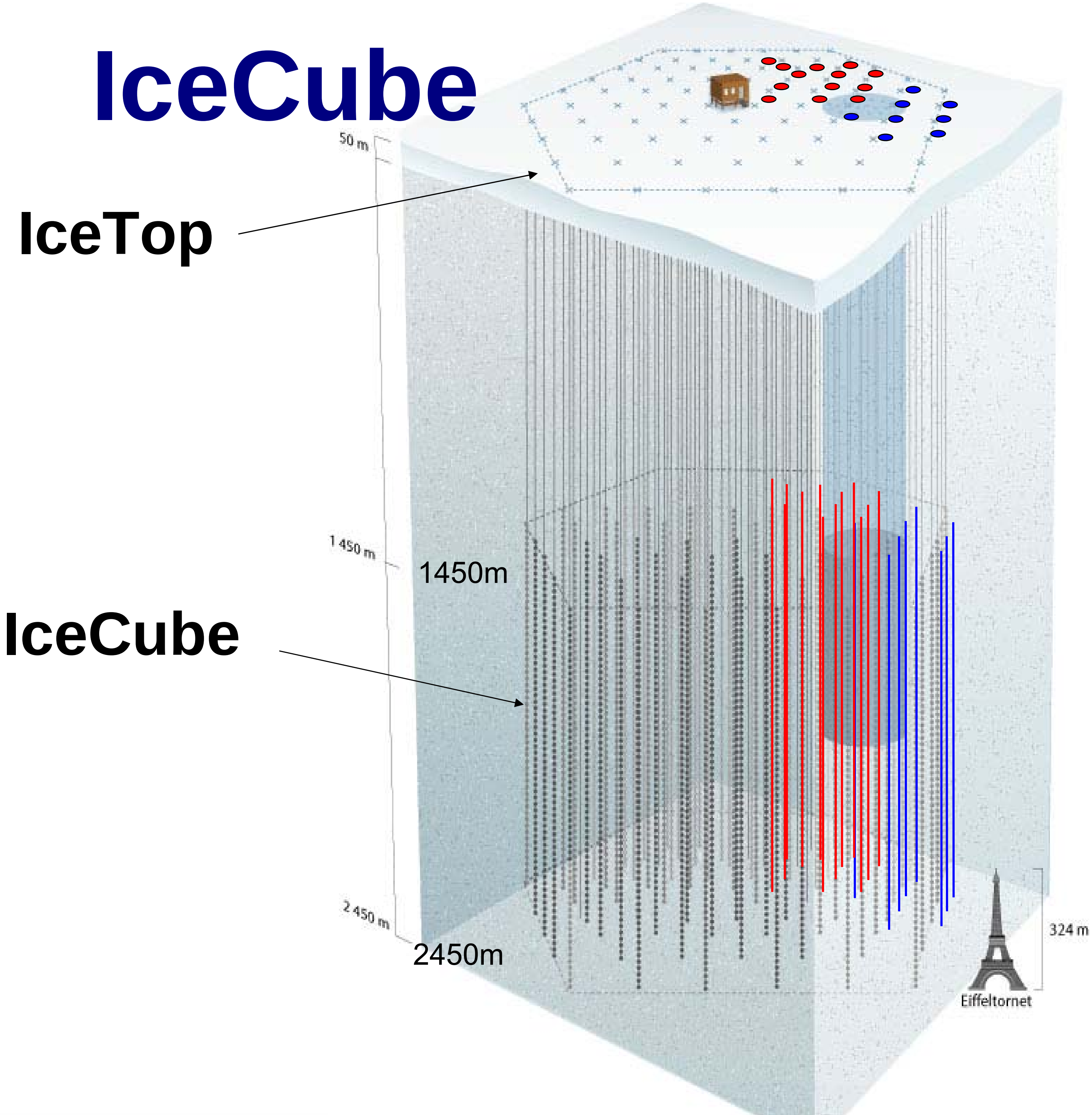
19 strings

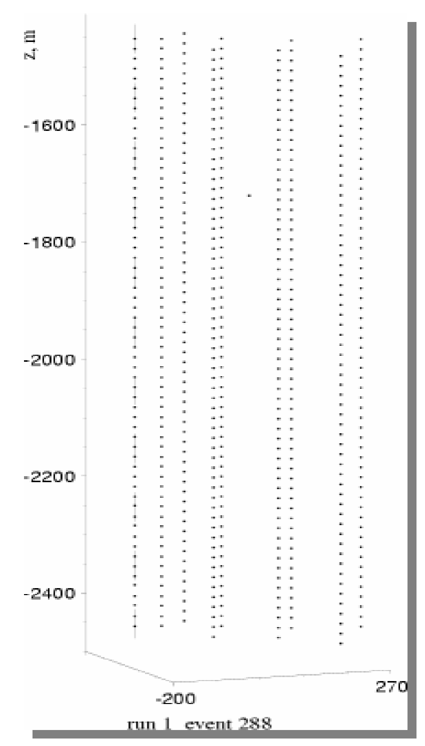
677 modules

2007/08: add 14 to 18 strings and tank stations

Completion by 2011.

