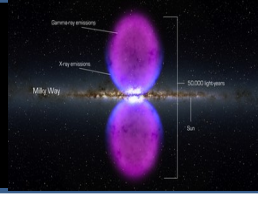


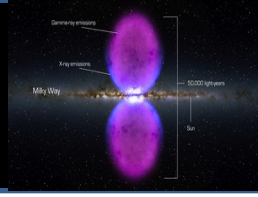
Fundamental Physics and Astrophysics with Neutrino Telescopes

Multi Messenger Winter Workshop 2019

Prague, Czech Republic – 4-7 December 2019

Bruny Baret
Astroparticule & Cosmologie, Paris
baret@in2p3.fr

Astrophysical high energiy neutrino sources



Galactic | Extra-galactic

Astrophysical Sources

Sun | Supernova (expl. acc.) | Binaries | AGN/GRB | UHECR

Energie

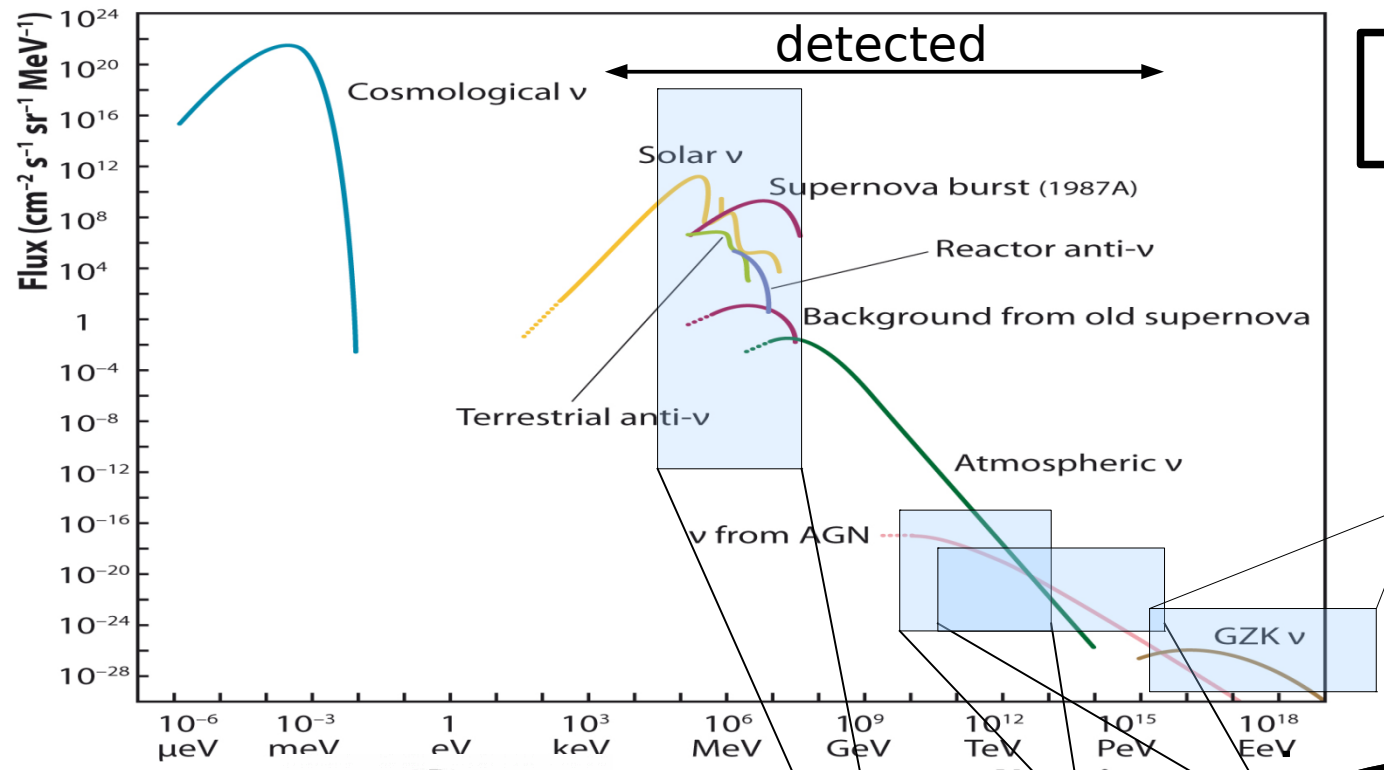
0.1-10 MeV | GeV | Tev-PeV | >PeV

Production mechanism

desint. beta | elec. capture | Hadronic interactions | (+top-down ?)

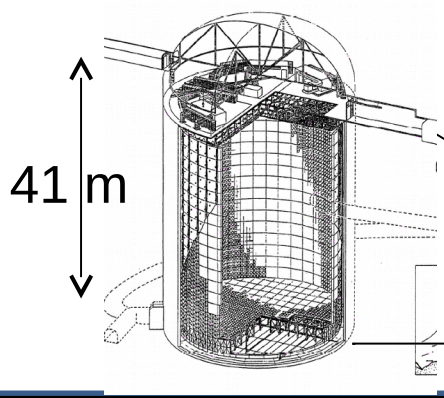
Nuclear reactions | accelerated hadrons + dense radiation/matter

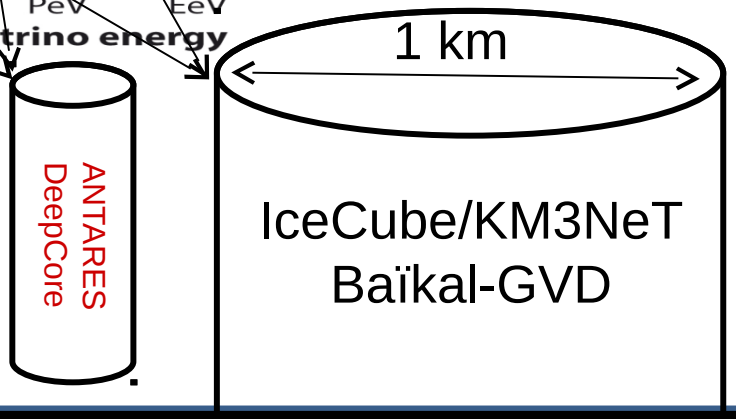
Hard to detect



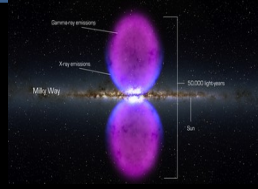
Level of atm. Muon Background 10^6 x atm ν

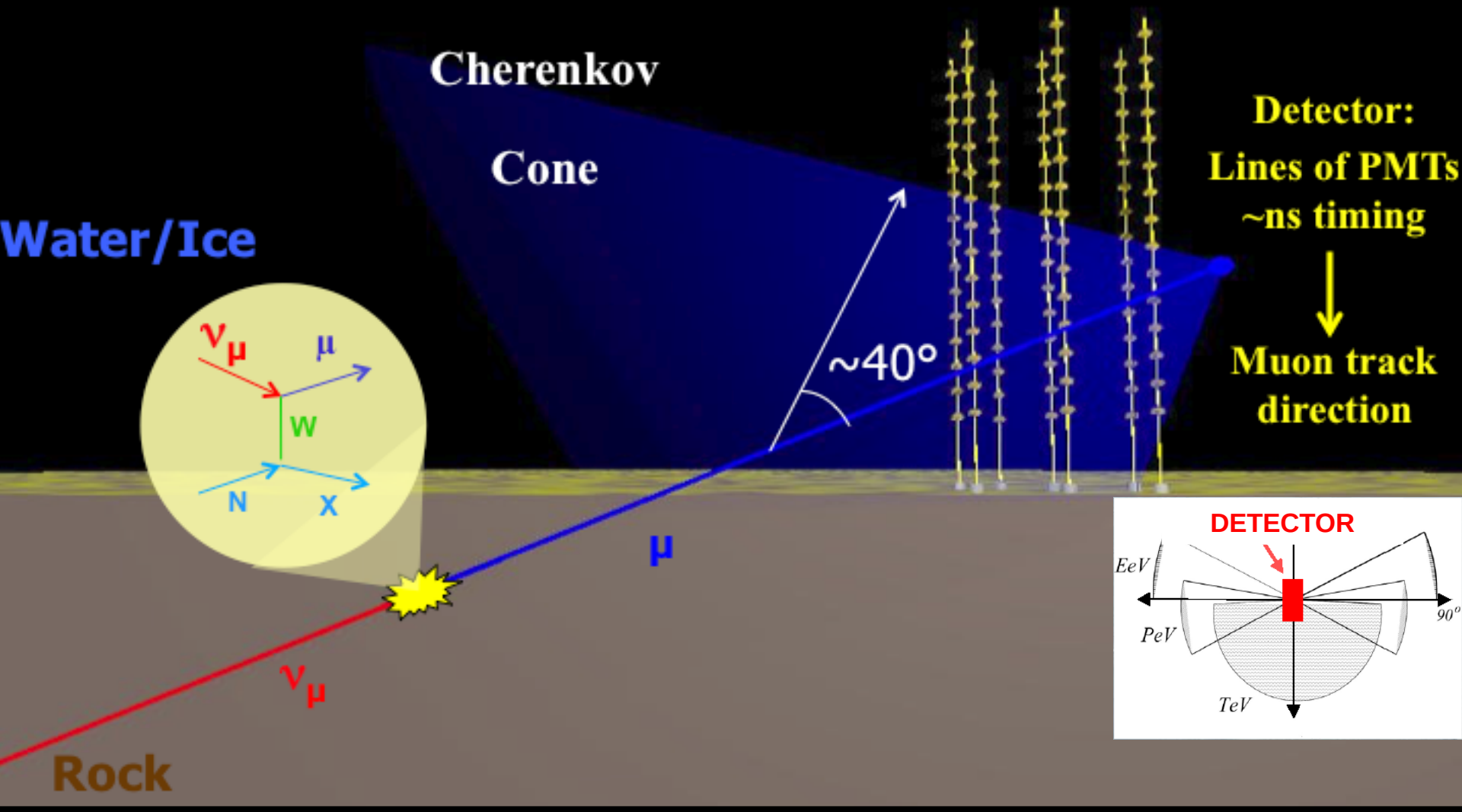
>100 km^3 effective UHE nu detectors



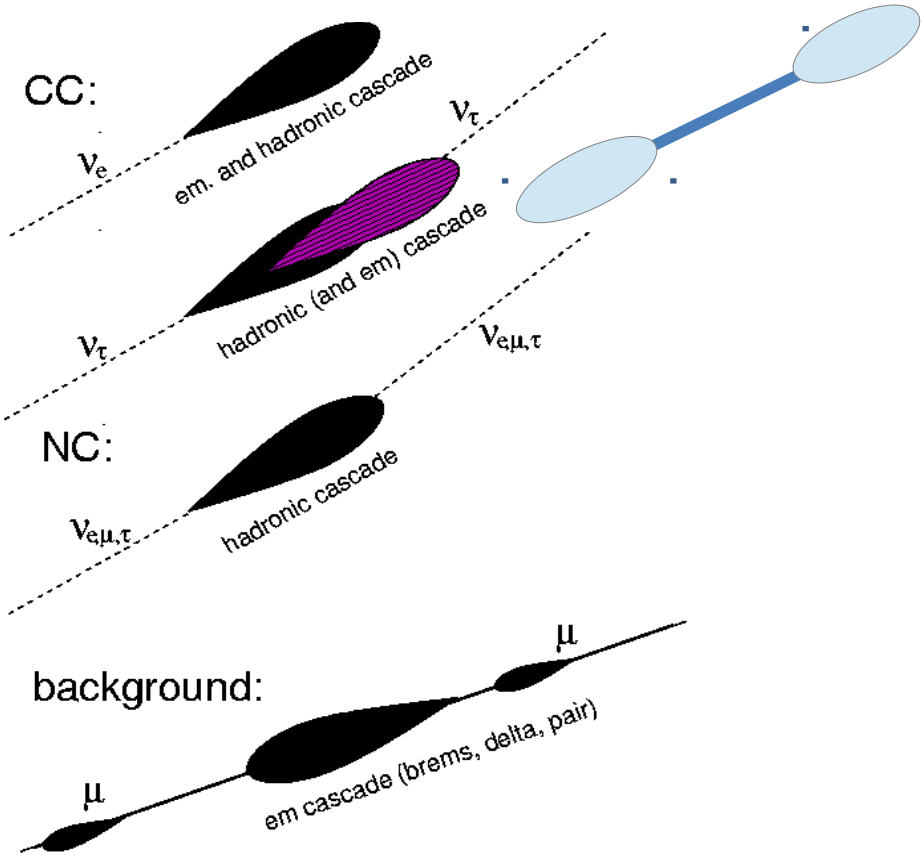


Practically

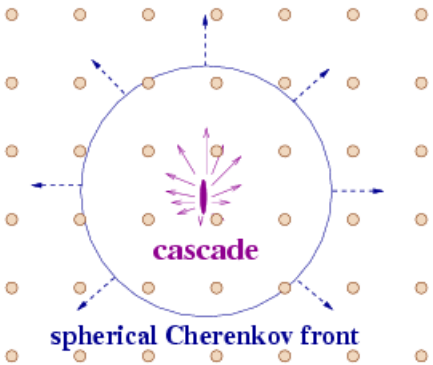




Other channels



"shower" events

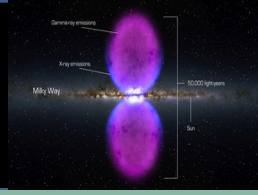


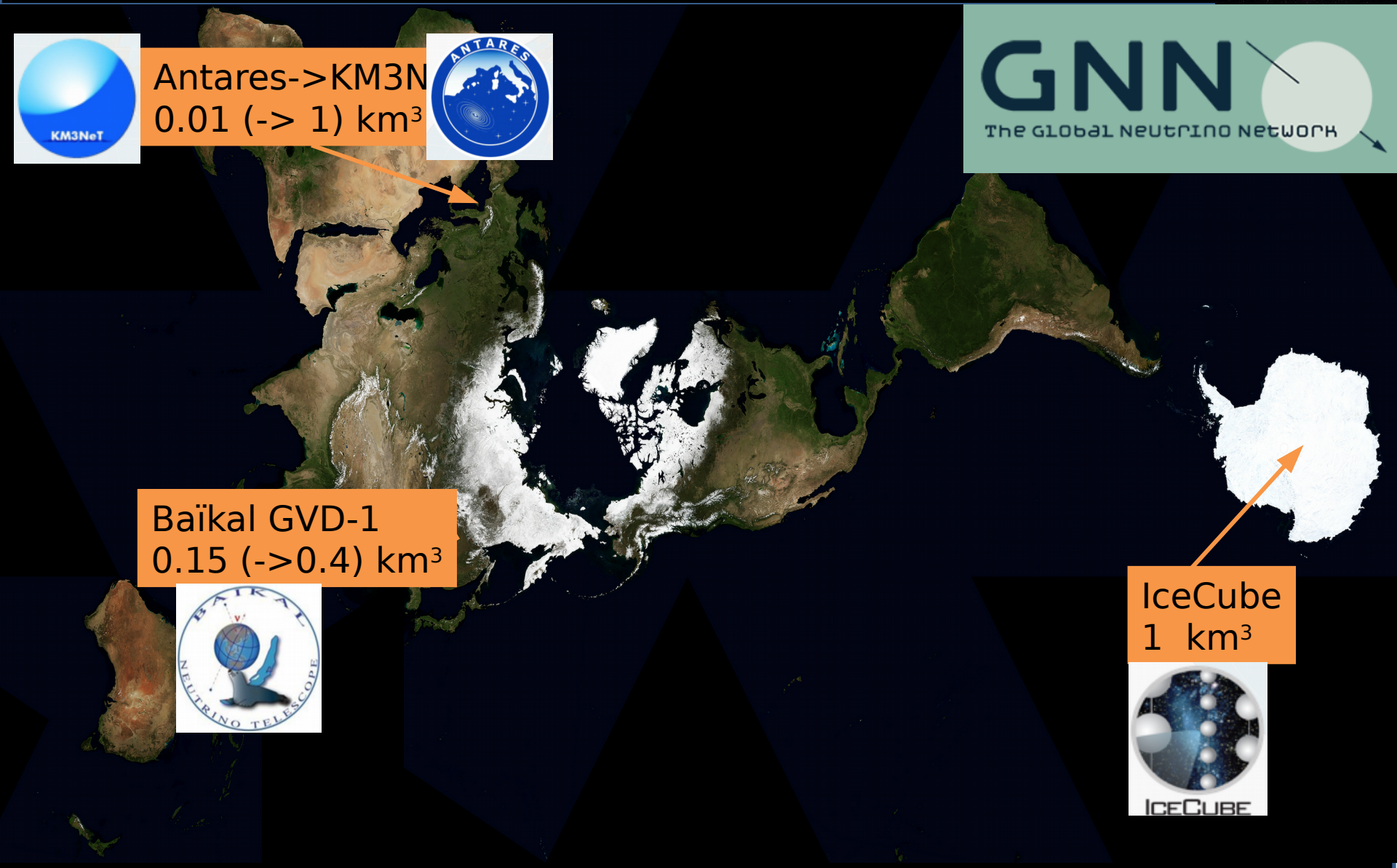
Contained events (~10m)
- + energy reconstruction
- - effective volume

topology
- + identification
- - angular resolution

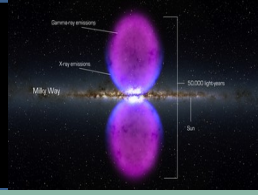
Diffuse flux (and...)

