Experimental searches for dark matter

- The Dark Matter problems
- Massive Compact Halo Objects
- Weakly Interactive Massive Particles

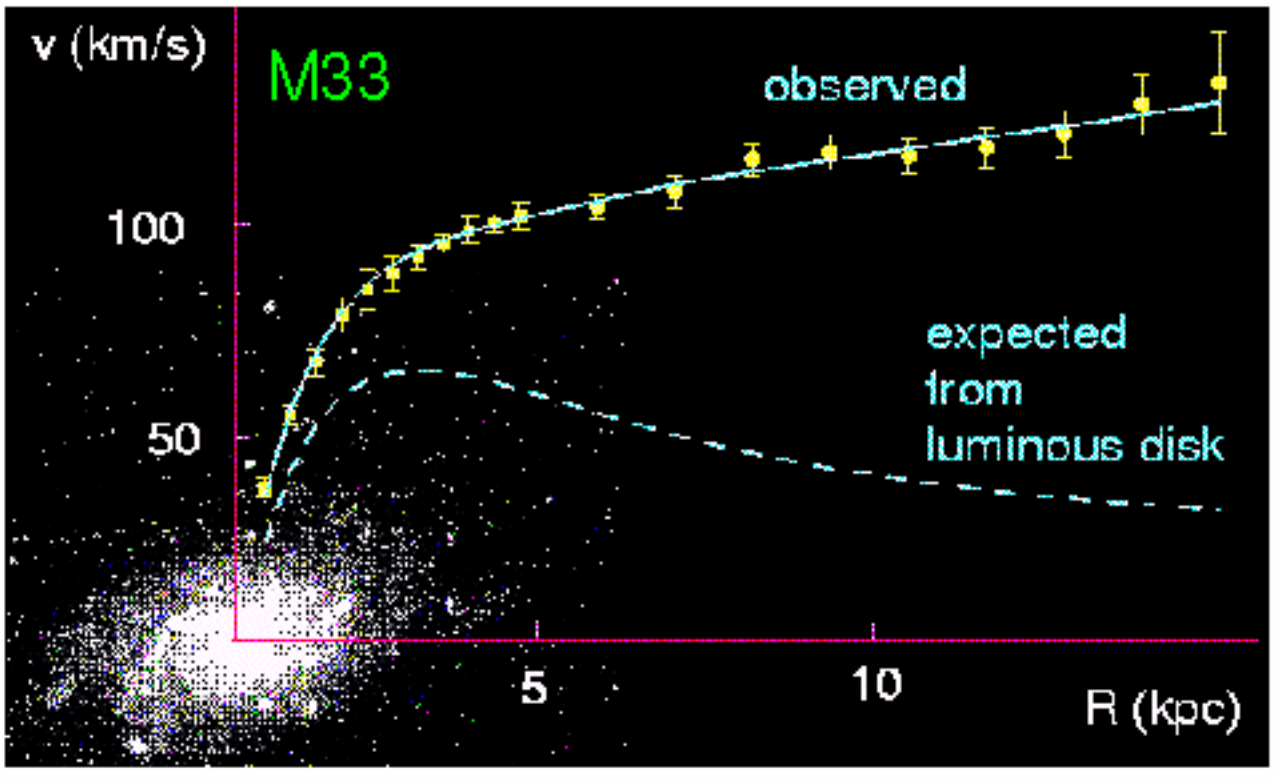
More matter in the universe than can be seen

theory of stellar evolution : luminosity <–> mass

=> mass of galaxies ~ 10^{10} to 10^{11} solar masses

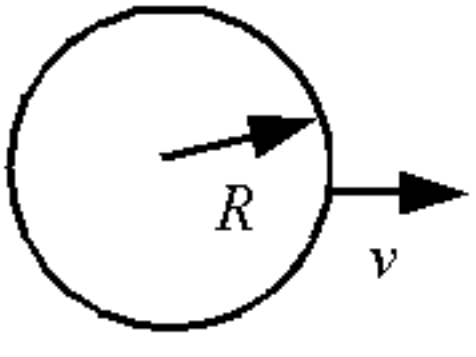
Zwicky in the 1930's : from speed and mass of galaxies,

galaxy clusters cannot hold together !



later on, same problem with galaxies :

stars, H clouds spin too fast to be bound by visible matter



universe

What is Ω ?

$$M = \frac{4}{3}\pi R^3 \rho \qquad \textbf{Hubble's law} \quad v = H R$$

kinetic + **potential** **energy of a unit mass :**

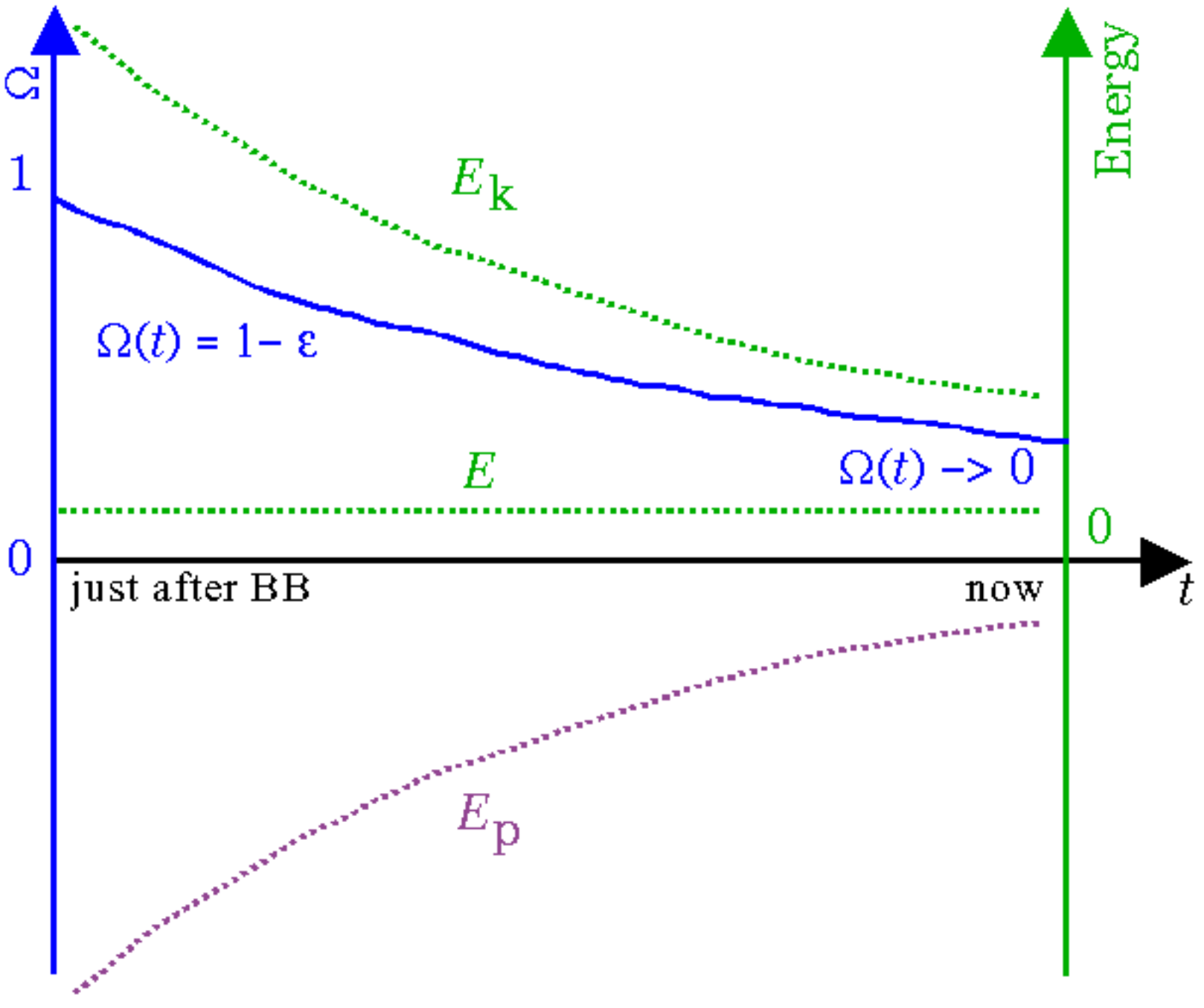
$$\frac{1}{2}v^2 - \frac{GM}{R} = \frac{H^2R^2}{2}\left(1 - \frac{2GM}{H^2R^3}\right) = \frac{H^2R^2}{2}\left(1 - \frac{8\pi G\rho}{3H^2}\right)$$

$$\frac{8\pi G\rho}{3H^2} = \Omega = \frac{\rho}{\rho_c} \qquad \textbf{with} \quad \rho_c = \frac{3H^2}{8\pi G} \sim \textbf{5 GeV/m}^3$$

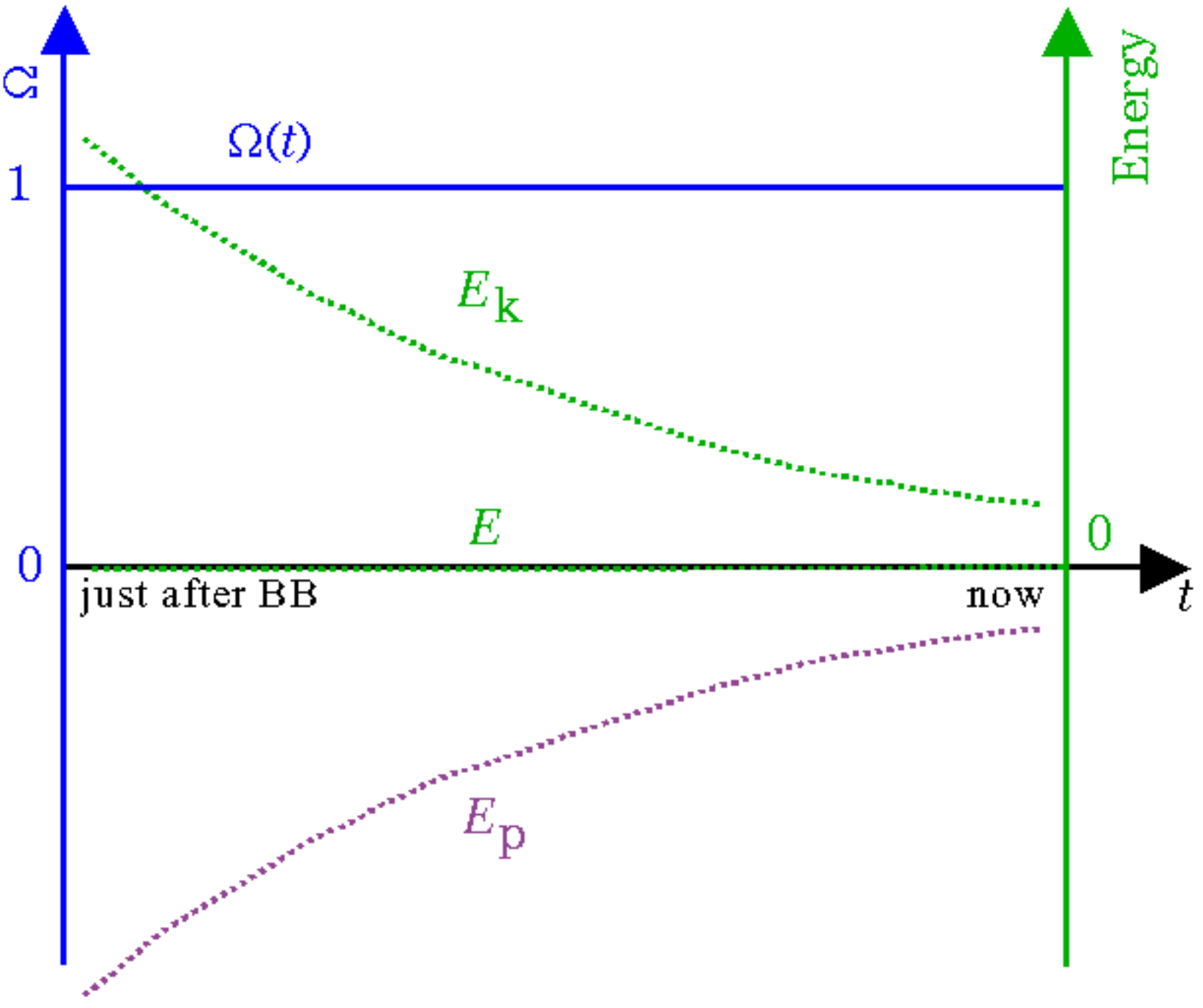
coming back to

$$E_k + E_p = E_k(1 + E_p/E_k)$$
$$= E_k(1 - \Omega) \Rightarrow \Omega = -E_p/E_k$$

Time evolution of Ω for $E = E_{\mathrm{k}} + E_{\mathrm{p}} > 0$



Time evolution of Ω for $E = E_{\mathrm{k}} + E_{\mathrm{p}} = 0$



Ω from Cosmic Microwave Background

$z > 1000$: matter and radiation coupled

density fluctuations due to oscillations

between gravity –> <– and radiation <– –>

at z=1000 : decoupling

CMB kept memory of fluctuations :

hot spots –> high density

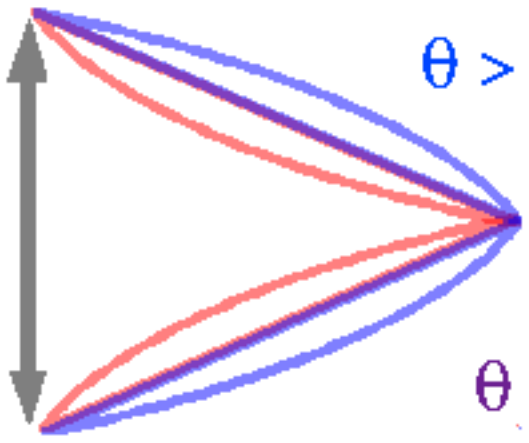
cold spots –> low density

now (z = 0), these spots are ~ 0.5° large

Ω from Cosmic Microwave Background

Spot size
at z=1000

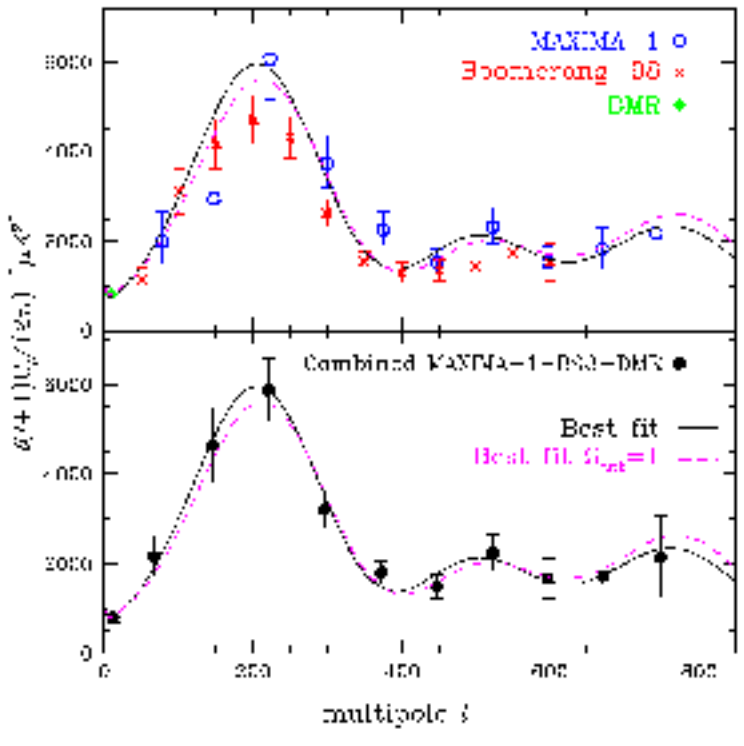
θ at z = 0



θ > θ_0 => closed geometry => Ω > 1

θ < θ_0 => open geometry => Ω < 1

θ = θ_0 => flat geometry => Ω = 1



maximal T fluctuations

for l ~ 200 (θ ~ 0.5°)

