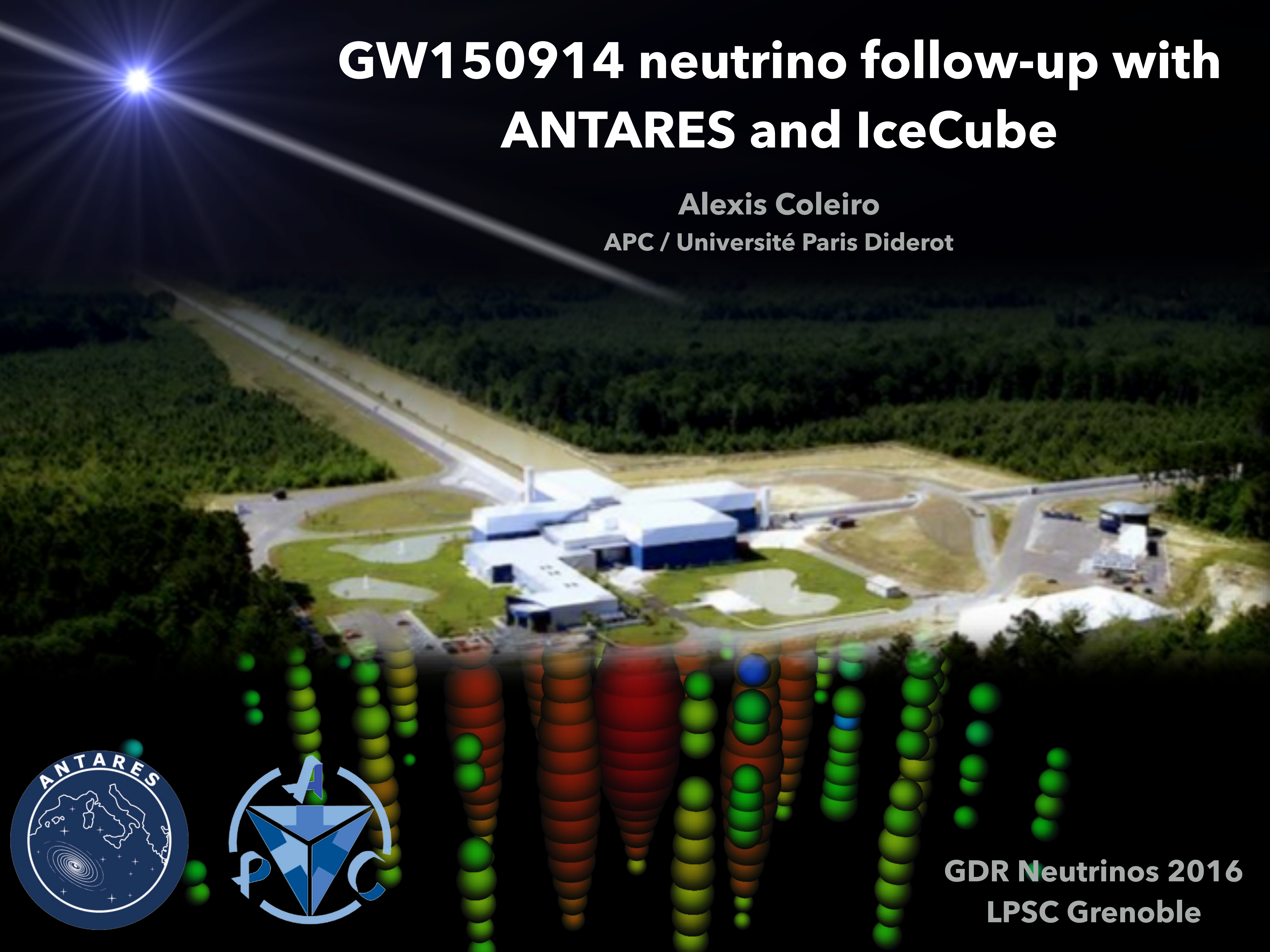
# GW150914 neutrino follow-up with ANTARES and IceCube

**Alexis Coleiro**
APC / Université Paris Diderot



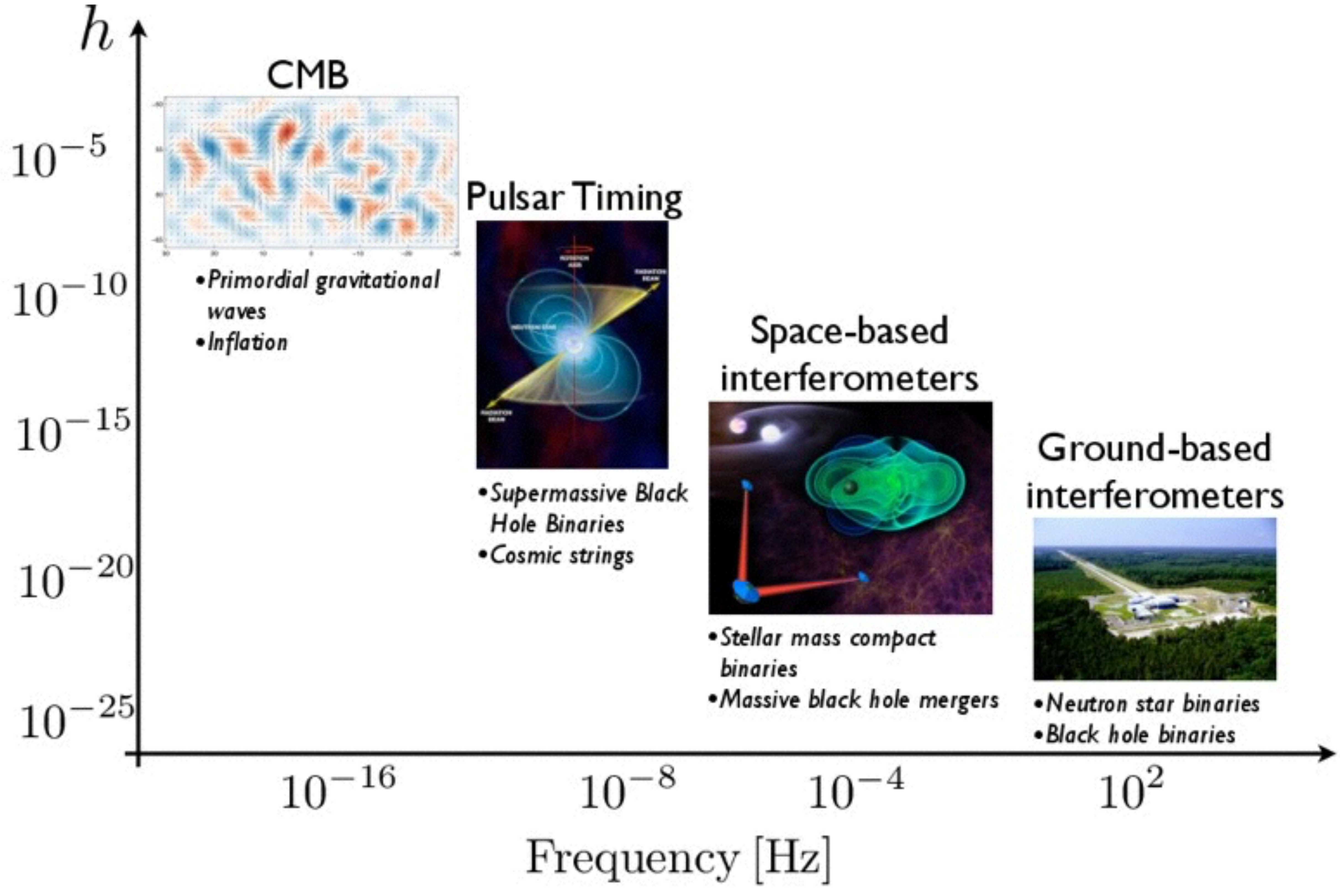
GDR Neutrinos 2016
LPSC Grenoble

# Outline

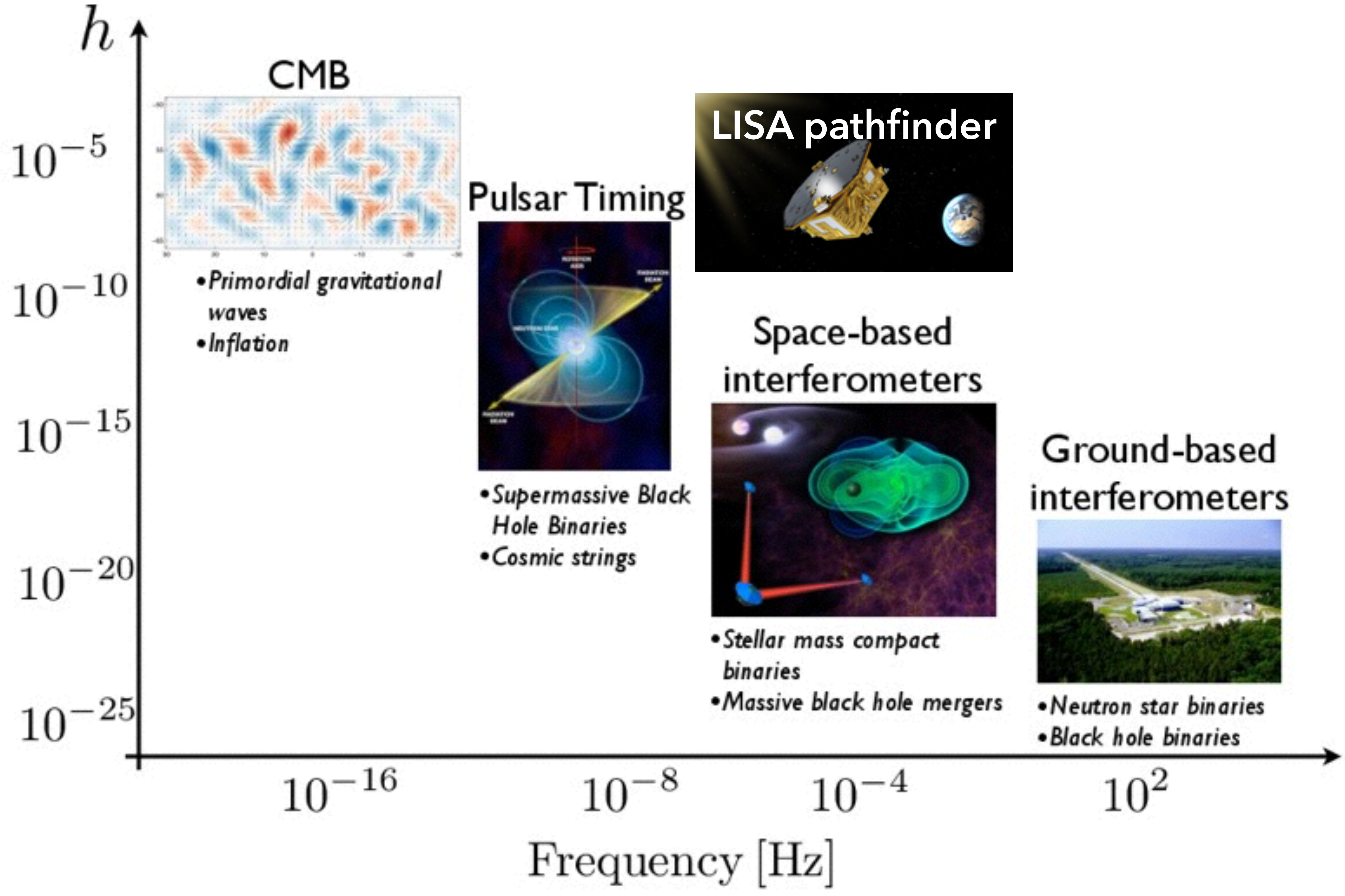
1) Astrophysical context
2) Neutrino follow-up of GW1501914

