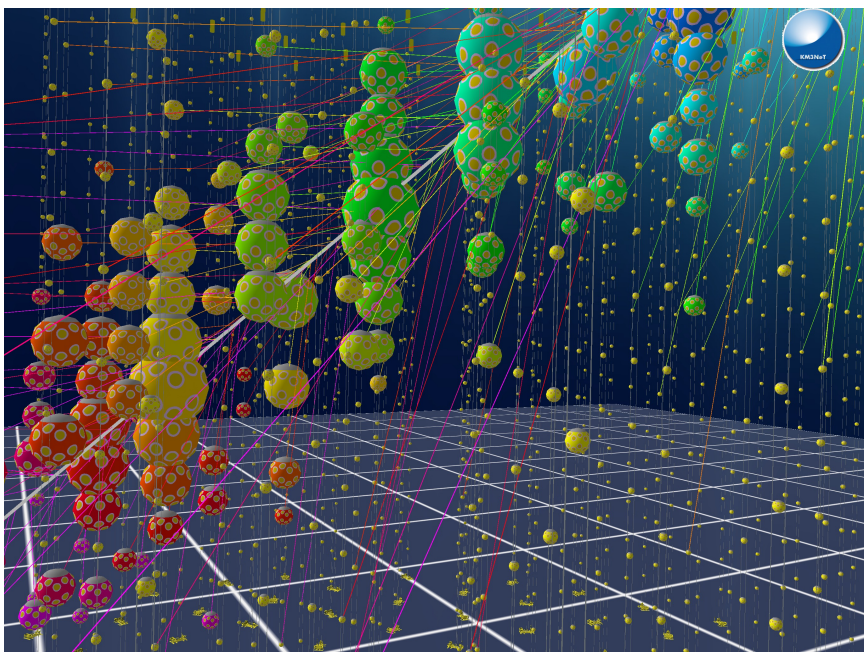
High Energy Neutrino Telescopes

&

Multi-Messenger Astronomy with IceCube and ANTARES

Thierry PRADIER

Université de Strasbourg & IPHC/DRS (IN2P3) - Strasbourg (France)



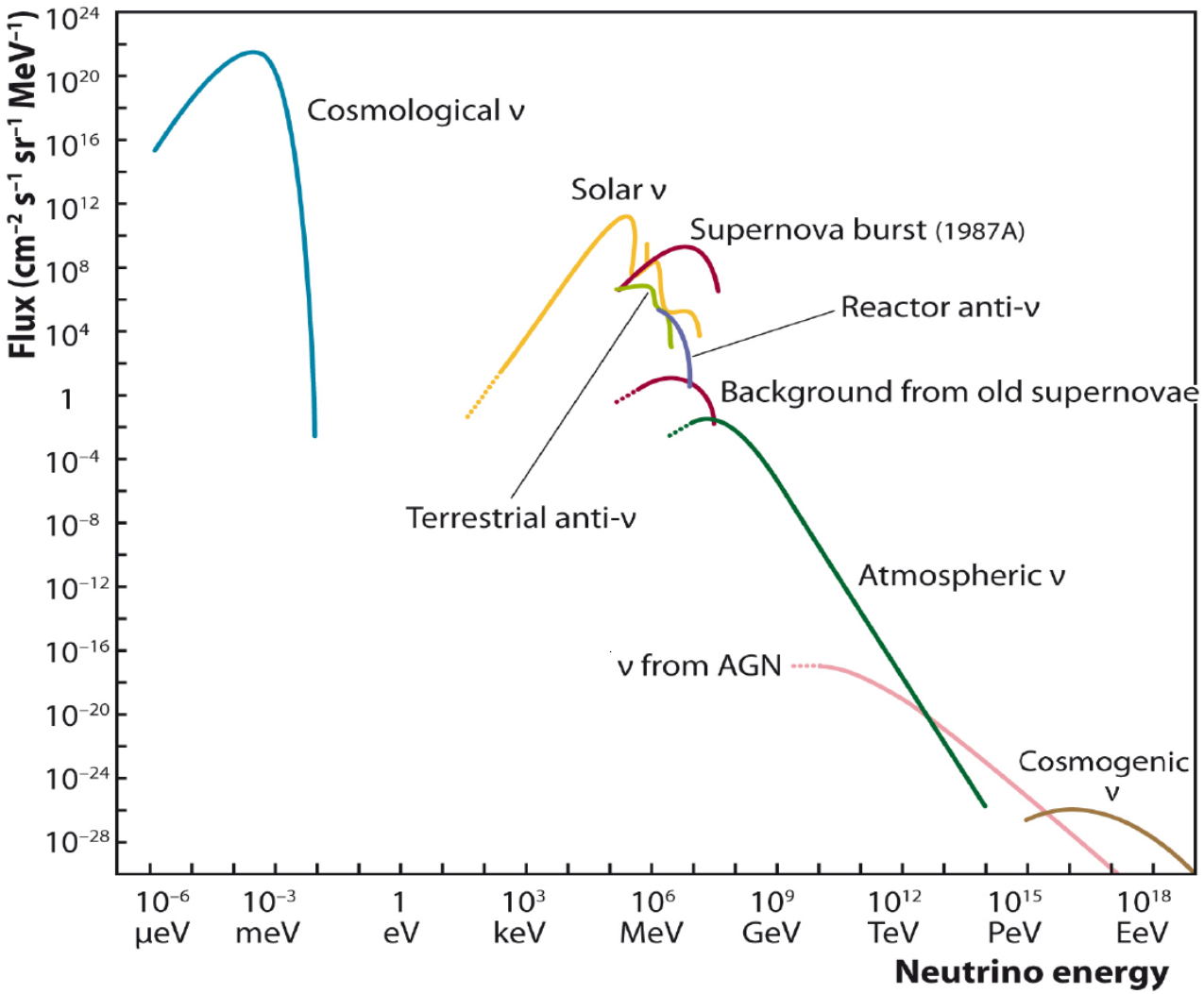
UNIVERSITÉ DE STRASBOURG

IPHC Institut Pluridisciplinaire Hubert CURIEN STRASBOURG

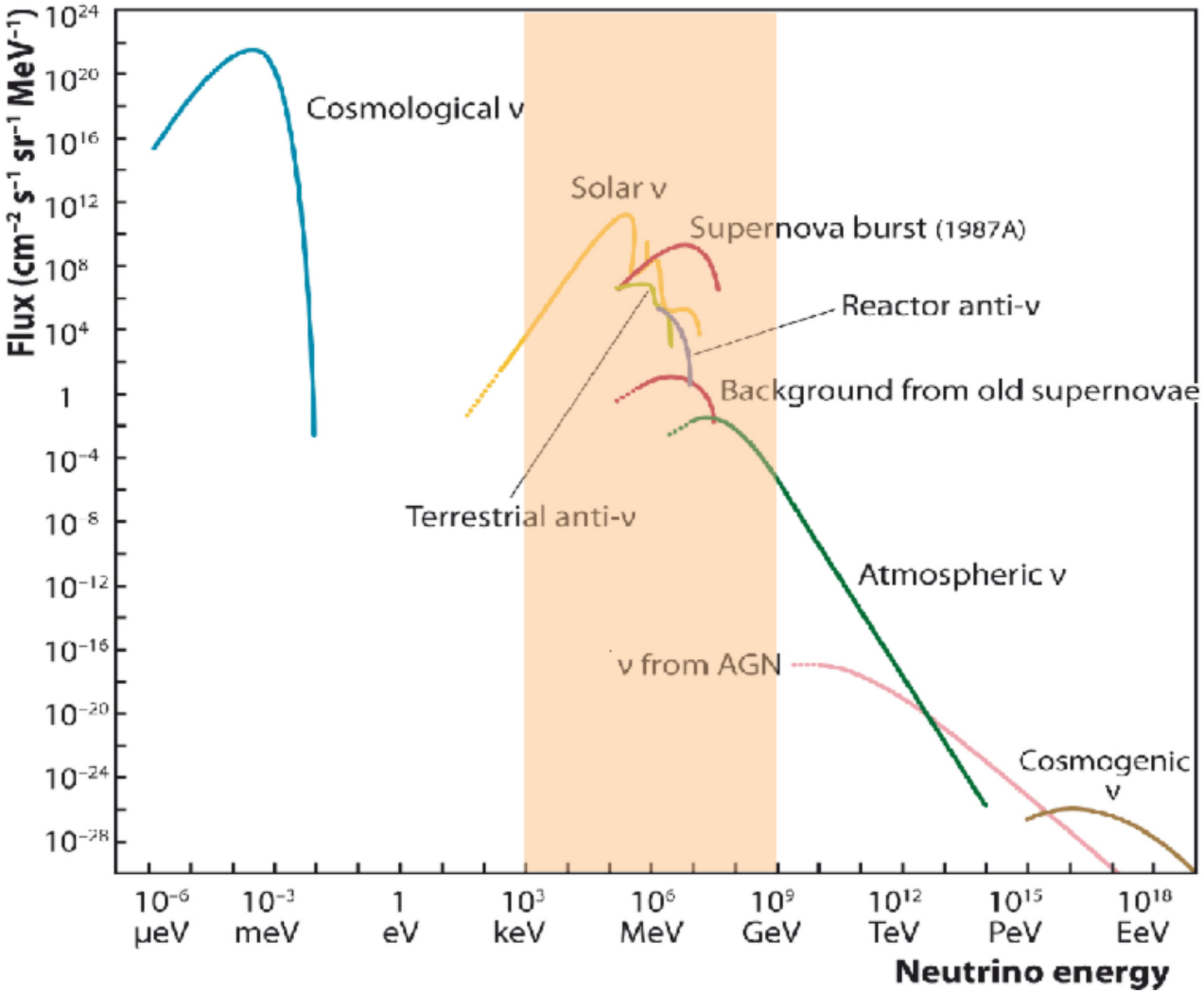
Outline of the Presentation

High Energy Neutrino Astronomy - Where do we stand ?

Detecting Neutrinos



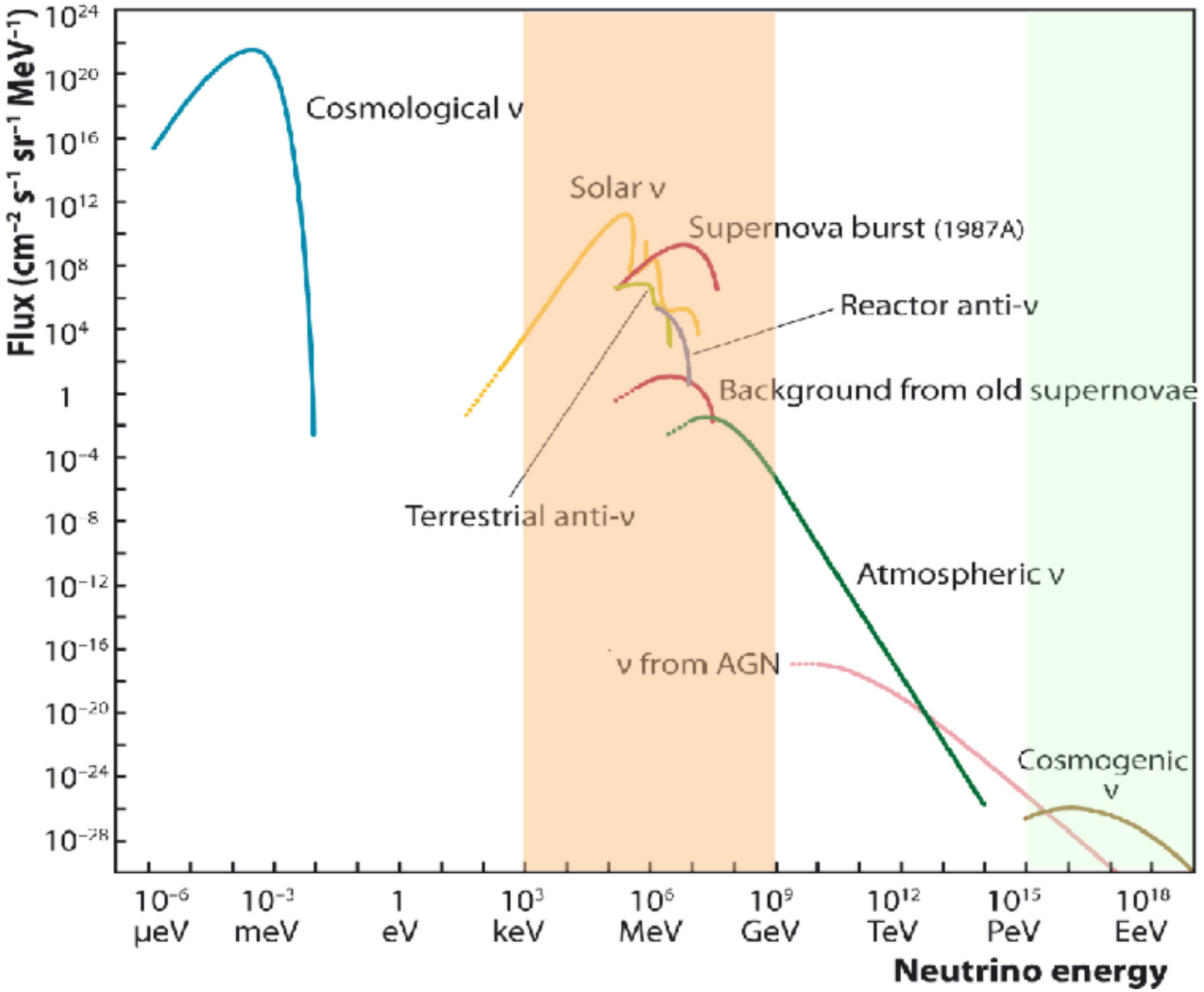
Detecting Neutrinos



Energy $\lesssim$ 1 GeV

- Under Rock + Cherenkov techniques : Borexino, Super-Kamiokande,. . .

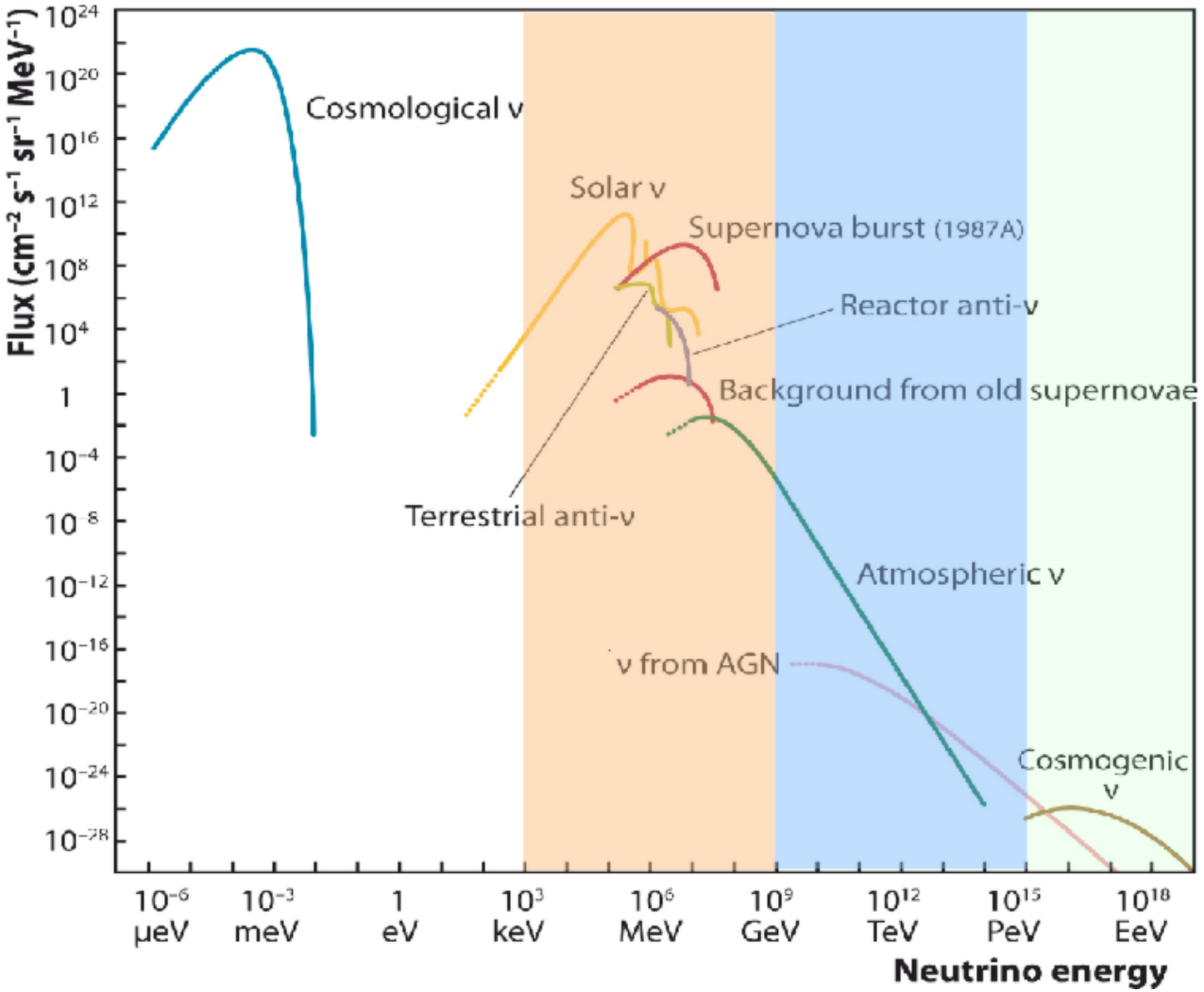
Detecting Neutrinos



Energy $\gtrsim 10^7$ GeV

- Giant Arrays + Acoustics/Radio techniques

Detecting Neutrinos



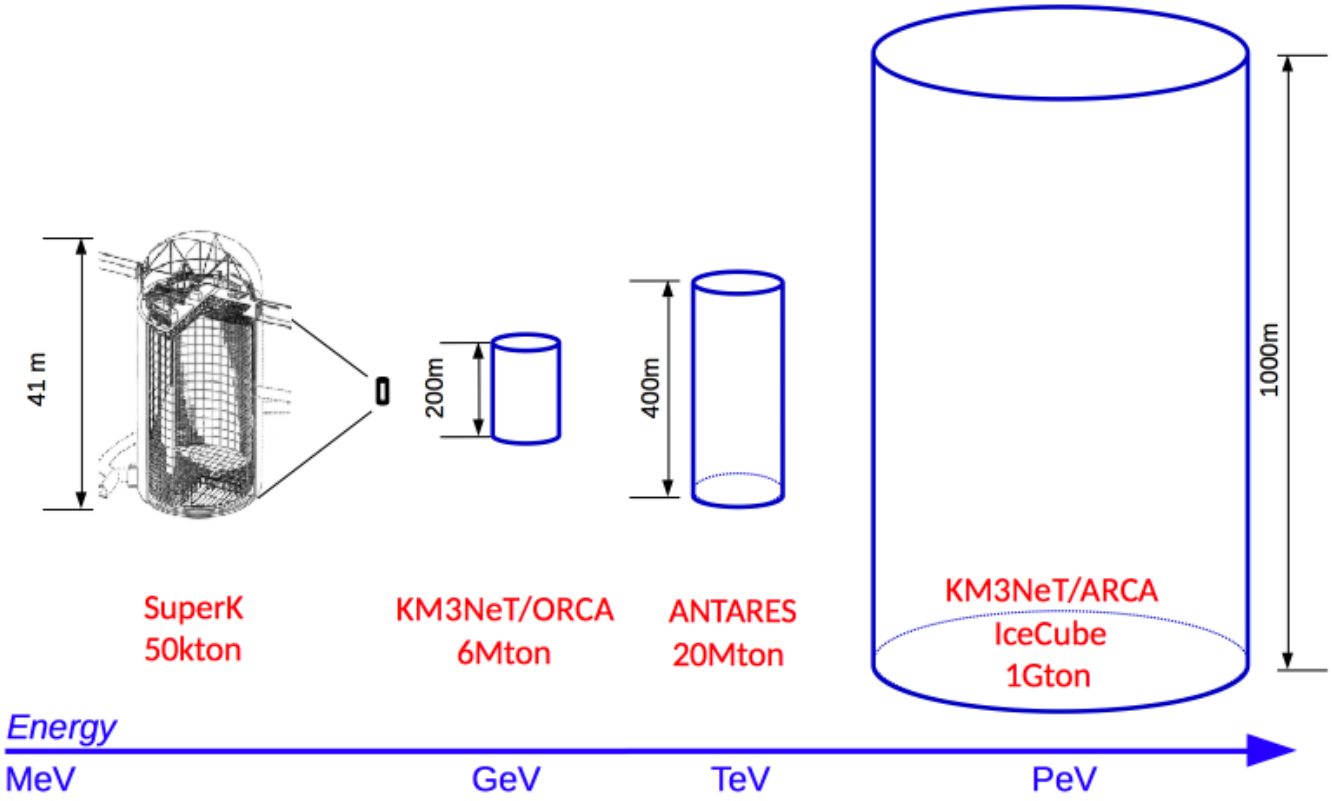
Energy $\in 1 - 10^9$ GeV

- Under Water + Cherenkov techniques

Detecting Neutrinos

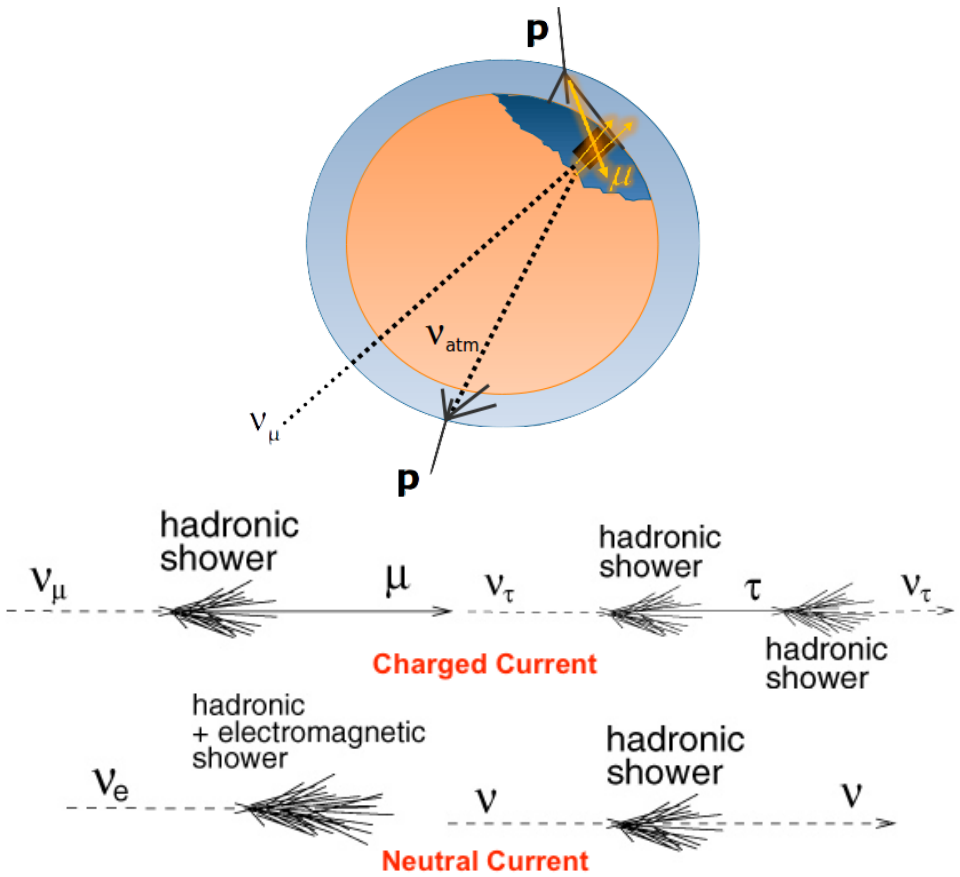
Energy $\in 1 - 10^9$ GeV

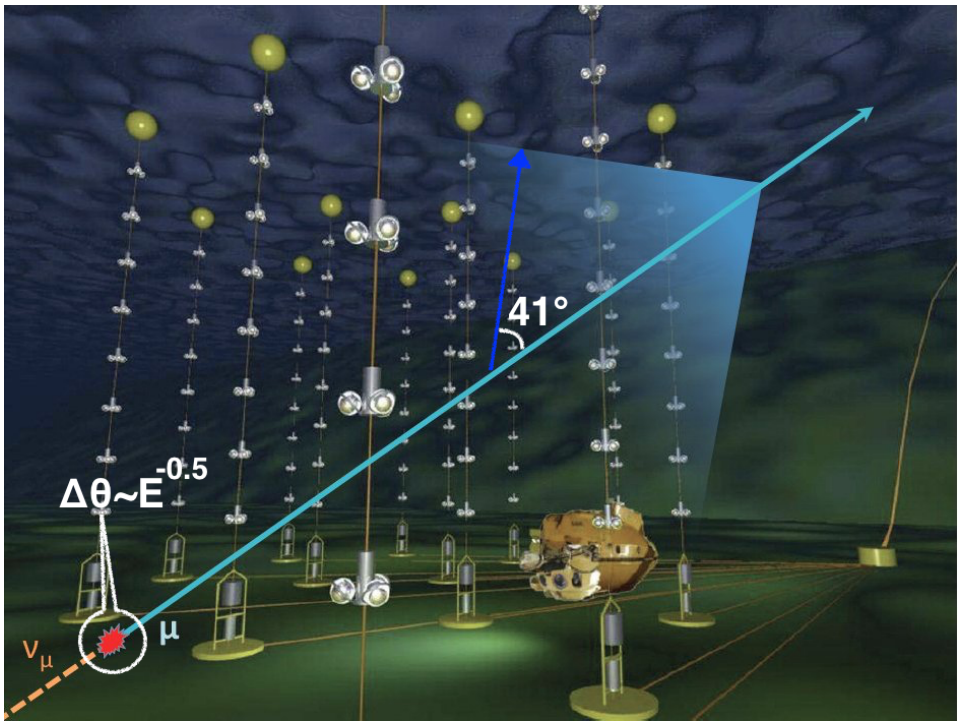
- Under Water + Cherenkov techniques



Low Fluxes + Small Cross-Sections $\Rightarrow$ Very large detectors needed

Detecting Neutrinos : Underwater Neutrino Telescopes

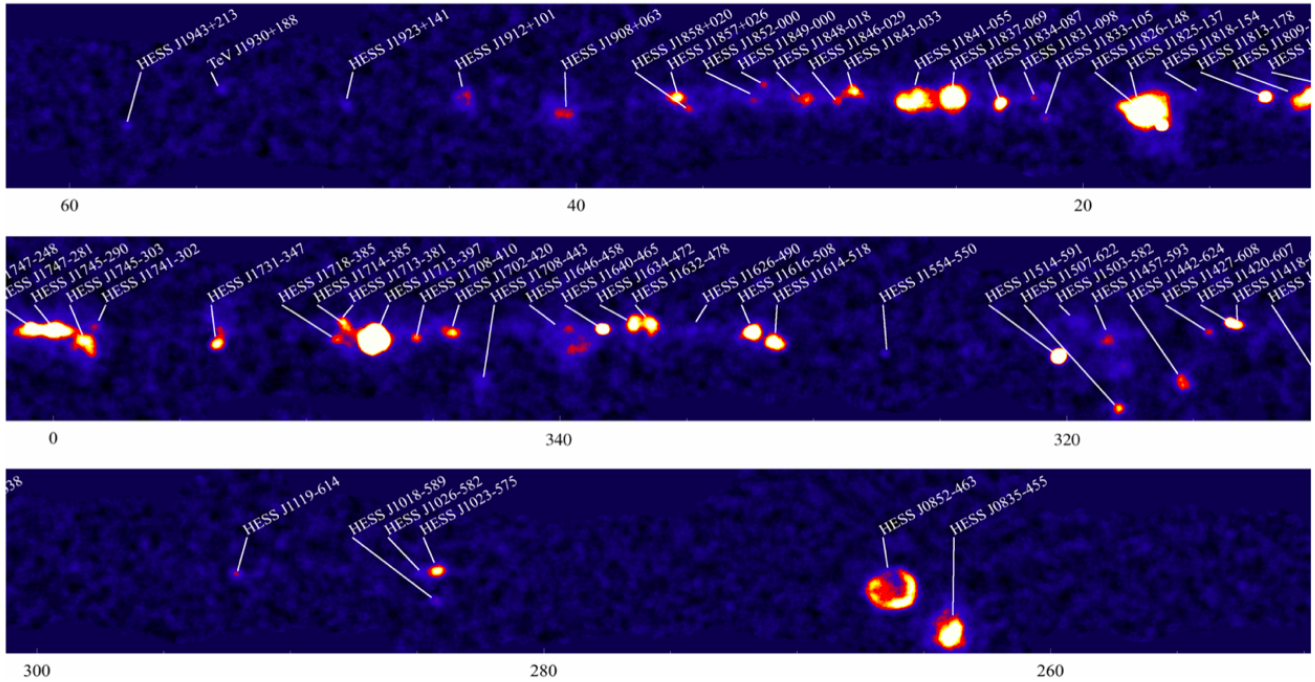




Event Topologies

- Track-like
  - → Cascade + track (ν_μ Charged Currents interactions)
- Shower-like
  - → 80% of all interactions → Charged Current ν_e, ν_τ + Neutral Currents all flavours

Neutrinos & Cosmic-Rays



[↪ S. Carrigan & HESS, Proceedings ICRC 2013 (Brésil)]

2012 : HESS Telescope (photons γ TeV) observe Galactic Sources

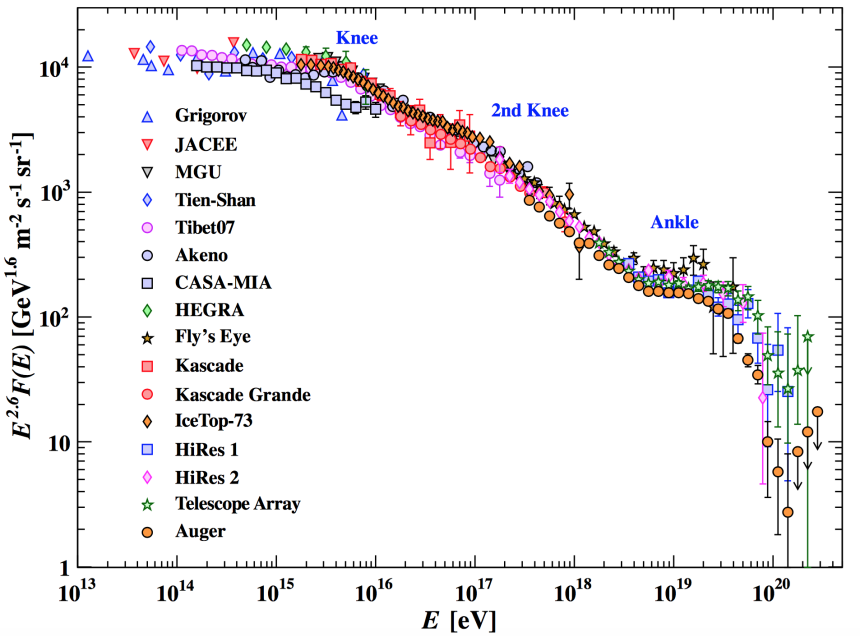
Leptonic Processes : $eB \rightarrow \gamma_{\text{Low Energy}}$, $\gamma_{\text{Low Energy}} + e \longrightarrow \gamma_{\text{High Energy}}$

or Hadronic Processes : $p/A + p/\gamma \longrightarrow \pi^0 \quad \pi^{\pm}\,?$

$\downarrow \quad \downarrow$

$\gamma\gamma \quad \mu\ \nu_\mu \longrightarrow \nu_\mu \nu_e e$

Neutrinos & Cosmic-Rays



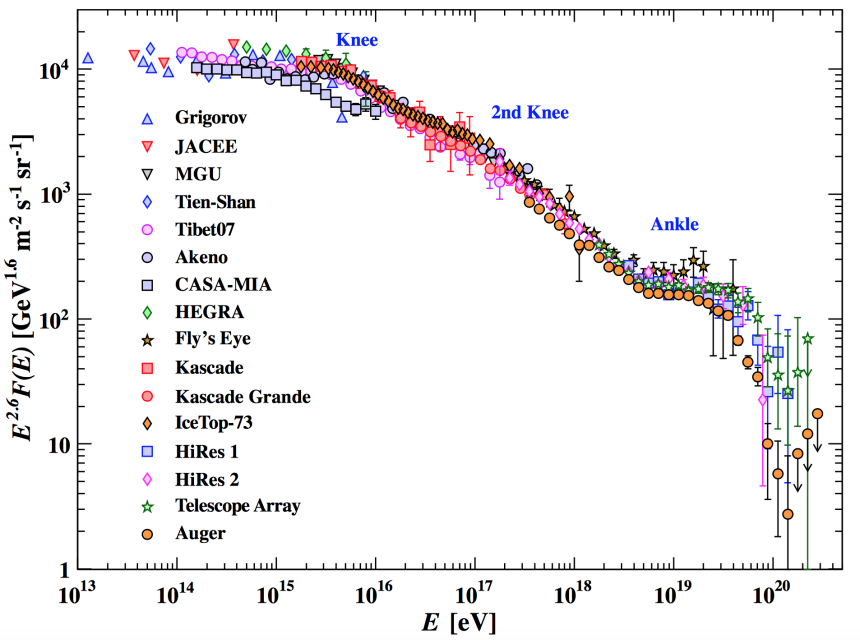
[↪ Particle Data Group (2015)]

A Hadronic « Radiation »

- 98% of protons and light nuclei
- High Energy Neutrinos are guaranteed

↪ Power-Law $E^{-3\pm0.25}$ ⟶ 100 J !