=> Ω = 1.1 +– 0.07

Supernovae 1a, a standard candle

white dwarf accretes matter from red giant companion

last straw breaks the camel's back

=> supernova occurs at a precise mass ($1.4\ M_{sun}$)

=> standard characteristics :

➔ maximal luminosity

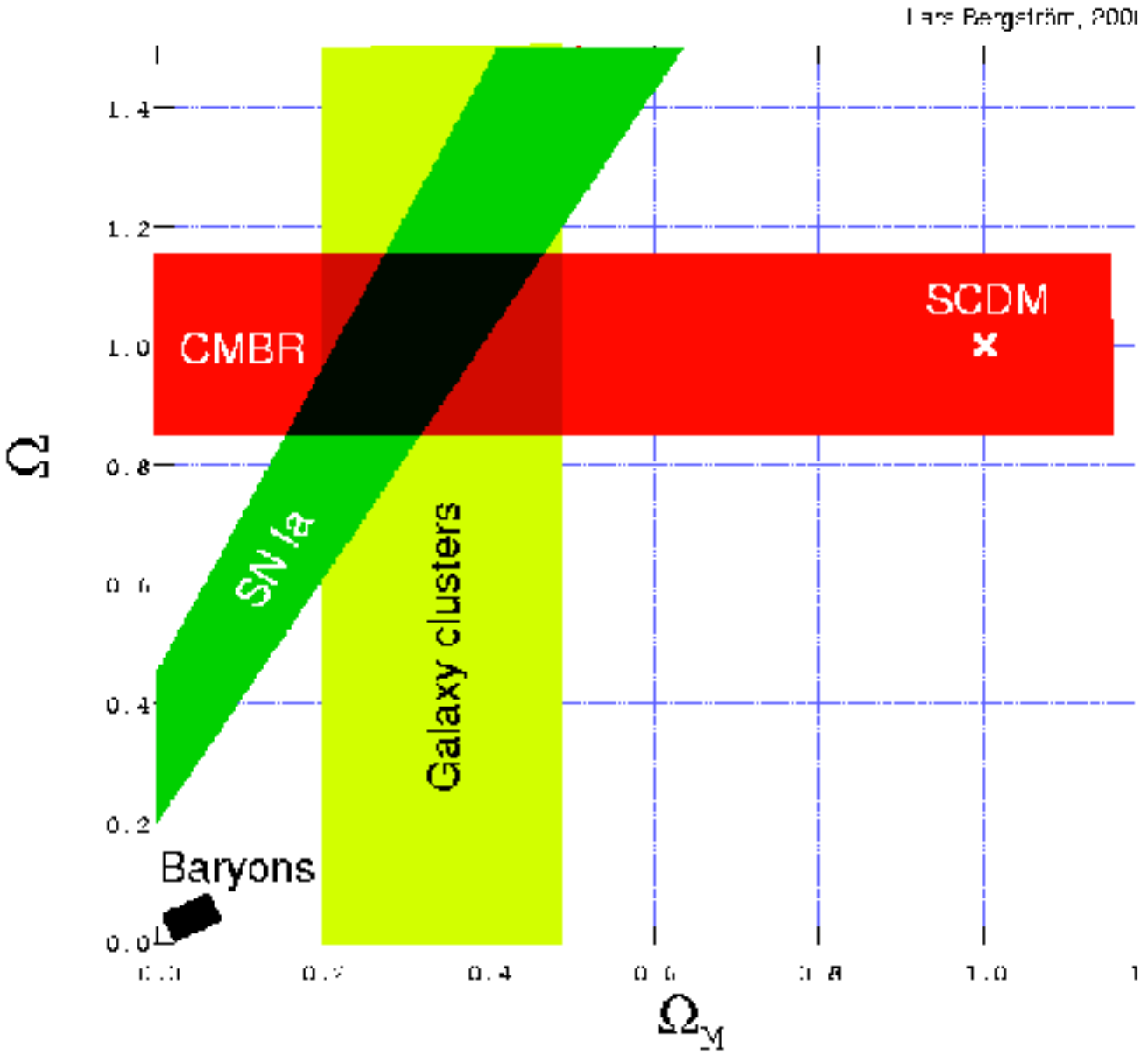
➔ luminosity curve in rest frame : $t \rightarrow t \times (1 + z)$

➔ colour in rest frame : $\lambda \rightarrow \lambda \times (1 + z)$

measure brightness, get distance : $B = L/4\pi D^2$

measure host galaxy **redshift** (z)

What is Ω made of ?



What is Ω made of ?

matter + **dark energy** (**cosmological constant**)

$\Omega = \Omega_M + \Omega_\Lambda = 0.3 + 0.7$ (**CMB fluctuations + SN1a**)

matter : baryons + ν + **Cold Dark Matter**

$\Omega_M = \Omega_b + \Omega_\nu + \Omega_{CDM}$

from big bang nucleosynthesis : $\Omega_b \sim 0.04$

from large structure formation (max. HDM) : $\Omega_\nu < 0.08$

$\Rightarrow \Omega_{CDM} > 0.2$

there is non-baryonic cold dark matter

What is Ω_{CDM} made of ?

there is non-baryonic cold dark matter :

$\Omega_{\mathrm{CDM}} > 0.2$

possibilities :

- **super heavy relics from the big bang**
- **axions**
- **neutralinos**

What is Ω_b made of ?

$\Omega_{visible} \sim 0.005$ from mass to luminosity relation for stars

what are the remaining 0.035 made of ?

in galaxy clusters : hot gas seen in X rays

locally :

➔ cold gas clouds ? ~ disfavoured

➔ brown dwarfs ?

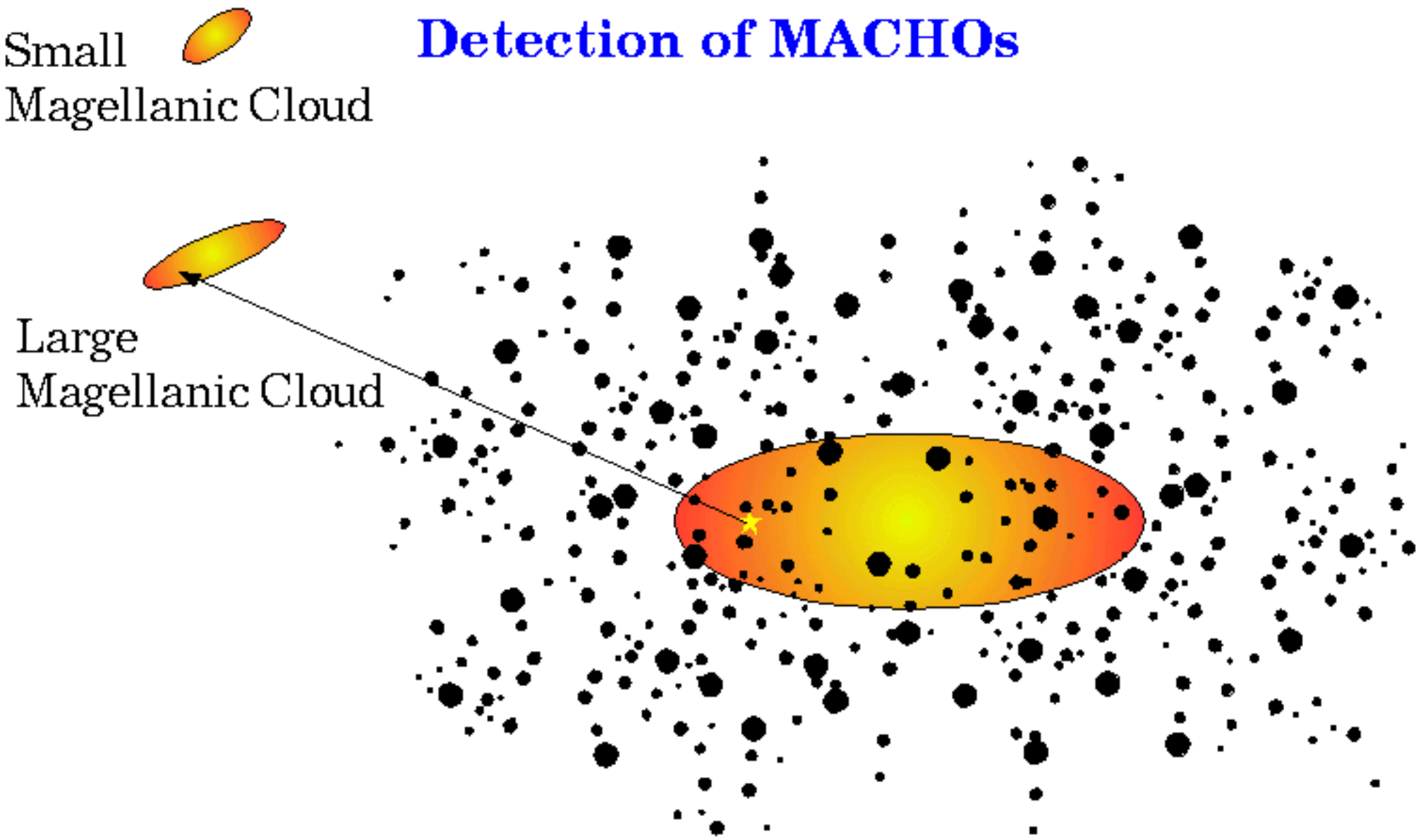
➔ planets ?

➔ stellar remnants : black holes, white dwarfs ?

➔ ???

=> Massive Compact Halo Objects (MACHOs)

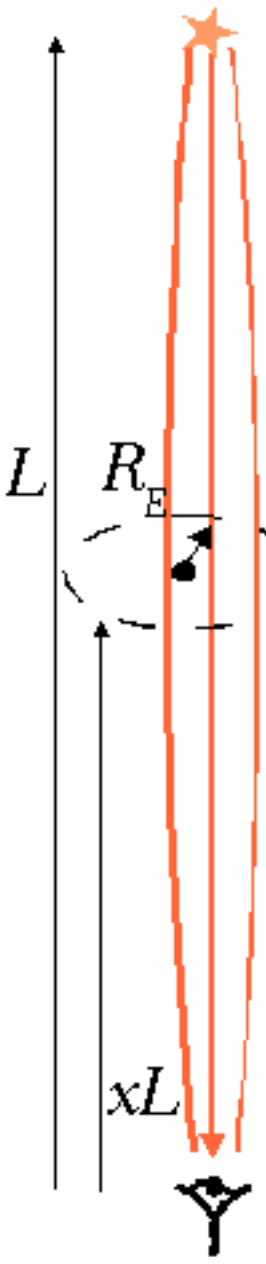
Detection of MACHOs



Look at LMC and SMC stars through the halo of our Galaxy

monitor millions of stars

Gravitational lensing



$$R_E \simeq 970\, R_{sun} \sqrt{\frac{M}{M_{sun}}} \sqrt{\frac{L}{10\,kpc}} \frac{\sqrt{x(1-x)}}{0.5}$$

$$\Delta T = \frac{R_E}{V_T} = \frac{7\,10^8}{200}\sqrt{5.5}\sqrt{\frac{M}{M_{sun}}}\frac{\sqrt{x(1-x)}}{0.5}$$

$$\Delta T\,(days) \approx \frac{8\,10^6\,s}{8\,10^4\,s}\sqrt{\frac{M}{M_{sun}}}\frac{\sqrt{x(1-x)}}{0.5}$$

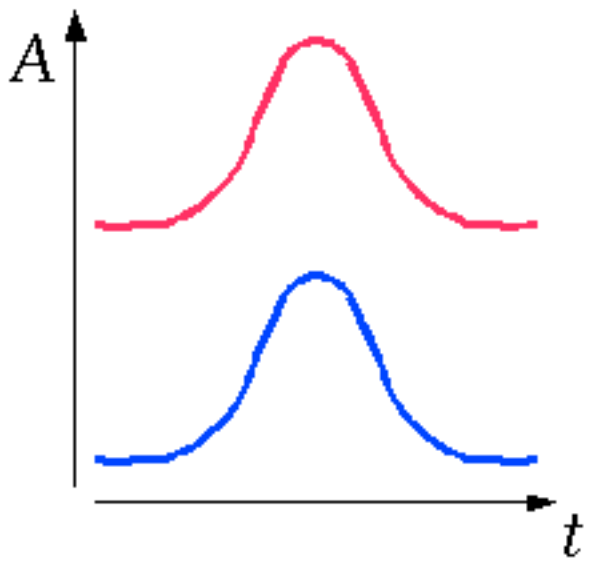
Light amplification

image unresolved => star brightens (microlensing)

amplication depends on distance $u = R / R_E$

$$A(t) = \frac{u(t)^2 + 2}{u(t)\sqrt{u(t)^2 + 4}}$$

$$u = 1 \quad A = 1.34$$



properties :

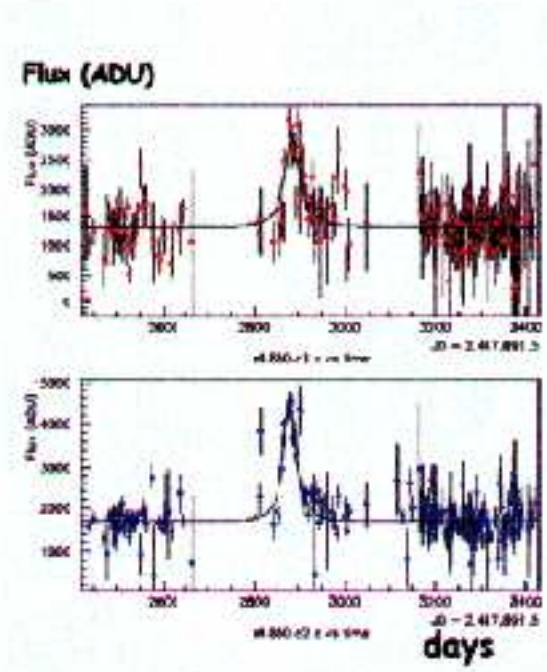
- **symmetric curve**
- **independent of colour** **=> reject variable stars**
- **occurs only once per star**