IceCube

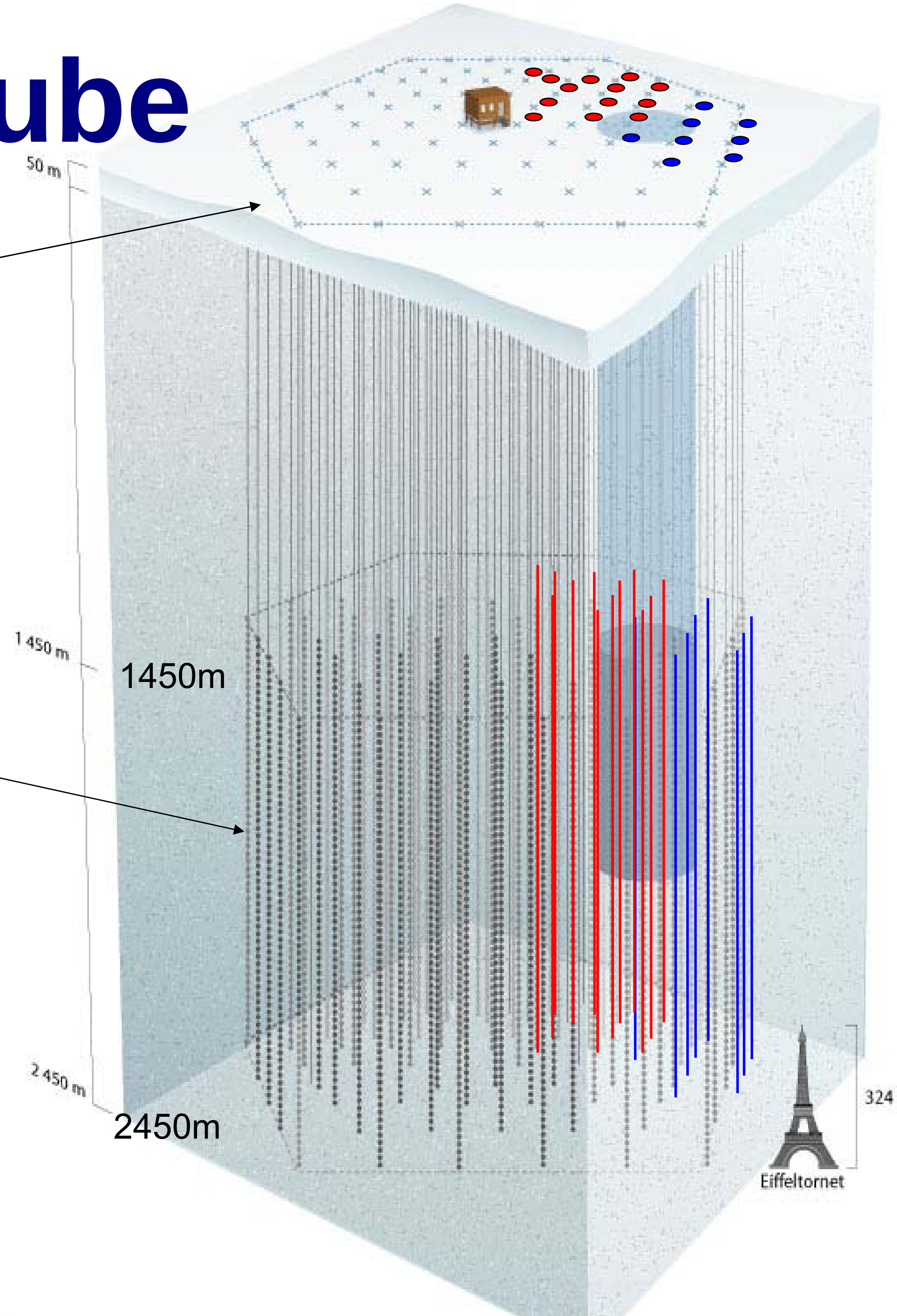

IceTop
IceCube
50 m
1 450 m
1450m
2 450 m
2450m
324 m
Eiffeltornet

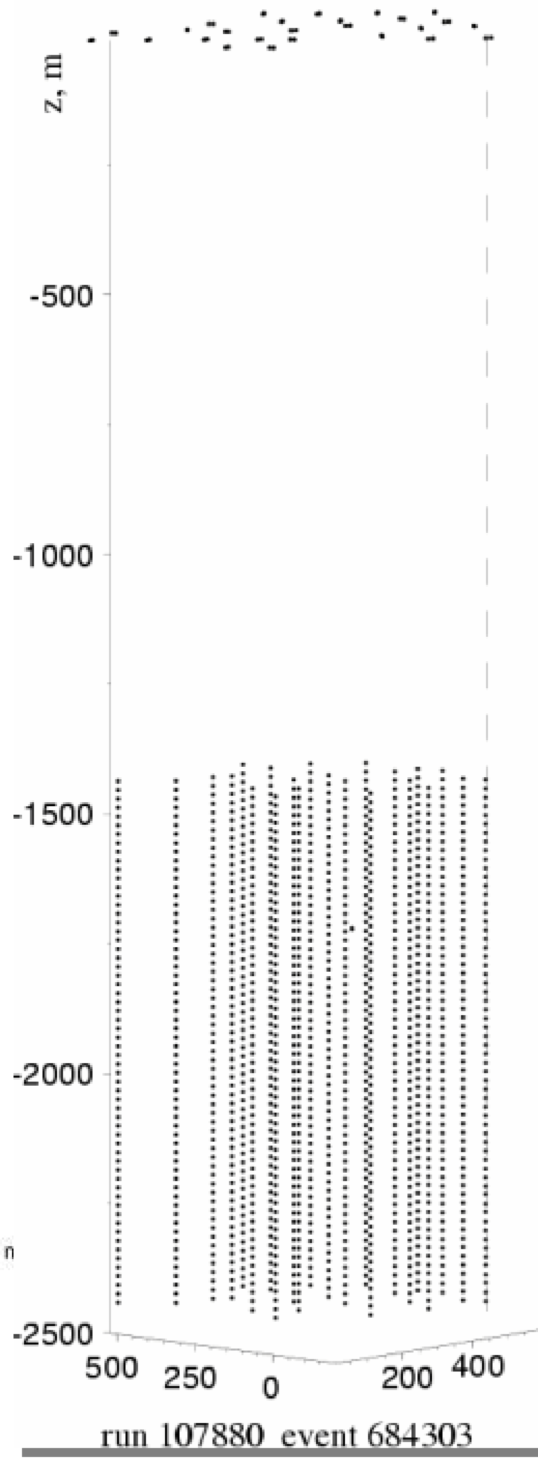

z, m
-1600
-1800
-2000
-2200
-2400
-200
270
run 1 event 288

IceCube

IceTop

IceCube

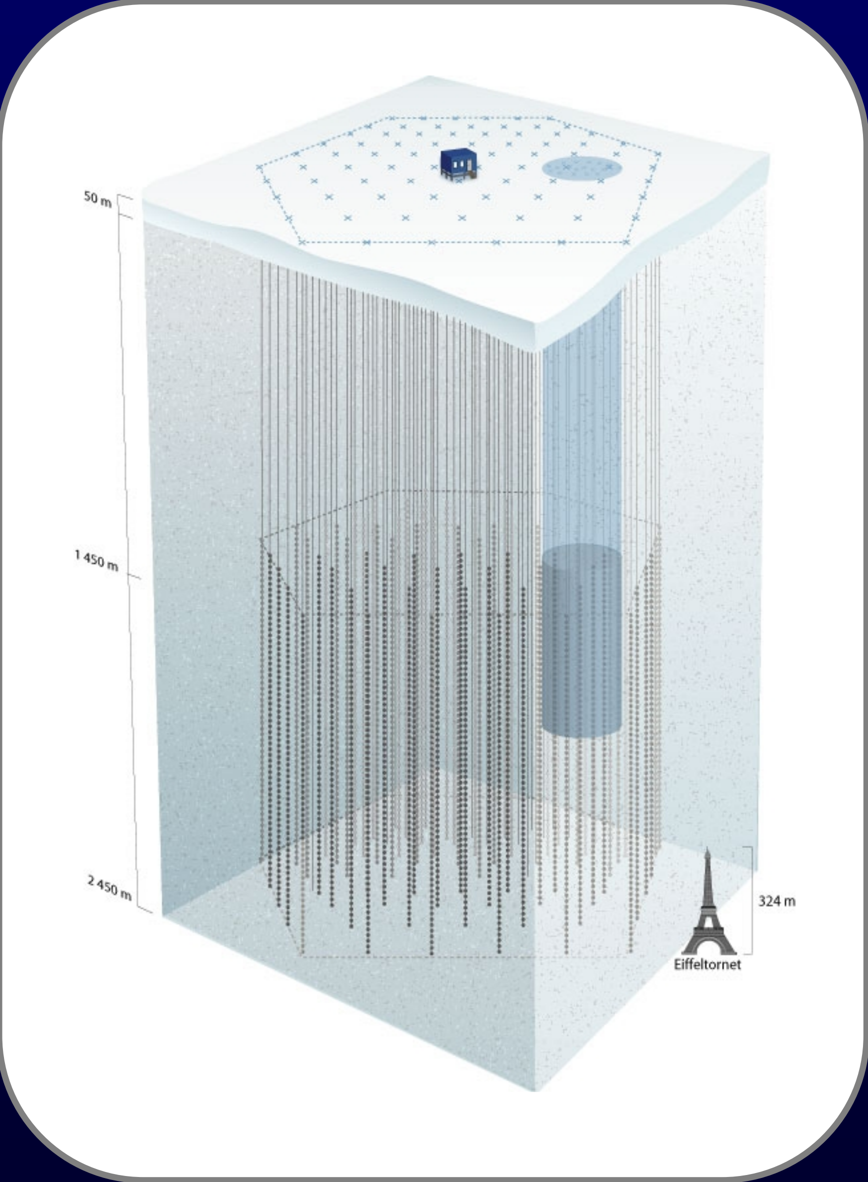




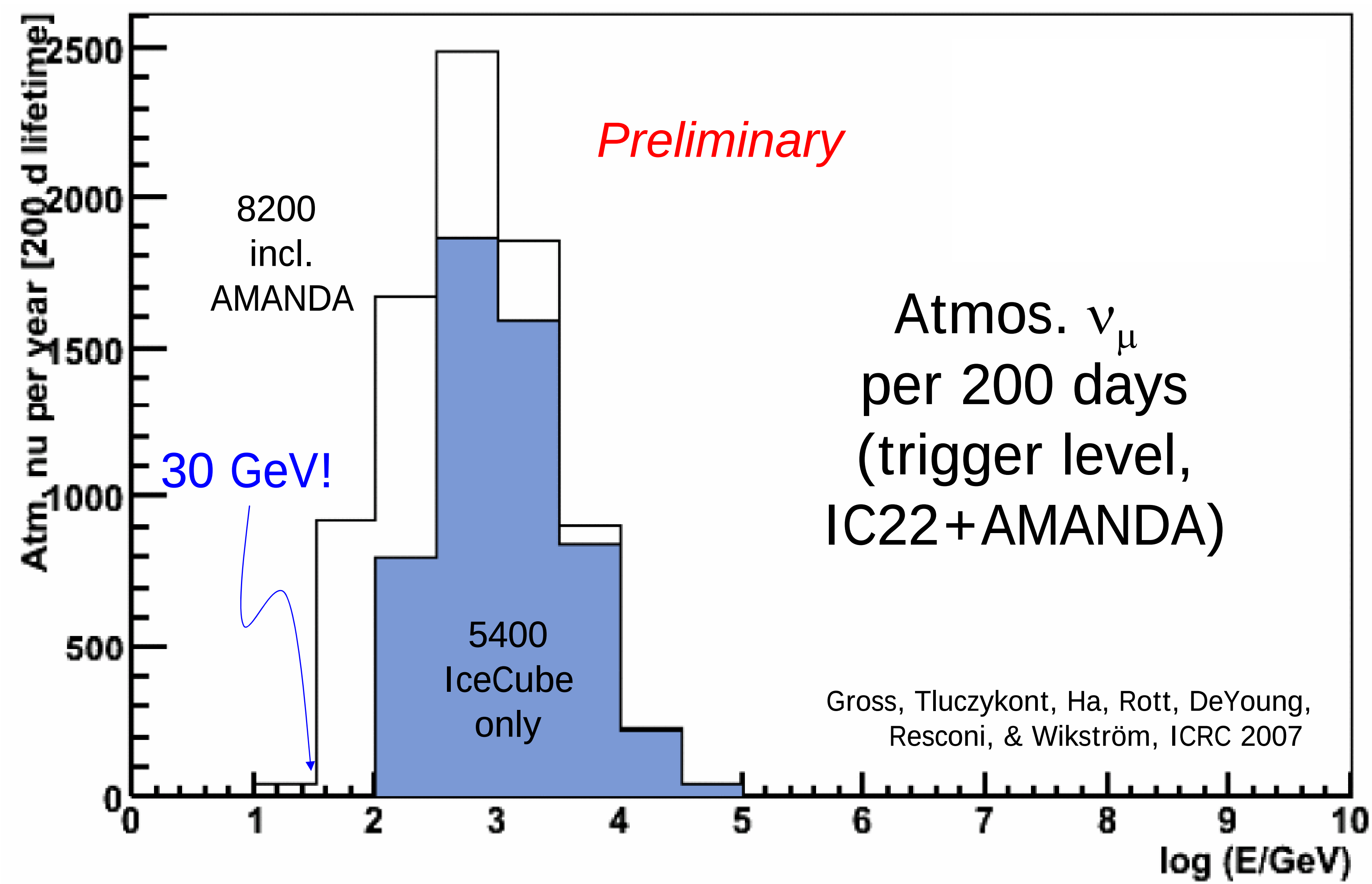
AMANDA as low energy subdetector of IceCube

Advantage for WIMP detection

IceCube threshold	100 GeV
IceCube with Amanda	30 GeV
Amanda without IceCube	50 GeV

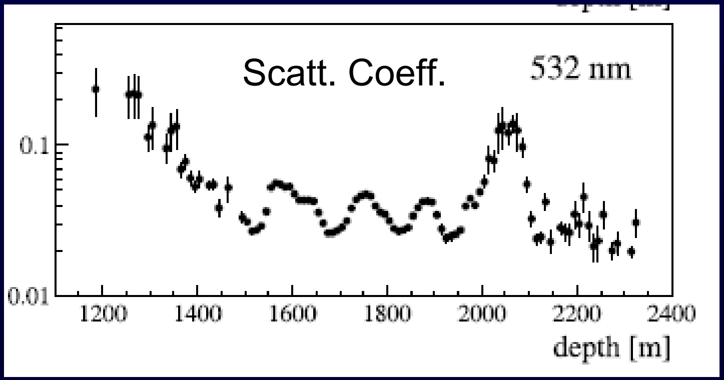


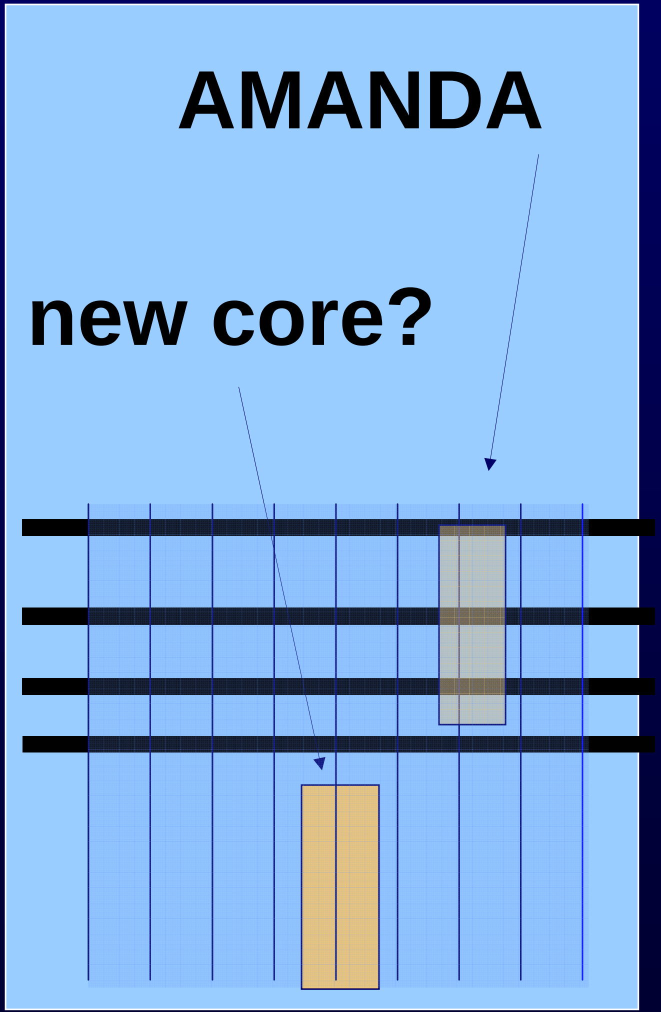
Effect on 22-string detector



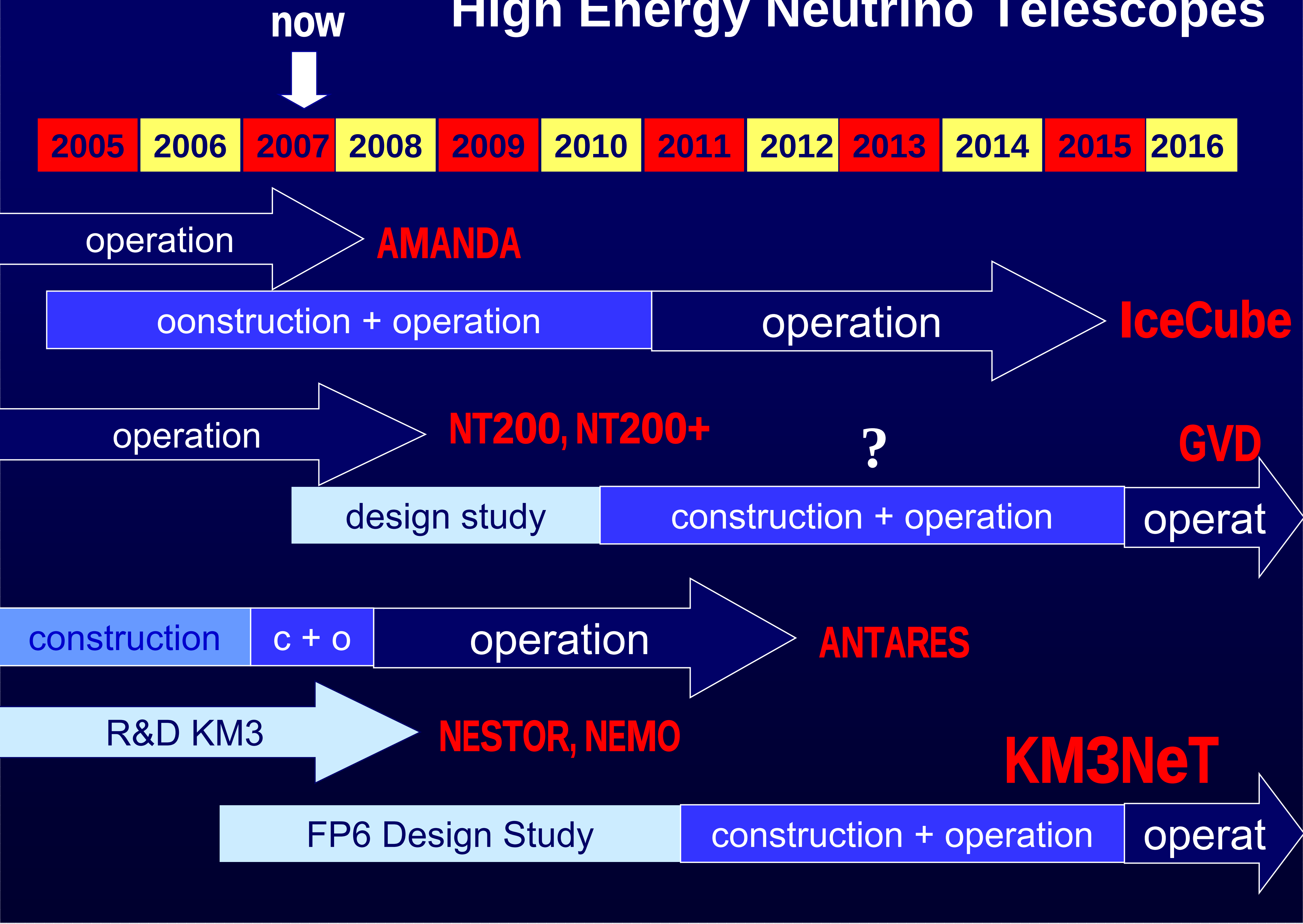
A new low energy subdetector for IceCube ?