Neutrinos & Cosmic-Rays



[↪ Particle Data Group (2015)]

A Hadronic « Radiation »

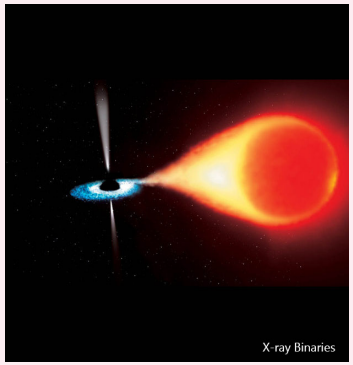
- 98% of protons and light nuclei
- High Energy Neutrinos are guaranteed

↪ Power-Law $E^{-3\pm0.25}$ ⟶ 100 J !

Compact Sources

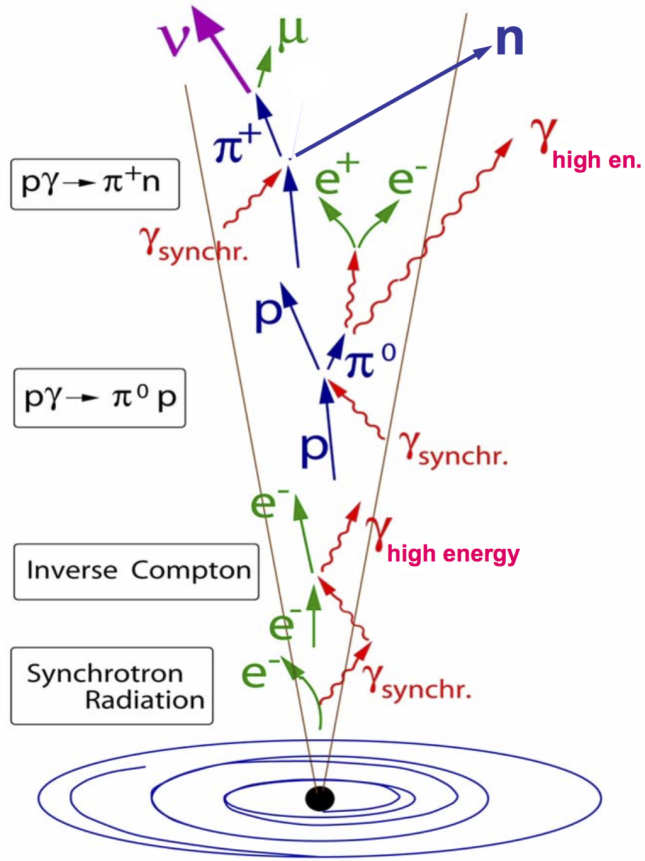
- Extra-Galactic :
  - ⇒ Active Galactic Nuclei
  - ⇒ Gamma-Ray Bursts

- Galactic :
  - ⇒ Supernova Remnants
  - ⇒ Microquasars



⇒ Matter jets, shocks

Neutrinos & Cosmic-Rays

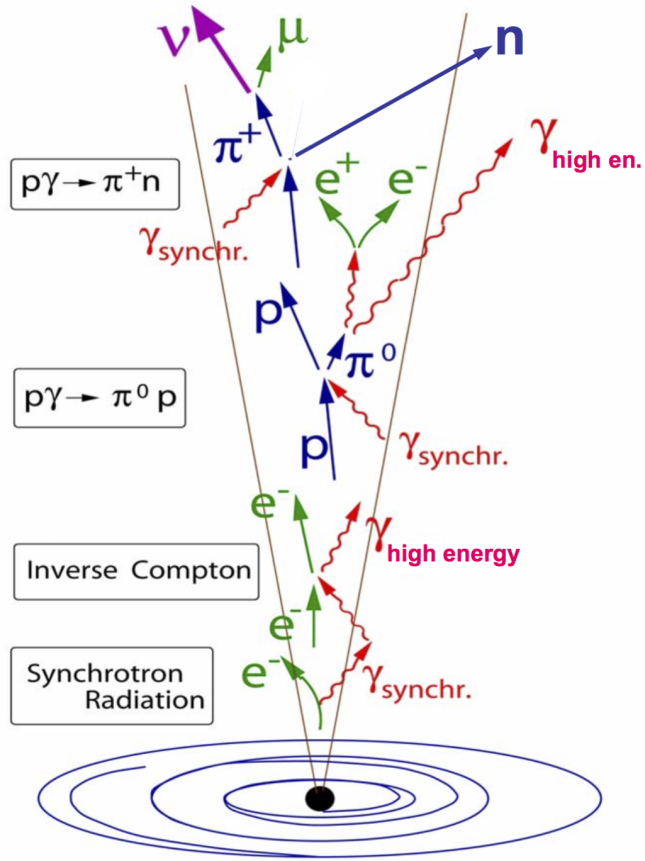


[↪ U. Katz, Prog. Part. Nucl. Phys. 67 (2012) 651-704]

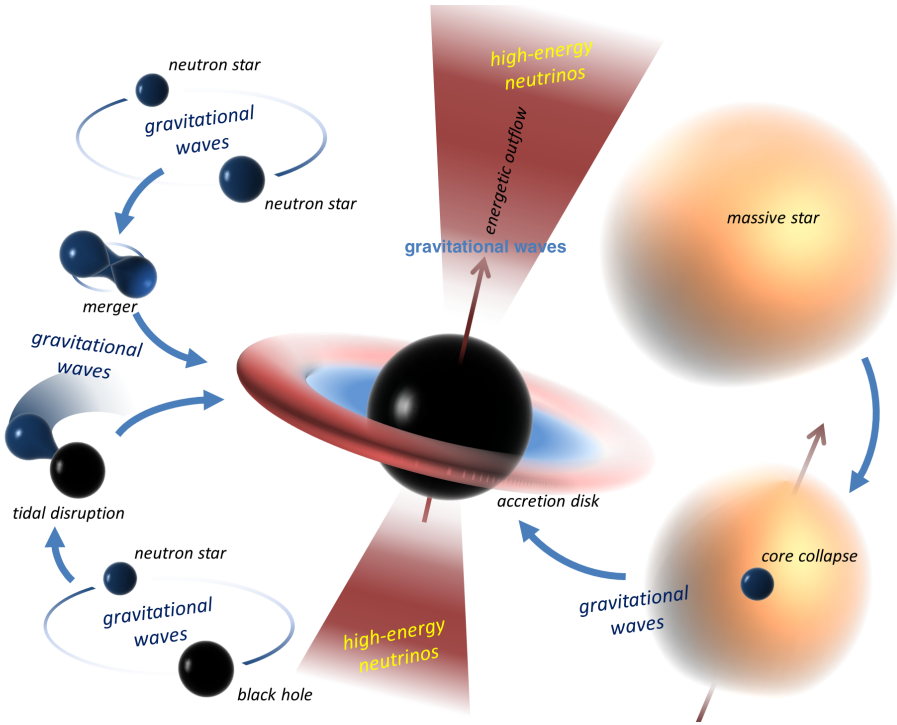
Astronomy with Neutrinos

- ν smoking gun for hadronic processes
- Aim : find the sources of CRs !

Neutrinos & Cosmic-Rays



[↪ U. Katz, Prog. Part. Nucl. Phys. 67 (2012) 651-704]



[↪ I. Bartos et al., Class. Quantum Grav. 30 (2013) 123001]

Astronomy with Neutrinos

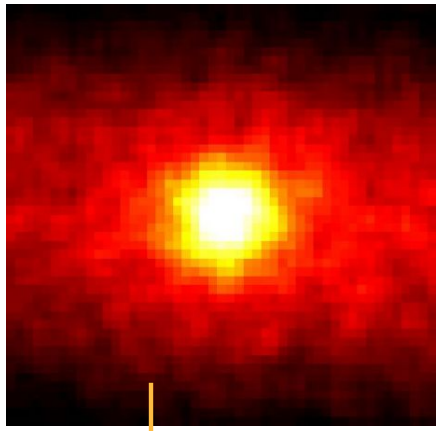
- ν smoking gun for hadronic processes
- Aim : find the sources of CRs !

Gravitational Astronomy

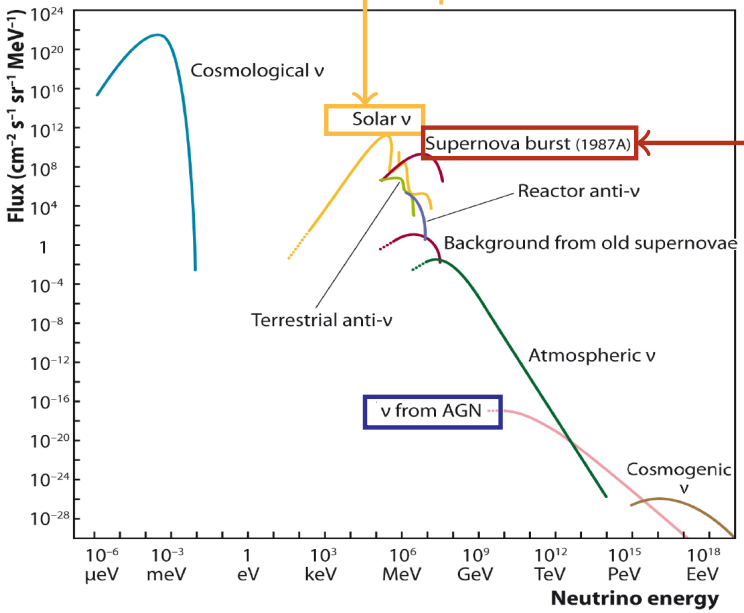
- $P \propto \text{asymmetry}^2 \times \text{compacity}^2 \times \text{speed}^6$

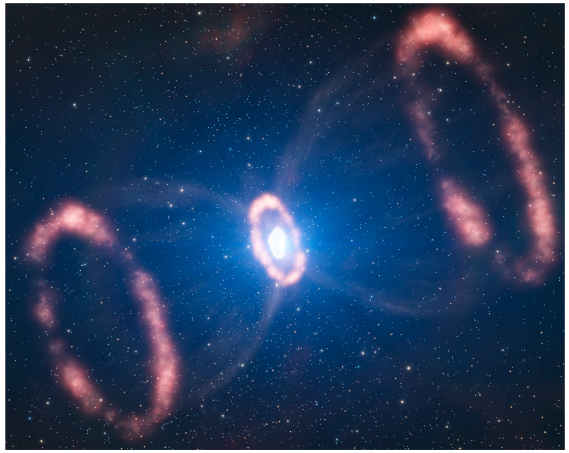
$\Rightarrow$ Sources of HEN !

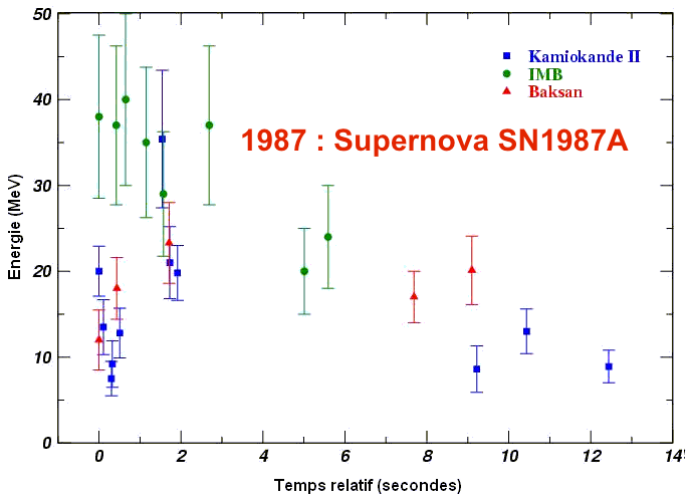
Low Energy Neutrinos : Sun & Supernovae



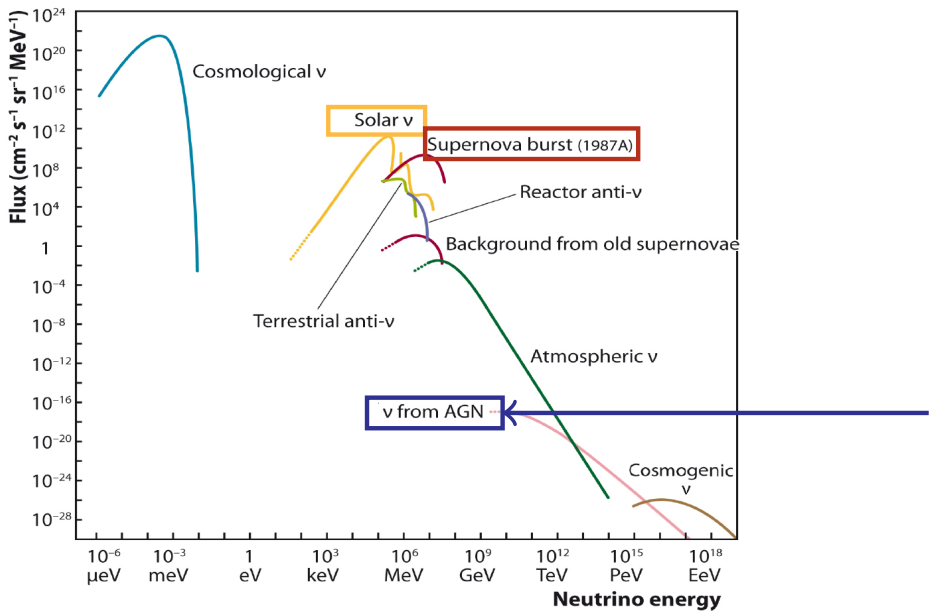
1968-2001 ⇒ Super-Kamiokande

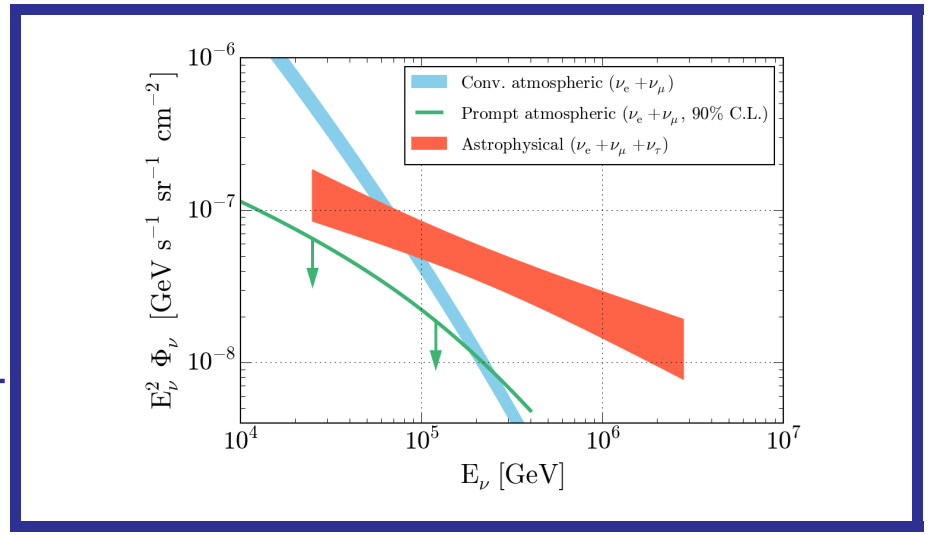






High Energy Neutrinos : origin of cosmic rays





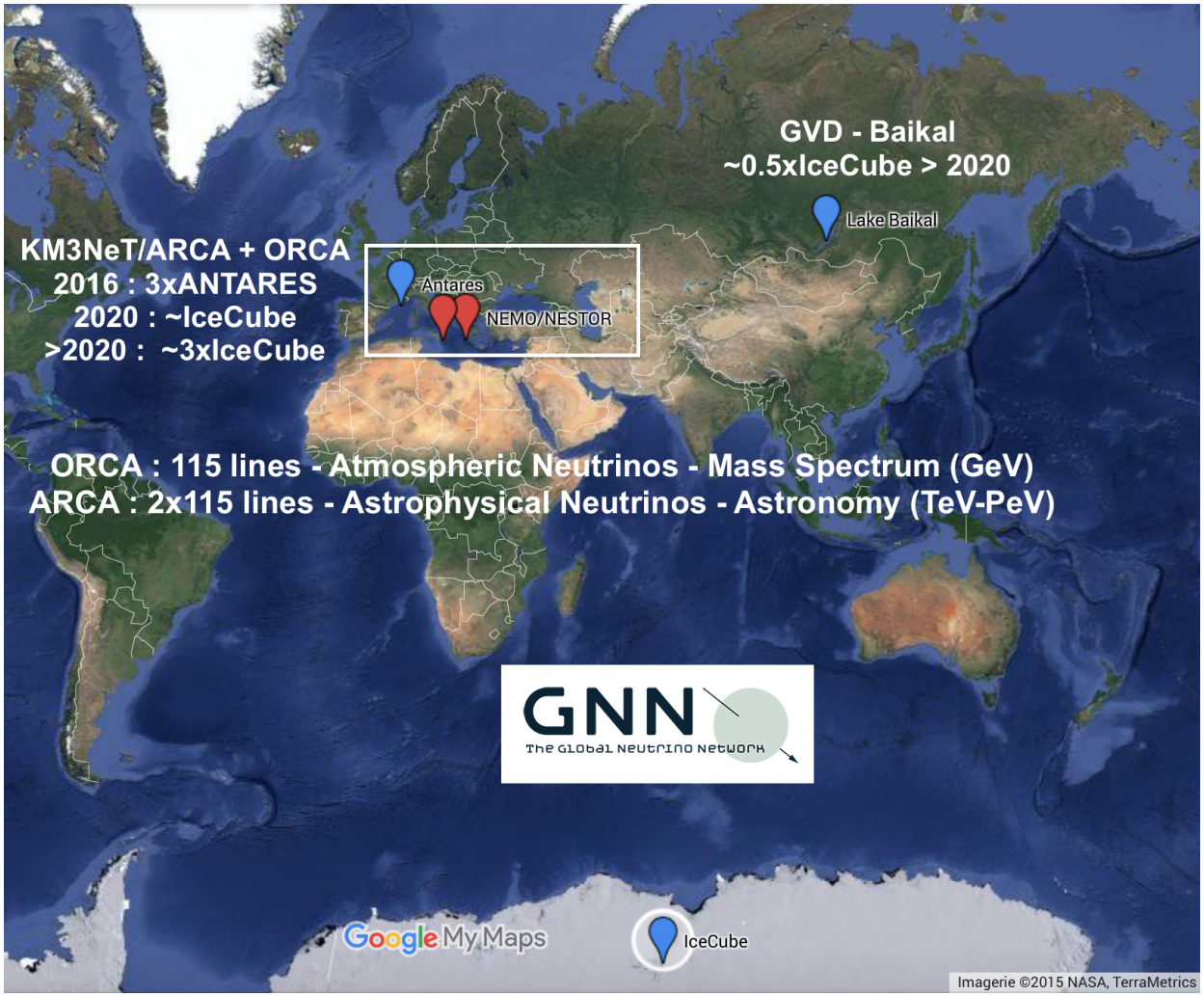
Discovery of IceCube- 2013

Astrophysical Diffuse Flux $\Phi_\nu = 6.7^{+1.1}_{-1.2} \times 10^{-18} \left(\frac{E_\nu}{10^5 \mathrm{GeV}}\right)^{-2.5 \pm 0.09} /\mathrm{GeV}/\mathrm{cm}^2/\mathrm{s}/\mathrm{sr}$

[↪ IceCube, Astrophysical Journal 809 (2015) 98]

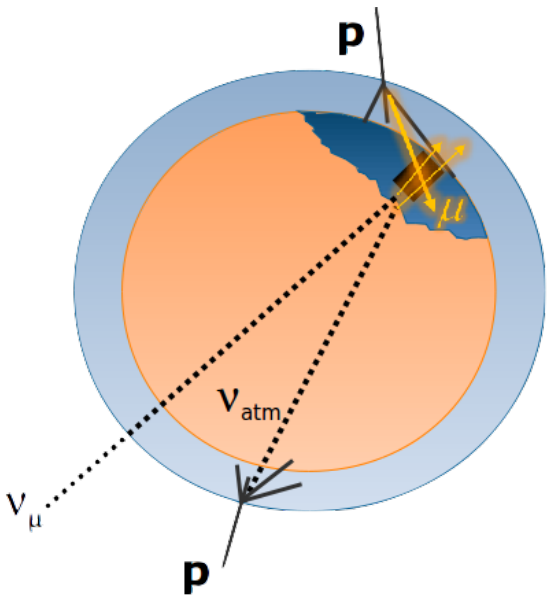
High Energy Neutrino Telescopes in the World

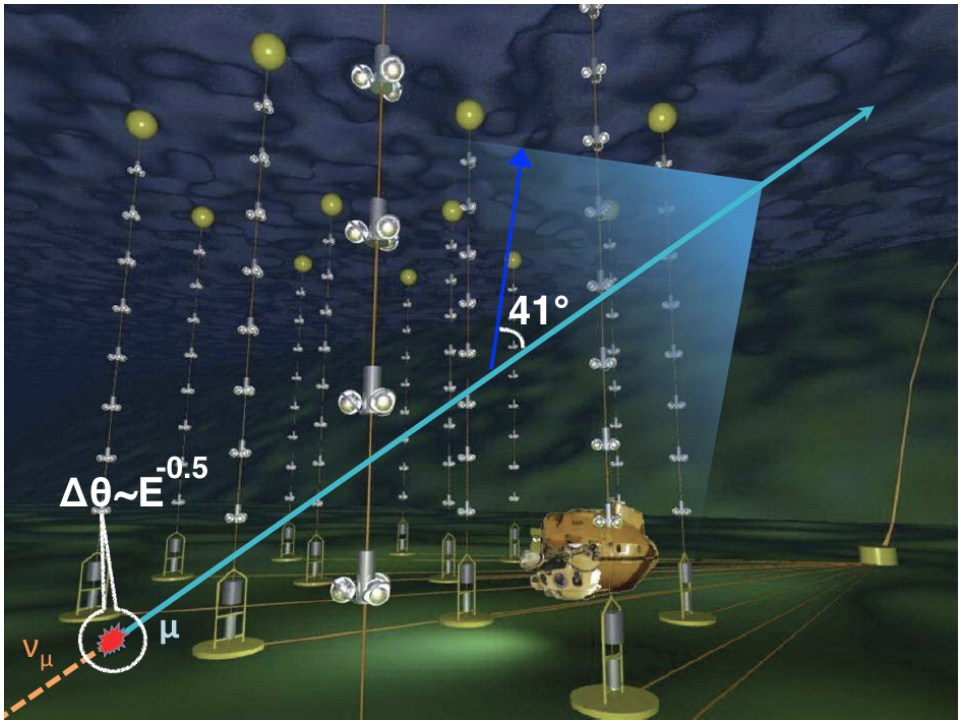
High Energy Neutrino Telescopes in the World



- ANTARES : **A**stronomy with a **N**eutrino **T**elescope and **A**byss **E**nvironmental **RES**earch
- KM3NeT/ARCA : **A**stroparticle **R**esearch with **C**osmics in the **A**byss
- KM3NeT/ORCA : **O**scillation **R**esearch with **Co**smics in the **A**byss

Detection of High Energy Neutrinos



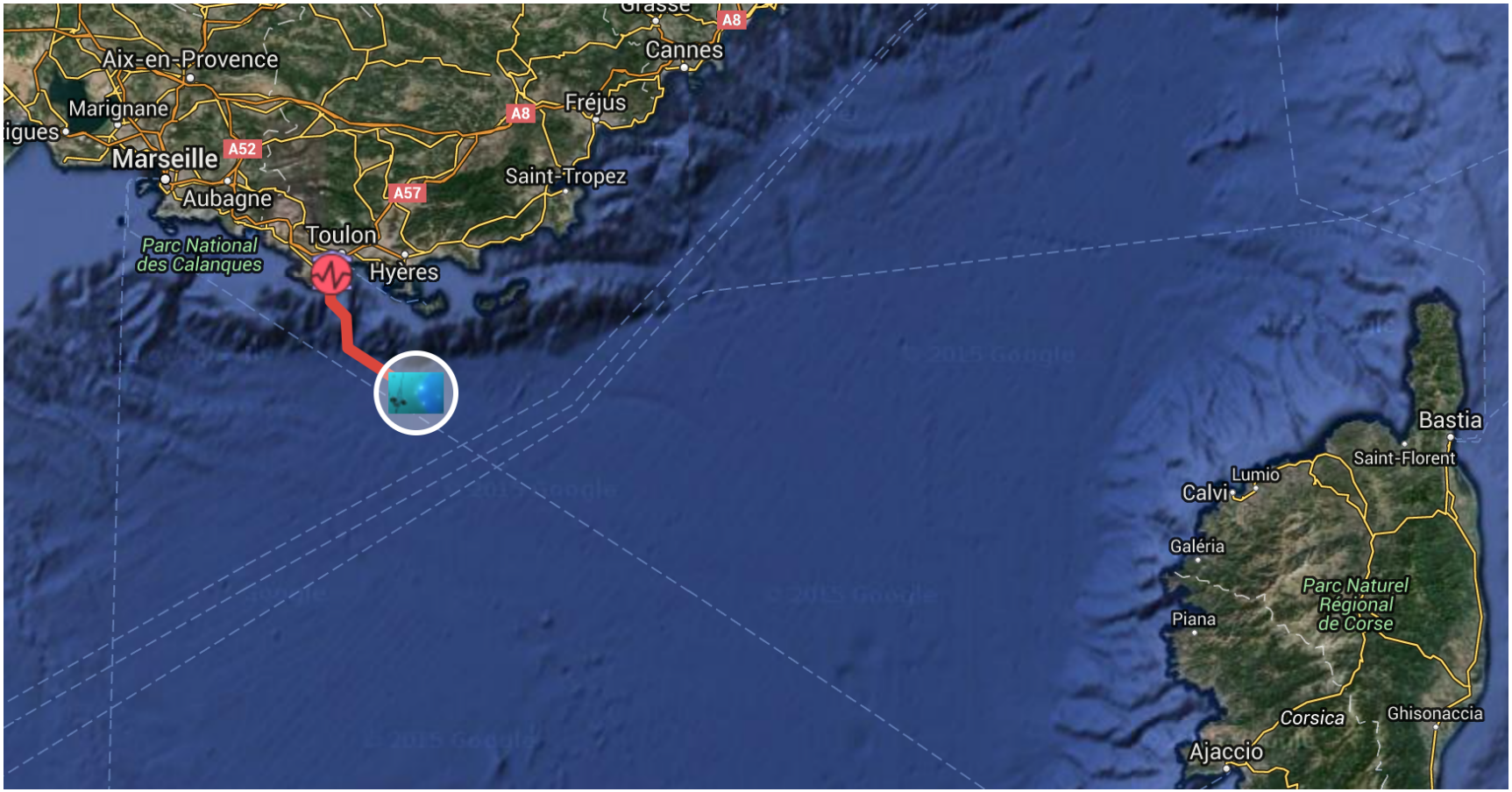


Concept : Markov, 1961

Medium	$L_{Absorption}$	$L_{Diffusion}$	L_{Total}	$\Delta\theta_{\nu_\mu}$ at 10 TeV
ANTARES - Sea Water	50-60m	>200m	40-50m	0.2°
Baikal Lake	15-30m	>100m	20m	1.5°
ICECUBE - Polar Ice	100m	25m	20m	3°

Measurements of : time $\mathcal{O}(ns)$, position $\mathcal{O}(10cm)$, amplitude $\mathcal{O}(10\%)$

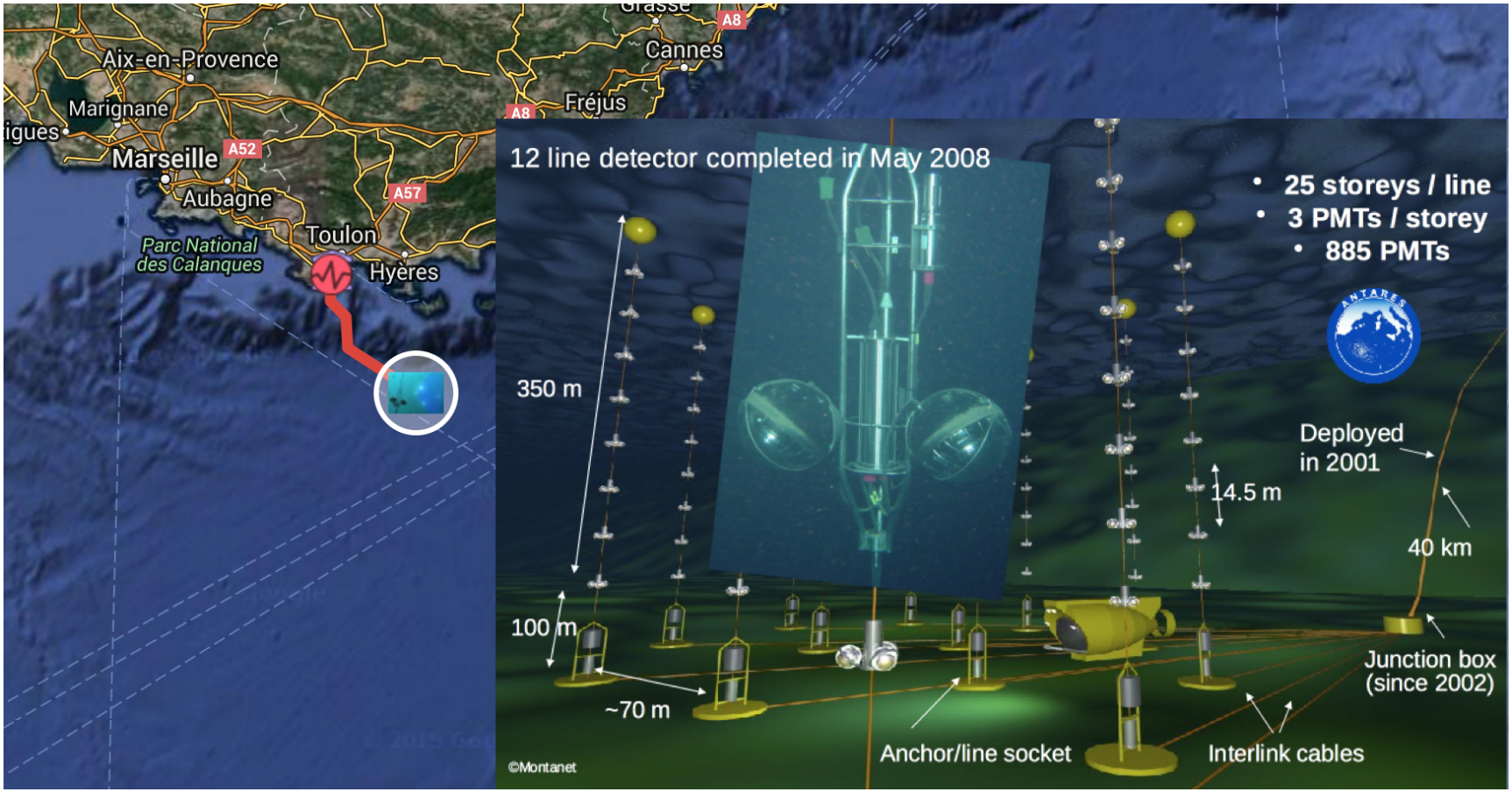
The ANTARES Telescope



Complementarity with IceCube

- Visibility of South Hemisphere (including Galactic Plane + Center)
- 10% instantaneous overlap - 40% integrated

