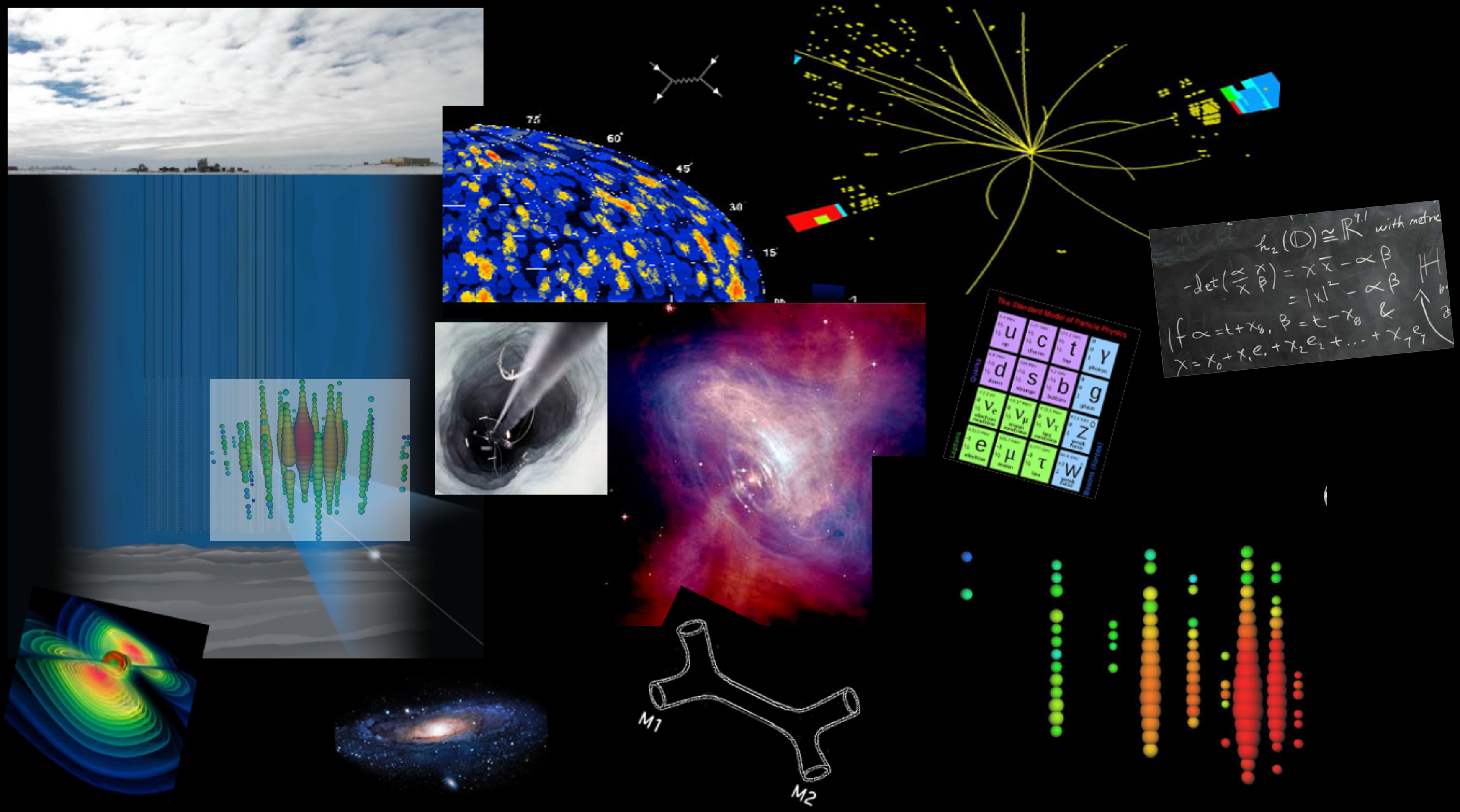
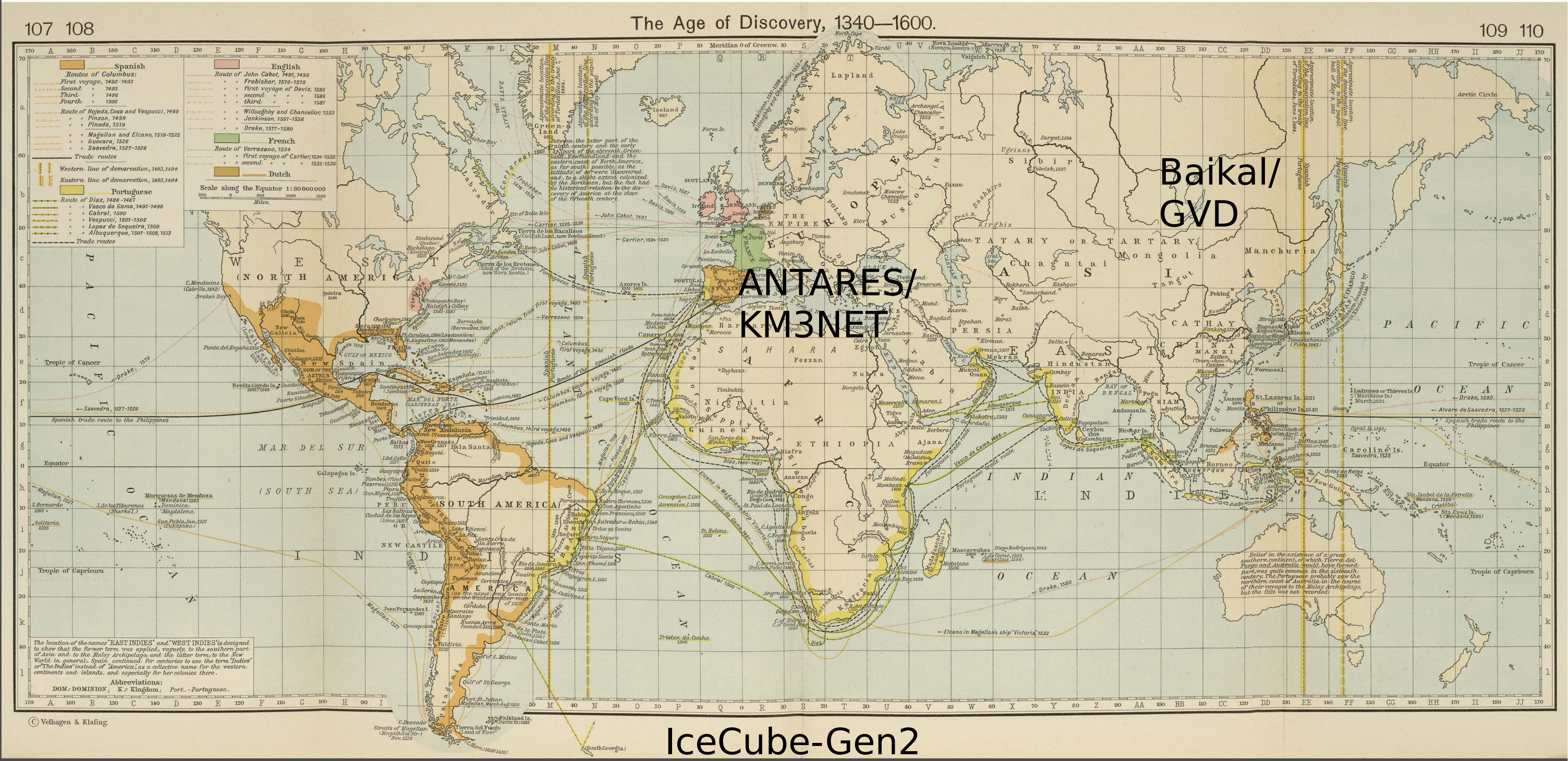
Particle Physics with Neutrino Telescopes



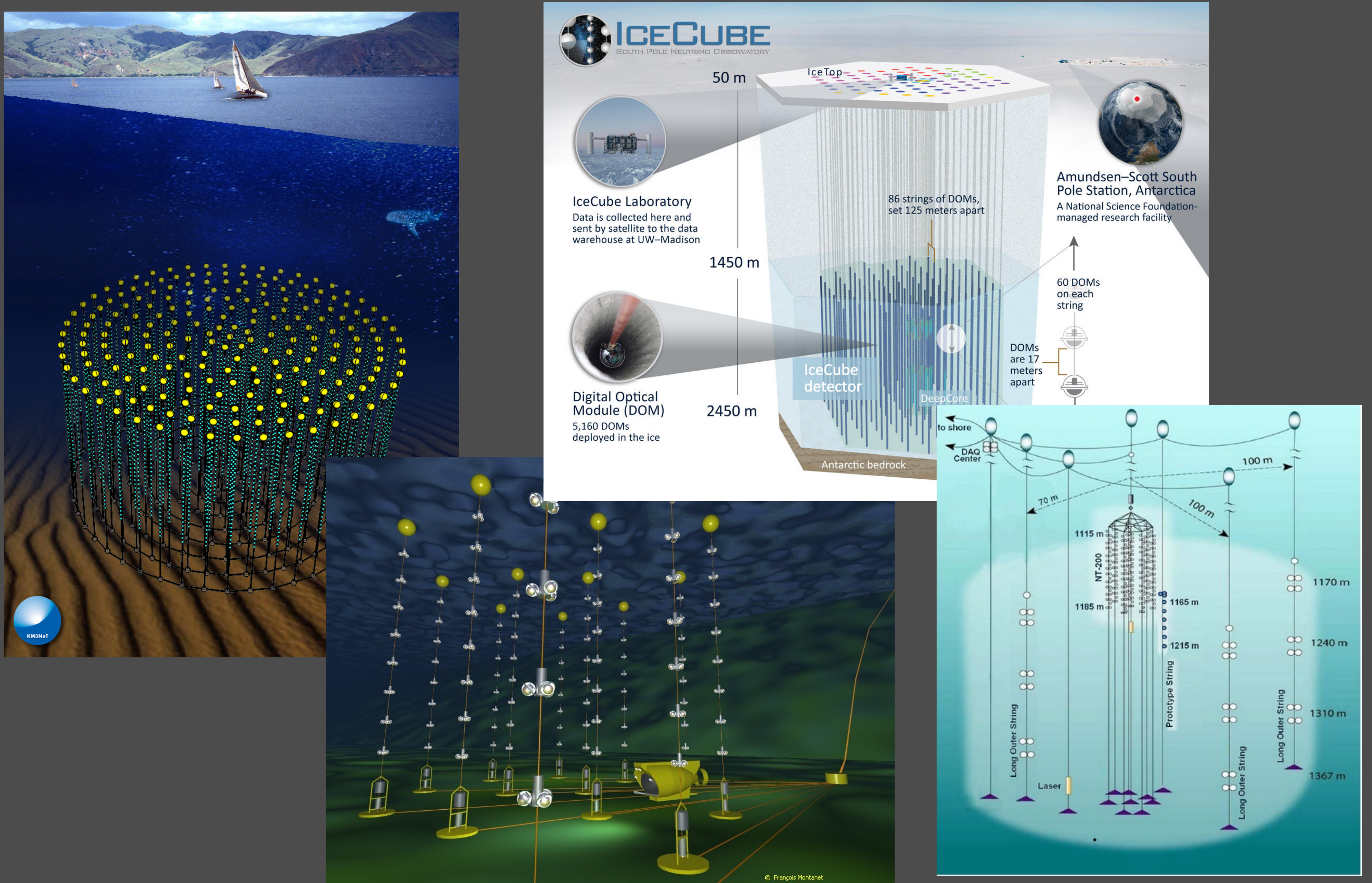
Carlos de los Heros, Uppsala University

Workshop on Perspectives in Astroparticle Physics from High Energy Neutrinos
Naples, September 25-26, 2017.

