Multi-messenger observations of gravitational wave sources

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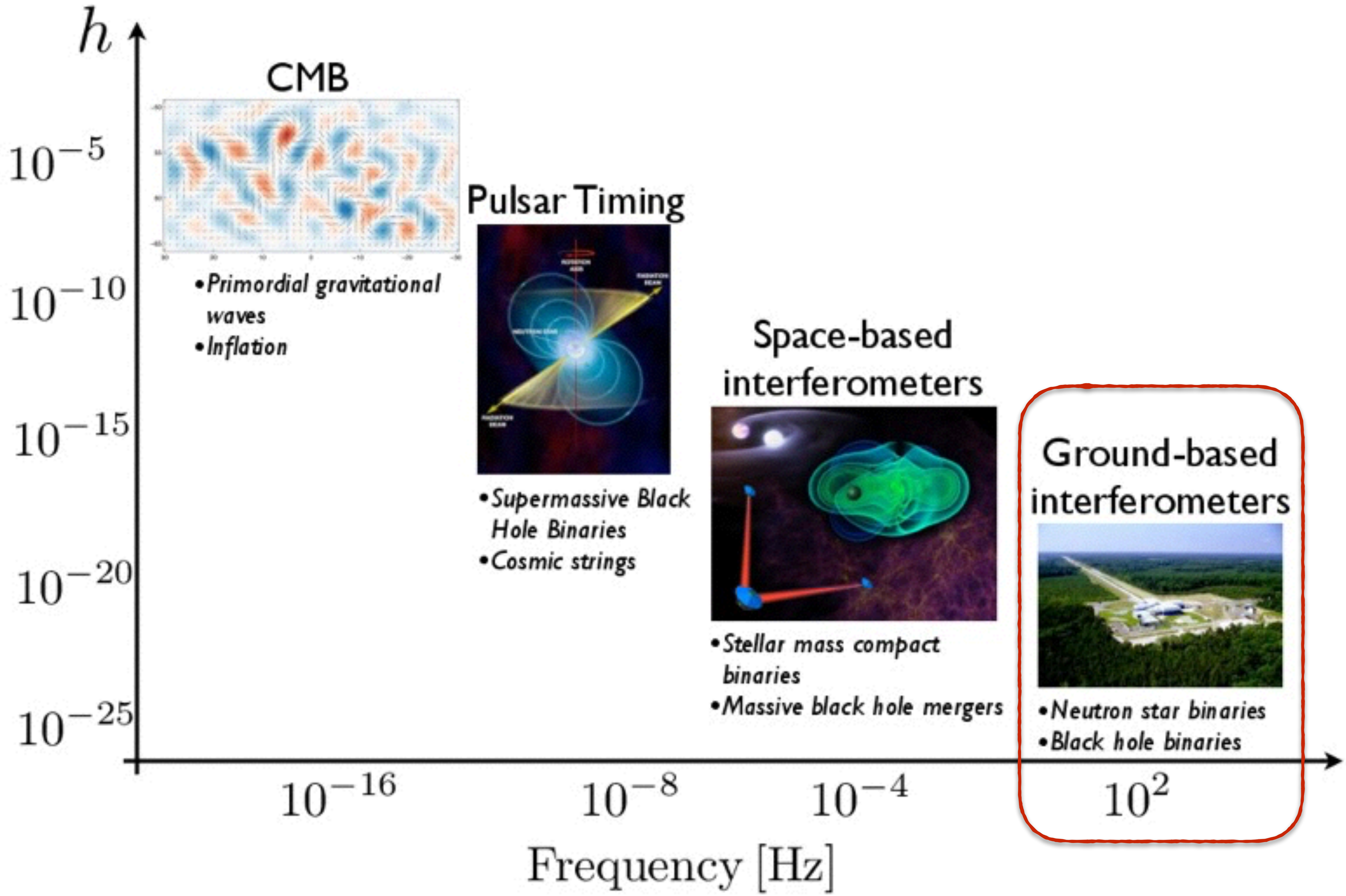
The big picture of gravitational wave astronomy



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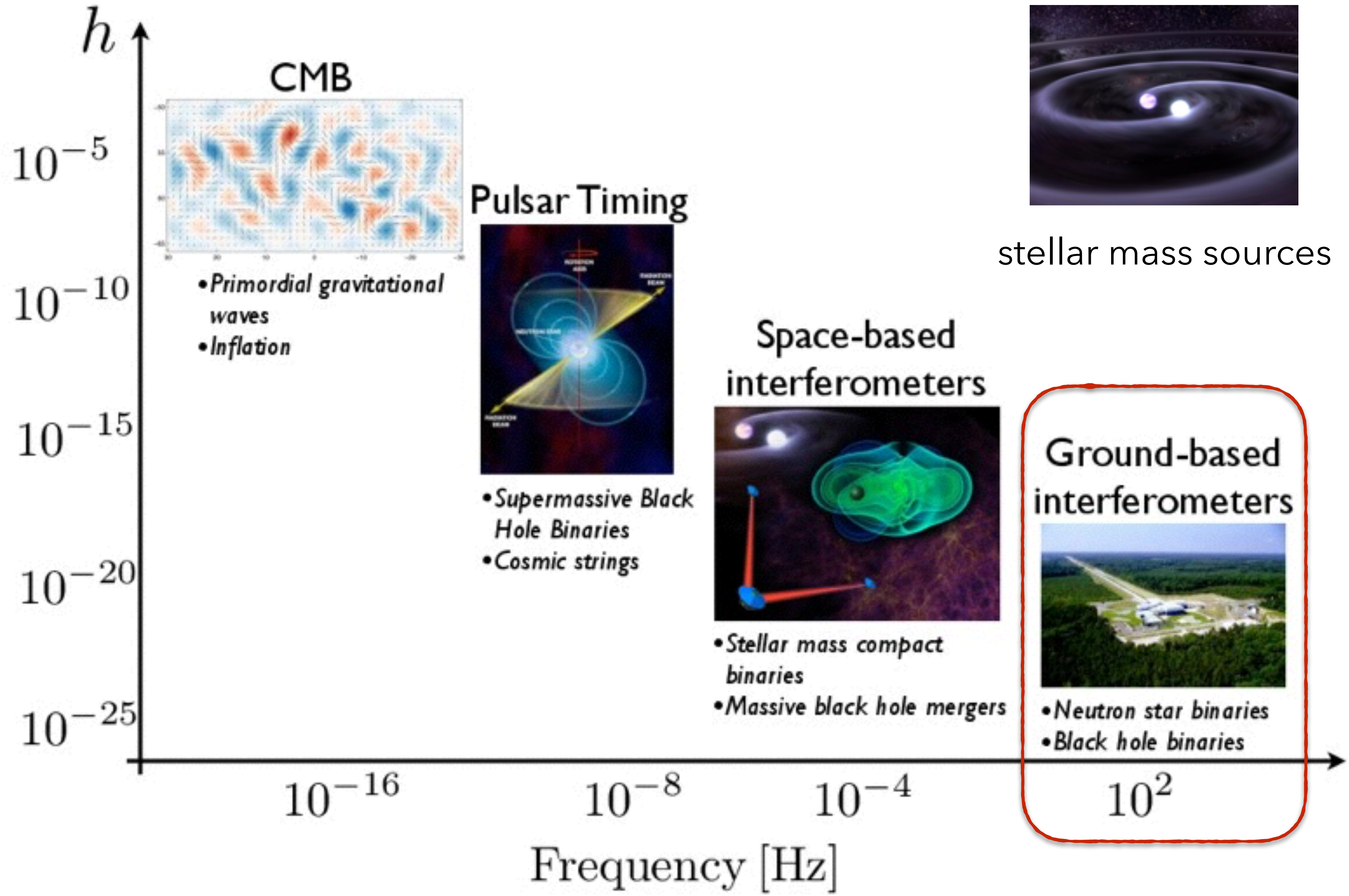


Outline

1) Why ? Multi-messenger astronomy

2) What ? Transient astrophysical sources and their multi-messenger emission

- Multi-wavelength emission
- Multi-messenger emission (ν)

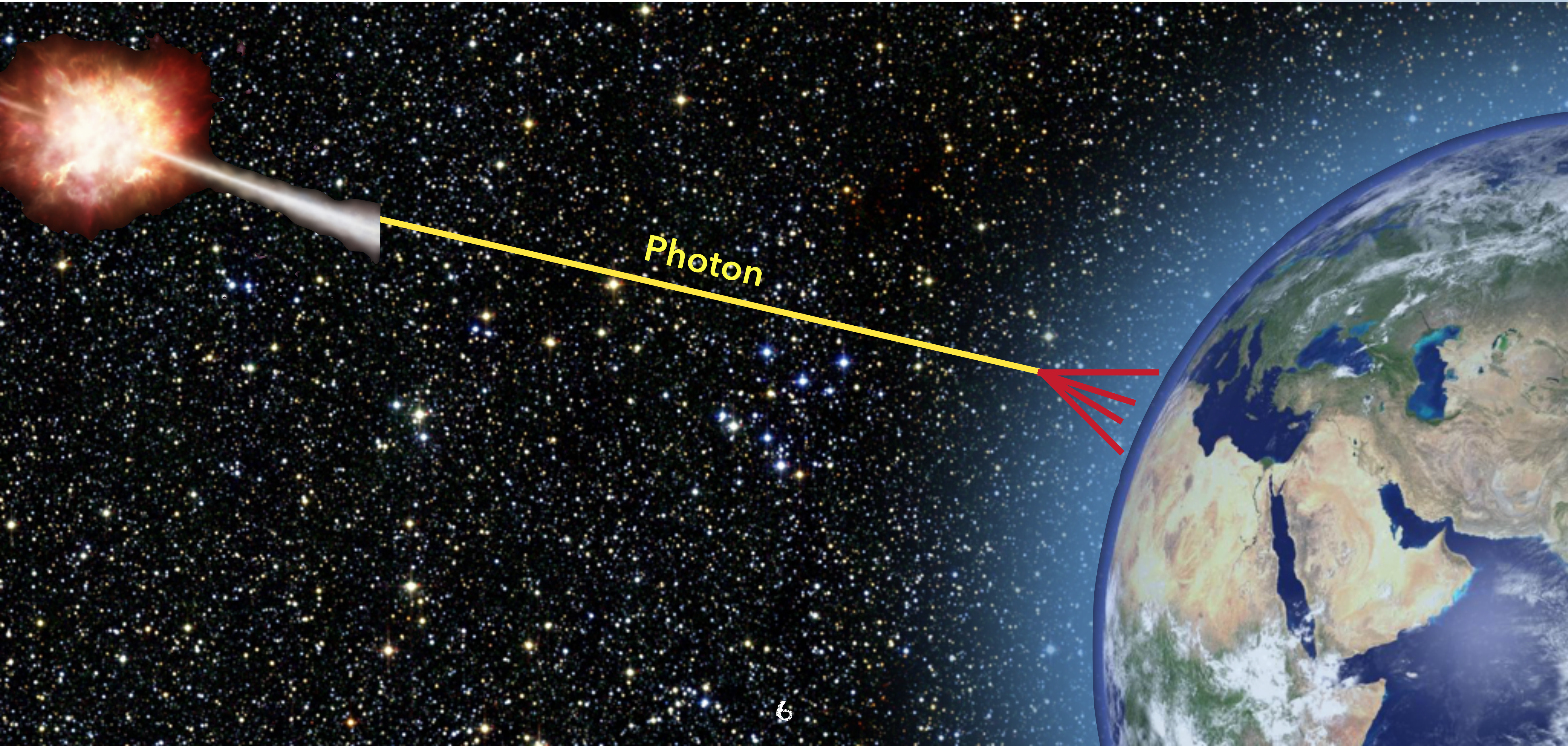
3) How ? Multi-messenger observational technics and strategies

4) Multi-messenger synergies

- EM and neutrino follow-up of GW events
- EM follow-up of neutrino events

Multi-messenger astronomy ?

Photons (ɣ-rays): absorbed and interact with CMB/IRB (pair production for d≳Mpc)



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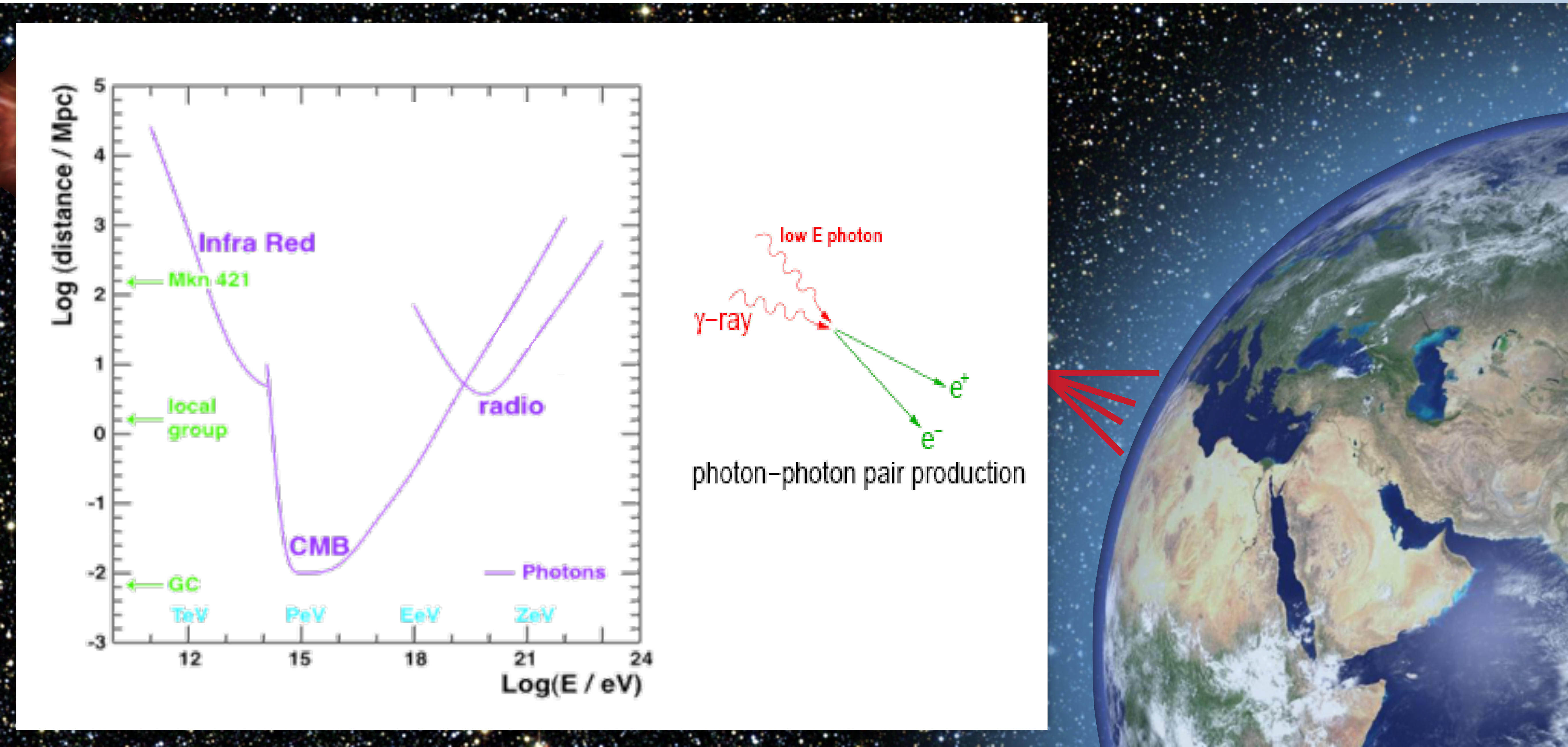
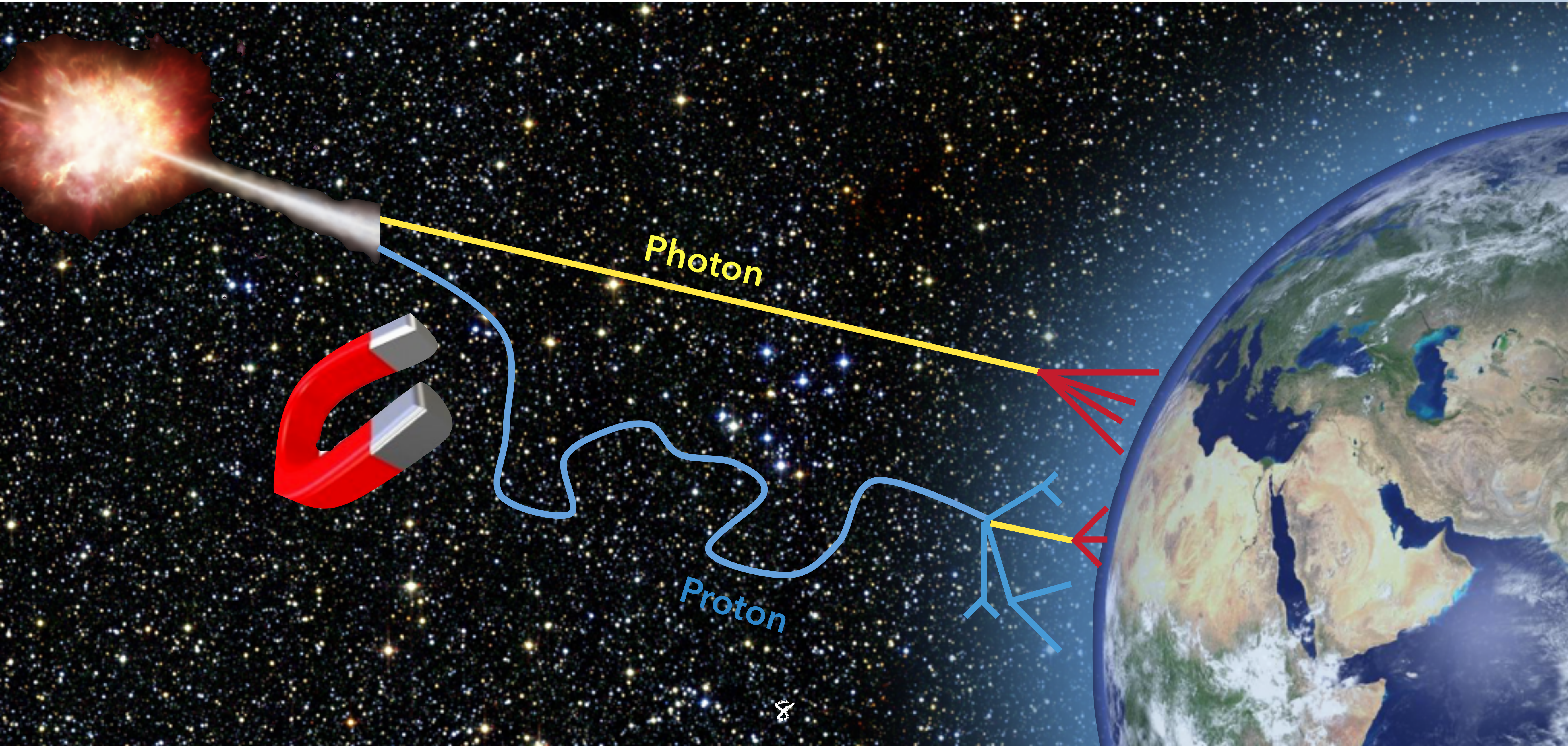


Photons (ɣ-rays): absorbed and interact with CMB/IRB (pair production for d≳Mpc)

Cosmic Rays: deflected by magnetic fields + GZK effect with CMB/IRB



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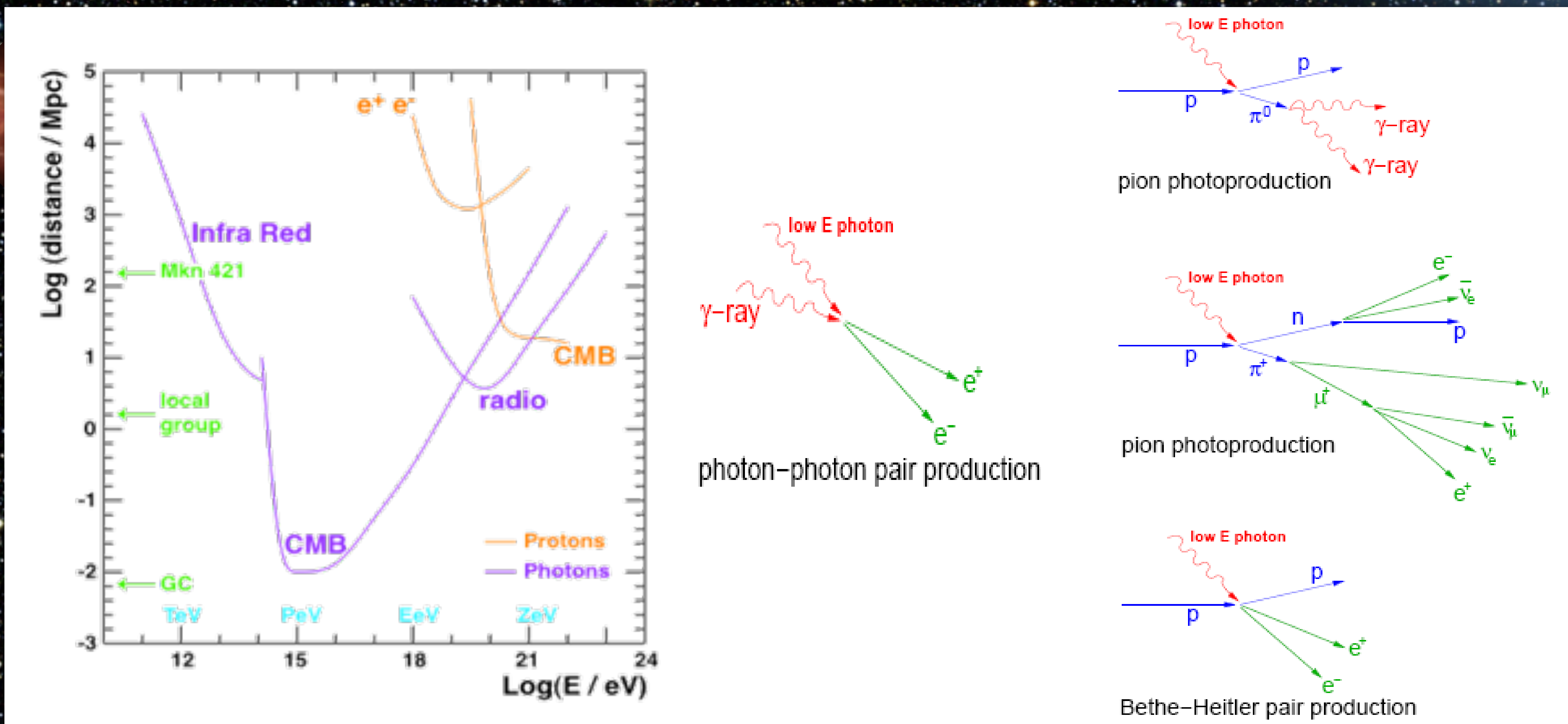

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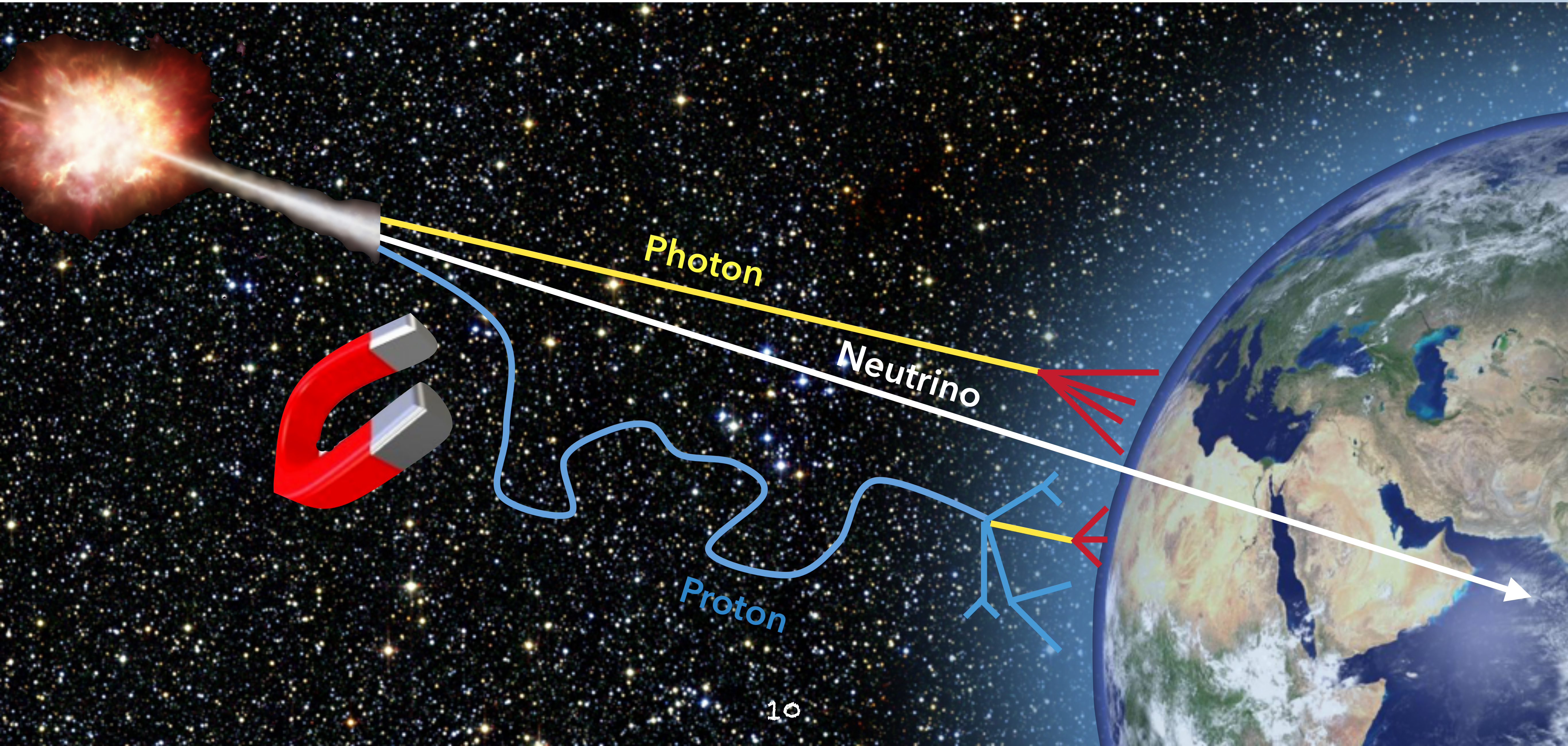
Neutrinos: neutral, weakly interacting particles, point to the source



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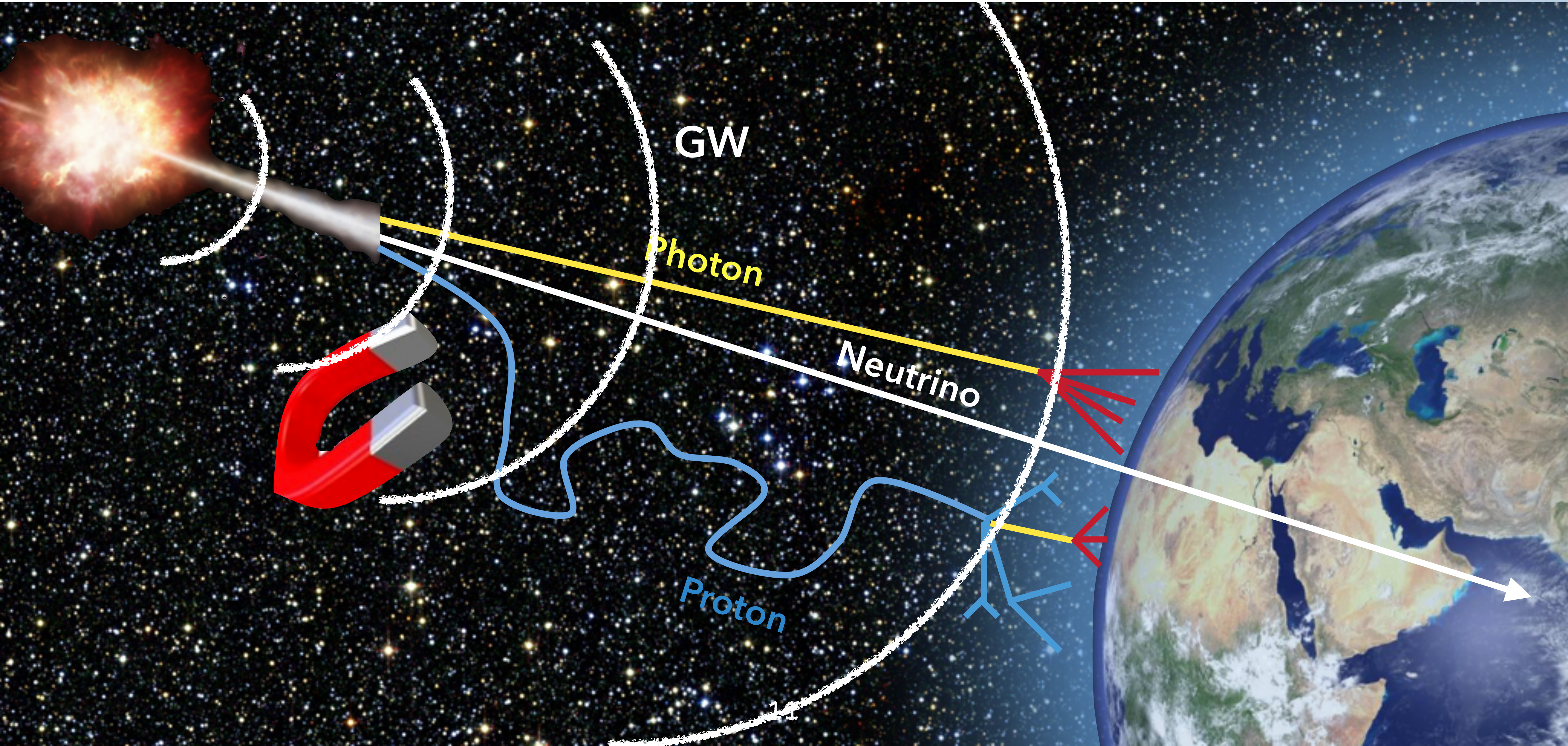

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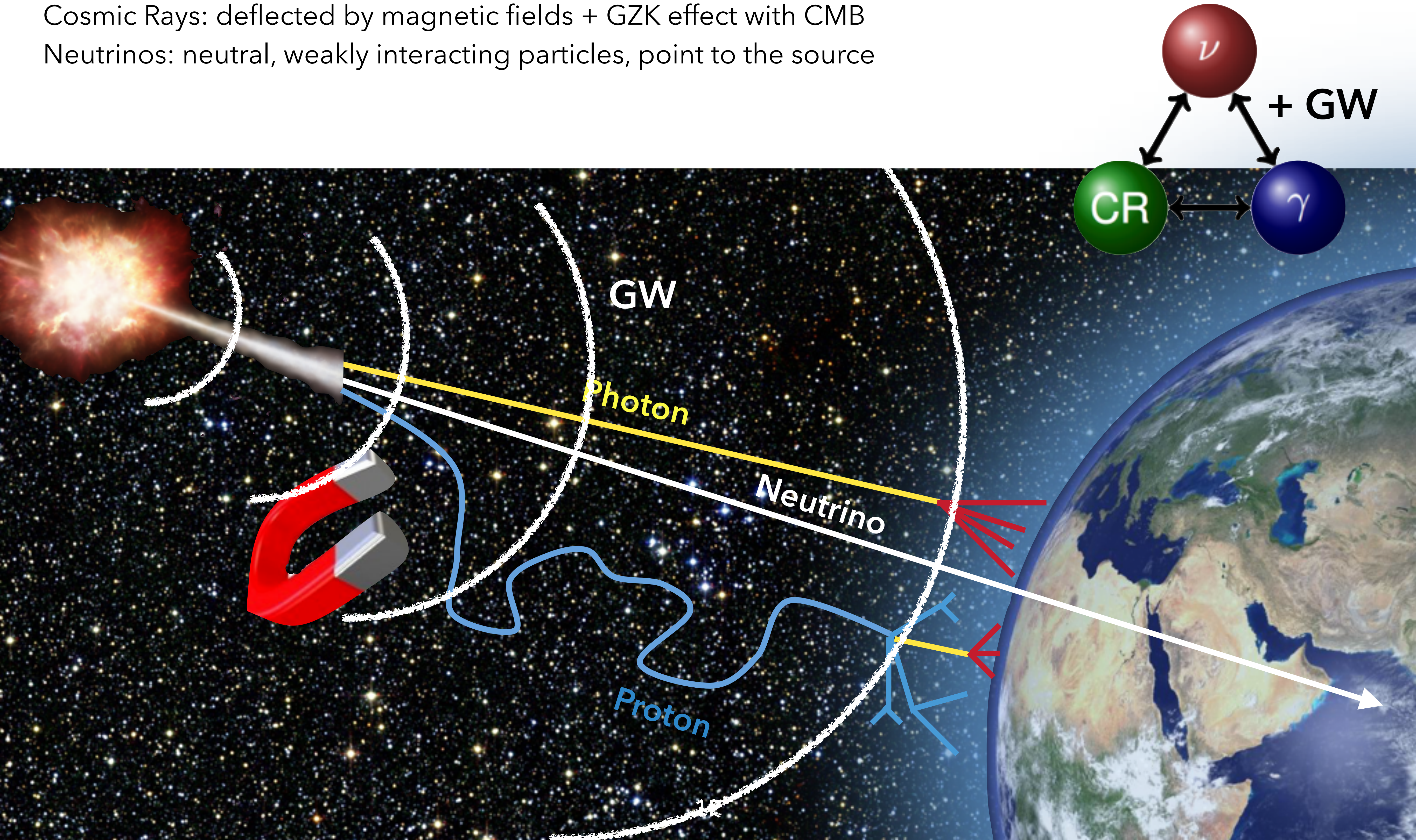


- **Hadronuclear** (e.g. starburst galaxies, galaxy clusters, galactic cosmic rays)

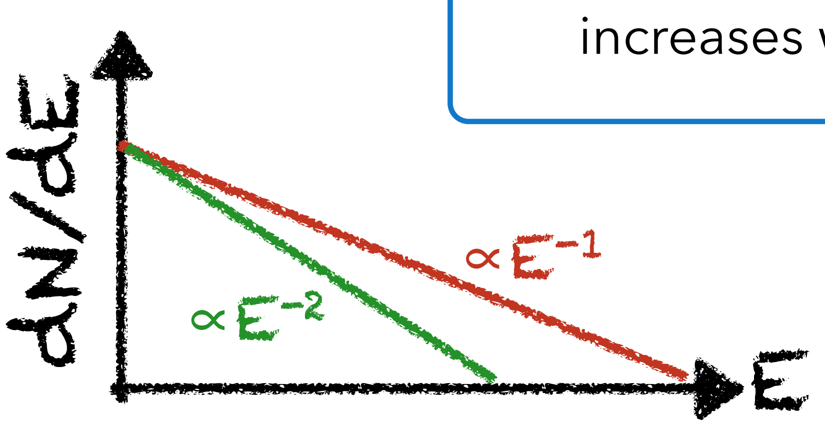
$$pp \rightarrow \begin{cases} \pi^0 \rightarrow \gamma\,\gamma \\ \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \nu_\mu \bar{\nu}_\mu \\ \pi^- \rightarrow \mu^- \bar{\nu}_\mu \rightarrow e^- \bar{\nu}_e \bar{\nu}_\mu \nu_\mu \end{cases}$$

- **Photohadronic** (e.g. gamma ray-bursts, AGN, microquasars,...)

$$p\gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p\,\pi^0 \rightarrow p\,\gamma\,\gamma \\ n\,\pi^+ \rightarrow n\,\mu^+ \nu_\mu \rightarrow n\,e^+ \nu_e \bar{\nu}_\mu \nu_\mu \end{cases}$$

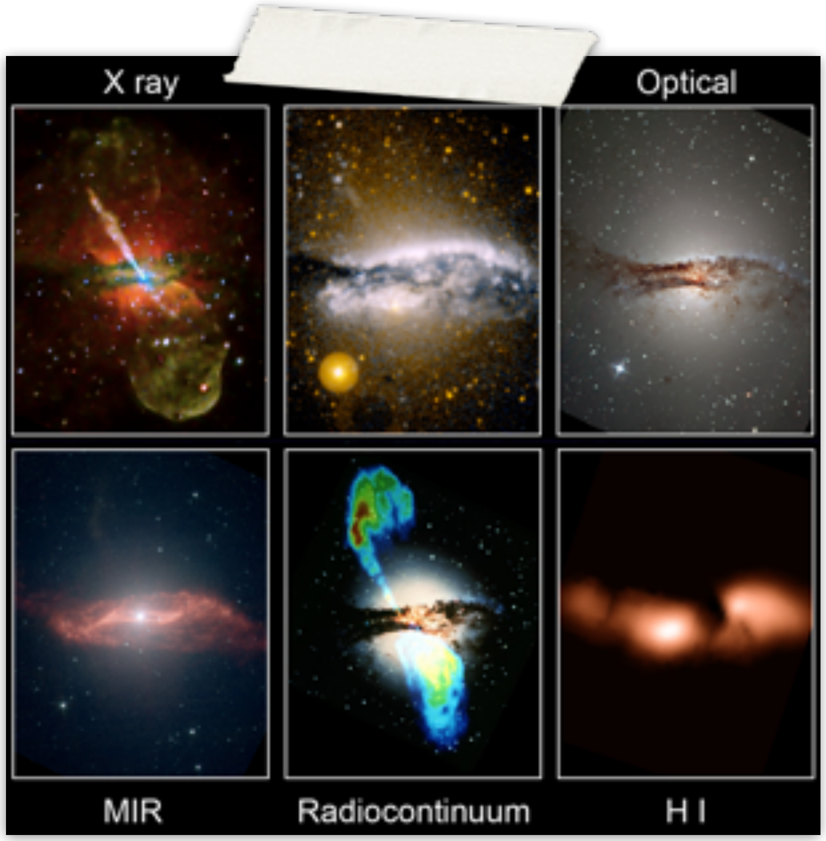
ν carries ~3-5% of p energy
⇒ TeV-PeV neutrinos + ɣ-rays

produced by p with PeV-100 PeV energies

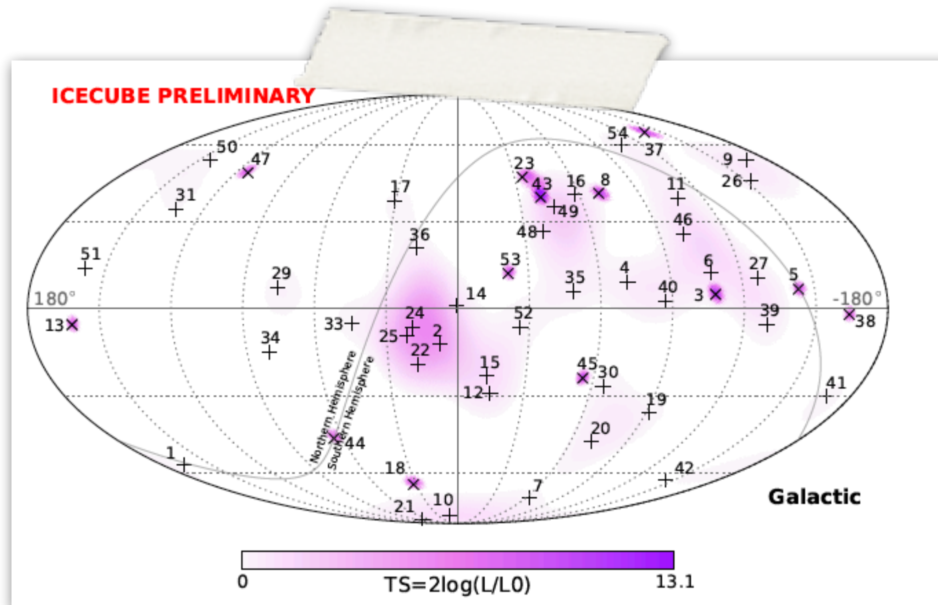


Neutrino spectral index ≈ 1-2 (harder spectrum for photohadronic processes since the density of target photons increases with proton energy)

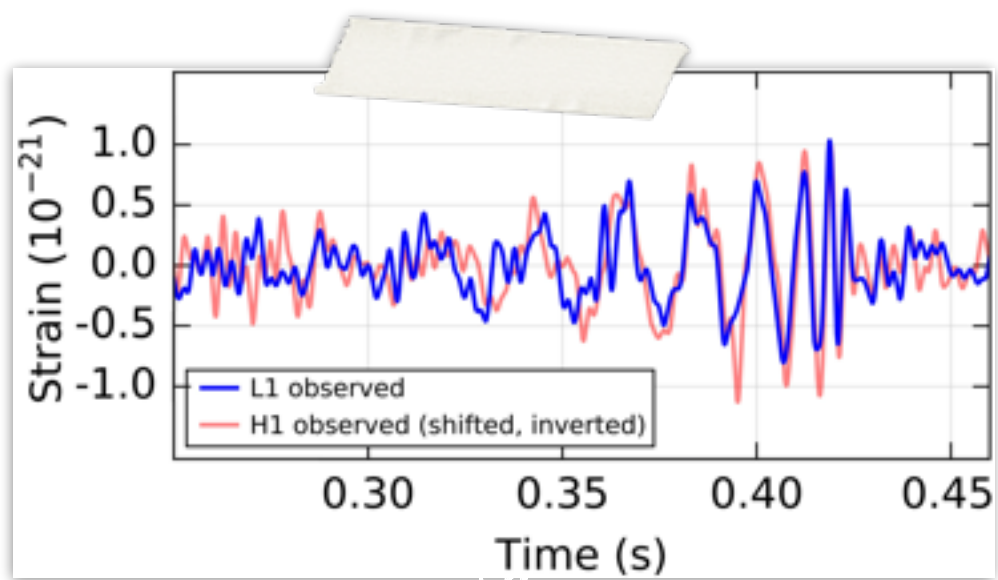
EM spectrum



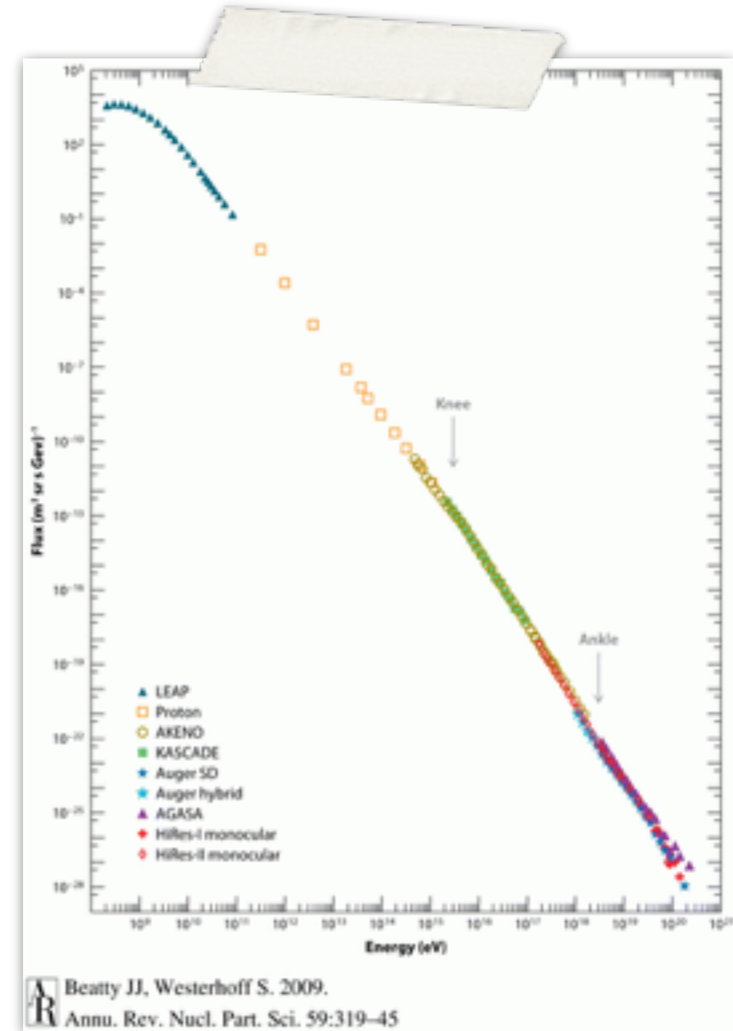
Neutrino diffuse flux

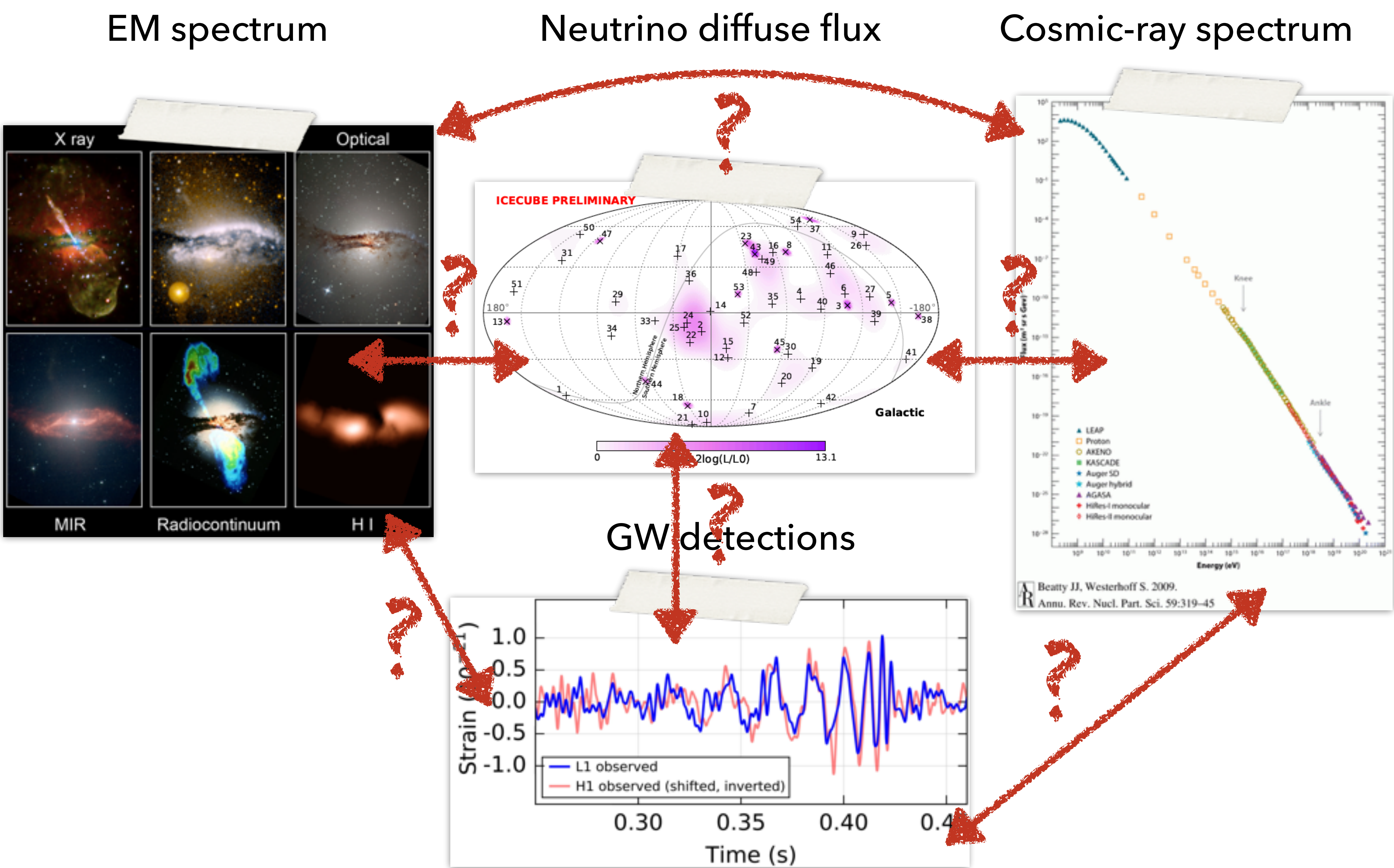


GW detections



Cosmic-ray spectrum




EM spectrum
Neutrino diffuse flux
Cosmic-ray spectrum
GW detections
X ray
Optical
MIR
Radiocontinuum
H I
ICECUBE PRELIMINARY
Galactic
2log(L/L0)
0
13.1
Knee
Ankle
Energy (eV)
LEAP
Proton
AKENO
KASCADE
Auger SD
Auger hybrid
AGASA
HiRes-I monocular
HiRes-II monocular
Beatty JJ, Westerhoff S. 2009.
Annu. Rev. Nucl. Part. Sci. 59:319–45
L1 observed
H1 observed (shifted, inverted)
Time (s)
Strain
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40

If we assume that a small fraction of the energy released through GW is released through photons and neutrinos, it should be detectable !

➜ *Which conversion mechanisms ?*

Consider the GW signals in its **astrophysical context**

Give an arcsec **localization**, estimate of the **redshift** of the source, identify the **host galaxy**

Provide further information on the sources and their **environment**

Constrain the **emission and acceleration processes**

Constrain **fundamental physics** parameters (equation of state of neutron star, neutrino mass hierarchy, …)

START MULTI-MESSENGER ASTRONOMY !!

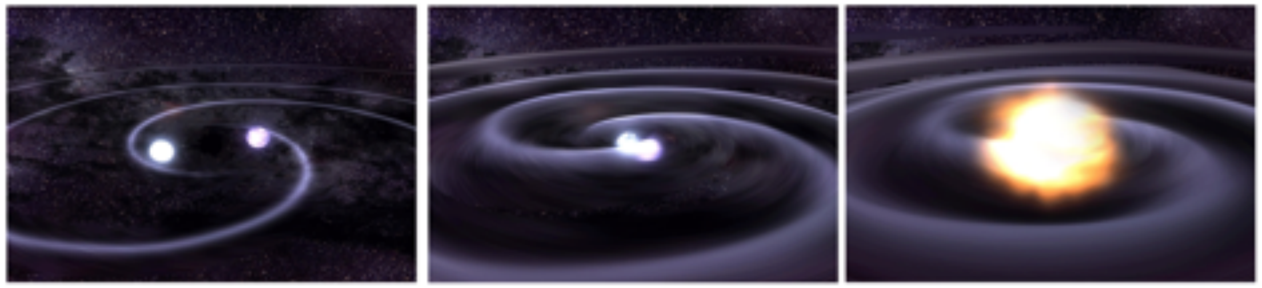
Transient sources and their multi-messenger emission

Transient GW signal with duration significantly shorter than the observation time and cannot be re-observed

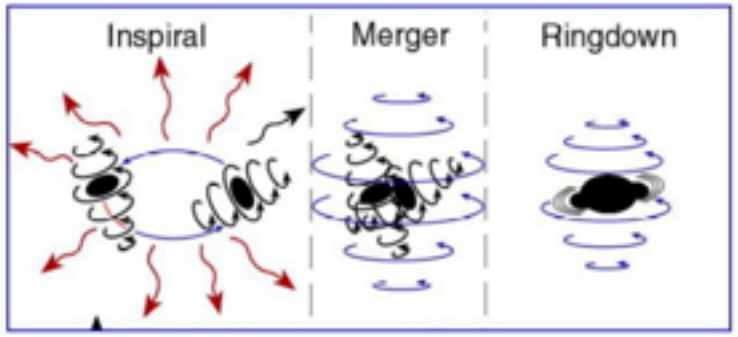
focus here on sources detectable by LIGO/Virgo

Binary mergers

NS/NS - BH/NS - BH/BH



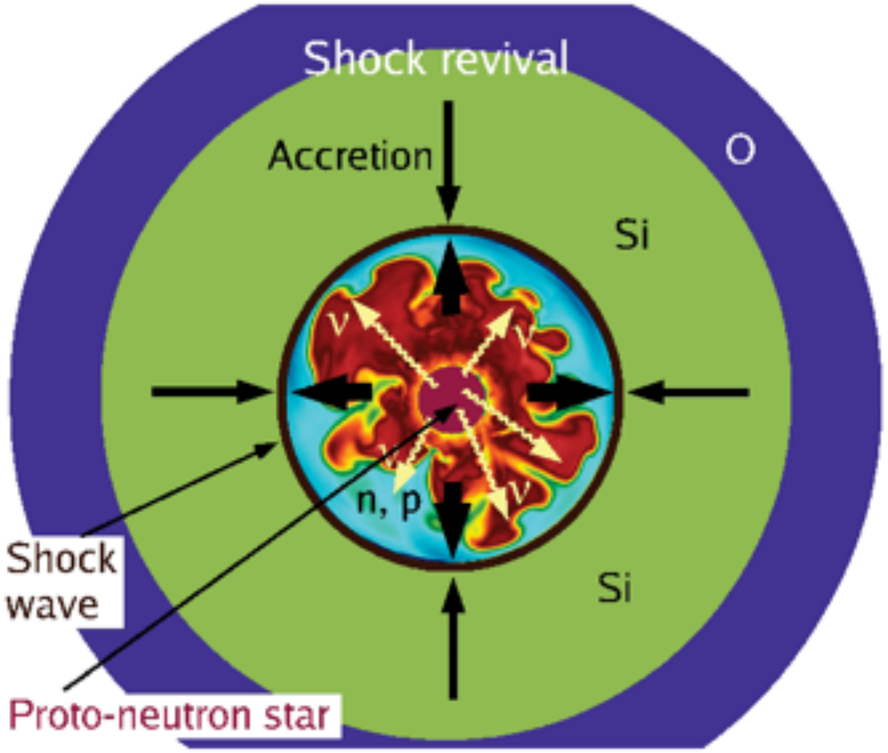
3 dynamic regims of GW emission:



Detection rates and horizons (adv. LIGO/ Virgo full sensitivity)

NS/NS: 0.04 - 100 / yr
BH/BH: ~35 / yr

Massive star core-collapse



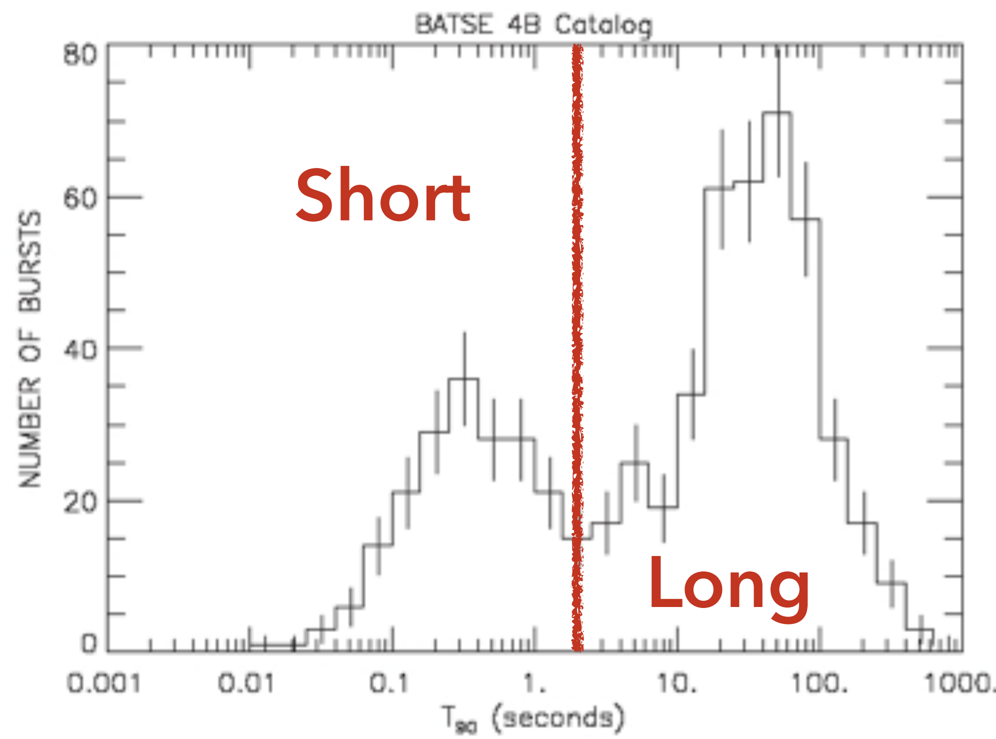
GW emission uncertain
energy emitted through GW:
$\sim 10^{-8} - 10^{-4}\ M_{\odot}c^2$

Detection rate poorly constrained

Both phenomena may be related to GRB !

