

Neutrino tomography of the Earth

Jordi Salvado

in collaboration with:

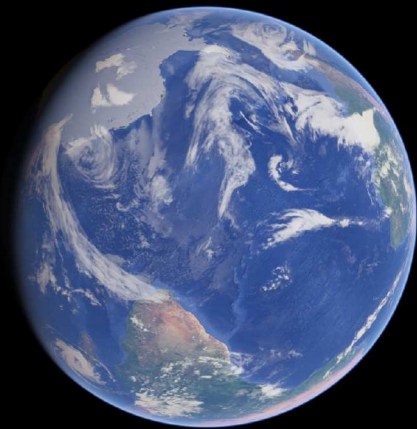
Andrea Donini

Sergio Palomares-Ruiz

Neutrino Oscillation Workshop 2018

Arxiv:1803.05901





Using a long range force

- ▶ The total (Gravitational) Mass

$$M_{\oplus} = \frac{4\pi}{3} \int_0^{R_{\oplus}} dr r^2 \rho(r) = 5.972 \times 10^{24} \text{kg}$$

$$I_{\oplus} = \frac{8\pi}{3} \int_0^{R_{\oplus}} dr r^4 \rho(r) = 0.3307144 M_{\oplus} R_{\oplus}^2$$

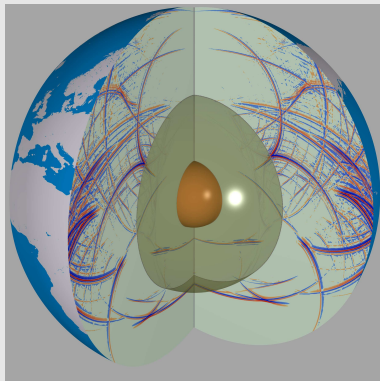
$$I_{\oplus}^{cnt} = 0.4 M_{\oplus} R_{\oplus}^2$$

The state of the art “sound” waves

- ▶ Seismic wave propagation S and P waves.
- ▶ Adams-Williamson equation.

$$\Phi = v_p^2 - \frac{4}{3}v_s^2$$

$$\frac{d\rho}{dr} = -\frac{\rho(r)g(r)}{\Phi(r)}$$

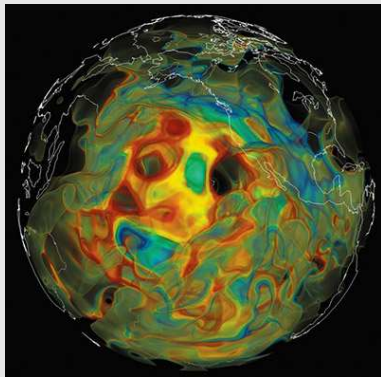


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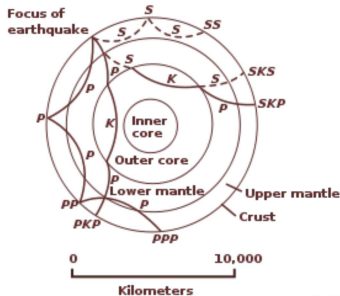


Ebru Bozdağ, University of Nice Sophia Antipolis, and
David Pugmire, Oak Ridge National Laboratory. from

phys.org

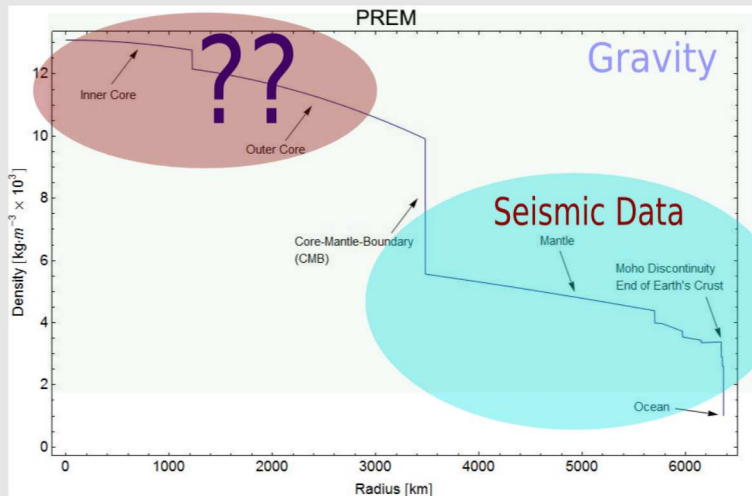
The Earth's core

A problem:
The OUTER CORE IS LIQUID:
EARTHQUAKE WAVES CANNOT CROSS
THE INNER CORE



We only have information about the
INNER CORE through global
constraints and extrapolations

