PANE 2018 - Closing Remarks

Advanced Workshop in Atmospheric Neutrino Physics 2018, ICTP, Trieste

Paschal Coyle

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE
CPPM

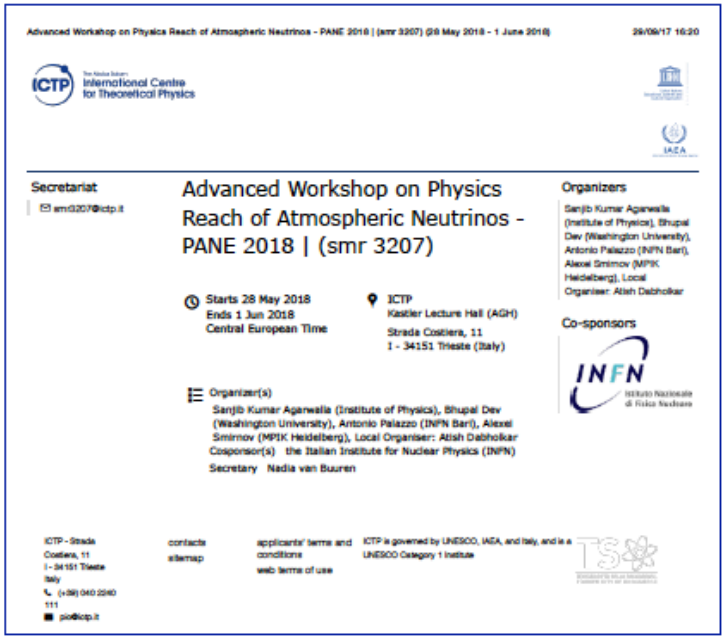
Trieste, 1 June 2018

PANE 2018

Agarwalla

The goal of the workshop is to further explore physics potential of atmospheric neutrinos and support the physics case of new experiments. We plan to bring together leading experts in both theory and experiment as well as young researchers to assess the state-of-the-art knowledge in this field and to foster further theoretical, phenomenological, and experimental studies in atmospheric neutrino physics.

Important Year



Advanced Workshop on Physics Reach of Atmospheric Neutrinos - PANE 2018 | (smr 3207) (28 May 2018 - 1 June 2018) 29/09/17 16:20

ICTP International Centre for Theoretical Physics

Secretariat

Advanced Workshop on Physics Reach of Atmospheric Neutrinos - PANE 2018 | (smr 3207)

Starts 28 May 2018
Ends 1 Jun 2018
Central European Time

ICTP
Kastler Lecture Hall (AGH)
Strada Costiera, 11
I - 34151 Trieste (Italy)

Organizer(s)
Sanjib Kumar Agarwalla (Institute of Physics), Bhupal Dev (Washington University), Antonio Palazzo (INFN Bari), Alexei Smirnov (MPIK Heidelberg), Local Organiser: Atish Dabholkar
Cosponsor(s) the Italian Institute for Nuclear Physics (INFN)
Secretary Nadia van Buuren

Organizers
Sanjib Kumar Agarwalla (Institute of Physics), Bhupal Dev (Washington University), Antonio Palazzo (INFN Bari), Alexei Smirnov (MPIK Heidelberg), Local Organiser: Atish Dabholkar

Co-sponsors

INFN Istituto Nazionale di Fisica Nucleare

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Year 2018

30 years from publication of atmospheric neutrino anomaly

20th anniversary of discovery of atmospheric neutrino oscillation

Important year for ORCA, PINGU, INO

What do we want to know?

Precision scrutiny of the three neutrino oscillation paradigm

Only 3 neutrinos

Mixing parameters, octant of theta23

Unitarity of the PMNS matrix

Tau appearance

Neutrino masses
Dirac vs Majorana

MSW effect in matter at GeV scale
Paramagnetic resonance in matter at GeV scale

Mass ordering

CP violation

Understand background for cosmic neutrino signal, proton decay

Any sign of new physics?

The Nitty Gritty !

Learned

Virtues of Atmospheric Neutrinos

including contrast to manmade neutrinos

- Free and beam always `on'
- Atm Neutrino Energy Range: ~10 MeV -> 100 TeV,
  ~7 orders of mag + 5 orders more in astro
  accel: ~ 1-2 orders of mag for given beam, <10 TeV so far
- Up/Down Going Symmetry, broken by oscillations
- Earth provides variable absorber, coded by zenith angle,
  ~0–10^{10} gm/cm^2
- mu/e at ~1 GeV: very reliable ratio
- Has small but useful tau content
- Venue for discovery of neutrino oscillations and mass

- Atm neutrino detectors can also detect accel beams

Goswami

Compared to LBL Expts?

Salient Features of Atmospheric & LBL experiment

Atmospheric Neutrinos

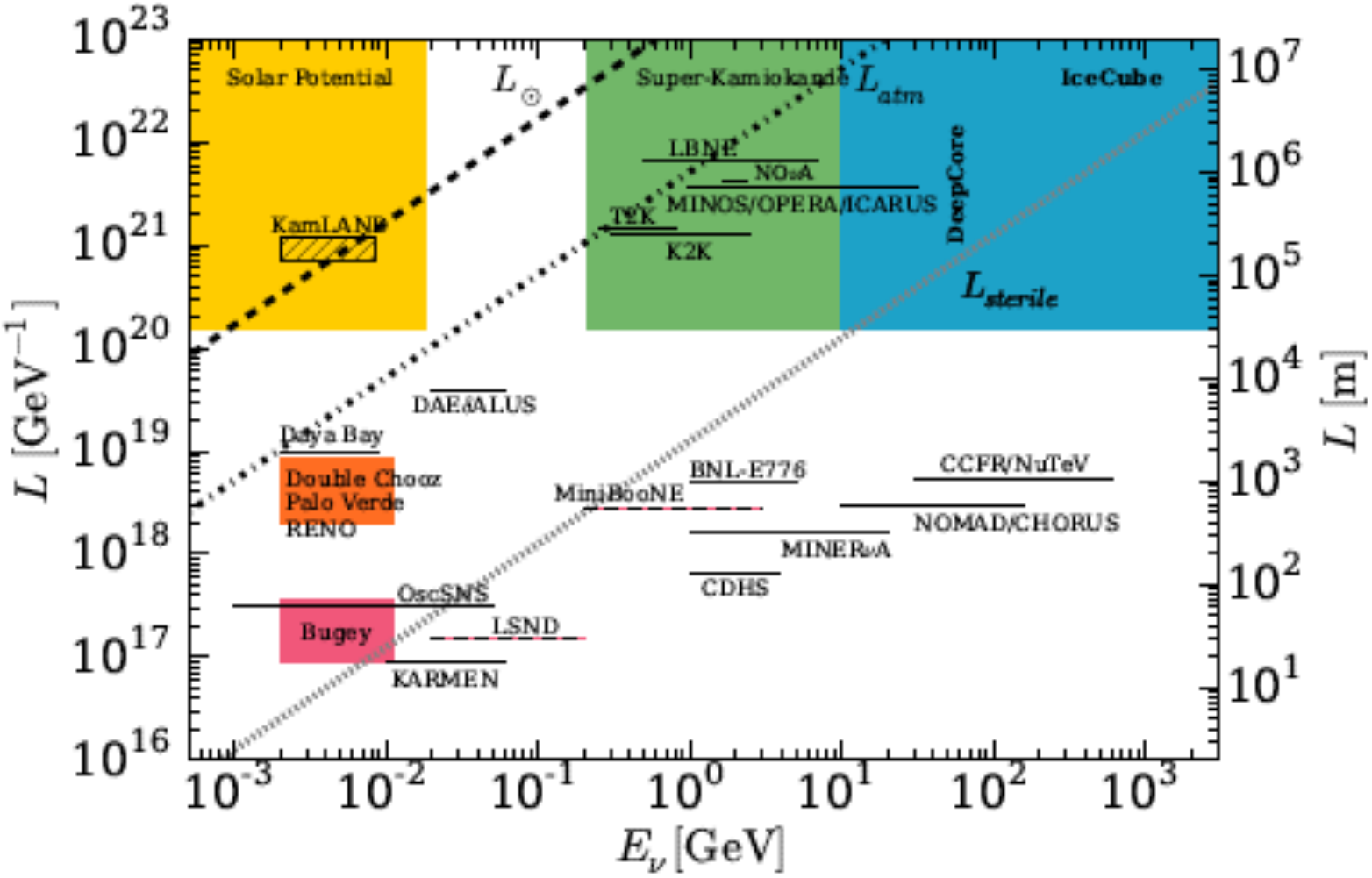
- Path length 10 – 10,000 km
- Broad range of energy compared to other natural or artificial sources
- Can probe resonant matter effects
- Source of ν_μ , $\bar{\nu}_\mu$, ν_e , $\bar{\nu}_e$
- $N_\mu \sim N^0_\mu P_{\mu\mu} + N^0_e P_{e\mu}$
- $N_e \sim N^0_\mu P_{\mu e} + N^0_e P_{ee}$
- Cannot disentangle disappearance and appearance channels
- Both neutrinos and antineutrinos and only detectors with chargeID can probe these separately

Long-baseline Neutrinos

- Fixed Path Length < 1500 km
- Narrow band and wide band beams, smaller range for latter
- Can't probe resonant matter effect
- Source of ν_μ or $\bar{\nu}_\mu$
- Disappearance channel $N_\mu \sim P_{\mu\mu} N^0_\mu$
- Appearance Channel $N_e \sim P_{\mu e} N^0_\mu$
- Can probe disappearance and appearance channels separately
- The same experiment can also run in antineutrino mode

- Hierarchy-CP degeneracy not present
- No significant degeneracy between CP and Sintheta23

Atmospheric Neutrinos



Baselines and energies inaccessible to LBL or reactor neutrino experiments

Very different systematics

Above tau production threshold

The Neutrino Saga

A Saga? Yes, a great scientific tale of persistence, dead ends, serendipitous discovery, redemption and glory

- Saga: "a long story of heroic achievement, especially a medieval prose narrative in Old Norse or Old Icelandic." (OED)
- Indeed the tale of atmospheric neutrino studies has much of this....

dreams in Russia and US in 1950's
ld fields in India and South Africa, 1960's
small groups of true believers on little support 1970's

propose mystical quest for finding proton decay in late 1970's

ound instruments in 1980's in US, Europe, Japan and Russia
n neutrino anomaly in 1983 onwards, but much struggle to make sense of
esults and even animosity amongst explorers

for Kamioka, IMB and Baksan
by radiochamical experiments, but Kamiokande gives gold

rings redemption, fame and fortune in 1998 with the discovery of muon
(and not electron neutrinos)
nail the lid on electron neutrino oscillations and neutrino mass

- Finally IceCube definitively finds cosmic HE neutrinos completing a 40 year quest to start neutrino astronomy.

Workshop Topics

Conventional Physics

Cosmic rays fluxes

Atmospheric neutrino fluxes
Prompt neutrino fluxes

Neutrino cross sections

Neutrino oscillations

Mass hierarchy

CP violation

Tomography of the Earth

New Physics

NSI
non-unitarity
sterile neutrinos
Decoherence
Invisible
long range force
extra dimensions
LIV
NSI+sterile

dark matter
Proton decay

Experiments

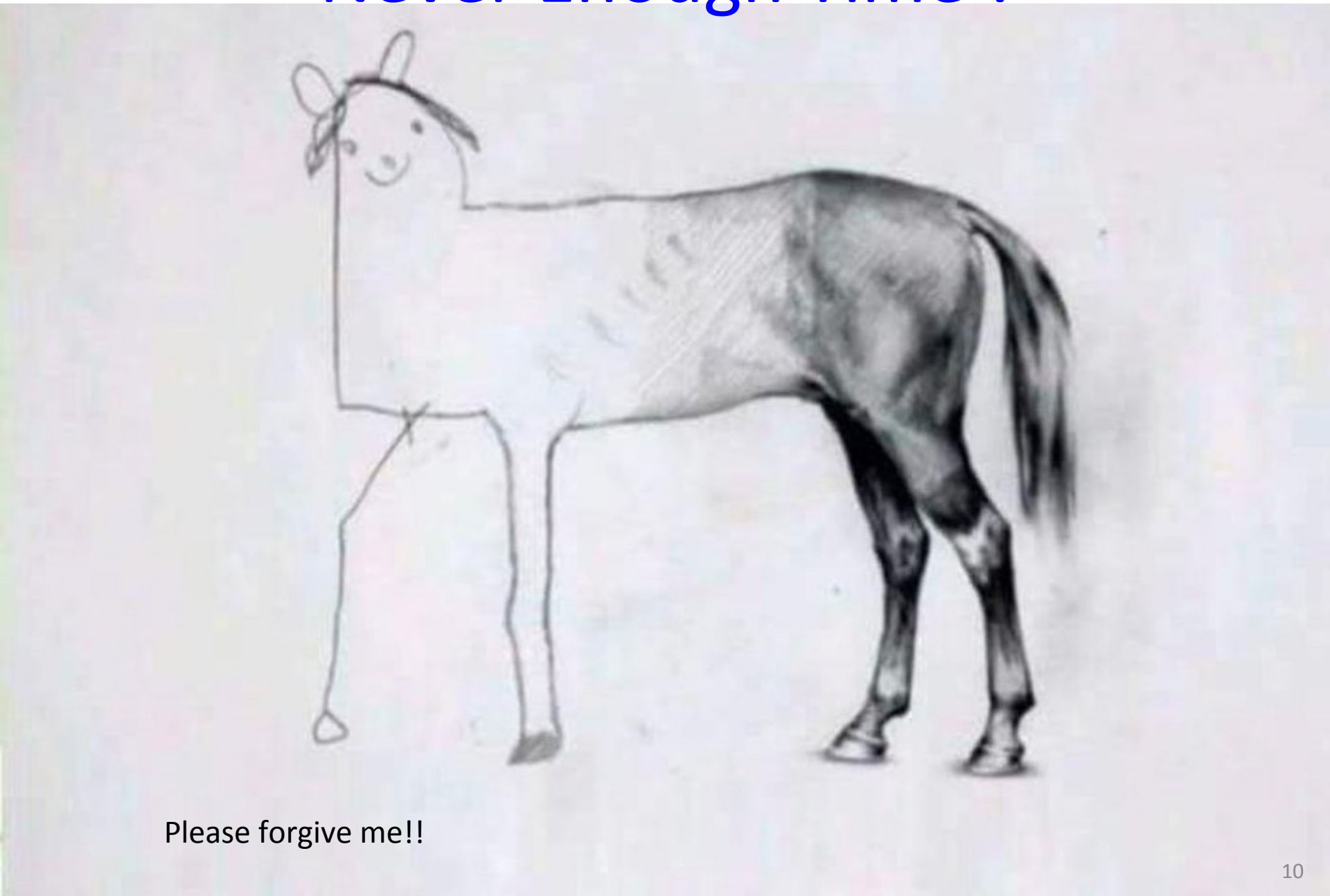
SuperK
SK-GD
HyperK

Amanda
IceCube/DeepCore
Gen2/Pingu

ANTARES
KM3NeT/ORCA/ARCA
(P2O)
(SuperORCA)

INO

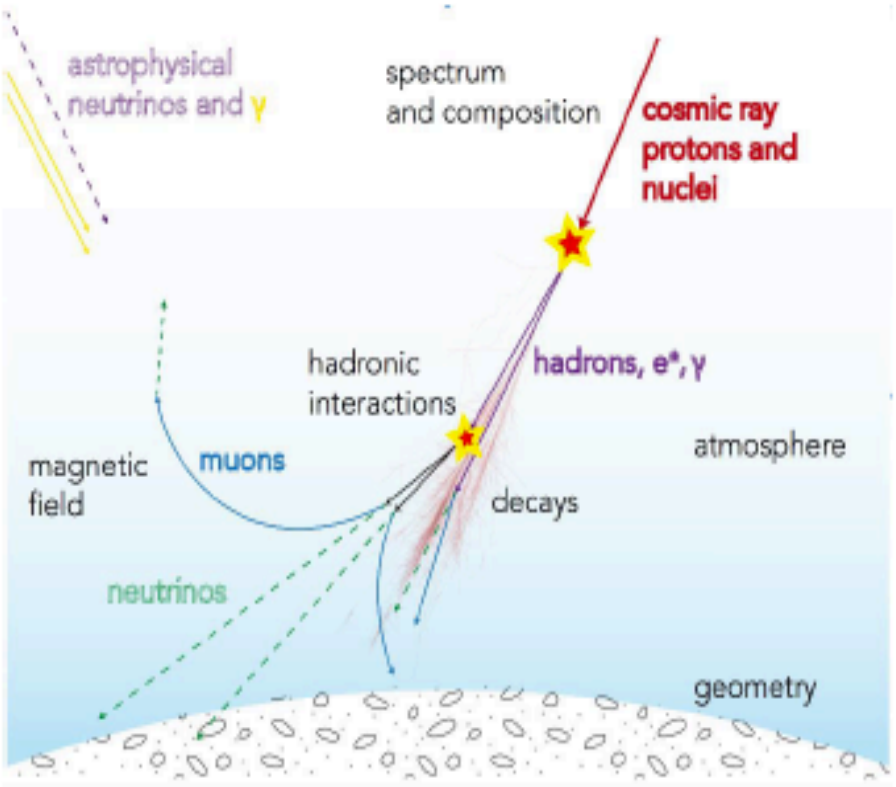
Never Enough Time !



Please forgive me!!

Ingredients for atmospheric neutrino flux calculations

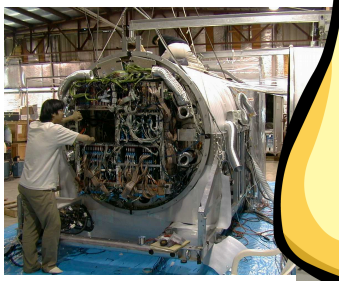
Fedynitch

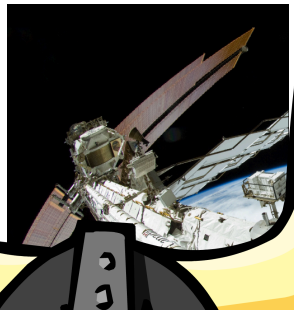


- For high precision calculations all phenomena need accurate modeling
- Uncertain "ingredients":
  - Cosmic ray spectrum and composition
  - Hadronic interactions
  - Atmosphere (dynamic, depends on use case)
  - (Rare) decays
  - Geometry, magnetic fields, solar modulation
- No clear prescription how to handle uncertainties.
- Energy range MeV – EeV!