- 6 strings each with 40 PM, spaced by 10 m
- better veto from top
- located in best ice (below 2100 m exceptionally clear)
- uses IceCube technology
- considerably better performance at low energy
- Physics targets
  - **Solar WIMPs**
  - **Look upward (contained events)**

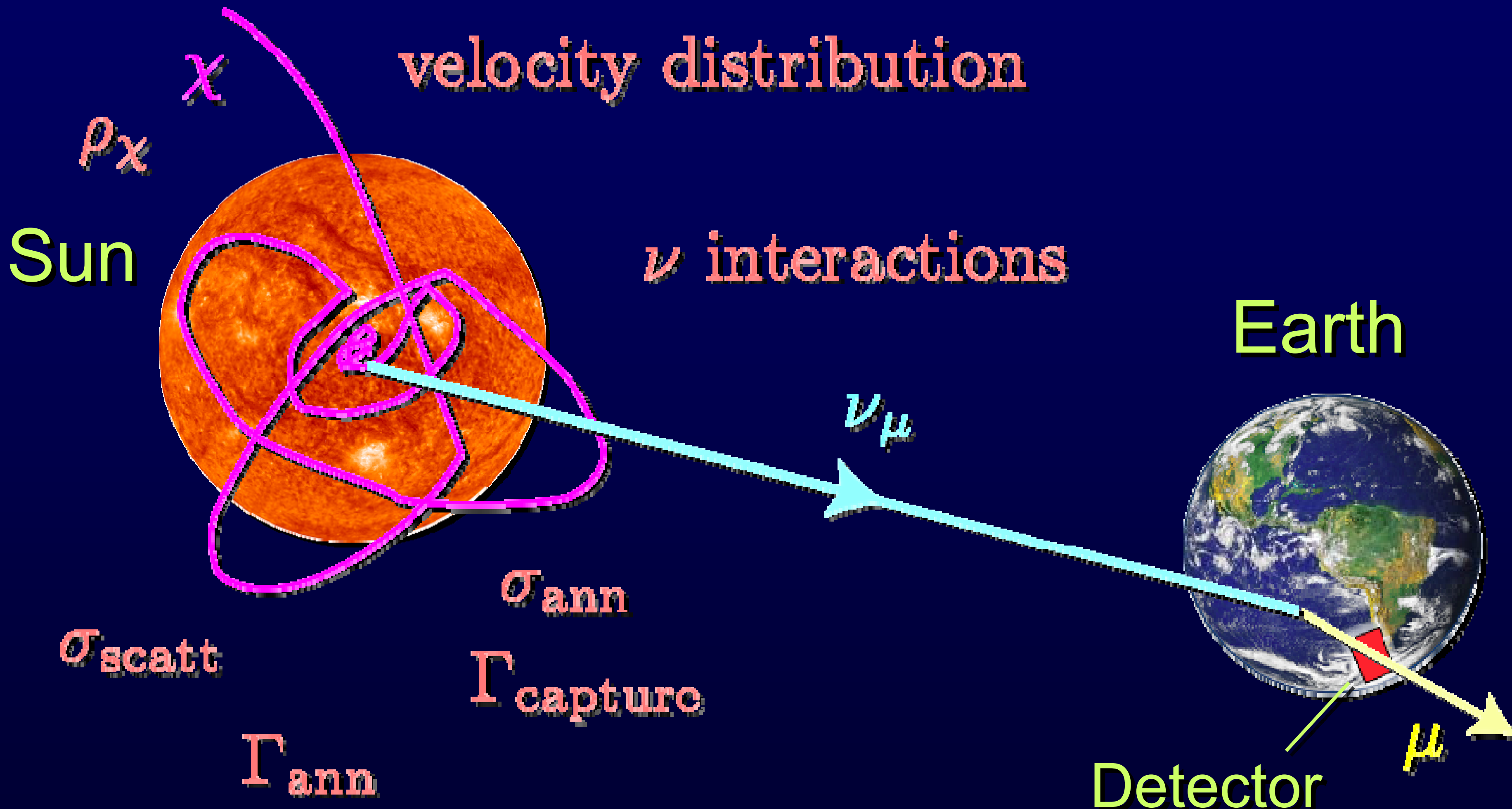




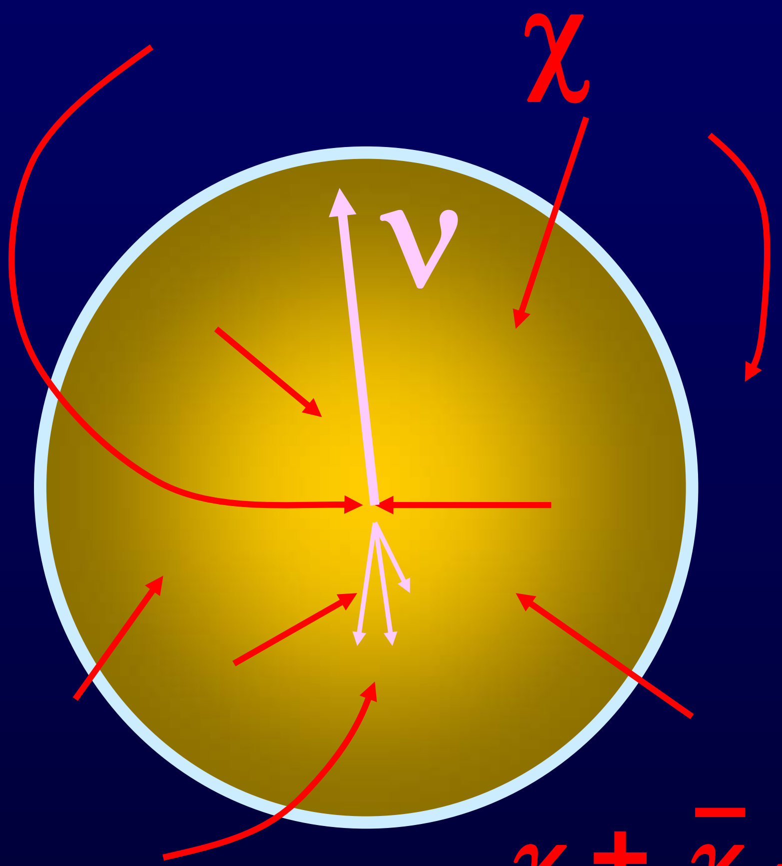
High Energy Neutrino Telescopes



Neutralino Capture in the Sun



Neutralino Capture in the Earth



Look for neutrinos from the center of the Earth.

$$\chi + \bar{\chi} \rightarrow b + \bar{b}$$

$$b \rightarrow c + \mu + \nu_\mu$$

Capture by Sun and Earth

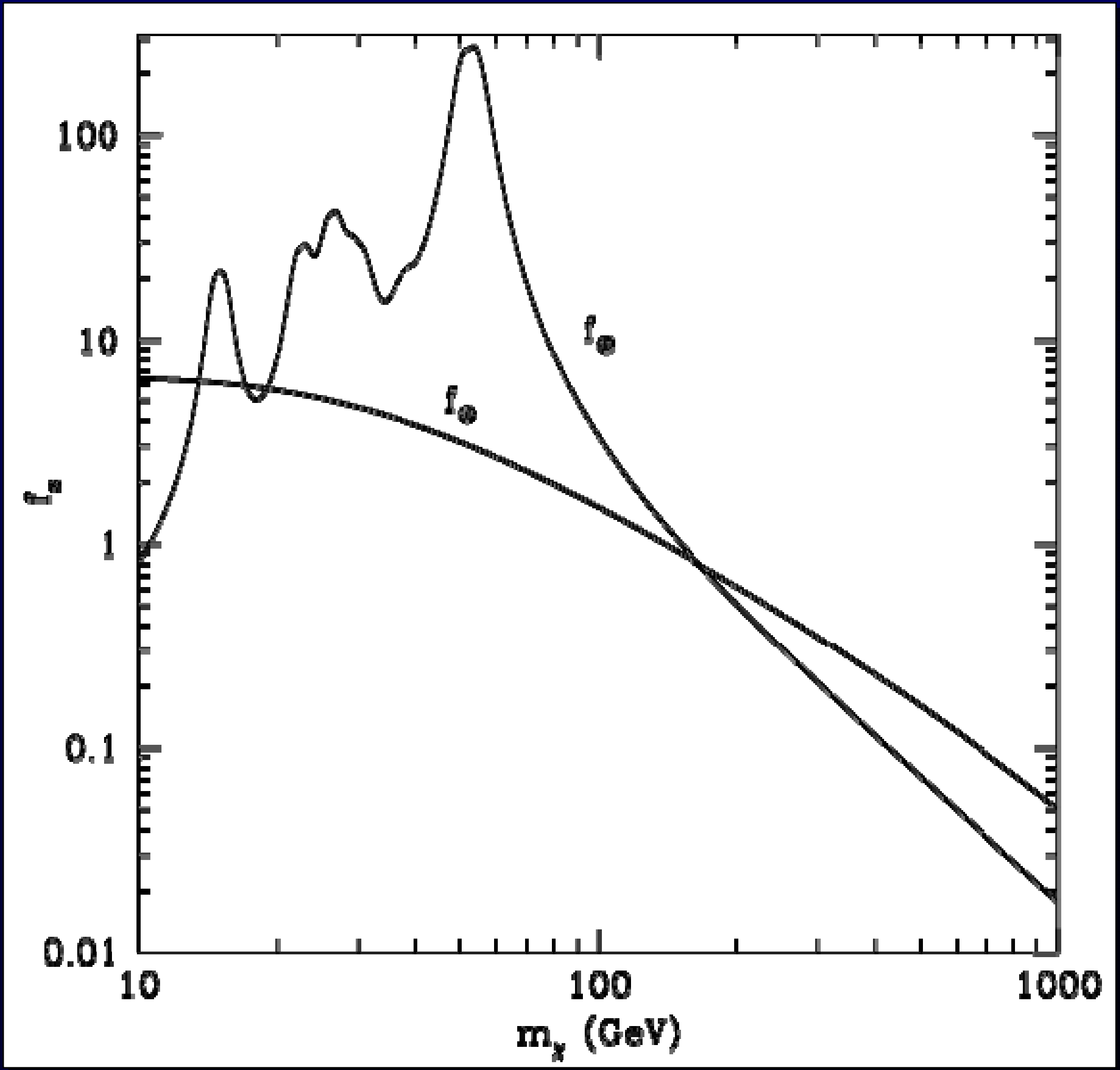


Figure from Jungman, Kamionkowski and Griest

- Capture in Sun
- Mostly on Hydrogen
- Both spin-independent and spin- dependent scattering

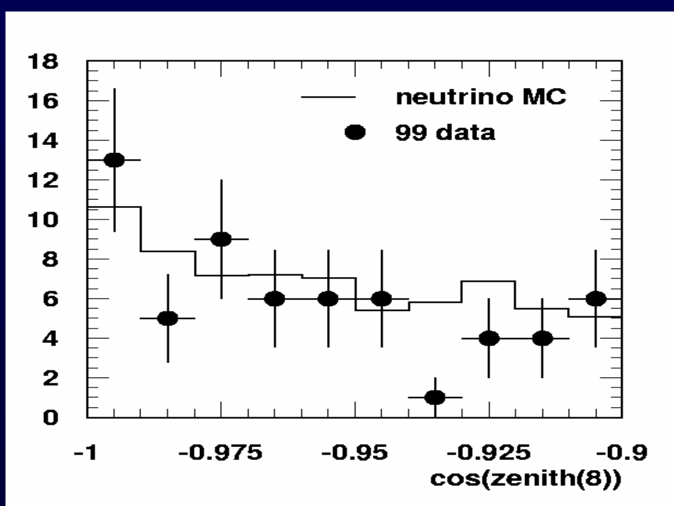
- Capture in Earth
- Mostly on Iron
- Essentially only spin-independent scattering
- Resonant scattering when mass matches element in Earth

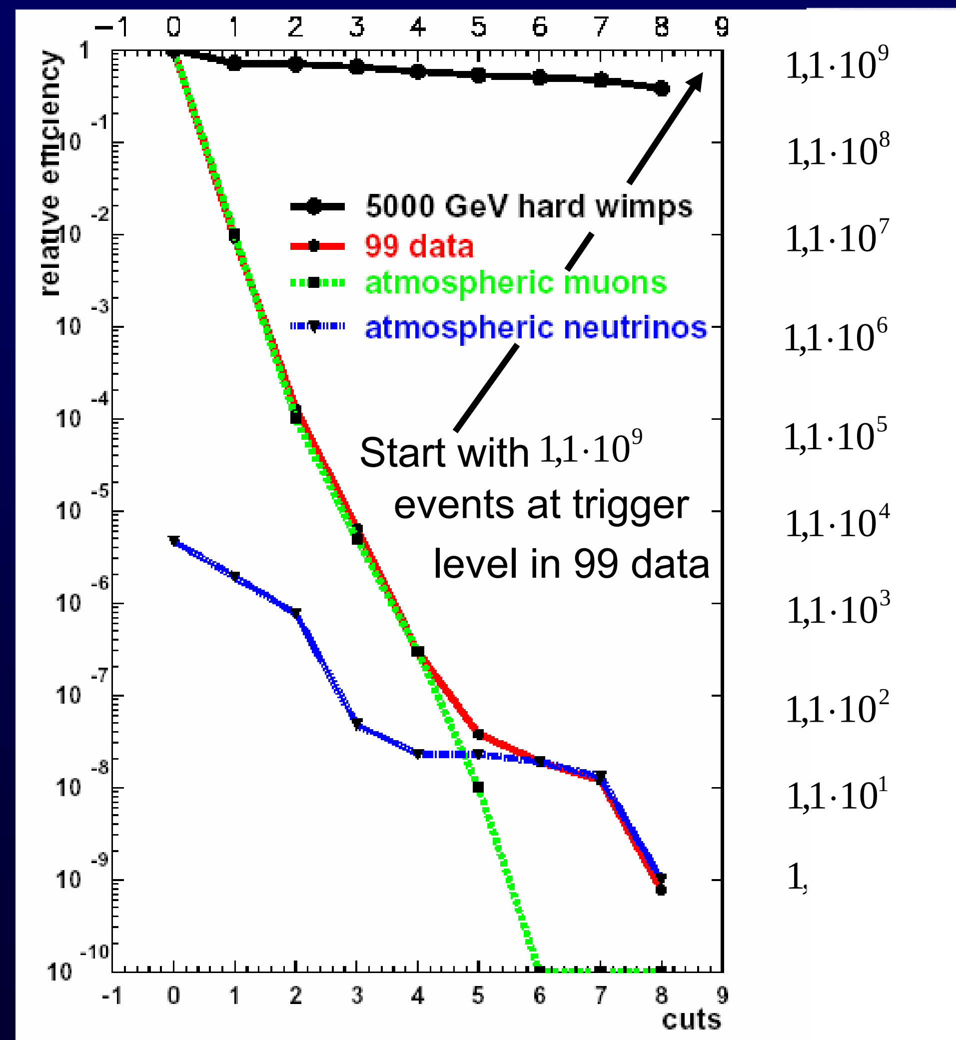
Amanda Analysis: Earth WIMPs 1999 as example