high-energy neutrino telescopes

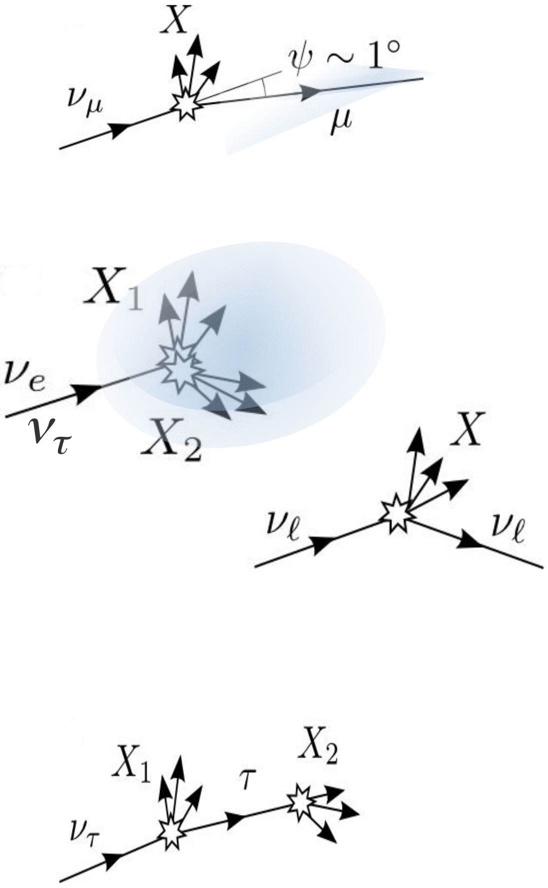


high-energy neutrino telescopes



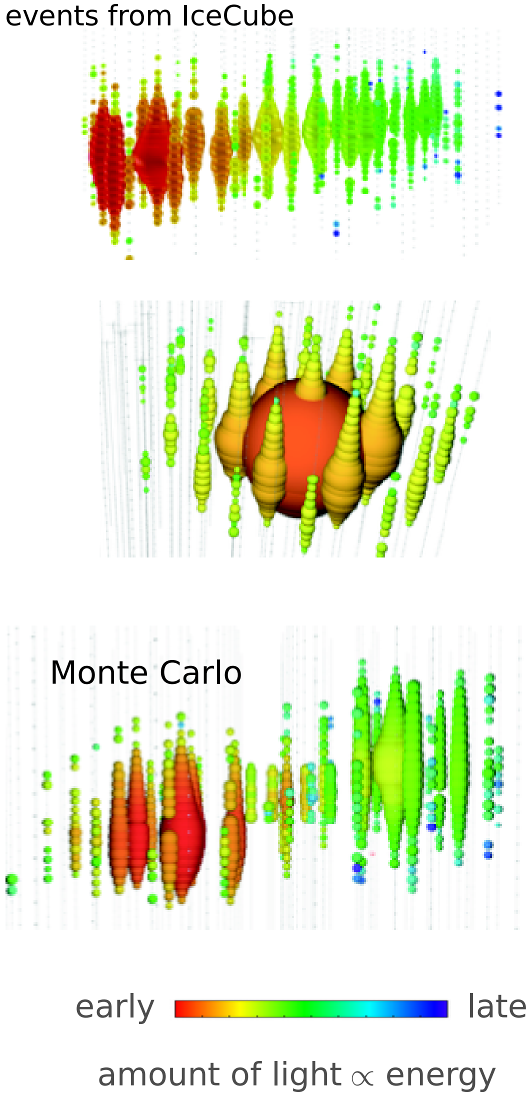
neutrino detection principle

Detect Cherenkov light of interaction products

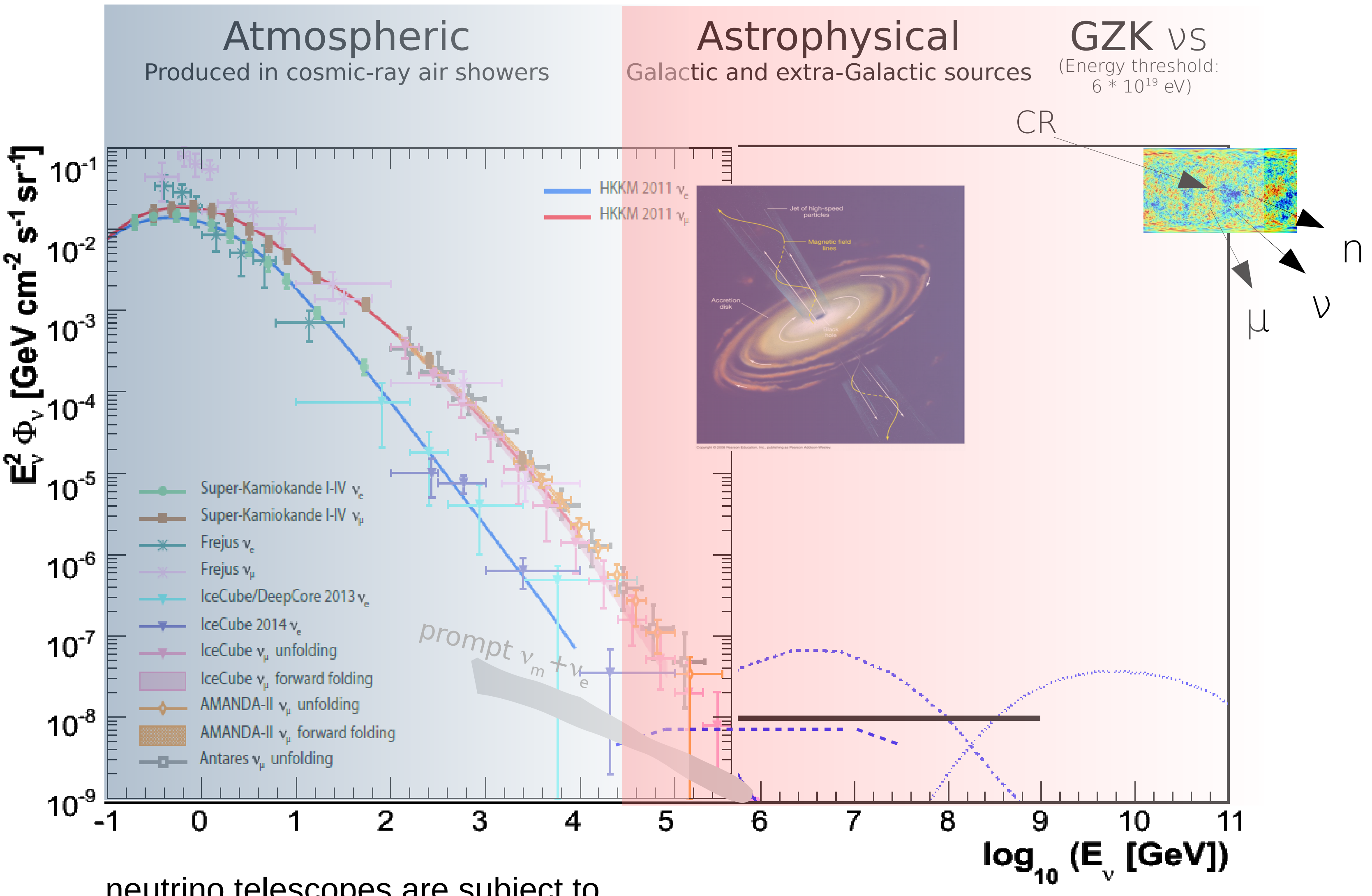


array of optical modules in a transparent medium

signature in the detector



neutrino beams in neutrino telescopes

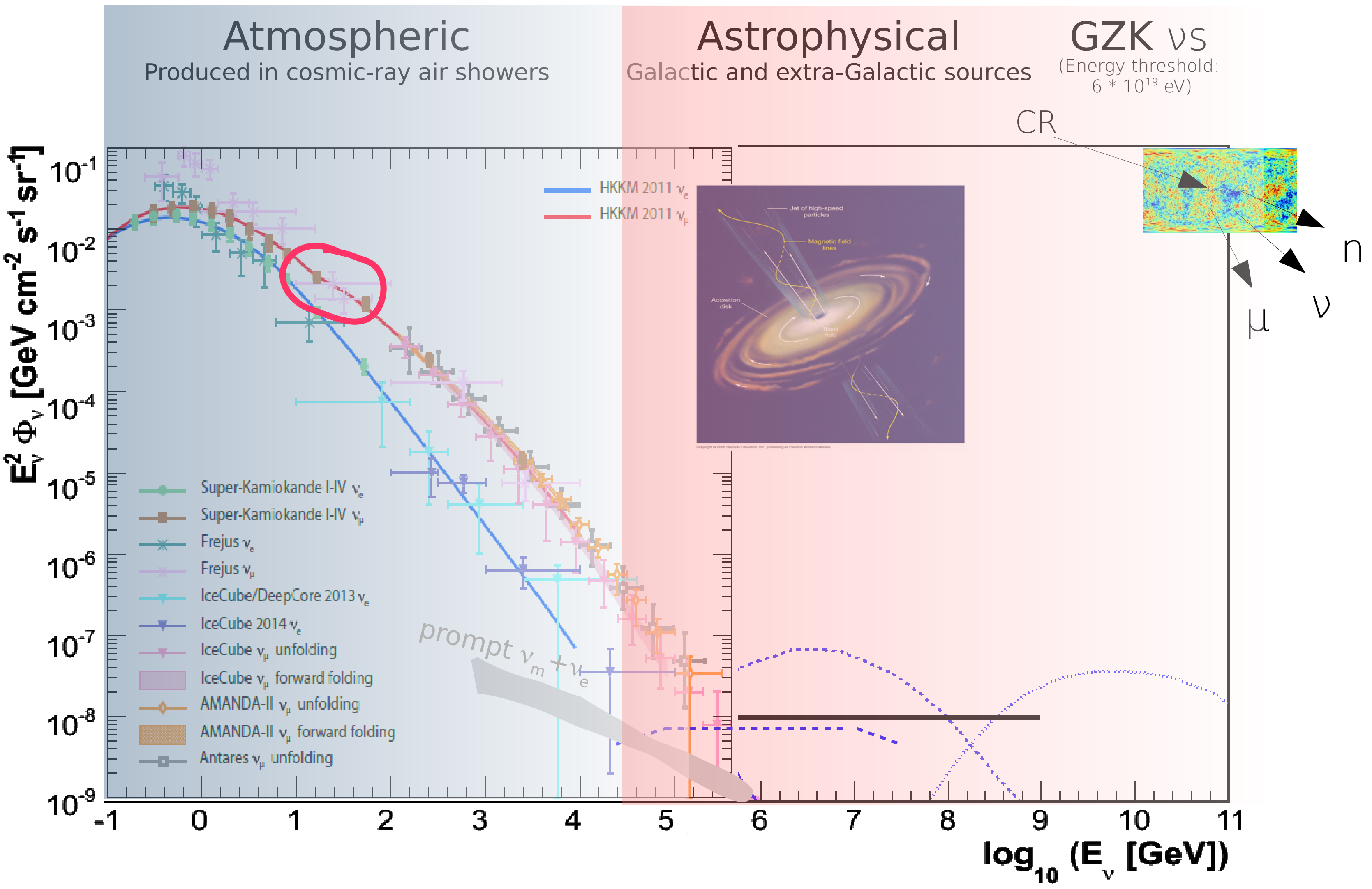


neutrino telescopes are subject to
a high statistics (~100.000 /y km³),
high-energy neutrino beam from
the atmosphere

plus...

an even higher-energy
astrophysical flux (~100 /y km³)

neutrino beams in neutrino telescopes



Atmospheric
Produced in cosmic-ray air showers

Astrophysical
Galactic and extra-Galactic sources

GZK νs
(Energy threshold: 6 * 10^{19} eV)

Both IceCube and KM3NET have, or plan to have, low-E extensions (DeepCore, PINGU, ORCA) to cover as low ν energies as possible

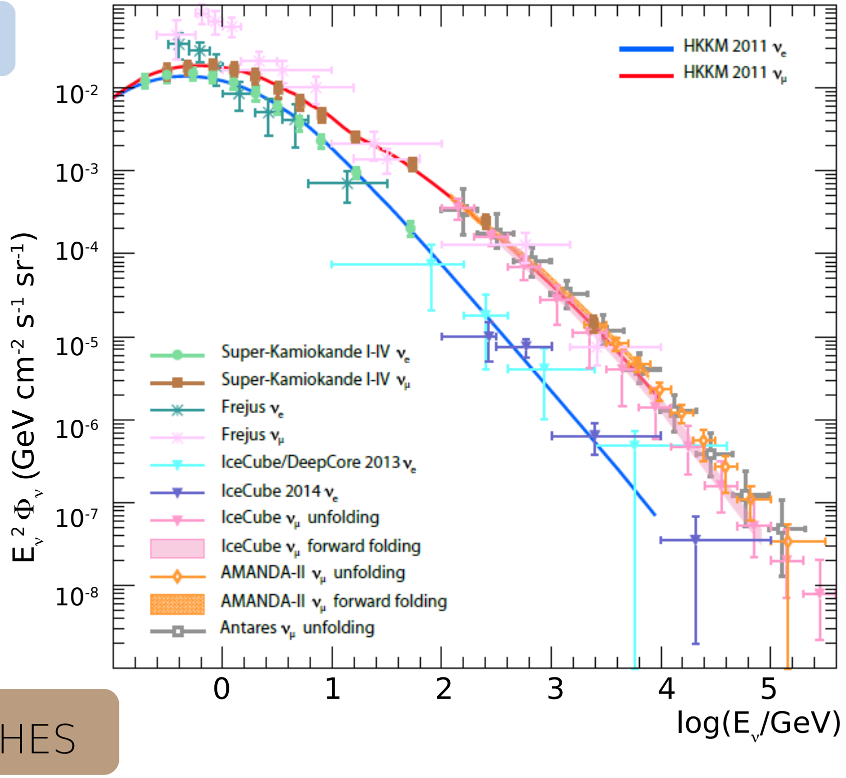
particle physics topics with neutrino telescopes