# Astrophysical context and sources of interest

# The big picture of gravitational wave astronomy



# The big picture of gravitational wave astronomy



**CMB**

- *Primordial gravitational waves*
- *Inflation*

**Pulsar Timing**

- *Supermassive Black Hole Binaries*
- *Cosmic strings*

**LISA pathfinder**

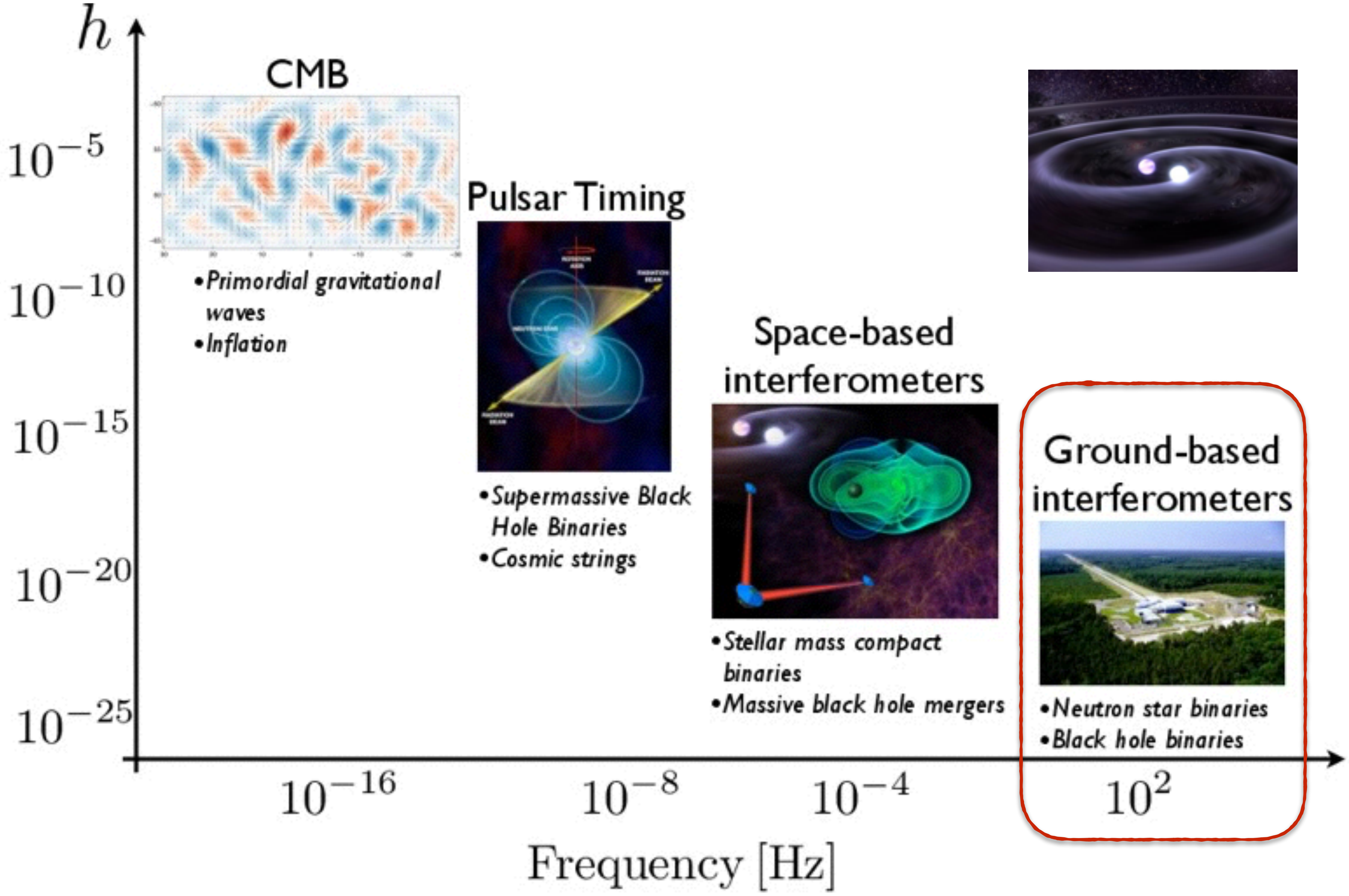
**Space-based interferometers**

- *Stellar mass compact binaries*
- *Massive black hole mergers*

**Ground-based interferometers**

- *Neutron star binaries*
- *Black hole binaries*

# The big picture of gravitational wave astronomy



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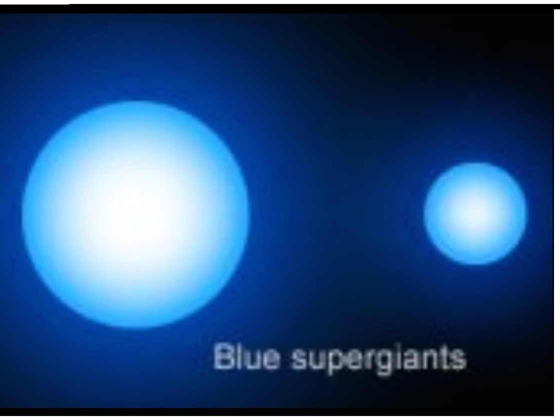
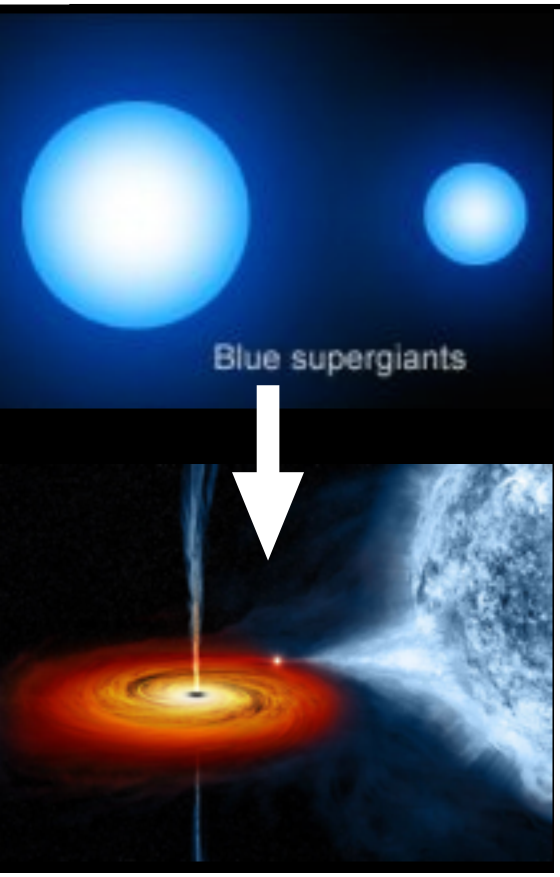
# Evolution of binary star systems



- Most of massive stars live in binary systems

# Evolution of binary star systems



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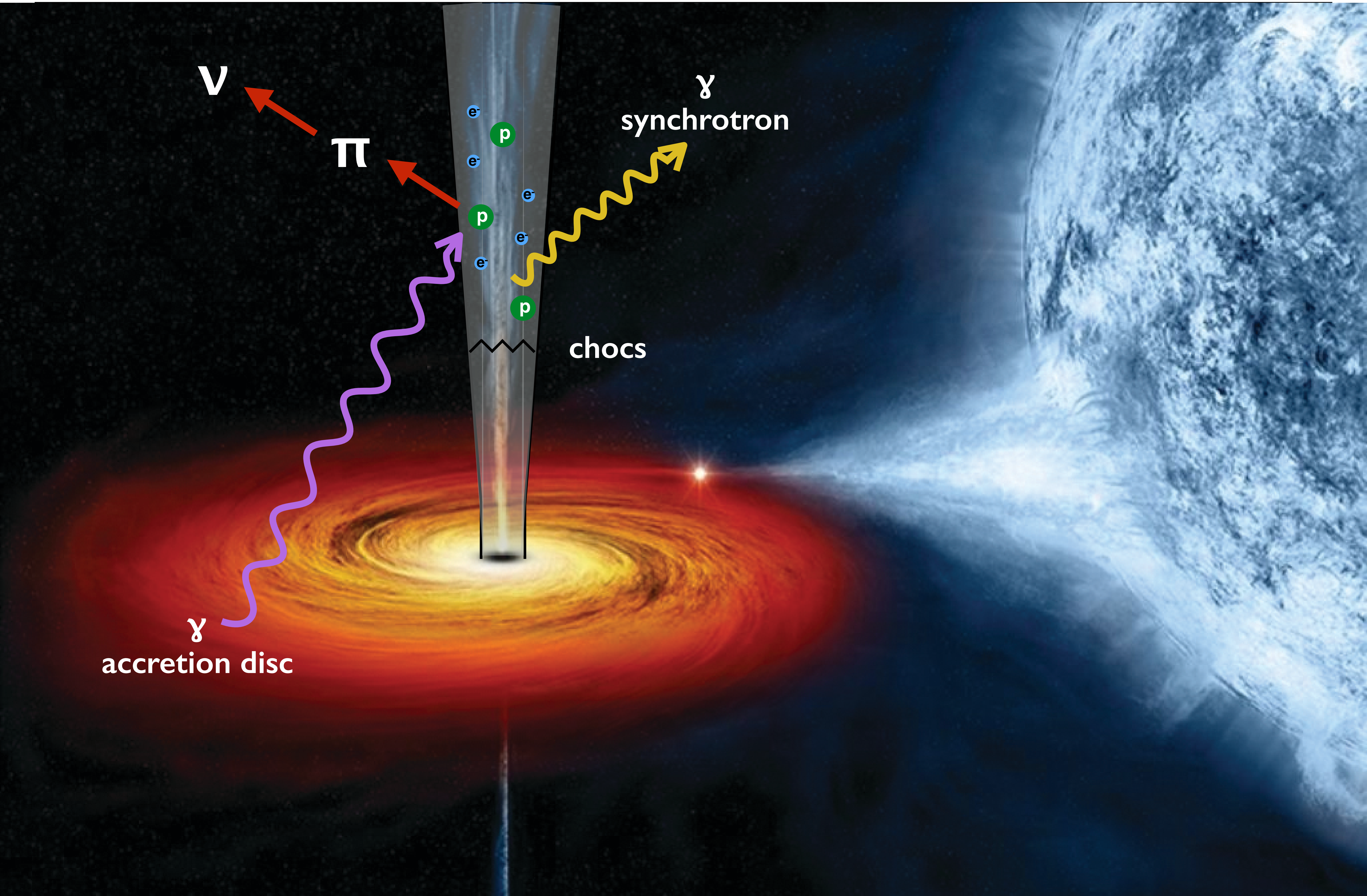
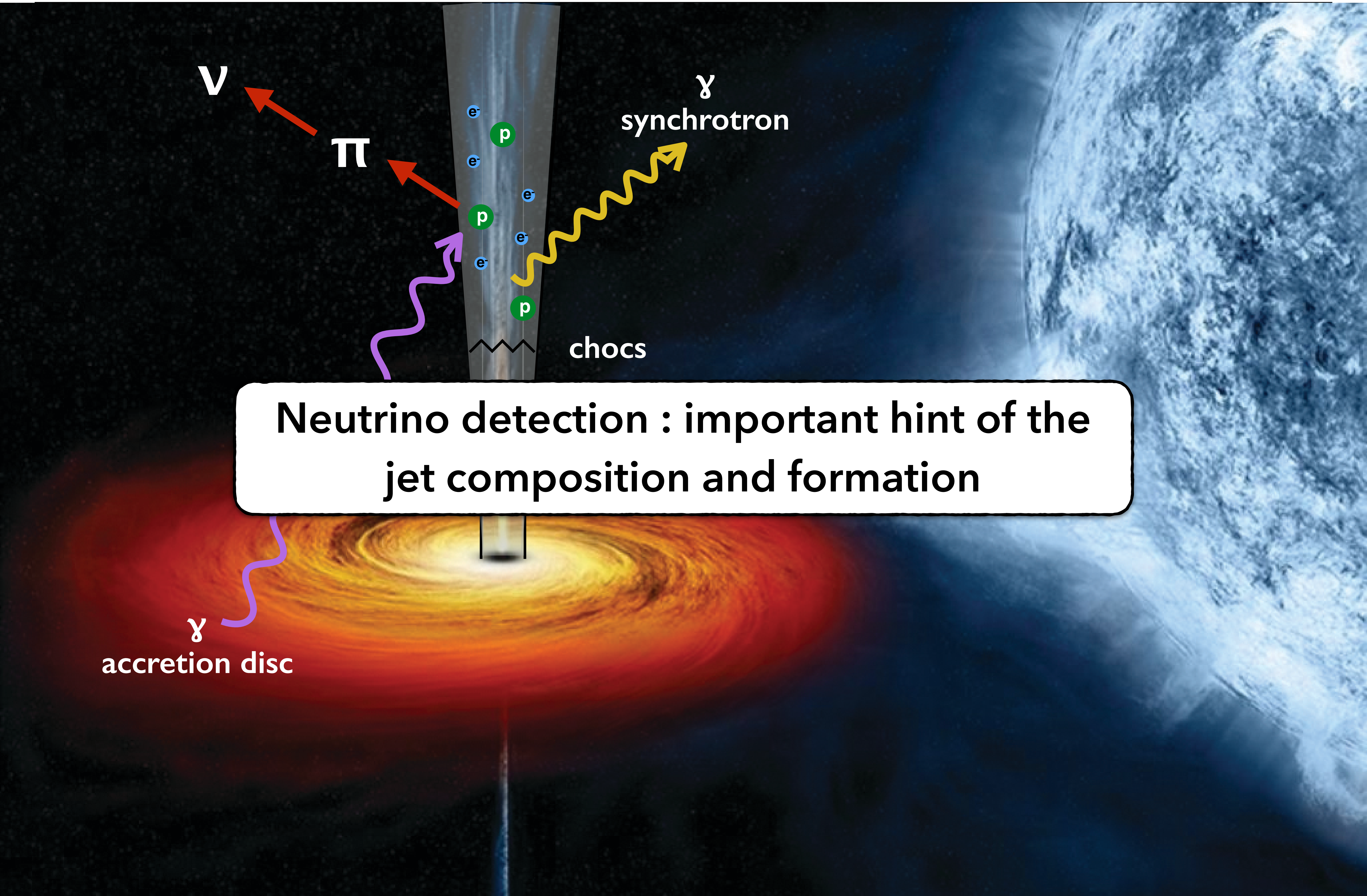
# X-ray binaries



