Neutrino telescopes in the Mediterranean Sea: the present, the future

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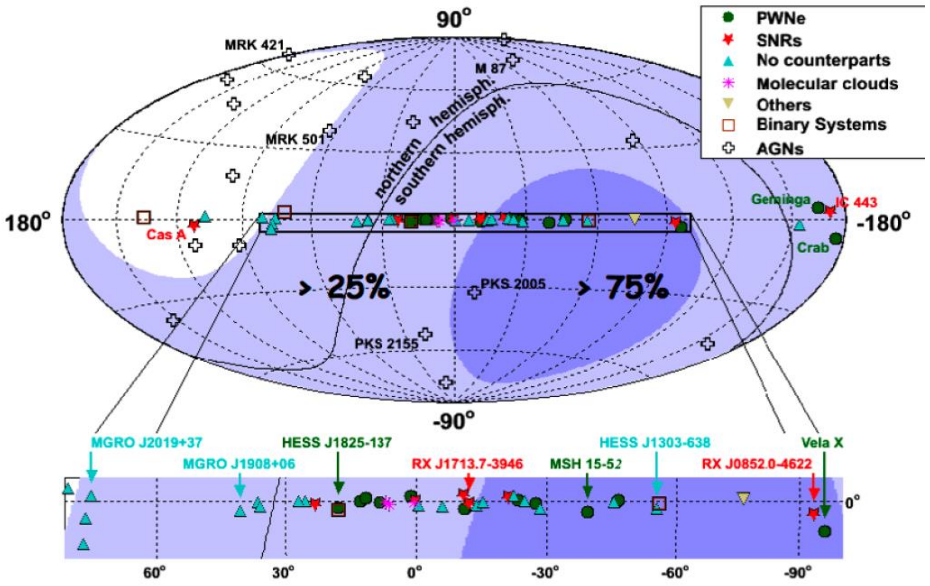
Neutrino telescopes in the Mediterranean sea

- Very high **duty cycle** (~100%)
- Large observation **solid angle** (2π upgoing events, 4π in fiducial volume)
- Telescopes in water optimized for E_ν<100 TeV
- ν's not significantly absorbed by the Earth for E_ν<100 TeV



- **Upgoing events**: O(0.1°) **angular resolution** for tracks; O(3°) for showers)
- **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, but detectors need for positioning calibrations due to sea currents **(offline analysis**)

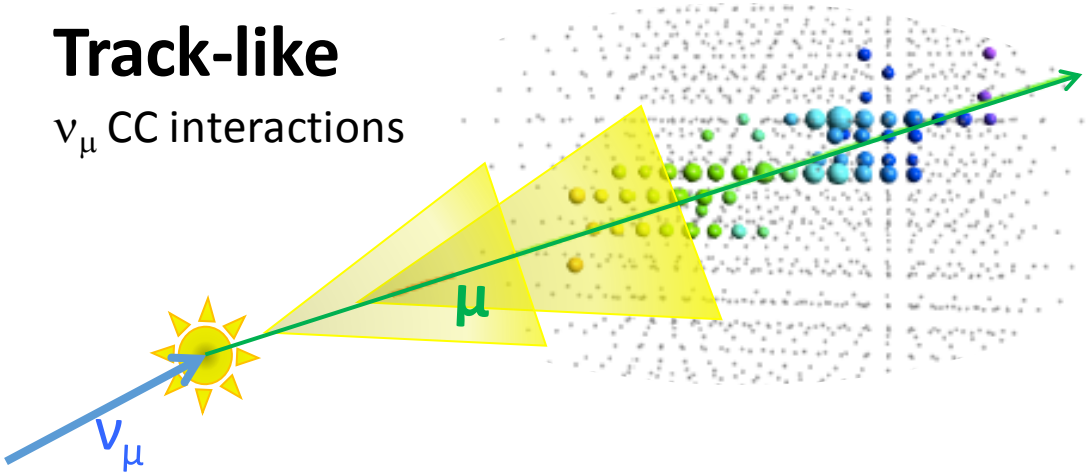
Two topology (track/showers) of events

Detection principle: Optical Cherenkov radiation

- 6 order of magnitude in energy (GeV-PeV)
- All flavour detection

Track-like

ν_μ CC interactions

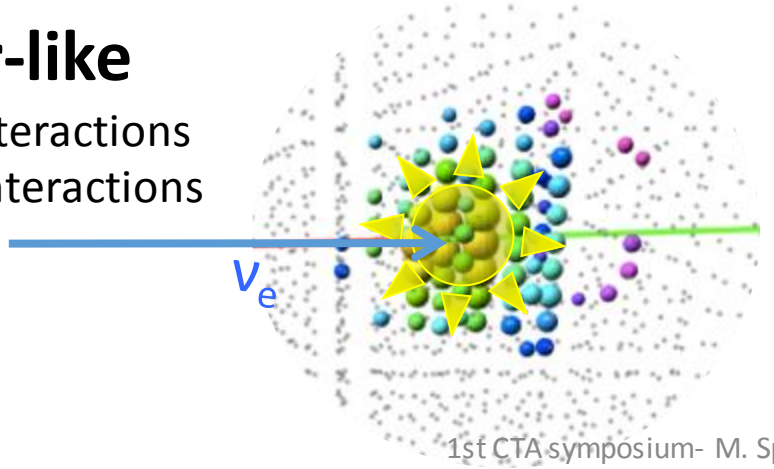


Angular resolution:
~0.1° (full, E>10 TeV)

Energy resolution:
<0.5 (log E_μ)

Shower-like

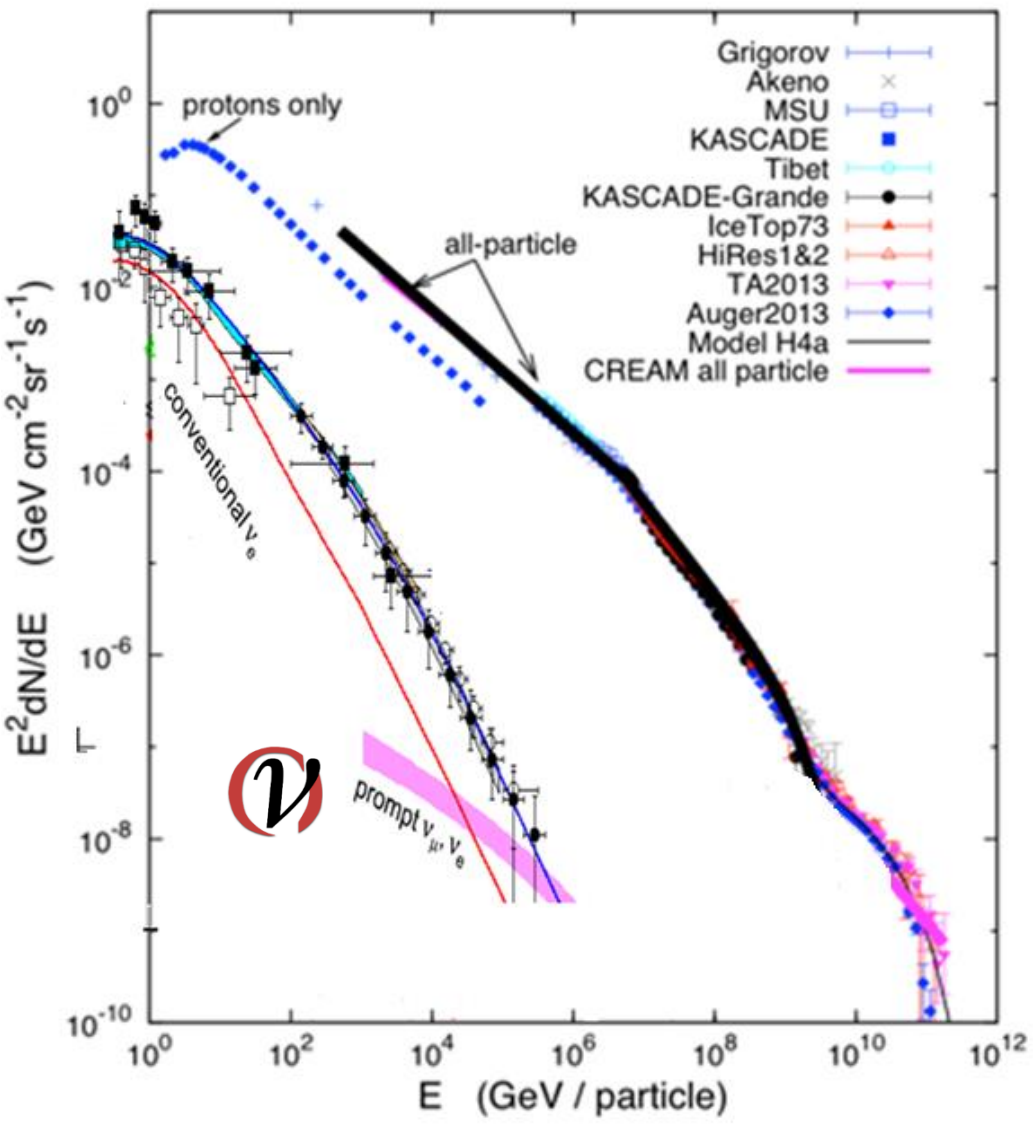
ν_e , ν_τ CC interactions
ν_X NC interactions



Angular resolution:
~3° (full, E>10 TeV)