Cosmic ray Fluxes

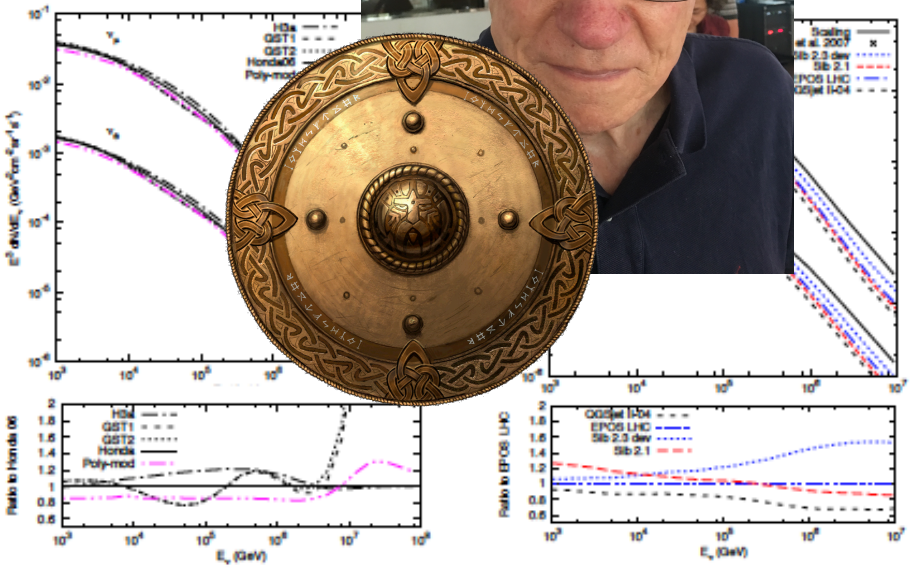
Honda
Gaisser





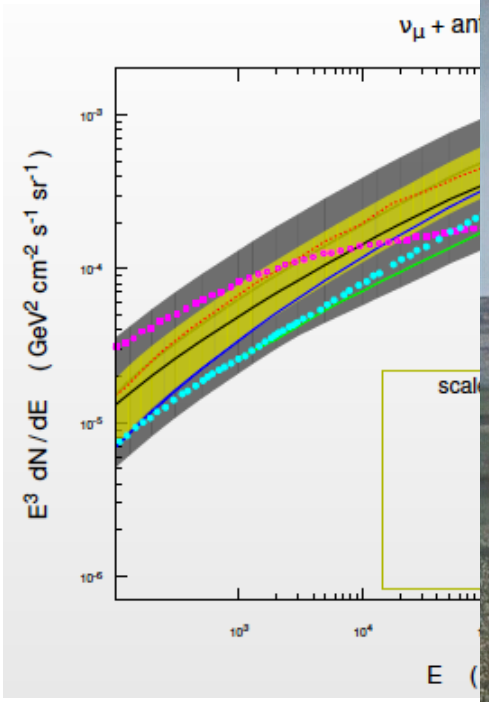
Uncertainties ir fluxes:

Different primary spectra raction models



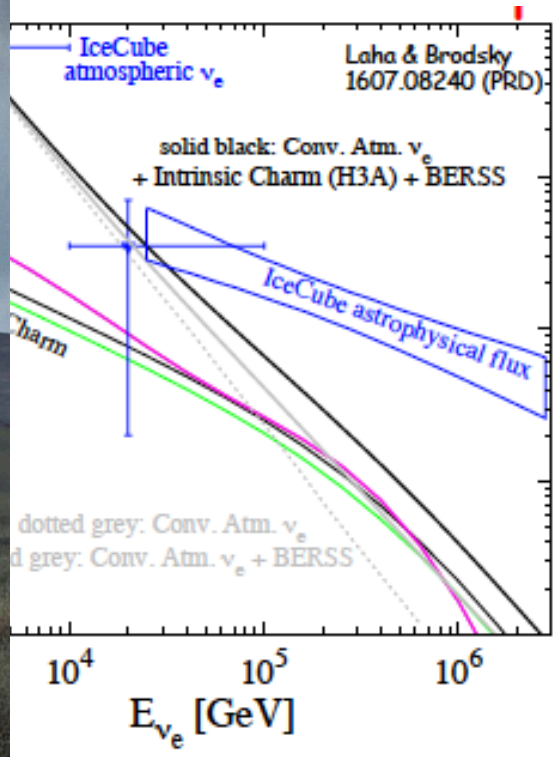
Prompt Neutrino Fluxes

Garzelli



Different predict
within uncertain

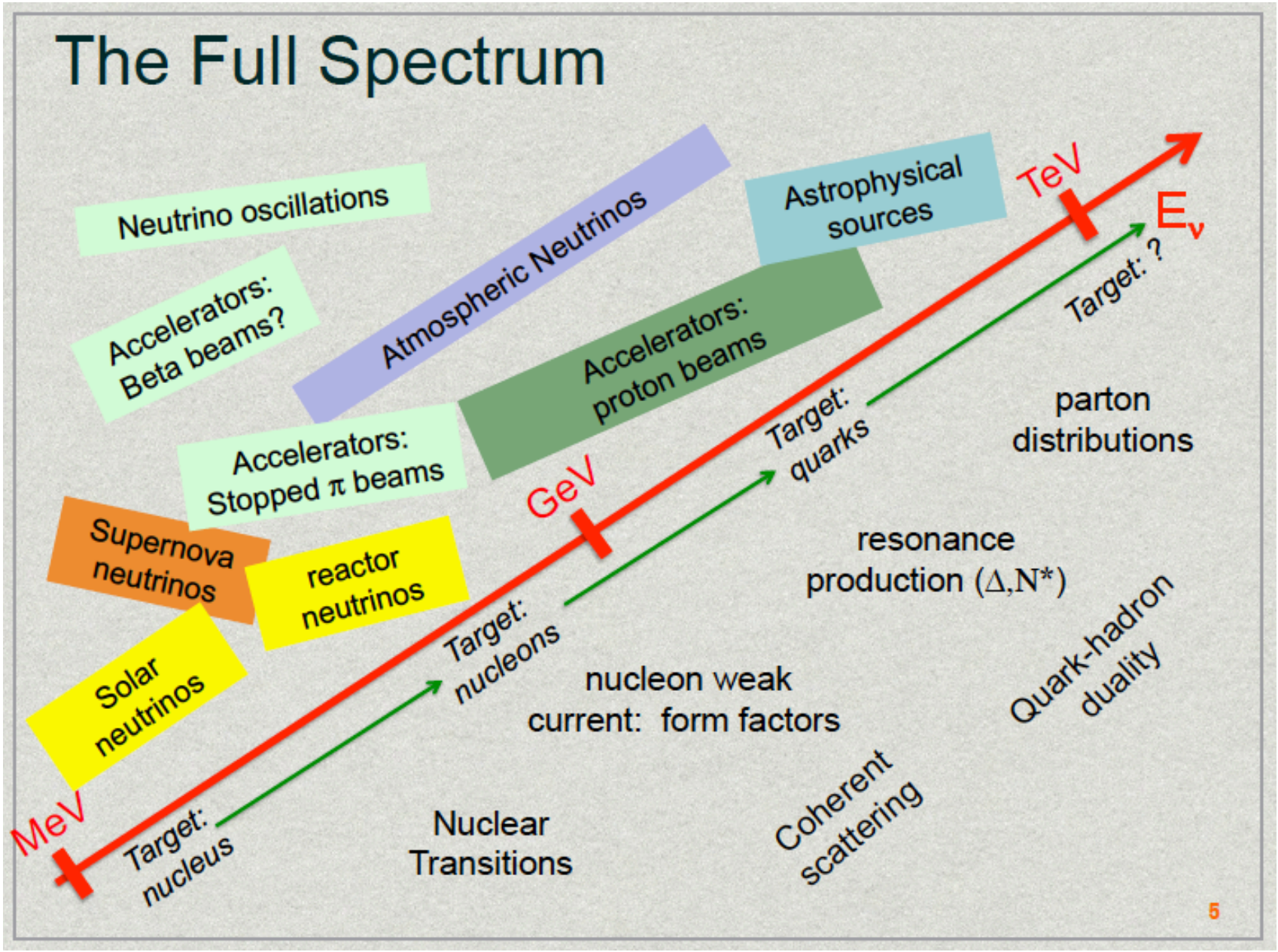
Intrinsic charm Laha



E/dx of tau tracks less - Laha

Neutrino Interactions

Gallagher

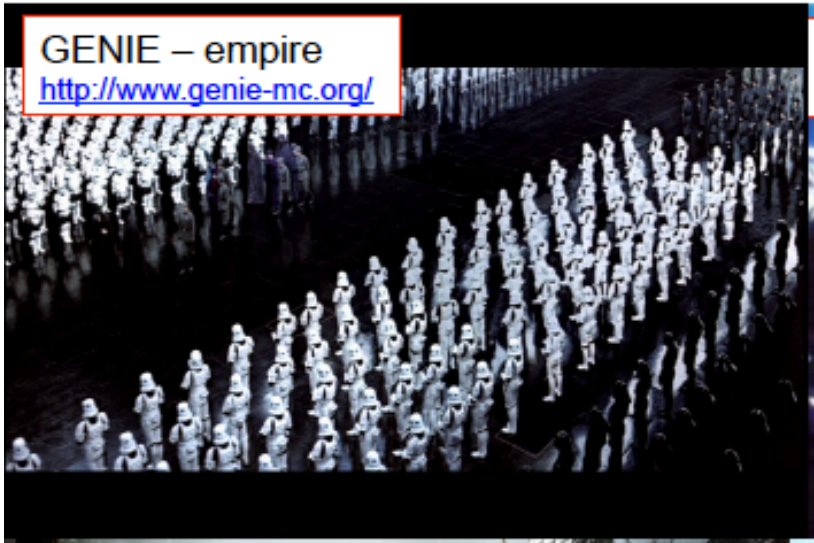


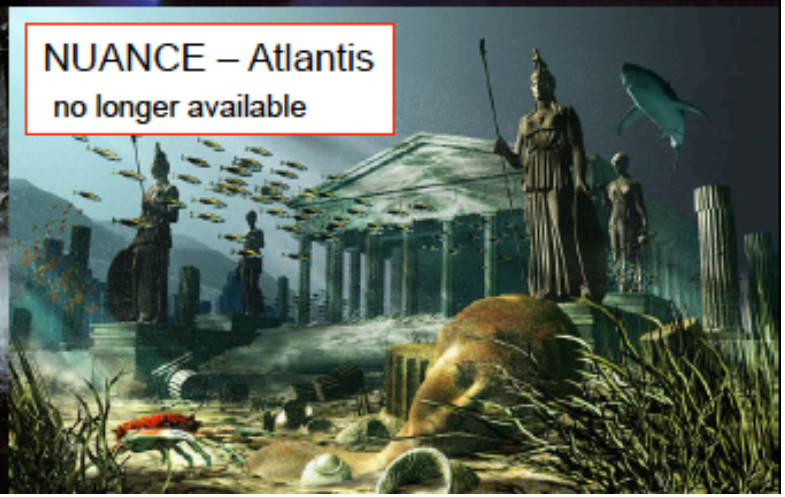
Neutrino Interactions

Katori

1. Neutrino Interaction generators

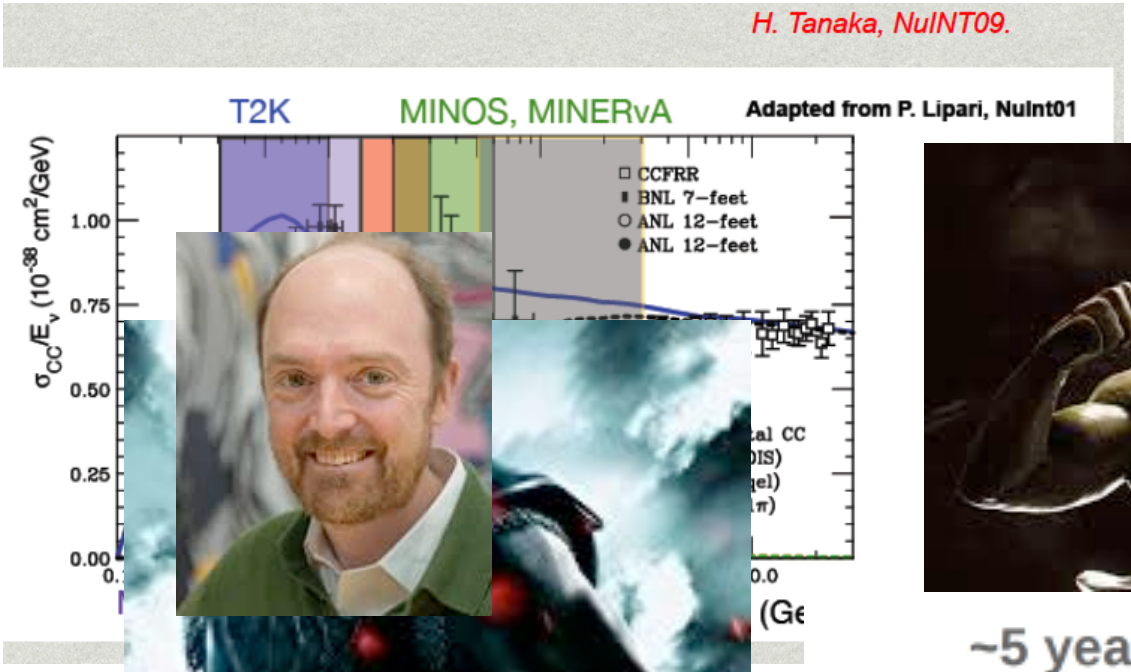
GiBUU is currently not available to use with detector simulation MC
https://gibuu.hepforge.org/trac/wiki

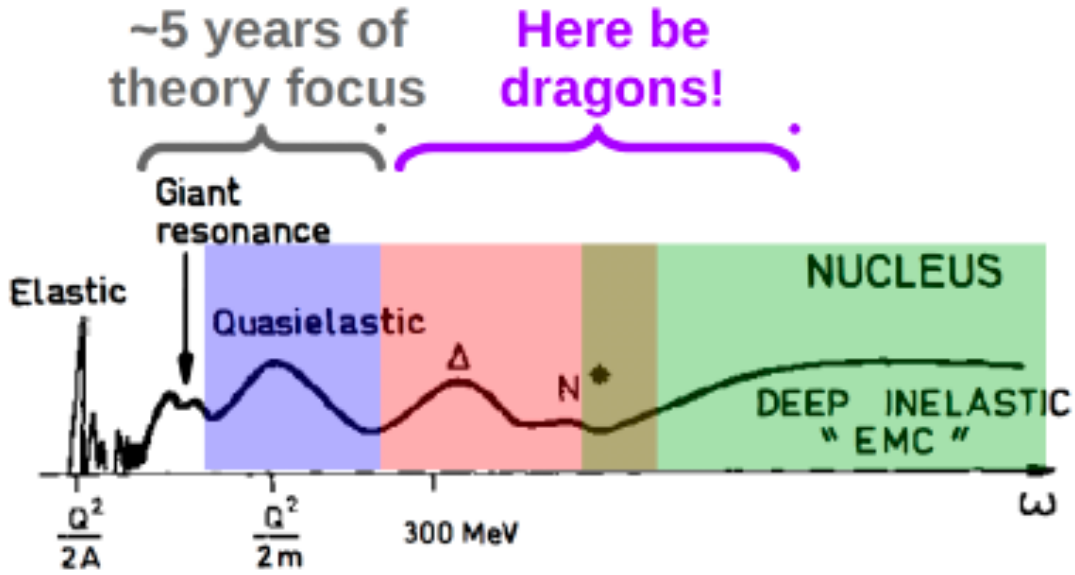




Neutrino Interactions

Gallagher



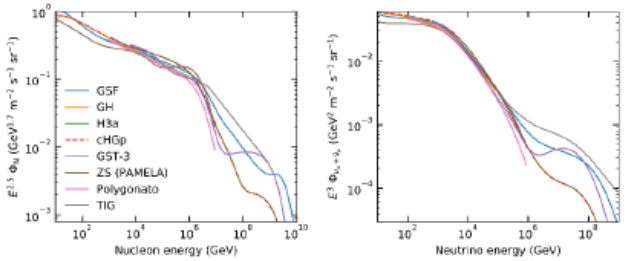


MCEq

Fedynitch

MCEq: models included in the package

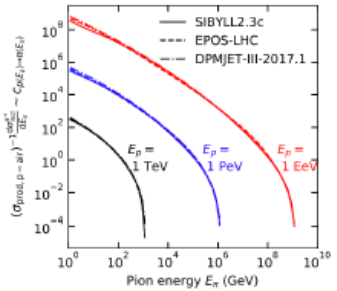
Cosmic ray flux at the top of the atmosphere



Short name	Reference	Description	Valid range [GeV]
H3a	[35]	three astrophysical populations, broken power laws, five mass groups, heavier composition at ultra-high energies (UHE)	$10^3 - 10^{11}$ GeV
H4a	[35]	same as H3a but with proton composition at UHE	$10^3 - 10^{11}$ GeV
GST-3	[36]	three population, broken power-law fit heavier composition between knee and ankle (second knee)	$10^3 - 10^{11}$ GeV
GST-4	[36]	like GST-3 but with an fourth extragalactic proton component at UHE	$10^3 - 10^{11}$ GeV
GH	[37]	power-law model with five mass groups, often used in atmospheric neutrino flux calculations below knee energies [7, 38, 6]	< PeV
cHGp	[8, 37, 35]	combination of GH at low energy and H4a above	tens -10^{11} GeV
cHGm	[8, 37, 35]	like cHGp but with H3a instead of H4a	tens -10^{11} GeV
Polygonato	[39]	broken power-law fit, based on renormalization of various cosmic ray measurements up to knee energies	few TeV – PeV
ZS	[40, 41]	original model by Zatsepin and Sokolskaya, also including re-fitted parameters by the PAMELA collaboration	tens GeV – PeV
TIG	[17]	simple broken power law spectrum of nucleons (protons)	TeV – PeV
GSF	add..	Global Spline Fit to recent cosmic ray observations with errors	10 GeV -10^{12} GeV

Hadronic interactions

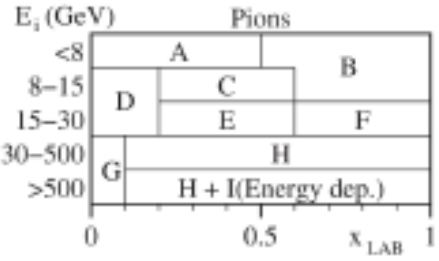
Name	Reference
Sibyll 2.1	[26]
Sibyll 2.3	[27, 28]
Sibyll 2.3c	[29]
Sibyll 2.3c (pp)	[29]
QGSJet 01-c, II-03, II-04	[30, 31]
Epos LHC	[32]
Dpmjet-III	[14]
Dpmjet-III 2017.1	[15]



- **New high-precision** (and high-performance) calculations available (MCEq) that well match full Monte Carlo

- This allows for a **new approach towards flux systematics** by replacing effective parameters with physical parameters (see next generation IceCube analyses)

Atmospheric flux		
ν flux template	discrete (7)	
ν / $\overline{\nu}$ ratio	continuous	0.025
π / K ratio	continuous	0.1
Normalization	continuous	none[1]
Cosmic ray spectral index	continuous	0.05
Atmospheric temperature	continuous	model tuned



People working in flux and detector systematics are the superheroes of our times!

"With great statistical power comes great systematic responsibility"

Many, many talks this week on this! Awesome talks/work by Fedynitch, Honda, Gaisser, Garzelli, and many others! Thank you guys!

Phenomenology

Smirnov
Raychaudhuri

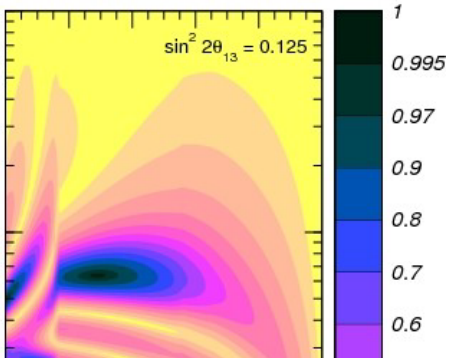
Content

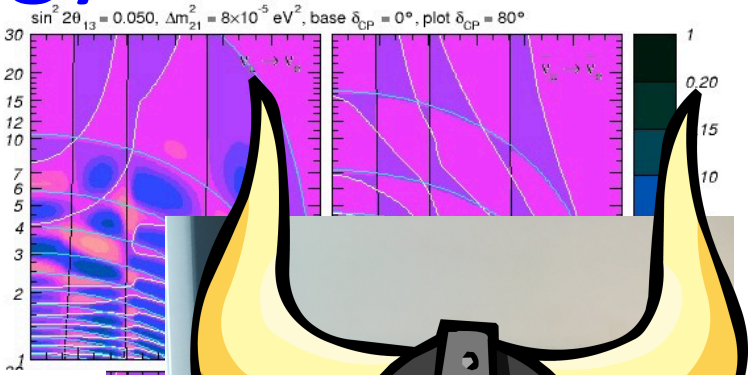
Oscillation set-up

Oscillation amplitudes and probal

Dynamics, oscillograms

Interference and CP



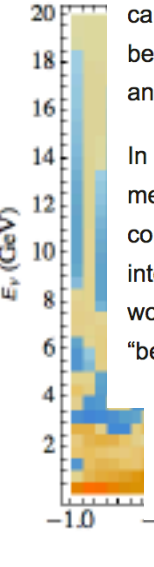


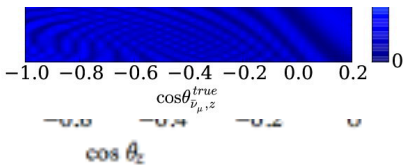
23 MARCH, 2014 - 00:24 APRILHOLLOWAY

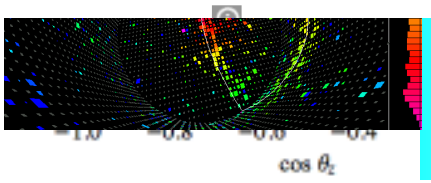
The Viking Berserkers – fierce warriors or drug-fuelled madmen?

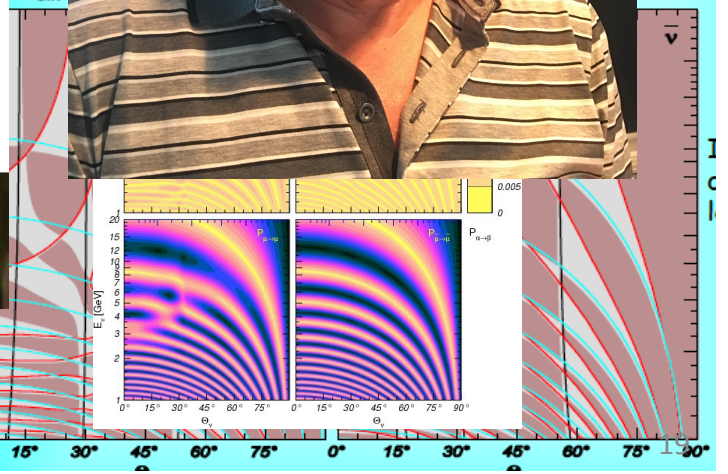
Today, the word 'berserk' is used to describe anyone in an irrational, agitated state of mind who cannot or does not control his or her actions. The meaning of the word originates with the Viking berserkers, the fierce warriors who were known for battling in an uncontrollable, trance-like fury, and were alleged to be able to perform seemingly impossible super-human feats of strength.