# X-ray binaries



Neutrino detection : important hint of the jet composition and formation

# Neutrino emission of X-ray binaries ?

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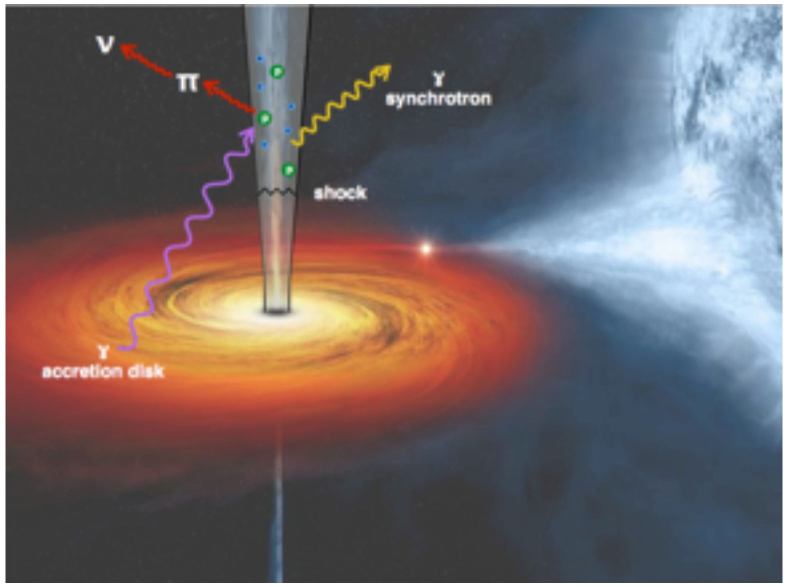
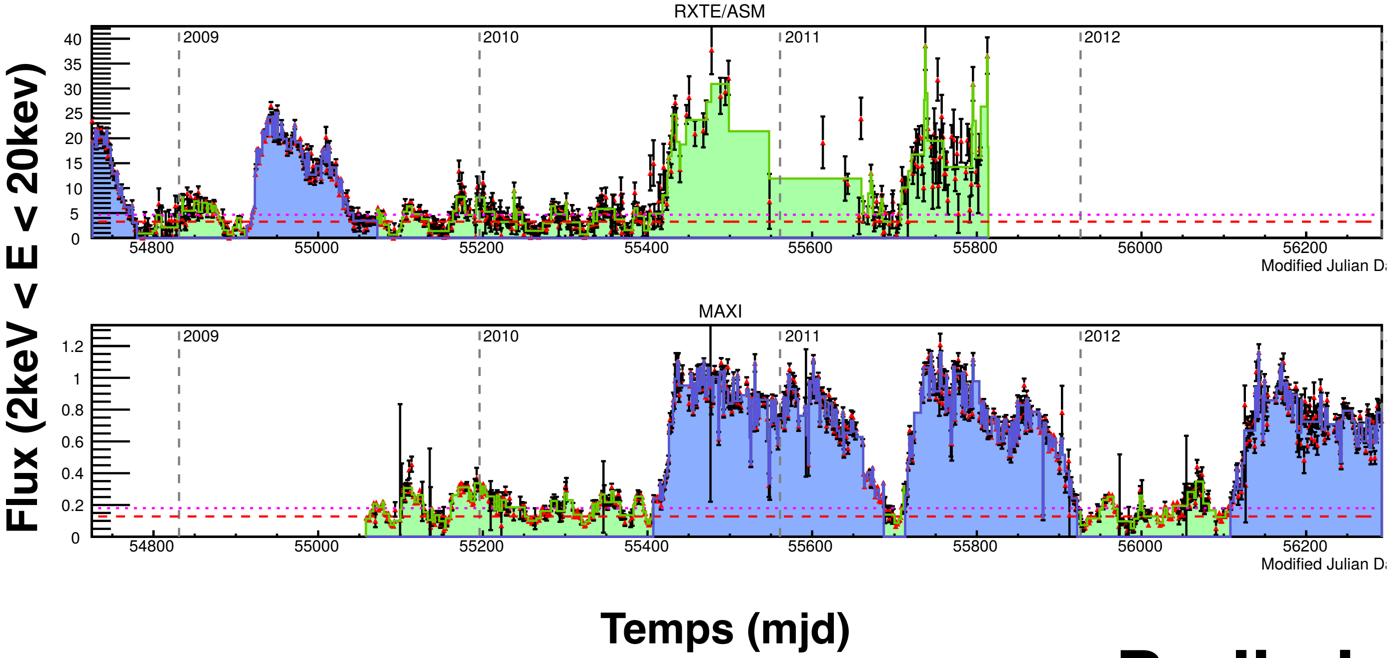
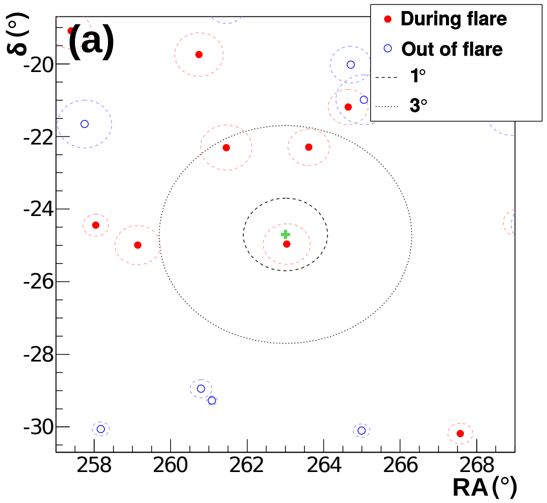
*Jet composition studied by ANTARES*





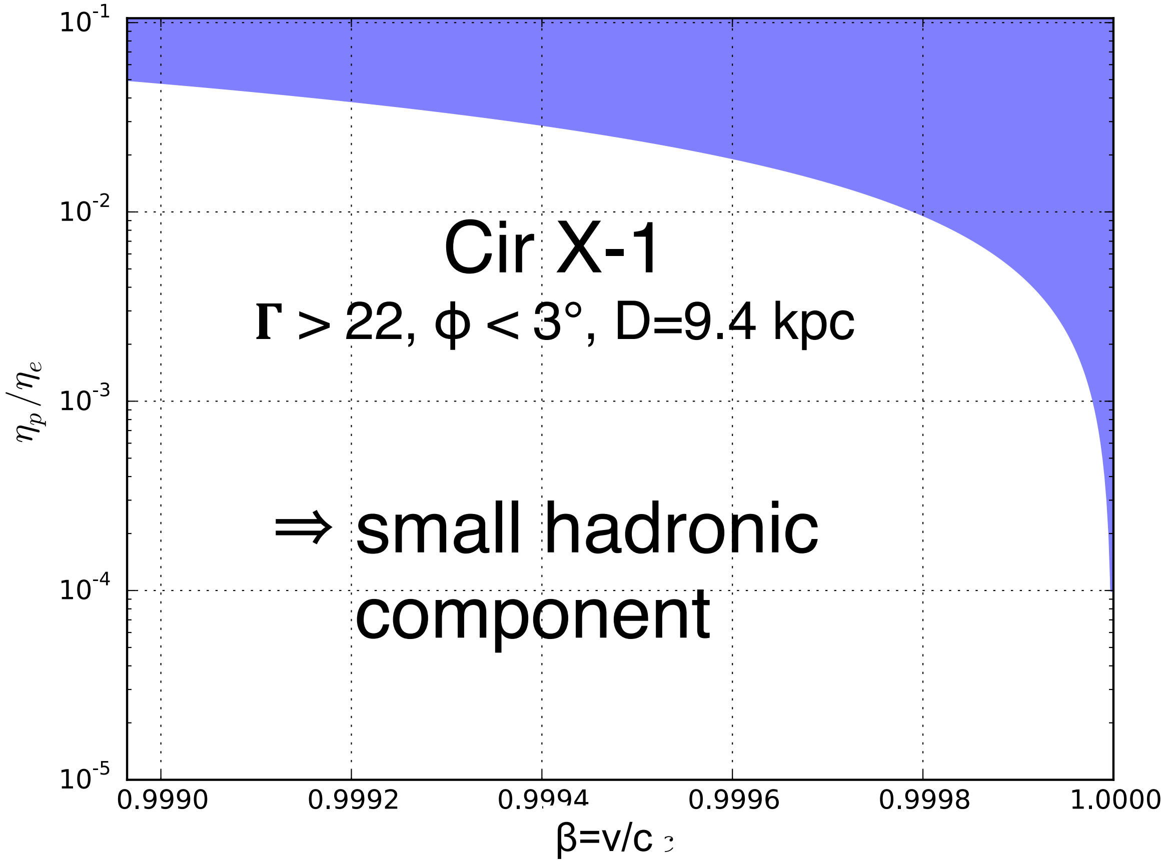


$$\ln\mathcal{L} = \left(\sum_{i=1}^{N} \ln[\mathcal{N}_{\mathrm{S}}\mathcal{S}_i + \mathcal{N}_{\mathrm{B}}\mathcal{B}_i]\right) - [\mathcal{N}_{\mathrm{S}} + \mathcal{N}_{\mathrm{B}}]$$

$$\mathcal{S}_i = \mathcal{S}^{\mathrm{space}}(\Psi_i(\alpha_s,\delta_s)) \cdot \mathcal{S}^{\mathrm{energy}}(dE/dX_i) \cdot \mathcal{S}^{\mathrm{time}}(t_i + lag)$$

$$\mathcal{B}_i = \mathcal{B}^{\mathrm{space}}(\delta_i) \cdot \mathcal{B}^{\mathrm{energy}}(dE/dX_i) \cdot \mathcal{B}^{\mathrm{time}}(t_i)$$