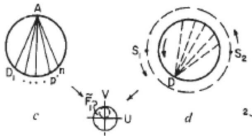
Earth picture



- Core still unknown but very relevant **geomagnetic dynamo**

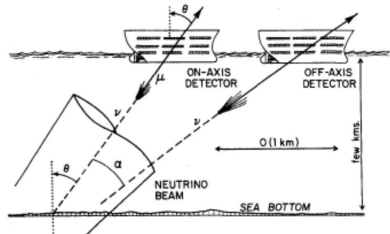
What if we use Neutrinos

- ▶ Proposed long time ago!
A. Piacci and E. Zavalni, submitted in Oct 1973 to Nuovo Cimento;
never published
- ▶ Talk:
L. V. Volkova and G. T. Zatsepin, Izv. Akad. Nauk. Ser. Fiz. 38N5
(1974)



De Rújula, Glashow, Wilson, Chrapak,
Phys. Rept. 99 (1983)

T. Wilson, Nature 309 (1984)



What if we use Neutrinos

- ▶ A lot of neutrinos cross the Earth coming from atmospheric cosmic ray showers.
- ▶ The propagation is affected by the amount of matter along the path.

Atmospheric ν are the best!

Where the matter enters?

$$\frac{dF_\nu(E)}{dx} = -i[H_o + \mathbf{V}m, F_\nu(E)] - \sum_\alpha \frac{1}{2\lambda^\alpha(E)} \{\Pi_\alpha, F_\nu(E)\}$$

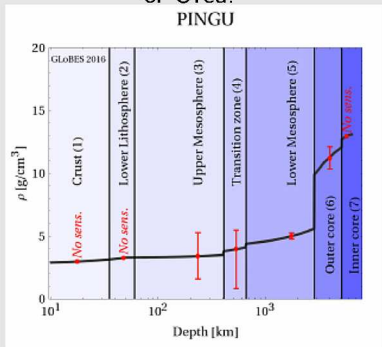
Matter interactions appear in ν propagation

- ▶ Coheren matter interaction.
- ▶ Attenuation due to scattering interactions

Coherent approach

$$\frac{dF_\nu(E)}{dx} = -i[H_o + Vm, F_\nu(E)]$$

Matter interactions appear in ν propagations After 10 yrs, Pingu or Orca.

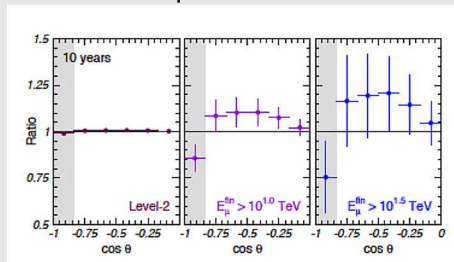


Winter, Nucl. Phys B908 (2016)

Incoherent (high E)

$$\frac{dF_\nu(E)}{dx} = -\sum_{\alpha} \frac{1}{2\lambda^{\alpha}(E)} \{\Pi_{\alpha}, F_\nu(E)\}$$

(Forecast) after 10 yrs, IceCube atmospheric ν .



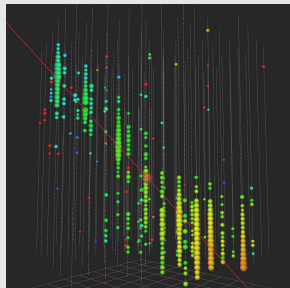
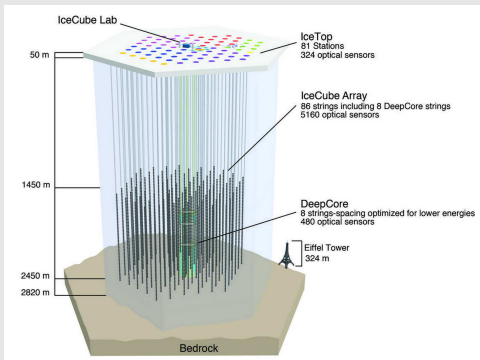
Gonzalez-García, Halzen, Maltoni, Tanaka, Phys.