The ANTARES Telescope

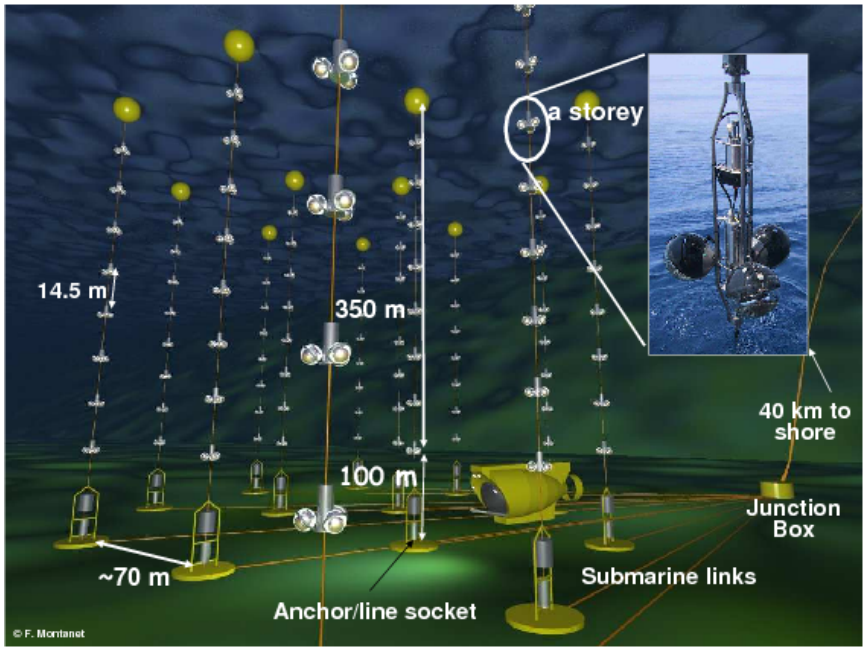


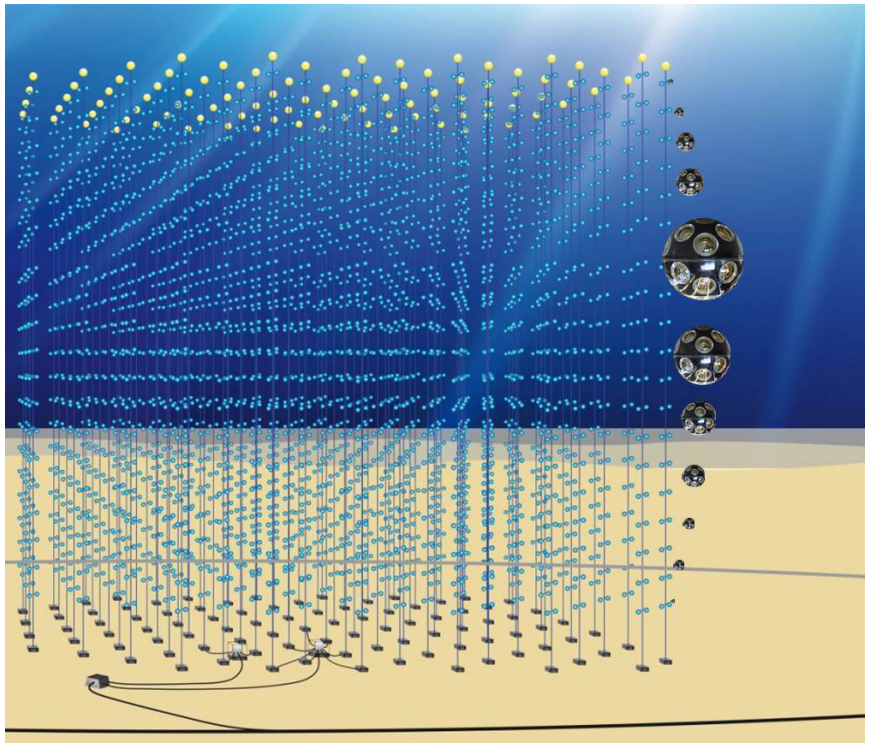
Astronomy with a **N**eutrino **T**elescope and **A**byss **E**nvironmental **RES**earch

Complementarity with ICECUBE

- Visibility of South Hemisphere (including Galactic Plane + Center)
- 10% instantaneous overlap - 40% integrated

ANTARES, KM3NeT & IceCube





ANTARES : TeV-PeV

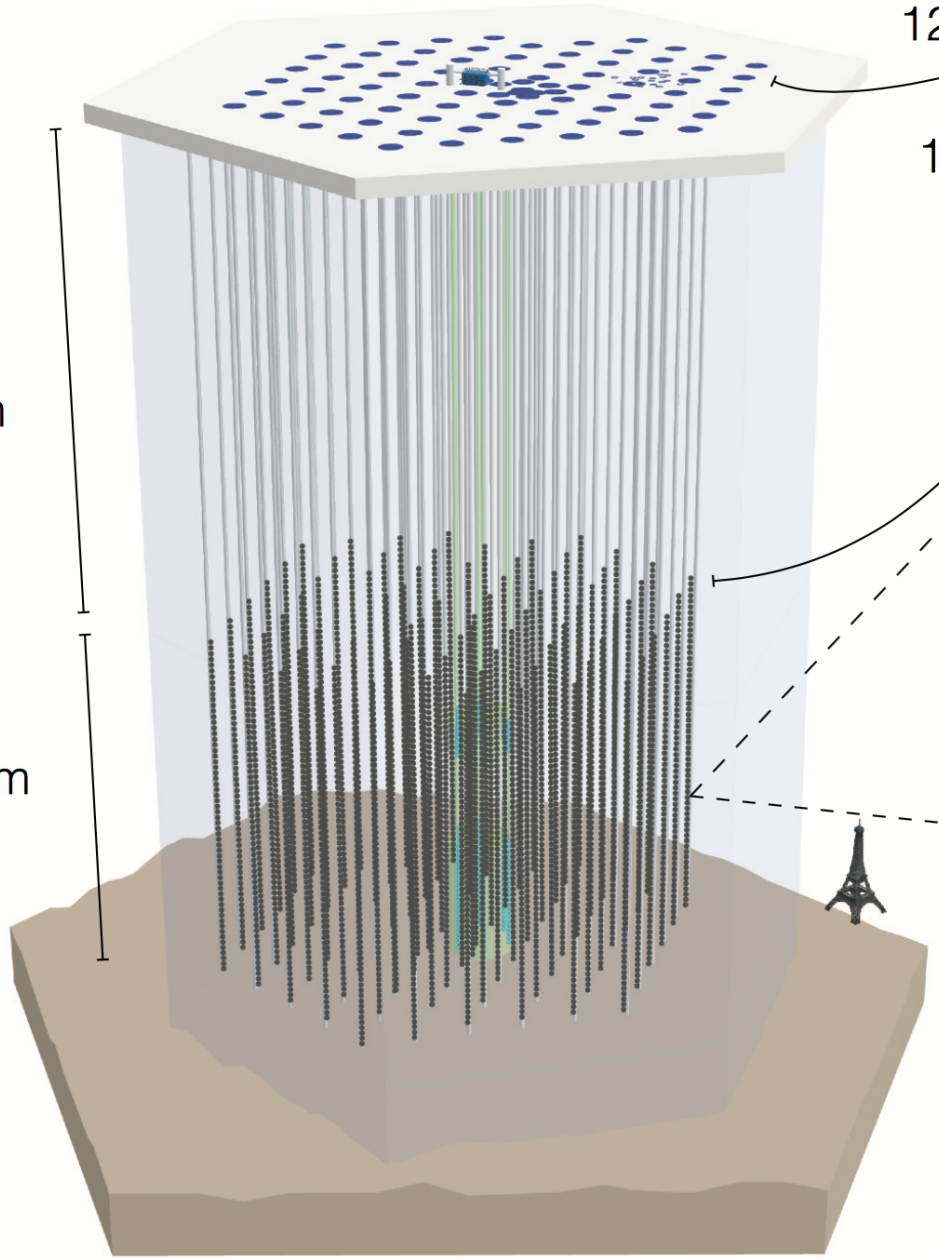
- 40km from Toulon, 2500m underwater
- 12 Lines, 15m between storeys, 70m between lignes
- Operation 2006-2018
- 120 members, 8 countries

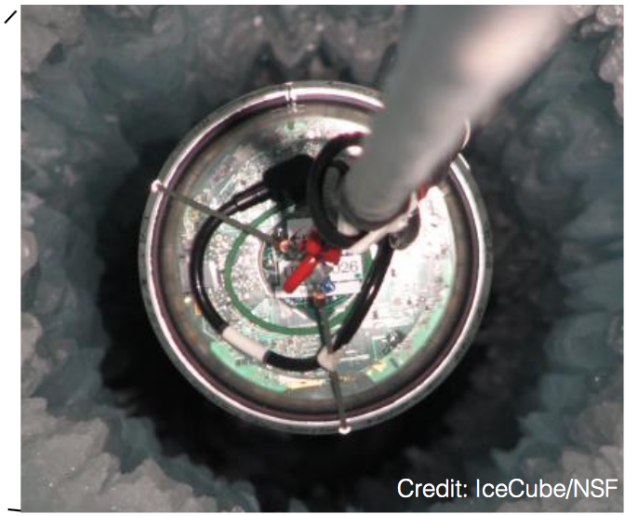
KM3NeT : GeV $\rightarrow$ PeV

- **KM**^{3} **Ne**utrino **T**elescope
- Construction (250 members)
- ORCA : Mass Hierarchy GeV
  - $\Rightarrow$ Toulon, 115 Lines (9m$\times$20m)
- ARCA : Cosmics TeV
  - $\Rightarrow$ Sicily, 2×115 lines (36m$\times$90m)

ANTARES, KM3NeT & IceCube

ANTARES, KM3NeT & IceCube





- Started full operation in 2011
- >99% uptime

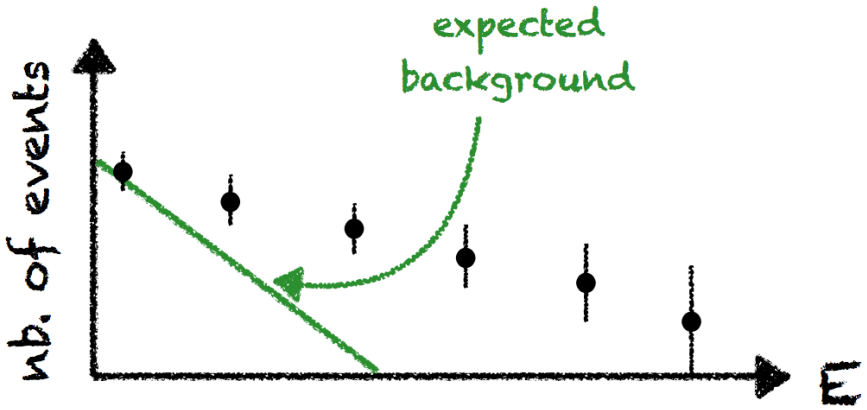
ANTARES, KM3NeT & IceCube

Looking for excess at high energies:

➜ diffuse flux analyses

Concerns mainly extragalactic sources

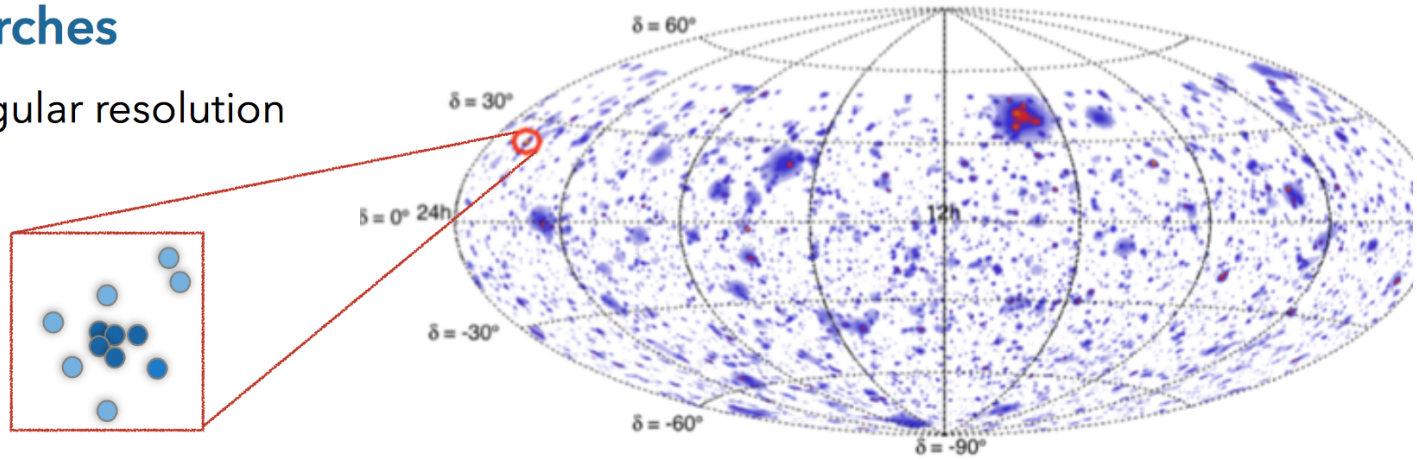
Requires good energy resolution



Looking for anisotropies (clusters of events) in the sky:

➜ point source searches

Requires good angular resolution



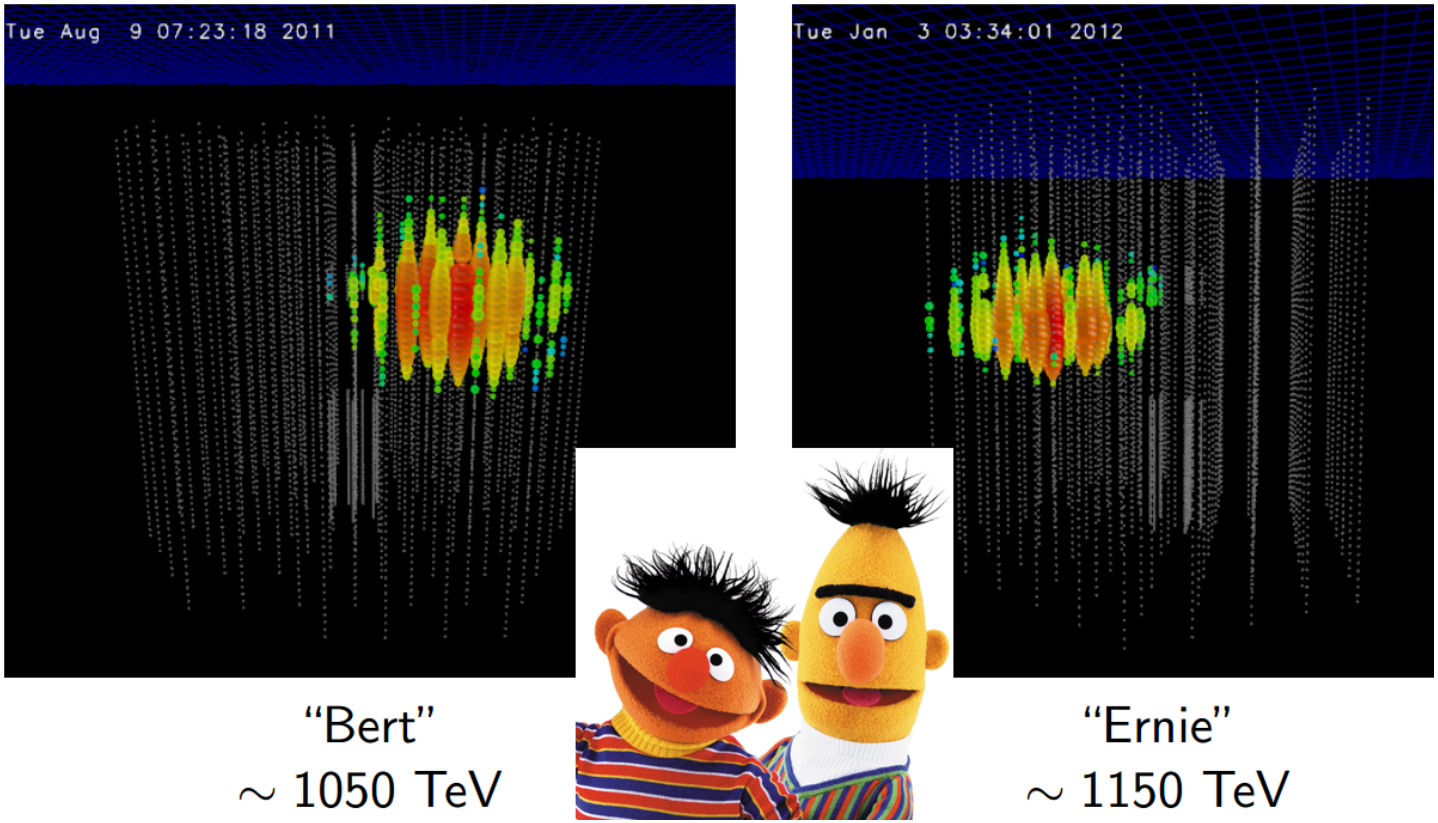
Looking for coincidences with other astrophysical signals:

➜ multi-messenger searches

Requires temporal coincidences with other probes (CR, GW, photons)

High Energy Neutrino Astronomy - Where do we stand ?

Observations by IceCube & Constraints from ANTARES

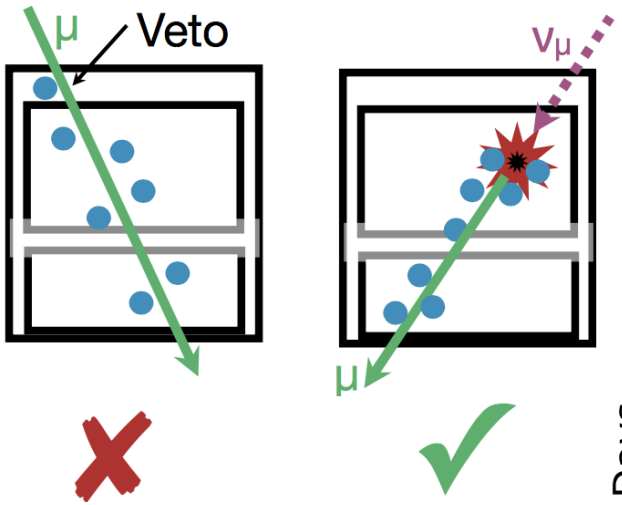


Amount of light detected in each PMT after interaction of a ν

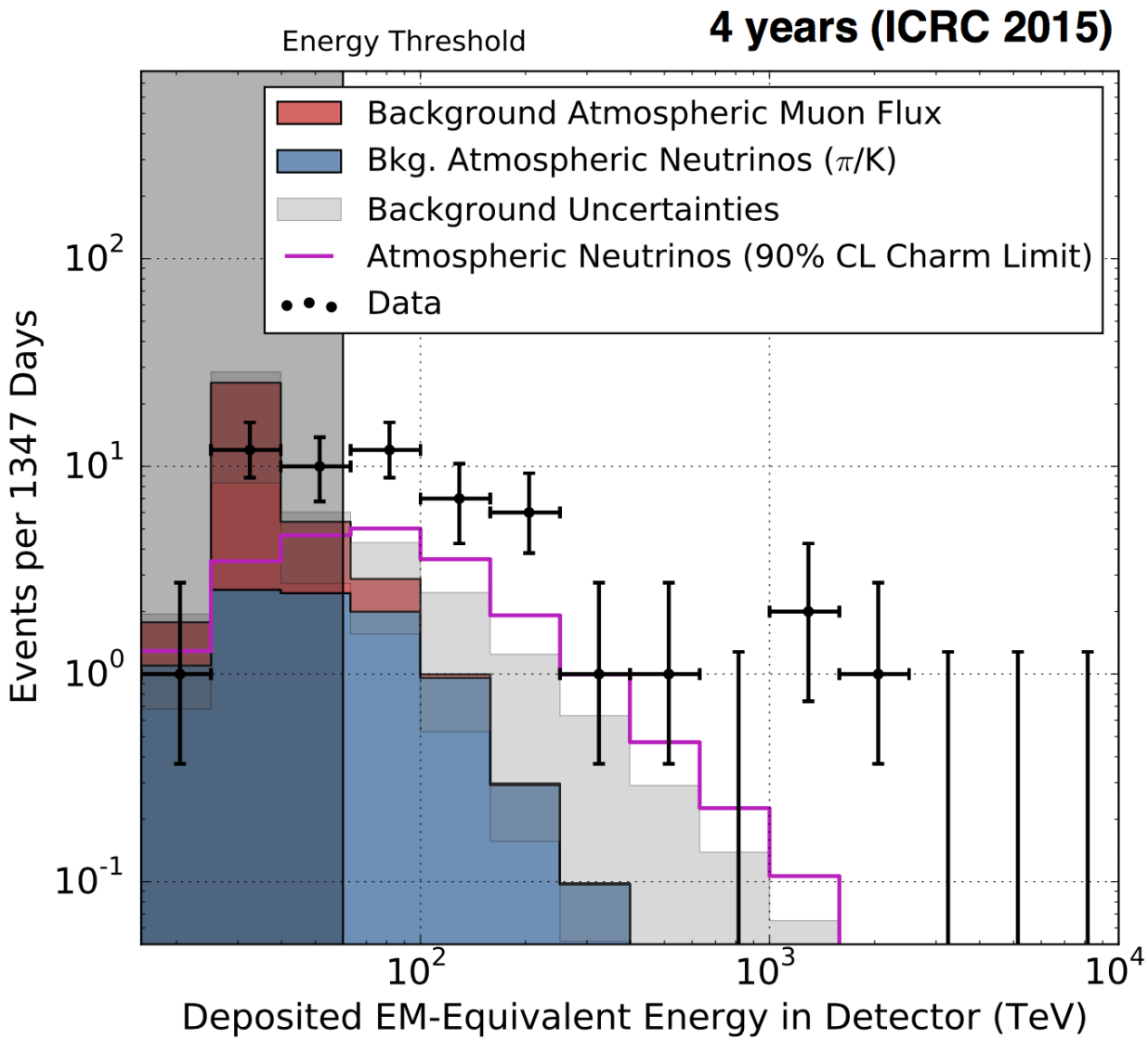
The dawn of High Energy Neutrino Astronomy

- May 2013 : IceCube (1 km^3 of instrumented Antarctic Ice, US) announces the first detection of cosmic PeV ν

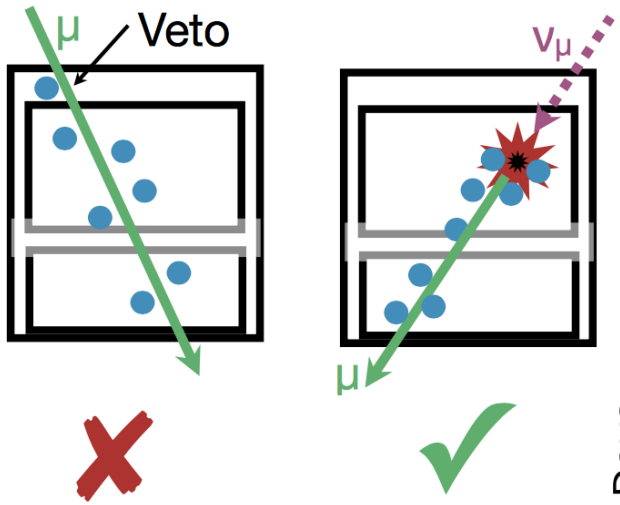
Observations by IceCube & Constraints from ANTARES



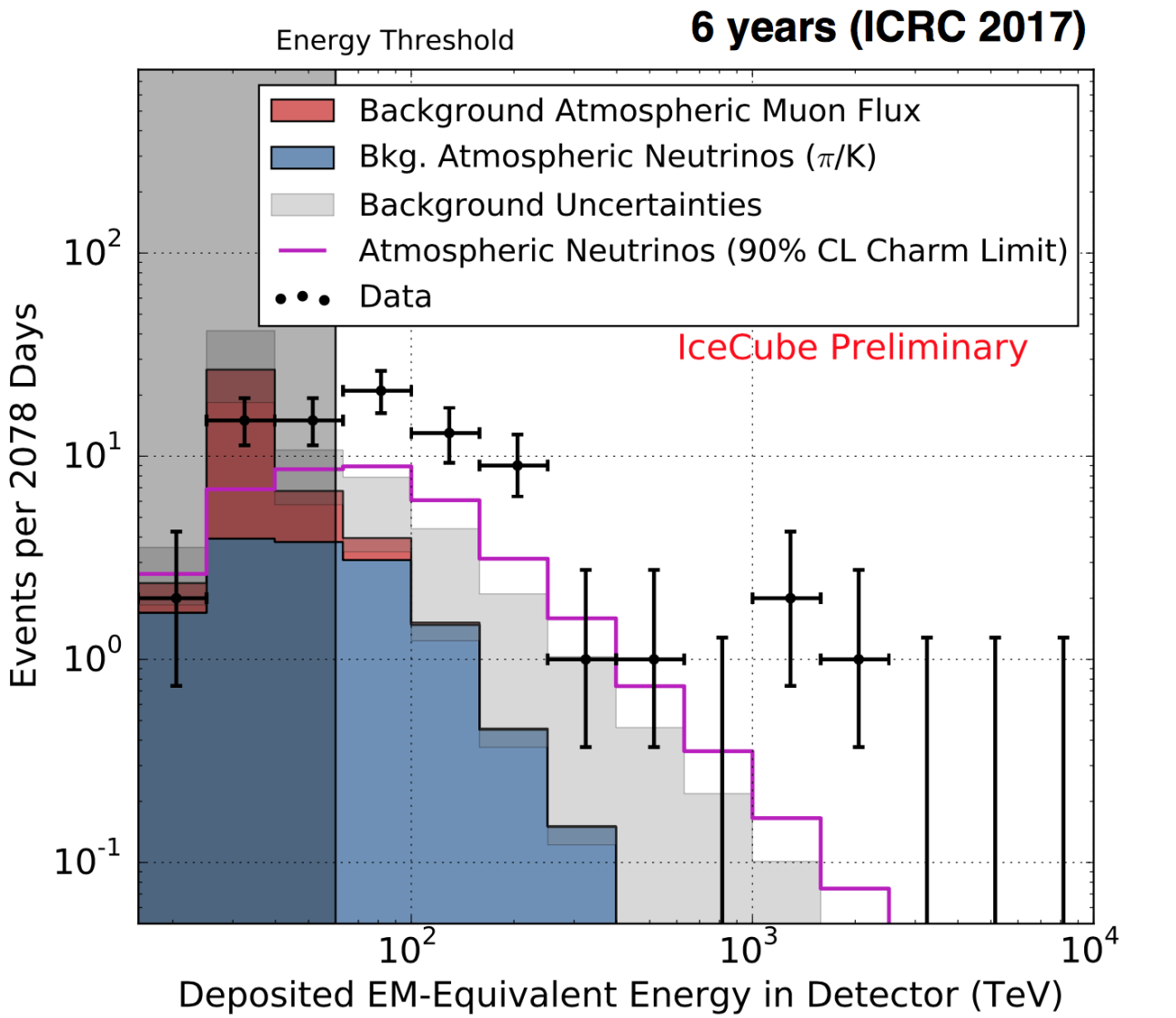
- Selected events that start in IceCube volume
- **82 events in 6 years** (54 in 4 years)



Observations by IceCube & Constraints from ANTARES

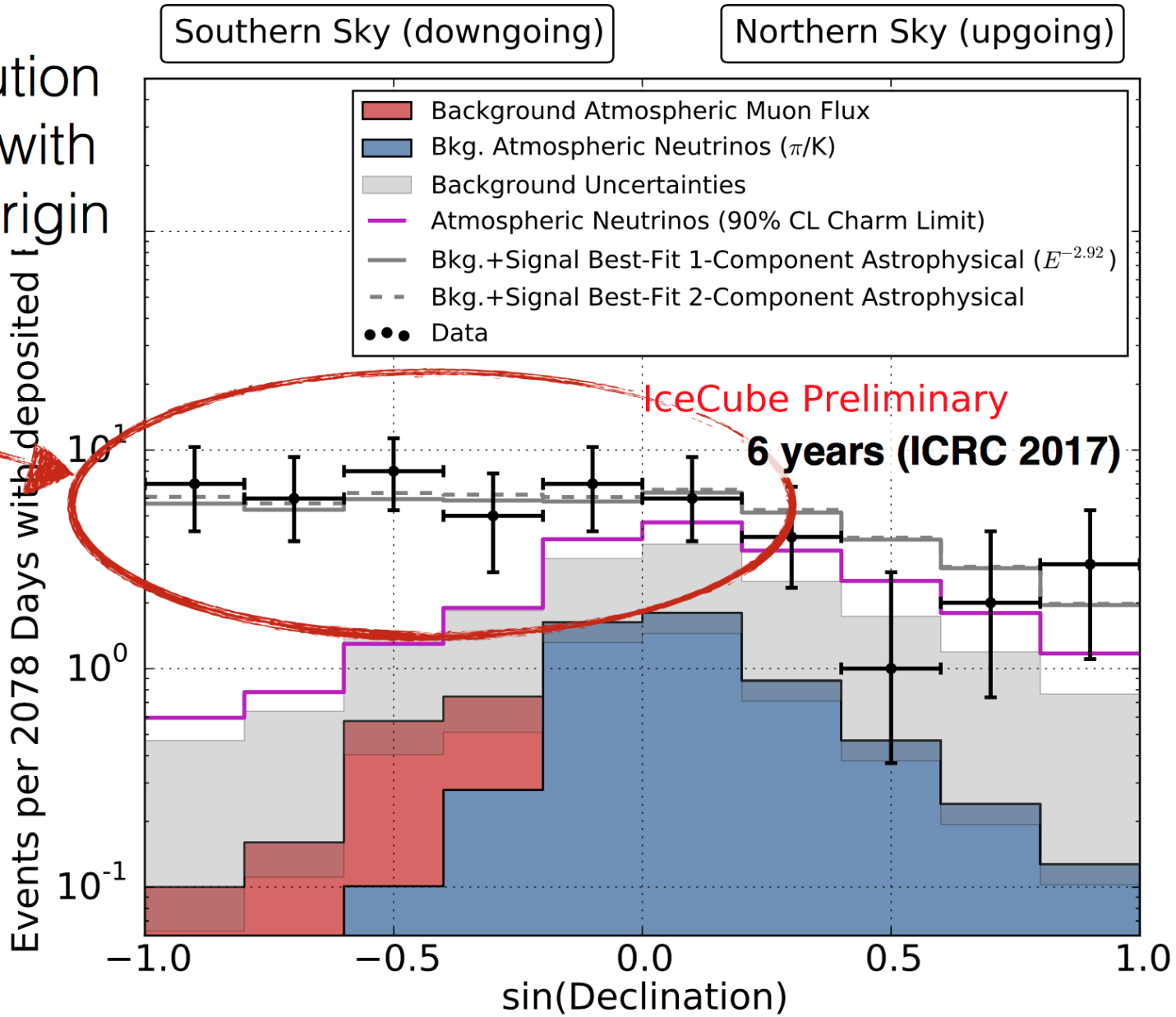


- Selected events that start in IceCube volume
- **82 events in 6 years** (54 in 4 years)