Background rejection

optimization = f (mass, decay mode)

Angular distribution

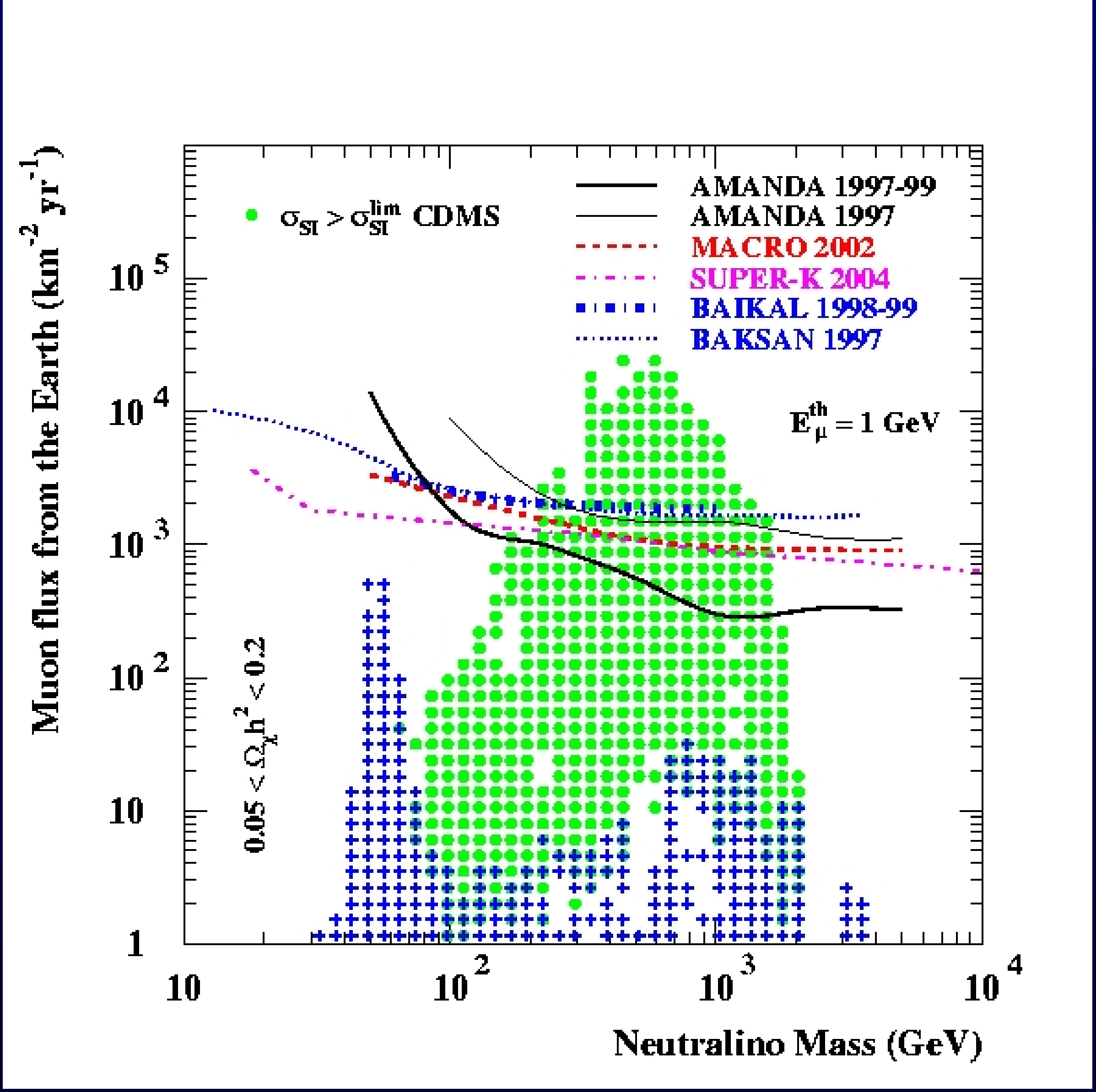




LIMIT

A_{eff}

Muon flux limits compared to MSSM predictions



Situation 2004

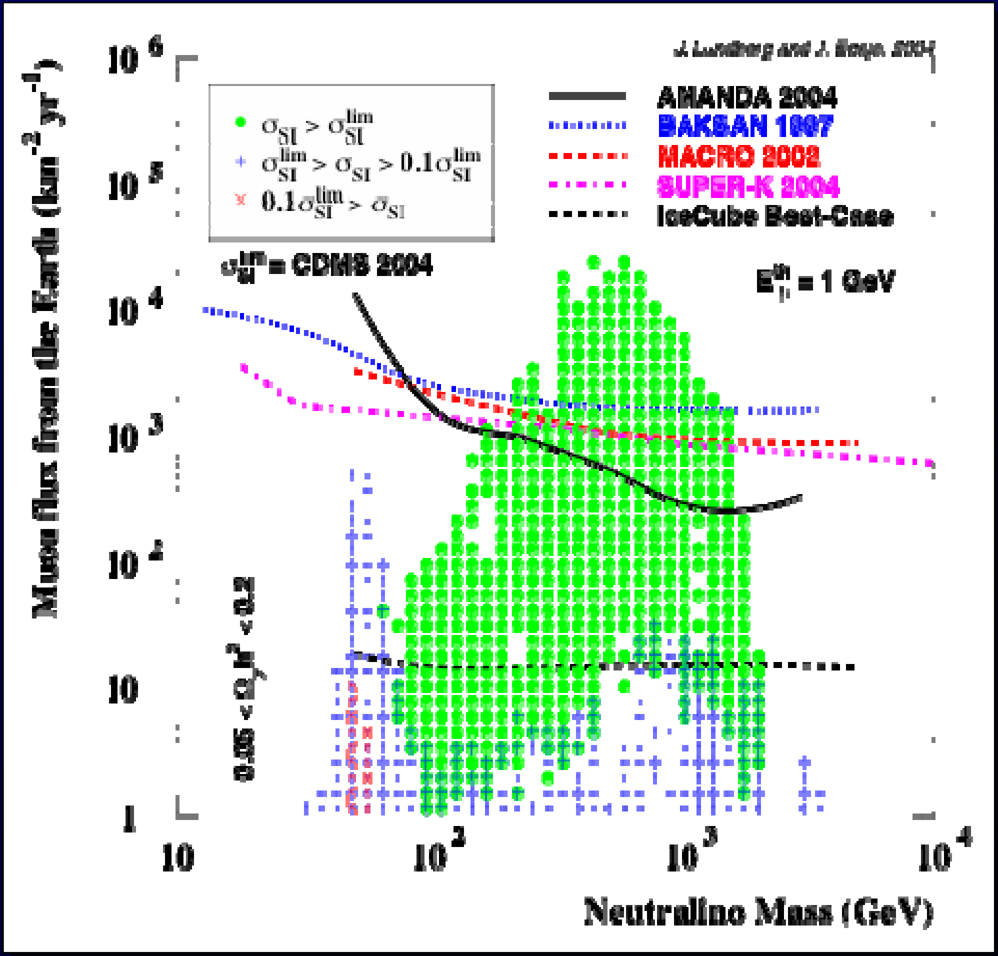
but … →

Lundberg & Edsjö, 2004:

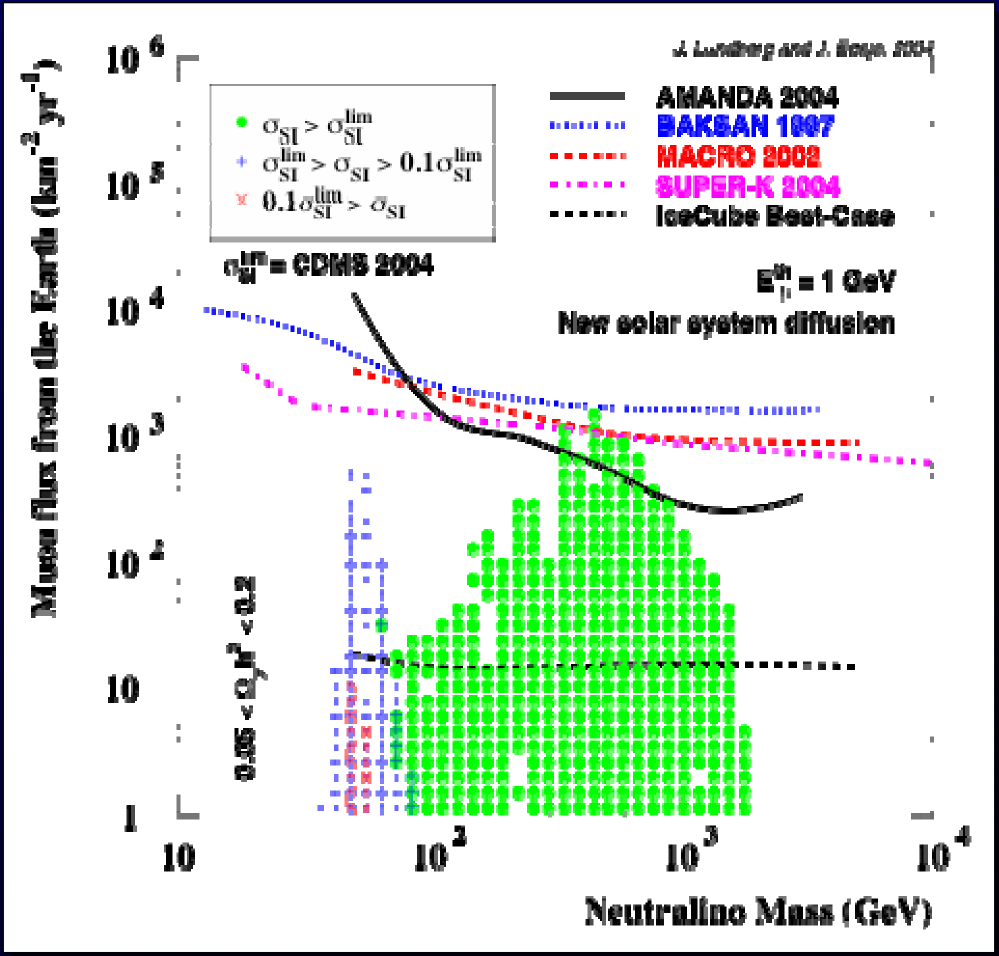
- When the halo WIMPs have reached the Earth, they have gained speed by the Sun’s attraction. Hence, capture is very inefficient.
- Halo WIMPs diffuse in the solar system by action of the other planets.

Neutrino-induced muon fluxes from the Earth center

Usual Gaussian approximation

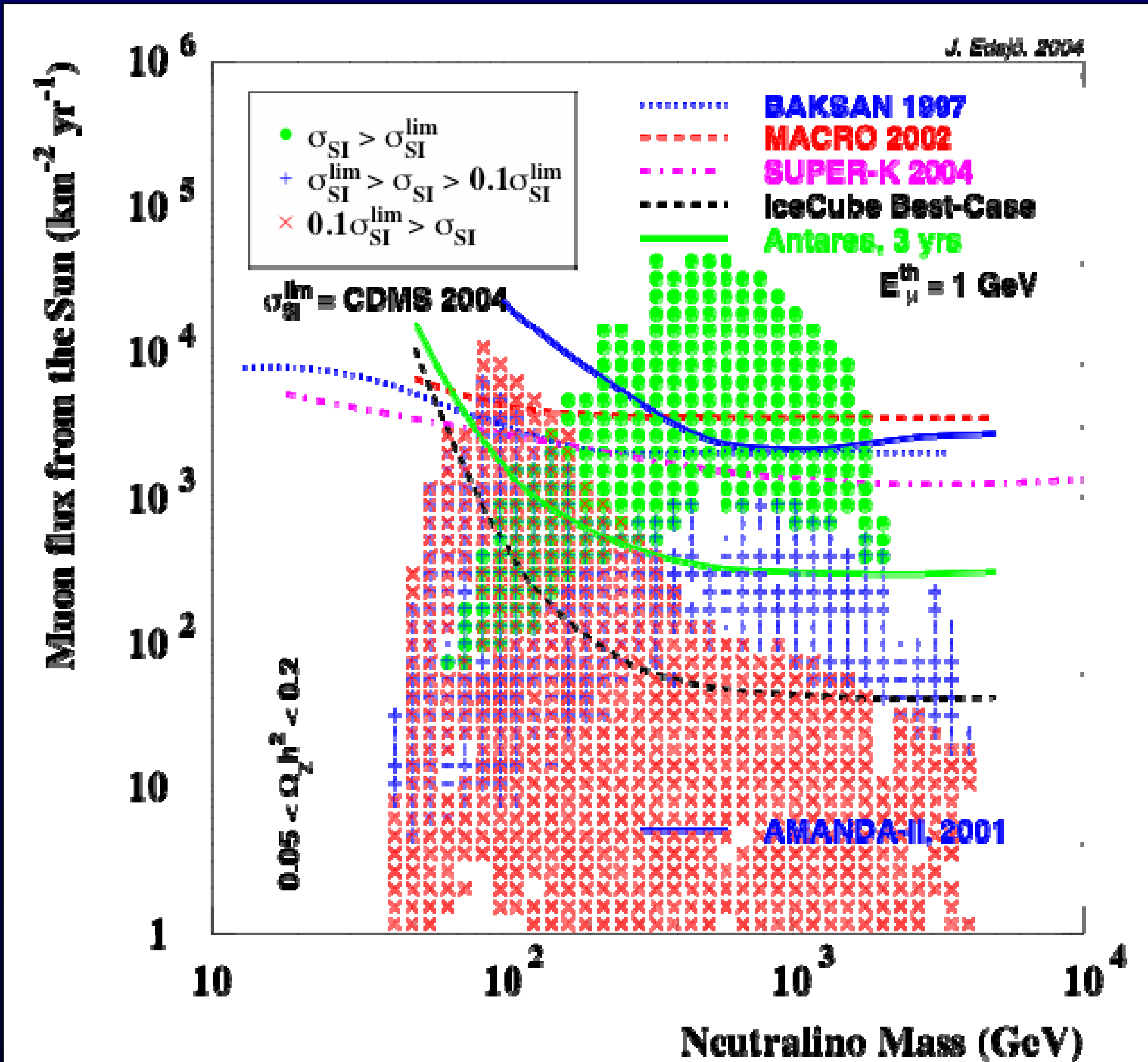


New estimate including solar capture



Maxwell-Boltzmann velocity distribution assumed.