Background stars

The Large Magellanic Cloud

1 m EROS telescope in la Silla, Chile

Event characteristics



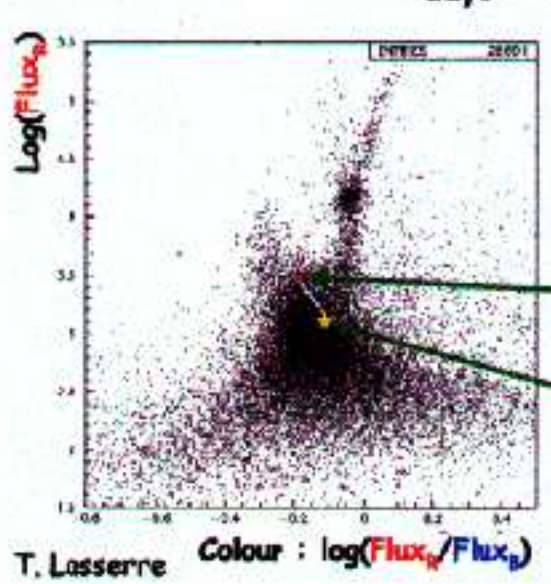
Microlensing fit

u_0 = 0.38(0.01)

t_E = 36(2) days

72% of the baseline flux is amplified

χ^2 / dof = 682/405



Colour magnitude diagram

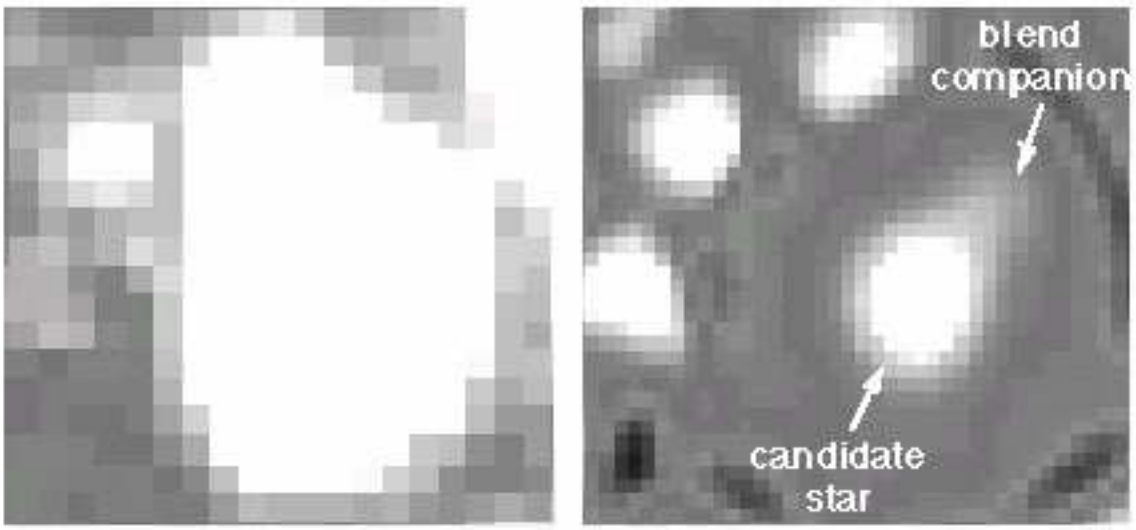
V~21.3 R~21.5

Source star at maximum magnification

Source star before magnification

amplified star in main sequence

Blending



template image correlation image

seeing ~ 0.4 arcsec = 2 10^4 AU at 50 kpc ~ 0.1 pc

=> crowded fields, blending

blending with a star of a different colour will violate $A_r = A_b$

Interpretation of data

one measurement, three unknown

mass distribution

$$\Delta T = \frac{R_E}{V_T} = \frac{7\,10^8}{V_T}\sqrt{5.5}\sqrt{\frac{M}{M_{sun}}}\frac{\sqrt{x(1-x)}}{0.5}$$

distance to deflector

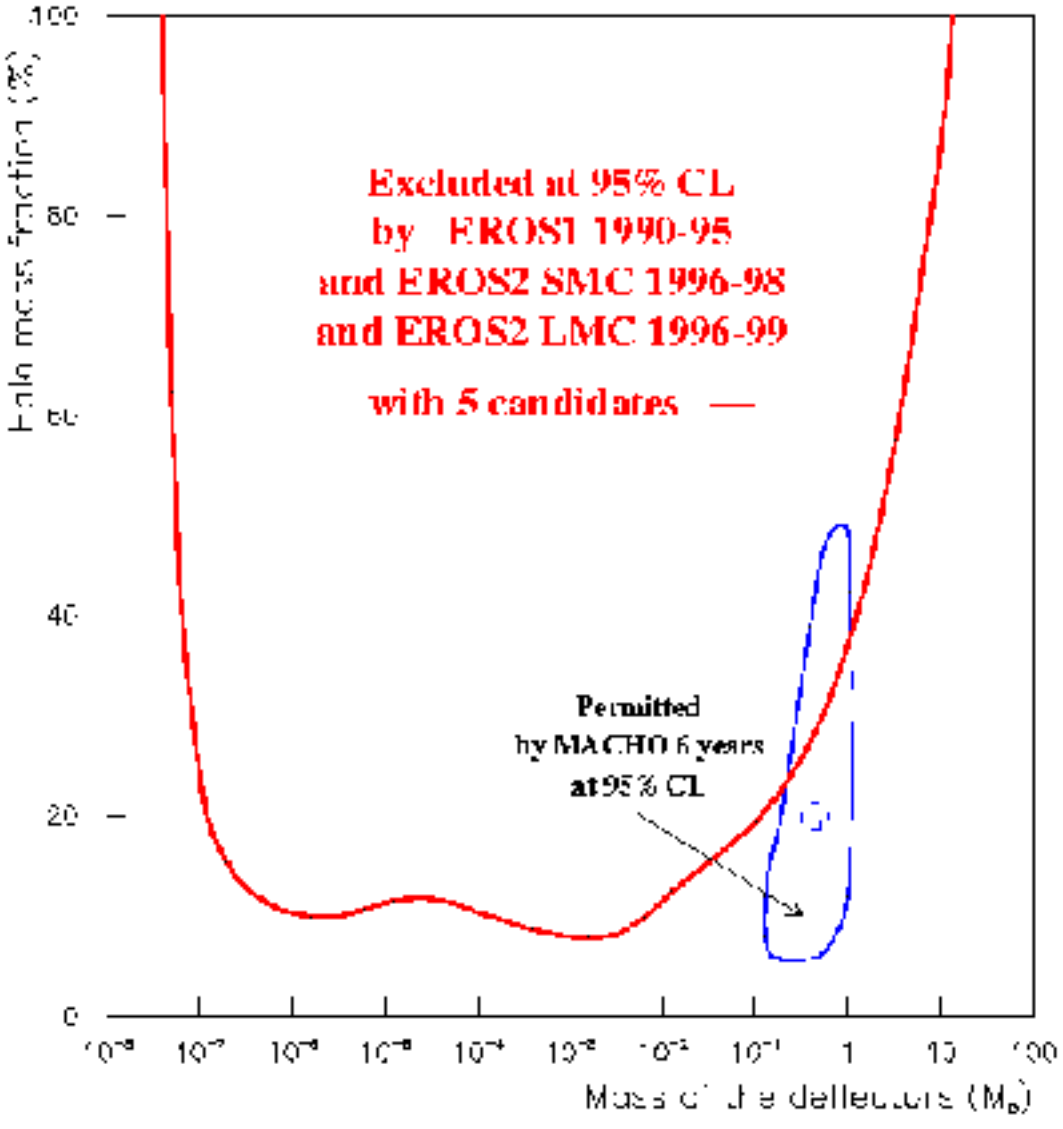
transverse velocity

use a halo model for x and V_T

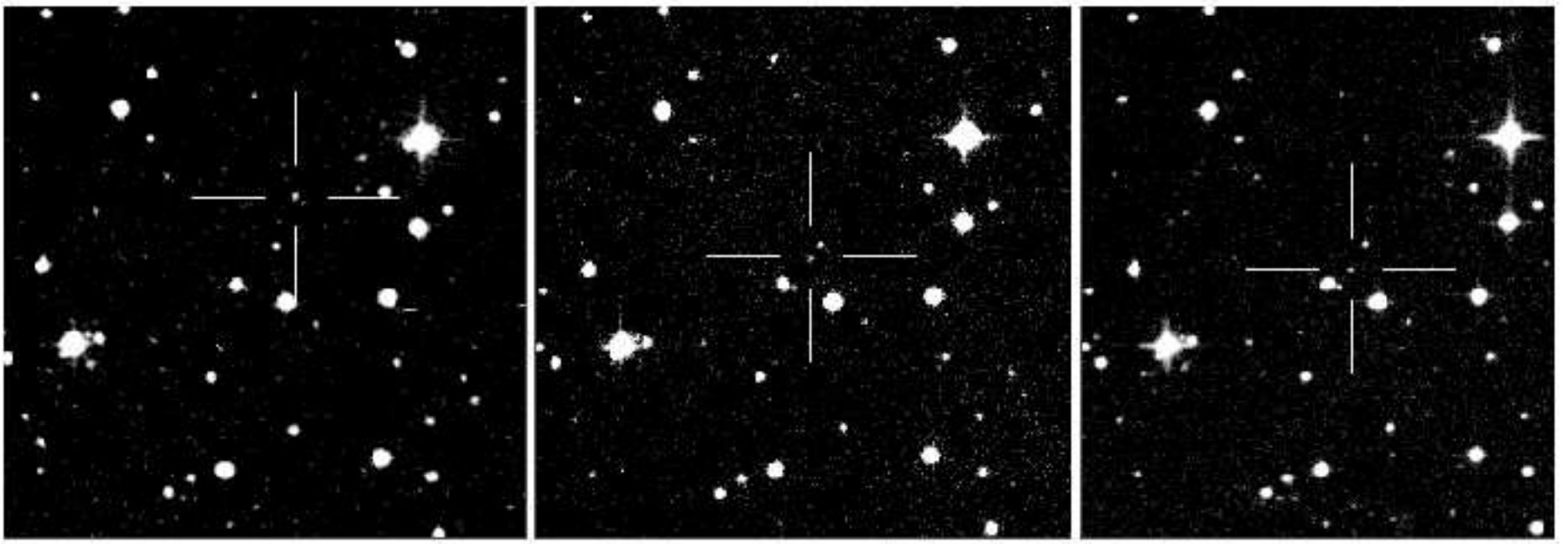
Monte Carlo for a given deflector mass M

derive 95% CL limit on halo mass fraction

Limits on halo content



White dwarfs



38 white dwarfs recently found in old plates :

→ fast moving => belong to the halo population

→ old (i.e. cold) => first population of stars in our Galaxy

may compose 3% to 35% of the halo

Conclusion

for a standard spherical halo $M = 4\ 10^{11}\ M_{sun}$

EROS excludes 100% MACHO halo from 10^{-7} to 10 M_{sun}

MACHO permits 10% to 50% halo fraction around 0.5 M_{sun}

=> not enough MACHOs to make up for Ω_b

=> room for non baryonic dark matter in the halo

Cold dark matter candidate

still around now => stable, weak interaction with matter

cold => massive

dark => no interaction with photons (transparent !)

Weakly Interactive Massive Particle (WIMP)

are there particle physics theories predicting WIMPs ?

most preferred : SUperSYmmetry

but : several possibilities (minimal, ...)

=> similar WIMP interaction and density

Properties of the neutralino (χ)

most likely lightest SUSY particle

R-parity conserved

=> lightest SUSY particle stable

mixture of Higgsinos, Zino and photino

=> weak interaction with ordinary matter

electrically neutral

=> dark

its own antiparticle

remnant from a hot period ($T > M_{\chi}$)

Neutralino abundance

remnant from a hot period ($T \sim M_\chi$)

for all massive particles :

$$\Omega_\chi \sim \frac{10^{-26}\,\mathrm{cm^3\,s^{-1}}}{\langle \sigma_A v \rangle}$$

σ_A : annihilation cross-section

v : velocity

<...> : average over T

$$\Omega_\chi \sim 1 \Rightarrow \sigma_A \sim \frac{10^{-26}}{v} \left(v \approx 300\,\mathrm{km/s} = 3\,10^{7}\,\mathrm{cm/s}\right) \Rightarrow \sigma_A \sim 3\,10^{-34}\,\mathrm{cm^2}$$

$$\left(\frac{\alpha \times 0.2\,10^{-13}\,\mathrm{GeV\,cm}}{M_W}\right)^2 = 4\,10^{-36}\,\mathrm{cm^2}$$

σ_A ~ electroweak scale if χ fill the universe

Direct detection

elastic shock on a target nucleus

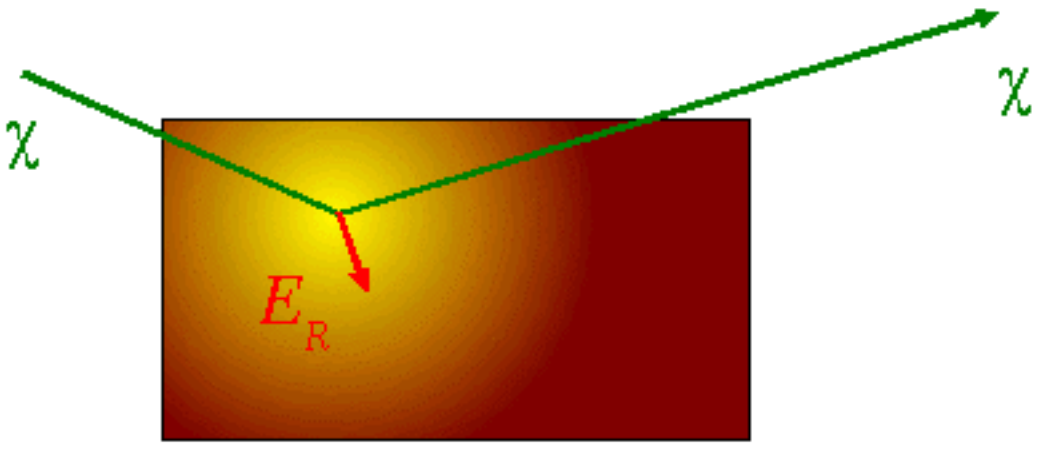
typical χ velocity : v ~ 250 km/s ($\beta \sim 10^{-3}$)

m_χ > 37 GeV (ALEPH limit)

$$E_k = \frac{1}{2} m_\chi c^2 \beta^2 \sim 10^{-6} m_\chi c^2$$

recoil energy E_R ~ 10 keV

- **scintillation**
- **ionisation**
- **phonons**



Phonon detection

displacement of the recoil nucleus may cause :

phonons => vibrations in cristal lattice (Al_2O_3, Si, Ge, ...)