**Preliminary**



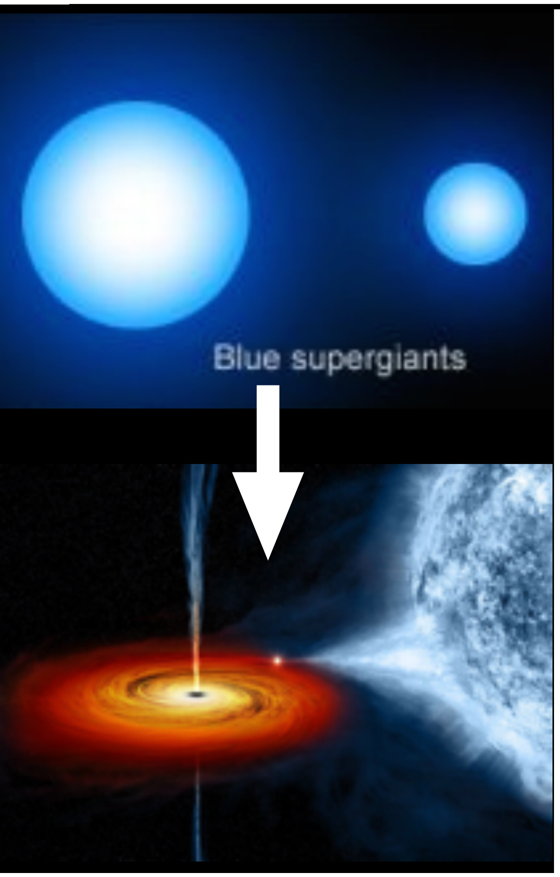
Cir X-1

$\Gamma > 22$, $\phi < 3°$, D=9.4 kpc

⇒ small hadronic component

**No detection** → **U.L. on the proton energy (based on a photo-hadronic model)**

# Evolution of binary star systems



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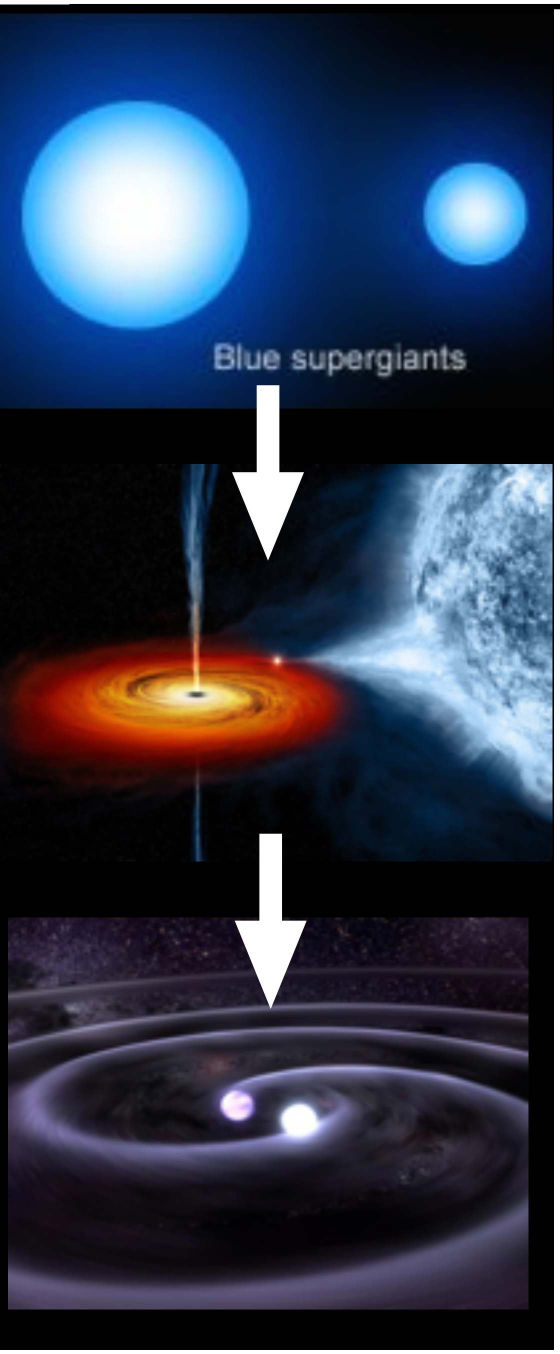

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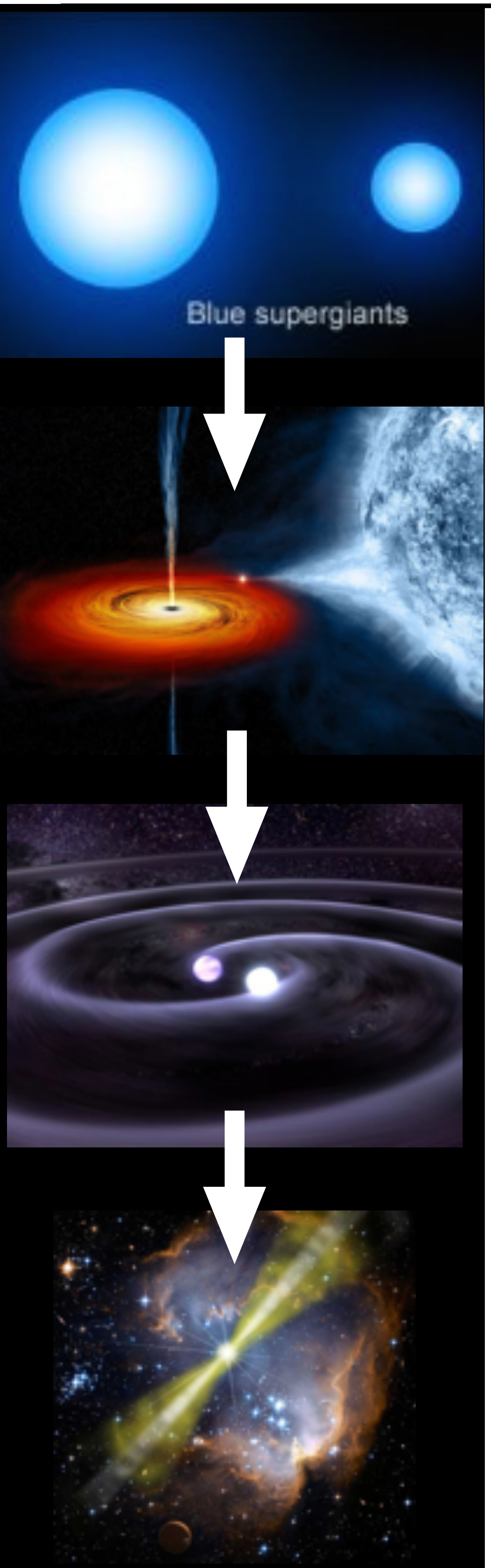

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- short GRB + GW emission during coalescence

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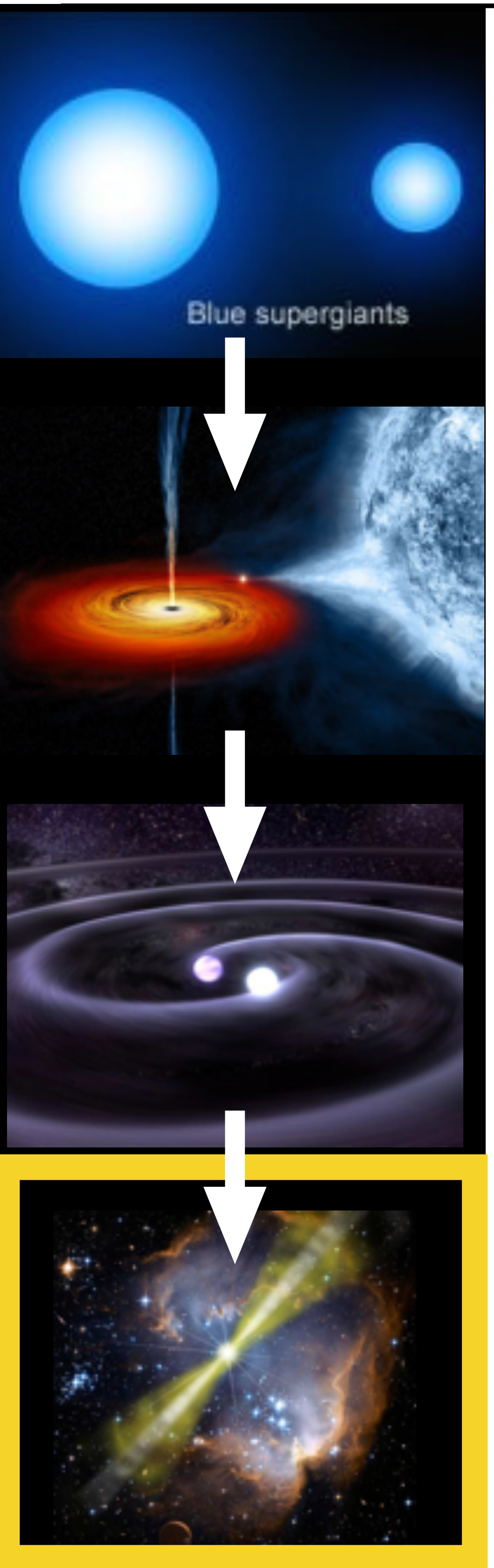

- Most of massive stars live in binary systems

- Undergo mass transfer
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- Finish their life as compact object binaries

