Neutrino telescopes in water:

Real-time and multi-messenger program (Northern Hemisphere)

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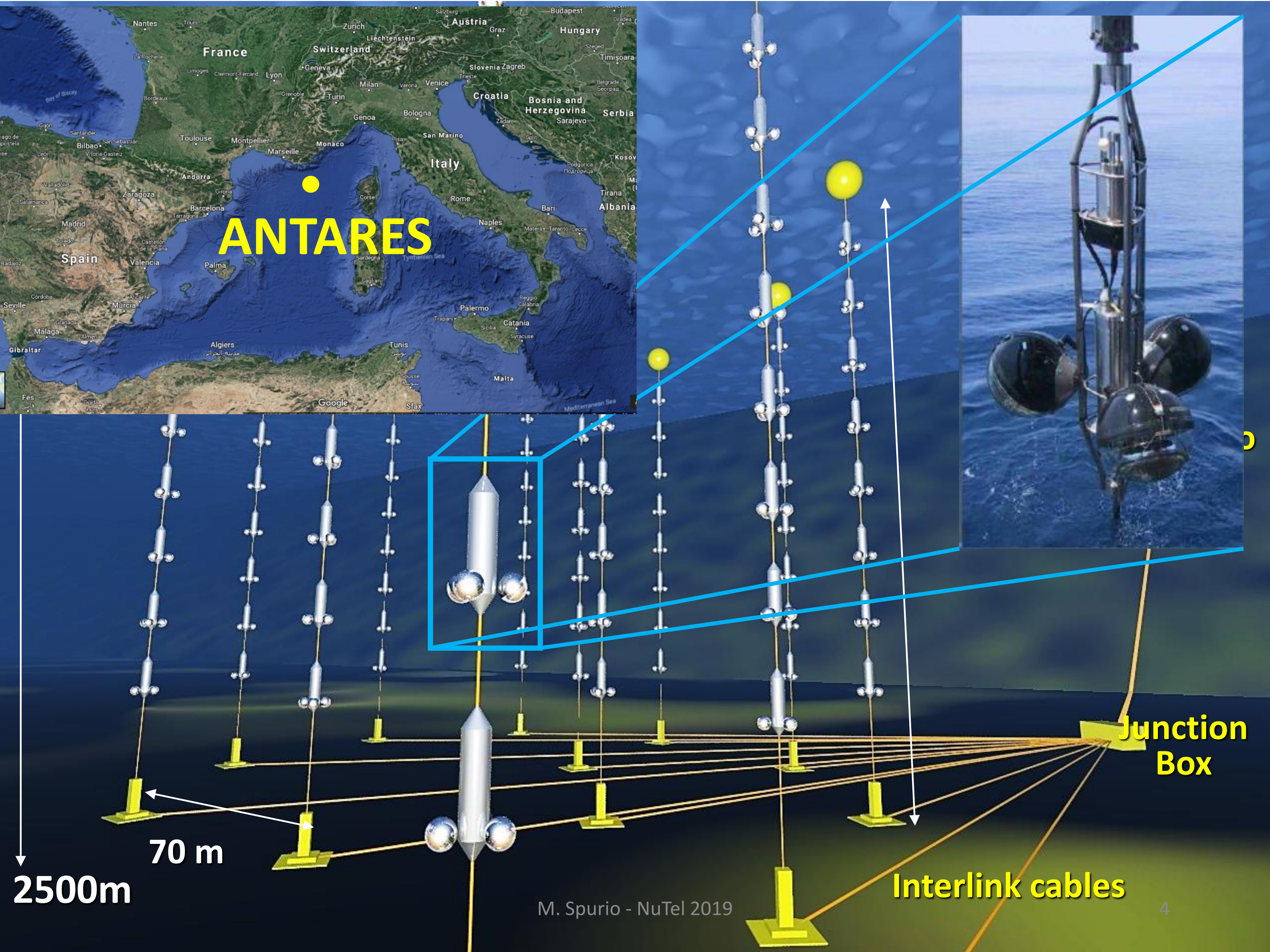
Open questions for neutrino astrophysics

- Origin of IceCube HE astrophysical neutrinos
- Disentangle astrophysical models with multimessenger observations: i.e., GRBs with GW, HEN and traditional astronomy (useful also in case of no ν observation)
- Production mechanisms of high energy cosmic particles
- Study of galactic (and extra galactic?) propagation of CR with neutrinos as tracers
- Test the neutrino sector of the SM and BSM physics
- Cosmic rays (p and nuclei): evidence of galactic "TeVatron" from γ-rays. No "LHC" o "PeVatrons" observed
- Neutrino: fundamental probe to identify **galactic** and **extragalactic** CR sources

Neutrino telescopes in water

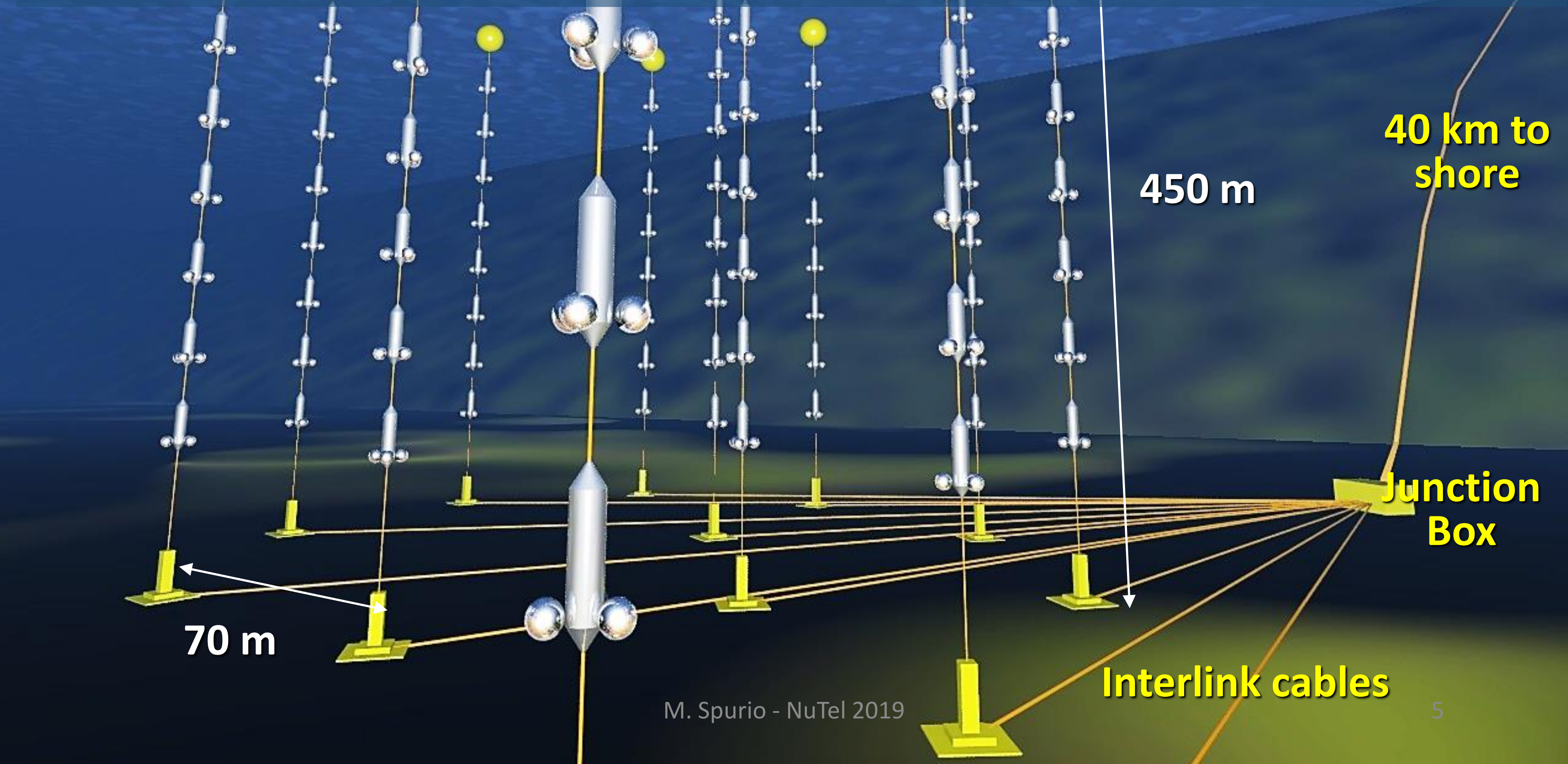
- Very high **duty cycle**
- Large observation **solid angle** (2π or 4π: different angular resolution, depending on background rejection)
- **Upgoing events**: Adequate **angular resolution**, depending on the ν direction, medium and track/shower ($0.1^o \rightarrow 3^o$ -4^o)
- Optimization for E_ν<100 TeV
- Neutrinos not significantly absorbed by Earth for E_ν<100 TeV
- **Complementary f.o.v.** for Mediterranean and South Pole detectors. Most of the Galactic plane seen as "upgoing events"
- **Online analysis**, fast response (few seconds), immediate alert
- Water is an homogeneous medium
- Optical activity due to ^{40}K and bioluminescence
- Water detectors: need for positioning calibrations due to sea currents **(offline analysis**)



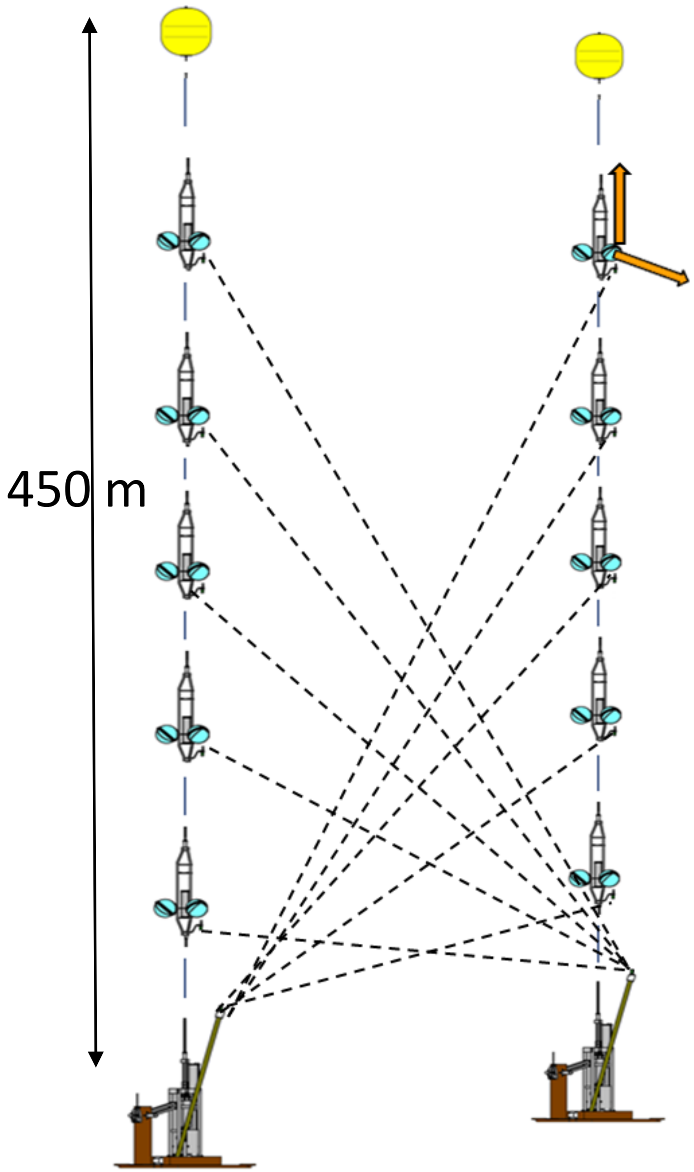
France
Switzerland
Austria
Hungary
Slovenia
Croatia
Bosnia and Herzegovina
Serbia
Italy
Spain
Albania
Marseille
Monaco
Toulouse
Barcelona
Rome
Naples
Palermo
Algiers
Tunis
Malta
ANTARES
2500m
70 m
Junction Box
Interlink cables

ANTARES in numbers:

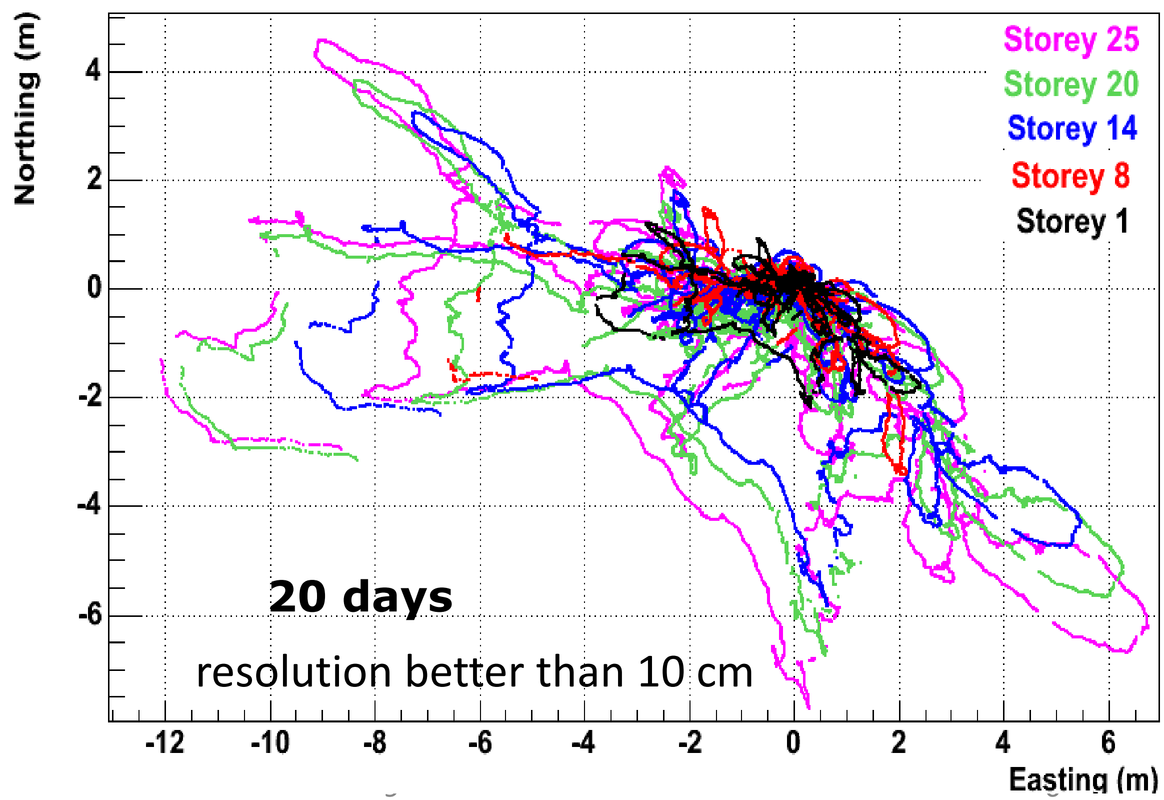
- Stable data taking since 2008 with high duty cycle (93-96%)
- Large field of view (2π instantaneously, upgoing)
- Quite good angular resolution: 0.3° -0.4° (median)
- But it is also small: $A^{eff} \approx 1m^2$ @ 30 TeV [O(12000) detected ν's]
- Real-time data processing