Neutrino-induced muon fluxes from the Sun



- Compared to the Earth, much better complementarity due to spin-dependent capture in the Sun.

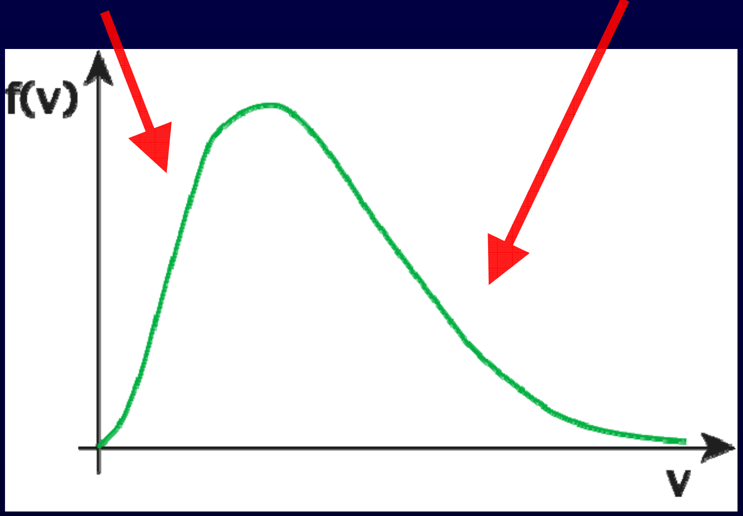
Comparing direct vs. indirect searches: a word of caution

indirect searches

- ~ density squared
- Density integrated over cosmological times
- Low-velocity region
- Branching ratios !

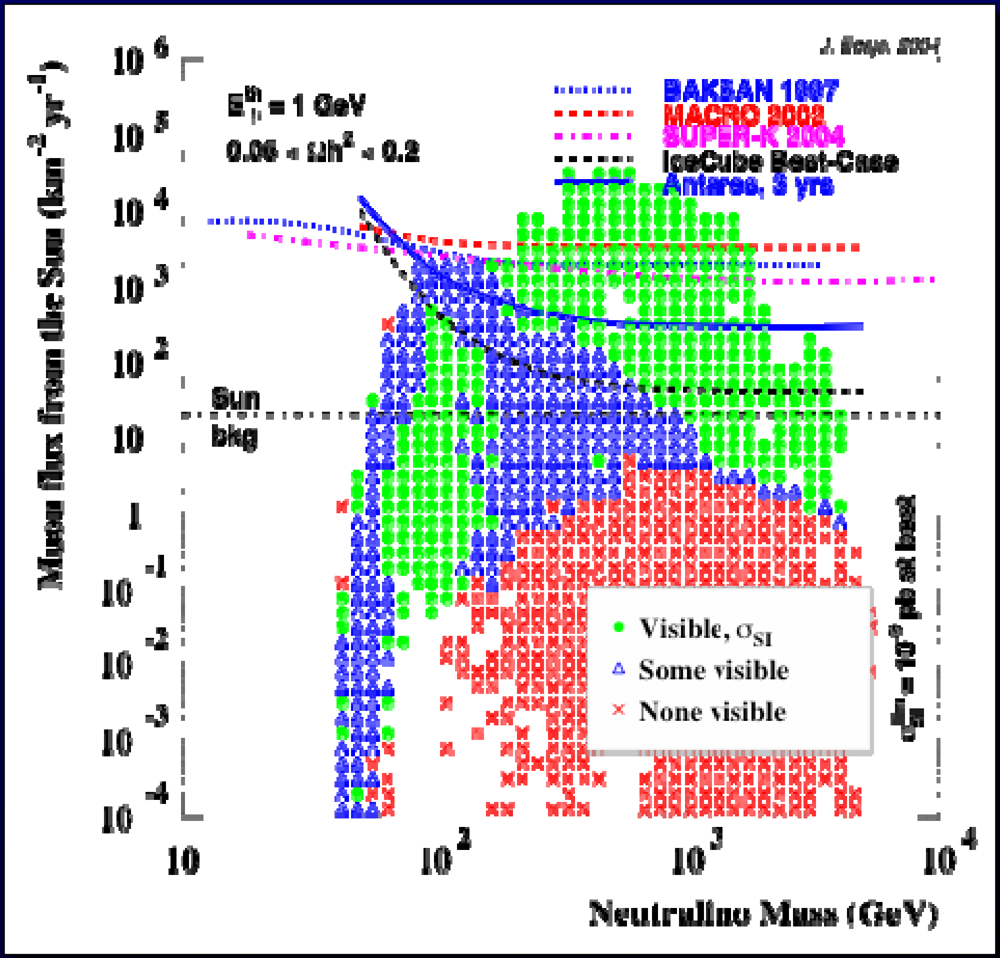
direct searches

- ~ density
- actual density
- High-velocity region

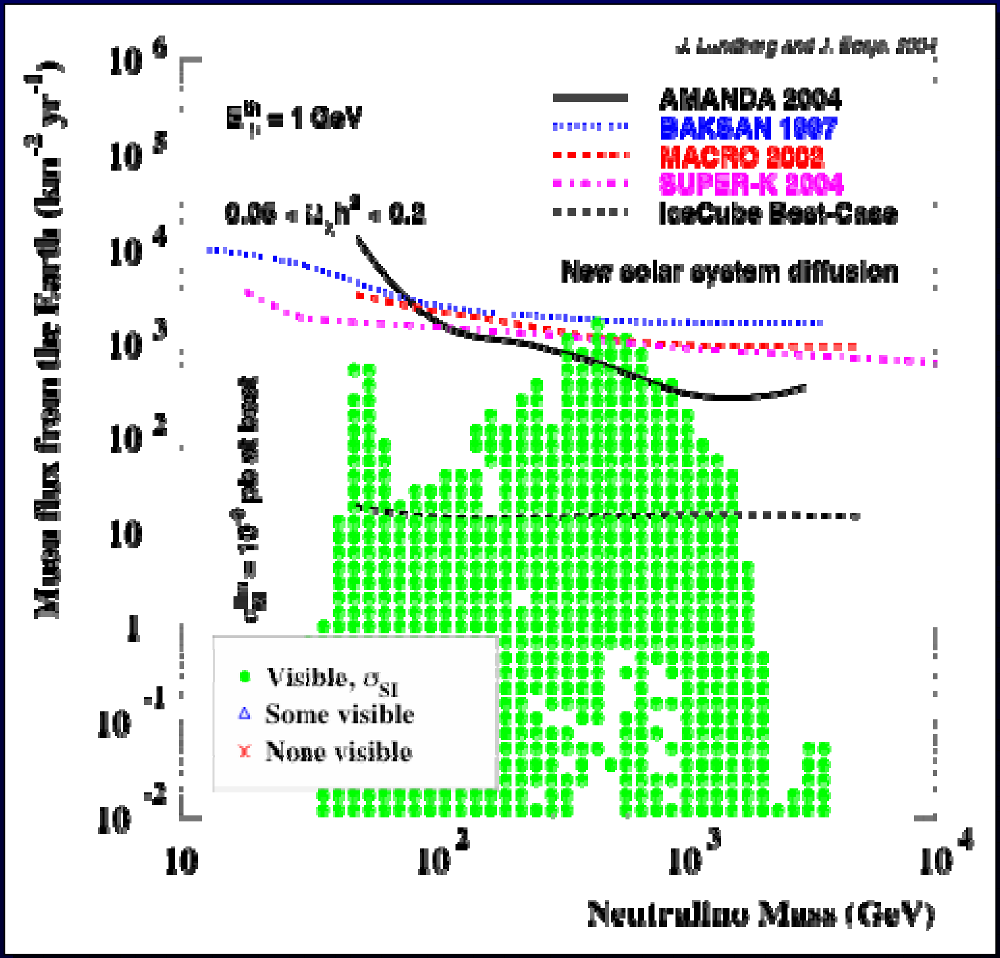


Neutrino-induced fluxes and future direct detection limits

Sun



Earth



Future direct detection sensitivity is assumed to be 10^{-9} pb.

Magnetic Monopoles

Nuclearites

Q-Balls

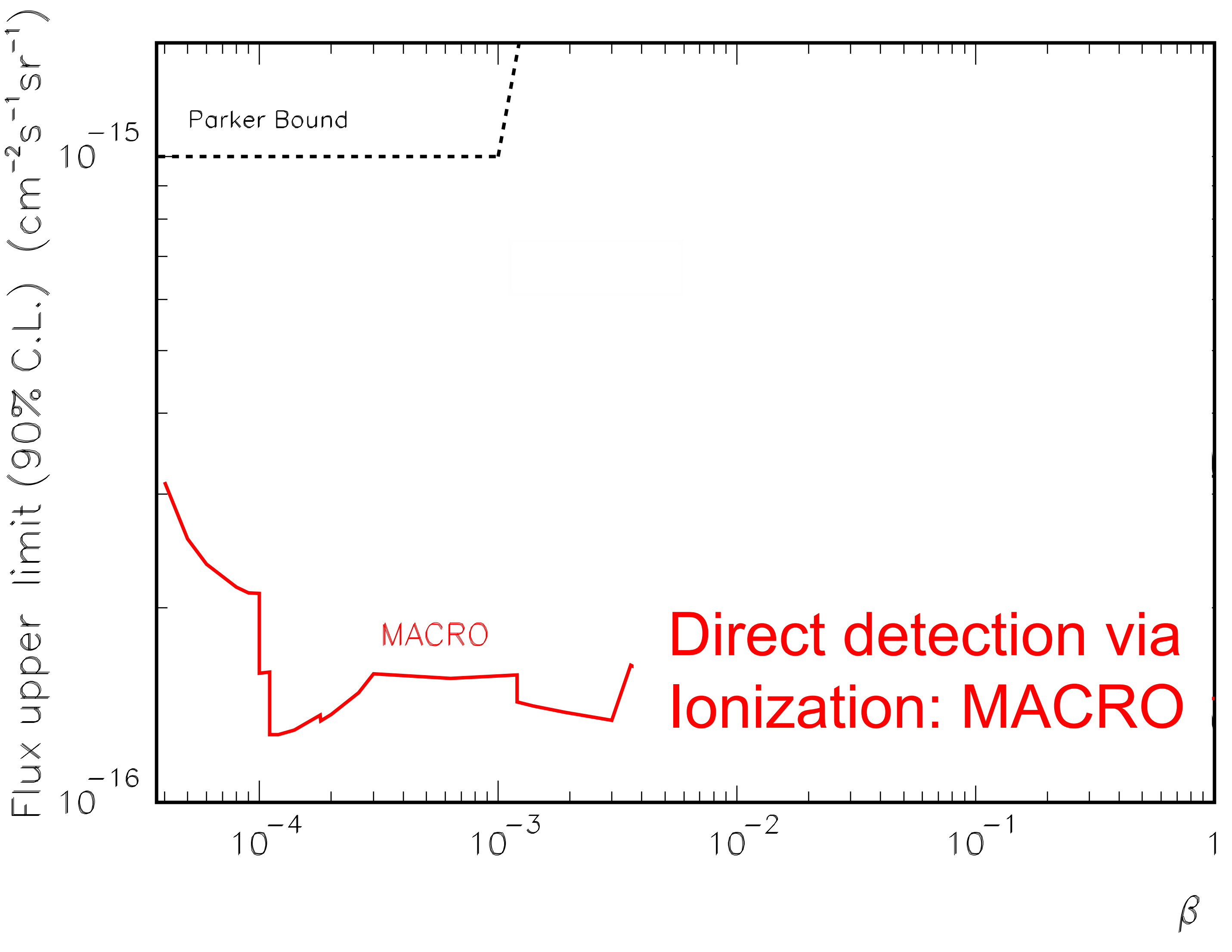
Magnetic Monopoles

- Dirac 1931
- Typical signature when crossing a superconducting coil (Cabrera)
- Strong Ionization: ~ $(g/e)^2$ with $g/e = 137/2$
- Astrophysical Parker Bound: ~ 10^{-15} cm^{-2} s^{-1} sr^{-1}
- GUT Monopoles may catalyze proton decay
- MACRO at Gran Sasso:

  most prominent monopole detector

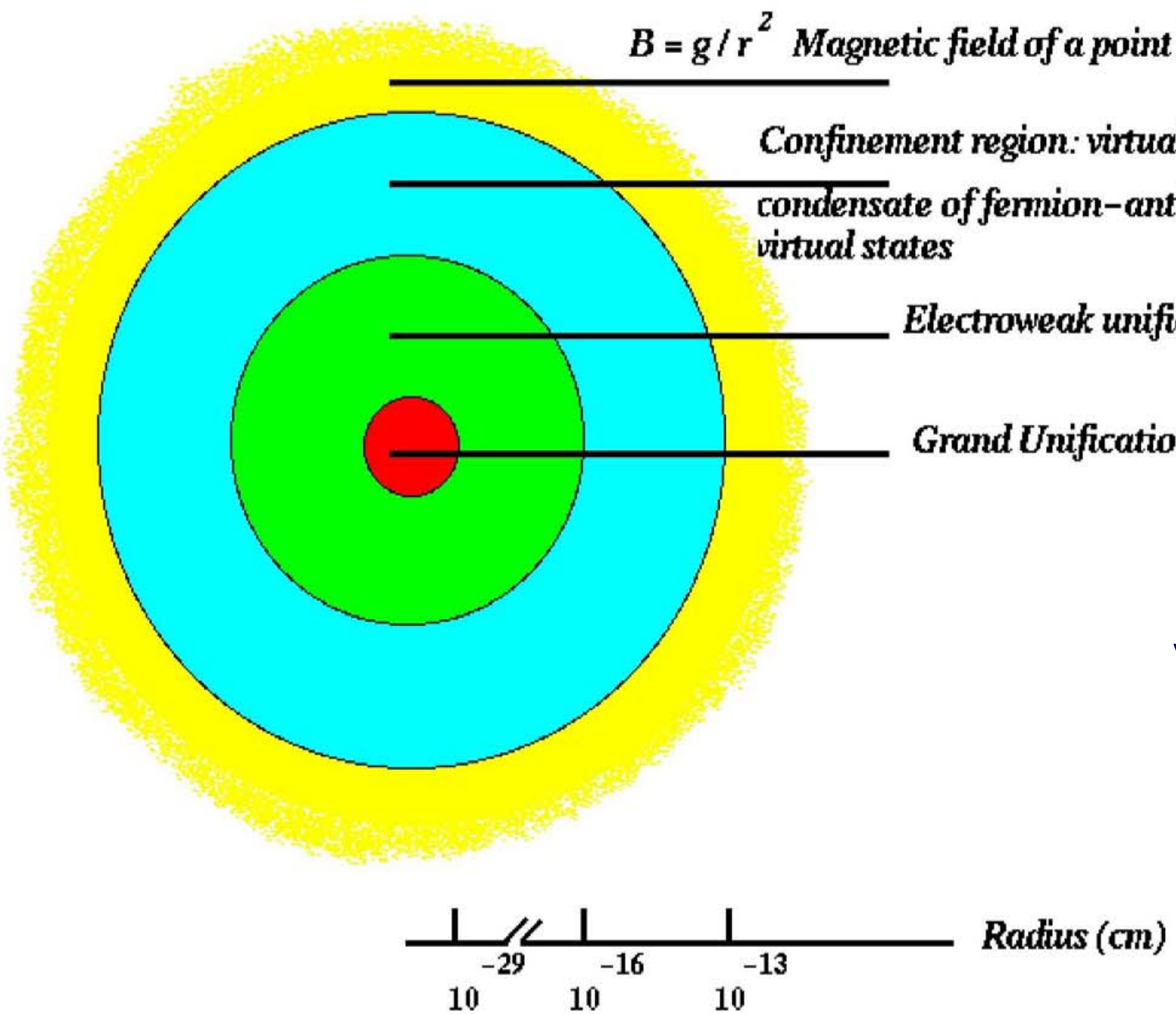
  (closed in 2000, ionization &ToF)

Flux upper limits for GUT Magnetic Monopoles



Direct detection via Ionization: MACRO

GUT Magnetic Monopoles



Mass $10^{16\text{-}17}$ GeV/c²

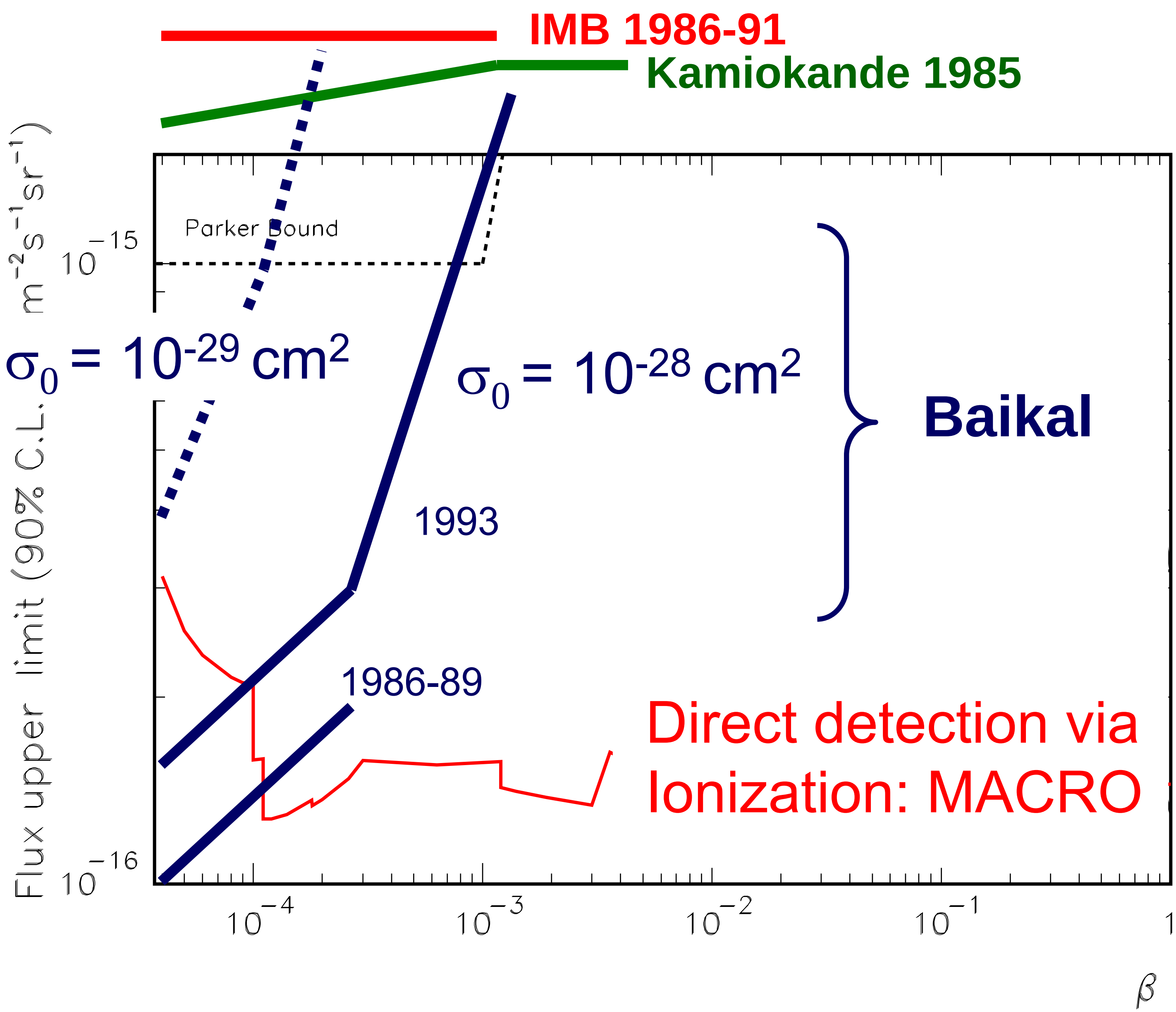
Velocity $\beta \sim 10^{-4}$

$M + p \rightarrow M + e^{+} + \pi^{0}$

May catalyze proton decay with $\sigma \approx \sigma_0 / \beta^2$

→ bright track from Cherenkov radiation from proton decay products in water detectors

Flux upper limits for GUT Magnetic Monopoles



… including limits from p-decay catalysis assumption

Intermediate mass Magnetic Monopoles

Mass 10^5 - 10^{12} GeV

→ Produced in the Early Universe in later phase transitions

→ Can be accelerated in the galactic B field to relativistic velocities

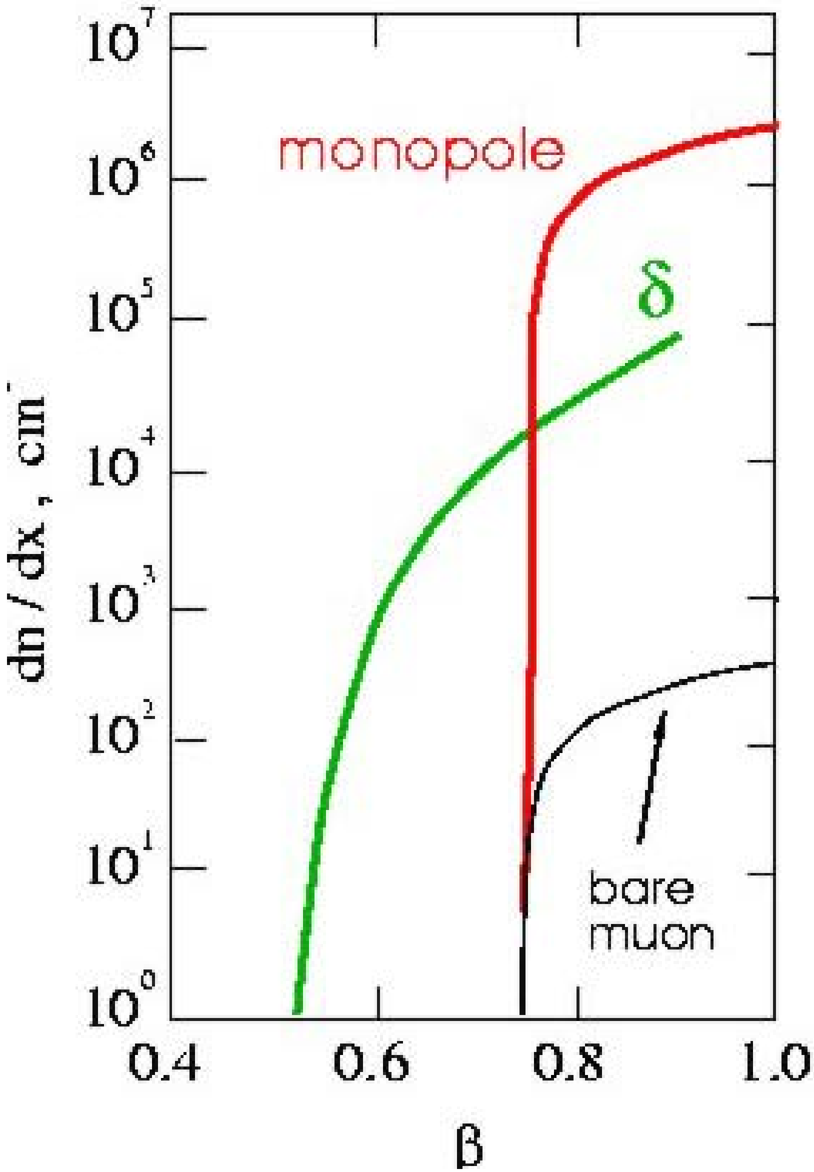
.

$\mathbf{W} = g_D\, B\, L \sim 6 \times 10^{19}$ eV $(B/3\times10^{-6}$ G) (L/300pc)

Galaxy	$W \sim 6 \times 10^{19}$ eV
Neutron stars	$W \sim 10^{20} - 10^{24}$ eV
AGN	$W \sim 10^{23} - 10^{24}$ eV

Connection to highest energy cosmic ray showers @ $E > 10^{20}$ eV ?