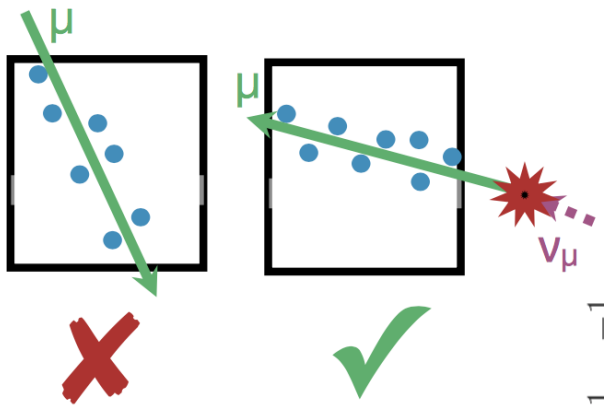


Observations by IceCube & Constraints from ANTARES

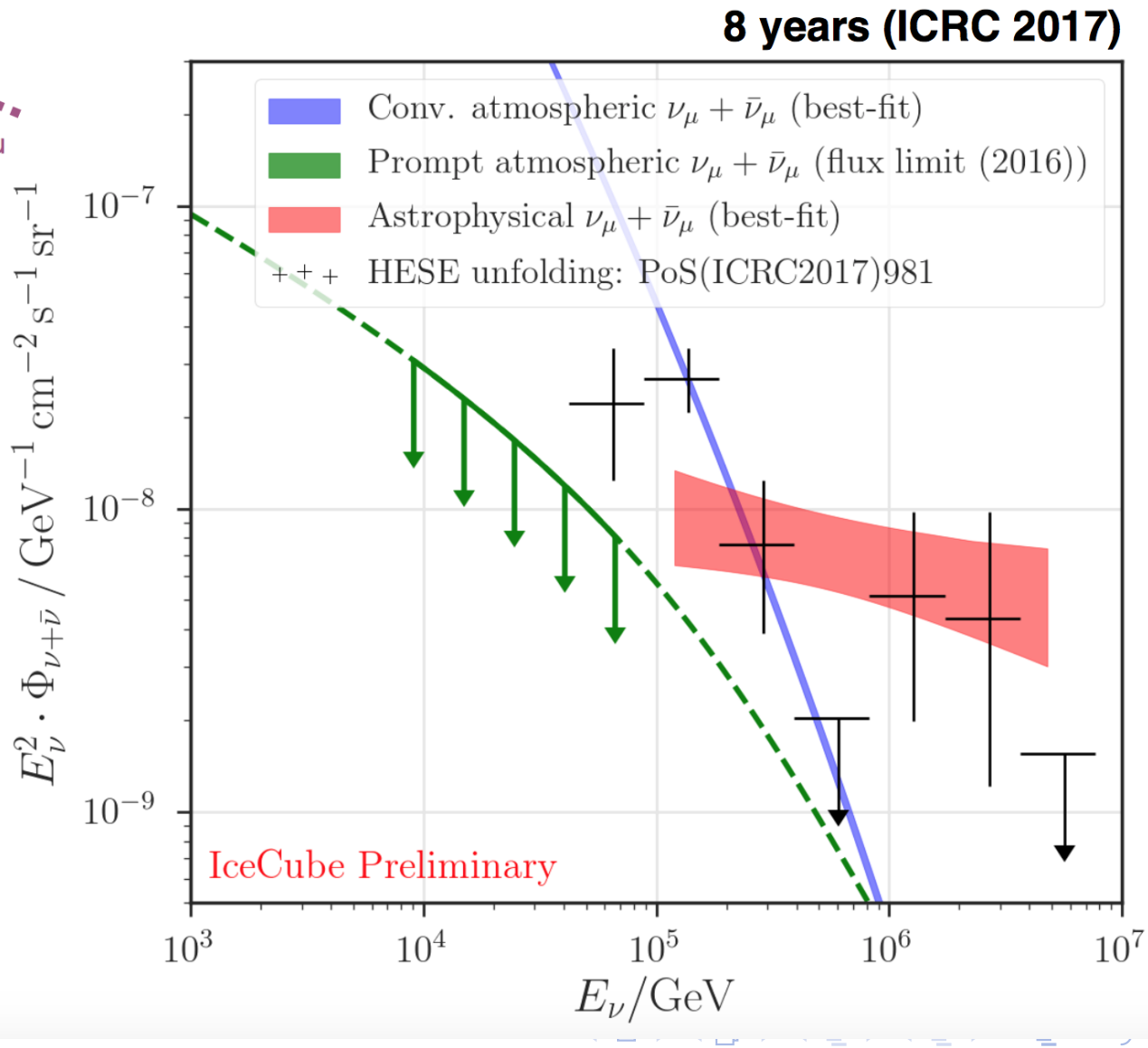
Zenith distribution incompatible with atmospheric origin



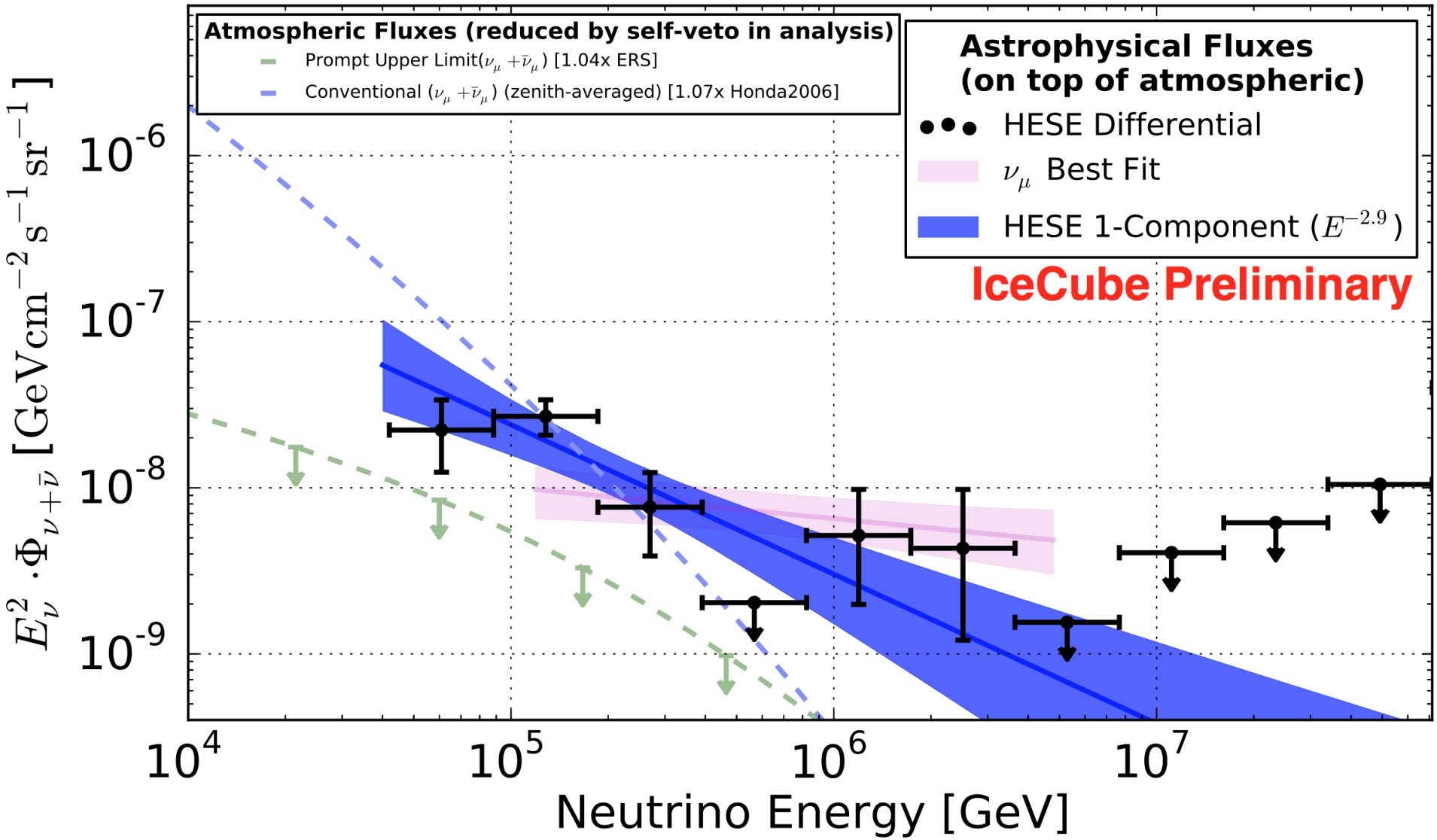
Observations by IceCube & Constraints from ANTARES



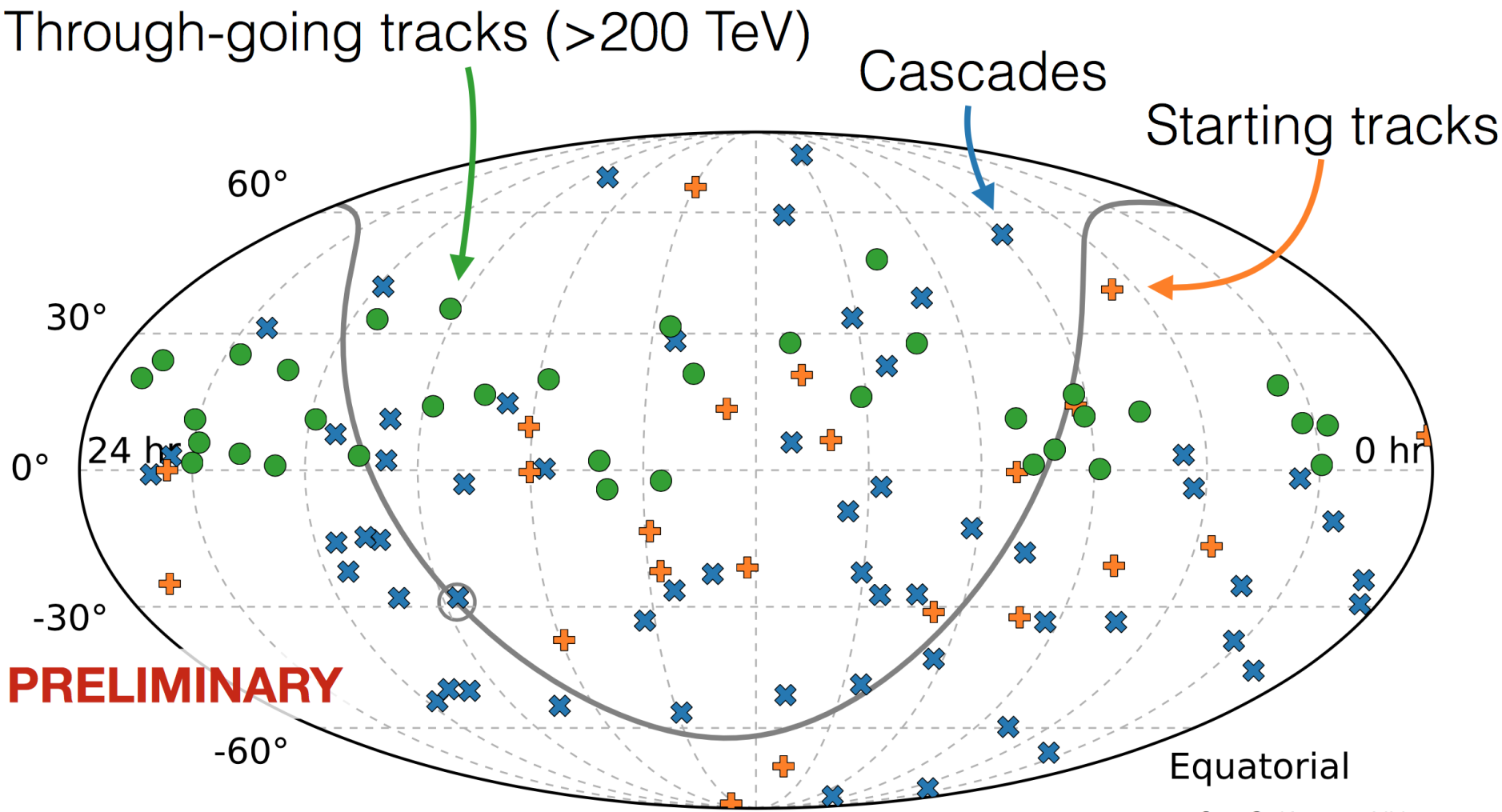
- Selected horizontal and up-going muon tracks
- Sensitive to astrophysical neutrinos above ~120 TeV
- Power law index: 2.19±0.10



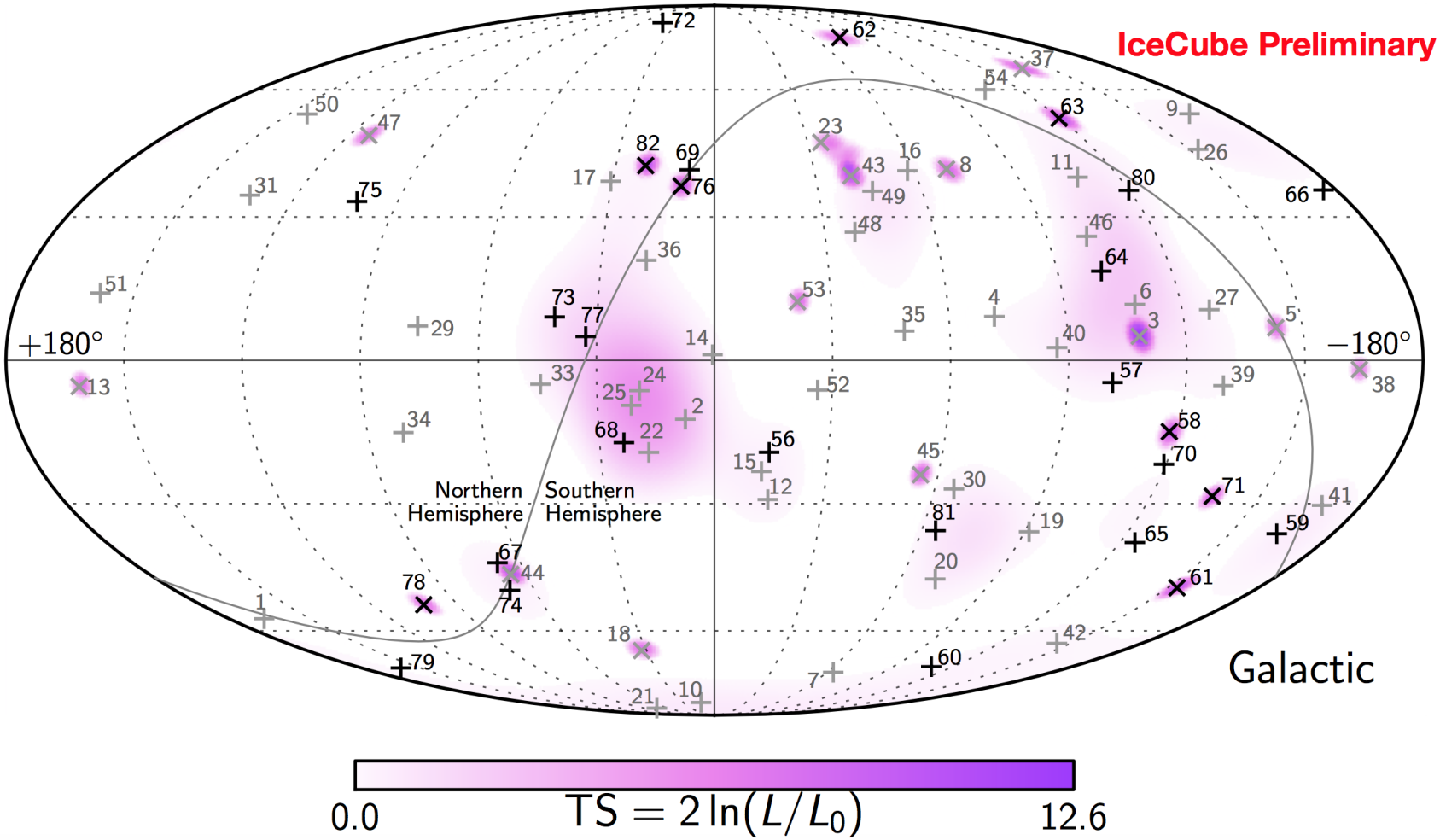
Observations by IceCube & Constraints from ANTARES



Observations by IceCube & Constraints from ANTARES



Observations by IceCube & Constraints from ANTARES

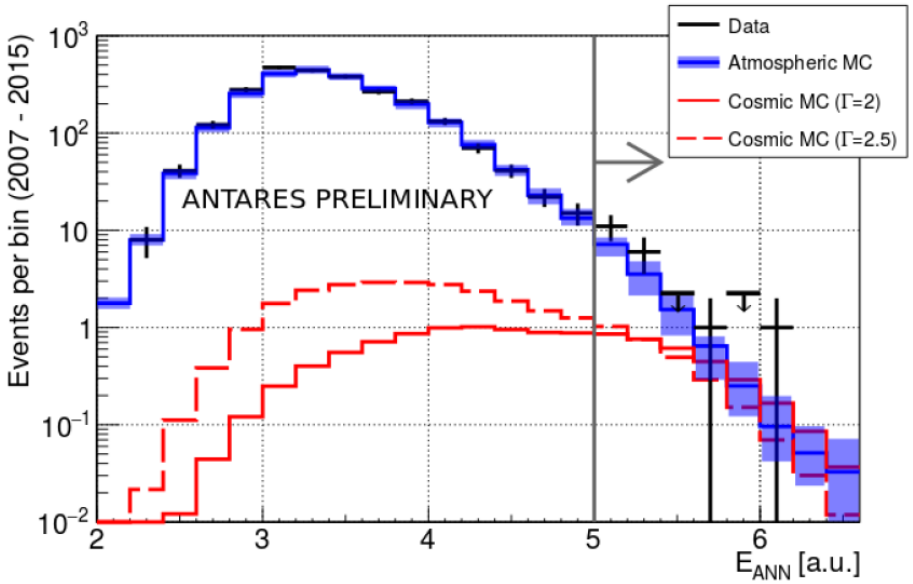


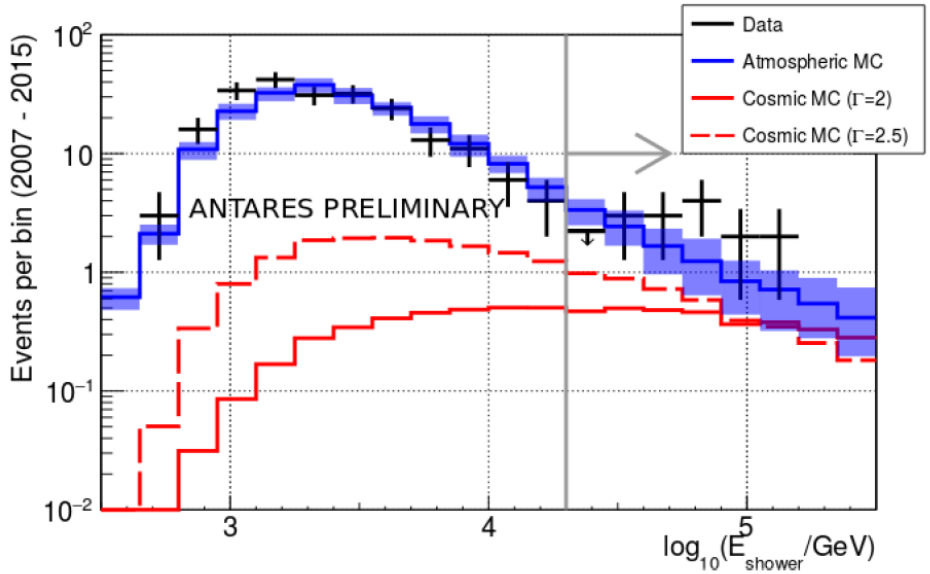
No evident clustering of events yet

Hotspot near Galactic Center ?

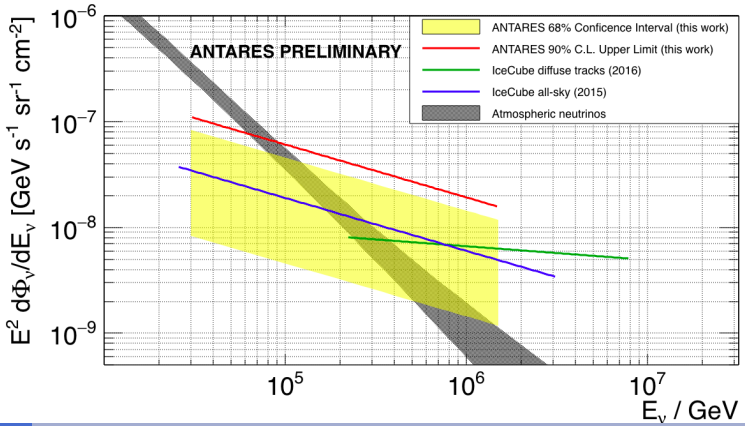
→ ANTARES

Does ANTARES see the astrophysical neutrinos ?

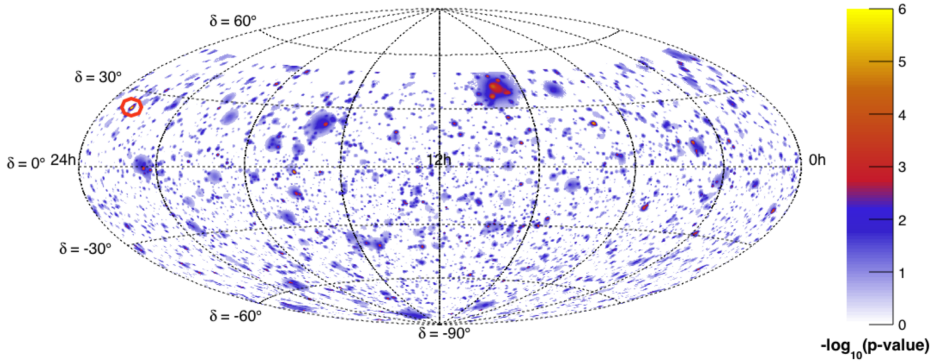


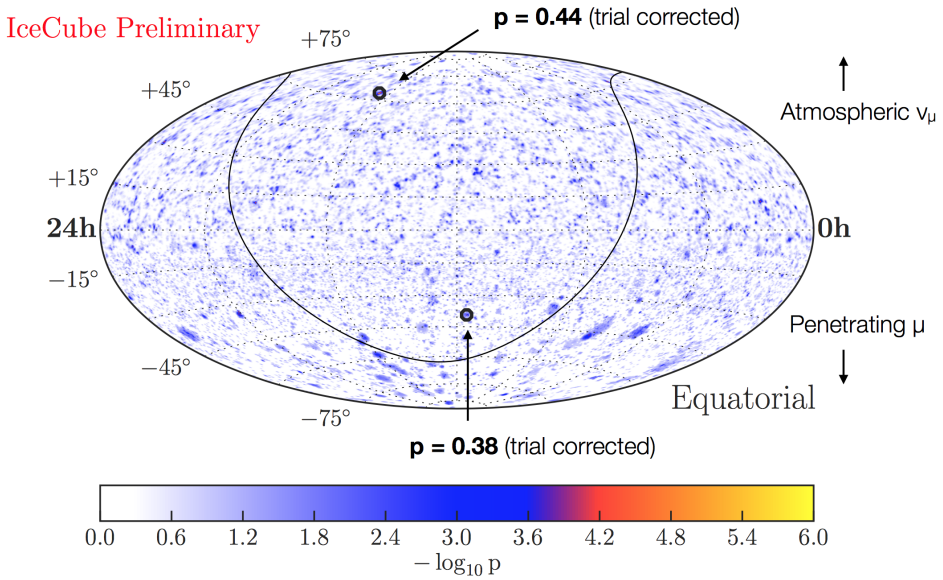


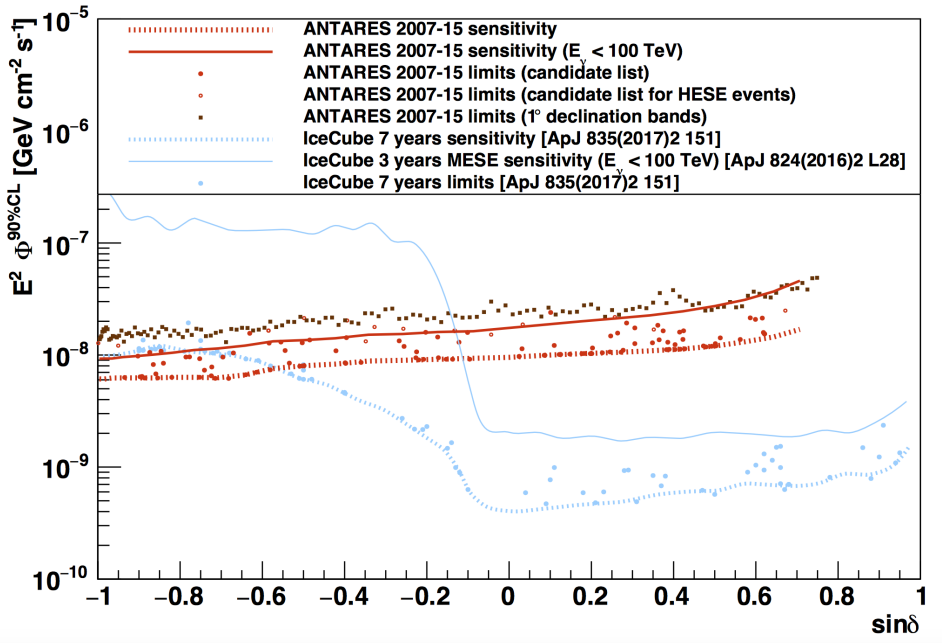
- 33 events observed, 24 ± 7 expected from Background, 8 from ICECUBE Flux
- 2008-2015 : Excess is not significant but compatible with ICECUBE Signal

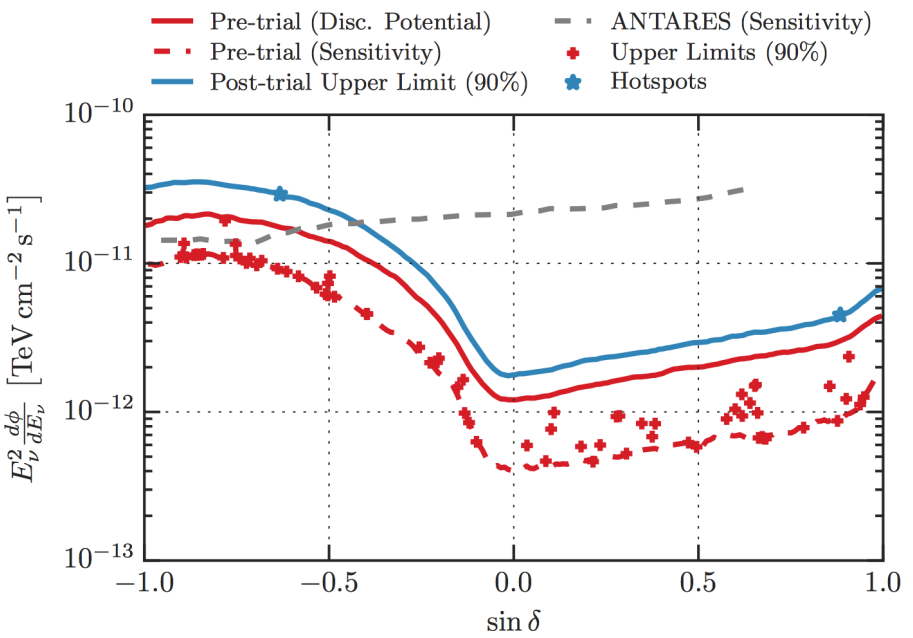


Where are the sources - Point-Source searches

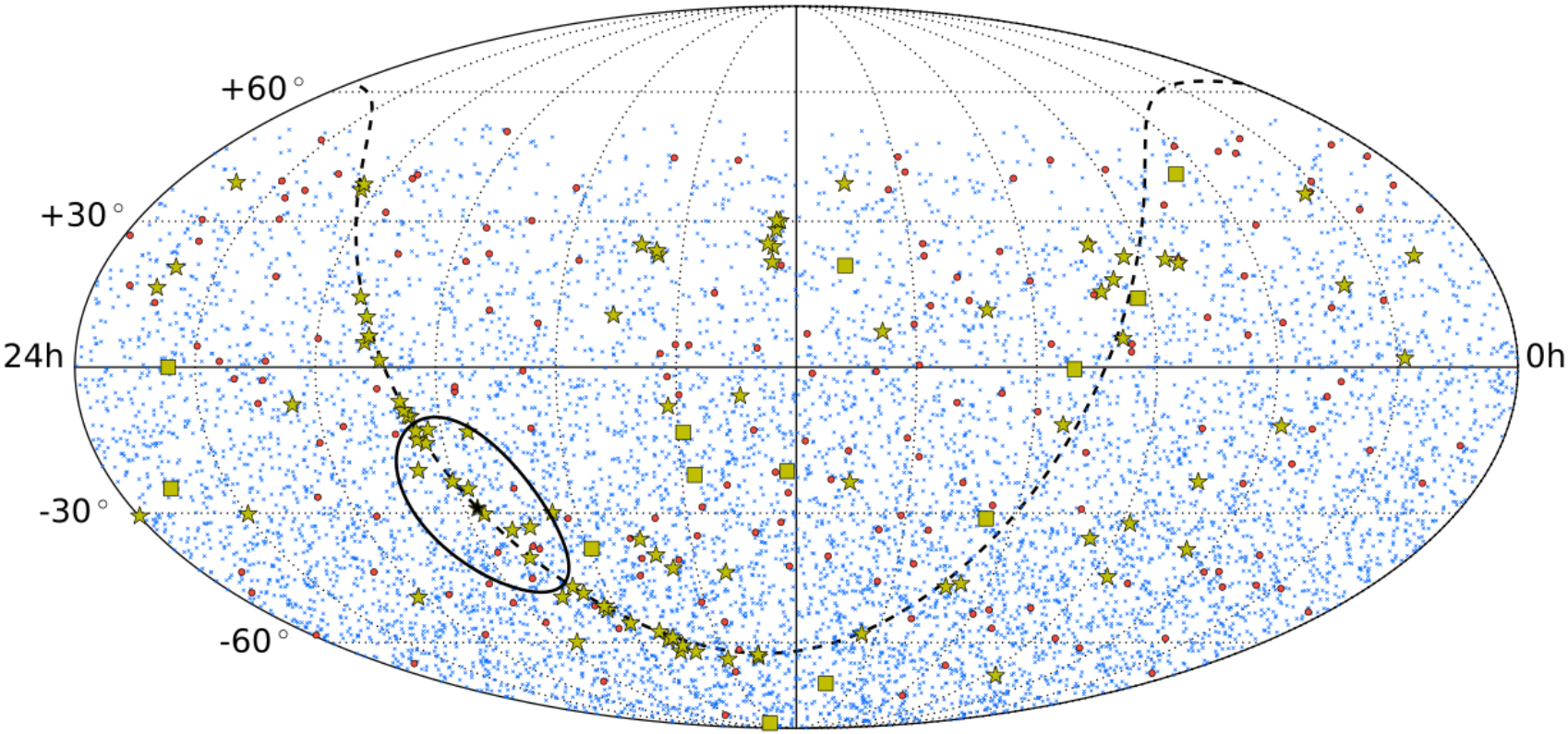




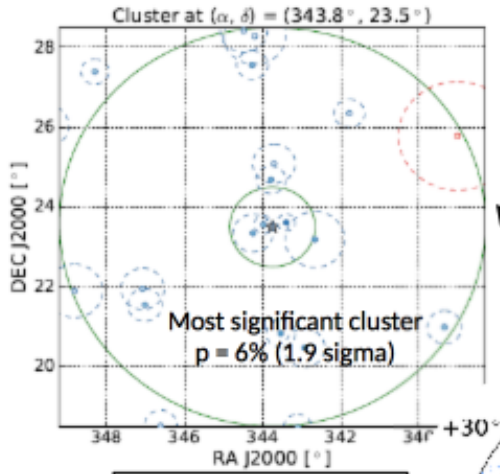




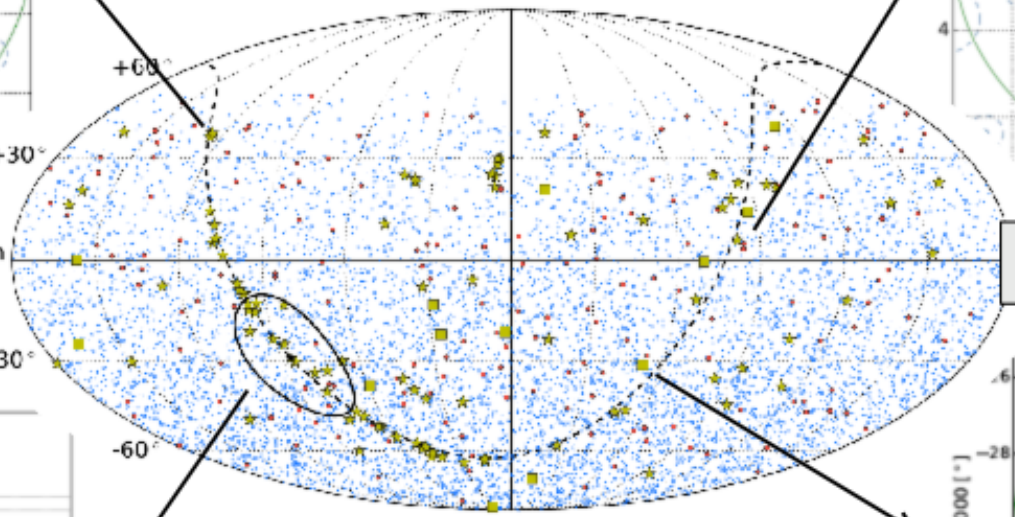
Where are the sources - Point-Source searches