In medieval Norse and Germanic history and folklore, the berserkers were described as members of an unruly warrior gang that worshipped Odin, the supreme Norse deity, and were commissioned to royal and noble courts as bodyguards and 'shock troops', who would strike fear into all who encountered them. Adding to their ferocity, and in order to intimidate the enemy, they would wear bear and wolf pelts when they fought, giving them the name Berserker, meanin "bear coat" in Old Norse.

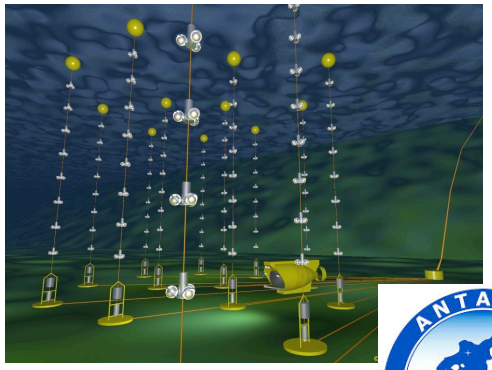








Current Detectors

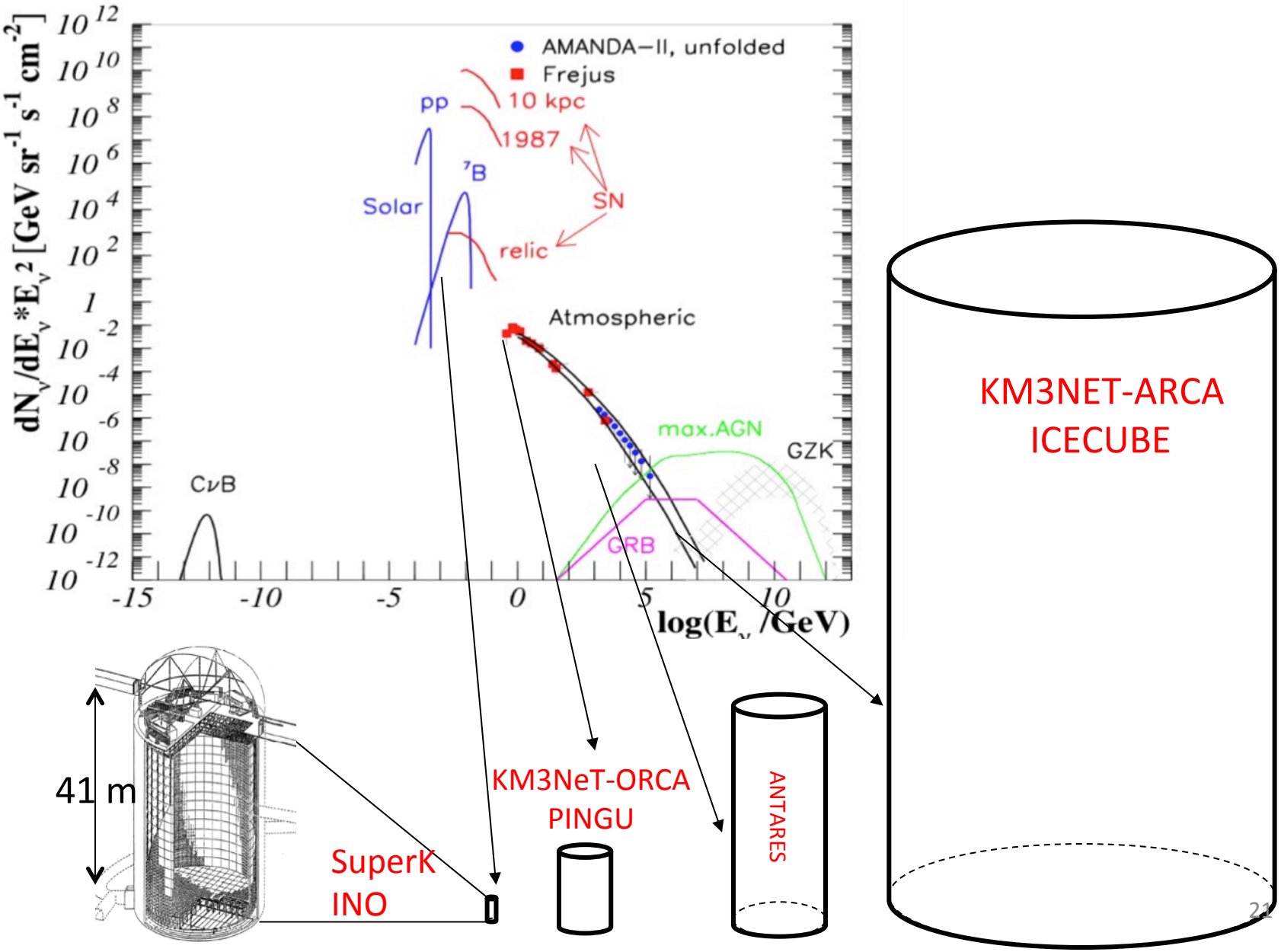


Brunner

Okumura
Bronner

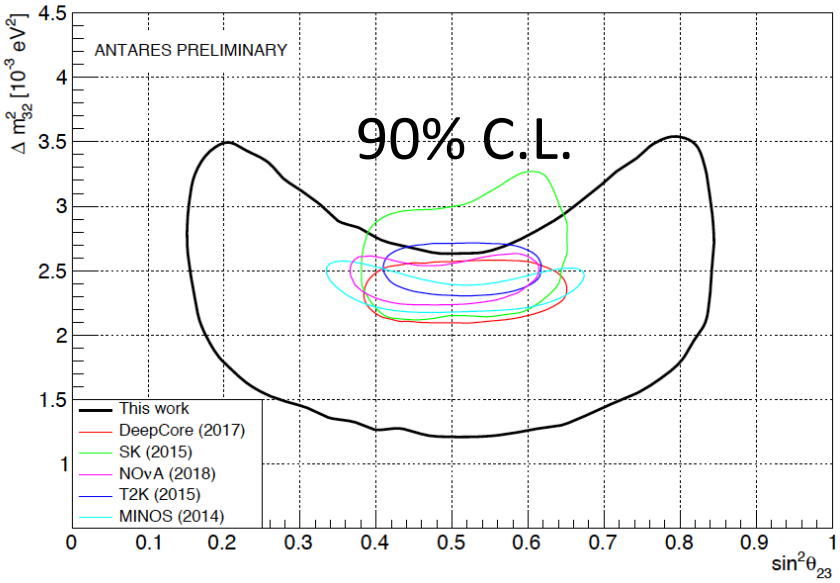
Stuttard
Bustamante
Yuan

Atmospheric Neutrino Detectors

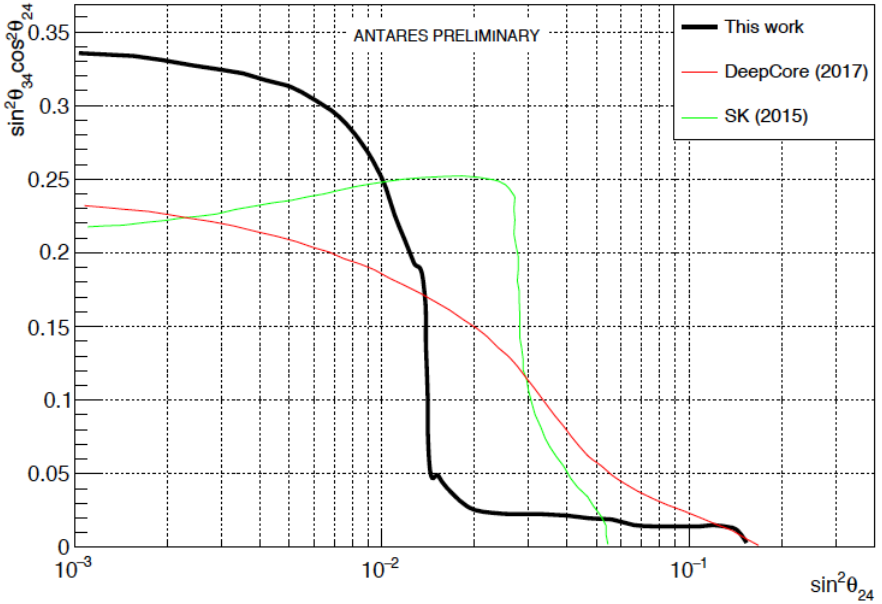


ANTARES

Brunner



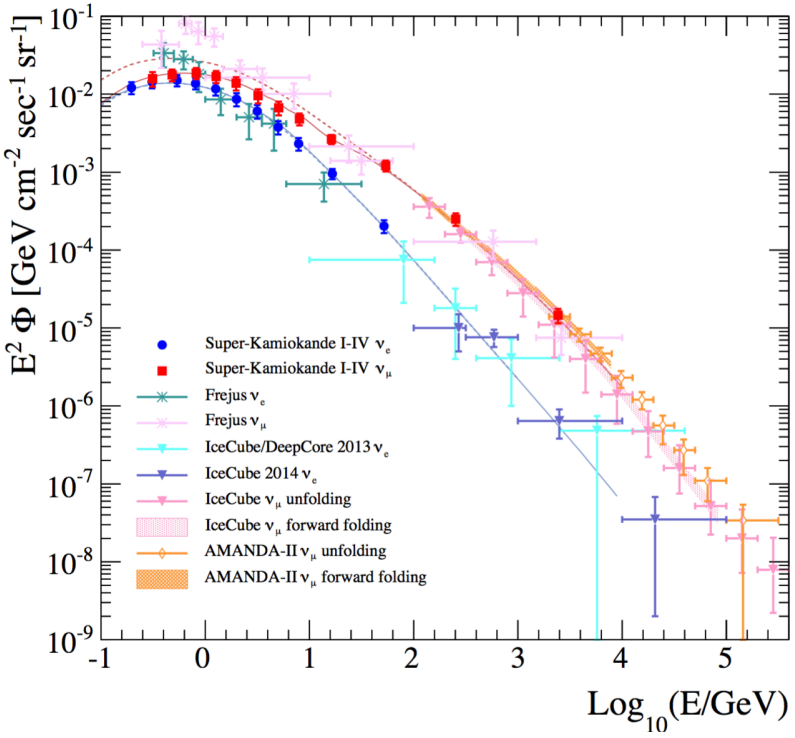
Sterile



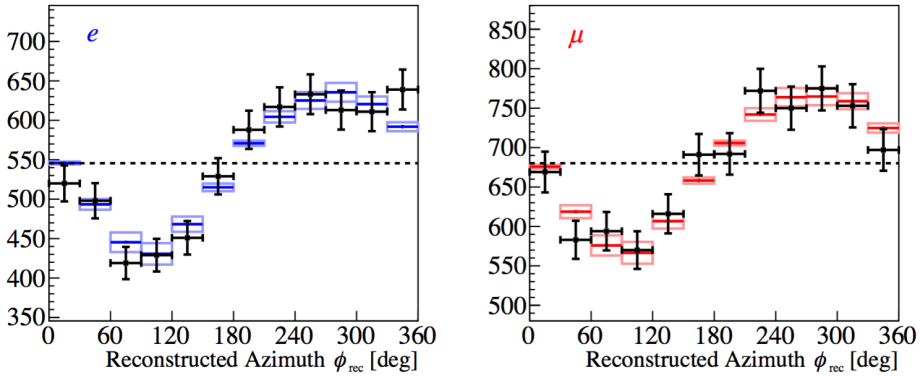
SK Results

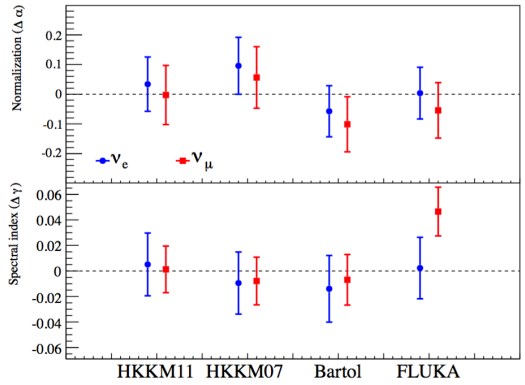
Okumura

Energy Spectrum



East-West Asymmetry





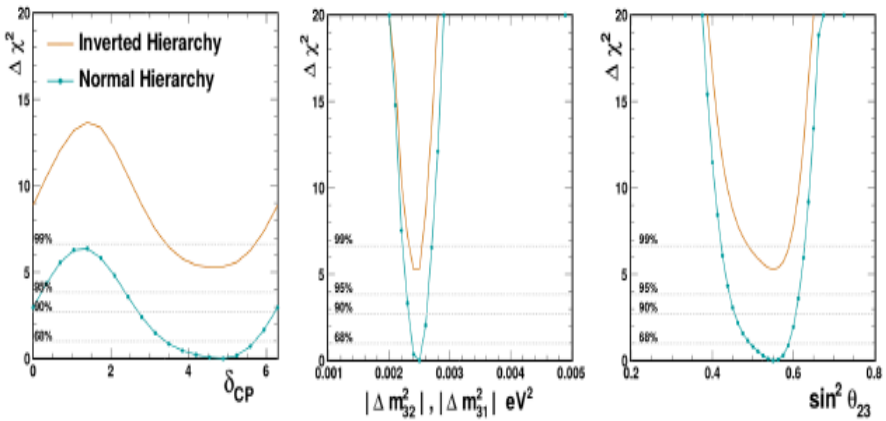
Small solar activity

SK Results

Bronner

Results with external constraints

23



	χ^2	$\lvert\Delta m^2_{32/31}\rvert$	$\sin^2(\theta_{23})$	δ_{CP}
Normal hierarchy	639.43	2.50×10^{-3}	0.550	4.88
Inverted hierarchy	644.70	2.40×10^{-3}	0.550	4.54

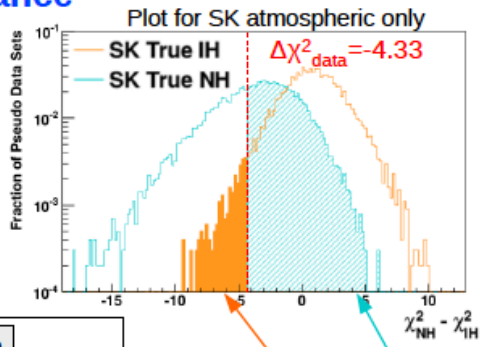
- $\chi^2(NH)-\chi^2(IH)=-5.27$
- P-value for this $\Delta\chi^2$ (true values of the parameters corresponding to the NH best fit point) is 0.023 for true IH
  → **Slightly stronger preference for the normal hierarchy**

Question about oscillogram?

Mass hierarchy Significance

24

- MH significance does not go as $\sqrt{(\chi 2)}$
  → compute p-values using toy MC
- Limited sensitivity at current statistics
  → Also compute CLs values
- Significance depend on true values of θ_{23} and δ
  → Compute for different true values



P-values and CLs for IH exclusion

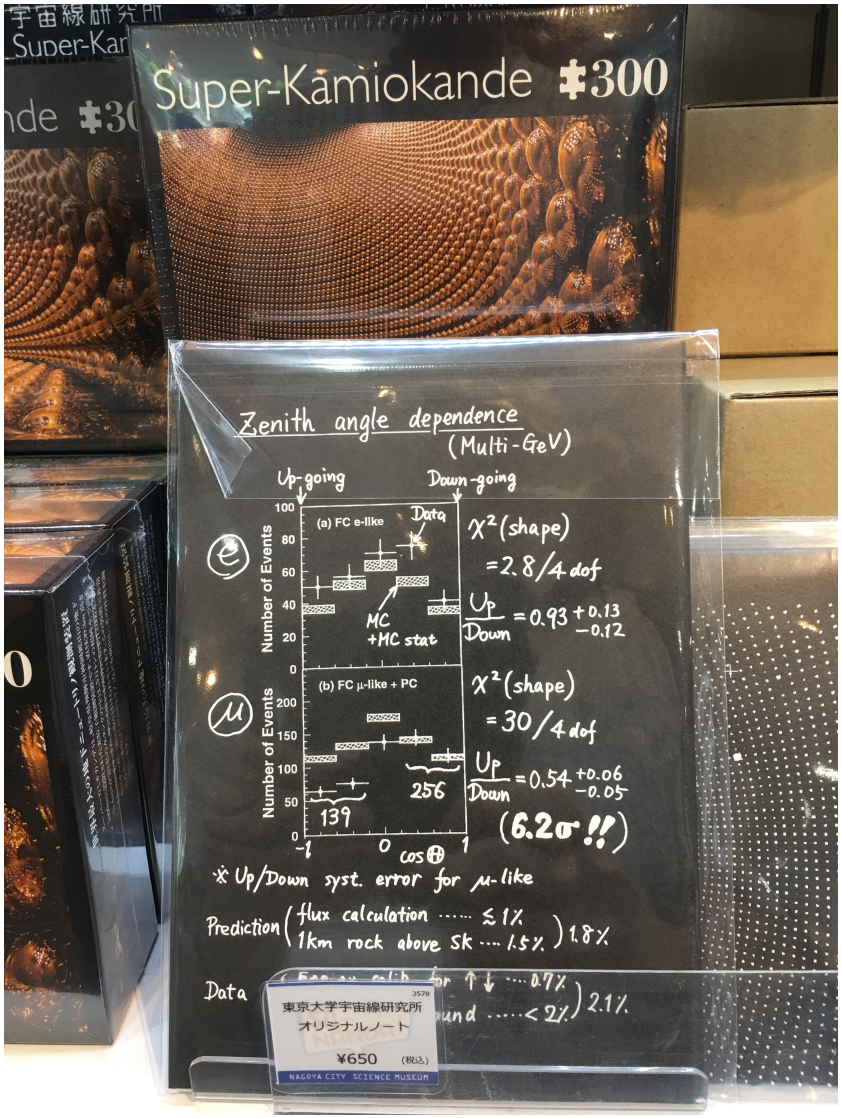
P-values	Lower	Best fit	Upper
SK only	0.012	0.027	0.020
SK+T2K model	0.004	0.023	0.024

CLs	Lower	Best fit	Upper
SK only	0.181	0.070	0.033
SK+T2K model	0.081	0.075	0.056

$$CL_s = \frac{p_0(IH)}{1 - p_0(NH)}$$

Lower/upper edges of the 90% CL intervals for $\sin^2(\theta_{23})$ and δ 24

Nagoya Science Museum: SK Jigsaw- 300 pieces (>100 systematics)

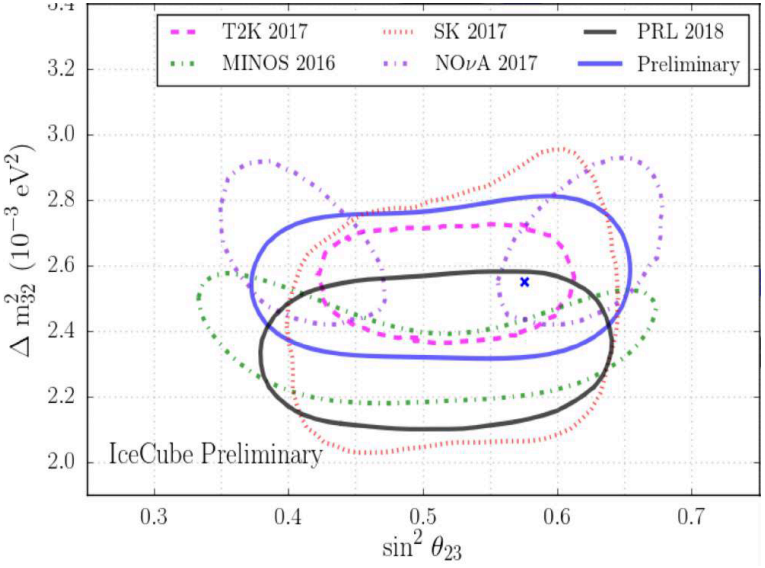


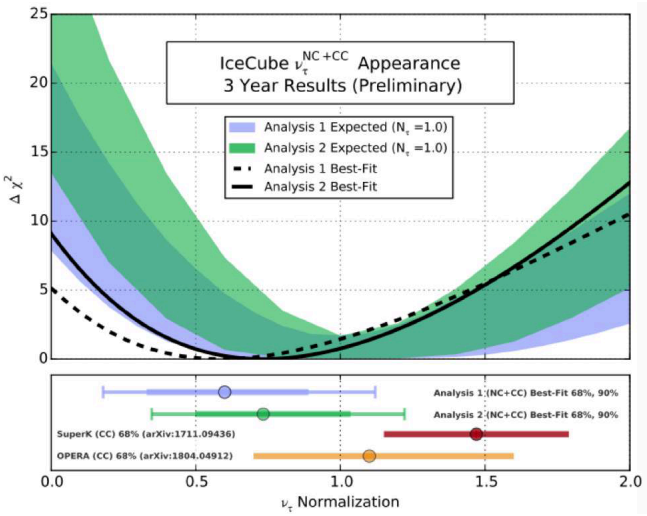
Price 650 Yen

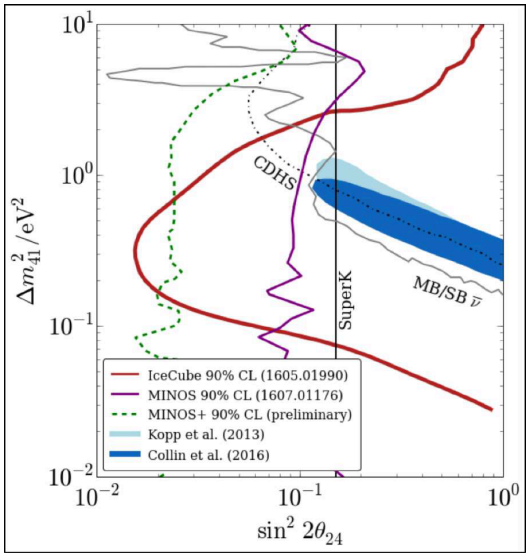
Good value for money!