Positioning of the detector



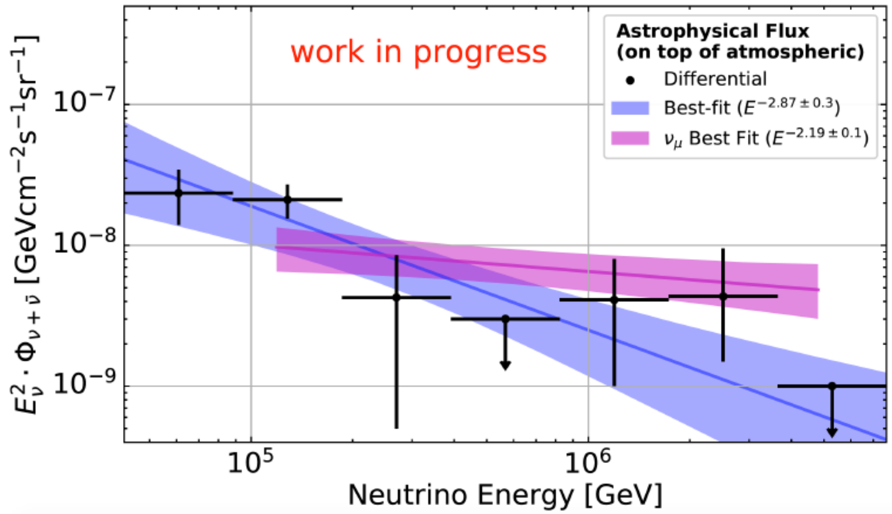
- Transceivers on the bottom of each line
- 5 hydrophones at specific heights on each line
- 4 autonomous transponders around the apparatus
- Sound velocimeters installed at various depths
- Tiltmeter and compass at each storey
- Measurements performed every 2 minutes



Detecting **cosmic** neutrinos: a threefold way

1. Excess of HE neutrinos over the background of atmospheric events. Estimate of the **neutrino energy (shower-dominated).**

- **No real improvement expected w.r.t. IceCube**



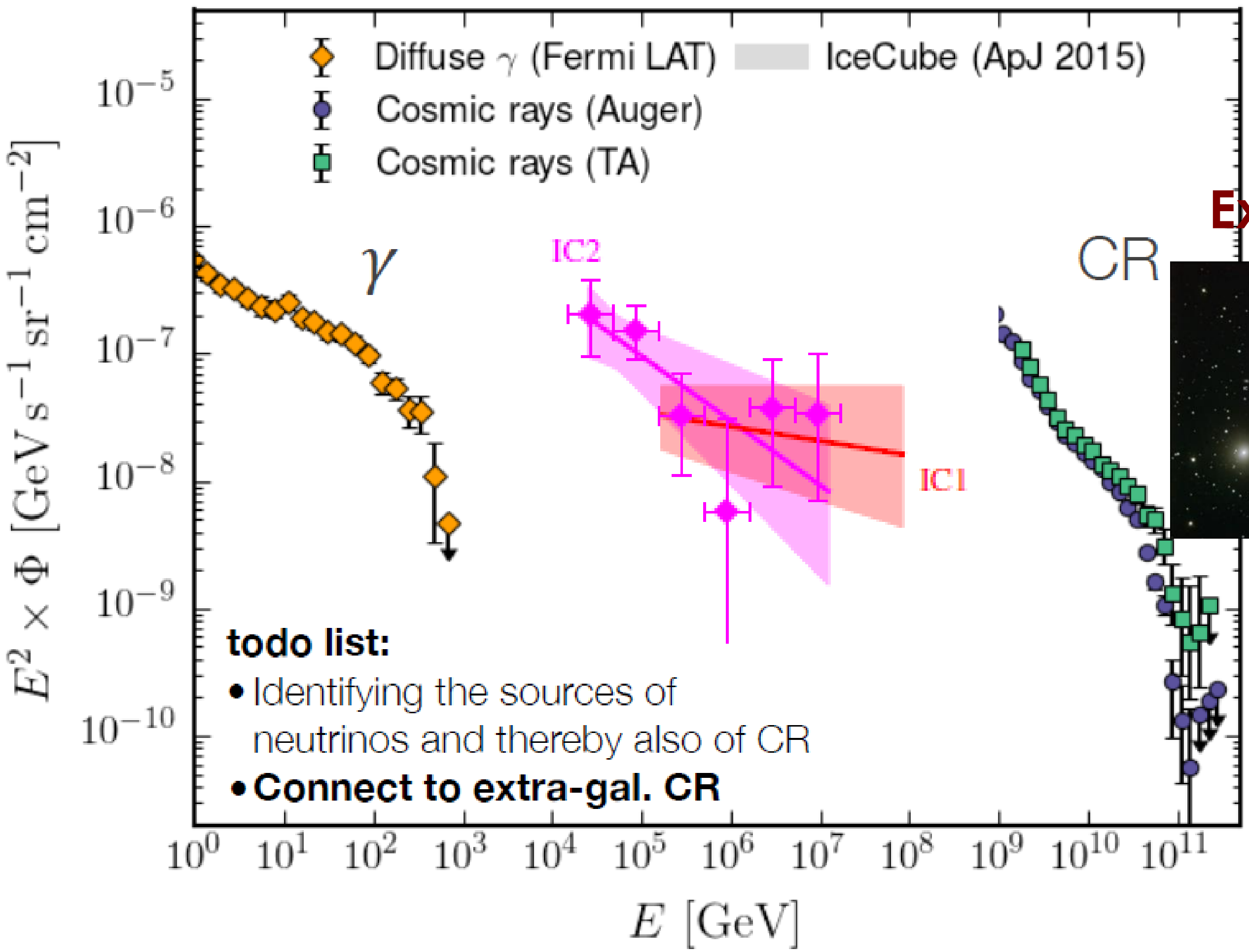
2. Point-like events, excess in the sky map. Rely on the precision of the **neutrino direction (track-dominated)** and background suppression.

- **Unsurpassable sensitivity for Galactic sources for E_ν<100 TeV and part of the Southern sky**

3. Coincident event in a restricted time/direction windows with EM/γ/GW counterparts. Relaxed energy/direction measurement + **transient/ multimessenger** information

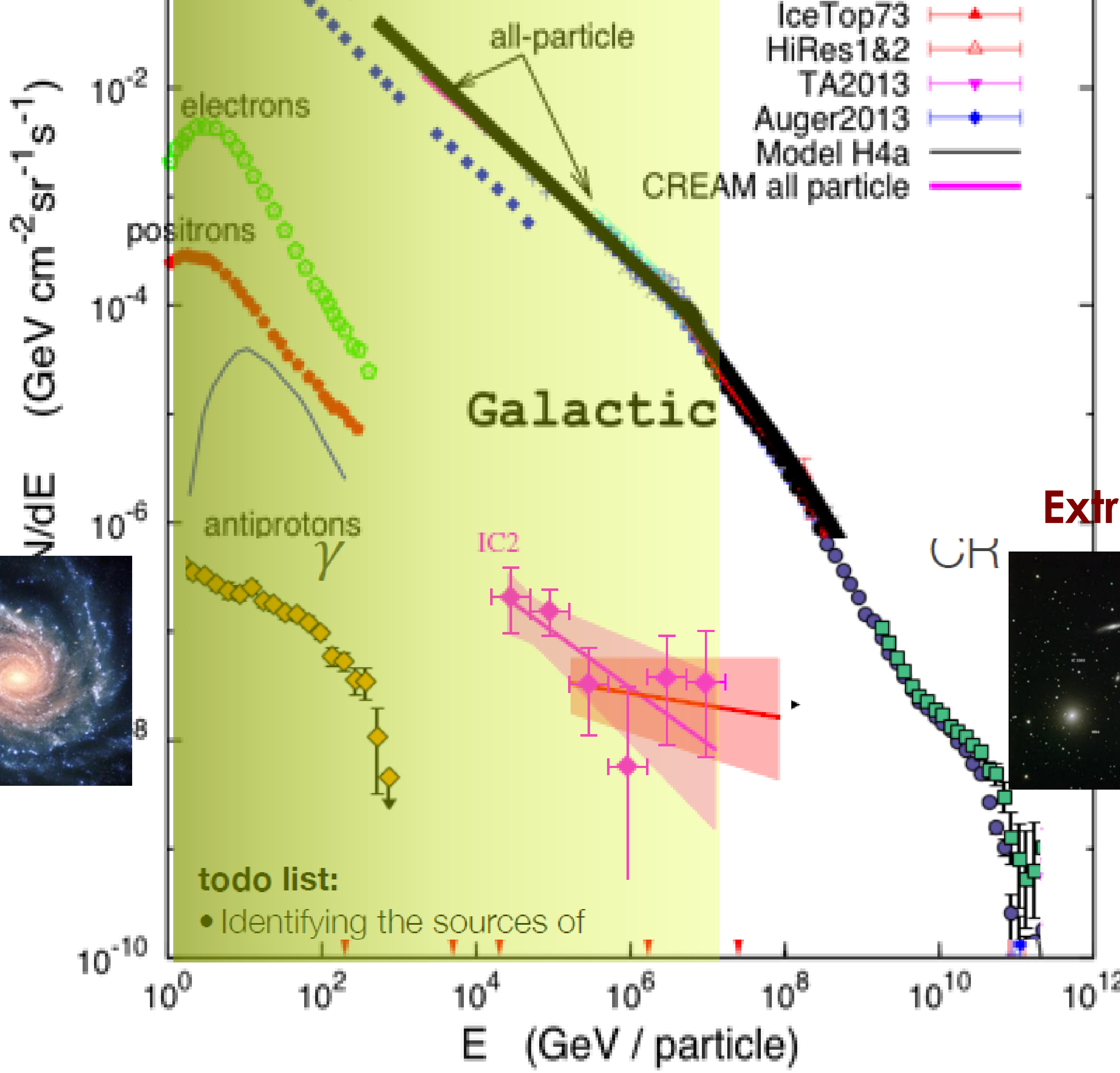
- **Real complementarity w.r.t. IceCube**