calorimetry : $\Delta t \sim \mu K$

superconducting sensor -> normal conductivity

phonons are collected in sensors

=> ~ independent of detector mass

operate at ~ 10 mK (dilution refrigerator)

Sensitivity

rate R_χ vs cross section : $\sigma_{\chi N} = \dfrac{R_\chi M_\chi}{N_t \rho_\chi v} \sim \sigma_{\chi n} \times A^2$

(enhancement due to coherent scattering in the nucleus)

for a 20 GeV χ and a 1 kg mass of Ge (A ~ 70)

1 count/day <=> $\sigma_{\chi n} = 10^{-41} cm^2$

need to explore $\sigma_{\chi n} \leqslant 10^{-42} cm^2$

Background

low rate and amplitude signal => lots of backgrounds

natural radioactivity :

β, γ : large ionisation or scintillation, small phonons

neutrons : will look more like a χ

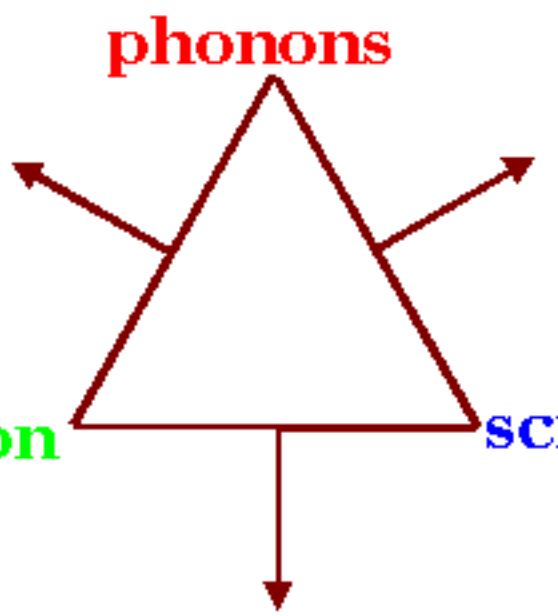
=> radiopure detector + shielding + sensors

cosmic rays : activate the detector, produce neutrons

=> underground laboratories

Experiments

CRESST 1 sapphire
ROSEBUD sapphire
Tokyo LiF
Milano TeO_2



EDELWEISS Ge, Si
CDMS 1, 2 Ge, Si

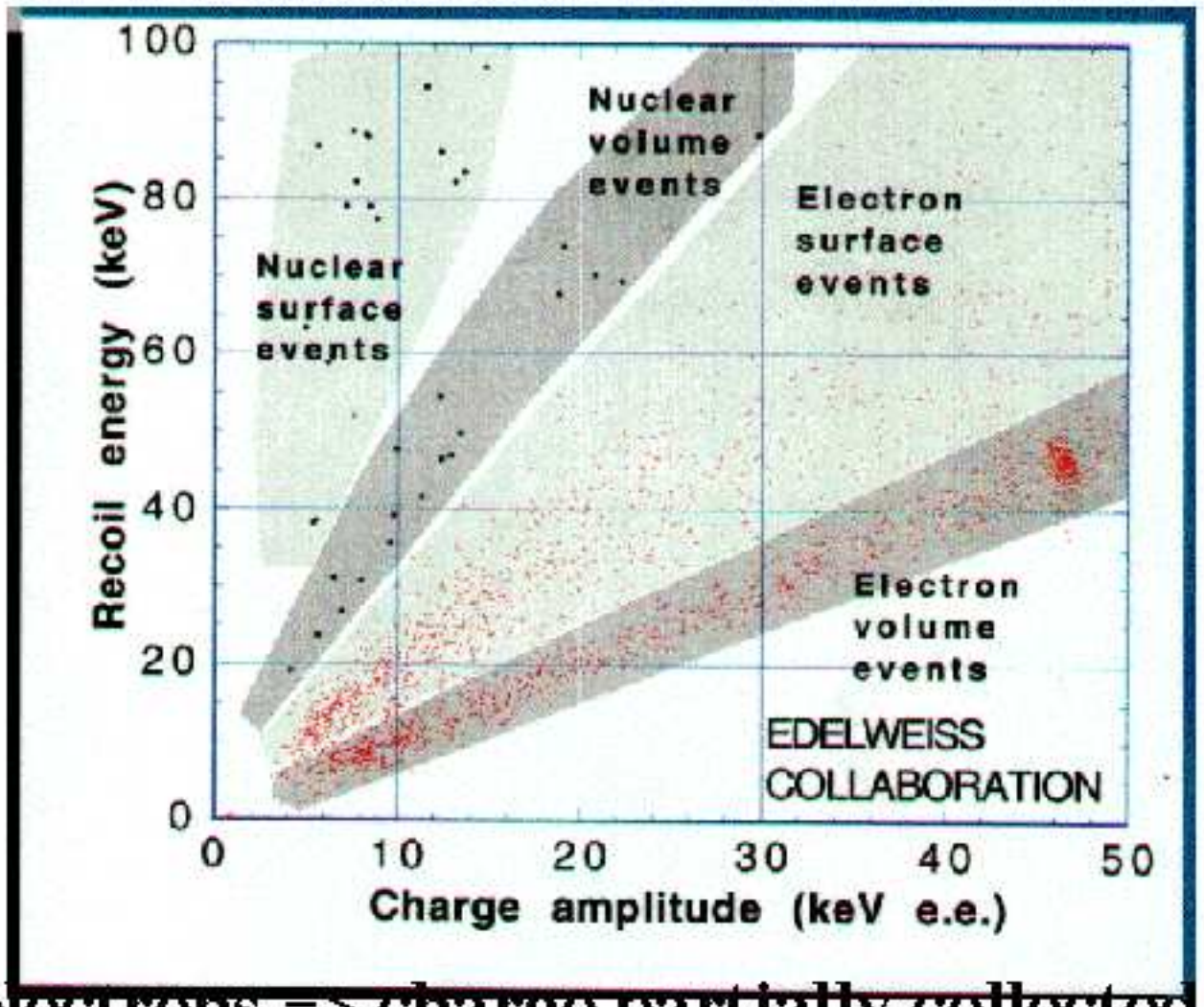
CRESST 2 $CaWO_4$

HD–Moscow
GENIUS

UKDMC Xe

UKDMC NaI
DAMA NaI

Ionisation vs phonons

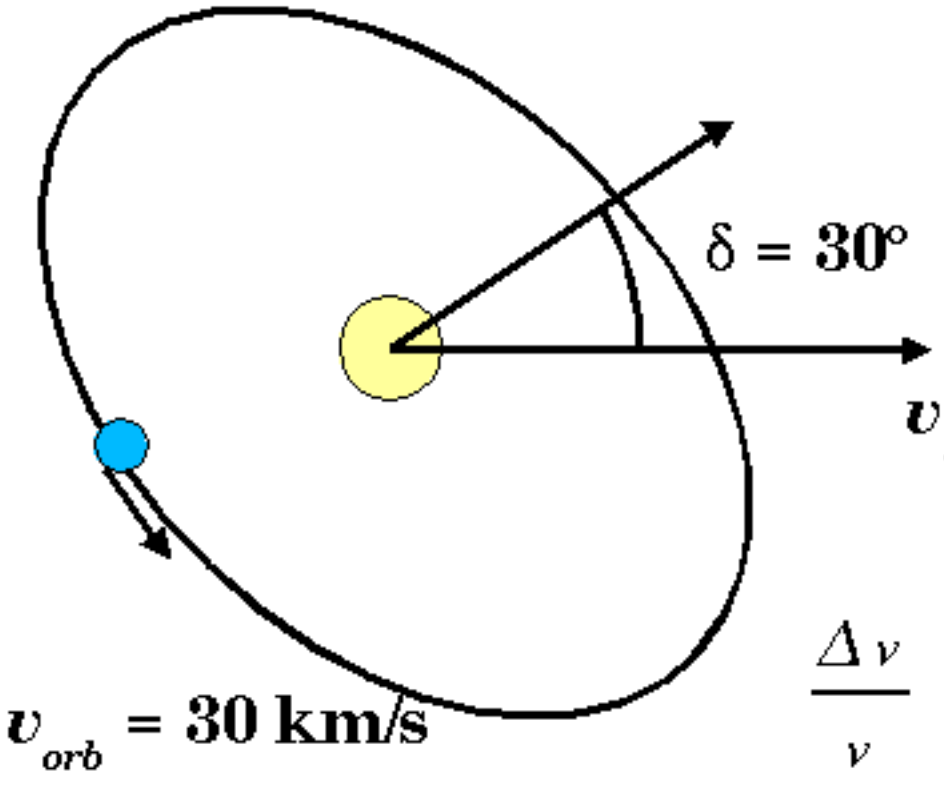


surface electrons => charge partially collected

$^{210}Po \rightarrow {}^{206}Pb + \alpha + 5\ MeV$, α escapes, $E_{Pb} \sim 100\ keV$

χ signal characteristics

variation of Earth motion in the χ wind (non rotating halo)

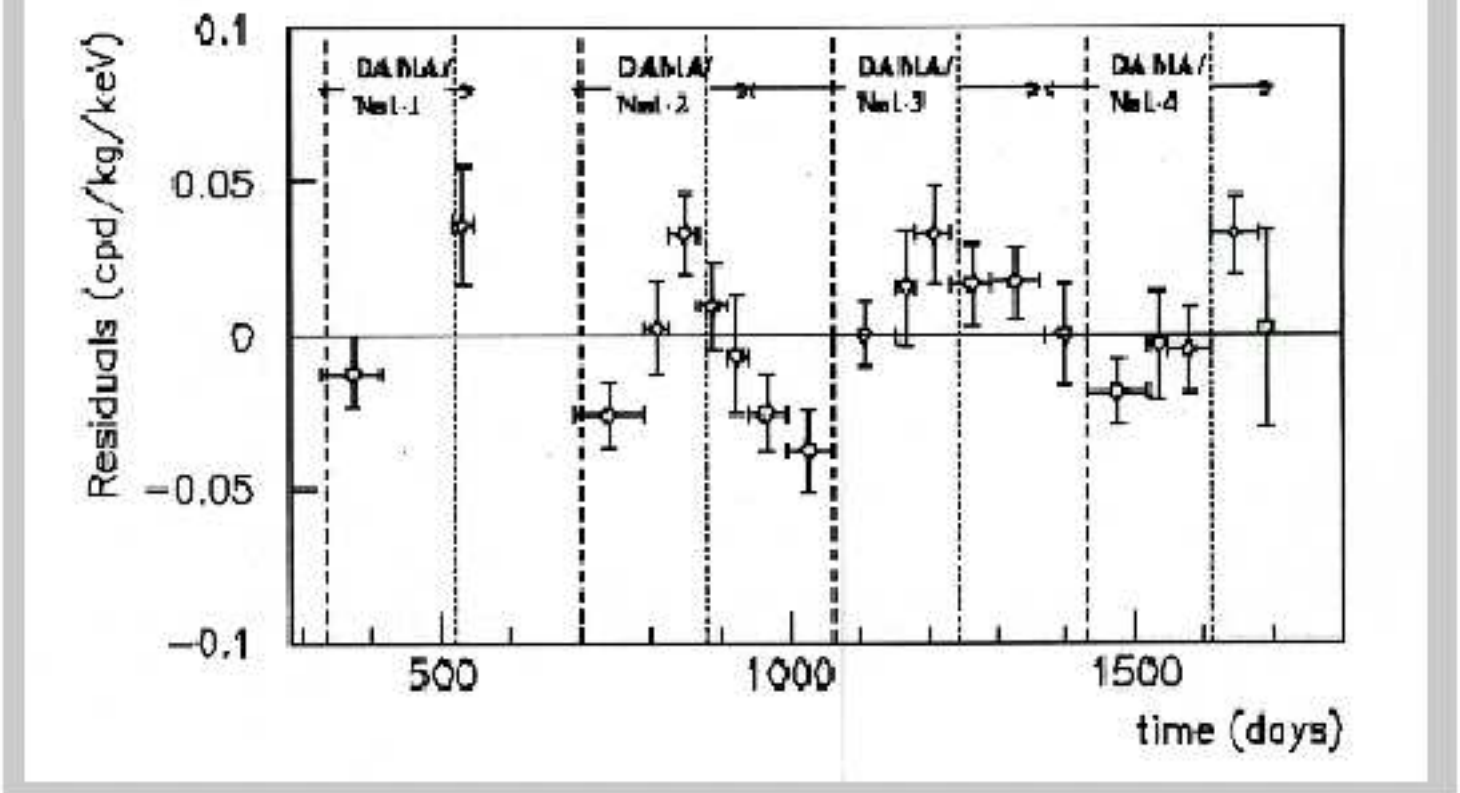


$$v_{earth} = v_{sun} + v_{orb} \sin\delta \cos[\omega(t - t_0)]$$

$$\frac{\Delta v}{v} \sim 0.07 \quad t_0 = \text{June } 2^{\text{nd}} \quad \omega = \frac{2\pi}{1\,\text{year}}$$