IceCube

Stuttard







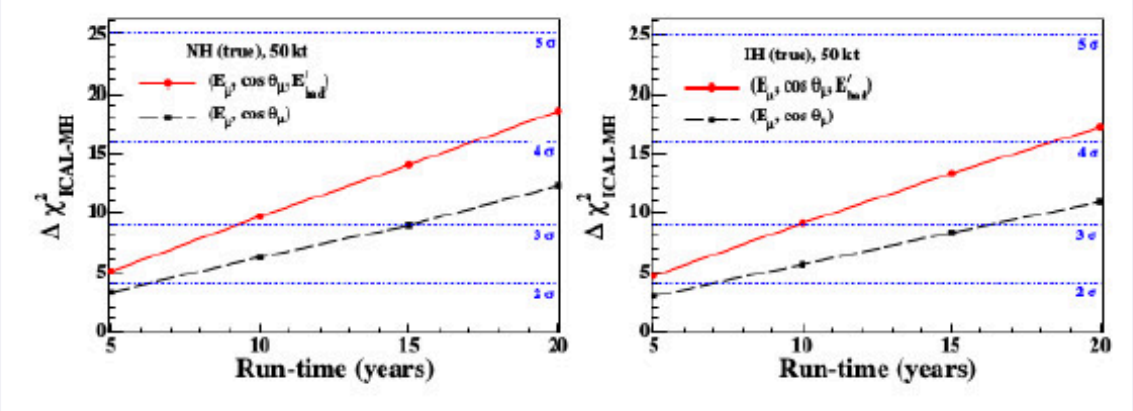
+ NSI
+ Decoherence
+ LV

Inelasticity

Dighe

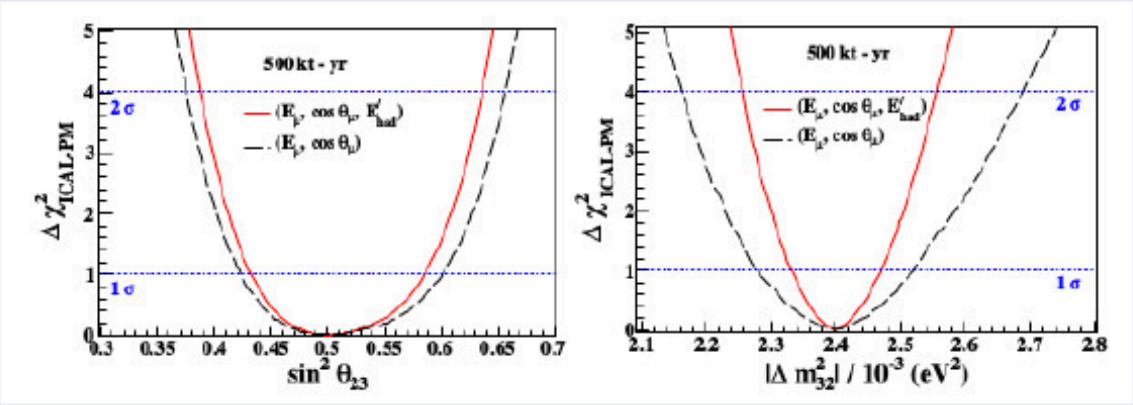
Detector performance improvement with E'_h

For mass ordering: $\sim 30 - 40\%$ improvement in $\Delta\chi^2$



M. M. Devi et al, JHEP 2014

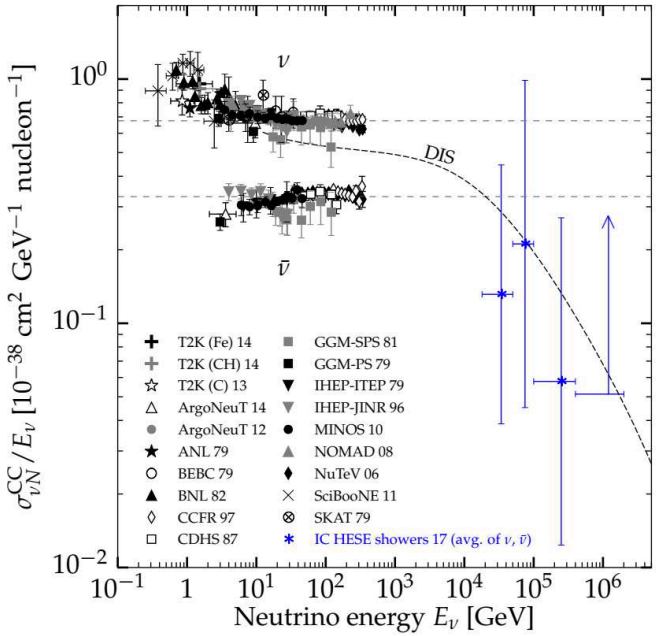
For precision measurements



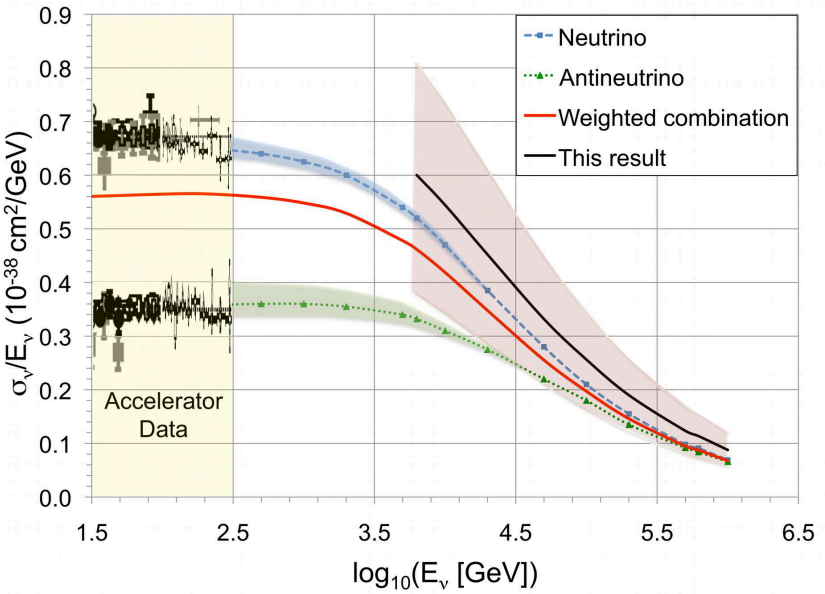
Towards High energy cross-section measurement

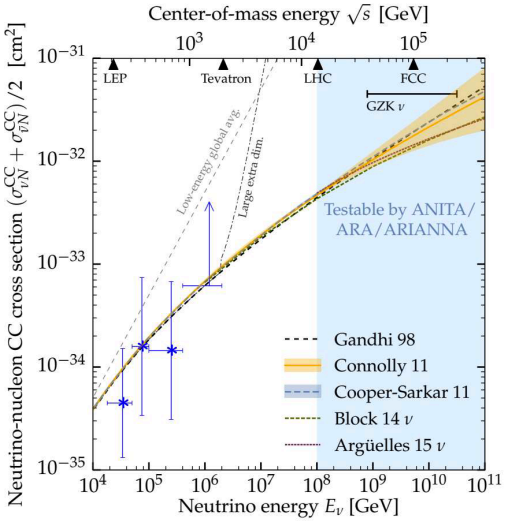
Bustamante

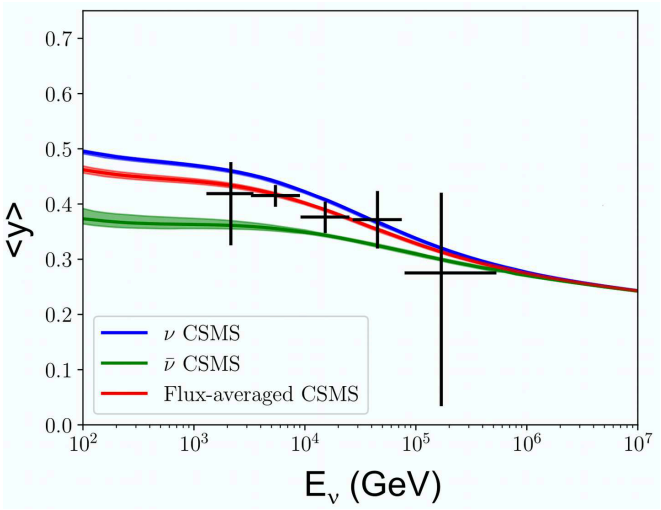
HESE showers



Through-going muons

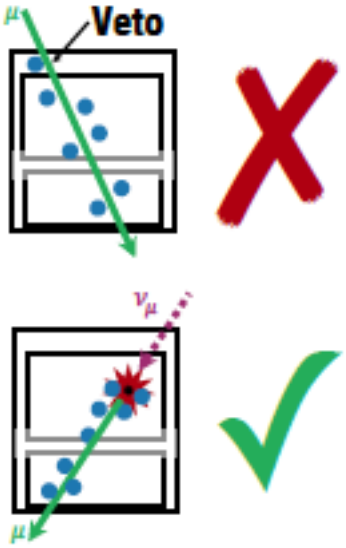






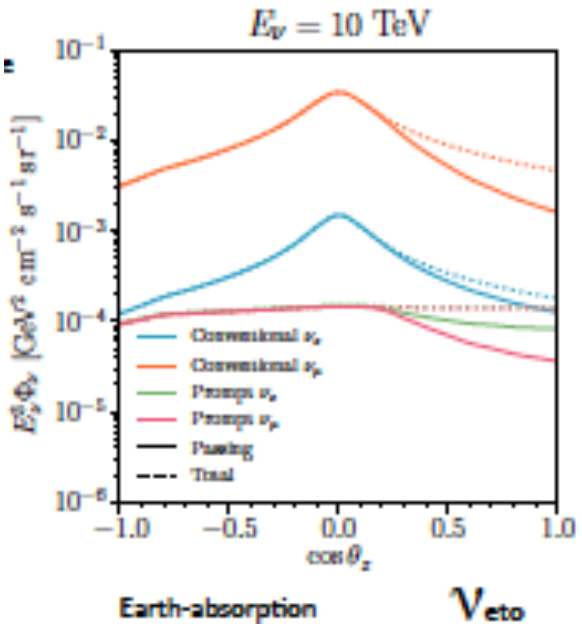
Veto Systematics

Yuan

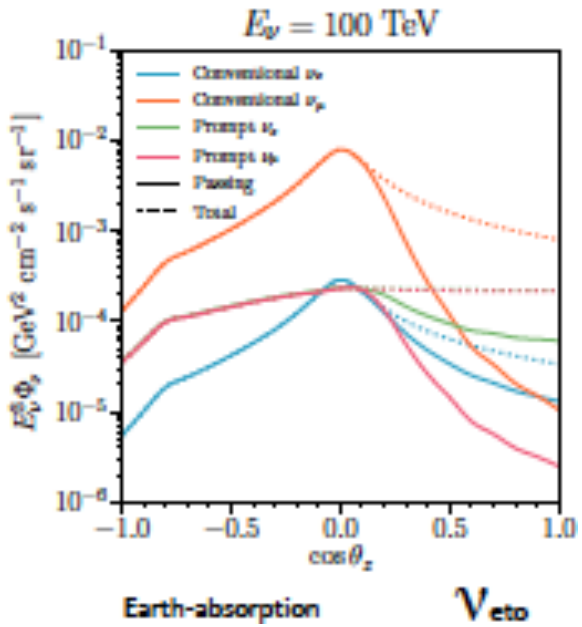


Veto is a framework for calculating the atmospheric neutrino background rate for large-scale detectors

Excellent agreement with CORSIKA and much less computationally intensive



Earth-absorption ν_{eto}

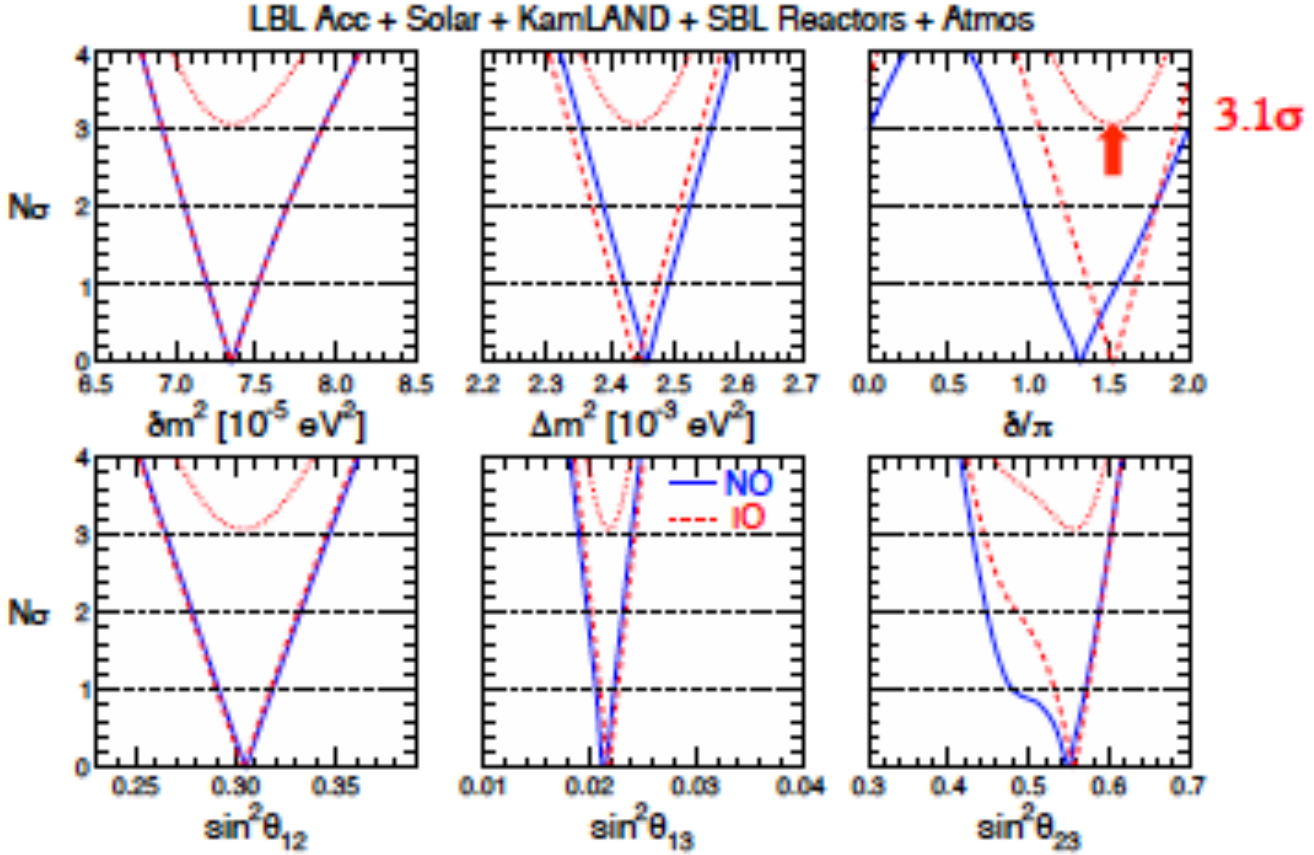


Earth-absorption ν_{eto}

Global Fits

Lisi

Global analysis of neutrino oscillation data, circa 2018 [arXiv:1804.09678]



New: Inverted Ordering disfavored at ~3σ

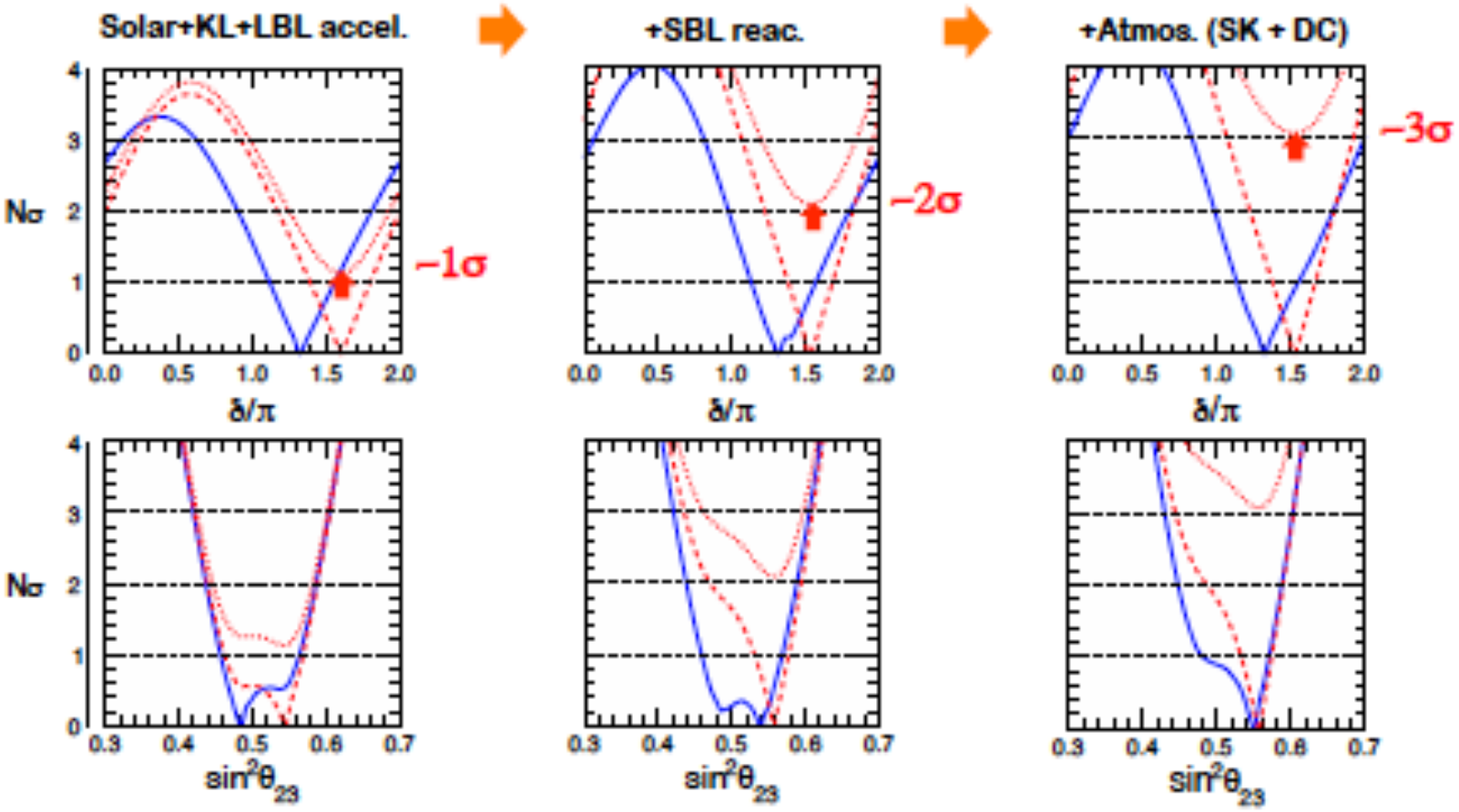
[Also: Improved constraints on δ, θ_{23}]

N.O. + 2nd octant hints = good news for atmospheric ν!

Global Fits

Lisi

Progression of bounds on 3ν oscillation unknowns



Atmospheric ν contribute ~1/2 of the IO-NO $\Delta\chi^2$ difference.