The CR, gamma and neutrino connection

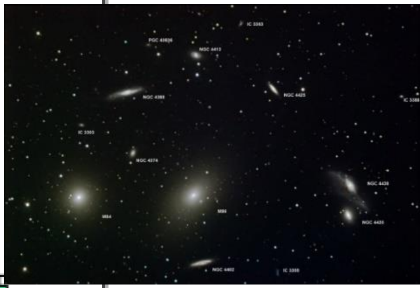


CR

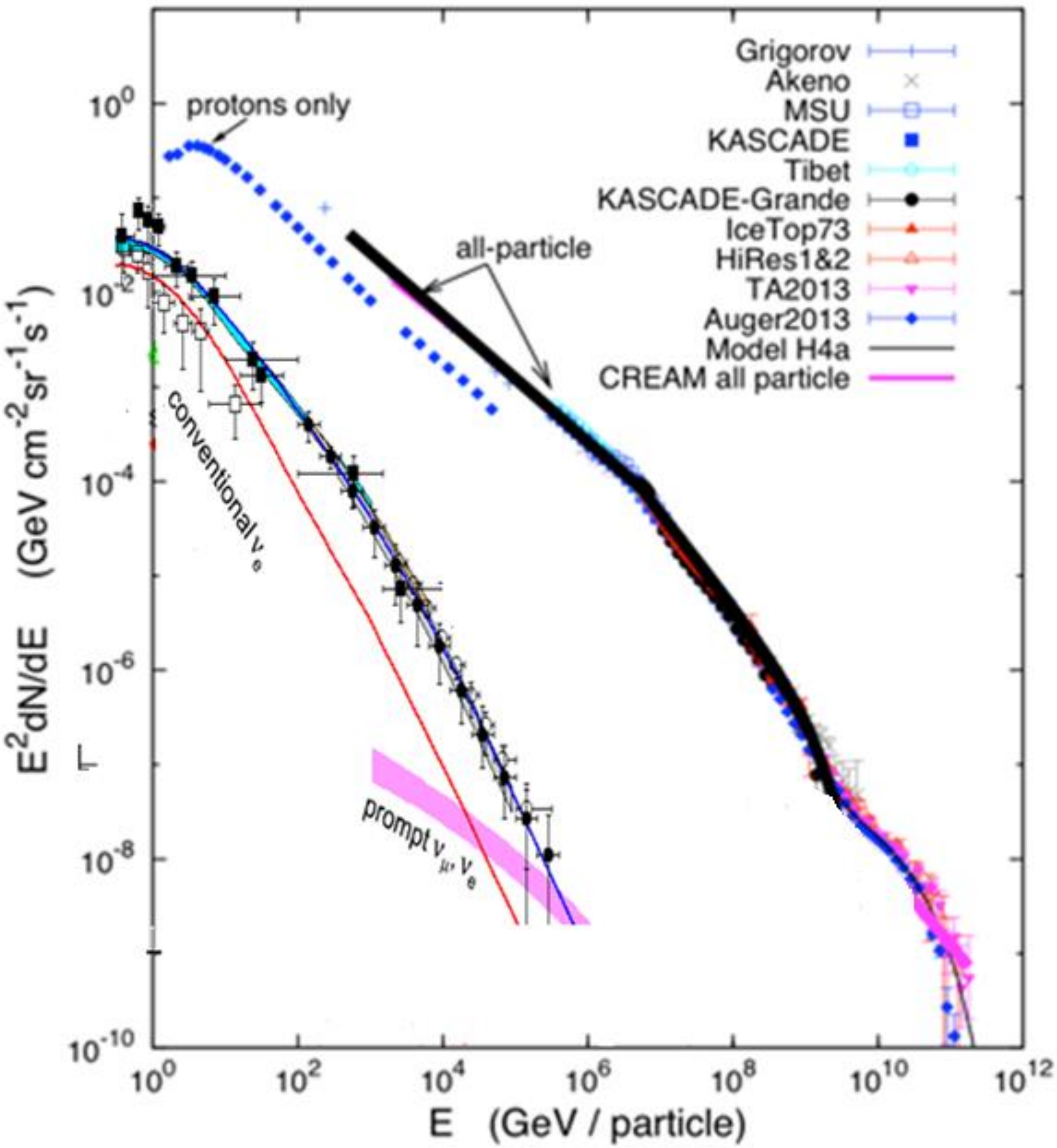
Galactic

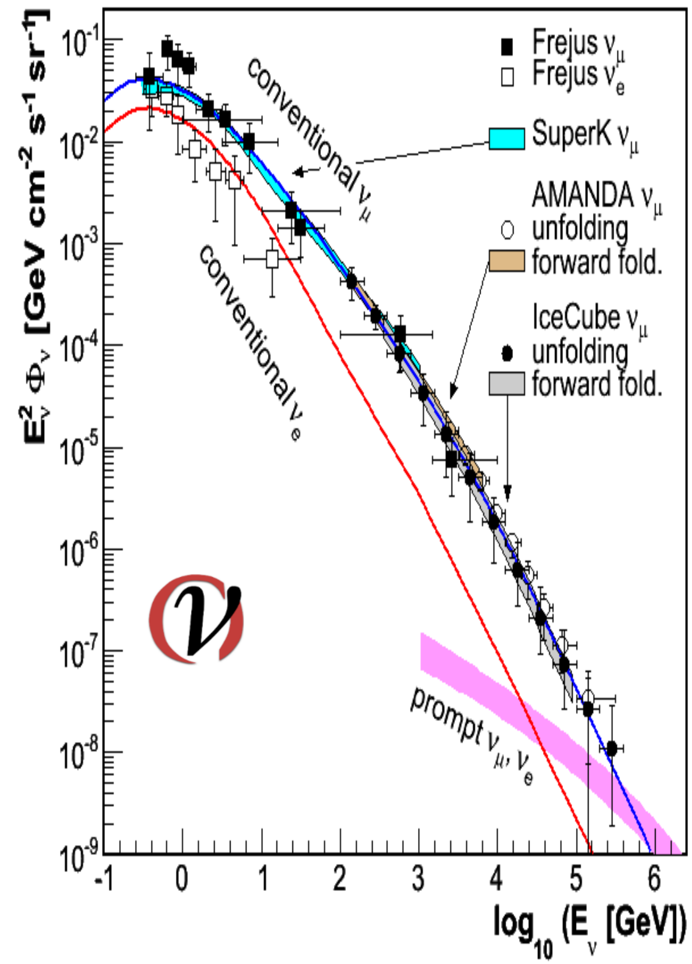


ExtraGalactic

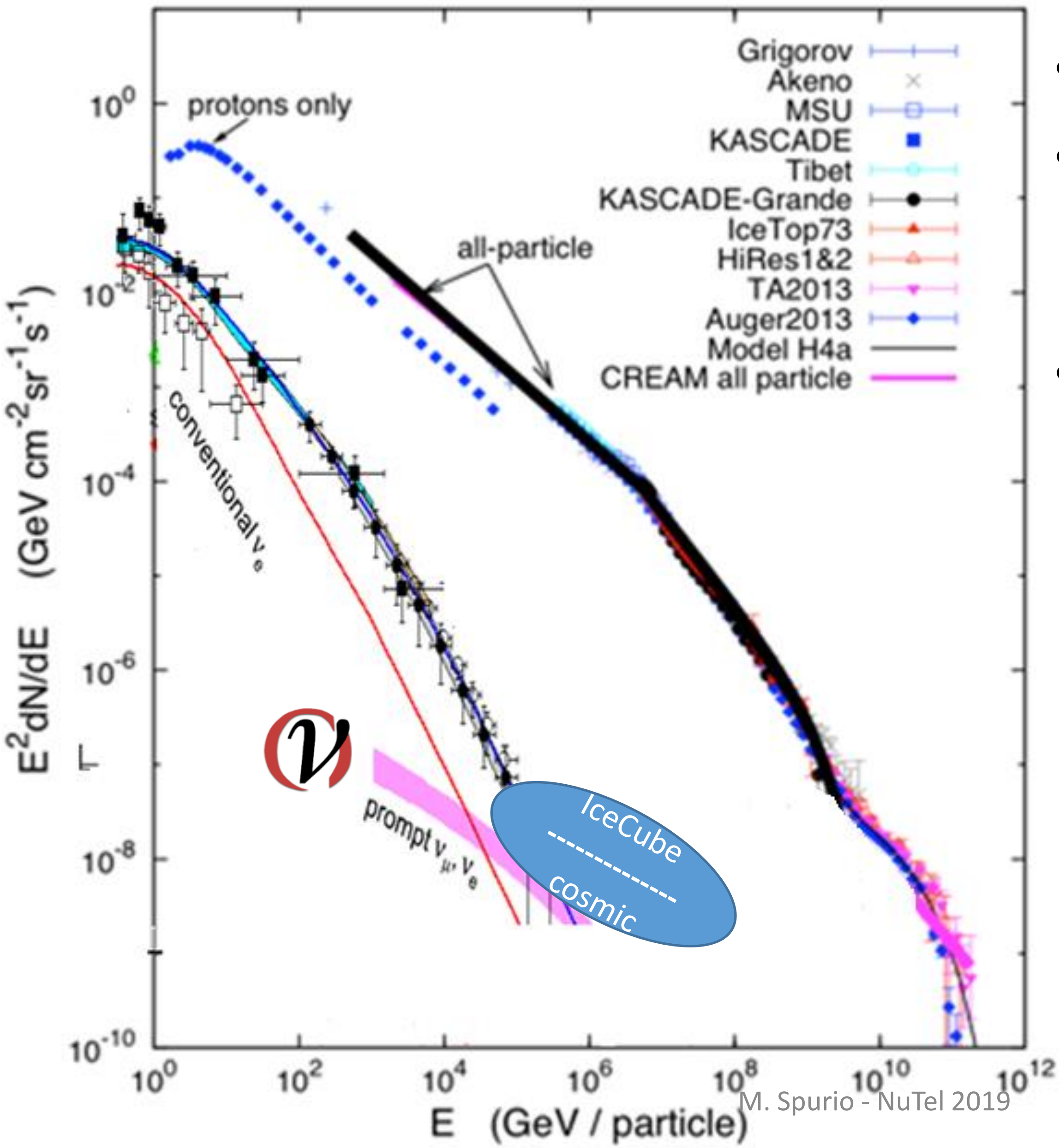


Cosmic rays and atmospheric neutrinos





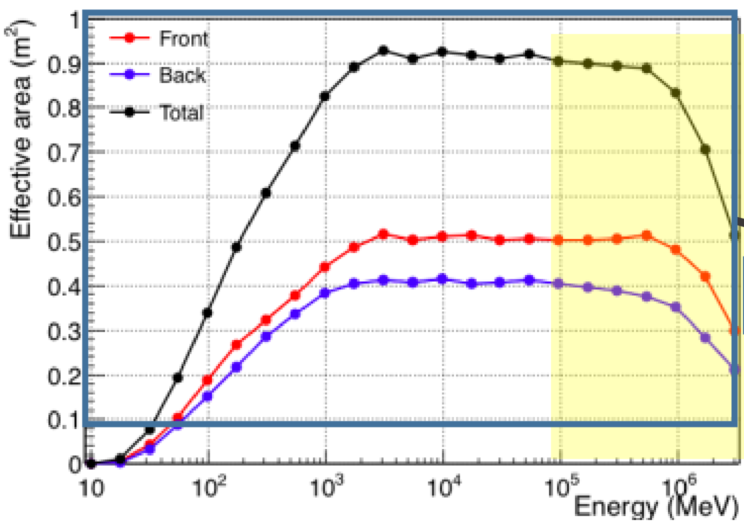
Cosmic rays and atmospheric neutrinos



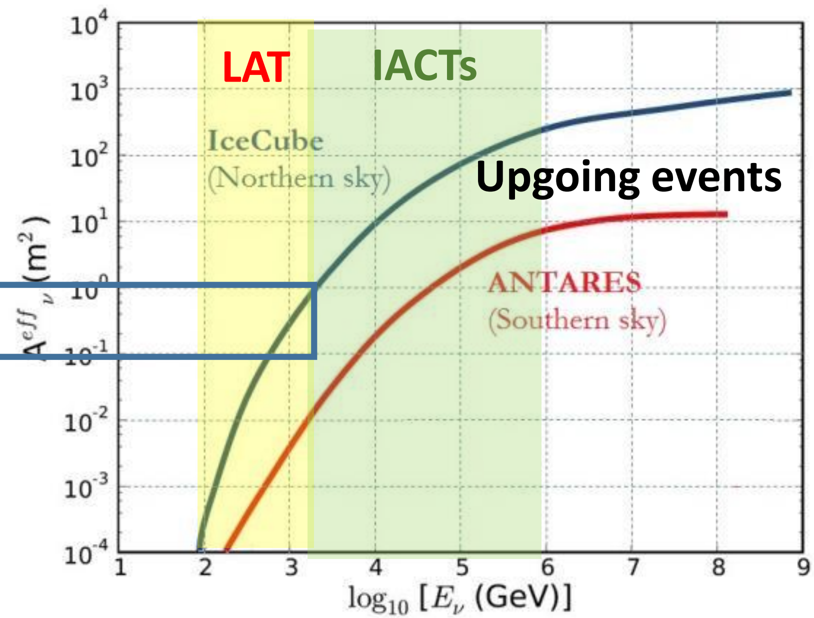
- PeVatrons in our Galaxy?
- Disantangle among lepton and hadrons not assured with γ-rays alone
- CR origin of the ν **signal** near source, origin of the ν **background** on Earth!

Detecting ν (I): the effective area A^{eff}

- Large background
  - Downward going atmospheric muons
  - Irreducible: atmospheric neutrinos
- Two event topologies in detectors: **(t)racks**, **(s)howers**
- Effective area A^{eff}= *function*[(t,s); ν energy; analysis cuts;δ]



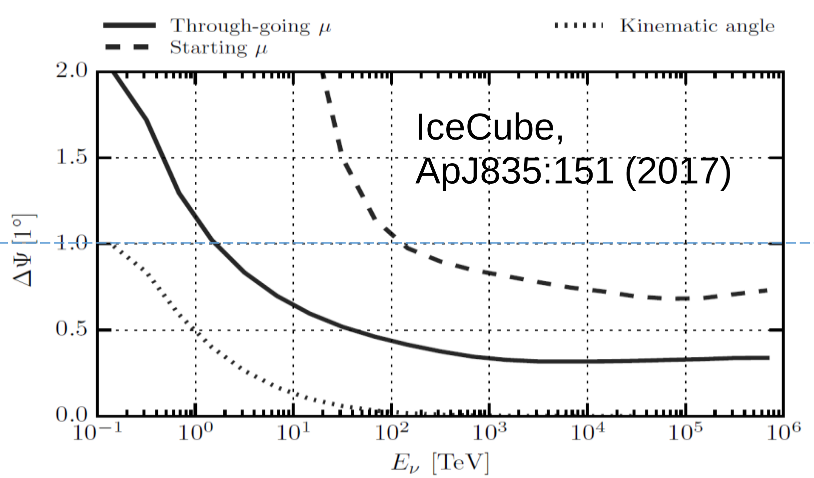
Fermi-LAT *effective area vs. E*



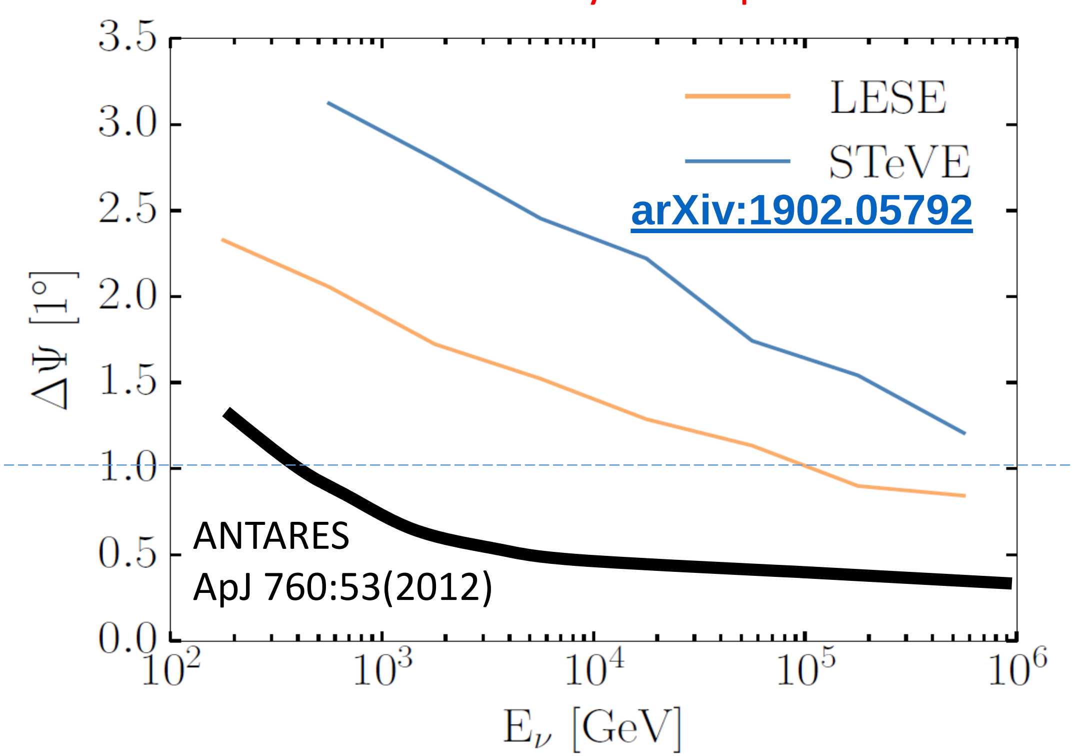
Detecting ν (II): the angular resolution Δψ

- A^{eff}= *function*[(t,s); ν energy; analysis cuts, δ]
- Angular resolution Δψ =*function*[(t,s); medium; ν energy]
- Only tracks (=upgoing events) reach sub-degree angular resolution

Northern sky Hemisphere



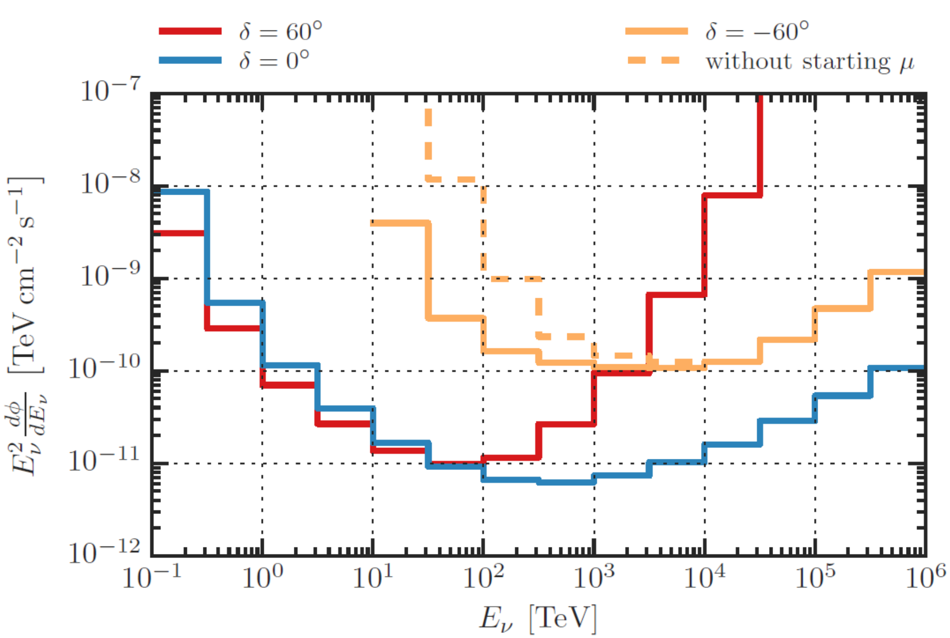
Southern sky Hemisphere



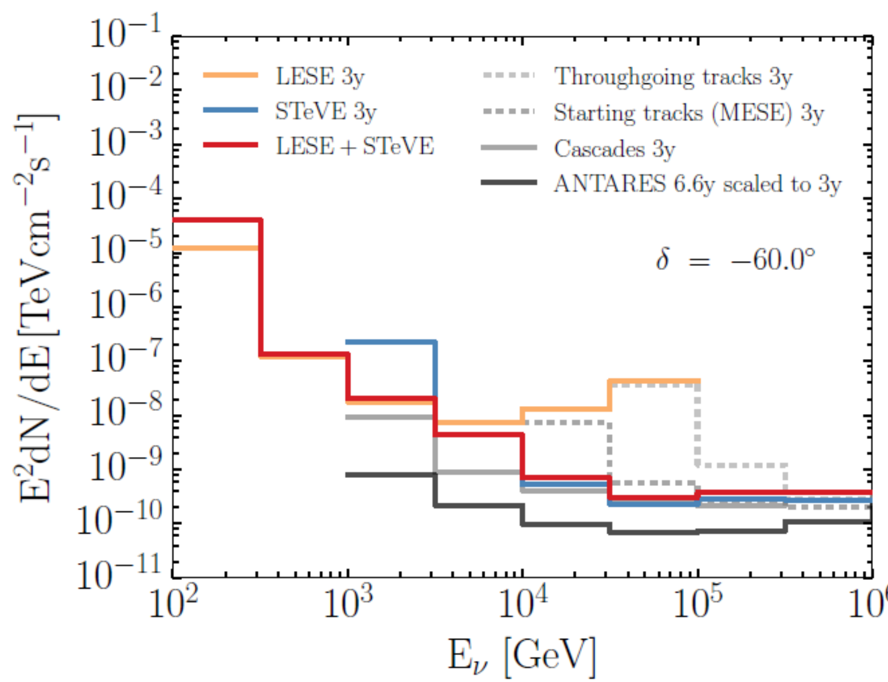
Detecting ν (III): the sensitivity (SED units)