NEUTRINO CROSS SECTION

NEUTRINO OSCILLATIONS

TESTS OF FUNDAMENTAL LAWS

STERILE NEUTRINOS



TEV GRAVITY

NON-STANDARD
NEUTRINO INTERACTIONS

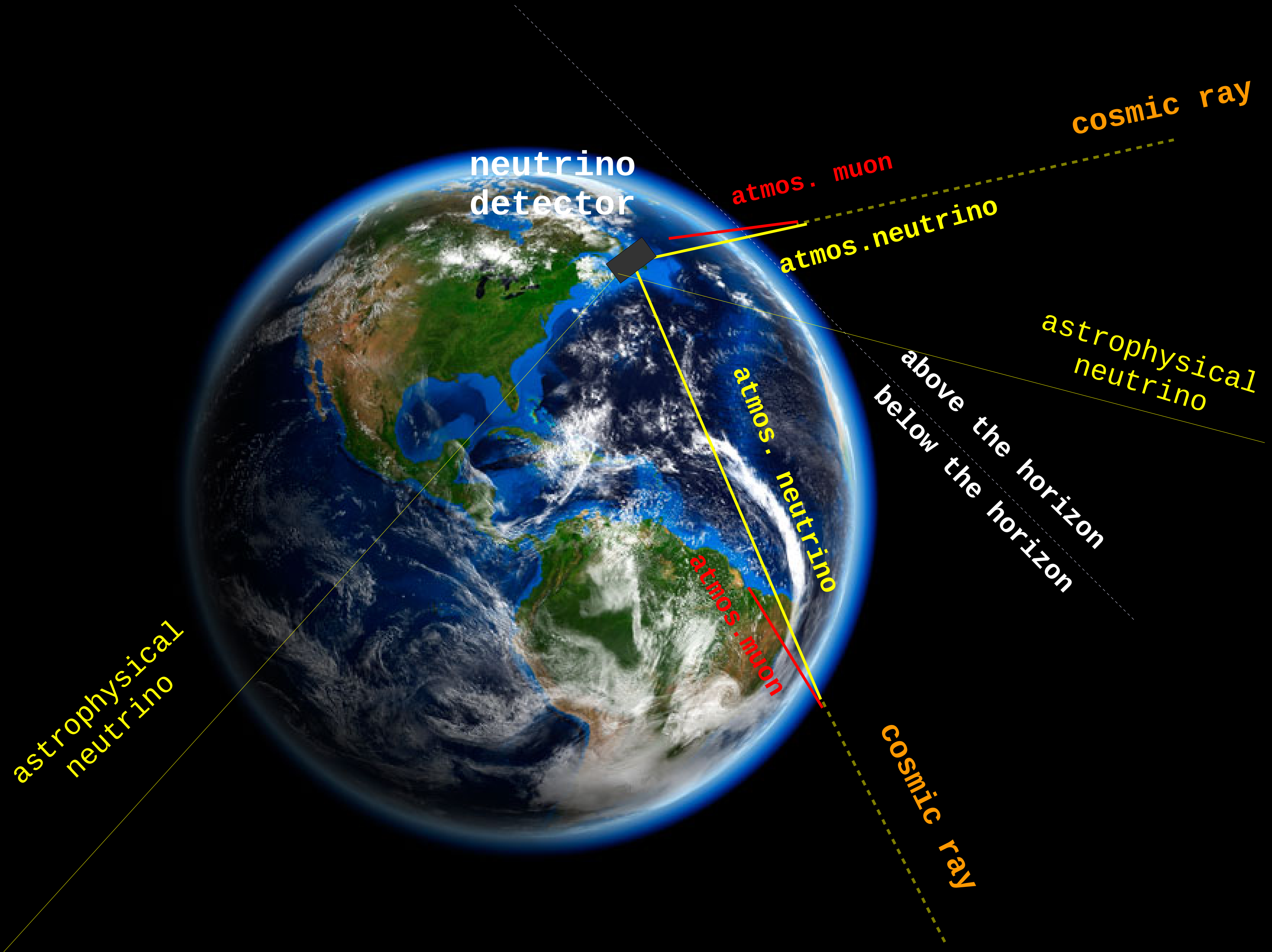
NEW PARTICLE SEARCHES

DARK MATTER

...

Check the contributions to the latest Workshop on Exotic Physics with Neutrino Telescopes for more ideas, indico.in2p3.fr/event/7381/

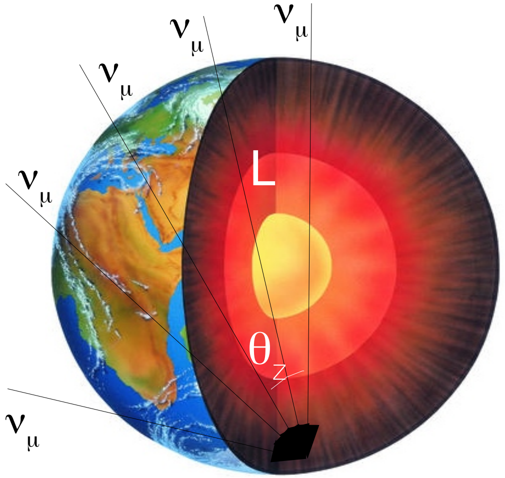
backgrounds: the new signal

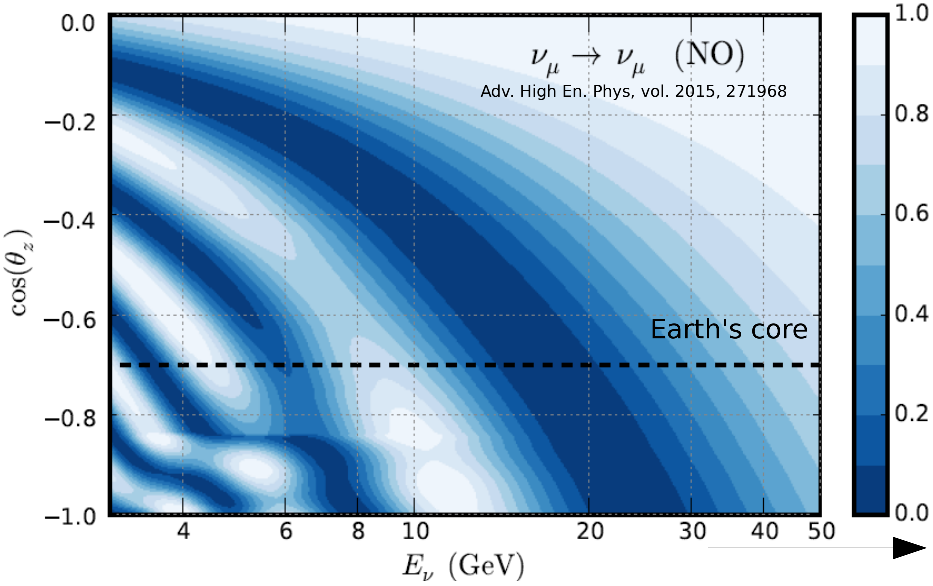


the atmospheric neutrino flux

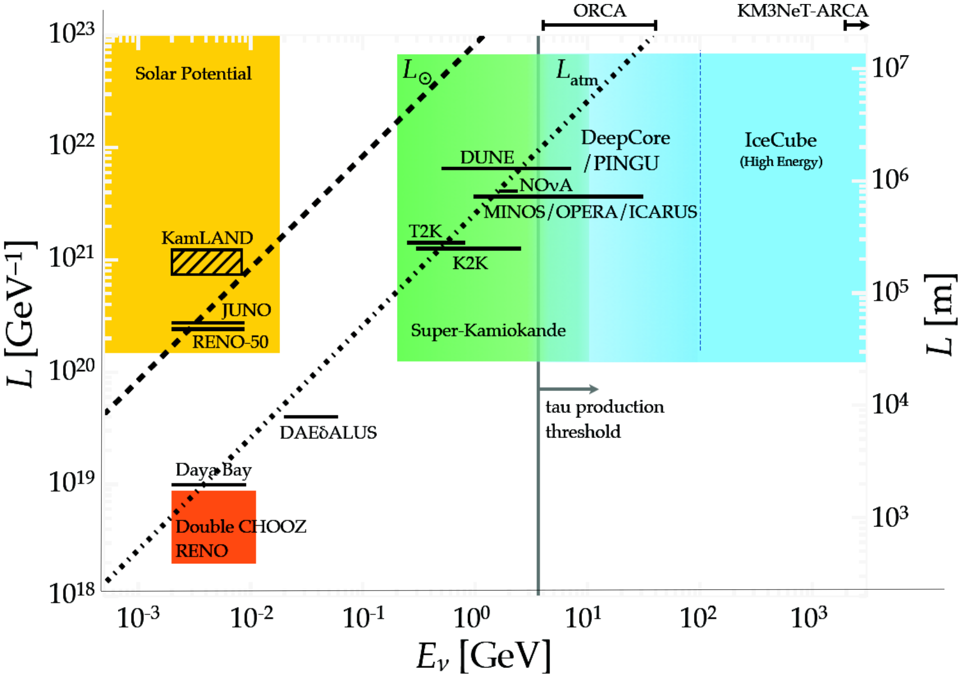
An enormous wealth of information can be obtained from the energy and pathlength of atmospheric neutrinos through the Earth to the detector

Neutrinos available over a wide range of baselines, with energies from a few GeV to ~100 TeV.

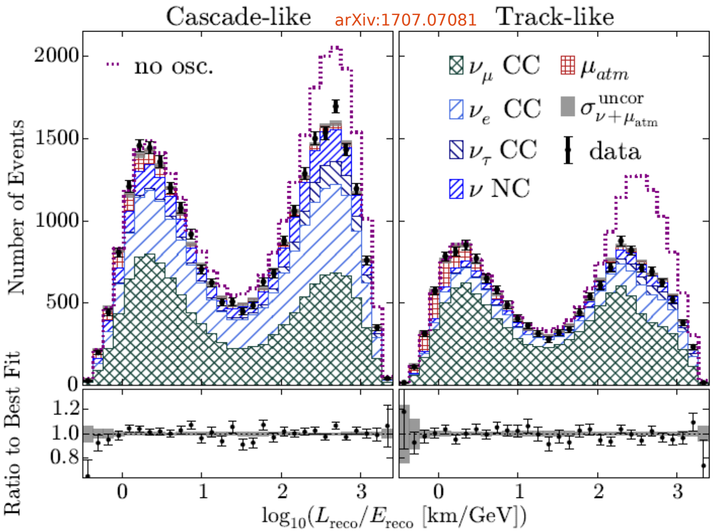


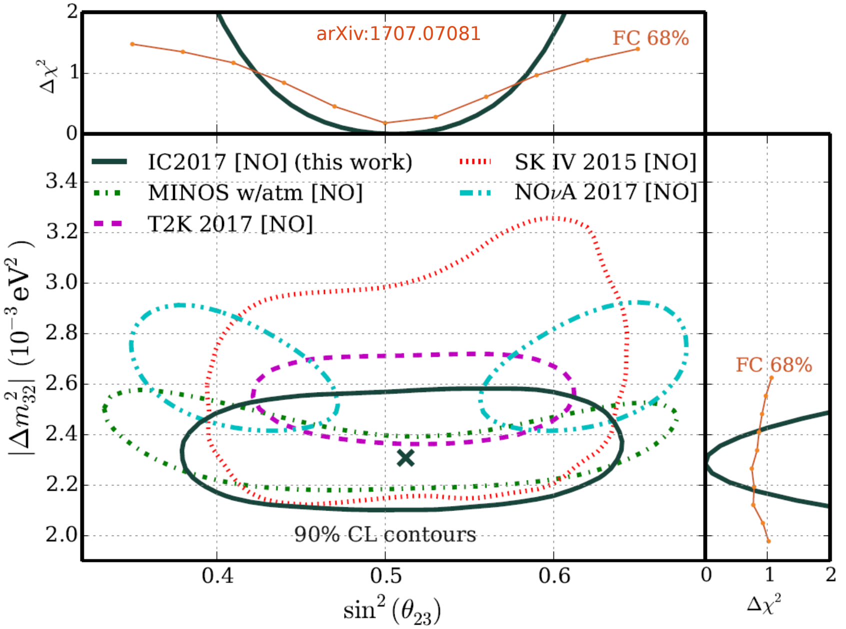


neutrino oscillations



NTs can cover L/E regions unaccessible to accelerators





Best fit: $\Delta m^2_{32} = 2.31^{+0.11}_{-0.13} \times 10^{-3}$ eV^2, $\sin^2\theta_{23} = 0.51^{+0.07}_{-0.09}$

sterile neutrinos

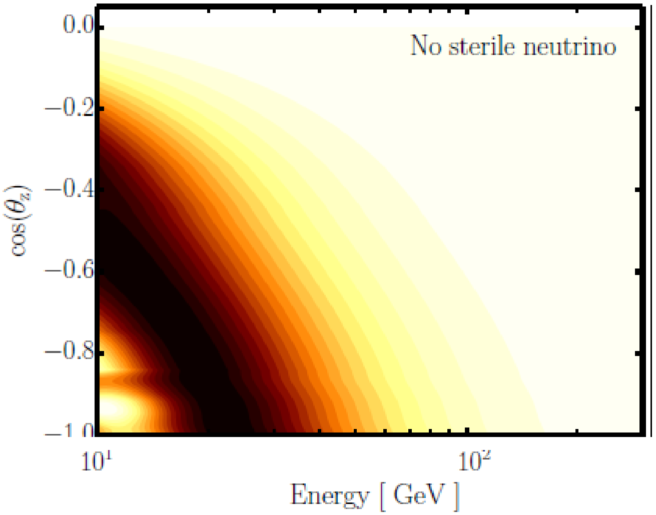
$$\nu_{\alpha L} = \sum_{k=1}^{3} U_{\alpha k} \nu_{kL} \quad (\alpha = e, \mu, \tau) \qquad\qquad \nu_{\alpha L} = \sum_{k=1}^{4} U_{\alpha k} \nu_{kL} \quad (\alpha = e, \mu, \tau, s)$$