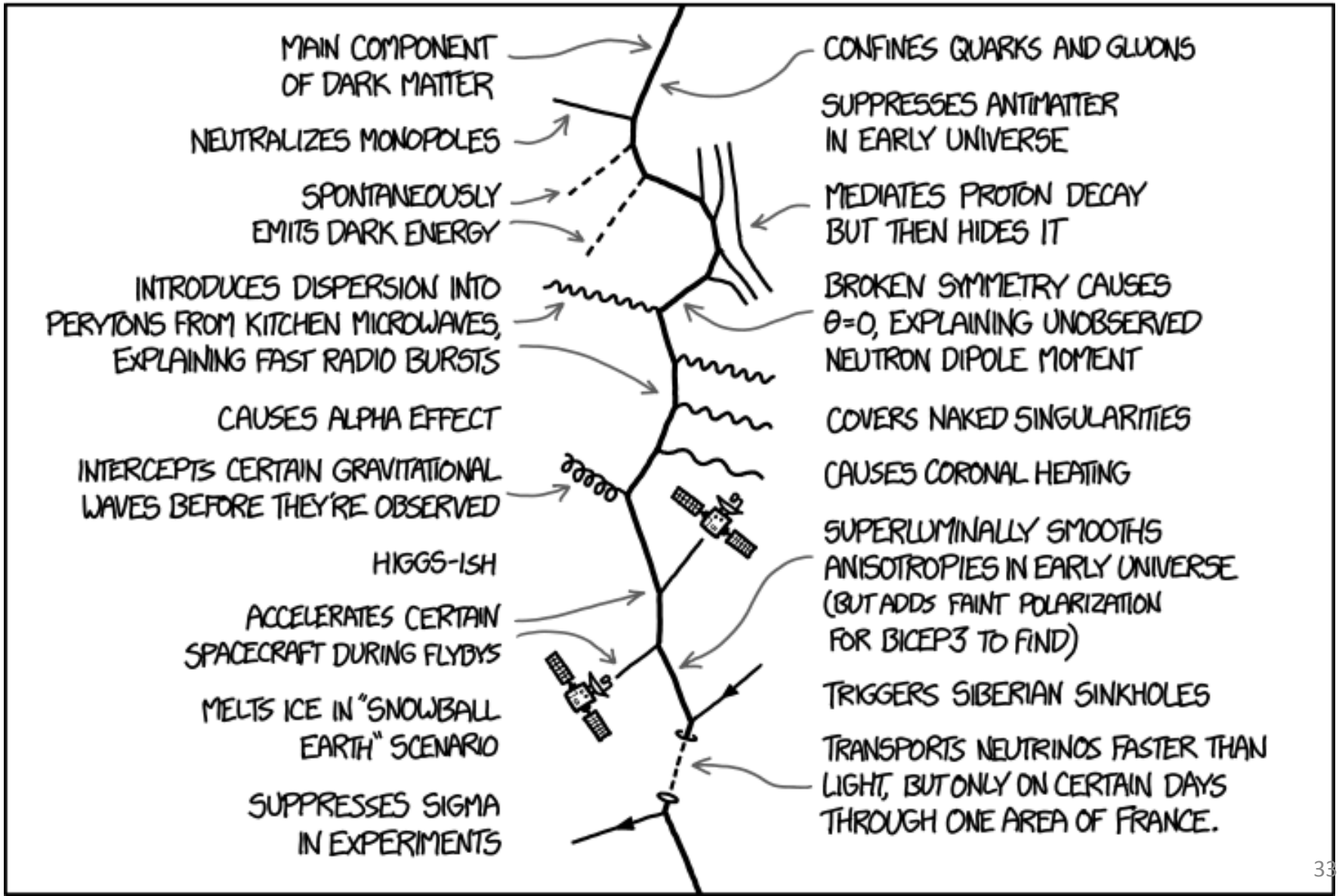
For the 1st time, we have used atm. χ^2 maps directly from SK (& DC). Why?

The Door to New Physics ?

A CHRISTMAS GIFT FOR PHYSICISTS:

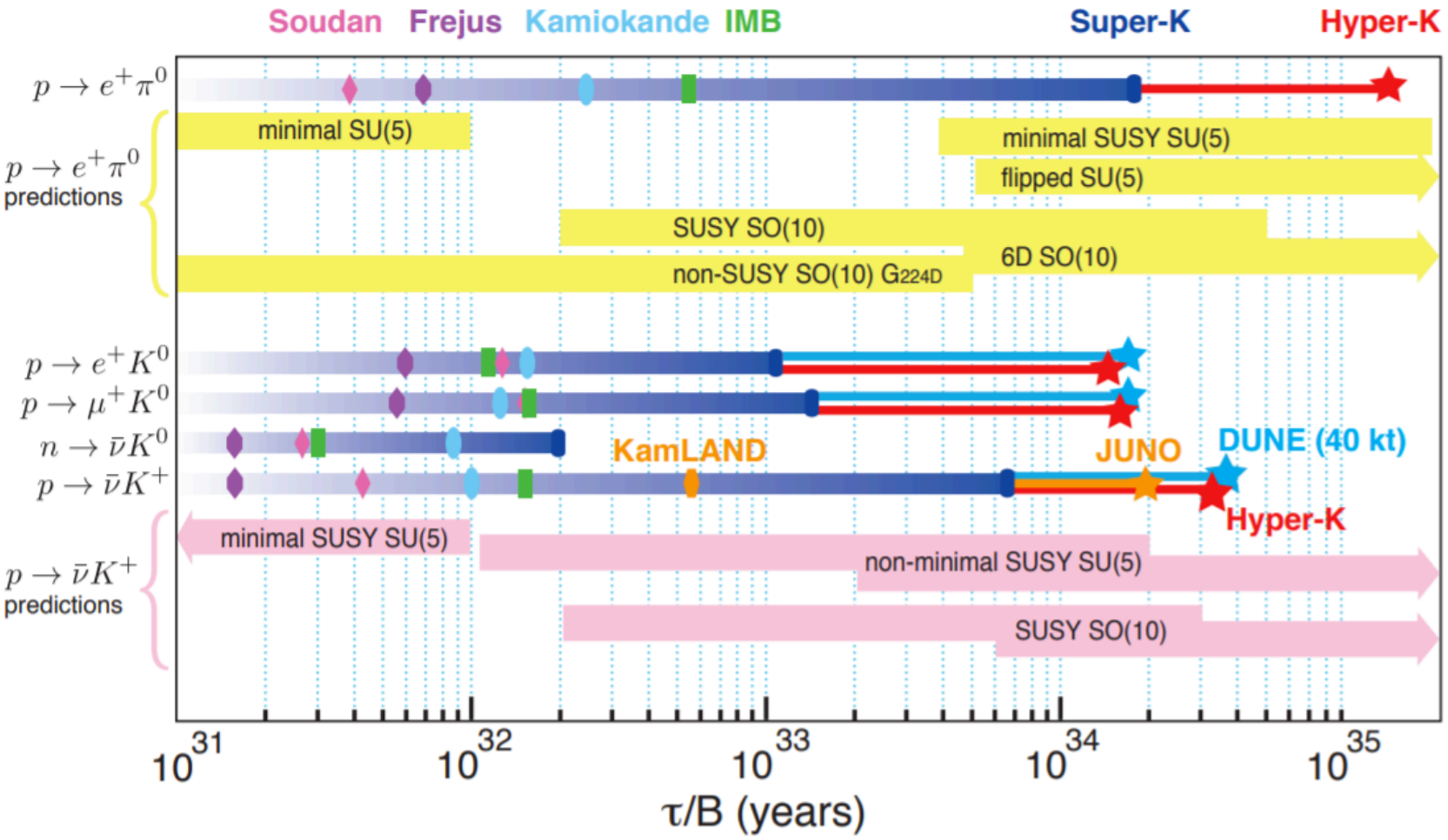
THE FIXION

A NEW PARTICLE THAT EXPLAINS EVERYTHING



Proton Decay

Takhistov

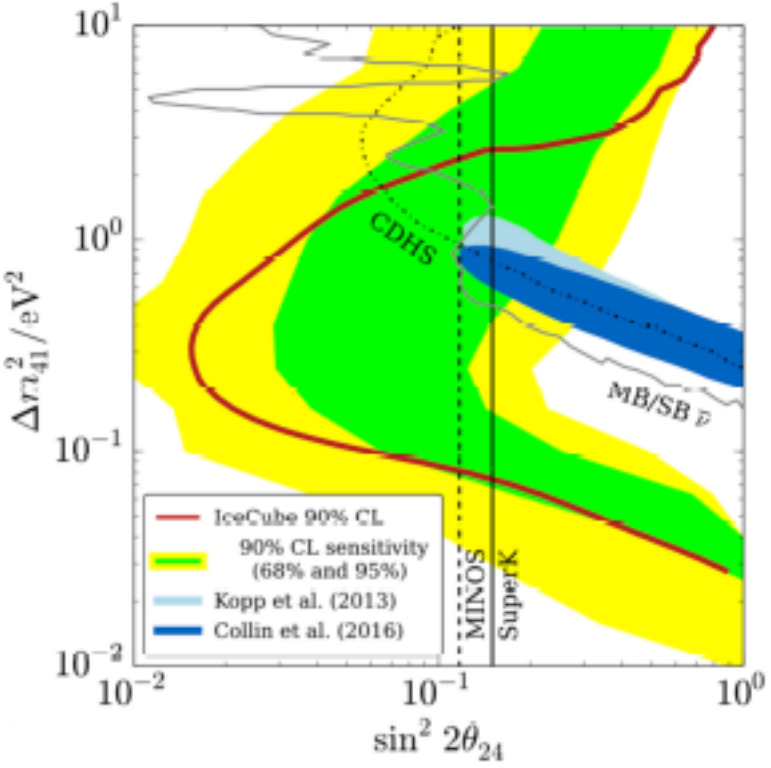


90% CL, 10 year nominal running

Sterile

Salvado

- MiniBoone $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance
  - No significant excess at high energies (E > 475 MeV)
  - Unexplained events at low energies, interpretation as oscillations similar to LSND: $\Delta m^2 \sim 1eV^2$
  - New result today! arxiv:1805.12028 4.5σ 6.1σ with LSND

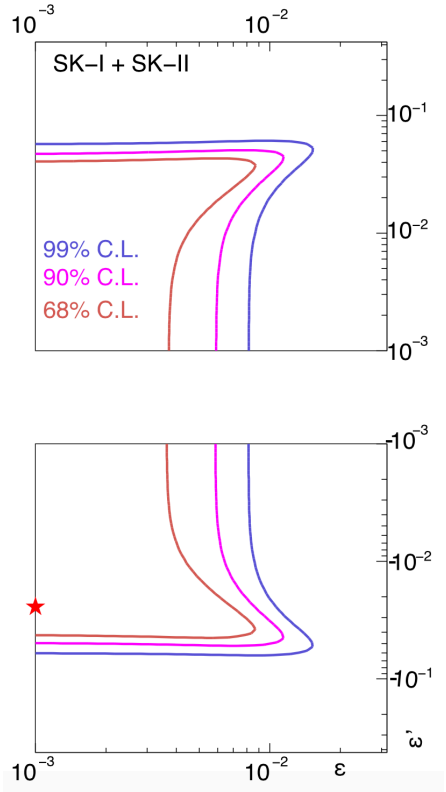


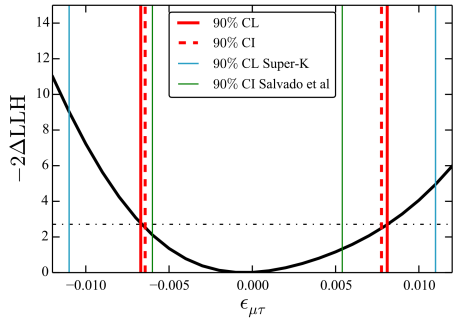
- Atm neutrinos are great! They constrain eV and heavier sterile neutrinos, specially in the high energy region due to the parametric resonance.
- Matter effect are essential in both cases(lowE and highE) therefore any modification of the matter effects change this bounds.(Yasaman Farzan and Danny Marfatia Talks)
- In the next updates O(10yrs) systematic errors are becoming important.
- Our knowledge of the flux is going to be limiting all the BSM searches in the future, better knowledge or treatment is very important (talks by Thomas K. Gaisser, Anatoli Fedynitch, Morihiro Honda)

NSI

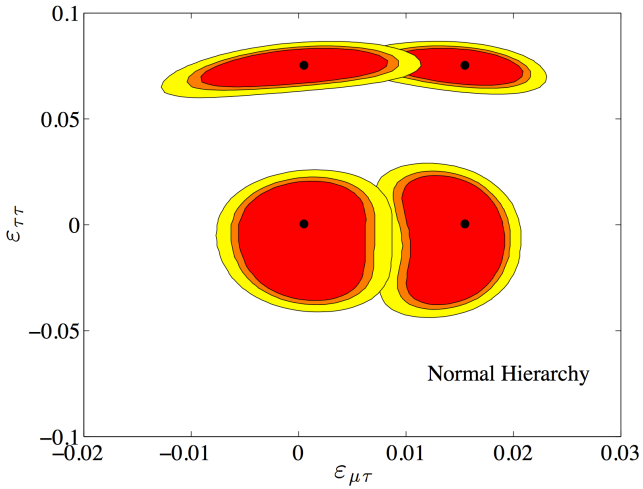
Farzan, Esmalli, Marfatia

SK

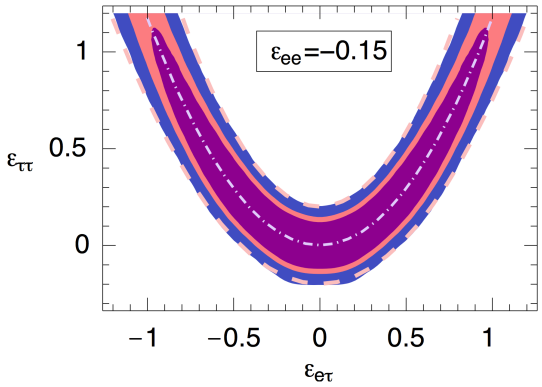




IC



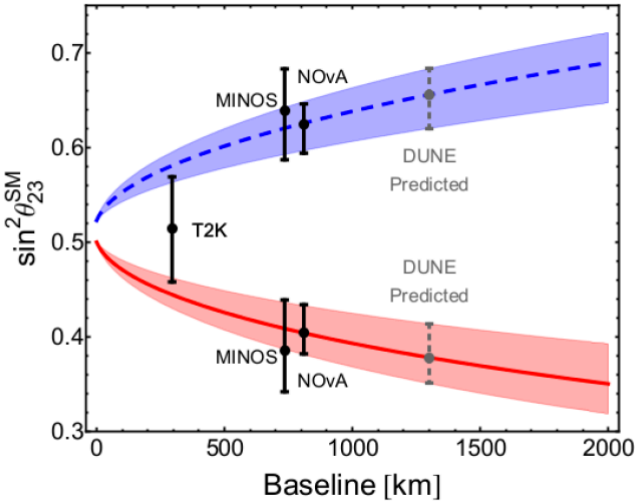
opening up the e-tau sector:

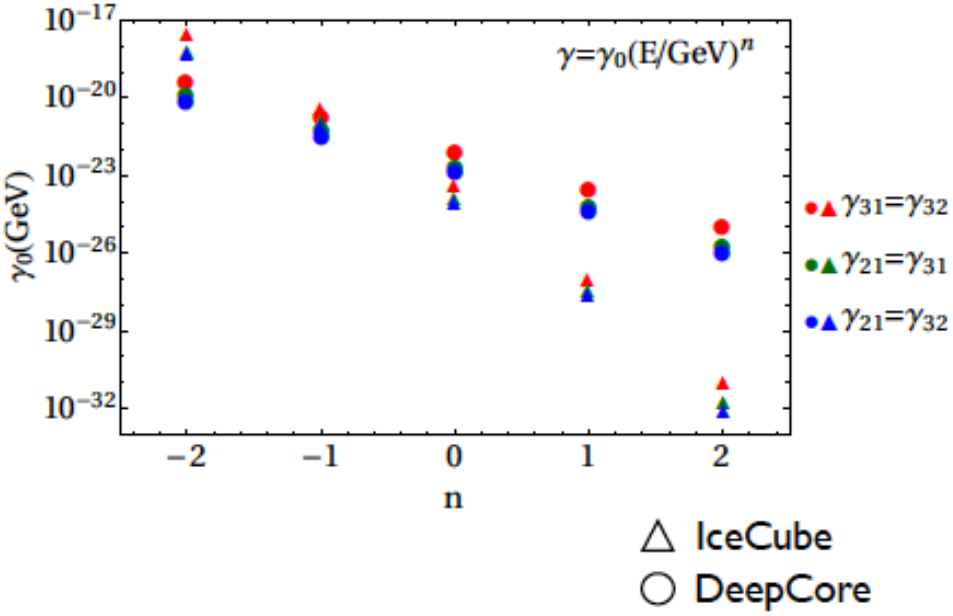


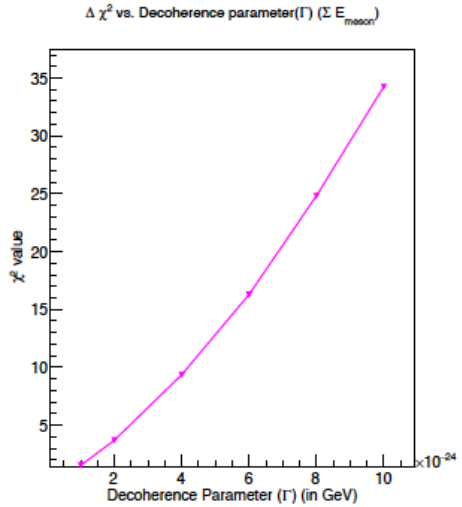
Can disentangle between NSI and sterile − Esmaili

Decoherence

Umasankar
Nunokawa
Stuttard





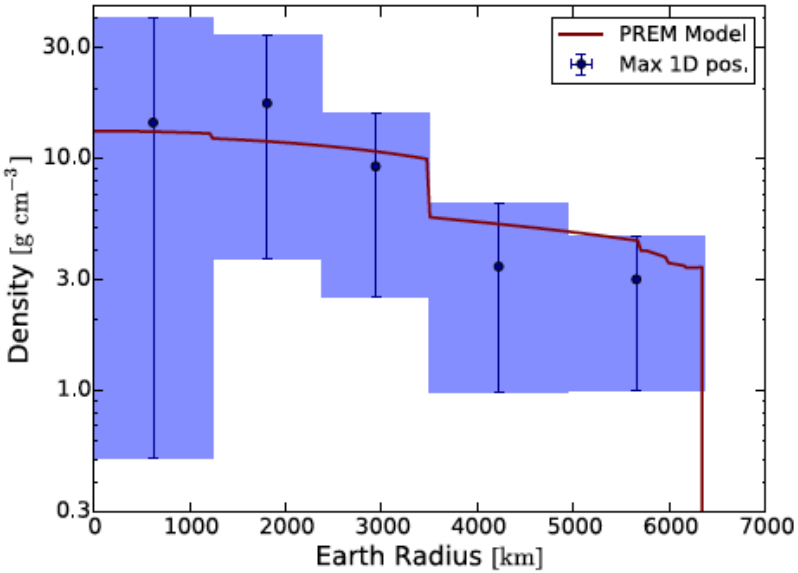


Neutrino Earth Tomography

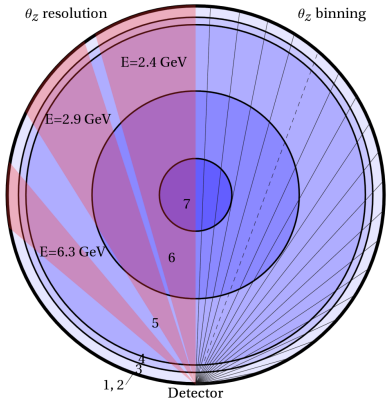
Winter
Donini

Neutrino Flux Attenuation

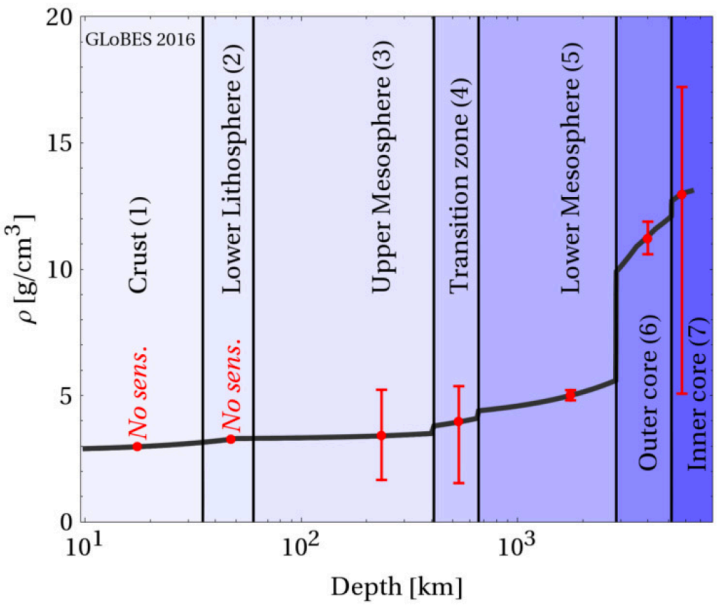
IceCube data



Neutrino Oscillations



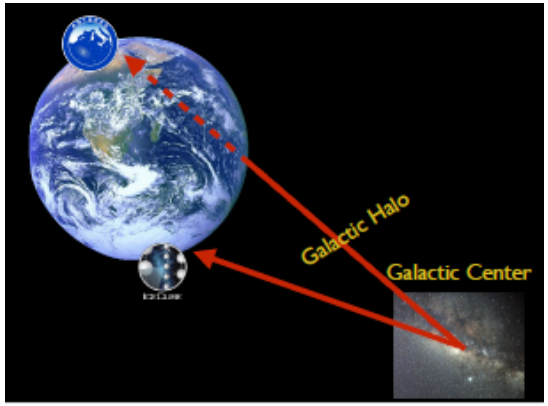
ORCA



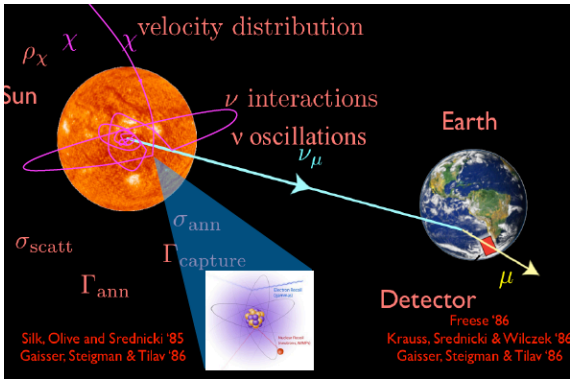
Dark Matter

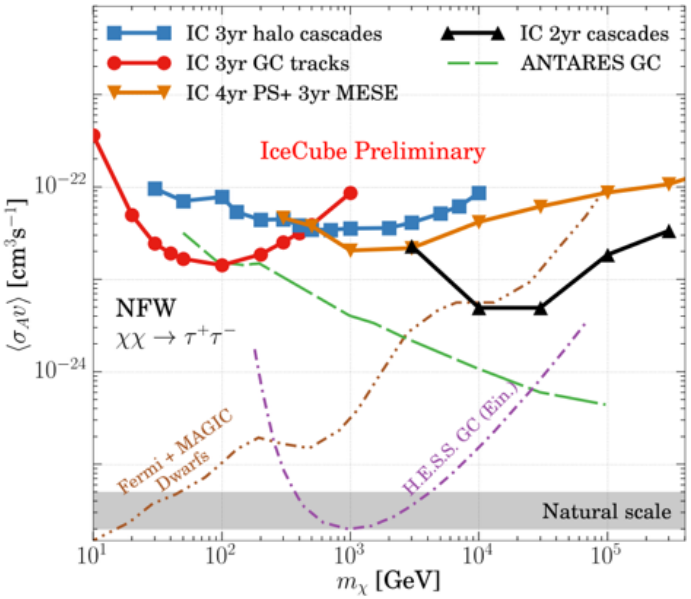
Rott (Beacon)