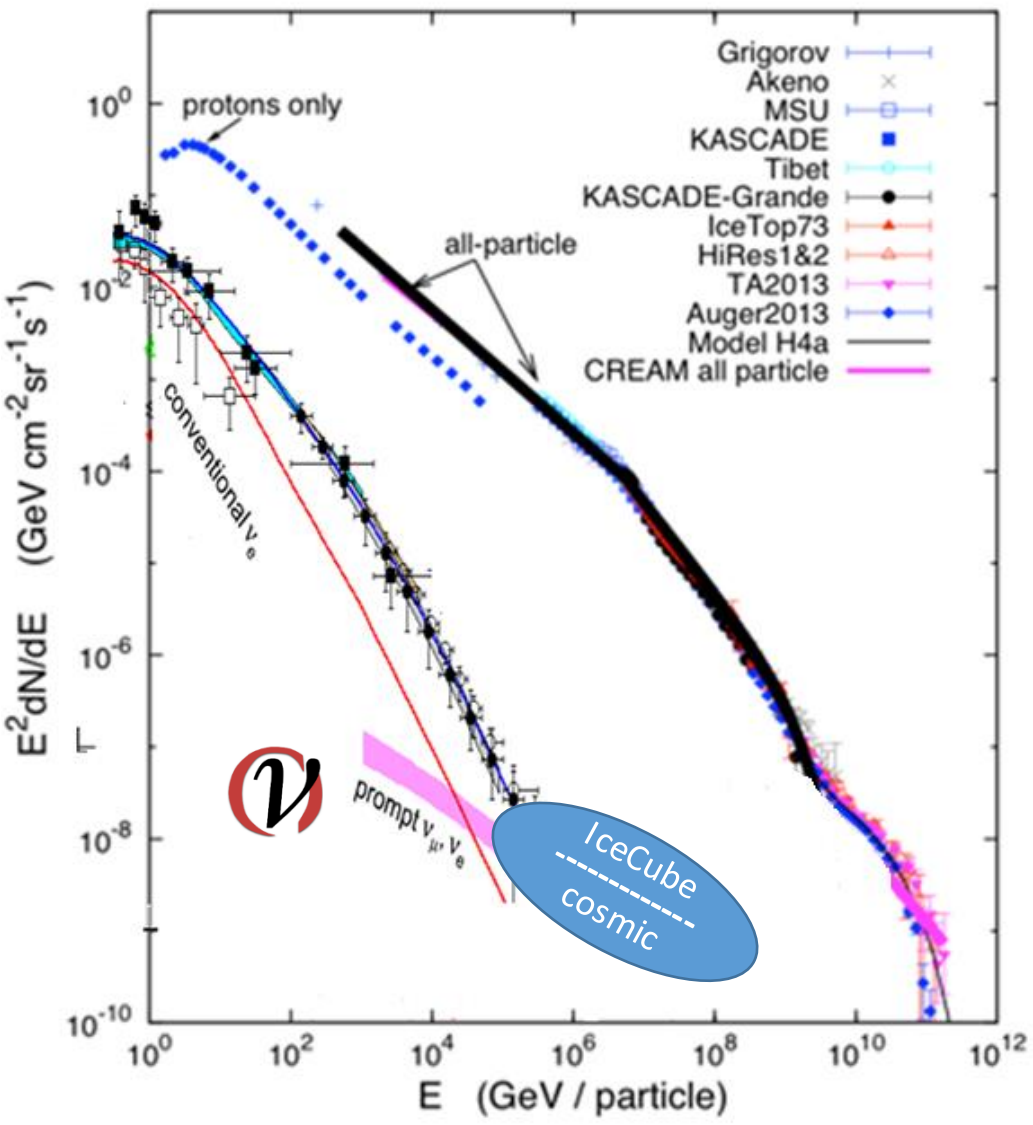
Energy resolution:
(E_ν) ~25%

Open questions for neutrino astrophysics



- Neutrino: fundamental probe to identify galactic and extragalactic CR sources
- **Origin** of IceCube HE astrophysical neutrinos
- **Production sites** 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
- **Galactic "TeV-PeVatrons": necessary a ν telescope in the Northern hemisphere**

Open questions for neutrino astrophysics



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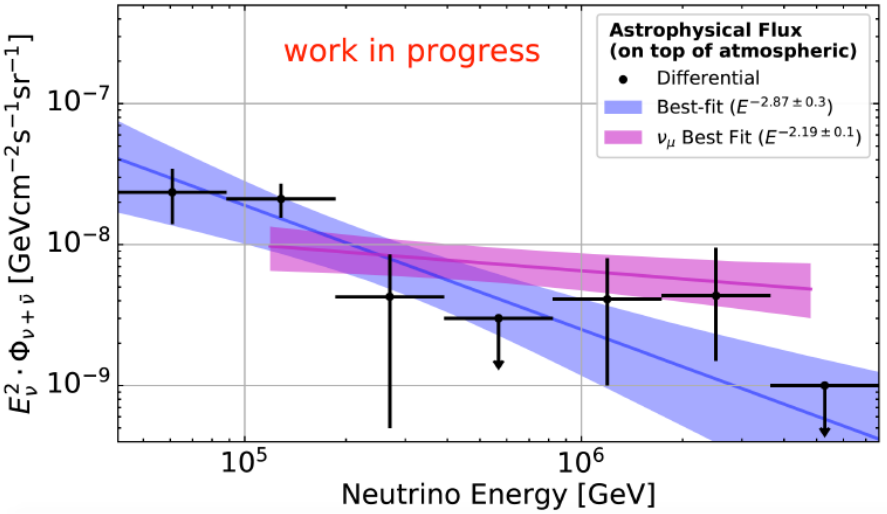
Detecting **cosmic** neutrinos: a threefold way

1. Excess of HE neutrinos over the background of atmospheric events. Estimate of the **neutrino energy (shower-dominated).**
   Mediterranean telescopes can confirm the diffuse flux



2. Coincident event in a restricted time/direction windows with EM/γ/GW counterparts. Relaxed energy/direction measurement + **transient/ multimessenger** information.
   Mediterranean telescopes: real complementarity w.r.t. IceCube

3. Point-like events, excess in the sky map. Rely on the precision of the **neutrino direction (track-dominated)** and background suppression.
   Mediterranean telescopes have unsurpassable sensitivity for Galactic sources for E_ν<100 TeV and part of the Southern sky

70 m

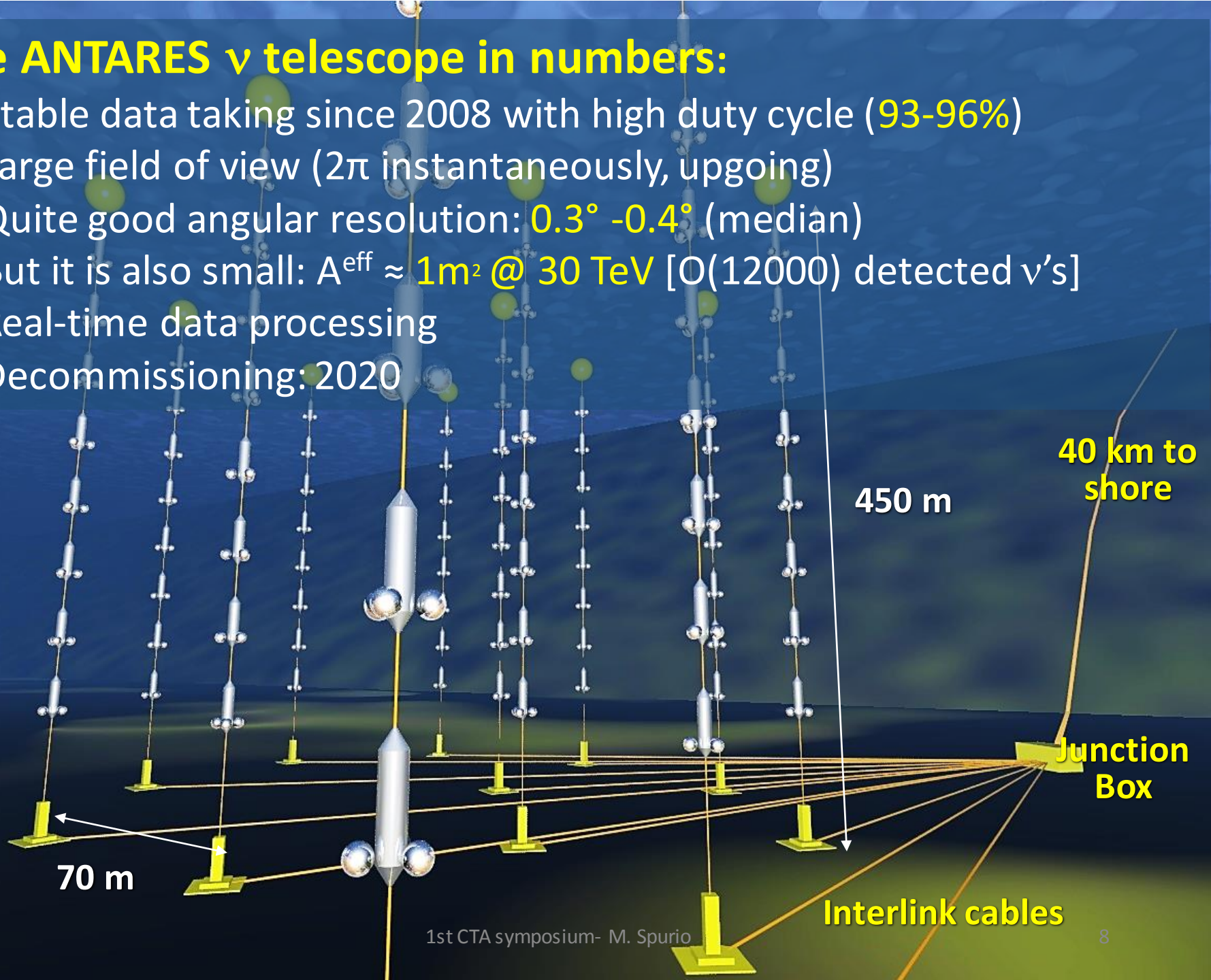
2500m

Junction Box

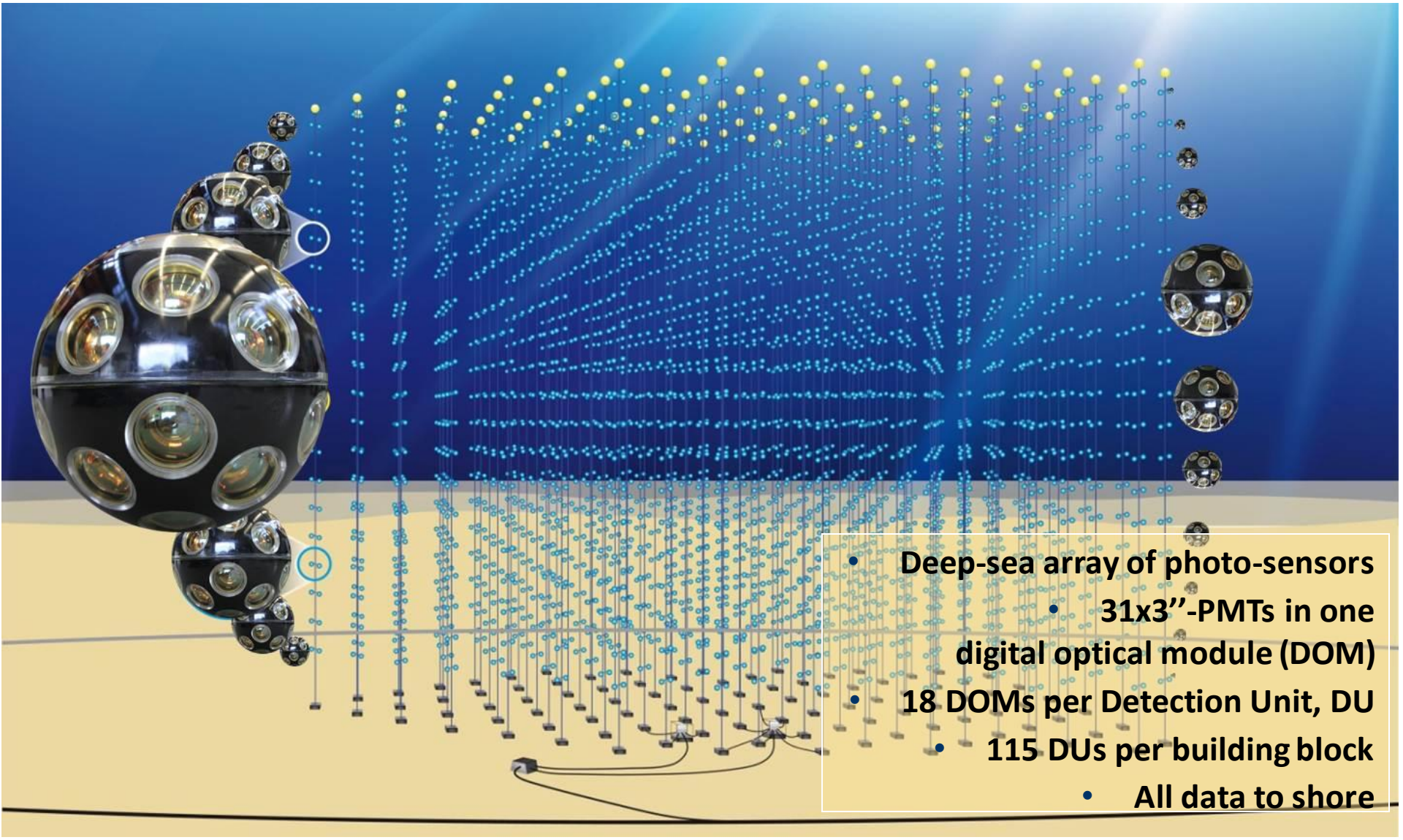
Interlink cables

The ANTARES ν telescope 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: $A^{eff} \approx 1 m^2$ @ 30 TeV [O(12000) detected ν's]
- Real-time data processing
- Decommissioning: 2020