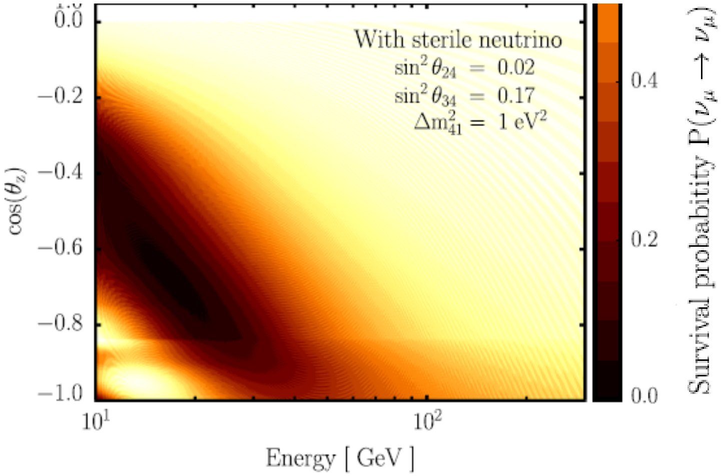
$$\downarrow \qquad\qquad\qquad\qquad \downarrow$$

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \xrightarrow{\text{3+1 sterile scenario}} \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

Minimal 3+1 scenario adds 6 parameters: Δm^2_{41}, θ_{14}, θ_{24}, θ_{34}, δ_{14} and δ_{34}

additional state to oscillate to → perturbation to standard oscillations

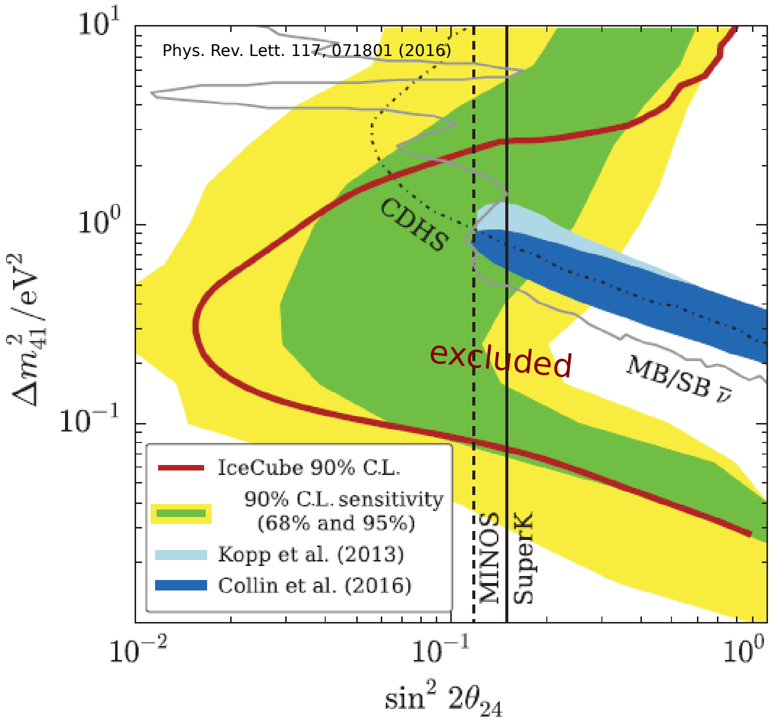




From solar, atmospheric and accelerator results: mixing with s must be small, $|U_{\alpha 4}| \ll 1$

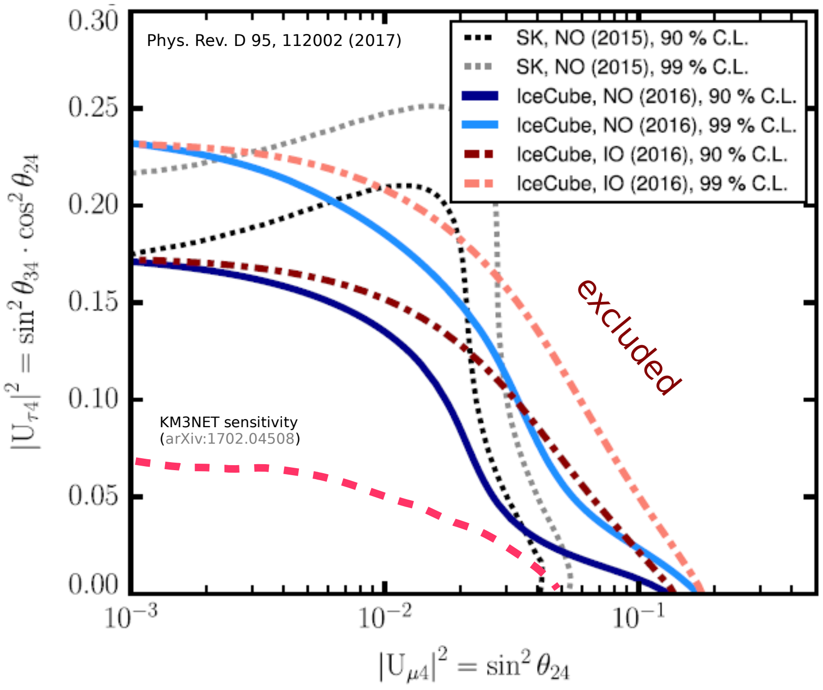
sterile neutrinos

NTs sensitive to disappearance effects in atmospheric neutrinos, ie, mainly to Δm^2_{41} and $\sin 2\theta_{24}$



Phys. Rev. Lett. 117, 071801 (2016)

$E_\nu \gtrsim 300$ GeV



Phys. Rev. D 95, 112002 (2017)

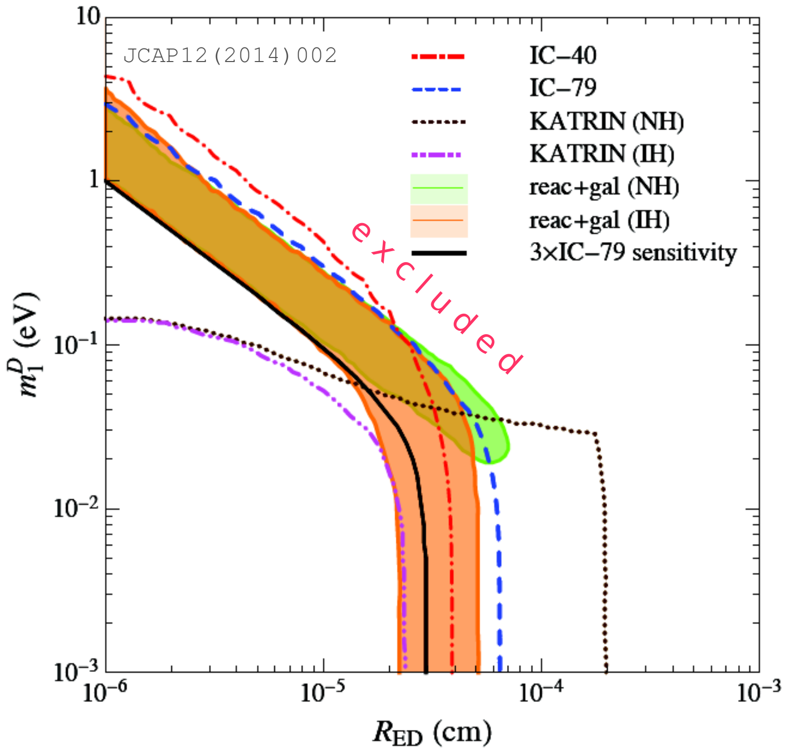
KM3NET sensitivity (arXiv:1702.04508)

$E_\nu \lesssim 60$ GeV

So far, results consistent with the standard three-neutrino hypothesis

sterile neutrinos in large extra dimensions (LED)

- LED ⇒ “sterile” neutrinos living in the extra dimensions (KK-tower)
- mixing with of KK modes with active neutrinos distorts standard oscillation pattern
- R_D and m_1 (lowest KK mode) can be constrained from oscillation analyses

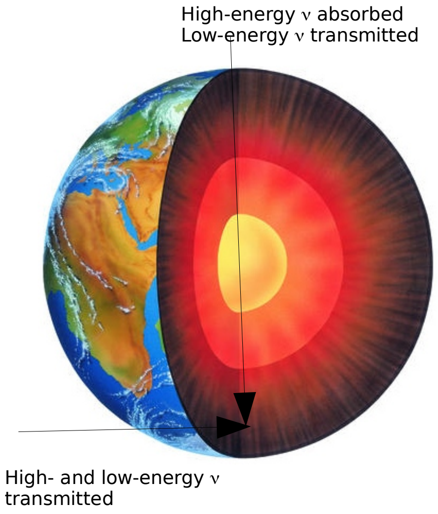


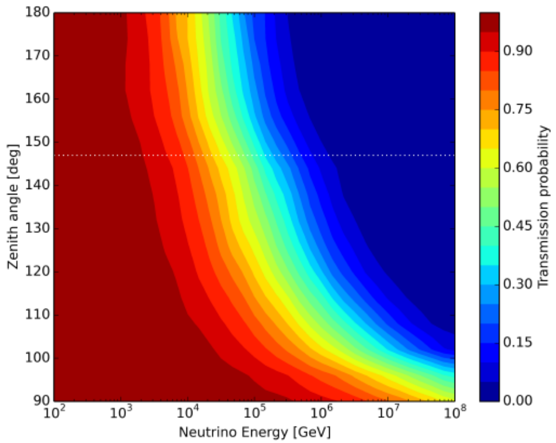
neutrino cross section

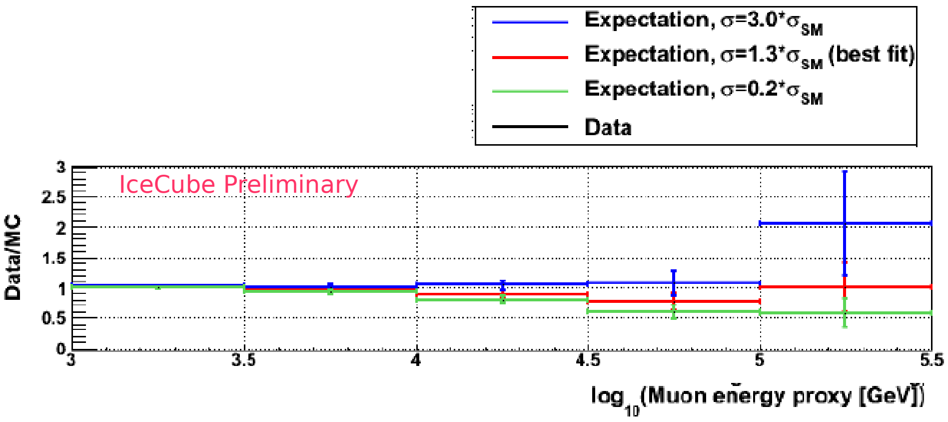
- Neutrino Xsection only measured below ~300 GeV
- Neutrino telescopes exposed to copious neutrino flux above TeV
- Look for deviations of expected flux due to anomalous neutrino interactions in matter

IceCube search:

fit ν_μ angle and energy distribution with $\sigma_{\nu\mu}$ as free parameter.