- A^{eff}= *function*[(t,s); ν energy; analysis cuts, δ]
- Δψ= *function*[(t,s); medium; ν energy]
- Sensibility=*function*(A^{eff}; Δψ; ν energy)

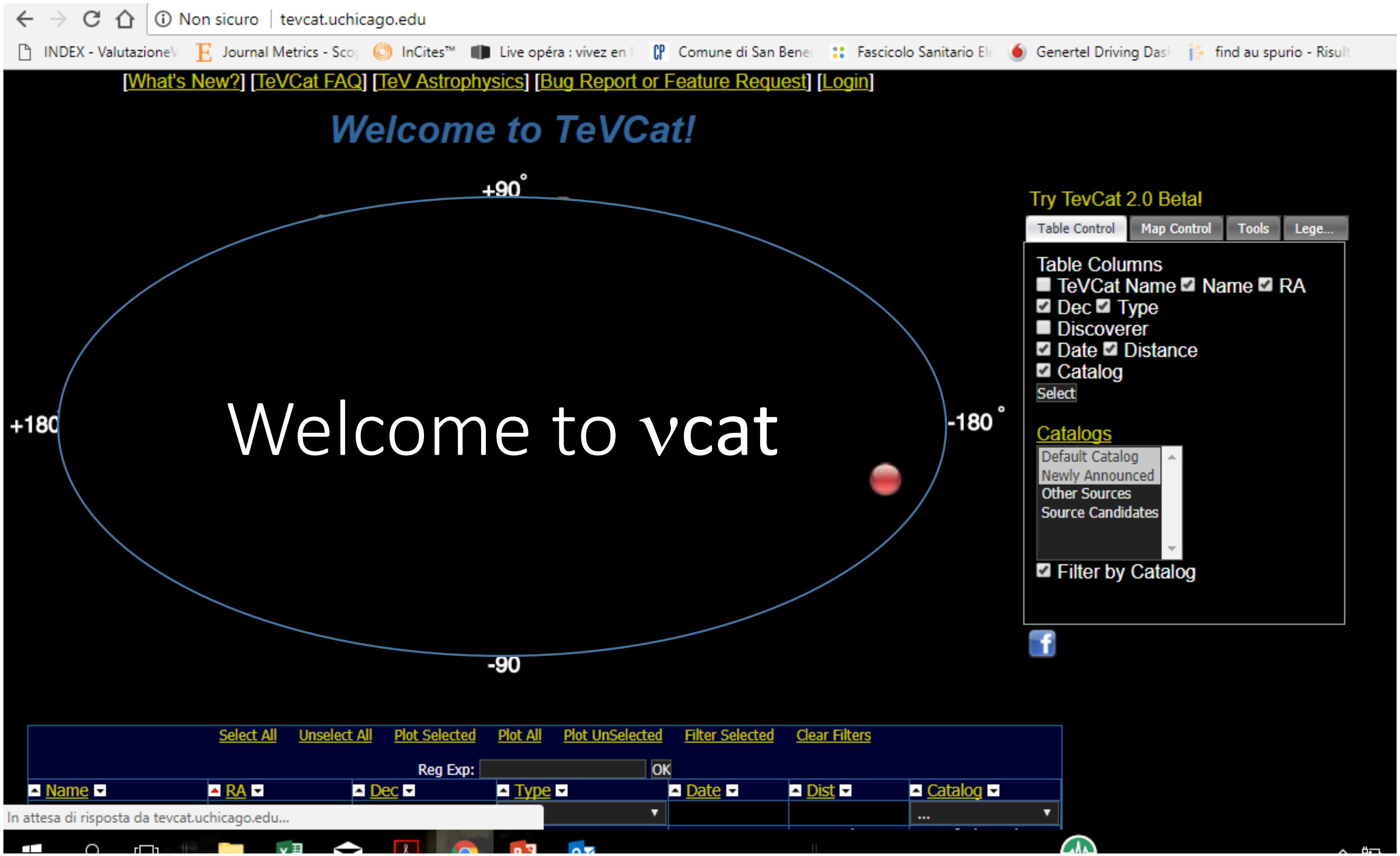
Northern sky Hemisphere
IceCube, ApJ835:151 (2017)



Southern sky Hemisphere
arXiv:1902.05792v1

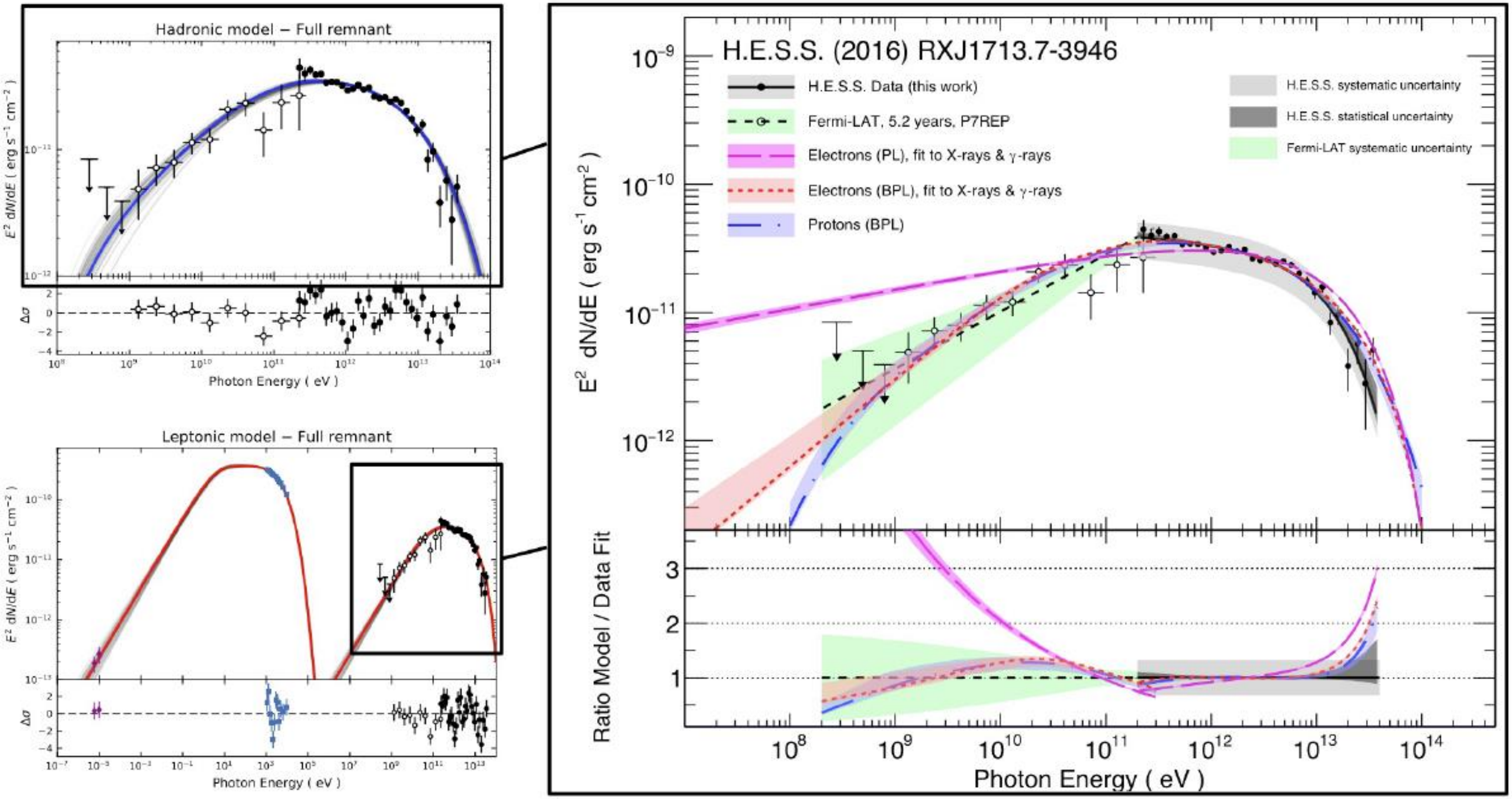


Why we do not have a “neutrino map”?

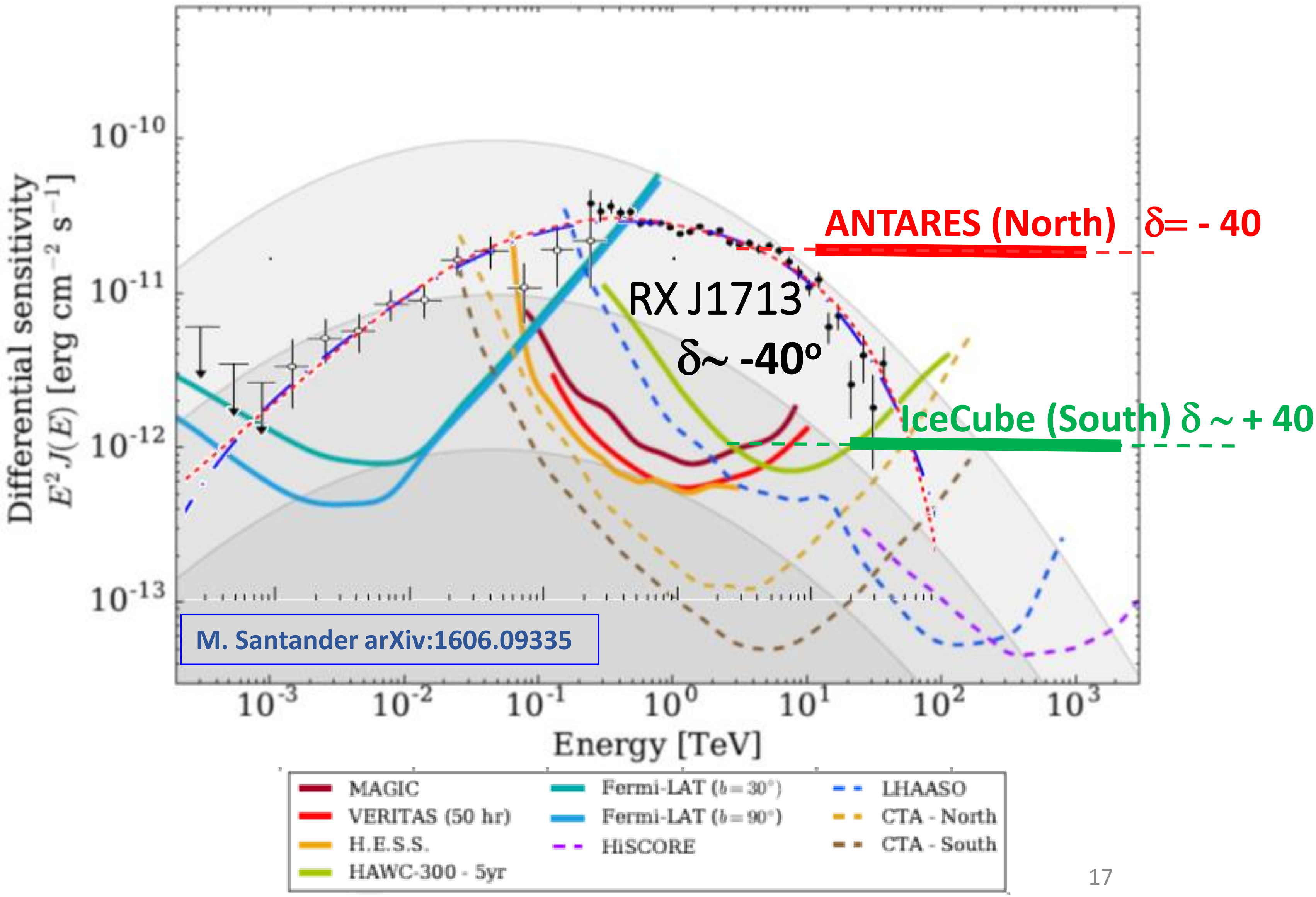


Multi-wavelength observation: RXJ 1713.7

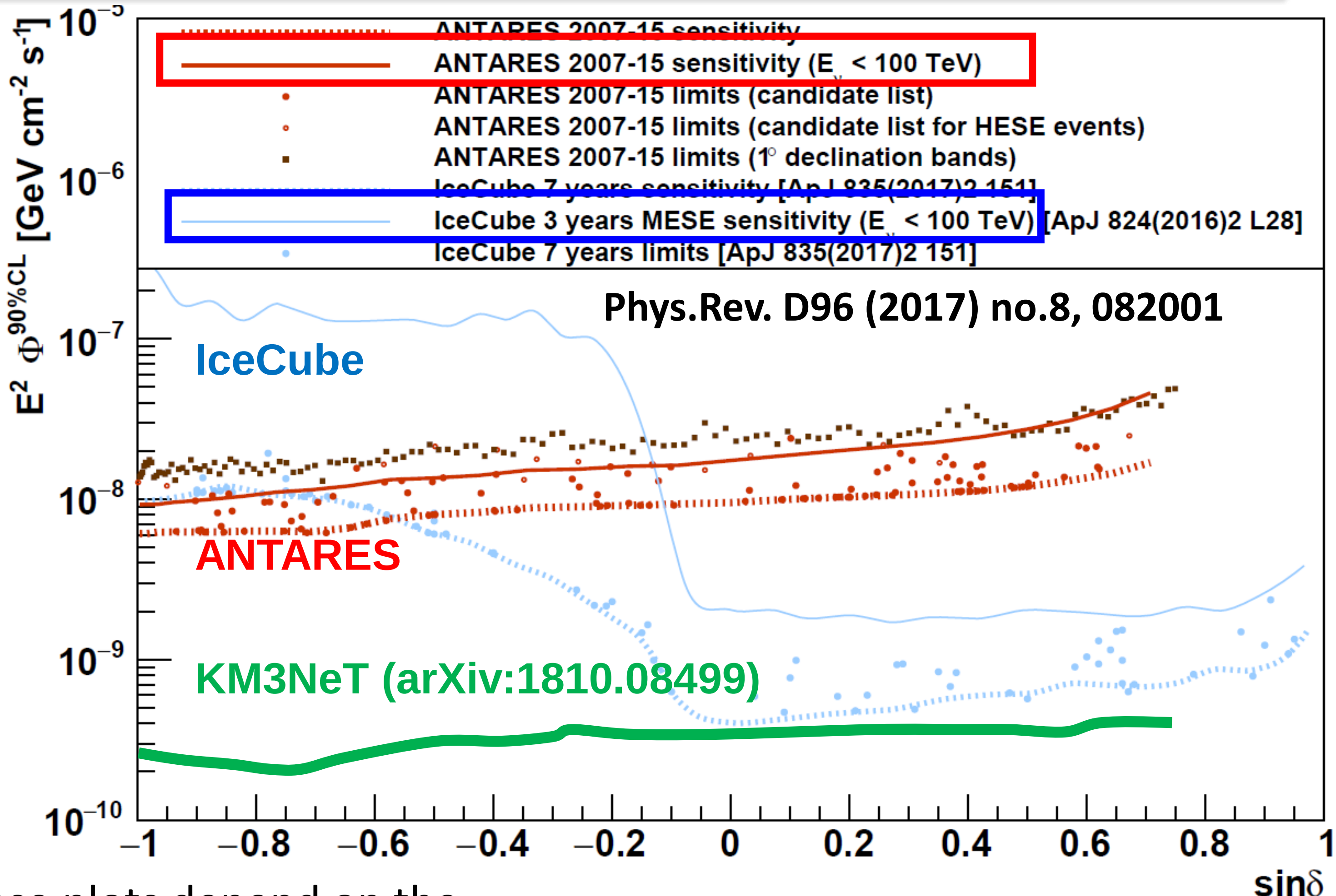
H.E.S.S. Collaboration: Observations of RX J1713.7−3946 2018 A&A, 612, A6