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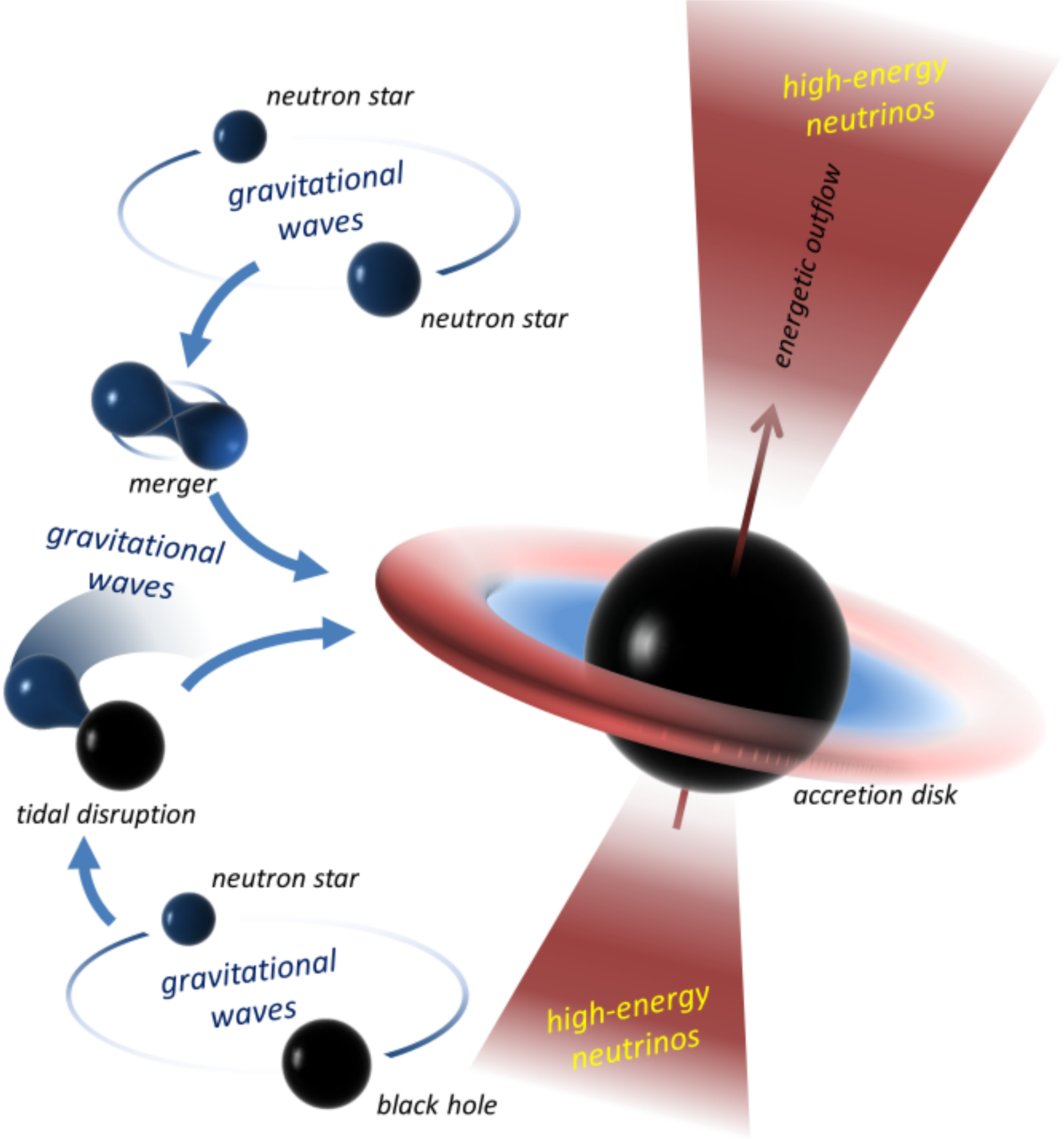
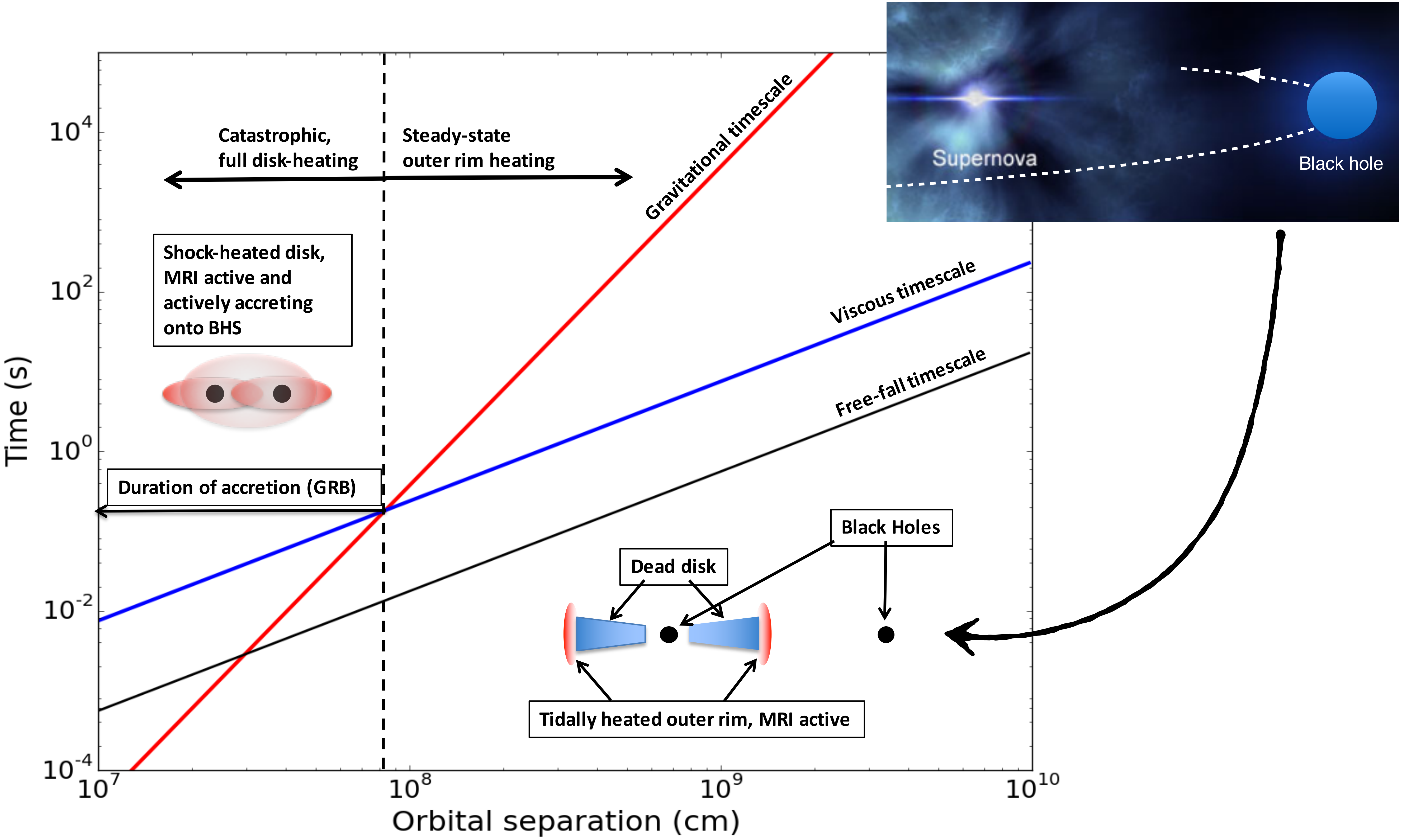
# Compact objects coalescence

**For BH/NS or NS/NS systems :**

gravitational waves
+ electromagnetic
+ neutrino emission
expected if ejection process with baryonic component



# Black hole binary coalescence



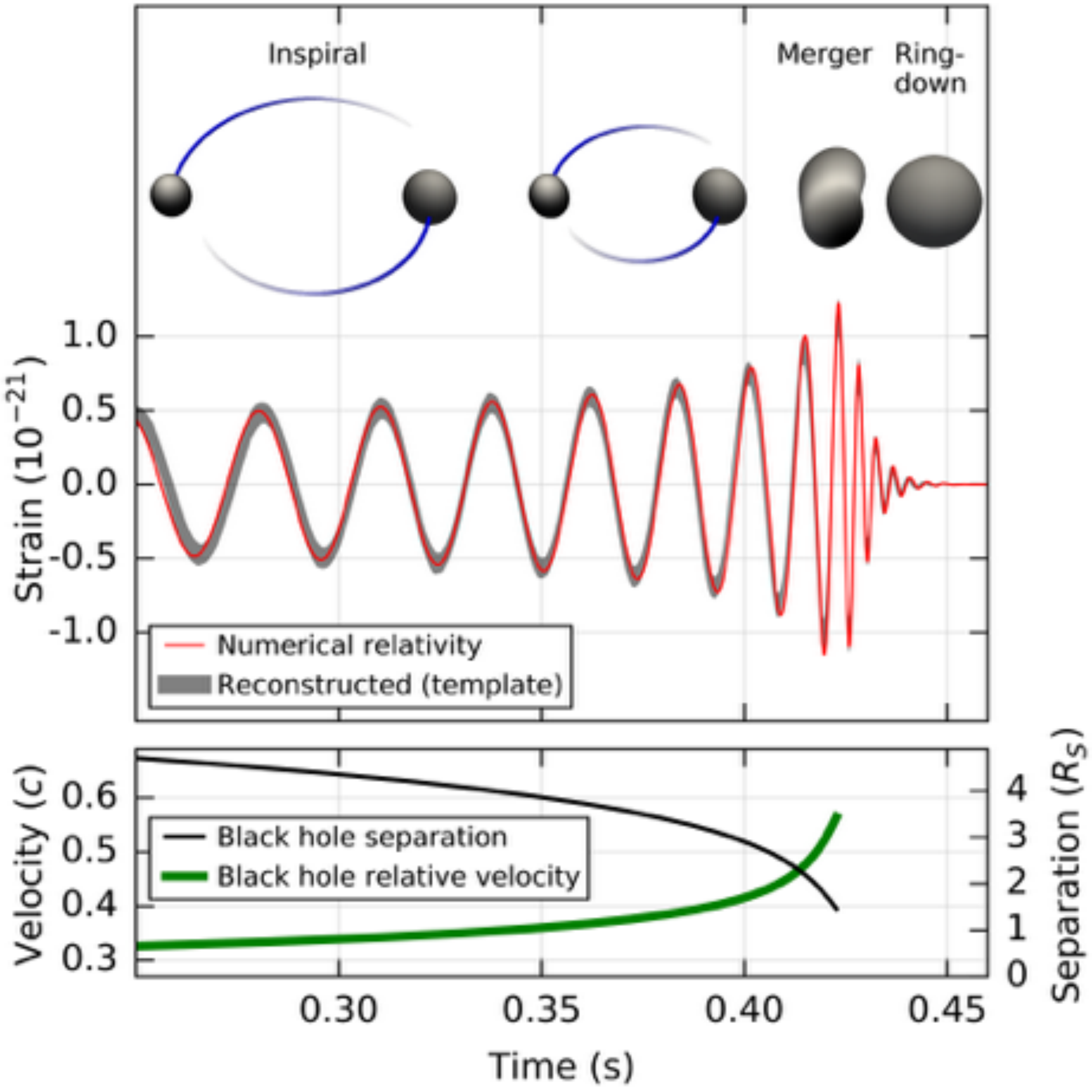
*Perna et al. (2016)*

# Discovery of GW150914

Sept. 14th, 2015 at 09:50:45 UTC

GW signal recorded by the LIGO Hanford and Livingston detectors

Produced by a stellar-mass binary black hole merger at redshift $z=0.09^{+0.03}_{-0.04}$ (~410 Mpc)