Rev. LeT. 100 (2008)

IceCube data set

Analysis for one year of **up-going** IceCube-86 **high energy** ν_μ data
(**Energy Range : 400 GeV to 30 TeV**) data and MC from IC sterile
search Phys.Rev.Lett. 117 (2016) no.7, 071801.

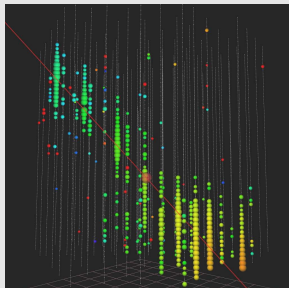
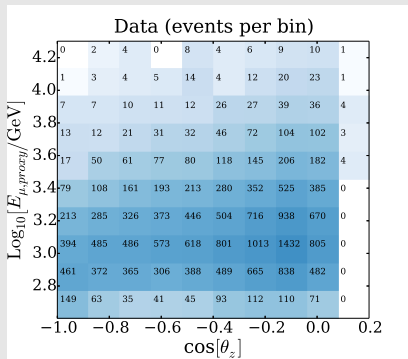
- ▶ Number of events ~ 20000 .
- ▶ Spans a zenith range from -1 to 0.2 in $\cos \theta_z$.
- ▶ 99% ν_μ purity.



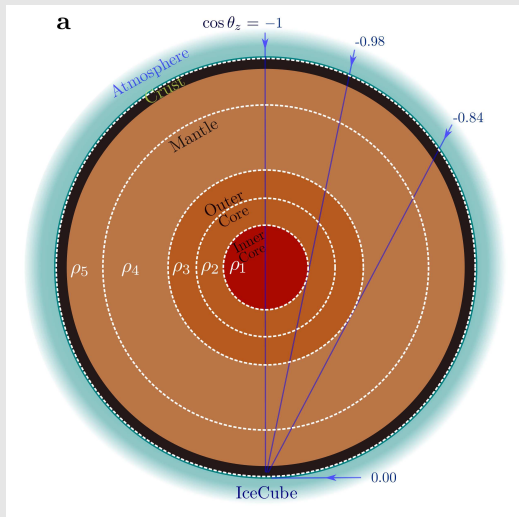
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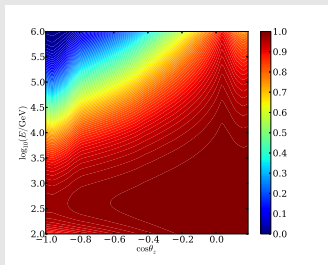
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Parametrization of the Earth



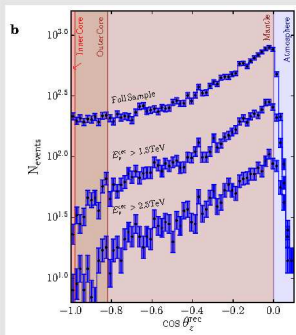
- ▶ We let the density free in 5 layers, 1-inner core, 2-outer core and 2-mantle.
- ▶ We propagate neutrinos with nuSQUIDS for every ρ_i
- ▶ We map the E_{real}, θ_{real} to E_{rec}, θ_{rec} using the official IceCube MC.



Statistics!

We did a standard binned maximum likelihood fit.

$$\log \mathcal{L}(\rho_1, \rho_2, \rho_3, \rho_4, \rho_5) = \min_{\vec{\theta}, \{d\}} \left(\sum_{i=1}^{N_{bins}} [x_i \log \lambda_i(\vec{\theta}, d) - \lambda_i(\vec{\theta}, d)] + \sum_{\eta} \frac{(\theta_{\eta} - \Theta_{\eta})^2}{\sigma_{\eta}^2} \right),$$