Galactic region: γ measurements and ν sensitivity



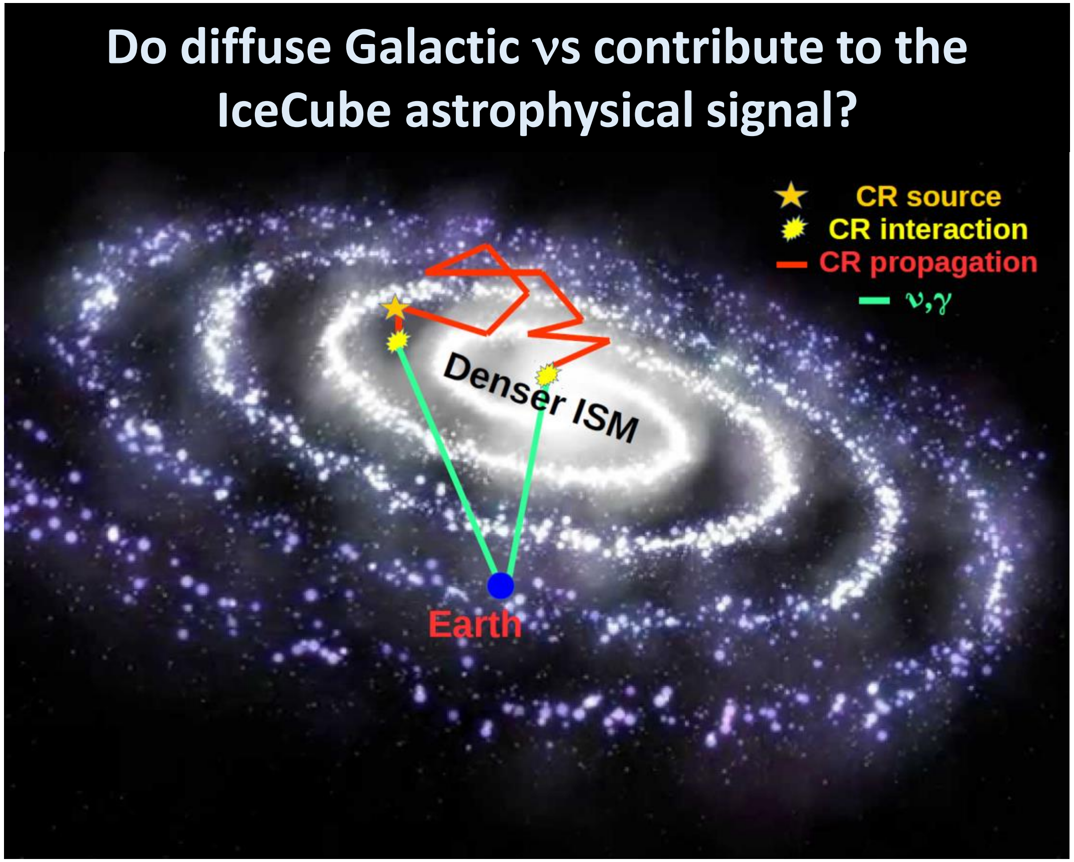
U.L. and Sensitivities (also E_ν<100 TeV)

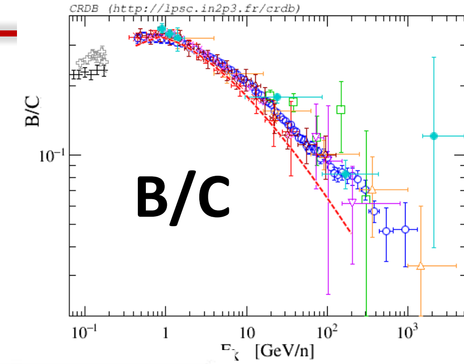


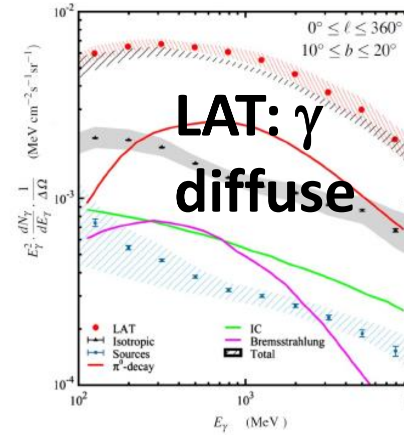
Note: these plots depend on the

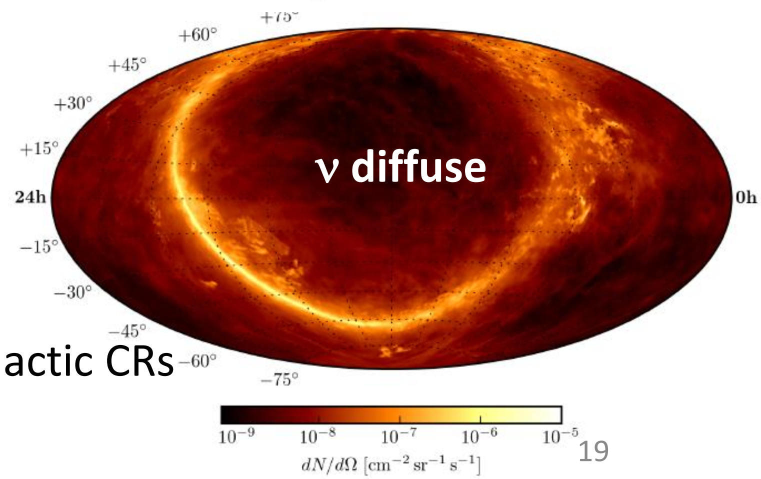
- assumed **spectral index** of the source
- differential **energy sensibility** of the detector

CR propagation in the Milky Way: γ and ν.







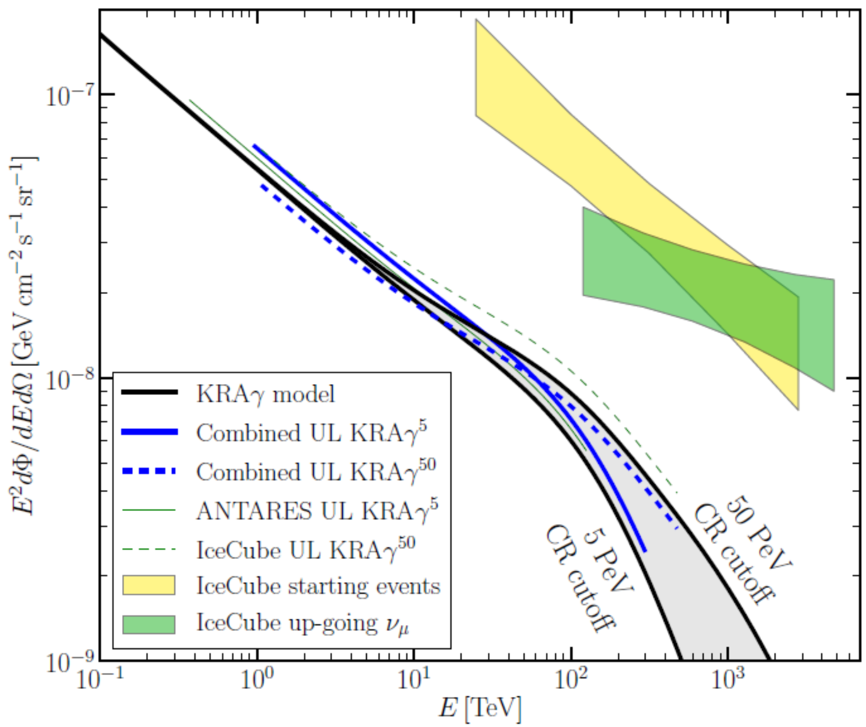


- Neutrinos allow testing **CRs propagation**
- Dense matter regions boost γ and ν fluxes
- Models can be tuned to γ and CR observations
- Northern Hemisphere optimal point of view for galactic CRs

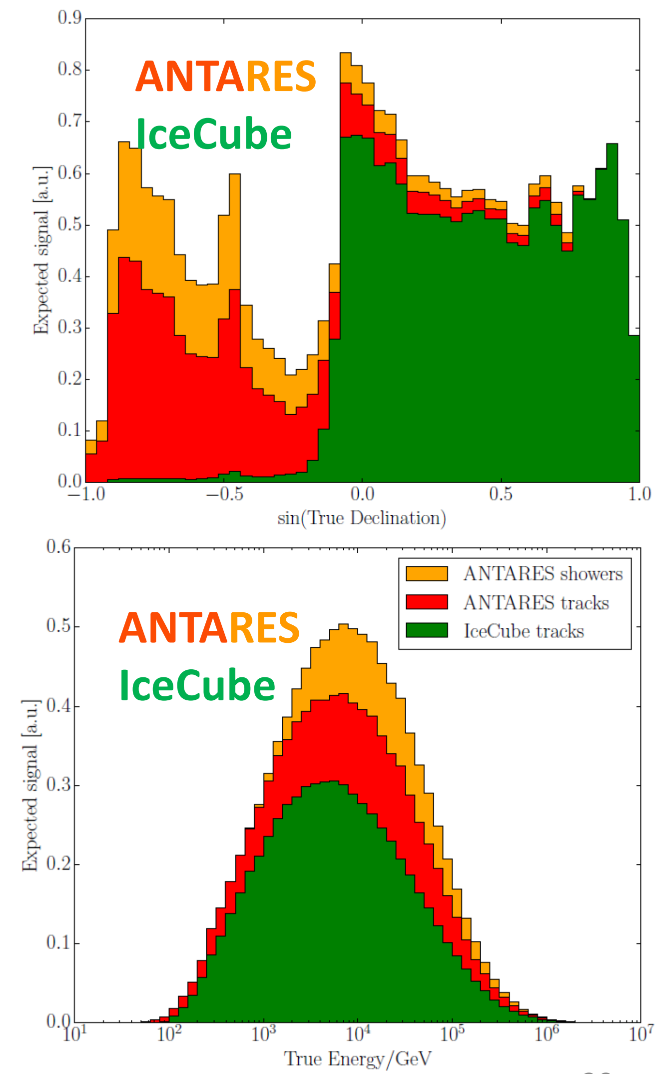
ANTARES+ IceCube from GP

(ANTARES) PRDD96 (2017) 062001
ANTARES+IC, ApJ 868:L20 (2018)

Combined U.L. at 90% CL (blue line) on the 3-flavor neutrino flux of the KRAγ model (5-50 PeV cutoff)



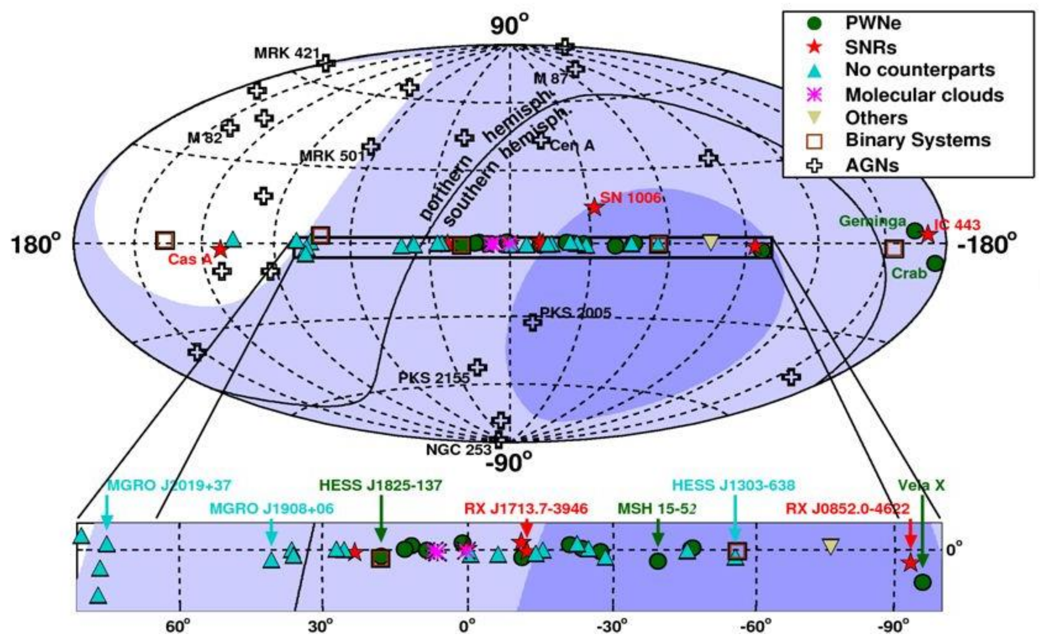
Stacked expected signal vs. δ (top) and energy (bottom). Colors represents the relative contribution to the sensitivity



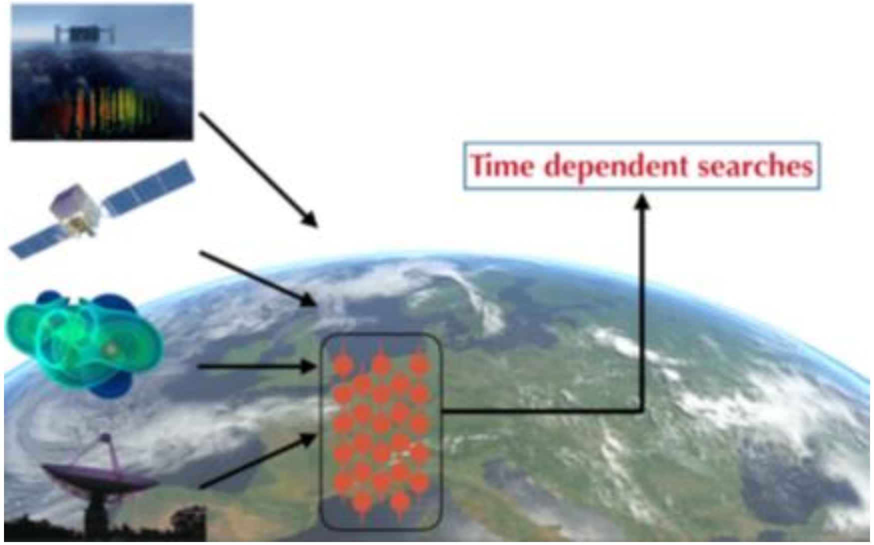
Result: total flux contribution of **diffuse Galactic neutrino** emission <8.5% *of the total diffuse IC astrophysical signal (E_ν >* 30 TeV) [ApJ 809:98(2015)].

