Fundamental Physics from Cosmology and Astrophysics

Winter Meeting ICCUB

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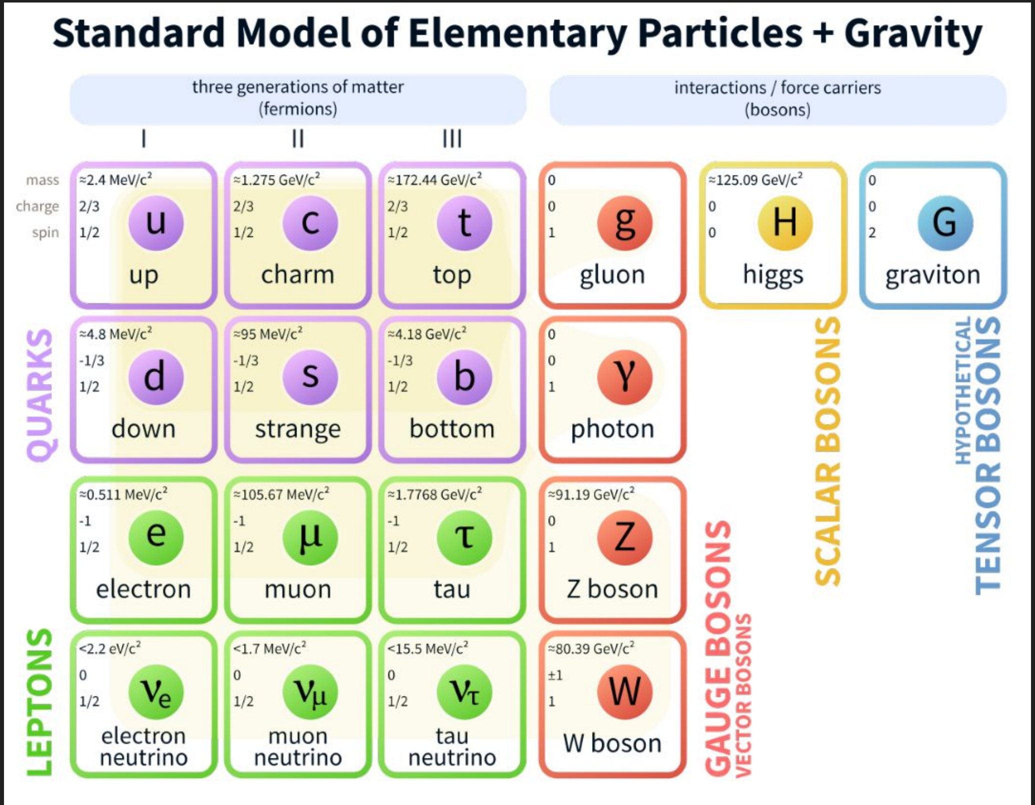
University of Barcelona

UNIVERSITAT DE BARCELONA

Main goal: Understand Fundamental Physics



It works extremely well

BUT:

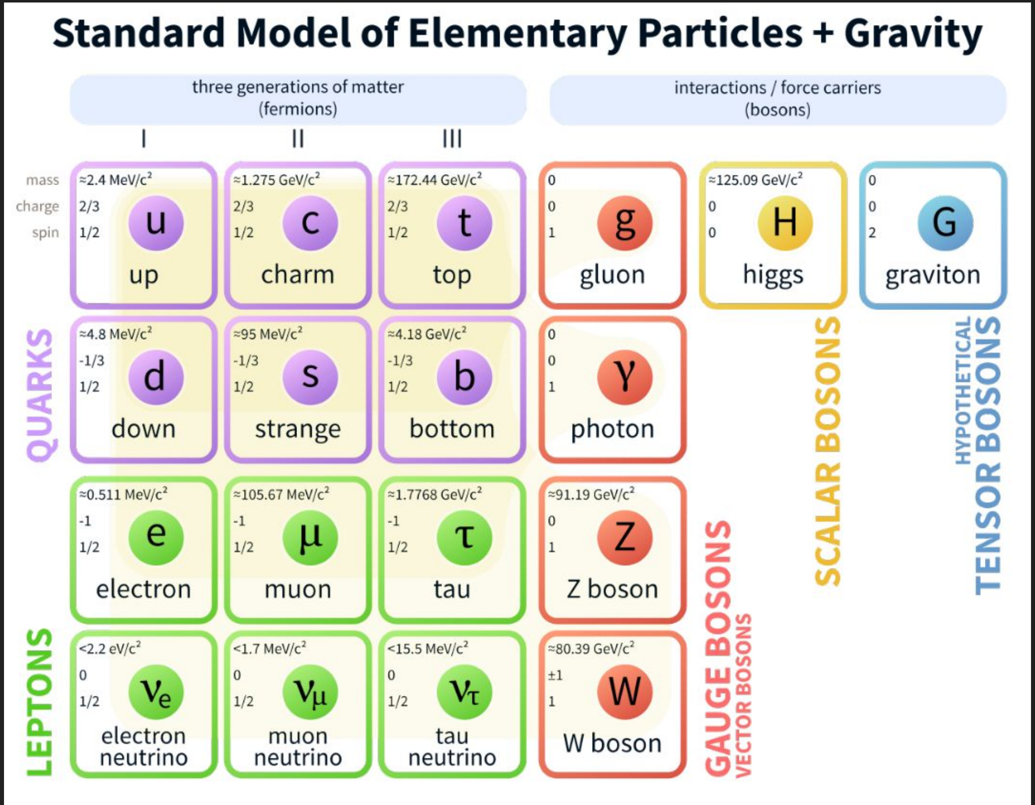
- Consistency problem:

  Quantum Gravity

- Other Conceptual Problems: (Why so strange, ugly…)

  Strong CP problem
  Hierarchy problem
  Flavor Problem
  Why 3 Families?
  …

Main goal: Understand Fundamental Physics



It works extremely well

BUT:

- Observational problems:
- **Dark Energy**
- **Dark Matter**
- **Asymmetry Mat-AntiMat**
- **Origin of Neutrino masses**

…

A brief story

Motivated by understanding better the Sun:
In the late 60s, Ray Davis and John N. Bahcall's Homestake Experiment was the first to measure the flux of neutrinos from the Sun and detect a deficit $O(1/3)$.

The Solar Neutrino Problem

What would you have thought?