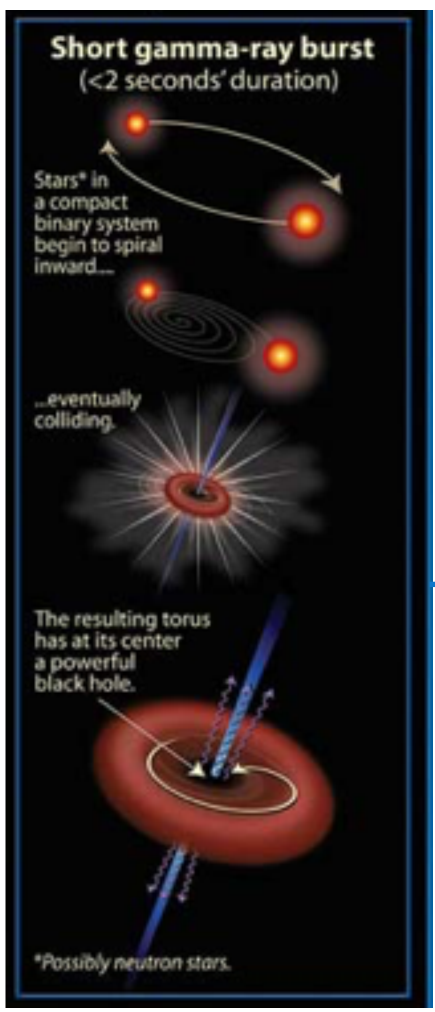
Short GRBs

- 10x closer than long GRB
- 100-1000 x less energetic
- association with older stellar pop.
- larger distance from the host galaxy center (~5-10 kpc)



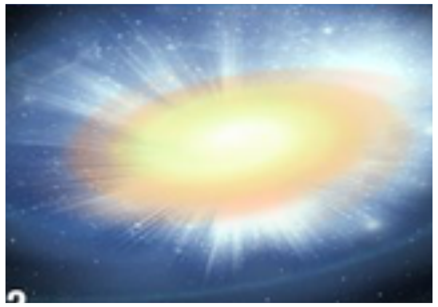
Long GRBs

- associated with SN Ic
- in star forming galaxies
- far away galaxies



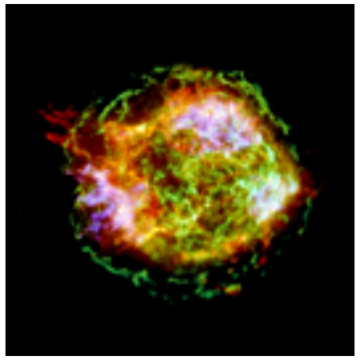
kilonovae (?)

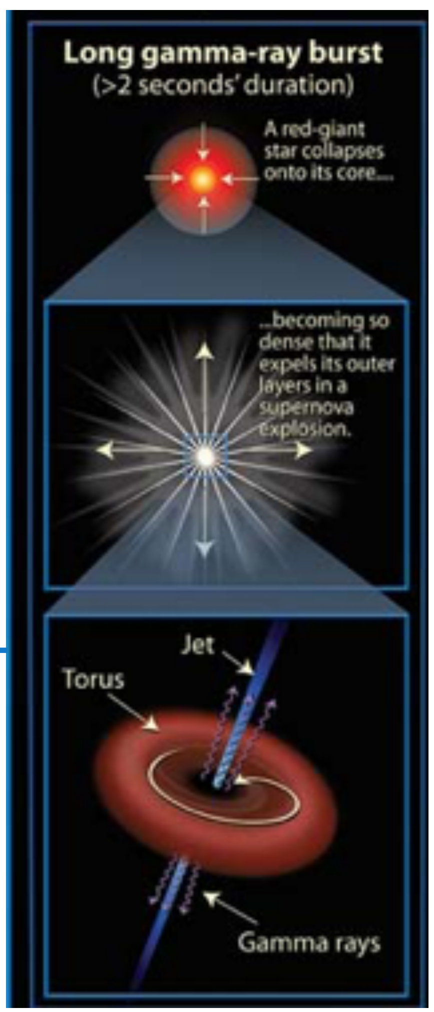
(Optical/IR, radio remnant)



Supernovae

Type II, Ib/c



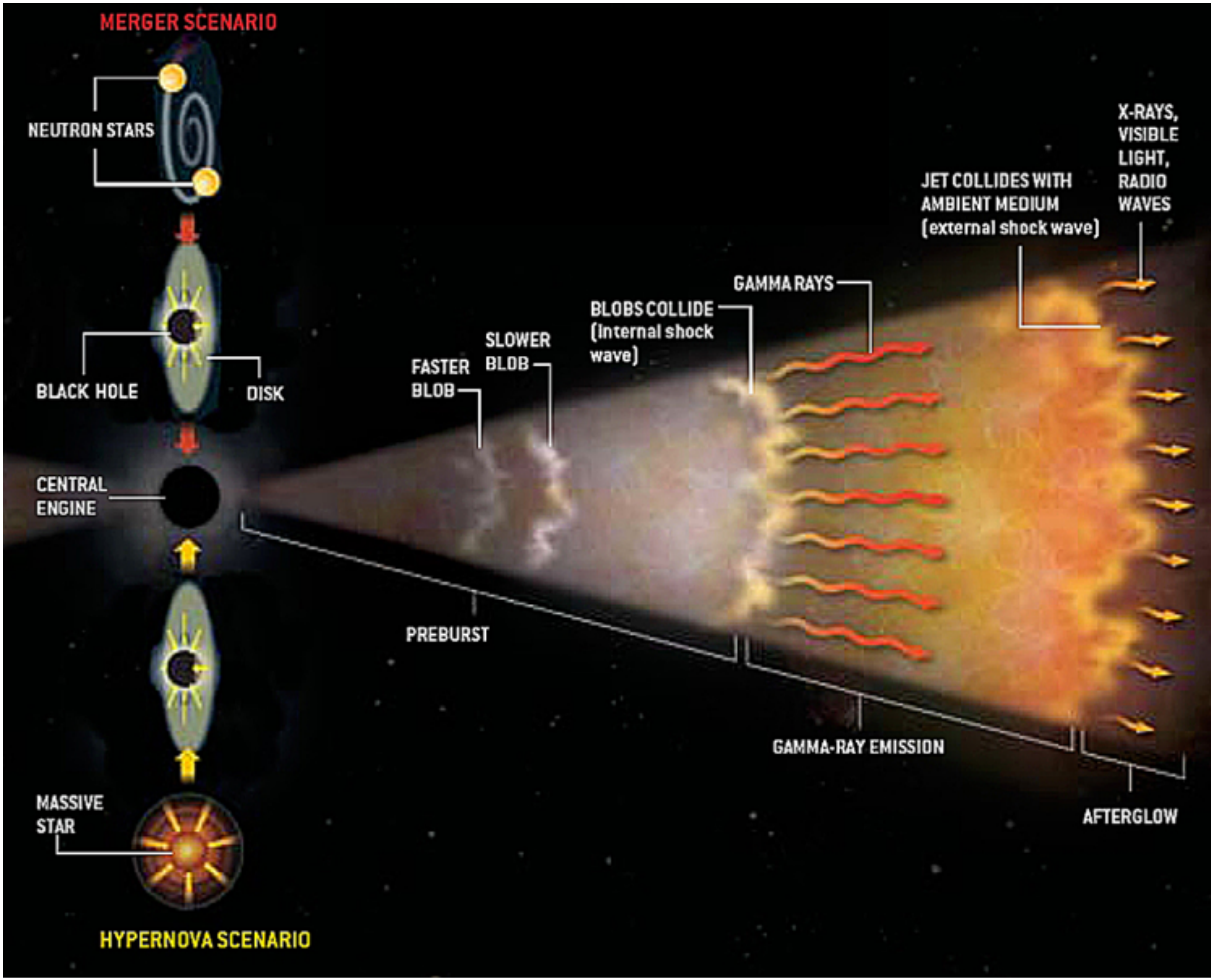


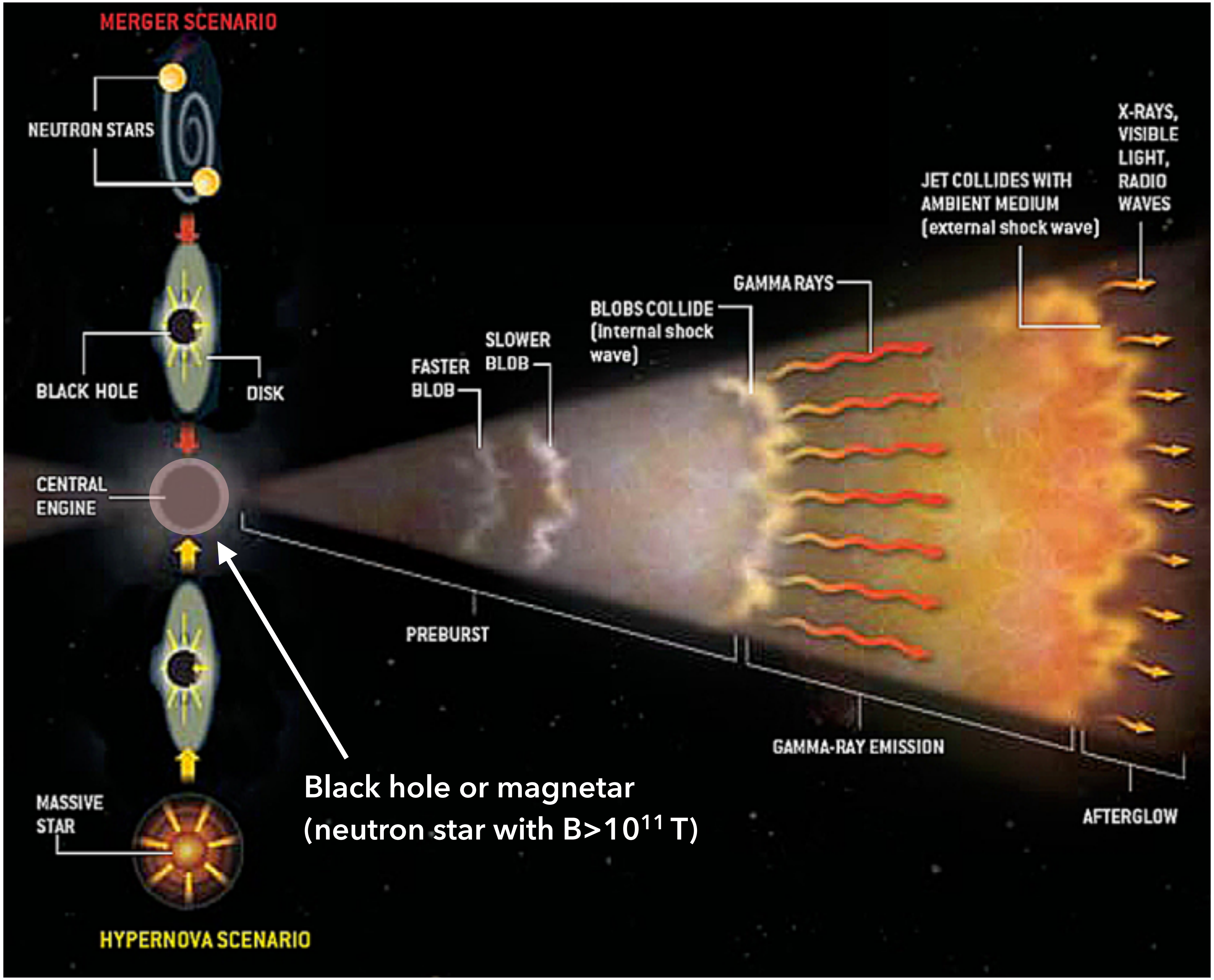
Multi-wavelength emission

What kind of EM emission can we expect from GW counterparts ?

(see e.g. Piran et al., 2013)

→ (short) GRBs are often considered as the most promising GW counterpart


MERGER SCENARIO
NEUTRON STARS
BLACK HOLE
DISK
CENTRAL ENGINE
MASSIVE STAR
HYPERNOVA SCENARIO
FASTER BLOB
SLOWER BLOB
PREBURST
BLOBS COLLIDE (internal shock wave)
GAMMA RAYS
GAMMA-RAY EMISSION
JET COLLIDES WITH AMBIENT MEDIUM (external shock wave)
X-RAYS, VISIBLE LIGHT, RADIO WAVES
AFTERGLOW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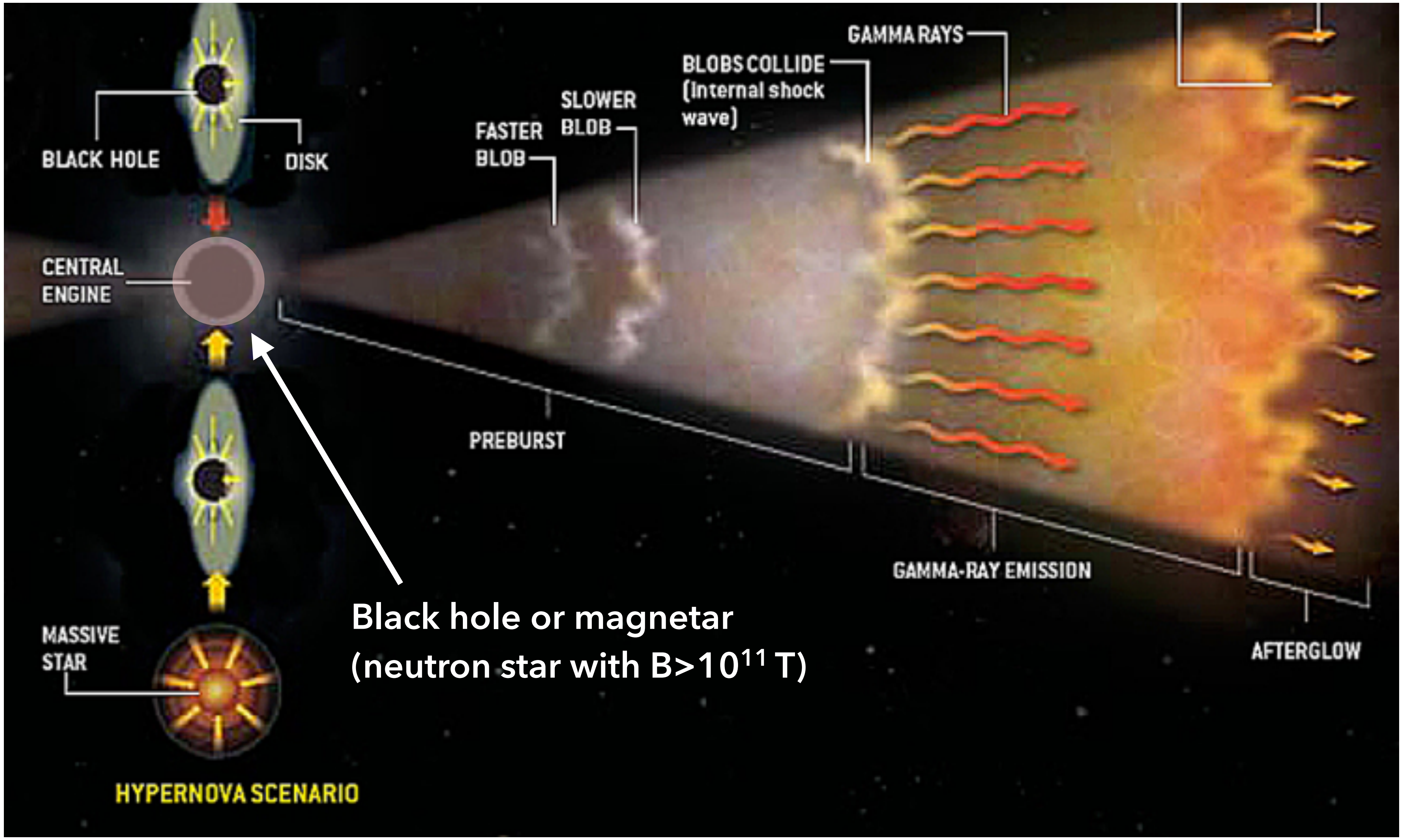
X-RAYS, VISIBLE LIGHT, RADIO WAVES
PREBURST
GAMMA-RAY EMISSION
AFTERGLOW
Black hole or magnetar
(neutron star with B>10^11 T)

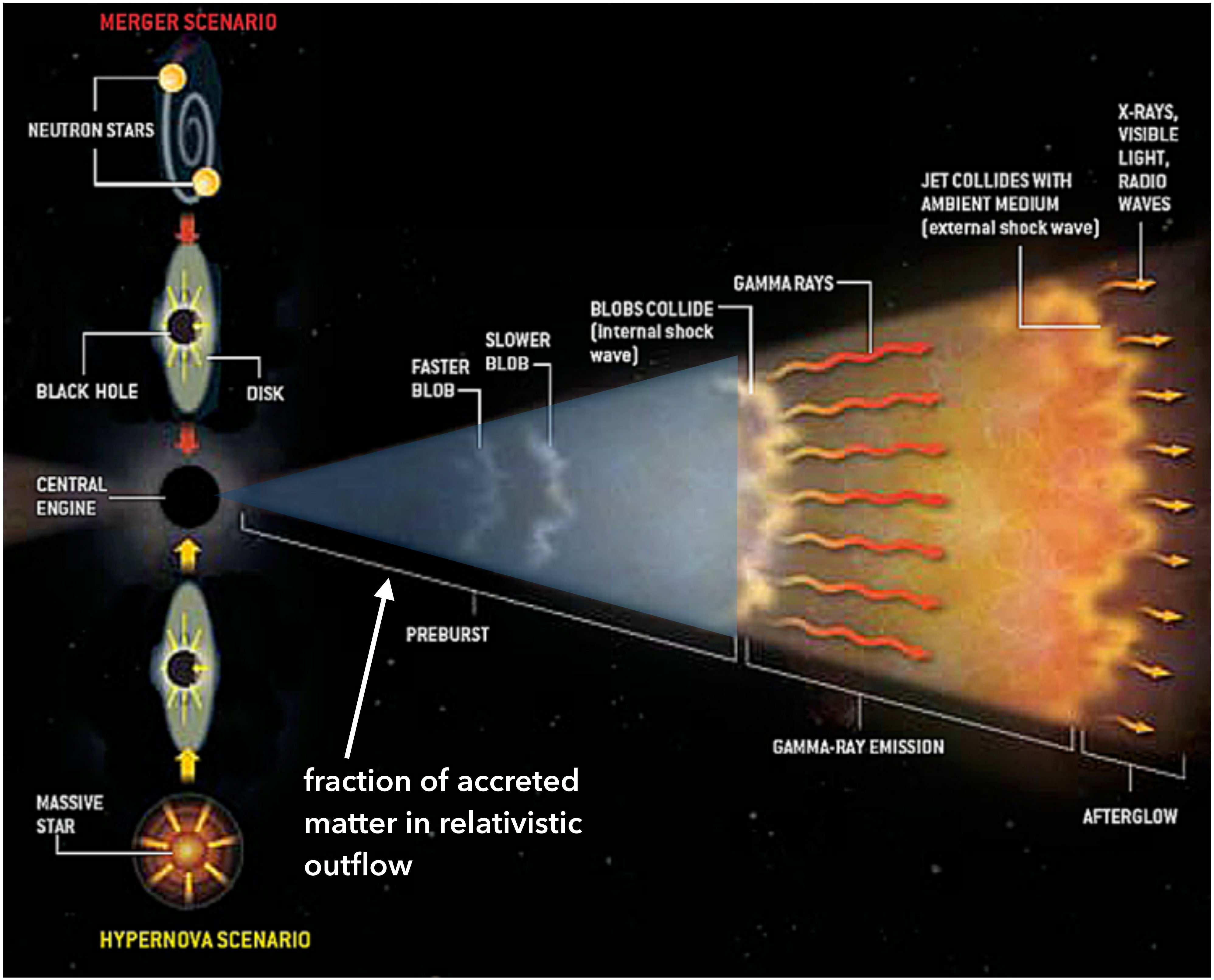
Available energy for different progenitors

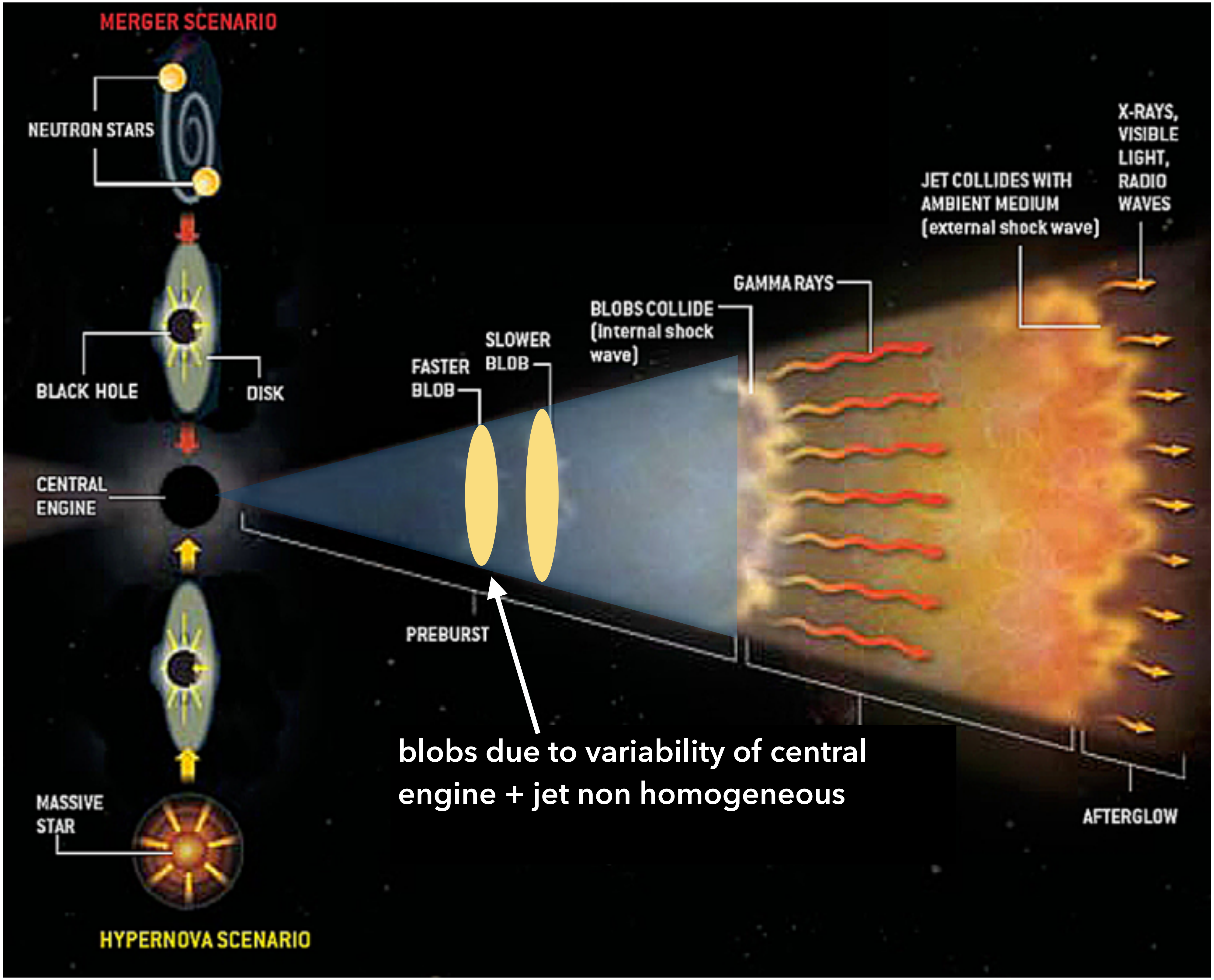
	Collapsar	Merger	Magnétar
M_{co}	$5 \rightarrow 15\ M_\odot$	$2.5 \rightarrow 10\ M_\odot$	$1.5\ M_\odot$
rotation	$a = 0.2 \rightarrow 0.8$	$a = 0.5 \rightarrow 1$	$P \simeq 1$ ms
E_{rot}	$\lesssim 5.2 \times 10^{54} (M/10\ M_\odot)$ erg	$\lesssim 2.6 \times 10^{54} (M/5\ M_\odot)$ erg	2×10^{52} erg $(P/1\ \mathrm{ms})^{-2}$
M_{disk}	$\gtrsim 10\ M_\odot$	$10^{-3} \rightarrow 0.1\ M_\odot$	$1\ M_\odot$?
E_{acc}	$\lesssim 8 \times 10^{54} (M_{disk}/10\ M_\odot)$ erg	$\lesssim 8 \times 10^{52} (M_{disk}/0.1\ M_\odot)$	$\lesssim 4 \times 10^{53}$ erg

R. Hascoët, PhD thesis

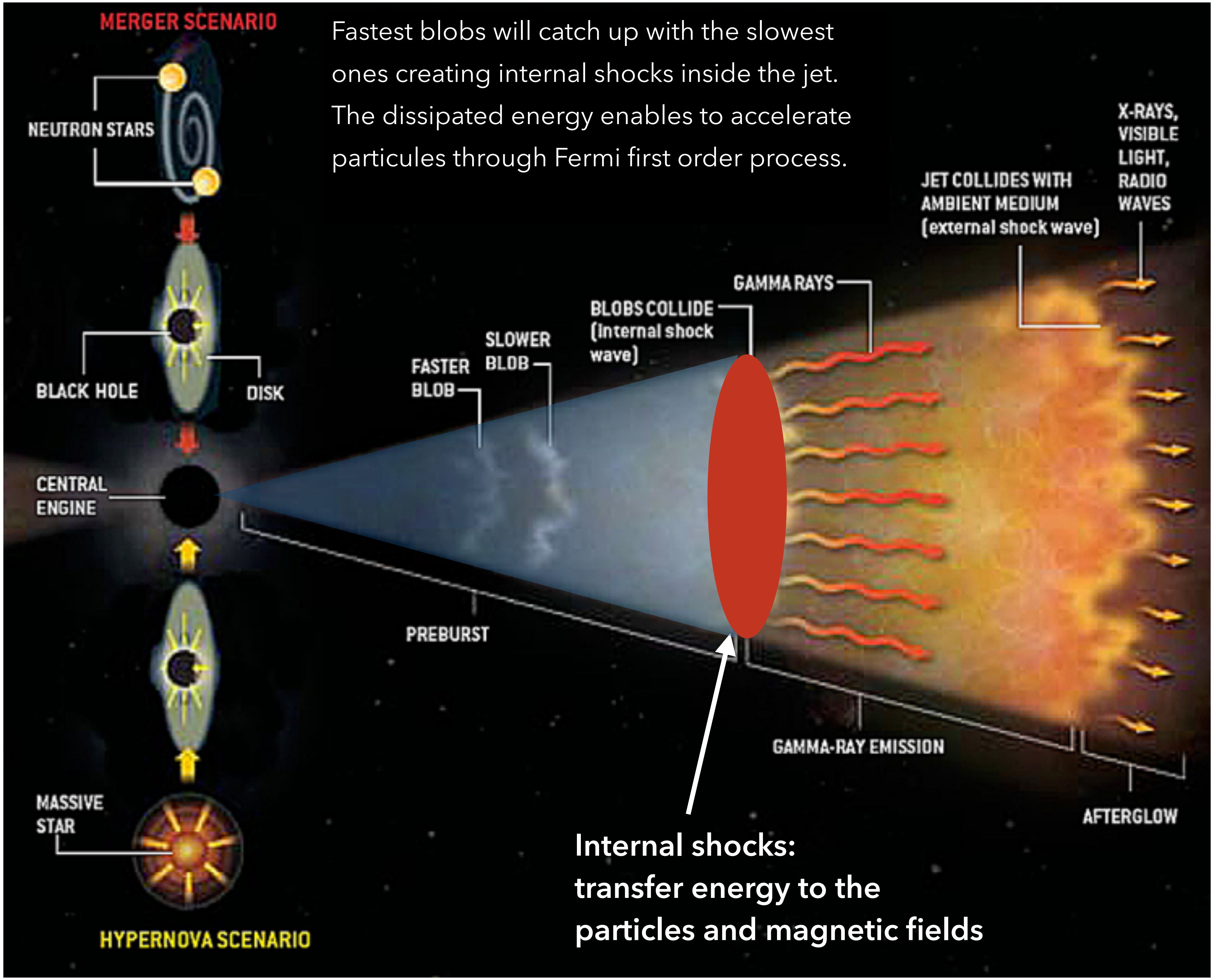


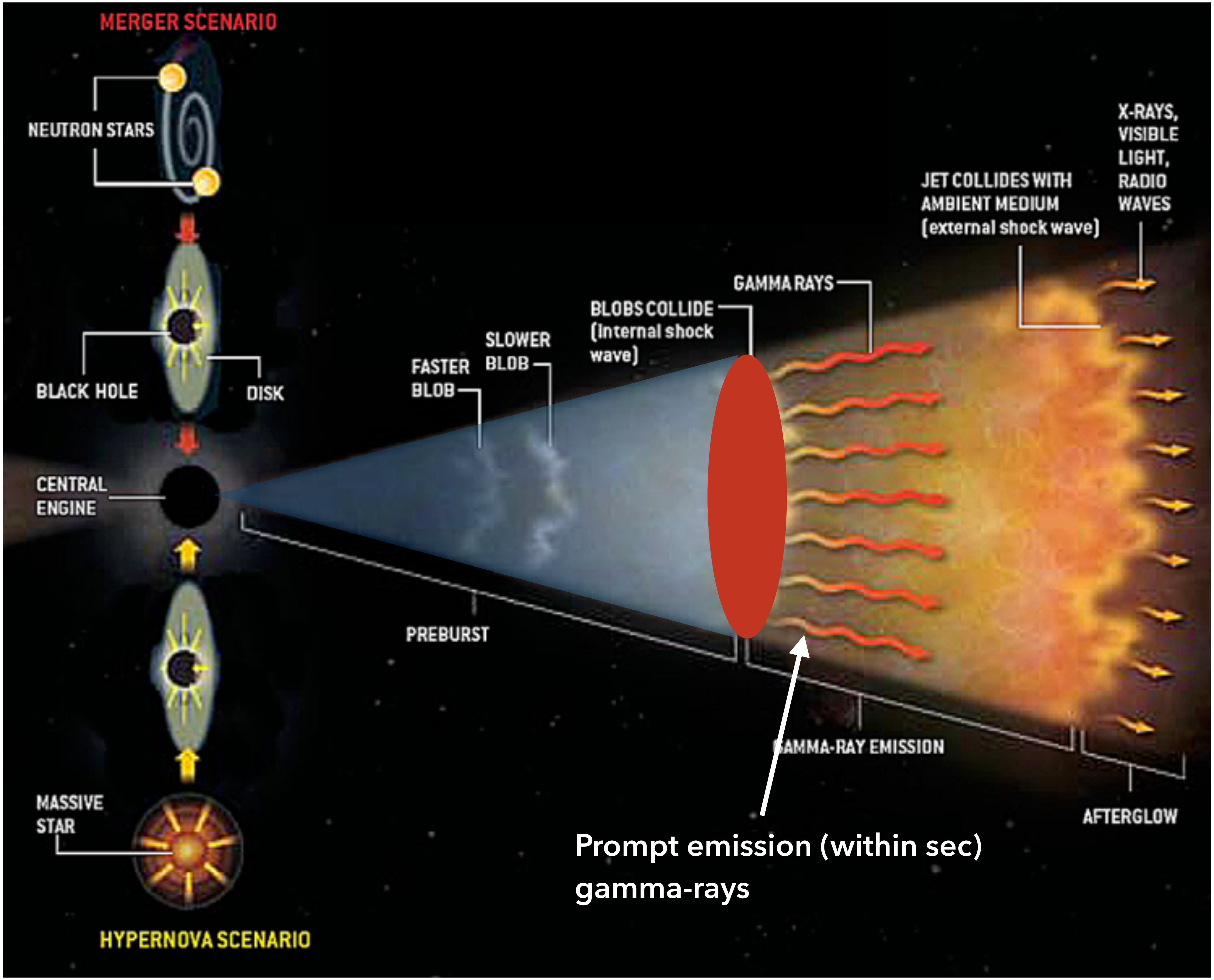
GAMMA-RAY BURST MECHANISM: FIREBALL MODEL




MERGER SCENARIO
NEUTRON STARS
BLACK HOLE
DISK
CENTRAL ENGINE
MASSIVE STAR
HYPERNOVA SCENARIO
FASTER BLOB
SLOWER BLOB
PREBURST
BLOBS COLLIDE (Internal shock wave)
GAMMA RAYS
JET COLLIDES WITH AMBIENT MEDIUM (external shock wave)
X-RAYS, VISIBLE LIGHT, RADIO WAVES
AFTERGLOW
blobs due to variability of central engine + jet non homogeneous

GAMMA-RAY BURST MECHANISM: FIREBALL MODEL




MERGER SCENARIO
NEUTRON STARS
BLACK HOLE
DISK
CENTRAL ENGINE
MASSIVE STAR
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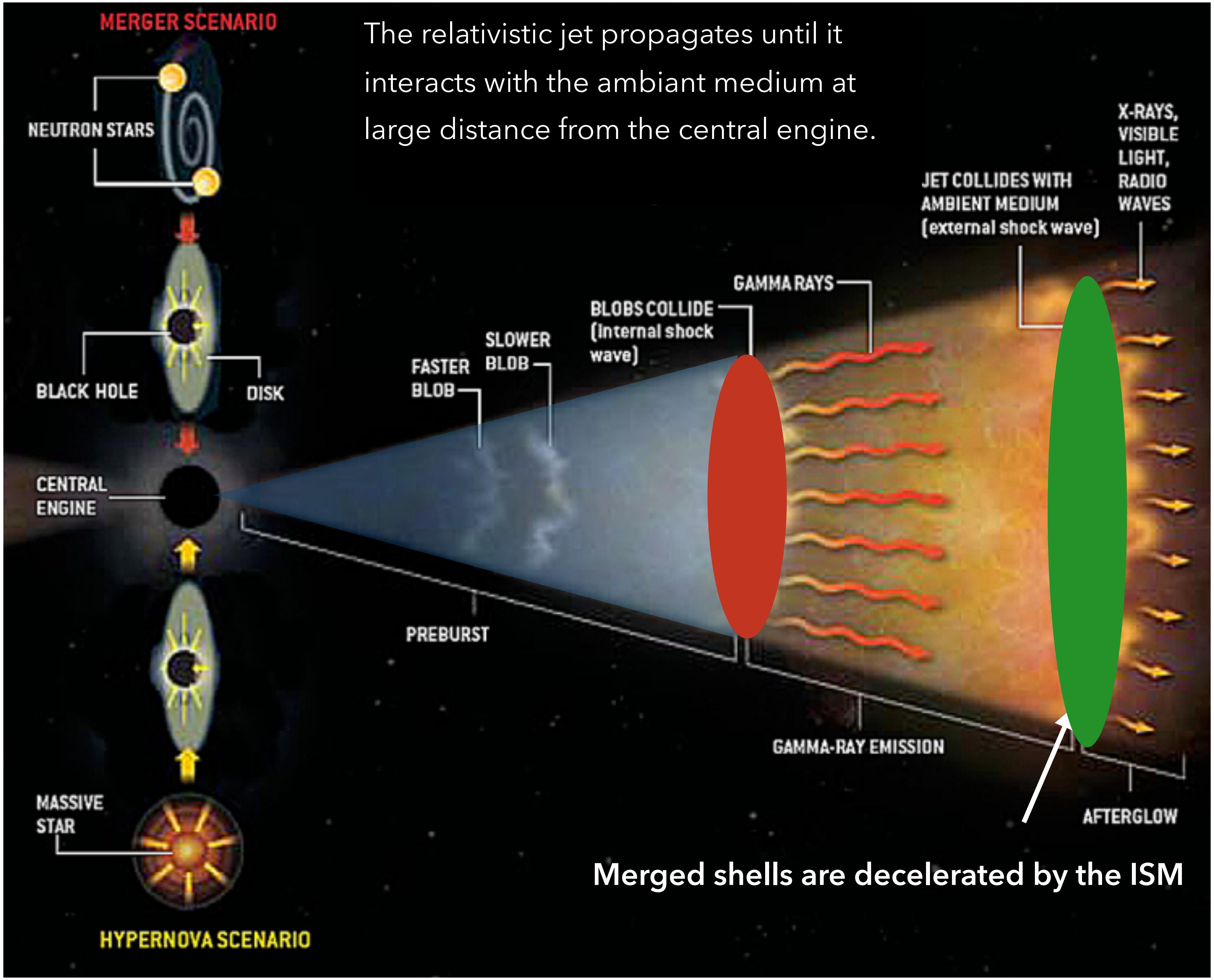
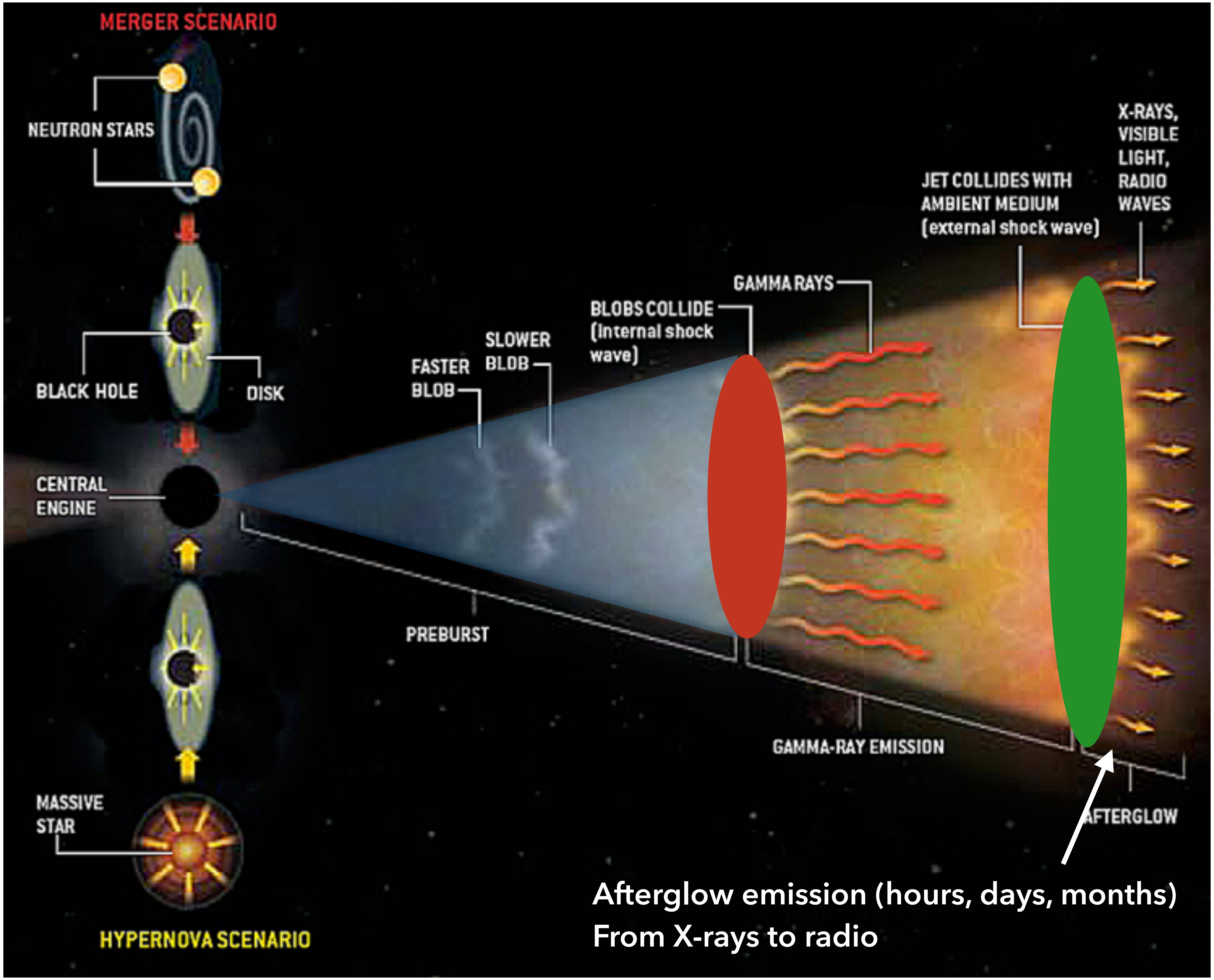
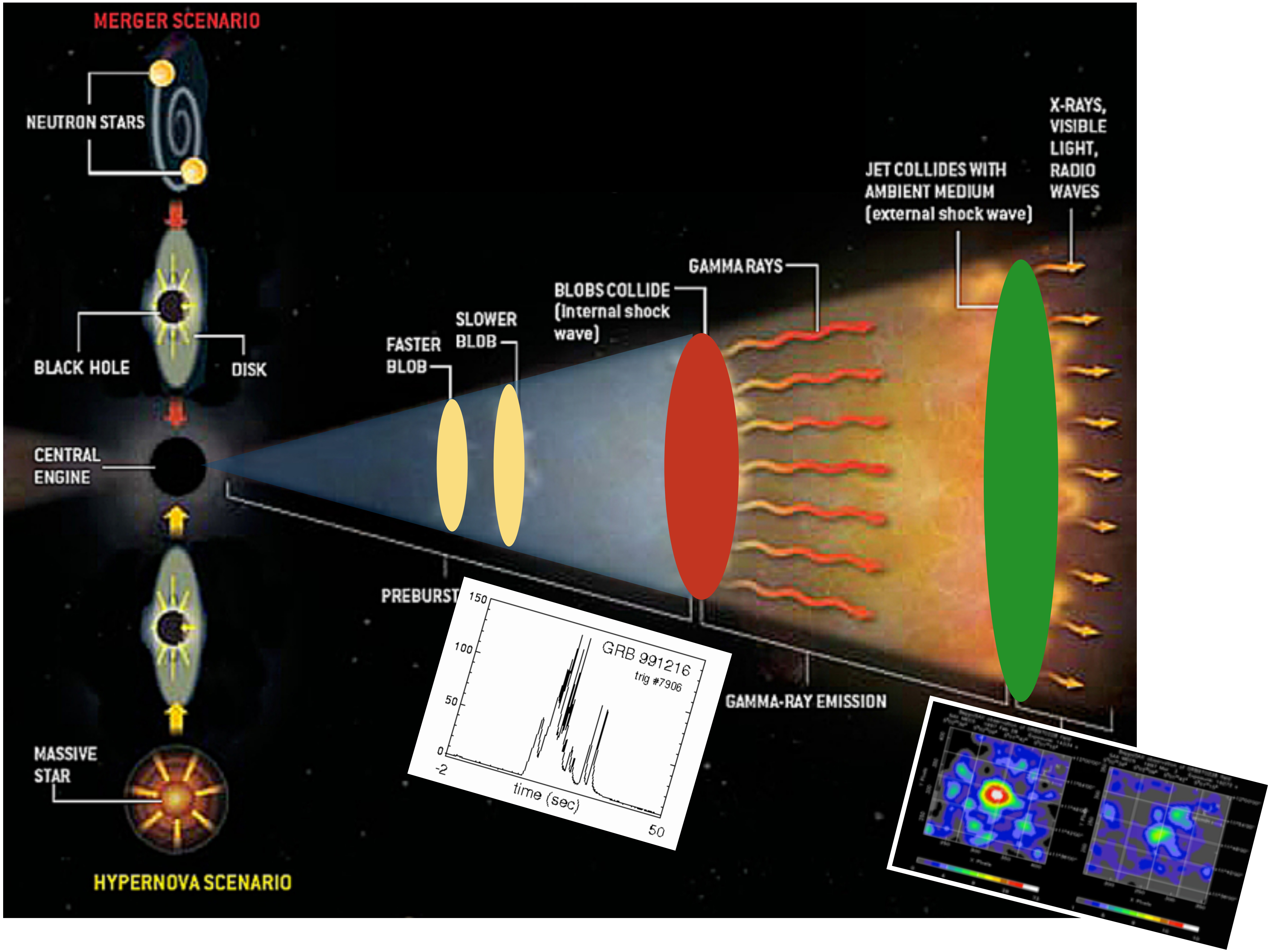
FASTER BLOB
SLOWER BLOB
BLOBS COLLIDE (Internal shock wave)
GAMMA RAYS
JET COLLIDES WITH AMBIENT MEDIUM (external shock wave)
X-RAYS, VISIBLE LIGHT, RADIO WAVES
PREBURST
GAMMA-RAY EMISSION
AFTERGLOW
Prompt emission (within sec)
gamma-rays


MERGER SCENARIO
The relativistic jet propagates until it interacts with the ambiant medium at large distance from the central engine.
NEUTRON STARS
X-RAYS, VISIBLE LIGHT, RADIO WAVES
JET COLLIDES WITH AMBIENT MEDIUM (external shock wave)
GAMMA RAYS
BLOBS COLLIDE (internal shock wave)
SLOWER BLOB
FASTER BLOB
BLACK HOLE
DISK
CENTRAL ENGINE
PREBURST
GAMMA-RAY EMISSION
AFTERGLOW
MASSIVE STAR
Merged shells are decelerated by the ISM
HYPERNOVA SCENARIO

GAMMA-RAY BURST MECHANISM: FIREBALL MODEL



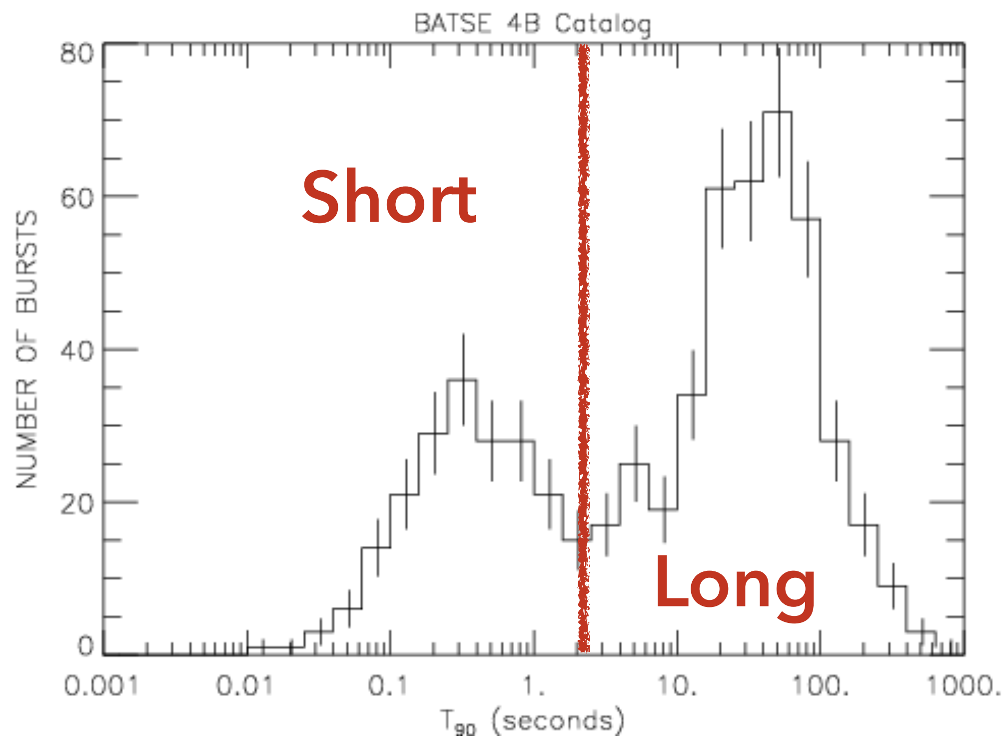
GAMMA-RAY BURST MECHANISM: FIREBALL MODEL

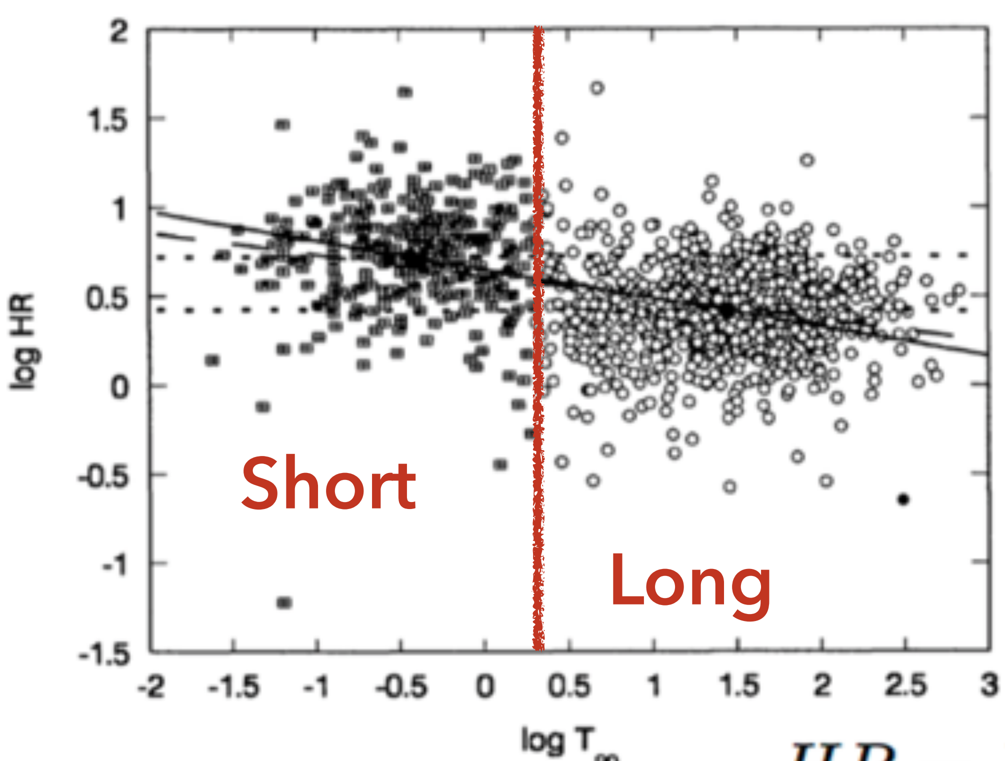


Prompt gamma-ray emission

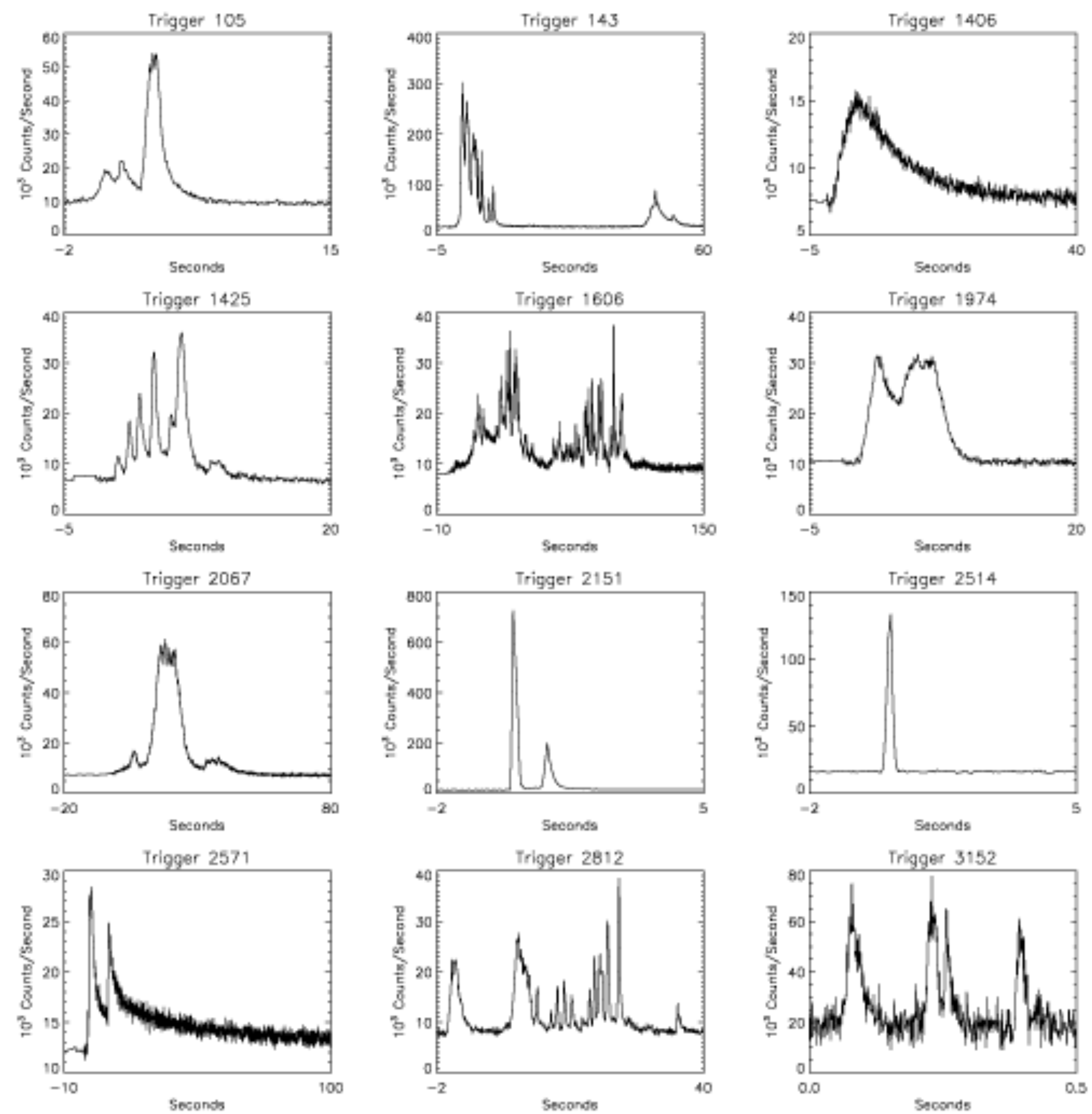
associated with the jet

Two classes of bursts





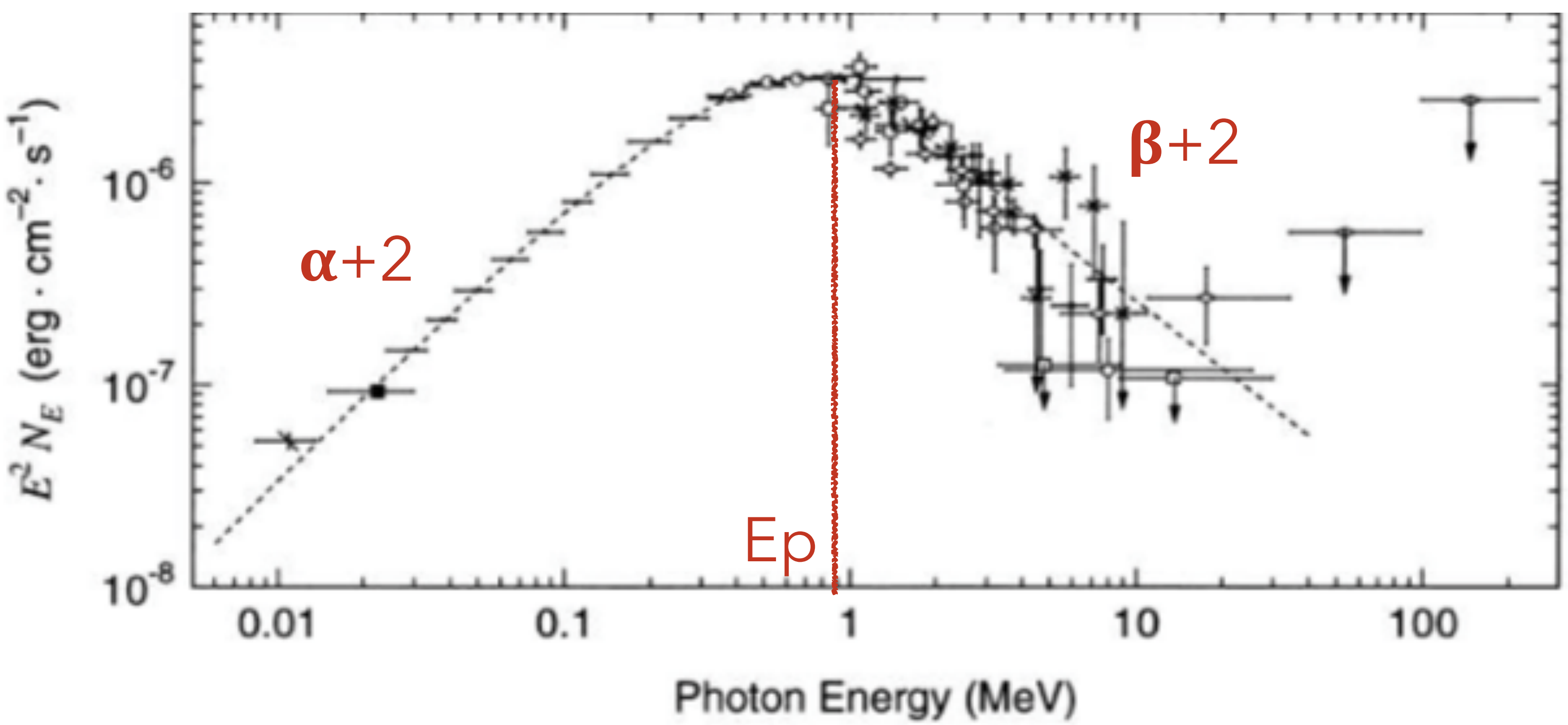
$$HR = F_{100-300}/F_{50-100}$$



Various lightcurves
(variability down to the ms timescale)

Prompt gamma-ray emission

associated with the jet



Prompt gamma-ray spectrum well fitted by Band function $B(x) = A \begin{cases} x^{\alpha} e^{-(2+\alpha)x} & , x < x_b \\ x^{\beta} x_b^{\alpha-\beta} e^{-(2+\alpha)x_b} & , x > x_b \end{cases}$

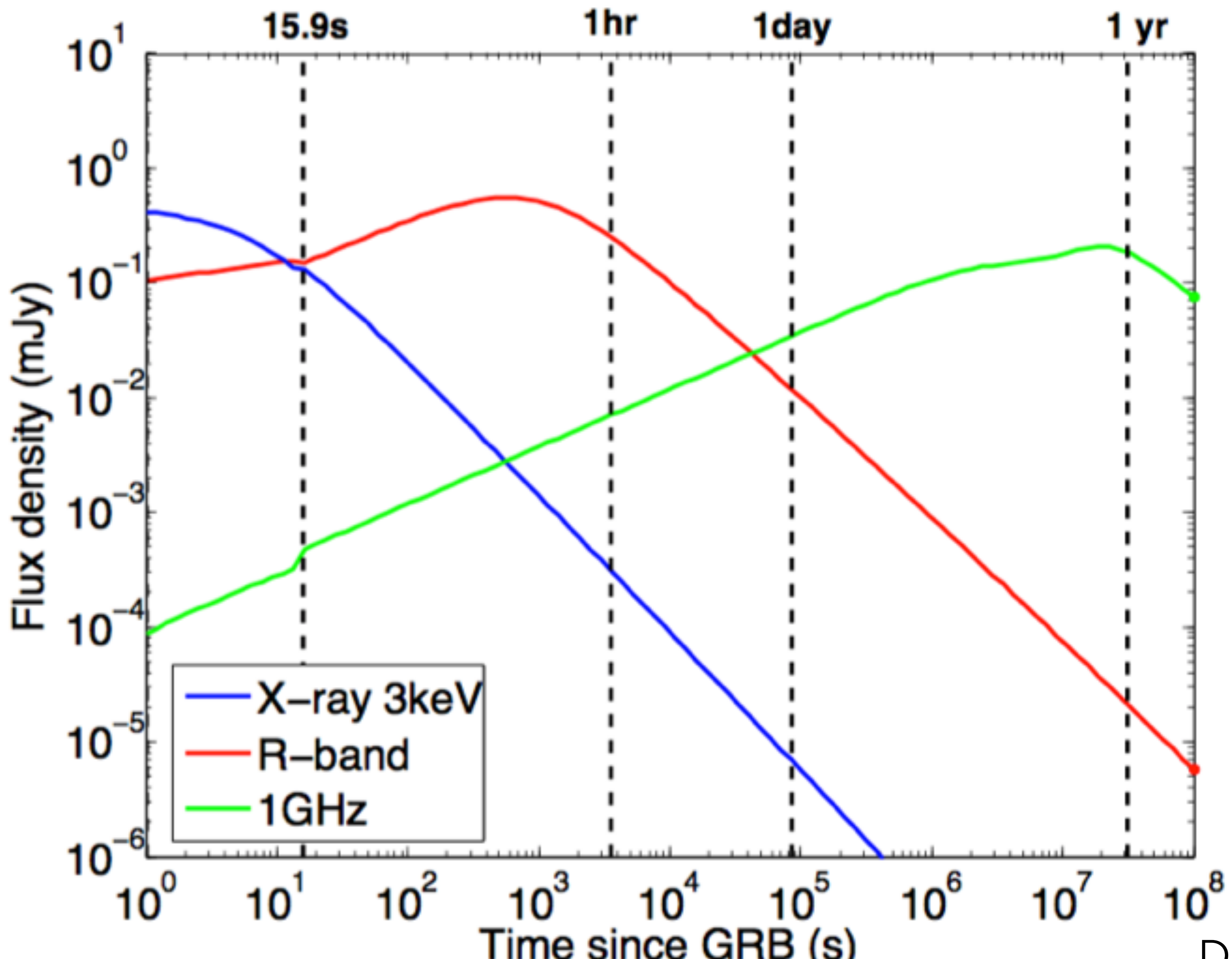
with $x = \frac{E}{E_p}$, $x_b = \frac{\alpha-\beta}{2+\alpha}$ (A, Ep, **α**, **β** are fitted).