The future: KM3NeT



- Deep-sea array of photo-sensors
- 31x3’’-PMTs in one digital optical module (DOM)
- 18 DOMs per Detection Unit, DU
- 115 DUs per building block
- All data to shore

The future: KM3NeT

- **KM3NeT** is the neutrino research infrastructure in the deep Mediterranean Sea
  - Study of high neutrino sources in the Universe

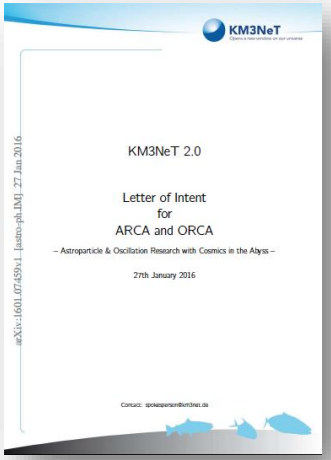
  ARCA (off shore Capo Passero, It @ 3500 m depth)
  - Determine neutrino mass hierarchy

  ORCA (off shore Toulon, Fr @2500 m depth)
- Same collaboration, same technology, two installation sites
  - 15 Countries
  - 55 Institutes
  - >240 Scientists
  - Number of Institutes and

  Scientists constantly increasing
- Here, ARCA (Astrophysics) features presented

KM3NeT: A Phased Approach

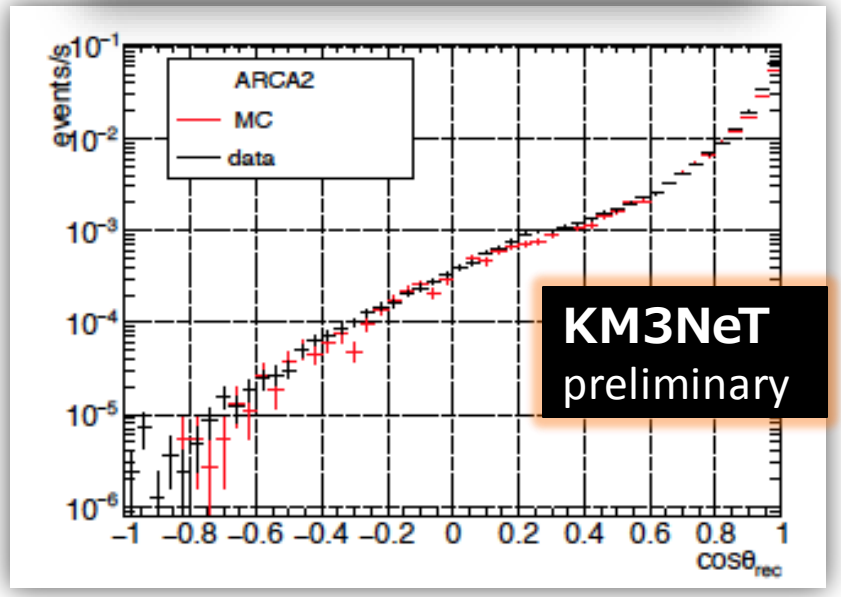
PHASE	BLOCKS	PRIMARY DELIVERABLES	FUNDS
1	0.2	Proof of feasibility and first science results **24 ARCA strings** + 6 ORCA	Fully funded
2	2+1	All flavor neutrino physics and astronomy **2 x 115 ARCA strings** 1 x 115 ORCA strings	Funding in progress
3	6	Neutrino astronomy including Galactic sources	Not yet



- **KM3NeT** LoI: *J. Phys. G*, **43** (2016) 084001
- H2020: funds to prepare the ERIC
- Since 2016 (2018) **KM3NeT** is back in the ESFRI (APPEC) roadmap
- The process to build the **KM3NeT** ERIC is in progress

The Detection Units (DUs)

DOM



- **18 DOM** in one DU string
- Strings arranged on the LOM, ready for deployment

ANTARES – Diffuse flux (ApJL 853, L7 (2018)

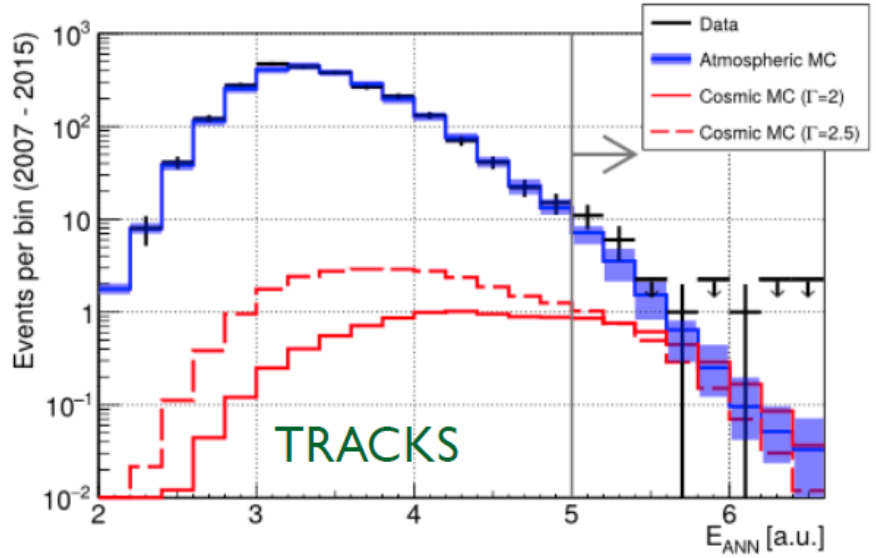
Sample:
- 2007 – 2015; livetime 2450 days
- All-flavour analysis (track+showers)

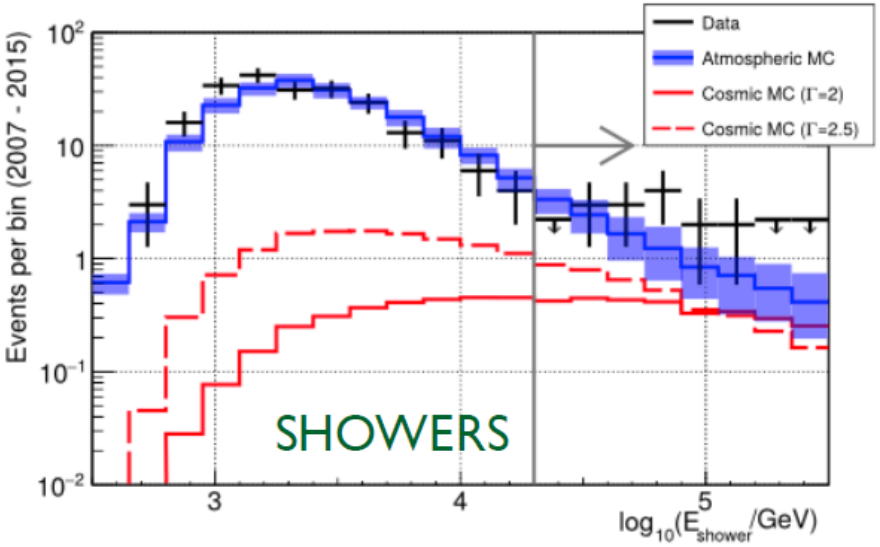
Event selection chain + energy-related cut applied to
- obtain a high-purity neutrino sample
- maximize sensitivity

Signal modeled according to the IceCube flux

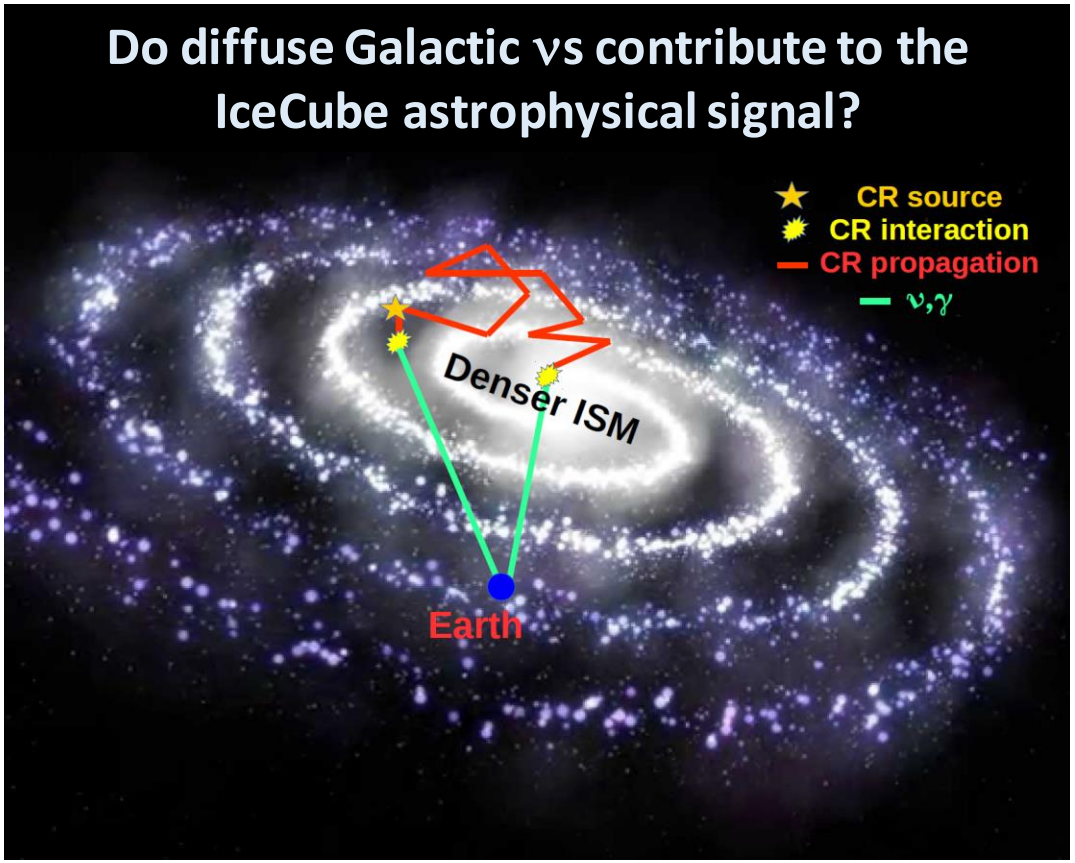
Result:
33 events (19 tracks + 14 showers) in data
24 ±7 (stat.+syst.) events background in MC