Detection via Cherenkov light



Cherenkov Light ∝ $n^2 \cdot (g/e)^2$

$n = 1.33$

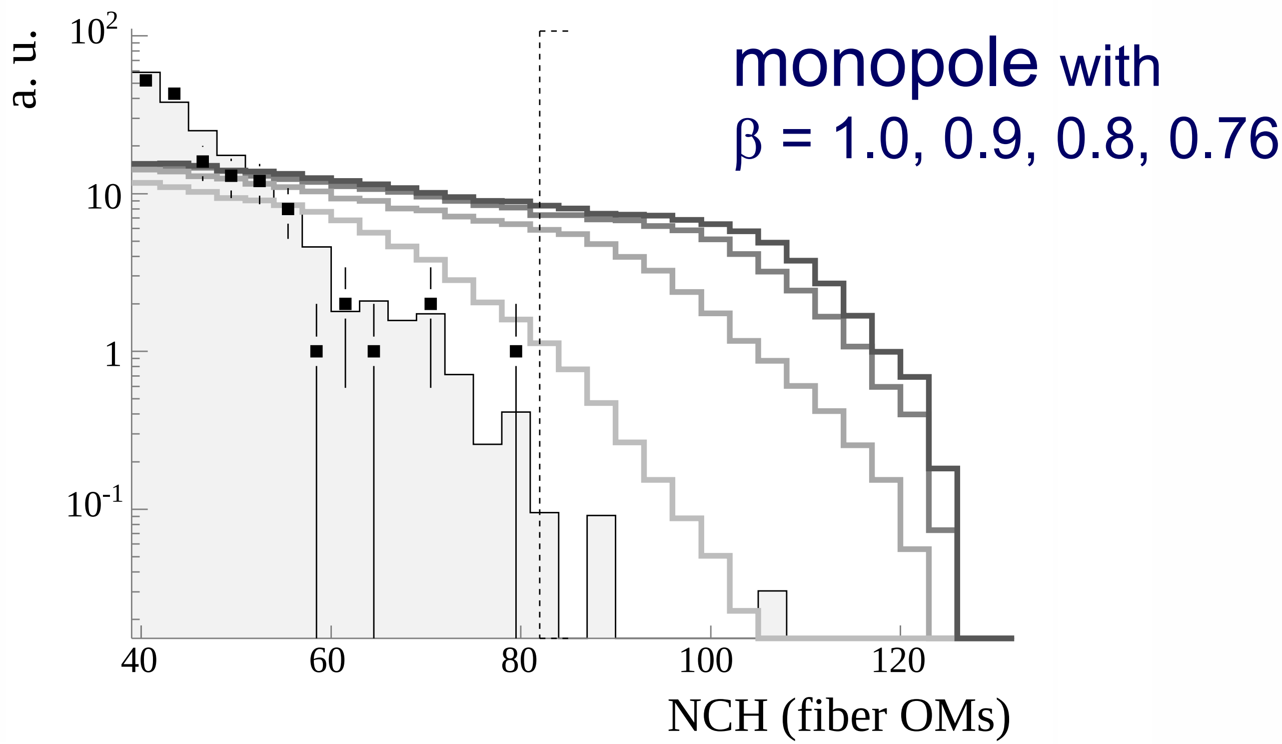
$(g/e) = {}^{137}/_{2}$

≈ 8300

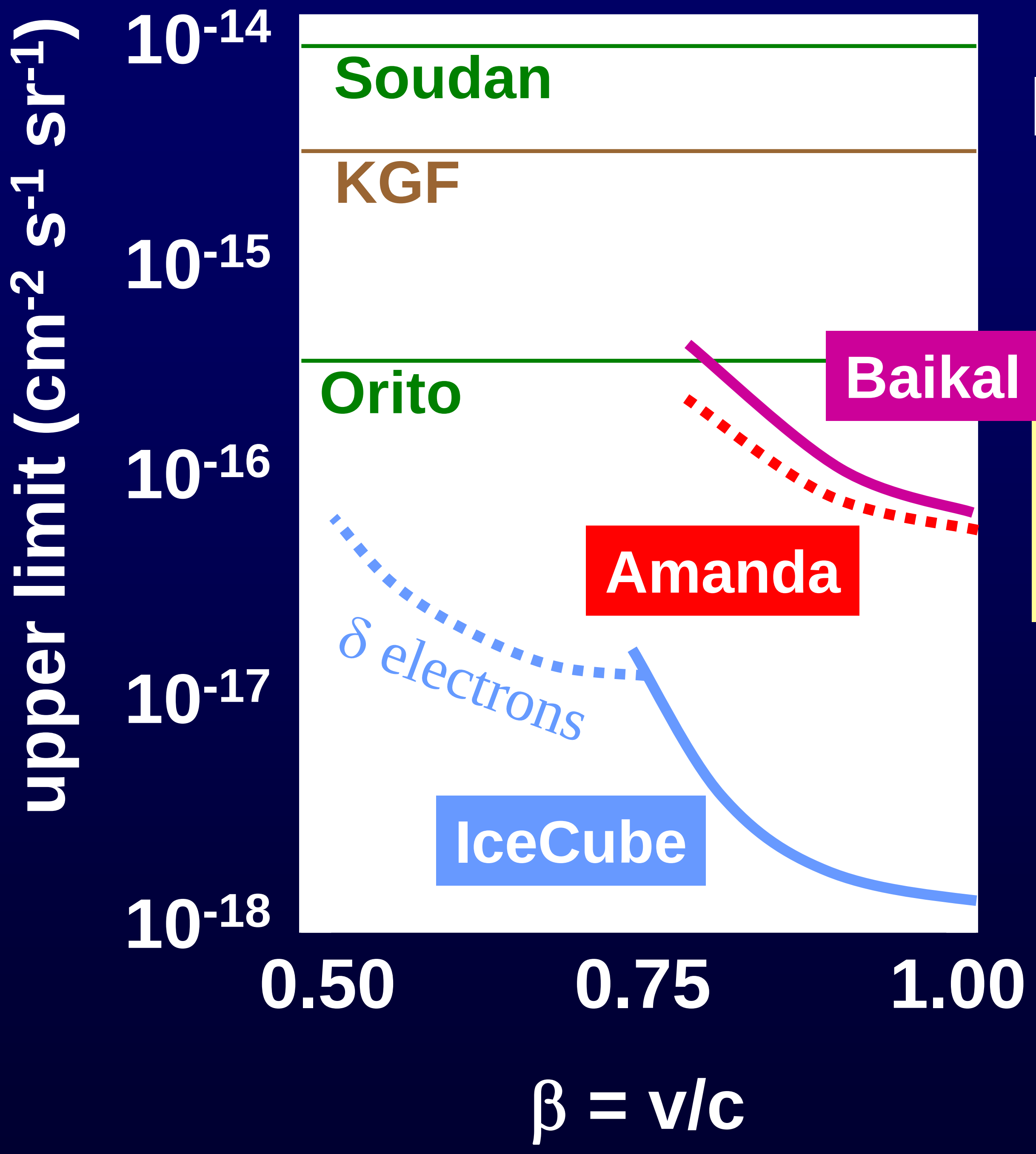
Amanda 2000

blue: background MC

dots: exp. data



Relativistic Magnetic Monopoles



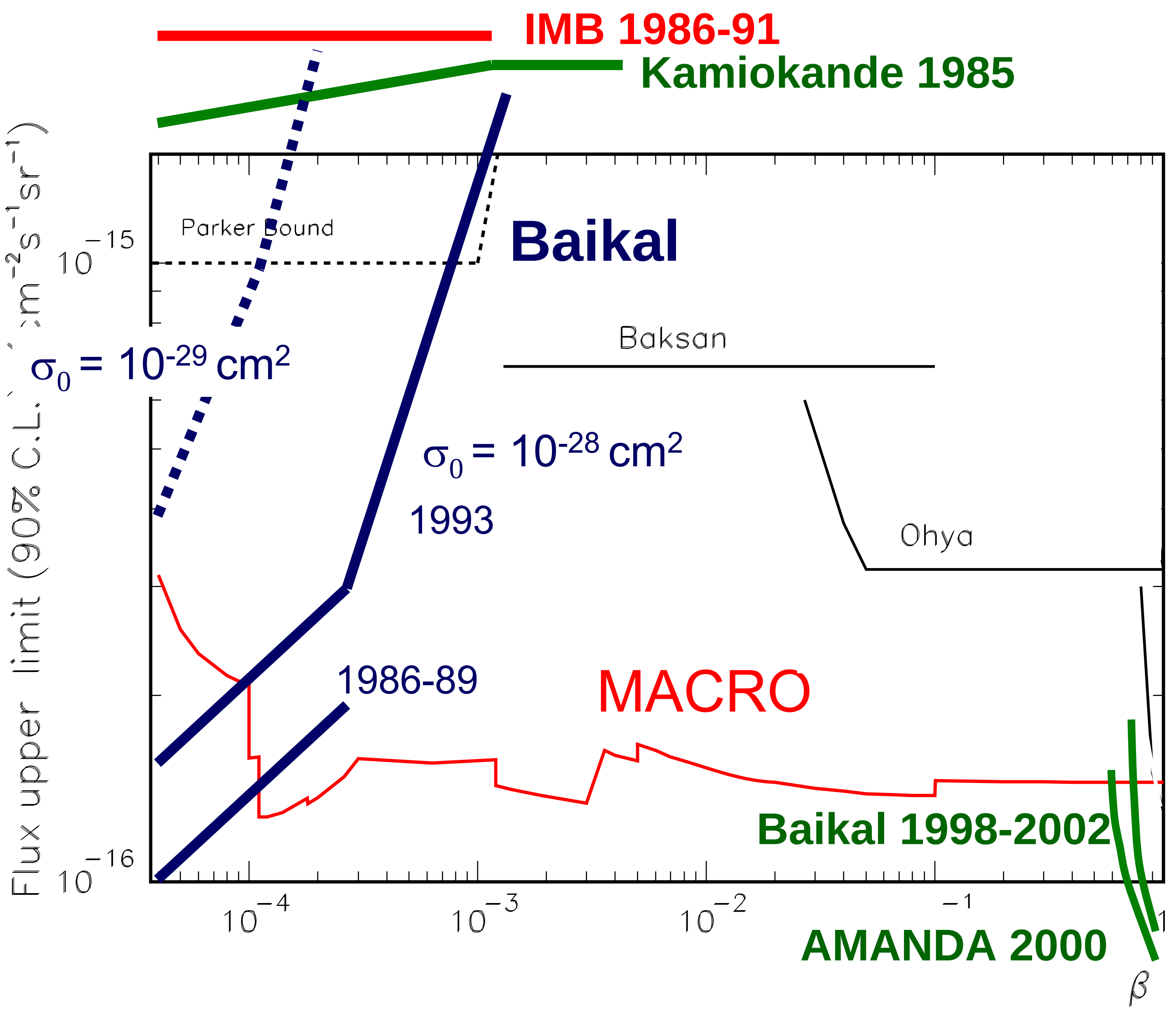
Cherenkov-Light ∝ $n^2 \cdot (g/e)^2$

$n = 1.33$

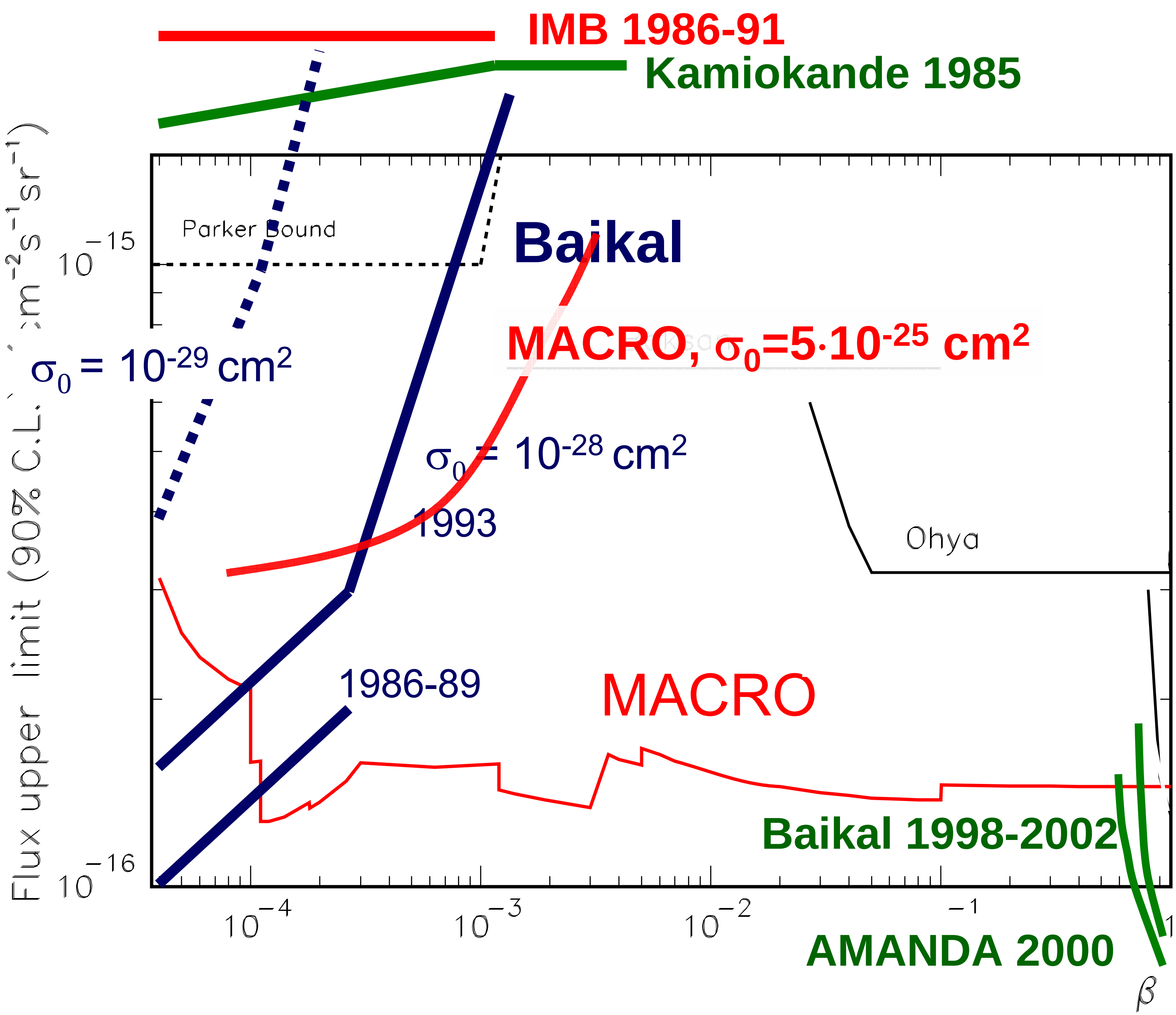
$(g/e) = {}^{137}/_{2}$

≈ 8300

Flux upper limits for Magnetic Monopoles



Flux upper limits for Magnetic Monopoles



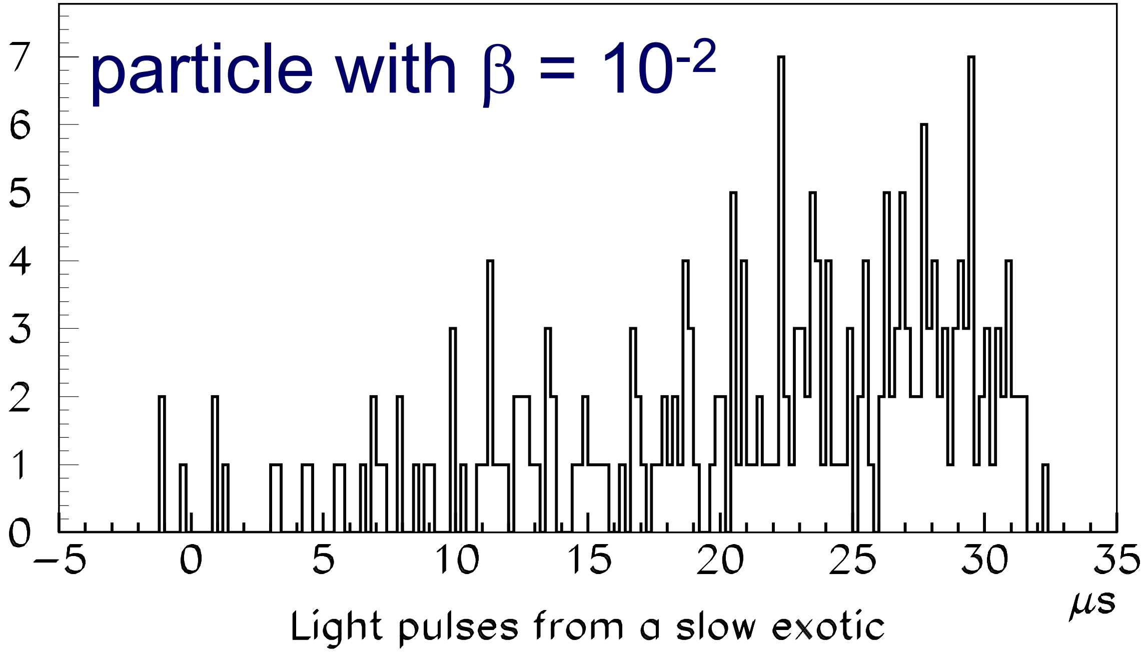
NUCLEARITES (Strange Quark Matter+electrons)