Spectra can be explained by **synchrotron mechanism** (leptonic component).
Hadronic component cannot be totally excluded: keV-MeV photons could be explained by synchrotron emission of p + e (or Inverse-Compton of secondary e^+e^-). **But would require** 100 x **more energy in protons and magnetic fields than in gamma-rays** (but depends on Γ which is poorly constrained).

Afterglow multi-wavelength emission

Timescales depend on wavelength (<days in X-rays, <month in optical, <year in radio)

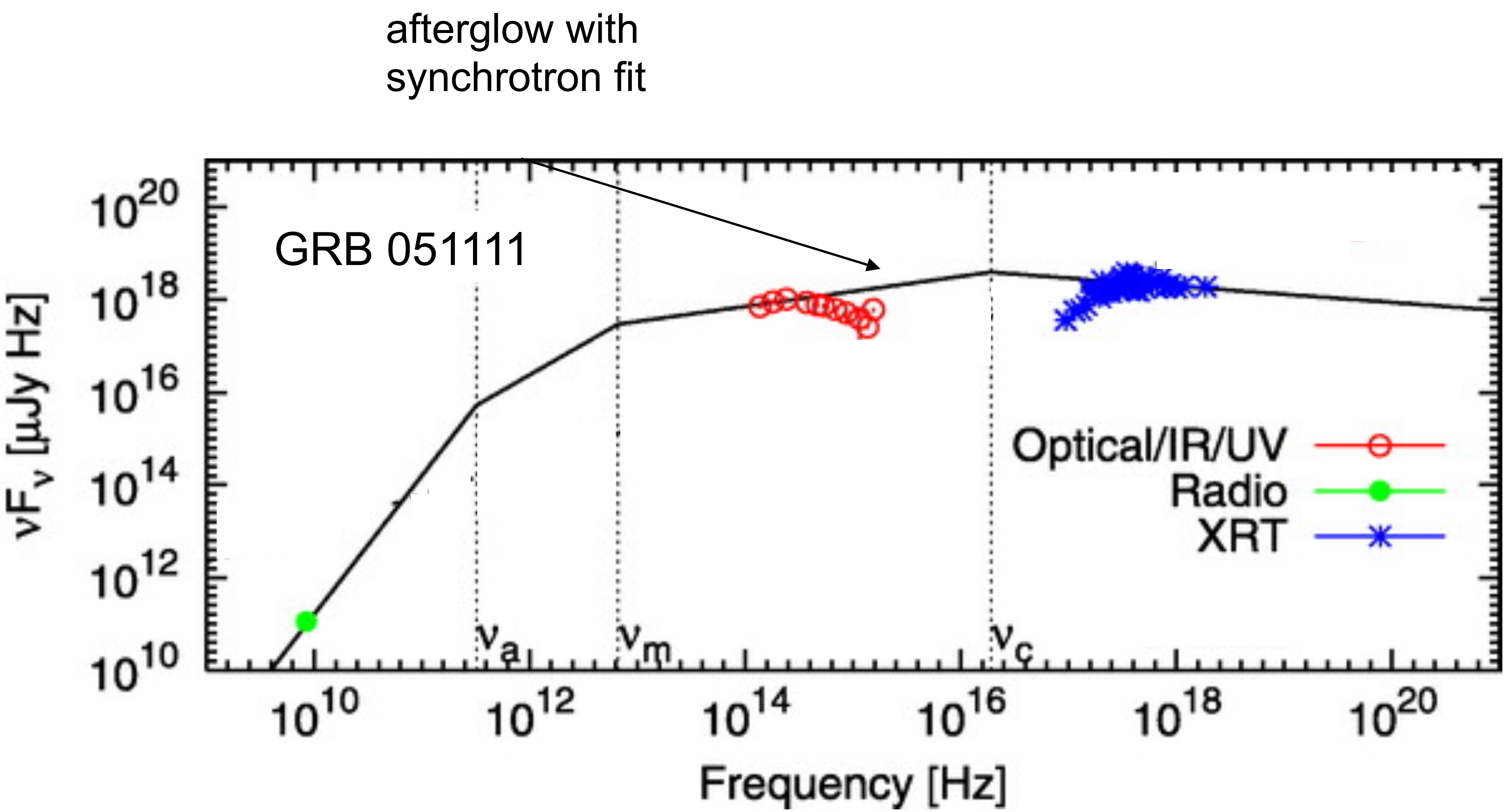
Results from the deceleration of the flow by the external medium (uniform or stellar wind)



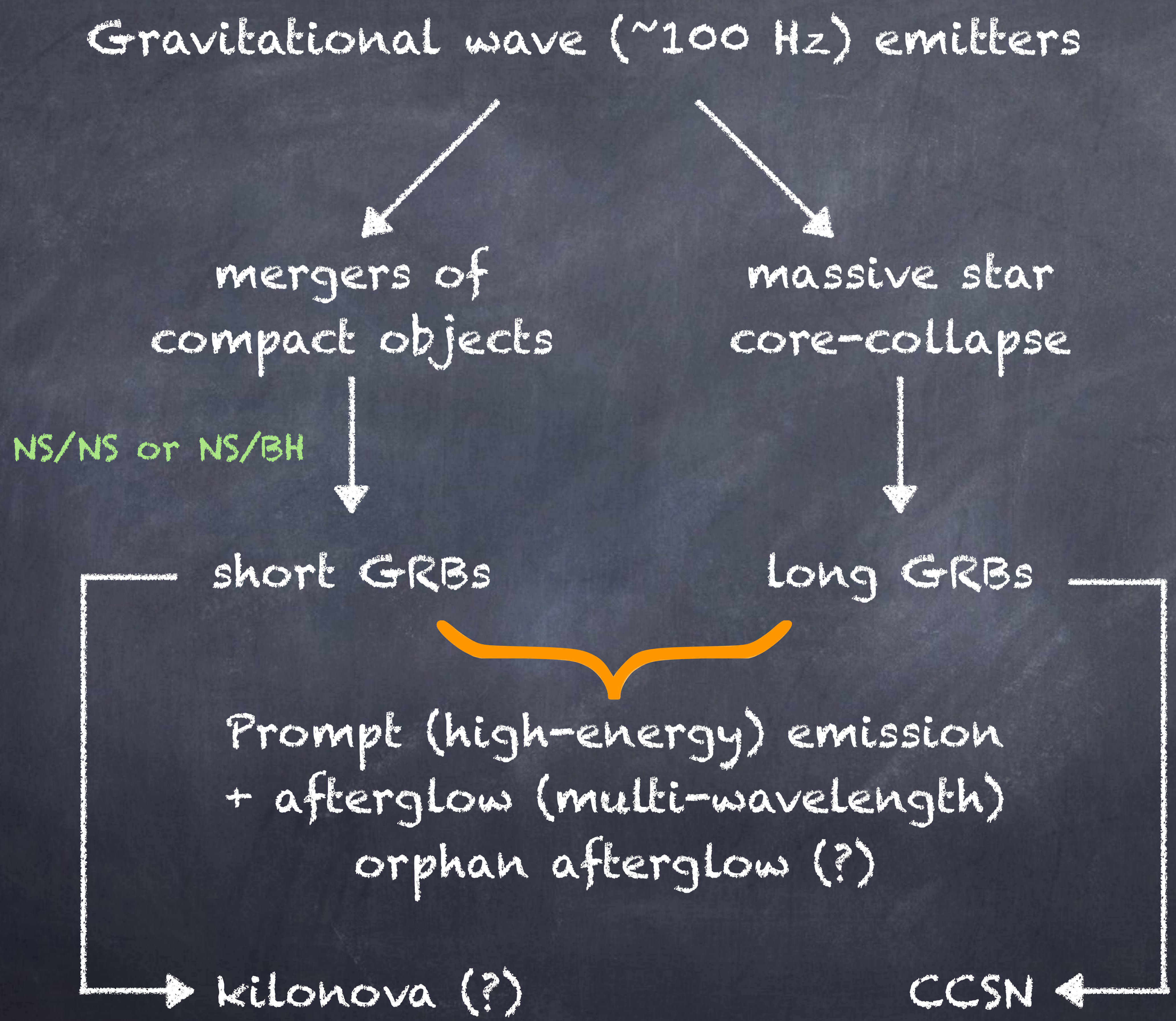
D. Turpin, PhD thesis

Afterglow multi-wavelength emission

Synchrotron emission from relativistic blast waves expanding into an external medium



Butler et al., 2006


Gravitational wave (~100 Hz) emitters
mergers of compact objects
massive star core-collapse
NS/NS or NS/BH
short GRBs
long GRBs
Prompt (high-energy) emission
+ afterglow (multi-wavelength)
orphan afterglow (?)
kilonova (?)
CCSN

Multi-messenger emission

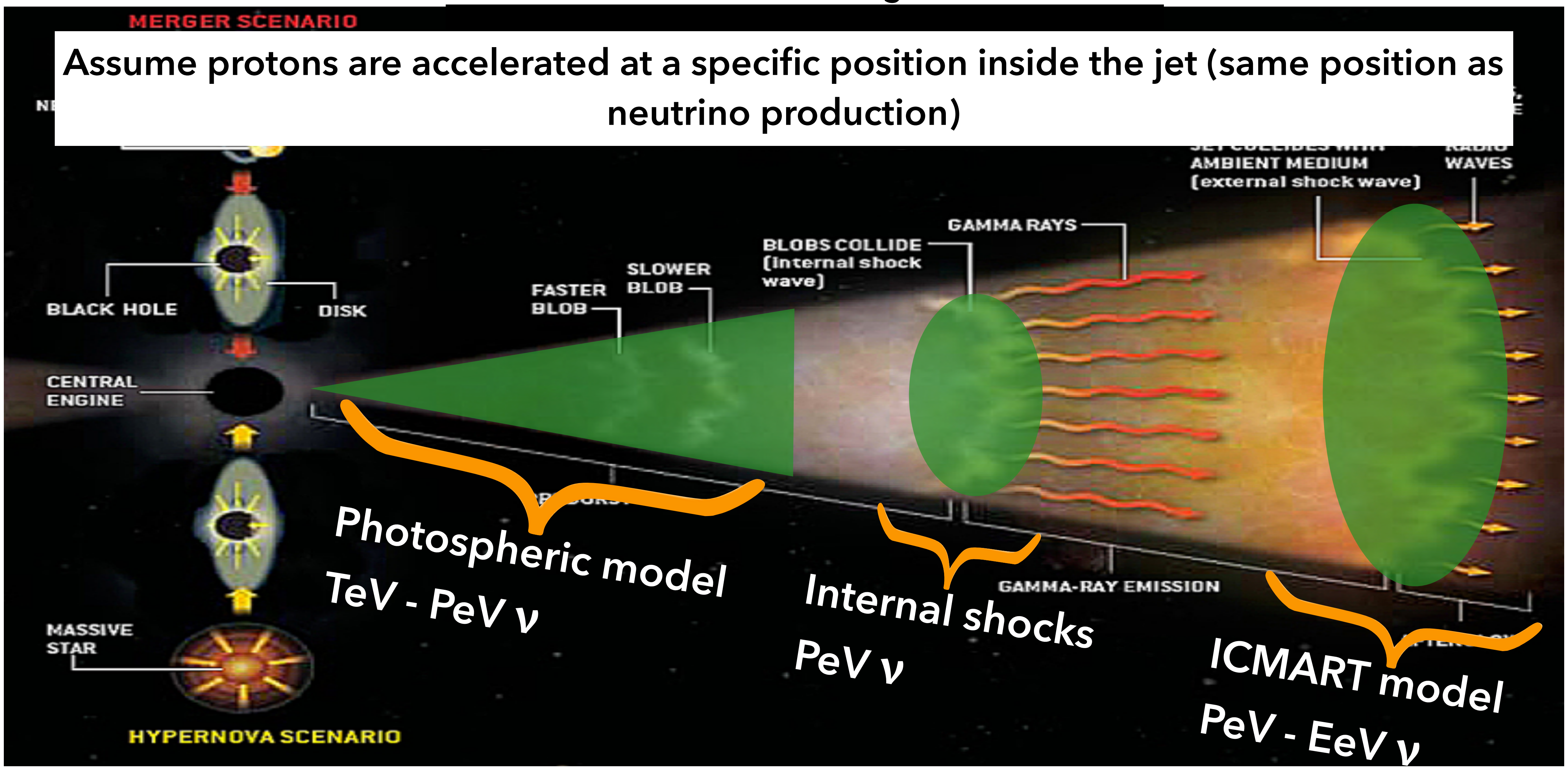
What kind of multi-messenger emission is expected from GW counterparts ?

Still assuming a GRB model:

- (Ultra-) High-energy cosmic rays ?
- High-energy neutrinos ?

Zhang & Kumar 2013

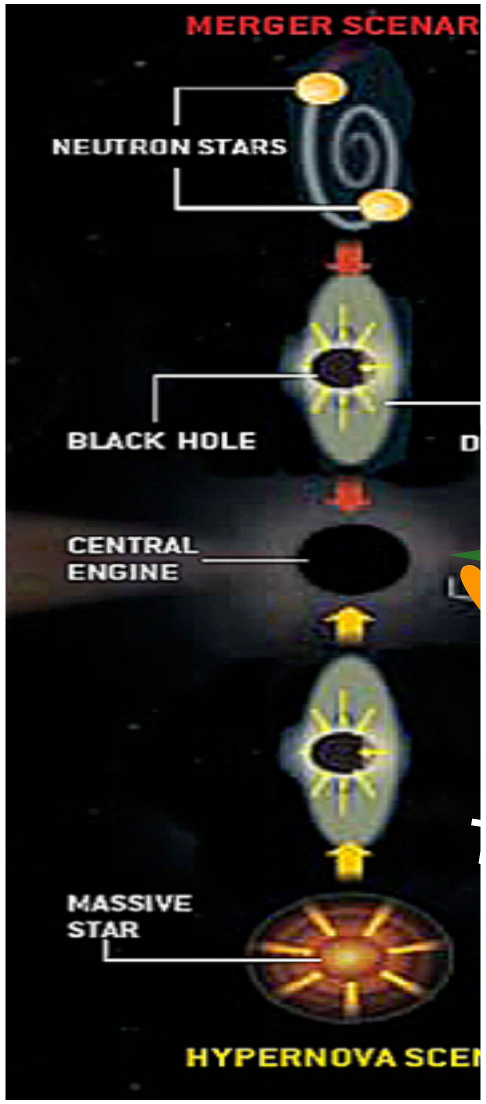
Assume protons are accelerated at a specific position inside the jet (same position as neutrino production)



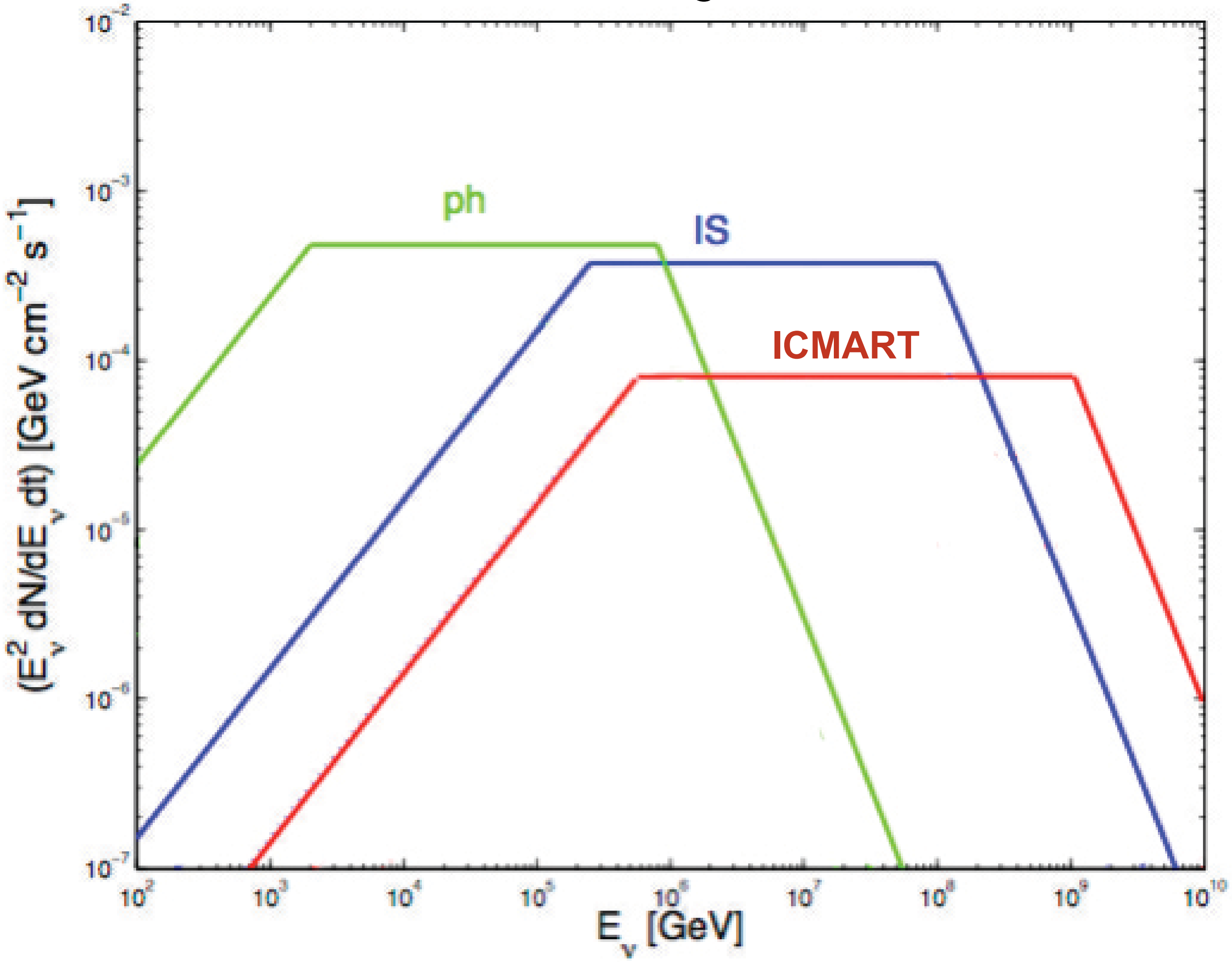
$$p+\gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p+\pi^0 \\ n+\pi^+ \end{cases} \rightarrow \begin{cases} \pi^0 \rightarrow \gamma+\gamma \\ n \rightarrow p+e^- + \bar{\nu}_e \\ \pi^+ \rightarrow \mu^+ + \nu_\mu \\ \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \end{cases}$$

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

$$K^+ \rightarrow \mu^+ + \nu_\mu$$



Zhang & Kumar 2013



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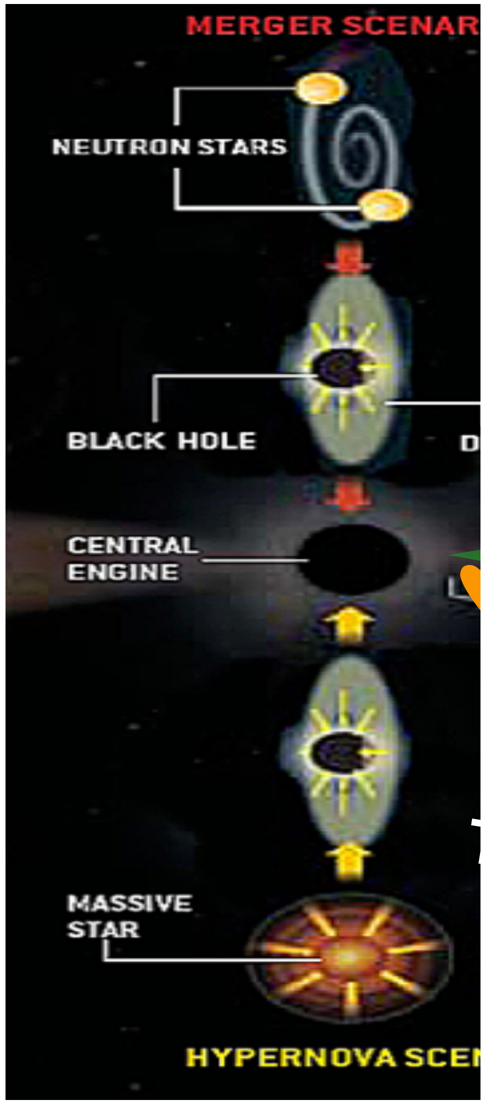
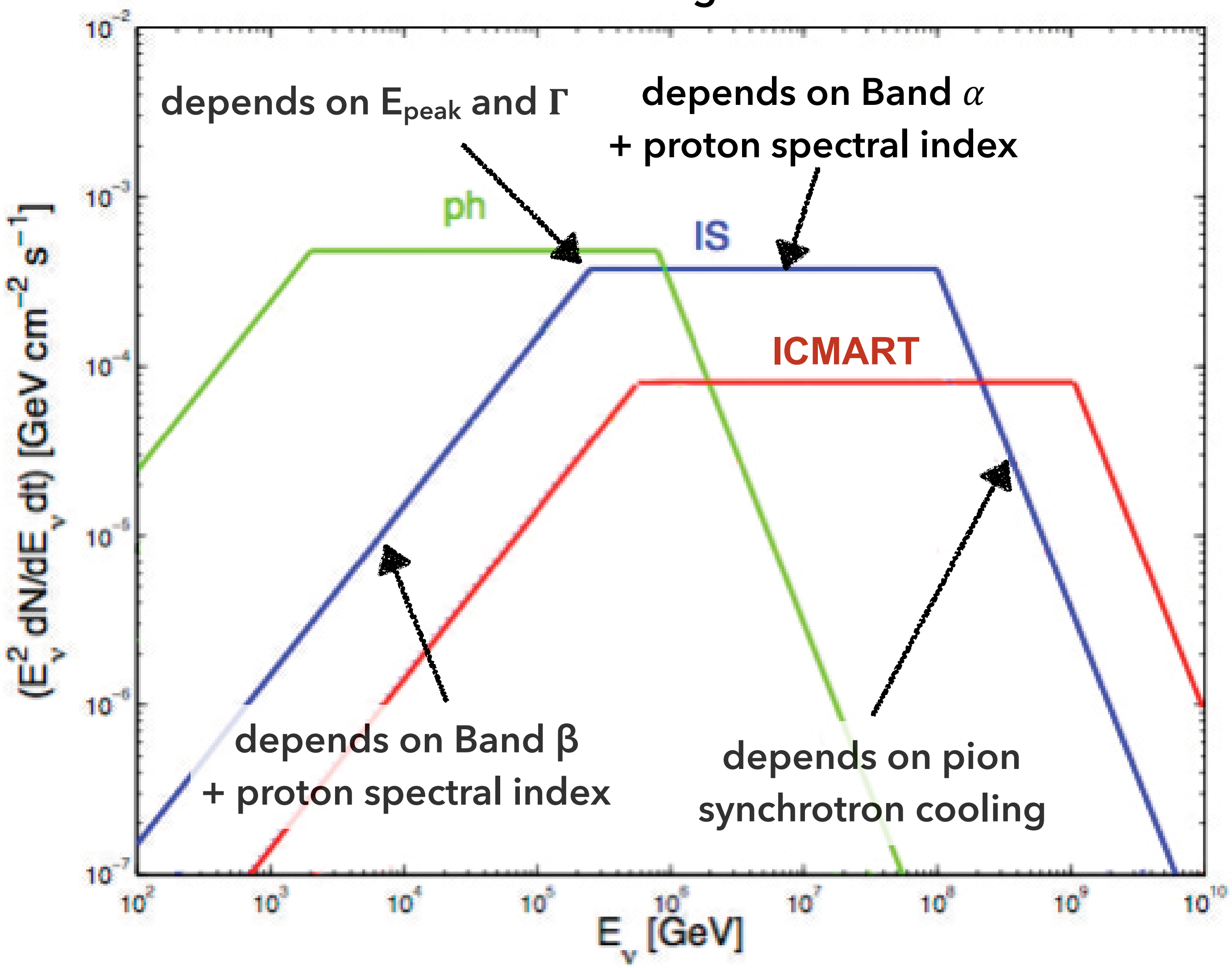
$$p+\gamma \rightarrow K^+ + \Lambda / \Sigma$$

$$K^+ \rightarrow \mu^+ + \nu_\mu$$



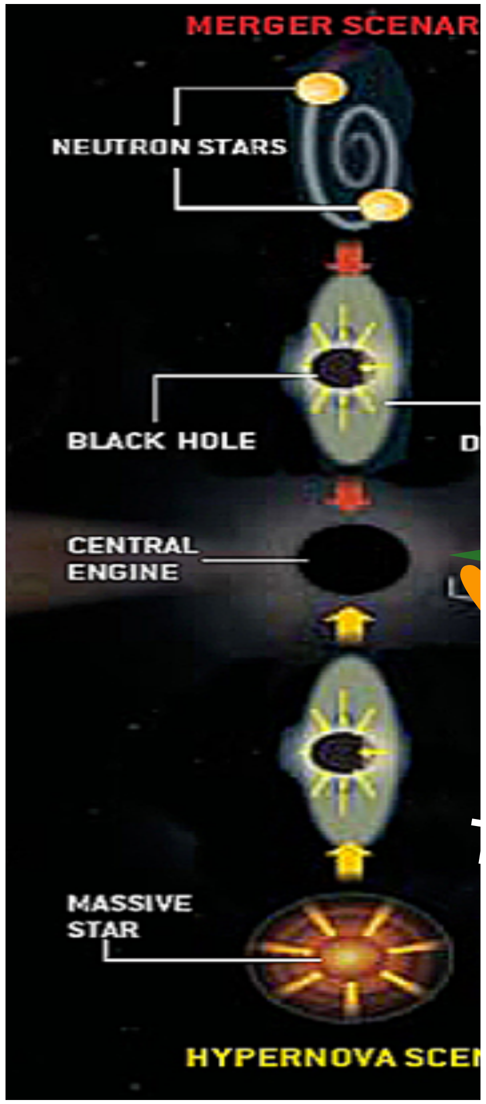
Zhang & Kumar 2013



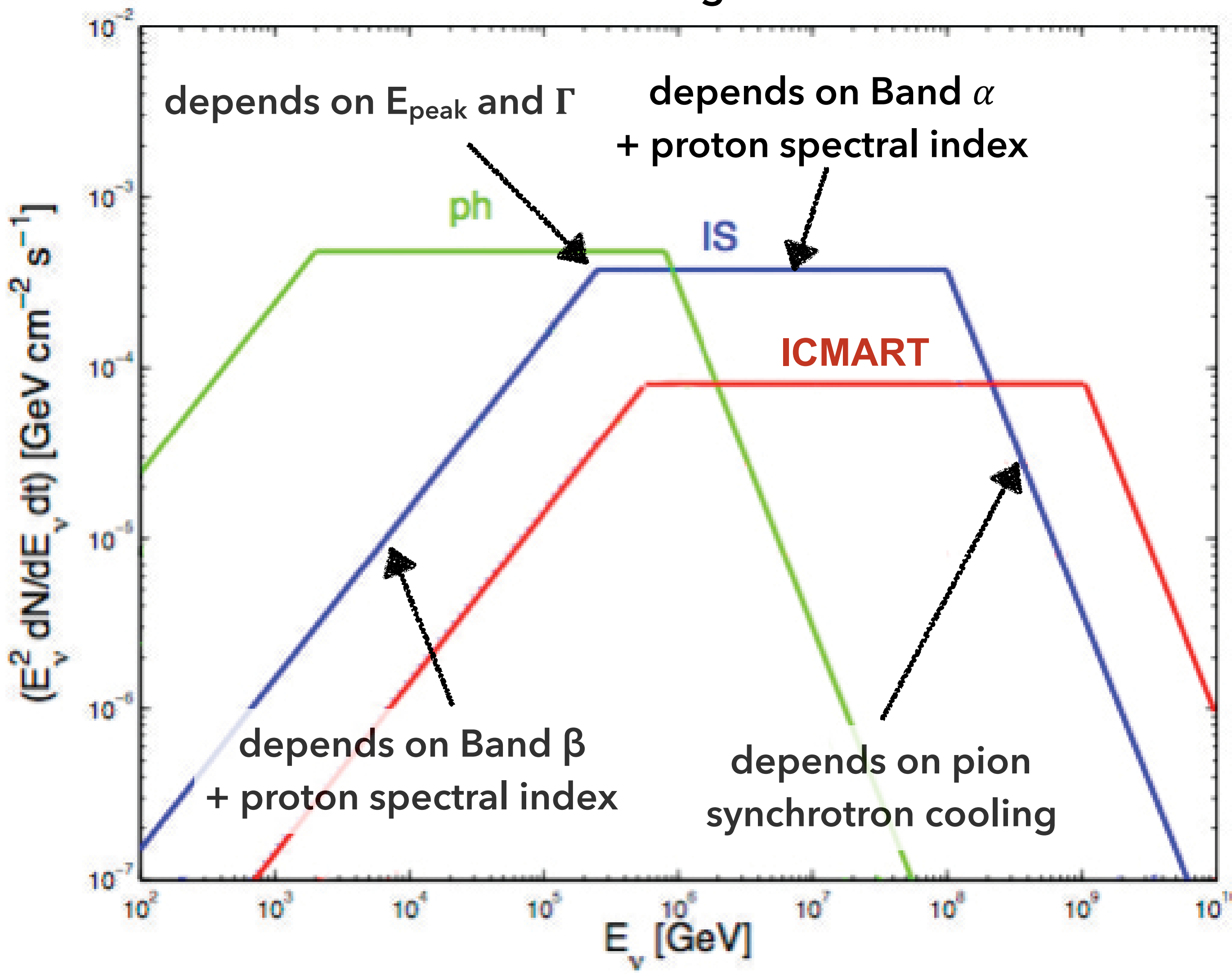
$$p+\gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p+\pi^0 \\ n+\pi^+ \end{cases} \rightarrow \begin{cases} \pi^0 \rightarrow \gamma+\gamma \\ n \rightarrow p+e^- +\bar{\nu}_e \\ \pi^+ \rightarrow \mu^+ +\nu_\mu \\ \mu^+ \rightarrow e^+ +\nu_e +\bar{\nu}_\mu \end{cases}$$

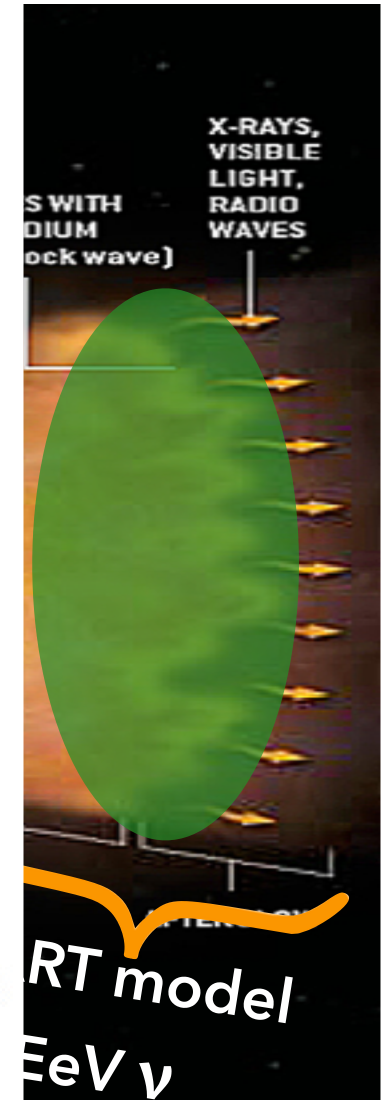
$$p+\gamma \rightarrow K^+ +\Lambda/\Sigma$$

$$K^+ \rightarrow \mu^+ +\nu_\mu$$



Zhang & Kumar 2013





One-zone models (assume that the bulk of neutrinos is produced at fixed radius) ➜ Start to be constrained by observations.
Multiple-zone models expect lower flux of neutrinos

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

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

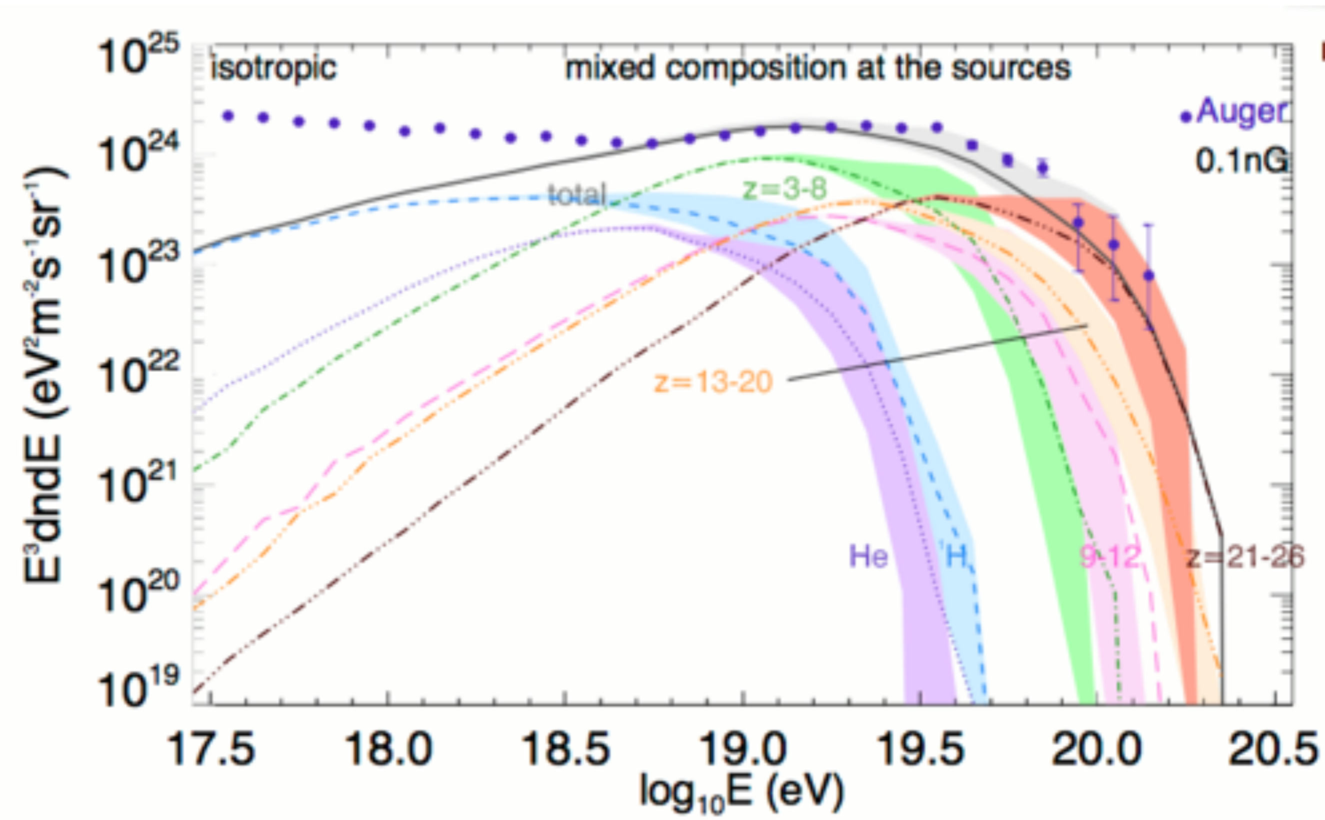
$$\rightarrow K^+ + \Lambda / \Sigma$$

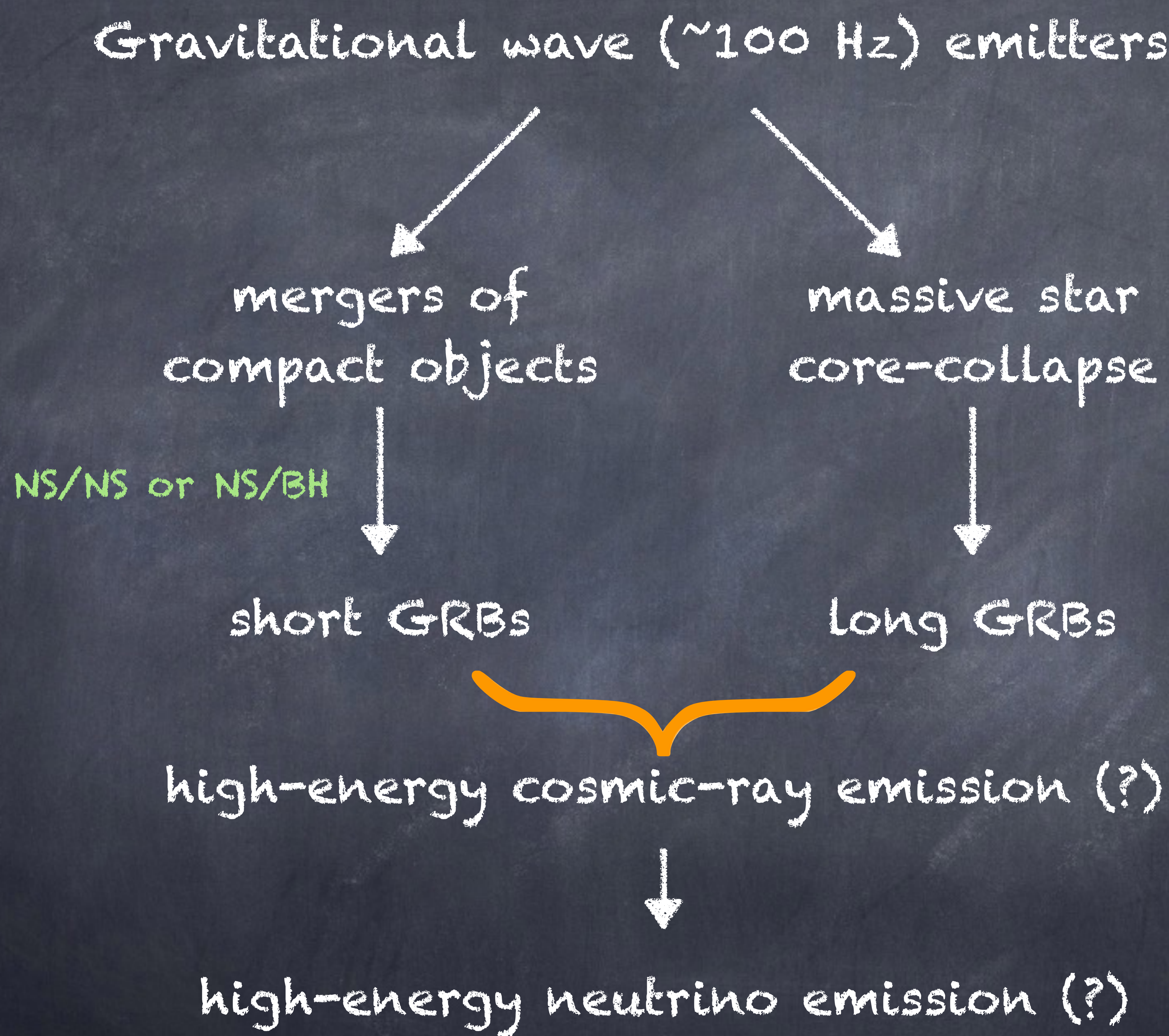
$$K^+ \rightarrow \mu^+ + \nu_\mu$$

For instance Globus et al., 2014

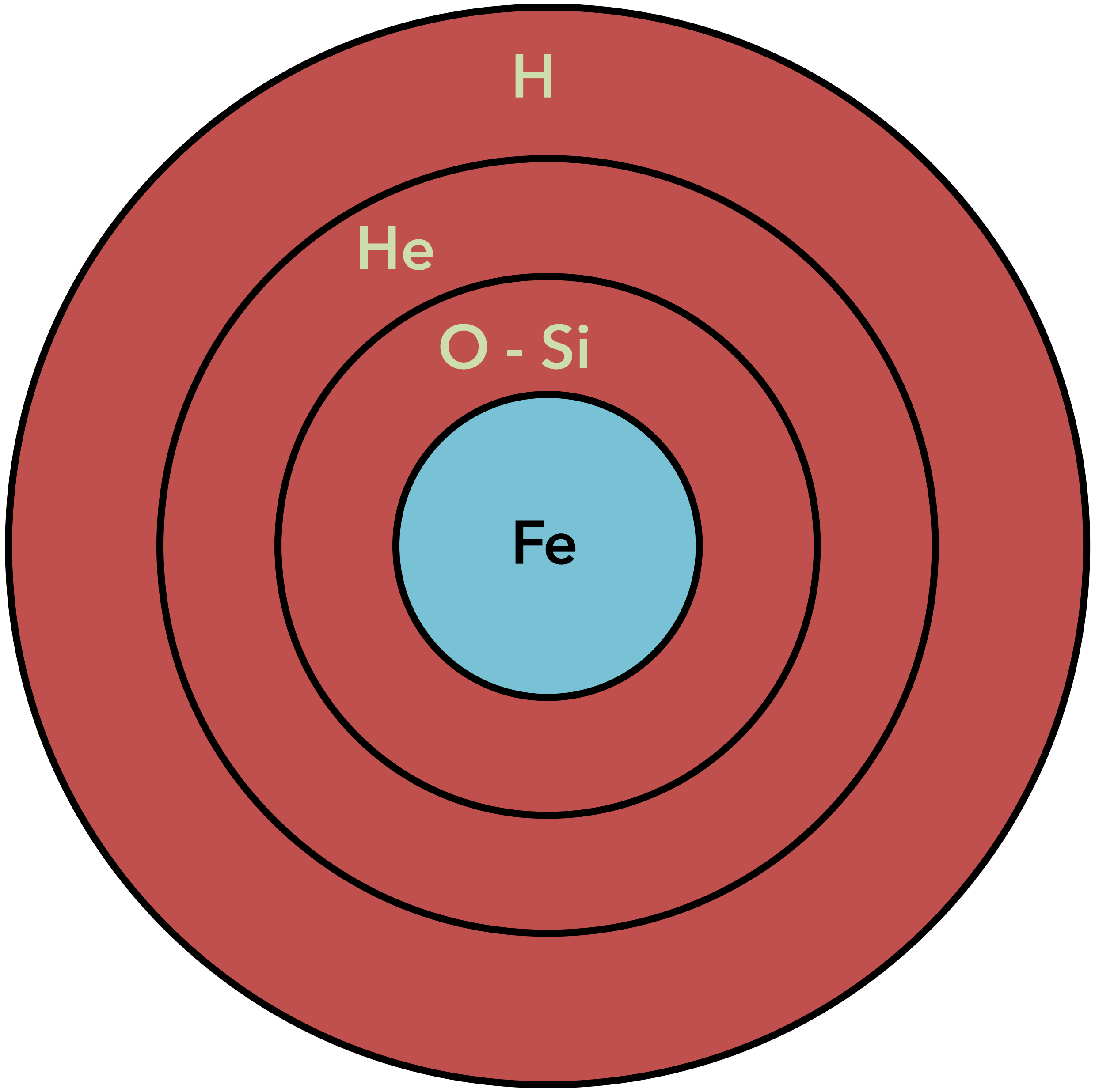
- **Modeling of the internal shock** according to Daigne & Mochkovitch 1998
  ⇒ gives an estimate of physical quantities (E, Γ, ρ, B,…) at internal shocks based on a few free parameters (distribution of the dissipated jet energy)
- **Calculate the SED of prompt emission** according to Daigne, Bosnjak & Dubus 2009
  ⇒ SED are used as soft photons target for the accelerated cosmic-rays
- **Midly relativistic acceleration of cosmic-rays** using the approach of Niemiec & Ostrowski 2004-2006 + **Shock parameters** are given by the internal shock model
- + including energy losses (photo-hadronic and hadron-hadron)
  ⇒ **cosmic-ray and neutrino output for a GRB** of a given luminosity
- **Cosmological evolution of GRB** (Piran & Wanderman 2010) ⇒ **diffuse UHECR (and neutrino) fluxes**

Compatible with UHECR observations from Auger if:
(i) the prompt emission represents only a very small fraction of the energy dissipated at internal shocks (especially for low and intermediate luminosity bursts)
(ii) most of this dissipated energy is communicated to accelerated cosmic-rays



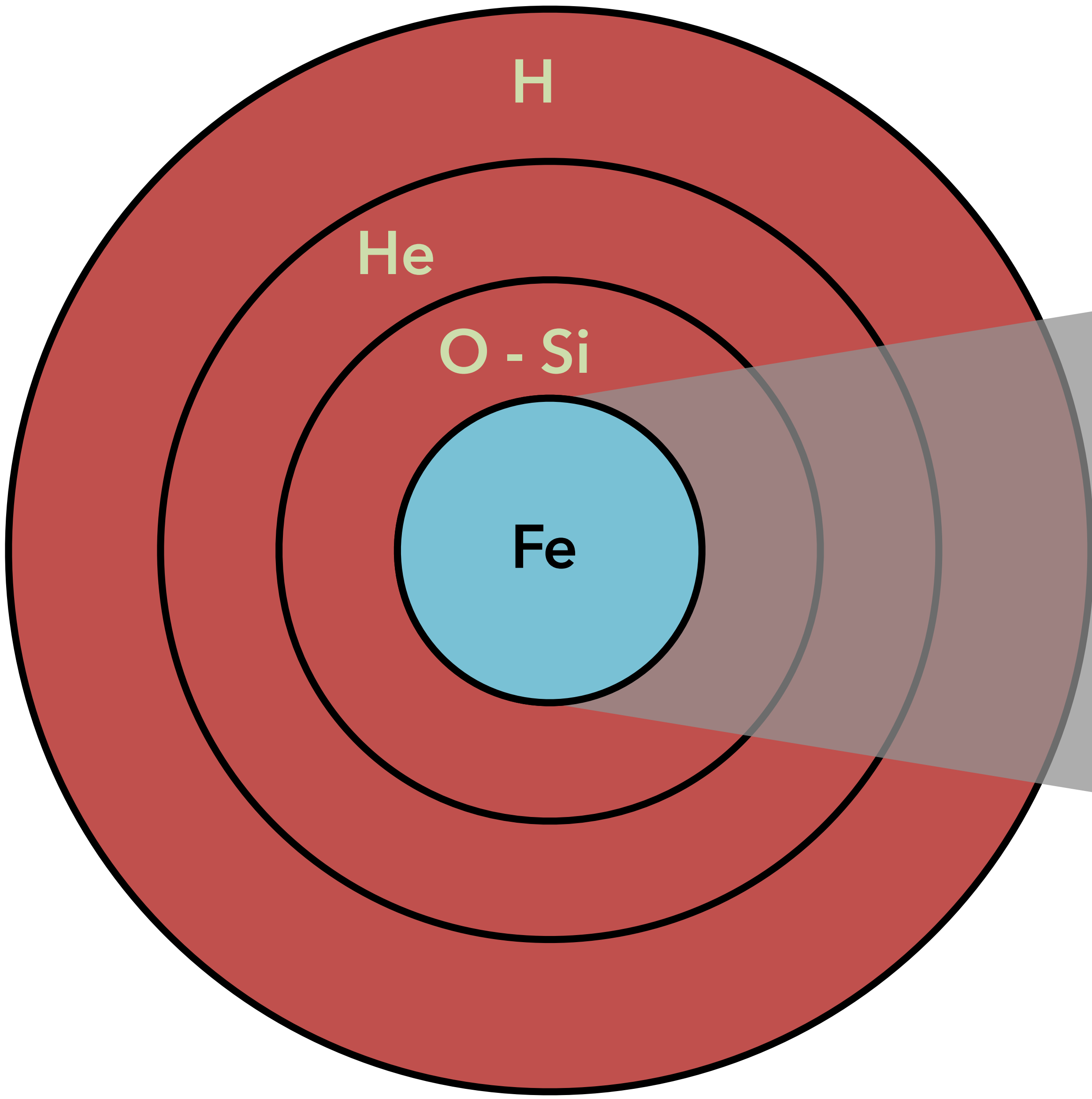

Gravitational wave (~100 Hz) emitters
mergers of compact objects
massive star core-collapse
NS/NS or NS/BH
short GRBs
long GRBs
high-energy cosmic-ray emission (?)
high-energy neutrino emission (?)

A core-collapse SN alone also produces neutrinos !