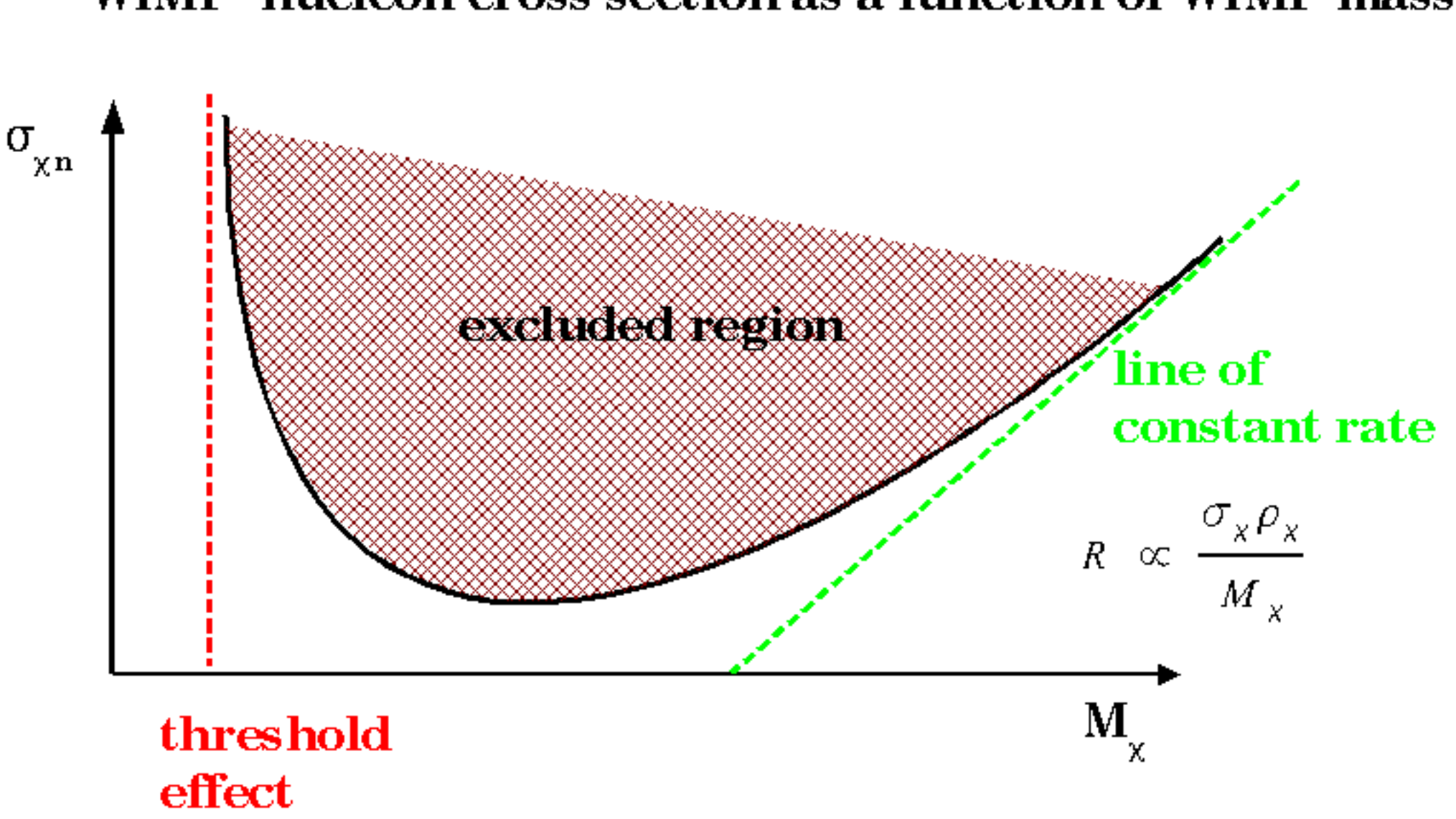
yearly modulation of rate < 7% (depending on threshold)

DAMA results

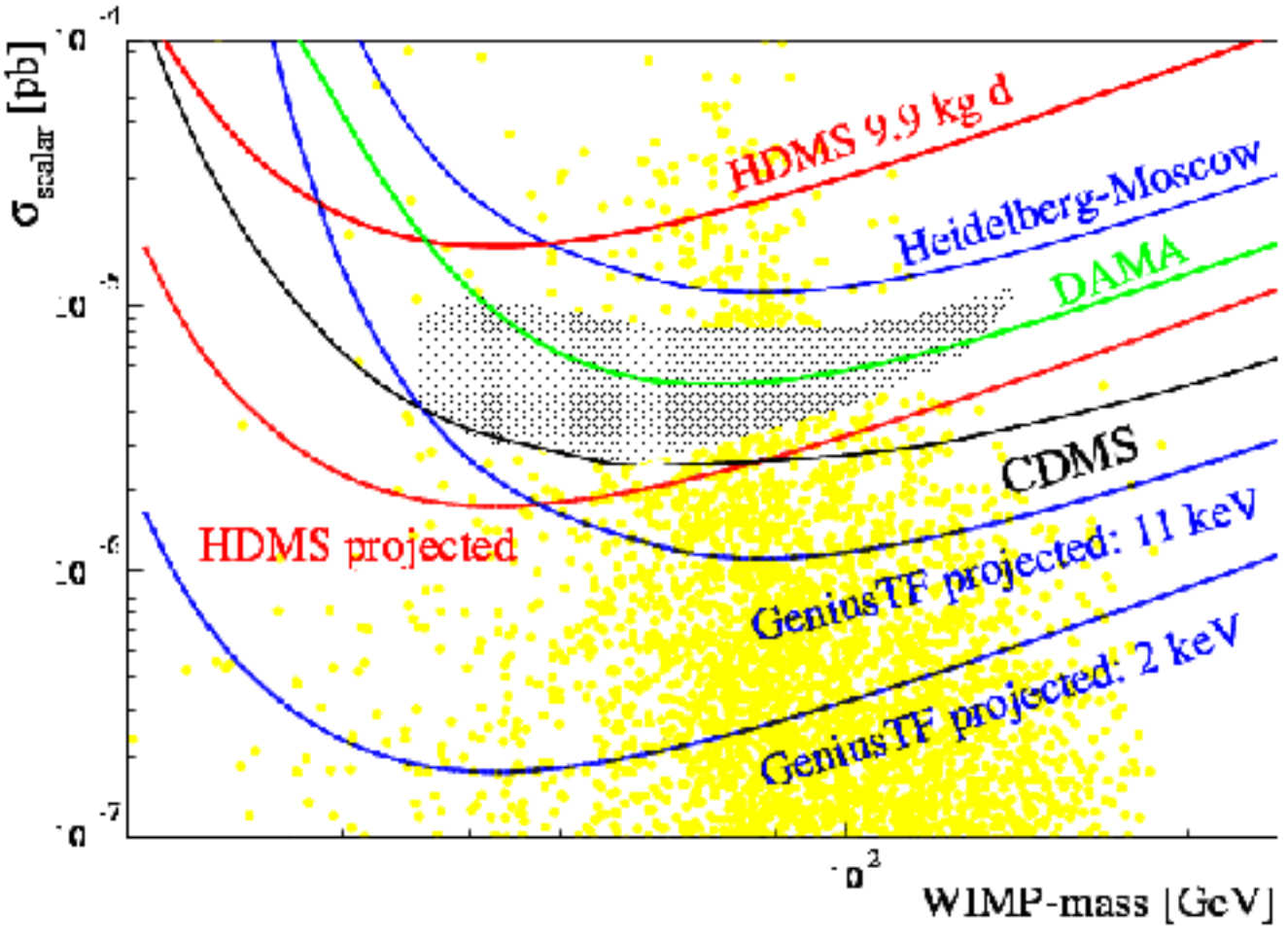


χ exclusion plots

WIMP–nucleon cross section as a function of WIMP mass



GENIUS plot


σ_{scalar} [pb]
HDMS 9.9 kg d
Heidelberg-Moscow
DAMA
CDMS
HDMS projected
GenitusTF projected: 11 keV
GenitusTF projected: 2 keV
WIMP-mass [GeV]

Gravitational capture of χ

halo WIMP traverses sun : elastic shock

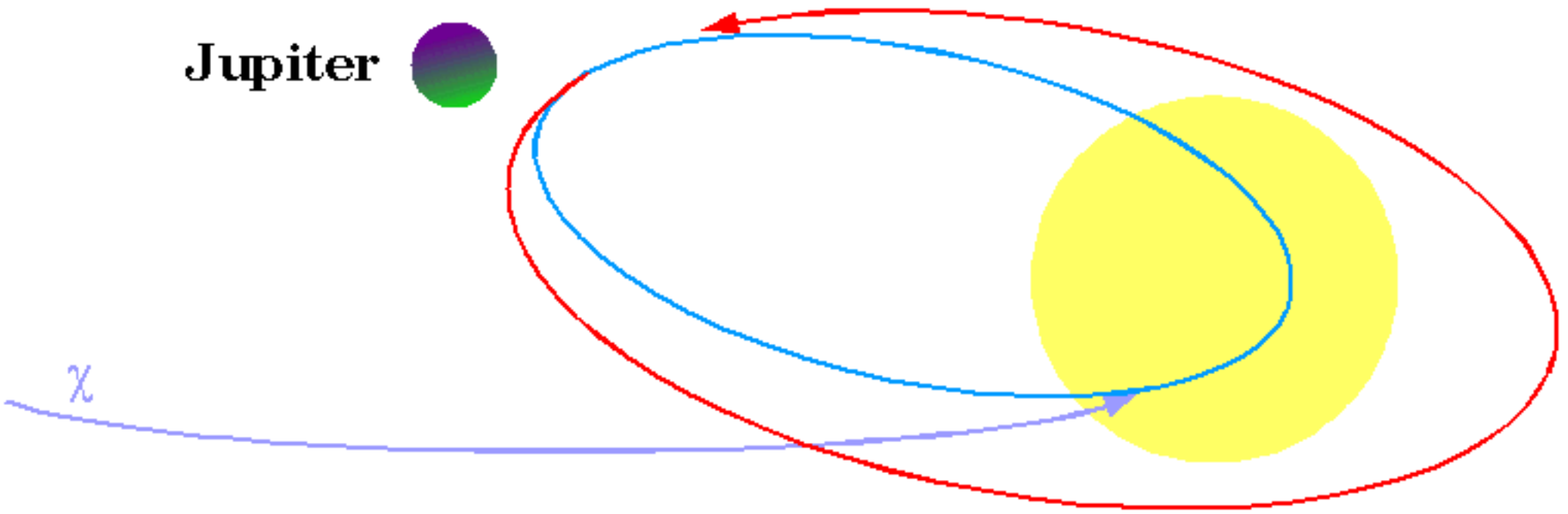
=> if $v < v_{escape}$, bound trajectory always crosses sun

=> next shock, closer ellipse

accumulation at the centre

capture + annihilation balance => constant density

Local χ density enhancement



Jupiter or Venus deviate bound χ

do not pass through sun anymore

increase density around Earth trajectory (up to x 10 ?)

may be captured by Earth later on

χ annihilation signal

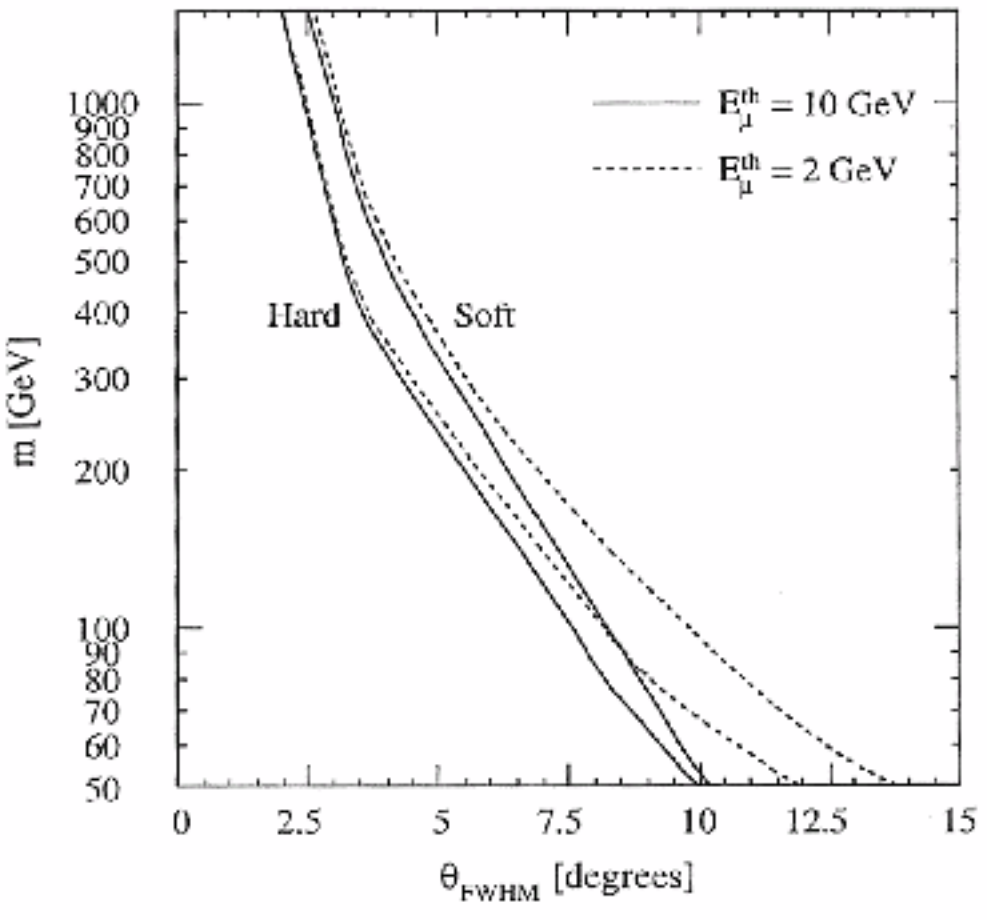
its own antiparticle : $\chi\,\chi$ –> τ, ***c***, ***b***, ***t***, ***W***, ***Z***, **...** –> ν