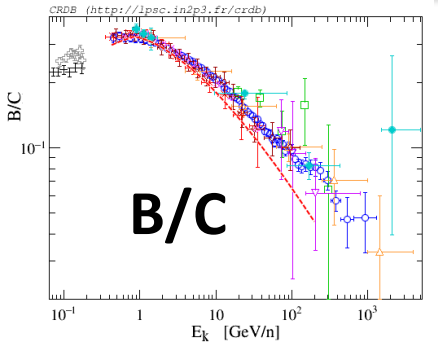
1.6σ excess, null cosmic rejected at 85% CL

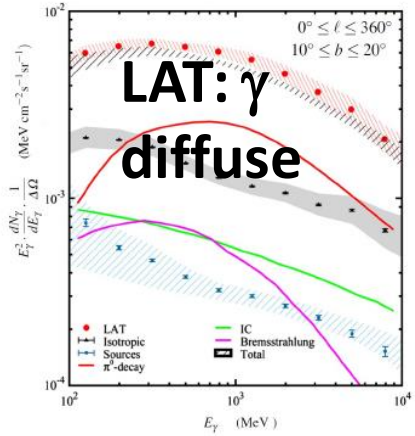


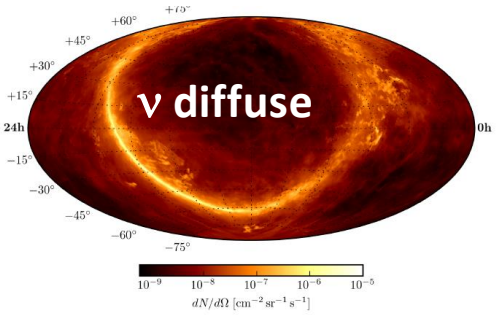


CR propagation in the Milky Way: γ and ν.







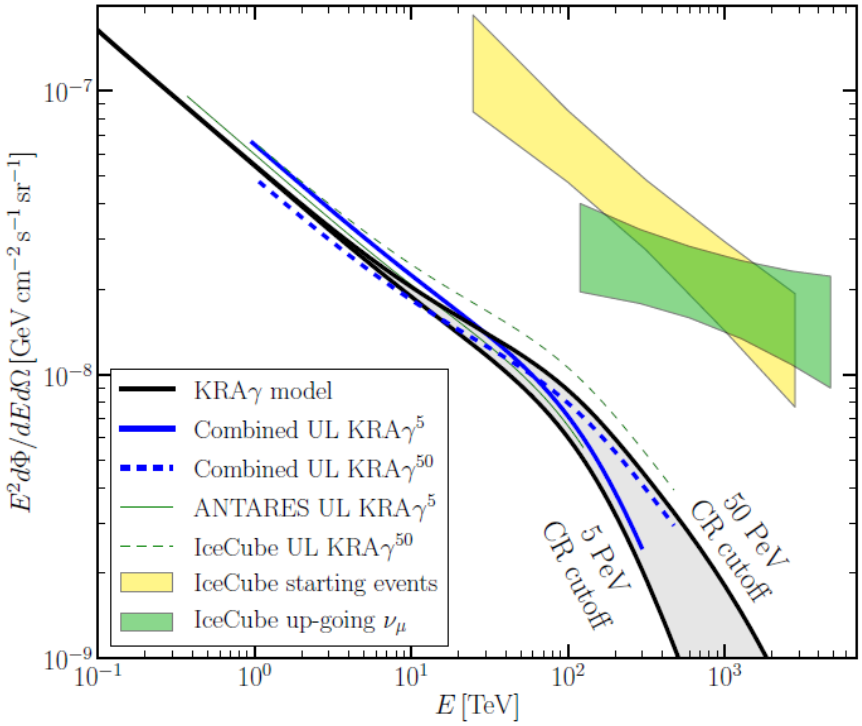


- Neutrinos allow testing **CRs propagation**
- Dense matter regions boost γ and ν fluxes
- Models can be tuned to γ and CR observations
- Northern Hemisphere optimal point of view for galactic CR

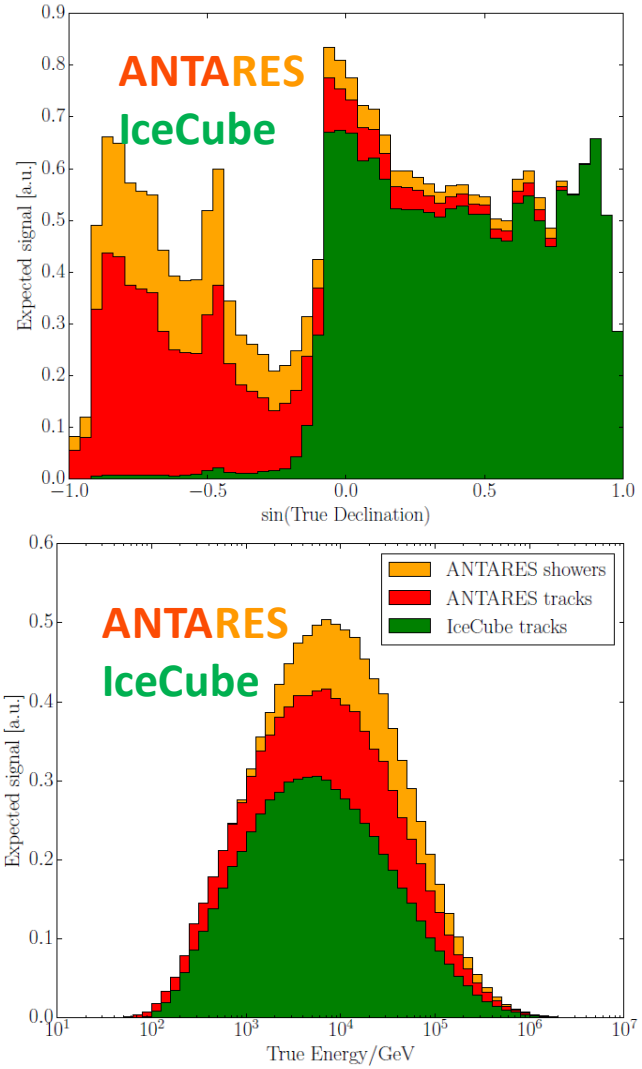
ANTARES+ IceCube

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

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

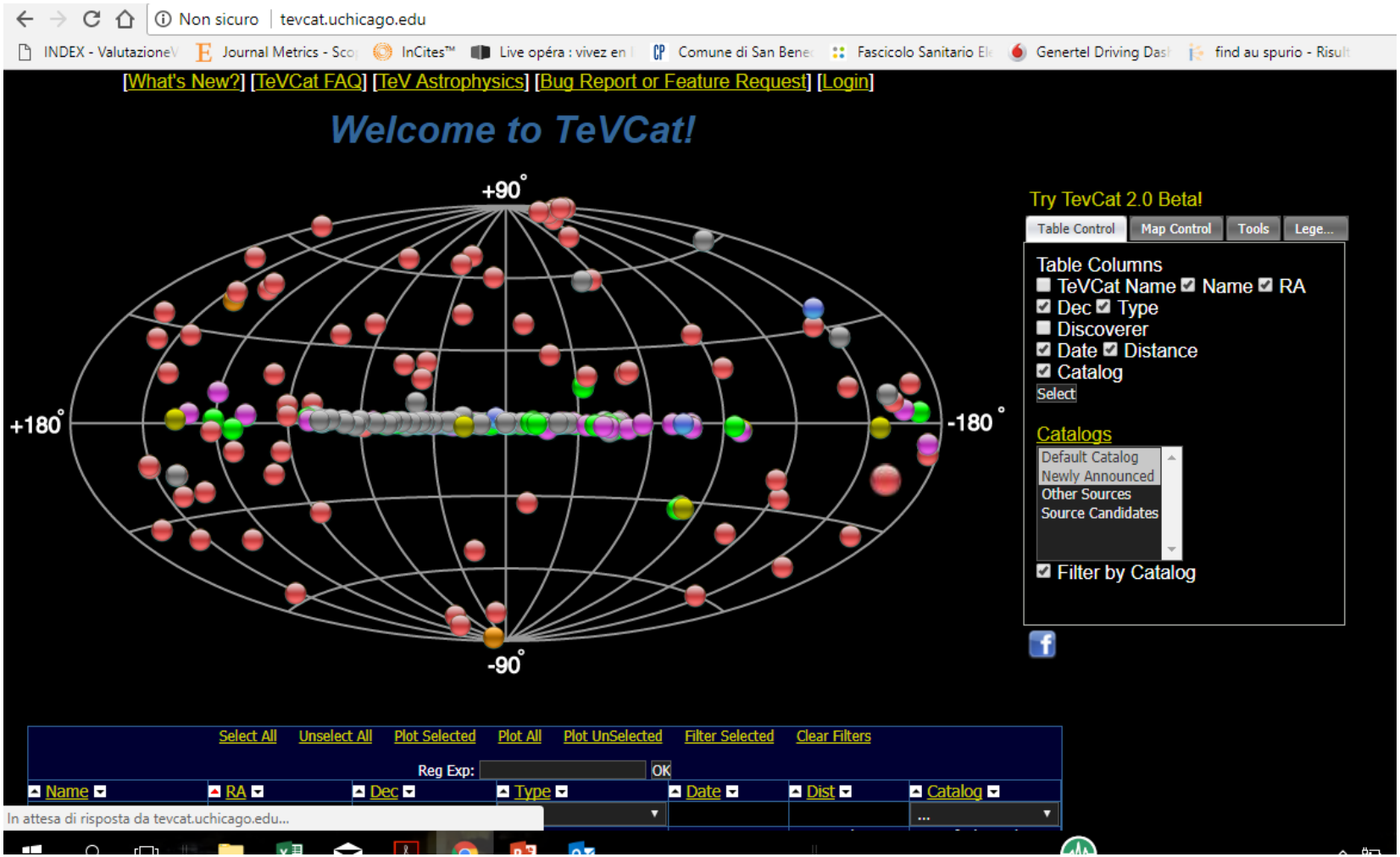


Stacked expected signal vs. δ (top) and energy (bottom). Colors represents the relative contribution to the sensitivity



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)].*

Why we do not have a “neutrino map”?