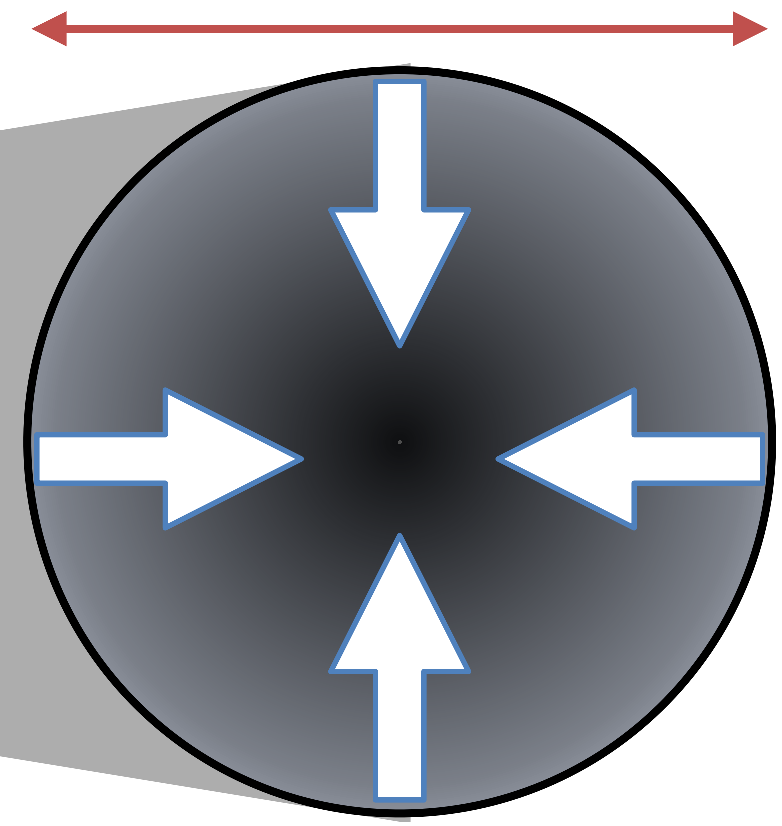
Massive star $M \gtrsim 10M_{\odot}$
Onion structure

T and density high enough to produce heavy elements up to iron by nuclear fusion



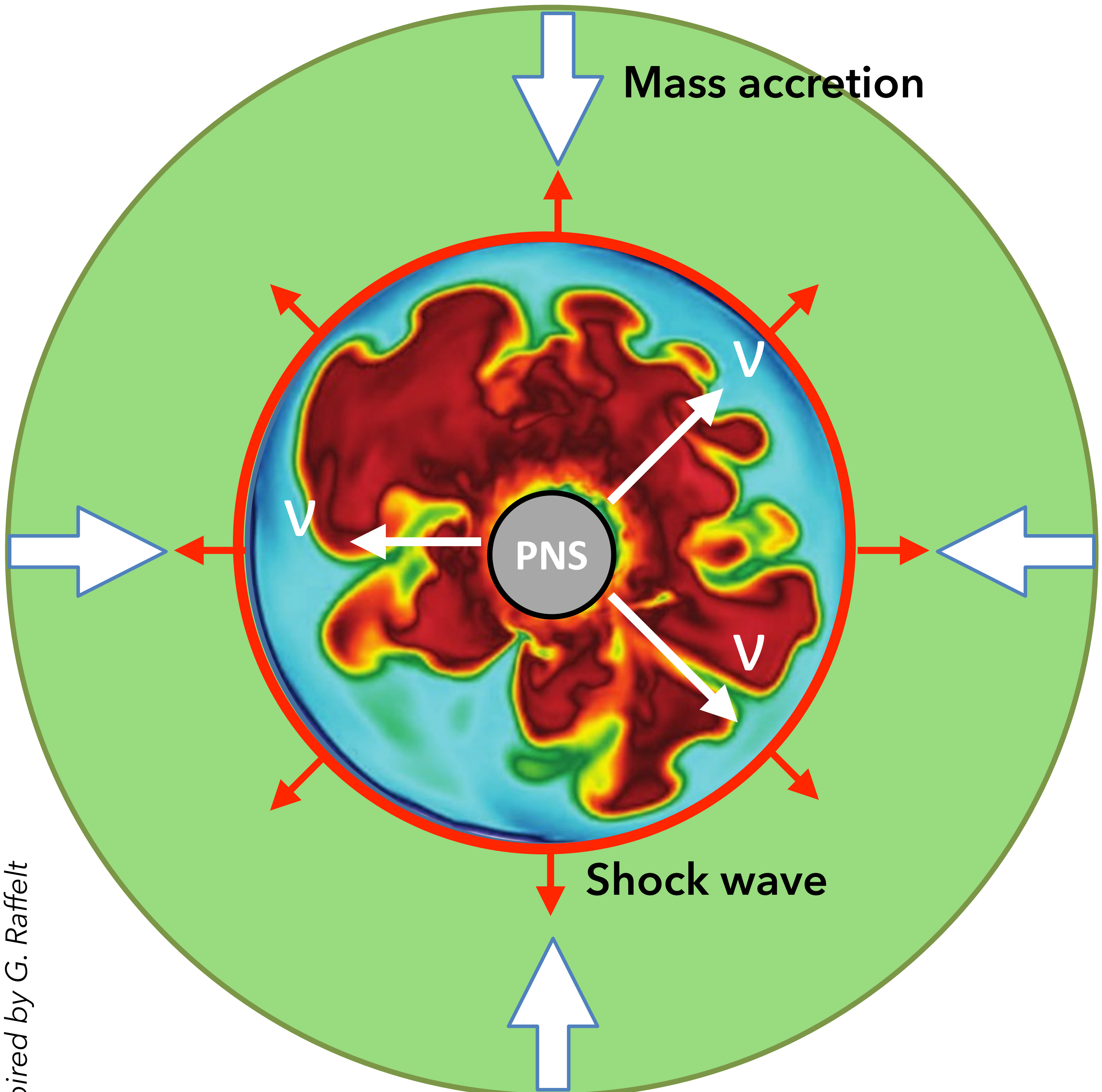
Massive star $M \gtrsim 10M_\odot$
Onion structure

Collapse of the degenerate core
(implosion)

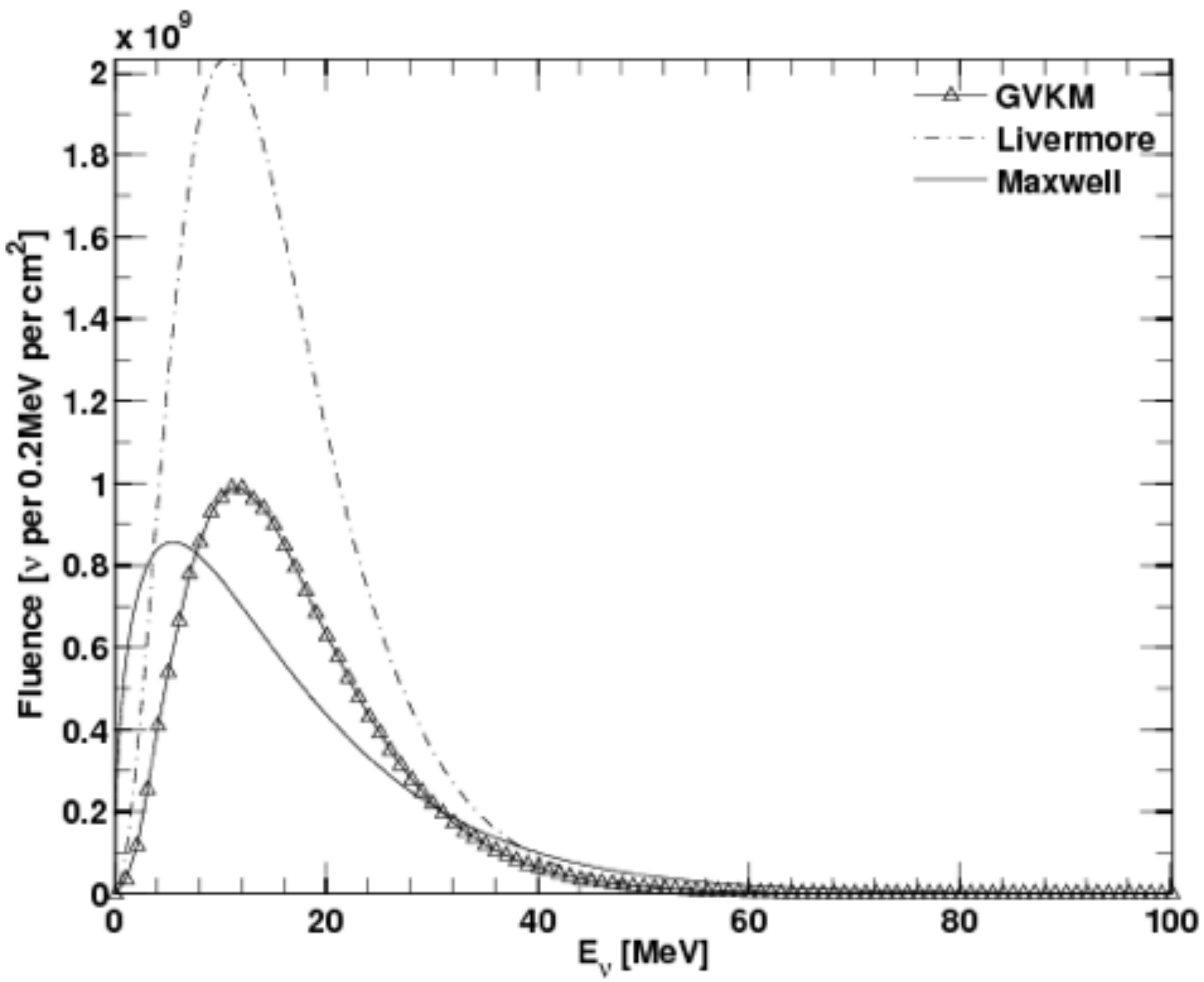


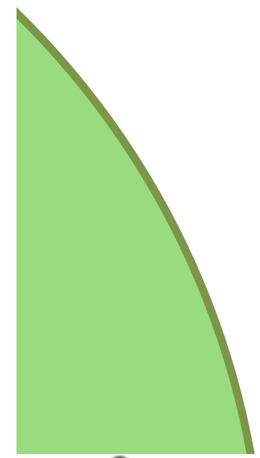
$$p + e^- \rightarrow n + \nu_e$$

As $M_{core} \sim M_{Chand}$, pressure of degenerate relativistic electrons decreases due to electron capture and becomes insufficient to resist gravity ➜ collapse



- After less than half a sec., a new equilibrium is reached between gravity and nuclear matter (mostly neutrons) with ⌀~10 km = protoneutron star
- Infalling matter bounces on this core
- Shock wave forms within the iron core
- Shock wave looses kinetic energy while propagating (via iron photodissociation + electron capture) ➜ star cannot explodes
- Shock wave gains energy from neutrinos (Colgate & White, 1966)
- Neutrino heating enhanced by convection and shock oscillations (SASI) ➜ star explosion
- **~99% of the energy released through neutrinos.**





- After less than half a sec., a new equilibrium is reached between gravity and nuclear matter (mostly neutrons) with ⌀~10 km = protoneutron star
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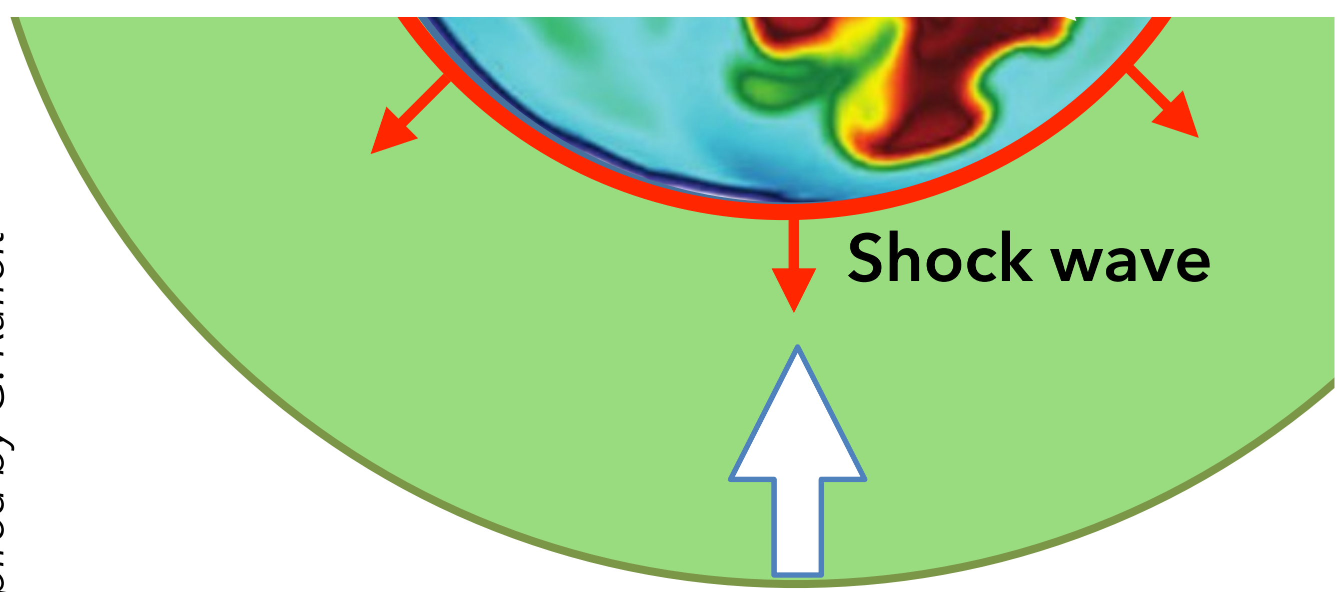
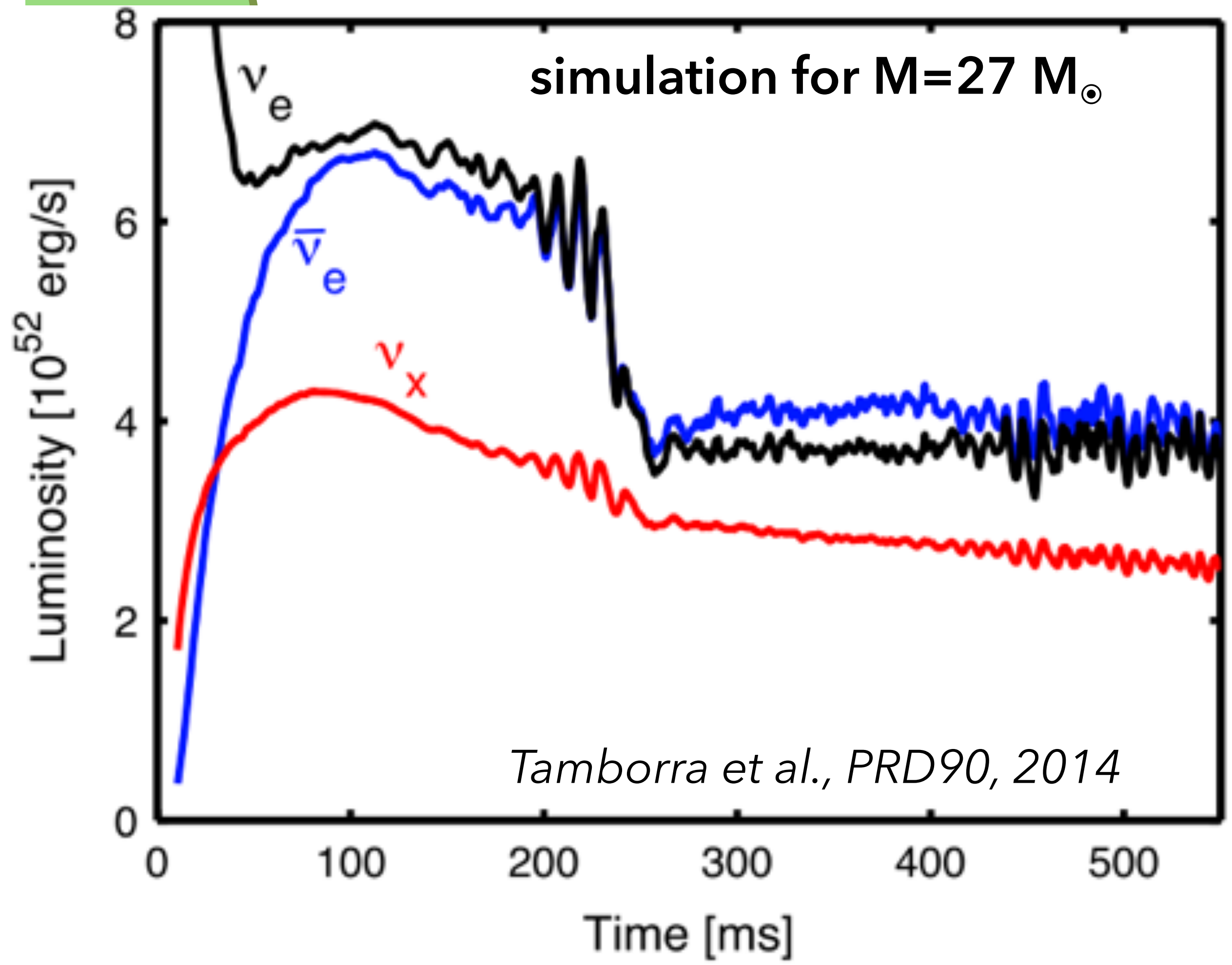
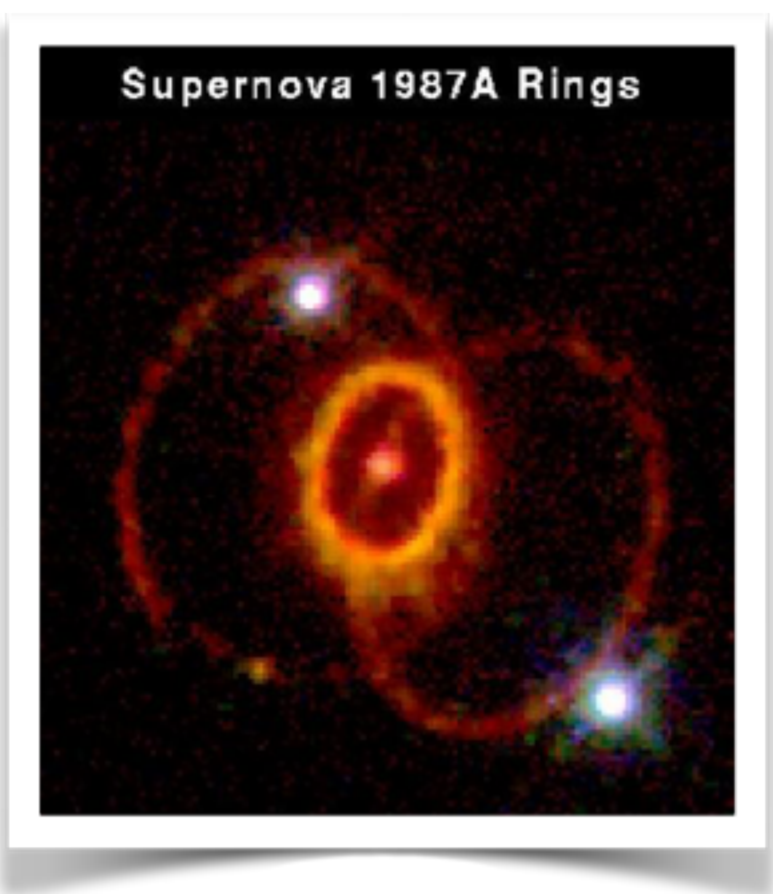


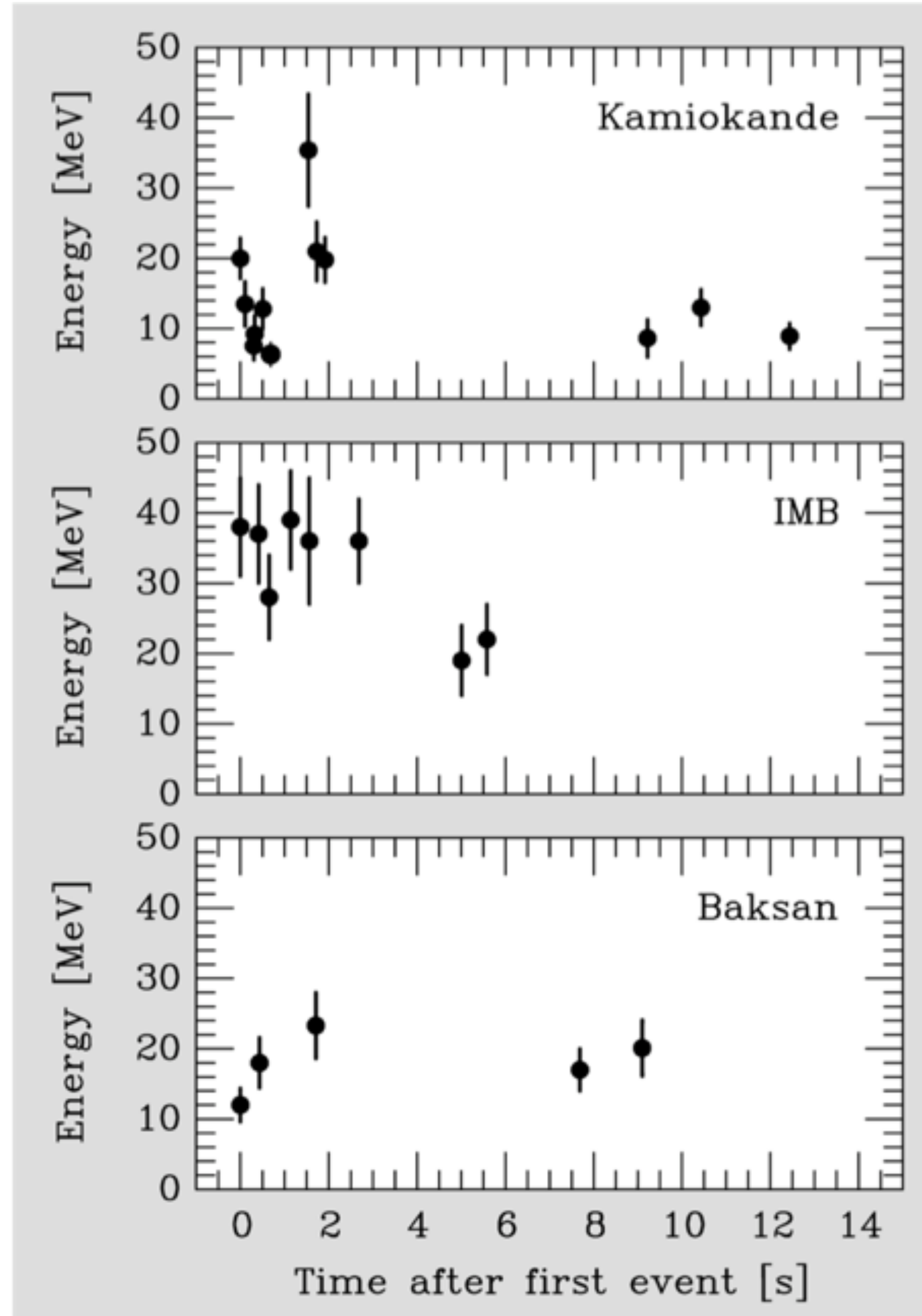


Inspired by G. Raffelt

SN1987A: 25 neutrinos observed by 3 separate observatories (>10σ) in 13 sec.

confirm the general picture of CCSN but too low statistics to resolve lightcurve





Gravitational wave (~100 Hz) emitters

mergers of compact objects → short GRBs

BH/BH

?

massive star core-collapse → long GRBs

Multi-messenger emission ?

Basic ingredients for GRB mechanisms (+ CR acceleration): magnetic fields + disk (baryonic environment).

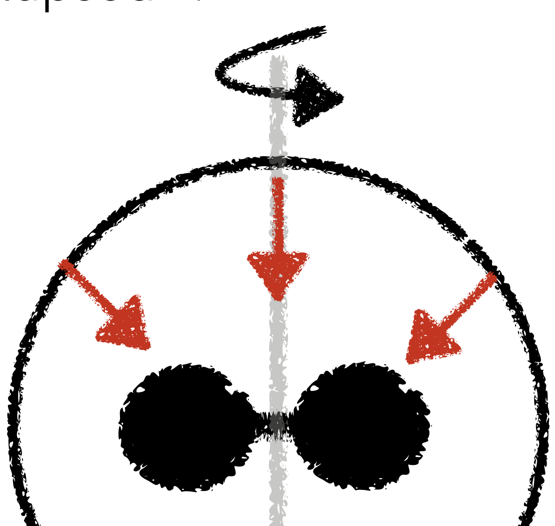
may come from MHD instabilities in the disk (?)

Where does the baryonic environment come from ? How can a disk remain bound around such a system ?

see here for more exhaustive review: http://iopscience.iop.org/journal/2041-8205/page/Focus_on_BBHM

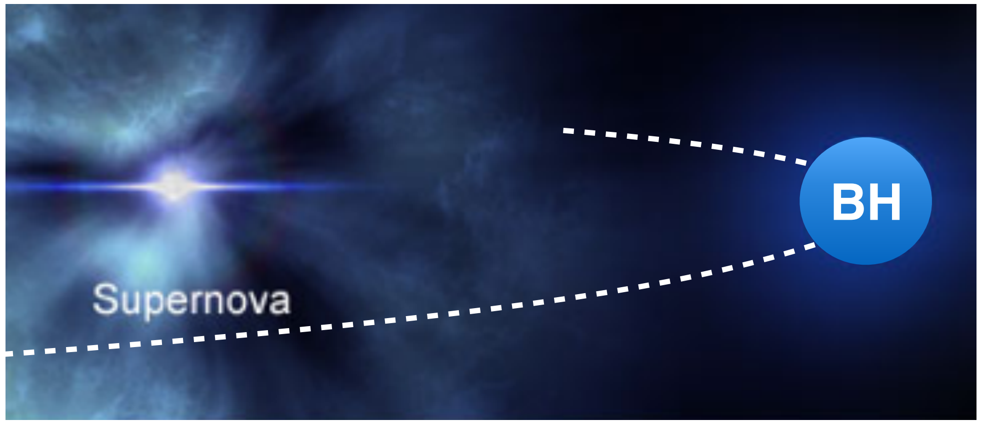
Two examples:

« two clumps in a dumbbell configuration that formed when the core of a rapidly rotating massive star collapsed ».

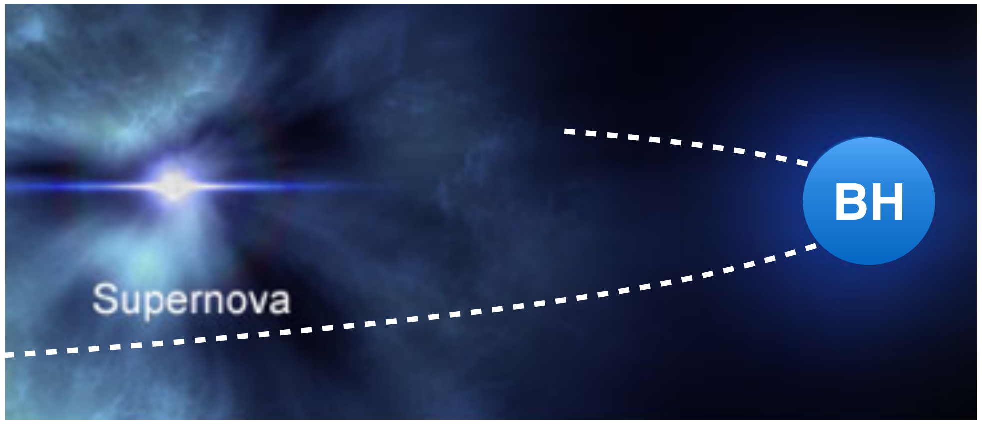


Loeb 2016
but see Woosley 2016
+ Dai et al. 2016)

dead disk remains bound in the BBH system



Perna et al., 2016



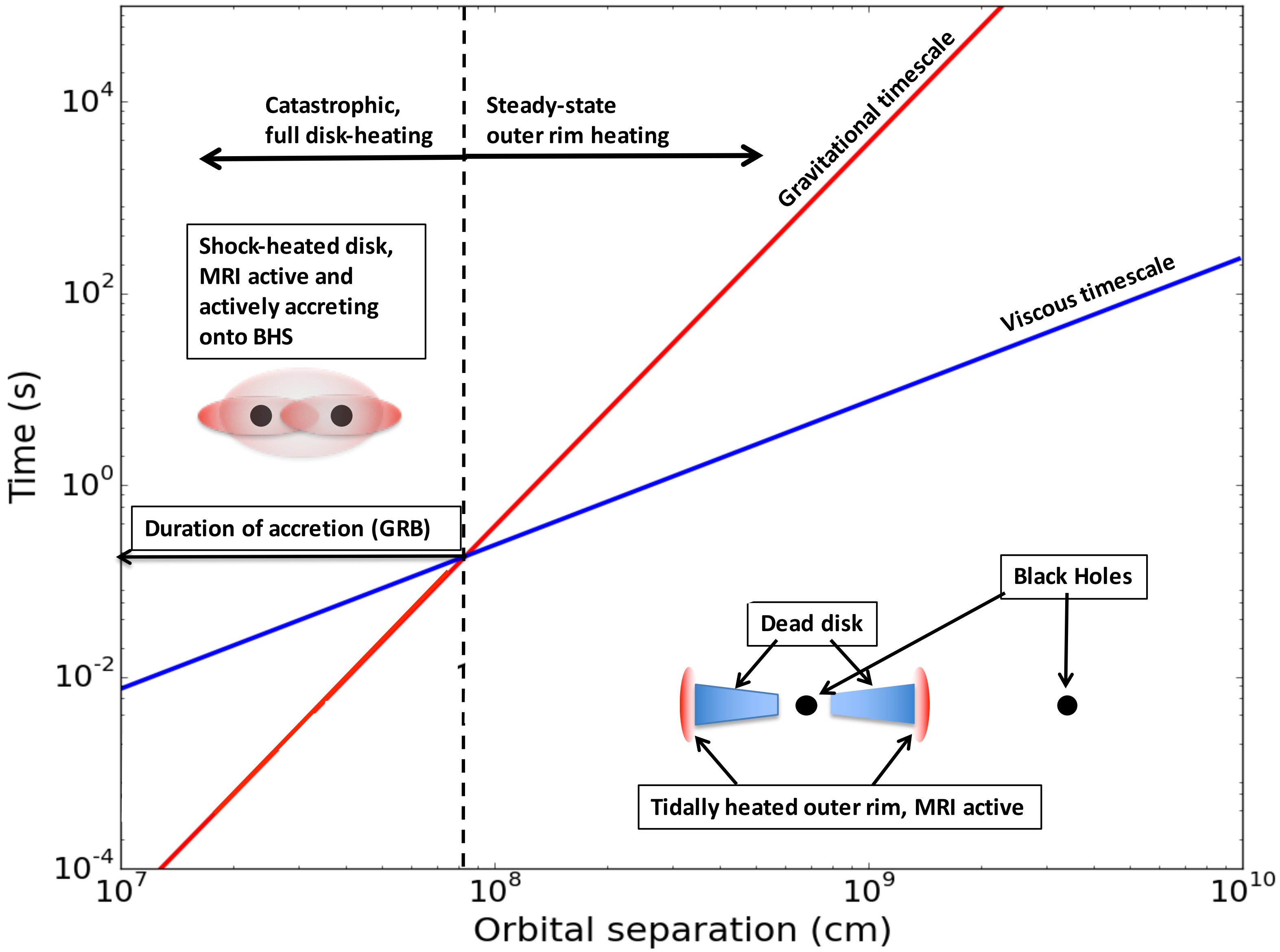
- Weak supernova ➜ part of the envelope remains bound (assuming $40M_{\odot}$, $Z<0.01Z_{\odot}$ + angular momentum outer layers high enough)

- Evolution of the disk depends on viscosity which drives transport of angular momentum

- For $t>t_{visc}$, T decreases ➜ angular momentum transport reduced ➜ « dead » disk (as observed by Wang et al. 2006 for NS)

- Final seconds: outer rim is heated by tidal effects (inner part still neutral)

- $t_{GW} < t_{visc}$: accretion activated

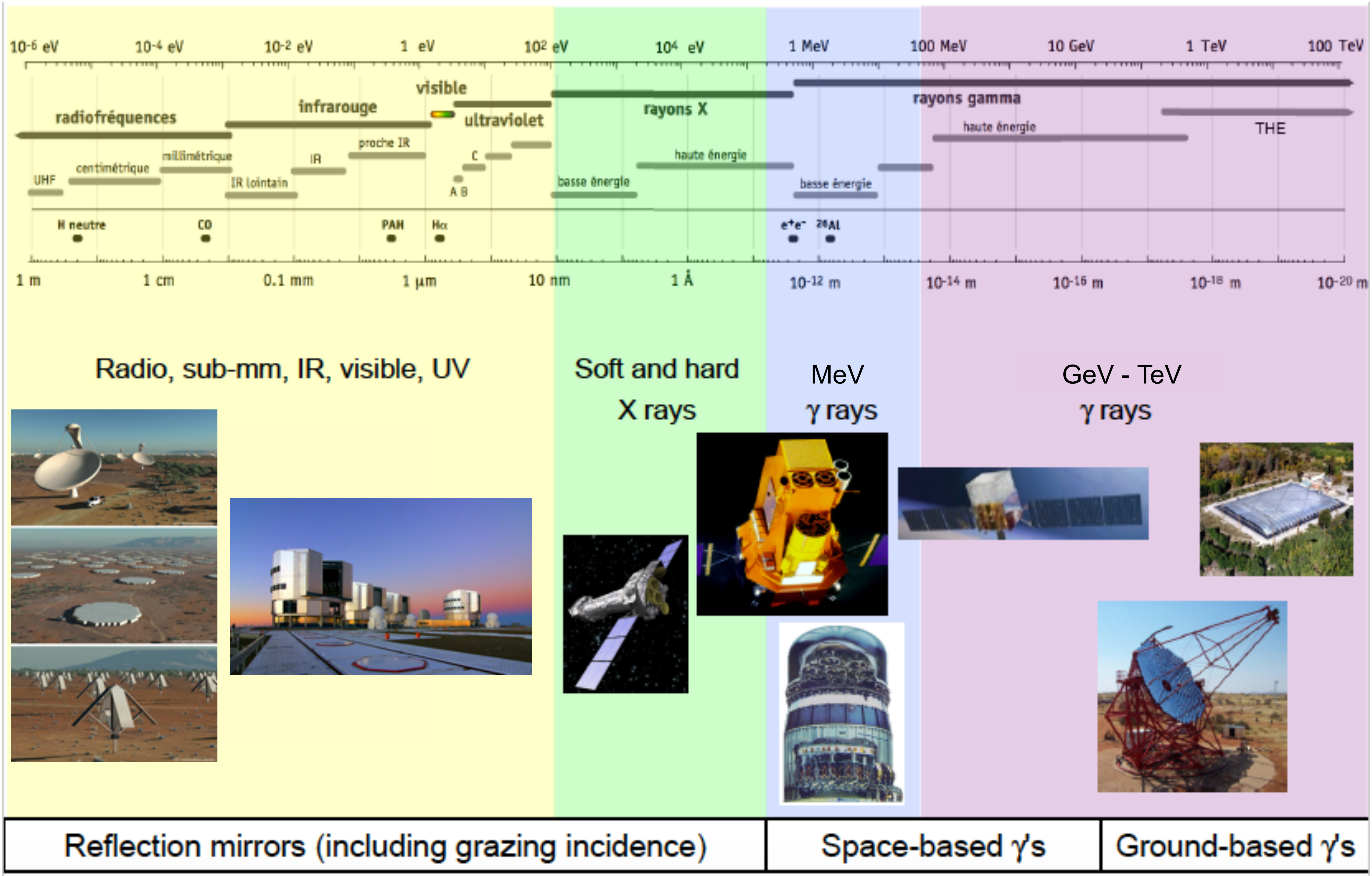


Perna et al., 2016

see however Kimura et al., 2016 (different timescale + EM too faint)

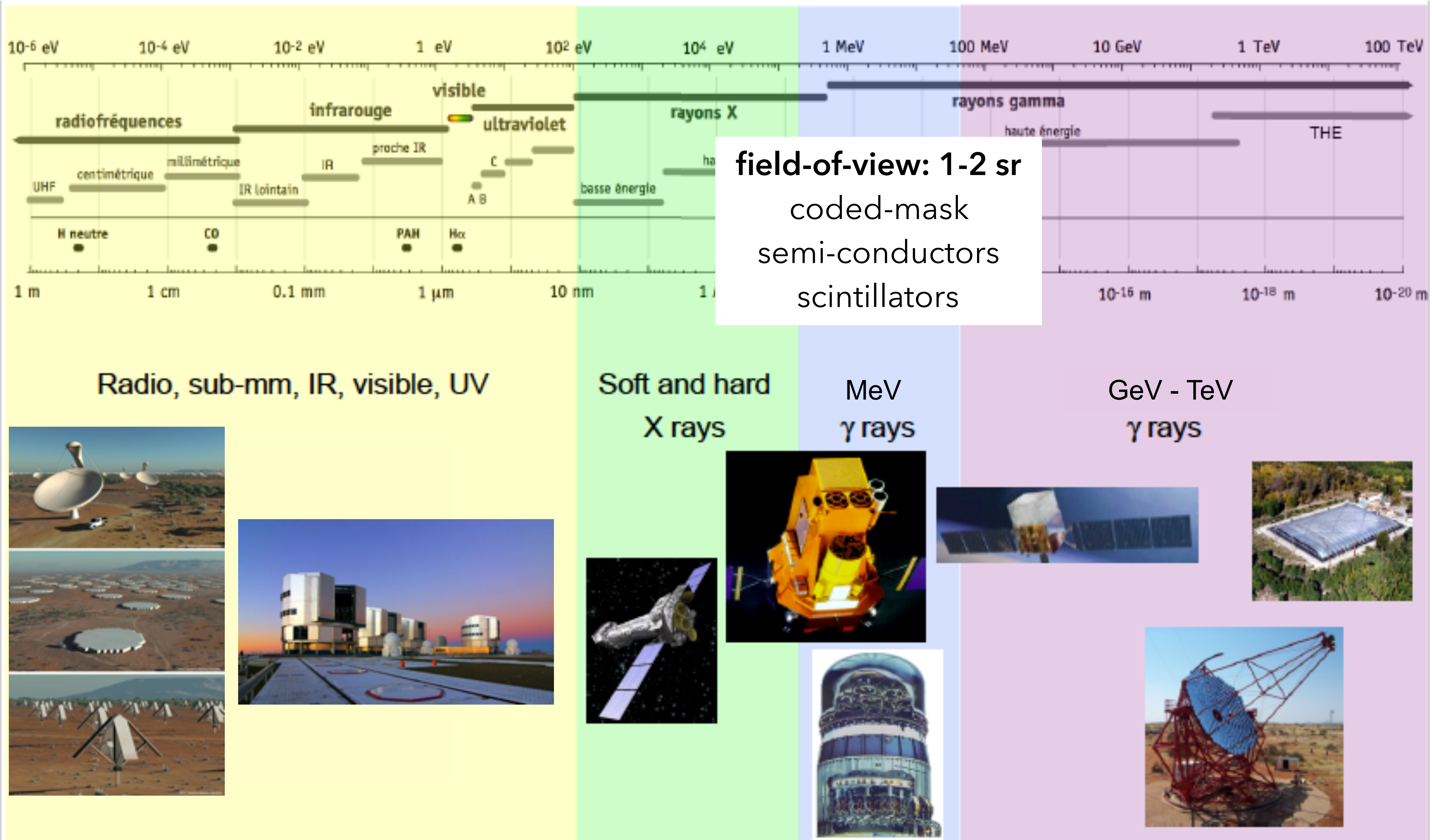
Multi-messenger observational strategies

Multi-wavelength observation techniques



Credit: F. Piron

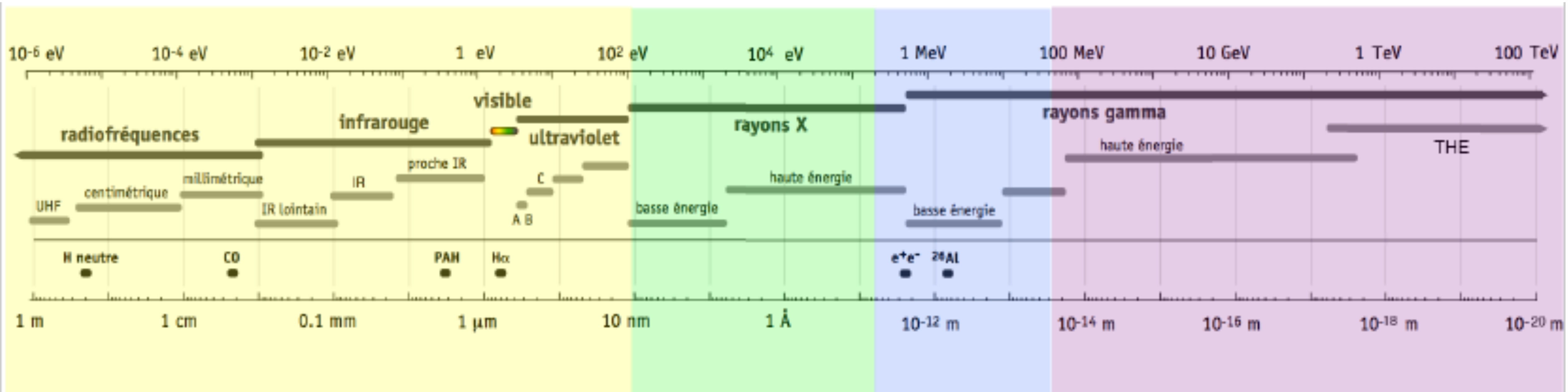
+antennas (for MHz > f > GHz)



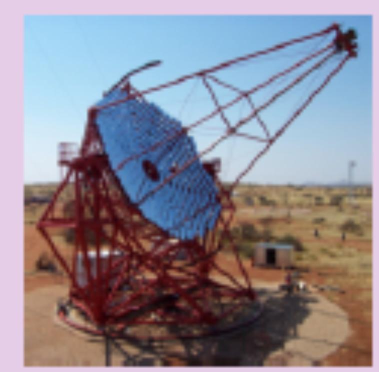
Reflection mirrors (including grazing incidence)	Space-based γ's	Ground-based γ's

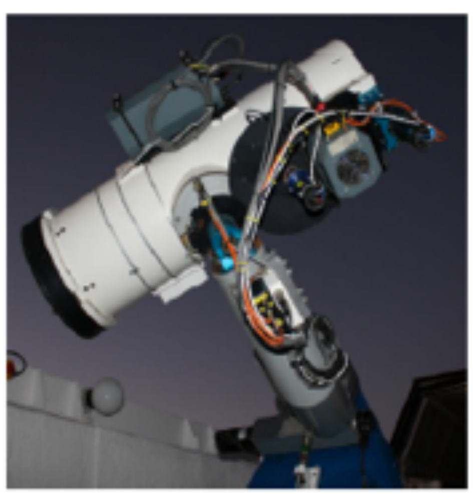
+antennas (for MHz > f > GHz)

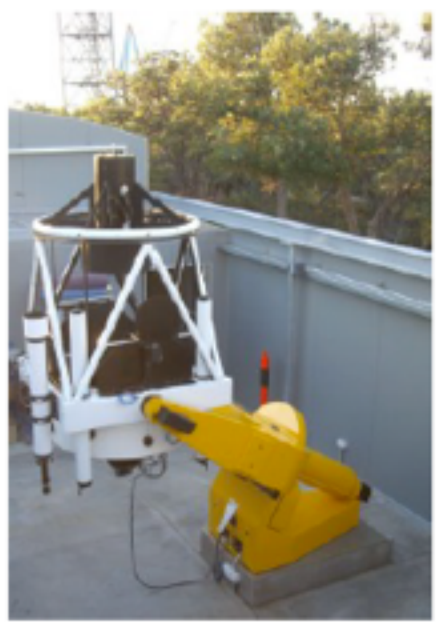
Credit: F. Piron

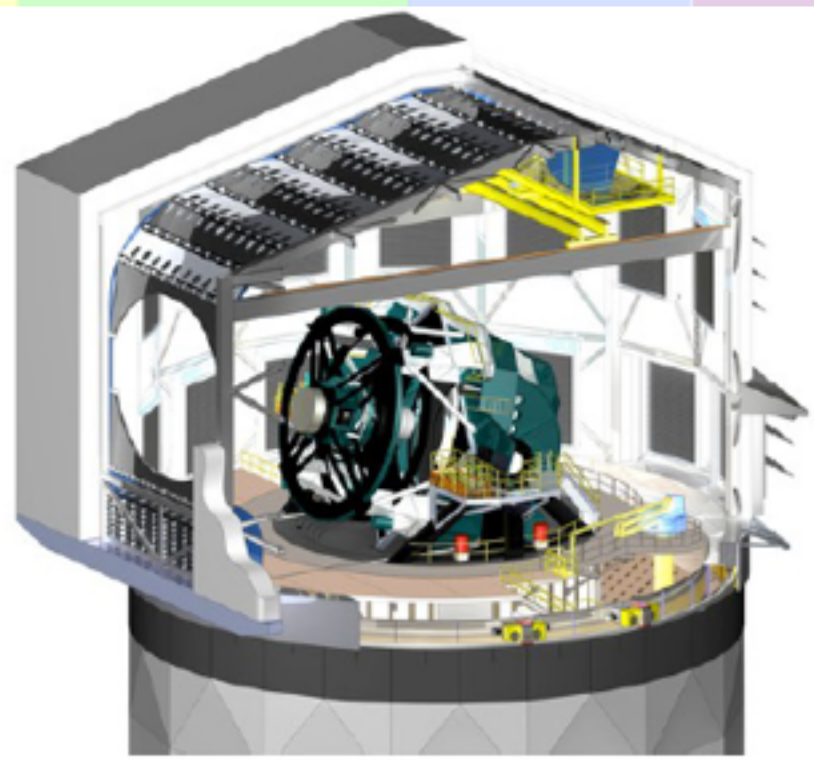


GeV - TeV
γ rays









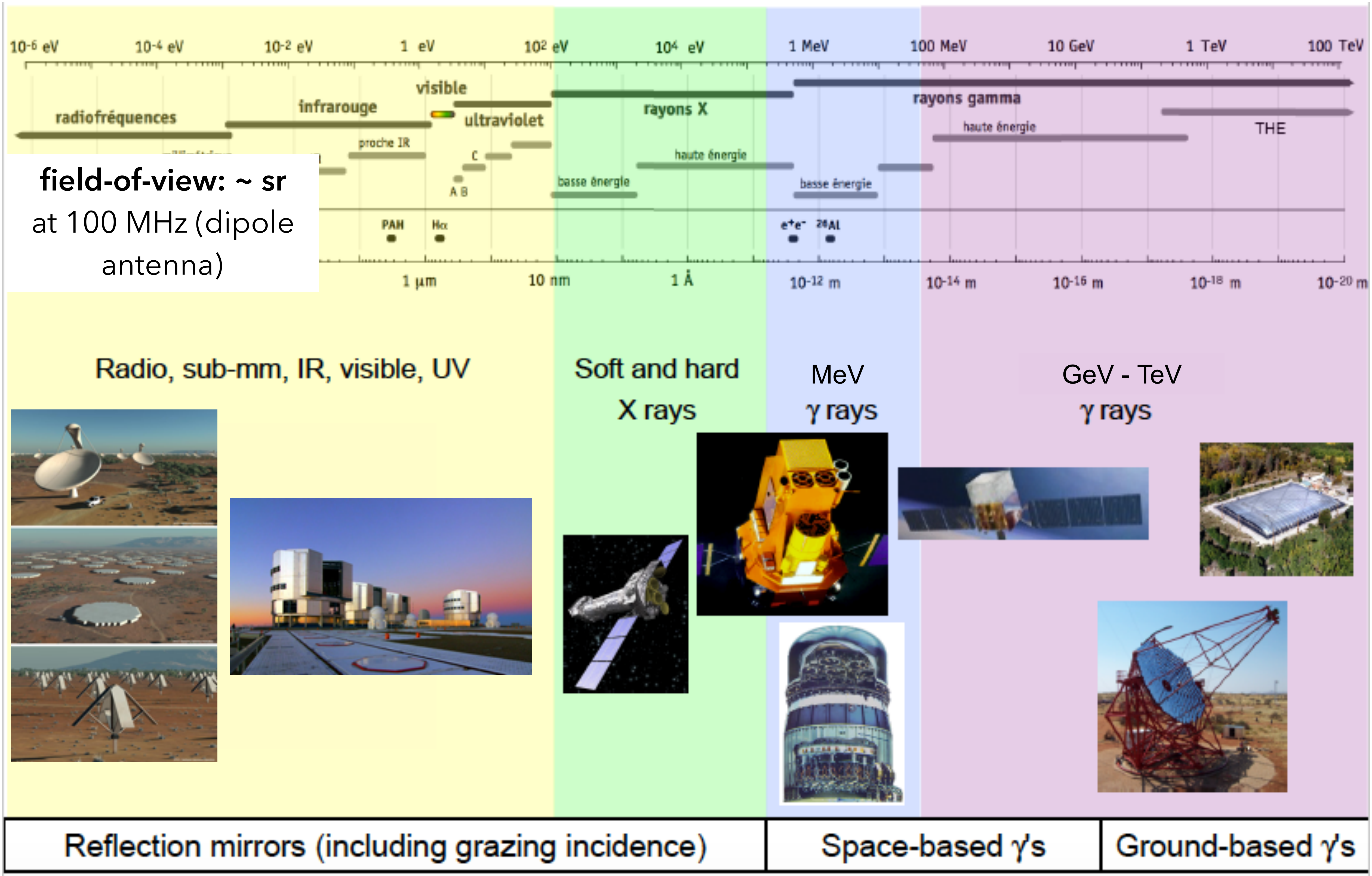
γ's	Ground-based γ's

TAROT
D=0.25m
FoV = 2° x 2°
First image in 10 s
Deepest mag = 20.4
Cost = 300 k€

Zadko
D = 1.0 m
FoV = 0.3° x 0.3°
First image in 80 s
Deepest mag = 21.6
Cost = 1 M€

LSST
D = 6.7 m
FoV = 3° x 3°
First image > 10 minutes
Deepest mag = 26.4
Cost = 500 M€

Credit: F. Piron

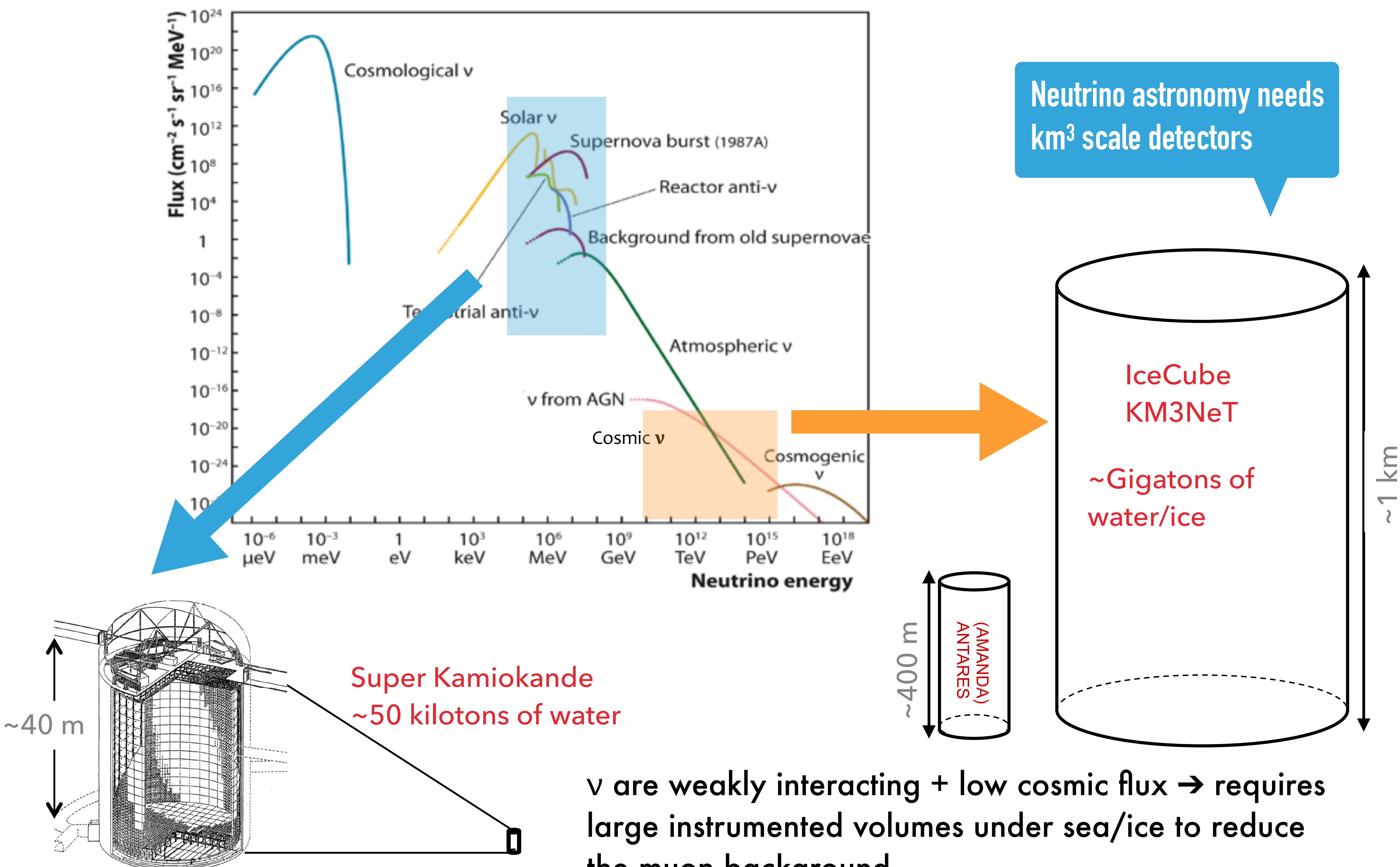


field-of-view: ~ sr
at 100 MHz (dipole antenna)

+antennas (for MHz > f > GHz)