1. The theoretical calculation is wrong.

2. The experiment is wrong.

3. There is some funny new physics beyond the standard model.

A brief story (part II)

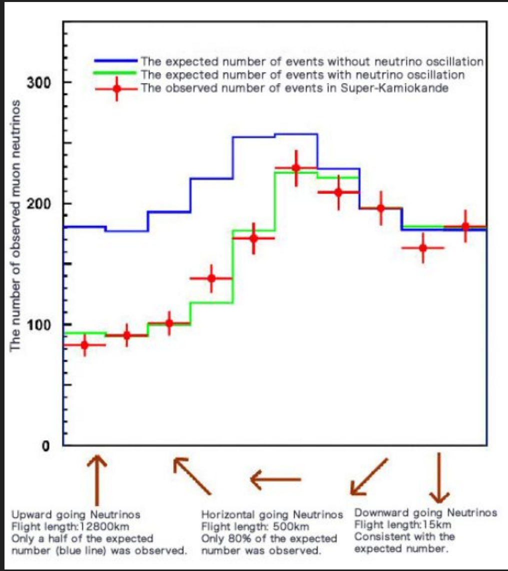
Motivated by Grand Unified Theories:
The University of Tokyo, was founded in 1983 to promote the Kamioka Nucleon Decay Experiment. The detector was filled with 3,000 tons of pure water. Upgraded in 1986 to measure solar neutrinos.

What would you have thought?

1. We discover GUT.

2. We will put a great bound to GUT.

3. The detailed study of a <u>background</u> will provide <u>two nobel prizes</u>.



The answer: Neutrino Oscillations

Theory:

Physics Letters B
Volume 28, Issue 7, 20 January 1969, Pages 493-496

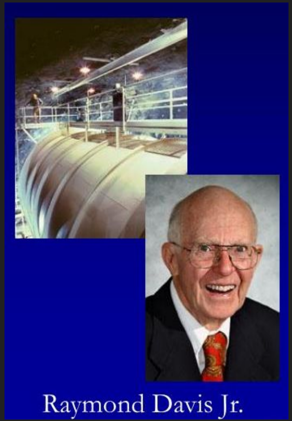
Neutrino astronomy and lepton charge

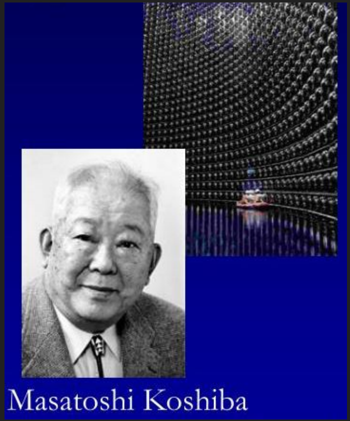
V. Gribov *, B. Pontecorvo

MSW effect

- Mikheyev, S. P.; Smirnov, A. Yu. (1985). "Resonance enhancement of oscillations in matter and solar neutrino spectroscopy". *Soviet Journal of Nuclear Physics*. **42** (6): 913–917. Bibcode:1985YaFiz..42.1441M.
- Wolfenstein, L. (1978). "Neutrino oscillations in matter". *Physical Review D*. **17** (9): 2369–2374. Bibcode:1978PhRvD..17.2369W. doi:10.1103/PhysRevD.17.2369.

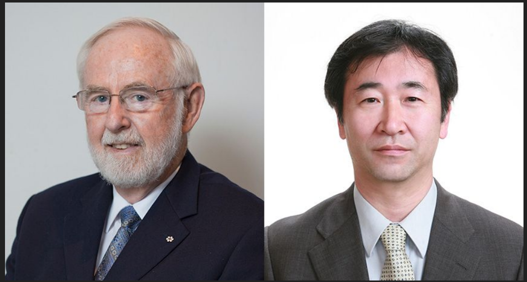
Nobel 2002





Nobel 2015

Arthur B McDonald   Takaaki Kajita



Today: (after a lot of experimental effort)

Current knowledge

- Neutrinos propagate in a non trivial way.
- Well described by 3D quantum mechanics coherent evolution.

$$H = U \begin{pmatrix} \varepsilon_1 & 0 & 0 \\ 0 & \varepsilon_2 & 0 \\ 0 & 0 & \varepsilon_3 \end{pmatrix} U^\dagger + \begin{pmatrix} V_{NC} + V_{CC} & 0 & 0 \\ 0 & V_{NC} & 0 \\ 0 & 0 & V_{NC} \end{pmatrix}$$

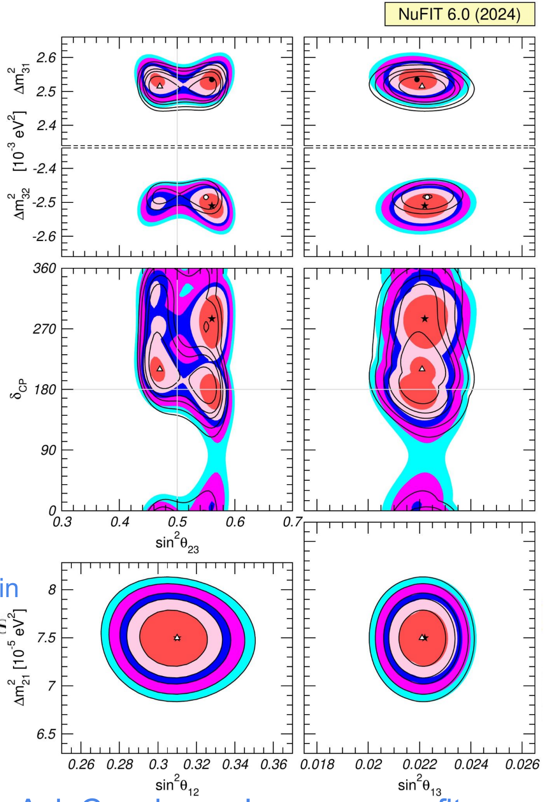
Using the dispersion relation $\varepsilon_i^2 = p^2 + m_i^2$

$$H = \frac{1}{2E} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} U^\dagger + \begin{pmatrix} V_{NC} + V_{CC} & 0 & 0 \\ 0 & V_{NC} & 0 \\ 0 & 0 & V_{NC} \end{pmatrix}$$

Matter Potential: Mikheyev–Smirnov–Wolfenstein

- Quantum interference is very sensible to small parameters $\Delta m_{21}^2 = 7.4 \times 10^{-5} \mathrm{eV}^2$ and $\Delta m_{31}^2 = 2.49 \times 10^{-3} \mathrm{eV}^2$

$\sum_i m_i, \delta_{cp}, \Delta m_{32}^2$, Dirac or Majorana ?