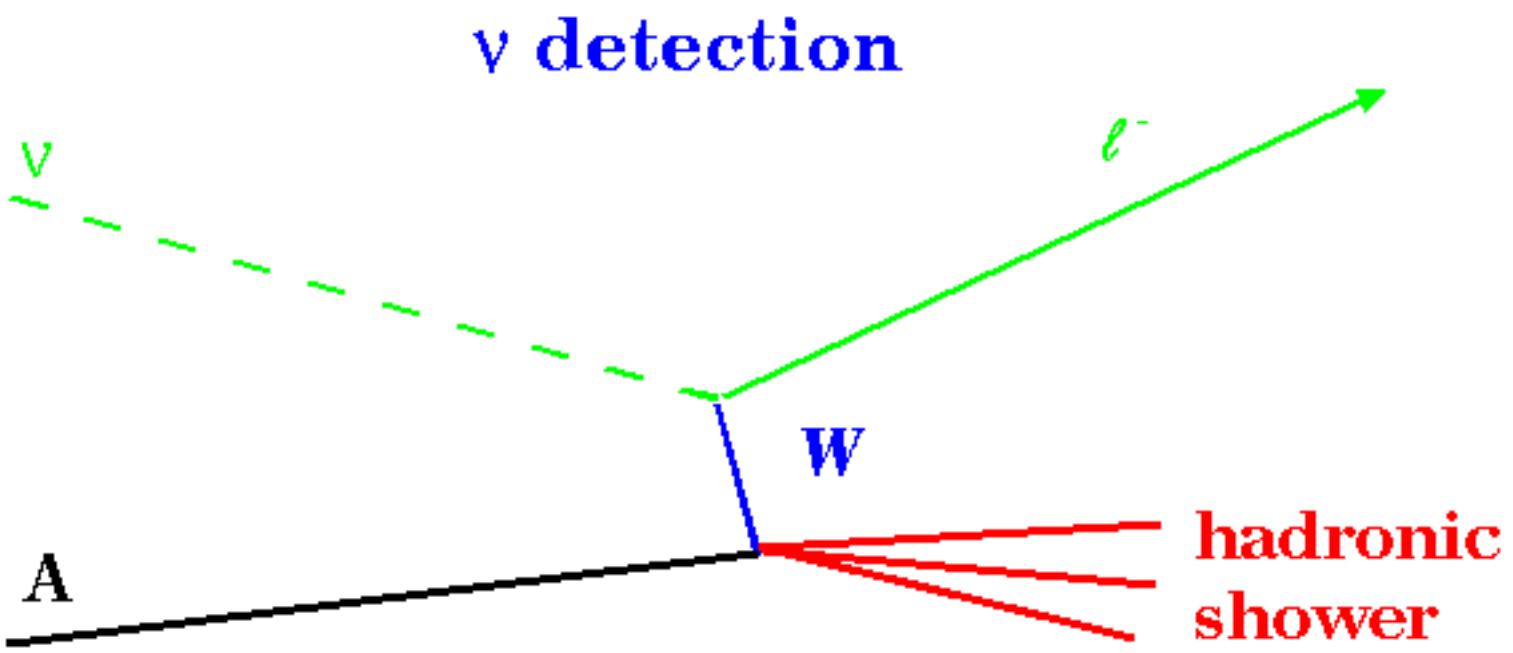
=> high energy ν flux from centre of Earth, Sun , Galaxy

characteristics : $E_\nu \sim 1/3\, M_\chi$

for Earth : not punctual

angular spread –> M_χ



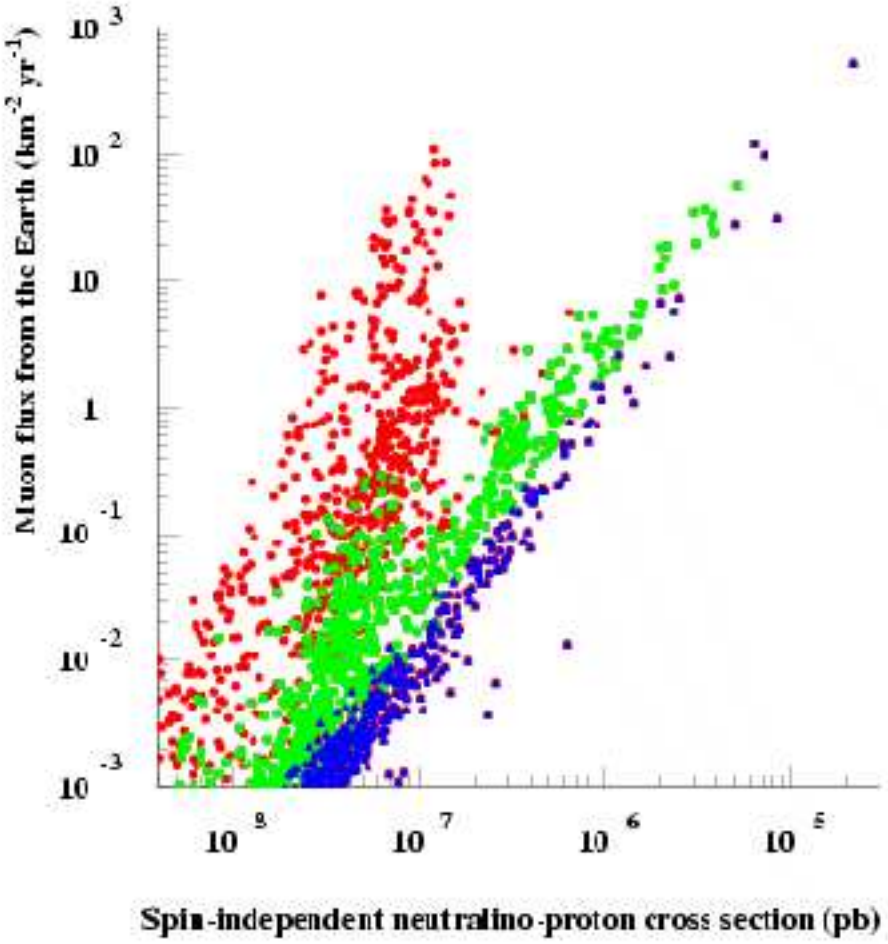


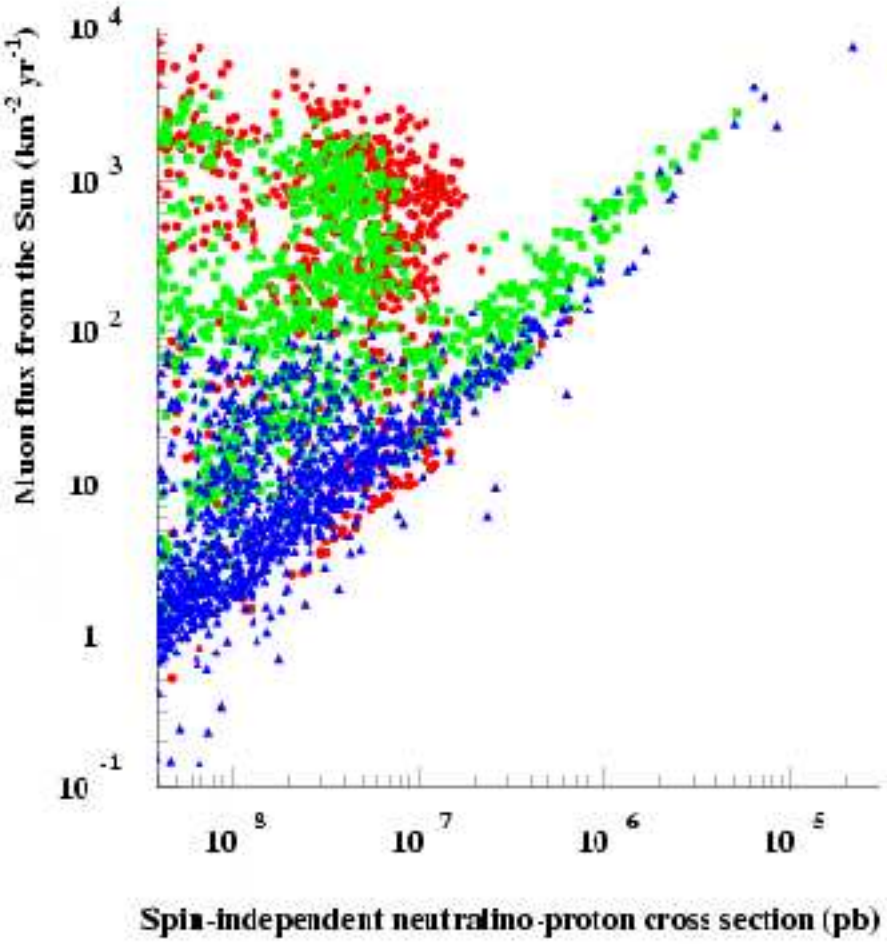
$\nu_e + A \rightarrow e^- + X$ stops quickly ~ 10 m

$\nu_\mu + A \rightarrow \mu^- + X$ big range ~ 1 km

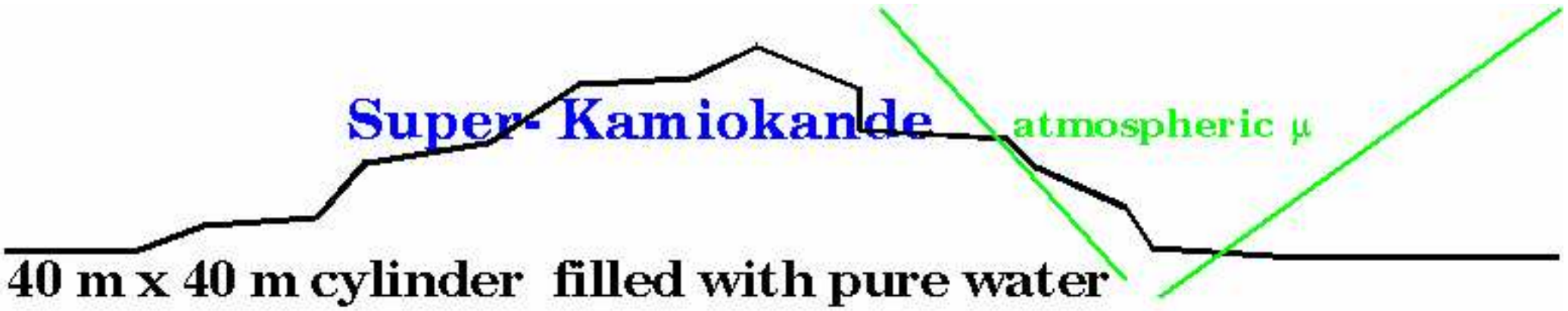
$\nu_\tau + A \rightarrow \tau^- + X$ decays quickly ~ 5 cm @ 1 TeV

Flux predictions





annihilation rate prop. $\sigma_{\chi p}$ (equilibrium)



40 m x 40 m cylinder filled with pure water

11 000 PMTs (50 cm)

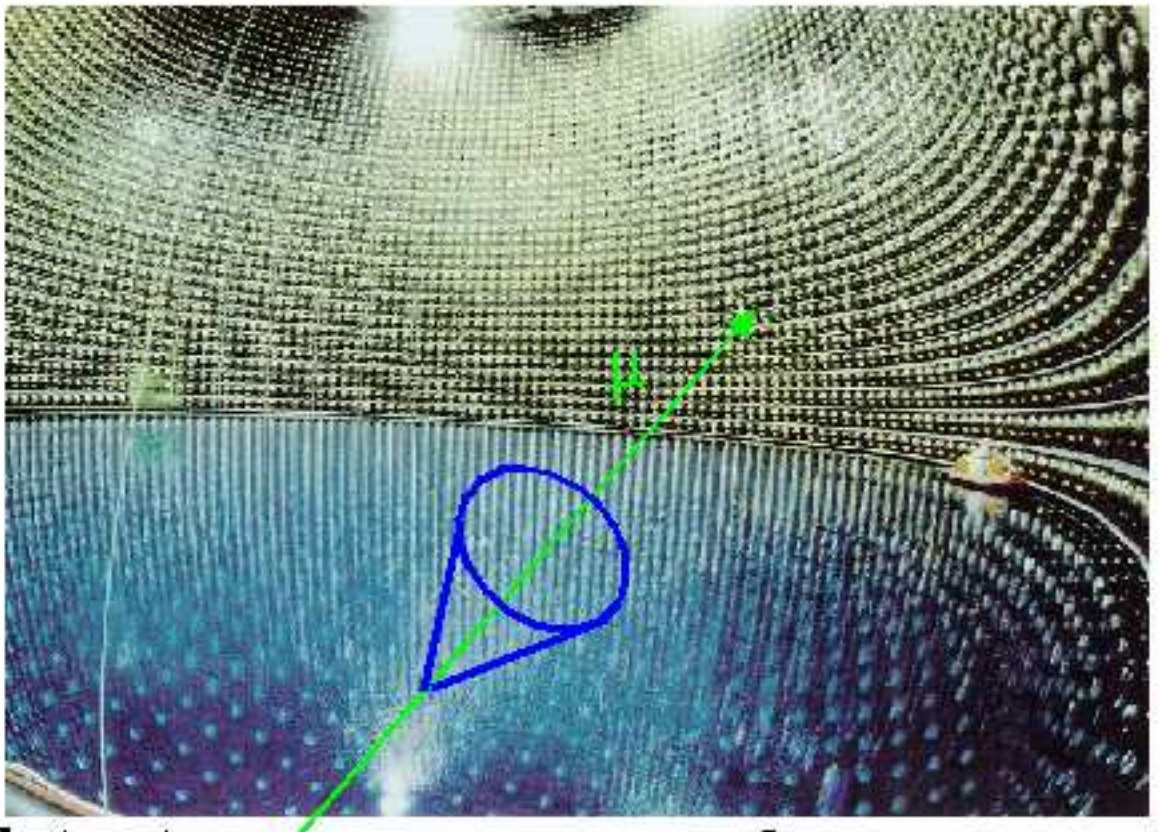
detect Cherenkov light

effective detection area

~ 1600 m^2 isotropic

7 m track =>

threshold ~ 1.5 GeV



c. c. reaction near (~ km) detector

μ keeps parent ν direction :

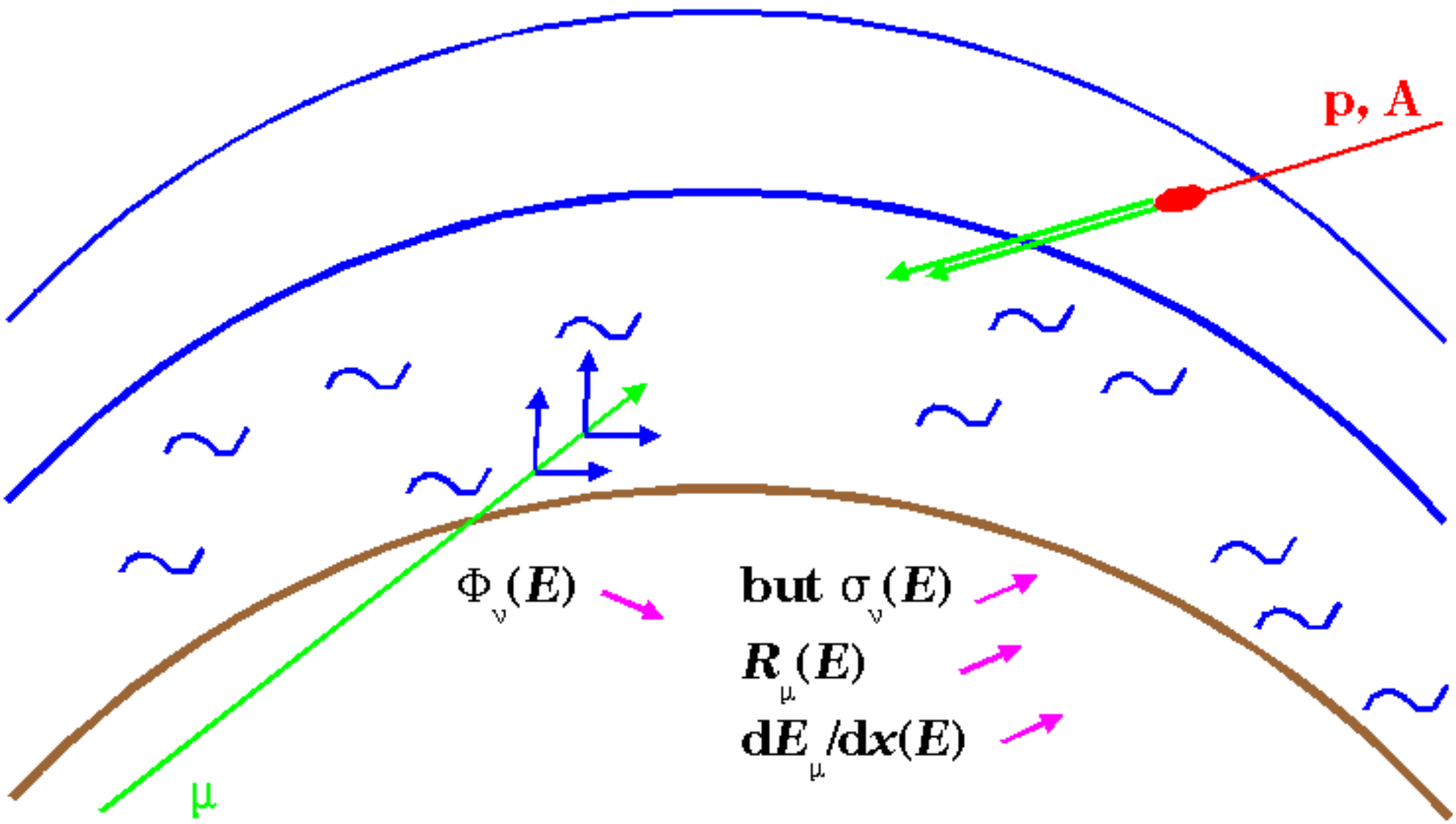
$$\vartheta_{\mu\nu} \approx \frac{0.7^\circ}{\sqrt{E_\nu / 1\,\mathrm{TeV}}}$$