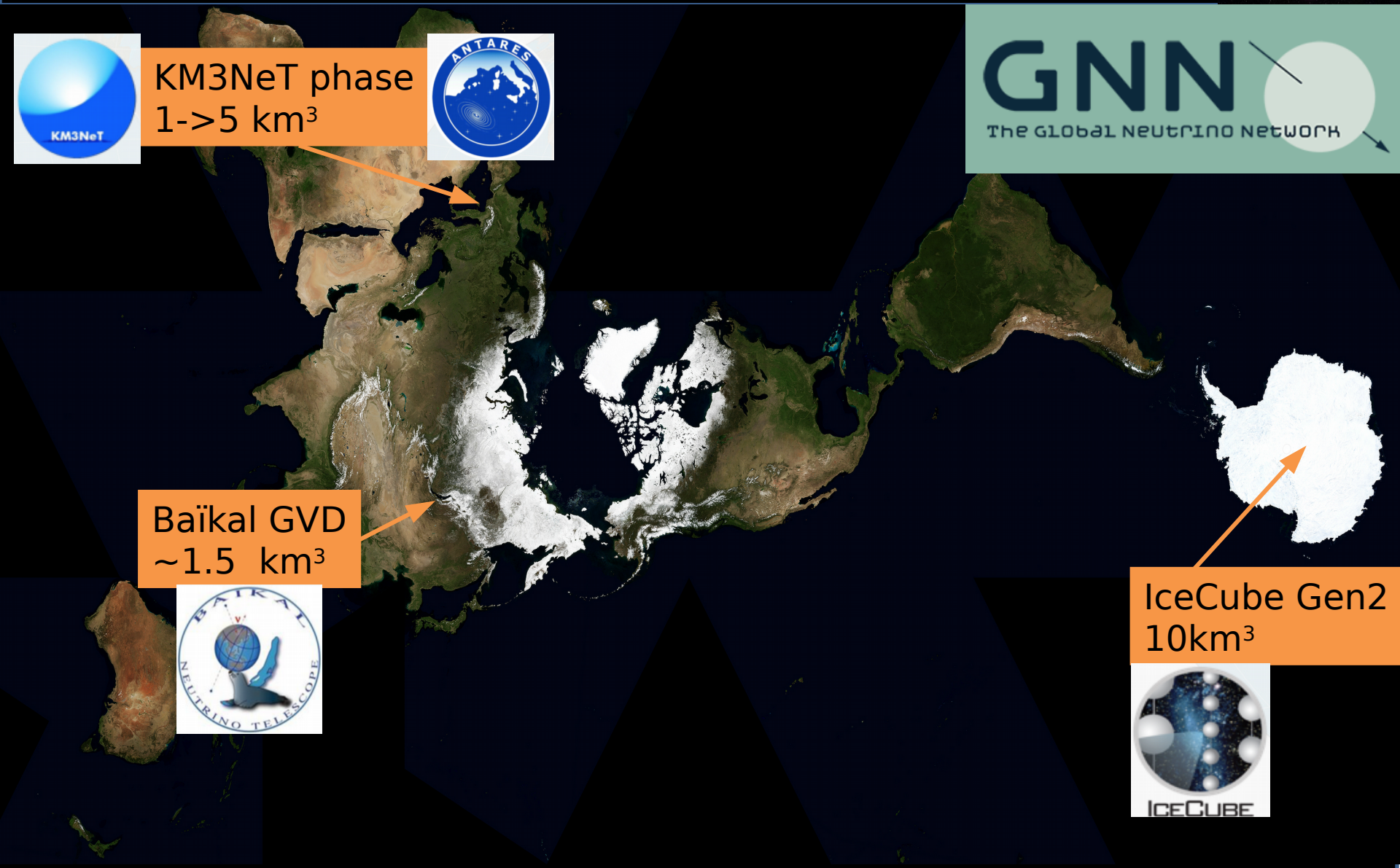
ν-Telescopes today





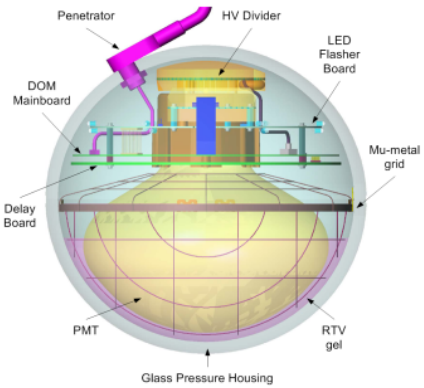
ν-Telescopes tomorrow

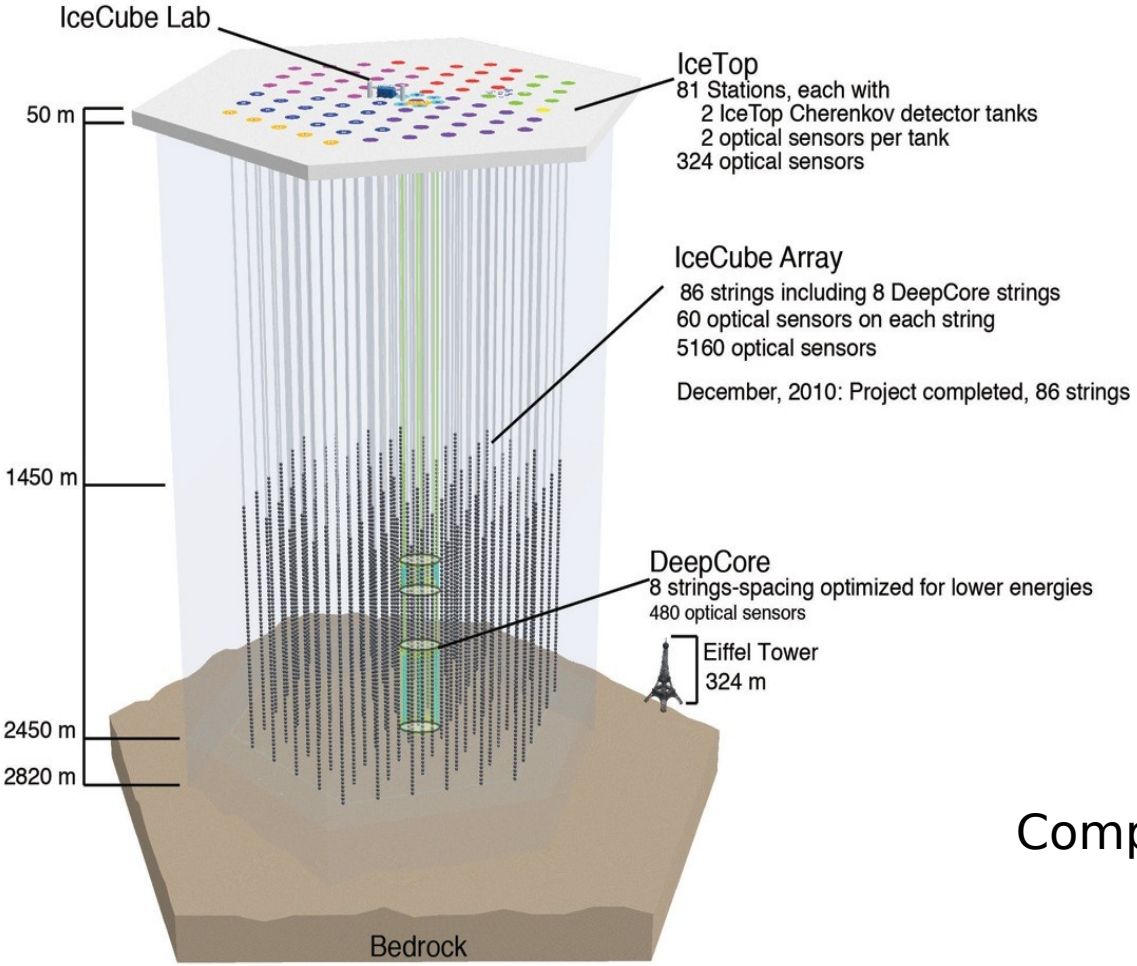




IceCube

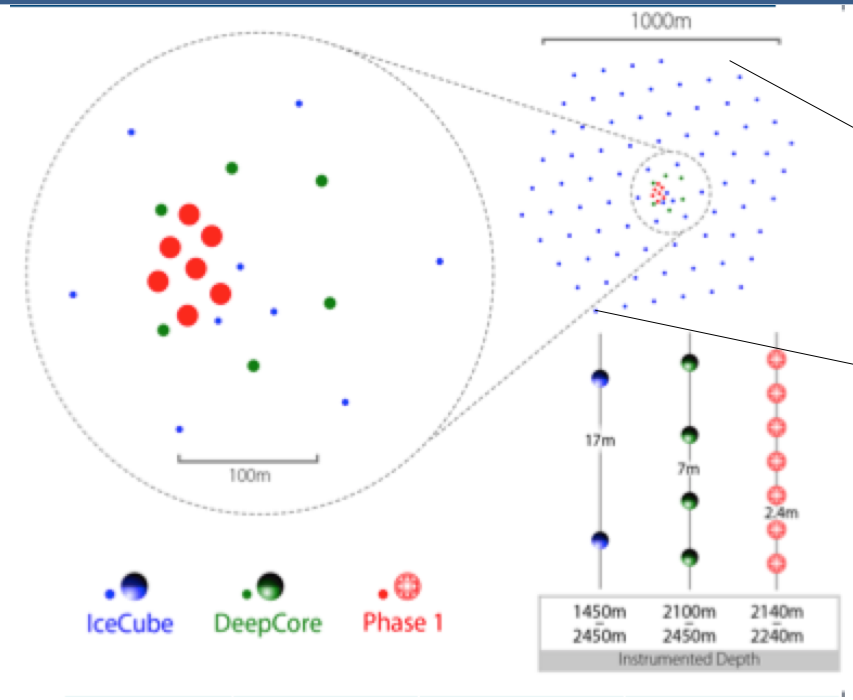
10” PMTs
Digitized Waveforms

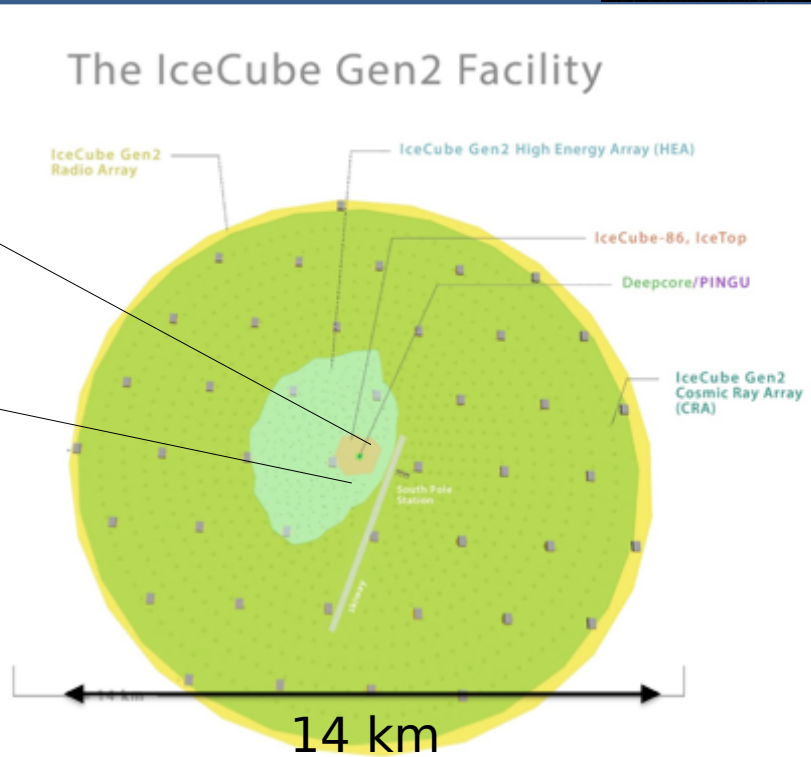




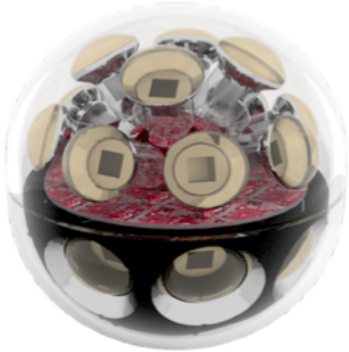
Complete since Dec. 2010

IceCube GEN 2





mDOM



Inspired by KM3NeT
24x3” PMTs
Borosilicate glass
Baseline design

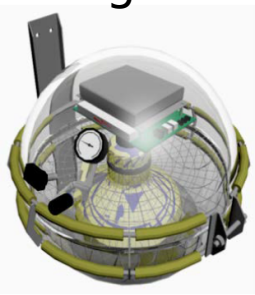
D-Egg

Developped by japanese groups
2 x 8” PMTs
UV-transparent glass

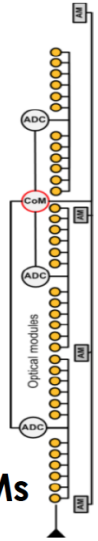
Baïkal GVD

Today: 5 clusters

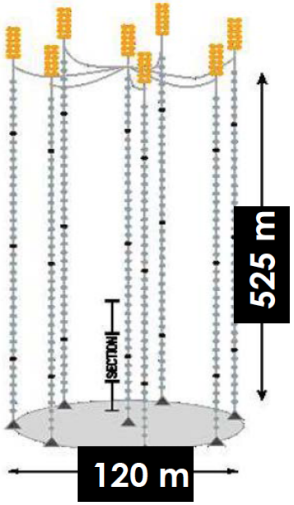
10” PMTs
digitized charge



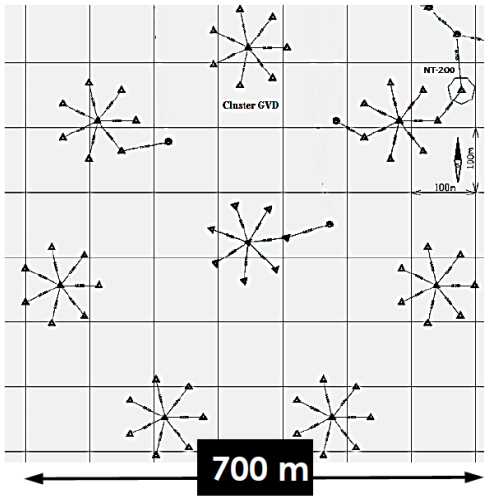
Optical module



String: 36 OMs



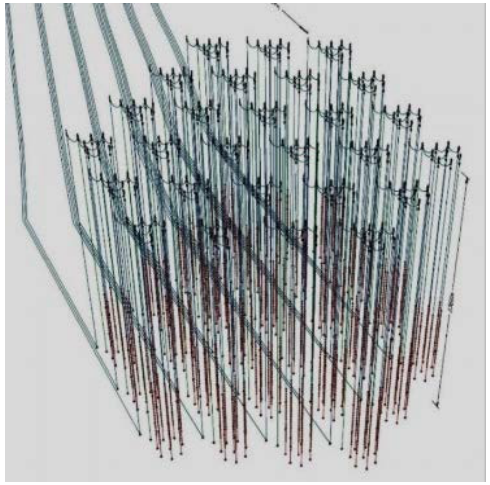
Cluster: 8 strings



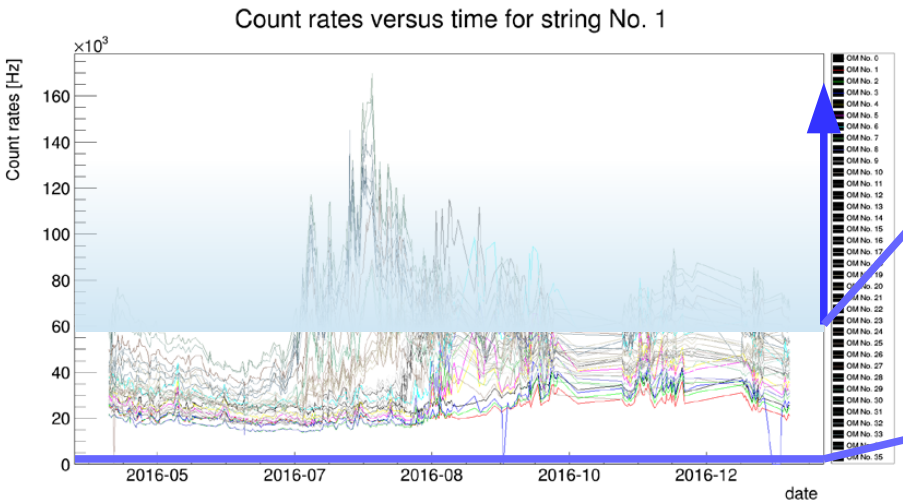
GVD-1: 8 clusters

1-2 clusters deployment per season (winter)

Final goal:
27 clusters: 1.5 km^3



Baïkal GVD it's alive !

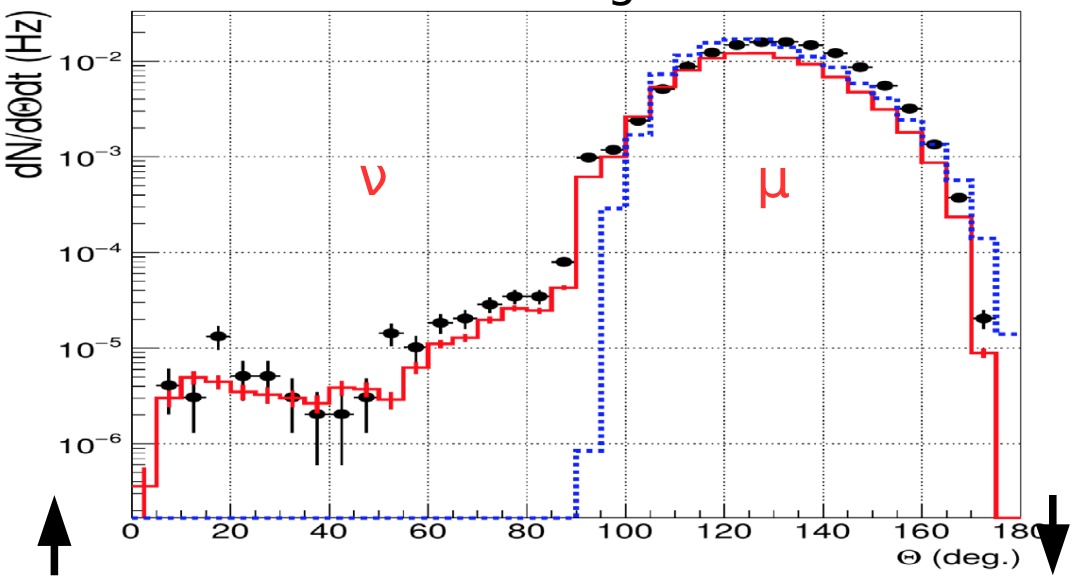


Antares

Rather low optical background

IceCube

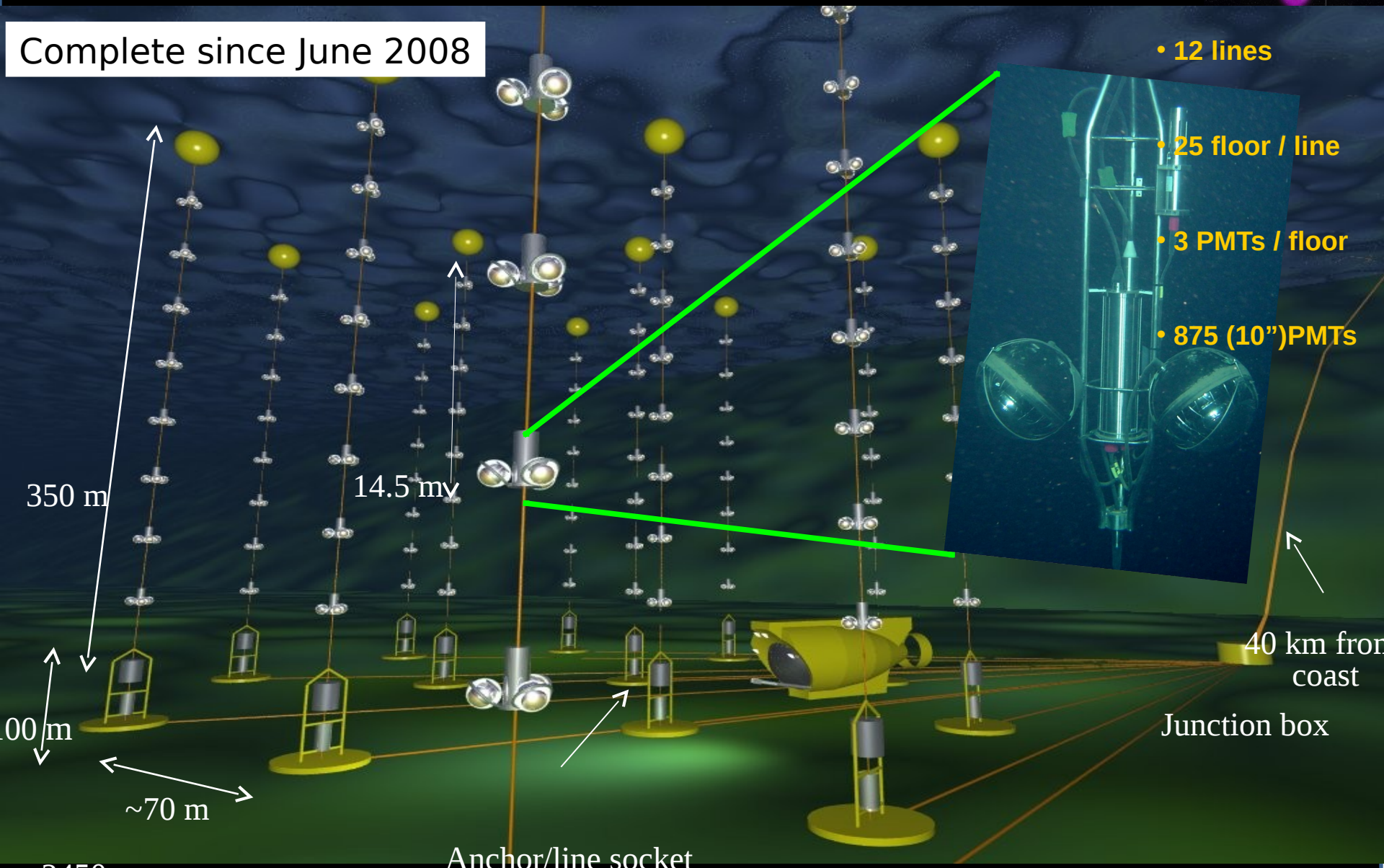
3 strings 2016



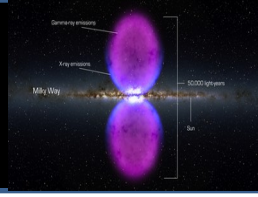
Seeing muons and neutrinos

ANTARES

Complete since June 2008



KM3NeT ARCA & ORCA



Phase-1:
24 ARCA DUs
6 ORCA DU
funded

Phase-2:
2 ARCA blocks
1 ORCA block
partially funded

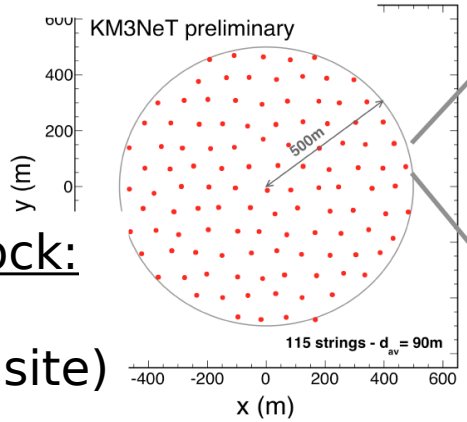
Phase-3:
6(+1) blocks

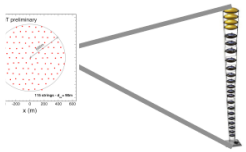
KM3NeT 2.0 Letter of Intent:
arXiv:1601.07459 and
J.Phys. G43 (2016) 084001

Multi-PMT DOM:
31 x3” pmts
ToT

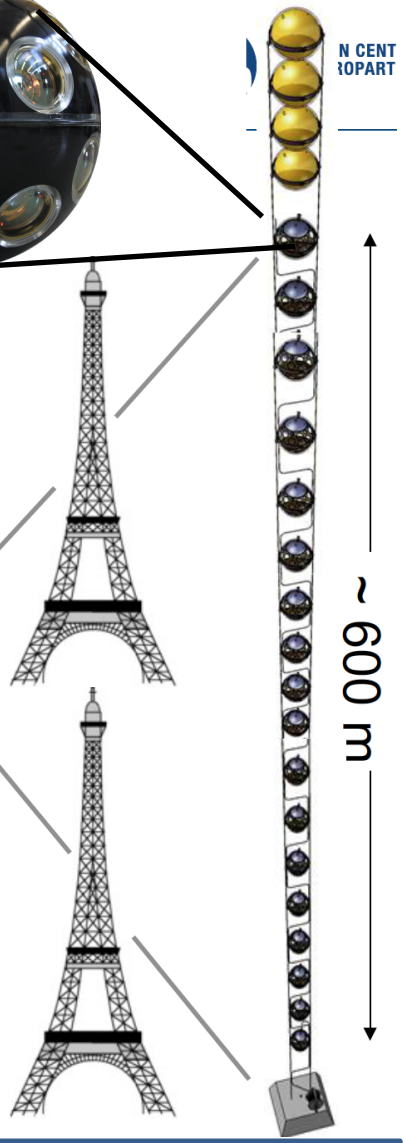
ARCA Block:
-3200m
90m/36m v./h. Spacing
TeV-PeV

ORCA block:
-2450m
(Antares site)
20m/9m
v./h. Spacing
GeV+





102 m



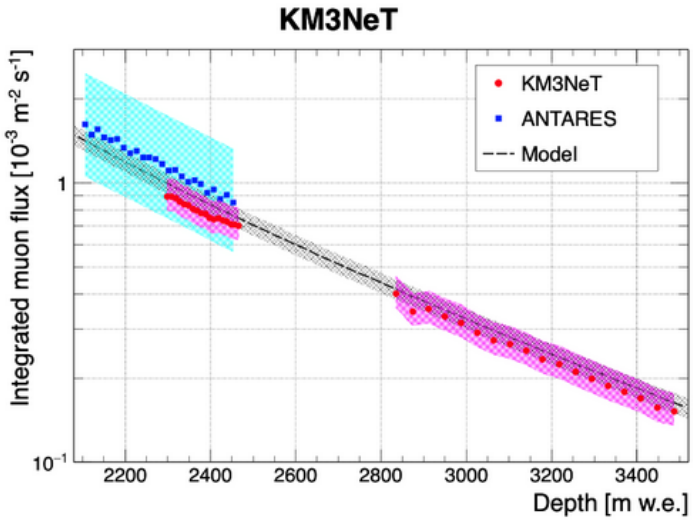
~ 600 m

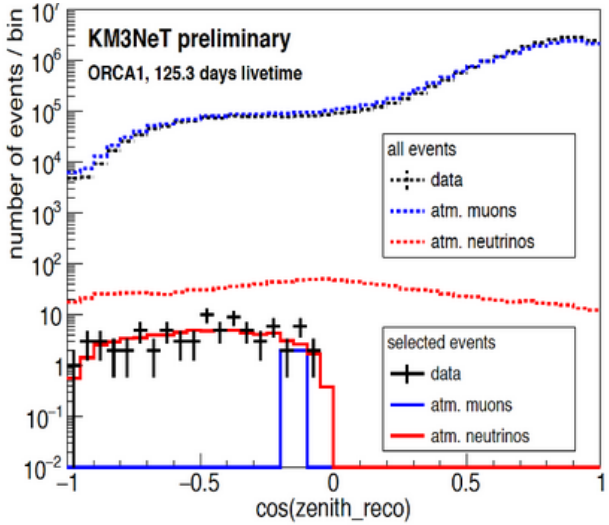
RC 2015

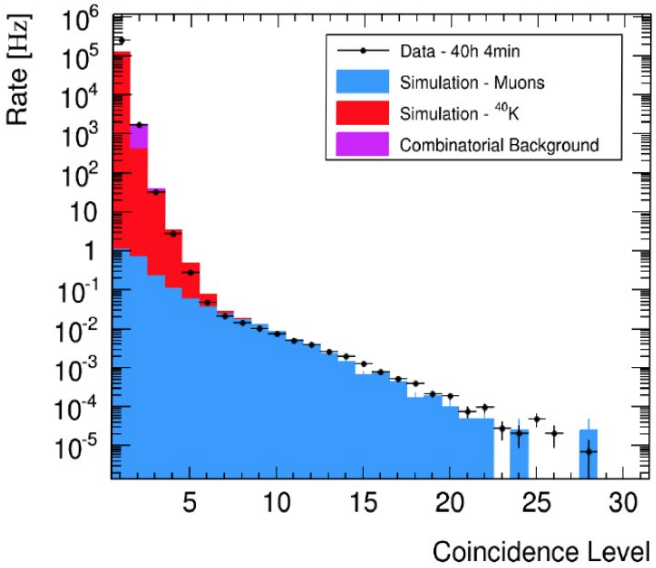
KM3NeT deployment & operation

ARCA:
- 2 strings deployed (one off)
- Full restoration of seabed network by mid 2020

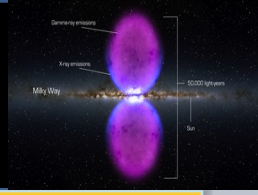
ORCA:
- 4 strings deployed
- 2 waiting to be deployed

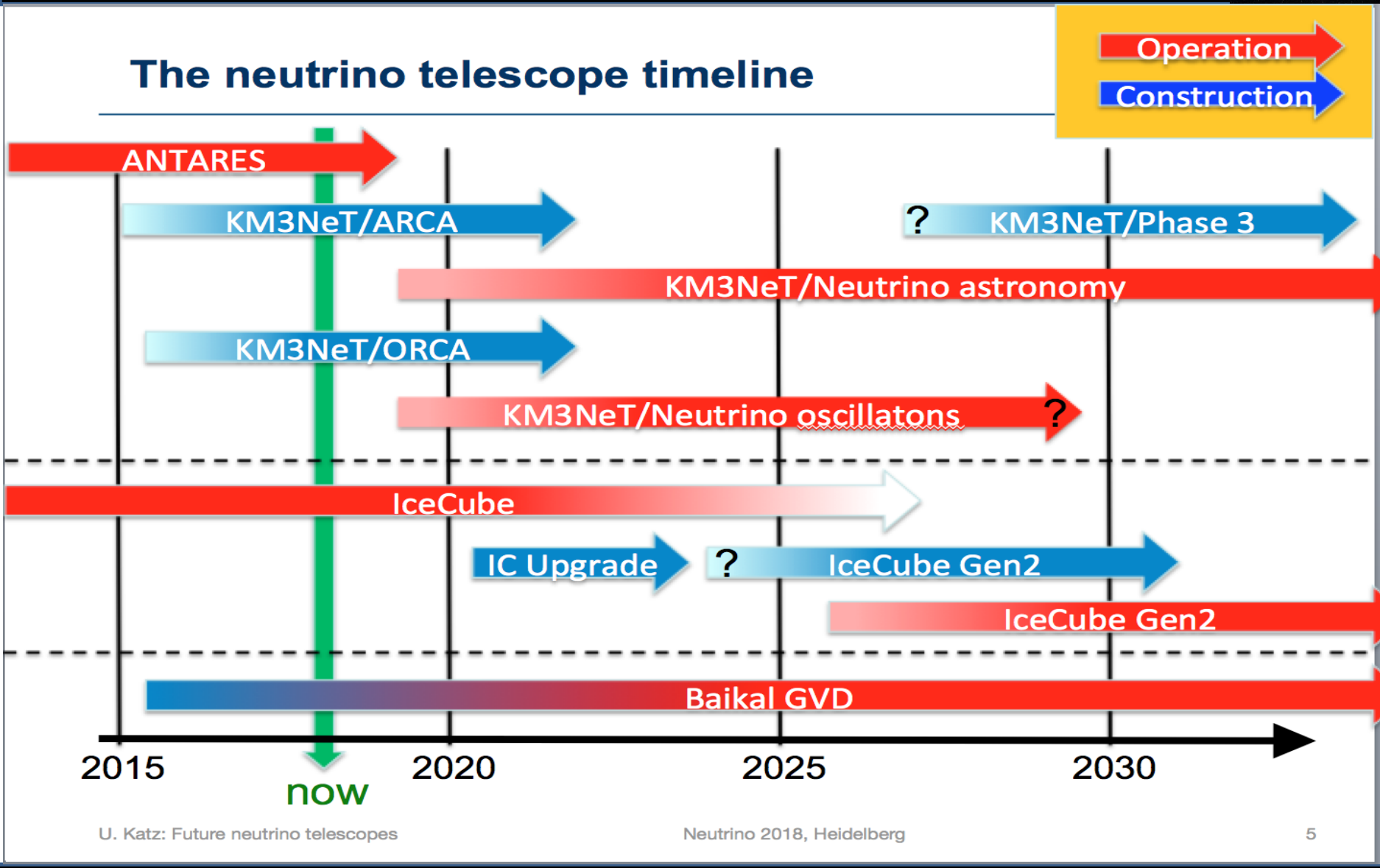






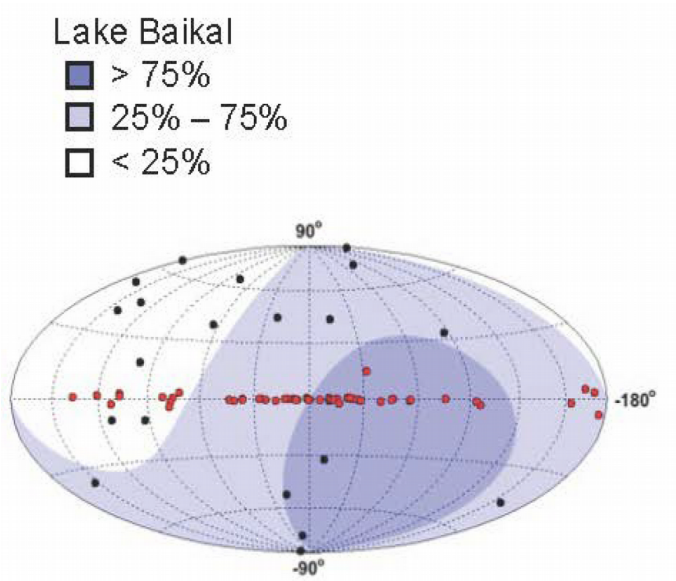
Timeline

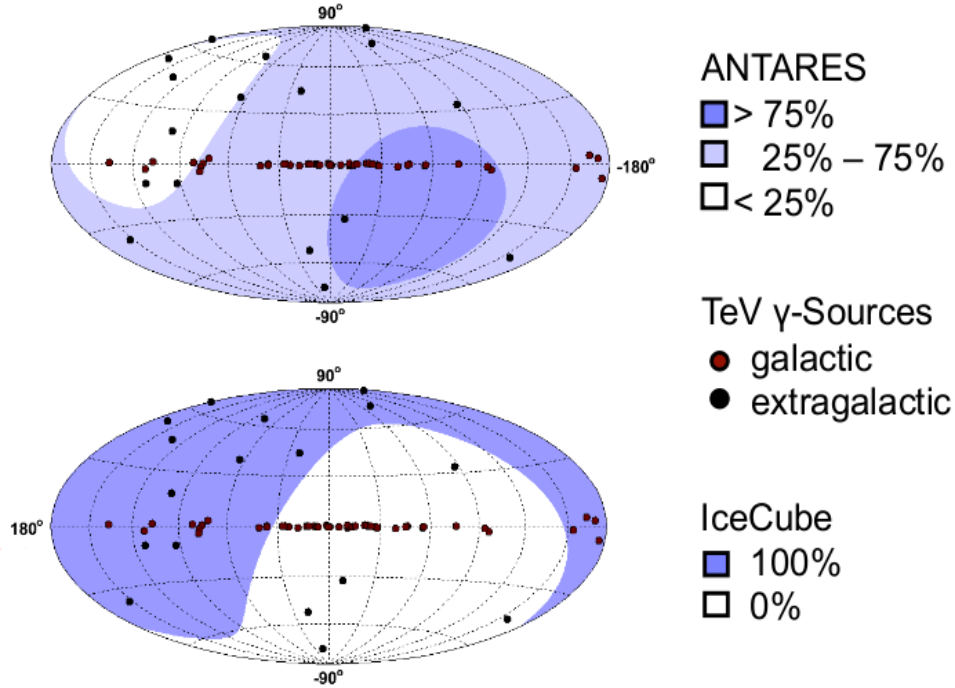



The neutrino telescope timeline
Operation
Construction
ANTARES
KM3NeT/ARCA
? KM3NeT/Phase 3
KM3NeT/Neutrino astronomy
KM3NeT/ORCA
KM3NeT/Neutrino oscillatons ?
IceCube
IC Upgrade
? IceCube Gen2
IceCube Gen2
Baikal GVD
2015
now
2020
2025
2030
U. Katz: Future neutrino telescopes
Neutrino 2018, Heidelberg
5