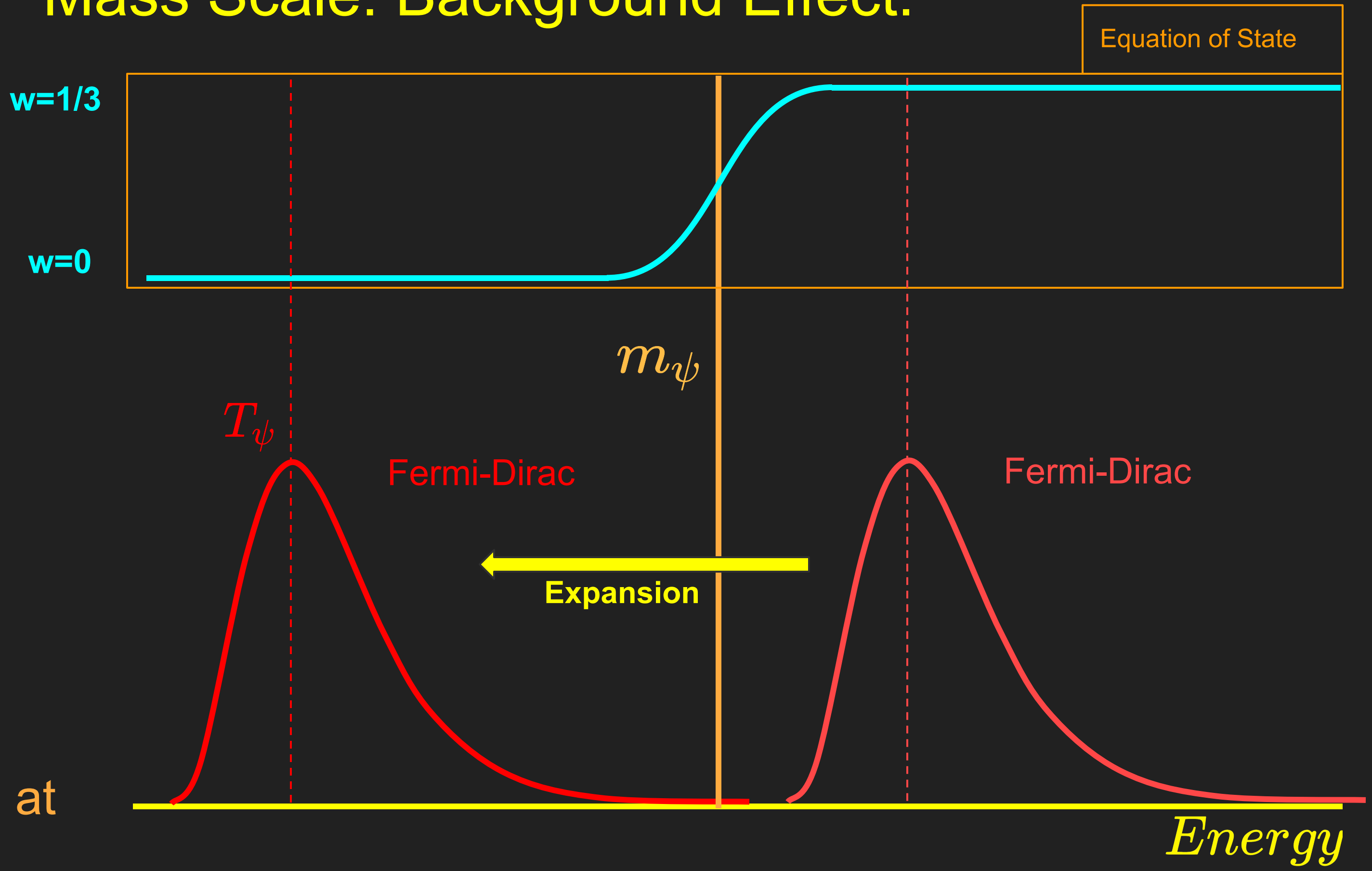


Ask Concha or Joao www.nu-fit.org

Cosmology
and the Neutrinos Mass

Mass Scale: Background Effect.

Neutrino Oscillations tell us neutrinos are massive particles!



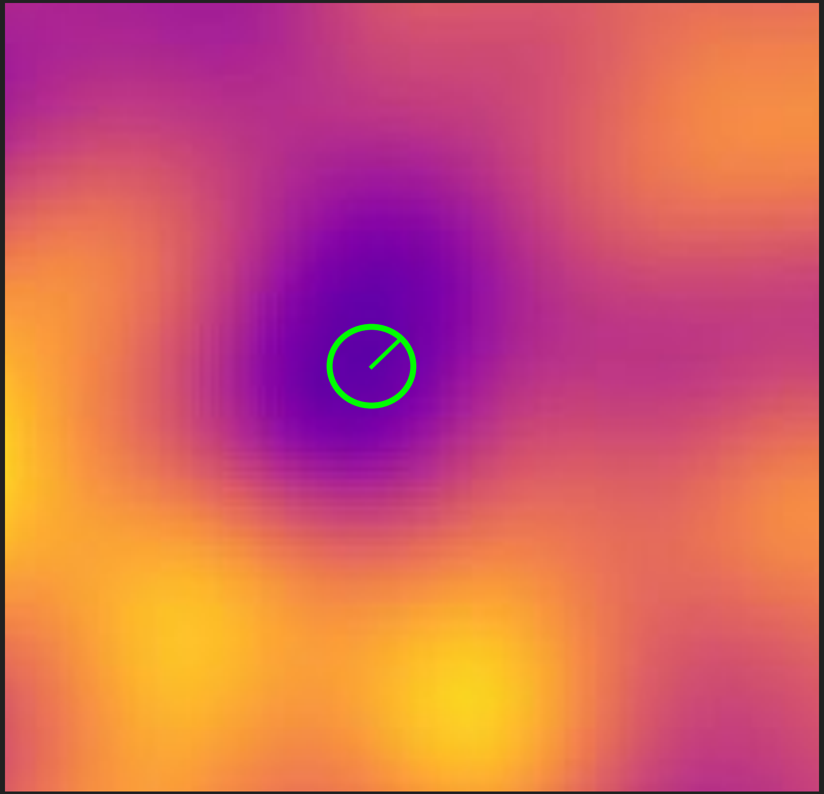
Neutrinos behave like matter once they become non-relativistic, impacting the Hubble expansion at late stages.

Mass Scale: Perturbations effect.

Small scale physics has an effect on the evolution of the cosmological perturbations.

$$d \approx \frac{T_\nu}{m_\nu} \frac{1}{H}$$

Larger perturbations don't get affected.