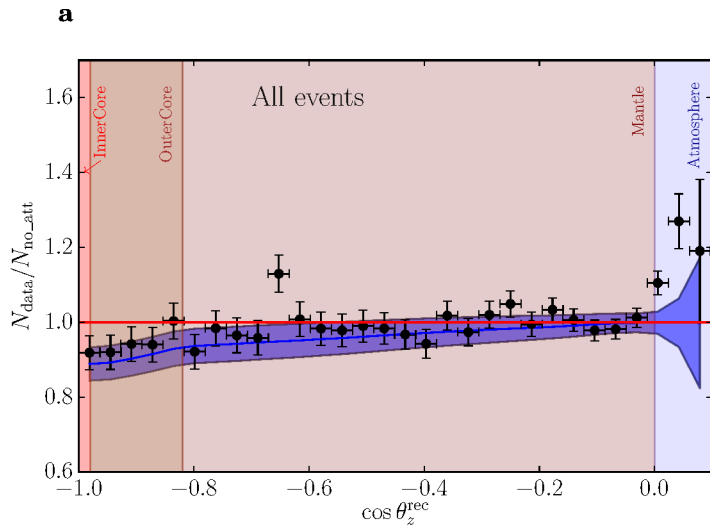


- ▶ DOM efficiency
- ▶ Flux continuous parameters
 - ▶ spectral index
 - ▶ π/K ratio
 - ▶ $\nu/\bar{\nu}$ ratio **Green Implementation**
- ▶ Air shower hadronic models **Marginally irrelevant check**
- ▶ Primary cosmic ray fluxes **Marginally irrelevant check**
- ▶ Neutrino cross sections **Marginally irrelevant check**
- ▶ Hole Ice **Not included**
- ▶ Bulk ice scattering/absorption **Not Included**

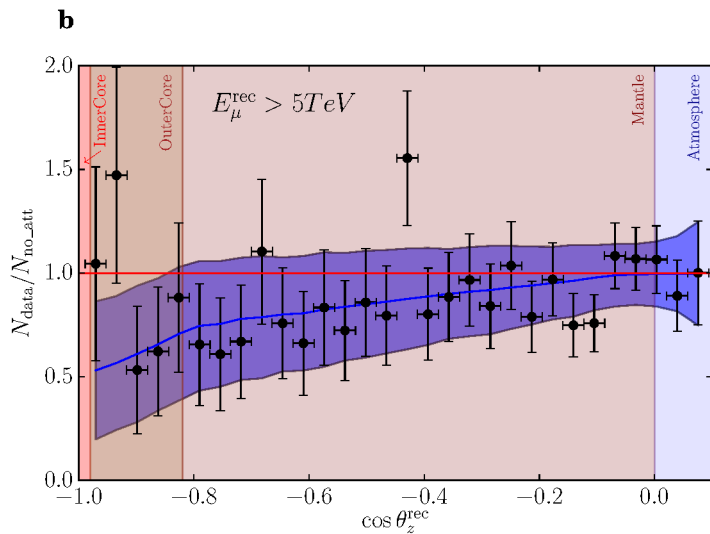


We use Multinest to perform a Bayesian inference for the systematic errors and $\{\rho_1, \rho_2, \rho_3, \rho_4, \rho_5\}$

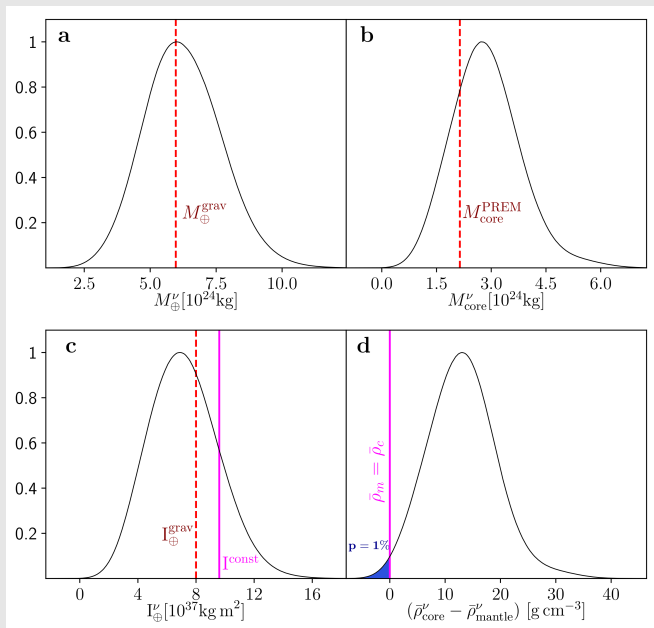
Is the earth there?