Mediterranean / South Pole

- Complementary coverage (μ channel)





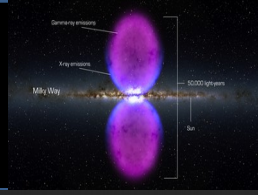
- Water v.s. Ice

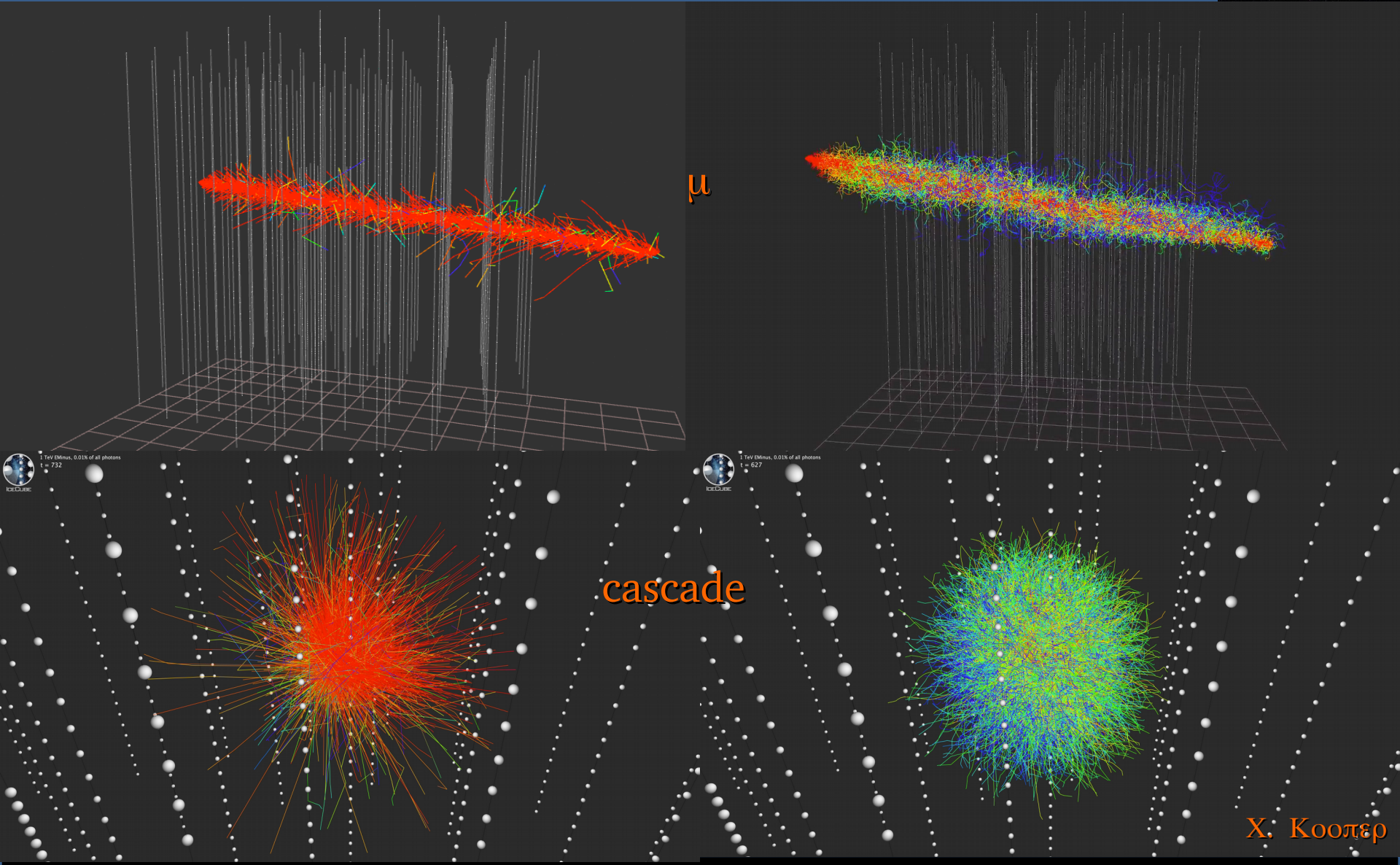
  Optical noise (biolum) / no noise

  absorption / diffusion

  pointing / calorimetry

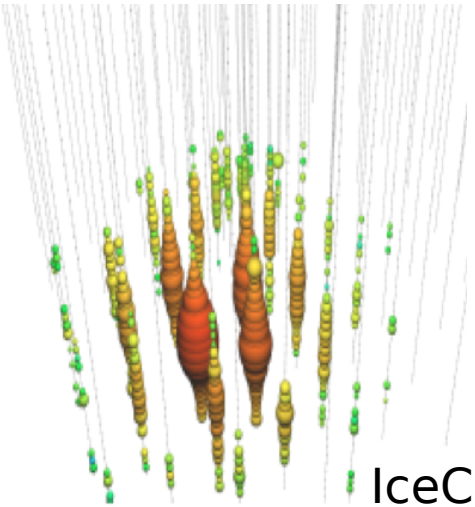
Water v.s. Ice (MC)



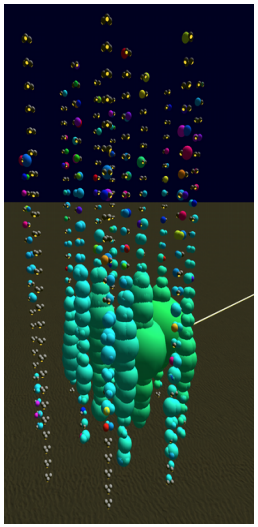


In real life

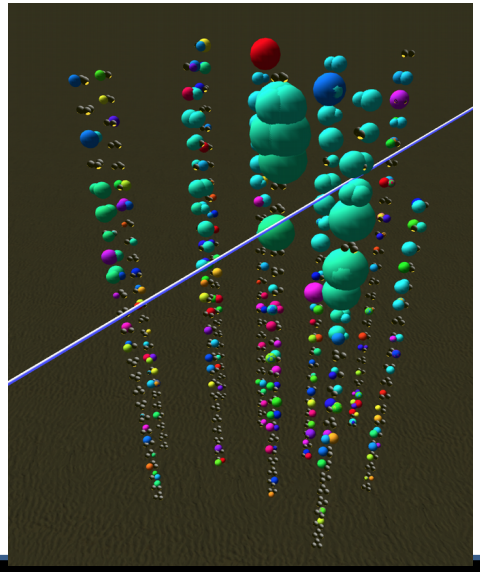
Cascades



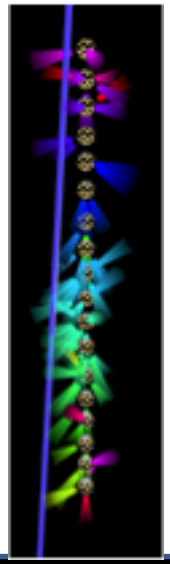
IceCube

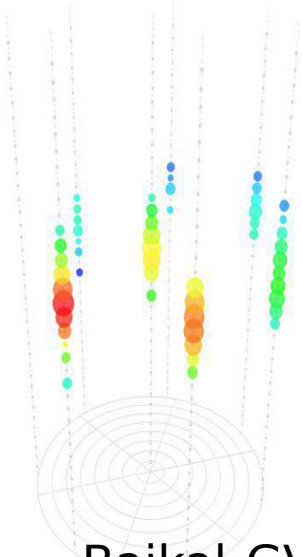


Antares

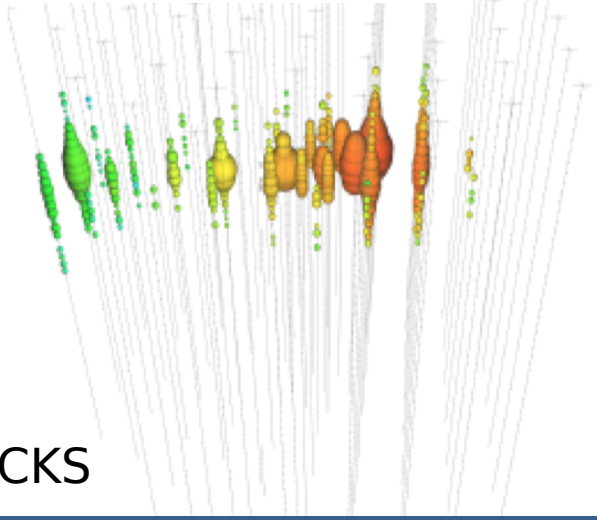


ORCA

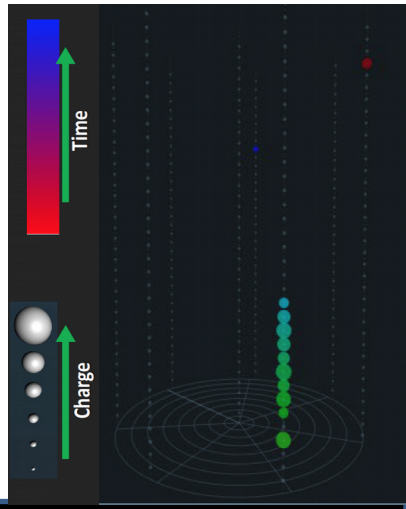




Baikal-GVD



TRACKS



Angular resolution with tracks

<u>Size of some astrophysical objects :</u>

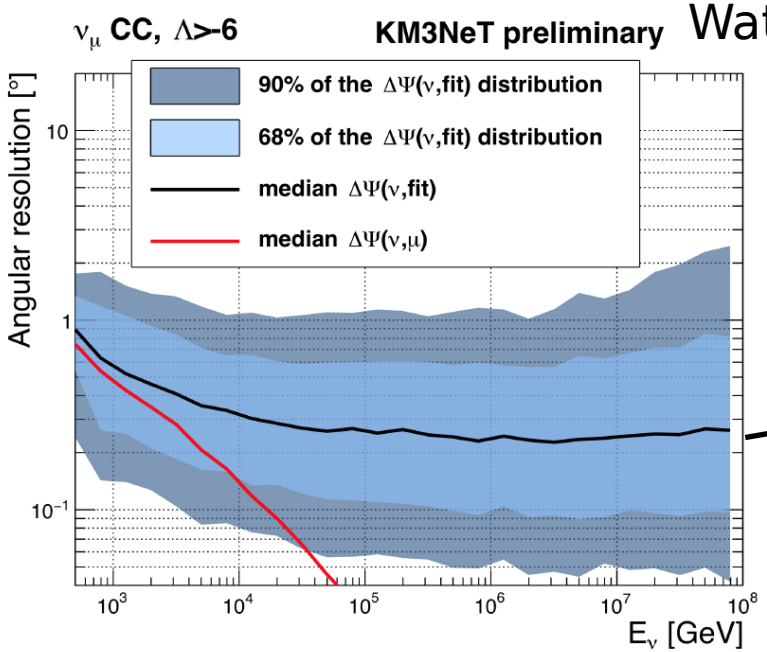
RXJ1713 (SNR):1°
Sun, Moon : 0.5°
Cen A (AGN) : 0.3°

Point sources search:
Signal/Noise : $1/\Delta\Omega^2$

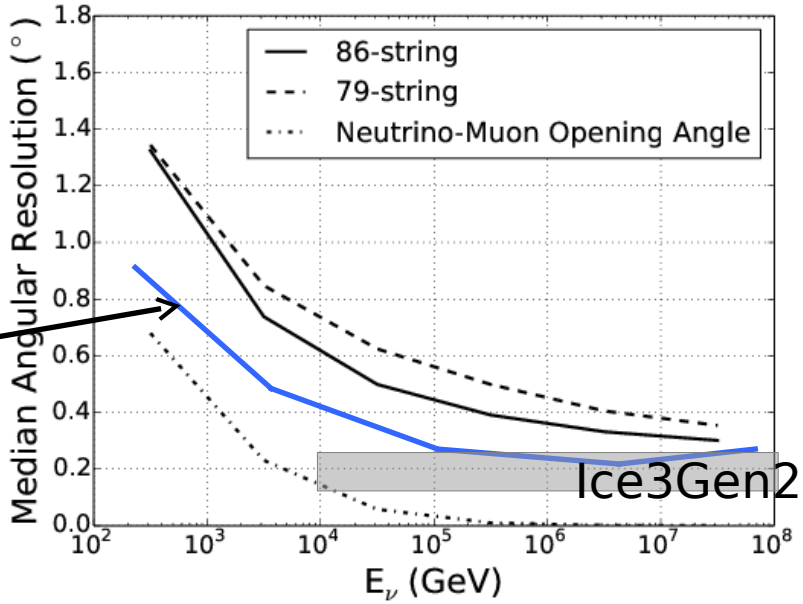
Based on photons time and position likelihood

<u>Muons</u>:

Water



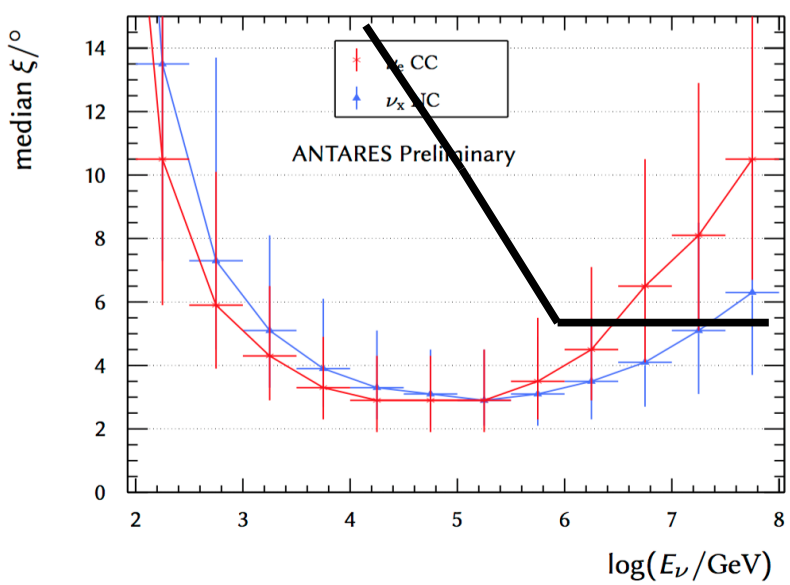
Ice



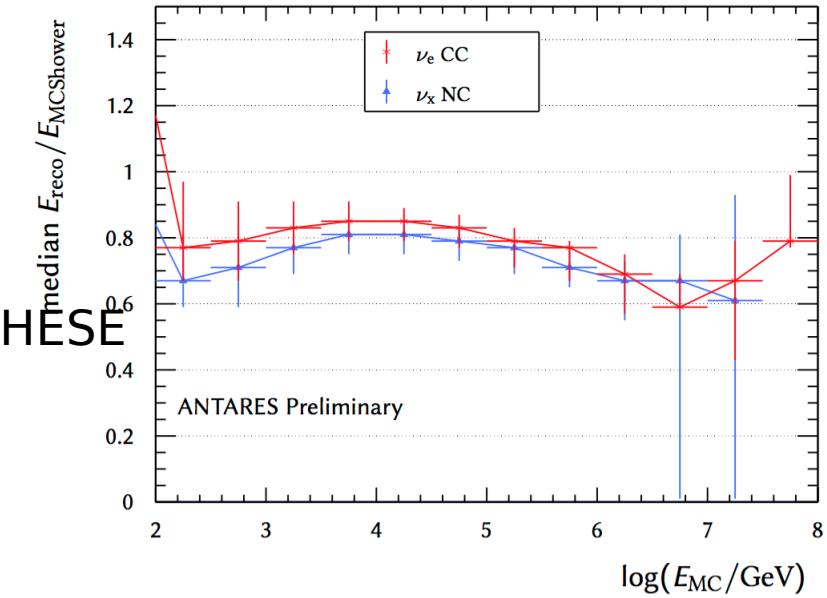
Shower reconstruction in water

Based on photons number and position likelihood

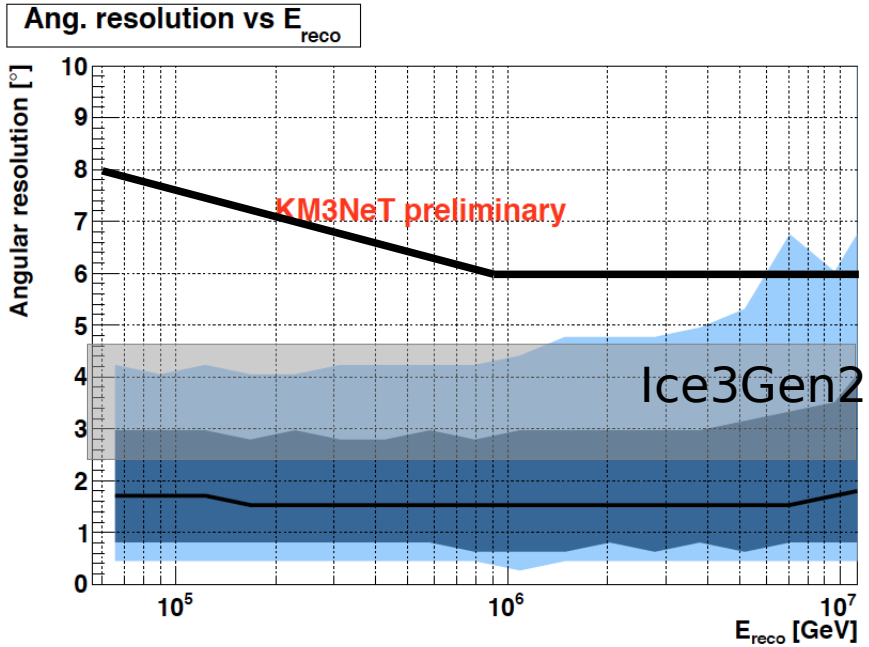
ANTARES & GVD: similar resolutions



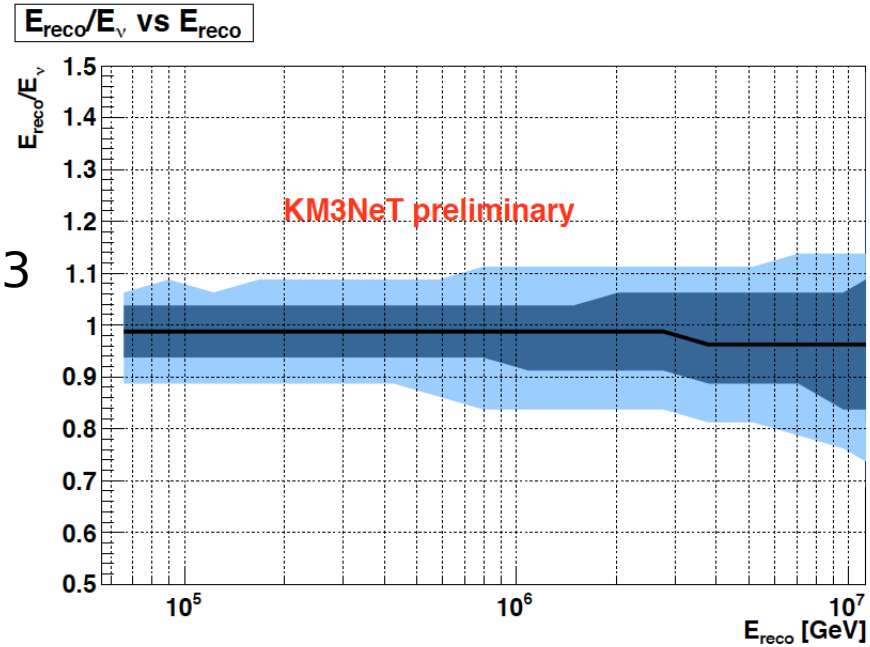
Ice3 HESE



Shower reconstruction prospects

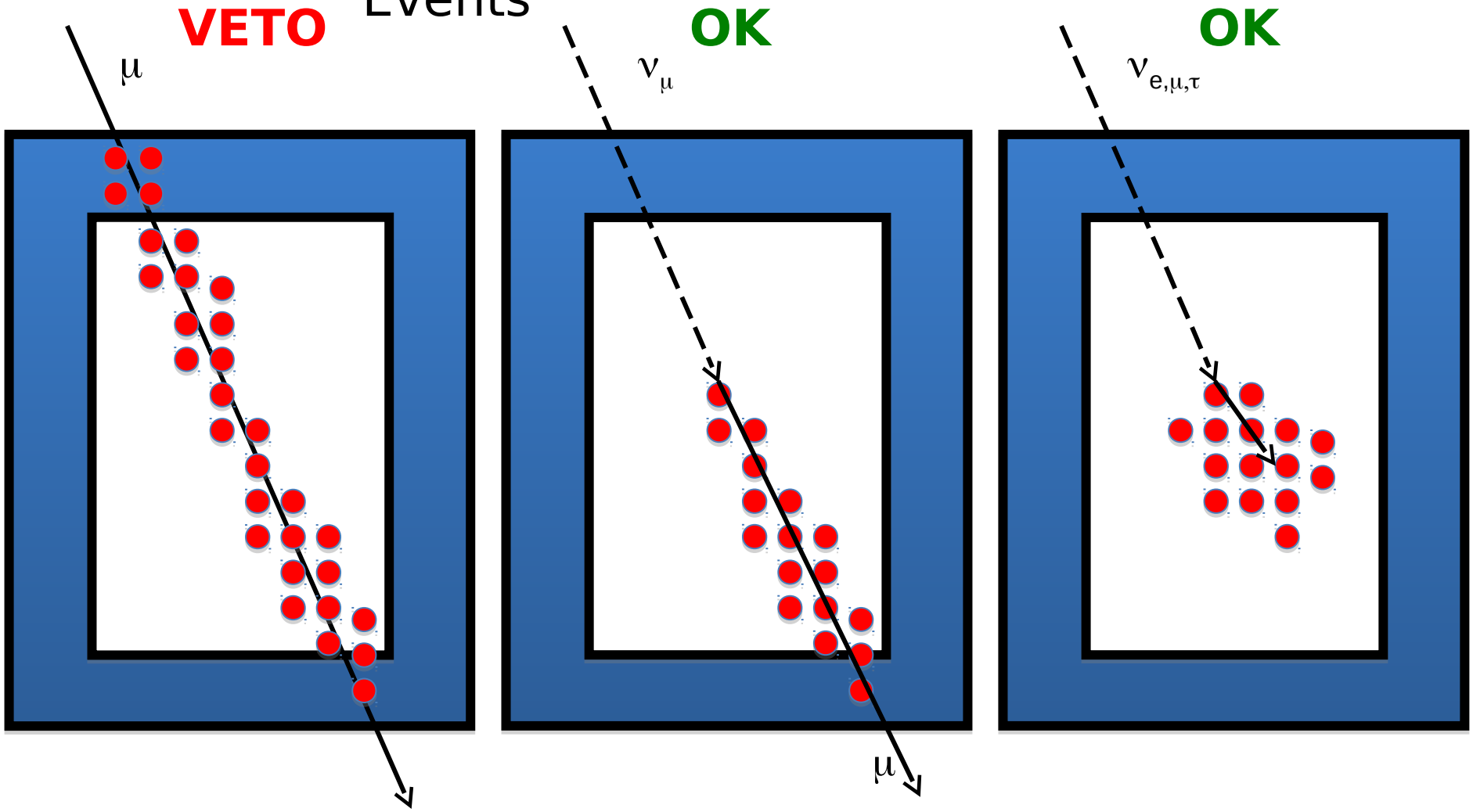


Ice3

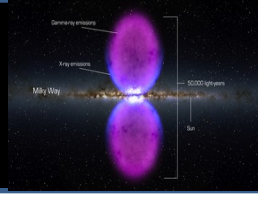


Another strategy : « HESE »

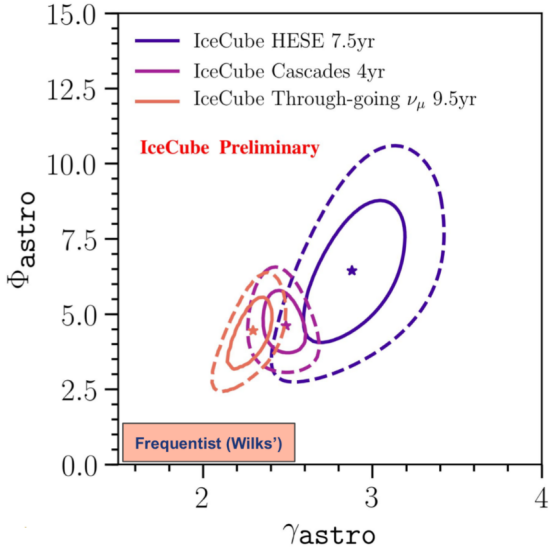
High Energy Starting Events

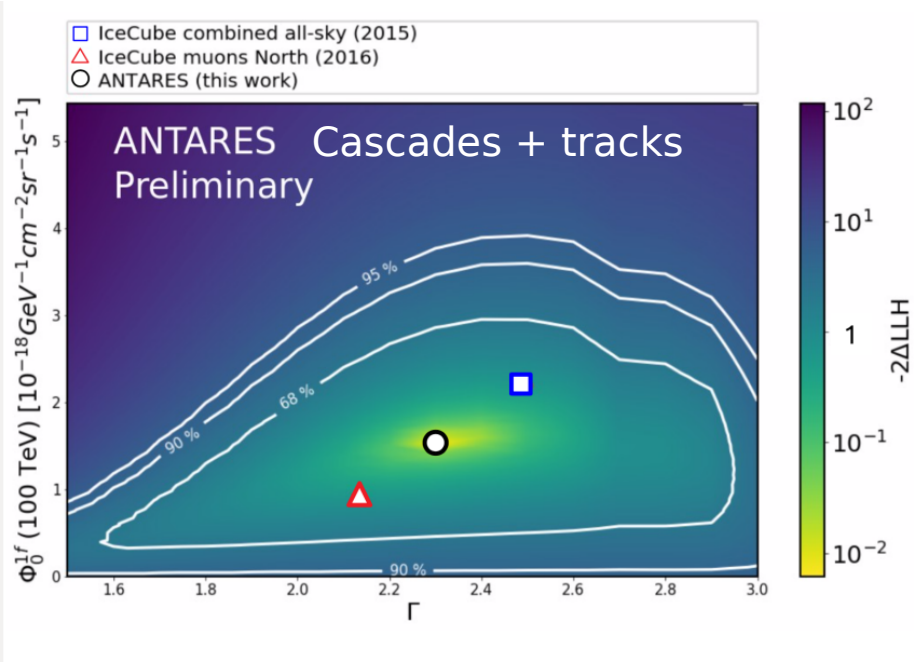


A Diffuse Flux



$$\frac{d\Phi_{6\nu}}{dE} = \Phi_{astro}\left(\frac{E_\nu}{100\text{TeV}}\right)^{-\gamma_{astro}} \cdot 10^{-18}\ [\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}]$$