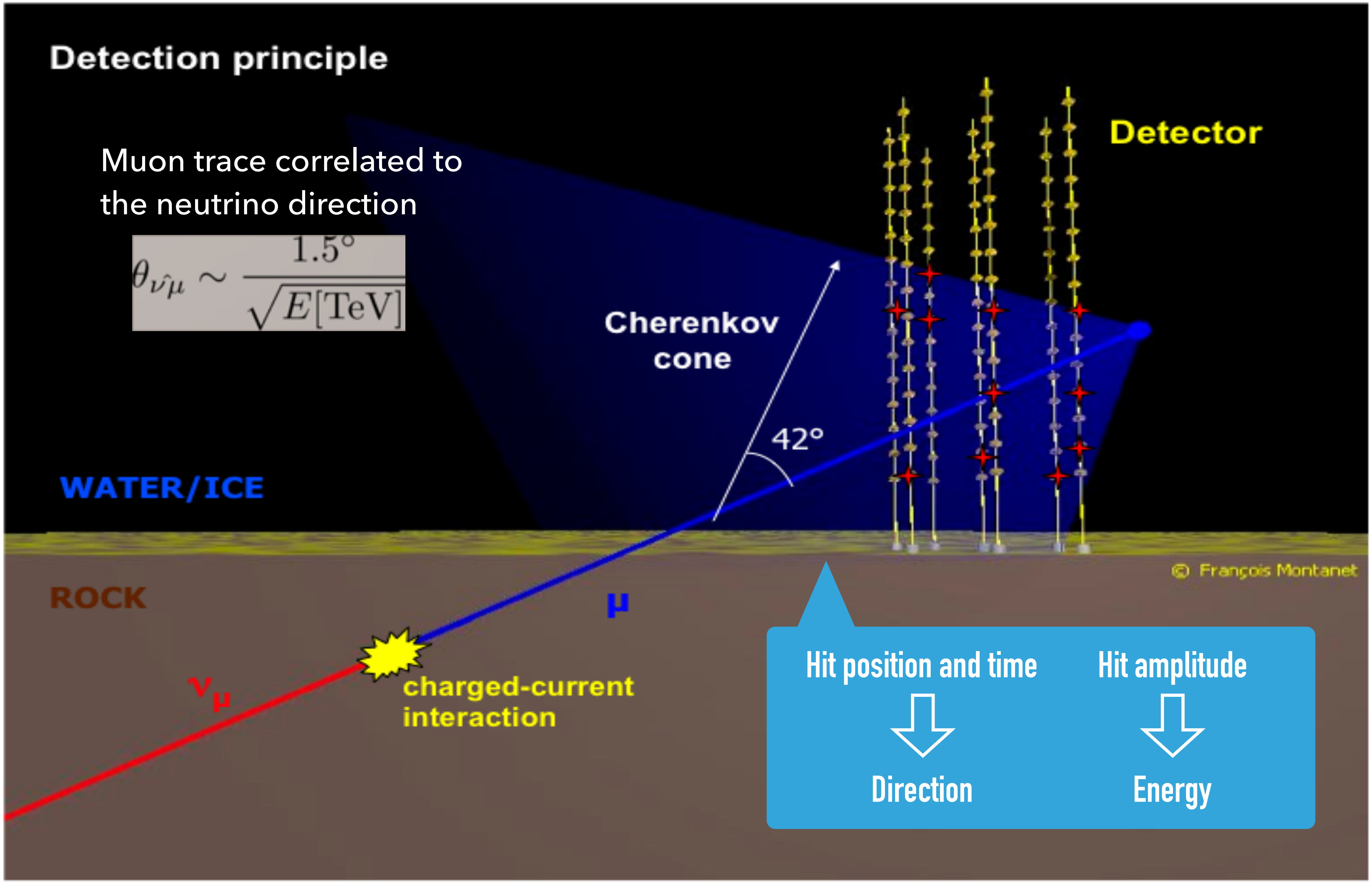
Credit: F. Piron

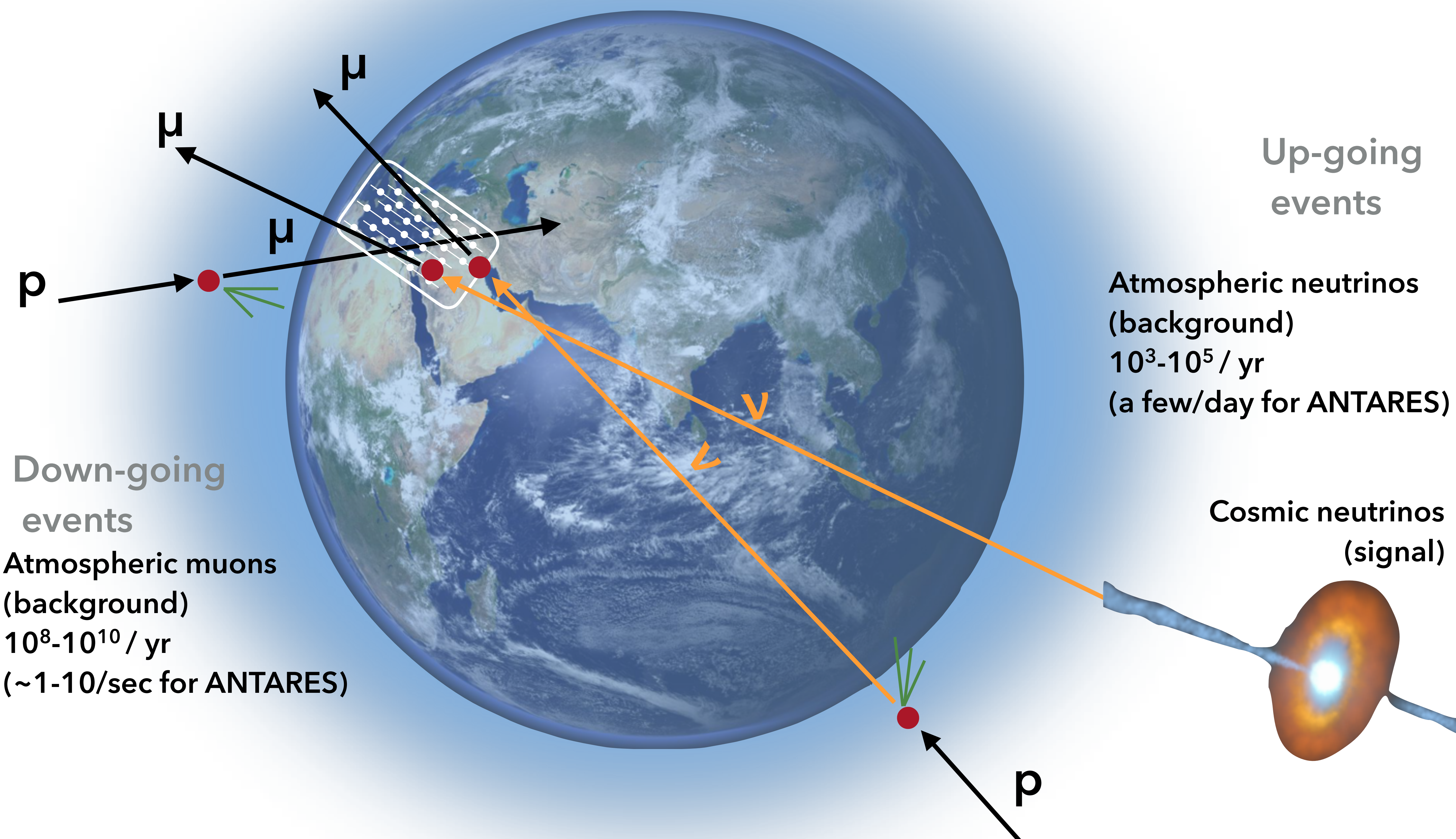
High-energy neutrino observation techniques

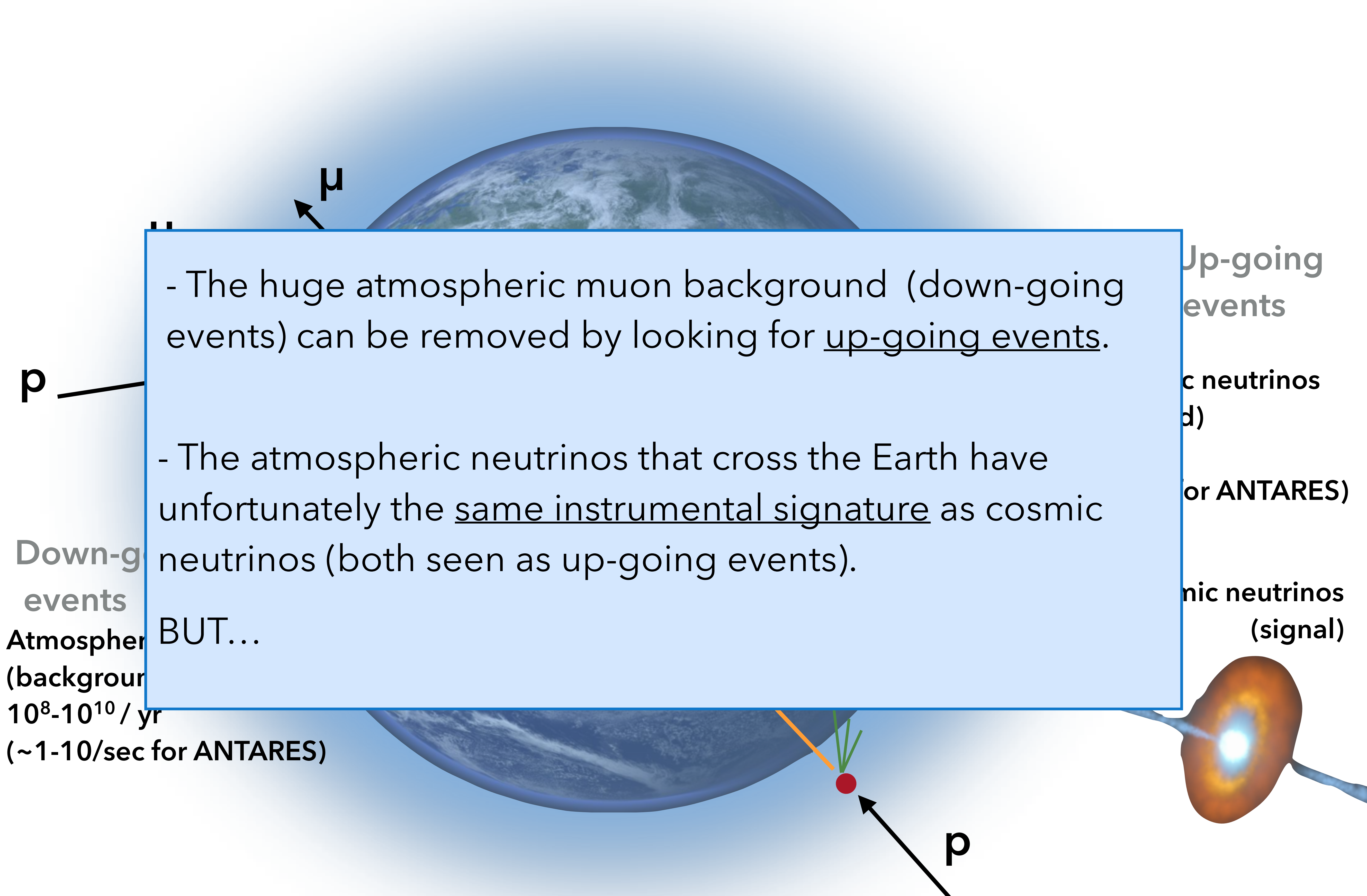


ν are weakly interacting + low cosmic flux ➔ requires large instrumented volumes under sea/ice to reduce the muon background

Different ways to detect HE ν.
One way particularly useful in astronomy:
observation of muons produced in CC interaction of ν_μ




μ
μ
μ
p
Up-going
events
Atmospheric neutrinos
(background)
10^{3}-10^{5} / yr
(a few/day for ANTARES)
ν
ν
Down-going
events
Atmospheric muons
(background)
10^{8}-10^{10} / yr
(~1-10/sec for ANTARES)
Cosmic neutrinos
(signal)
p

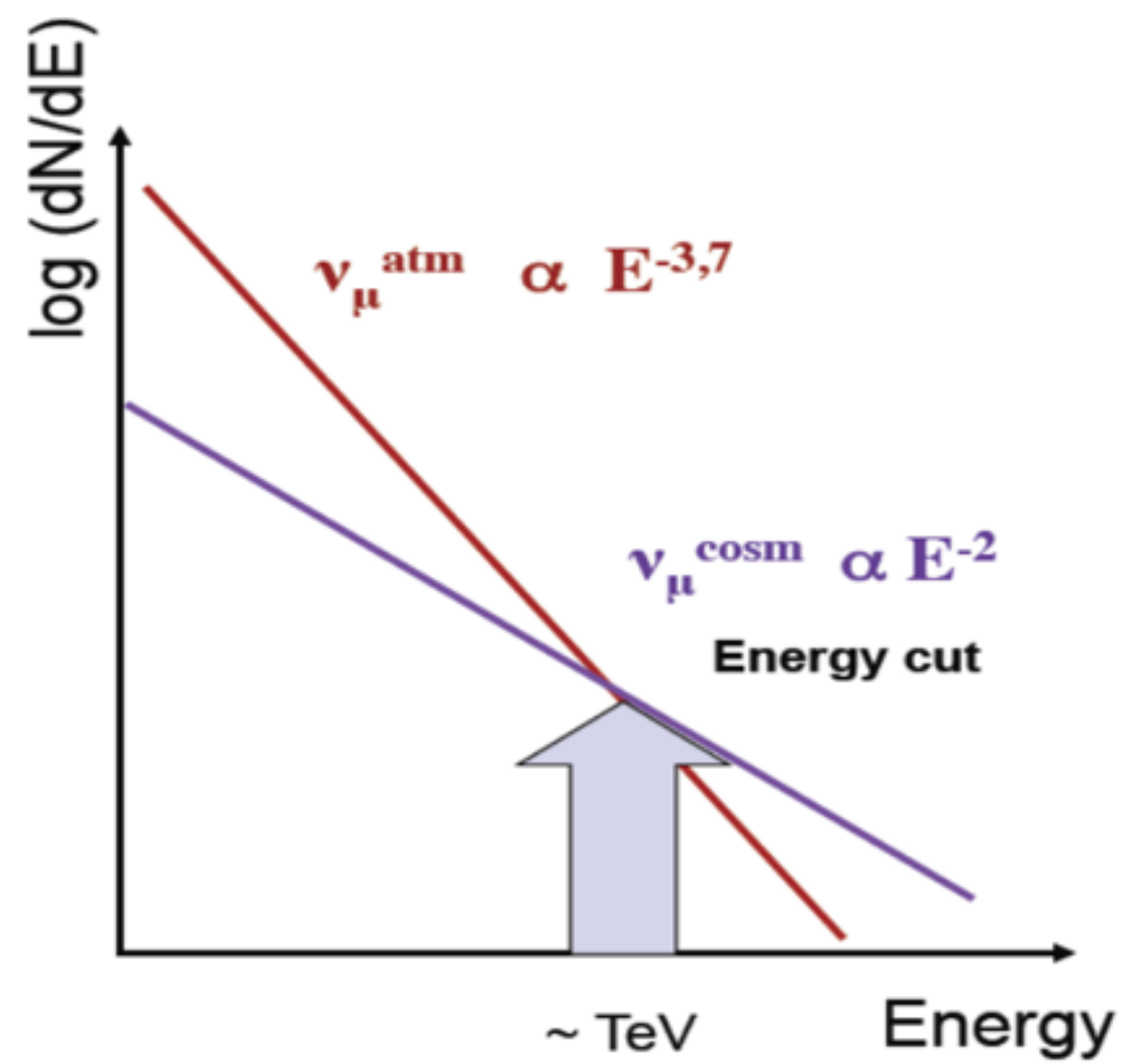


- The huge atmospheric muon background (down-going events) can be removed by looking for up-going events.

- The atmospheric neutrinos that cross the Earth have unfortunately the same instrumental signature as cosmic neutrinos (both seen as up-going events).

BUT…

How to identify cosmic neutrinos ?



But spectrum of atmospheric neutrinos expected to be softer than neutrino spectra from astrophysical sources

Below ~TeV: difficult to extract astrophysical signal

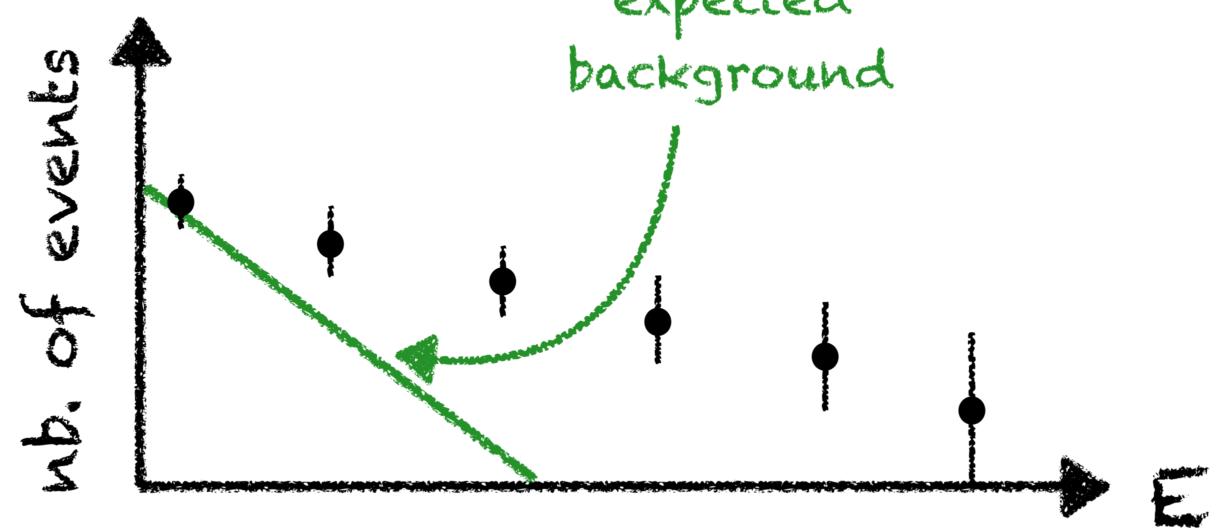
At high energy: the background should be reduced

Applying a cut in energy should remove most of the atmospheric neutrino background !

Looking for excess at high energies:
➜ diffuse flux analyses

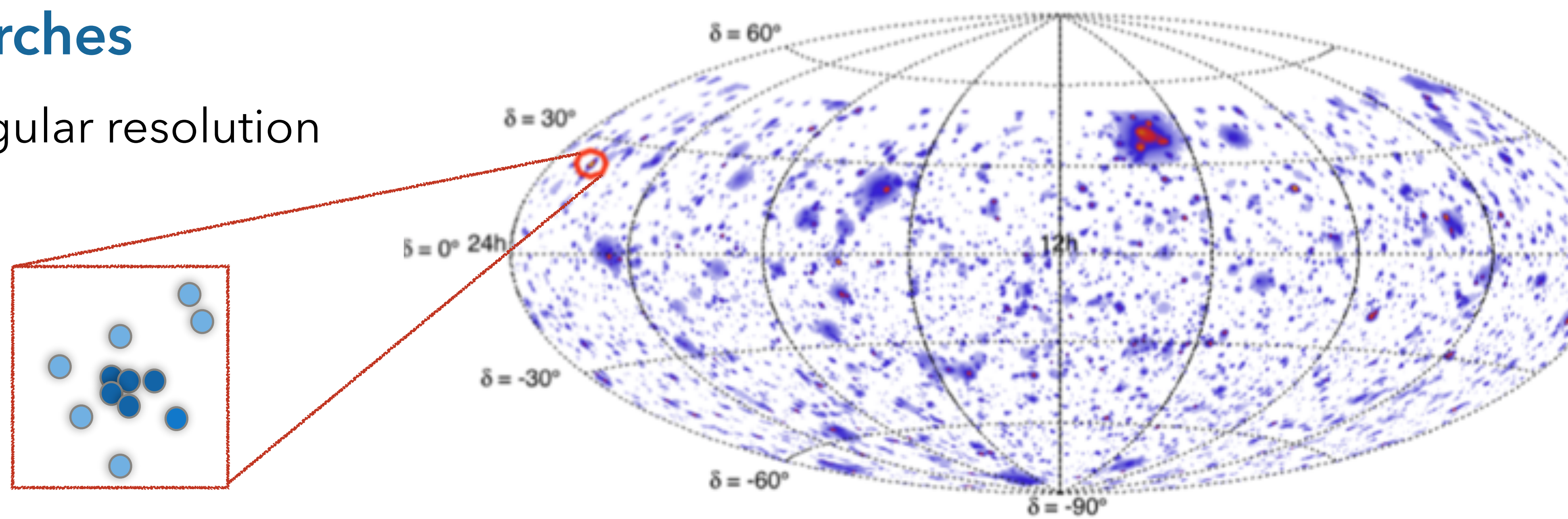
Concerns mainly extragalactic sources

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)

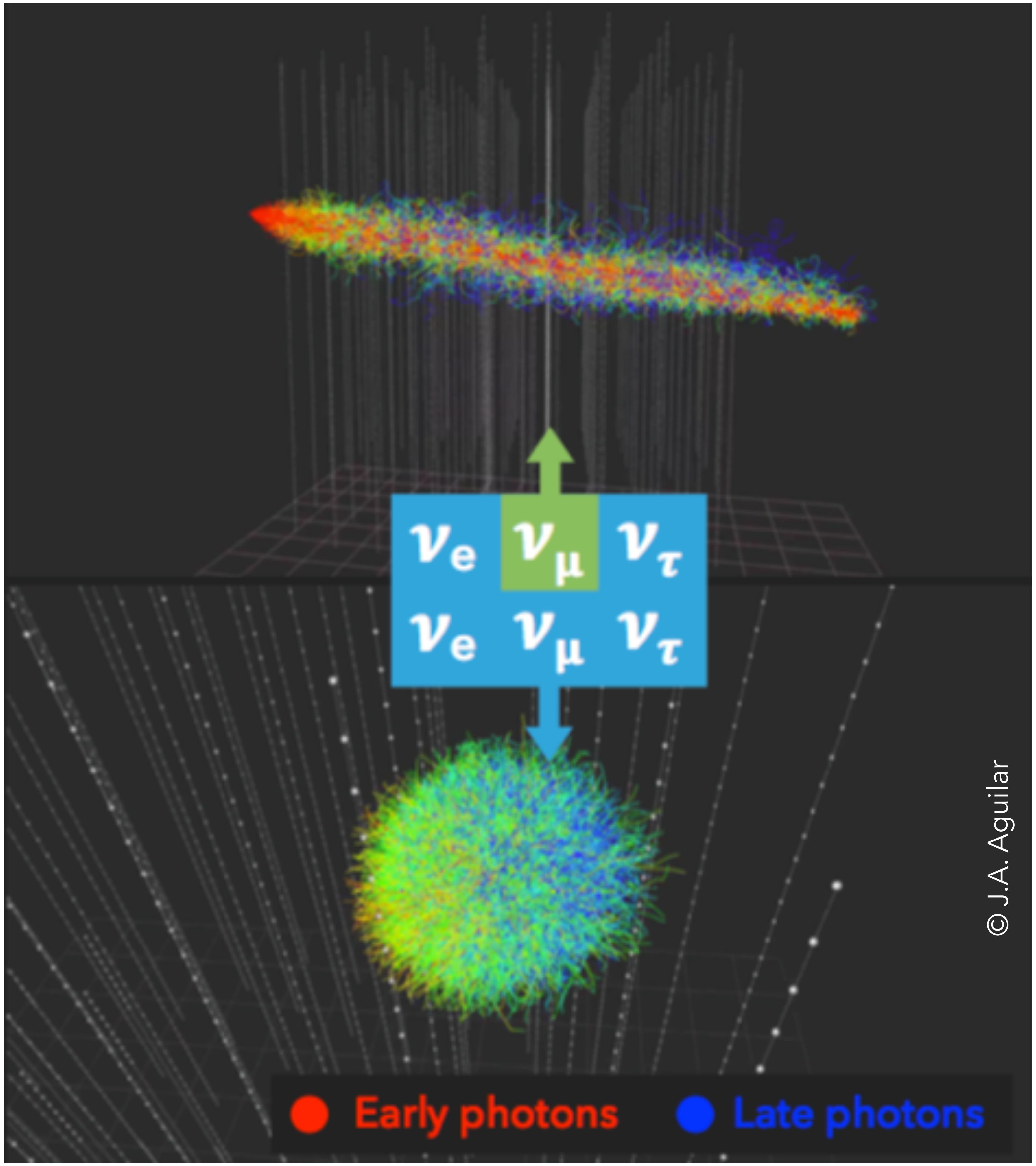
Neutrino can interact outside the detector (larger effective volume)

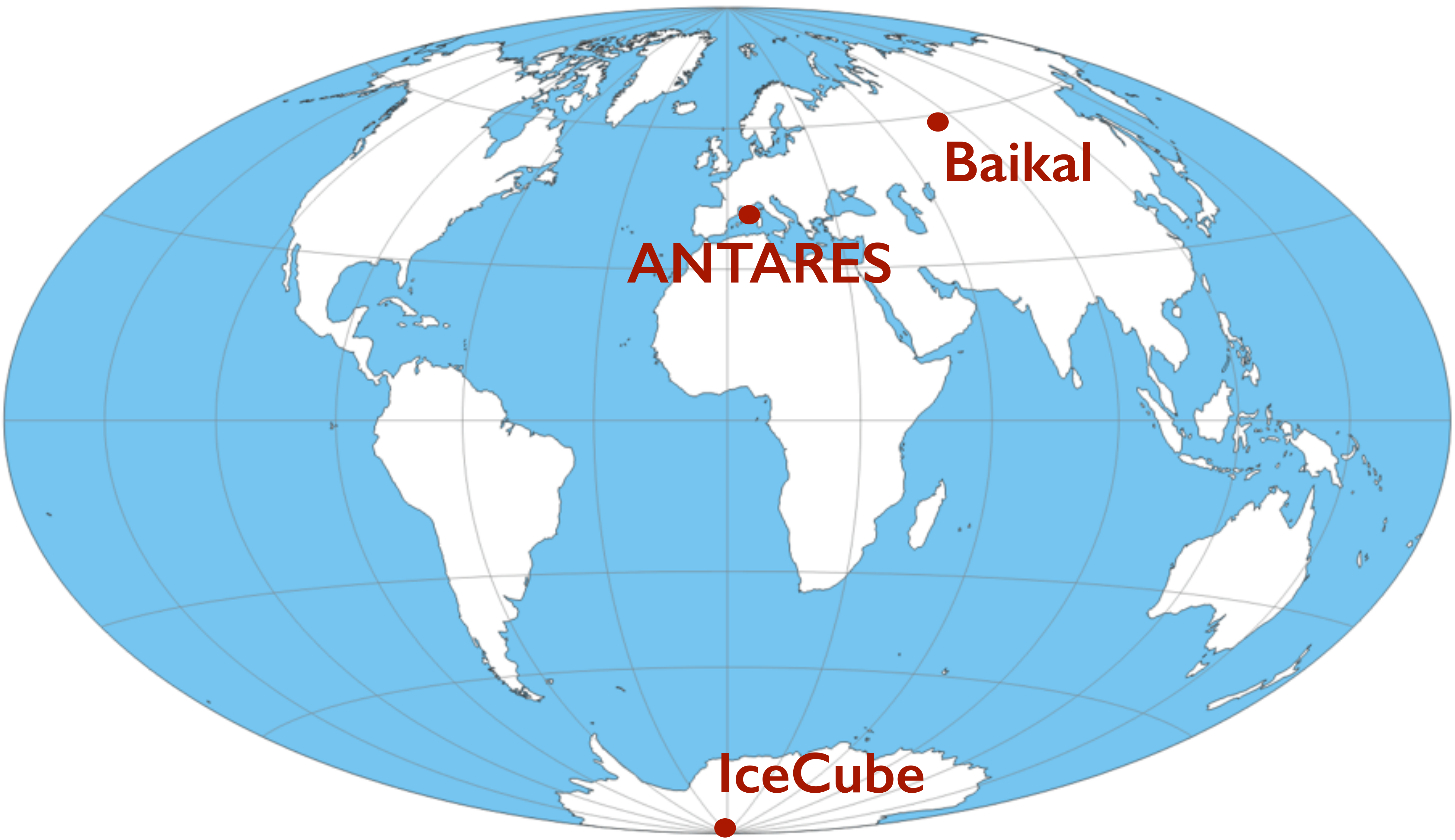
Good angular resolution (~0.2° in the sea)

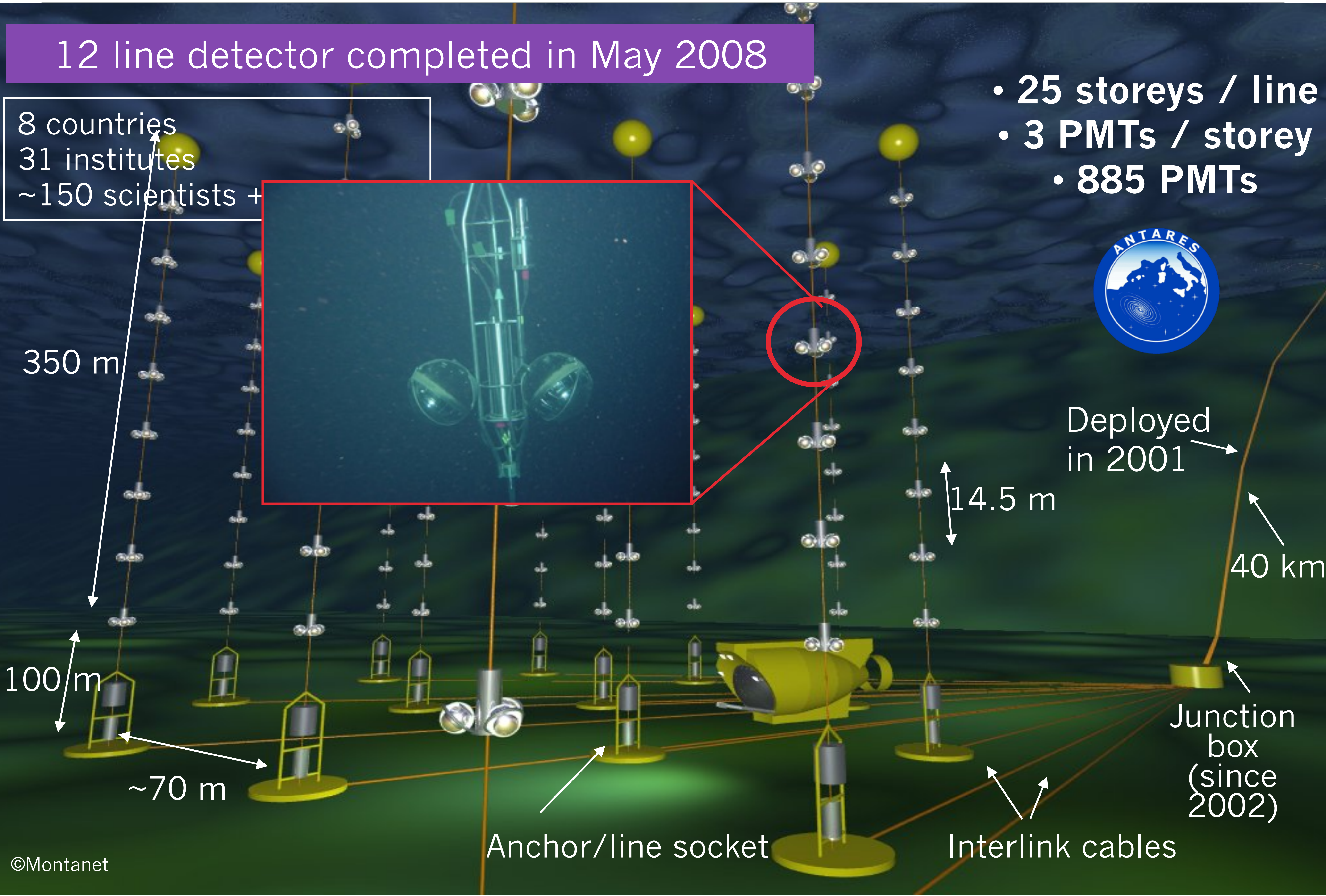
Quasi-spherical events

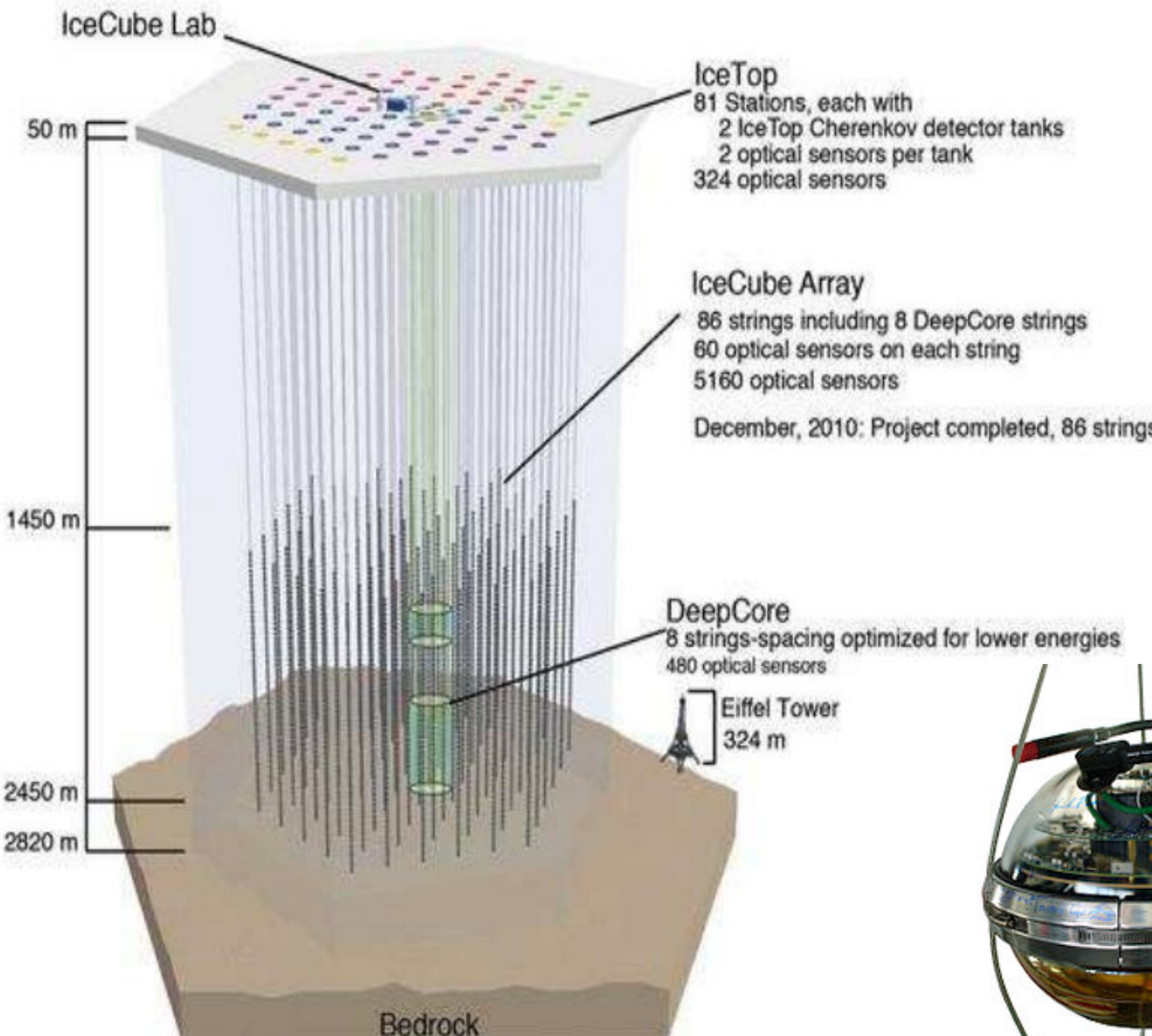
Limited angular resolution (2-10°)

Good energy resolution (10-15%)




Baikal
ANTARES
IceCube


12 line detector completed in May 2008
8 countries
31 institutes
~150 scientists +
• 25 storeys / line
• 3 PMTs / storey
• 885 PMTs
ANTARES
350 m
14.5 m
Deployed in 2001
40 km
100 m
~70 m
Anchor/line socket
Interlink cables
Junction box (since 2002)
©Montanet



86 lines, completed end 2010
1 km^3 instrumented volume
DeepCore: denser (8 strings)
IceTop: air shower detectors

Different media: different technical challenges

Complementary coverage

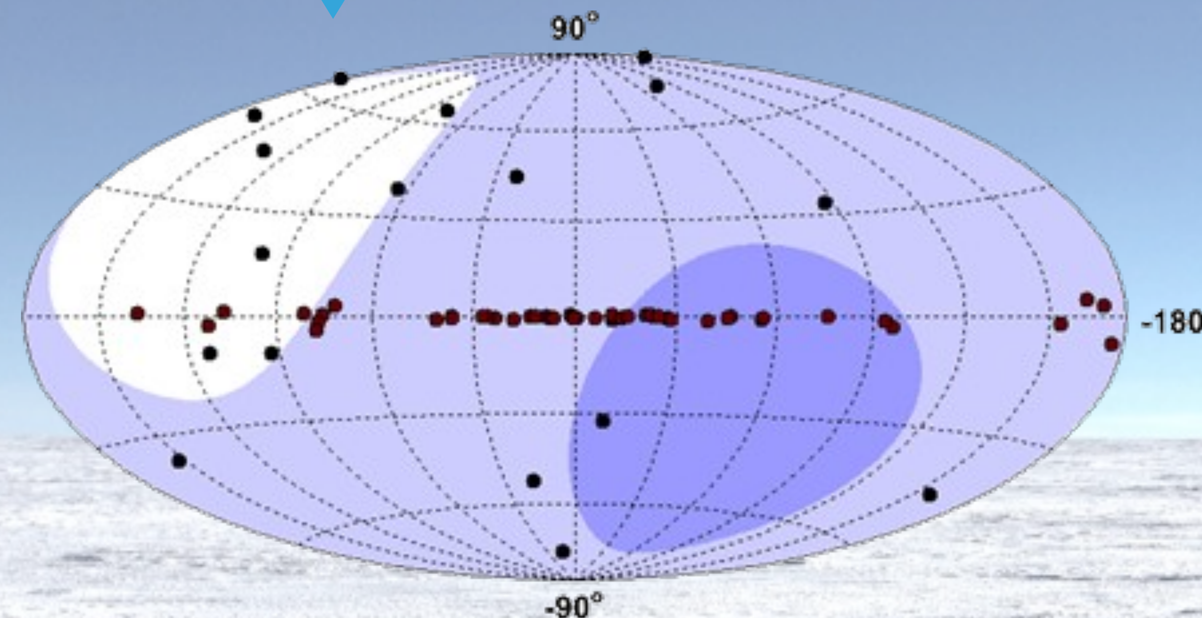
Optical noise (biolum) + ^{40}K / no noise

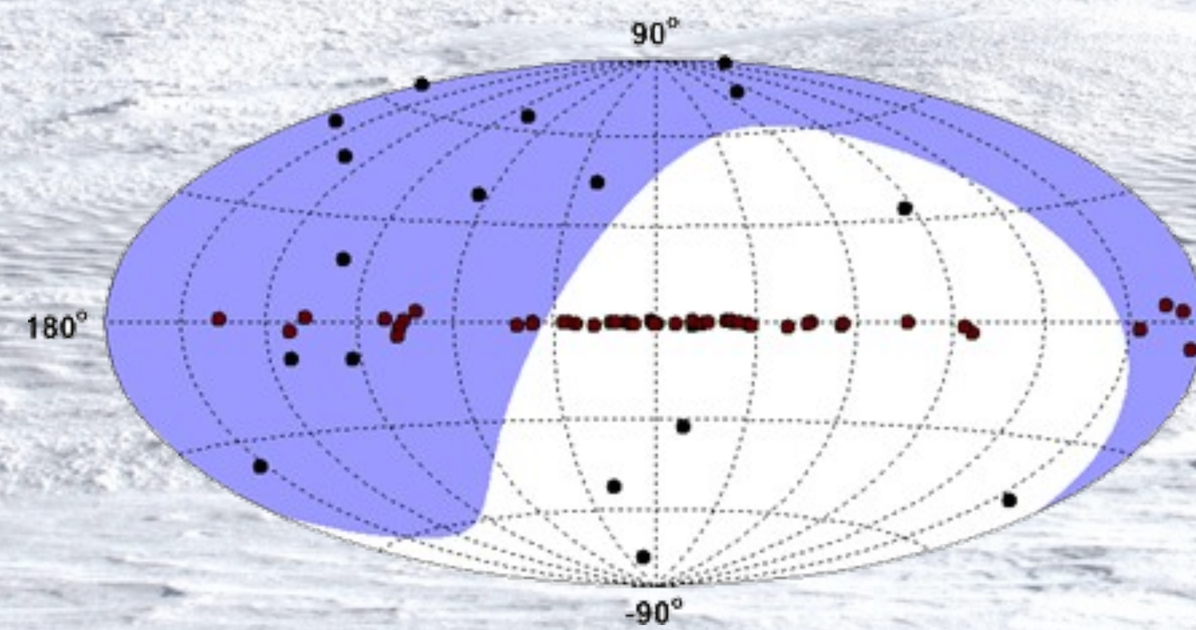
Mediterranean : logistically attractive

Absorption / diffusion

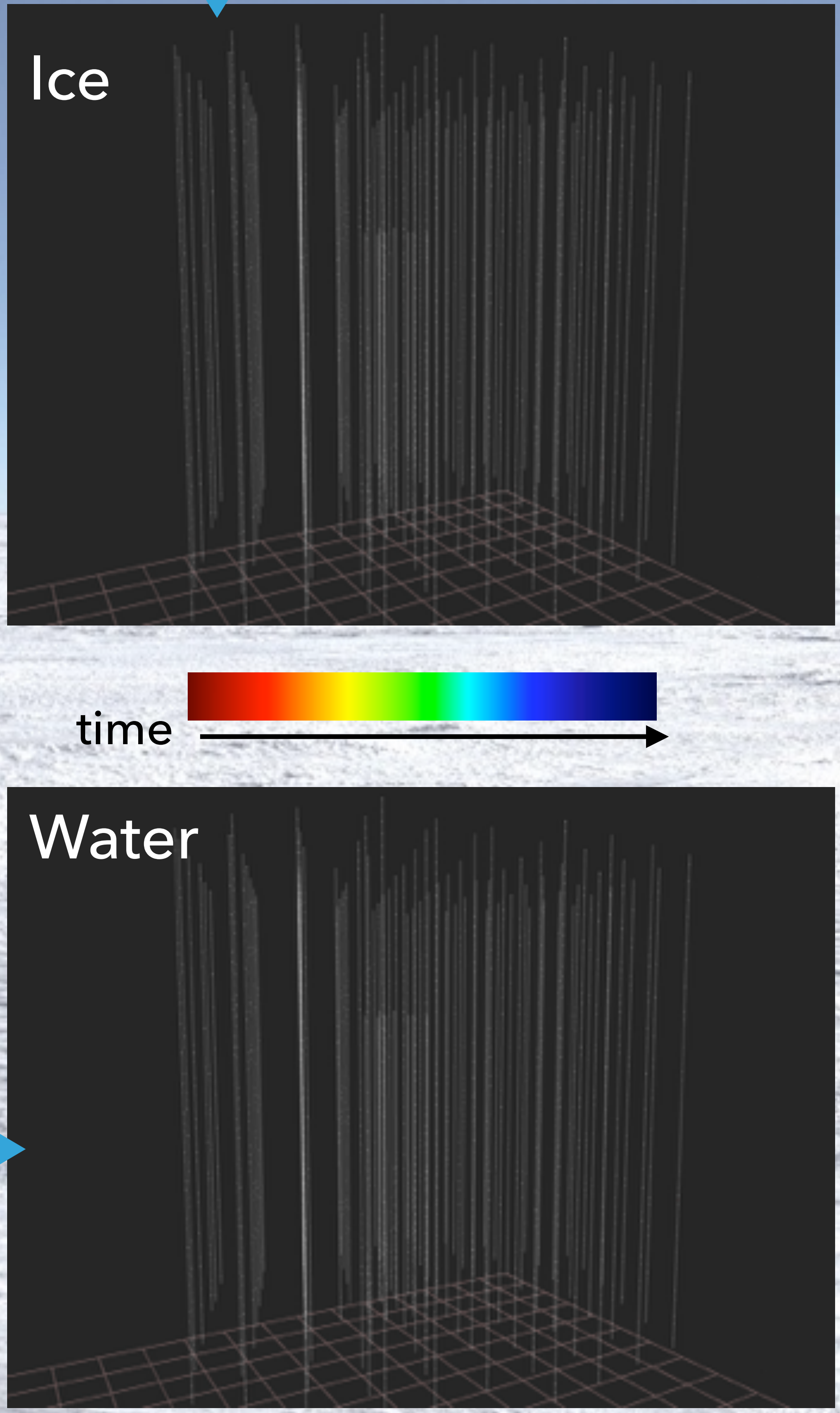
Good pointing accuracy / Calorimetry

Complementary coverage:
galactic center / extragalactic sources
(true for energy < 100 TeV)





Ice: stronger scattering but lower absorption than water: better calorimeter



Complementary coverage

Optical noise (biolum) + ^{40}K / no noise

Mediterranean : logistically attractive

Absorption / diffusion

Good pointing

Water: lower scattering of light than ice

⇒ Better angular resolution

High-energy neutrino detection

TeV-PeV cosmic neutrinos

small cross-section
+ very low flux

huge instrumented volumes
(~km^3 scale) - Cherenkov detection

atmospheric muon + neutrino background

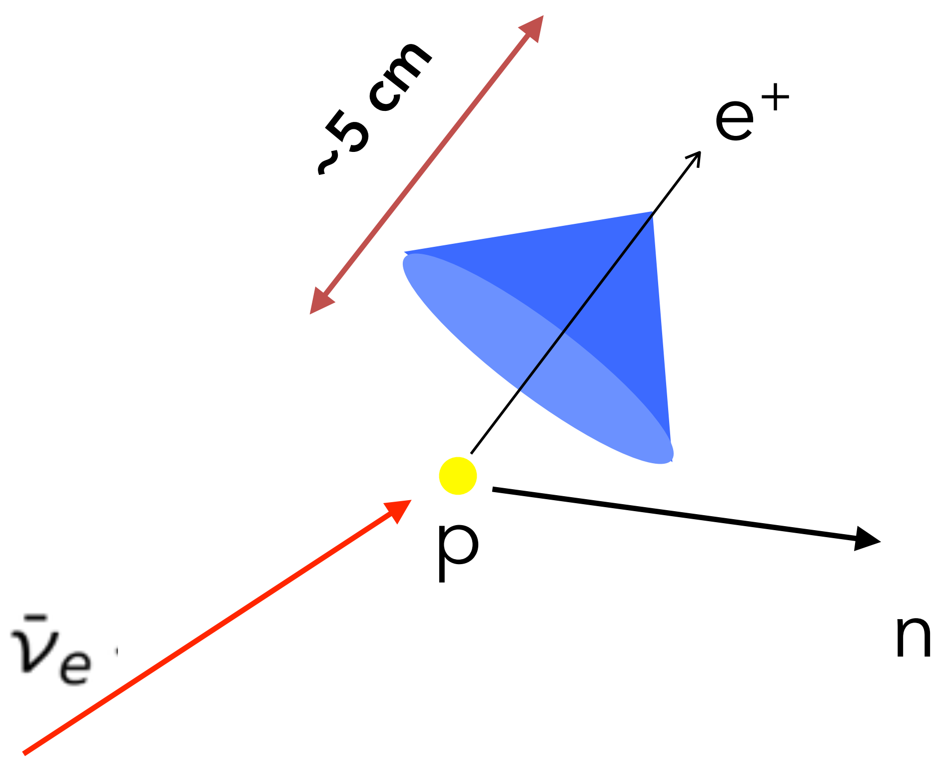
high-energy cut
(diffuse flux)

spatial
clustering

transient /
multi-messenger

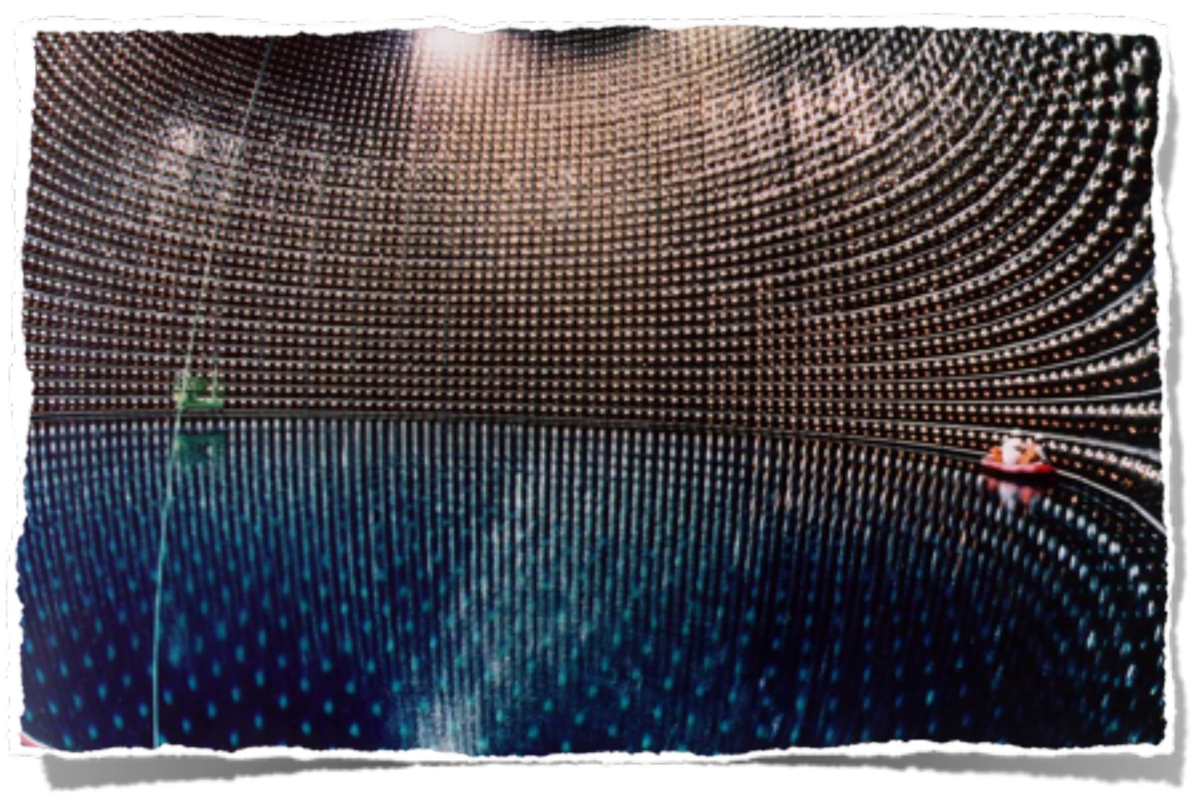
Core-collapse SNe neutrino detection at MeV energies

Detecting supernova neutrinos
(with Cherenkov detectors)

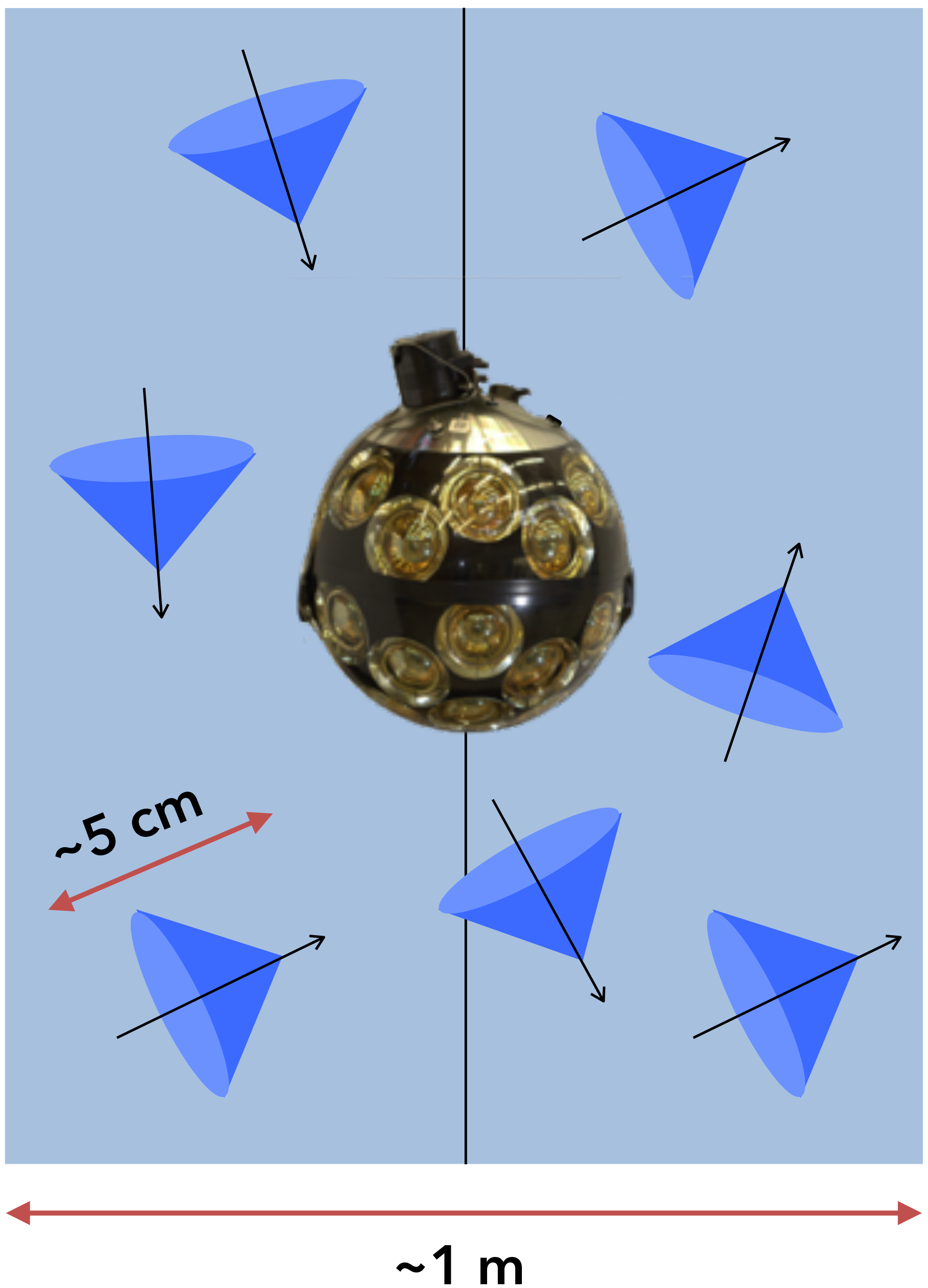


- Neutrino interactions dominated by
  $\bar{\nu}_e + p \rightarrow e^+ + n$ at ~10 MeV

- Positron track of some cm detected by photomultipliers through UV/optical Cherenkov light



Detecting supernova neutrinos
(with Cherenkov detectors)