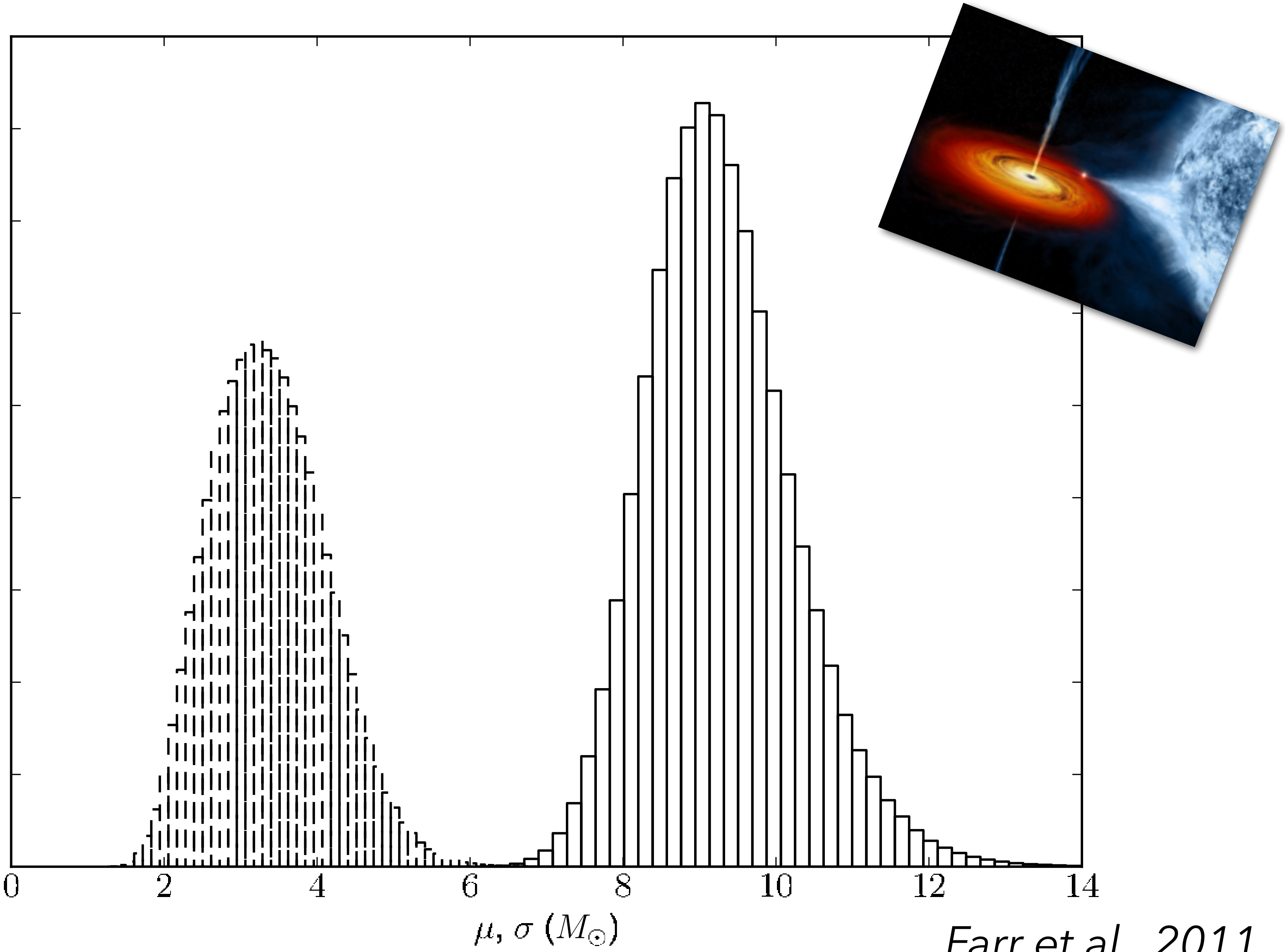


*LIGO-Virgo collaborations*
*PRL 116, 061102, 2016*

# Discovery of GW150914

**GW150914 black hole masses : $M_1=36^{+5}_{-4}\,M_\odot$ and $M_2=29^{+4}_{-4}\,M_\odot$**

**From black hole masses in X-ray binaries :**



*Farr et al., 2011*

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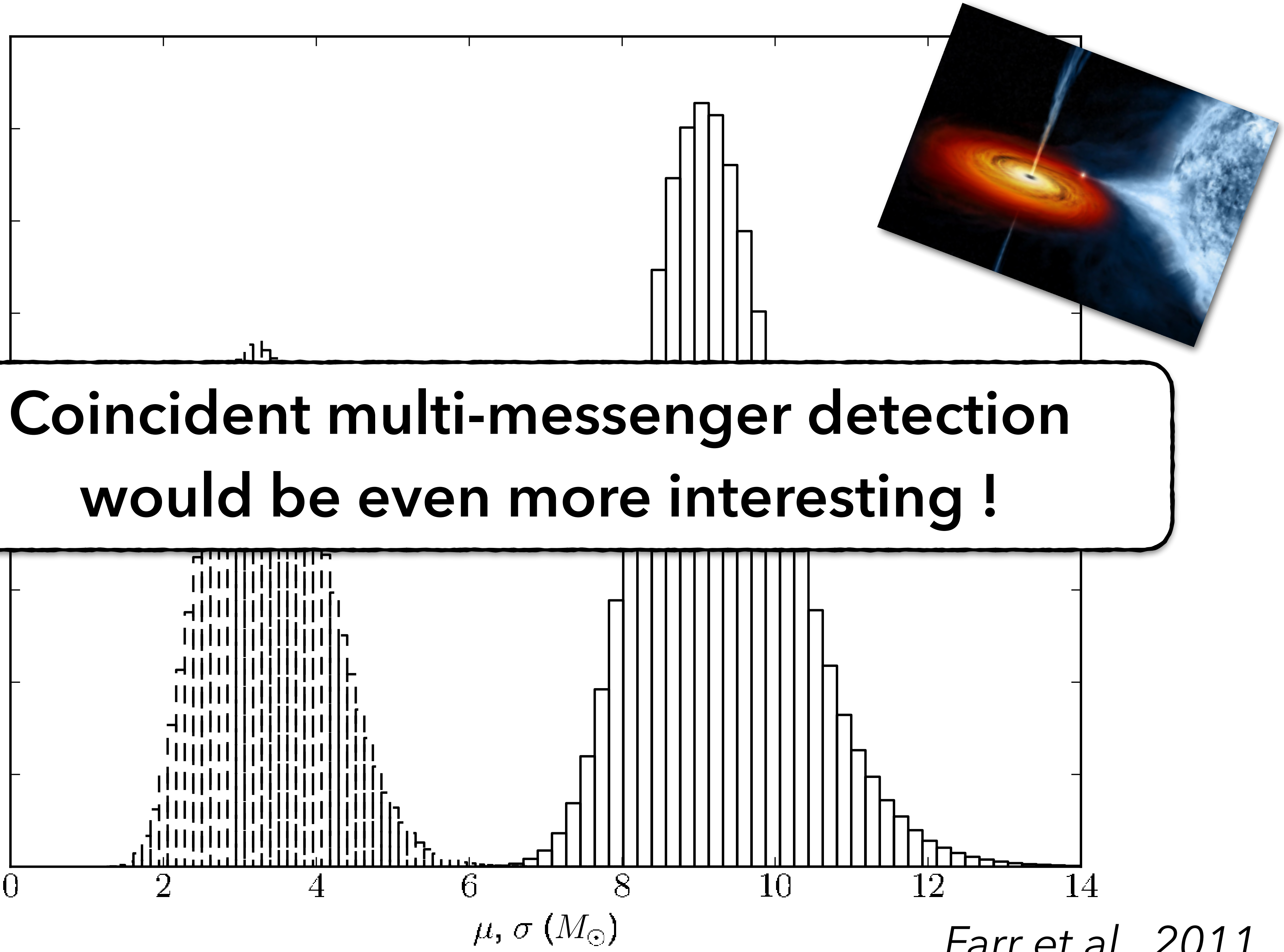