$$E_\mu \approx E_\nu / 3 \approx M_\chi / 10$$

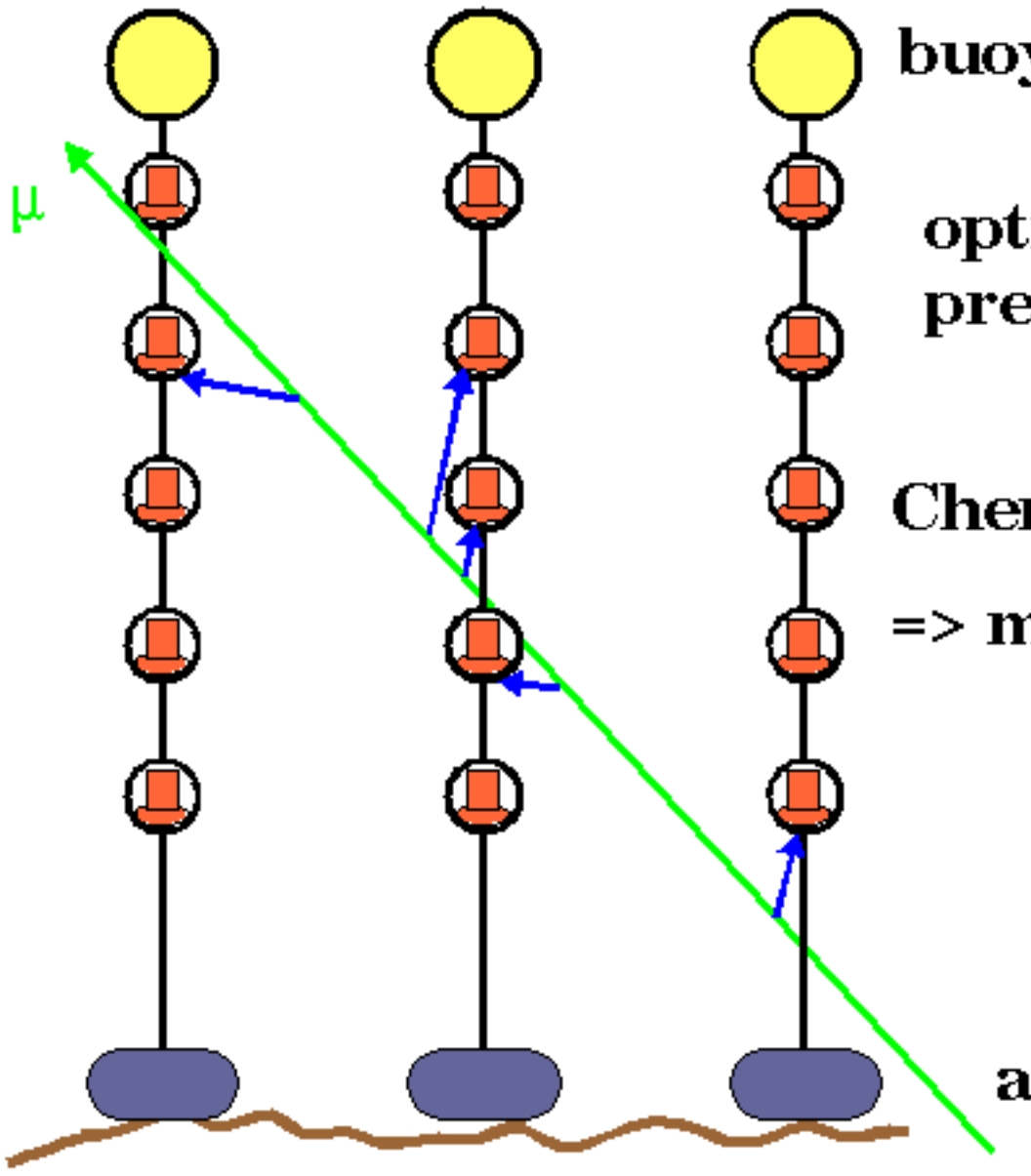
Markov's idea

not easy to go beyond Super-K : cost, water transparency

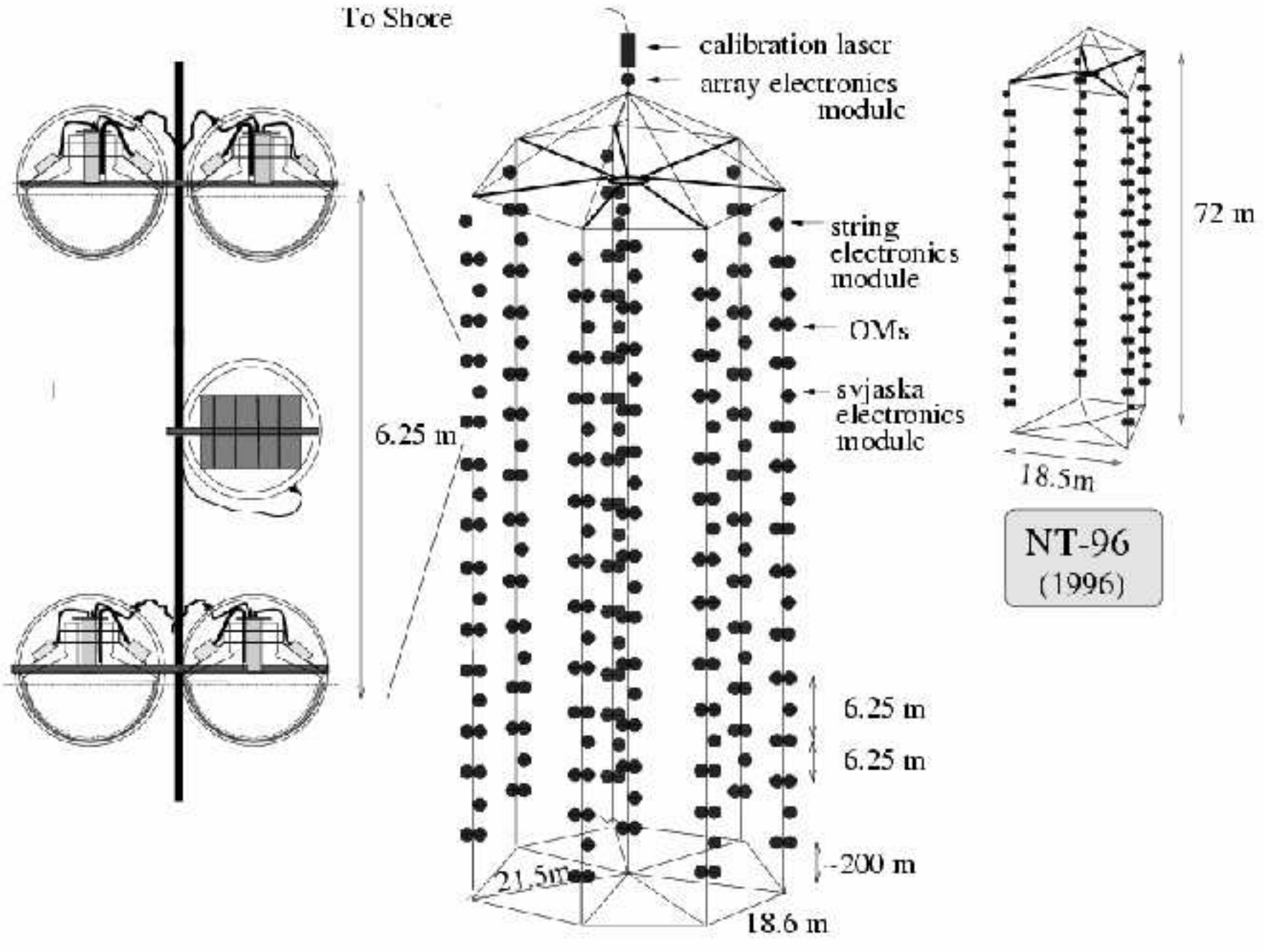
=> use deep sea water : free, clean, provides shielding