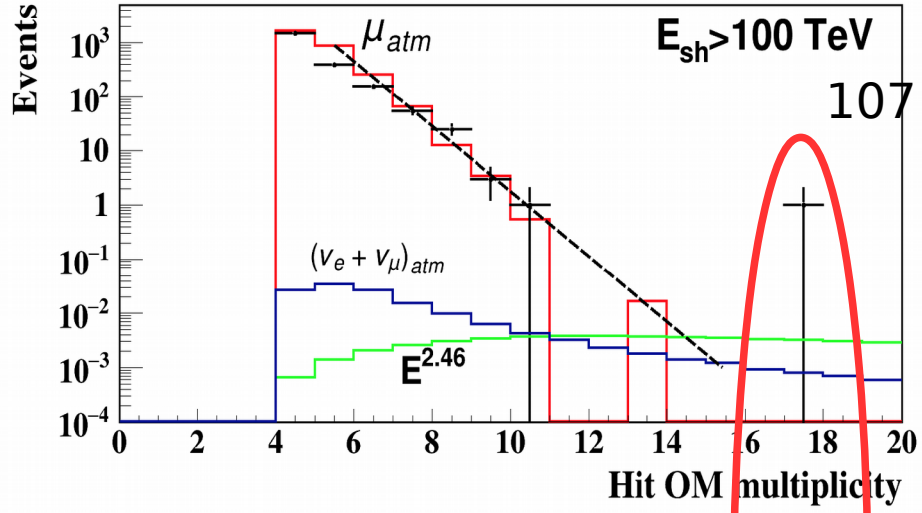




Name	Approx. Neutrino Energy	Direction	Dominant Flavor	Unbroken Spectral Index
HESE	50 TeV - 5 PeV	All-sky	e, μ, τ	2.89
Cascades	5 TeV - 5 Pev	All-sky	e, τ	2.48
NuMu	50 TeV - 10 PeV	Northern sky	μ	2.28

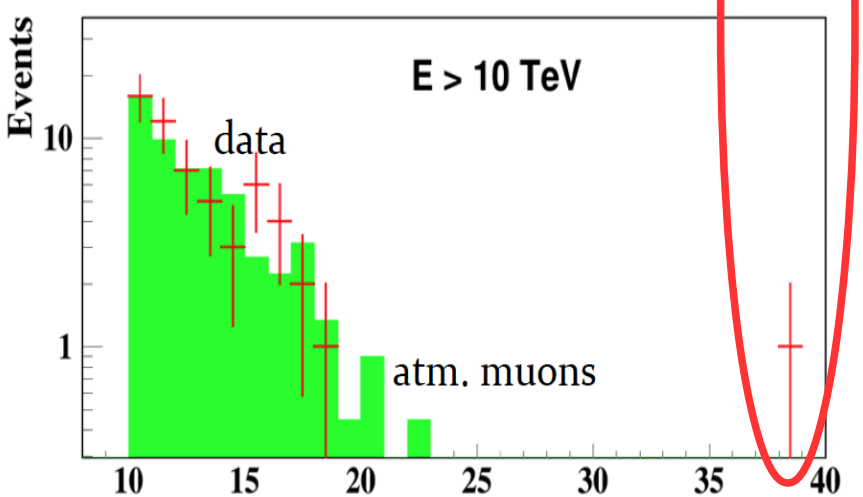
Baïkal GVD diffuse search

2015:42d.

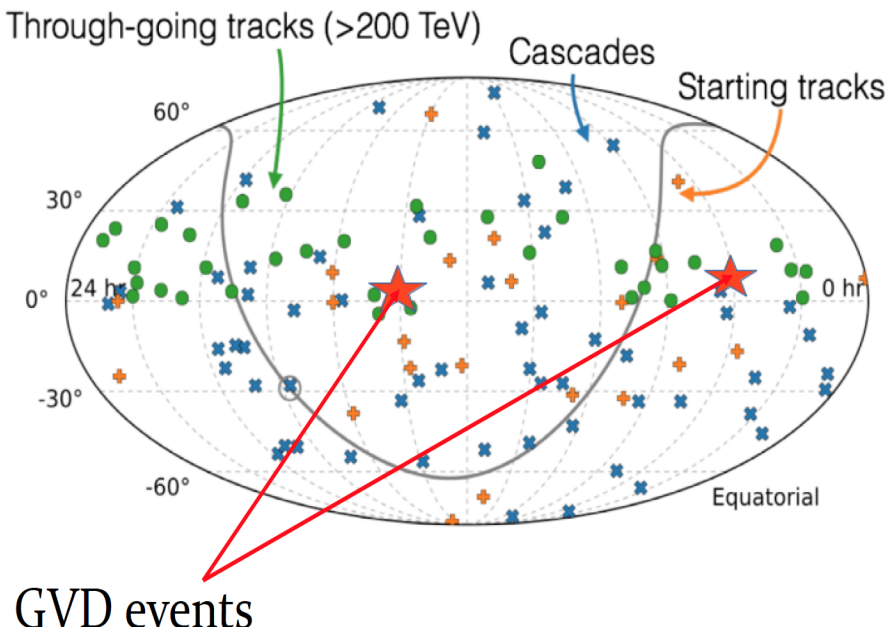


107 TeV

2016: 182 d.

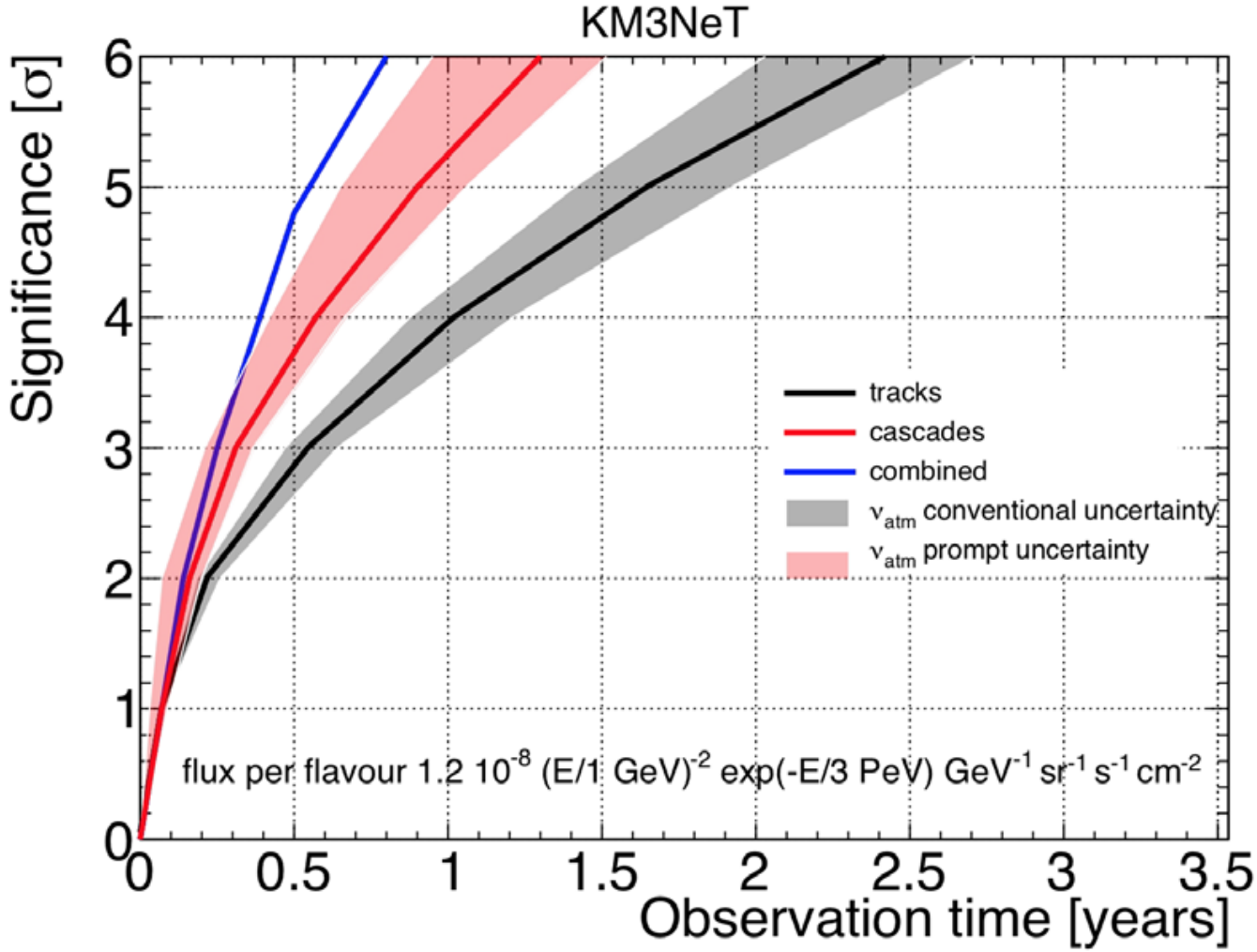


157 TeV

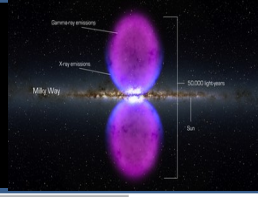


A. Dzhilkibaev QUARKS2018

KM3NeT perspectives



Existing Data Samples Characteristics



Sample	Ang. Res.	Energy Res.	Stat.
IceCube trck Up-going Down-going	O(0.3) °	0.2xLog(E)	HE ν tracks, 80k evt/yr VHE μ tracks 35k evt/yr
Antares trck Up-going	O(0.2)°	0.3xLog(E)	HE ν tracks a few k evt/yr
IceCube Casc	~5-15°	1-10%	O(10) evt/yr
Antares Casc.	2.5-10°	10%	1-10 evt/yr
Baïkal cascades	4.5°	30%	5 evt/yr (>100TeV)

Available “Open samples”:

HESE and HE Alerts
~10/yr >50%, “signalness”

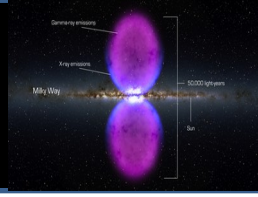
muon samples
high statistics/overwhelming background
Searched signal dependent

Potential sources I

- **Galactic:** (full or partial contribution)
  - diffuse Galactic γ-ray emission [MA & Murase'13; Joshi J C, Winter W and Gupta'13] [Kachelriess and Ostapchenko'14; Neronov, Semikoz & Tchernin'13] [Neronov & Semikoz'14; Guo, Hu & Tian'14; Gaggero, Grasso, Marinelli, Urbano & Valli'15]
  - unidentified Galactic γ-ray emission [Fox, Kashiyama & Meszaros'13] [Gonzalez-Garcia, Halzen & Niro'14]
  - supernova remnants [Mandelartz & Tjus'14]
  - pulsars [Padovani & Resconi'14]
  - microquasars [Anchordoqui, Goldberg, Paul, da Silva & Vlcek'14]
  - Sagitarius A* [Bai, Barger, Barger, Lu, Peterson & Salvado'14; Fujita, Kimura & Murase'15]
  - *Fermi Bubbles* [MA & Murase'13; Razzaque'13] [Lunardini, Razzaque, Theodoseau & Yang'13; Lunardini, Razzaque & Yang'15]
  - Galactic Halo [Taylor, Gabici & Aharonian'14]
  - heavy dark matter decay [Feldstein, Kusenko, Matsumoto & Yanagida'13] [Esmaili & Serpico '13; Bai, Lu & Salvado'13; Cherry, Friedland & Shoemaker'14]

from M. Ahlers

Potential sources I



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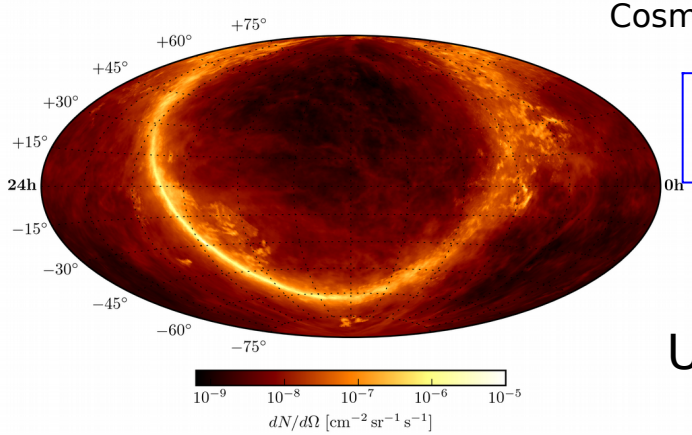
from M. Ahlers

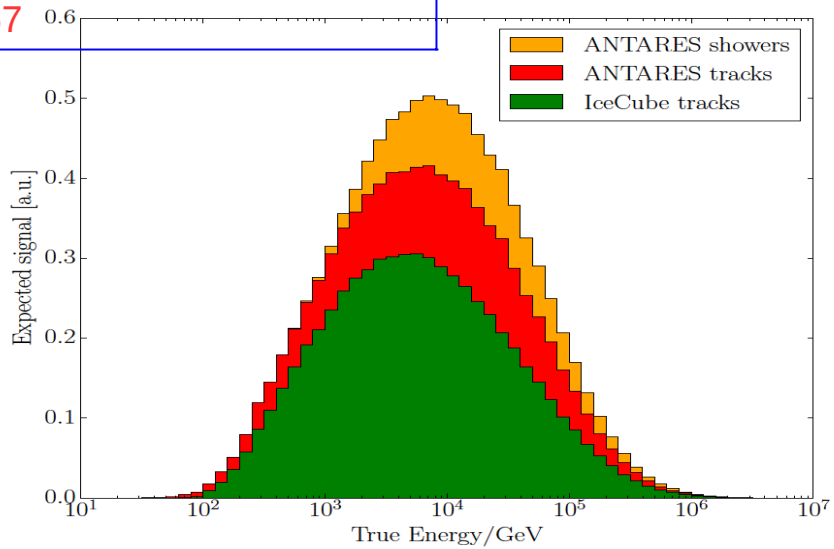
Galactic Plane search (by Antares+IceCube !)

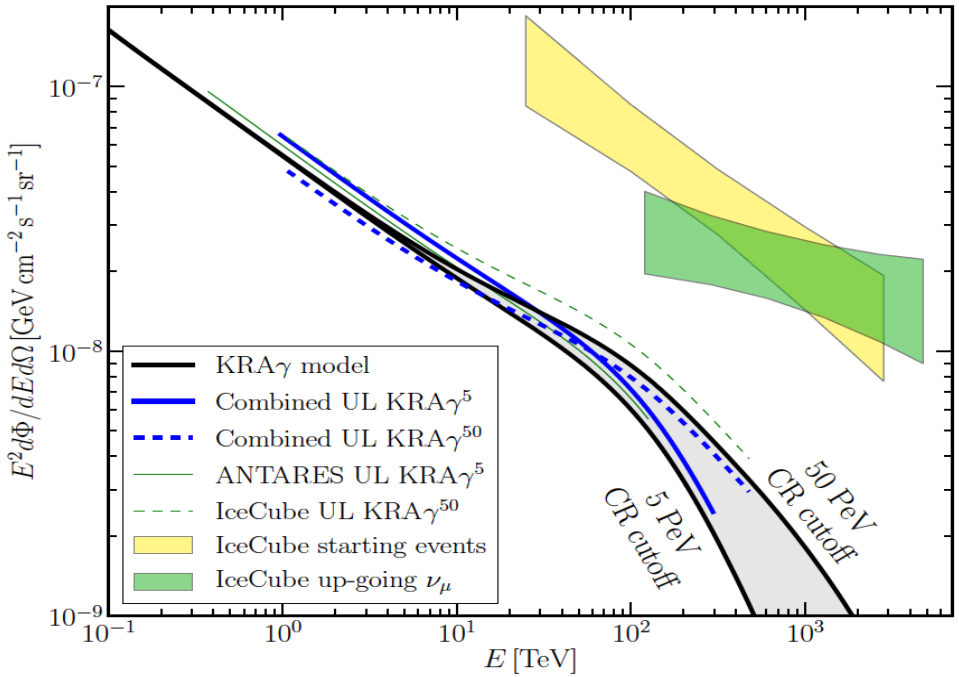
Cosmic Ray interaction with gas during propagation in the galaxy

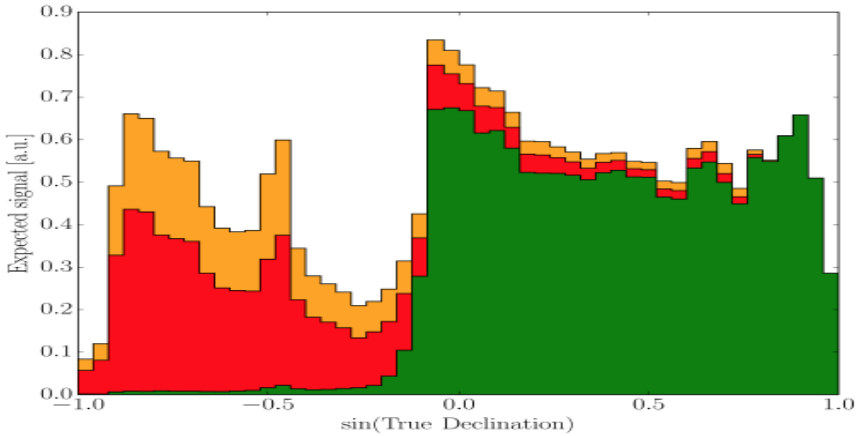


Phys. Rev. D96 (2017) 062001
ApJ 849 (2017) 67

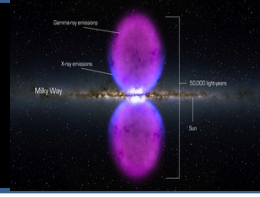
Update soon!

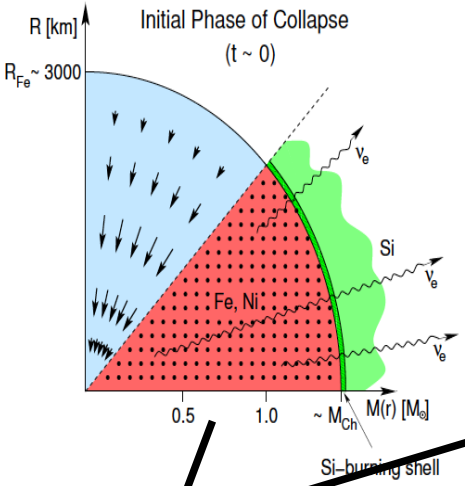


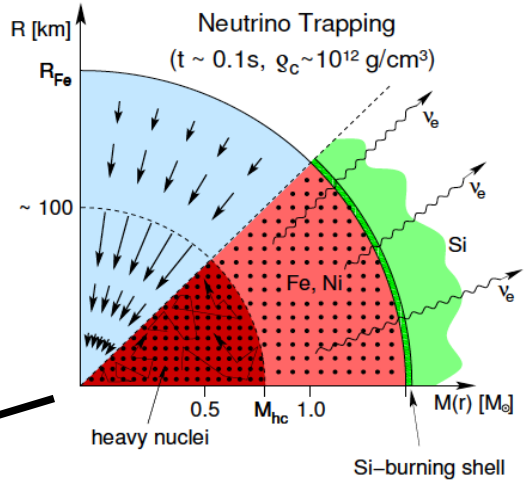


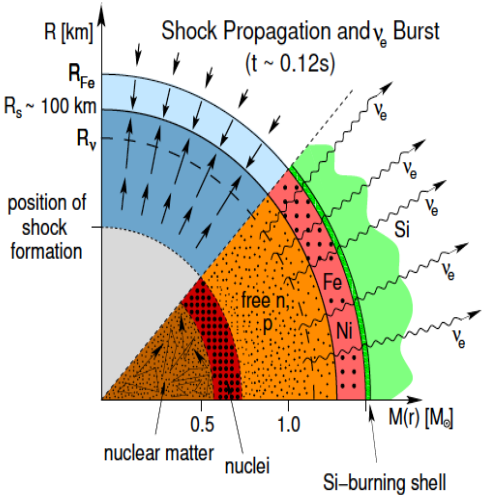


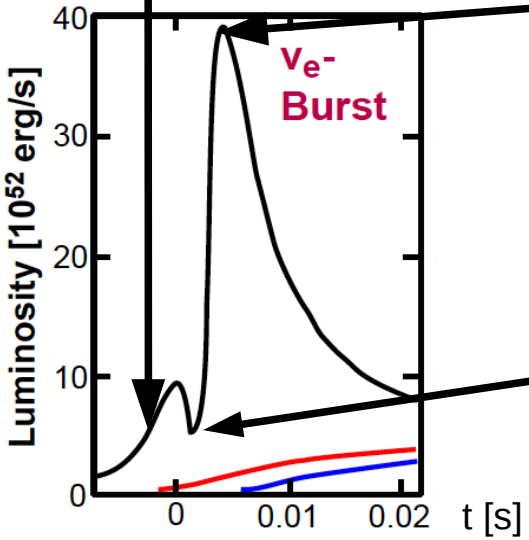
Low Energy Galactic source: Supernovae - Phase I