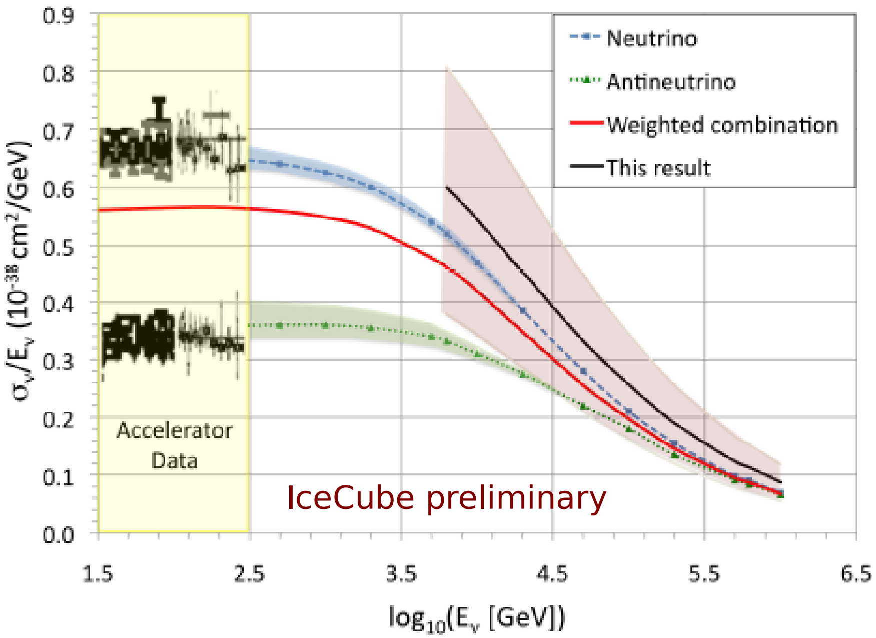






No deviation from SM found

$\sigma_{\nu\mu} = 1.3^{+0.21}_{-0.19}\ \text{(stat)}\ ^{+0.39}_{-0.43}\ \text{(sys)} \times \sigma_{\nu\mu}^{SM}$



non-standard neutrino interactions (NSI)

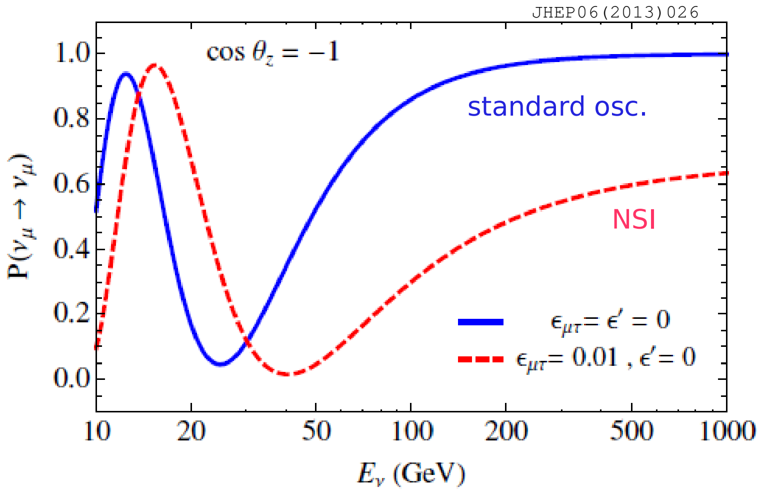
- Additional disappearance effect to MSW
- Mediated by non-SM bosons.

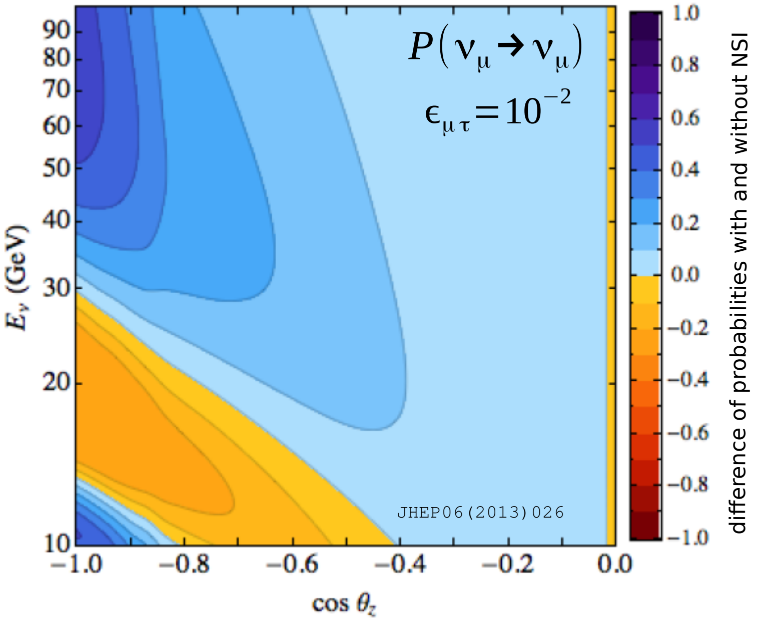
$$H_{\alpha\beta} = \frac{1}{2E} U_{\alpha j} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} (U^\dagger)_{k\beta} + V_{\text{MSW}} + \sqrt{2} G_F N_f \begin{pmatrix} \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau} & \varepsilon_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}$$

standard MSW NSI

→ 9 additional “interaction terms”
(6, if requirements of hermicity and unitarity are imposed)

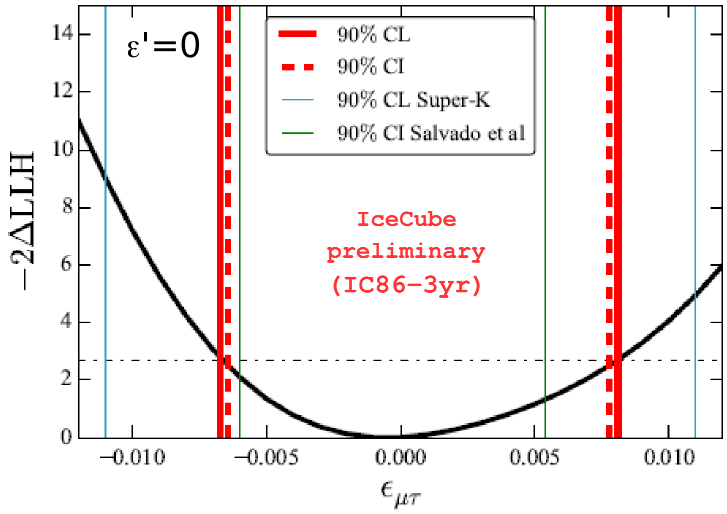
- Modify the rate of neutrinos detected at different energies and angles
- Effect proportional to LxE
- Shows in complementary range of parameter space wrt standard oscillations

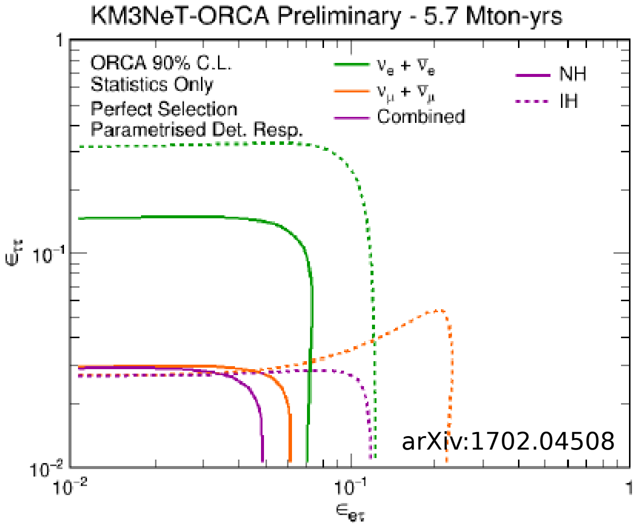




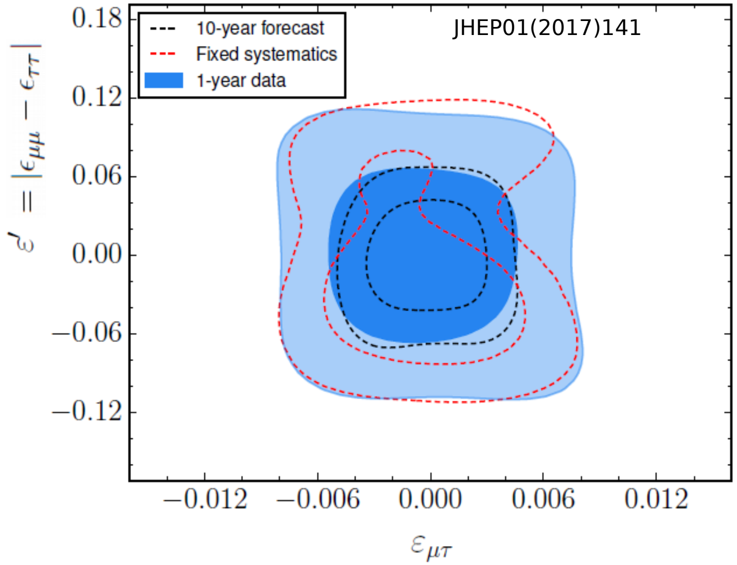
non-standard neutrino interactions (NSI)

So far, results from IceCube and SK compatible with no NSI (see also MINOS results, Phys. Rev. D 88, 072011 (2013))

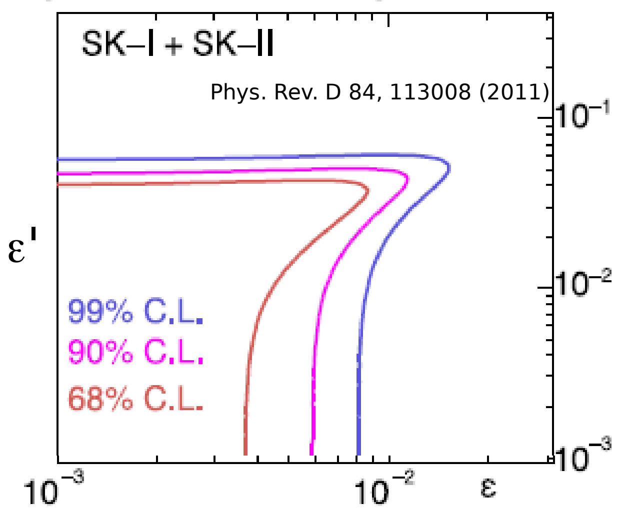




arXiv:1702.04508



JHEP01(2017)141



Phys. Rev. D 84, 113008 (2011)

search for heavy neutrino states...

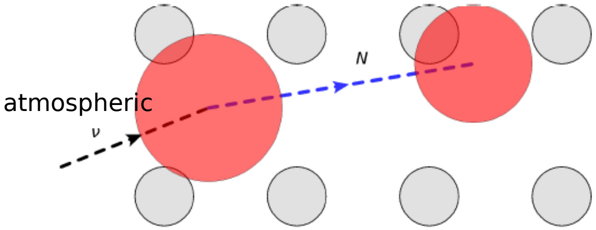
- Low-energy “Double-bang” events from heavy neutrino production and decay, without intermediate track

$$\nu_{\alpha L} = \sum_{i=1}^{3} U_{\alpha i}\nu_{iL} + \boxed{U_{\alpha 4} N^c_{4R}}$$

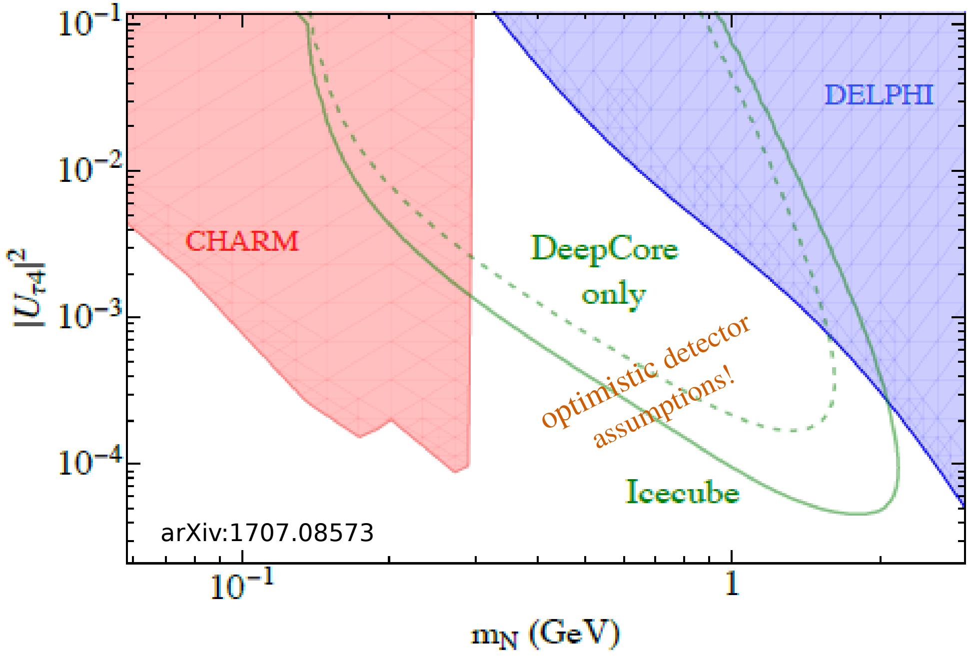
additional mixing matrix components that can be probed