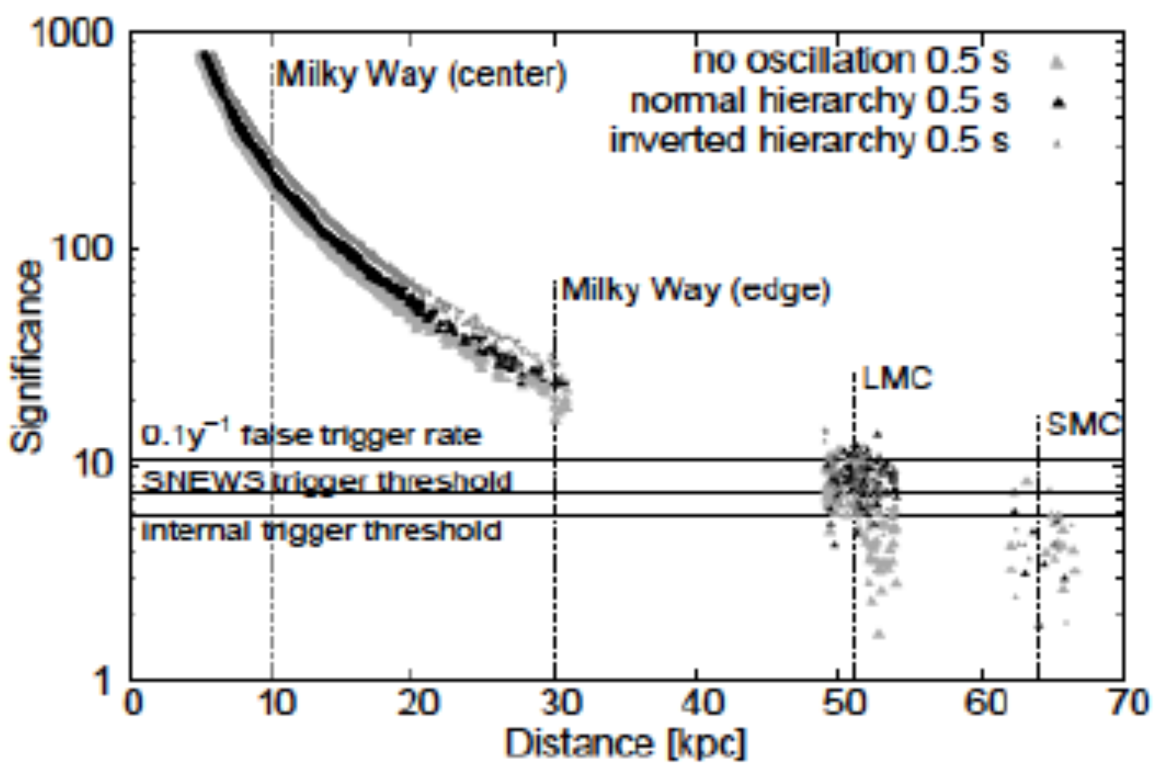


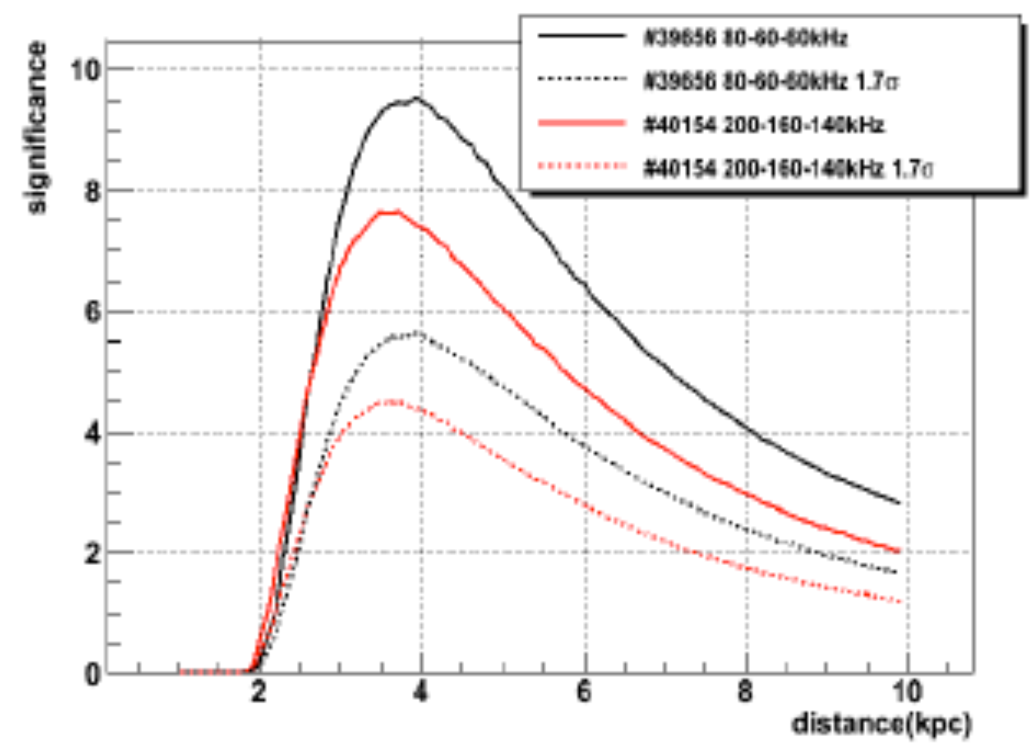
- **HE neutrino telescopes:** optimized for >GeV neutrino detection (cannot resolve MeV events individually)
- Each optical module detects Cherenkov light from its neighborhood
- Increase of the counting rate not significant
- SN signal appears as a collective rise in all optical modules above noise
- Huge volume ⇒ high statistics (might help to resolve the neutrino lightcurve)

Detecting supernova neutrinos
(with Cherenkov detectors)

$$Significance = \frac{Signal}{\sigma_{measurement}}$$

Single rate method





IceCube collaboration, A&A 535 A109 2011

Antares , 32 ICRC proceedings
ArXiv 1112.0478

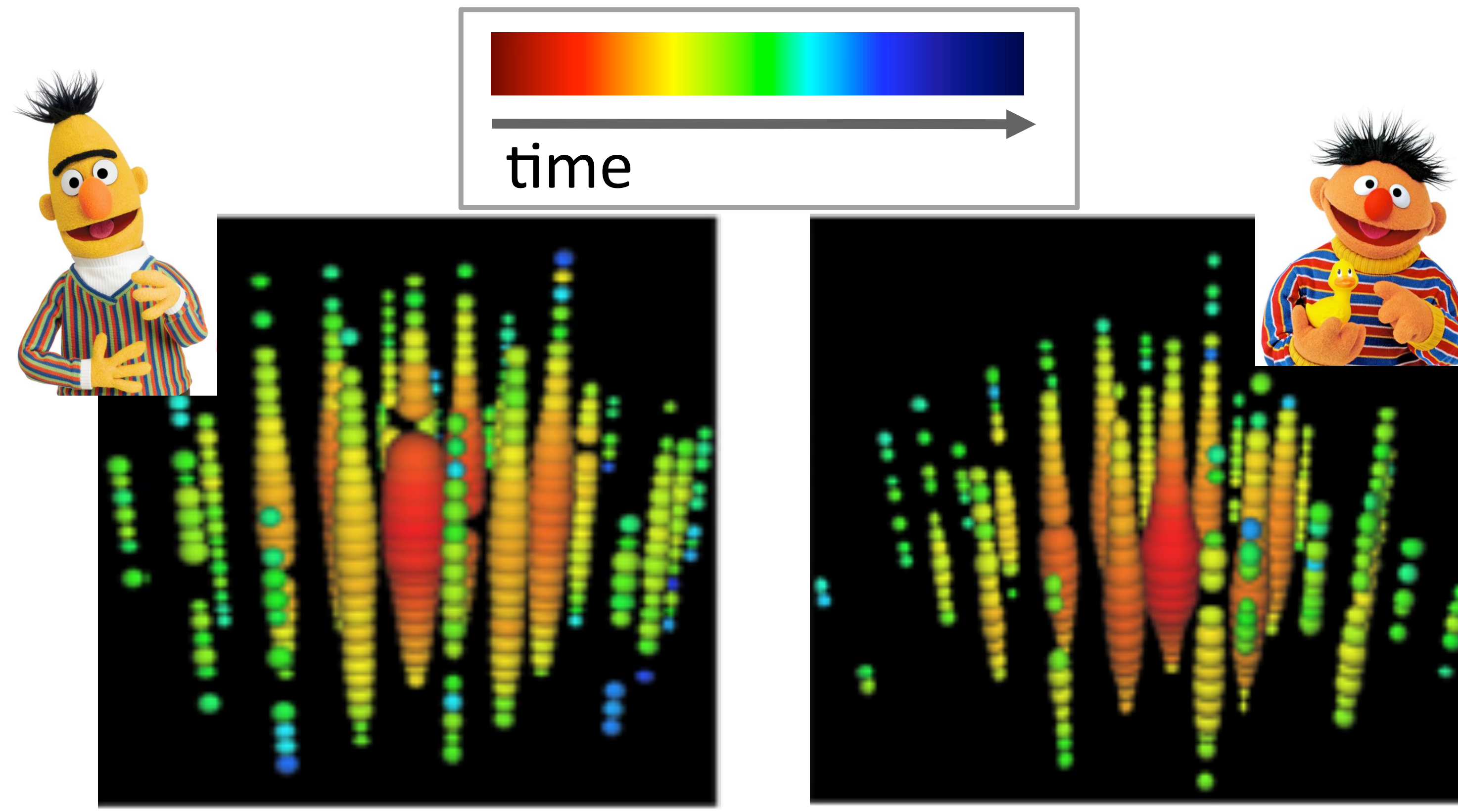
Latest results of high-energy neutrino telescopes

2012 : observation of two very energetic cascade events ($E>10^{15}$ eV) by IceCube

Energy very well reconstructed

Very poor resolution on the neutrino direction

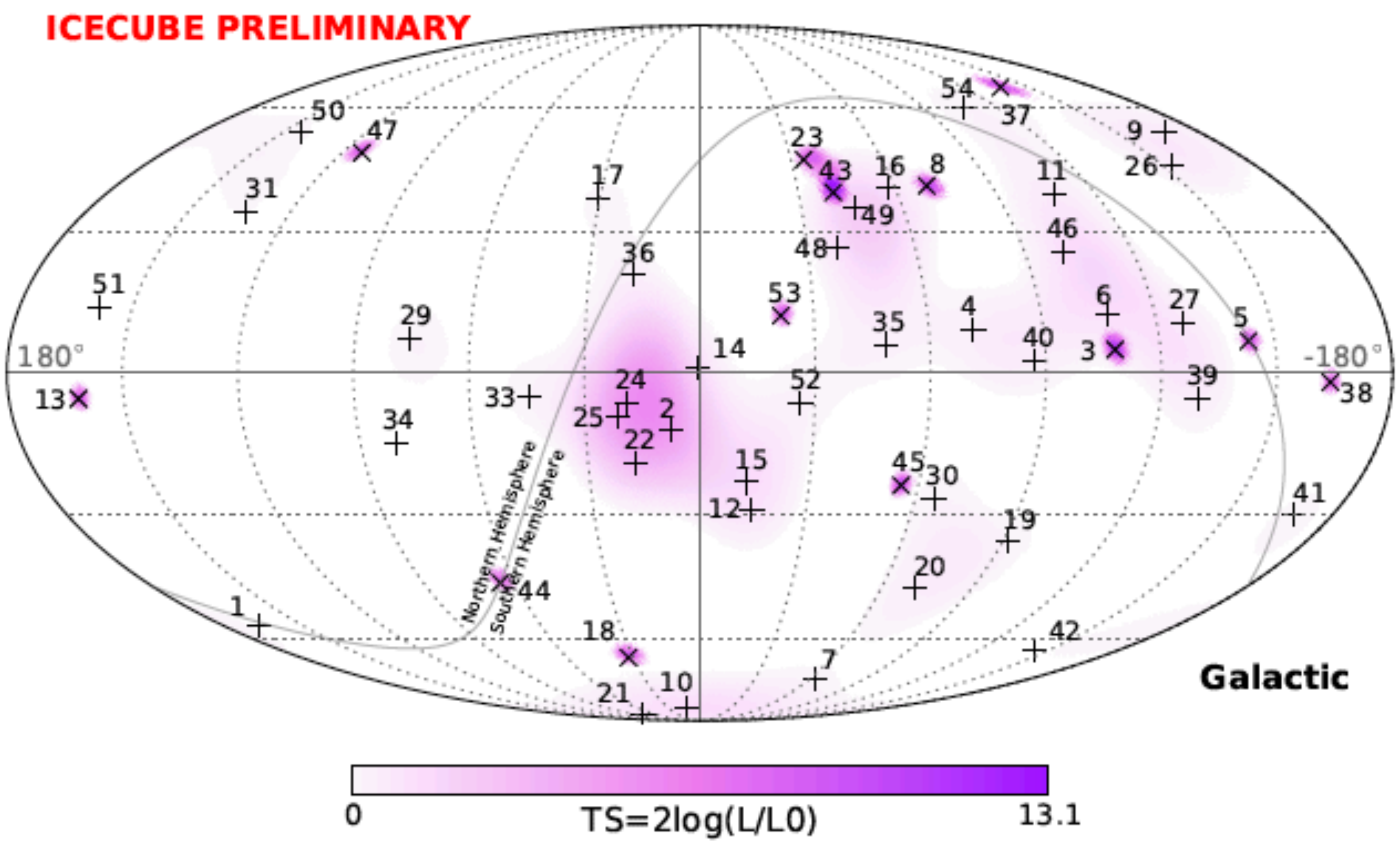
Published in 2013



1.0 +/- 0.2 PeV   1.1 +/- 0.2 PeV

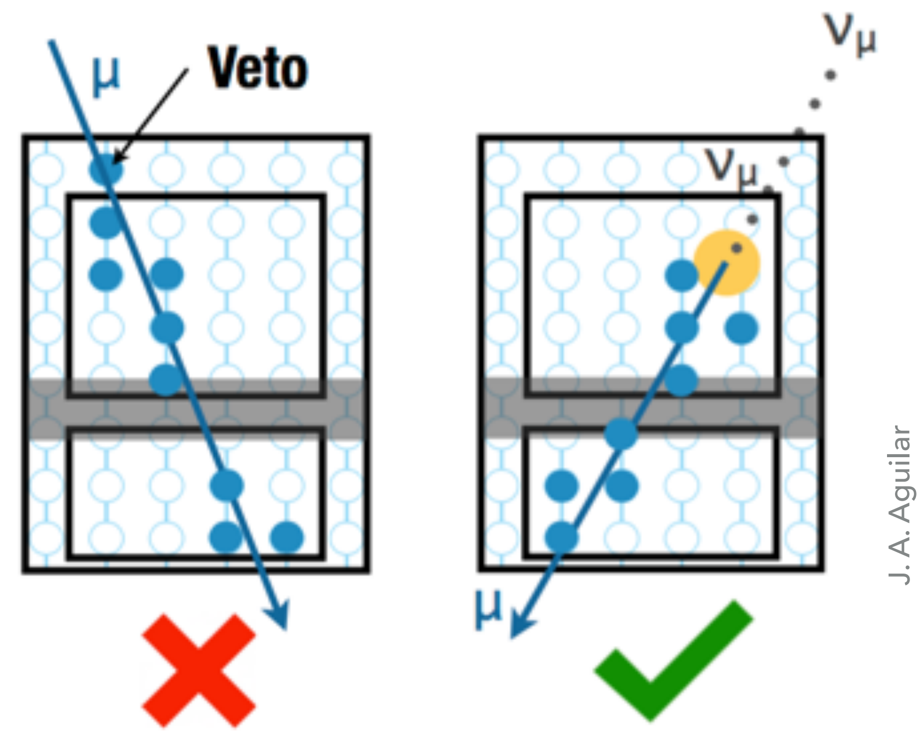
➜ World premiere: first two "certified" astrophysical neutrinos ever observed

In the months following the detection of Ernie & Bert, IceCube pointed a clear excess of events above ~100 TeV w.r.t the atmospheric ν background



now ~7σ significance

HE starting events - 4 years - all flavors



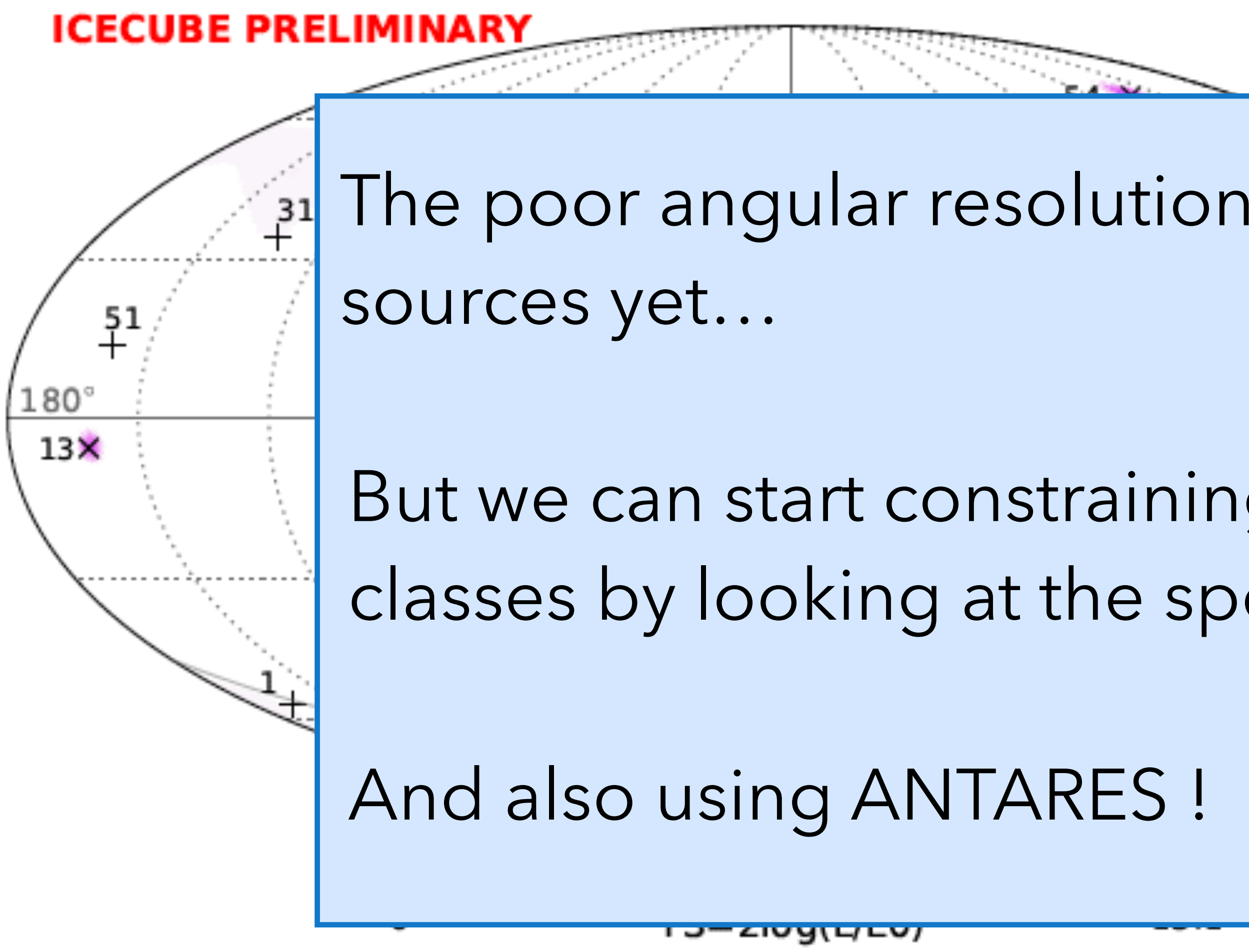
Compatible with isotropy

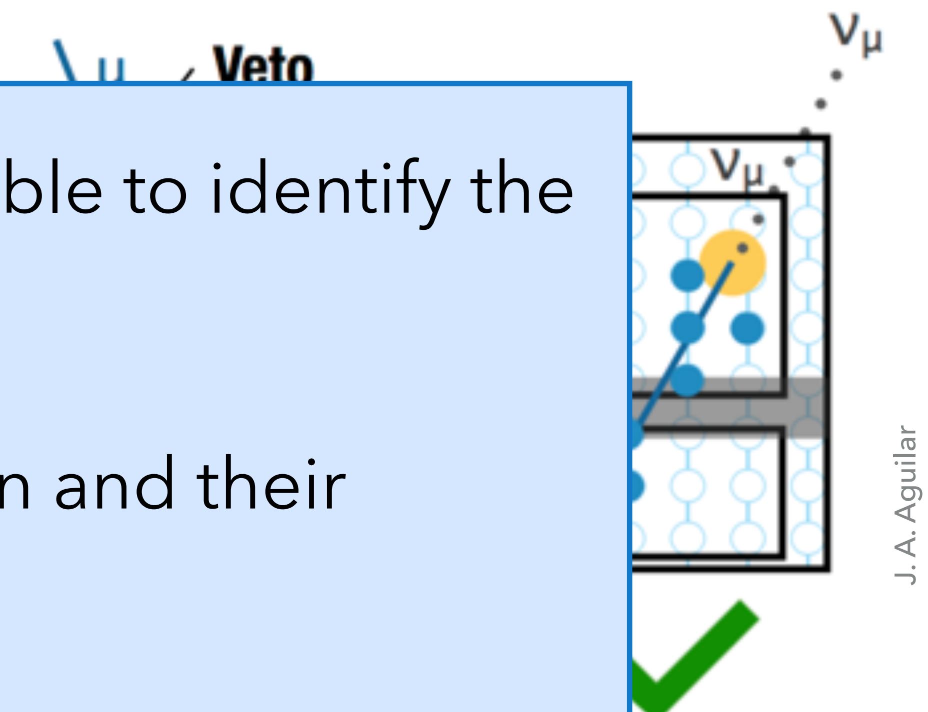
Sources non identified yet

Excess also visible in track channel (5.6σ)

In the months following the detection of Ernie & Bert, IceCube pointed a clear excess of events above ~100 TeV w.r.t the atmospheric ν background

HE starting events - 4 years - all flavors





The poor angular resolution does not enable to identify the sources yet…

But we can start constraining their location and their classes by looking at the spectrum…

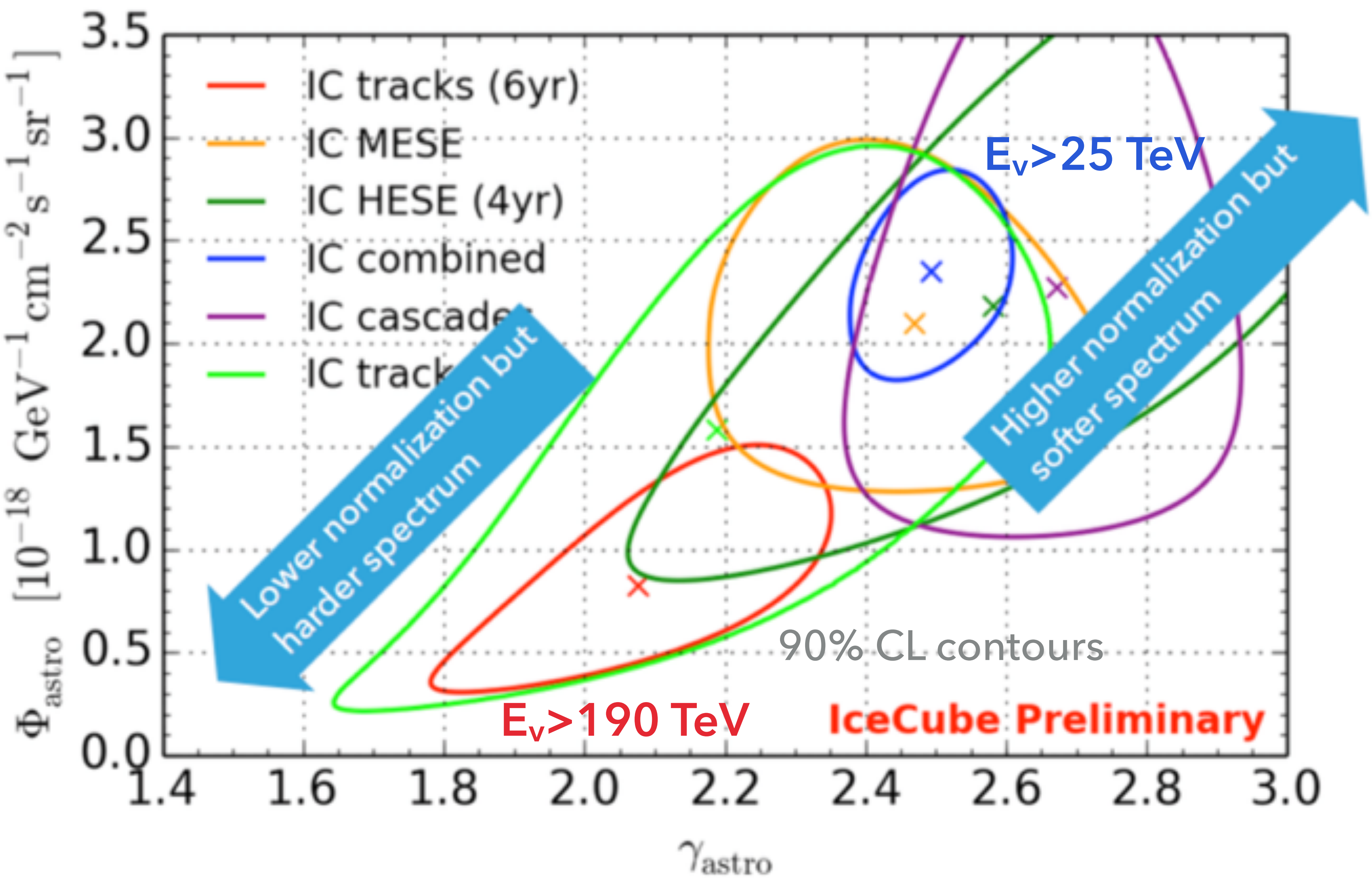
And also using ANTARES !

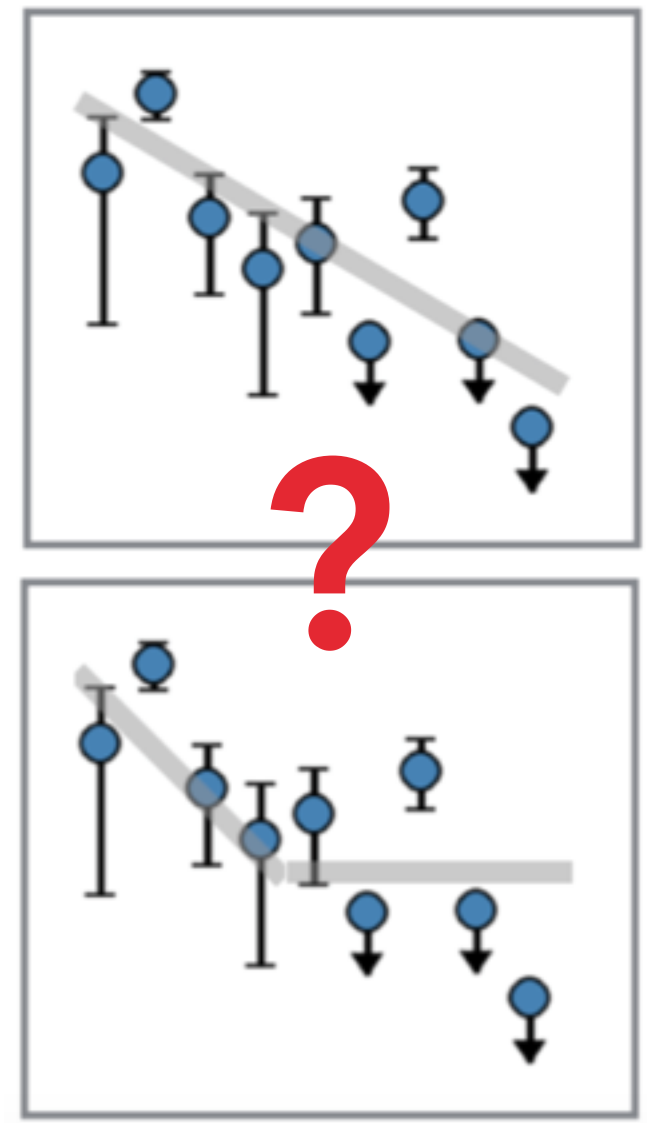
Sources non identified yet

now ~7σ significance

Excess also visible in track channel (5.6σ)

Adapted from Juan A. Aguilar (RICAP 2016) + M. Kowalski (Neutrino2016)

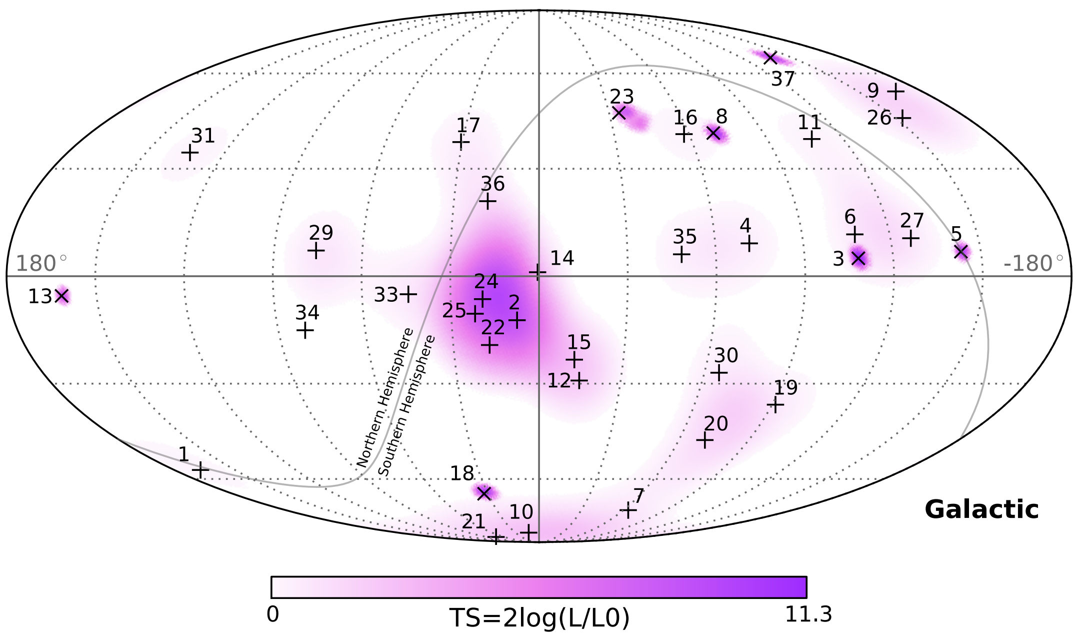




Results of IC tracks(6yr) and IC combined not compatible at > 3.6σ level

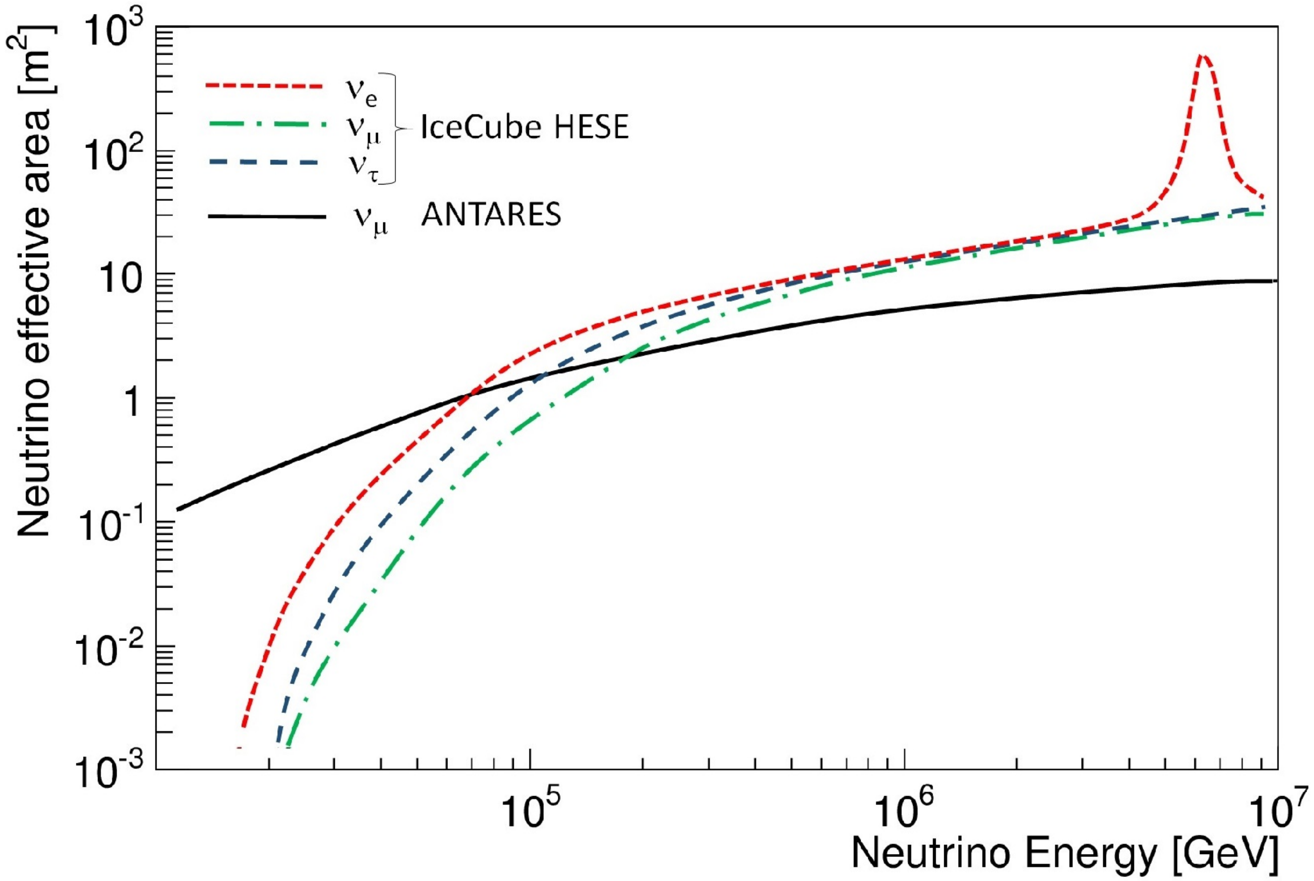
Indication of spectral break (different energy thresholds) ?

Indication of Galactic and extra-galactic contributions (different hemispheres) ?

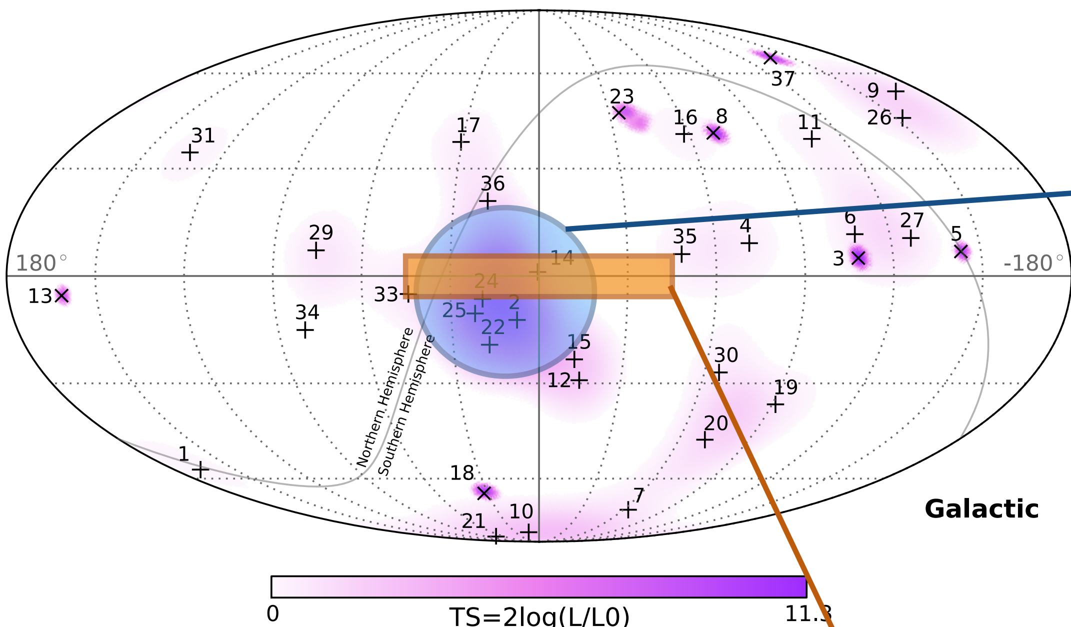


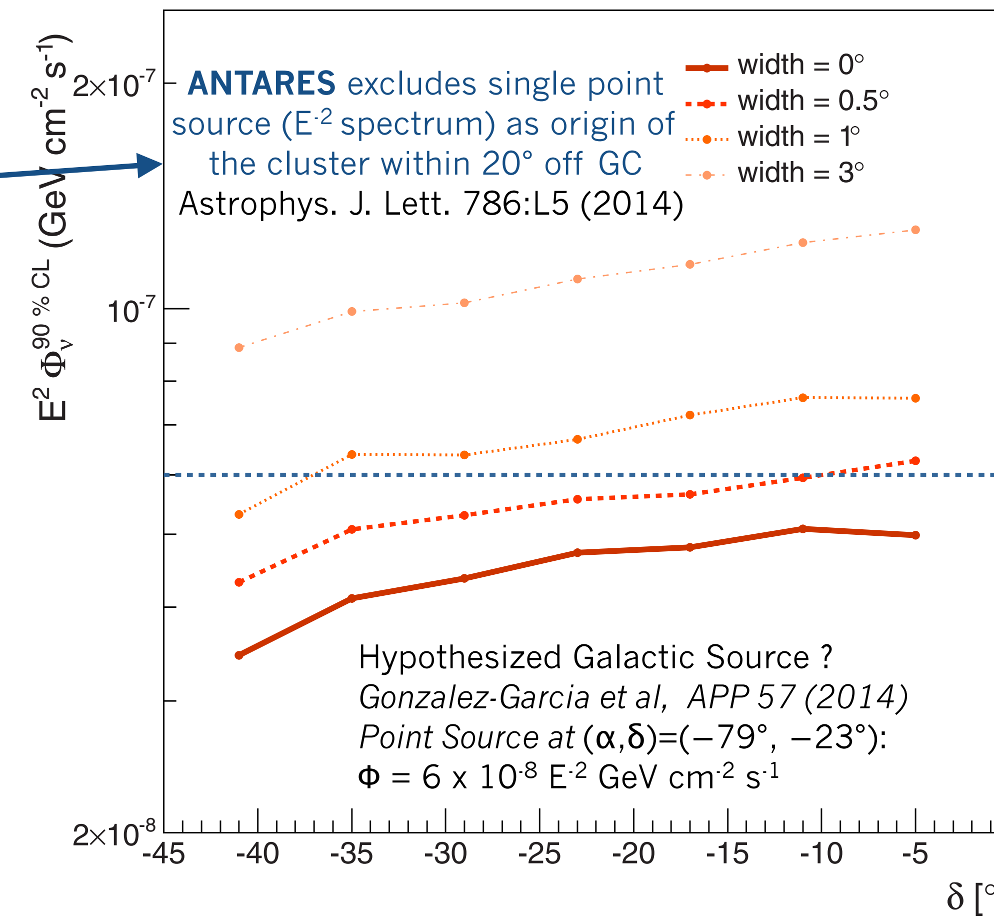
Just one example !

Effective area in the Galactic Center region



ANTARES has a good sensitivity in the Galactic center region.
➜ can constrain the origin of the IceCube events

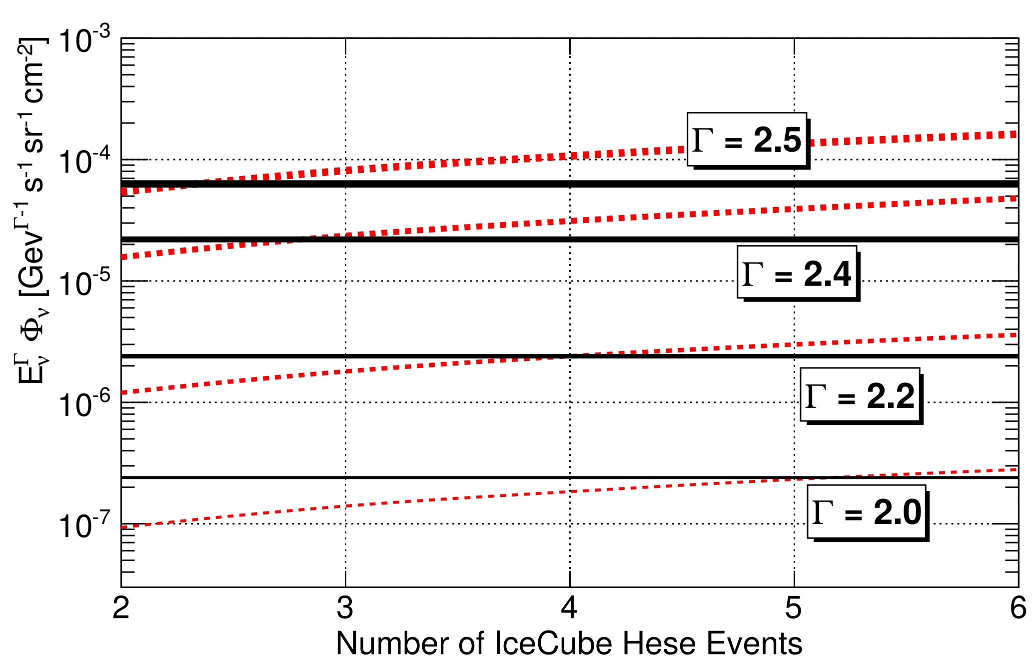




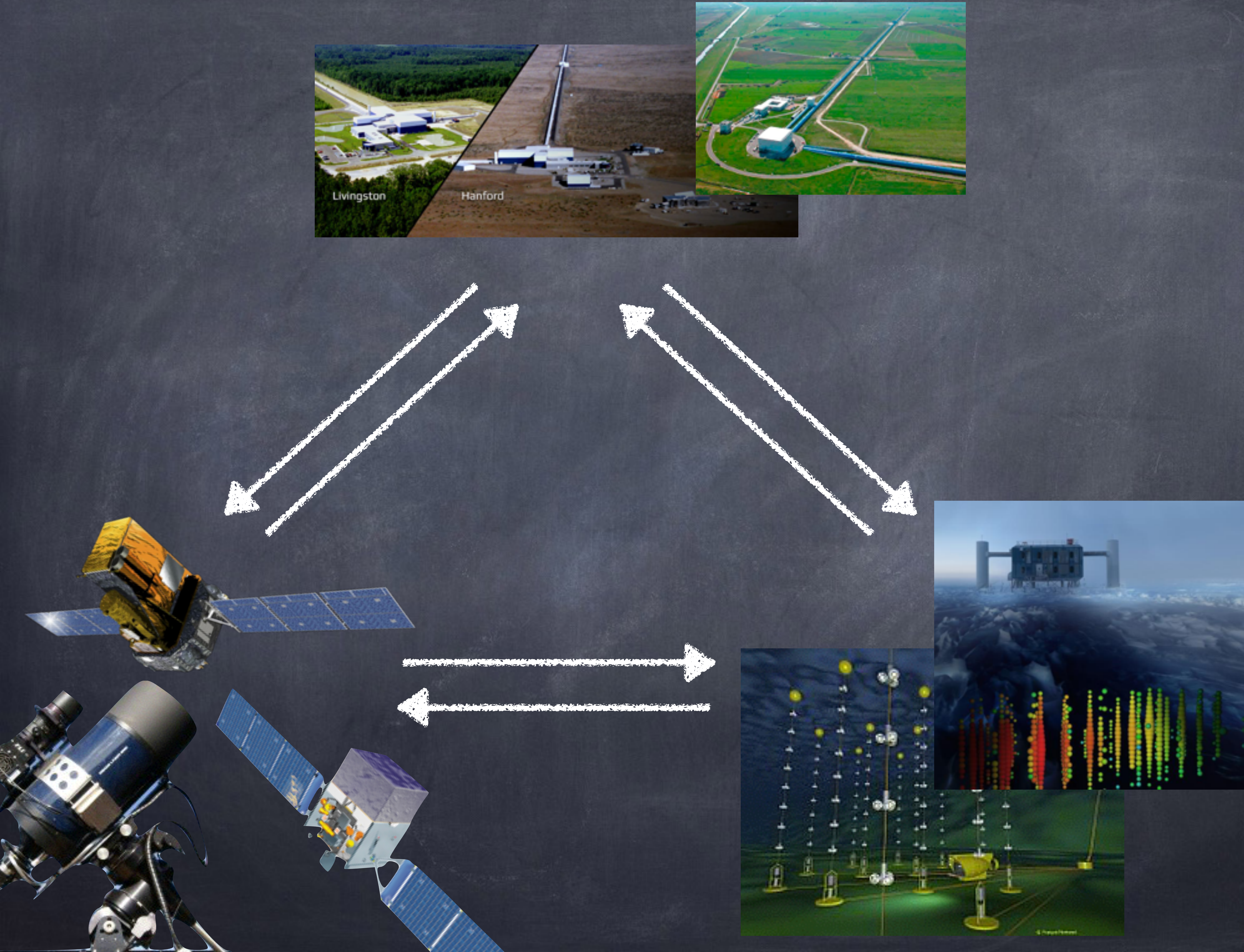
ANTARES excludes single point source (E^{-2} spectrum) as origin of the cluster within 20° off GC
Astrophys. J. Lett. 786:L5 (2014)

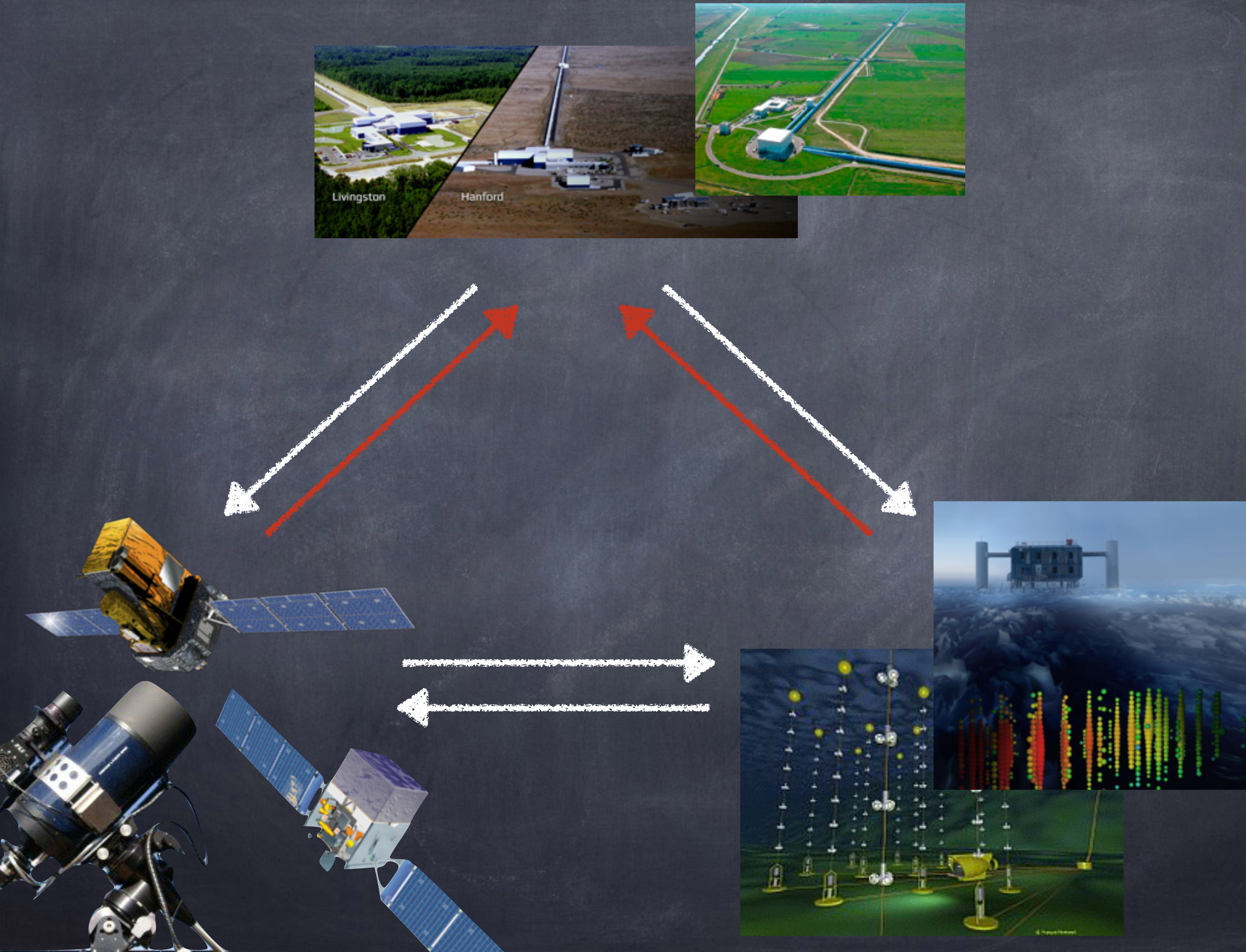
Hypothesized Galactic Source ?
Gonzalez-Garcia et al, APP 57 (2014)
Point Source at $(\alpha,\delta)=(-79°, -23°)$:
$\Phi = 6 \times 10^{-8}\ E^{-2}$ GeV $cm^{-2}\ s^{-1}$

ANTARES constrains the IceCube signal event contribution to a diffuse neutrino flux in the Galactic Plane
arXiv:1602.03036



Multi-messenger synergies


Livingston
Hanford


Livingston
Hanford

1) Search for GRB neutrino counterparts

2) EM and neutrino follow-up of GW events

3) EM follow-up of neutrino events

1) Search for GRB neutrino counterparts

2) EM and neutrino follow-up of GW events

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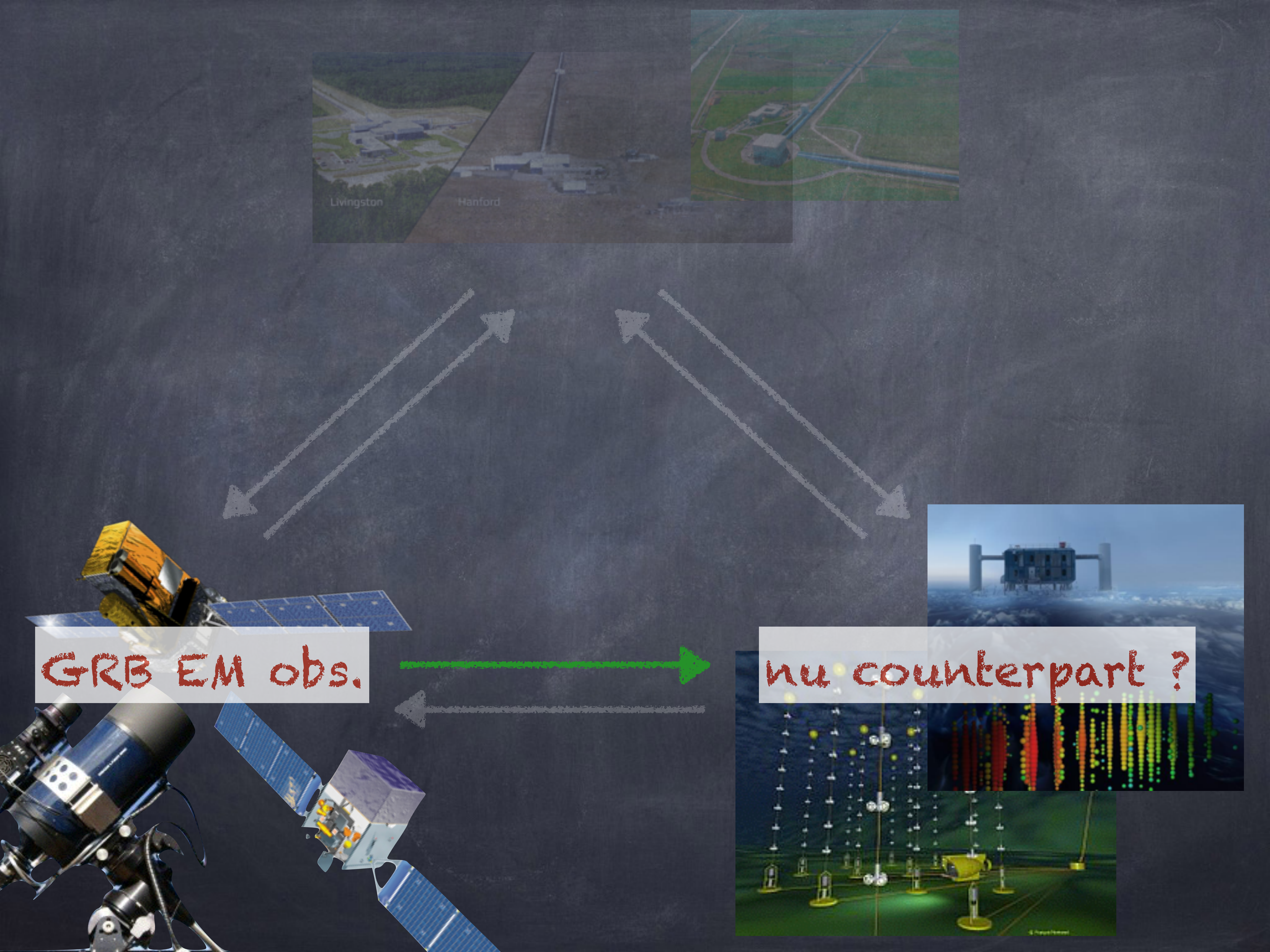
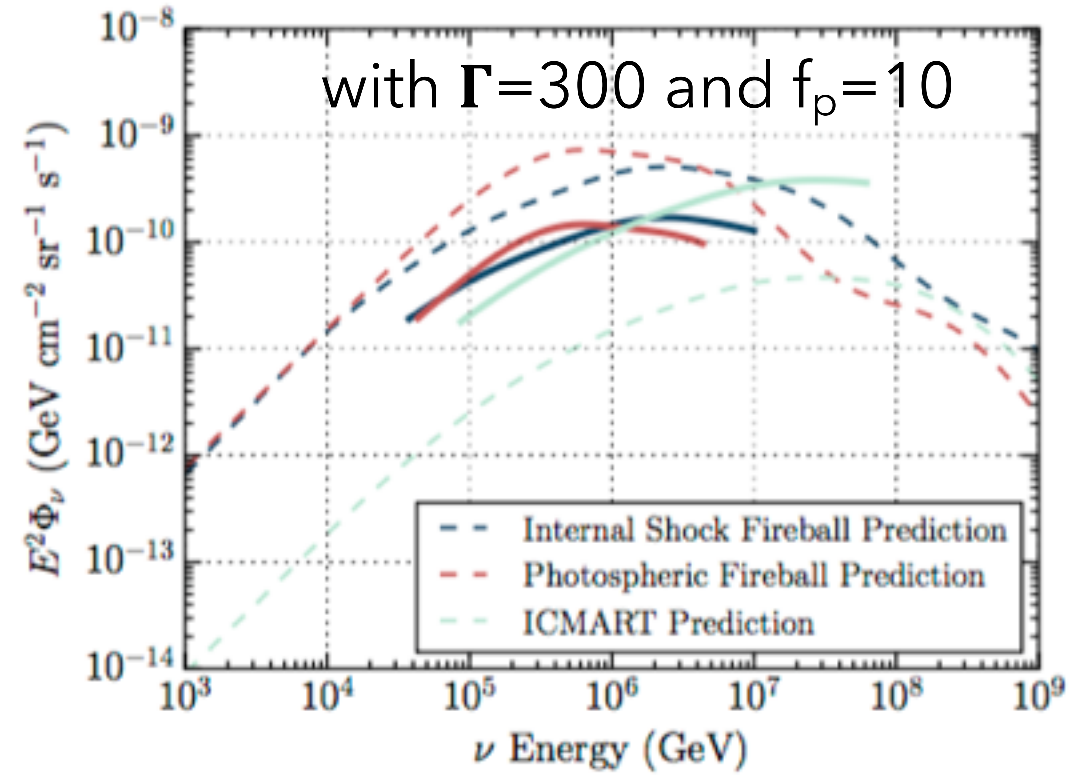

Livingston
Hanford
GRB EM obs.
nu counterpart ?