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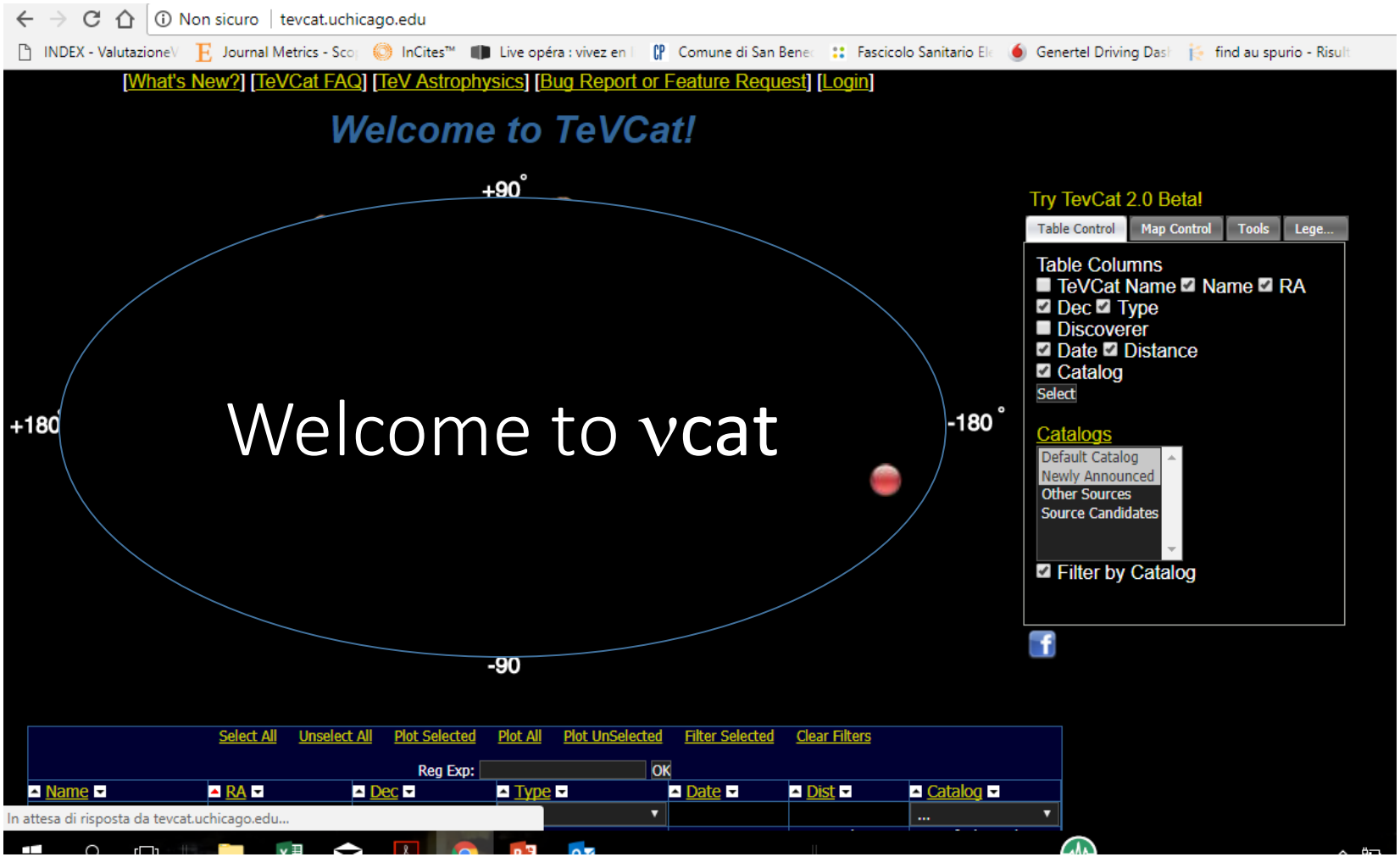
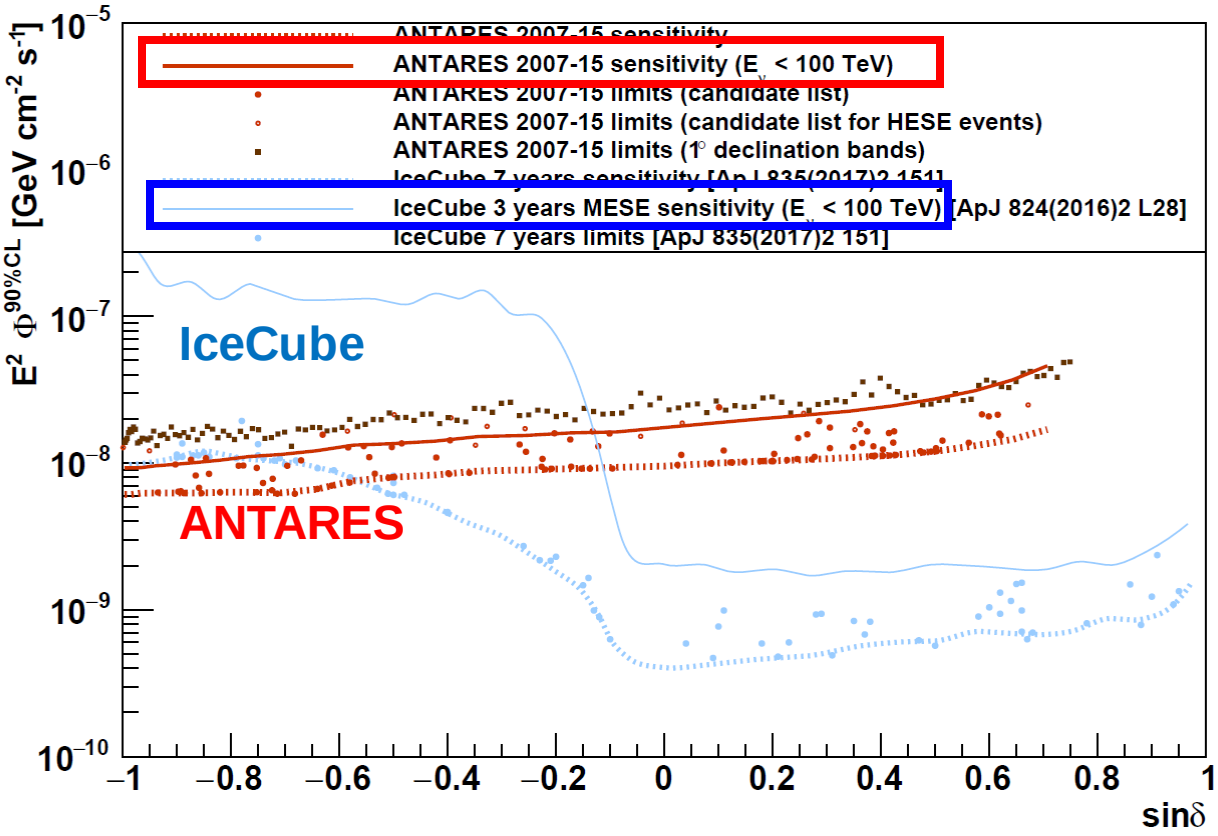


Limits and sensitivities

PRD96 (2017) 082001

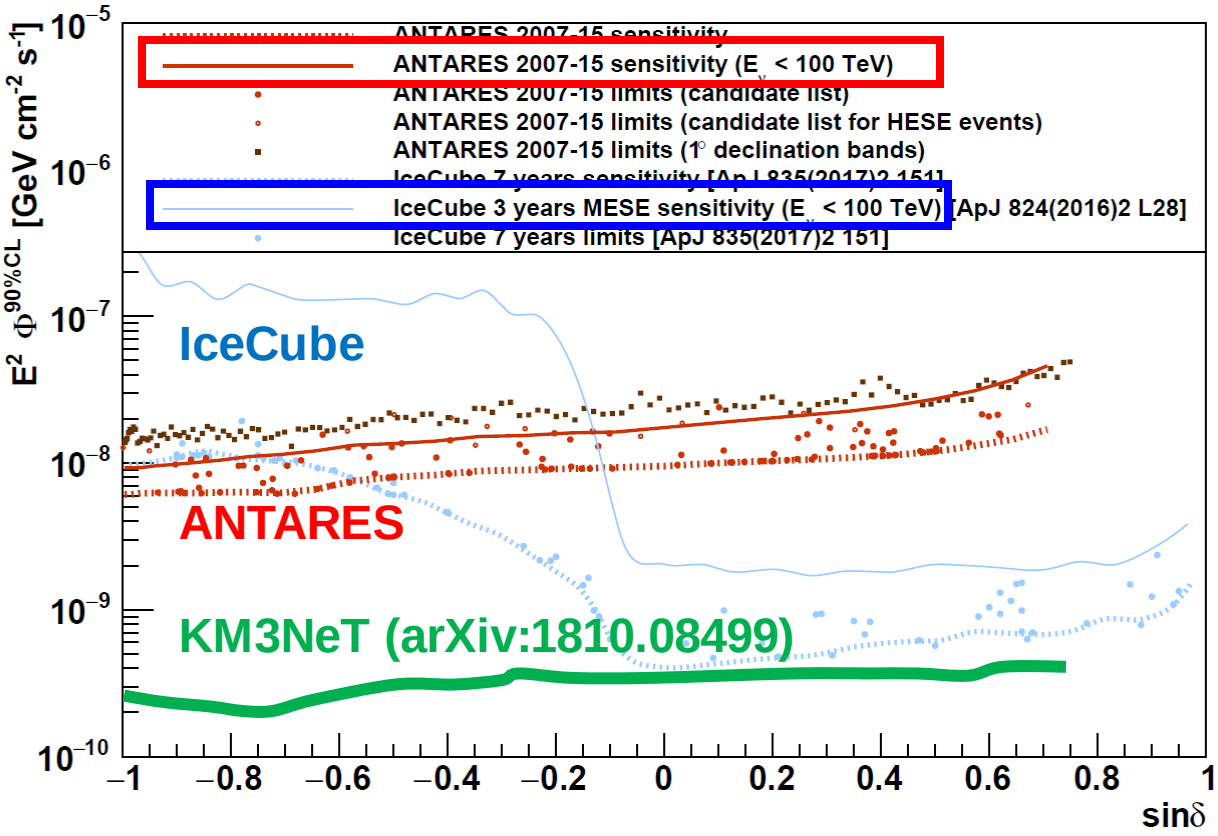


Note: these plots depend on the

- assumed **spectral index** of the source (here, α=2.0 is assumed)
- differential **energy sensibility** of the detector