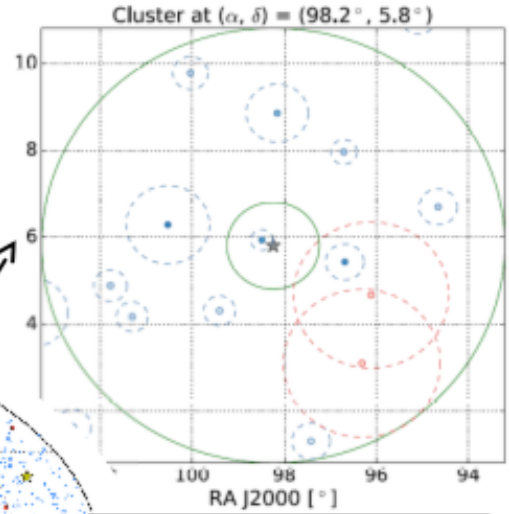


Where are the sources - Point-Source searches



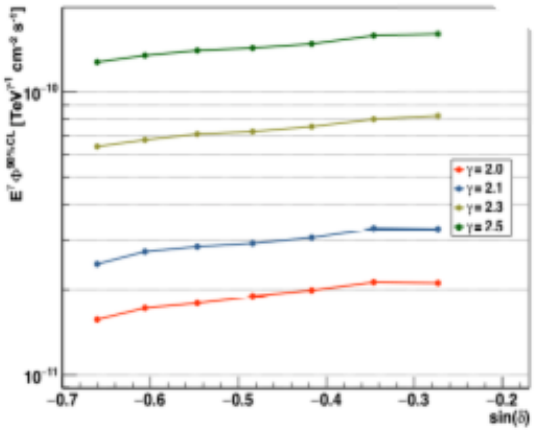
Most significant cluster
p = 6% (1.9 sigma)

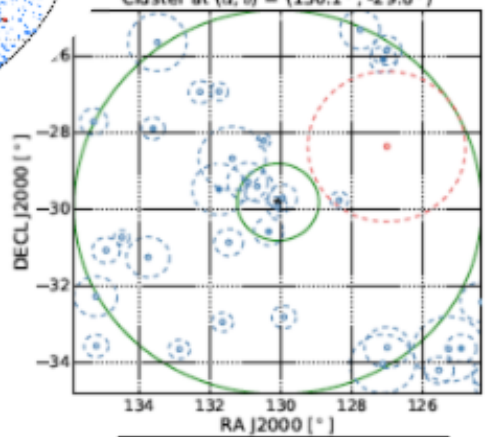




Most significant candidate source
HESSJ0632+057 **p = 13%**

Exclude point source near
Galactic Center

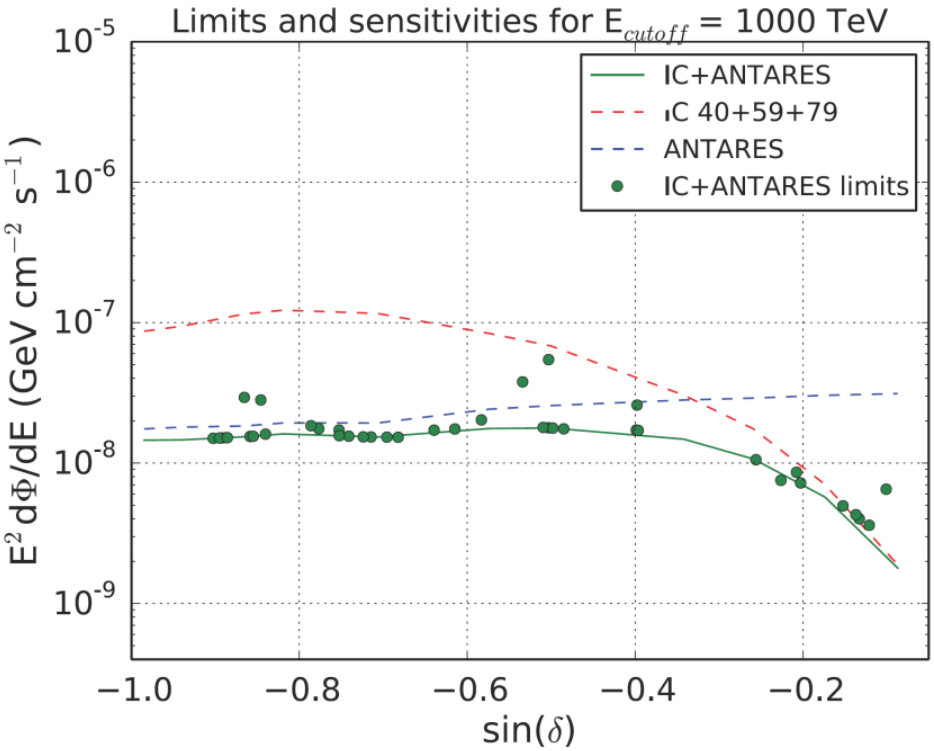


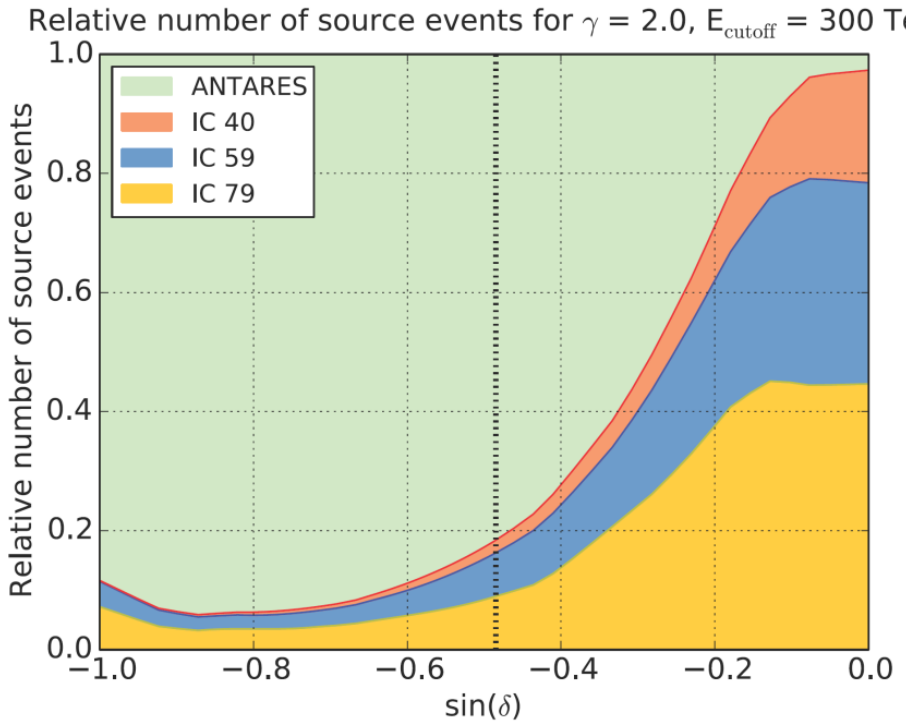


Most significant HESE track
p = 20%

- Track
- Cascade
- Source candidate
- HESE track

Where are the sources - Point-Source searches





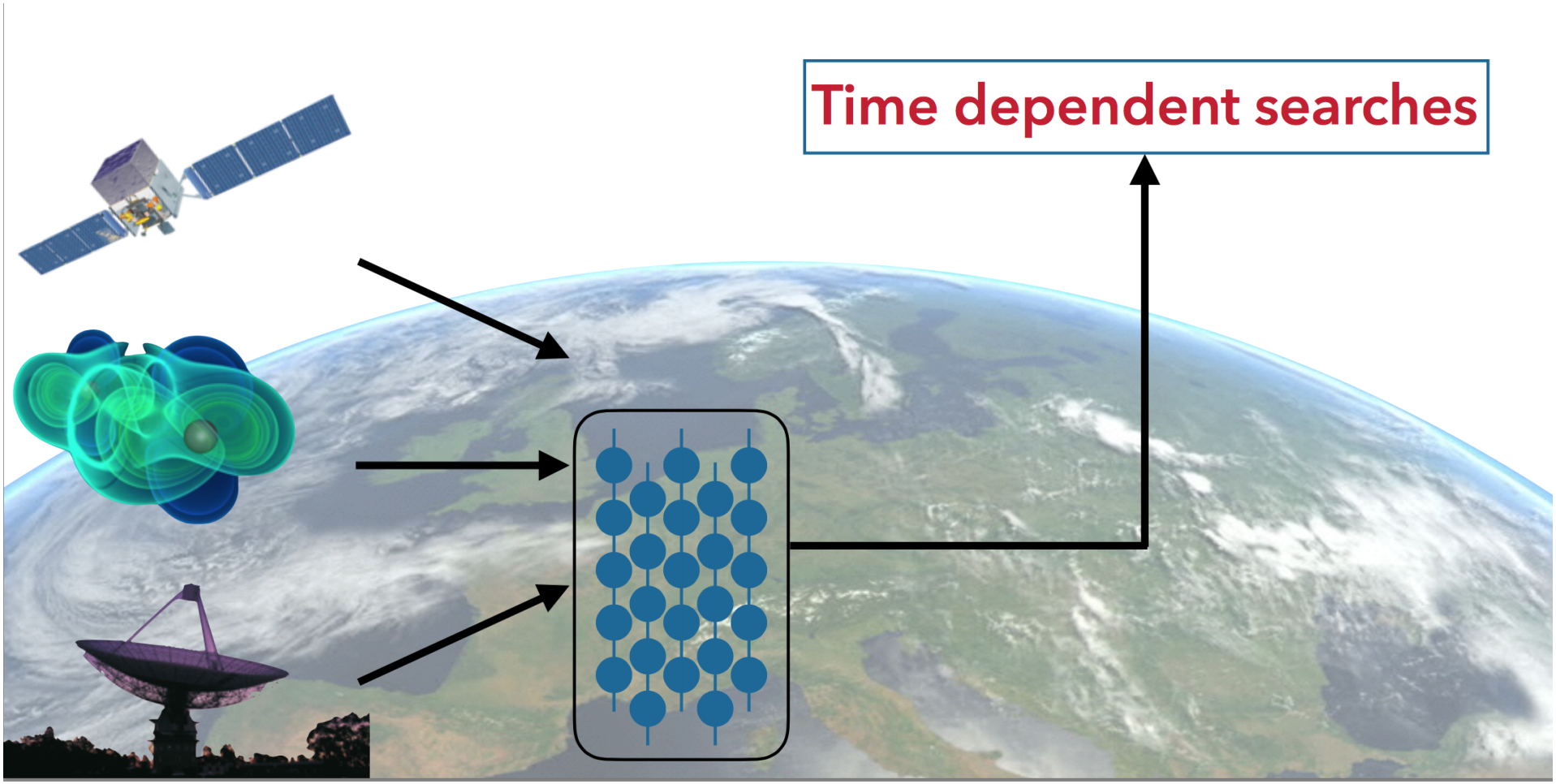
A real complementarity between IceCube and ANTARES

- ANTARES below 100 TeV + Southern Sky
- IceCube above PeV + Northern Sky

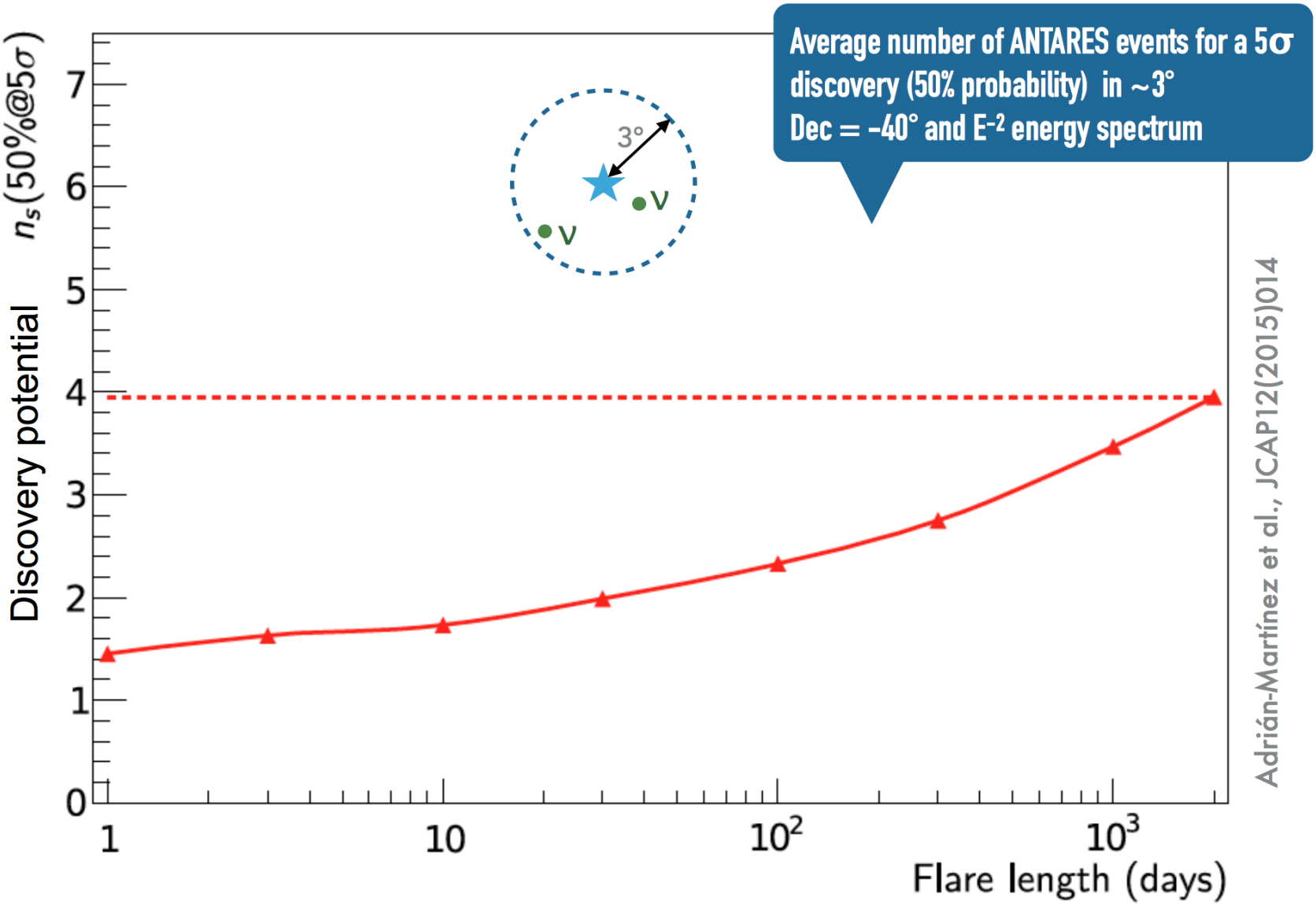
Astrophys. J. 823 :65,2016 - arxiv.org/abs/1511.02149

High Energy Neutrino Astronomy - Where do we stand ?

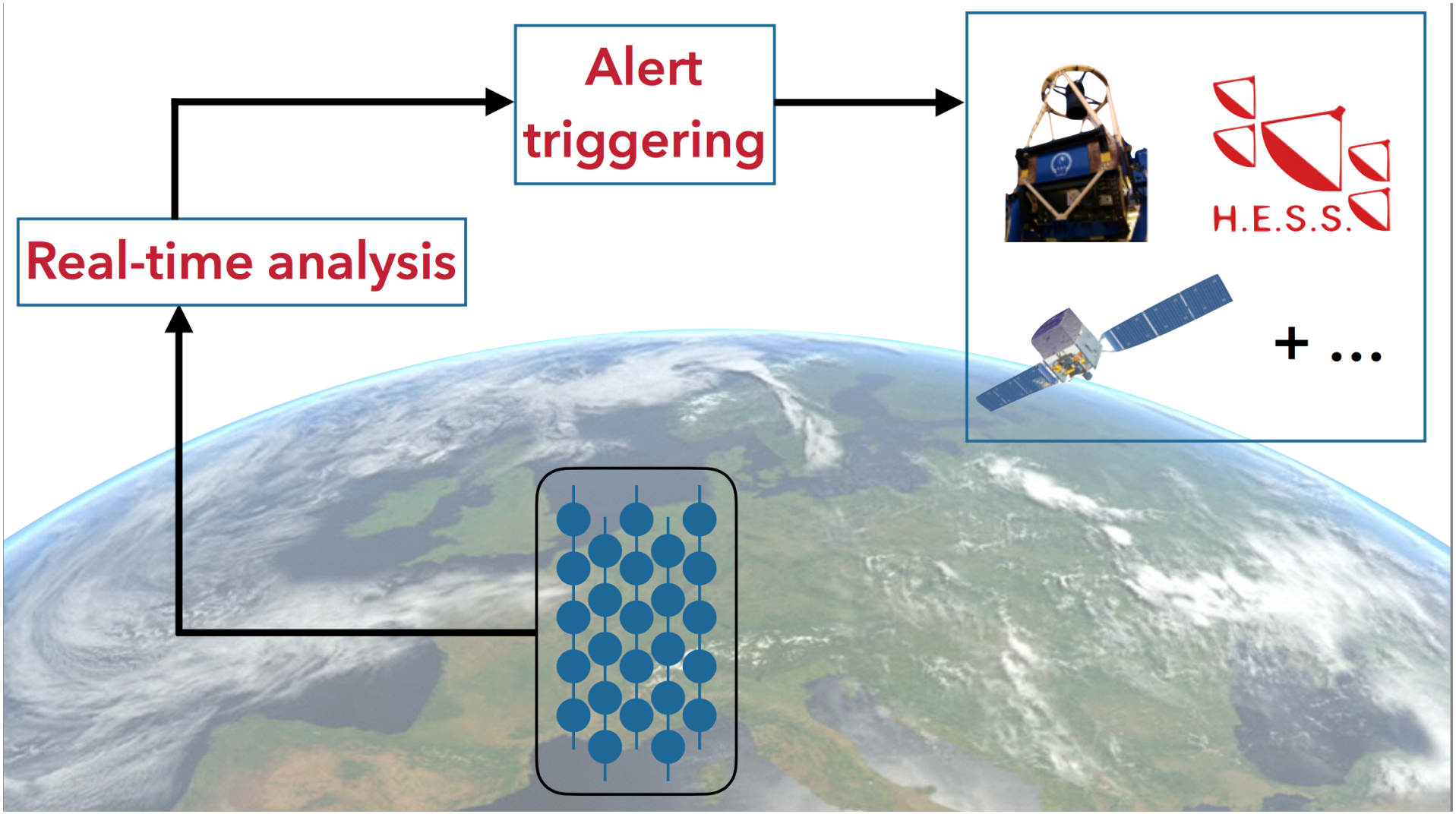
Multi-Messenger Searches



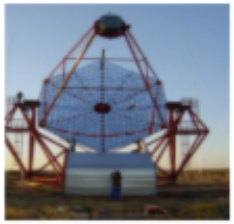
Multi-Messenger Searches

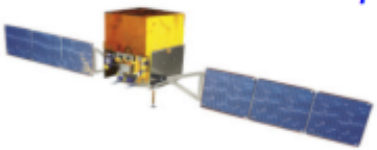


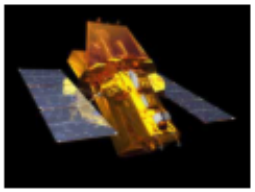
Multi-Messenger Searches



Multi-Messenger Searches







GeV-TeV γ-rays

Fermi, HESS, HAWC

UHECR

Auger, TA

HE neutrinos

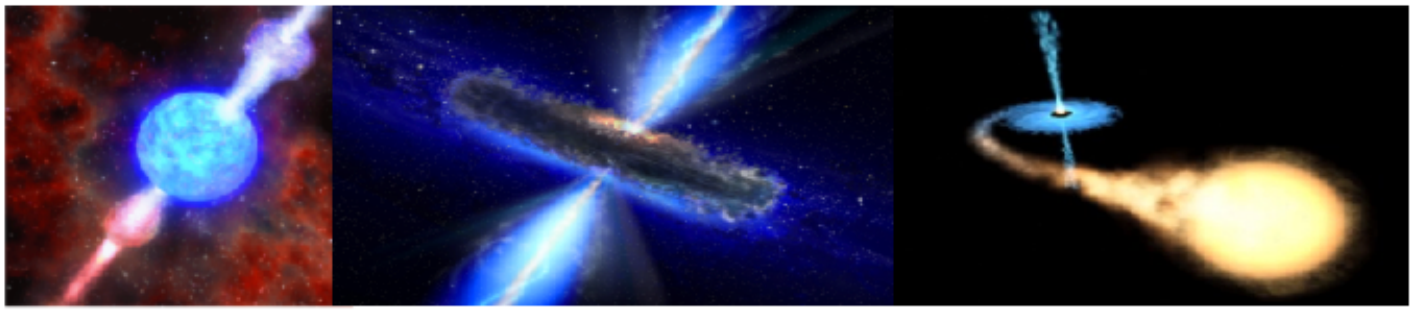
Radio-Visible-X

MWA, SUPERB
TAROT, ZADKO, MASTER,
Swift

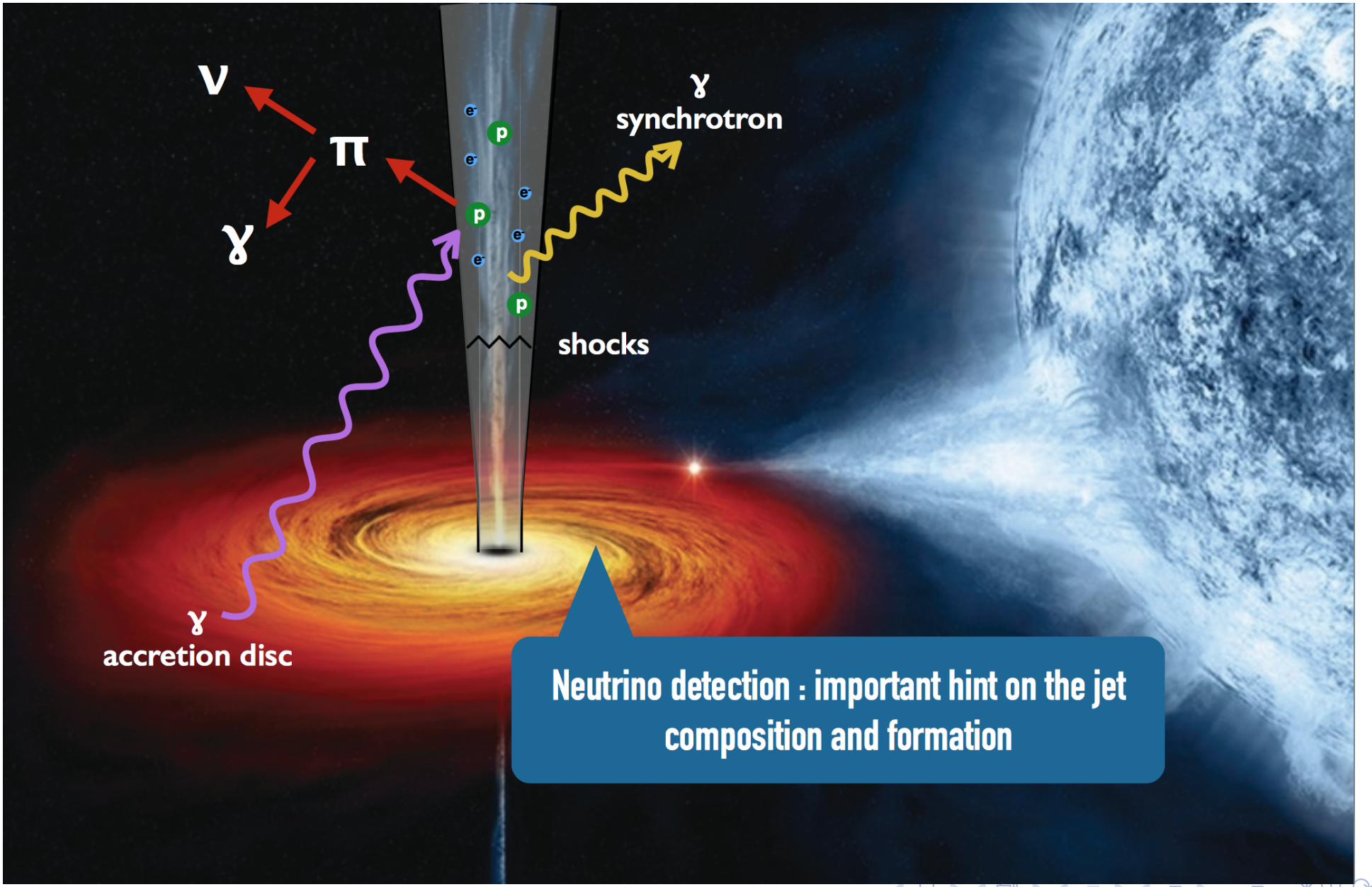
Grav. Waves

LIGO-VIRGO-EGO

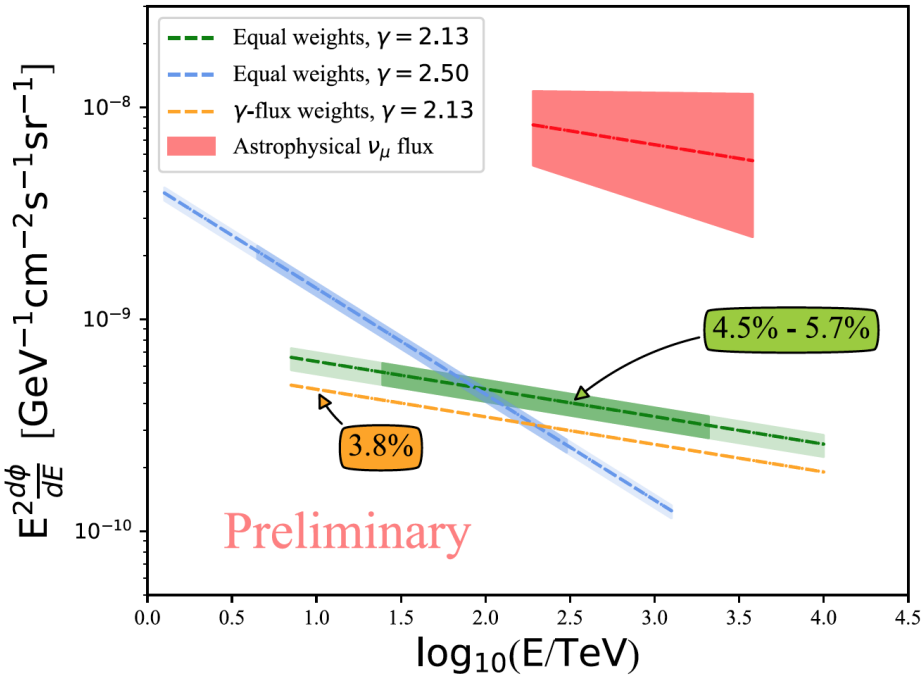
GRBs **AGNs** **X-Ray Binaries**

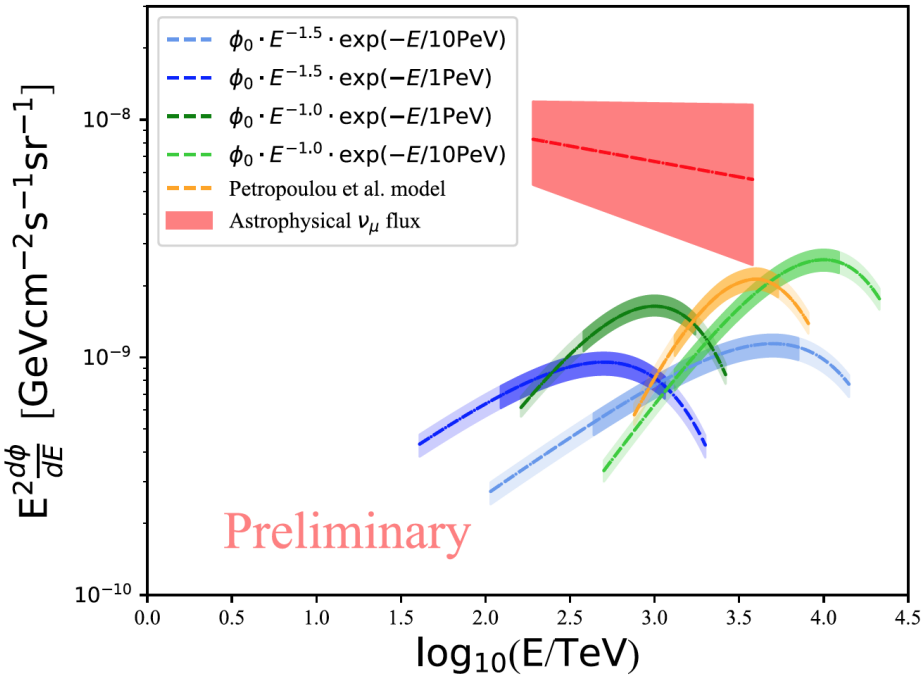


Targeted Searches : Blazars ?



Targeted Searches : Blazars ?