Galactic Centre

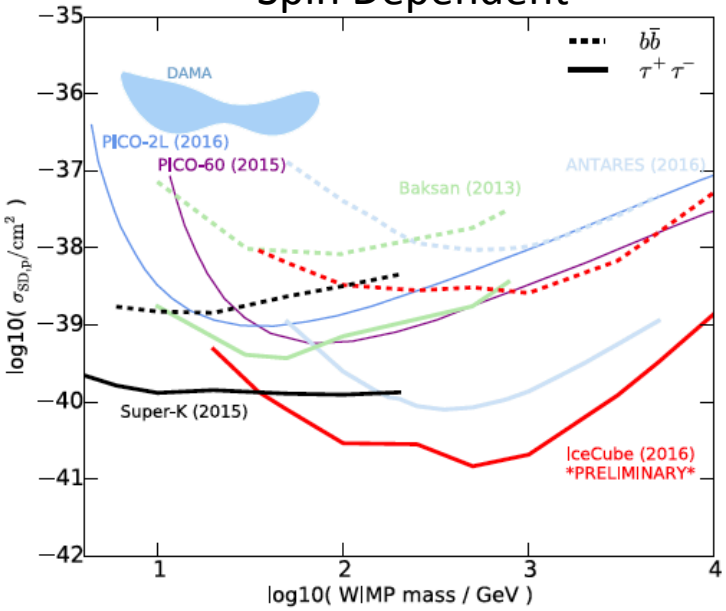


Sun





Spin Dependent

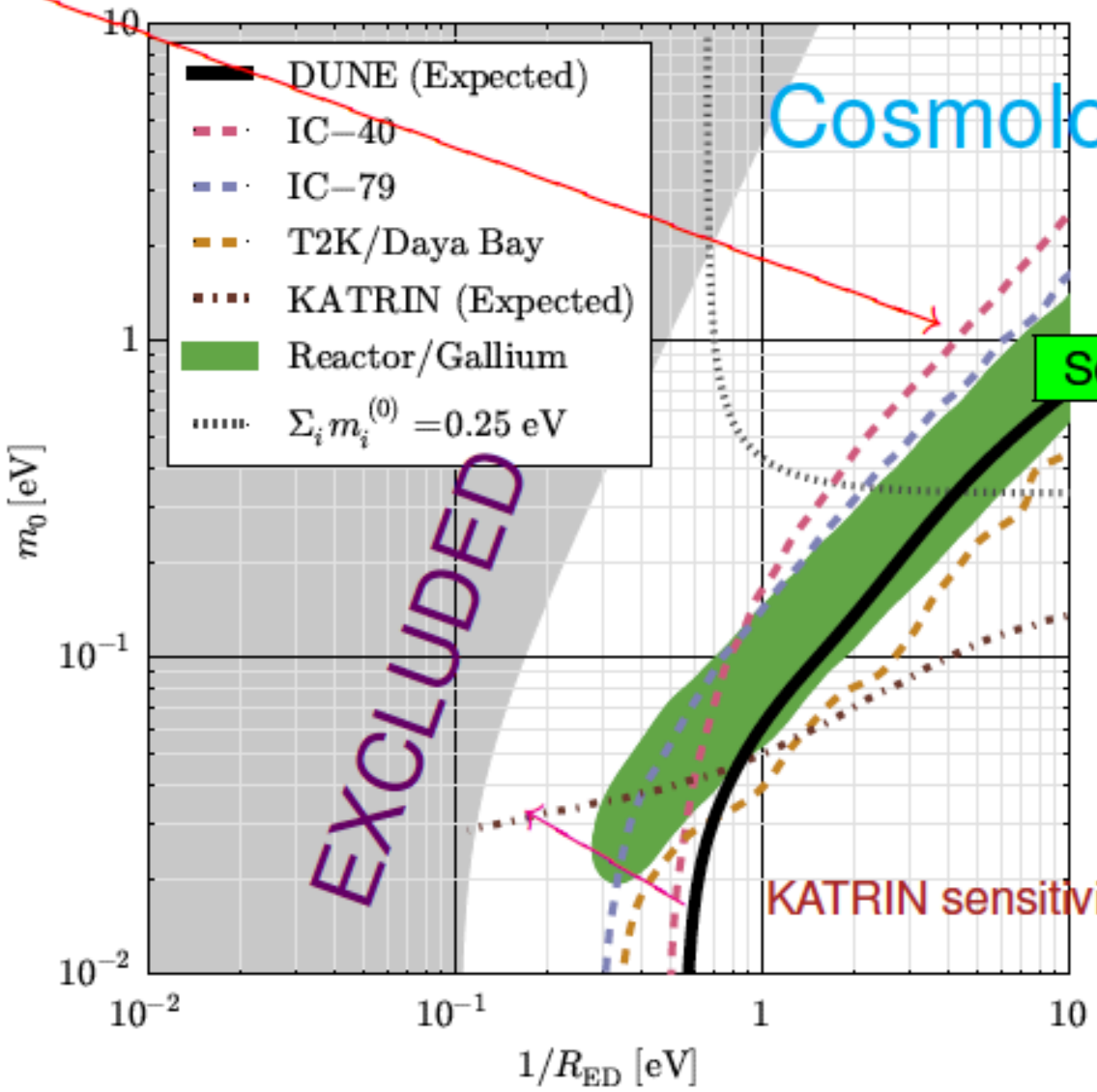


+ secluded, heavy decaying DM, CR interactions in Sun

Extra Dimensions

Peres

IC-40/IC-79: ICECUBE analysis by O. L. G. P., Esmaili and Tabrizi (USP)



Cosmology excluded

Solution for sterile ν anomalies

Machado, Nunokawa and Funchal

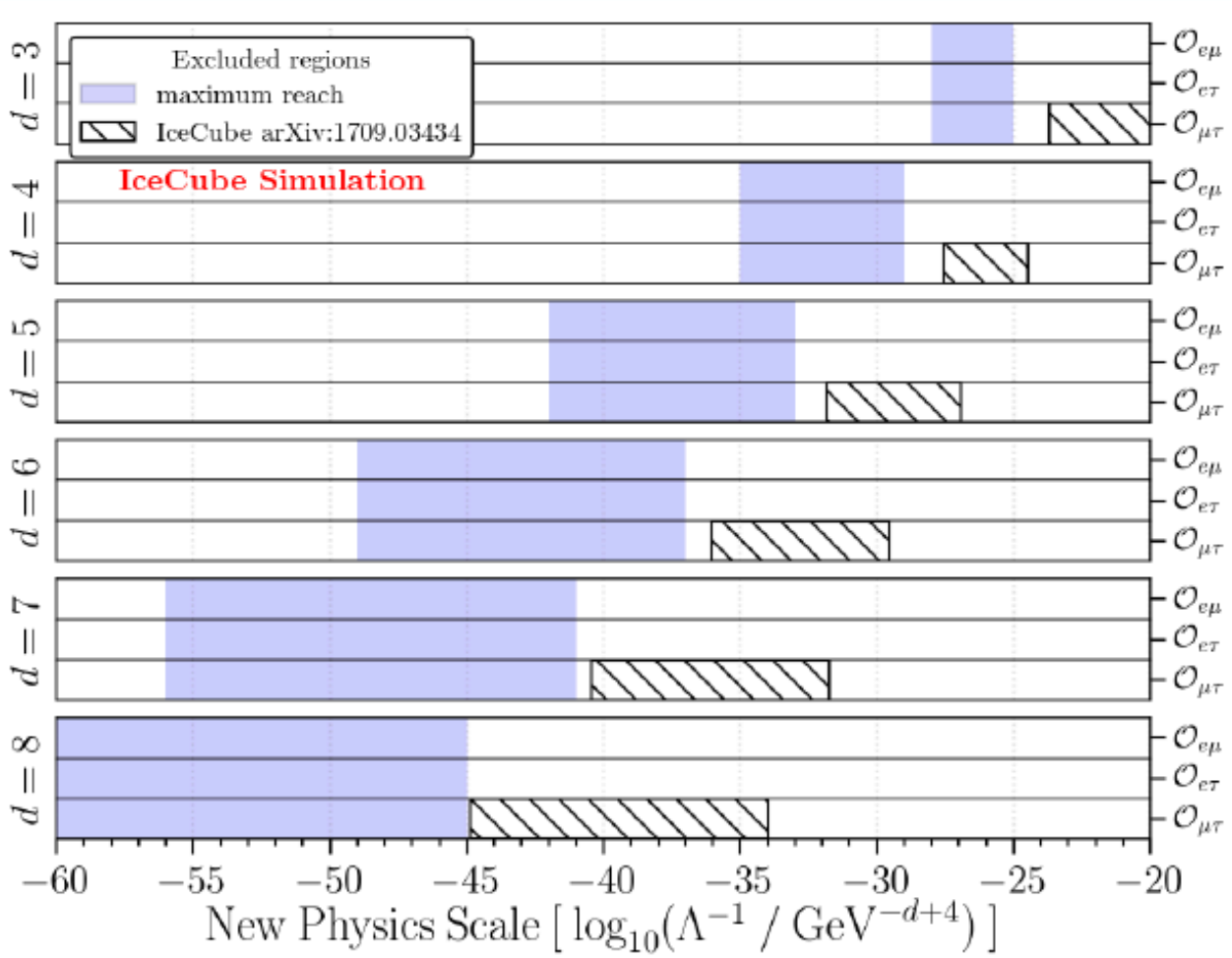
KATRIN sensitivity: neutrino mass!!

GEFAN

CPT and LIV

Arguelles

Summary of IceCube sensitive + limits



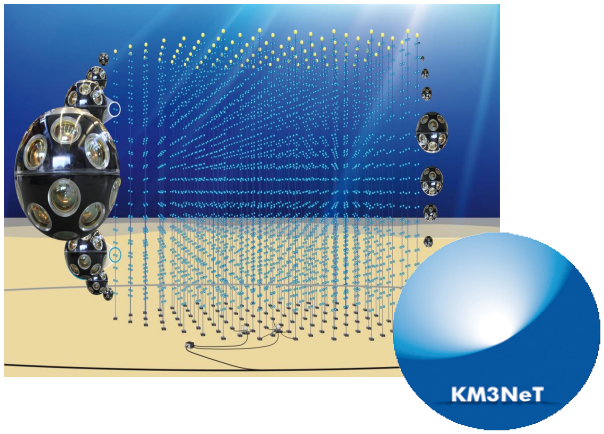
dashed: atmospheric neutrinos, solid cosmic neutrinos

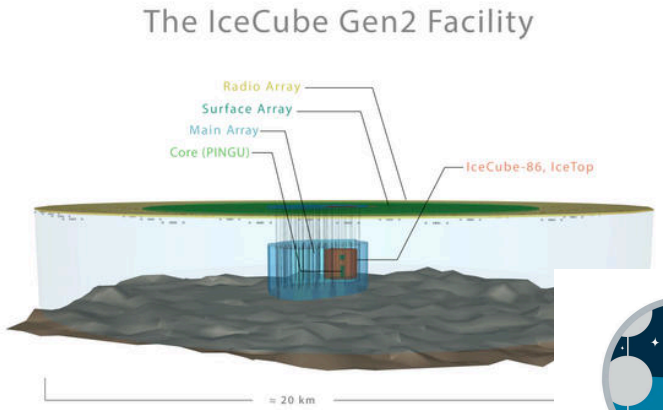
Long range forces

Khatun

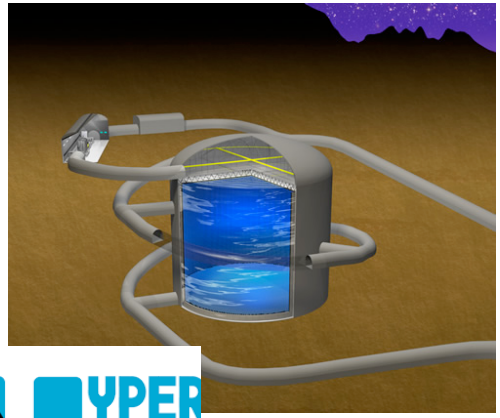
The joy of building!

Planned Detectors

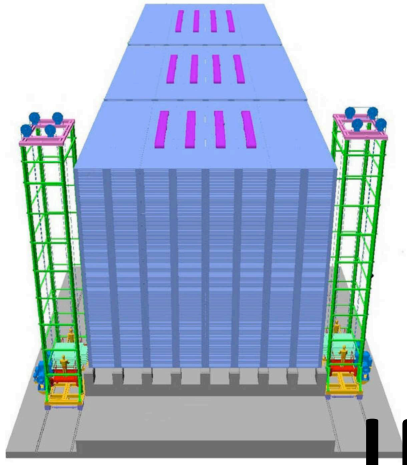




ICECUBE GEN2



HYPER HK



INO

But some not yet completely funded

ORCA - half funded, additional requests ongoing

GEN2 − soon? for the phase 1

HyperK − Soon?

INO − funds, but environmental issues

Each generation of particle physicists has to fight and win the battle to convince governments that our science is important, that our experiments need to be funded and that our theorists need support.

This fight has gotten, and will get, harder as public money gets tighter and tighter.

To win the fight we need new ideas and new initiatives, need new young heroes!

Project Uncertainty Principle

Support of the community needed

Competition with GW, gamma-rays, radio, accelerators is fierce

PANE18 is very timely….

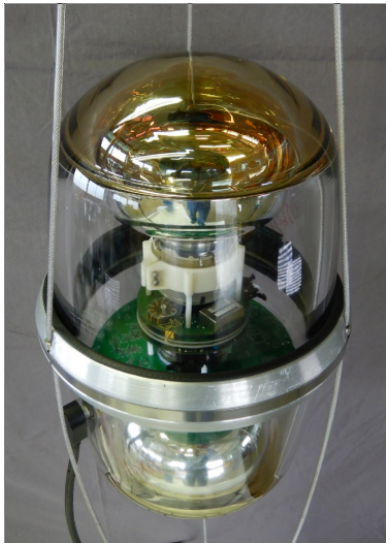
Support of the community (and beyond) is mandatory
to convince funding agencies/ministries

We should also support each others projects !

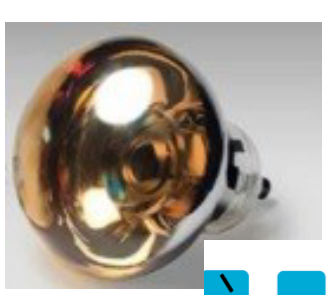
Theorists - help motivate physics case
- mention all relevant expts in your paper!
- please pin down the systematics