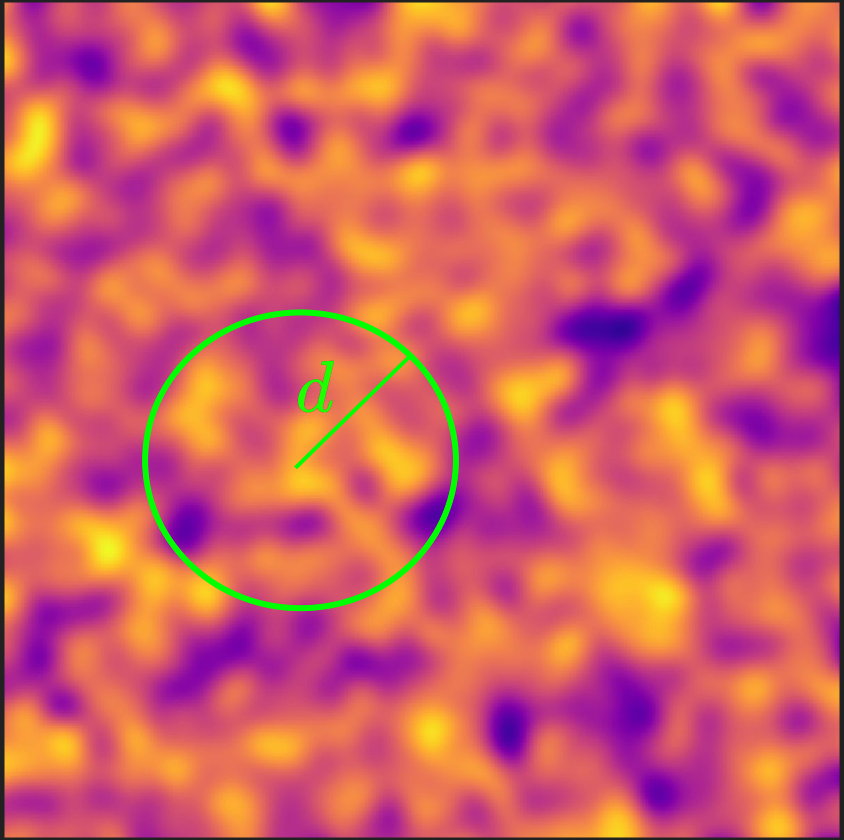
Mass Scale: Perturbations effect.

Small scale physics has an effect on the evolution of the cosmological perturbations.

$$d \approx \frac{T_\nu}{m_\nu}\frac{1}{H}$$

Perturbation at smaller scales get suppressed.

This is called **free streaming length**, don't confuse with **mean free path**, this second is related with scattering interactions (has essentially the same effect).



Mass Scale: Can We Disentangle Its Effects?

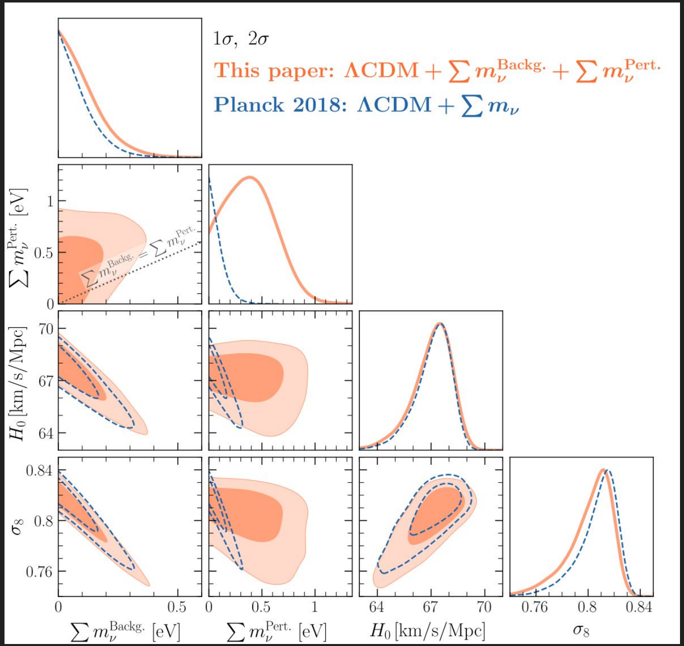
Origin of cosmological neutrino mass bounds: background *versus* perturbations

Toni Bertólez-Martínez (Barcelona U. and ICC, Barcelona U.), Ivan Esteban (Basque U., Bilbao and IKERBASQUE, Bilbao), Rasmi Hajjar (Valencia U., IFIC), Olga Mena (Valencia U., IFIC), Jordi Salvado (Barcelona U. and ICC, Barcelona U.)

Nov 21, 2024

8 pages

e-Print: 2411.14524 [astro-ph.CO]



Next:

- Study LSS measurements in this framework.
- Study other BSM scenarios (BBN, Nu NSI,...)

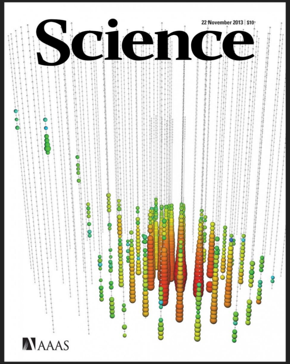
If we measure consistently both physical effects for the neutrino mass, even particle physicist may believe the cosmological result.

With the new surveys this is a very exciting time for the neutrino community to look at cosmology, the ICC brings significant expertise with projects like DESI and Euclid.

Astrophysics
and ?

On November 2013

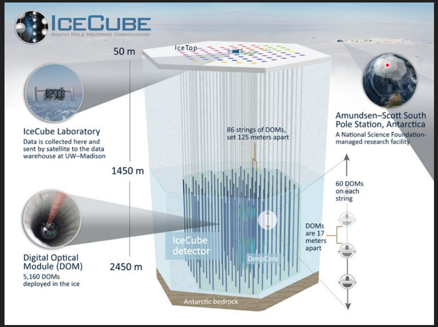
A New Window to the very high energy universe

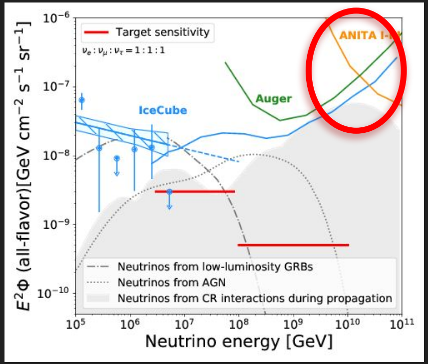


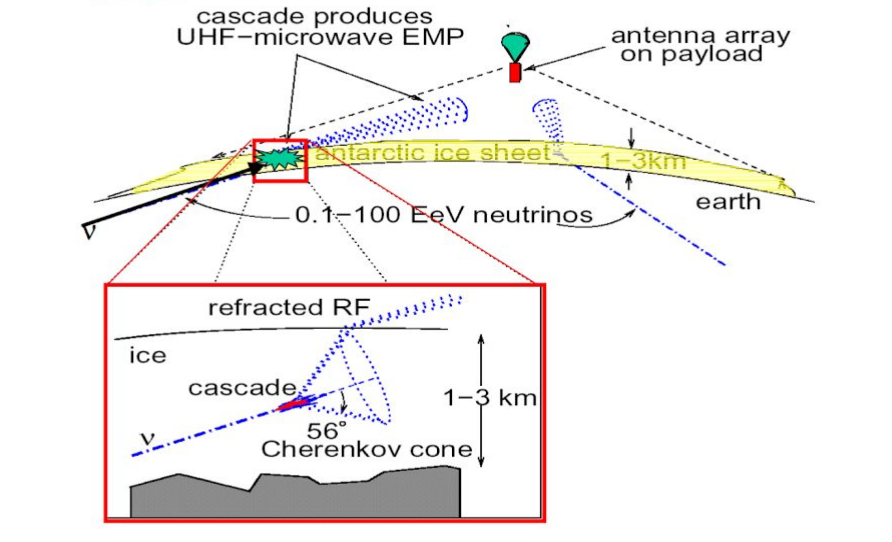
IceCube found astrophysical neutrinos

IceCube Collaboration, Science 342, 1242856 (2013)

ANtarctic Impulsive Transient Antenna
ANITA concept:







- IceCube has a kilometer cube of instrumented volume.
- ANITA has a much larger target mass but only one detection point that measures a secondary product of the EM cascade (a radio pulse).
- The events need to be HUGE!