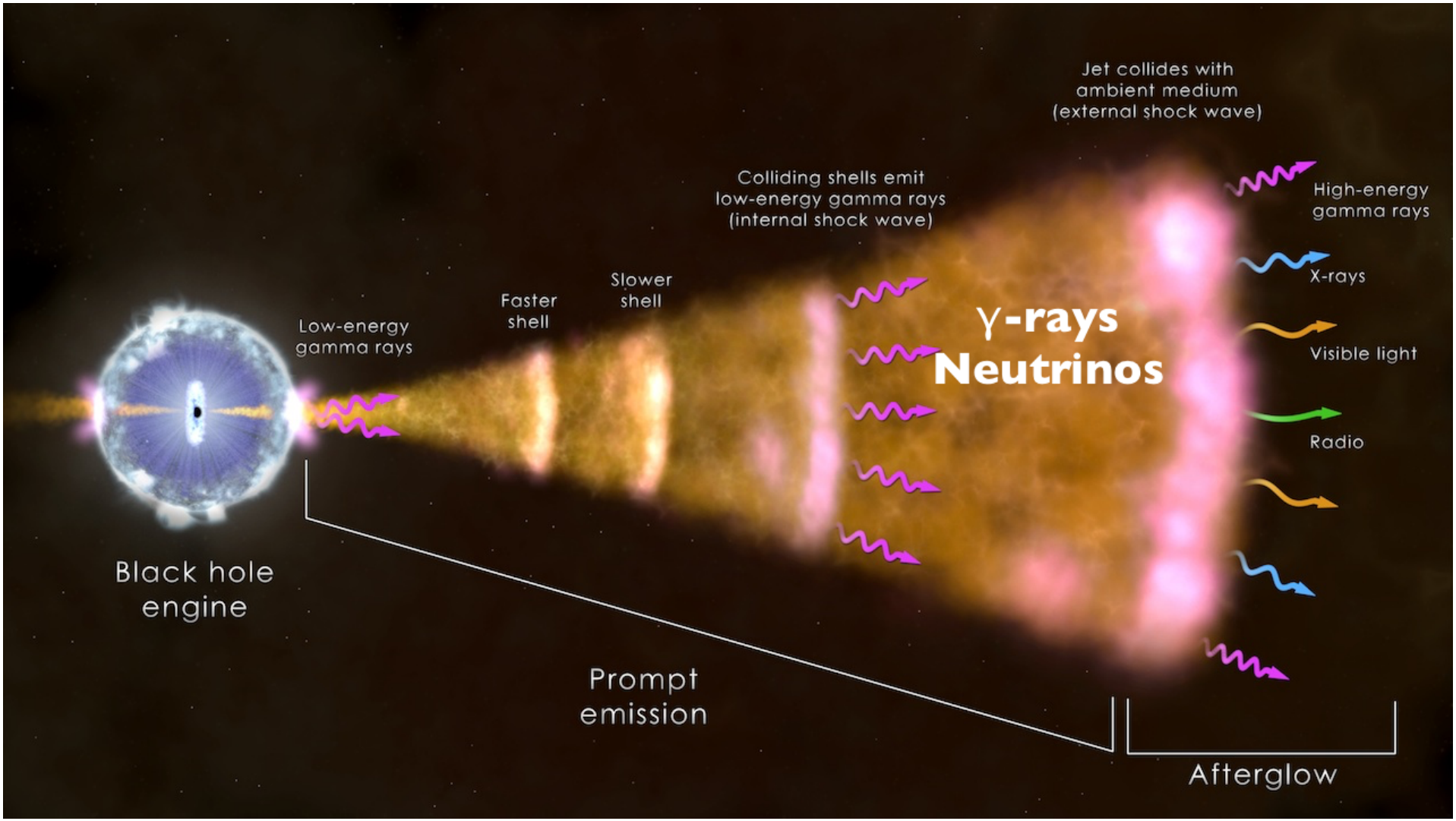




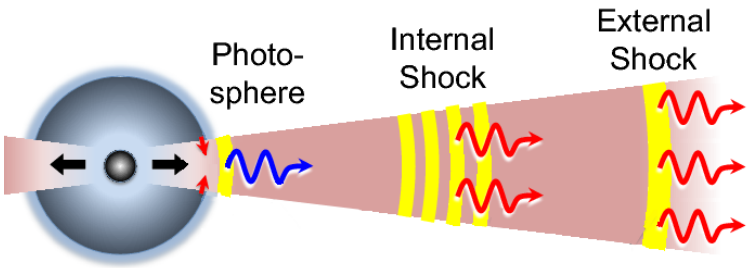
Blazars account for :

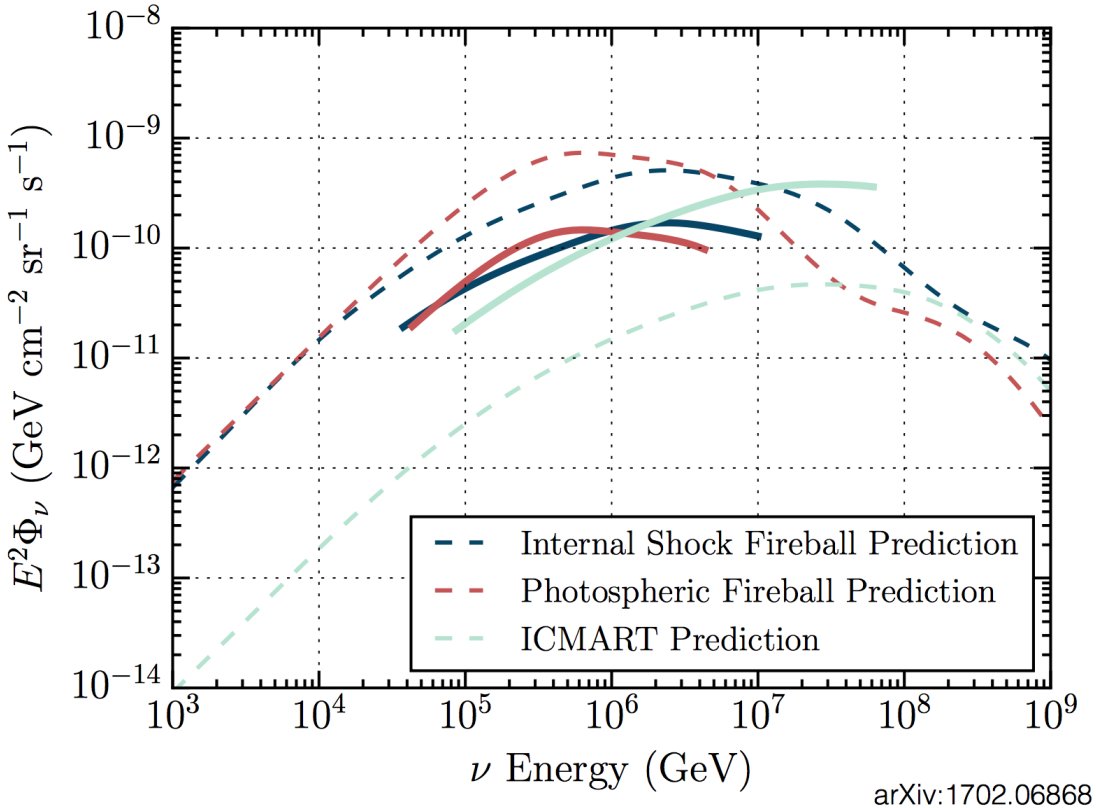
- 85% of extragalactic γ background
- but $< 6 - 27\%$ of the IceCube neutrino flux

Targeted Searches : Gamma-Ray Bursts ?



Targeted Searches : Gamma-Ray Bursts ?

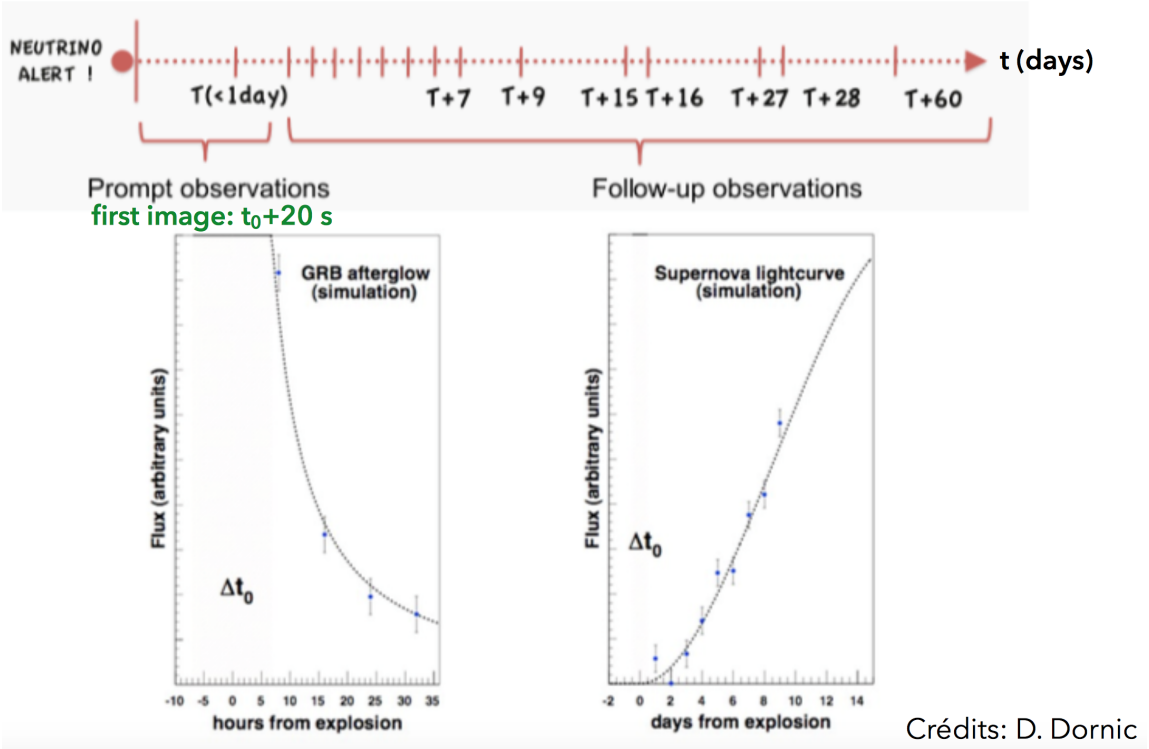




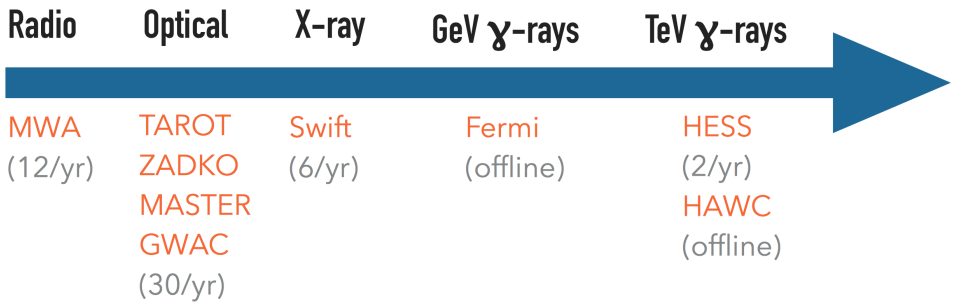
arXiv:1702.06868

Prompt emission from GRBs can produce <1% of the observed neutrino flux

Neutrino Alerts : Rapid Follow-up in ANTARES

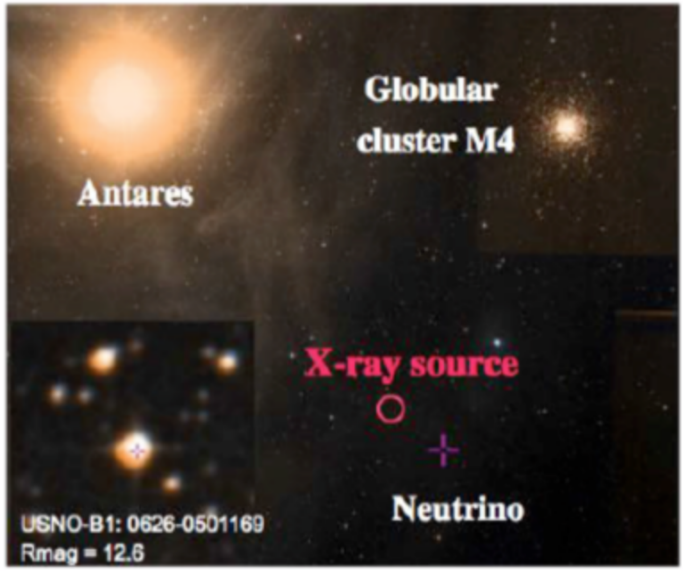


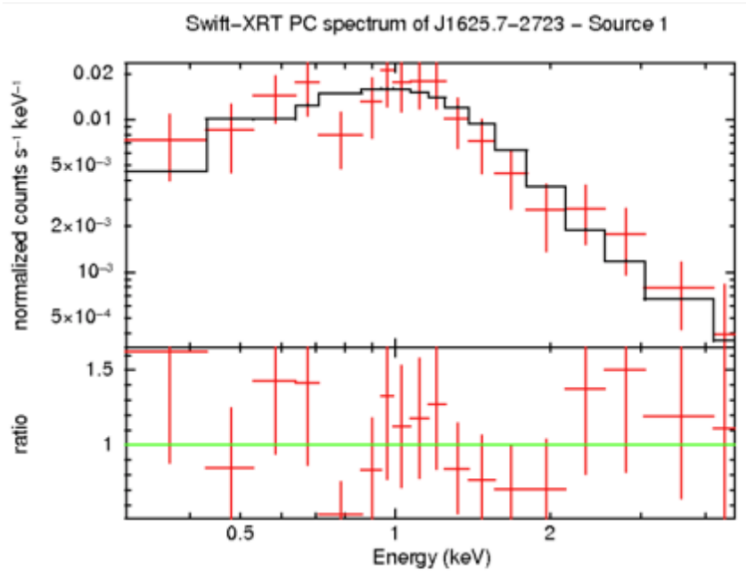
See ICRC2017 in Korea : PoS(ICRC2017)

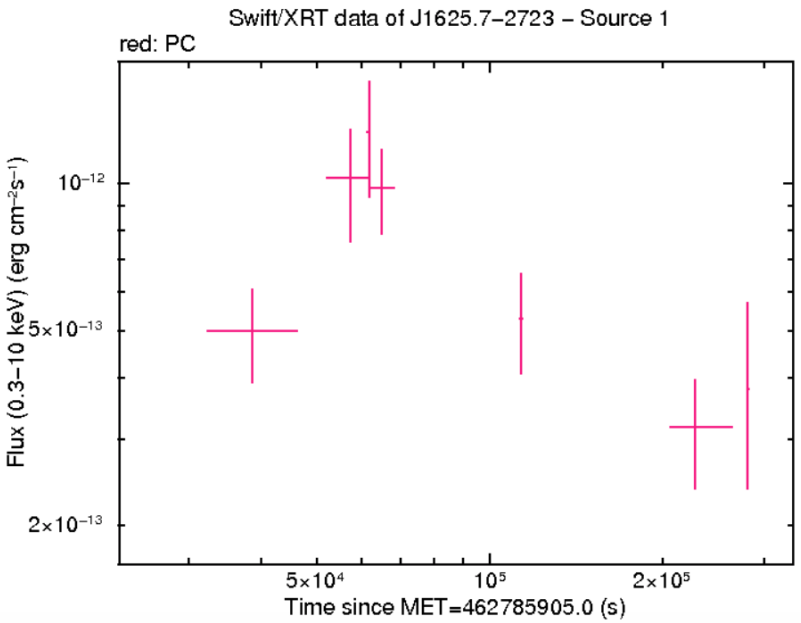


Neutrino Alerts : ANTARES TAToO - ANT150109A

- E ~50-100 TeV
- Error box=18 arcmin
- Sent in 10s to Swift and Master
- Swift obs: +9h
- Master obs: +10h

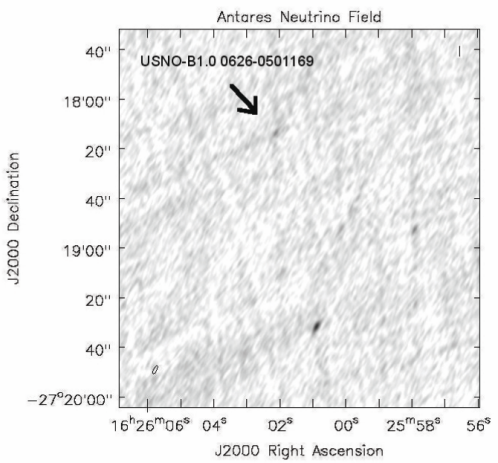


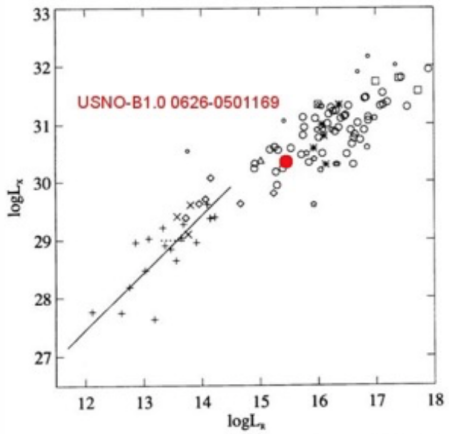




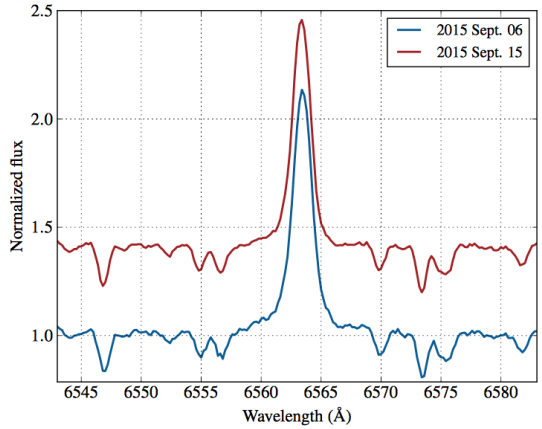
Neutrino Alerts : ANTARES TAToO - ANT150109A

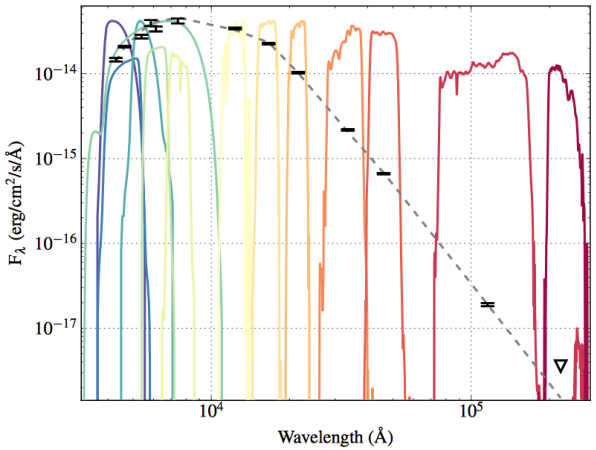
VLA follow-up ATel #7999

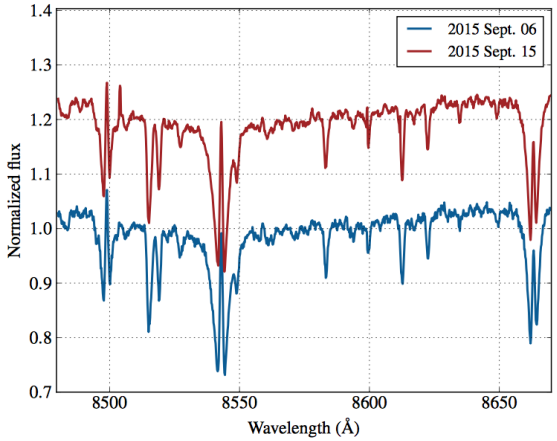




VLT / X-Shooter follow-up







Probably an active X-ray star in a binary system (RS CVn)
Probability of chance coincidence : $\sim 3\%$

Neutrino Alerts : IceCube neutrinos

Date	Type	RA	Dec	50% Error
2016/04/27	HESE	240.6 deg	9.3 deg	0.6 deg
2016/07/31	EHE + HESE	214.5 deg	- 0.3 deg	0.35 deg
2016/08/06	EHE	122.8 deg	- 0.7 deg	0.11 deg
2016/08/14	HESE	200.3 deg	- 32.4 deg	
2016/11/03	HESE	40.9 deg	12.6 deg	

Optical

Observer	Result
iPTF	3 transients, all AGN
MASTER	no detection
PanSTARRS	7 SN candidates

Gamma-Rays

Observer	Result
IPN	no detection
Fermi-LAT	5 unrelated blazars
Fermi-GBM	no detection
FACT	no detection
VERITAS	no detection
HAWC	no detection
MAGIC	no detection

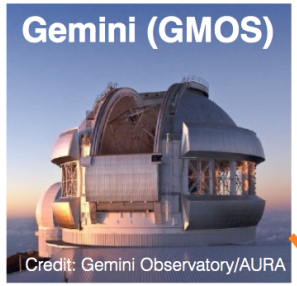
- No credible association detected yet, either in IceCube or ANTARES

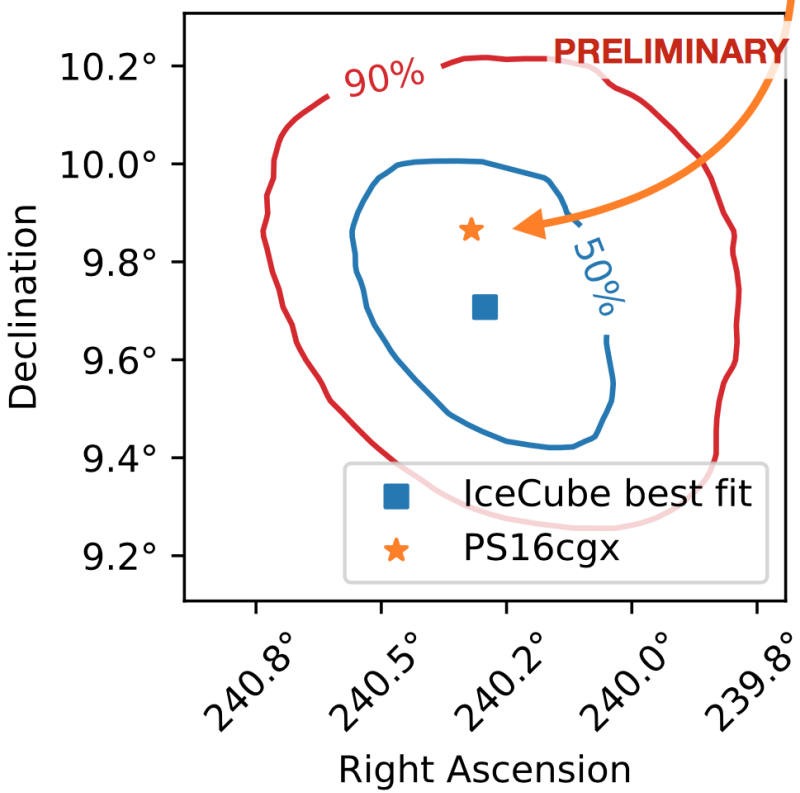
EHE : Extremely High Energy (> 10 PeV)
HESE : High Energy Starting Event (20 TeV - 10 PeV)

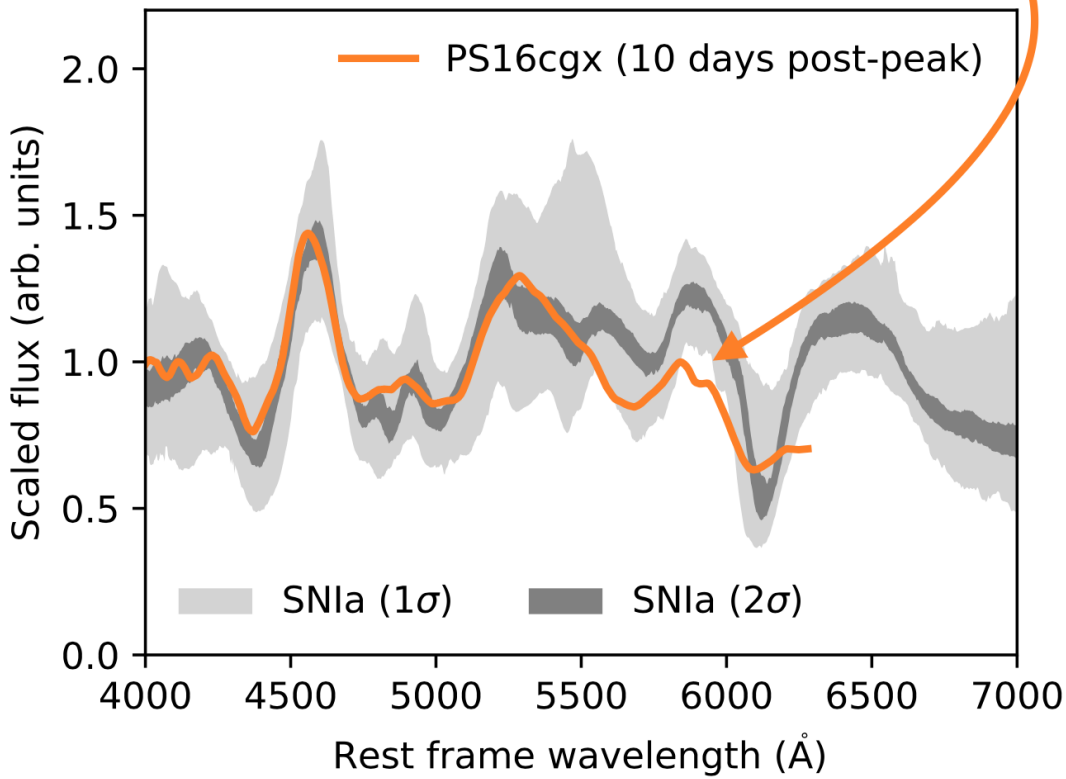
Neutrino Alerts : IceCube neutrinos

PAN-Starrs followed up IceCube HESE alert on 2016-04-27 and found a recent supernova at z=0.3:

- Optical spectroscopy 10, 20 days post-peak
- Features atypical for SNIa, but not sufficient to exclude

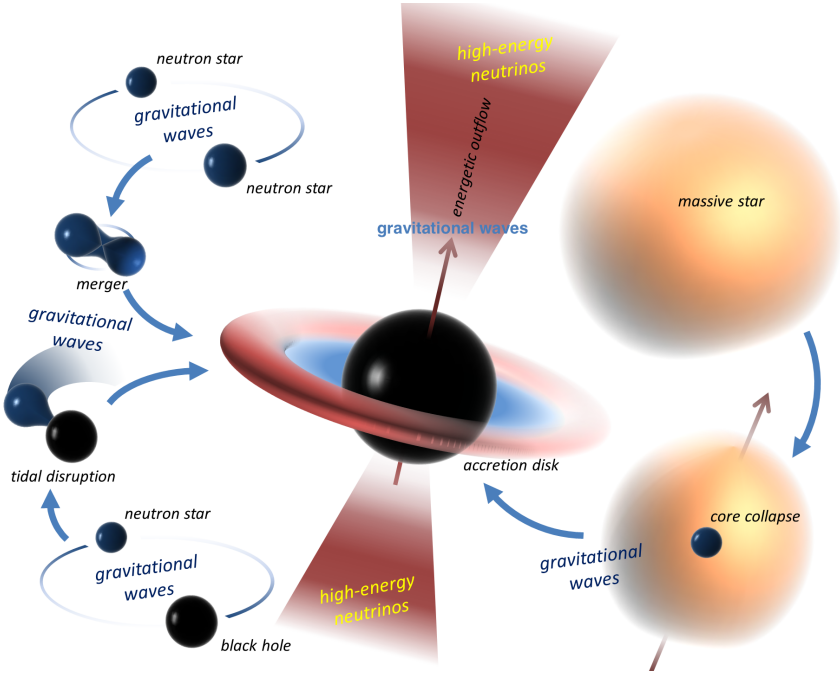




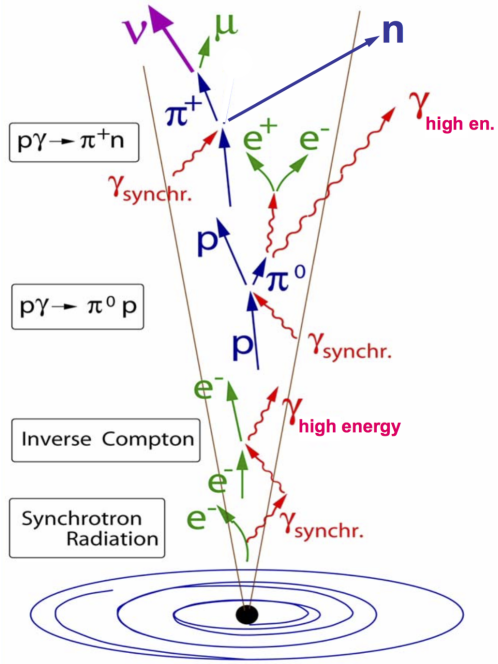


Chance probability { if **Ic** (associated with GRBs): **<1%**
if **Ia** (no HE neutrinos expected): **<10%**

Gravitational Waves (GW) + High Energy Neutrinos (HEN)



[↪ I. Bartos et al., Class. Quantum Grav. 30 (2013) 123001]



[↪ U. Katz, Prog. Part. Nucl. Phys. 67 (2012) 651-704]

Astronomy with GW

- Collapse/Merger ⇒ Jet ?

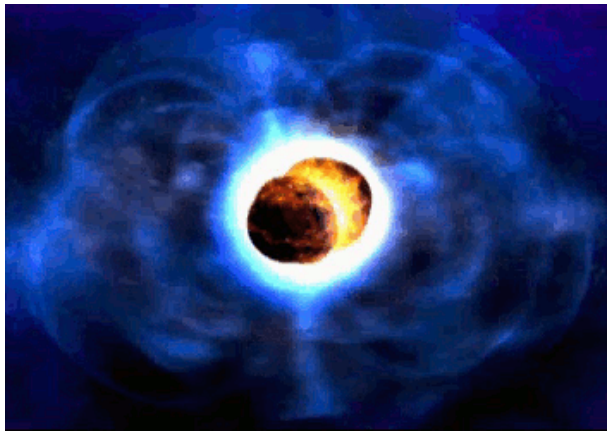
- ADVANCED LIGO : since 09/2015
- ADVANCED VIRGO : Summer 2017

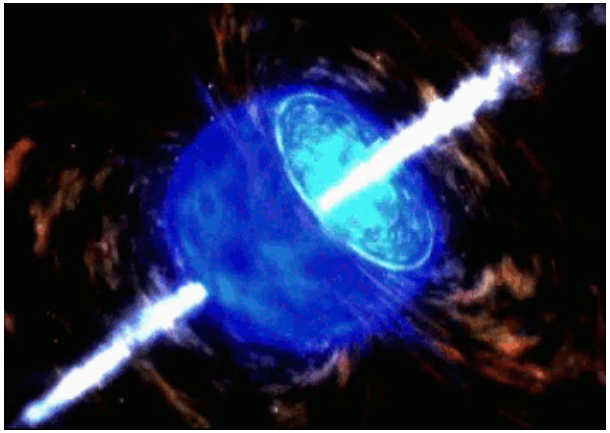
Astronomy with HEN

- HEN produced in Jet

- ANTARES continuously since 2008
- Angular resolution $\approx 0.4°$ above 10 TeV

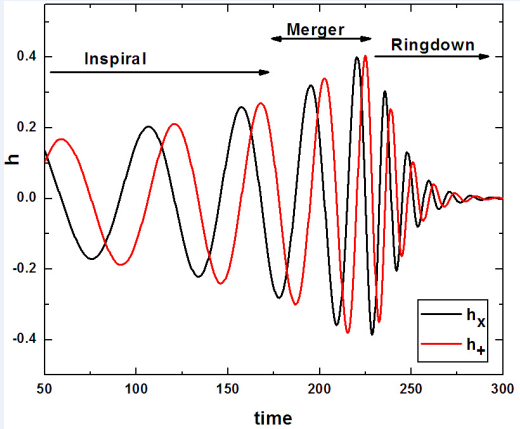
Gravitational Waves (GW) + High Energy Neutrinos (HEN)





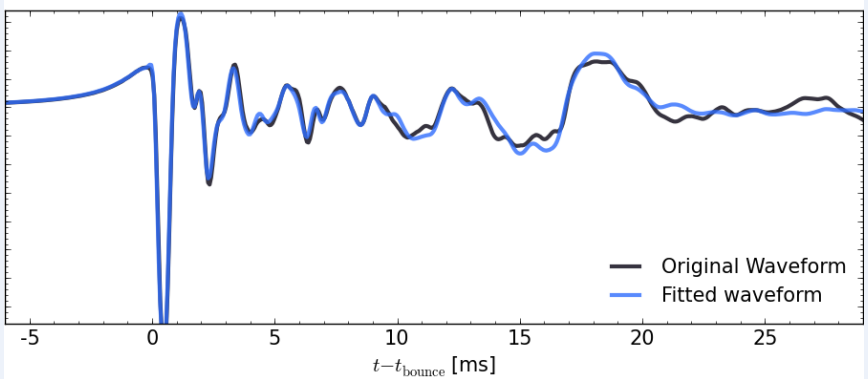
Short Gamma-Ray Bursts (GRBs)

Merger of Black Holes/Neutron Stars



Long GRBs

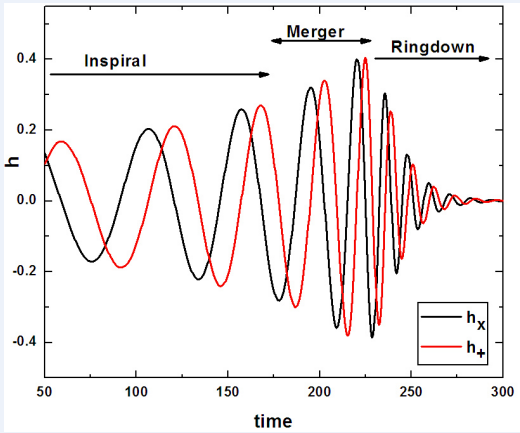
Collapsars - massive star collapse



Gravitational Waves (GW) + High Energy Neutrinos (HEN)

Short Gamma-Ray Bursts (GRBs)