**Coincident multi-messenger detection would be even more interesting !**

*Farr et al., 2011*

# Neutrino follow-up of GW150914

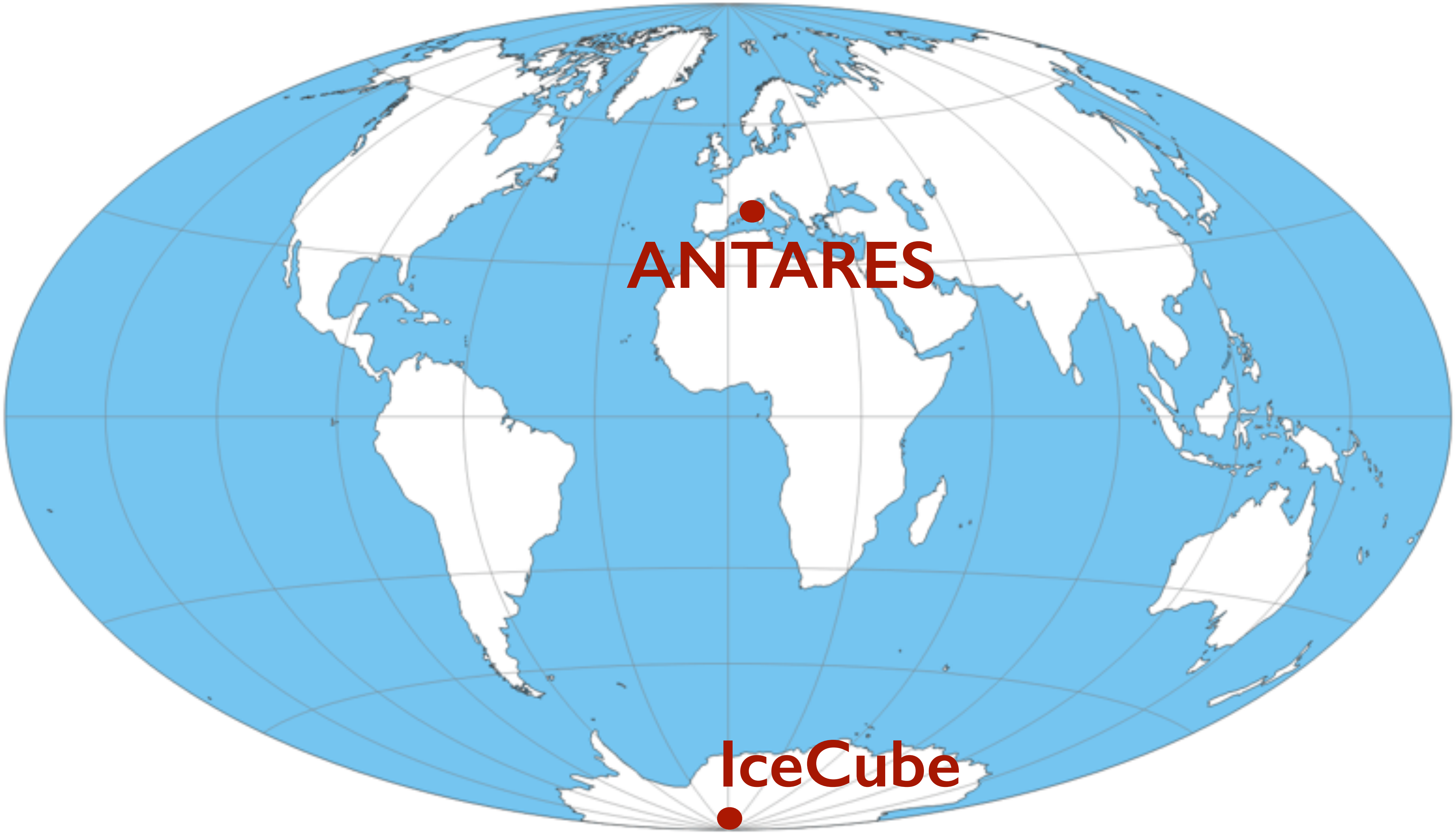
# Neutrino follow-up

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

**Is a fraction of this energy emitted in neutrinos ? + Demonstrate synergies**

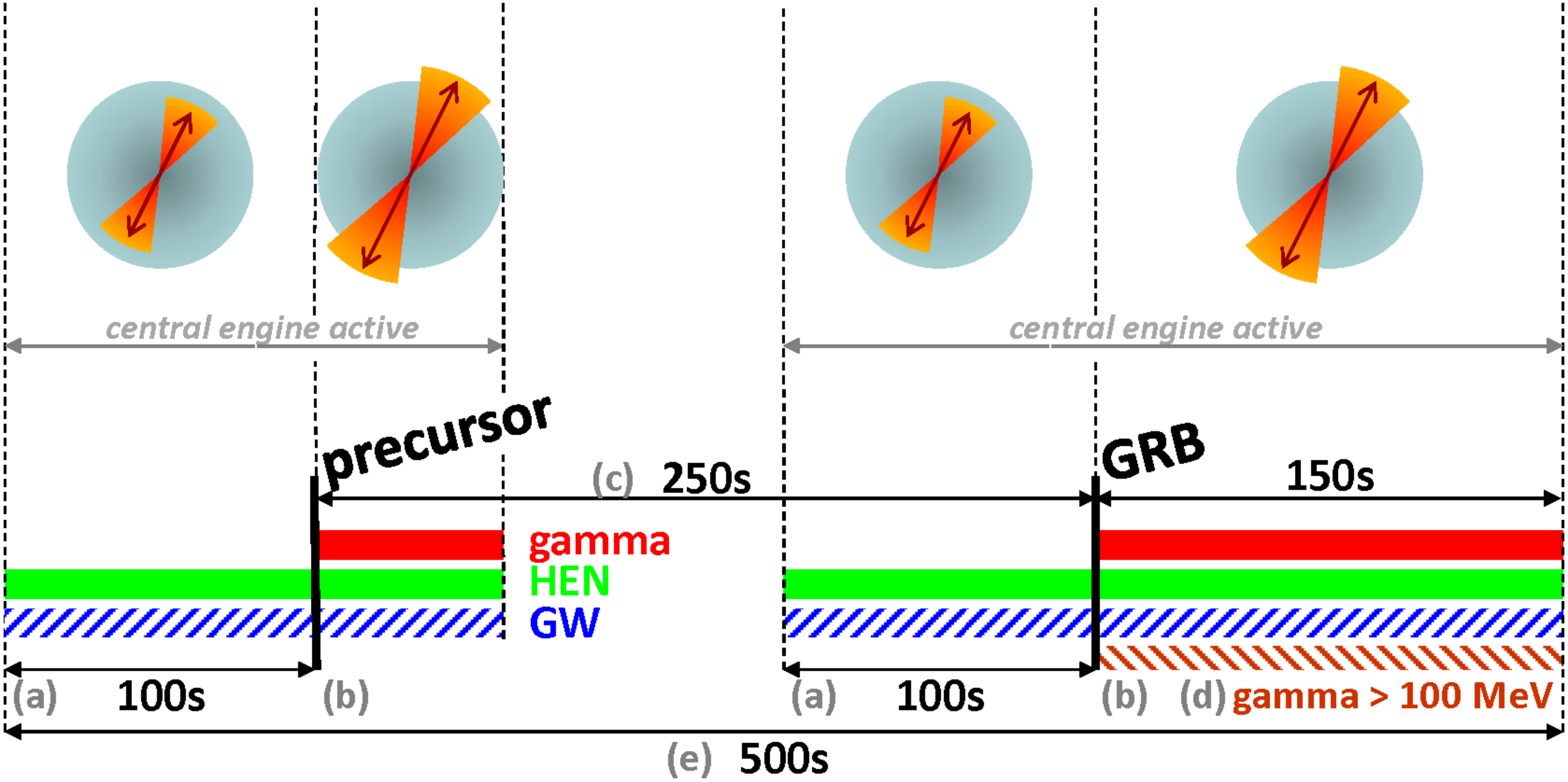
Joint ANTARES - IceCube - LIGO/Virgo analysis

Phys. Rev. D (in press) : arXiv 1602.05411



# Neutrino follow-up

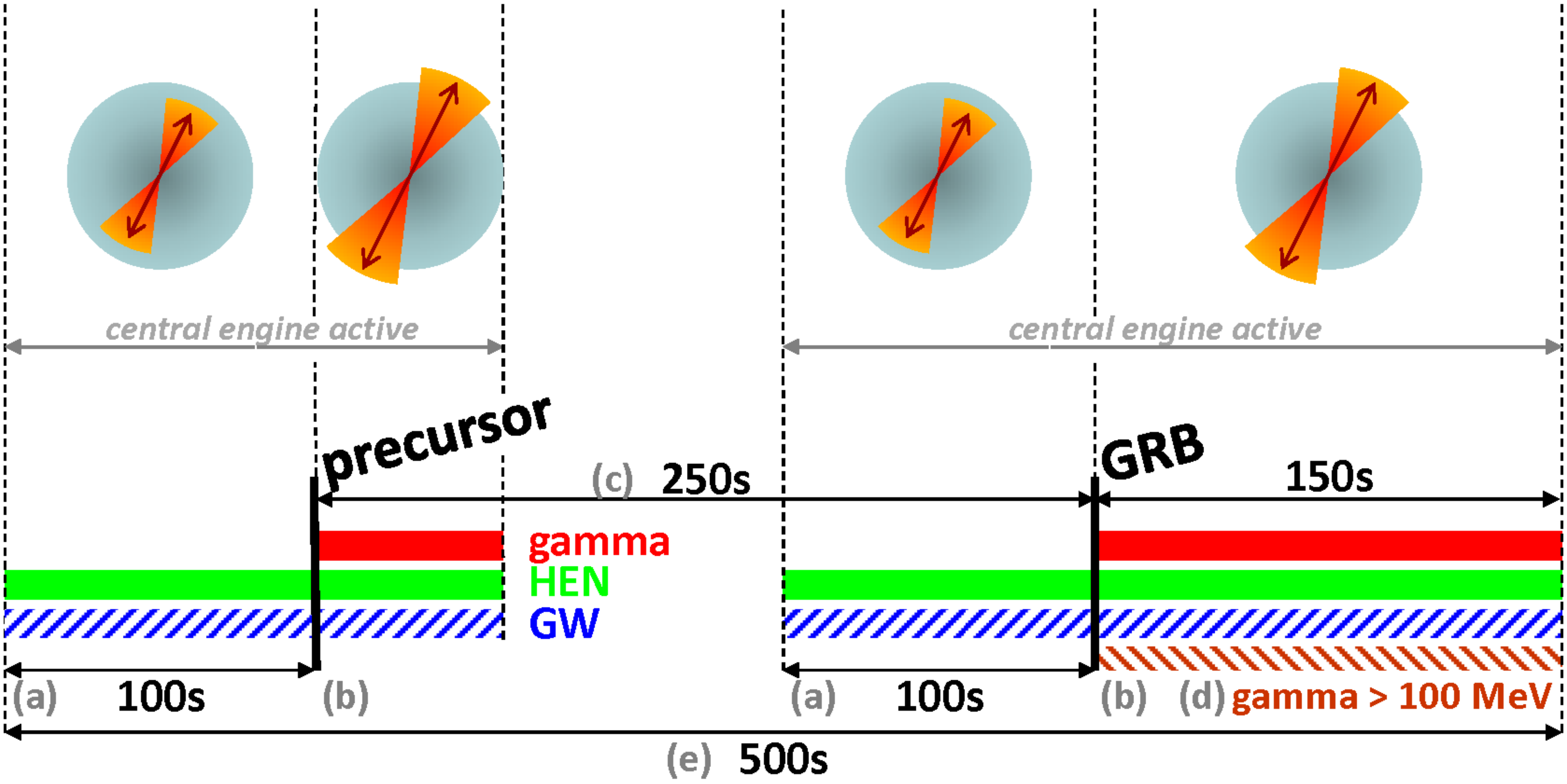
In the case of a short GRB



*Baret et al., 2011*

# Neutrino follow-up

In the case of a short GRB



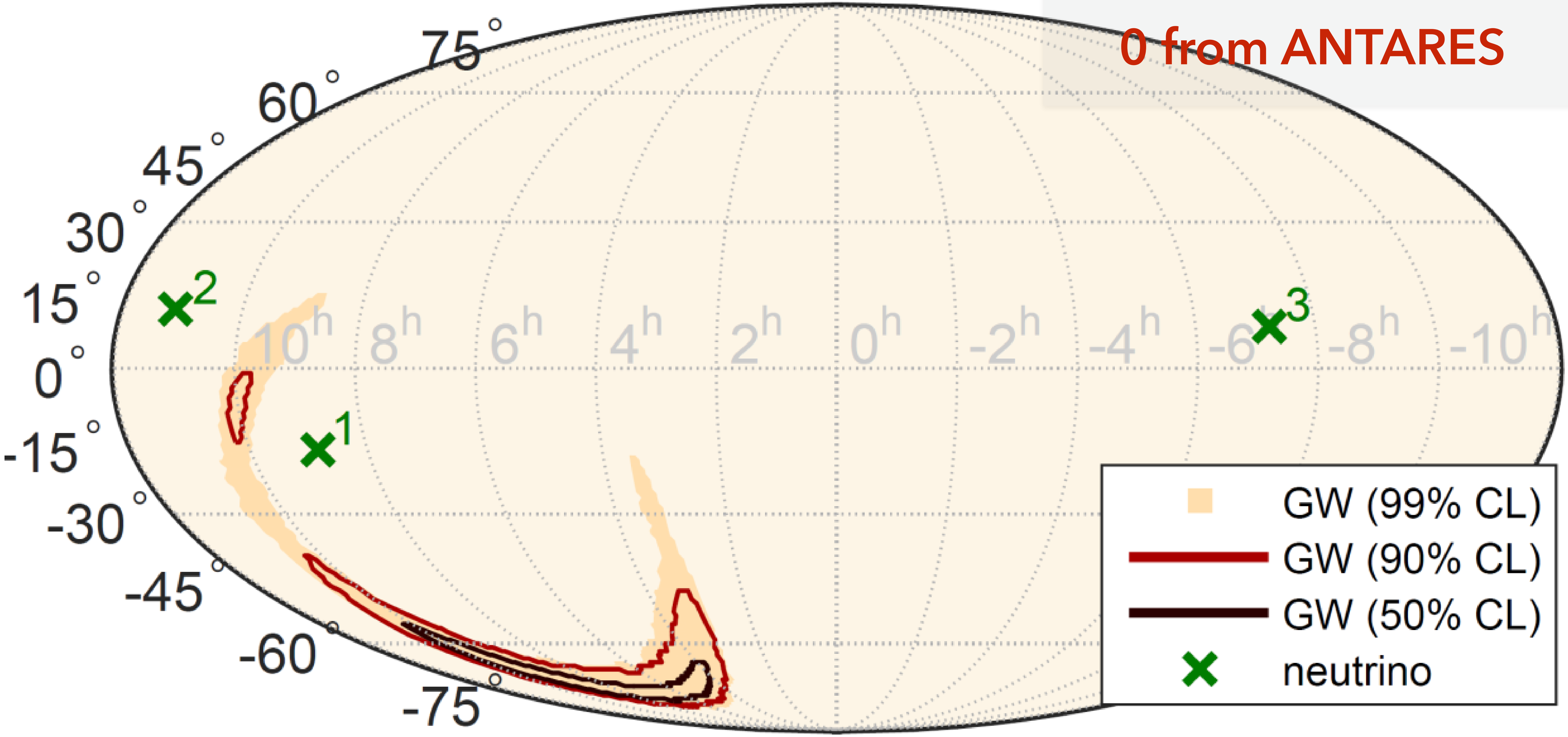
*Baret et al., 2011*

- ➜ Online ANTARES and IceCube data
- ➜ Event selection from neutrino point-source searches

# Neutrino follow-up

Within ±500 s from GW alert

**3 IceCube candidates**
**0 from ANTARES**



➜ Consistent with the background expectations (4.4 events for IceCube; $10^{-2}$ for ANTARES)