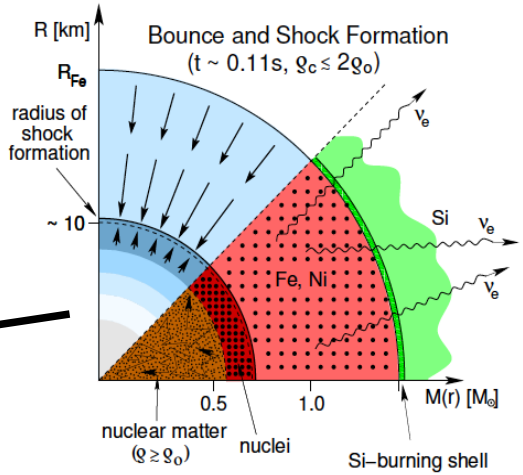






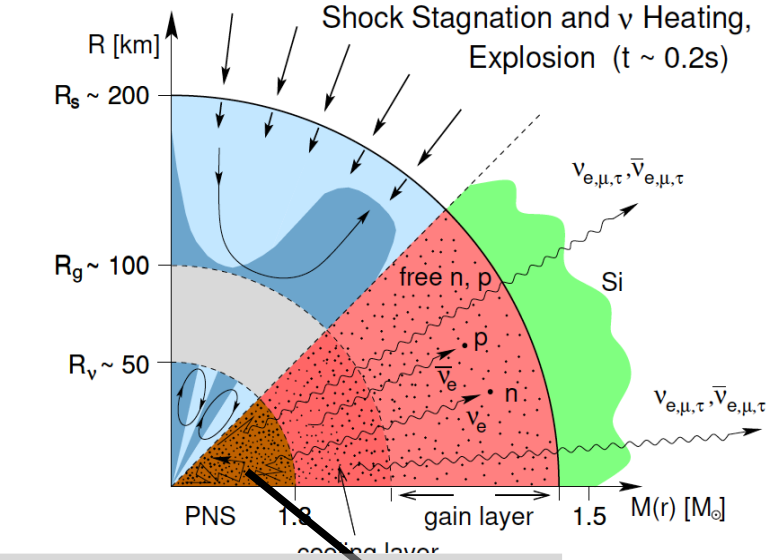


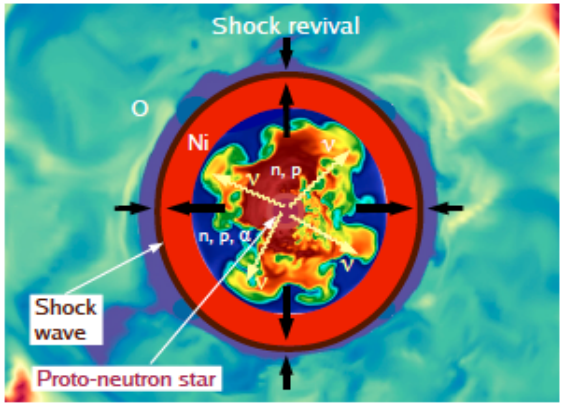


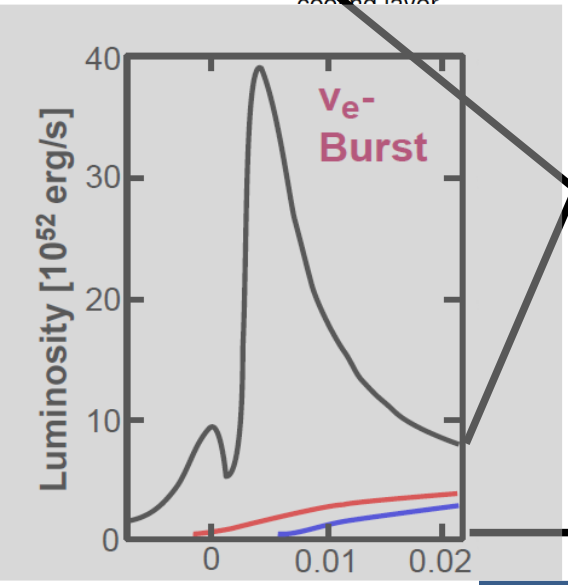


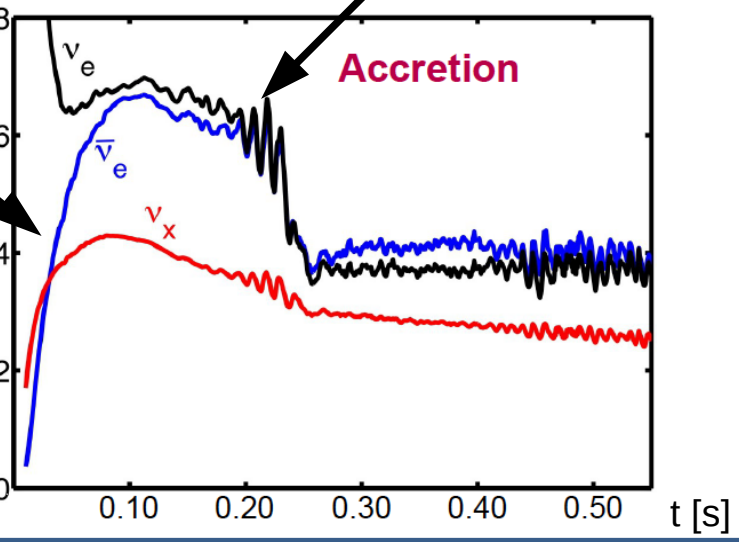
H. Janka

Supernovae – Phase II



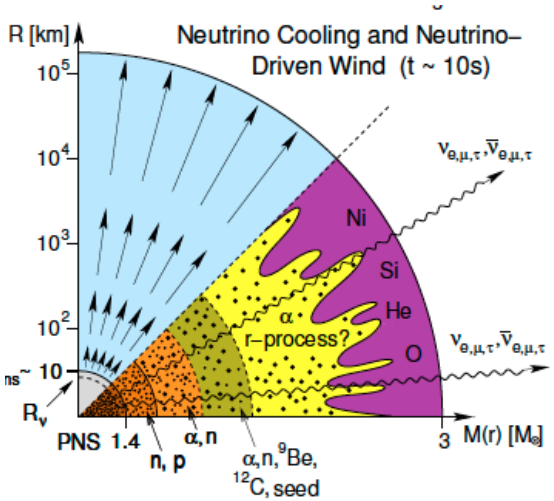


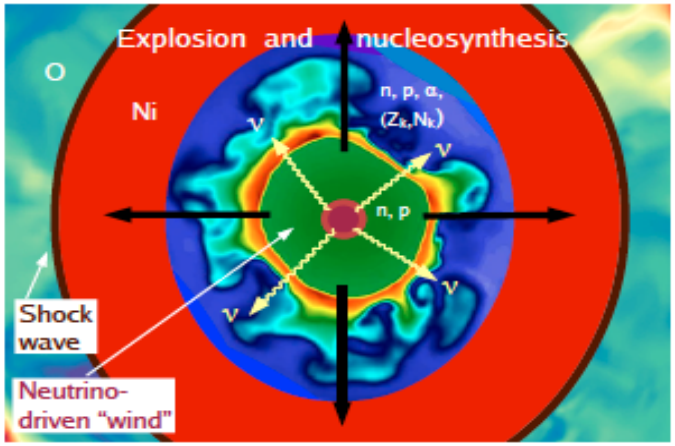


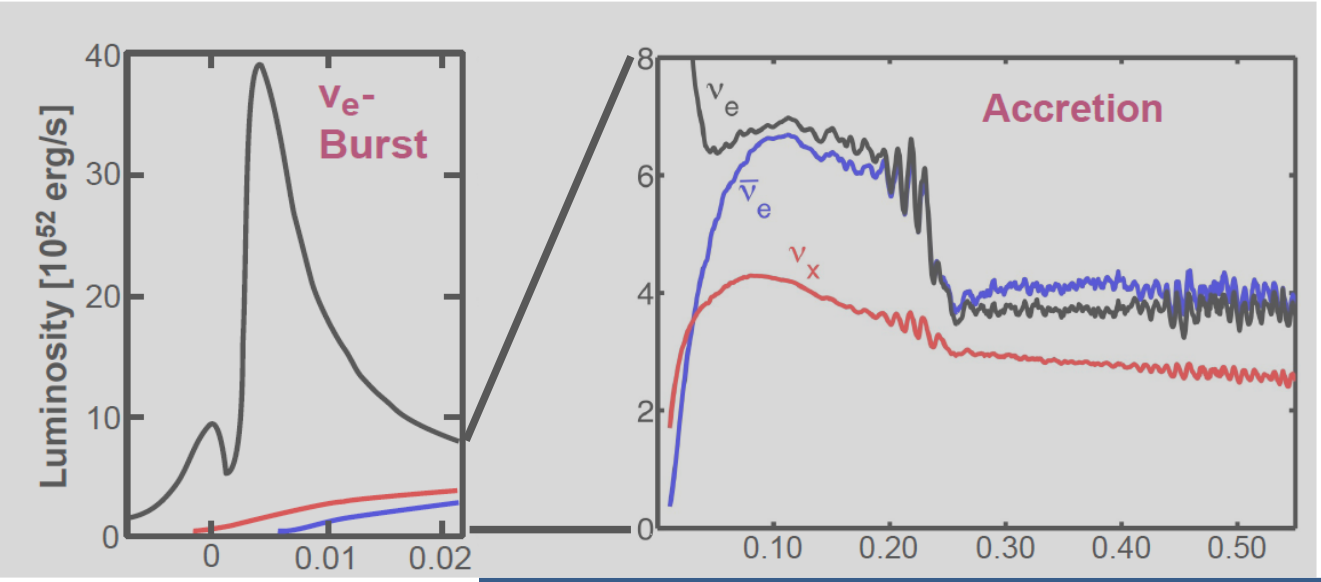


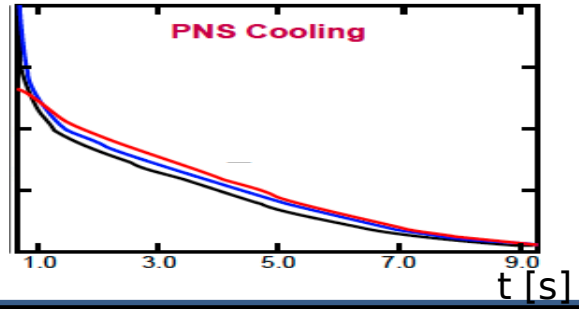
H. Janka

Supernovae – Phase III

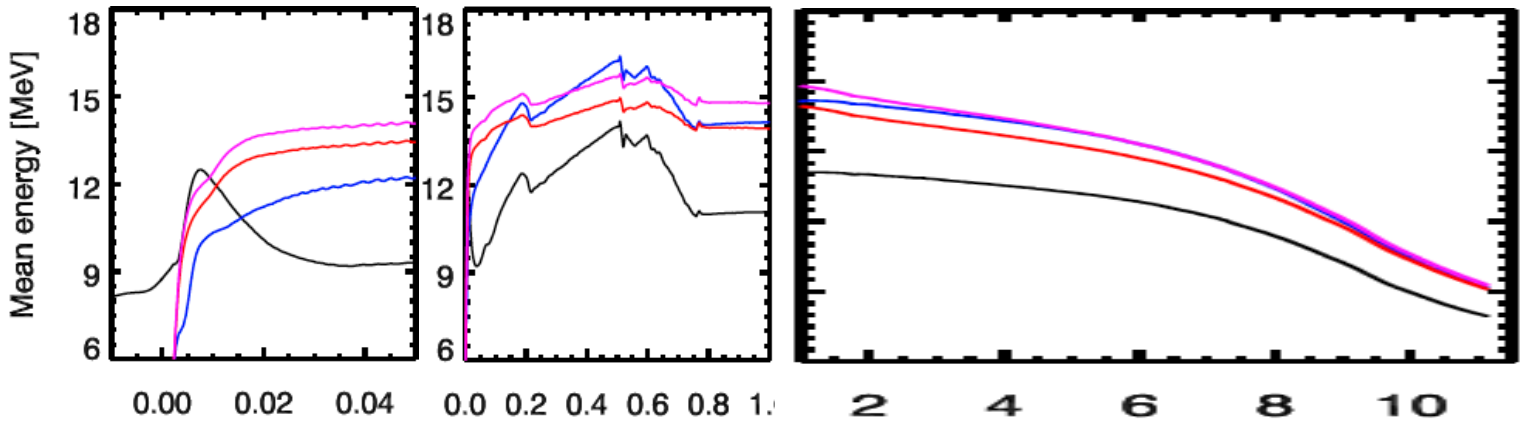


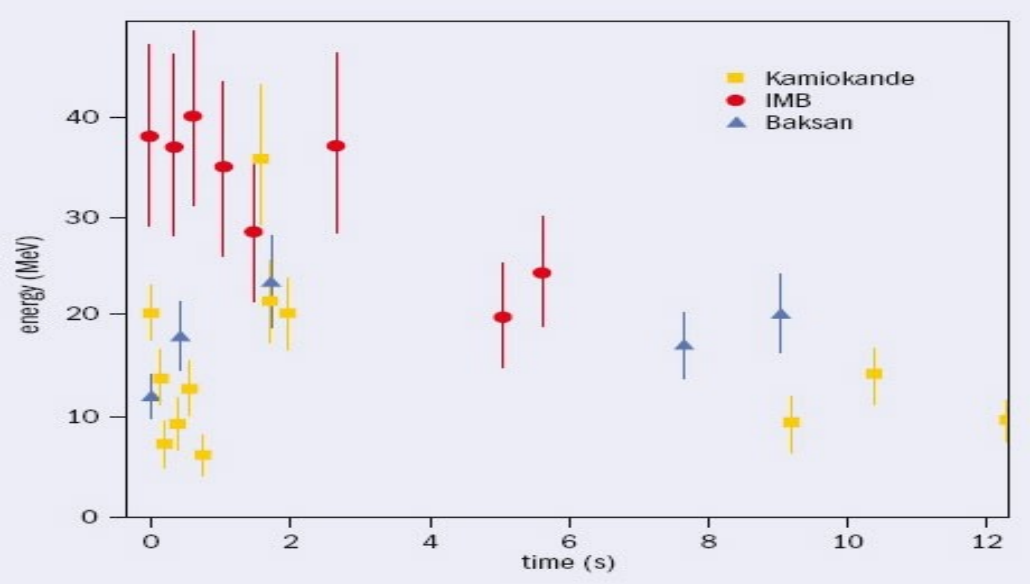






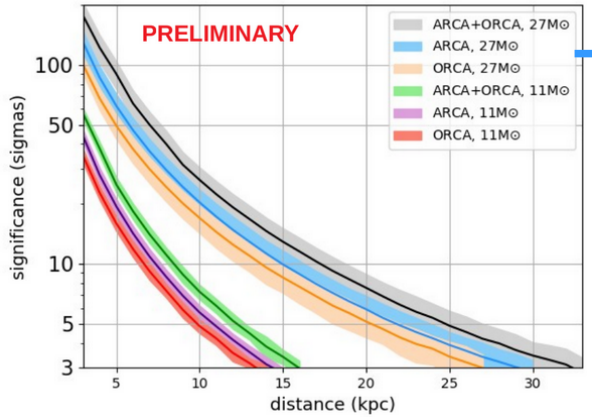
1987 A

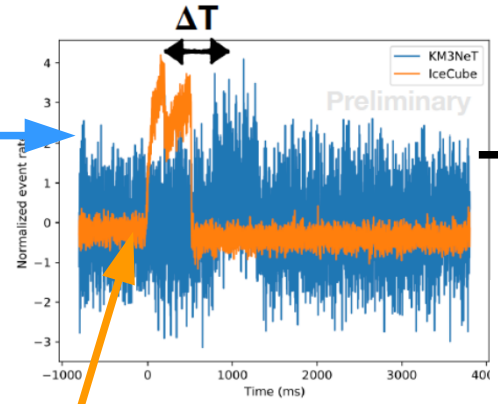




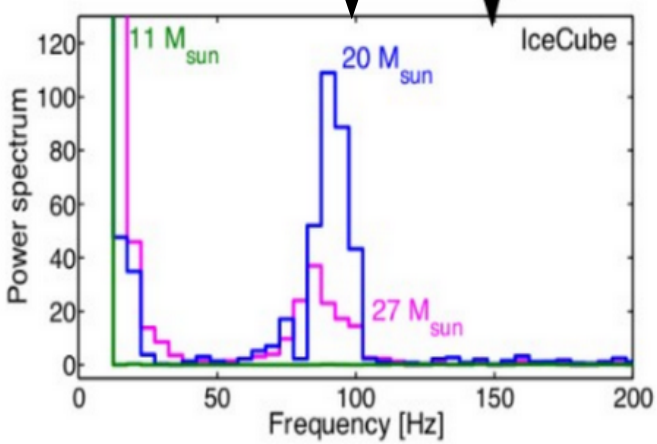
NB : synchronisation
a posteriori

Sensitivities on galactic CCSN – SASI detection

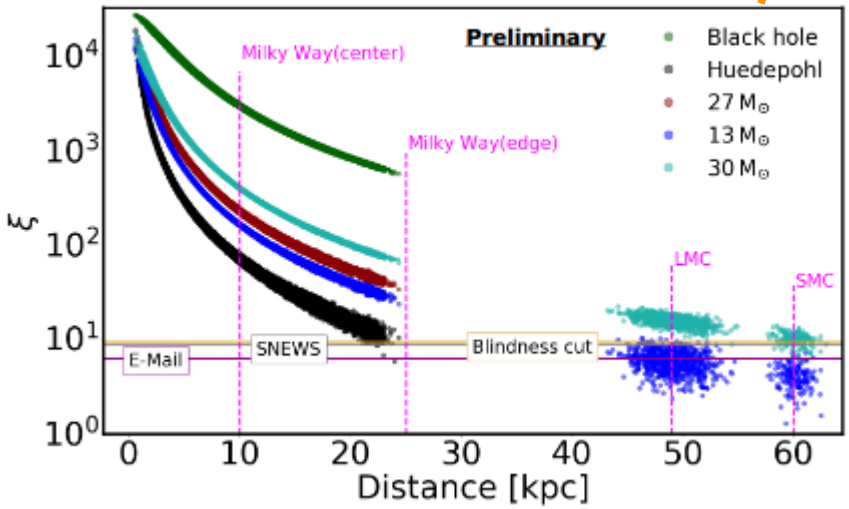


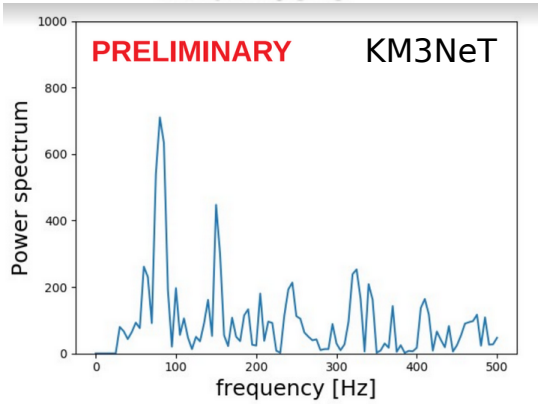


Fourrier transform



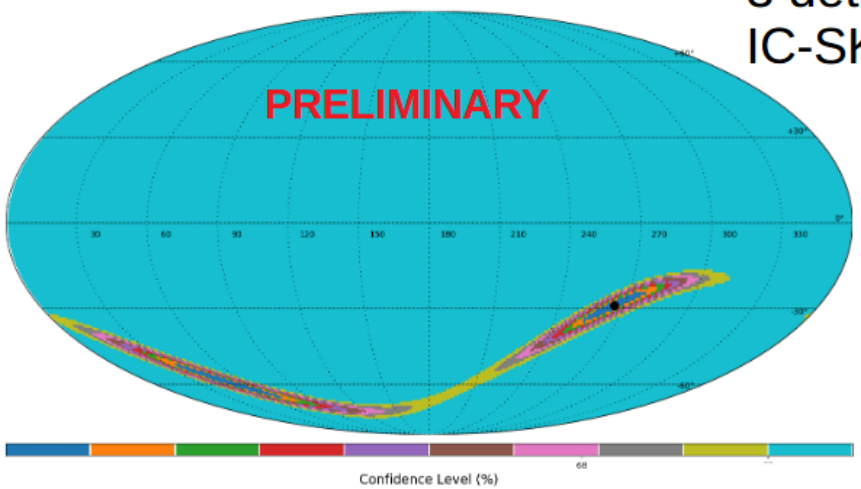
From L. Köpke

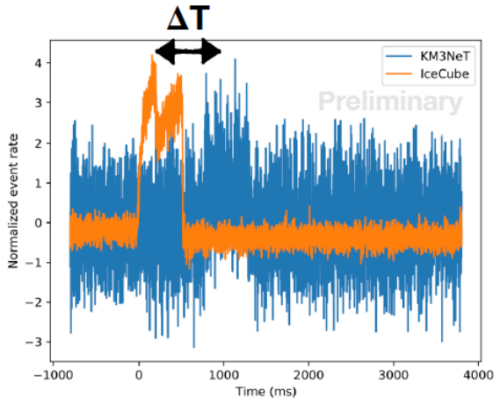




Localising next galactic CCSN

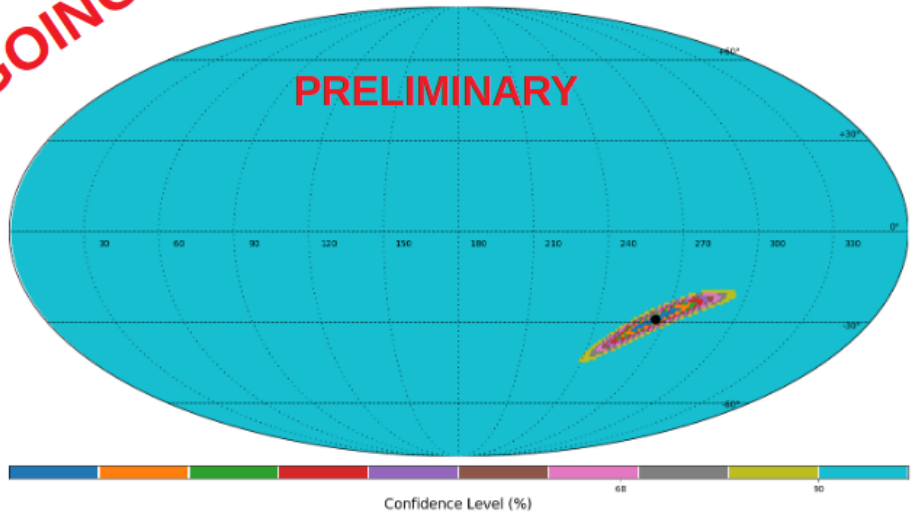
3 detectors:
IC-SK-KM3NeT





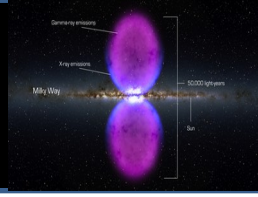
ONGOING WORK...

4 detectors:
IC-SK-KM3NeT-JUNO



Assumptions:
- Source at Galactic Center
- δt = 10ms if combined with KM3NeT
- δt = 1ms for other combinations
- Distance: 10 kpc

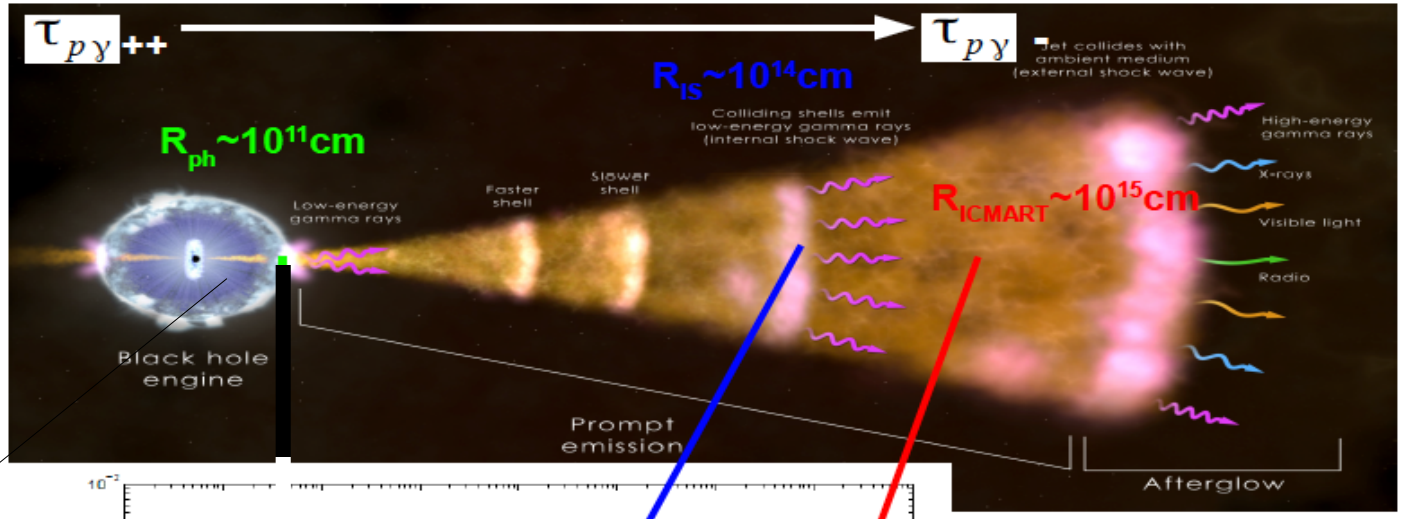
Potential sources II



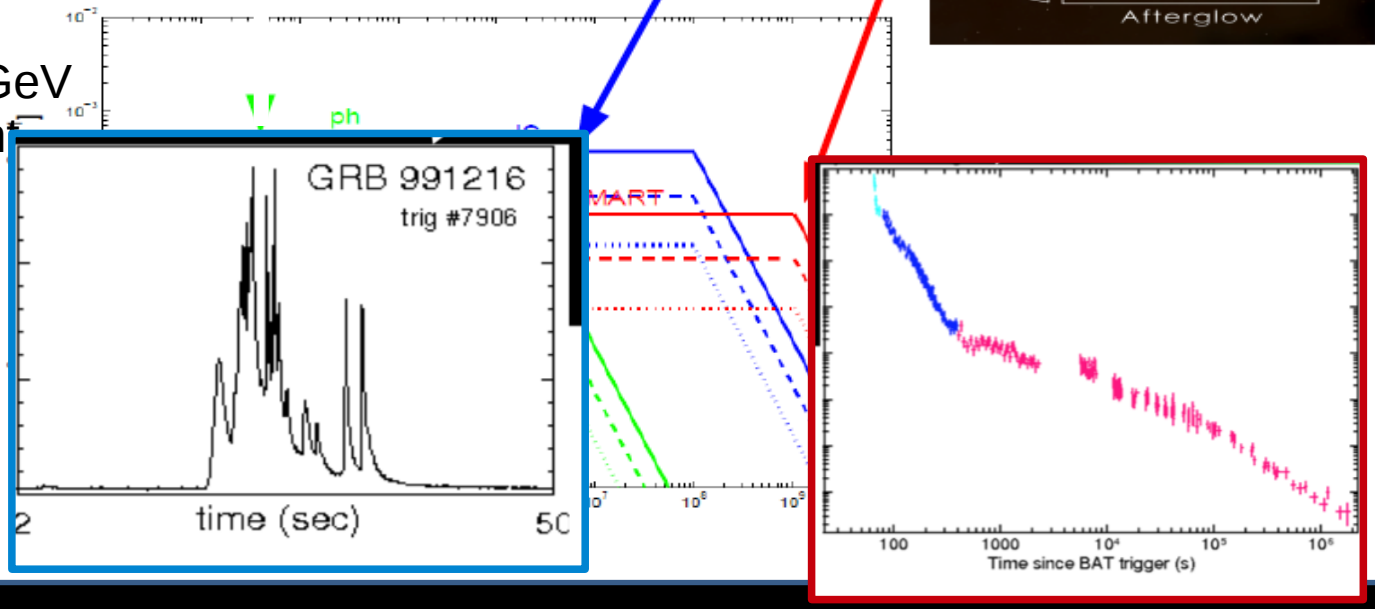
- **Extragalactic:**
  - association with sources of UHE CRs [Kistler, Stanev & Yuksel'13]
    [Katz, Waxman, Thompson & Loeb'13; Fang, Fujii, Linden & Olinto'14]
  - association with diffuse γ-ray background [Murase, MA & Lacki'13]
    [Chang & Wang'14; Ando, Tamborra & Zandanel'15]
  - active galactic nuclei (AGN) [Stecker'13;Kalashev, Kusenko & Essey'13]
    [Murase, Inoue & Dermer'14; Kimura, Murase & Toma'14; Kalashev, Semikoz & Tkachev'14]
    [Padovani & Resconi'14; Petropoulou, Dimitrakoudis, Padovani, Mastichiadis & Resconi'15]
  - gamma-ray bursts (GRB) [Murase & Ioka'13; Dado & Dar'14; Tamborra & Ando'15]
  - galaxies with intense star-formation
    [He, Wang, Fan, Liu & Wei'13; Yoast-Hull, Gallagher, Zweibel & Everett'13]
    [Murase, MA & Lacki'13; Anchordoqui, Paul, da Silva, Torres& Vlcek'14]
    [Tamborra, Ando & Murase'14; Chang & Wang'14; Liu, Wang, Inoue, Crocker& Aharonian'14]
    [Senno, Meszaros, Murase, Baerwald & Rees'15; Chakraborty & Izaguirre'15]
  - galaxy clusters/groups [Murase, MA & Lacki'13; Zandanel, Tamborra, Gabici & Ando'14]
  - ...

from M. Ahlers

Gamma=O(100)

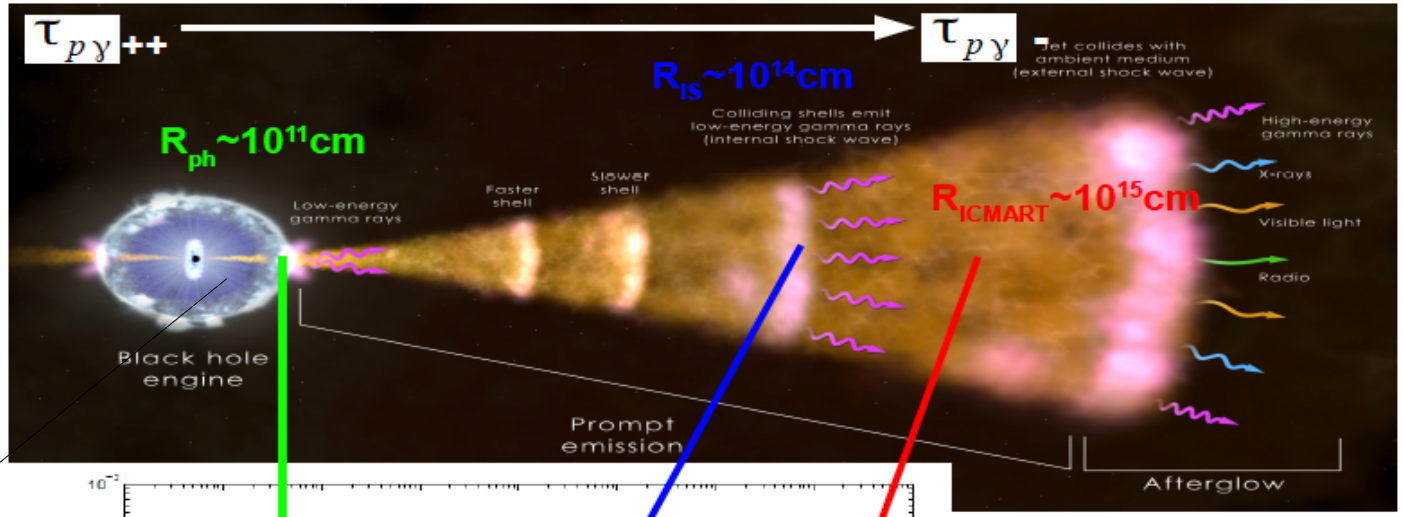


pp->10-100GeV
echappement
des n

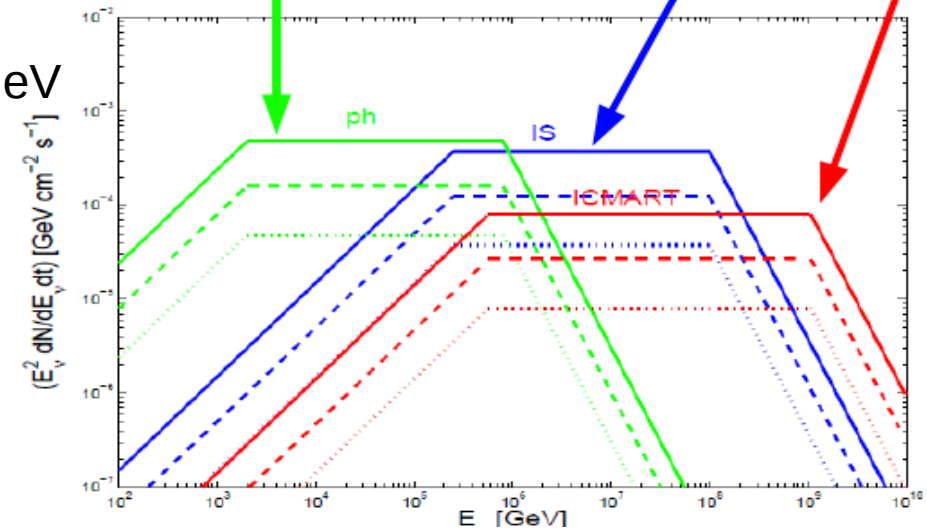


Gamma=O(100)

Constrain baryon loading ?