Mediterranean vs. South Pole telescopes

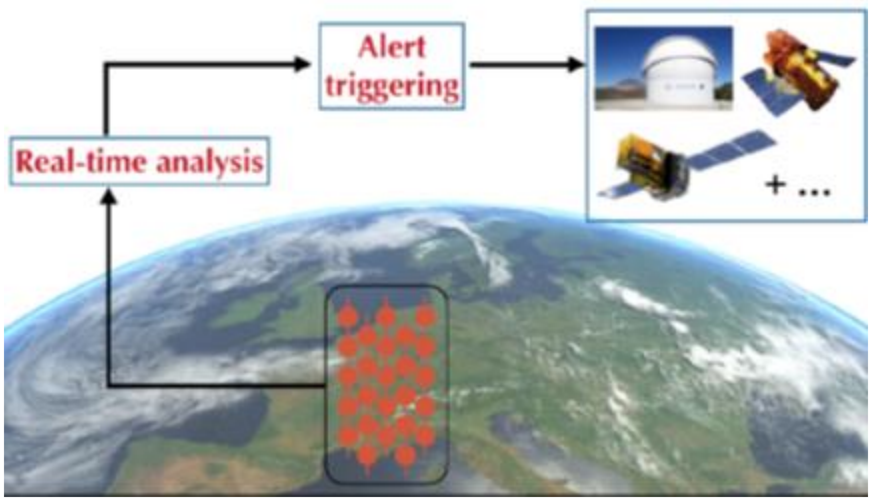
- Most **galactic sources** produce upgoing events in the "**golden channel**" (ν_μ)
- Sub-degree **angular resolution** for upgoing events
- KM3NeT: OM segmentation with small PMTs (further background reduction)
- Larger depth (~2.5 km for ANTARES, ~3.5 km for KM3NeT/ARCA) allows larger reduction of atmospheric muons
  - Signal/background $\propto \Delta\theta^{-2}$
  - **Looser cuts** select more low-energy events
  - Lower scattering in water w.r.t. ice → better **angular resolution** $\Delta\theta$;



Multimessenger: two approaches

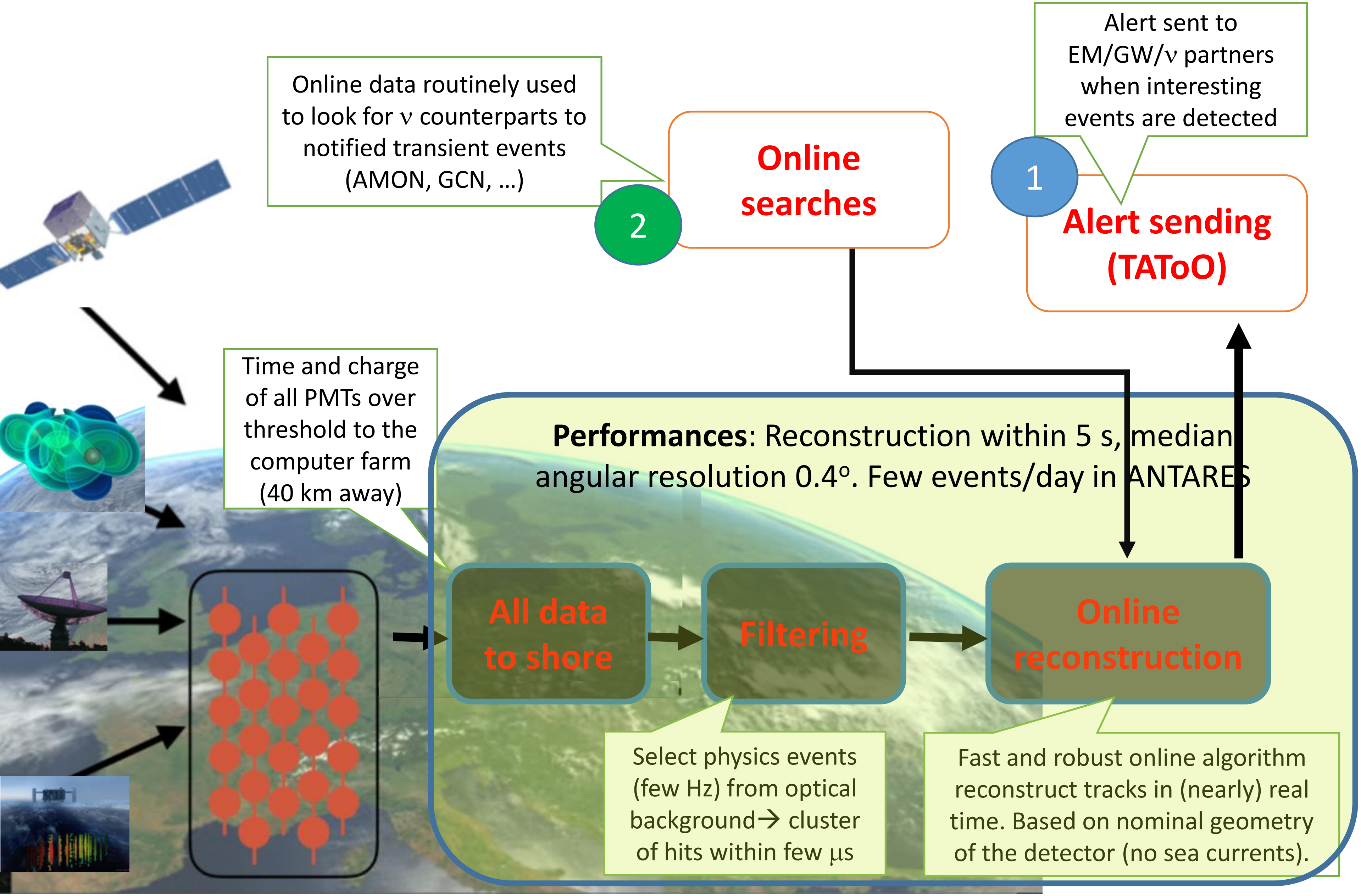


- Looking in the neutrino data stream in real time or in offline for space/time correlation: IceCube neutrinos, LVC gravitational waves, PARKES/UTMOST/ASKAP fast radio bursts, Swift/Fermi gamma-ray bursts, Fermi/IACT blazars…

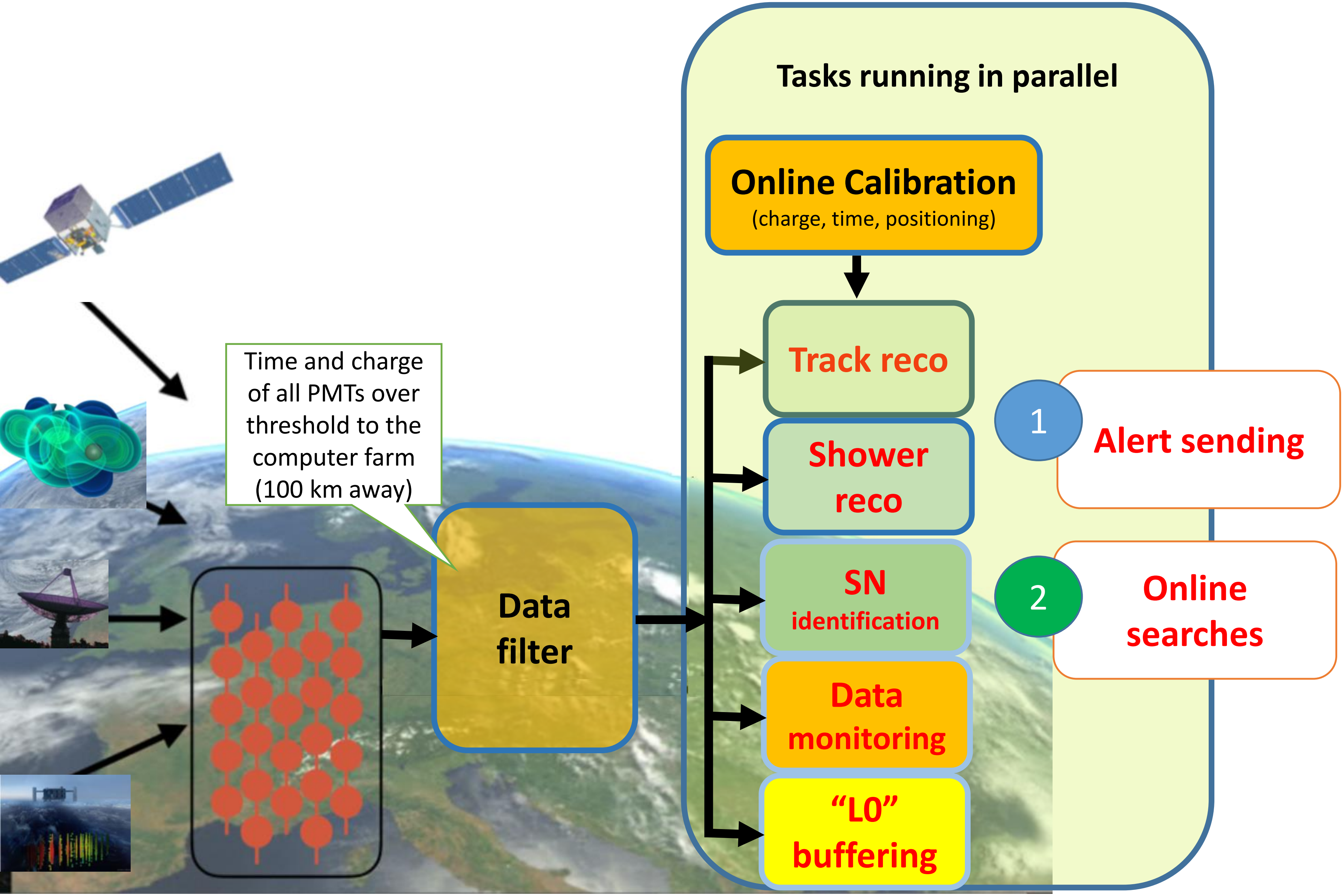


- Reconstructing and selecting the most interesting neutrinos in realtime and send the direction to EM partners.

ANTARES online system (past and present)



KM3NeT improved version



ANTARES neutrino alerts → KM3NeT

Radio	Optical	X-ray	GeV γ-rays	TeV γ-rays
MWA	TAROT, ZADKO MASTER, GWAC	Swift INTEGRAL	Fermi	HESS HAWC

EM frequency/γ energy →

ANTARES real time alerts:

- **Time to send an alert: ~5 s**
- **Track median angular resolution: 0.4°**
- Doublet of neutrinos: ~0.04 events/yr
- Single neutrino with direction close to local galaxies: ~1 TeV, ~10 events/ yr
- Single HE neutrinos: ~5 TeV, 20 ev/ yr
- Single VHE neutrinos: ~30 TeV, ~3-4 ev/yr

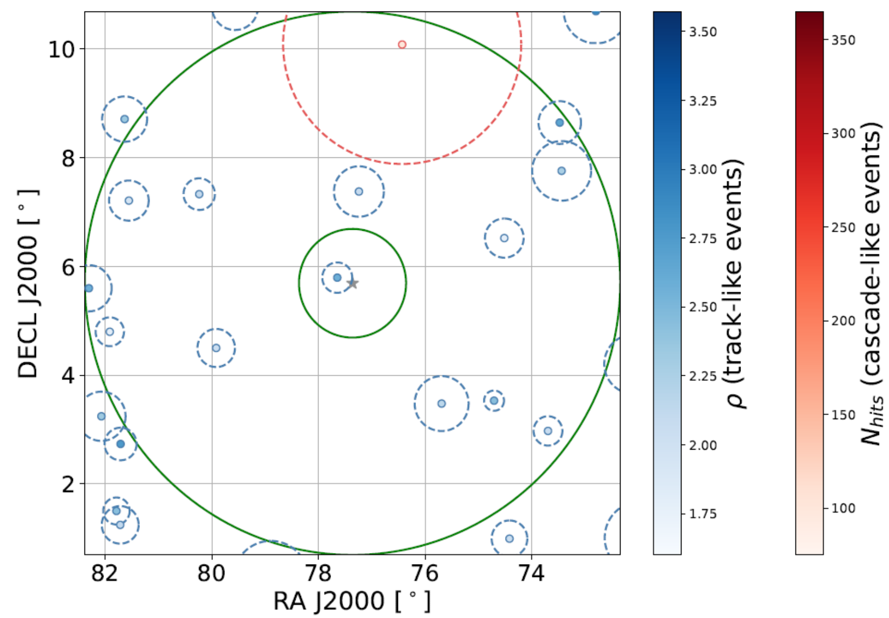
Sent neutrino alerts (2009-2018)

- 281 to robotic telescopes — APP 35 (2012)530, JCAP 02 (2016) 062
- +15 to Swift
- +15 to INTEGRAL
- +22 to MWA (radio) — Croft S. et al, ApJ 820 (2016) 24
- +2 to H.E.S.S.

TXS 056+056: ANTARES follow-up

- Direction in ANTARES of IC170922A: 14.2° below horizon.
- **Online algorithm** → No ν candidate in a cone of 3° within ±1 h (ATEL #10773), ± 1 day
- ν fluence upper limit set for E^{-2} (F< 15 GeV cm^{-2} integrated from 3 TeV-3 PeV)

- Time-integrated analysis as other 106 sources as in [PRD**96**, 082001]
- Expected background in 3136 days:
  - 0.23/deg^2 for track-like
- 1 track (12/12/2013) 0.3° from source (# fitted events: μ_{sig} **= 1.03**).
- Pre-trial p-value 3.4% (post-trial 87%)
- Flux U.L. (@100 TeV) for E^{-2}: 1.6×10^{-18} GeV^{-1} cm^{-2} s^{-1} in [2 TeV-4 PeV]
- In the list of 107 pre-selected sources, only two have smaller p-value

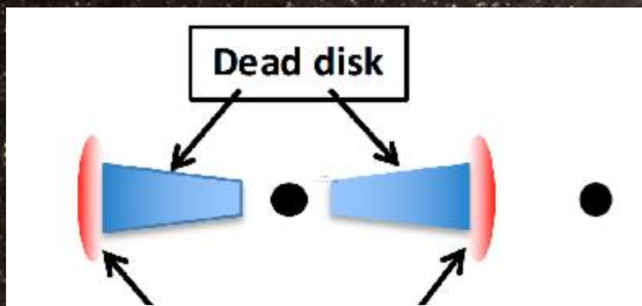


Distribution of the 13 tracks +1 shower events around (=1° and 5°) TXS 0506+056. The dashed circles indicate the angular error estimate of each event..

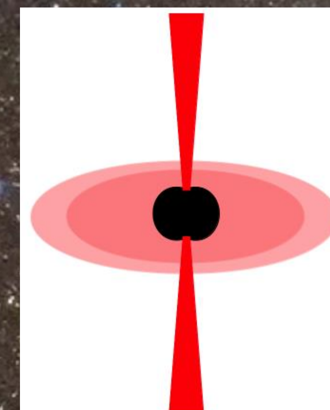
ApJ 863:L30 (2018)

Searching for HEN from BBH coalescences (O1-O2)

HEN emission coincident with GW signals expected ?
If hadronic/magnetic environment



Tidally heated outer rim; active magnetorotational instabilities



ν

- Online neutrino searches (ANTARES/IceCube) for every GW alert during O2: results to LIGO/Virgo on private GCN
- Offline optimized event-by-event searches for
  - **GW150914**: HEN emission<20% of GW energy; PRD93 (2016) 122010
  - **GW151226+LVT151012**: HEN <1-15% of GW energy; PRD96 (2017) 022005
  - **GW170104**: first full sky search, optimization. EPJC 77(2017) 911
  - **O1** sub-threshold events ApJ 870:134(2019)

Binary NS Mergers and HEN?