$10^{19}eV$ to compete with IceCube

Last flight ANITA-IV launched in December 2016

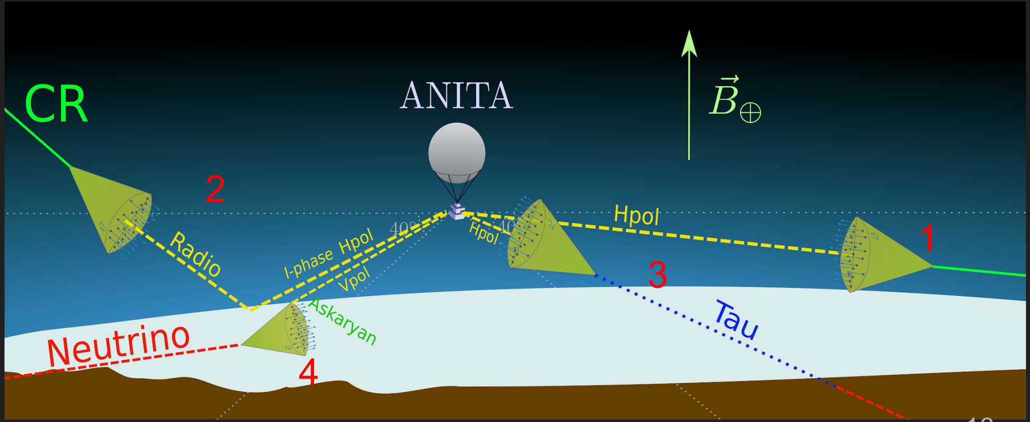
Last flight ANITA IV

event #	mm dd hh mm ss UTC 2016	Apparent source location Lat.°,Lon.°, alt., m	elev. angle[a] degrees
4098827	12 03 10 03 27	-75.71, 123.99, 3184	-6.17 ± 0.21
9734523	12 05 12 55 40	-71.862, 32.61, 19000[b]	-5.64 ± 0.20
19848917	12 08 11 44 54	-80.818 , -79.87, 758	-6.71 ± 0.20
50549772	12 16 15 03 19	-83.483, 14.73, 2572	-6.73 ± 0.20
51293223	12 16 19 08 08	-74.800, 11.43, 18600[b]	-5.38 ± 0.24
72164985	12 22 06 28 14	-86.598, 0.35, 2589	-6.12 ± 0.10

- ANITA-IV
  a. Search: Isolated, impulsive, signal shape selected.
  b. No Askarian neutrino events.
  c. 2 type (1) and 23 type (2) found.
  d. 4 upgoing CR like (3).

- Elevation is ***closer*** to the horizon for all 4 events.

This events have the energy of the most energetic CR and cross large amount of matter, **too much even for neutrinos**



Phys.Rev.Lett. 126 (2021) 7, 071103 ANITA collaboration

Last flight ANITA IV

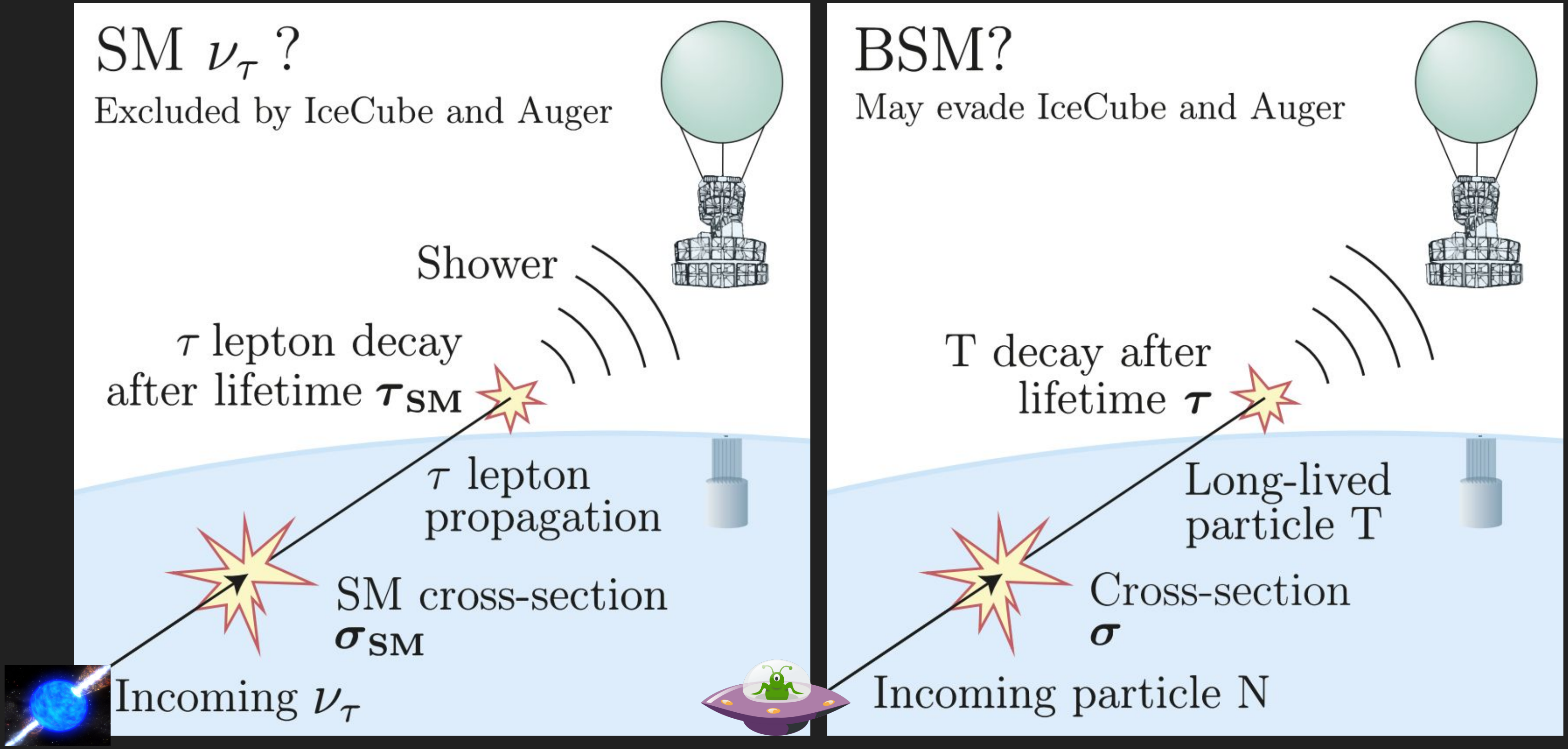
Assumptions:

- Isotropic flux.
  - A population of transients with the average observed rate should be equivalent.