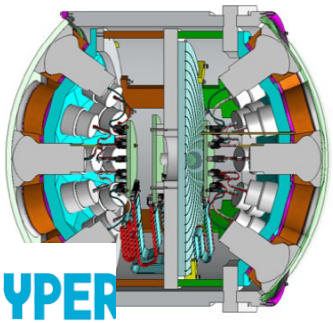
Technologies

Brunner



Hignight



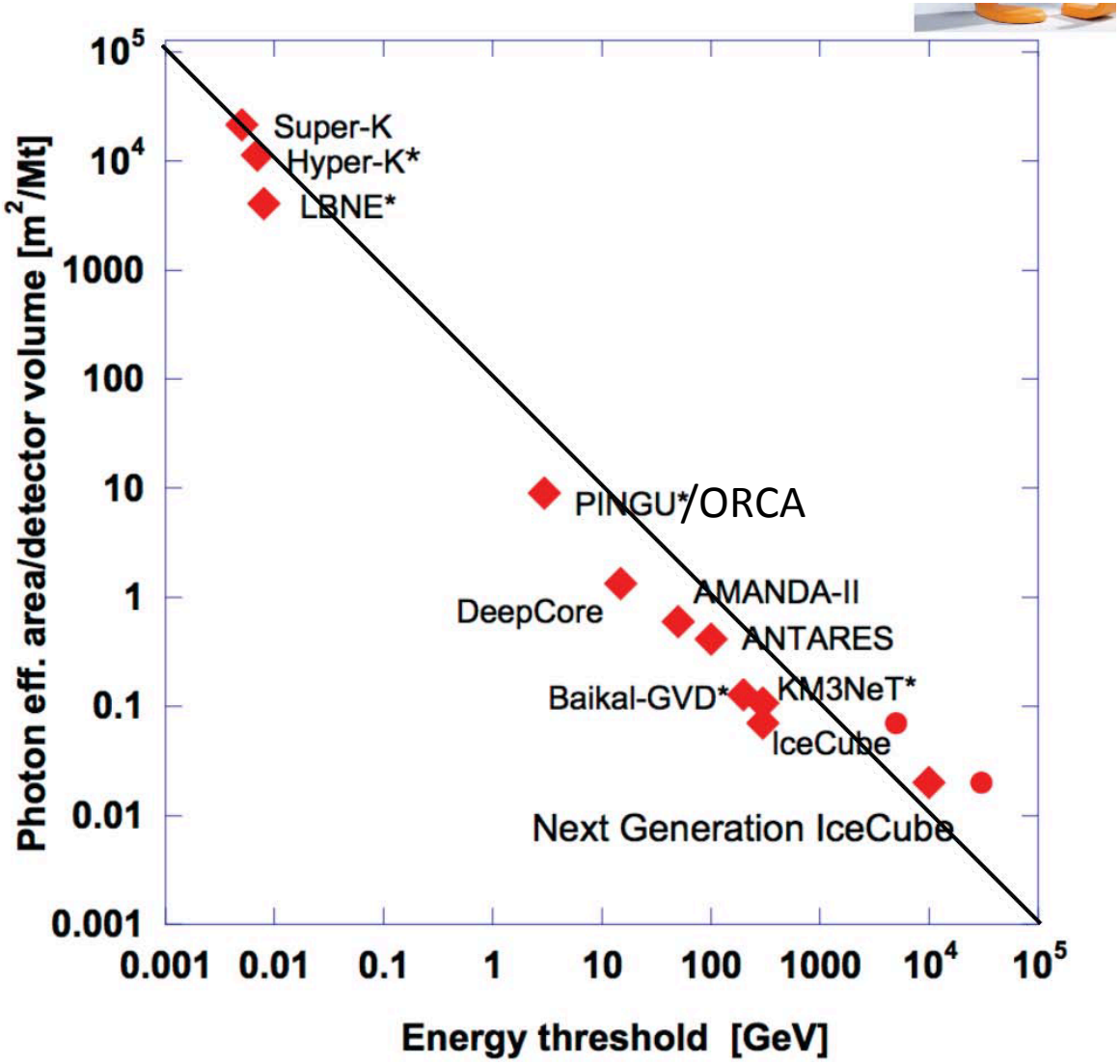


De Rosa

Datar

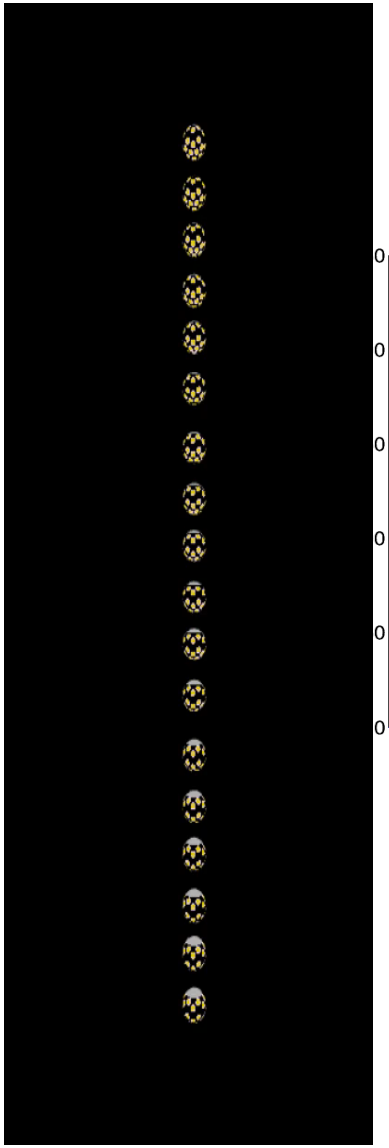
INO

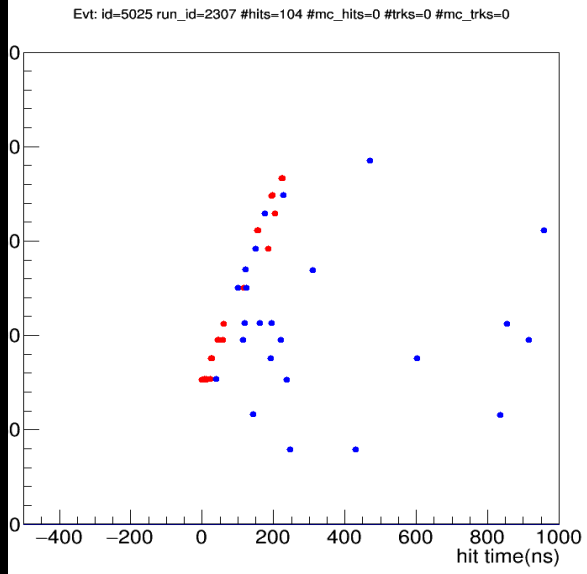
Photocathode area

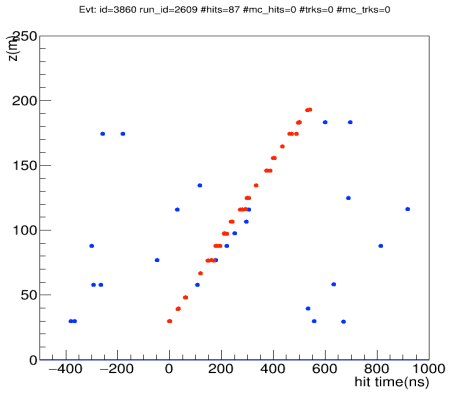


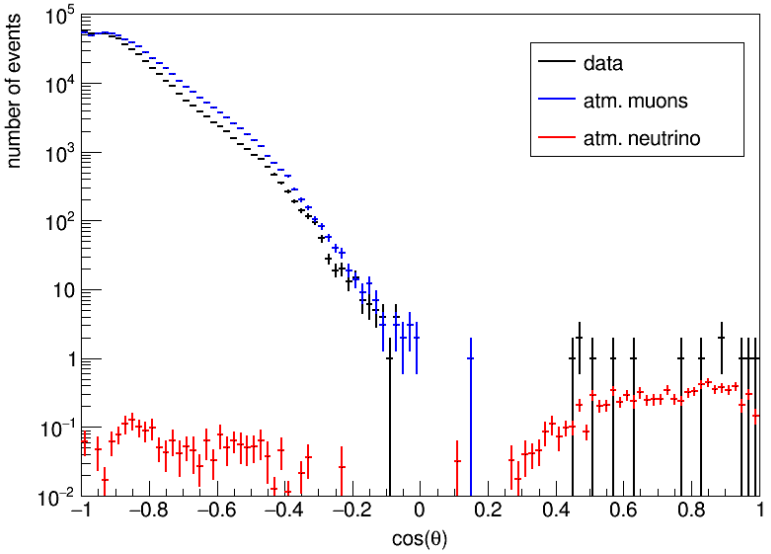
KM3NeT/ORCA first data

Brunner

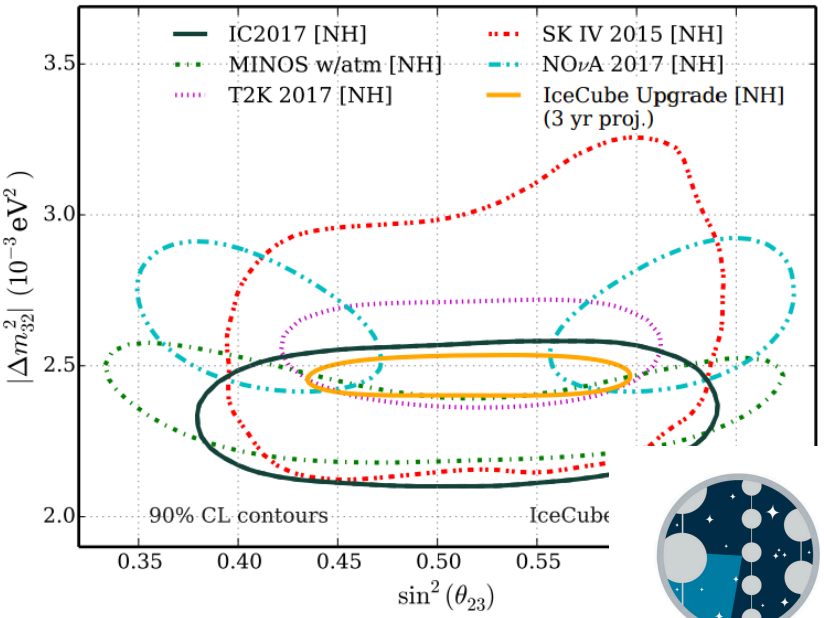


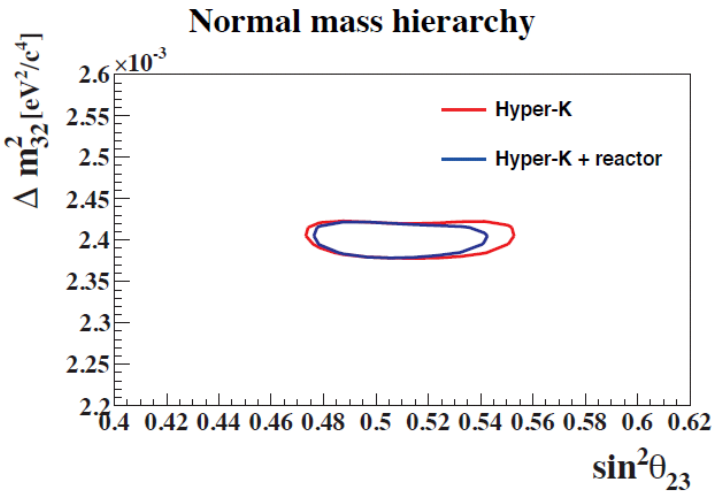


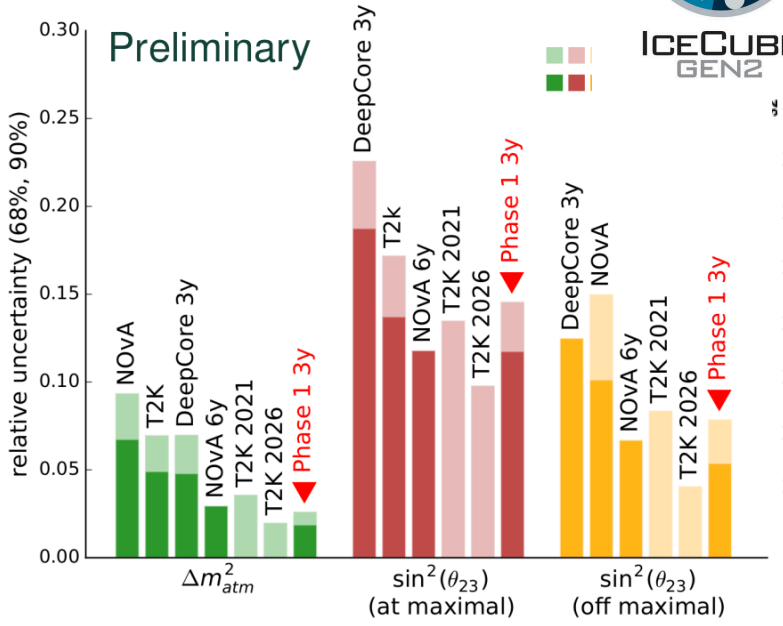


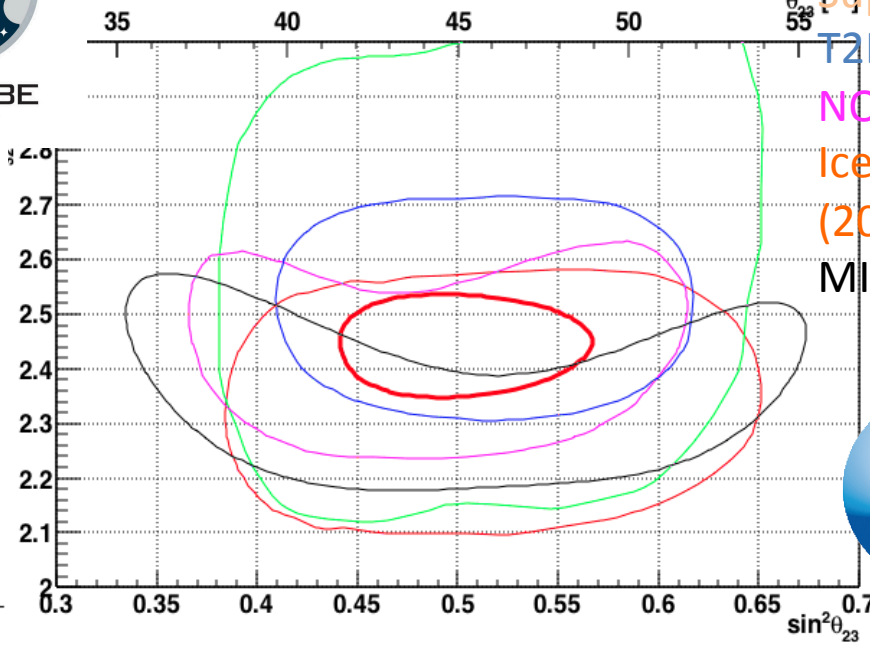


Oscillation parameters

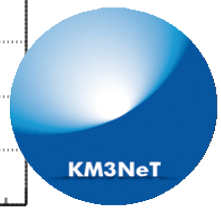




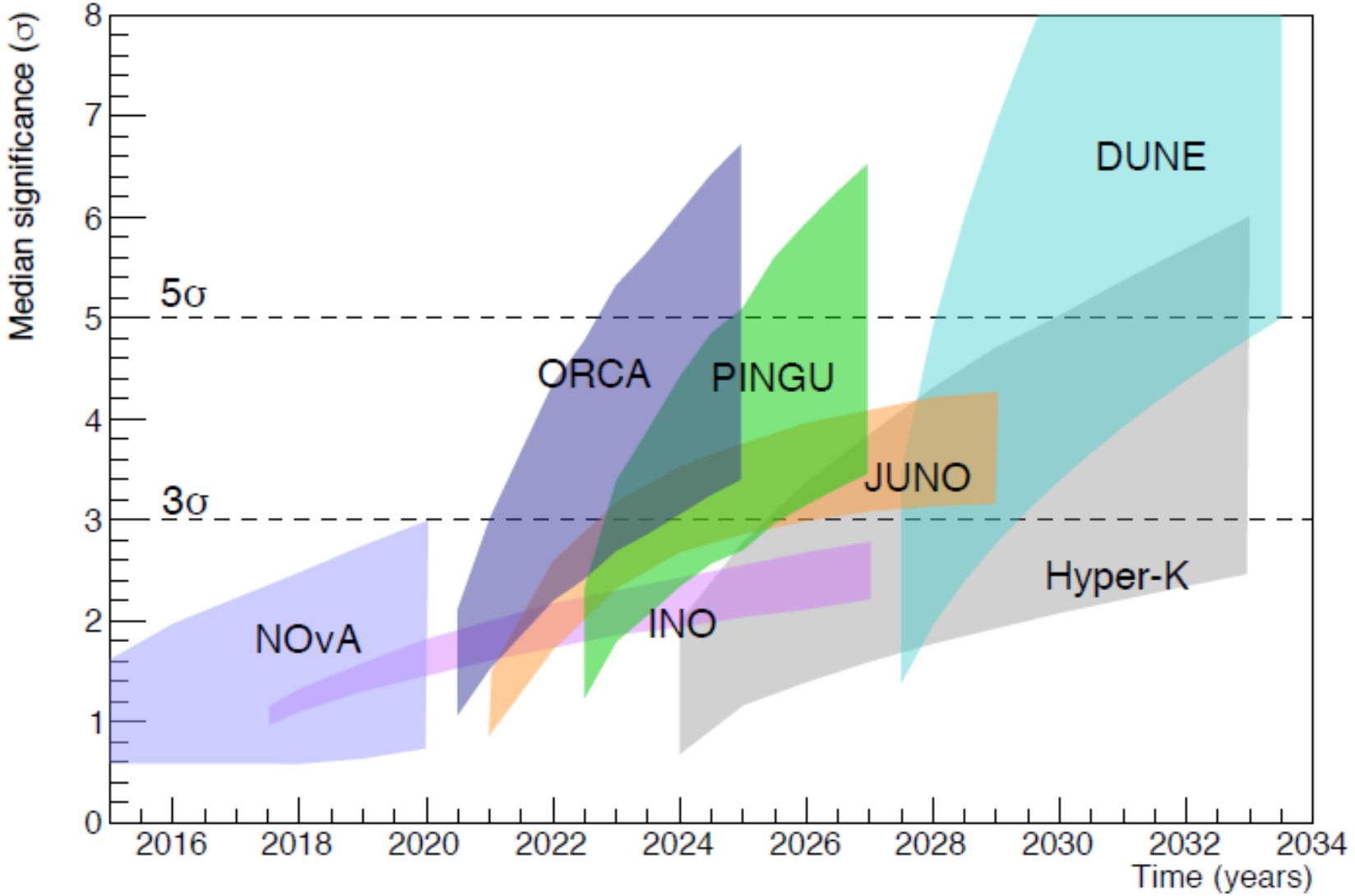




SuperK (2015)
T2K (2015)
NOVA (2018)
IceCube (2017)
MINOS (2014)



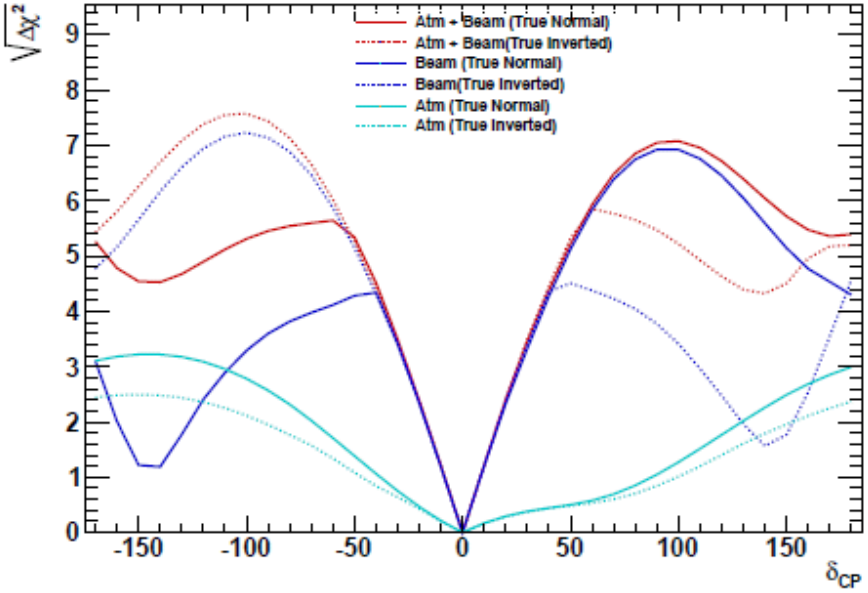
MH expected sensitivities vs time (time scales indicative!)

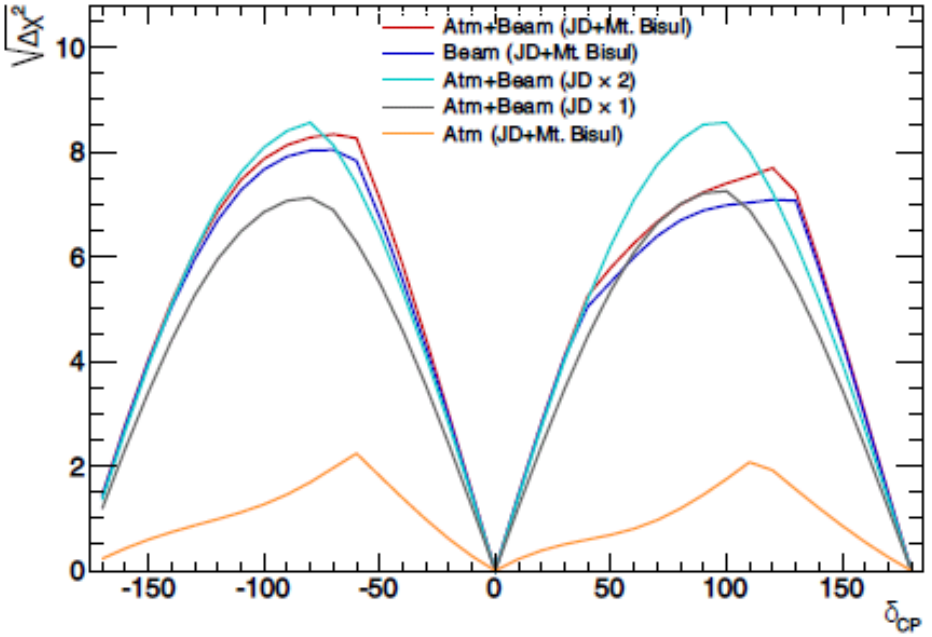


(adopted from Blennow)

CP violation with T2HK and T2HKK

De Rosa

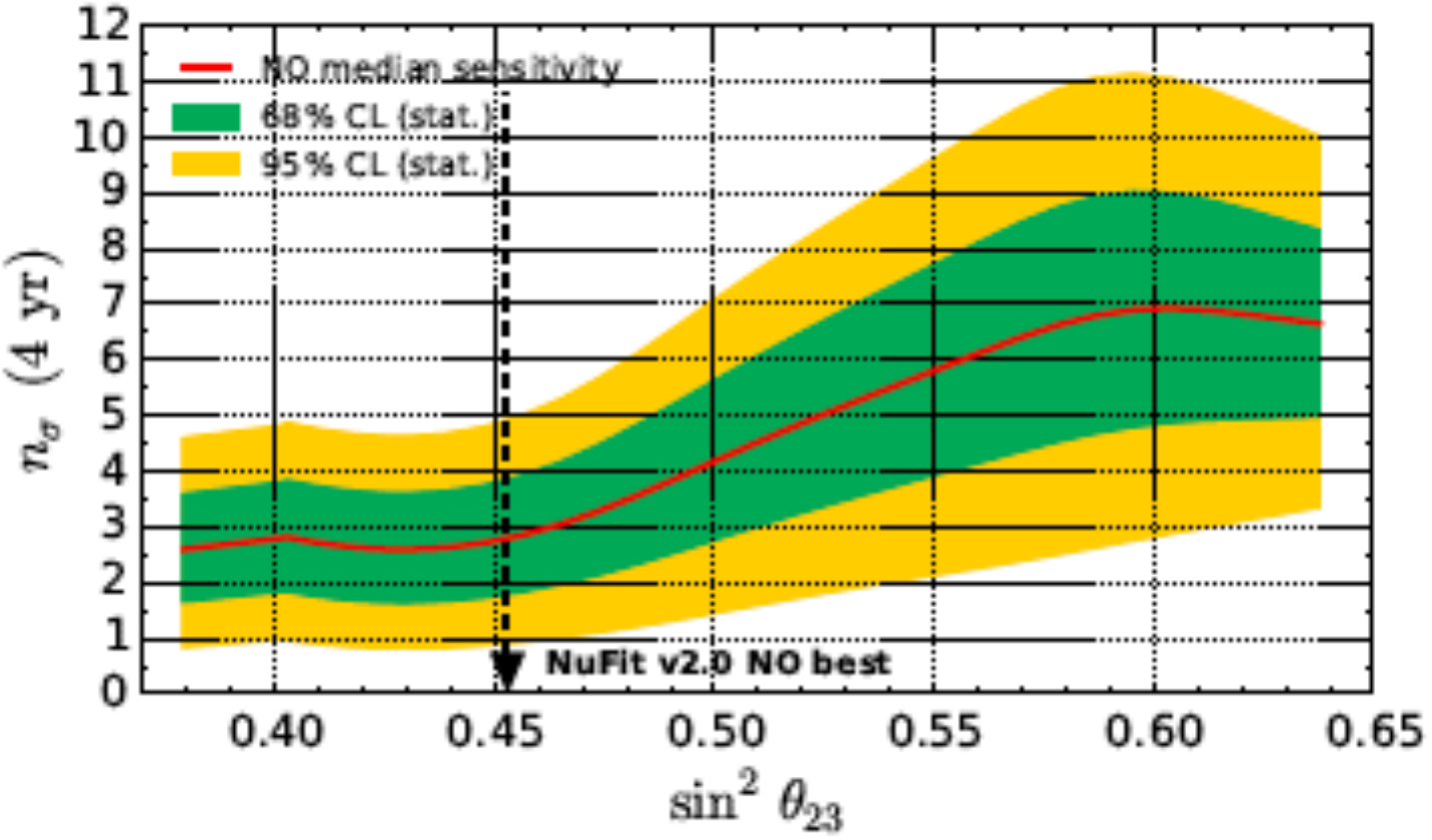




beam + atmospheric neutrinos, 10 year exposure

But there are Risks!...