- Aggregates of u, d, s quarks + electrons
- Stable for baryon number $\sim 300 < A < 10^{57}$
- $\rho_N \sim 3.5 \times 10^{14}$ g cm^{-3} ($\rho_{nuclei} \sim 10^{14}$ g cm^{-3})
- Produced in Early Universe, candidates for sub-dominant dark matter
- May be produced also in neutron stars
- Light generation via Planck radiation
- Virial velocities

Supersymmetric Q-balls

- Coherent states of squarks, sleptons and Higgs fields
- $10^8 < M_Q$ 10^{25} GeV
- Produced in Early Universe, candidates for (sub-dominant) dark matter
- Light generation via ionization (SECS) or catalysis of proton decay (SENS)
- Virial velocities

Slow Particles in AMANDA / IceCube

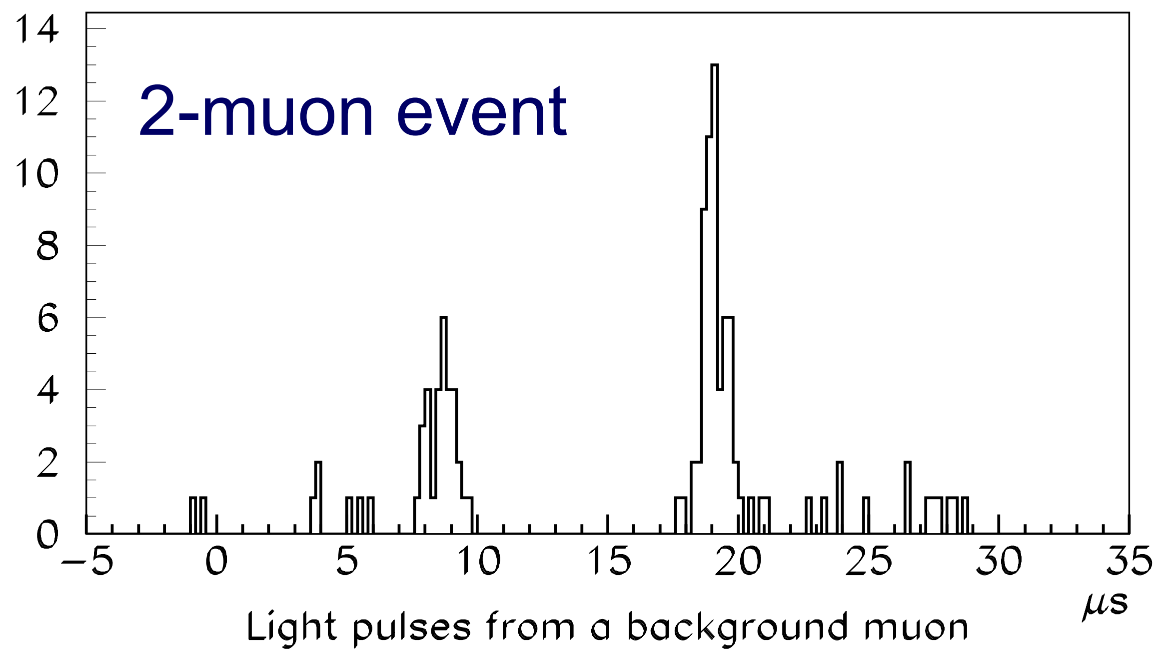


$\beta \geq 5\times10^{-3}$ (AMANDA)

$\beta : \geq \ 10^{-4}$ (IceCube):

elongated events

IceCube trigger under design.



Slow Particles in AMANDA / IceCube

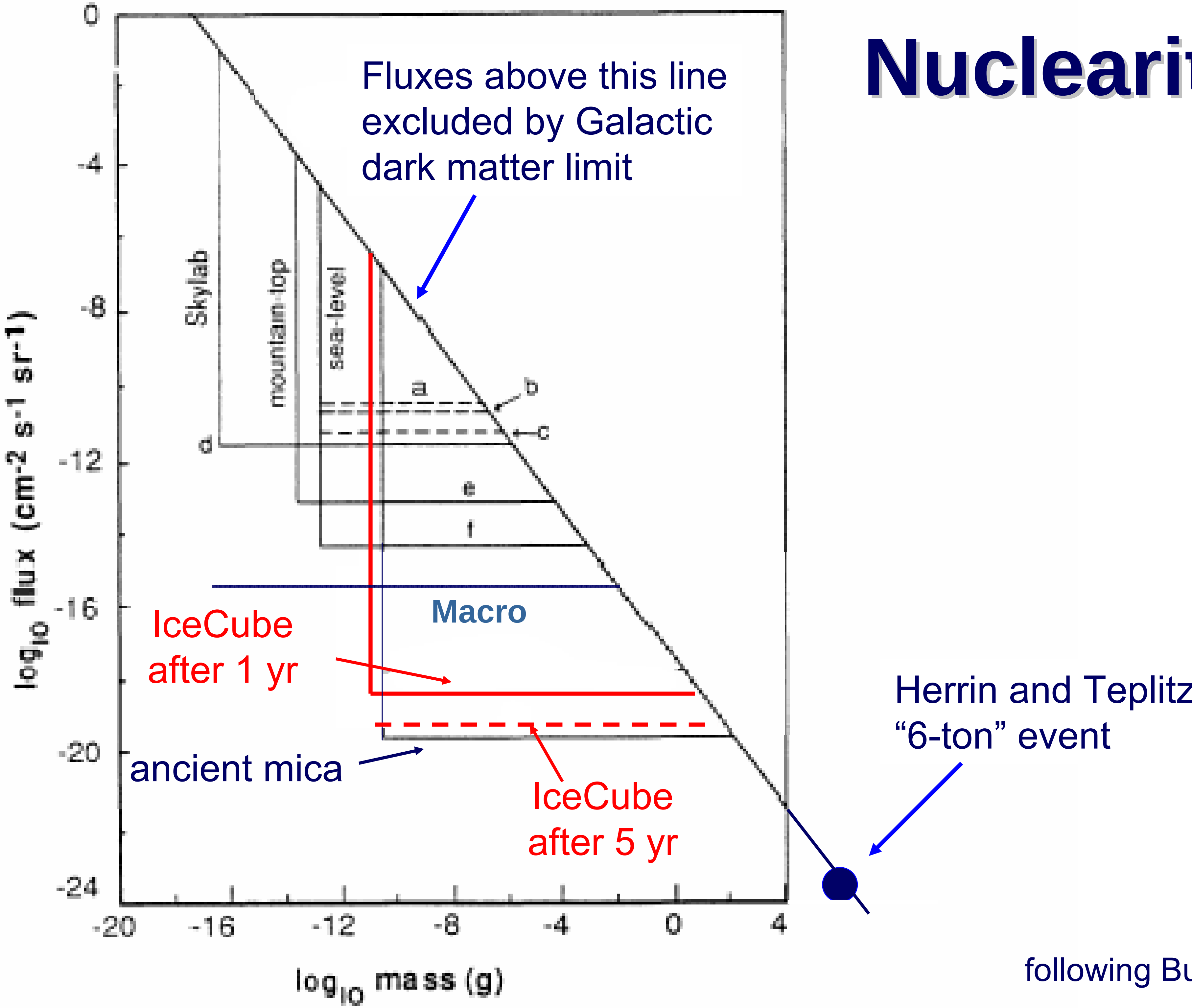
$\beta \sim 10^{-5} - 10^{-4}$

- increased counting rates of individual PMs (msec windows, “Supernova Trigger”)

  or

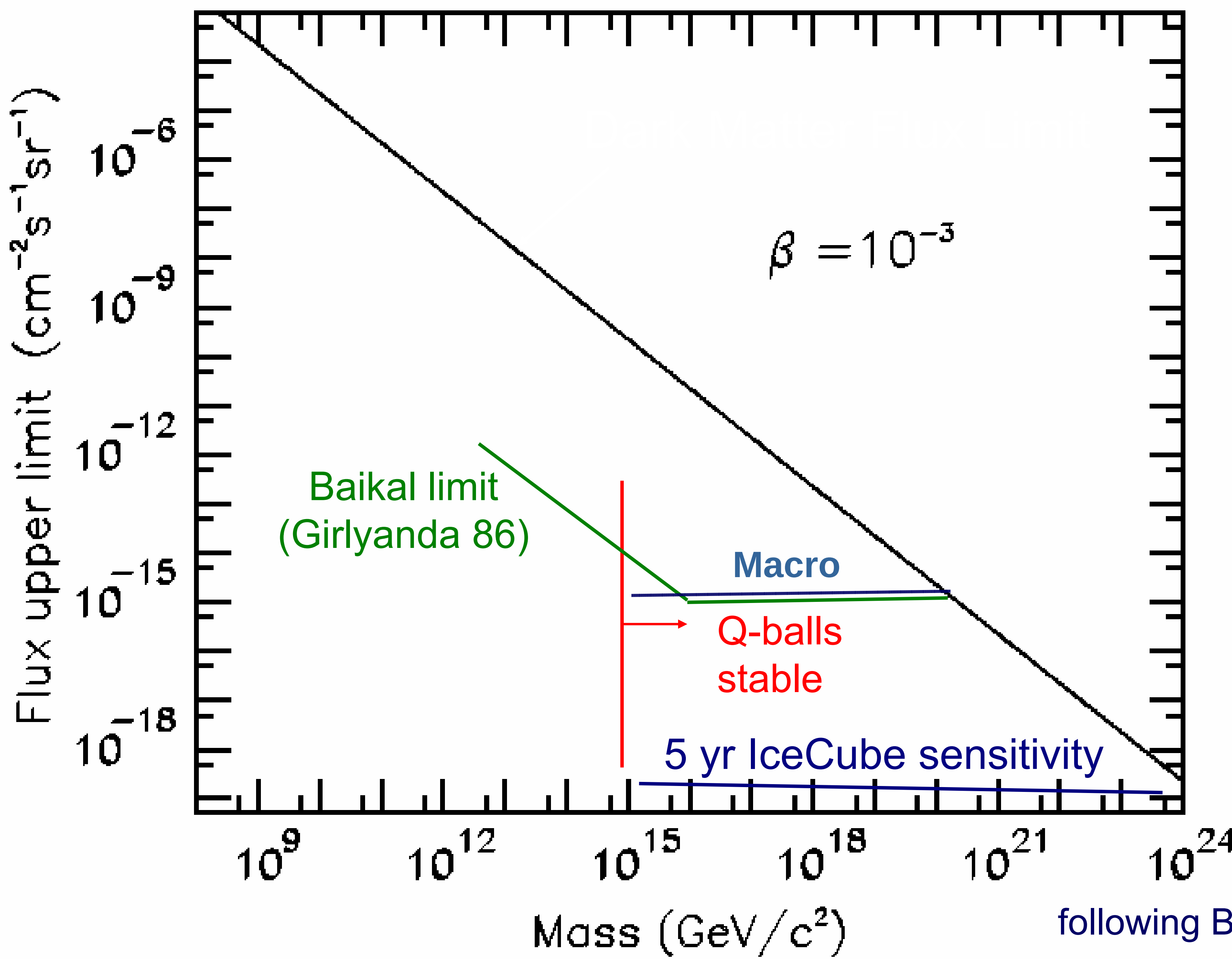
- several sequential events aligned along a straight path

Nuclearites



following Buford Price

Neutral Q-Balls



following Buford Price

Conclusions

- Neutralino is favored DM SUSY candidate. To confirm, one needs:
  - Neutralino is LSP of SUSY. Confirmation from LHC
  - Direct detection
    - Different nuclei
    - Annual modulation (possibly directional signature)
  - Indirect detection
    - Gammas: GLAST, CTA;   charged CRs: AMS
    - Neutrinos: Earth disfavoured , Neutrino flux from Sun complementary to direct searches due to spin-dependent capture in Sun
- Highest discovery potential with direct methods if they reach a sensitivity below 10^{-10} pb.
- Next 5 years: IceCube well competes with direct 10^{-9} pb searches.
- Exotic superheavy particles (Q-balls, monopoles, ..): sensitivity will improve by 1-2 orders in the next years.

End