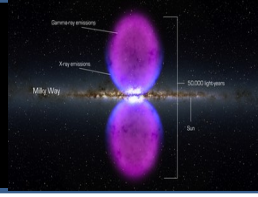


pp->5-100GeV
N escape

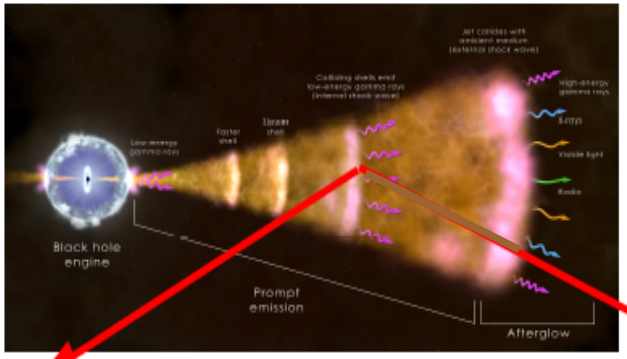


GW included

From Zhang&Kumar 2013



Photohadronic interactions in internal shocks



Pions and muons production via Δ^+ resonance

Kaons and multiple pions production

TeV-PeV regime :

$$p+\gamma \xrightarrow{\Delta^+} \begin{cases} p+\pi^0 \\ n+\pi^+ \end{cases}$$

$$\pi^0 \longrightarrow \gamma+\gamma$$

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \longrightarrow e^+ + \nu_e + \overline{\nu}_\mu$$

$$n \longrightarrow p^+ + e^- + \overline{\nu}_e \, .$$

Fraction of p^+ energy that goes to π

$\langle x_{p\to\pi} \rangle \sim 20\%$

EeV regime :

$$p+\gamma \longrightarrow K^+ + \Lambda/\Sigma$$

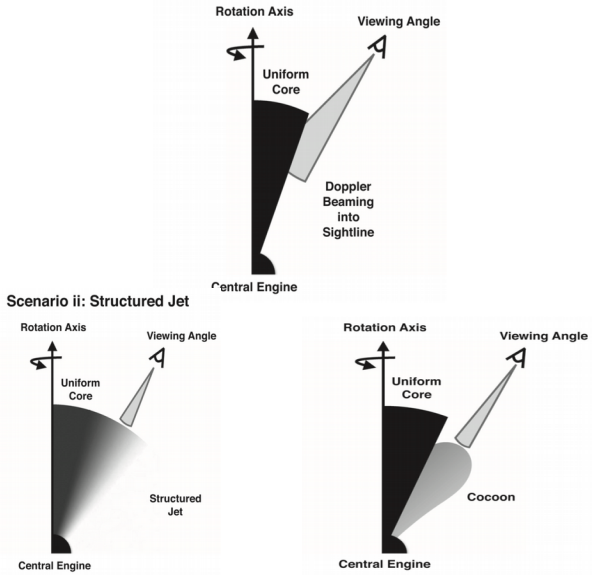
$$K^+ \longrightarrow \mu^+ + \nu_\mu$$

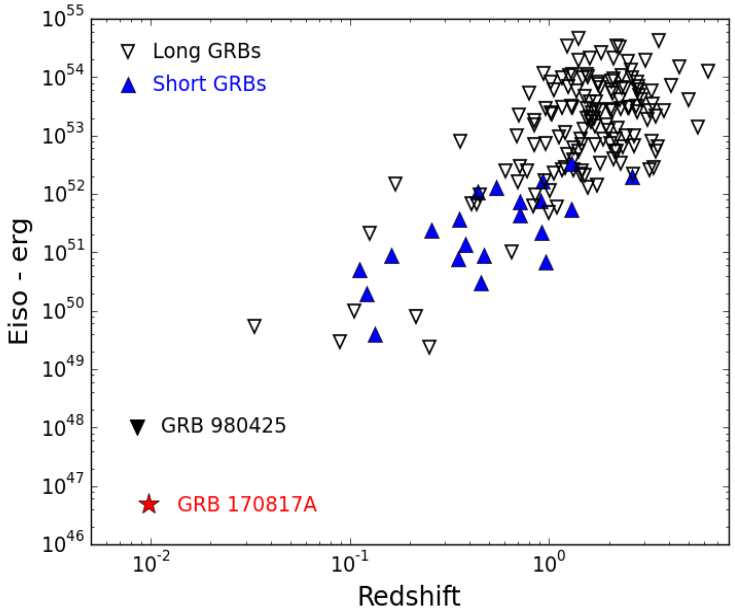
$$\pi^- \longrightarrow \mu^- + \overline{\nu}_\mu$$

$$\pi^- \longrightarrow \mu^- + \overline{\nu}_\mu$$

$$\mu^- \longrightarrow e^- + \overline{\nu}_e + \nu_\mu \, .$$

Many degenaries/uncertainties yet





Unknowns :

Shock propagation
Effective accelaration of p
Details of neutrons (important!)
cascades
B field
time varaiability
Photosphere

UHECR acc.

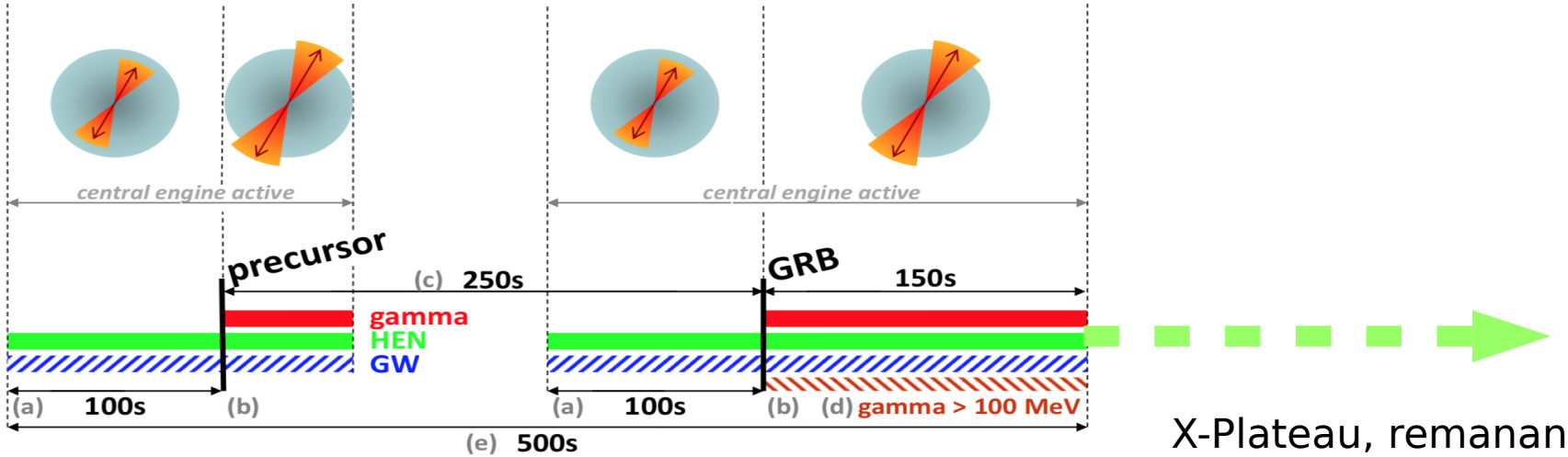
Diffuse flux
below current limits

Individual
Light curves

Full MC approaches needed (but hard!)

- N. Globus et al.
Mon.Not.Roy.Astron.Soc. 451 (2015) no.1, 751-790
- M. Bustamante et al.
Astrophys.J. 837 (2017) no.1, 33

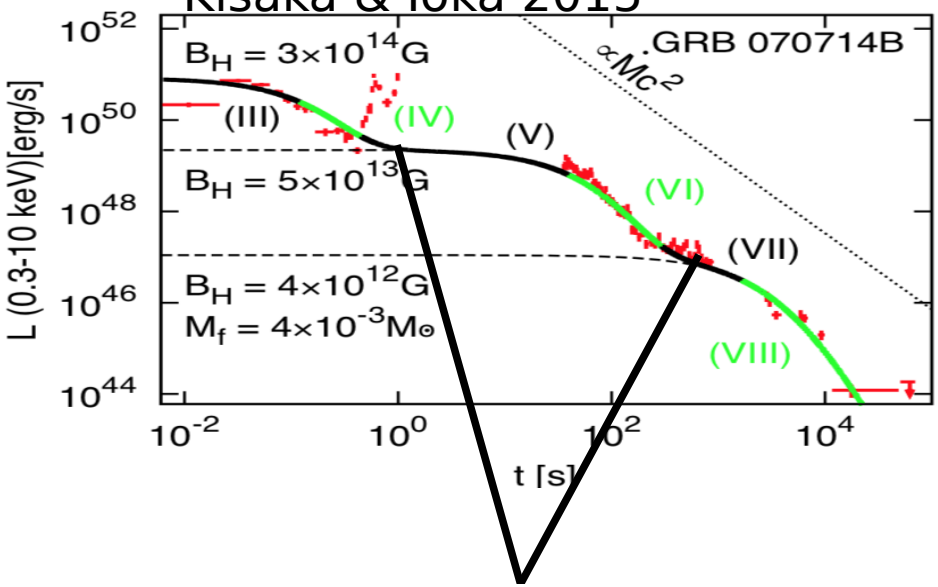
Potential signal outside the prompt emission

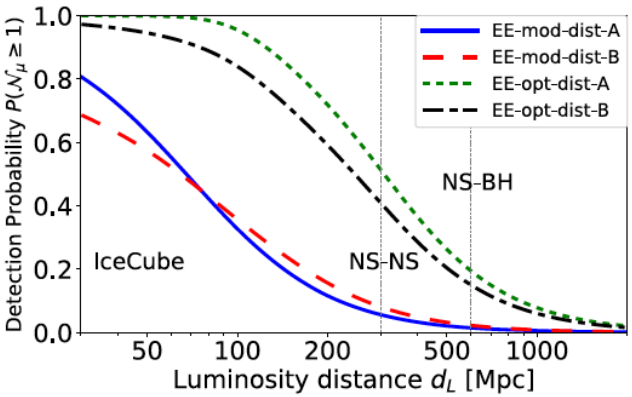


Baret et al. PRD 2011

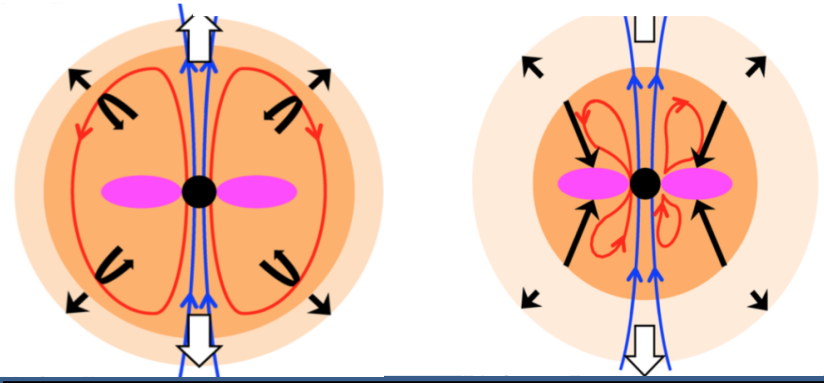
Beyond the prompt emission I

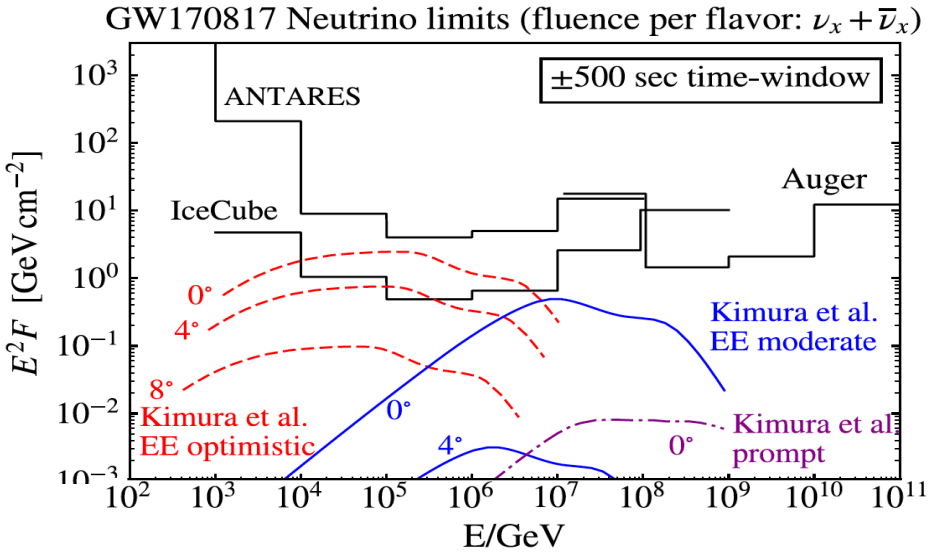
Kisaka & Ioka 2015



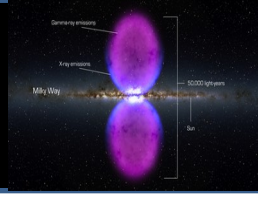


Extended Emission :
« accretion fallback »





Au delà du prompt II



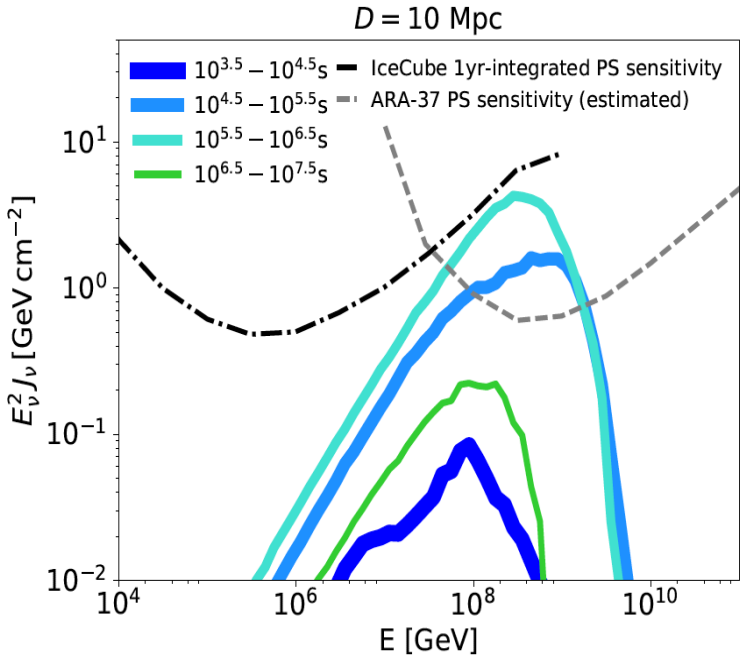
Fang and Metzger 2017 :
Pulsar ms + Ejecta + Rad.

▼

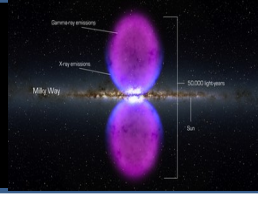
UHECR acc. & int.

▼

HE neutrinos

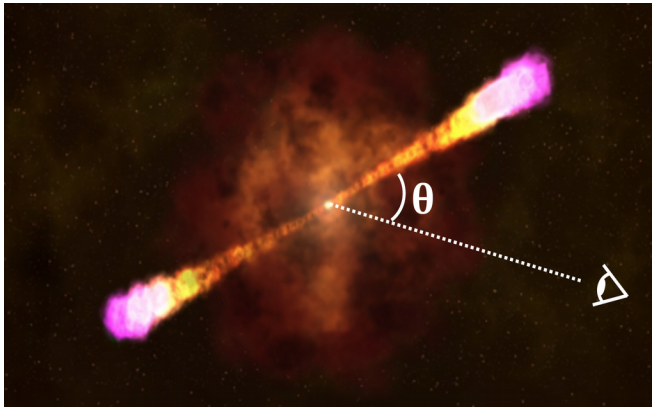


No signal yet but constrains

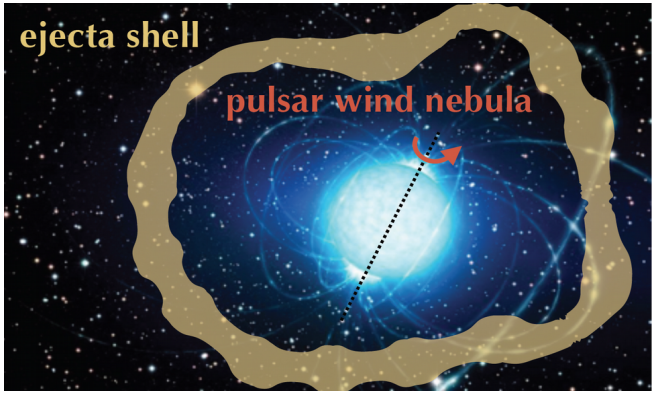


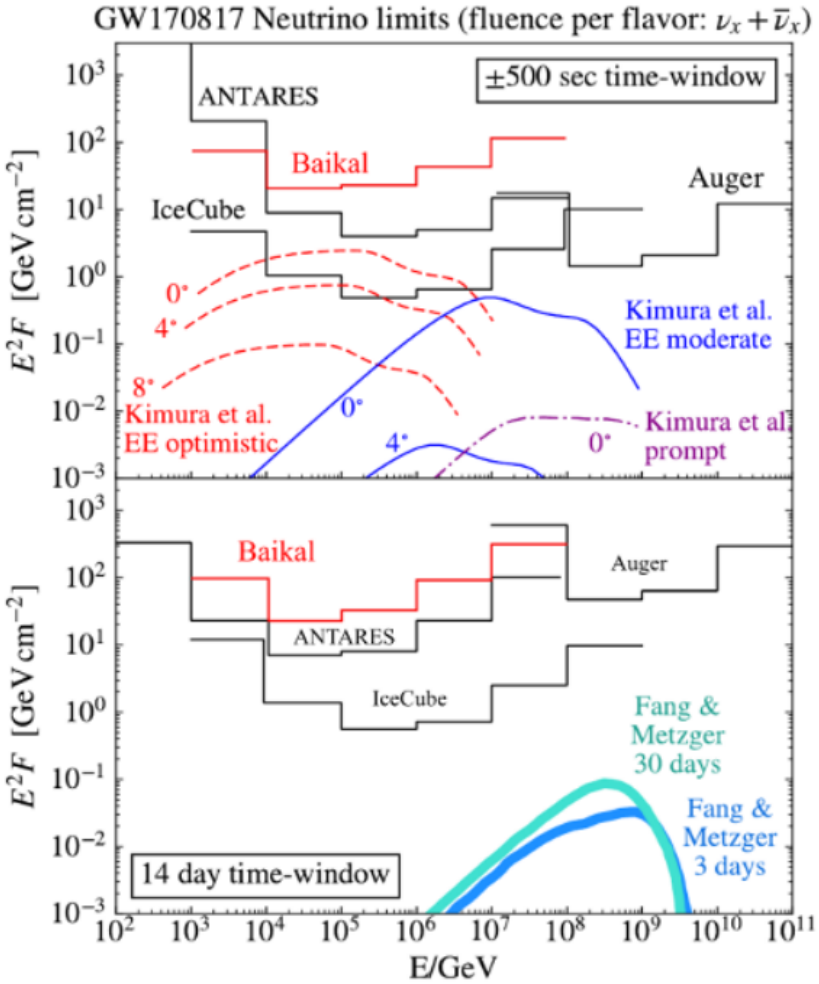
GW170817/ GRB 170817A (40Mpc)

Prompt -> constrain angle



Late -> constrain magnetar existence

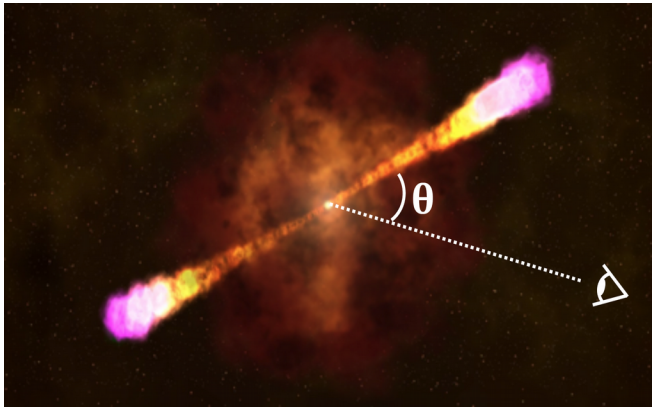


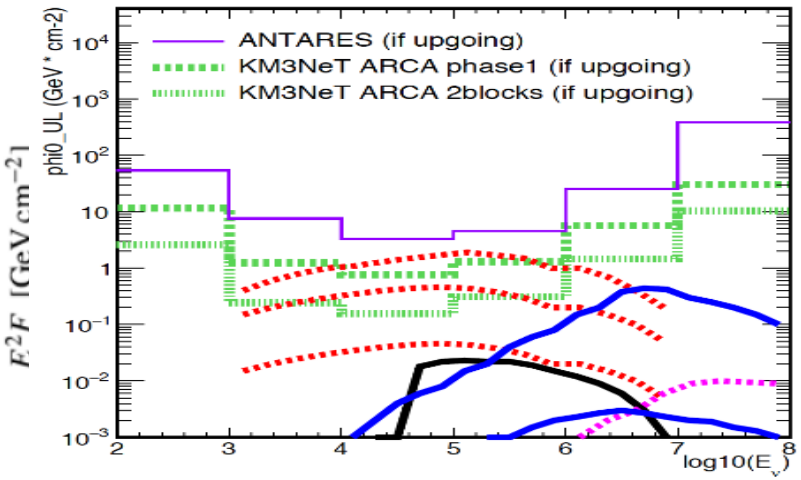


If we're more lucky int he future

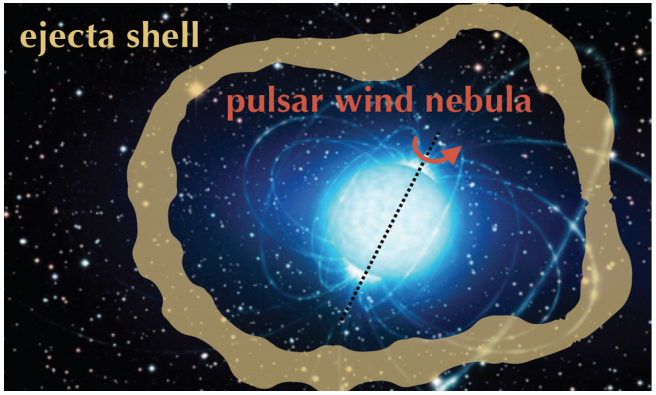
GW170817/ GRB 170817A (40Mpc)

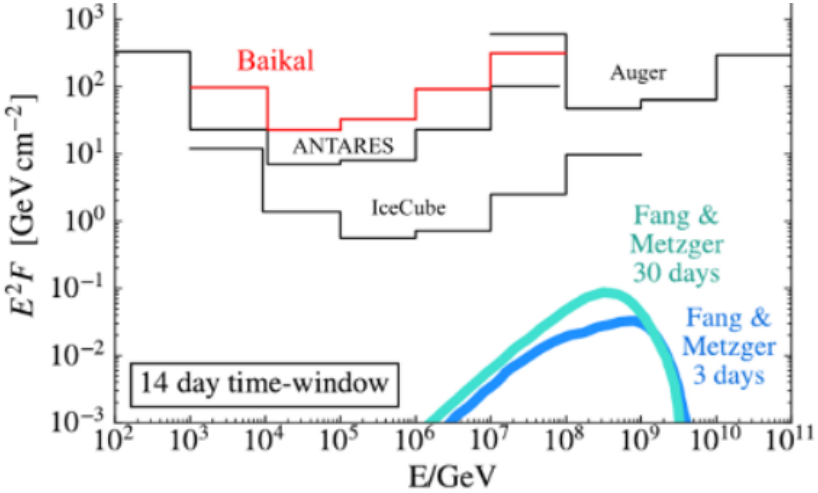
Prompt -> constrain angle





Late -> constrain magnetar existence



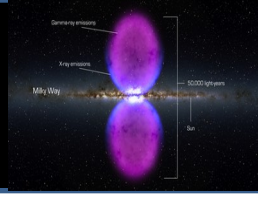


Potential sources II

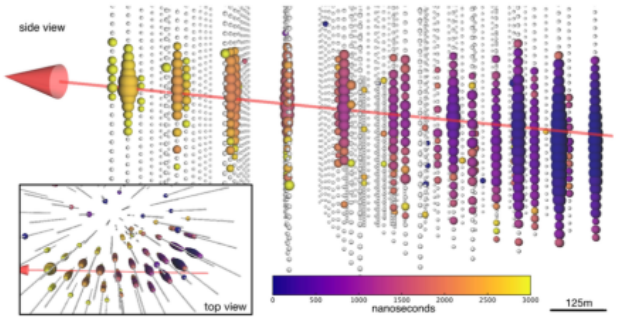
- **Extragalactic:**
  - association with sources of UHE CRs [Kistler, Stanev & Yuksel'13]
    [Katz, Waxman, Thompson & Loeb'13; Fang, Fujii, Linden & Olinto'14]
  - association with diffuse γ-ray background [Murase, MA & Lacki'13]
    [Chang & Wang'14; Ando, Tamborra & Zandanel'15]
  - active galactic nuclei (AGN) [Stecker'13;Kalashev, Kusenko & Essey'13]
    [Murase, Inoue & Dermer'14; Kimura, Murase & Toma'14; Kalashev, Semikoz & Tkachev'14]
    [Padovani & Resconi'14; Petropoulou, Dimitrakoudis, Padovani, Mastichiadis & Resconi'15]
  - gamma-ray bursts (GRB) [Murase & Ioka'13; Dado & Dar'14; Tamborra & Ando'15]
  - galaxies with intense star-formation
    [He, Wang, Fan, Liu & Wei'13; Yoast-Hull, Gallagher, Zweibel & Everett'13]
    [Murase, MA & Lacki'13; Anchordoqui, Paul, da Silva, Torres& Vlcek'14]
    [Tamborra, Ando & Murase'14; Chang & Wang'14; Liu, Wang, Inoue, Crocker& Aharonian'14]
    [Senno, Meszaros, Murase, Baerwald & Rees'15; Chakraborty & Izaguirre'15]
  - galaxy clusters/groups [Murase, MA & Lacki'13; Zandanel, Tamborra, Gabici & Ando'14]
  - ...