- The source only emits in ultra high energy range of the ANITA observed events.
  - Any astrophysical source should produce also a low energy contribution but we will focus on BSM, ex. DM decay, …

Last flight ANITA IV

Generic BMS scenario:

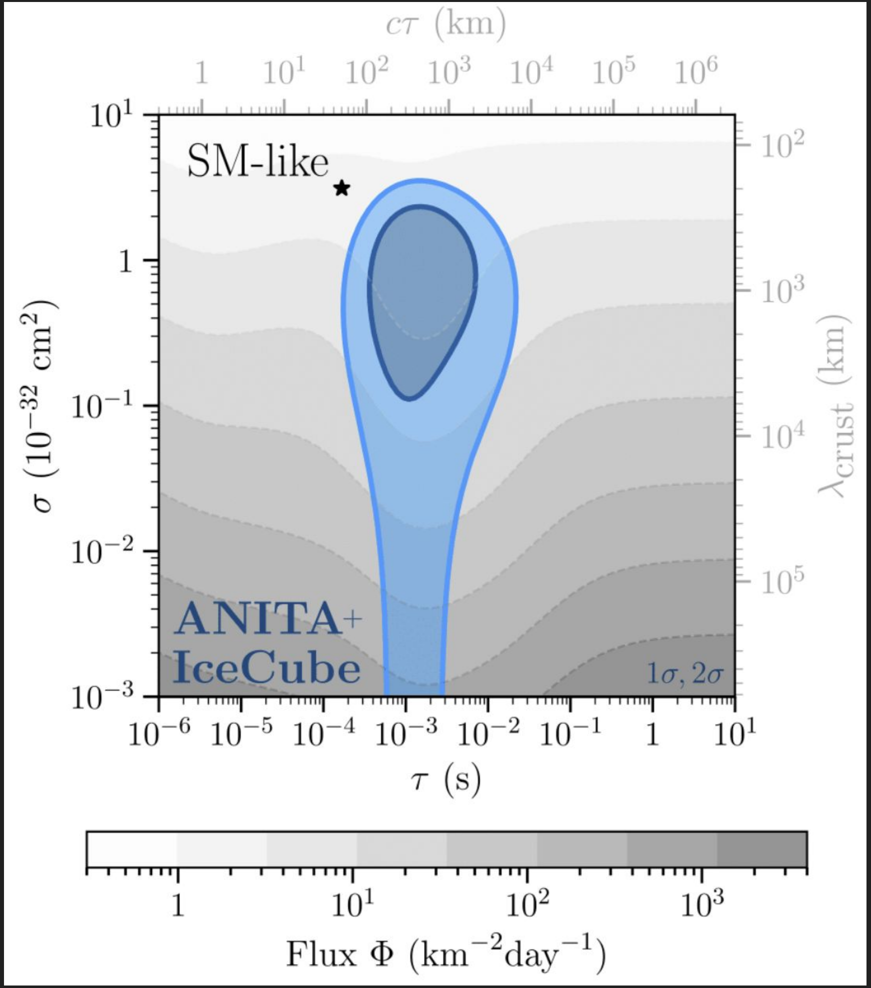


ANITA IV + IC

The combined result strongly constrains the parameter space for BMS physics.

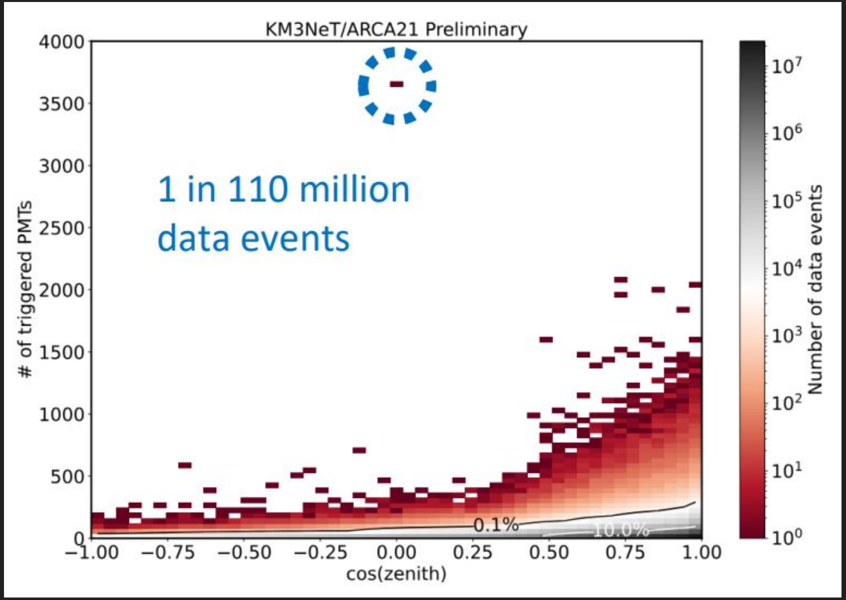
The best fit predicts O(1) event in IceCube. Consistent with not observing any.

It may be wrong antarctica is full of penguins and other stuff!!



Surprise, KM3net!

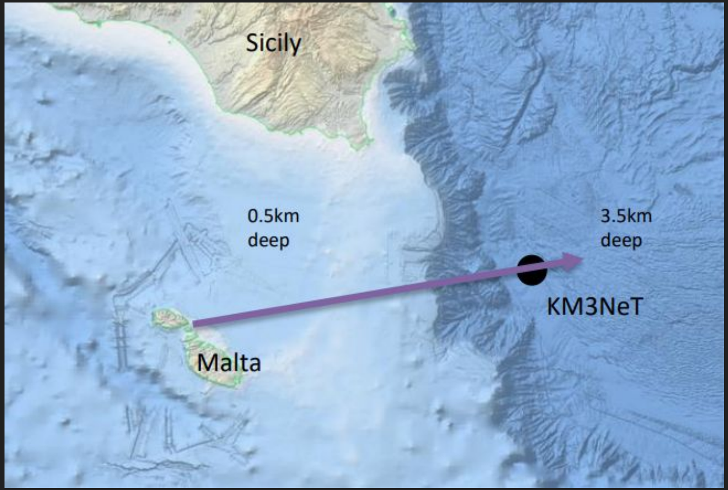
Km3Net also found an event very close to the horizon with extremely high energy very different technology. **O(100s) PeV**



Result presented in Neutrino 24
The paper should appear in Nature in the next few days…

- Is this consistent with ANITA?
- Is it consistent with the SM?
- What is it?
- Why Malta?