- $|U_{\tau 4}|^2$ up to ~10^{-2} still allowed for a window of masses

- $m_N \geq 1$ GeV → $L_{detector} \geq 20$ m



$$\sigma_{\nu_\tau N} \simeq \sigma_\nu^{NC} \times |U_{\tau 4}|^2$$



arXiv:1707.08573

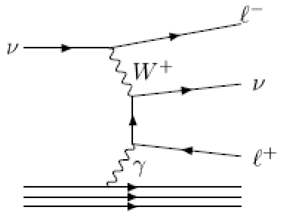
…or search for heavy neutral mediators

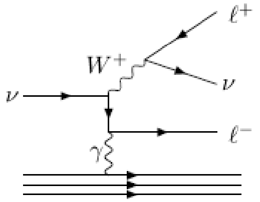
- Simultaneous double μ tracks from ν-N interactions with new vector (Z') or scalar (S') mediators,

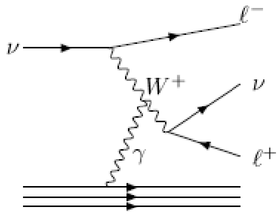
- Wide range of allowed Z'/S' mass: ~MeV to TeV and couplings.

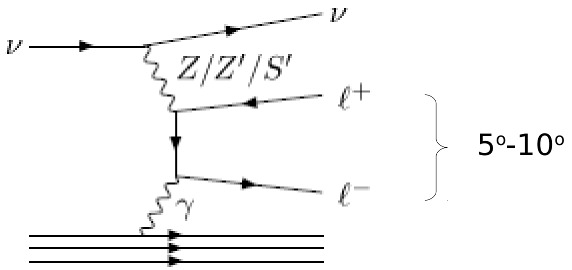
- Parameter space of the new mediator can be constrained

- SM background: ~ 0.5 evt/yr in a km3 detector

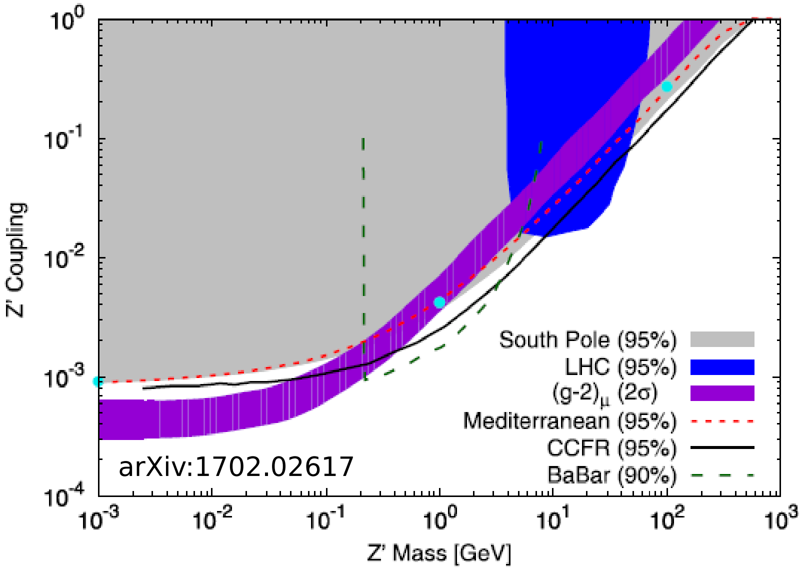








$$\overset{(-)}{\nu_\ell}\, N \rightarrow \overset{(-)}{\nu_\ell}\, \ell^+\ell^- X$$



arXiv:1702.02617

Lorenz invariance violation

violation of Lorentz invariance

- Leads to modified dispersion relation:

$$E_a^2 = p_a^2 c_a^2 + m_a^2 c_a^2$$

- Different maximum attainable velocities c_a for different flavour states: $\Delta E \sim (\delta c/c)E$
- “oscillation” effect $\propto$ L×E instead of L/E

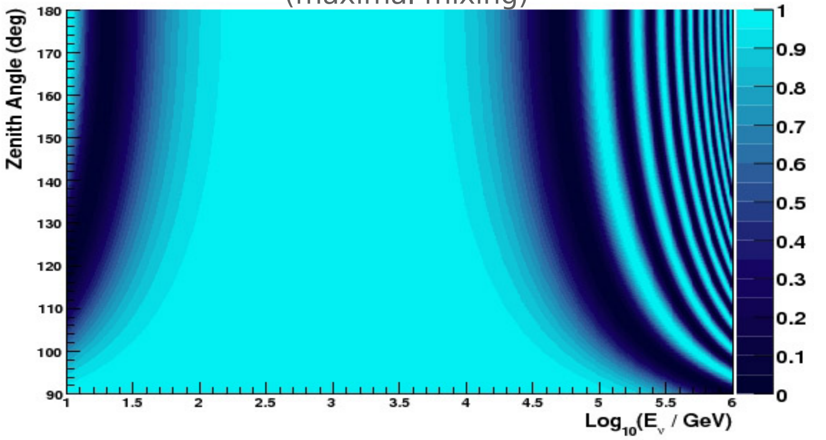
quantum decoherence

- Signature of quantum gravity
- Heuristic picture: foamy structure of space-time. Pure states interact with environment

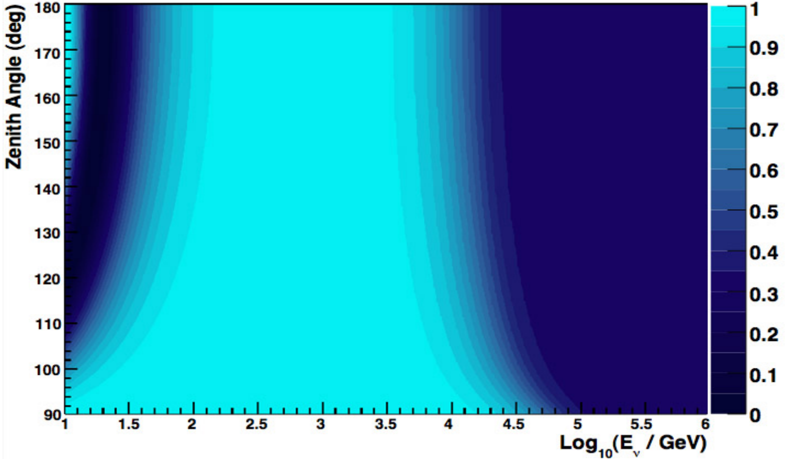
$$E_a^2 = p_a^2 + m_a^2 + f_a(p, E)$$

- “oscillation” effect $\propto E^n$ (n=1,2,3...)

VLI Atmospheric ν_μ Survival Probability (maximal mixing)



QD Atmospheric ν_μ Survival Probability (n=1)



could have consequences for timing in multimessenger searches

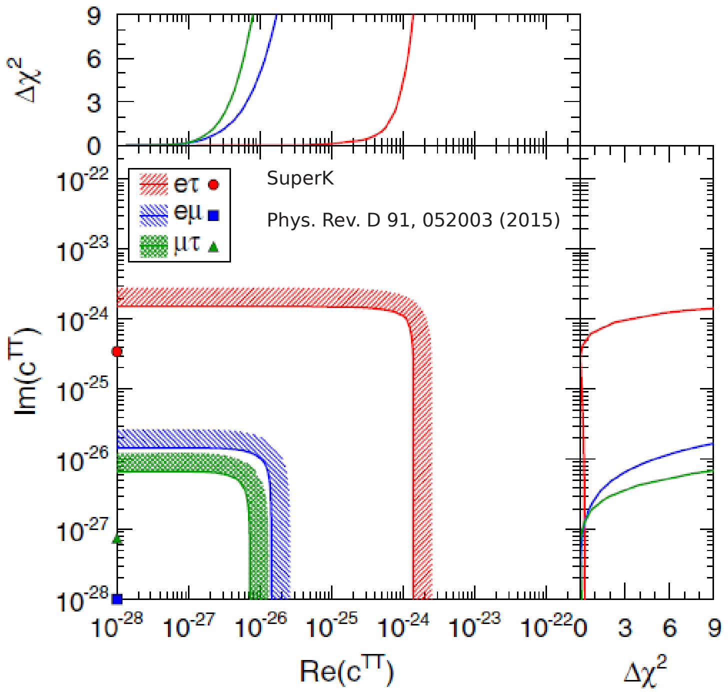
Lorenz invariance violation

in the SME

$$H_{\alpha\beta} = \frac{1}{2E} U_{\alpha j} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} (U^\dagger)_{k\beta} + V_{\mathrm{MSW}} + \frac{p_\lambda}{E} \begin{pmatrix} a^\lambda_{ee} & a^\lambda_{e\mu} & a^\lambda_{e\tau} \\ a^{\lambda *}_{e\mu} & a^\lambda_{\mu\mu} & a^\lambda_{\mu\tau} \\ a^{\lambda *}_{\mu\tau} & a^{\lambda *}_{e\tau} & a^\lambda_{\tau\tau} \end{pmatrix} - \frac{p_\lambda p_\sigma}{E} \begin{pmatrix} c^{\lambda\sigma}_{ee} & c^{\lambda\sigma}_{e\mu} & c^{\lambda\sigma}_{e\tau} \\ c^{\lambda\sigma *}_{e\mu} & c^{\lambda\sigma}_{\mu\mu} & c^{\lambda\sigma}_{\mu\tau} \\ c^{\lambda\sigma *}_{\mu\tau} & c^{\lambda\sigma *}_{e\tau} & c^{\lambda\sigma}_{\tau\tau} \end{pmatrix}$$

(arXiv:1608.02946)

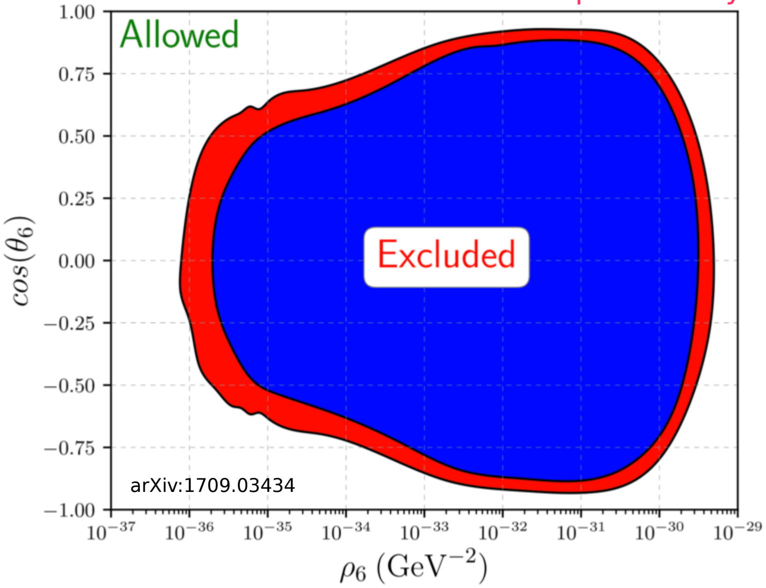
standard MSW LVI terms



SuperK

Phys. Rev. D 91, 052003 (2015)

IceCube preliminary



arXiv:1709.03434

(strength of LV)

magnetic monopoles

$$\vec{\nabla}\cdot\vec{E}=4\pi\rho_e \qquad \vec{\nabla}\cdot\vec{B}=4\pi\rho_m \qquad -\vec{\nabla}\times\vec{E}=\frac{1}{c}\frac{\partial\vec{B}}{\partial t}+\frac{4\pi}{c}\vec{j}_m \qquad \vec{\nabla}\times\vec{B}=\frac{1}{c}\frac{\partial\vec{E}}{\partial t}+\frac{4\pi}{c}\vec{j}_e$$