Limits and sensitivities

PRD96 (2017) 082001



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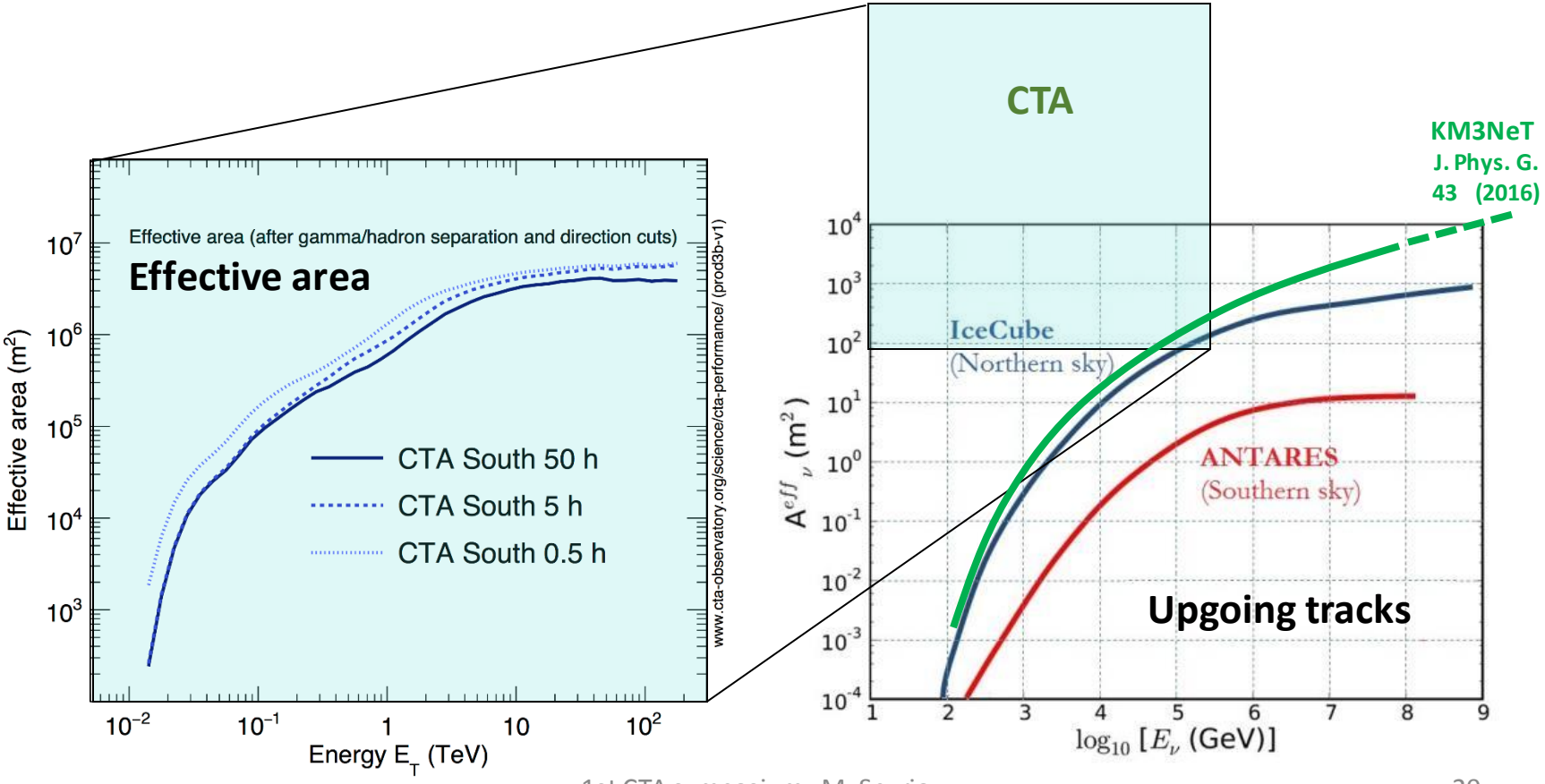
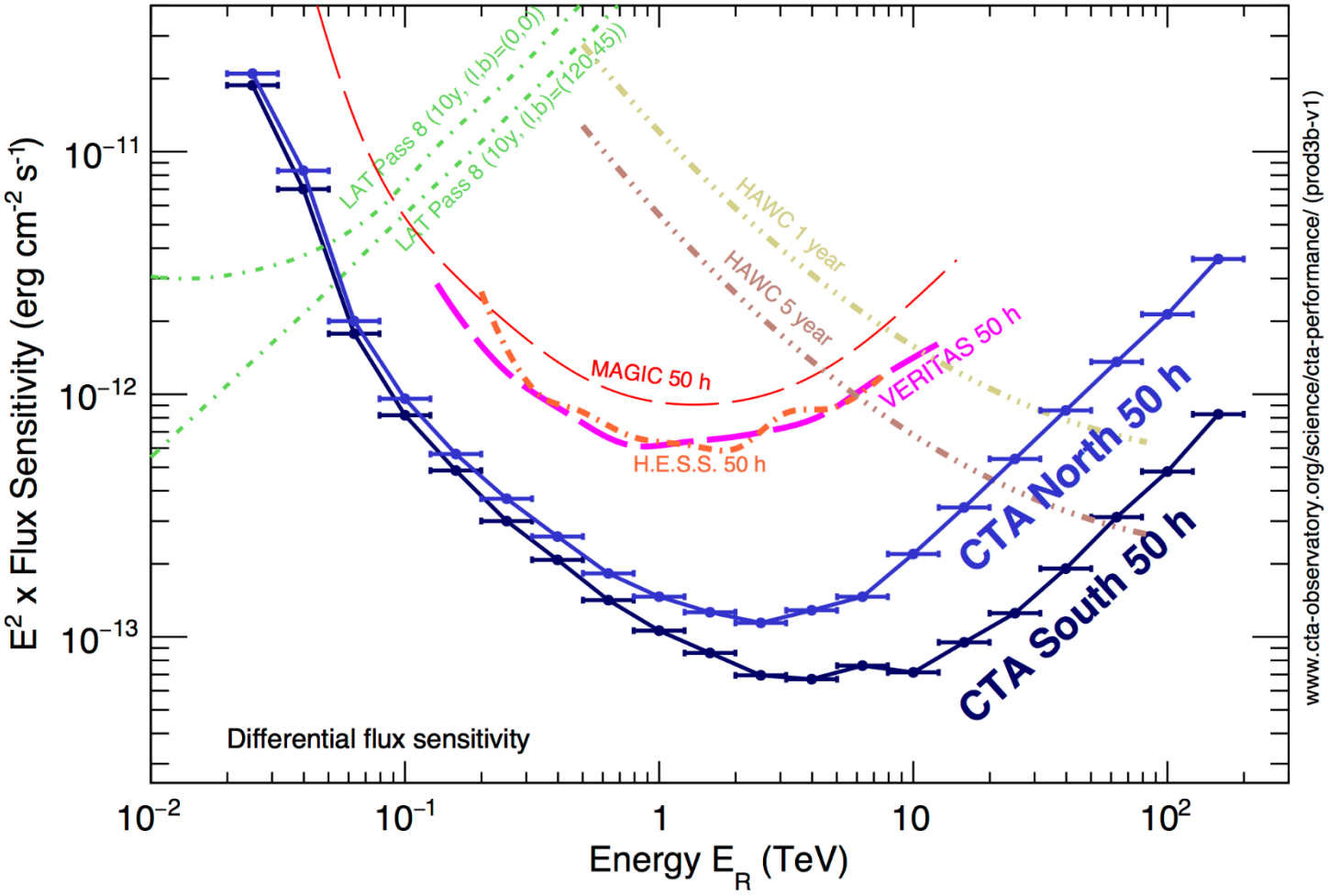
Detecting ν: effective area + angular resolution

- **2π of the sky**: upgoing neutrinos**, almost 100% duty cycle;**
- **4π of the sky:** including semi-contained events, better energy determination
- **Effective area A^{eff}**= *function*[(t,s); ν energy; analysis cuts;δ]
- **Angular resolution**: O(0.1°) for upgoing tracks