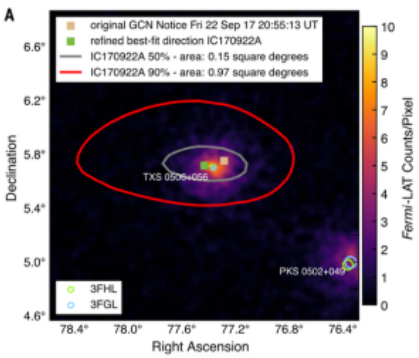
from M. Ahlers

TXS 0506+056



Sept. 22, 2017:
A neutrino in coincidence with a blazar flare



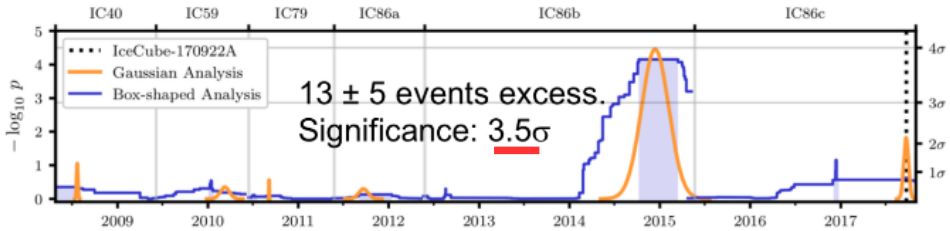


Observed by Fermi-*LAT* and MAGIC

Significance for correlation: 3σ

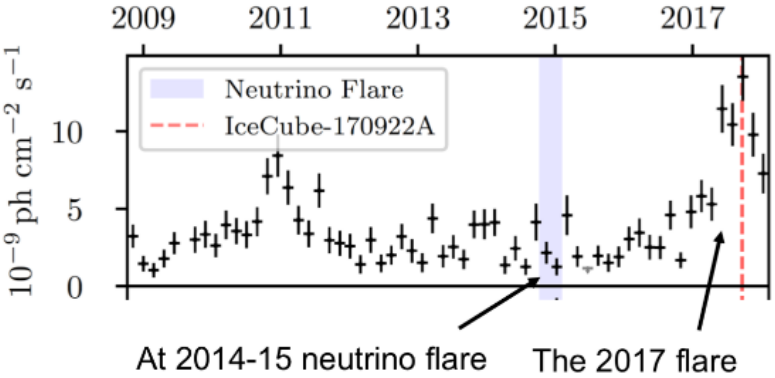
Science 361 (2018) no. 6398, eaat1378

2014-2015: A (orphan) neutrino flare found from the same object in historical data



Science 361 (2018) no. 6398, eaat2890

Fermi-*LAT* data; Padovani et al, MNRAS 480 (2018) 192



Adapted from A. Kappes

What kind of VHE gamma emitting blazar ?

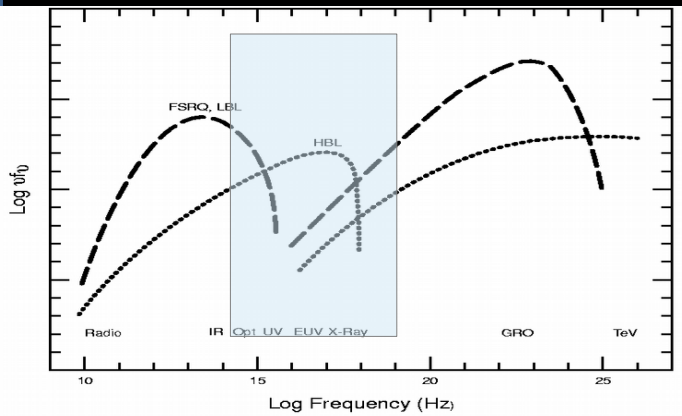
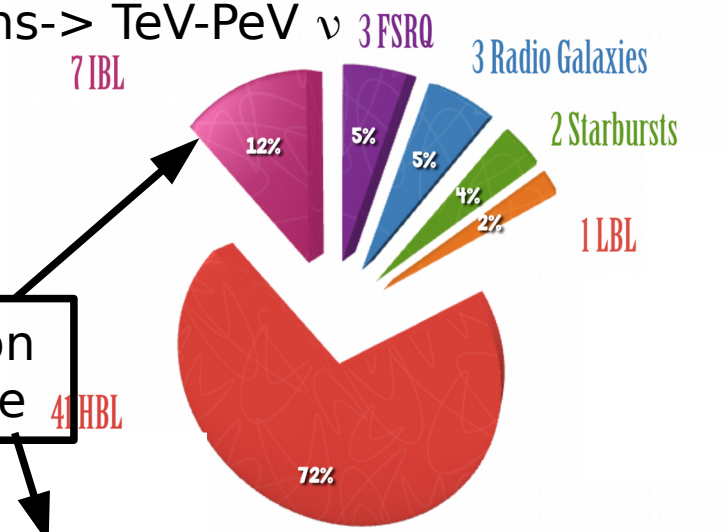
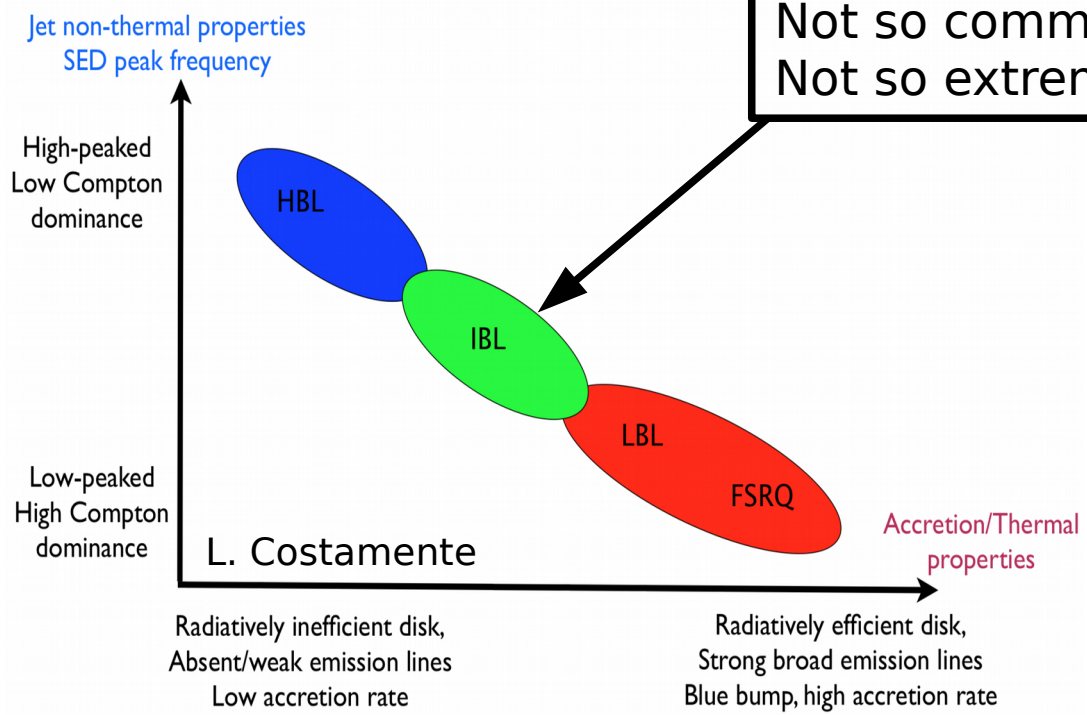
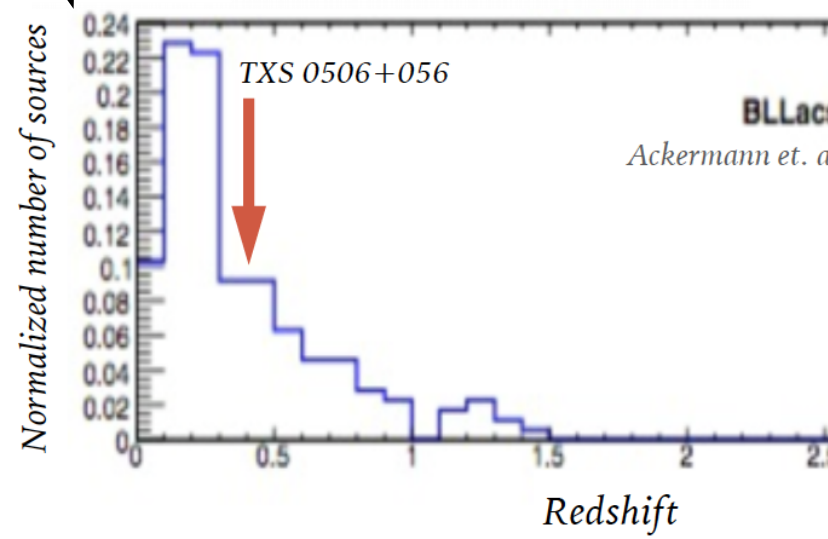


Photo-hadronic production
UV target photons-> TeV-PeV ν



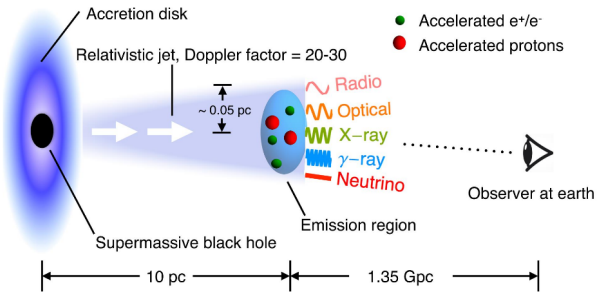
Not so common
Not so extreme





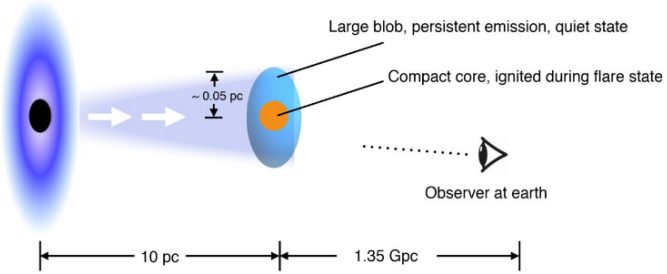
More on TXS

1 zone model

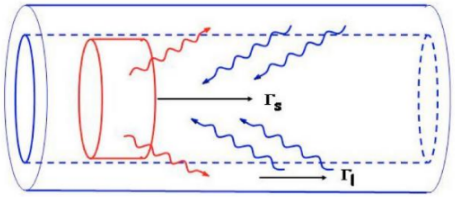


S. Gao et al. 2019

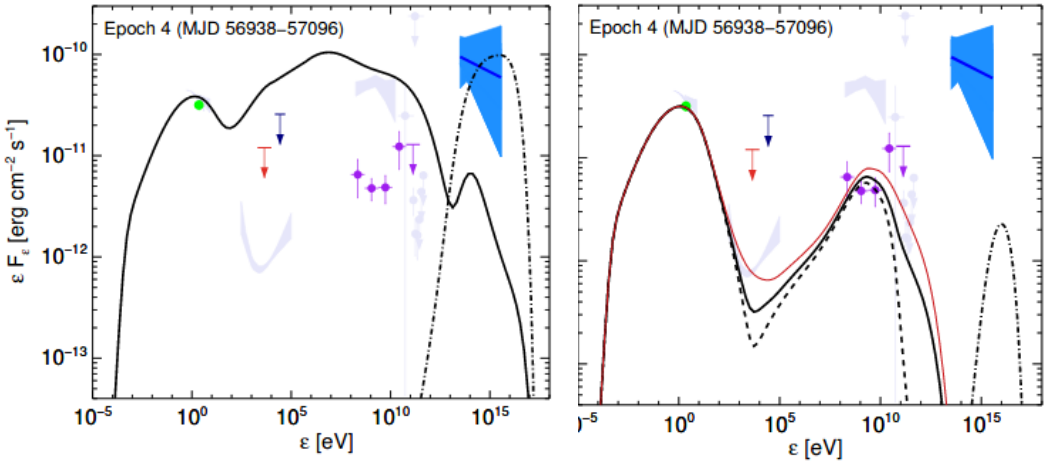
2 zones models

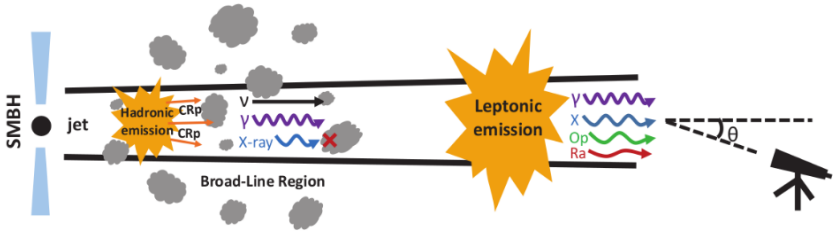


F. Tavecchio



Overshoots X and Gamma ray data
at given times or undershoots Icecube



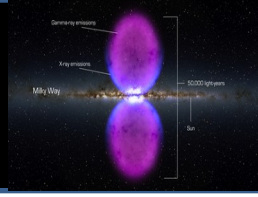


And/or UHECR injection

Petropoulou et al. 2019

Adapted from A. Fedynitch vlvnt18

Testing Quantum Gravity with Lorentz Symetry



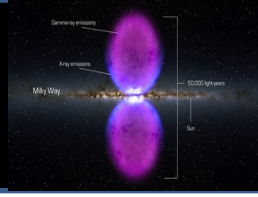
Extremely light → extreme Lorentz factor

Weak interaction → travel cosmological distances

↓

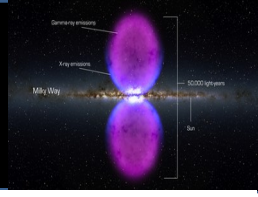
Accumulate potential spacetime
Interaction effects

How to search for L.I.V. or D.S.R.



	Gamma-rays	Neutrinos	Sources	
TOF difference	γ @ diff. E	$\nu - \gamma$	AGNs, GRBs	ν telescopes
Evolution of	polarisation	flavor	VHE diffuse	
Flux suppr.	VHE	UHE	“GZK”	UHE ν det

QG searches



T. Jacobson et al. Ann. Phys. 321, 150 (2006),

- Theories of Quantum Gravity (deformed relativity, LQG, non-communtative geometry, some string theories...

-> Lorentz Invariance Violation at the Planck scale

- Some QG can be effectively parametrized at "low energy"

G. Amelino-Camelia, et al., Nature 393, 763 (1998).
D. Colladay et al. Phys. Rev. D 55, 6760 (1997),
V. A. Kostelecký et al. Phys. Rev. D 80, 015020 (2009)

Propagation dispersion relation :

$$E^2 - p^2c^2 = \pm E^2 \cdot (E/M_{\mathrm{LIV}})^n + \cancel{m_r^2 \times c^4}$$

$$v = \partial E / \partial p$$

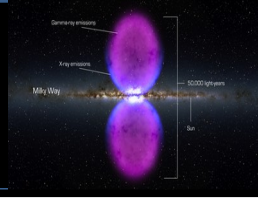
sizeable effect : n=1

$$\Delta t_{\mathrm{LIV}} = (\pm 1) \cdot E/M_{\mathrm{LIV}} \cdot D(z)/c$$

$$D_{\mathrm{LIV}}(z) = \frac{c}{H_0} \int_0^z \frac{(1+z')dz'}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}}$$

U. Jacob and T. Piran, JCAP 0801 (2008)
G. Amelino-Camelia et al., Astrophys. J. 806(2), 269 (2015)

TOF with TXS 0506-056



Caution: might be random coinc.

J. Ellis et al. Phys.Lett. B789 (2019) 352-355:

IceCube – MAGIC detections: delay of 10 days, distance of 4 Gl.y.

E(IC170922A)=200TeV, E(MAGIC) negl. ,

$$M_1 = (M_{1,\gamma} \times M_{1,\nu})/(M_{1,\gamma} - M_{1,\nu})$$

or

$$M_1 \rightarrow \text{the smaller of } M_{1,\gamma} \text{ and } M_{1,\nu}$$

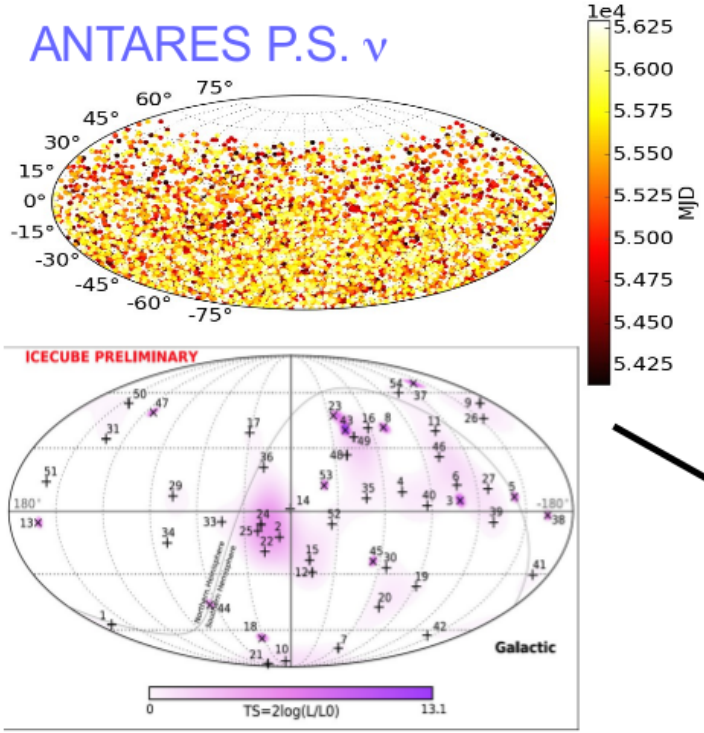
$$\Delta v_{\nu\gamma} = -E/M_1 \longrightarrow M_1 \gtrsim \frac{H_0^{-1}}{\Delta t} E \int_0^{z_{\rm src}} \frac{(1+z)}{\sqrt{\Omega_\Lambda + \Omega_M (1+z)^3}} dz \approx 3 \times 10^{16} \text{ GeV}$$

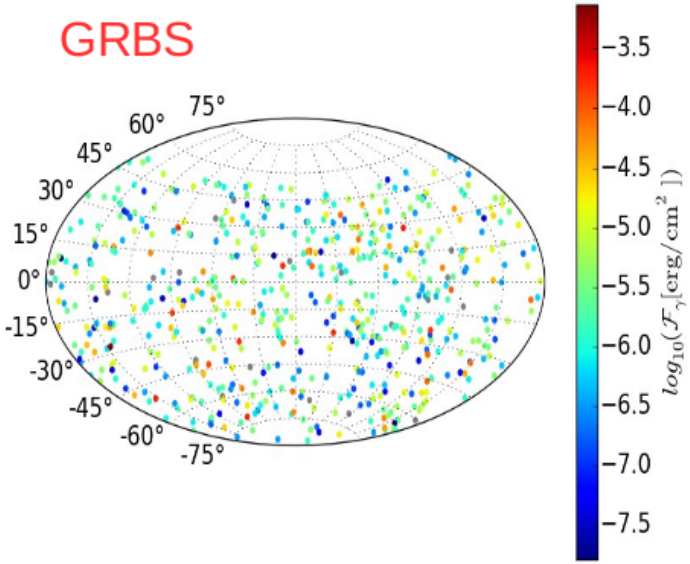
$$\Delta v_{\nu\gamma} = -E^2/M_2^2 \longrightarrow M_2 \gtrsim \left[\frac{3}{2} \frac{H_0^{-1}}{\Delta t} E^2 \int_0^{z_{\rm src}} \frac{(1+z)^2}{\sqrt{\Omega_\Lambda + \Omega_M (1+z)^3}} dz \right]^{1/2} \approx 10^{11} \text{ GeV}$$

Using GRBs and time of flight

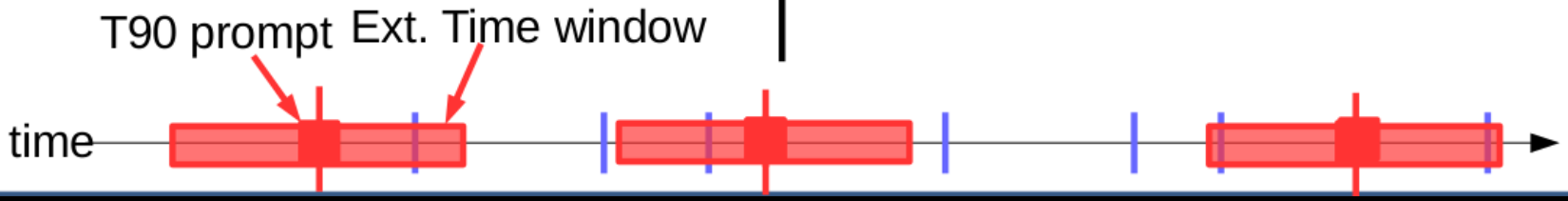
Search for:

- neutrinos shifted w.r.t. the prompt emission out of the T90 time window
- Correlation between time shift and energy





coincidences



Hints? (theorist view)

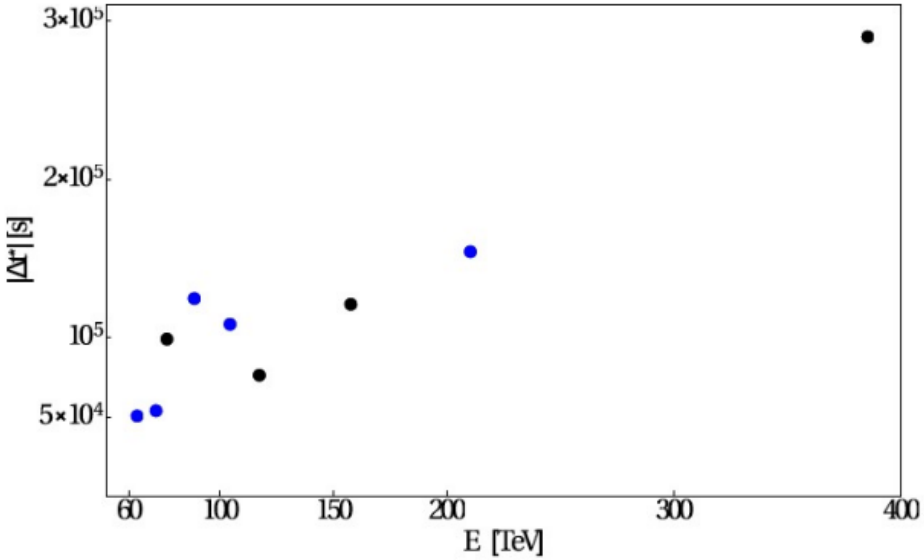
Amelino-Camelia et al (2015):
track channel data -> 2010 : 2 low significance events 2-3x10^3 s before 2 GRBS

Amelino-Camelia et al (2016) arXiv:1605.00496v1:
cascade channel data 2010-> 2014

Correlation=0.8-0.95 p-value=1%

$$\Delta t^* \equiv \Delta t \frac{D(1)}{D(z)}$$

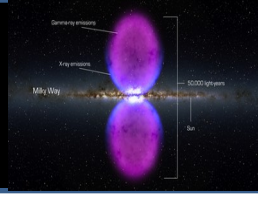
$$\Delta t^* = \eta \frac{E}{M_P} D(1) \pm \delta \frac{E}{M_P} D(1)$$



- Directional coincidence:
Within 2σ of instrument resolution
- Time coincidence: <6 days
- Energy: 60-500TeV
- Unknown z -> default values

Avoid multiple coincidences

Hints? (theorist view)



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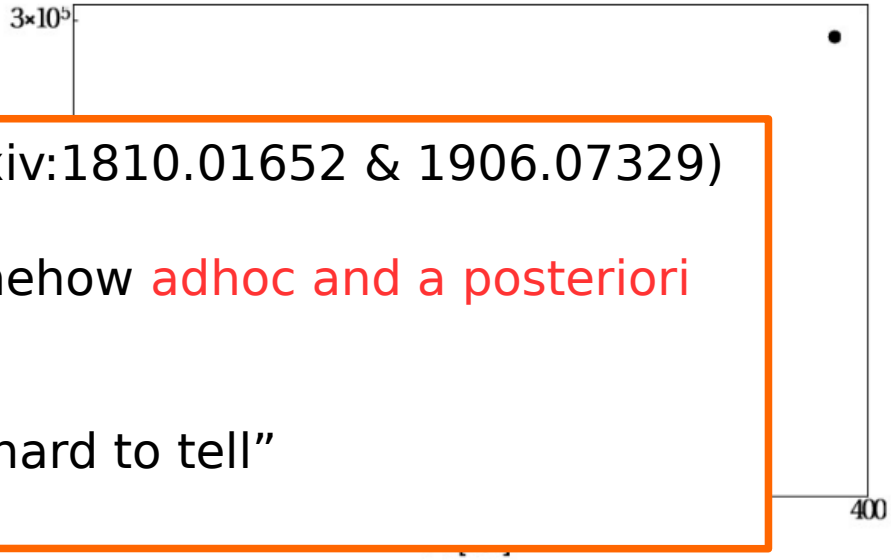
$$\Delta t^* = \eta$$