- Predicted from charge quantization (Dirac):

  elementary charge $g_D=\frac{\alpha}{2}e\approx 68.5\,e$

- Most GUTs predict them

  mass range: $\sim 10^{7}$ GeV $\lessapprox$ m_M $\lessapprox$ 10^{19} GeV

- Typical galactic B-fields (μG) and galactic sizes (kpc) can accelerate MMs to

$$K=g_d\int_{path}B\cdot dl\simeq g_D B\,l\approx 10^{12}\,GeV$$

- MMs with masses below $\lessapprox 10^{12}$ GeV can be relativistic

- Different signatures in NTs, depending on speed, but always track-like

magnetic monopoles

slow
$(\beta \lesssim 0.1c)$

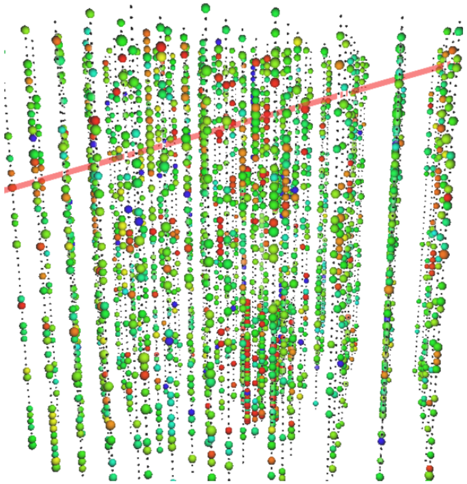
light from EM showers of p-decay products

$\sigma_{CAT} = \sigma_{CAT}(\beta) = \sigma_0/\beta$

Estimated: 10^{-21} cm^2 < σ_{CAT} < 10^{-27} cm^2

Mean free path between p-decays: $1/\sigma_{CAT}$

Long passage time (~ms) → detector noise

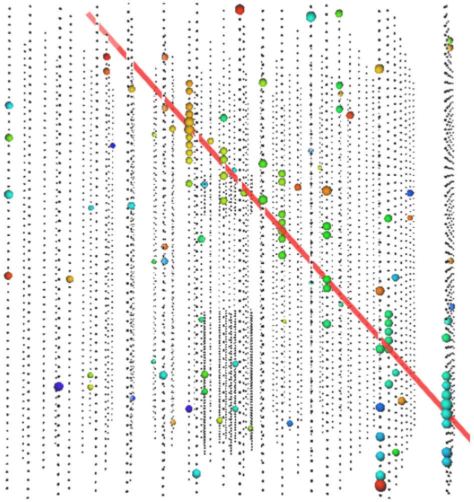


“mildly relativistic”
$(0.2c \lesssim \beta \lesssim 0.5c)$

isotropic light from luminescence due to electronic excitation-deexcitation

dim events

access to “intermediate” β range



relativistic

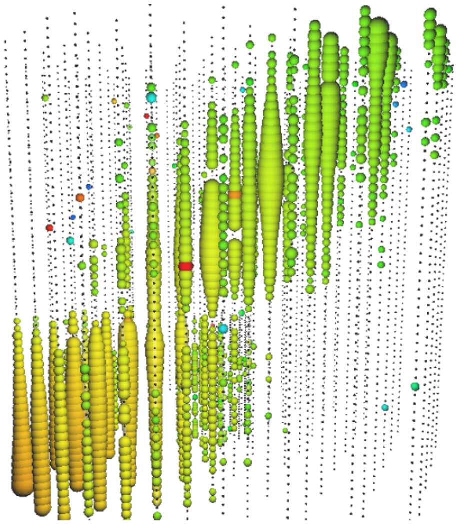
direct Cherenkov light $(\beta \gtrsim 0.75c)$

or from secondary δ electrons $(\beta \gtrsim 0.6c)$

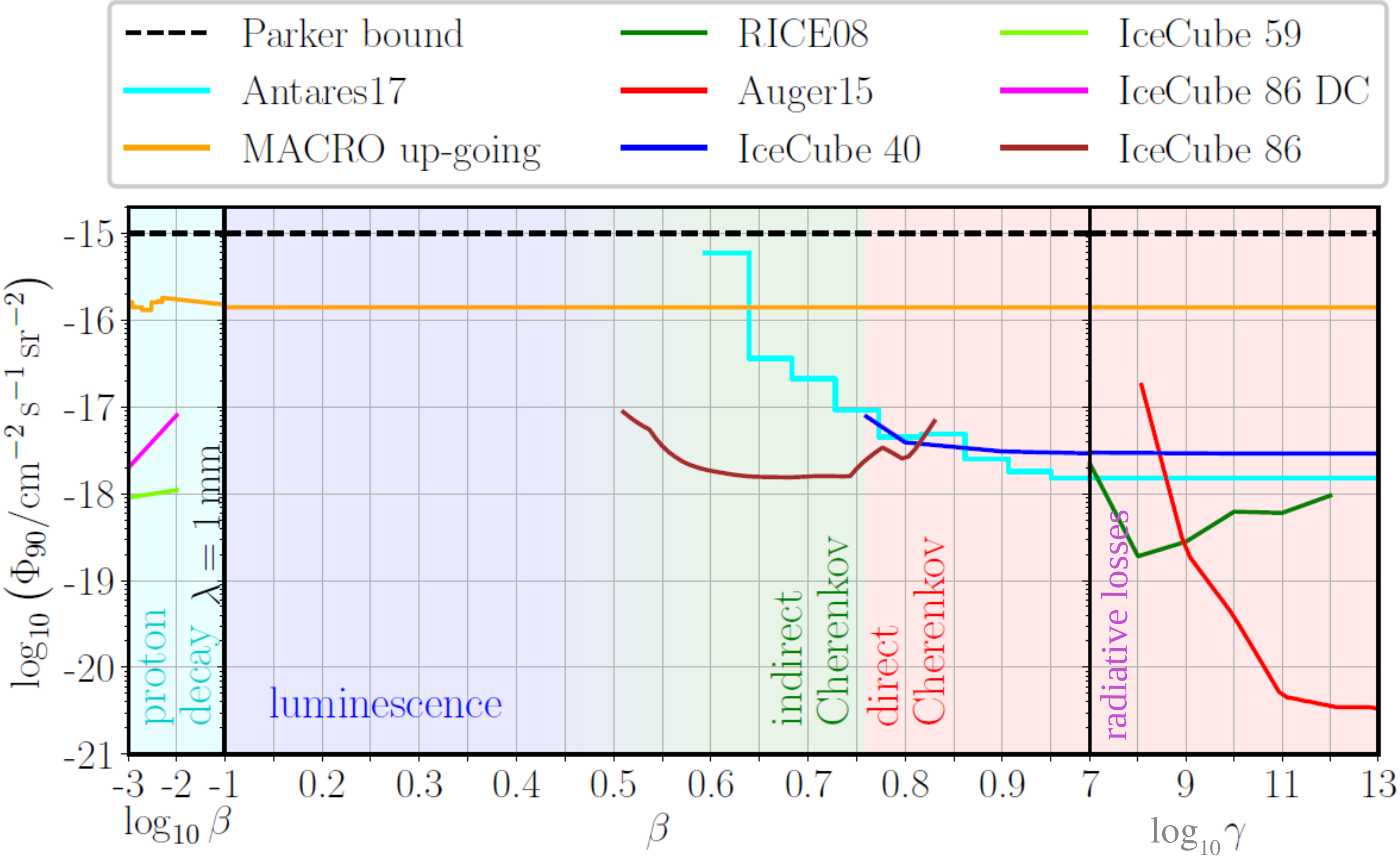
Vey bright events (g~68e).

Nb. of Cherenkov photons

x8200 min ionizing muon



current results



nuclearites & strangelets

- QCD allows for neutral, stable “chunks”

of strange matter (u, d, s)

stranglets → mass $\mathcal{O}$(heavy nuclei)

nuclearites → mass >> standard nuclei ($\gtrsim 10^{10}$ GeV)

- Neutral ⇒ difficult to accelerate

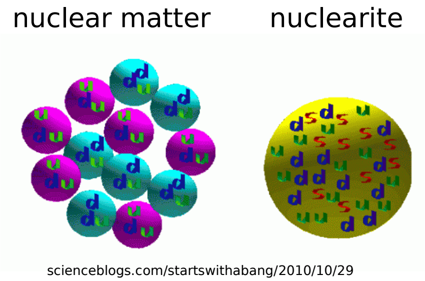
Gravitationally trapped in the galaxy ⇒ $\beta \sim 10^{-3}$

→ non-relativistic: elastic collisions along their path

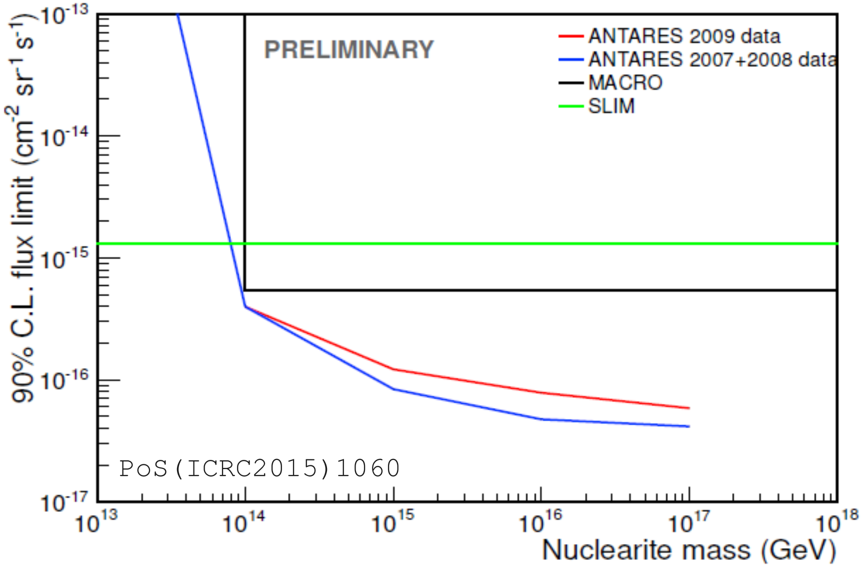
- Heat matter locally as they traverse it →

light from a cylindrical expanding thermal shock wave

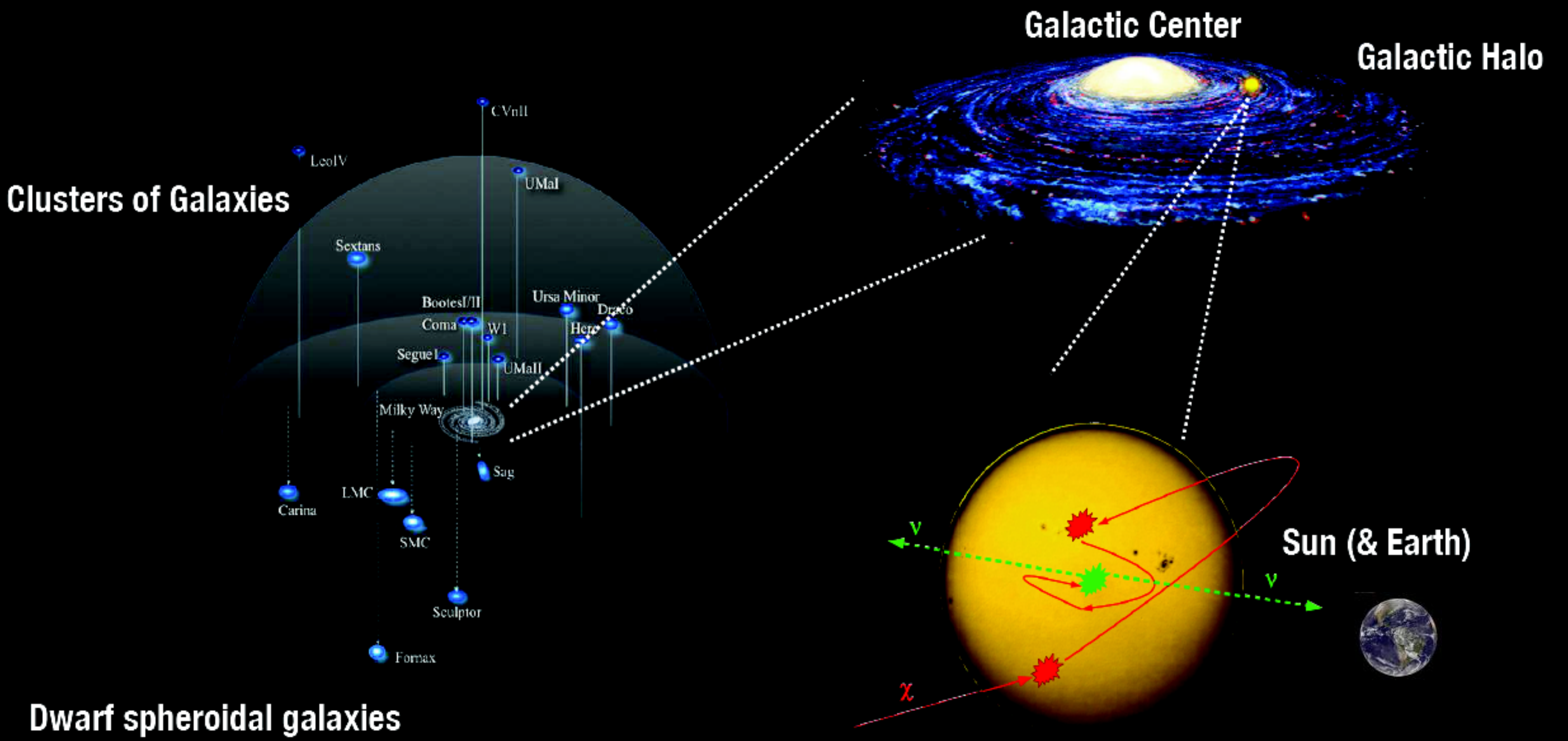
⇒ signature in a NT as a slow, bright track