Alba Burgos and Toni Bertolez



What next?

1. PUEO: The next generation experiment is about to start.

2. If km3net is seeing something we must look at our trusted neutrino telescope (IceCube)

Supported by Harvard University, we became an associate member of the IceCube collaboration to conduct these studies.

HARVARD UNIVERSITY

Anne Katherine and Toni Bertolez

Stay tuned for more!!

Something may be happening with this flux at EeV = 1000000 TeV
We may need more theory! BSM? Is it related with DM? QG?

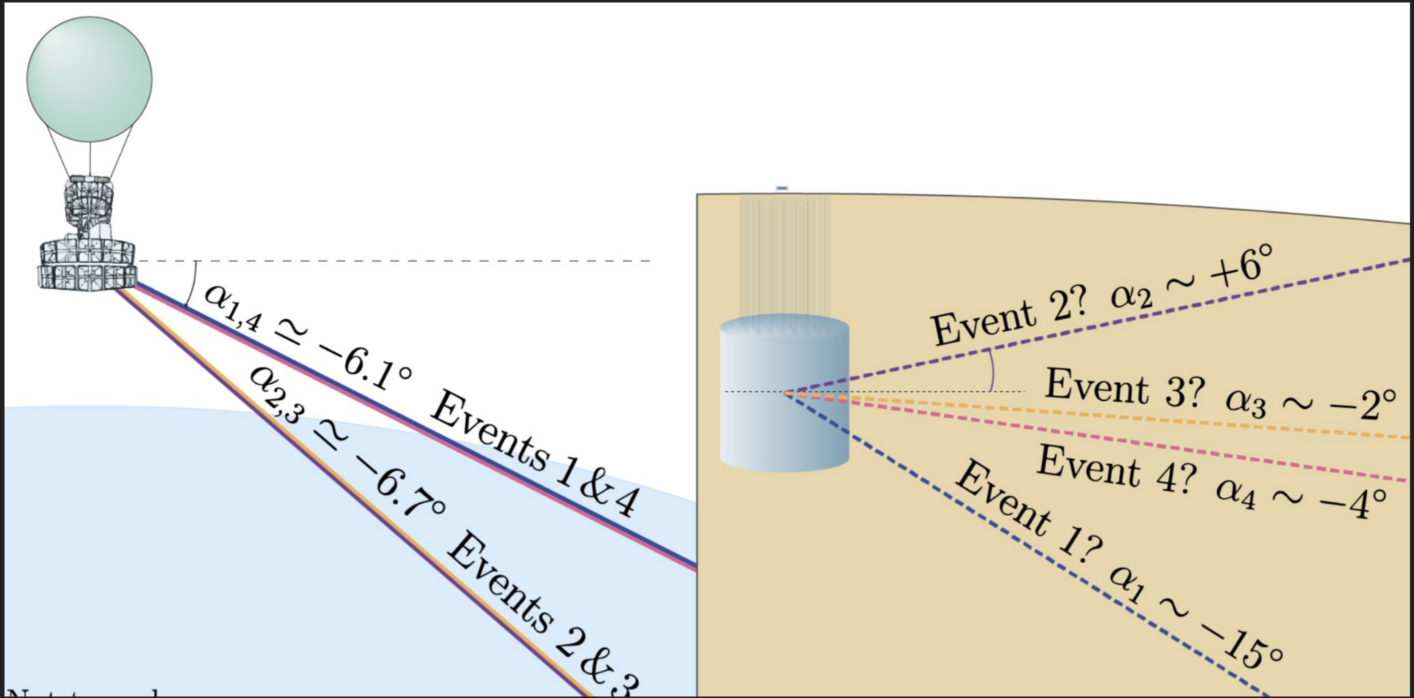
Thanks!

BKP

Last flight ANITA IV

ANITA and IceCube

Where do they come from?



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ANITA and IceCube

The no observation by

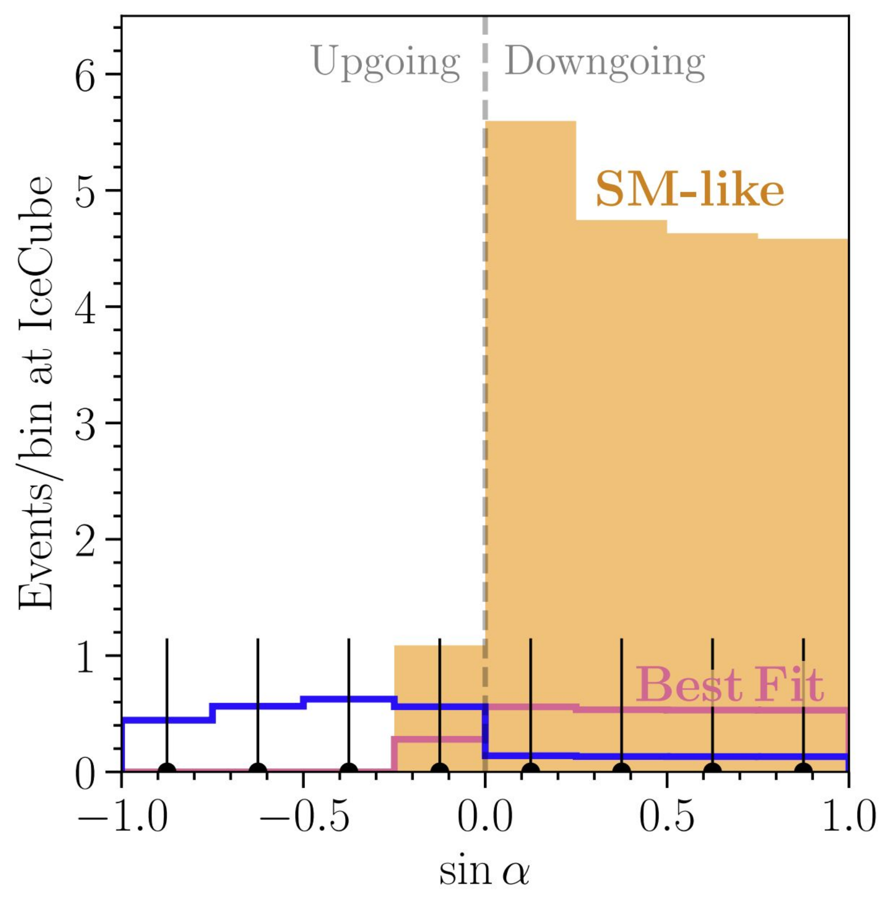
IceCube

SM-like

$$\sigma = \sigma_{\mathrm{SM}} = 3 \times 10^{-32}\,\mathrm{cm}^2,$$
$$\tau = \tau_{\mathrm{SM}} = 2 \times 10^{-4}\,\mathrm{s}$$