Update by Yanqi Huang et al. (arxiv:1810.01652 & 1906.07329)

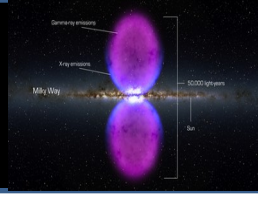
However, selection criteria somehow adhoc and a posteriori

Significance “hard to tell”

- Direc
Within
- Time
- Energy: 60-500TeV
- Unknown z -> default values

Avoid multiple coincidences

Time stacking (experimentalist view)



Blind selection of GRBs

Stacked variables :

$\tau_{\rm obs} = t_\nu - t_{\rm GRB}$ Generic time delay

$\tau_z = \tau_{\rm obs}/(1+z)$ Fixed delay at the source

$\tau_{\rm LIV} = \dfrac{\tau}{E_{\rm est} \cdot D(z)}$ L.I.V. efffects

Test Statistic :

$$\psi = -10 \log_{10} p(D|H,I)$$
$$= -10 \left[\log_{10} n! + \sum_{k=1}^{m} n_k \log_{10} p_k - \log_{10} n_k! \right]$$

- Maximum time delay 42 days:

set by maximum expected L.I.V. shift (other effects shorter OR arbitrarily long)

Directional coincidence:

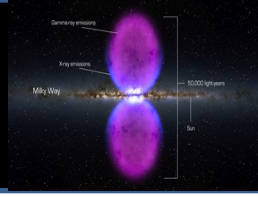
$$\delta_{\rm cut} = 1.58 \cdot \max(\sigma_\nu,\ min(\Delta_{\rm err}, \Delta_{\rm err}^{\rm max}))$$

coinc. $\Delta_{\rm err}^{\rm max}$) < 10 # coinc. σ_ν)

maximise Sig/Bgd — ν resolution — GRB error box

Compute z dependent quantities for measured z only. ← Avoid bias

Results



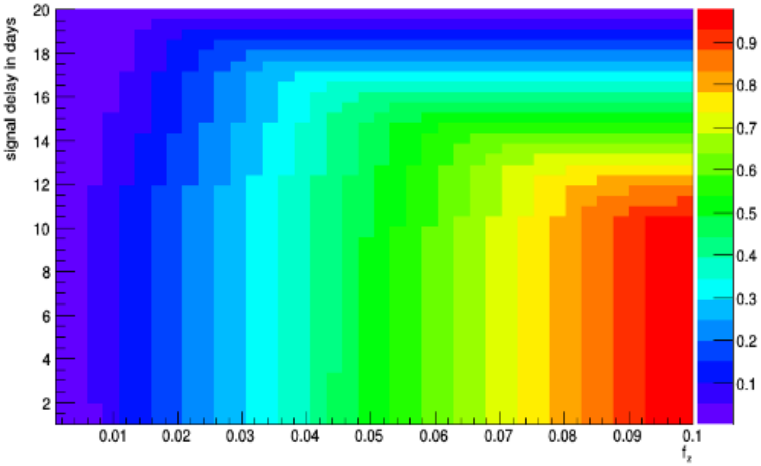
Eur.Phys.J. C77 (2017) no.1, 20

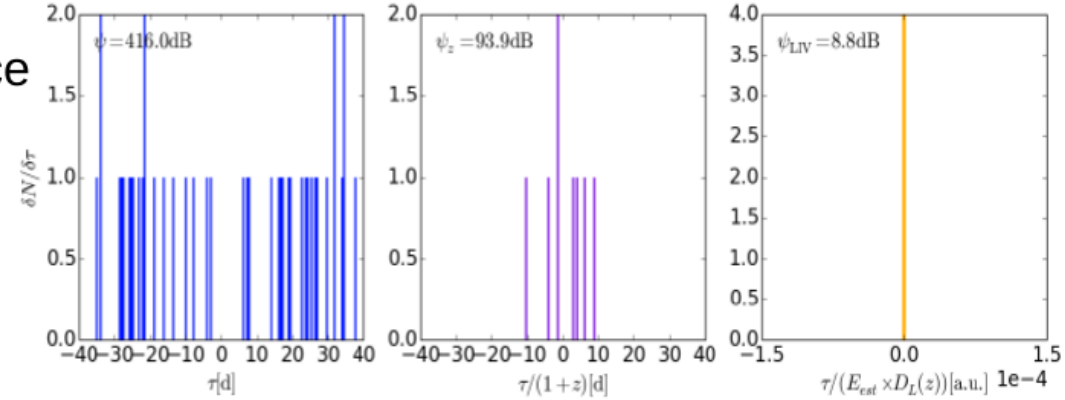
Results:

ν telescope data	τ_{tot} (d)	N_{events}	$m(\delta)$ (°)	δ_{max} (°)	τ_{max} (d)	N_{GRB}	$N_{GRB,z}$	n_{coinc} (uncorrelated)	$n_{coinc,z}$ (uncorrelated)	Meas. w. z	Meas. w.o. z	P-value w. z	P-value w.o. z
ANTARES (07-12)	2154	5516	0.38	0.51 – 1.59	40	563	150	3.9	0.7	0	0	1.2%	51.4%
IC40 (08-09)	408	12876	0.70	0.95 – 2.99	40	60	12	35.0	4.0	42	8	13.5%	5.1%

Sensitivity (Antares):

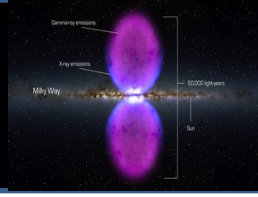
Signal delayed of 5 days at the source





Test Statistic	Sensitivity at 90% CL f_{all}	Sensitivity at 90% CL f_z	Sensitivity at 99% CL f_{all}	Sensitivity at 99% CL f_z	$\mathcal{MDP}$ 3σ f_{all}	$\mathcal{MDP}$ 3σ f_z	$\mathcal{MDP}$ 5σ f_{all}	$\mathcal{MDP}$ 5σ f_z
r	0.8%	3%	1.5%	5.5%	2.4%	9%	4.5%	17%
ψ	0.6%	2.2%	1.3%	5%	1.3%	5%	2.4%	9%
ψ_z	0.3%	1.1%	0.8%	3%	0.6%	2.3%	1.2%	4.5%
ψ_{LIV}	0.3%	1.1%	0.8%	3%	1.5%	5.5%	3%	12.5%

Results



Eur.Phys.J. C77 (2017) no.1, 20

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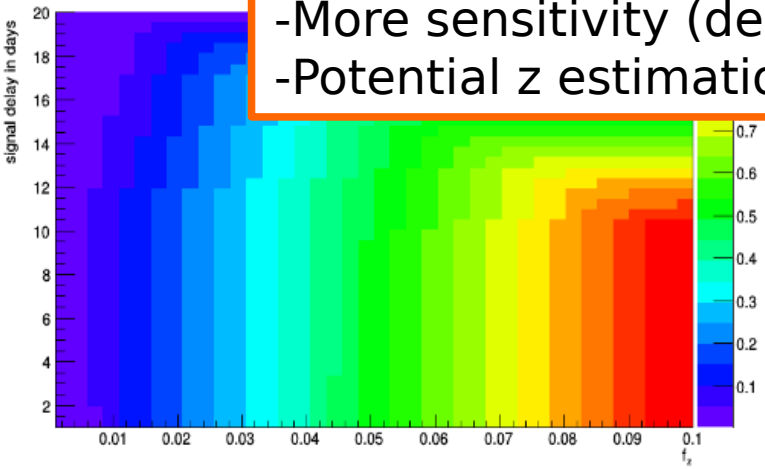
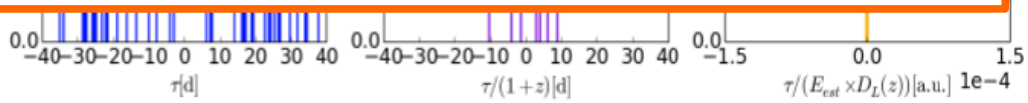
Sensitivity
Signal del

UPDATE soon with:
-More data (2007-2018 => x 2)
-More flavors (adding cascades, signal x 1.2)
-More sensitivity (dedicated “cuts”=> sensitivity x 1.5)
-Potential z estimation from other GRB parameters when missing





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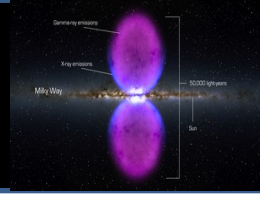
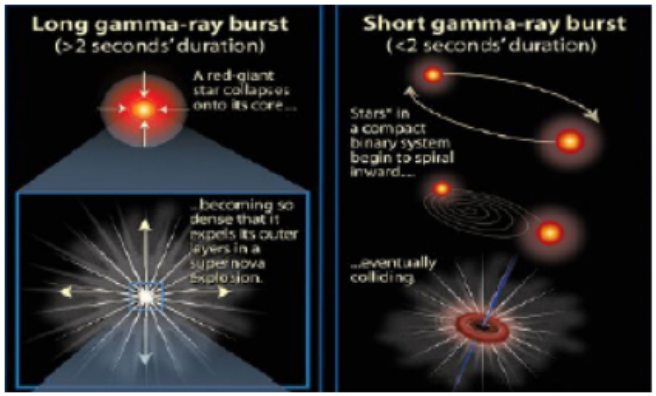
ψ_z	0.3%	1.1%	0.8%	3%	0.6%	2.3%	1.2%	4.5%
ψ_{LIV}	0.3%	1.1%	0.8%	3%	1.5%	5.5%	3%	12.5%

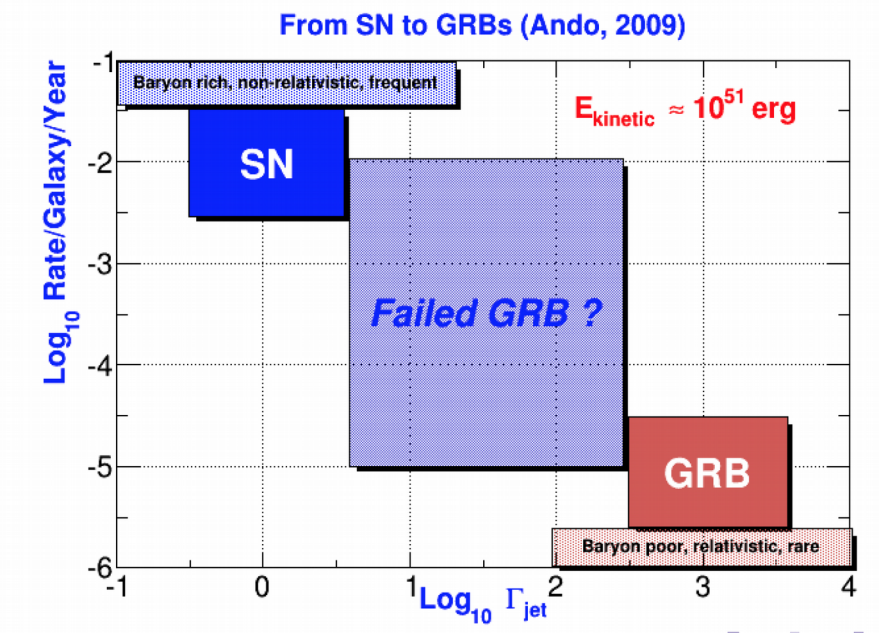


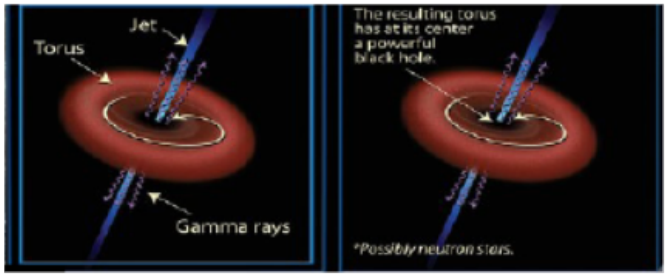


Asymetrical collapse → GW

Baryon loaded jets -> HEN

- Dark electromagnetic sources



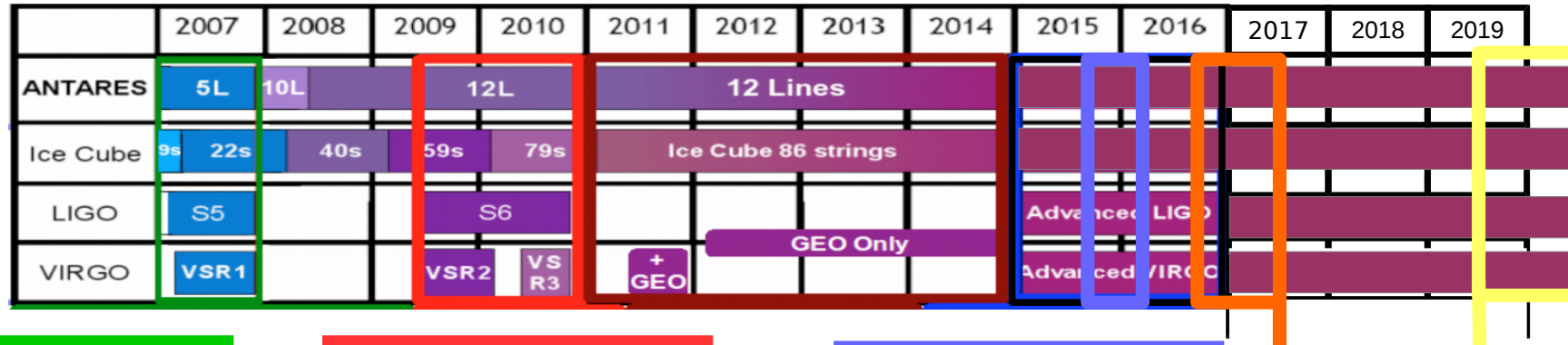


~Model independent search

Transient + diff. Detectors -> better sensitivity

Population study

Subthreshold Searches



ANTARES+iLigo+iVirgo
JCAP 06 (2013) 008

IceCube+eLigo+eVirgo
PRD 90 102002 (2014)

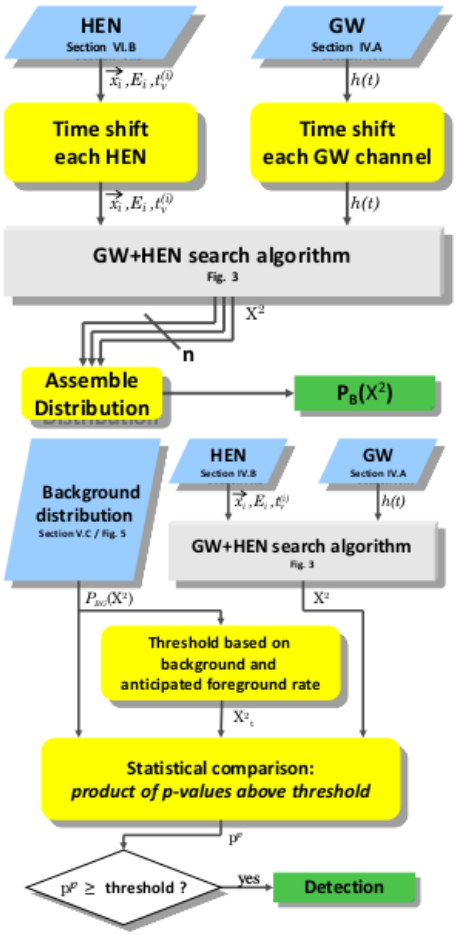
Antares+Ice3+aLigo O1
ApJ 870:134 (2019)

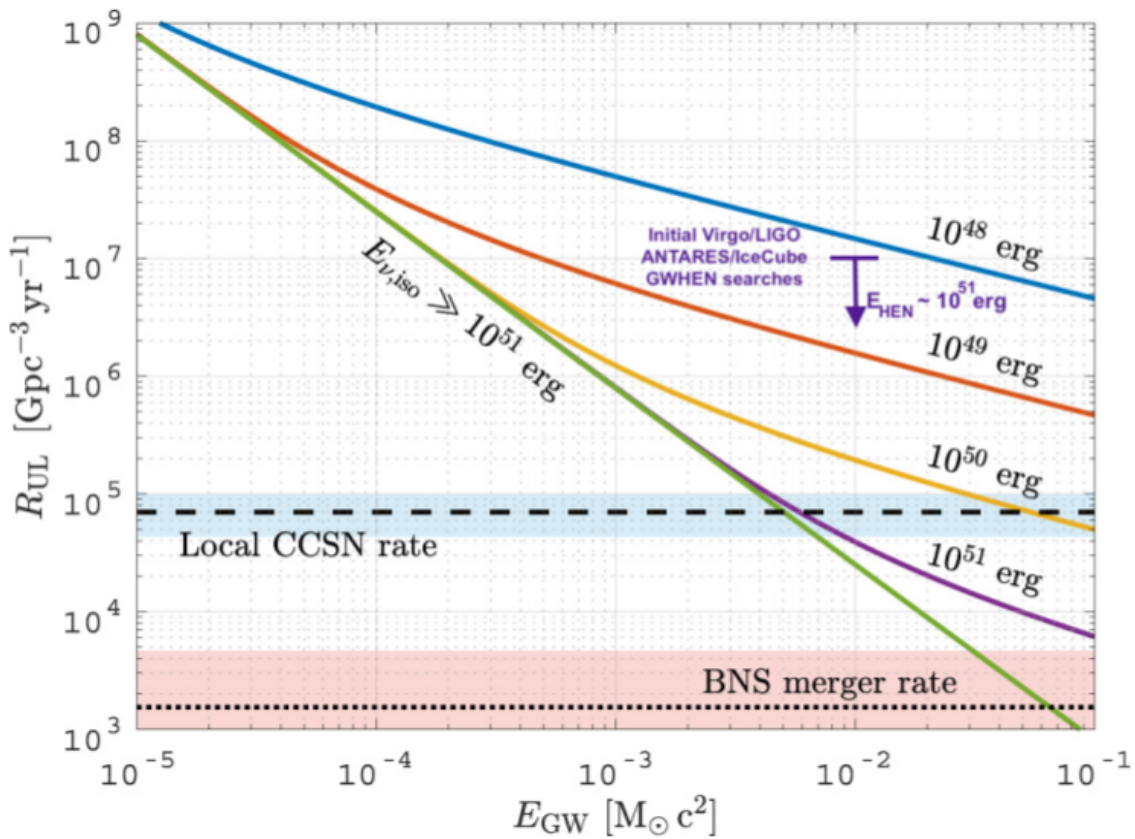
O2 in prep.

O3

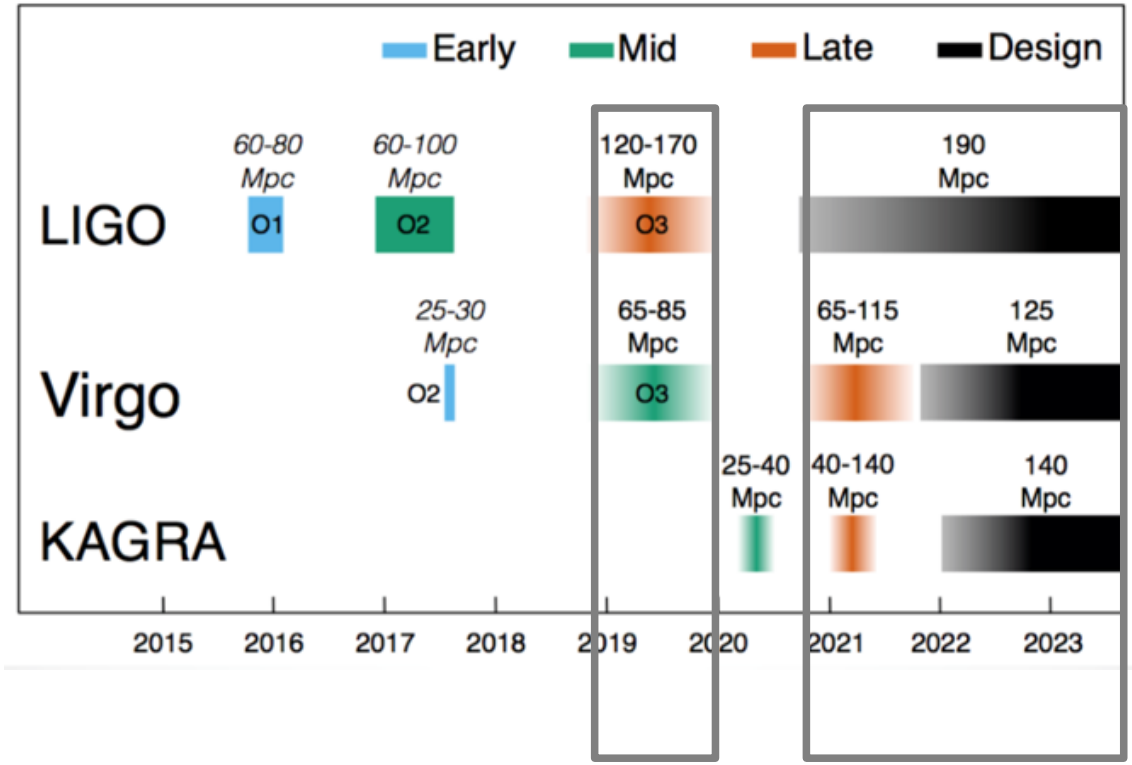
GW+HEN population constraints

Antares+IceCube+Ligo-Virgo: ApJ 870:134 (2019)





Future?

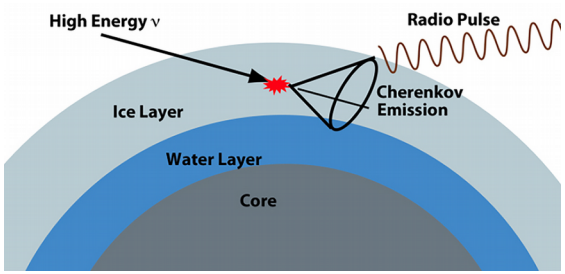


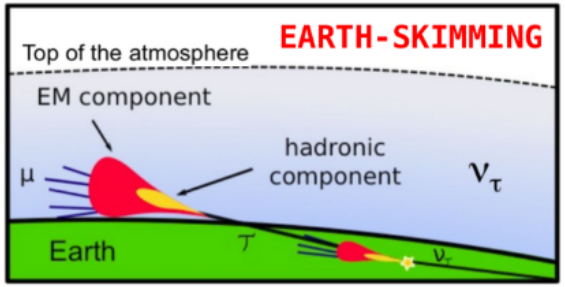
Antares
Baïkal
IceCube

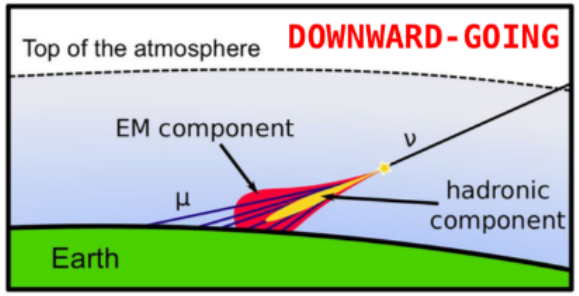
KM3NeT
Baïkal
IceCube

UHE detection (just a word)

So far, no unambiguous detection



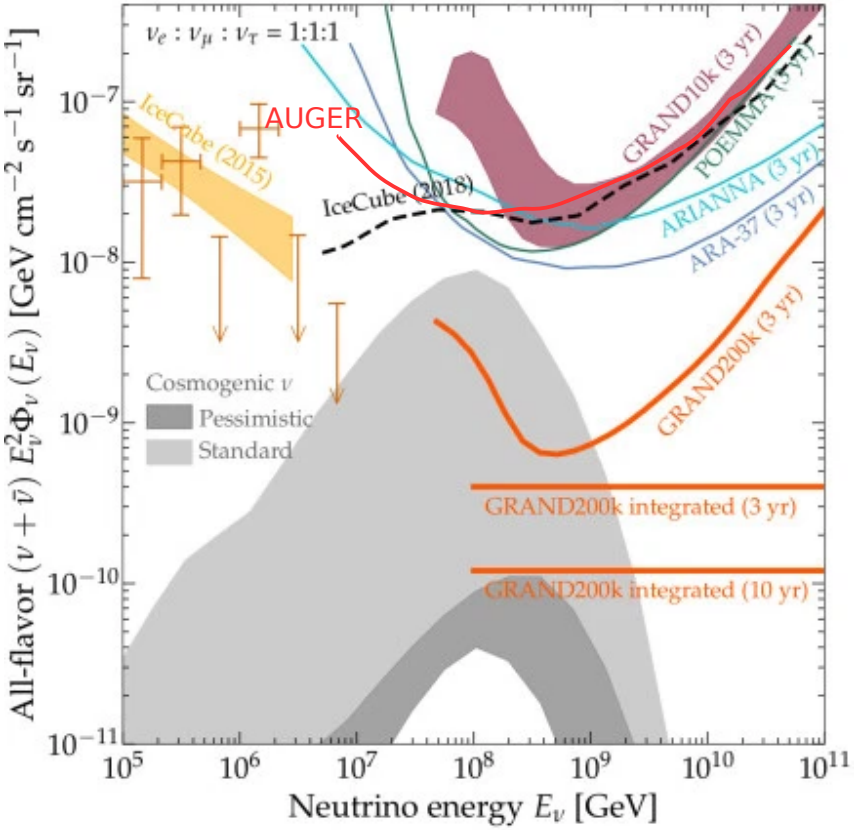




Radio
ARA, ARIANNA, ANITA
(GRAND, ...)

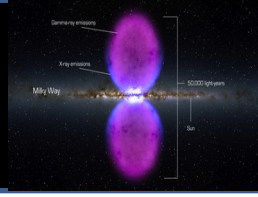
Fluorescence
&
Cherenkov
AUGER, (POEMMA,...)

& MAGIC from selected transient sources



Adapted from GRAND White paper

Summary & Perspectives



- High energy neutrino astronomy is born BUT only one identified possible source (TXS...)
- multimessenger exploration of the non themal Universe
    - AGNs, GRBs, FRBs, ...
    - Galactic C.R. acceleration & C.R. diffusion
    - Galactic SuperNovae (MeV),
    - +...
- Exploration of other physics (bonus of low energy exploration):
    - indirect DM searches, Q-balls, nuclearites, ...
    - neutrino mass hierarchy, CP violation, x-sections,...
    - sterile neutrinos, non std. osc., Lorentz Invaraince Violation, ...
    - Earth tomography
    - +...
- Exciting times ahead wit 3 km-size complementory (coverage, systématics) observatories in the next decade!
- Data anlysis complex, if you want to play contact an experimentalist*!

*Not necessarily me of course...