Merger of Black Holes/Neutron Stars



- GW $\approx$ 100 Mpc

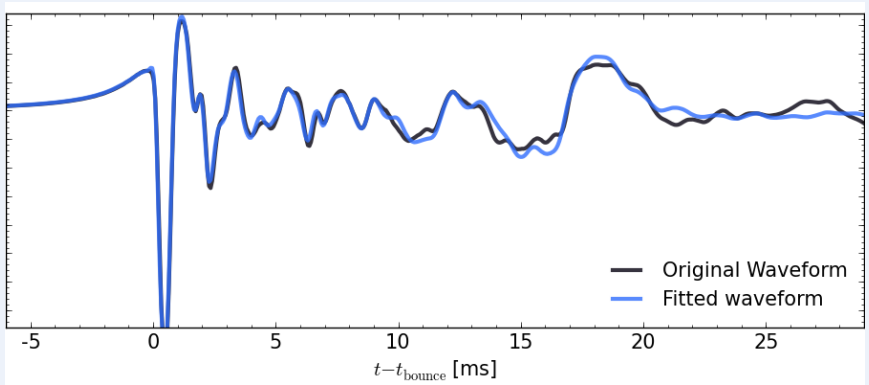
  [LIGO/VIRGO, ApJL, L21 (2016)]

- HEN $\approx$ 10 Mpc (ANTARES)

  [ANTARES, JCAP 06 (2013) 006]

Long GRBs

Collapsars - massive star collapse



- GW : realistically $\ll$ Mpc - $\mathcal{O}(10)$ Mpc

  [e.g. Gossan et al., PRD93 042002 (2016]

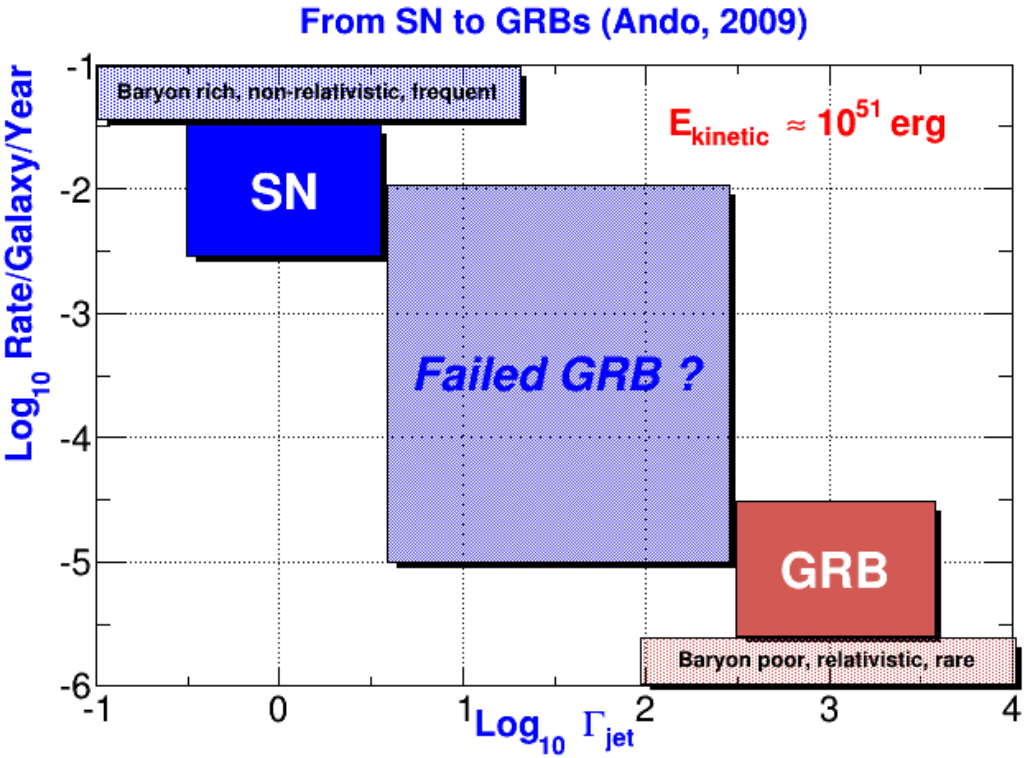
- HEN $\approx$ 20 Mpc (ANTARES)

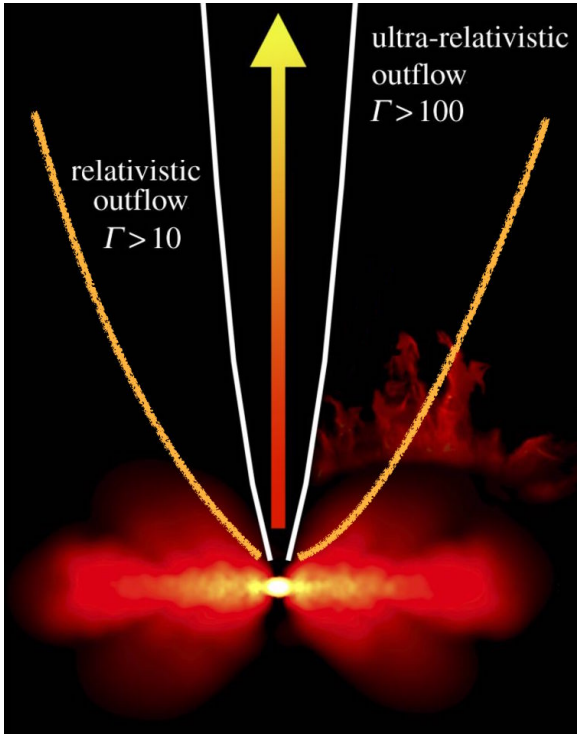
  [ANTARES, JCAP 06 (2013) 006]

Extragalactic sources potentially observable

Ideal GWHEN analysis = adjust GW+HEN selections to maximize Nb of detectable sources

Gravitational Waves (GW) + High Energy Neutrinos (HEN)



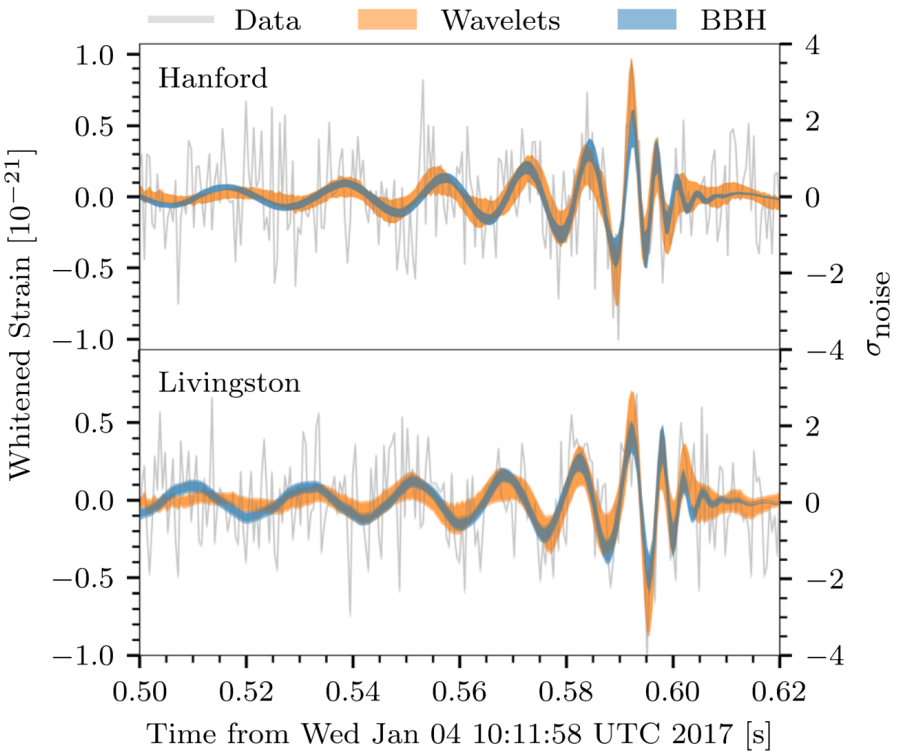


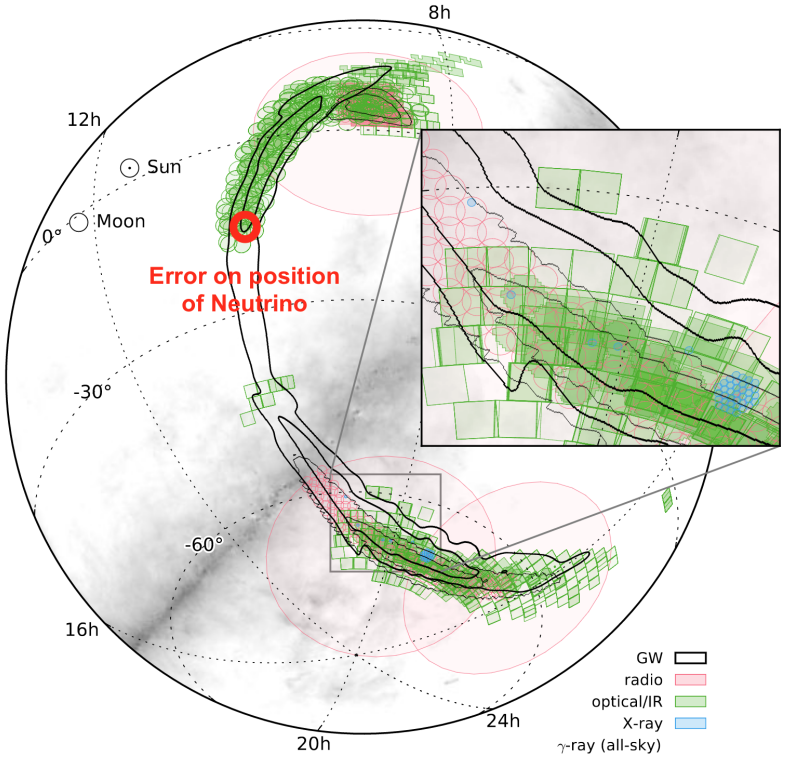
From Supernovae to Gamma-Ray Bursts

- SNe : frequent, baryon-rich, $\Gamma \sim 1$ + emission poorly beamed
- GRBs : rare, baryon-poor, $\Gamma \gg 1$ + emission in $\theta \sim 5°$
- Failed/low luminosity GRBs : $\theta \sim 30°$ + **no/weak electromagnetic emissions**

▸ S. Ando et al., Reviews of Modern Physics 85 (2013) 1401-1420

Gravitational Waves (GW) + High Energy Neutrinos (HEN)





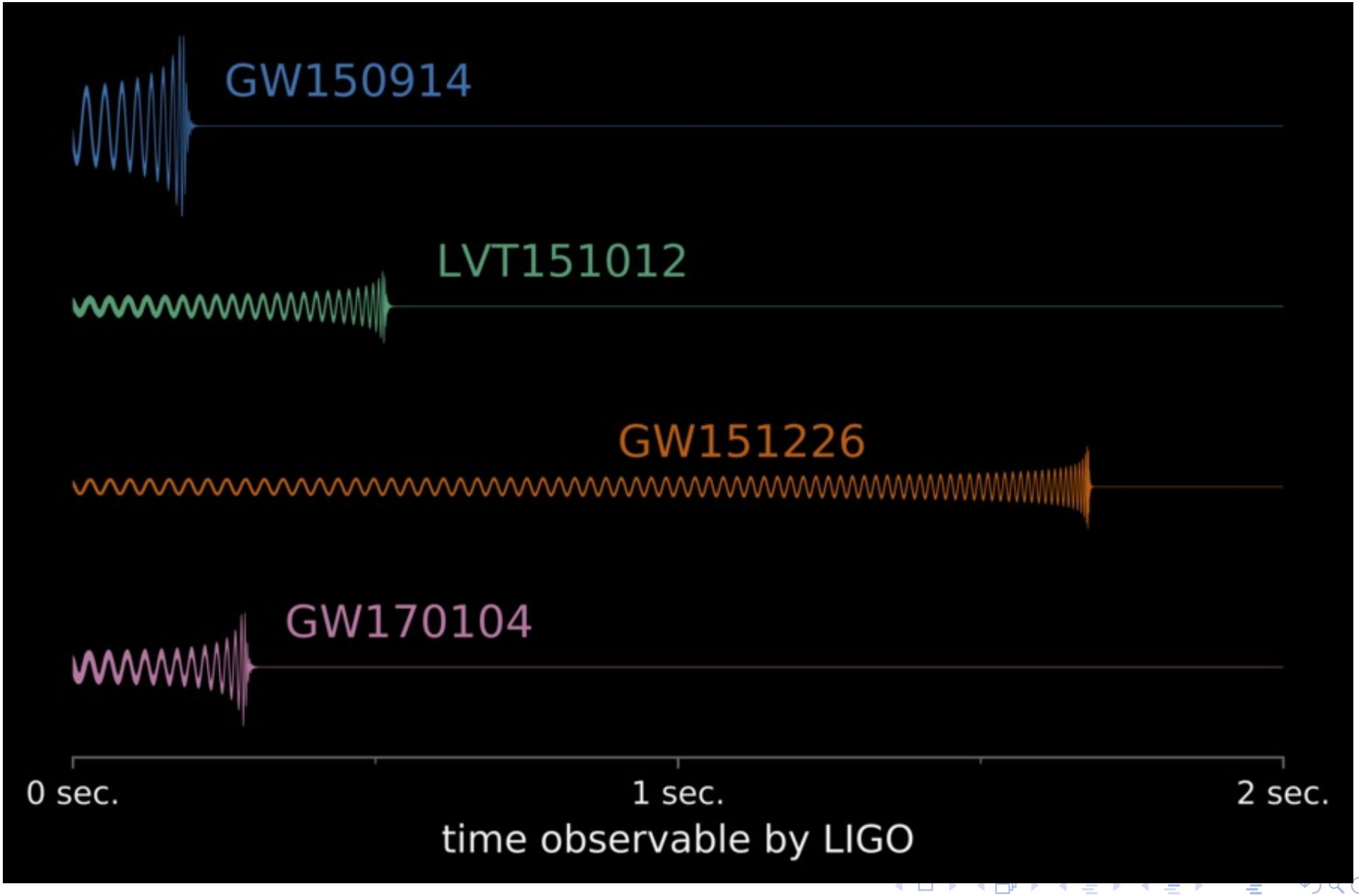
Accretion Disk not ruled out ?
[Here GW170104]

Perna et al ApJ Let.821 18 (2016)

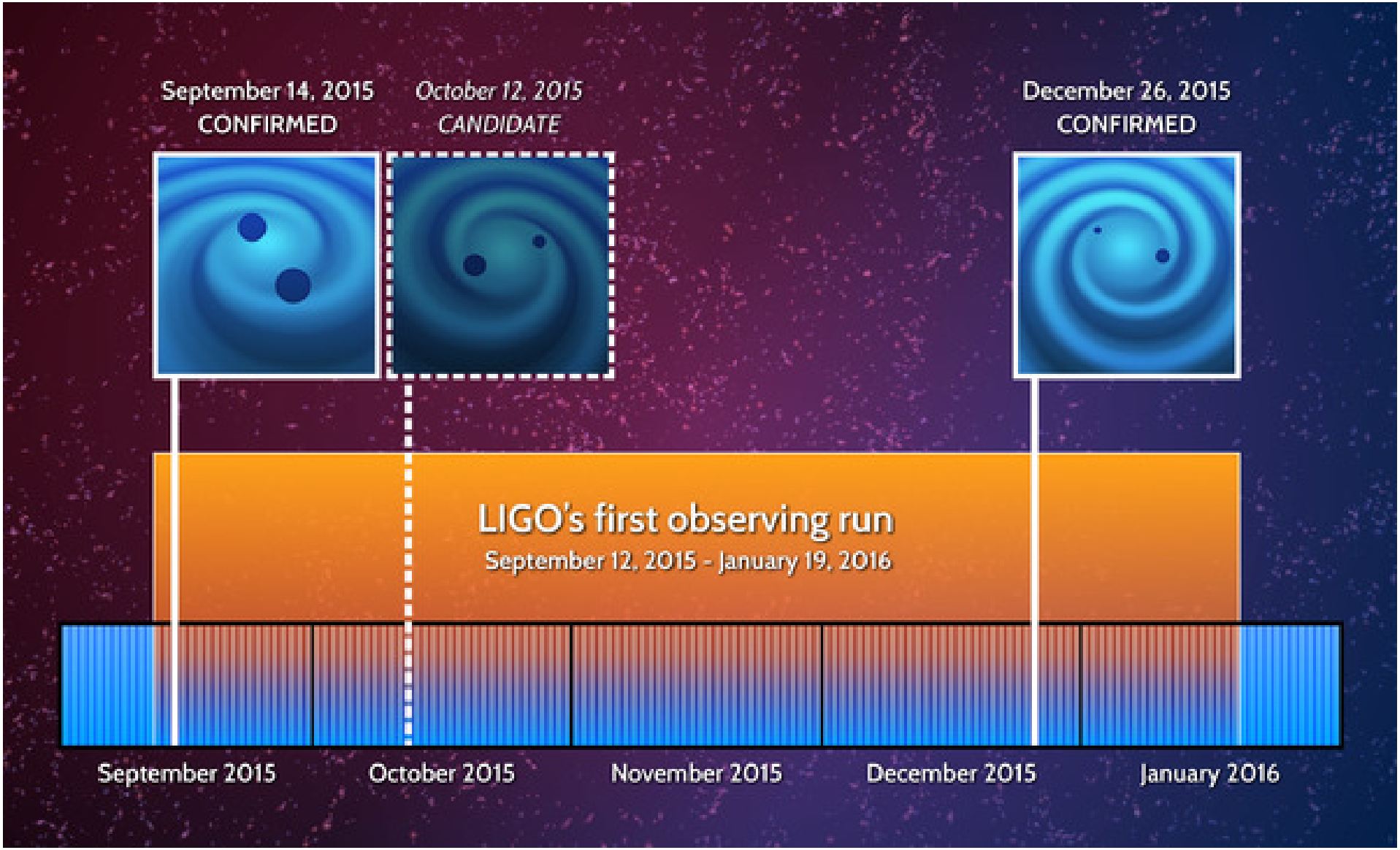
Better localization of source with HEN
[Here GW150914]

Precious informations from HEN Telescopes !

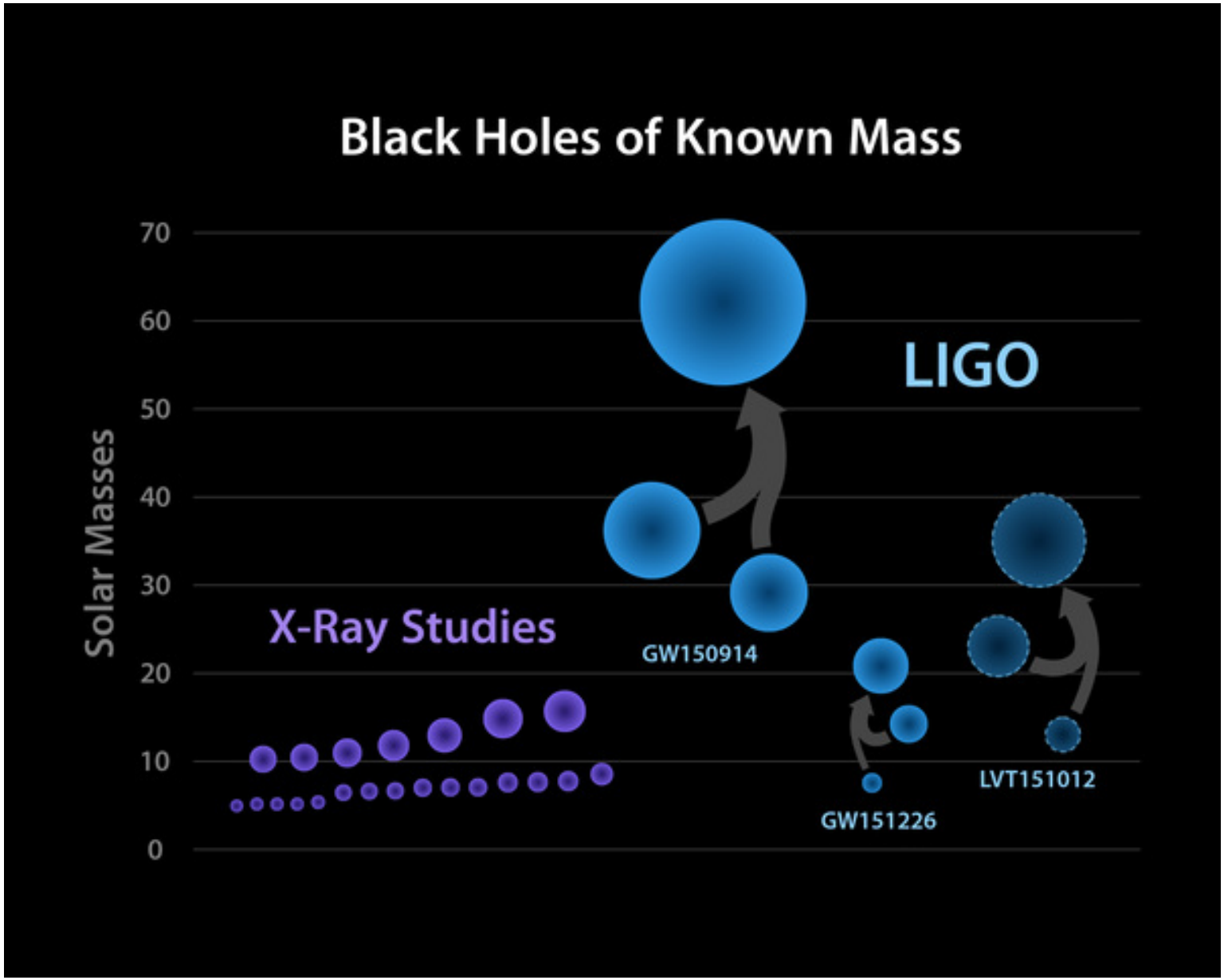
Searching for HEN for BBH coalescences during O1



Searching for HEN for BBH coalescences during O1



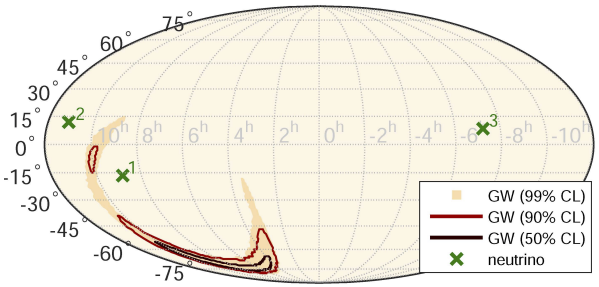
Searching for HEN for BBH coalescences during O1

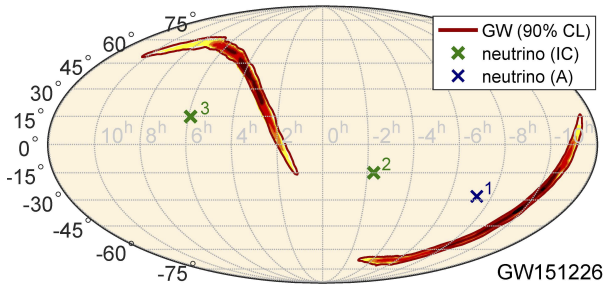


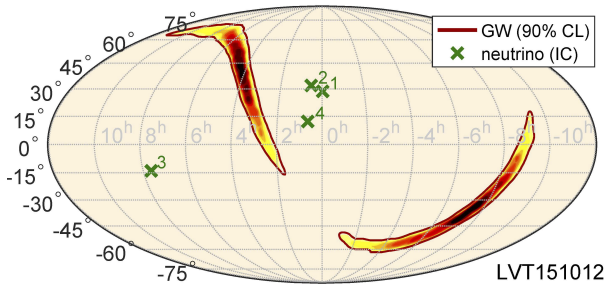
Searching for HEN for BBH coalescences during O1

ANTARES HEN search optimized

1 event in 90%-contour in ± 500s would have 3σ significance







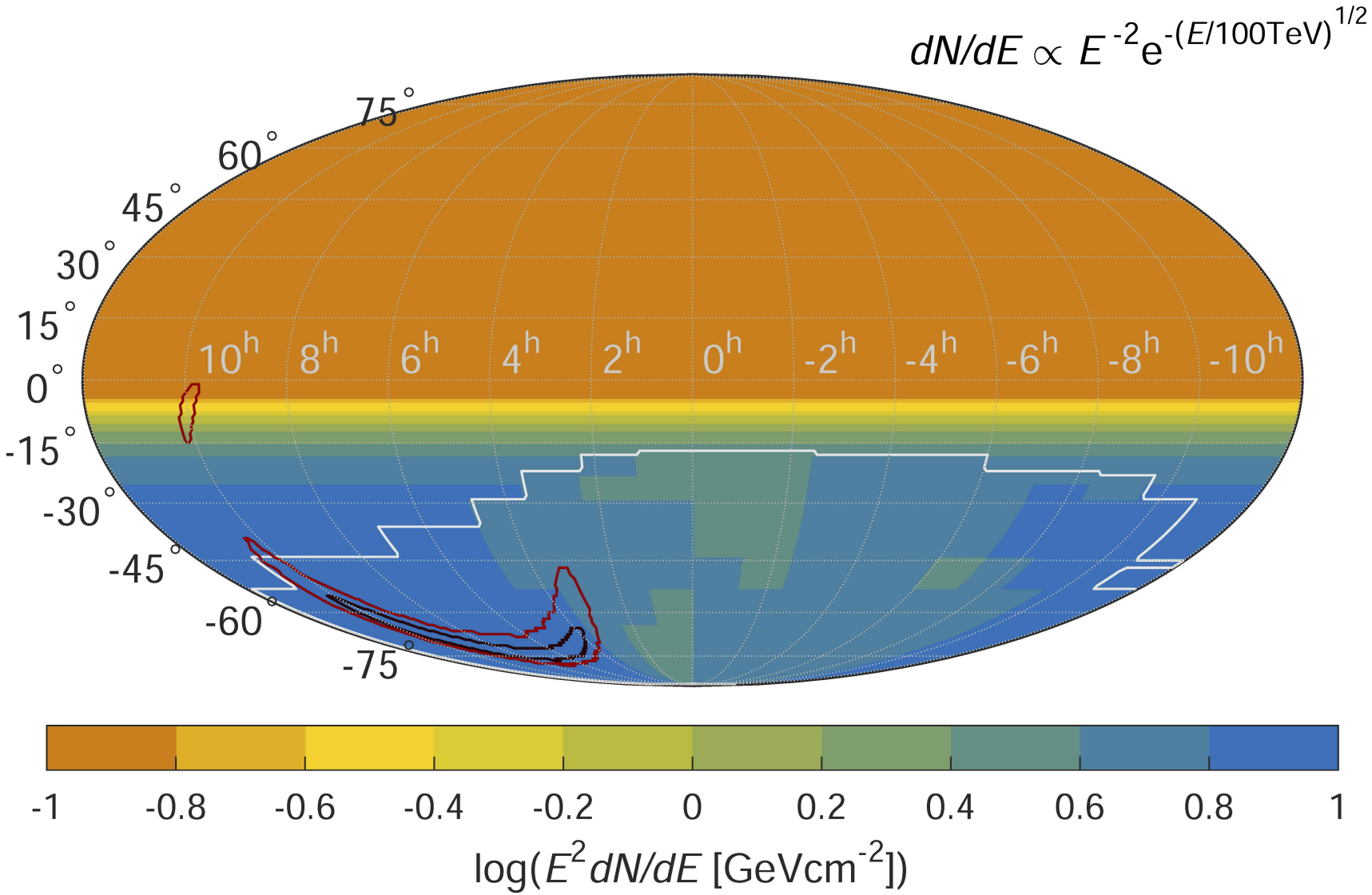
Event	#	Detector	ΔT [s]	RA [h]	Dec [°]	σ_μ^{rec} [°]	E_μ^{rec} [TeV]
GW150914	1	IceCube	+37.2	8.84	−16.6	0.35	175
	2	IceCube	+163.2	11.13	12.0	1.95	1.22
	3	IceCube	+311.4	−7.23	8.4	0.47	0.33
GW151226	1	ANTARES	−387.3	16.7	−28.0	0.7	9
	2	IceCube	−290.9	21.7	−15.1	0.1	158
	3	IceCube	−22.5	5.9	14.9	0.7	6.3
LVT151012	1	IceCube	−423.3	24.0	28.7	3.5	0.38
	2	IceCube	−410.0	0.5	32.0	1.1	0.45
	3	IceCube	−89.8	7.7	−14.0	0.6	13.7
	4	IceCube	147.0	0.6	12.3	0.3	0.35

Consistent with background ⇒ No HEN counterpart

⇒ Upper limits on HEN emissions with ANTARES and IceCube

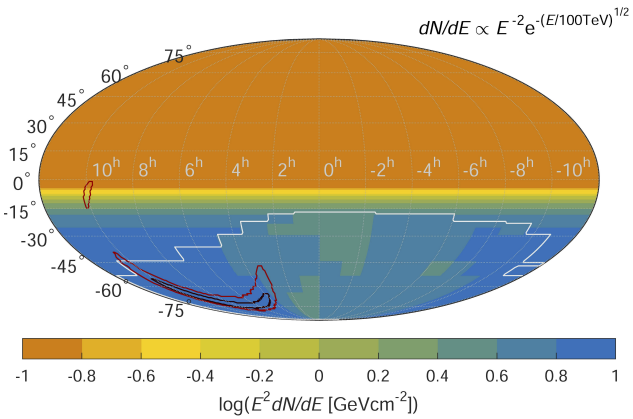
- ANTARES+IceCube+Virgo/LIGO - *PRD* **93** 122010 (2016)
- ANTARES+IceCube+Virgo/LIGO - 1703.06298, PRD

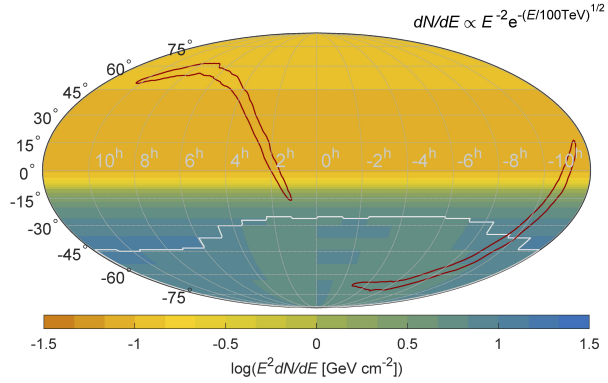
Limits on HEN emissions from BBH

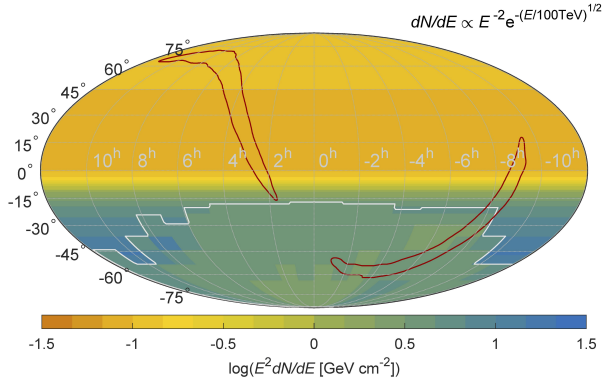


GW150914

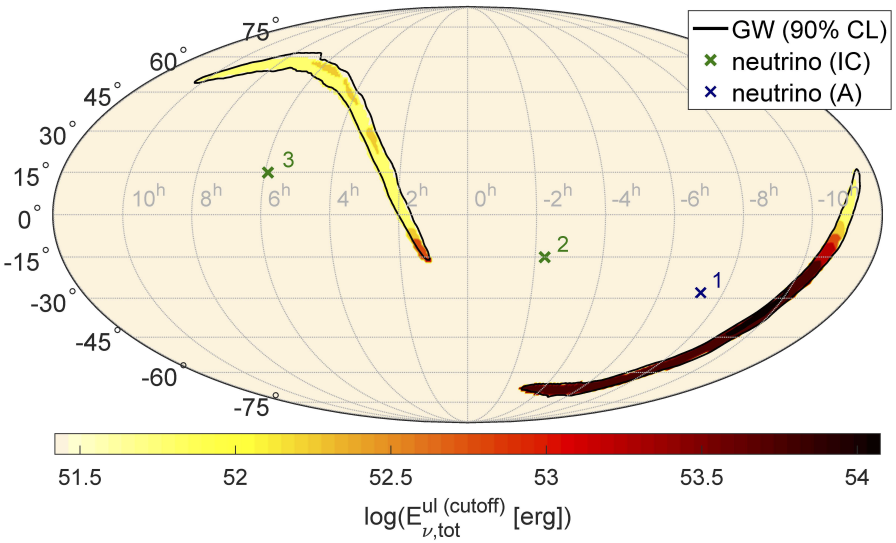
Limits on HEN emissions from BBH

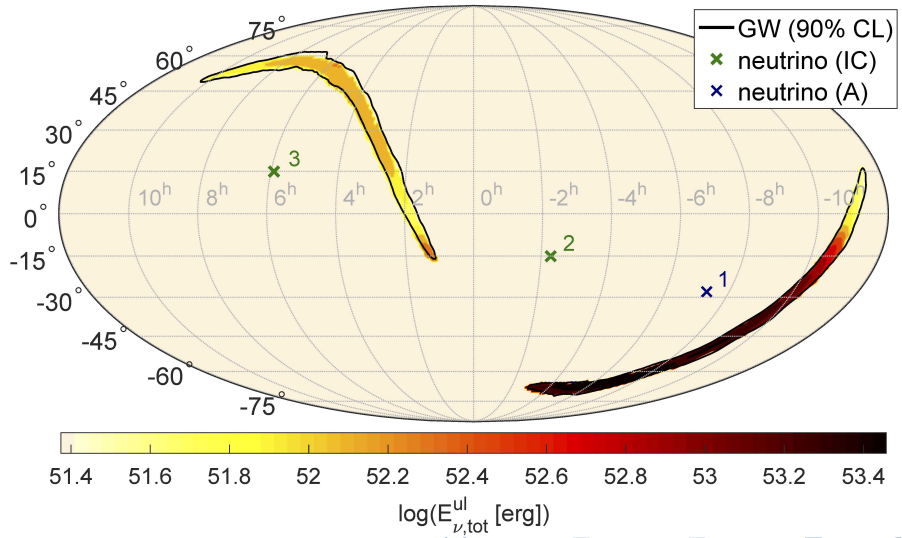






GW Event	D_L^{GW} [Mpc]	E_{GW}^{iso} [erg]	$E_{HEN}^{iso}/E_{GW}^{iso}$ E^{-2}	$E_{HEN}^{iso}/E_{GW}^{iso}$ E^{-2} with cutoff	Ref
GW150914	410^{+160}_{-180}	5×10^{54}	$0.11\% - 26\%$	$0.13\% - 74\%$	*PRD* **93** 122010 (2016)
GW151226	440^{+180}_{-190}	1.8×10^{54}	$0.11\% - 17\%$	$0.17\% - 100\%$	1703.06298, PRD





More discoveries to come !