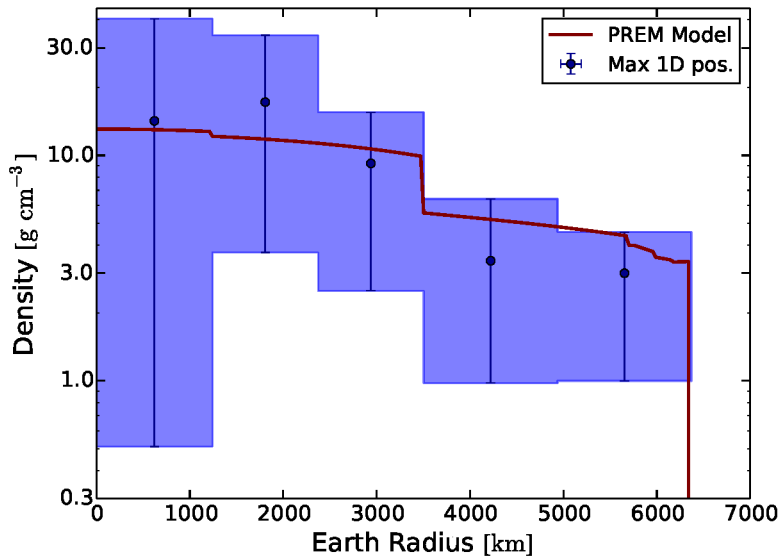
Is the earth there?



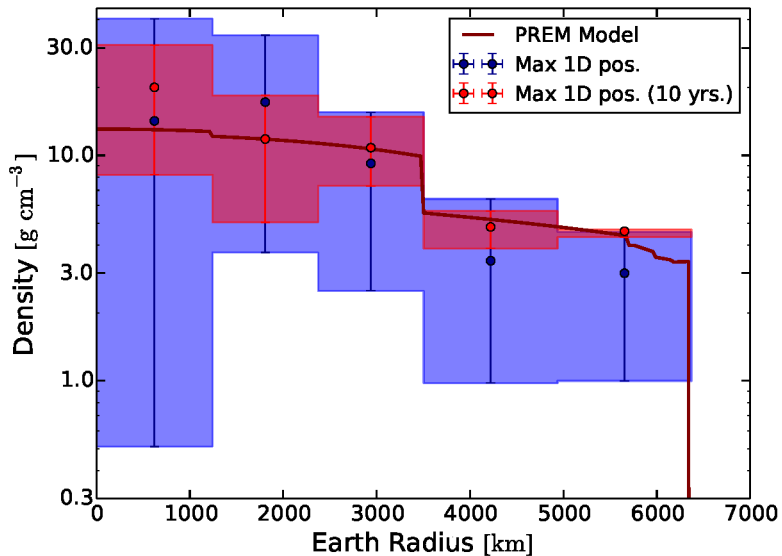
Posterior Probabilities for relevant parameters



Main result



Main result



Conclusions

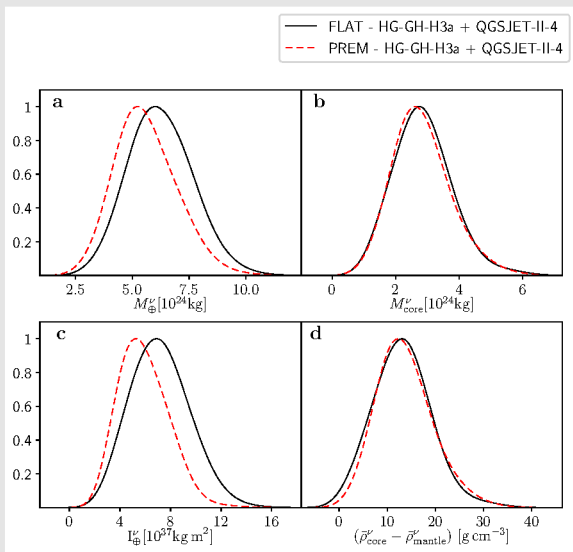
- ▶ We used **one year of IceCube-86 data** to do a **tomography of the planet Earth**.
- ▶ For the first time neutrinos give **sensitive result** measuring the earth and the density slope.
- ▶ As a tool to study the earth interior is **complementary to seismology**, allowing to explore the inner parts.
- ▶ The result is dominated by **statistical errors** and IceCube already collect **more years of data**.
- ▶ Other experiments such **Antares, KM³** may give an interesting complementary result from another point in the earth.
Spherical core?, inner core?