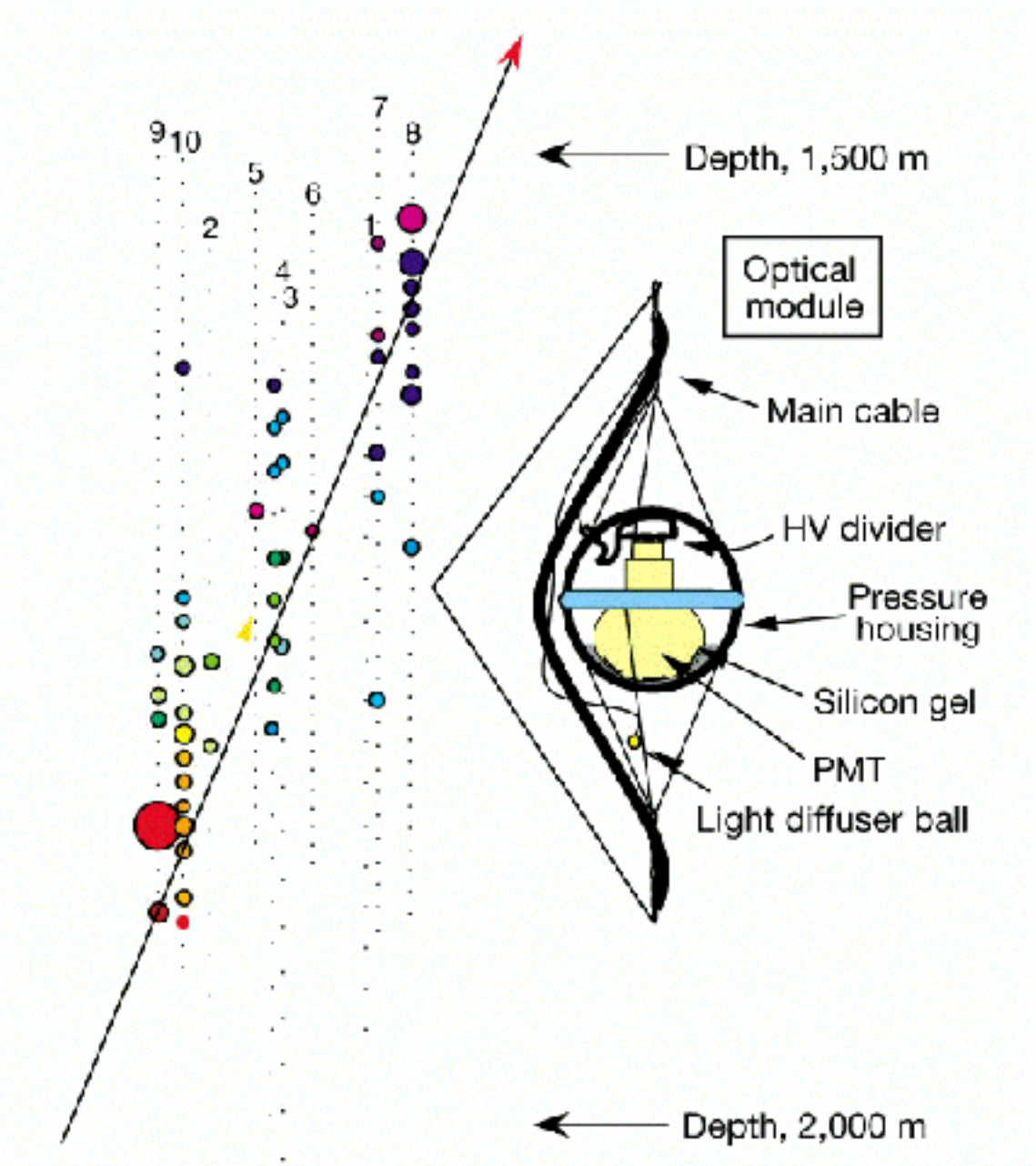
Detection principle

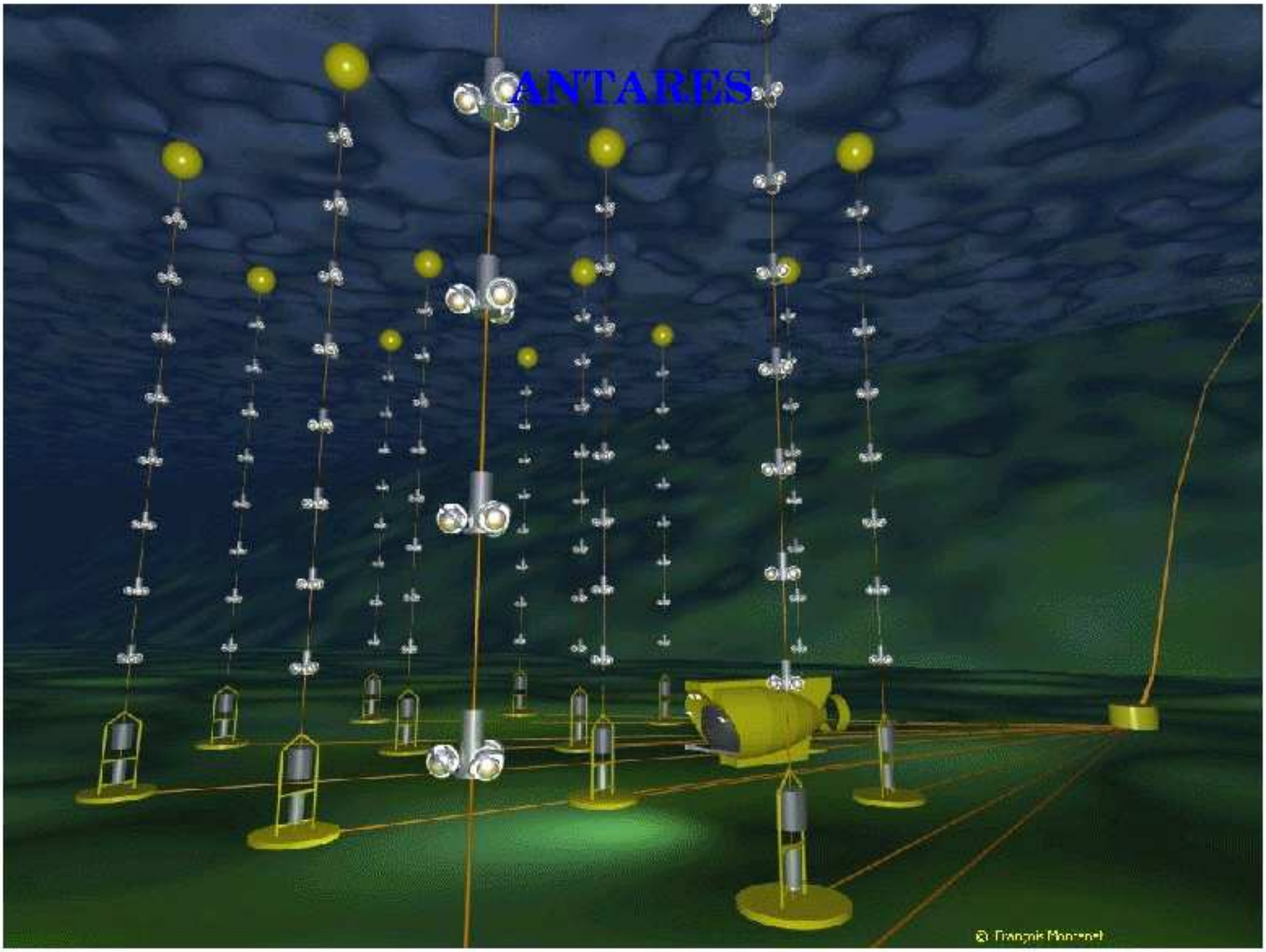


Baikal

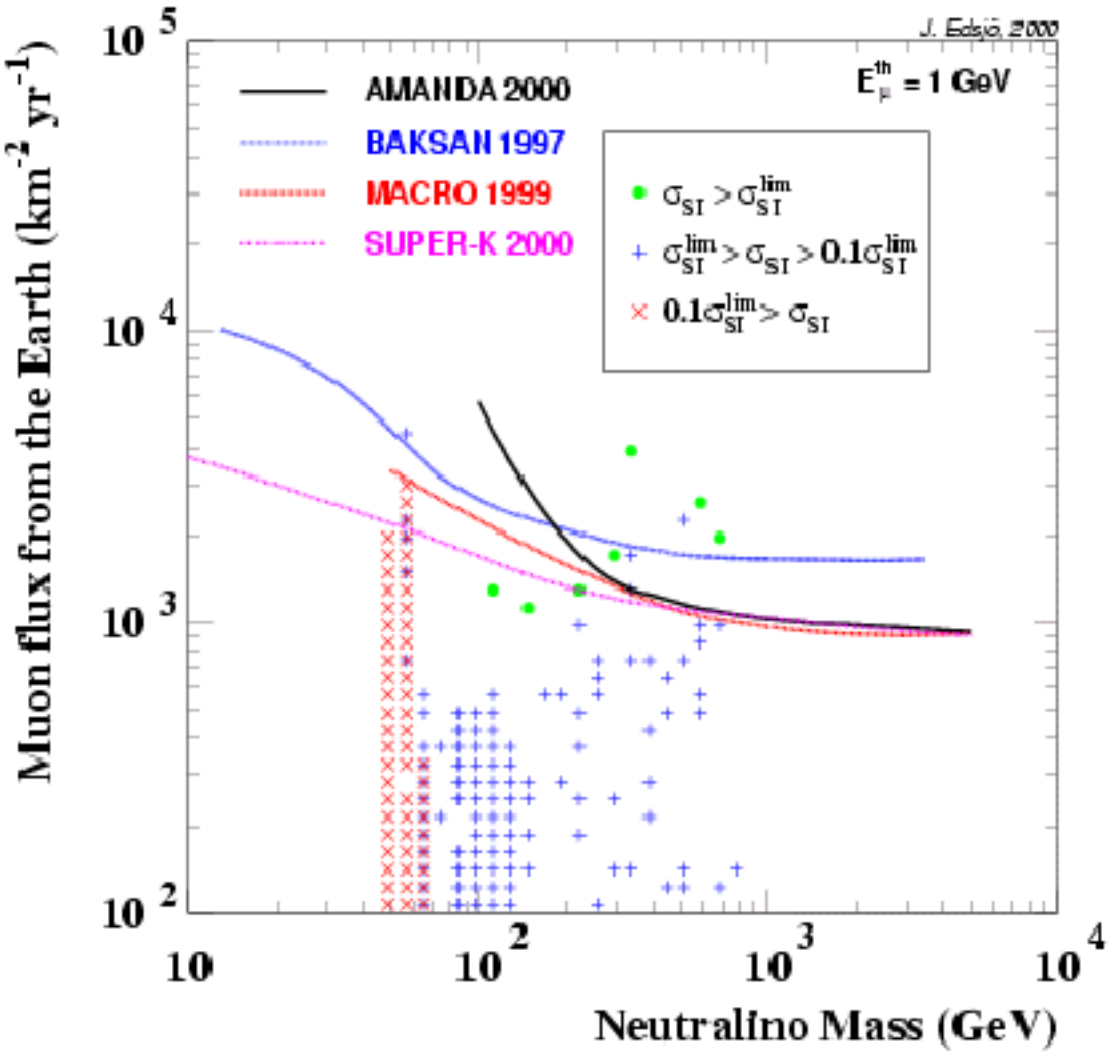

To Shore
calibration laser
array electronics module
string electronics module
OMs
svjaska electronics module
6.25 m
6.25 m
6.25 m
~200 m
21.5m
18.6 m
72 m
18.5m
NT-96
(1996)

AMANDA

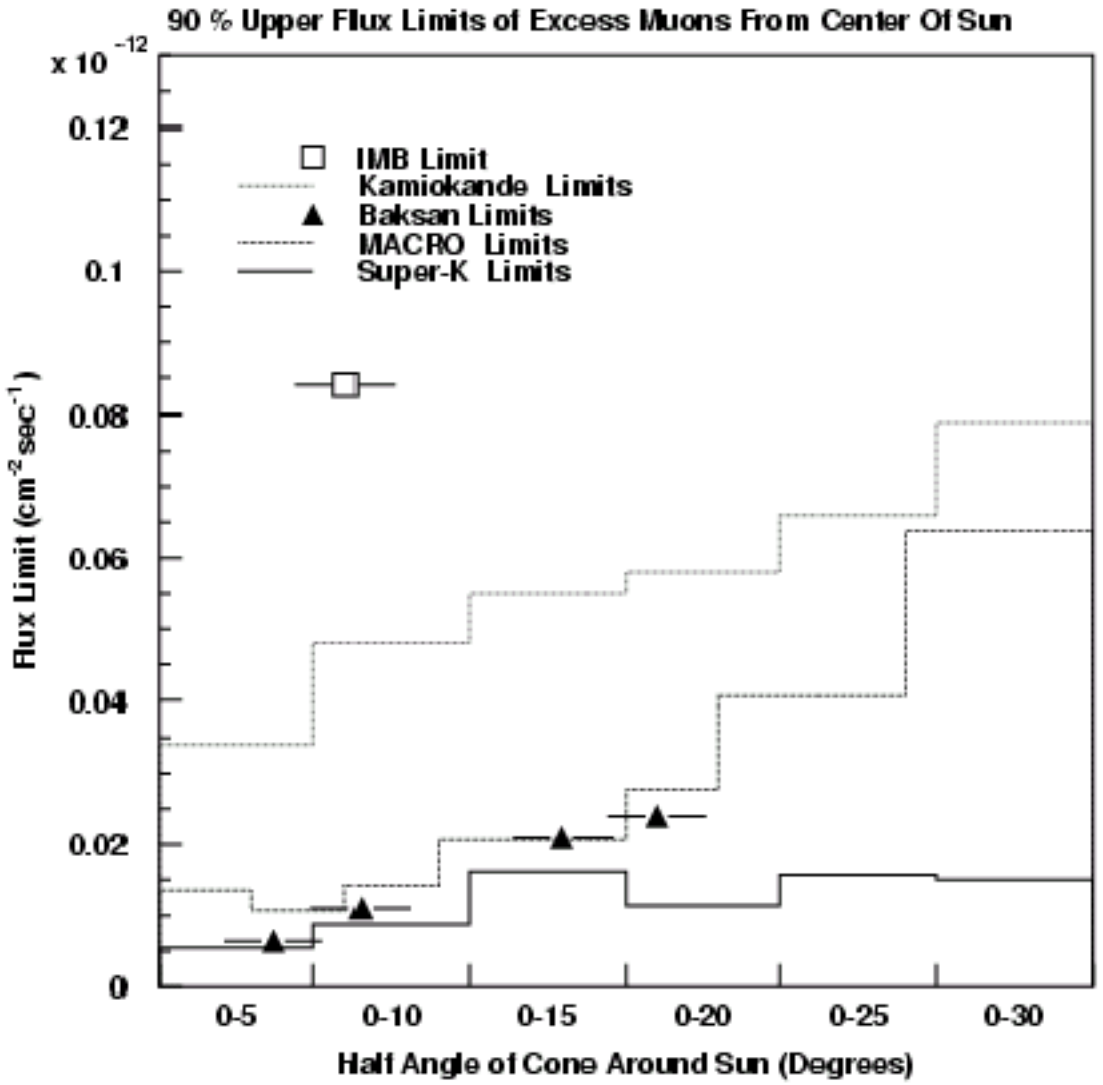

9
10
5
6
7
8
2
1
4
3
Depth, 1,500 m
Optical module
Main cable
HV divider
Pressure housing
Silicon gel
PMT
Light diffuser ball
Depth, 2,000 m


ANTARES
© François Montmerle

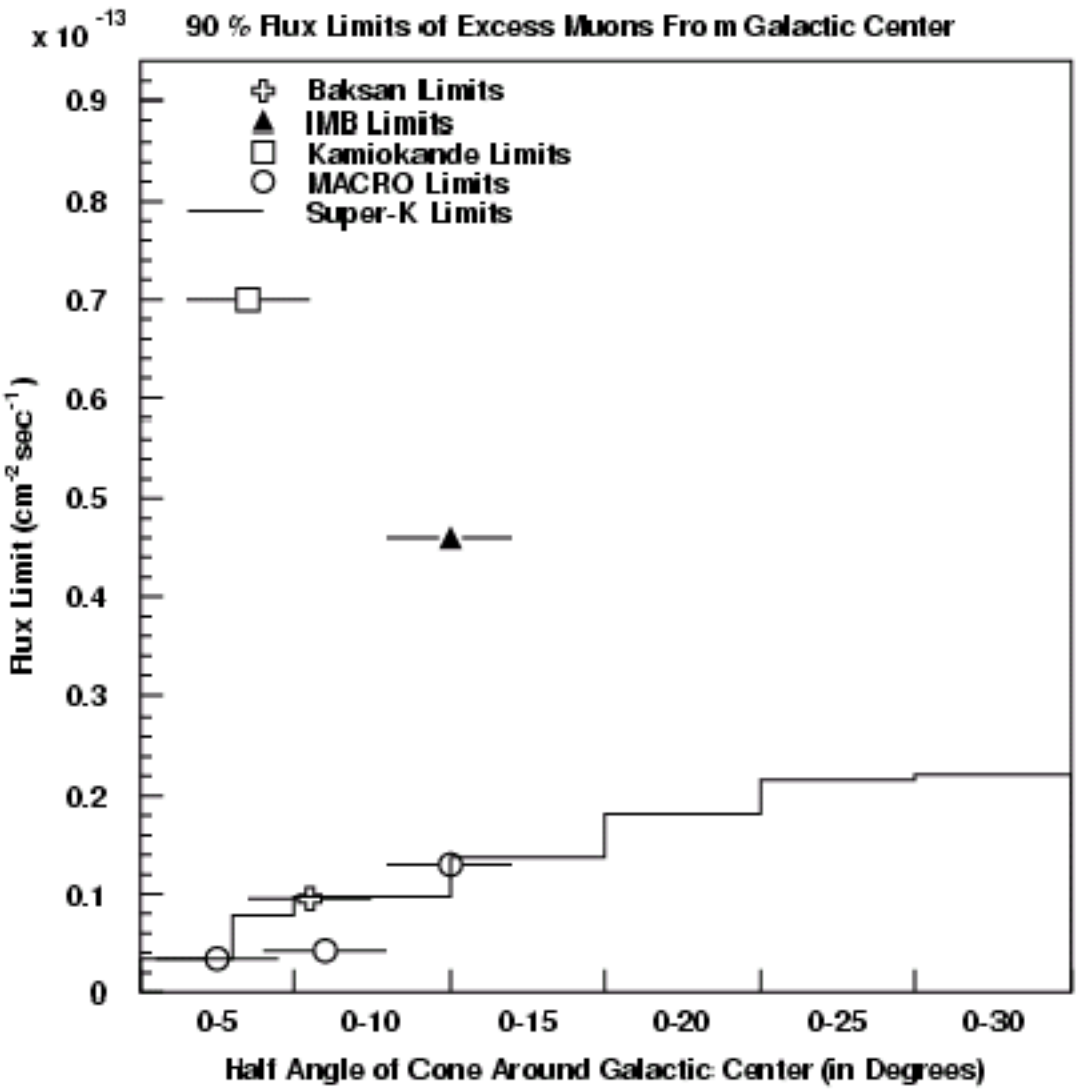
Centre of the Earth



Centre of the Sun



Centre of Galaxy



Outlook and conclusion

direct detection : combine ion. + phonons or scint. + phonons

DAMA region starts to be probed by others => excluded ?

next expts -> SUSY-allowed region : $\sigma_{\chi n} < 10^{-6}$ pb, $M_\chi > 40$ GeV

indirect detection : complementary for $M_\chi > 100$ GeV

underwater/ice ν telescopes : ~ 10 000 m^2 @ 100 GeV

next generation : Icecube, km^3 in water : ~ 100 000 m^2

$\chi\chi \rightarrow \gamma\gamma$ => γ line at $E_\gamma = M_\chi$ coming from galactic centre

look for it with HESS, VERITAS, GLAST