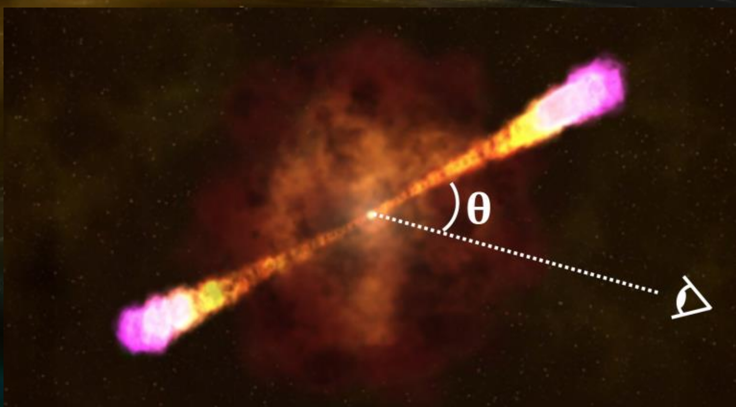
- Prompt neutrino production on-axis
- Off-axis scenario, neutrino-production related to the extended γ-ray emission (Kimura et al. 2017).
- (Later) Extended emission from a relativistic wind with its rotational energy, (Fang&Metzger. ApJ 2017).

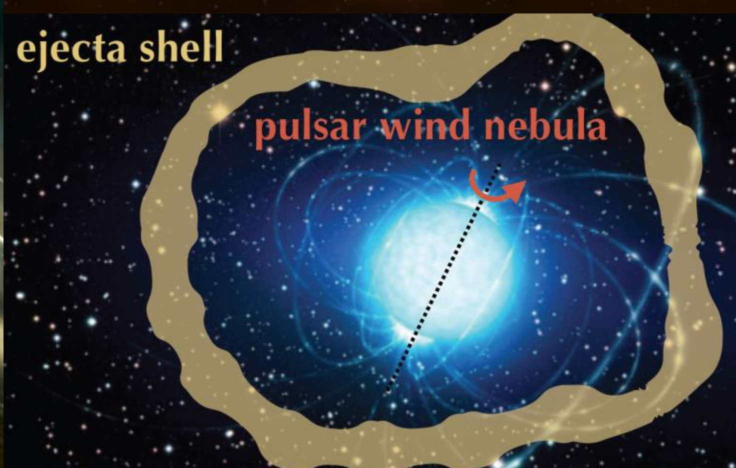
GW170817

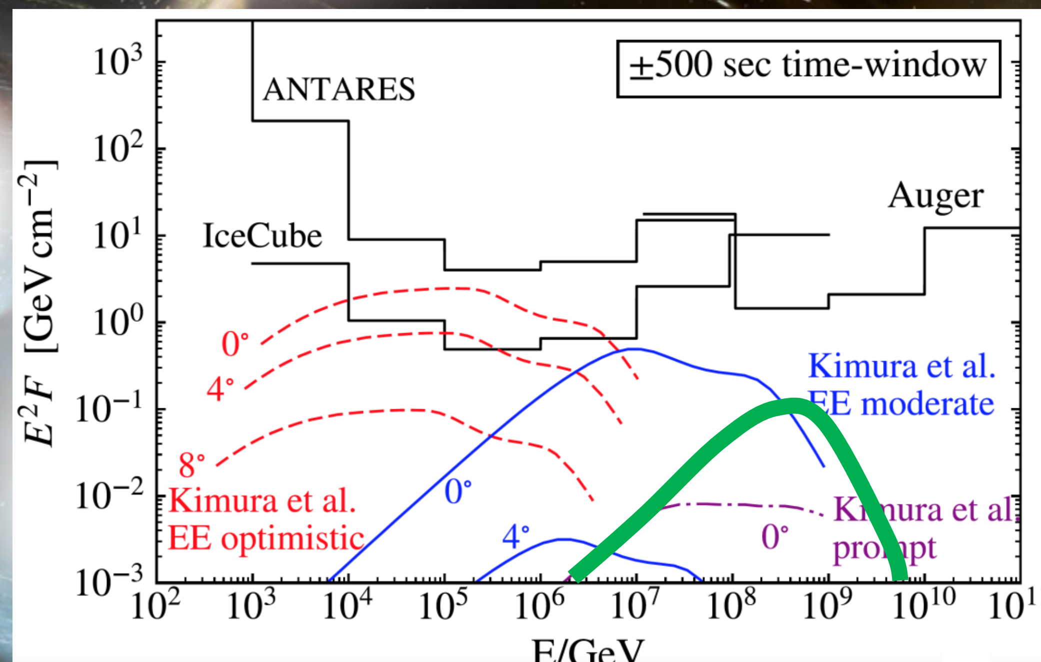
ν ?

ApJL 850:L35 (2017)

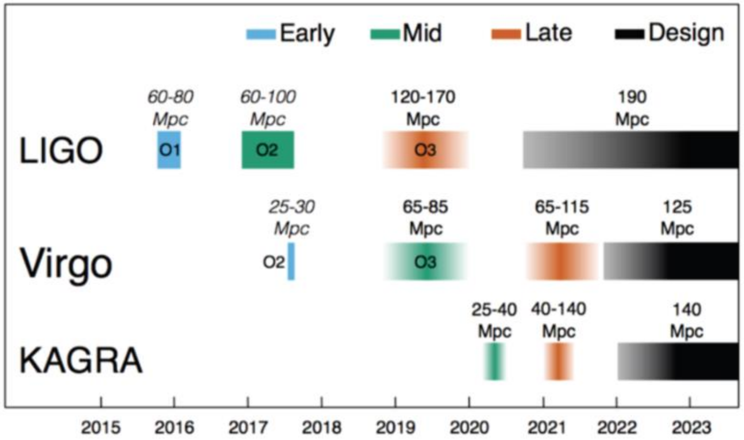
(multimessenger): ApJL 848 L12 (2017)





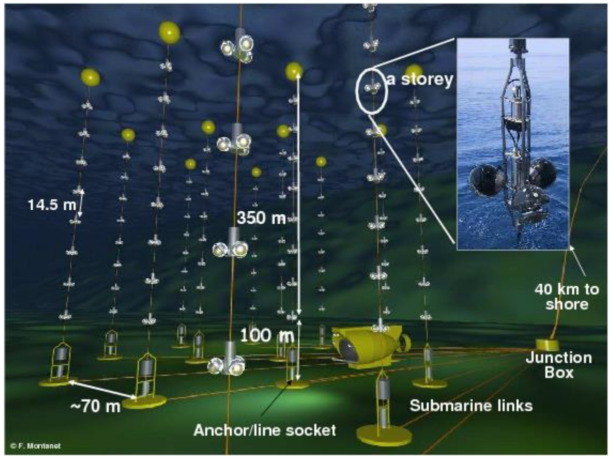


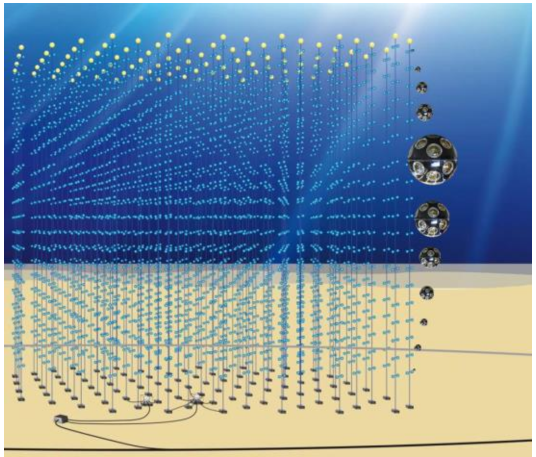
Next GW + HEN observations



Exciting period ahead for Multi-Messenger Astronomy

- Run O3 will start early 2019. Possibly several alerts/week
- Neutrino follow-ups: ANTARES (up to early 2020), KM3NeT (2020), IceCube + AUGER + BAIKAL

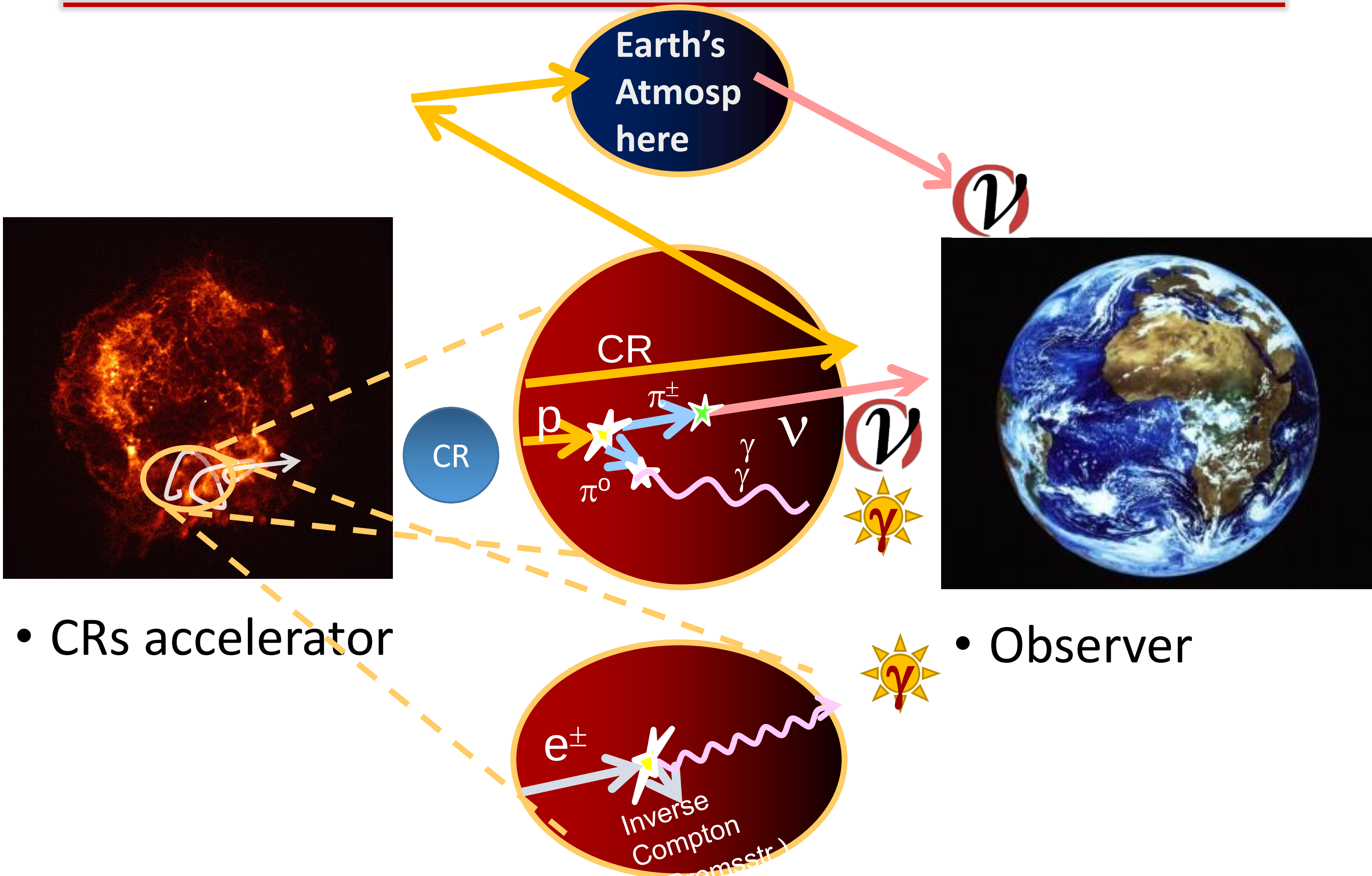




Conclusions

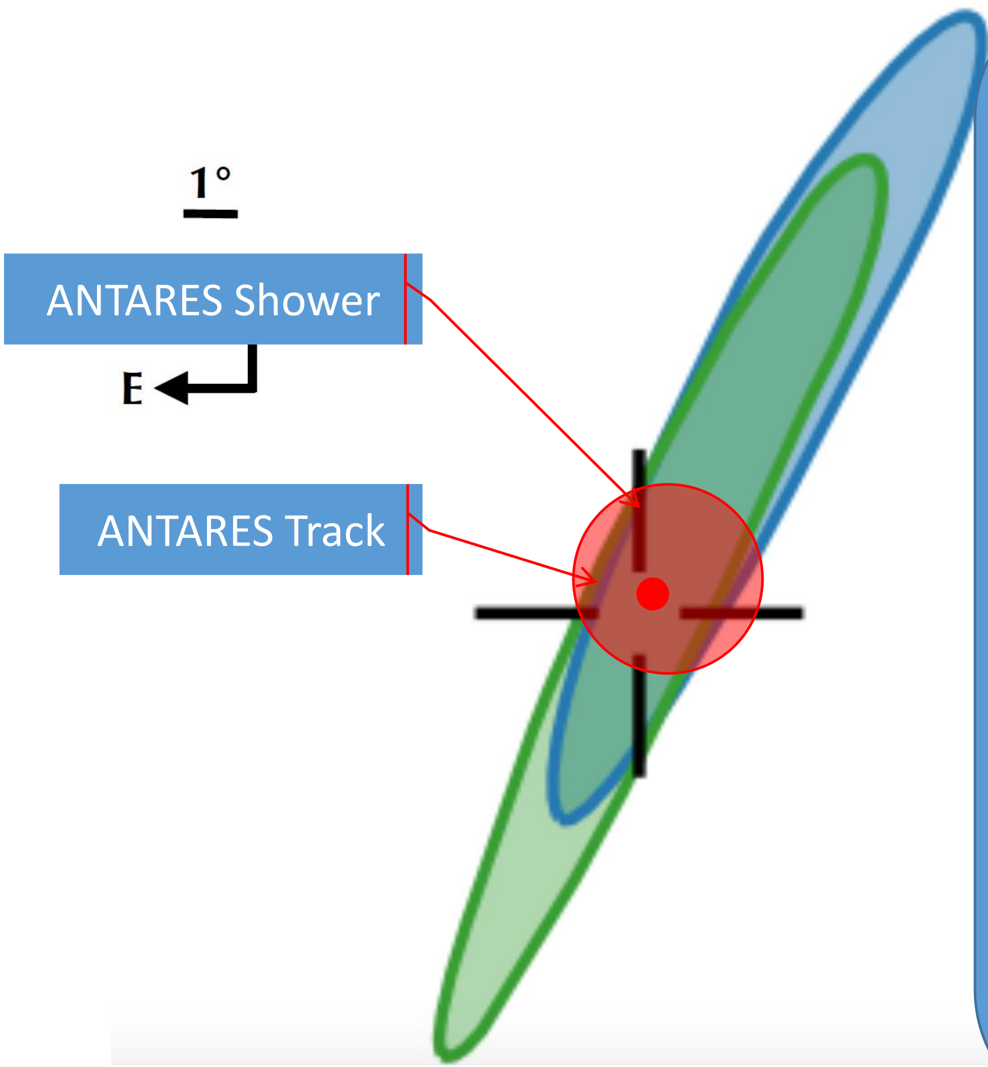
- **Neutrino catalog**: needs the use of the "golden channel" (=ν_μ CC interactions). Full KM3NeT for Galactic sources!
- Waiting for larger detectors (IceCube gen2, GVD) and with better angular resolution (KM3NeT), first neutrino sources discovered also with the help of **transient phenomena**
- **ANTARES Trigger alert**: Very performant and efficient alert sending system → Able sending in ~5s with a precision of 0.3°-0.4° (3 different neutrino triggers)
- **KM3NeT** improvement of calibrations
- **Patience!**