ANITA+IC Best Fit

$$\sigma = 0.4\sigma_{\mathrm{SM}},\ \tau = 5\tau_{\mathrm{SM}}$$
$$\sigma = 0.004\sigma_{\mathrm{SM}},\ \tau = 5\tau_{\mathrm{SM}}$$



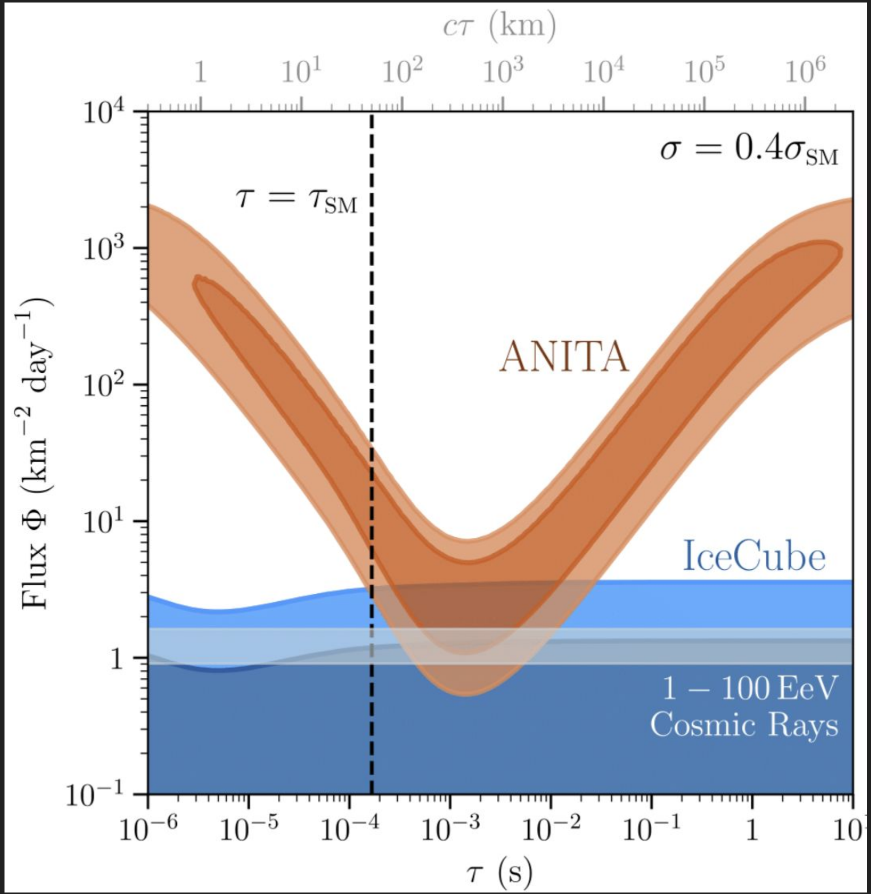
Last flight ANITA IV

ANITA and IceCube

The no observation by IceCube can be accommodated with the ANITA result in BSM with relatively large fluxes.

O(10) the expected for neutrinos at this energies, similar to the UHECR in 1-100EeV

In BSM scenario this can be achieved by heavy DM-decay.



Where in the equations are this effects?

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T^{\mu\nu}$$

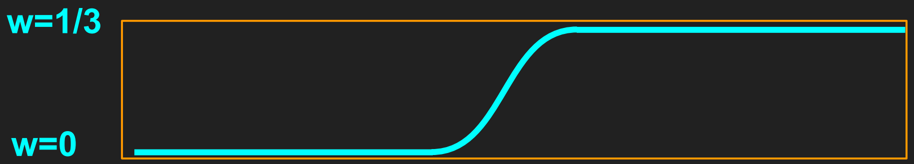
$$\nabla_\mu T^{\mu\nu} = 0$$

By using this for the first order perturbations we generically get.

$$\dot{\delta} = -(1+w)(\theta - 3\dot{\phi}) - 3\frac{\dot{a}}{a}\left(c_s^2 - w\right)\delta$$

$$\dot{\theta} = -\frac{\dot{a}}{a}(1-3w)\theta - \frac{\dot{w}}{1+w}\theta + \frac{c_s^2}{1+w}k^2\delta - k^2\sigma + k^2\psi$$

Variable that relates how energy change when we change the volume (EOS) **The only one that appears at O(0).**



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Variables associated to small scale physics, involved in damping and propagation of the initial **perturbations. Not Constants.**

Where in the equations are this effects?

$$\dot{\Psi}_0 = -\frac{q}{\epsilon}\Psi_1 - \frac{d\ln f_0}{d\ln q}\dot{\phi}$$

$$\dot{\Psi}_1 = \frac{q}{3\epsilon}(\Psi_0 - 2\Psi_2) - \frac{\epsilon}{3q}\frac{d\ln f_0}{d\ln q}\psi$$

$$\dot{\Psi}_\ell = \frac{q}{(2\ell+1)\epsilon}[\ell\Psi_{\ell-1} - (\ell+1)\Psi_{\ell+1}]$$

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T^{\mu\nu}$$

All can be computed from the Boltzmann eq.

$$\nabla_\mu T^{\mu\nu} = 0$$

$$\dot{\delta} = -(1+w)(\theta - 3\dot{\phi}) - 3\frac{\dot{a}}{a}(c_s^2 - w)\delta$$

$$\dot{\theta} = -\frac{\dot{a}}{a}(1-3w)\theta - \frac{\dot{w}}{1+w}\theta + \frac{c_s^2}{1+w}k^2\delta - k^2\sigma + k^2\psi$$

Neutrinos are far from being a perfect fluid, they do have "viscosity" due to the efficient transfer of energy damping the density fluctuations. They do not interact!

Using a more sophisticated fluid approx.

Flows for the masses: A multi-fluid non-linear perturbation theory for massive neutrinos

Joe Zhiyu Chen (New South Wales U.), Amol Upadhye (New South Wales U. and Liverpool John Moores U., ARI), Yvonne Y.Y. Wong (New South Wales U.)

Oct 28, 2022

An accurate fluid approximation for massive neutrinos in cosmology

Caio Nascimento