Remember 3σ±1σ



Multiple experiments desirable

Beware Systematics

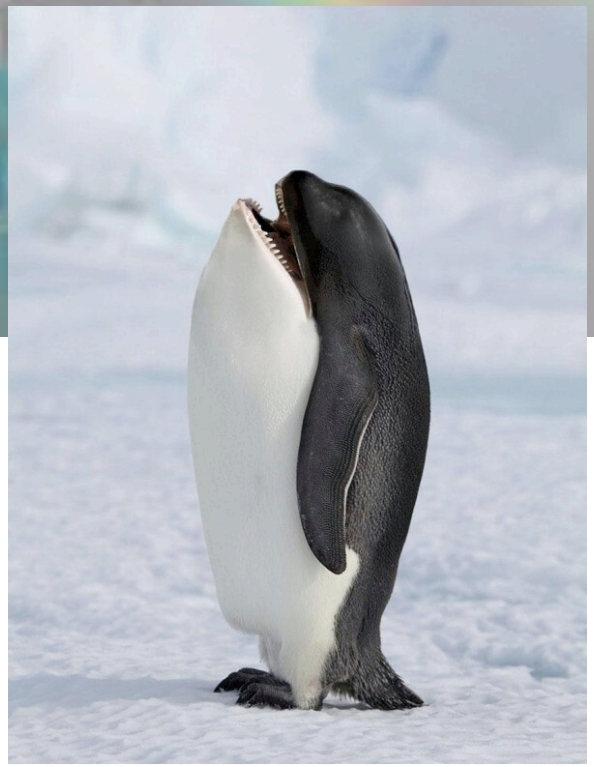
Lisi

N^{α}_{NH} (smeared) + smooth 2D variations

Bands correspond to $\sin^2\theta_{23}$ spanning the range [0.4, 0.6]
Note abscissa scaling as sqrt(T)

Pot of gold at end of the rainbow?

Global Neutrino Network →
Global Neutrino Observatory



Tremendous potential of the sea-based technology

Accelerators and caverns are very expensive!

Free neutrino beam and free (very large) cavern

Small and well known light scattering

Lots of accessible sea (>1000m) all around the World !

Self-veto -> depth not imperative

In built K40 efficiency calibration

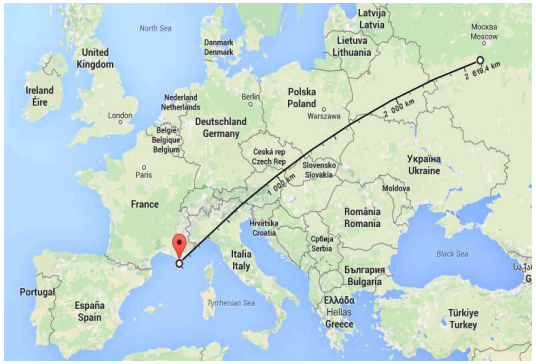
Reconfigurable

KM3NeT has developed cost effective technology (ORCA 50ME)

Important synergies with Environmental and Sea sciences

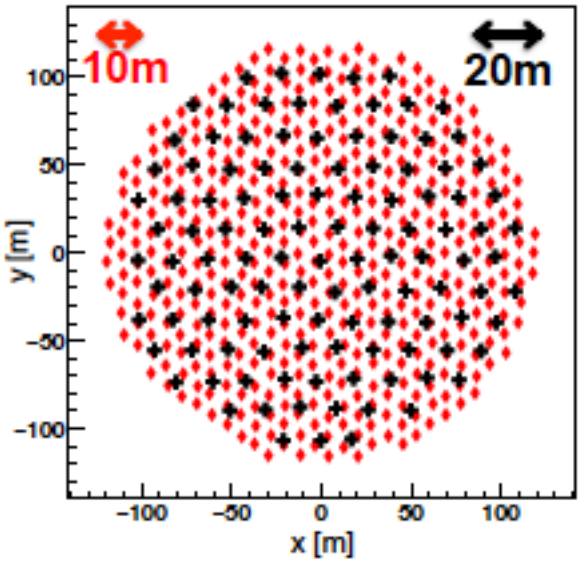
go for it !….

Beyond the planned detectors?



P2O

Brunner



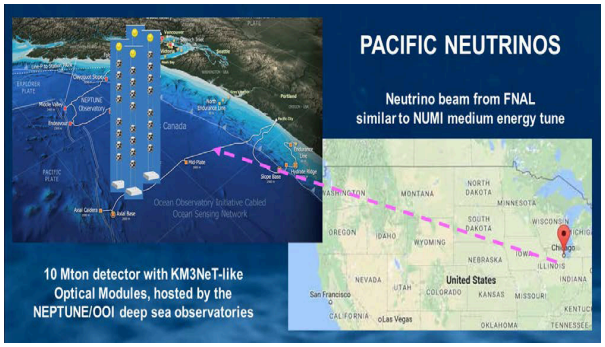
SuperORCA

Hofestadt

Razzaque

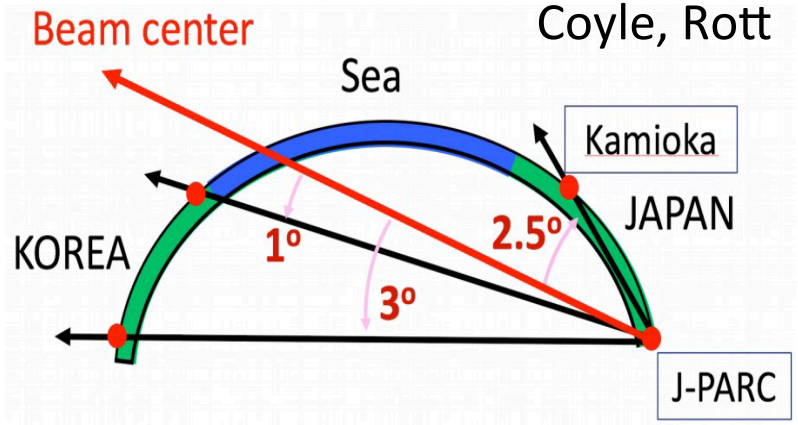
Pacific neutrinos

Vallee, Grant



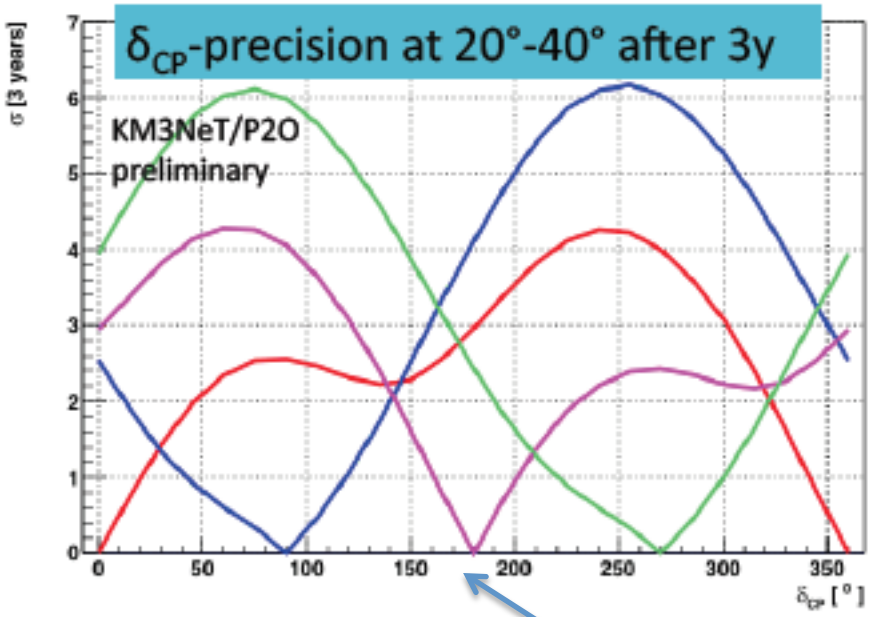
T2OK

Coyle, Rott



CP with P2O/SuperOrca

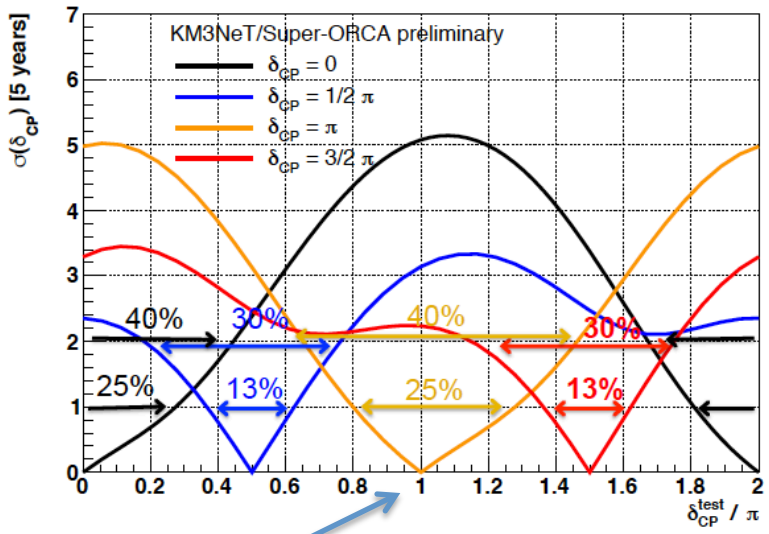
P2O ($1.2*10^{21}$ PoT)



SuperORCA

- Maximal distinguishability between $\delta_{CP}=0$ and $\delta_{CP}=\pi$ with 5σ
- 60% (70%) disfavoured with ≥2σ for $\delta_{CP}=0$, π ($\delta_{CP}=\pi/2$, $3/2\pi$)

10x denser than ORCA
NH known
θ_{23}=42°
4Mton*5yr



Complementary CP resolutions as a function delta

Learned

The Curious Luck in Neutrinos

(Odin is kind to neutrino hunters!)

Distance about 1000 km between arrival direction hemispheres.
Full oscillation for upcoming and little for downgoing (about 1 GeV

Mixing angle theta 23 near maximum 45 deg (if were tiny: unsee

4 MeV nu_e oscillation lengths 2km and 150km and mixing angle

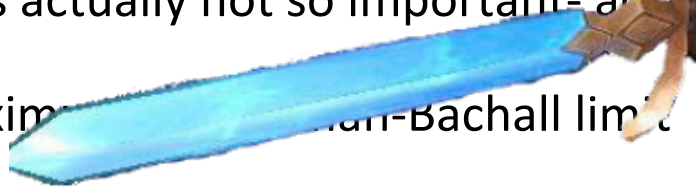
MSW matter effect distance about radius of the Earth

In Sun oscillation transitions actually not so important- adi

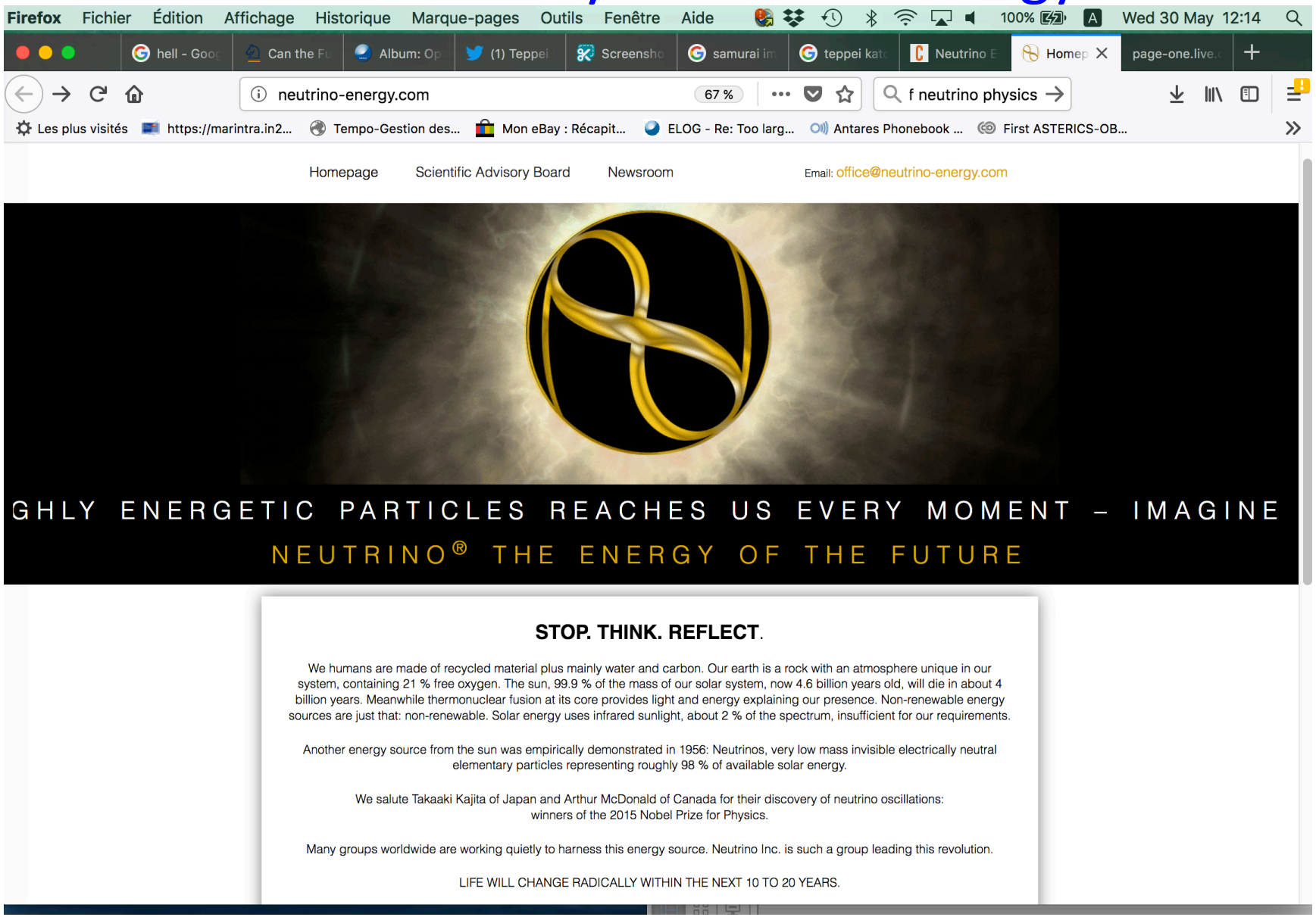
Cosmic neutrino flux at maxim ian-Bachall lim

Hierarchy tending towards normal?
theta23 tending to be large?
LSND/mini-BooNE sterile?
Anita tau events?

Next SN should wait till ORCA/SK-GD/Gen2-phase 1 online !



And if we are not lucky-
there is always Neutrino Energy!



Personal Remarks

Amazing progress in the last decade
- -more physics results and better performances than ever expected
- -the dreams of the DUMAND proceedings becoming reality
- -weighing the Earth with neutrinos!
- -delighted to see Tomography on the radar!
- -approaching neutrino floor from CR on the Sun!

New detectors/upgrades just around the corner
- -ORCA coming online
- -SK adding GD
- -Gen2-Phase1
- -INO

Maximise our physics potential
- -get those systematics reduced

Many new detector ideas yet to be fully explored (SuperORCA, P2O,…)

Exciting decade ahead
- – Let's stay lucky

Will be surprised if we have no surprises!

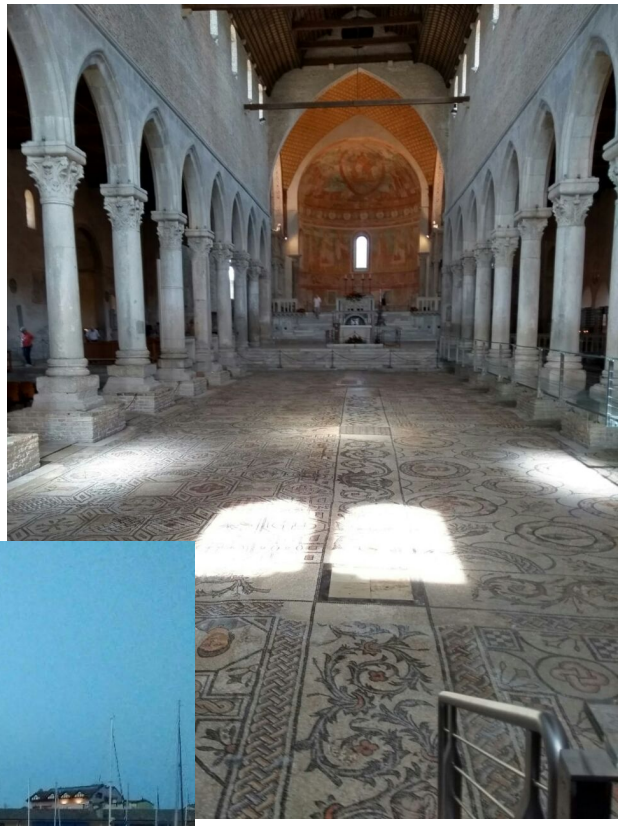
Thanks to Posters

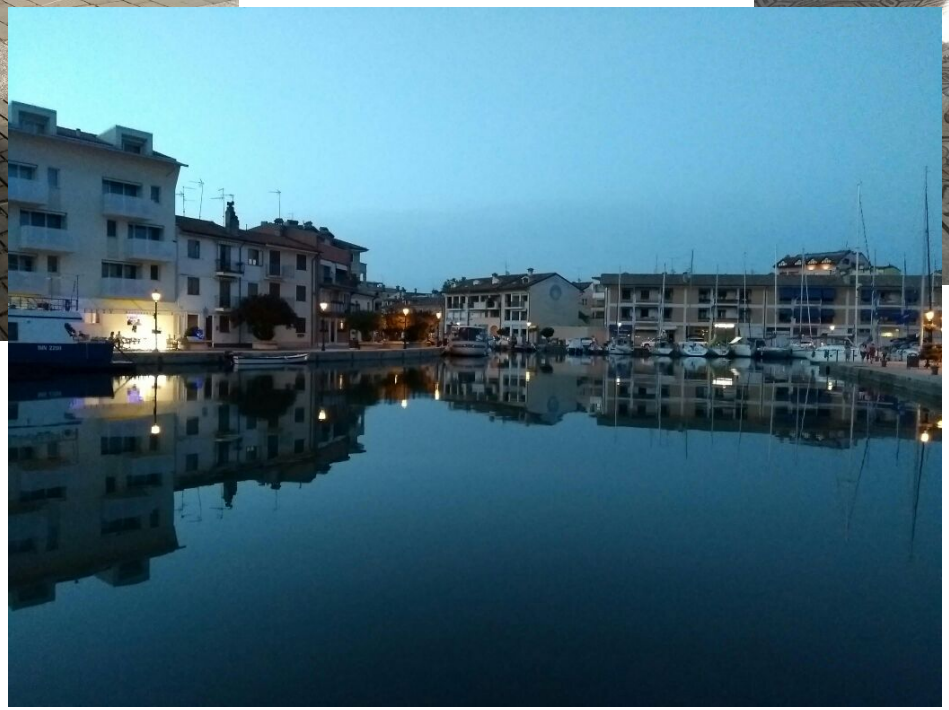
Thanks Twitter Masuta! - Teppei Katori

Traduire le Tweet

Wonderful Trip!

Brunner





Thanks organisers for a Great Workshop!

Various Committees

Organizing Committee

1) Sanjib Kumar Agarwalla
2) Bhupal Dev
3) Antonio Palazzo
4) Alexei Smirnov

Local Organizer

1) Atish Dabholkar

Secretary

1) Nadia van Buuren

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7) Ed Kearns
8) Eligio Lisi
9) John G. Learned
10) Naba Kumar Mondal
11) Michele Maltoni
12) Orlando Peres
13) Ina Sarcevic
14) Walter Winter

A perfect mix of cultures from around the World
Appreciated the strong representation from the women

Thank you all!


20
General
Draw
Rov
KM3NeT