Multimessenger transient: space and time



- CRs accelerator
- Observer

Gravitational Waves (GW) + HE Neutrinos (HEN)



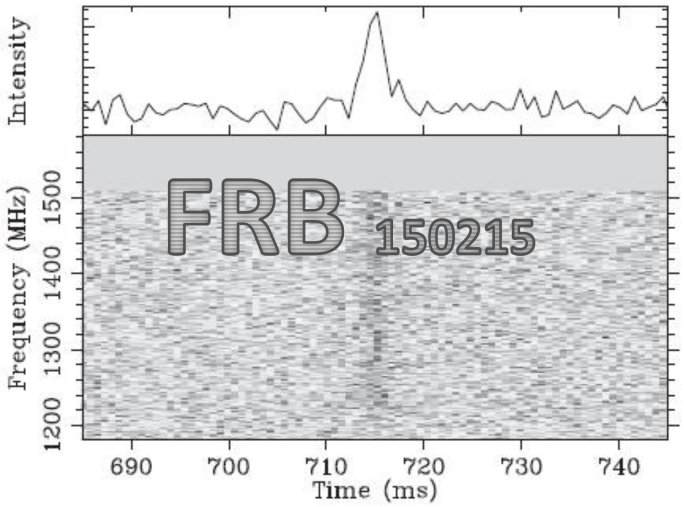
ANTARES (2020)-
KM3NeT(>2020)

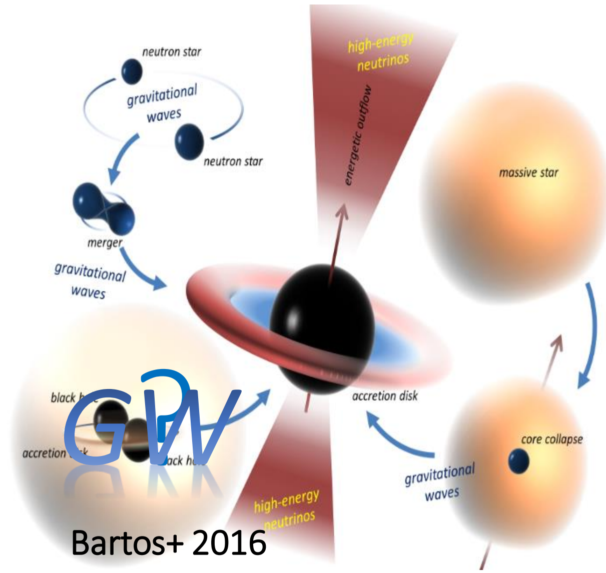
Field-of-view: 2π sr

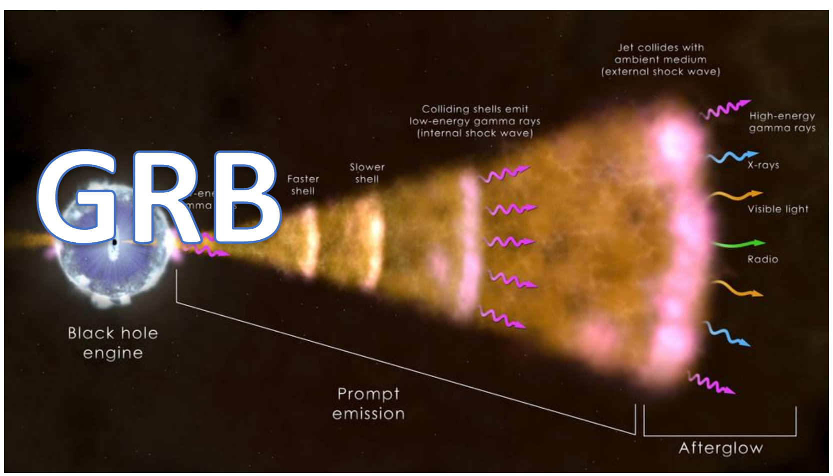
Angular resolution:

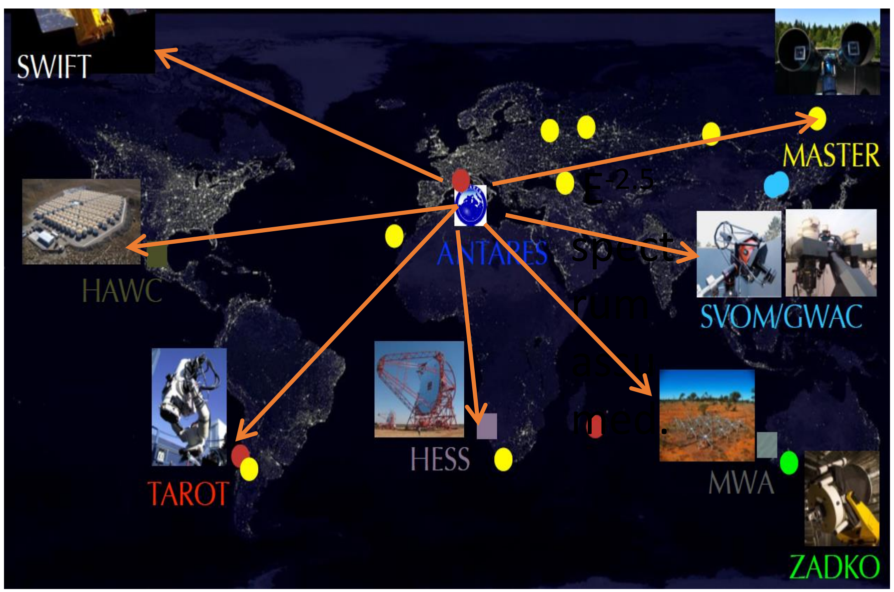
- <0.5° (tracks)
- 2°-3° (showers)

Multimessenger



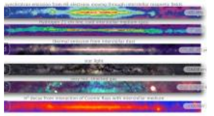






ANTARES Multimessenger program

- **A way to better understand the related physics mechanisms**
- **A way to increase the detector sensitivities**



Up to July 2017:

→ 256 alerts sent
→ 13
→ 2
→ 20

Real-time (follow-up of the selected neutrino events):

- optical telescopes [TAROT, ROTSE, ZADKO, MASTER]
- X-ray telescope [Swift/XRT]
- GeV-TeV γ-ray telescopes [HESS, HAWC]
- radio telescope [MWA]
- Online search of fast transient sources [GCN, Parkes]

Multi-messenger correlation with:

- Gravitational wave [Virgo/Ligo]
- UHE events [Auger]

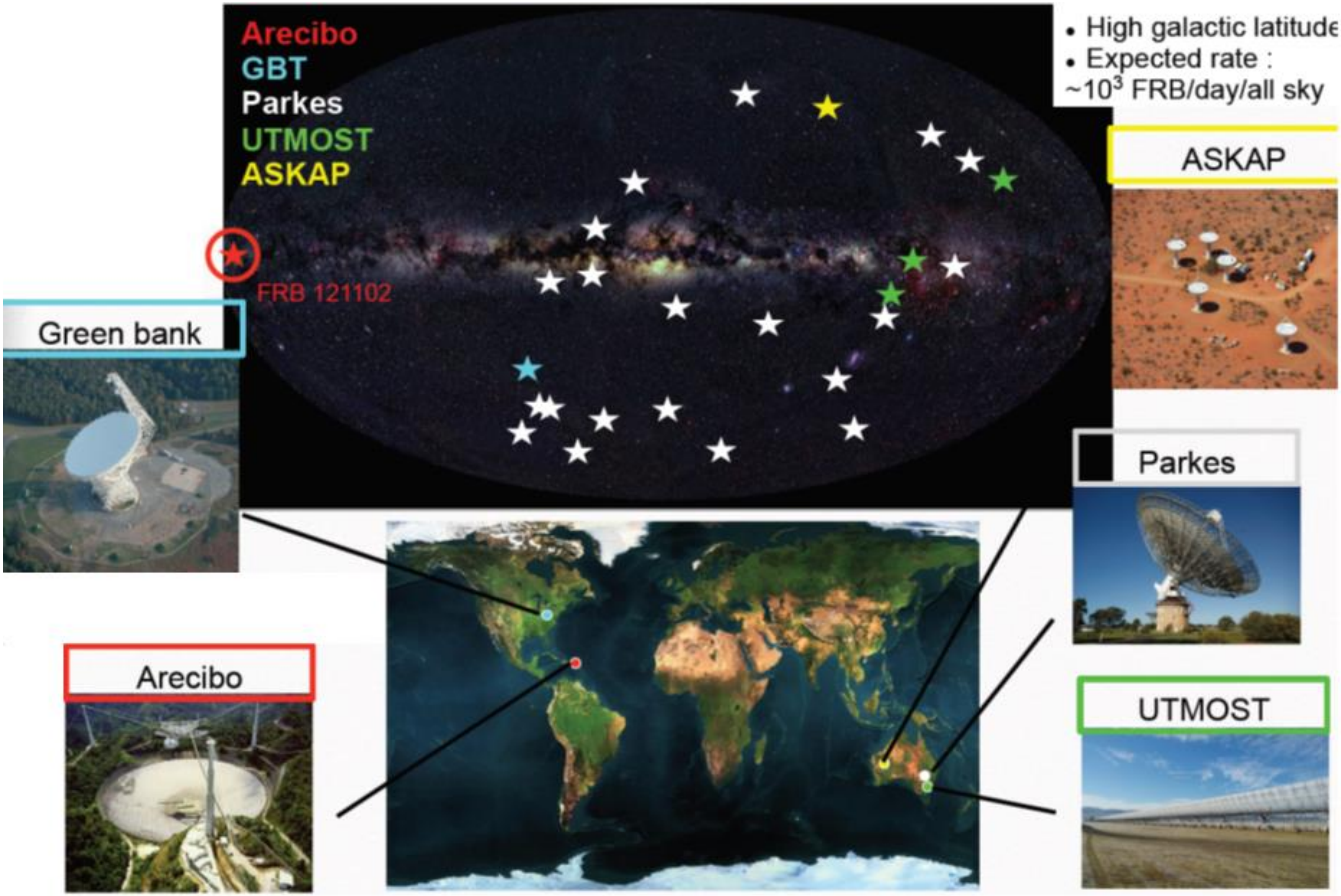
Time-dependent searches:

- GRB [Swift, Fermi, IPN]
- Micro-quasar and X-ray binaries [Fermi/LAT, Swift, RXTE]
- Gamma-ray binaries [Fermi/LAT, IACT]
- Blazars [Fermi/LAT, IACT, TANAMI…]
- Crab [Fermi/LAT]
- Supernovae Ib,c [Optical telescopes]
- Fast radio burst [radio telescopes]

ANTARES **multimessenger** and transients

Object(s)	Messenger	Telescope
Flaring Blazars	γ-rays	FERMI/LAT
Flaring X-ray binaries	X & γ-rays	Swift, MAXI, RXTE/ASM, Fermi/LAT
Flares from Mrk 421 and Mrk 501	γ-rays (TeV)	HAWC
HAWC 2-year catalog	γ-rays (TeV)	HAWC
Gamma Ray Bursts	γ-rays	Swift, Fermi, GCN
IceCube Events	**ν**	**IceCube**
UHECR	CRs	Auger, TA
Galactic Plane	**CR & γ-rays**	**Fermi, Milagro**
Fast Radio Bursts	**Radio**	**SUPERB@Parkes**
Fermi Bubbles	γ-rays	Fermi
Galactic Plane	CRs	HAWC
BH/NS mergers	**Gravitational waves + EM + γ-rays+ ν**	**Ligo/Virgo (+ IceCube and Pierre Auger Observatory)**

The FRB sky (http://www.astronomy.swin.edu.au/pulsar/frbcat/)



What FRBs are?



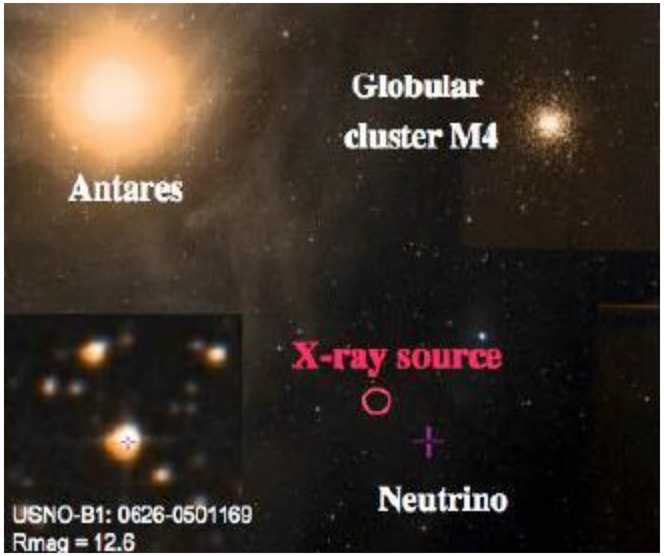
- Distance: same history of GRBs before Beppo-SAX
- Distance: dispersion measure DM*. *Cosmological distances*

  *total column density of free electrons between the observer and the source
- Identification of host Galaxy: only one case FRB121102*
  - White dwarf at z=0.19
- Repetition: only one case FRB121102, no other EM counterparts
- **Progenitors**: nearby extragalactic origin (100-200 Mpc)
  - Supergiant flares in the magnetosphere of young (<100 y) and fast (ms) rotating NS embedded in a dense environment
- **Progenitors**: cosmological origin (1-20 Gpc)
  - Massive NS's collapse: magnetic blast wave, shock front within the SNR.
  - Merger: Magnetic reconnection between the two merging magnetospheres.
  - Magnetar: flares in the magnetosphere of a magnetar (associated to SGR).
- Neutrino production mechanism?

A particular event: ANT150901

Alert **VHE (Sept. 1, 2015)**
E ~ 50-100 TeV
RA=246.306°; dec=-27.468°
Uncertainty: ~18 arcmin (radius, 50%)

Sent after 10 s to MASTER, Swift-XRT
Follow-up with **Swift-XRT after 9h**
Follow-up with **MASTER after 10h**



Multifrequency observations:
16 ATEL + 6 GCN

- Neutrinos
  - IceCube: ATel 8097
- Optical
  - Pan-STARRS: ATel 7992, 8027
  - SALT: ATel 7993
  - NOT: ATel 7994 GCN18236
  - WiFeS: ATel 7996
  - CAHA: ATel 7998, GCN18241
  - MASTER: ATel 8000 GCN18240
  - LSGT: ATel 8002
  - NIC: ATel 8006
  - ANU: GCN18242
  - GCM: GCN18239
  - VLT/X-shooter
- X-rays
  - Integral: ATel 7995
  - MAXI: ATel 8003
  - Swift: ATel 8124, GCN18231
- Radio
  - Jansky VLA: ATel 7999, 8034
- Gamma-rays
  - MAGIC: ATel 8203
  - Fermi-GBM: GCN18352
  - HAWC
  - HESS

GCN CIRCULAR NUMBER: 18236
(Optical + NIR spectroscopy from NOT)
..All this points to USNO-B1.0 0626-0501169 being a young accreting G-K star, undergoing a flaring episode that produced the X-ray emission. We also note that this object is close to the nearby Rho Ophiuchi star forming region, being probably associated with it.

Binary NS Mergers and HEN?

- Prompt neutrino production on-axis
- Off-axis scenario, neutrino-production related to the extended γ-ray emission (Kimura et al. 2017).
- (Later) Extended emission from a relativistic wind with its rotational energy, (Fang&Metzger. ApJ 2017).

GW170817

ν ?

ApJL 850:L35 (2017)

(multimessenger): ApJL 848 L12 (2017)