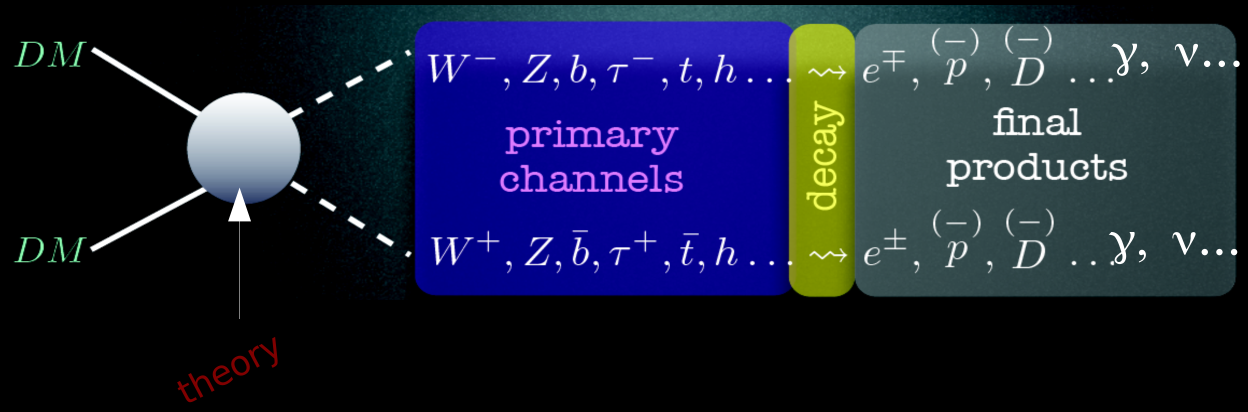


scienceblogs.com/startswithabang/2010/10/29



searches dark matter





DM

DM

$W^-, Z, b, \tau^-, t, h \ldots$ $\rightsquigarrow$ $e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots \gamma, \nu \ldots$

primary channels

decay

final products

$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots$ $\rightsquigarrow$ $e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ldots \gamma, \nu \ldots$

theory

$$\Phi_\mu \to \Gamma_A \to C_C \to \sigma_{\chi p}$$

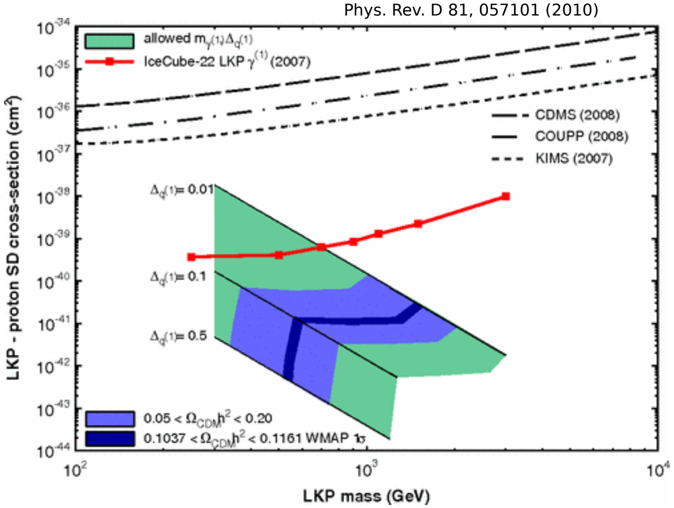
$$\Phi_\mu \to \Gamma_A \to \sigma_{\chi\chi}$$

dark matter searches beyond MSSM

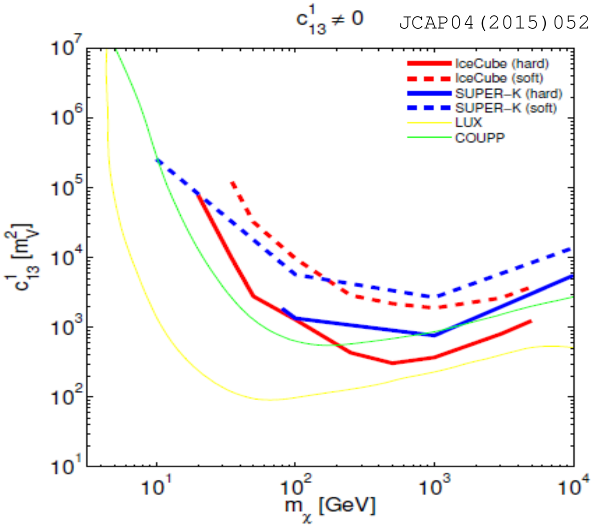
Possibility to test more exotic scenarios than the plain MSSM neutralino:

Kaluza-Klein dark matter
(extra dimensions)

Phys. Rev. D 81, 057101 (2010)

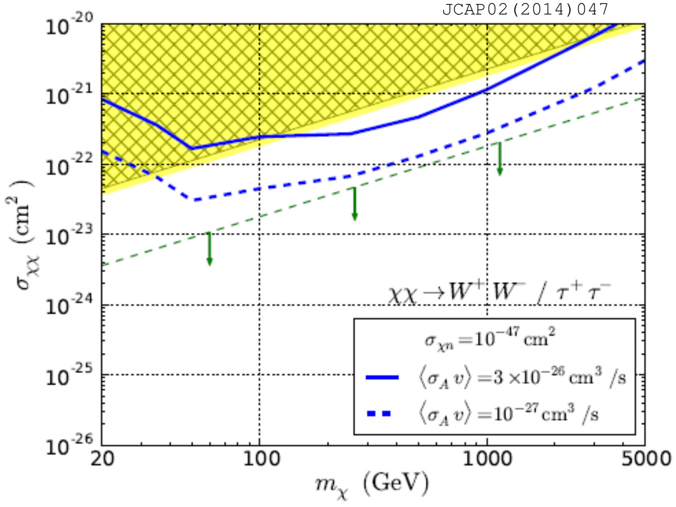


JCAP04(2015)052



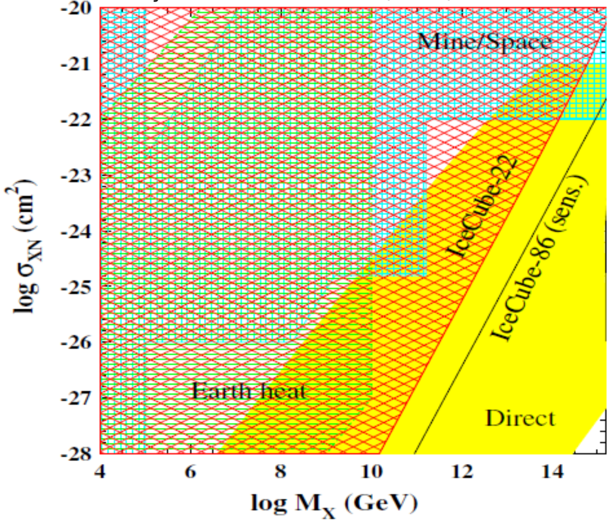
self interacting dark matter with
momentum-dependent self-interaction Xsection

JCAP02(2014)047



self interacting dark matter

Phys Rev D 81, 063510 (2010)



Superheavy, non-thermal
dark matter

Plus many more...

outlook

Rich particle physics program for neutrino telescopes (I skipped many topics)

Complementary in many aspects to accelerator physics

NT's have access to a high-statistics, high-energy neutrino beam (atm. neutrinos)

NT's are sensitive to other highly ionizing particles besides muons → monopoles...

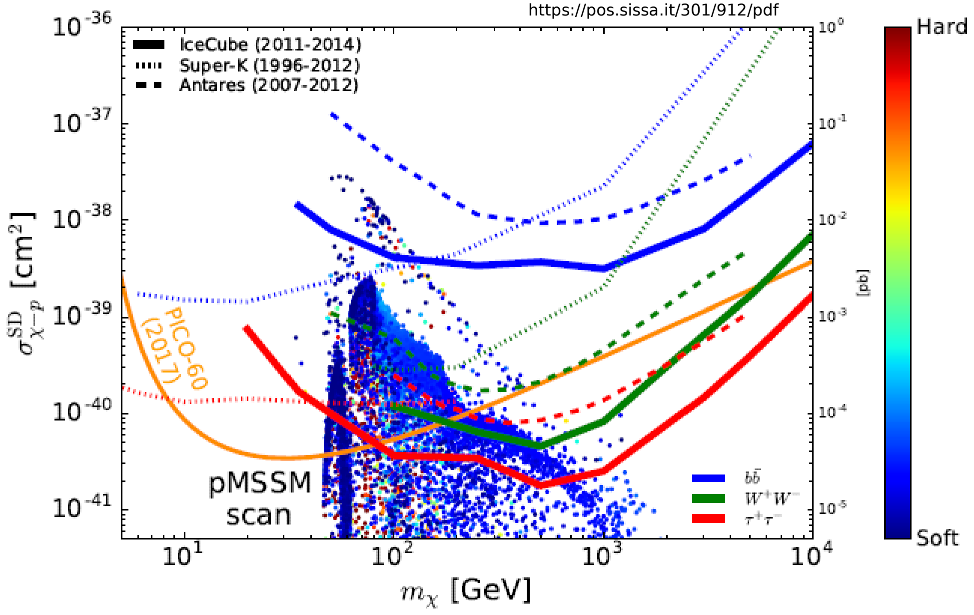
The old adage is rapidly coming true: yesterday's signals are today's backgrounds

- Astrophysical neutrinos constitute a background for some of the mentioned topics
- They open the window to cosmological distances and >PeV energies


THE END

IceCube searches for dark matter

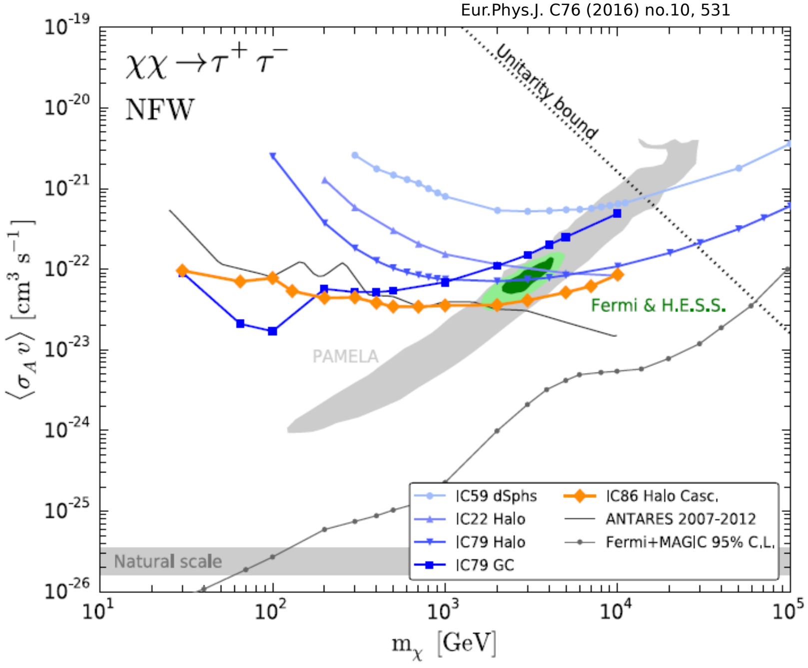
$$\Phi_\mu \rightarrow \Gamma_A \rightarrow C_c \rightarrow \sigma_{\chi p}$$



https://pos.sissa.it/301/912/pdf

$$\Phi_\mu \rightarrow \Gamma_A \rightarrow \sigma_{\chi\chi}$$

Eur.Phys.J. C76 (2016) no.10, 531



$$\frac{d\phi_\nu}{dE} = \frac{\langle \sigma_A v \rangle}{2} \frac{1}{4\pi m_\chi^2} J_a(\psi) \frac{dN_\nu}{dE}$$