Different approaches:

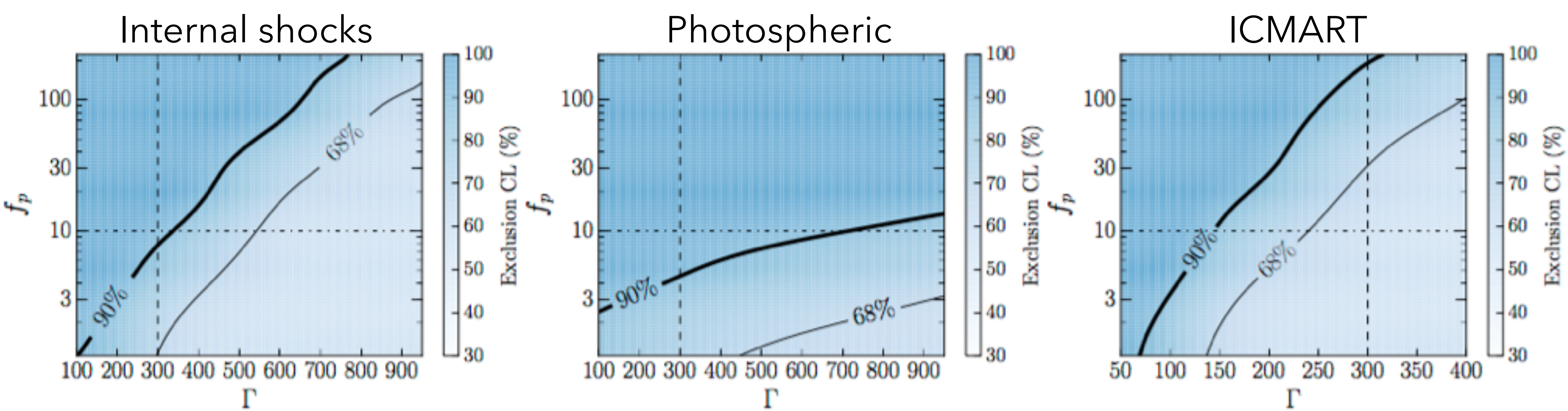
- likelihood search based on GRB samples (e.g. *Aartsen et al., 2016-2017*)
- focus on some bright GRBs (e.g. *Albert et al., 2017*)
- stacking of a large sample of GRBs (e.g. *Adrian-Martinez et al., 2016*)

➜ no neutrino counterpart found so far !

IceCube ν_μ 6-year dataset
likelihood maximization (1172 GRBs)
(Aartsen et al., 2017)



+ IceCube all sky/3 flavors search
likelihood maximization (3 years of IC data)
(Aartsen et al., 2017)



➜ The average burst likely exhibits Γ and f_p values that are largely excluded for neutrino production. But only valid for one-zone models !

Consequences of non-detection ?

These models assume **proton acceleration** at a **single location** (one zone) where γ-rays are also produced and emitted.
➜ Predicted prompt neutrino fluence will scale linearly with the proton content of the fireball. When **acceleration location constraint is relaxed** (dynamic GRB outflow is considered ➜ predicted **prompt neutrino fluence significantly reduced** (~10x) (Bustamante et al. 2015; Globus et al. 2015).

Prospects: simulation of multiple emission regions within the jet (e.g. Bustamante et al., 2017):

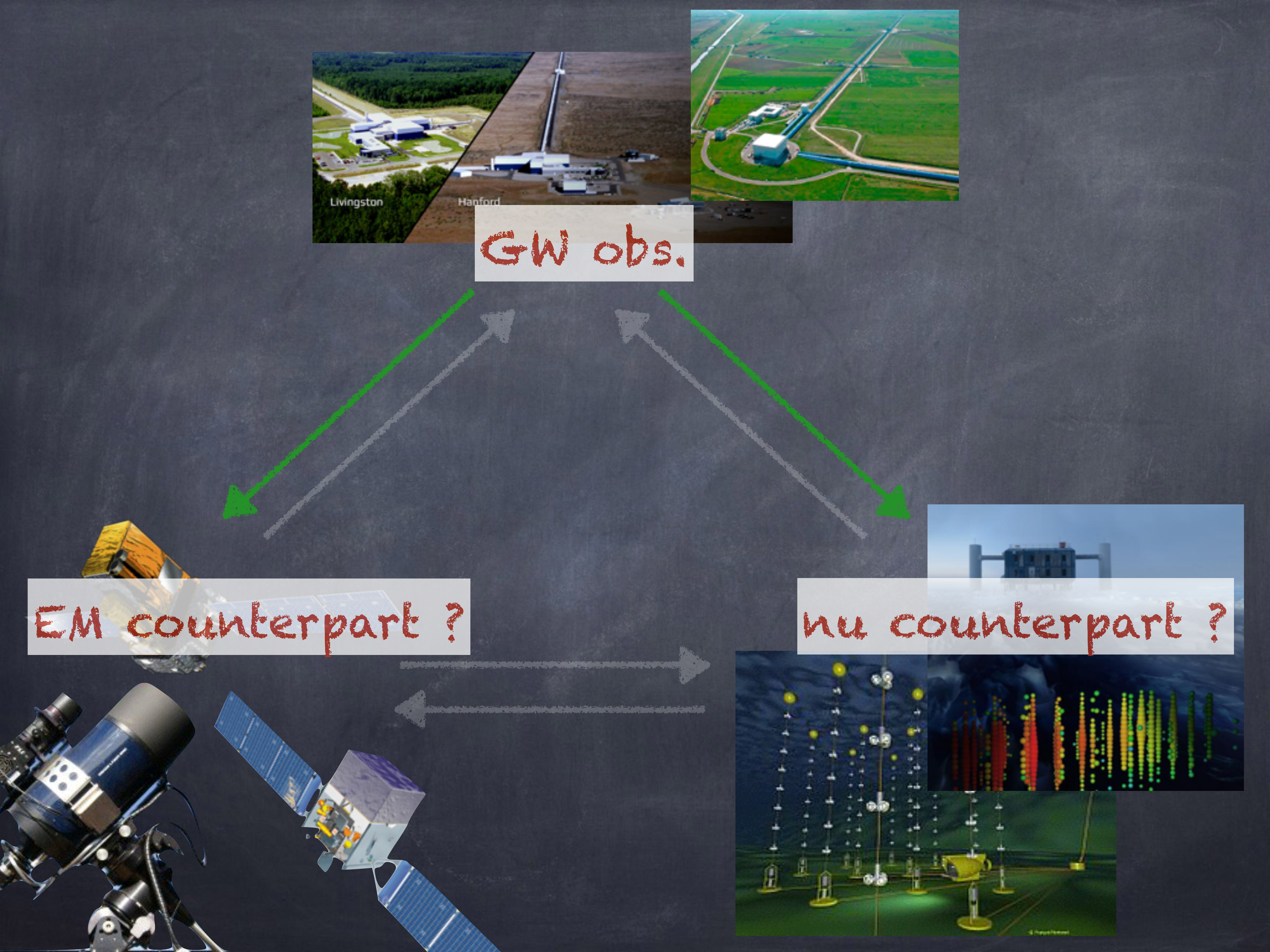
➜ new prediction for the minimal diffuse GRB neutrino flux, likely within the reach of the planned detector upgrades, IceCube-Gen2 & KM3NeT.

+ Looking for features in the shape of the GRB gamma-ray light curve, can allow to assess whether a particular burst is likely to be an intense neutrino source.

1) Search for GRB neutrino counterparts

2) EM and neutrino follow-up of GW events

3) EM follow-up of neutrino events


Livingston
Hanford
GW obs.
EM counterpart ?
nu counterpart ?

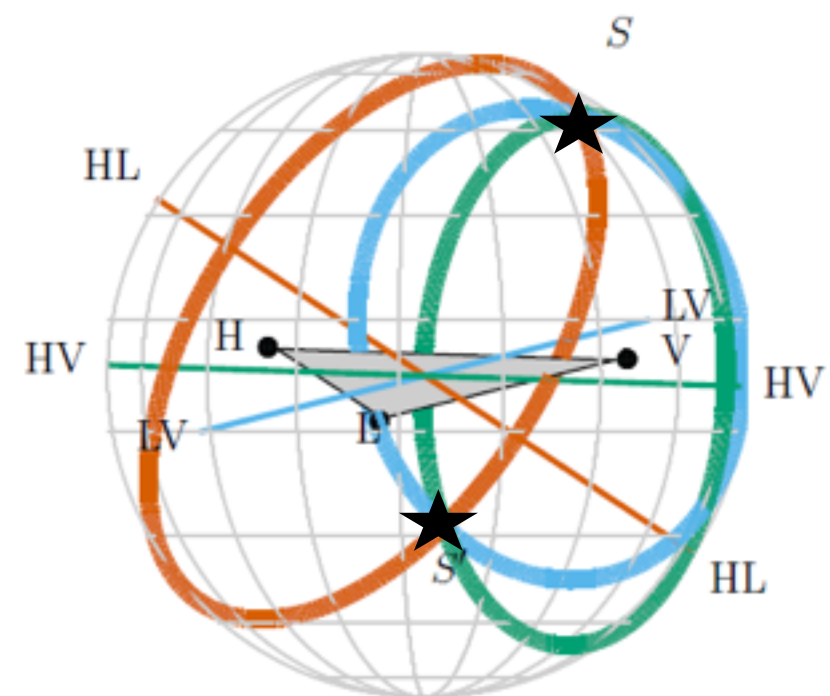

Livingston
Hanford
GW obs.
EM counterpart ?
nu counterpart ?

Challenges to identify the source + host galaxy

Sky position mainly evaluated by **triangulation** based on arrival time delay between detectors.

Two detectors ➜ locus of constant time delay forms a ring on the sky (with additional info. on signal amplitude, … resolve this to **parts of the ring**).

Three detectors ➜ rings intersect in **2 locations** (including source real location)

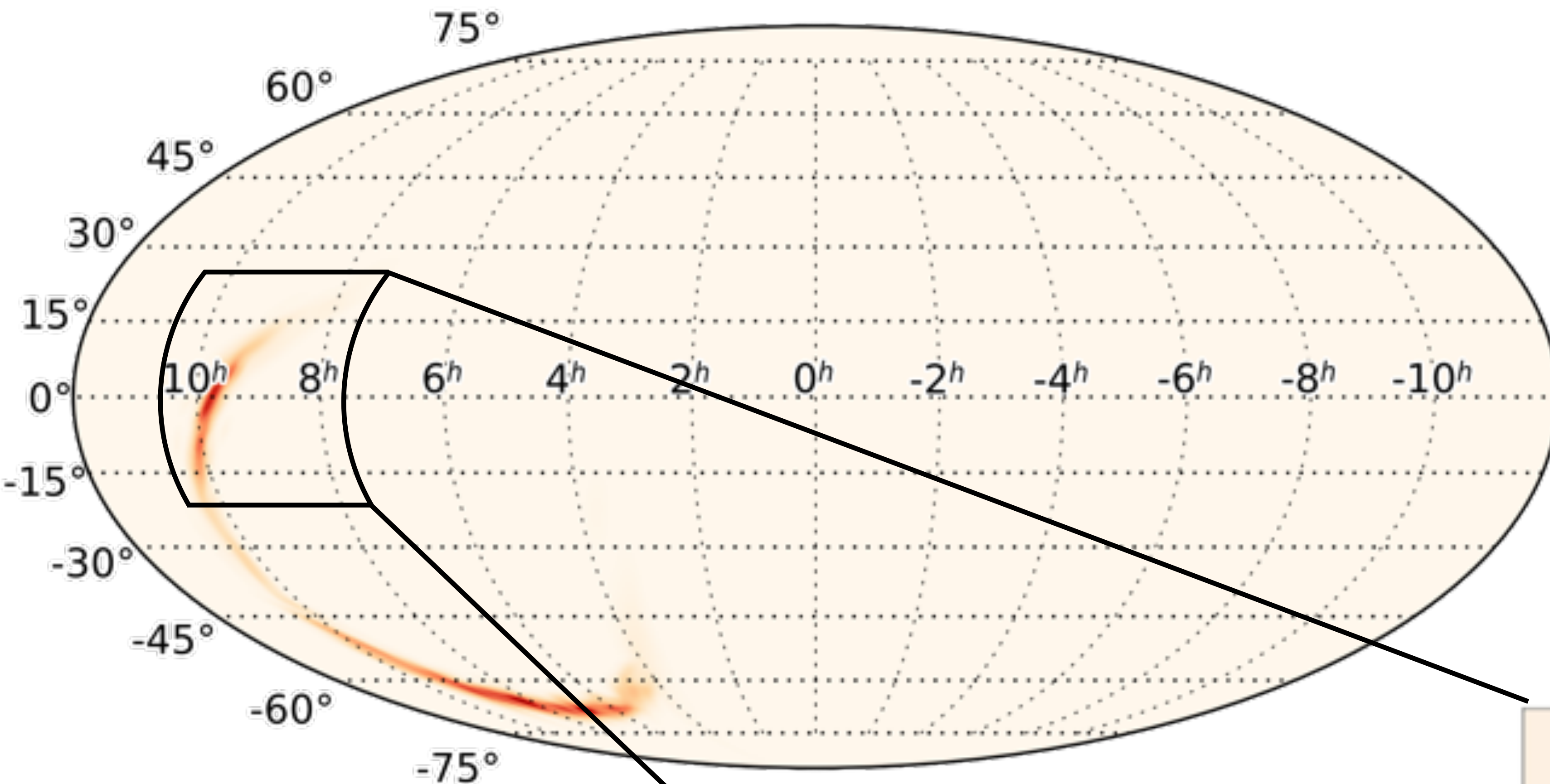


Event	GW150914	GW151226	LVT151012
Sky localization $\Delta\Omega/\mathrm{deg}^2$	230	850	1600

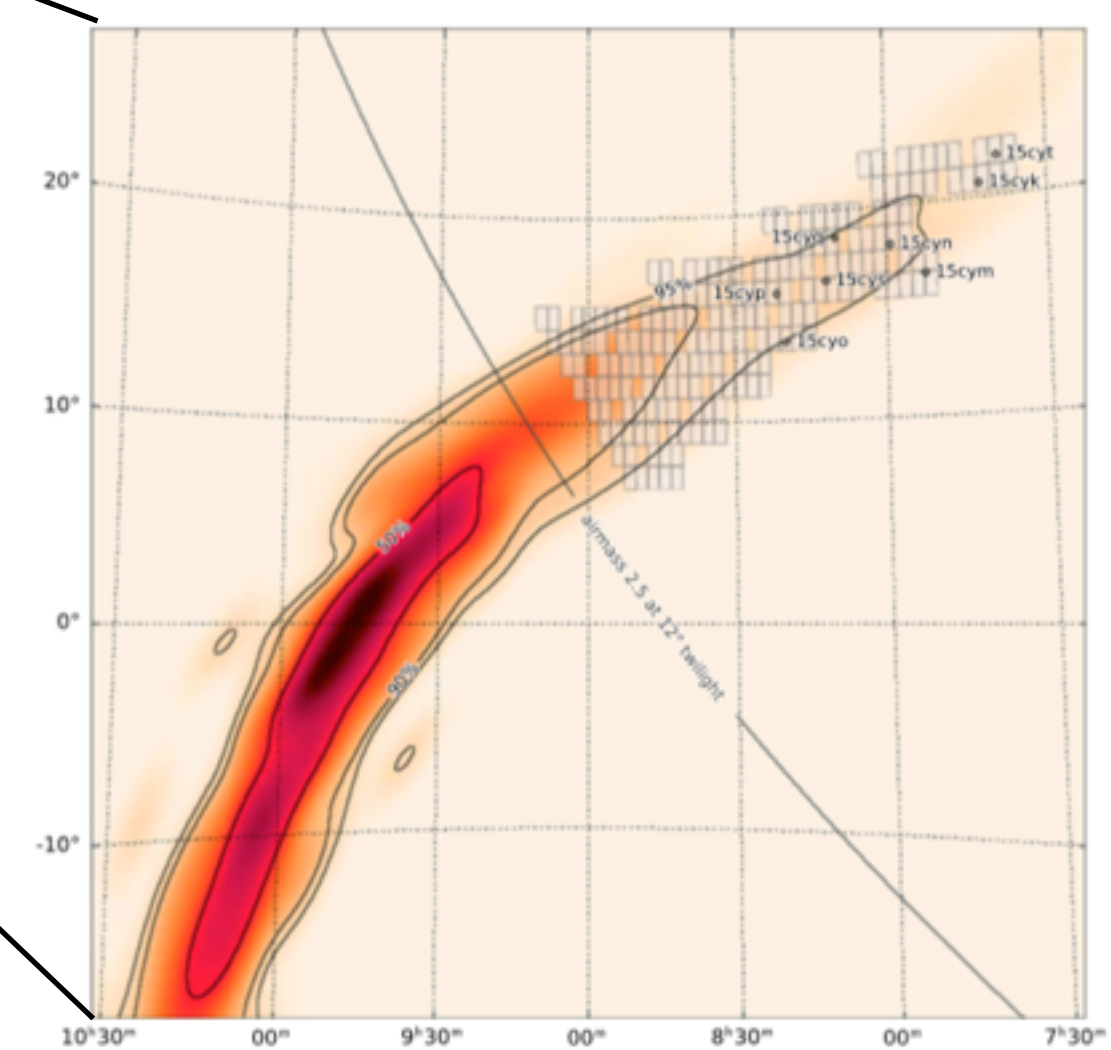
(depends on the signal-to-noise ratio)

Prospects (*LVC, LRR 2016*):

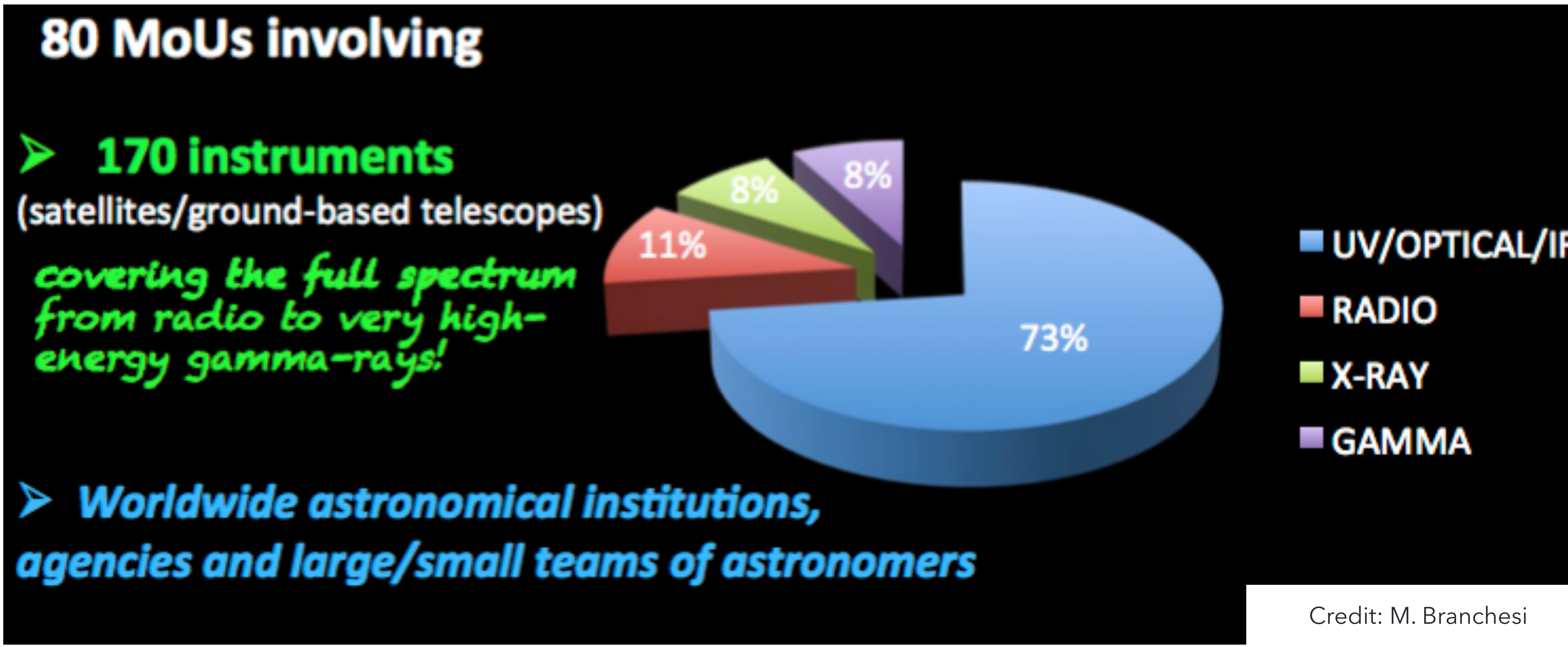
Epoch			2015 − 2016	2016 − 2017	2017 − 2018	2019+	2022+ (India)
Estimated BNS detections			0.0005 − 4	0.006 − 20	0.04 − 100	0.2 − 200	0.4 − 400
90% CR	% within	5 deg^2	< 1	2	> *1 − 2*	> *3 − 8*	> *20*
		20 deg^2	< 1	14	> *10*	> *8 − 30*	> *50*
	median/deg^2		480	230	—	—	—



GW150914 follow-up by iPTF
(7.1 deg^2 / observation)
Kasliwal et al., 2016



MoU with EM + neutrino collaborations

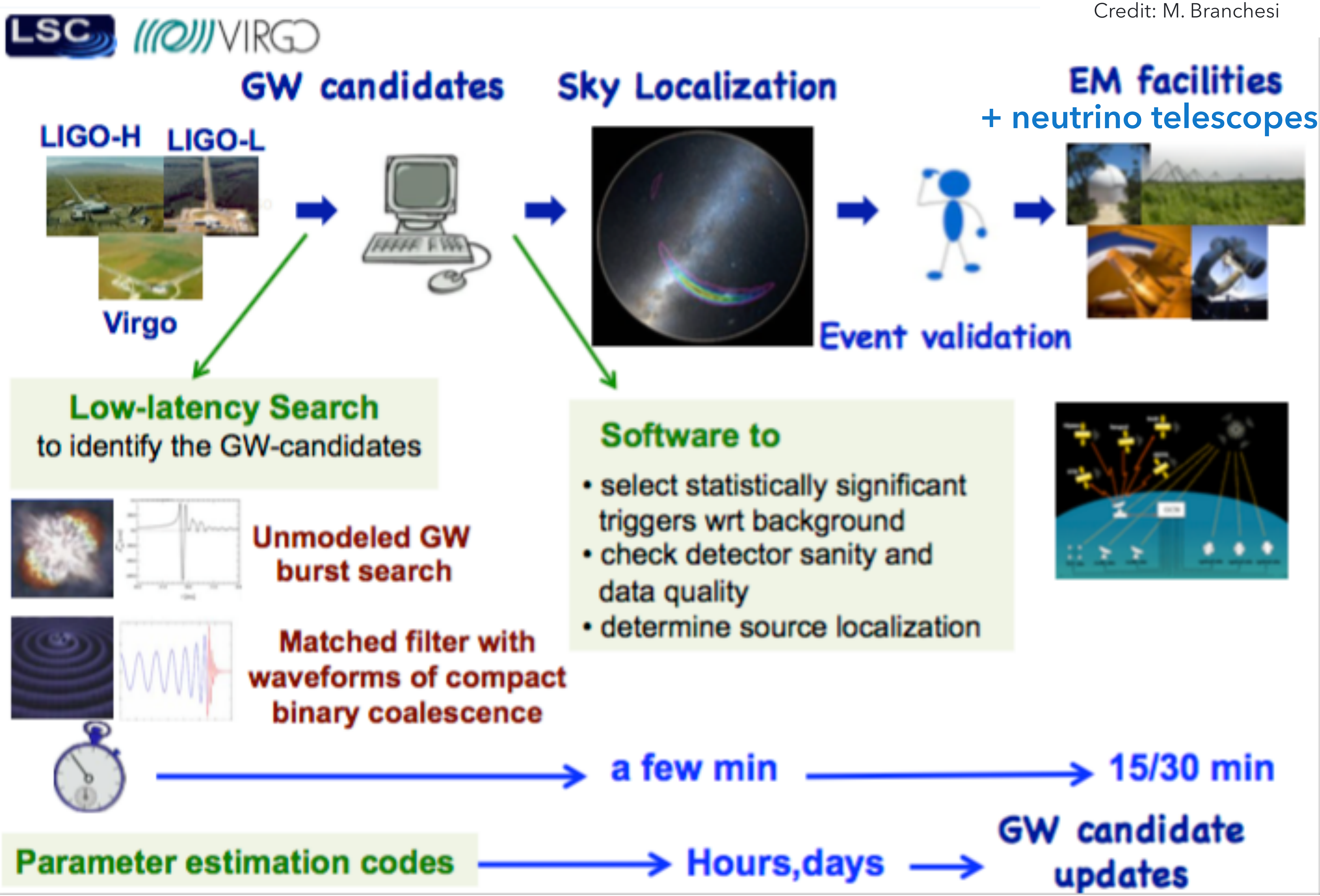


Credit: M. Branchesi

+ neutrino telescopes

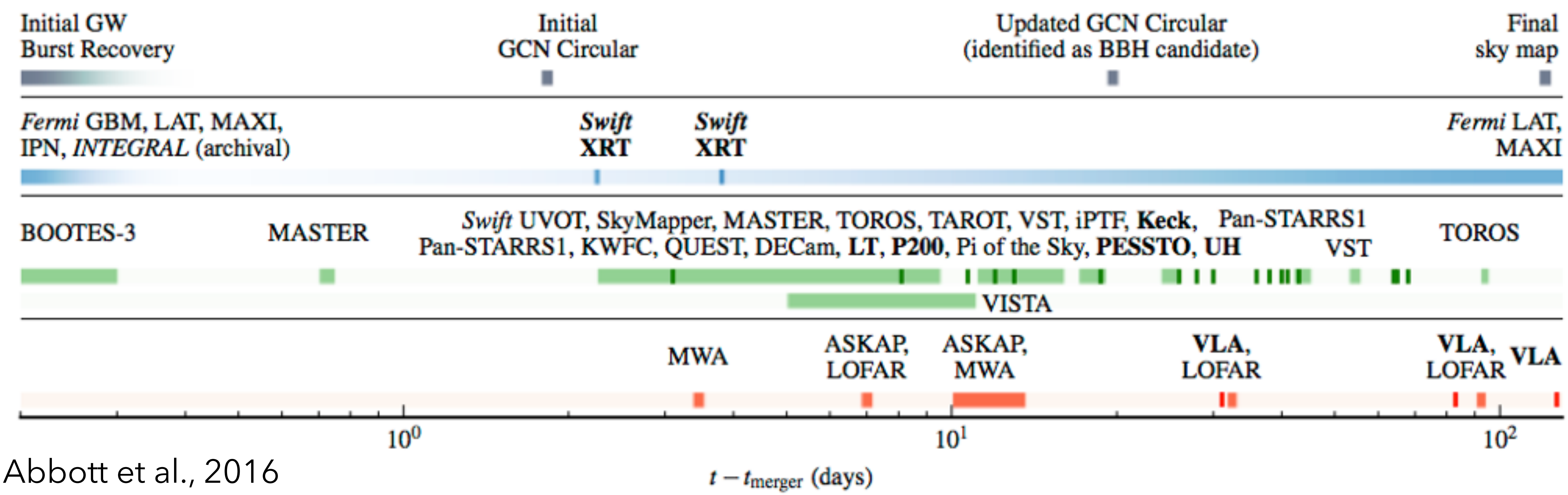
can significantly constrain the source localization (angular error < 1° on the sky)

Credit: M. Branchesi



GW150914 ➜ alert sent 2 days after the detection ➜ update 19 days after (BBH nature) ➜ 4 months later: final FAR + skymap

25 follow-up teams responded to the GW alert



Abbott et al., 2016

Credit: M. Branchesi

LVC+astronomers arXiv1602.08492
LVC+astronomers arXiv1604.07864
Connaughton et al. arXiv:1602.03920
Savchenko et al. 2016 ApJL 820, 36
Smartt et al. arXiv160204156S
Evans et al. MNRAS 460, L40
Annis et al. arXiv:1602.04199
Kasliwal et al. arXiv:1602.08764
Morokuma et al. arXiv:1605.03216
Fermi-LAT collaboration APJL, 823,2
Lipunov et al. arXiv:1605.01607
Soares-Santos et al. arXiv:1602.04198

Most complete coverage in the **gamma-ray** down to 10^{-7} erg cm^{-2} s^{-1}

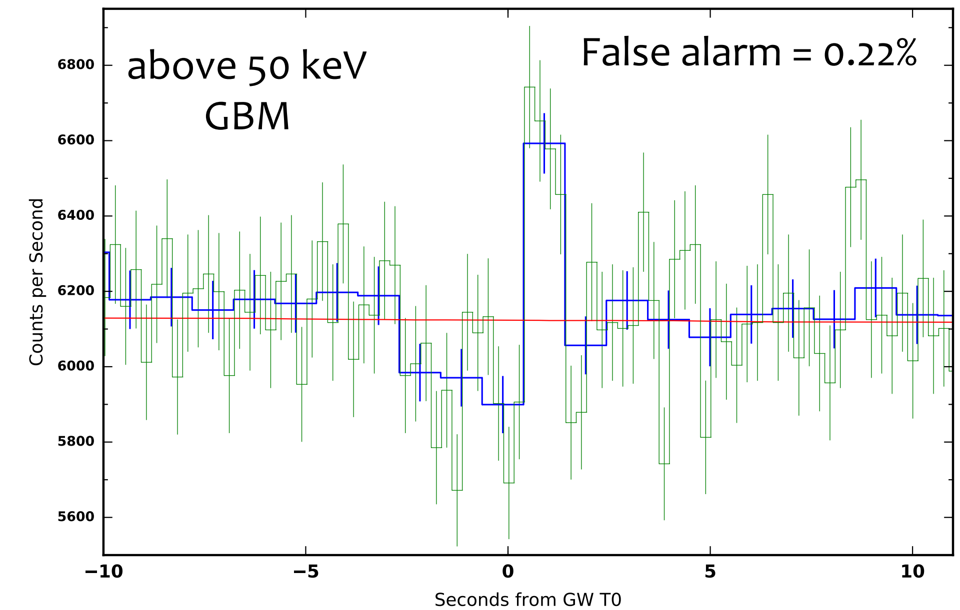
X-rays coverage complete down to 10^{-9} erg cm^{-2} s^{-1} (MAXI), relatively spare at fainter flux with the Swift XRT (< 10^{-11} erg cm^{-2} s^{-1}).

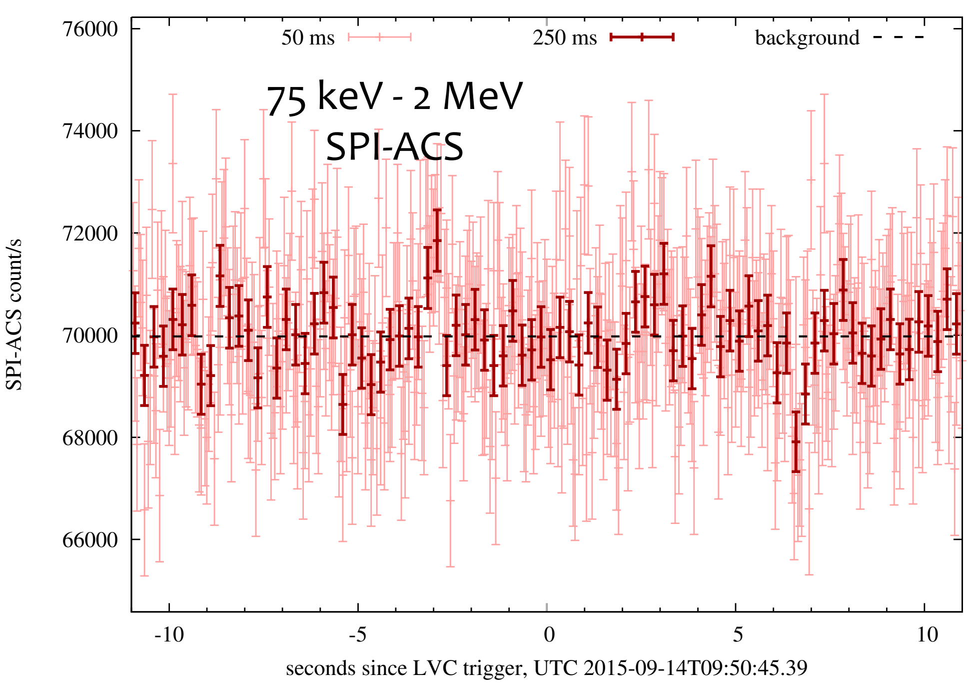
Potential gamma-ray counterpart ?

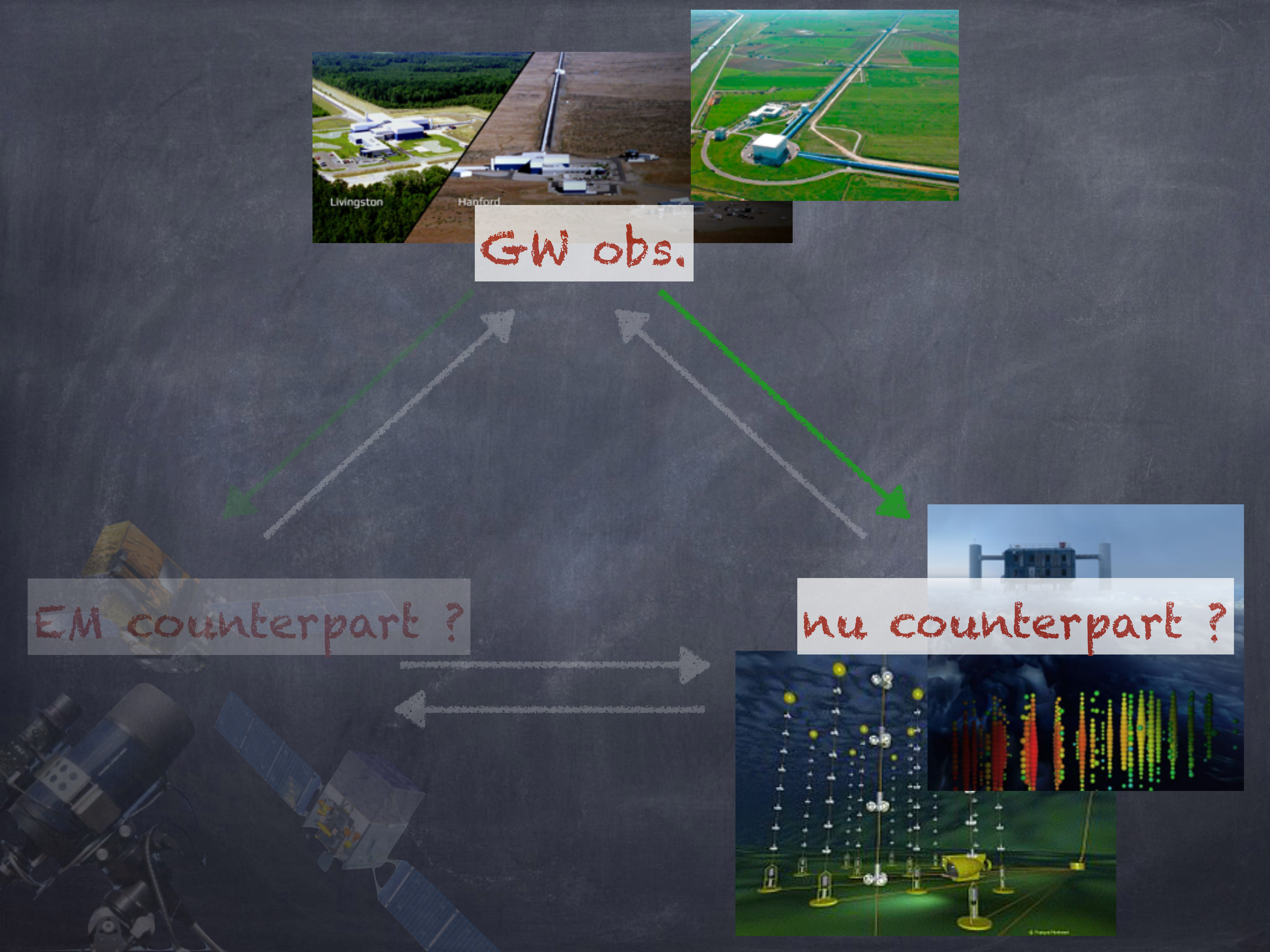
Fermi-GBM ➜ weak signal of 1 sec, 0.4 s after the alert. Fluence (1keV-10 MeV)=2.4 10^{-7} erg cm^{-2} (FAR=4.79 10^{-4} Hz) (Connaughton et al., arXiv:1602.03920)

INTEGRAL ➜ no signal but stringent upper limit (Savchenko et al., 2016 ApJL, 820).

MAXI & AGILE ➜ no signal detected.






Livingston
Hanford
GW obs.
EM counterpart ?
nu counterpart ?

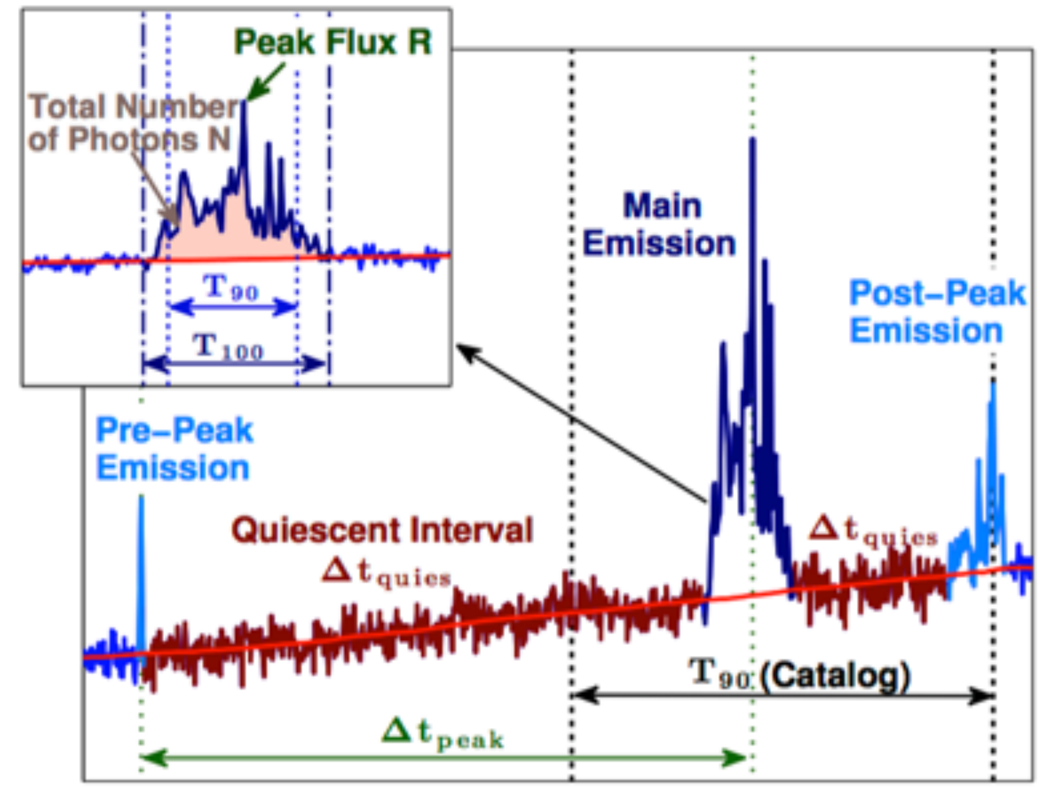
neutrino telescopes: large field of view

➜ can search for counterpart « offline »

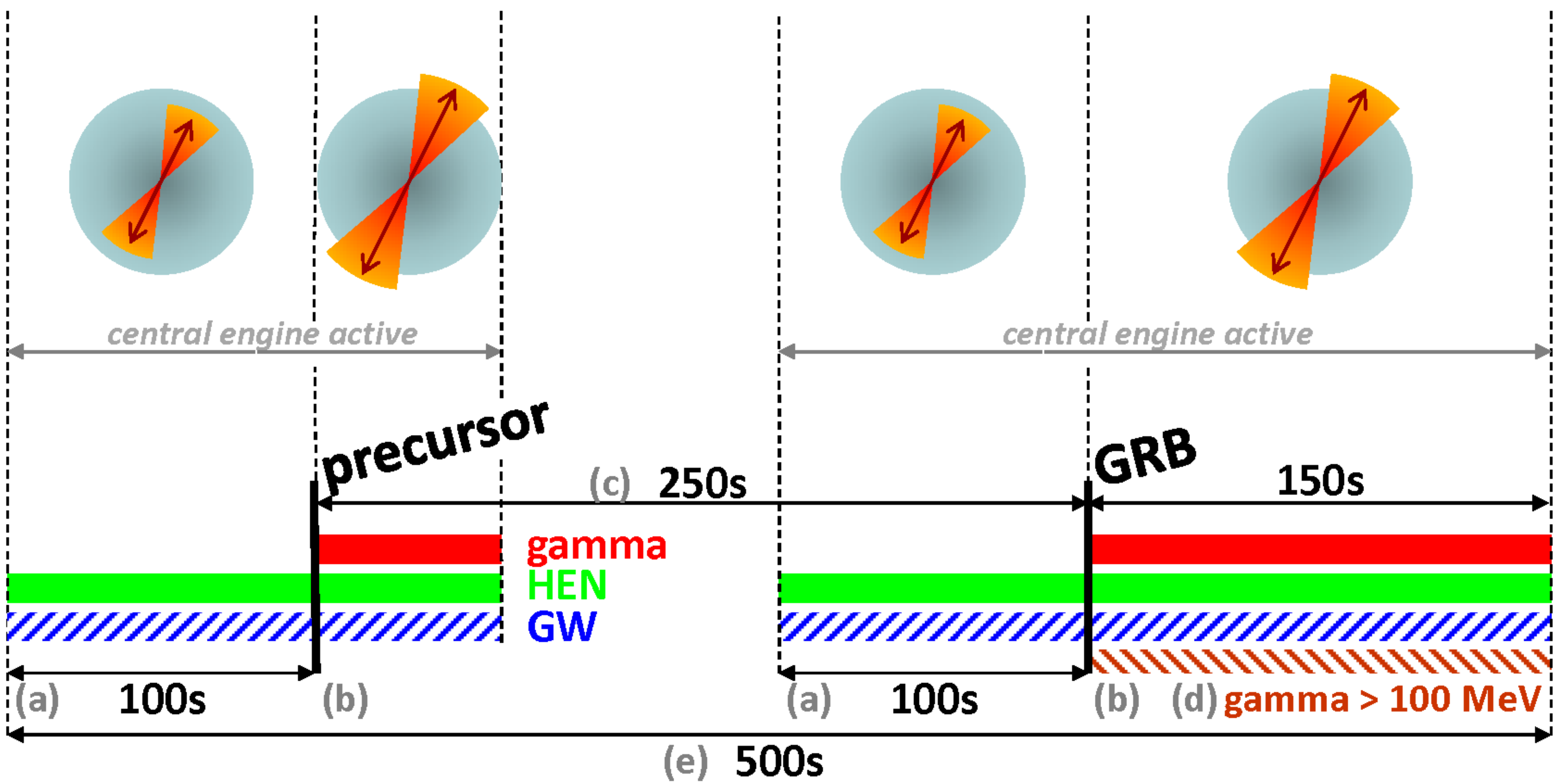
t_{HEN} - t_{GW} ∈[-500s; +500s]

(Baret et al., 2011)

if GW related to GRB event



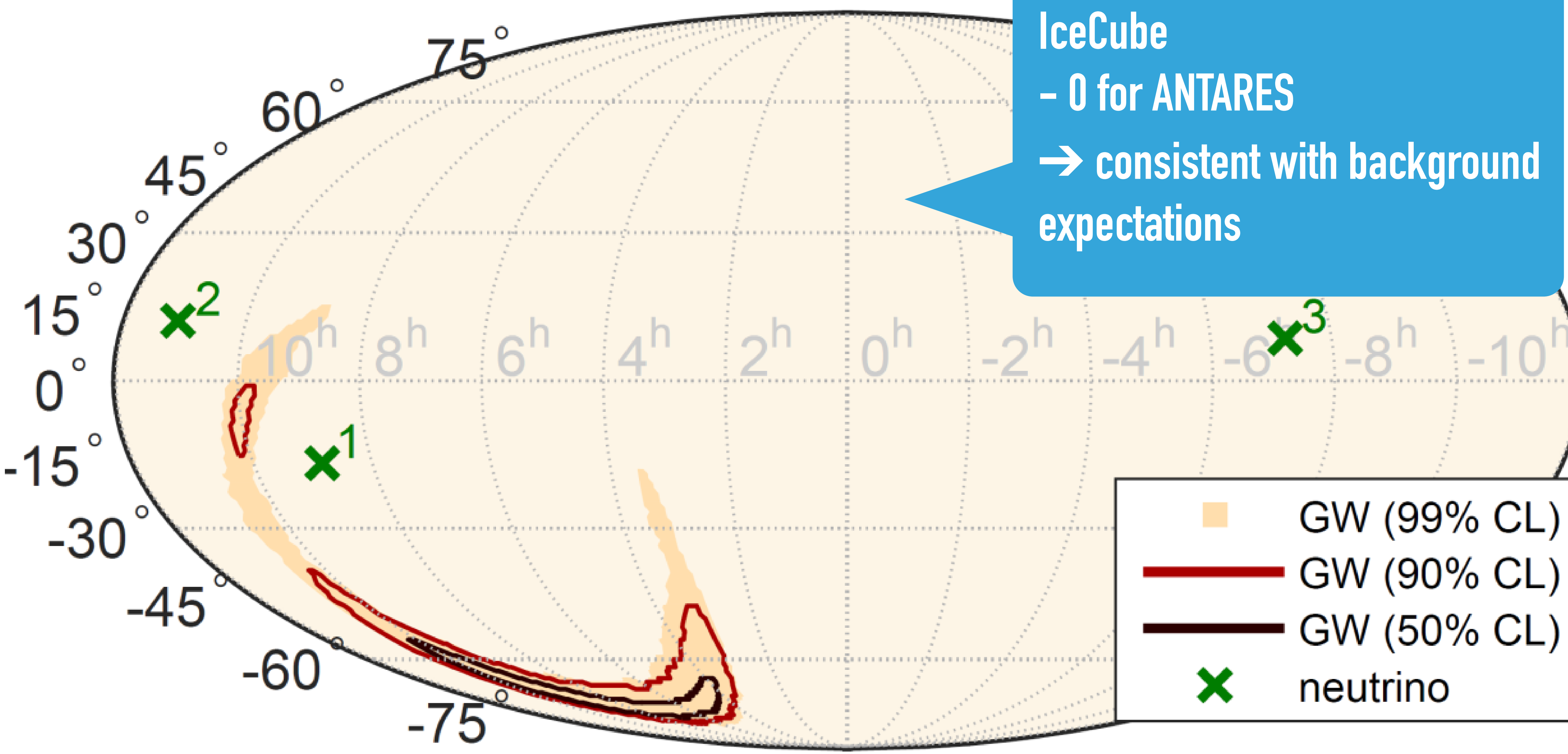
Charisi et al. 2014



GW150914 (search for potential neutrino counterpart within ±500 s)

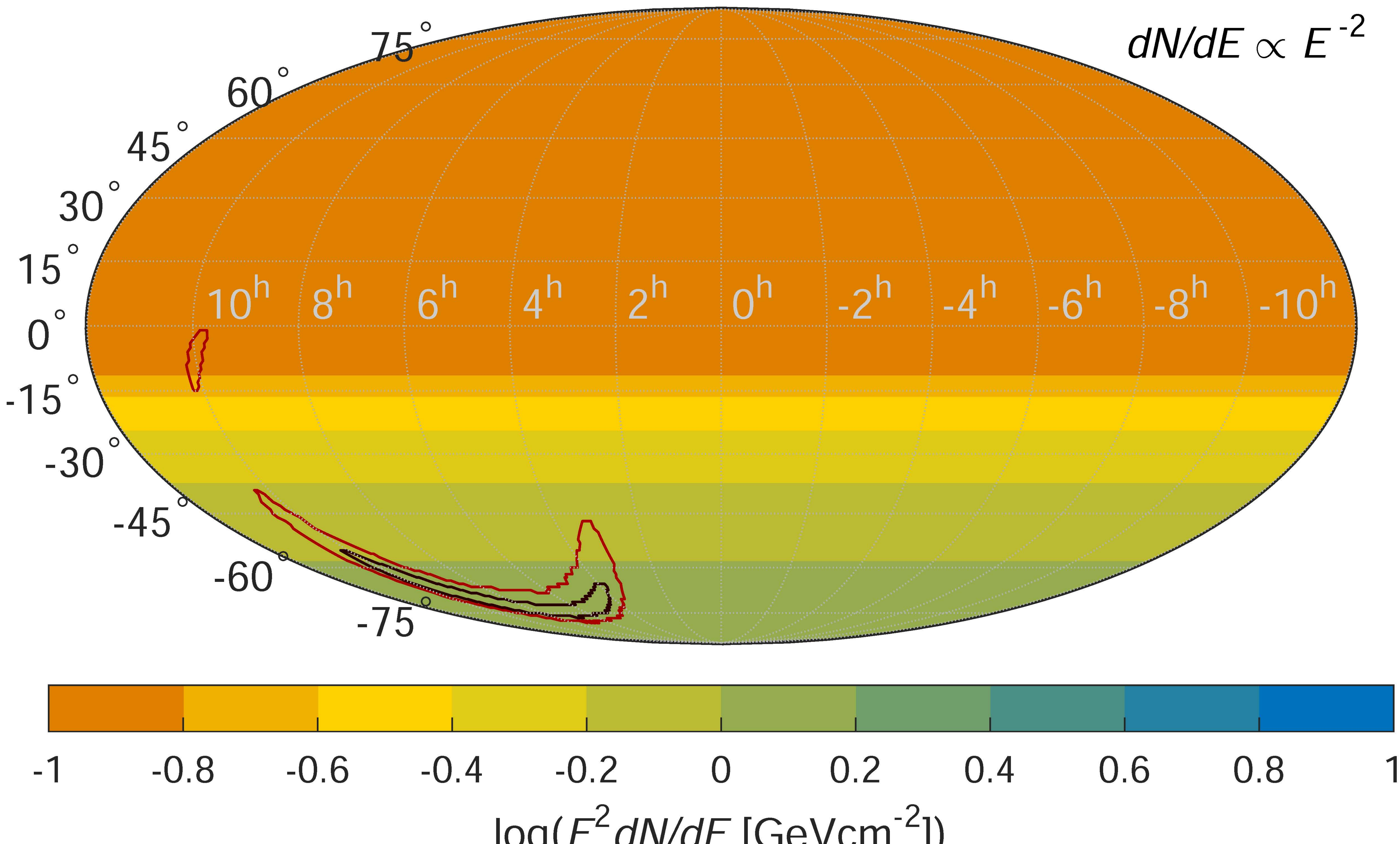
- 3 neutrino candidates for IceCube
- 0 for ANTARES

→ consistent with background expectations



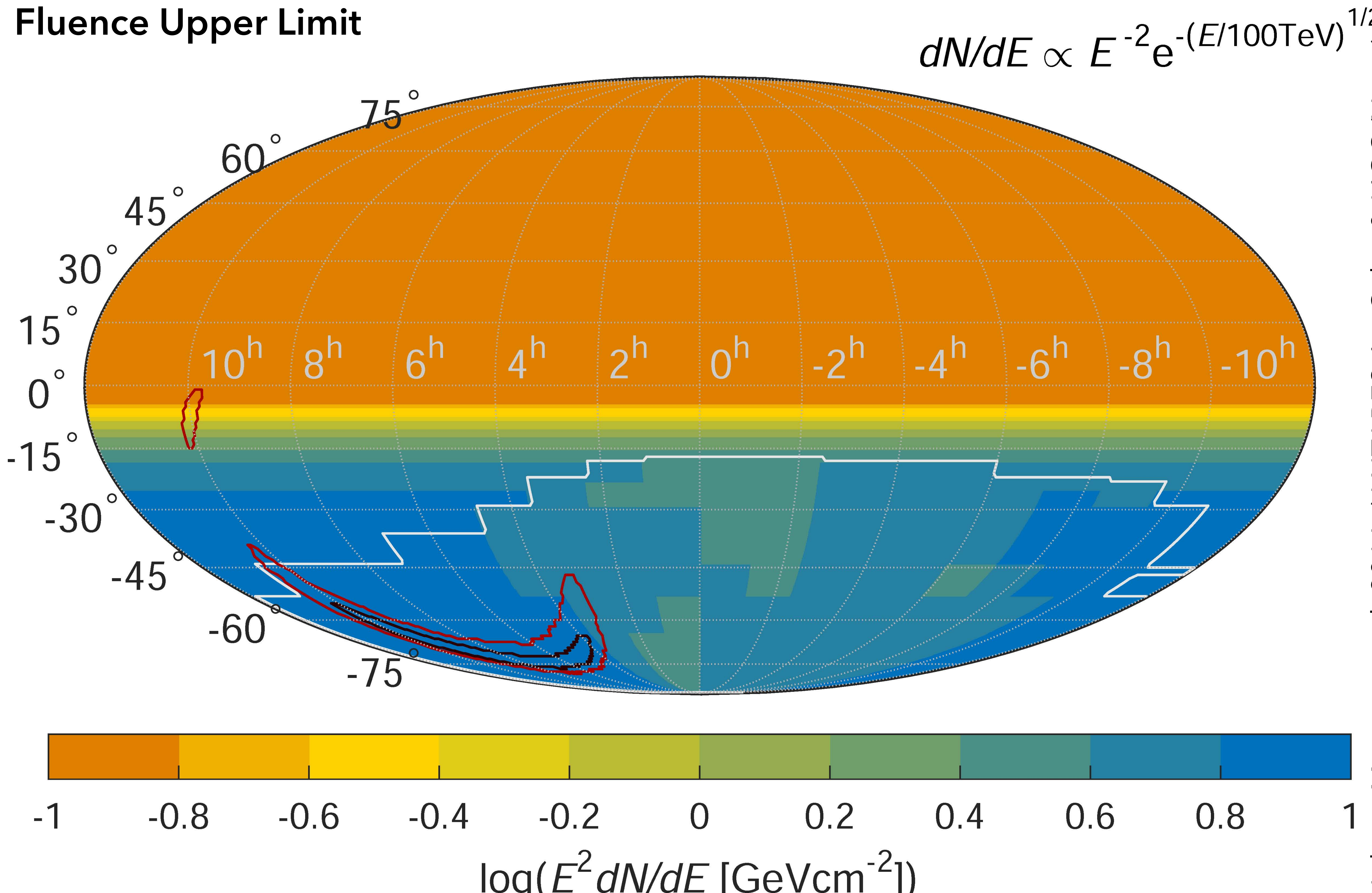
Adrian-Martinez et al. 2016, (ANTARES, IceCube & LIGO/Virgo)

Fluence Upper Limit



Adrian-Martinez et al. 2016, (ANTARES, IceCube & LIGO/Virgo)

Fluence Upper Limit



Adrian-Martinez et al. 2016, (ANTARES, IceCube & LIGO/Virgo)

Constraints on the total energy radiated in neutrinos

$$\mathrm{E}^{\mathrm{ul}}_{\nu,\mathrm{tot}} \sim 10^{52}\text{–}10^{54} \left(\frac{D_{\mathrm{gw}}}{410\,\mathrm{Mpc}} \right)^2 \ \mathrm{erg}$$