Thanks!

BKP:

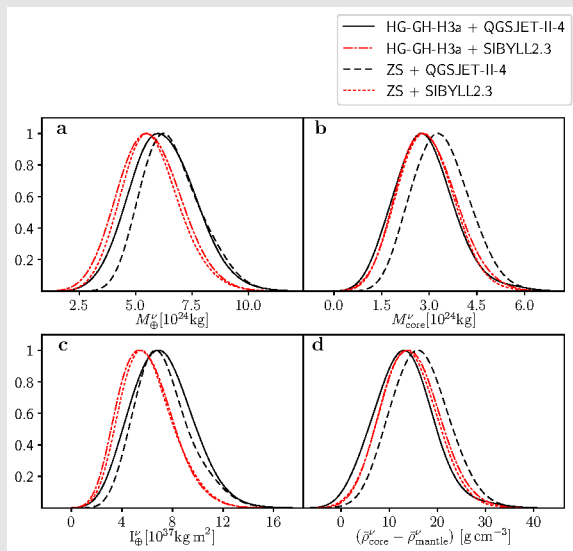
Checks!

- ▶ Is the assumption of constant density in the bins affecting the result?



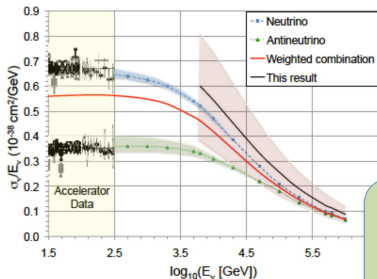
Checks!

- ▶ How it affects the initial flux, CR fluxes and Hadronic models?



Neutrino-nucleon interaction

Parton distribution functions: HERAPDF



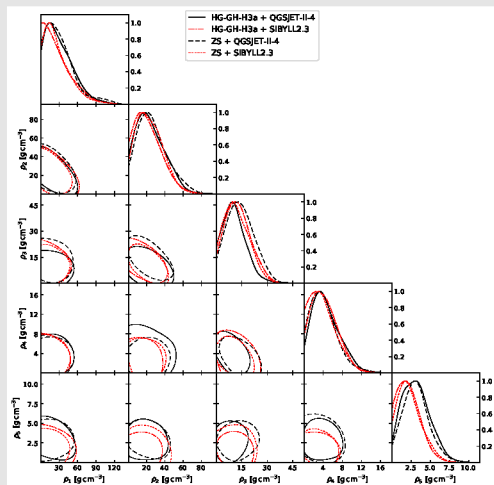
Aarsten et al, Nature 551 (2017)

νN ($\bar{\nu} N$) cross-sections
at 2-3% (4-10%) errors

ICECUBE MEASUREMENT
 $1.30^{+0.21}_{-0.19} \text{ (stat)}^{+0.39}_{-0.43} \text{ (syst)} \times \sigma_{SM}$

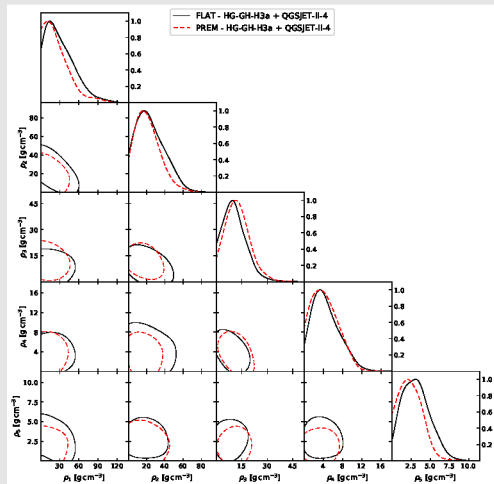
Checks!

- ▶ How it affects the initial flux, CR fluxes and Hadronic models?
also OK



Checks!

- ▶ Is the assumption of constant density in the bins affecting the result? **Not really**



Forecast

- ▶ Soon IceCube will have 10yrs of data! what can we do?