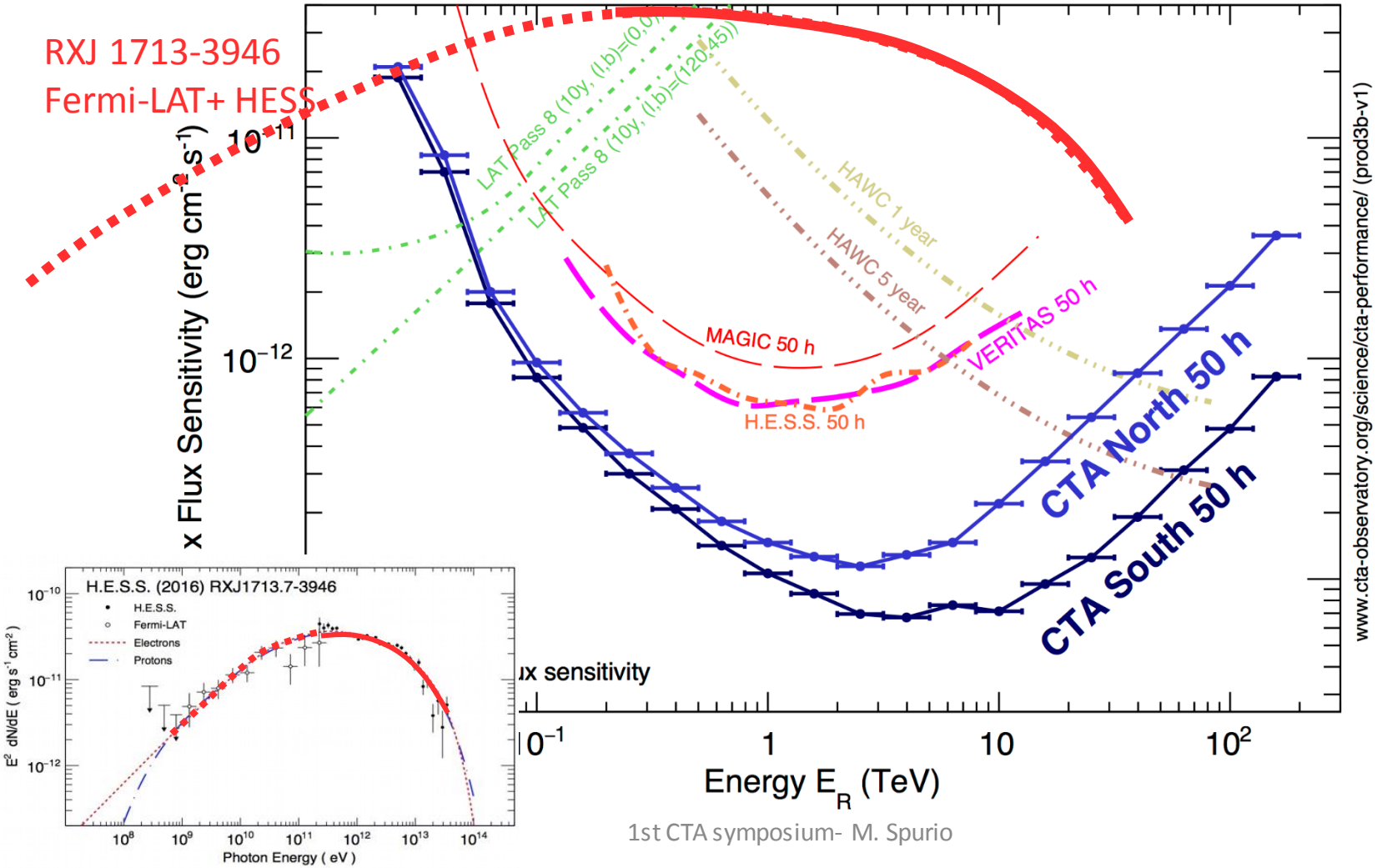


Differential sensitivities: CTA and Neutrinos



Differential sensitivities: CTA and Neutrinos

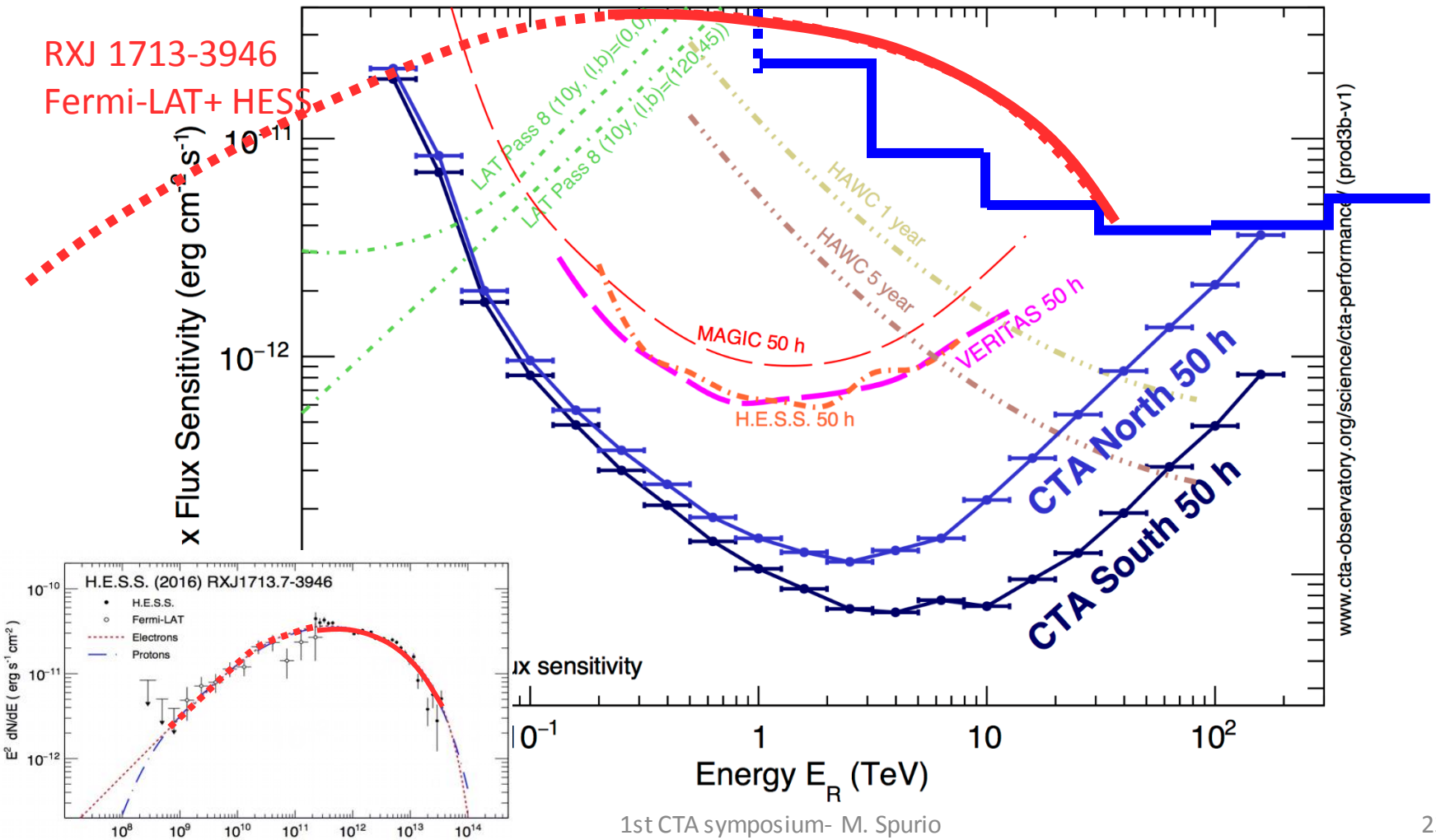
RXJ 1713-3946
Fermi-LAT+ HESS



Differential sensitivities: CTA and Neutrinos

$\frac{1}{10}$ ×ANTARES 5σ discovery potential (3y)

RXJ 1713-3946
Fermi-LAT+ HESS

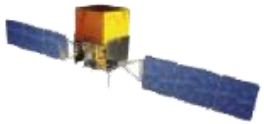


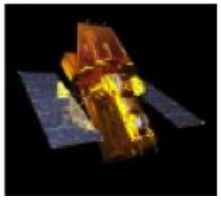
ANTARES: Multi-messenger

APP35 (2012)530
JCAP02(2016)062

* participation to AMON Astrophysical Multimessenger Observatory Network

Gamma-ray Coordinates Network (GCN) https://gcn.gsfc.nasa.gov/




neutrinos
IceCube, GVD, SNEWS

GeV-TeV γ-rays
Fermi, HESS, HAWC, CTA

UHECR
Auger, TA

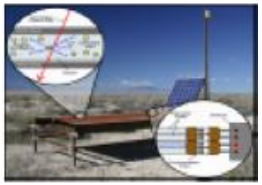
only spatial coincidence

ANTARES

Receive alerts
Generate alerts

Radio/Optic /X-ray
TAROT, MASTER, Swift, INTEGRAL, MWA

Gravitational Waves
VIRGO, LIGO

ANTARES neutrino alerts

JCAP 02 (2016) 062

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

ANTARES real time alerts:

- **Time to send an alert: ~5 s**
- **Track median angular resolution: 0.5°**
- 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)

277 to robotic telescopes
+15 to Swift
+8 to INTEGRAL
+22 to MWA (radio)
+2 to HESS

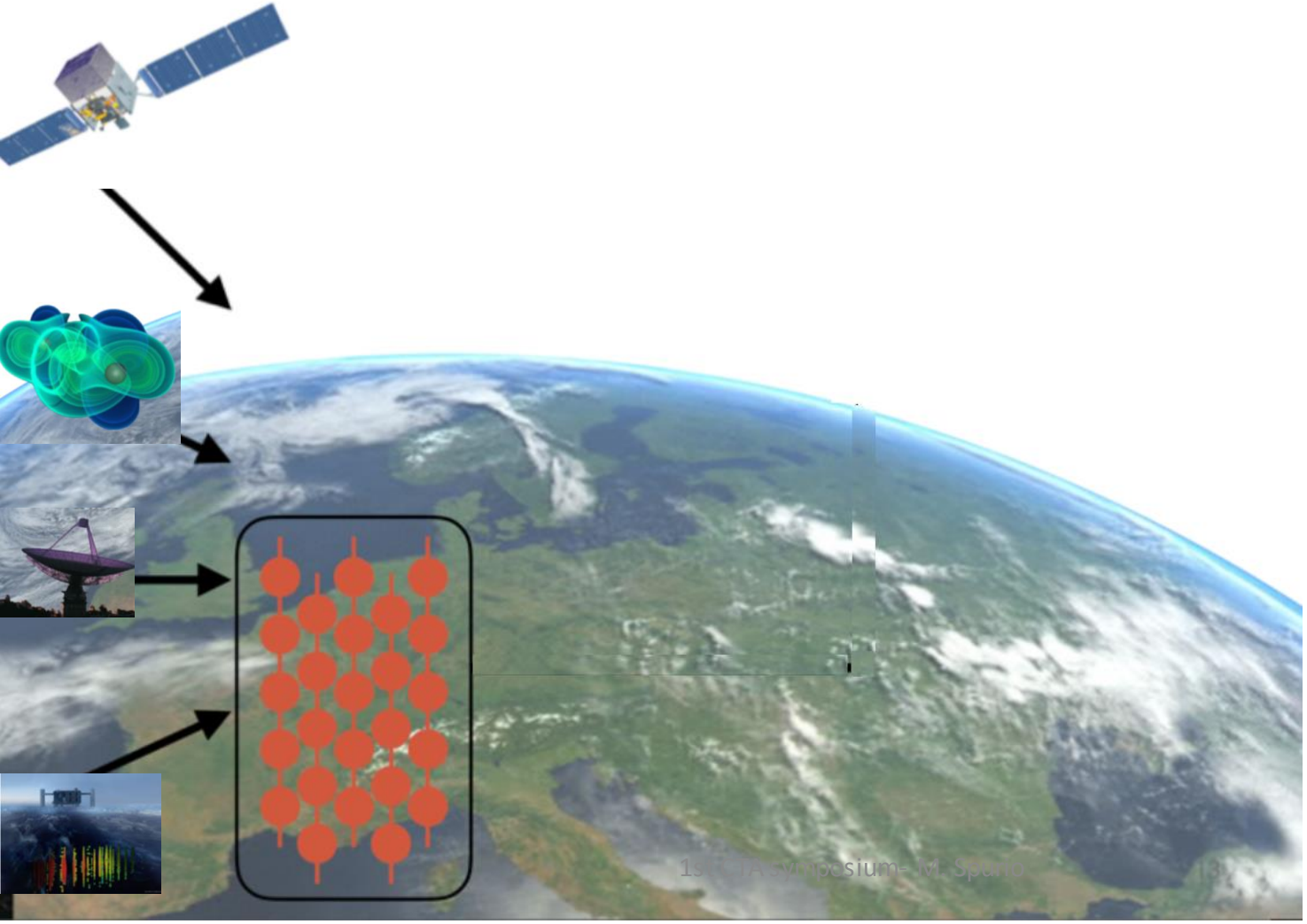
Croft S. et al, ApJ 820 (2016) 24

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)**

KM3NeT online alert system

ANTARES Performances: Online, no calibrated, reconstruction within 5 s, median angular resolution 0.4^{o}.