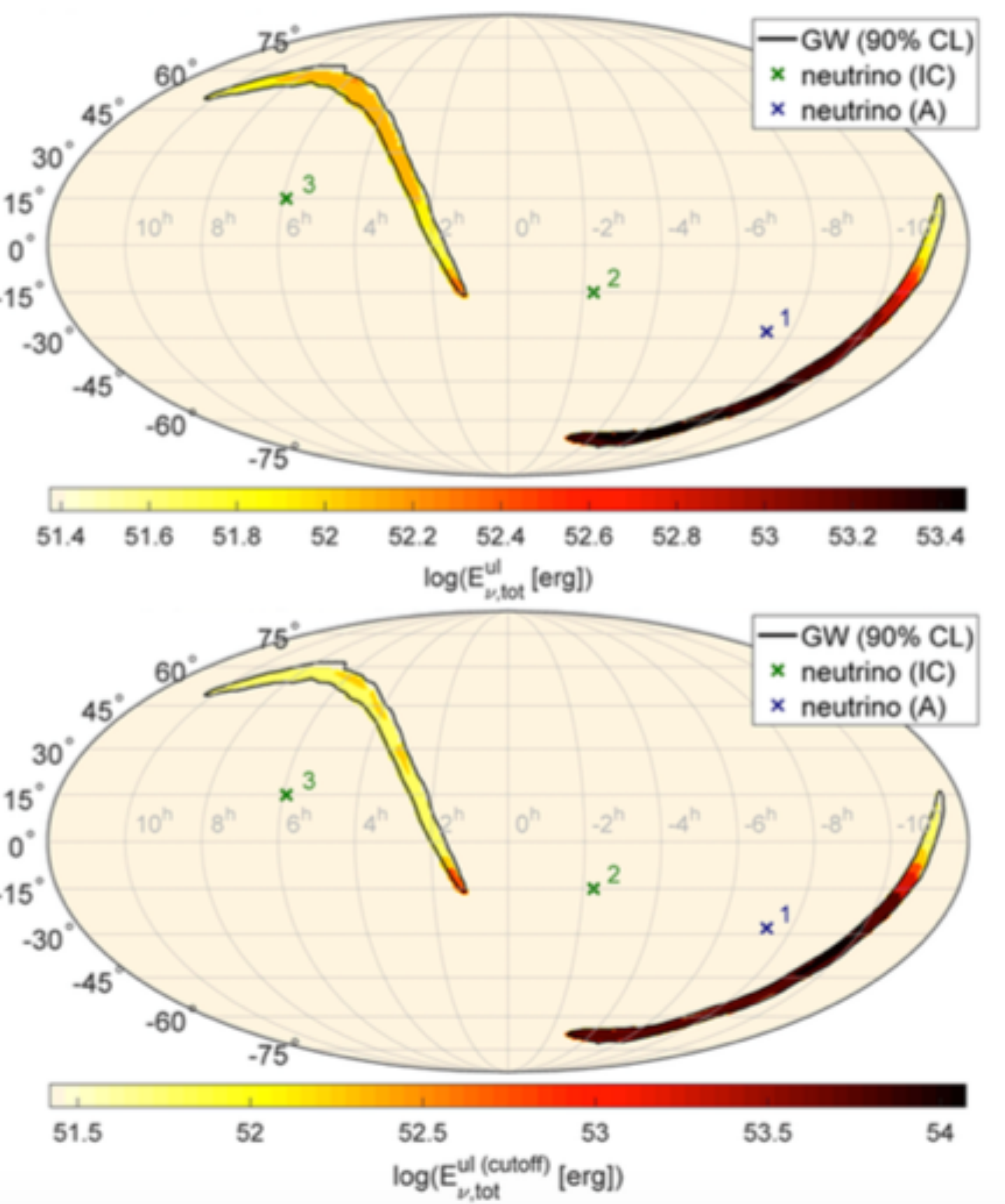
Energy radiated in GW: ~5 x 10^{54} erg

Typical GRB isotropic-equivalent energies are ~10^{51} erg (long GRB) and ~10^{49} erg (short GRB)

May be similar to total energy radiated in neutrinos in GRBs *(Mészaros 2015; Bartos et al., 2013)*

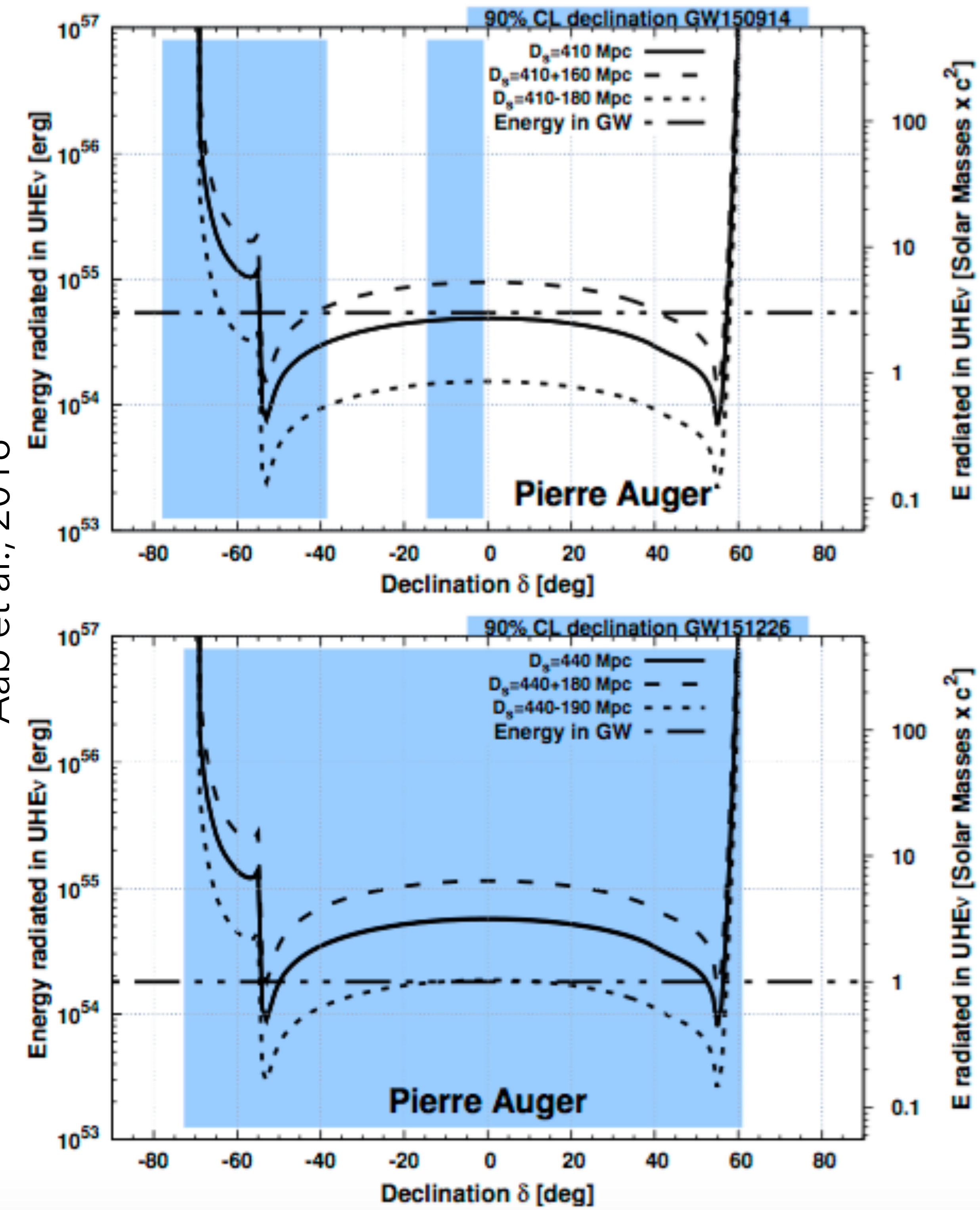
ANTARES & IceCube (TeV-PeV neutrinos)

Adrian-Martinez et al. 2017, (ANTARES, IceCube & LIGO/Virgo)



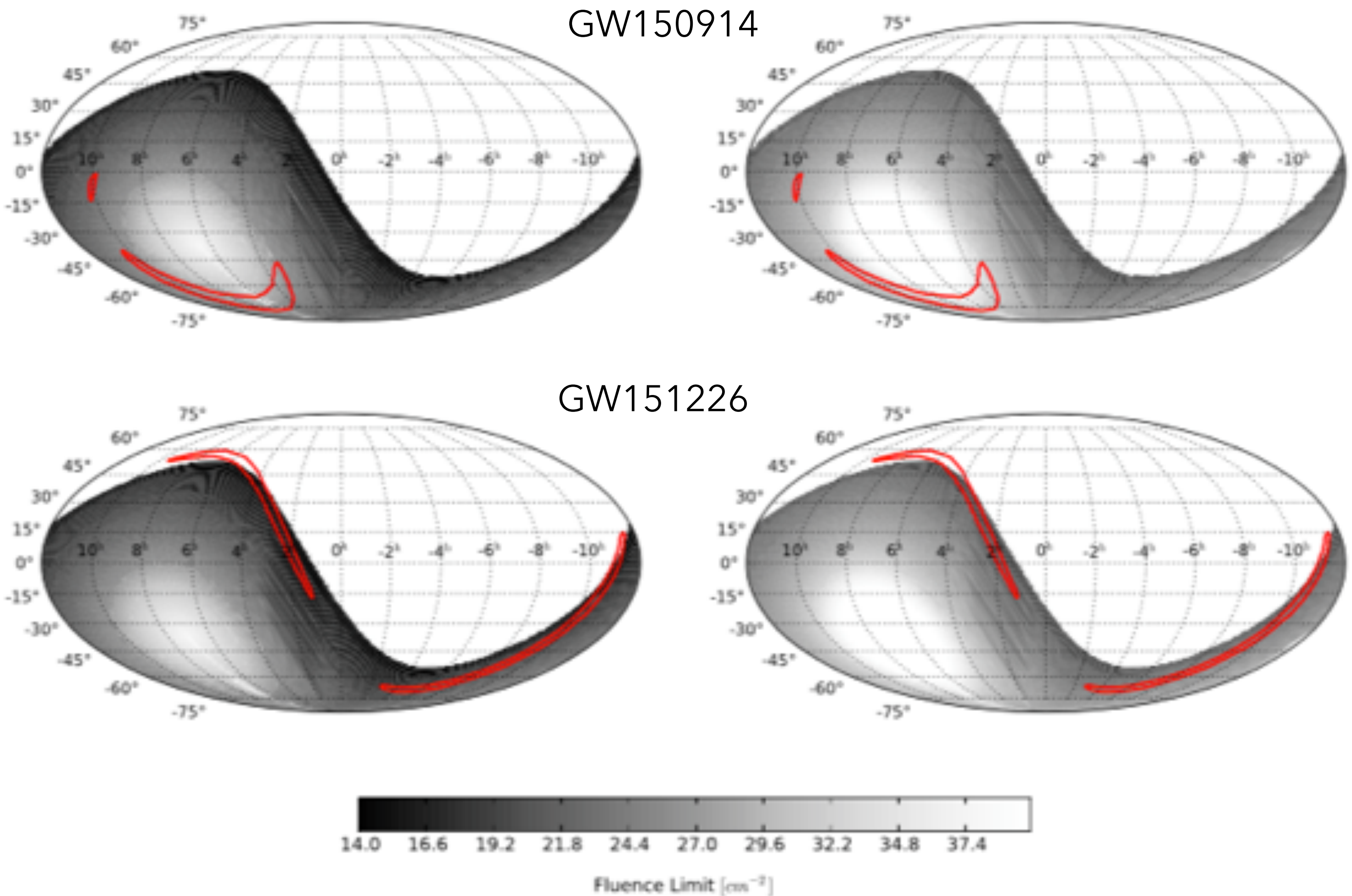
Pierre Auger Observatory (100 PeV; 25 EeV neutrinos)

Aab et al., 2016



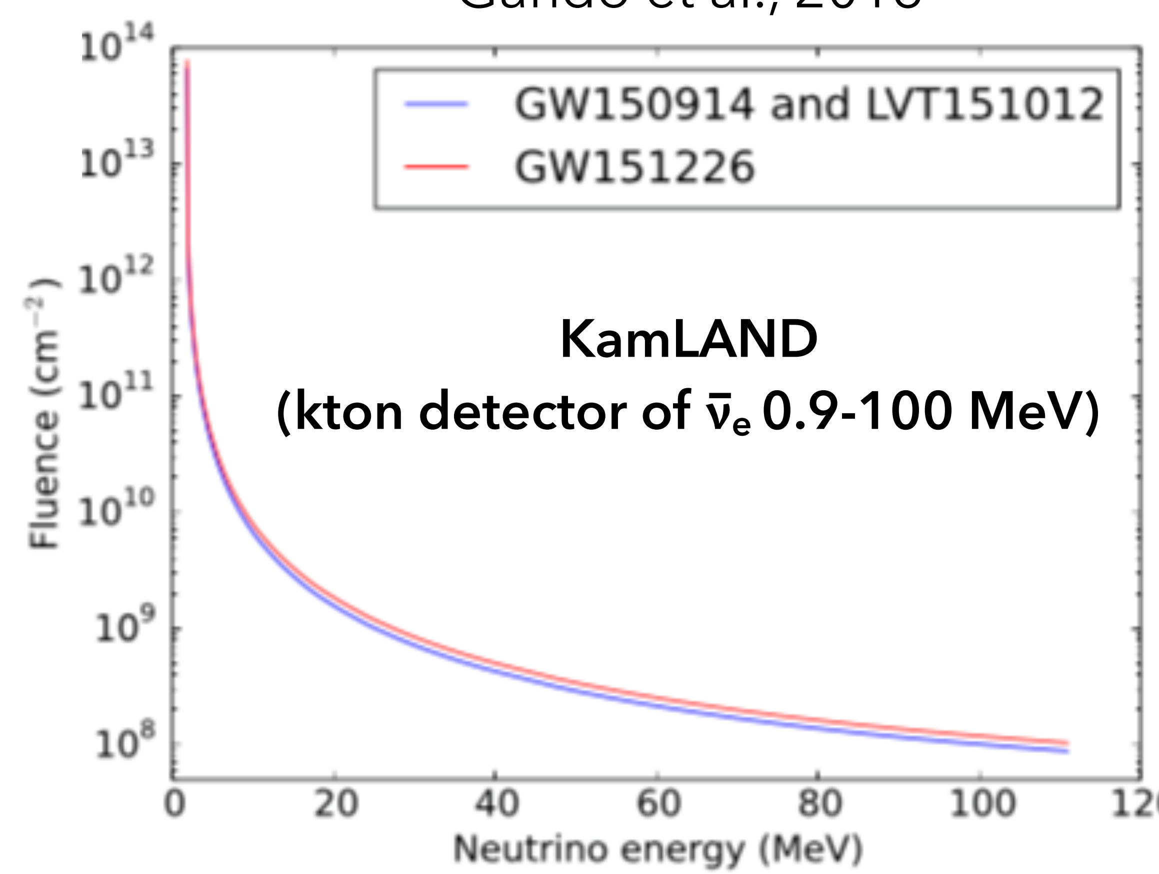
SuperKamiokande (1.6 GeV - 100 PeV)

neutrinos **antineutrinos**



Abe et al., 2016

Gando et al., 2016

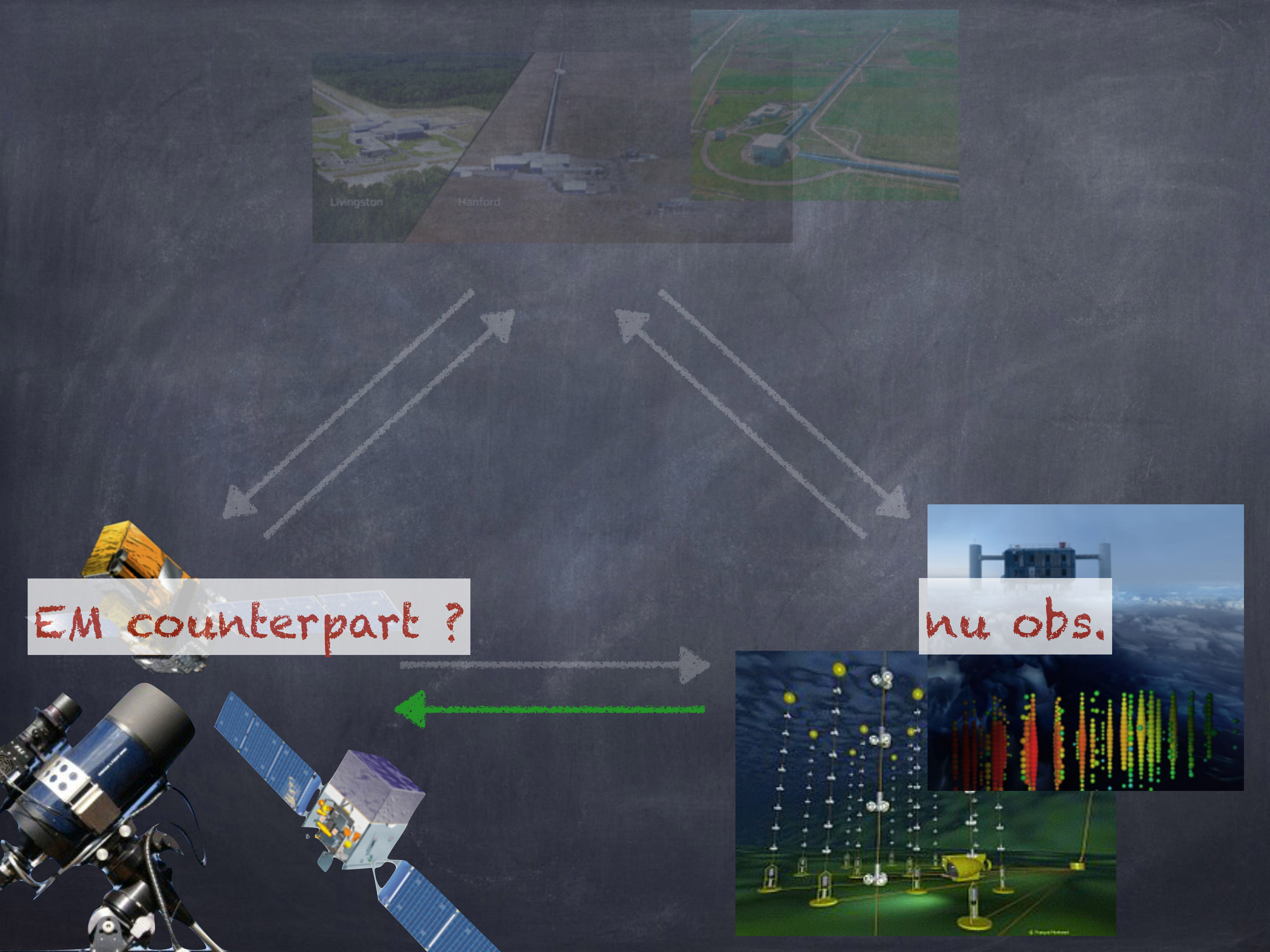


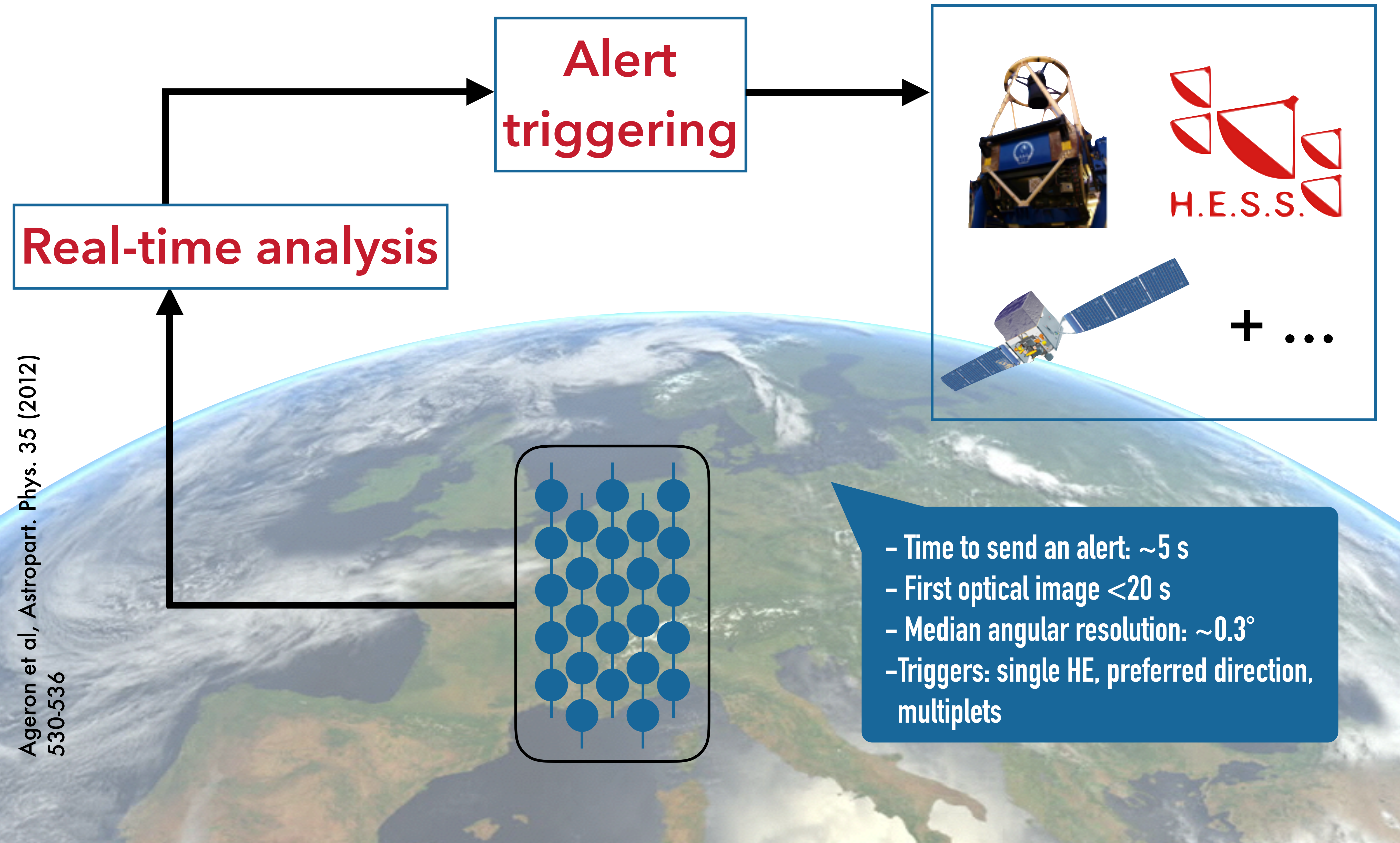
➜ « The absence of MeV neutrino emission is inconsistent with the source of the gravitational wave signals being a near-by core-collapsed astronomical object »

1) Search for GRB neutrino counterparts

2) EM and neutrino follow-up of GW events

3) EM follow-up of neutrino events


Livingston
Hanford
EM counterpart ?
nu obs.

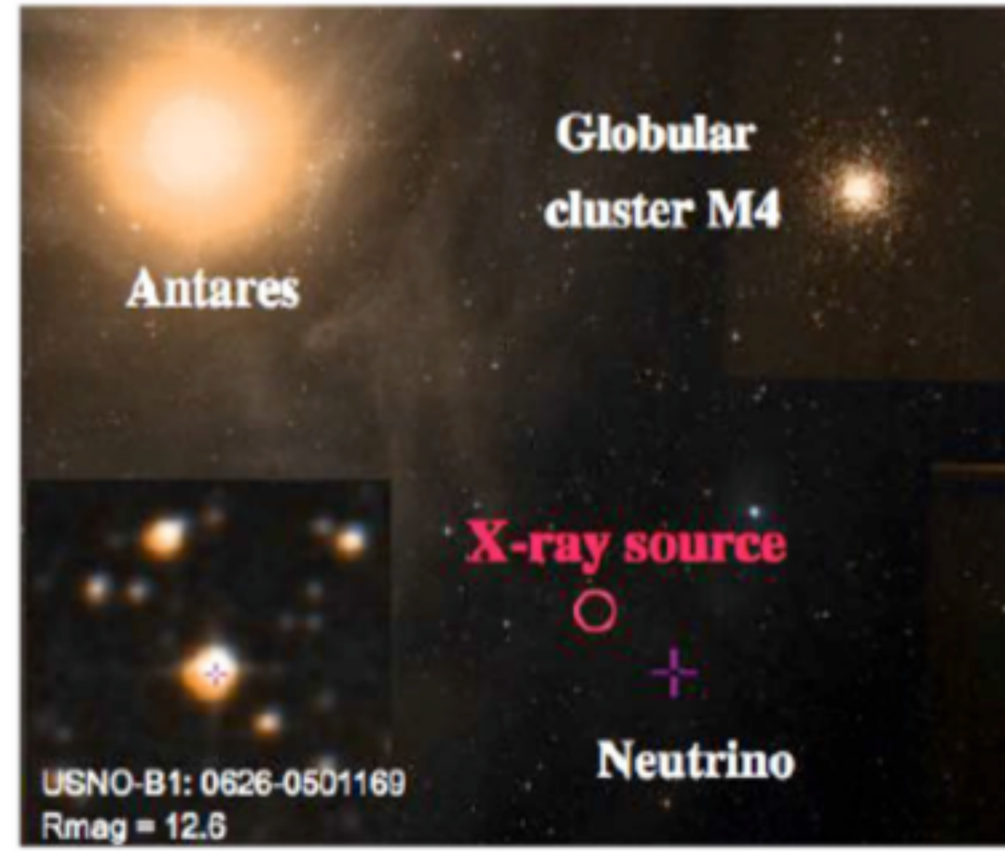

Alert triggering
Real-time analysis
H.E.S.S.
+ ...
- Time to send an alert: ~5 s
- First optical image <20 s
- Median angular resolution: ~0.3°
-Triggers: single HE, preferred direction, multiplets
Ageron et al, Astropart. Phys. 35 (2012) 530-536

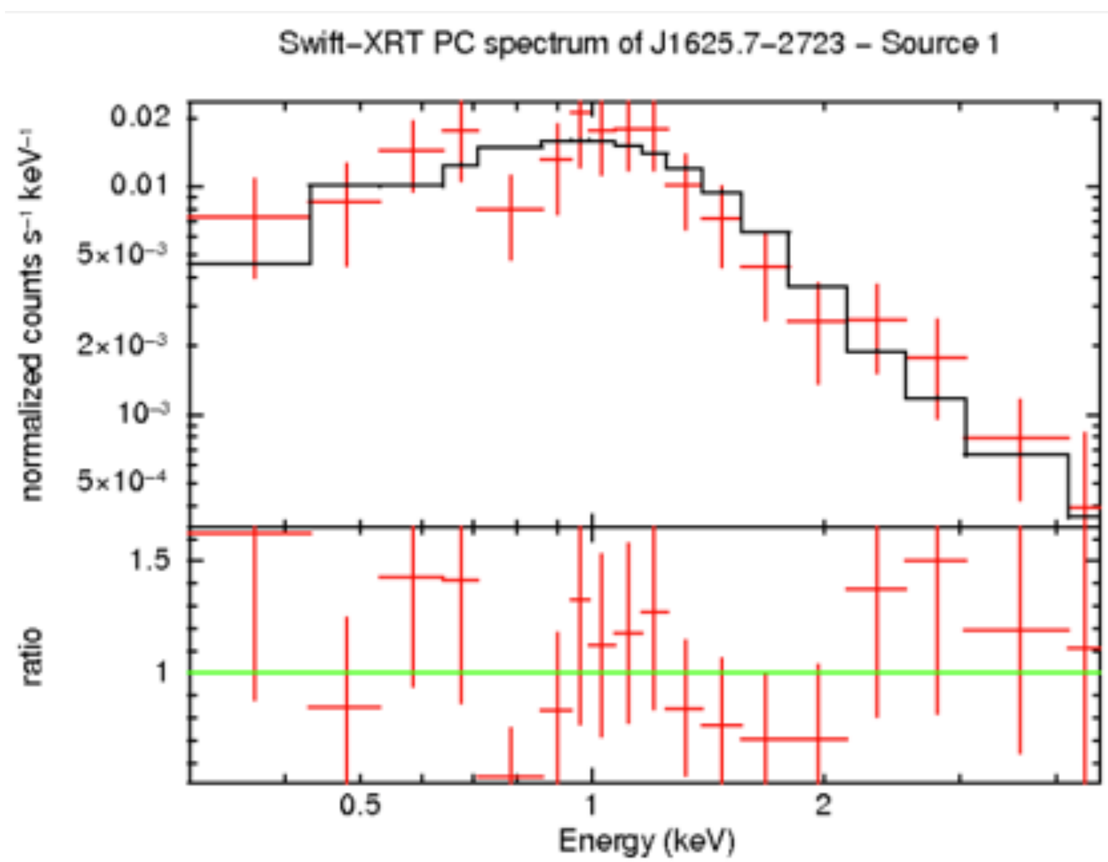
Radio	Optical	X-ray	GeV ɣ-rays	TeV ɣ-rays
MWA (12/yr)	TAROT ZADKO MASTER (GWAC) (30/yr)	Swift (6/yr)	Fermi (offline)	HESS (2/yr) HAWC (offline)

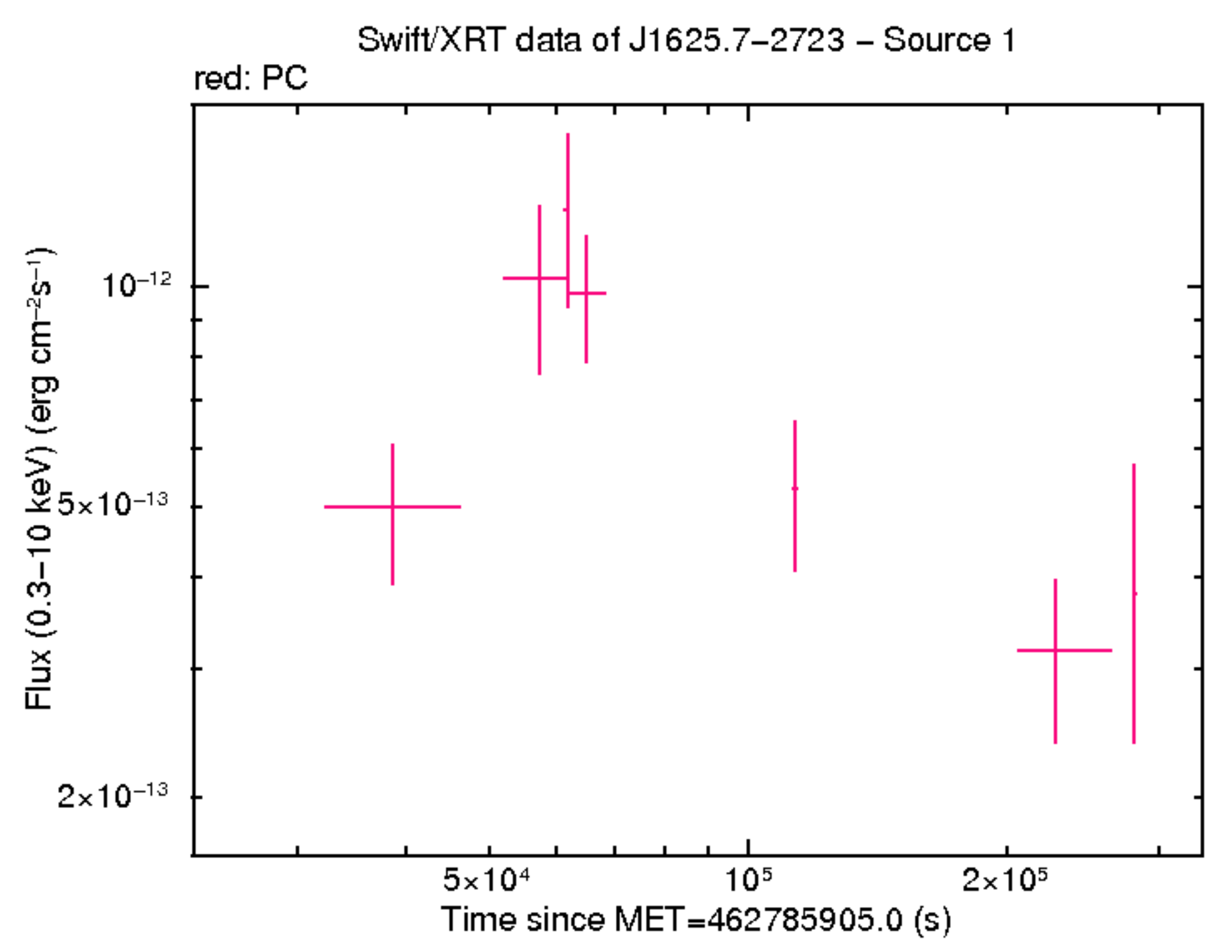
- Private MoU with all the observatories

237 alerts sent to optical telescopes since mid 2009
+13 to Swift since mid 2013

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



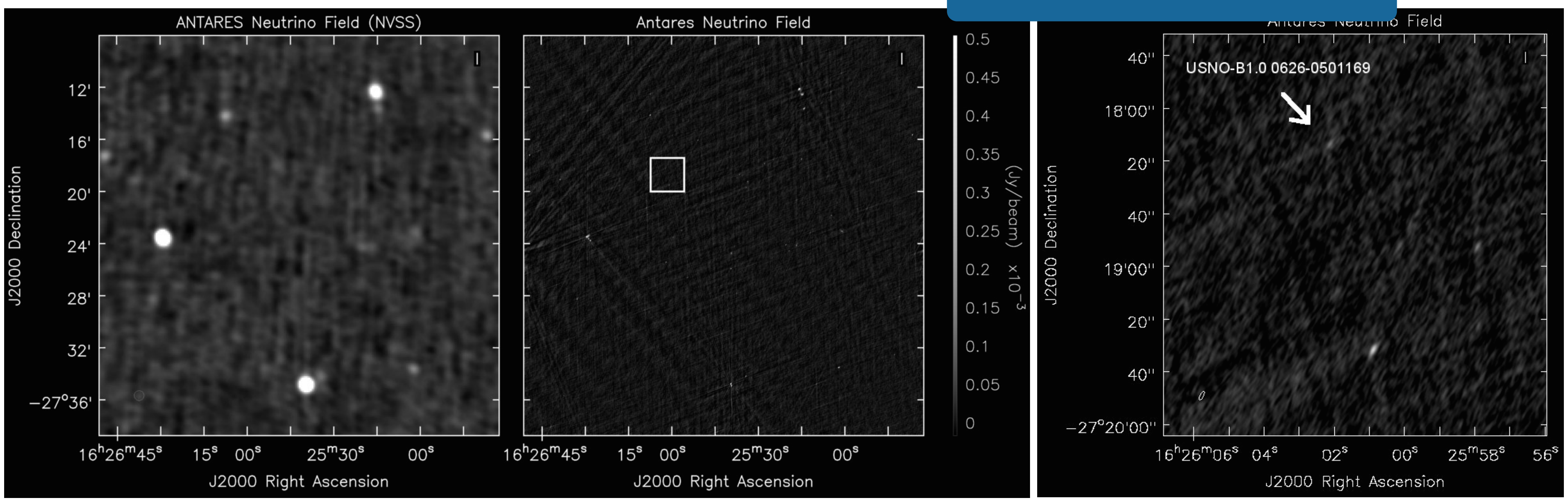


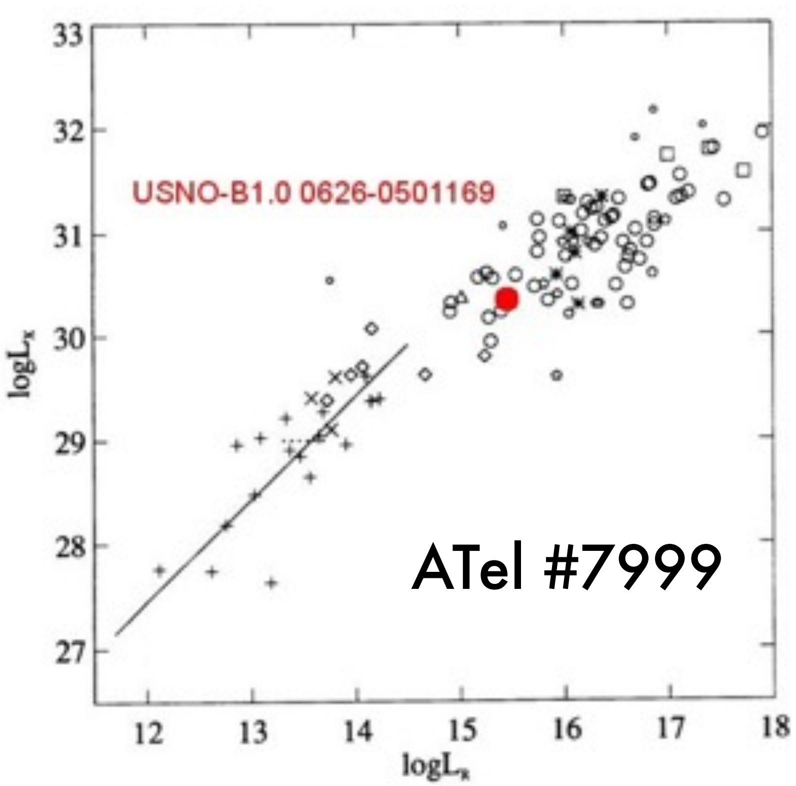


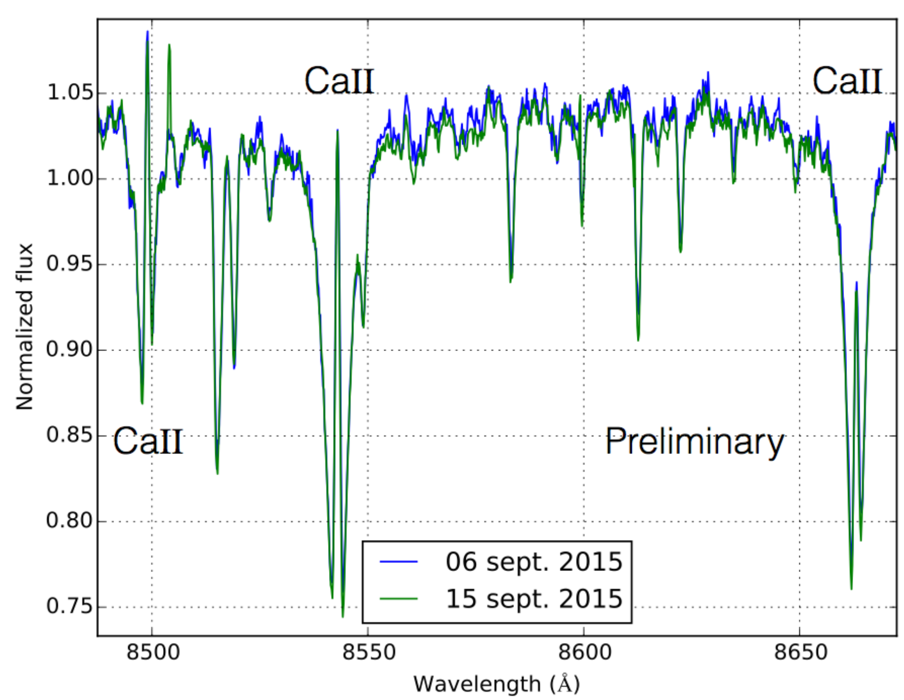
- Neutrinos
  - IceCube: ATel 8097
- Optical
  - Pan-STARRS: ATel 7992, 8027
  - SALT: ATel 7993
  - NOT: ATel 7994 GCN18236
  - WiFeS: ATel 7996
  - CAHA: ATel 7998, GCN18241
  - MASTER: ATel 8000 GCN18240
  - LSGT: ATel 8002
  - NIC: ATel 8006
  - ANU: GCN18242
  - GCM: GCN18239
  - VLT/X-shooter
- 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

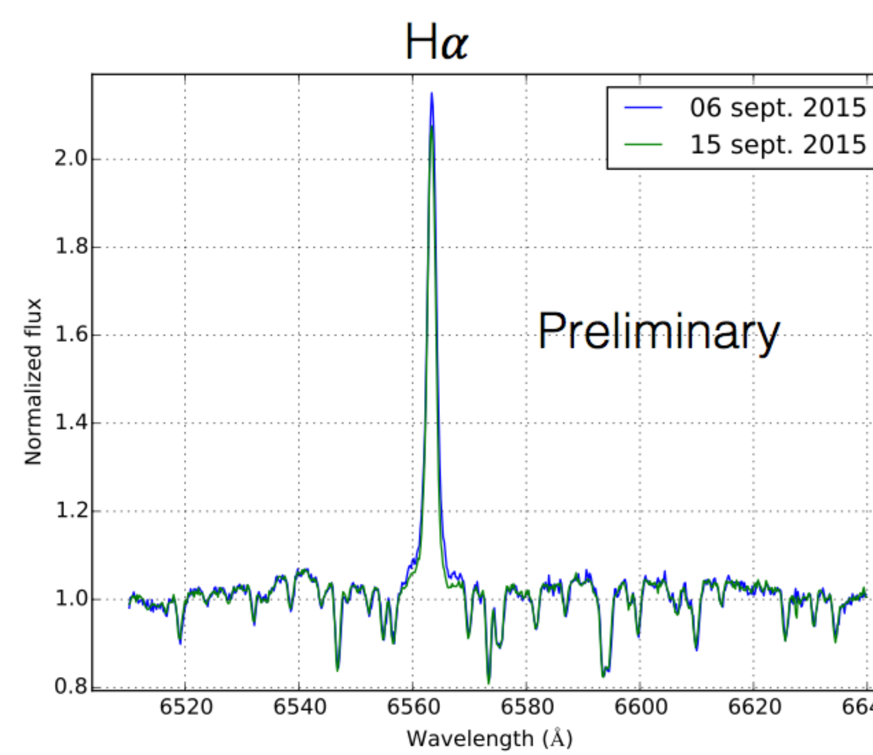
Great interest by astro-community

Active X-ray star



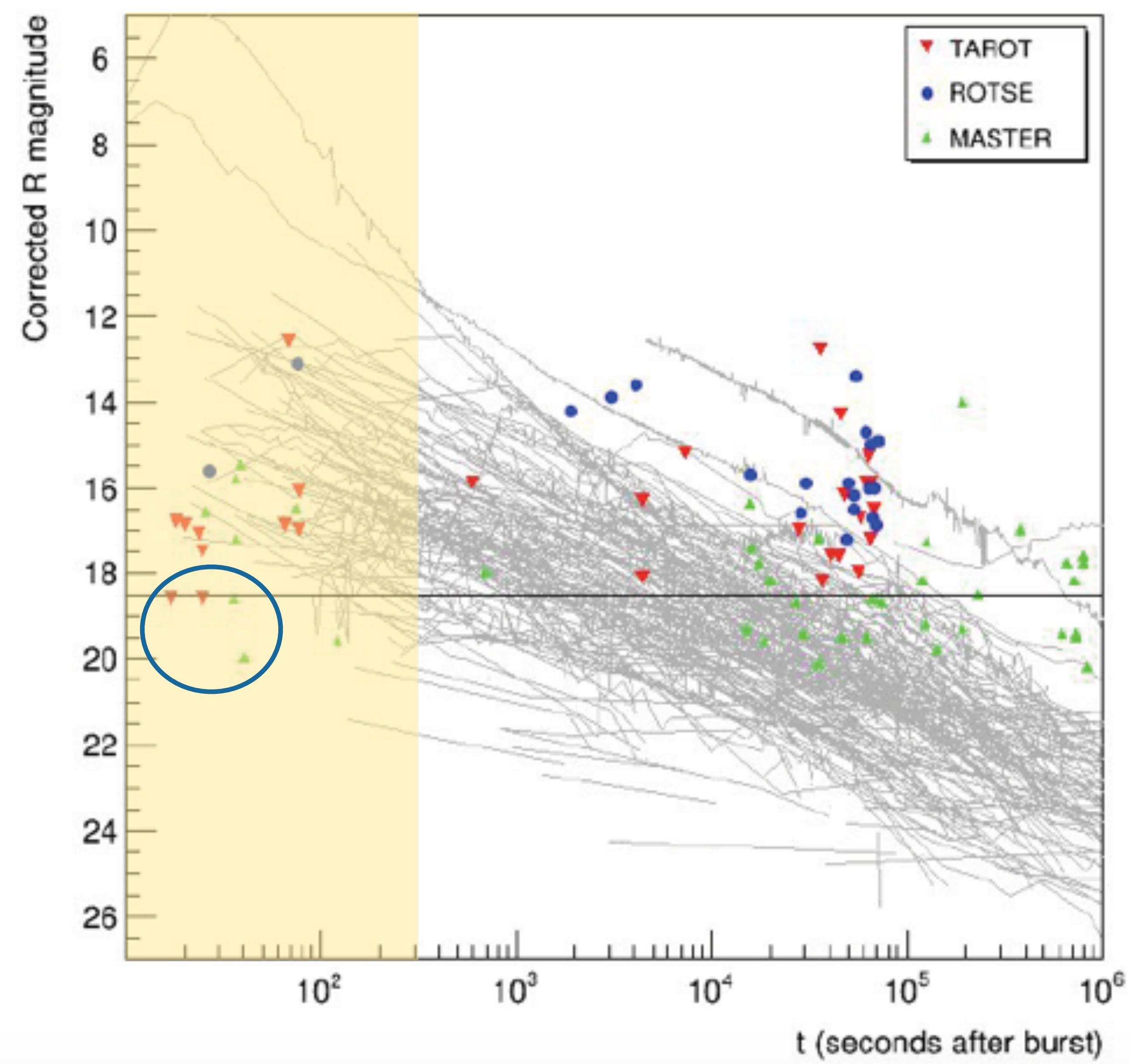






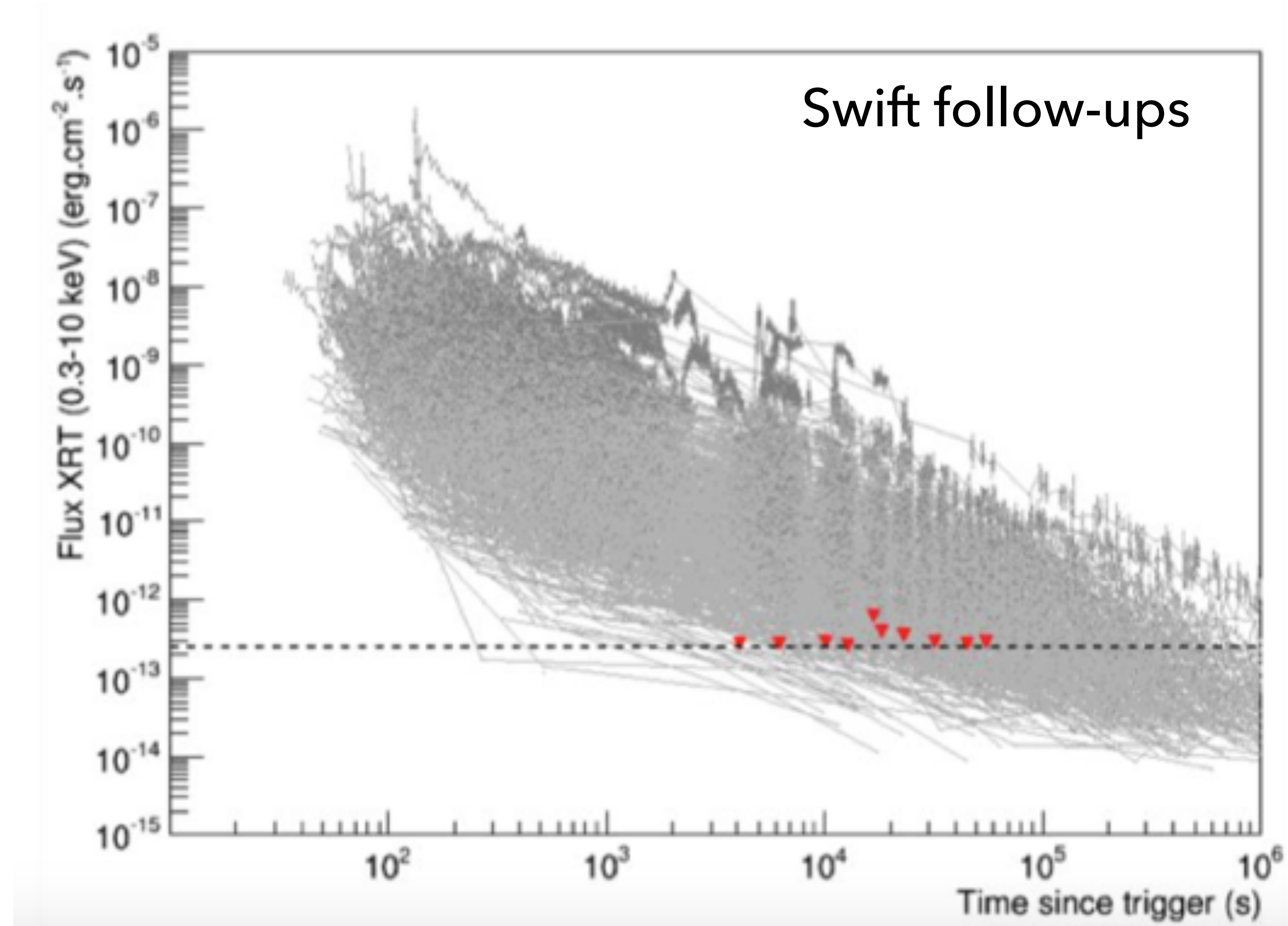
ANTARES COLLABORATION JCAP 02:062, 2016

- 93 alerts with early (<24h) optical follow-up analyzed (01/2010 - 01/2016)
- 13 follow-ups with delay <1min (best: 17s)
- no transient candidate associated to neutrinos
- Constraints on origin of individual neutrinos
- GRB origin unlikely



ANTARES COLLABORATION JCAP 02:062, 2016

- 13 X-ray follow-ups
- delay of 5-6 h on average
- no transient candidate associated to neutrinos
- Constraints on origin of individual neutrinos
- GRB origin unlikely

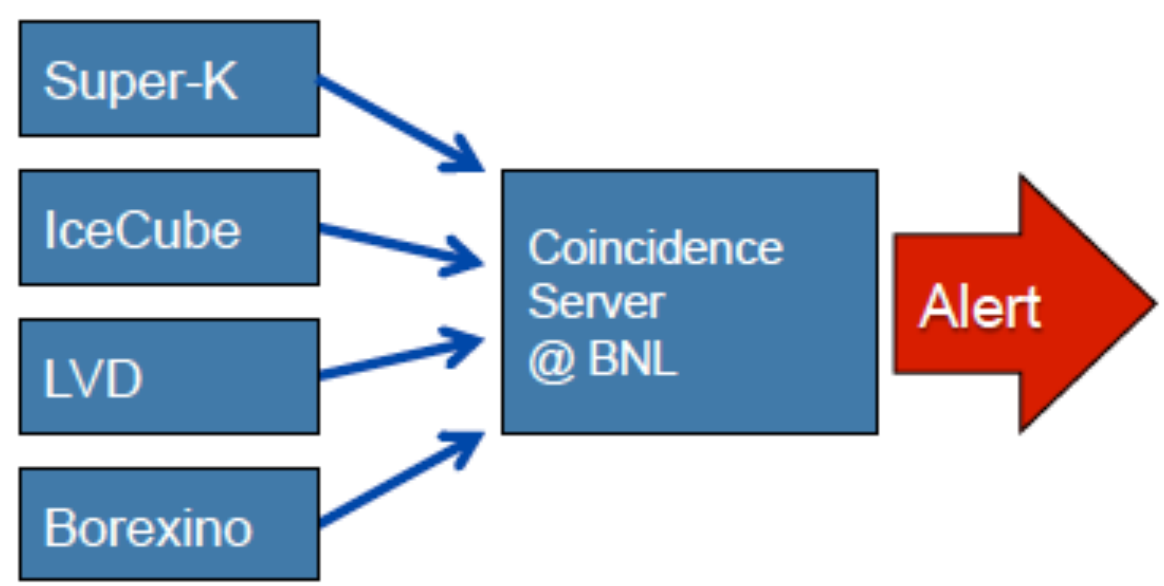


The detection of even a single neutrino in association with a nearby supernova would reduce the uncertainty on the start time from ~ 1 day to ~ 10 seconds, which would help for GW searches for instance.

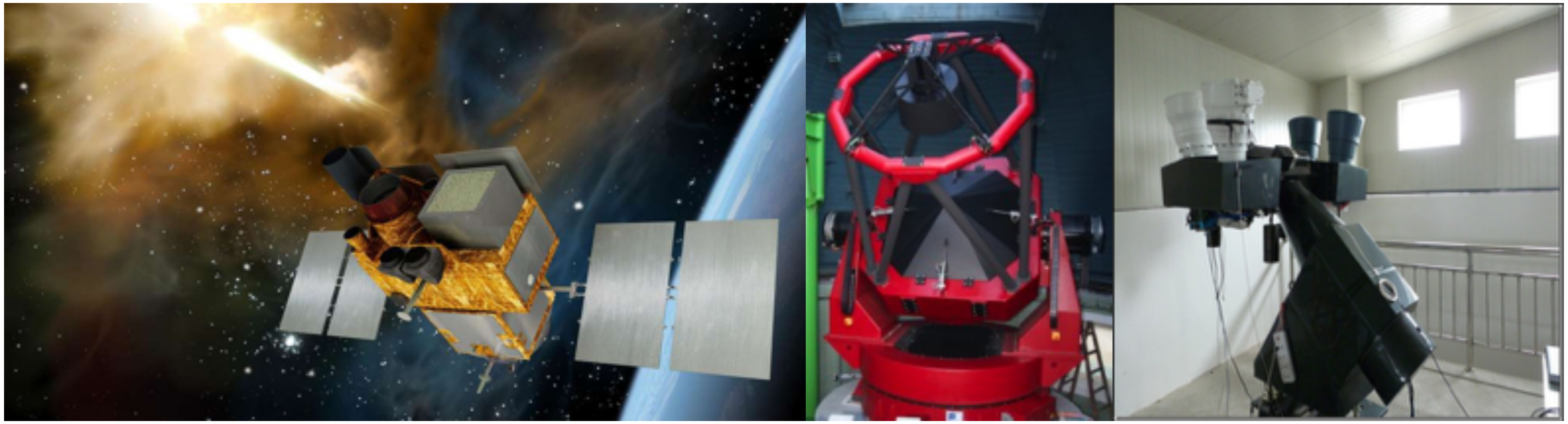
+ trigger of EM observations

http://snews.bnl.gov

- Neutrinos arrive several hours before photons
- Can alert astronomers several hours in advance

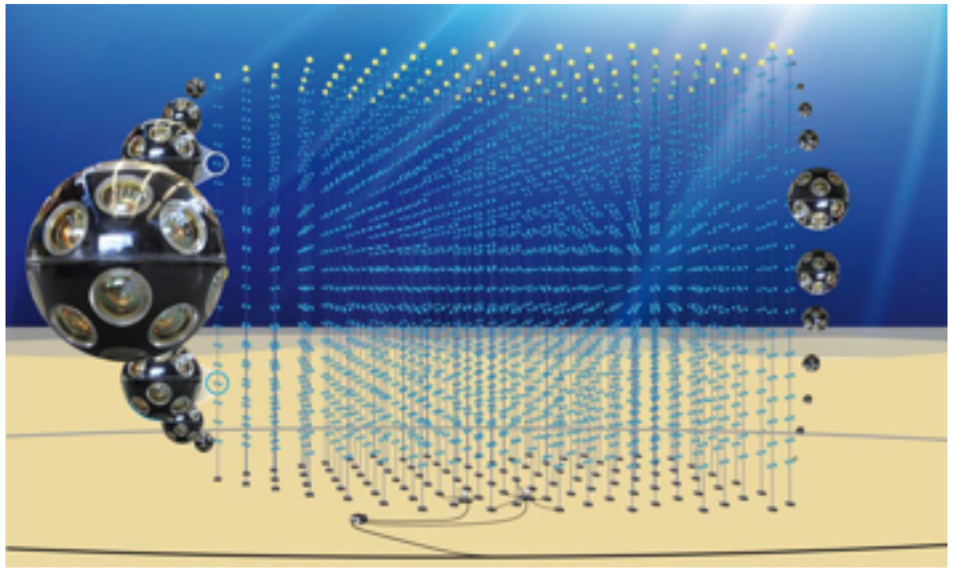


SVOM (multi-wavelength capabilities)



LSST

KM3NeT



SKA