O1 : 09/2015-01/2016 - Joint ANTARES/ICECUBE Analyses

- **GW150914 : Total HEN emission <** $0.2 - 20$**% of GW energy [**E^{-2}**]**
- **GW151226 : Total HEN emission <** $1 - 15$**% of GW energy [**E^{-2}**]**
  - $\Rightarrow$ 100 GeV - 100 PeV
  - $\Rightarrow$ ANTARES $\approx$ 1 TeV - 1 PeV - ICECUBE $\approx$ 100 TeV - 100 PeV

- HEN ULs still > $E_{\rm iso}^{\rm em}$ for Short GRBs (10^{49}erg) or Long GRBs (10^{51}erg)

  [P. Meszaros, Rep. Prog. Phys. 69, 2259 (2006) arxiv/0605208]
- But in some cases, expect $E_{\rm iso}^{\rm HEN} > E_{\rm iso}^{\rm em}$

  [K. Murase et al Phys. Rev. Lett. 111, 121102 (2013), 1306.2274]

- Sub-Threshold joint analysis to be completed, using ANTARES+ICECUBE HEN candidates

ICRC Proceedings : PoS(ICRC2017)947

More discoveries to come !

O2 : Nov 30, 2016 → Aug. 25, 2017

- ANTARES receives GW online alerts from LIGO
- July 7th Status : 8 alerts sent, using a loose false-alarm-rate threshold of one per month
  - ⇒ ANTARES HEN follow-ups [Coleiro & Dornic - PoS(ICRC2017) 984]
- VIRGO has joined the network in August !
  - ⇒ Improved GW area but still ≫ HEN uncertainty

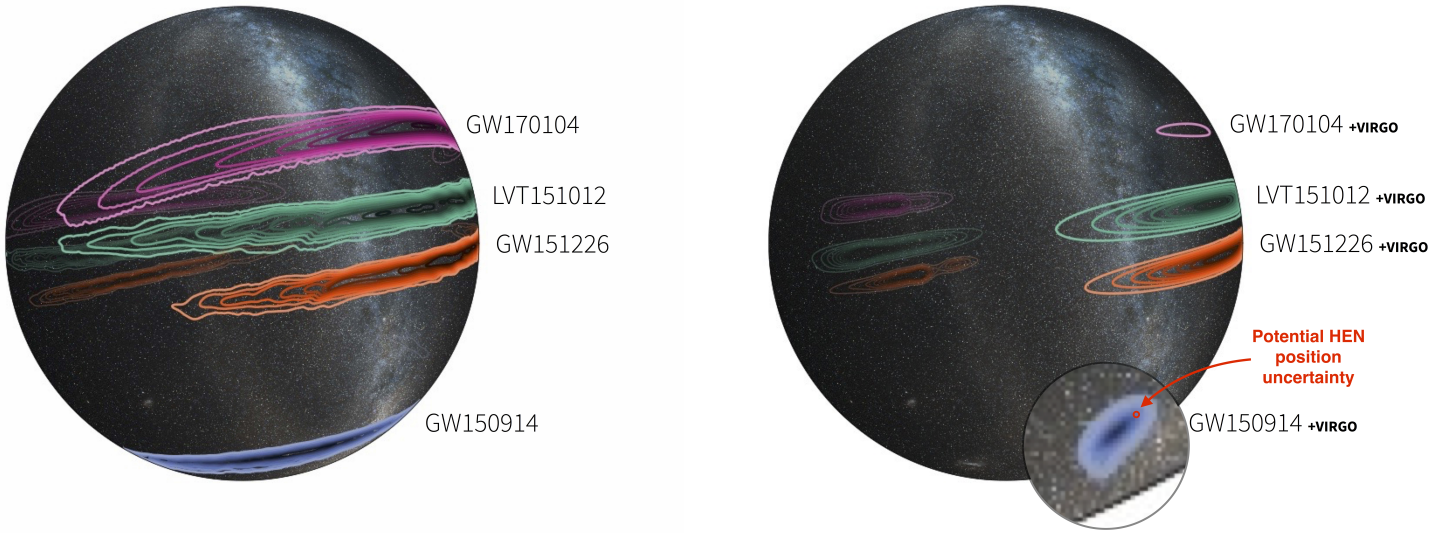
Credit : LIGO/Caltech/MIT/Leo Singer (Milky Way image : Axel Mellinger)

⇒ HEN constraints from ANTARES can be decisive !

More discoveries to come !

O2 : Nov 30, 2016 → Aug. 25, 2017

- ANTARES receives GW online alerts from LIGO
- July 7th Status : 8 alerts sent, using a loose false-alarm-rate threshold of one per month
  - ⇒ ANTARES HEN follow-ups [Coleiro & Dornic - PoS(ICRC2017) 984]
- VIRGO has joined the network in August !
  - ⇒ Improved GW area but still ≫ HEN uncertainty



Credit : LIGO/Caltech/MIT/Leo Singer (Milky Way image : Axel Mellinger)

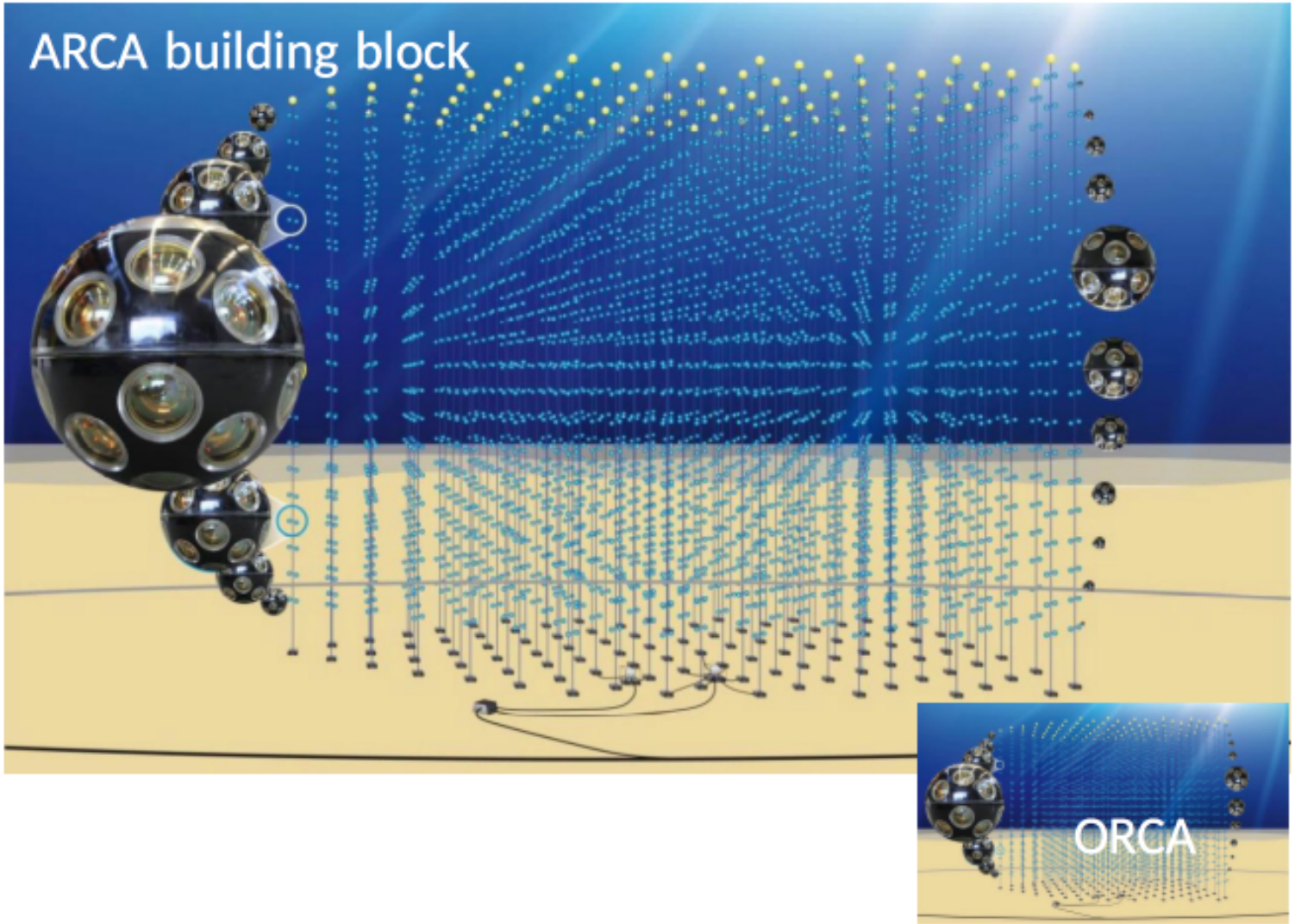
⇒ HEN constraints from ANTARES can be decisive !

More discoveries to come !

A Neutron Star+Neutron Star Binary Merger would be nice...→ Neutrinos !

High Energy Neutrino Astronomy - Where do we stand ?

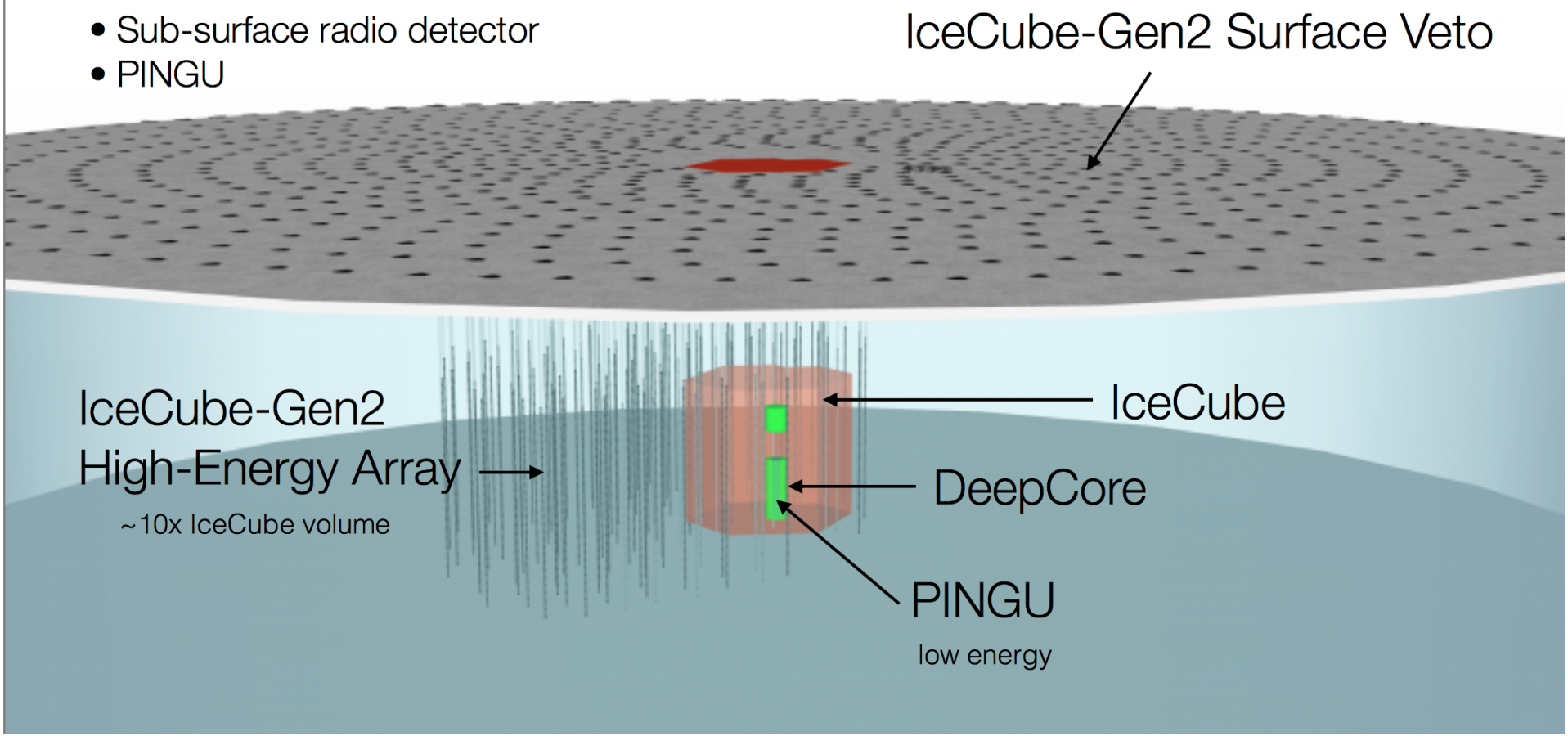
What's next : KM3NeT telescopes



What's next : IceCube

Multi-component observatory:

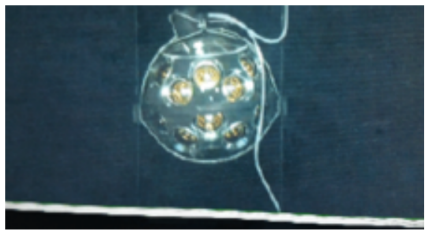
- IceCube-Gen2 High-Energy Array
- Surface air shower detector
- Sub-surface radio detector
- PINGU



What's next : Timeline

24 lines @ARCA + 7 lines @ORCA
already funded (currently under deployment)

IceCube Gen-2 phase 1
NSF proposal (7 lines)



2017

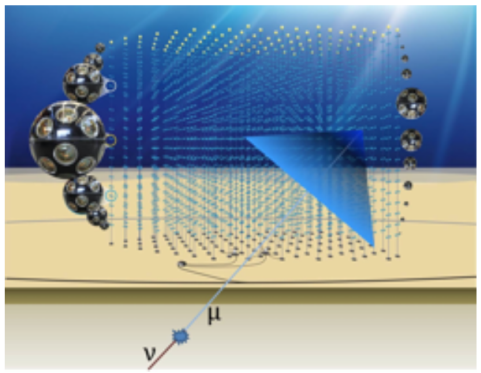
2022

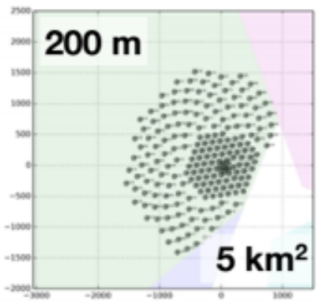
KM3NeT deployment

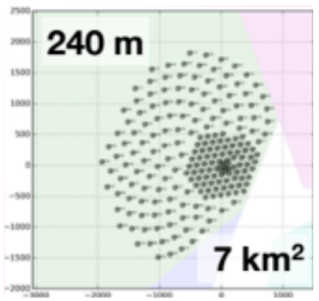
IceCube Gen-2 deployment

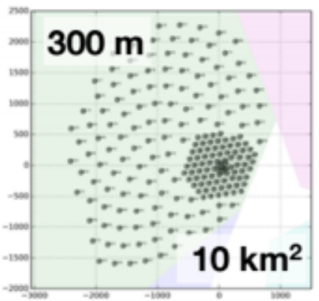
2021

...





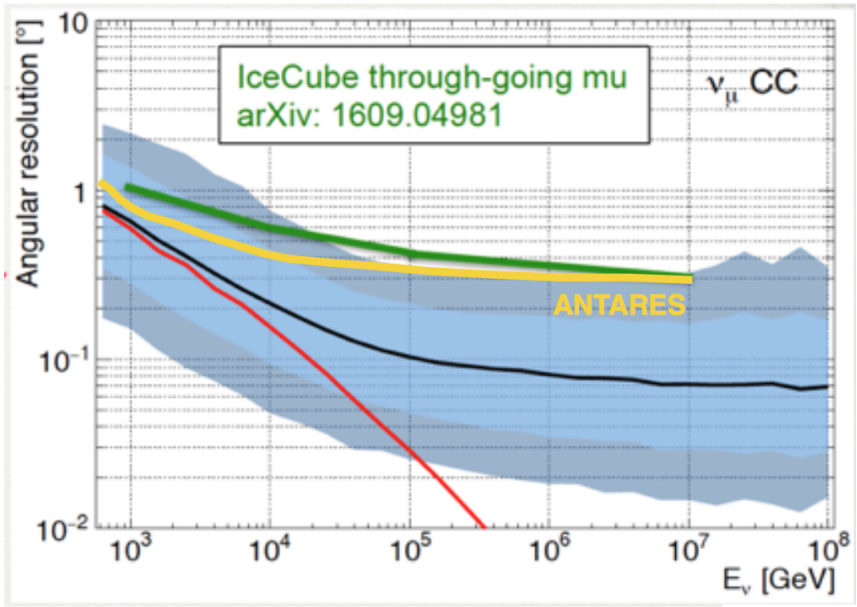


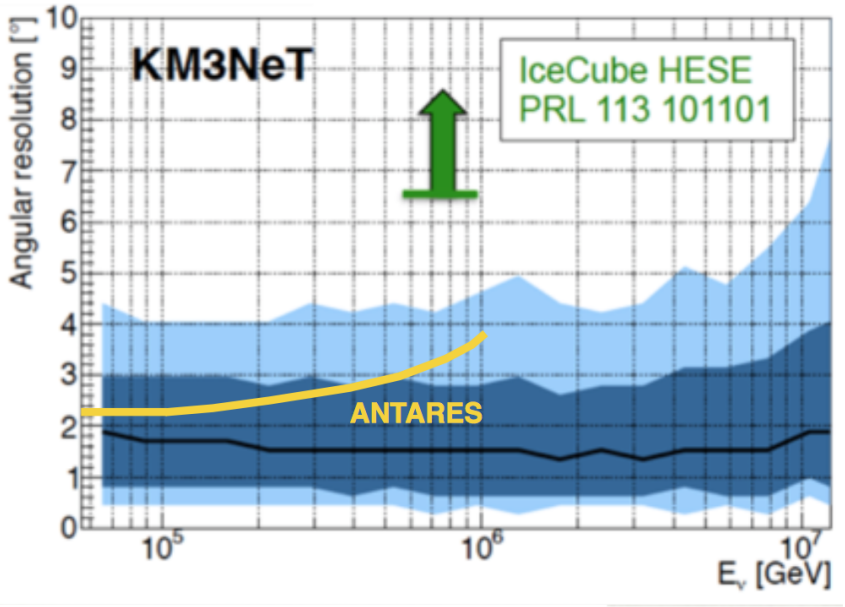


2x115 lines in Sicily (ARCA)
115 lines in France (ORCA)

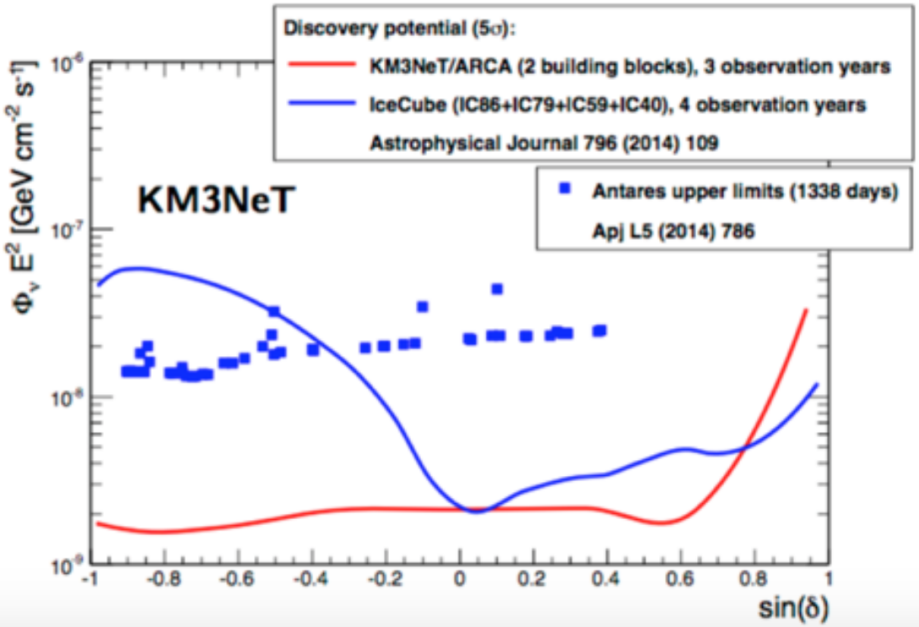
~120 new lines
Perf. increased by 1 order of mag.

What's next : Improvements ANTARES/KM3NeT→ KM3NeT

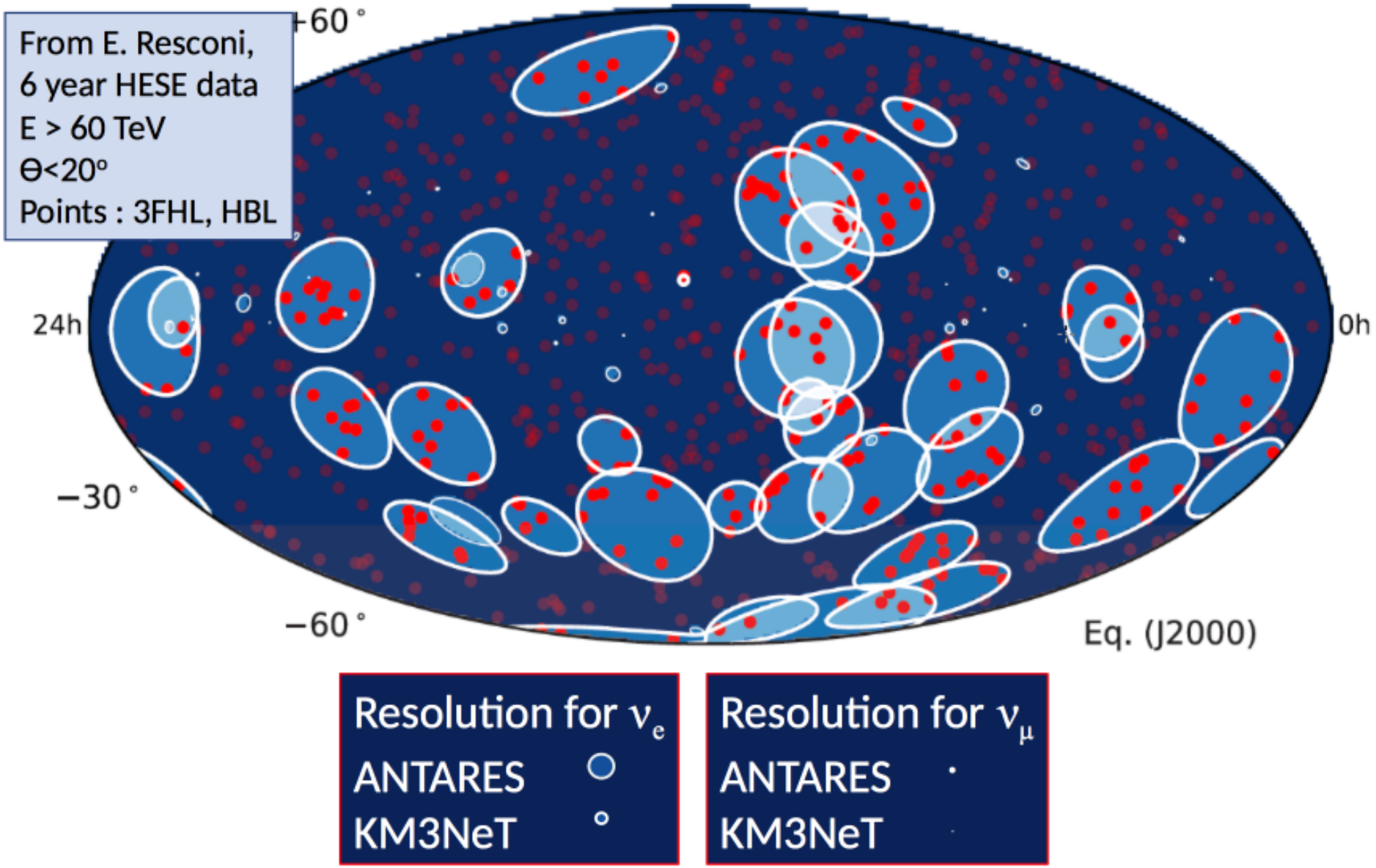




Point-source discovery potential



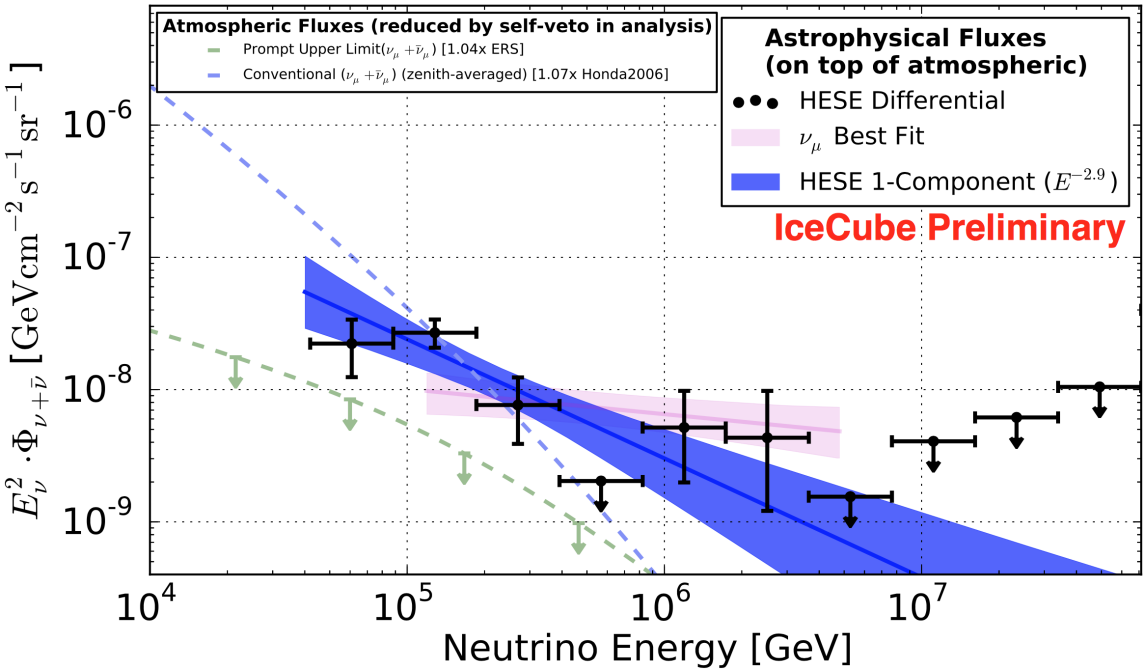
What's next : Improvements ANTARES/KM3NeT→ KM3NeT



Conclusions

Neutrinos from Cosmic-Ray Sources exist

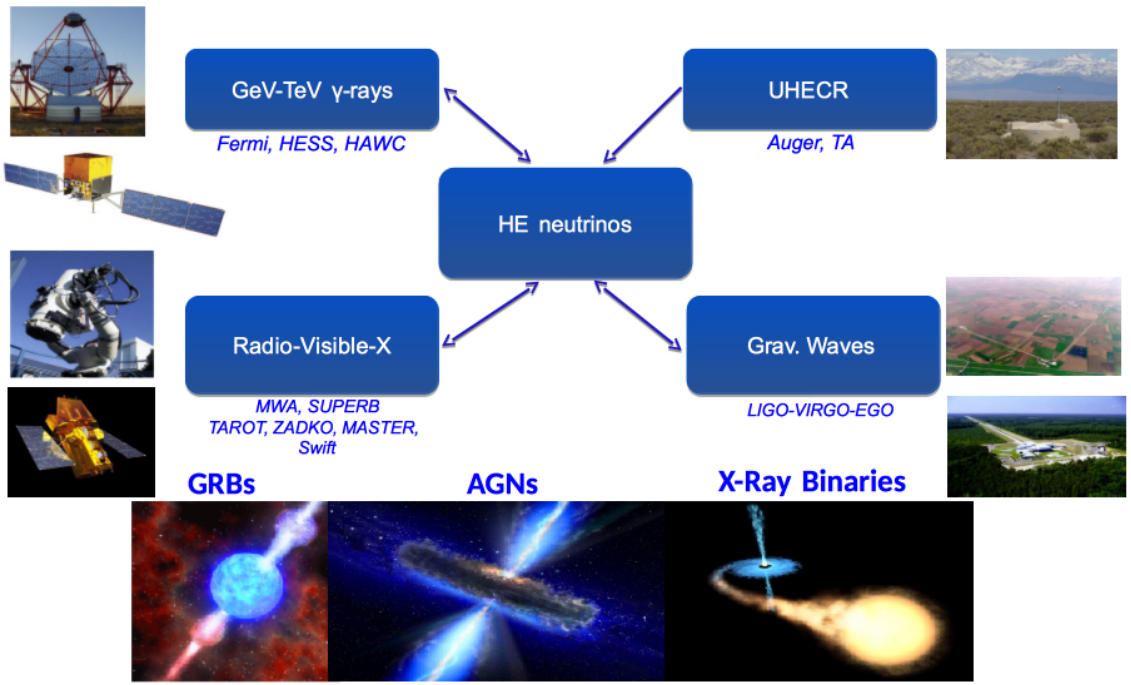
- Hadronic CRs produce astrophysical neutrinos
- IceCube observe this neutrinos in multiple channels
  - ⇒ Energy spectrum seems not trivial
  - ⇒ Different in North/South ?
- Not observed yet in ANTARES, but consistent



Conclusions

Cosmic Neutrino Sources are still unknown

- Real-time follow-up programs are in place to detect transient sources.
  - ⇒ 1 neutrino is enough !
  - ⇒ Different in North/South ?
- ANTARES good angular resolution compensates volume



Conclusions

Next Generation Telescopes are in construction

- ICECUBE-Gen2 and KM3NET : $\times 2 \rightarrow 8$ in instrumented volume !
  1– Oscillation Physics / Neutrino Mass Spectrum [ICECUBE/PINGU - KM3NET/ORCA]
  2– Astrophysics of Neutrino Sources [KM3NET]
- KM3NET good angular resolution paramount
  → Already 3 ARCA lines deployed undersea
  → 1st ORCA lines 2017

Thank you !

Additional Material