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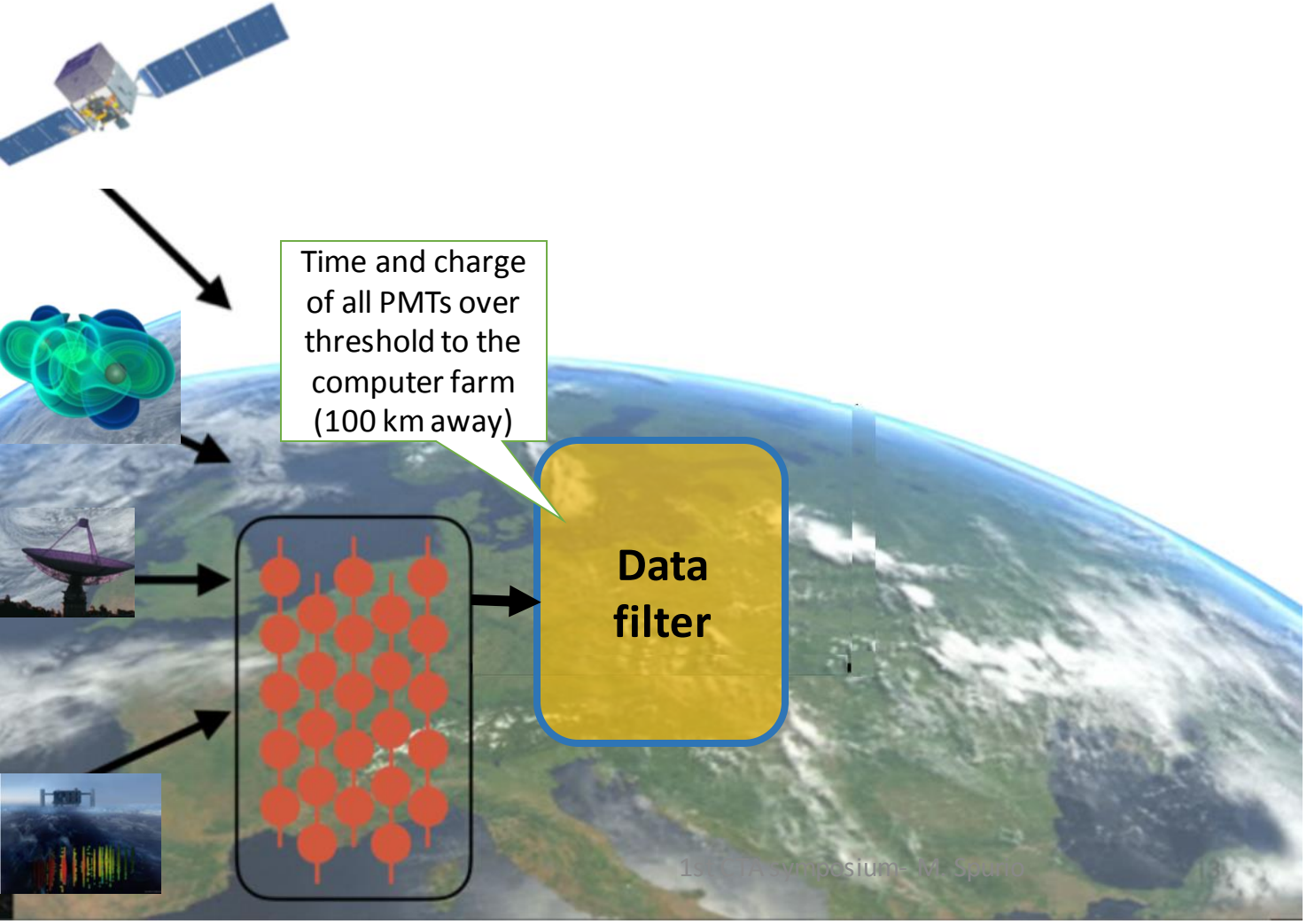

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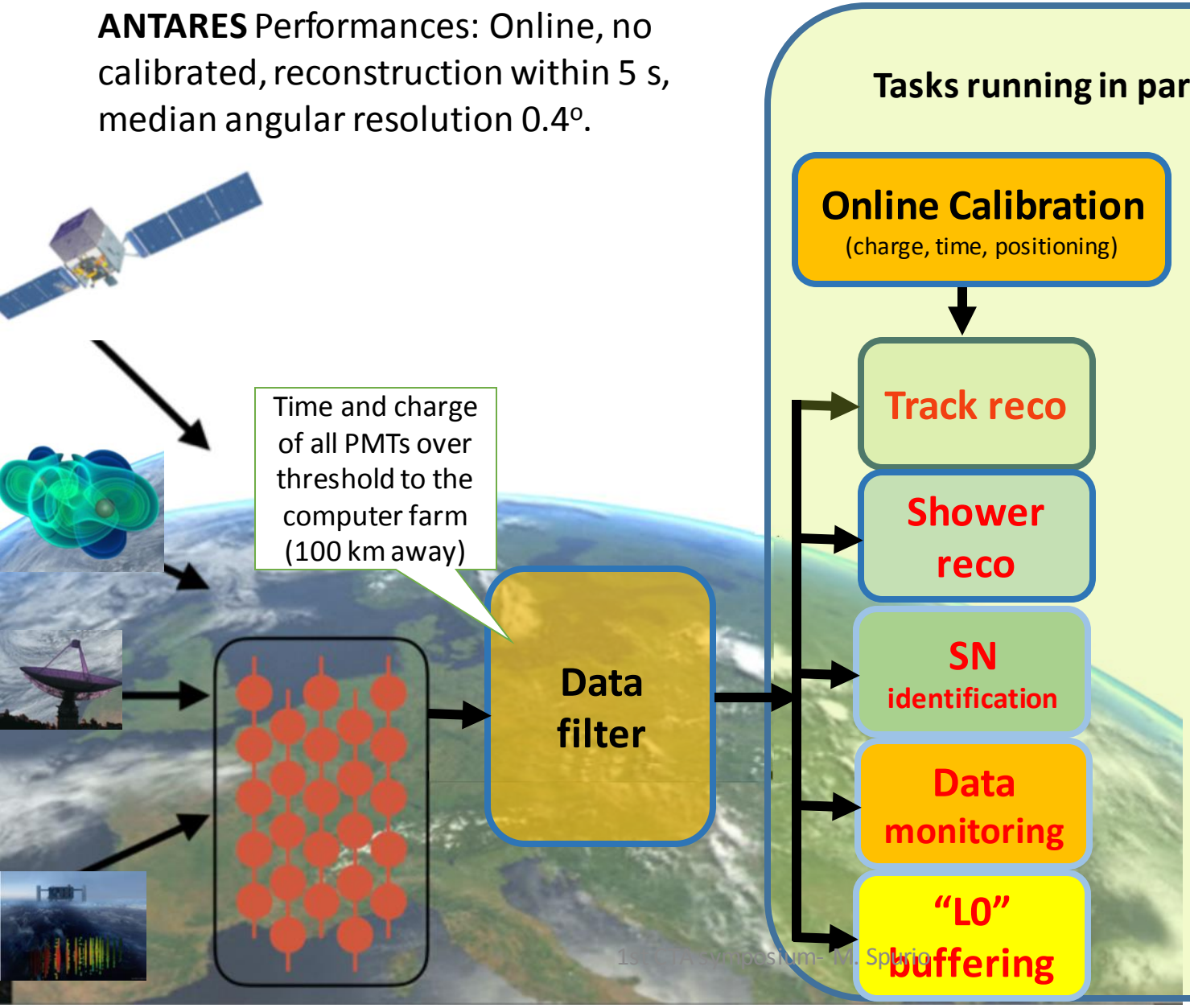

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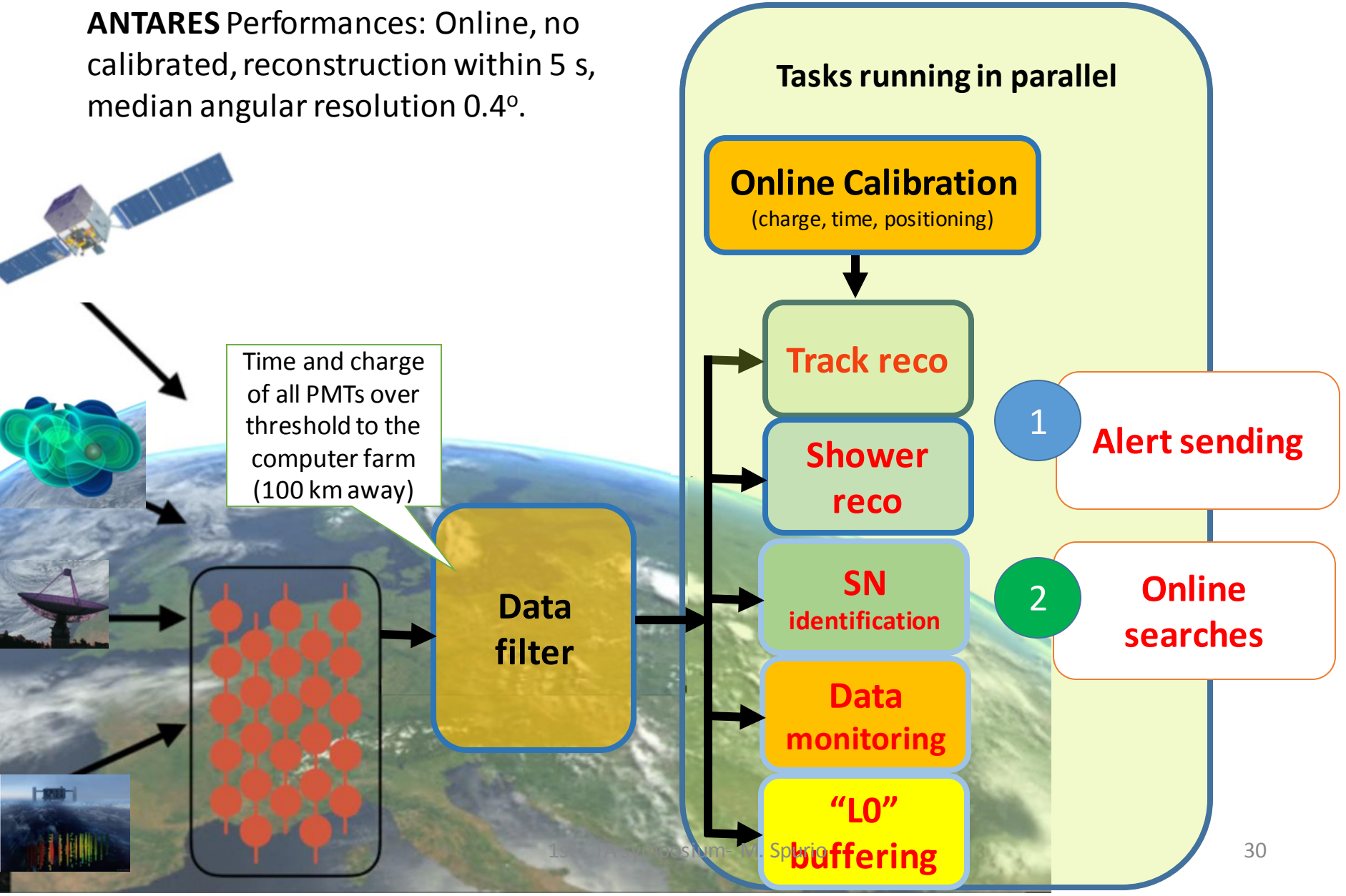

Summary and Perspectives

- ν astronomy is on its way to increased sensitivity and full sky coverage
- ν are an indispensable ingredient of multi-messenger astronomy
- ν telescopes: opportunities for precision measurements in ν physics
- ANTARES: more than 10 years of continuous data taking!
- ANTARES data taking continues up to the end of GW O3
  - then, pass the baton to KM3NeT
- ANTARES results from various searches of astrophysical ν emission.
  - (point-like, diffuse, extended regions, dark matter, …)
- ANTARES active multi-messenger program:
  - Neutrino alerts distribution, participation to GCN and AMON
  - External alerts reception, prompt analysis
  - Offline multi-messenger analysis.
  - Combined analyses with IceCube (point sources, galactic plane, …).
- Best practice and multi-messenger collaborations ported to KM3NeT!

KM3NeT- DU deployment