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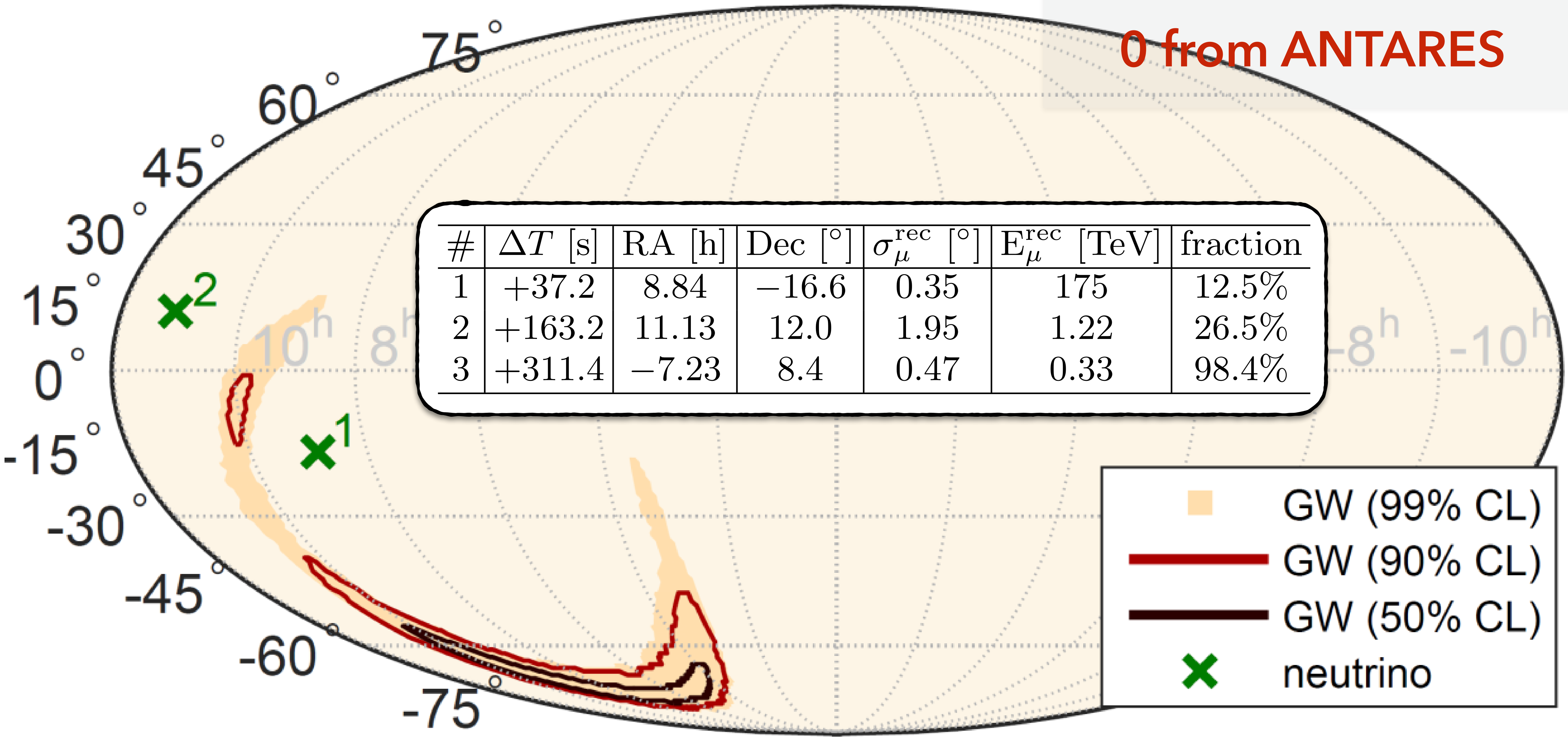

| # | $\Delta T$ [s] | RA [h] | Dec [°] | $\sigma_\mu^{\text{rec}}$ [°] | $E_\mu^{\text{rec}}$ [TeV] | fraction |
|---|---|---|---|---|---|---|
| 1 | +37.2 | 8.84 | −16.6 | 0.35 | 175 | 12.5% |
| 2 | +163.2 | 11.13 | 12.0 | 1.95 | 1.22 | 26.5% |
| 3 | +311.4 | −7.23 | 8.4 | 0.47 | 0.33 | 98.4% |

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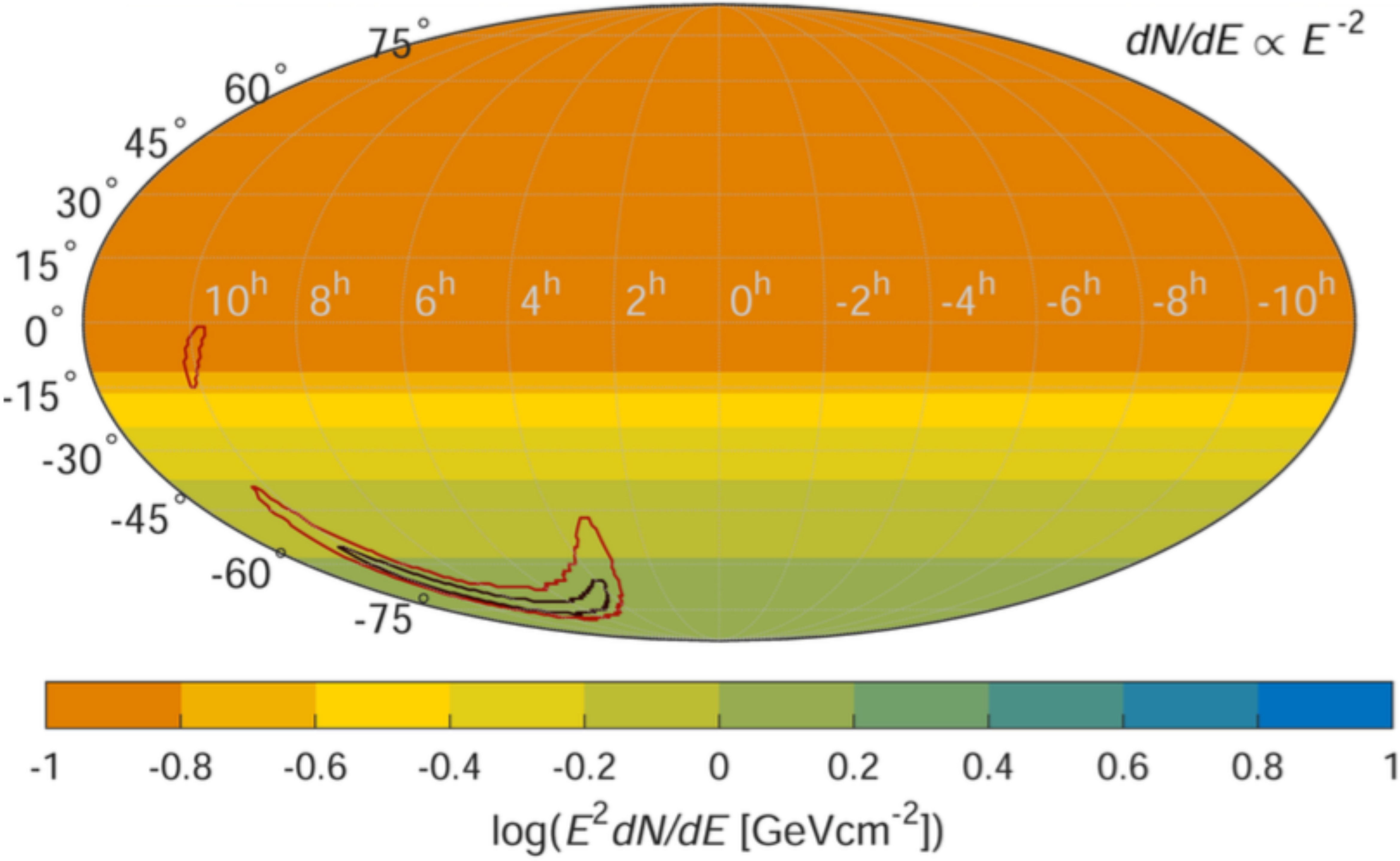
# Neutrino follow-up

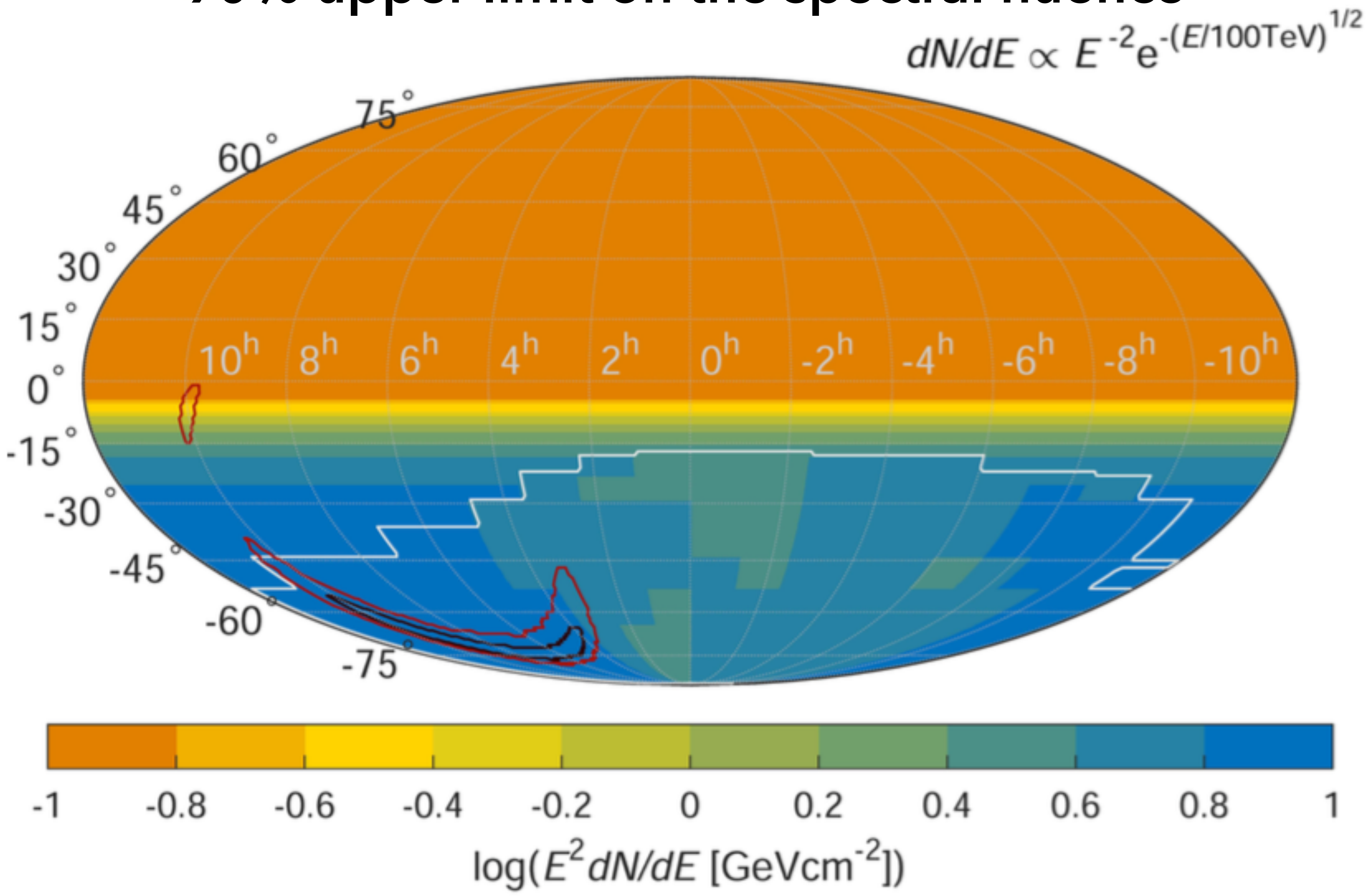
## 90% upper limit on the spectral fluence



http://arxiv.org/abs/1602.05411

# Neutrino follow-up

**90% upper limit on the spectral fluence**



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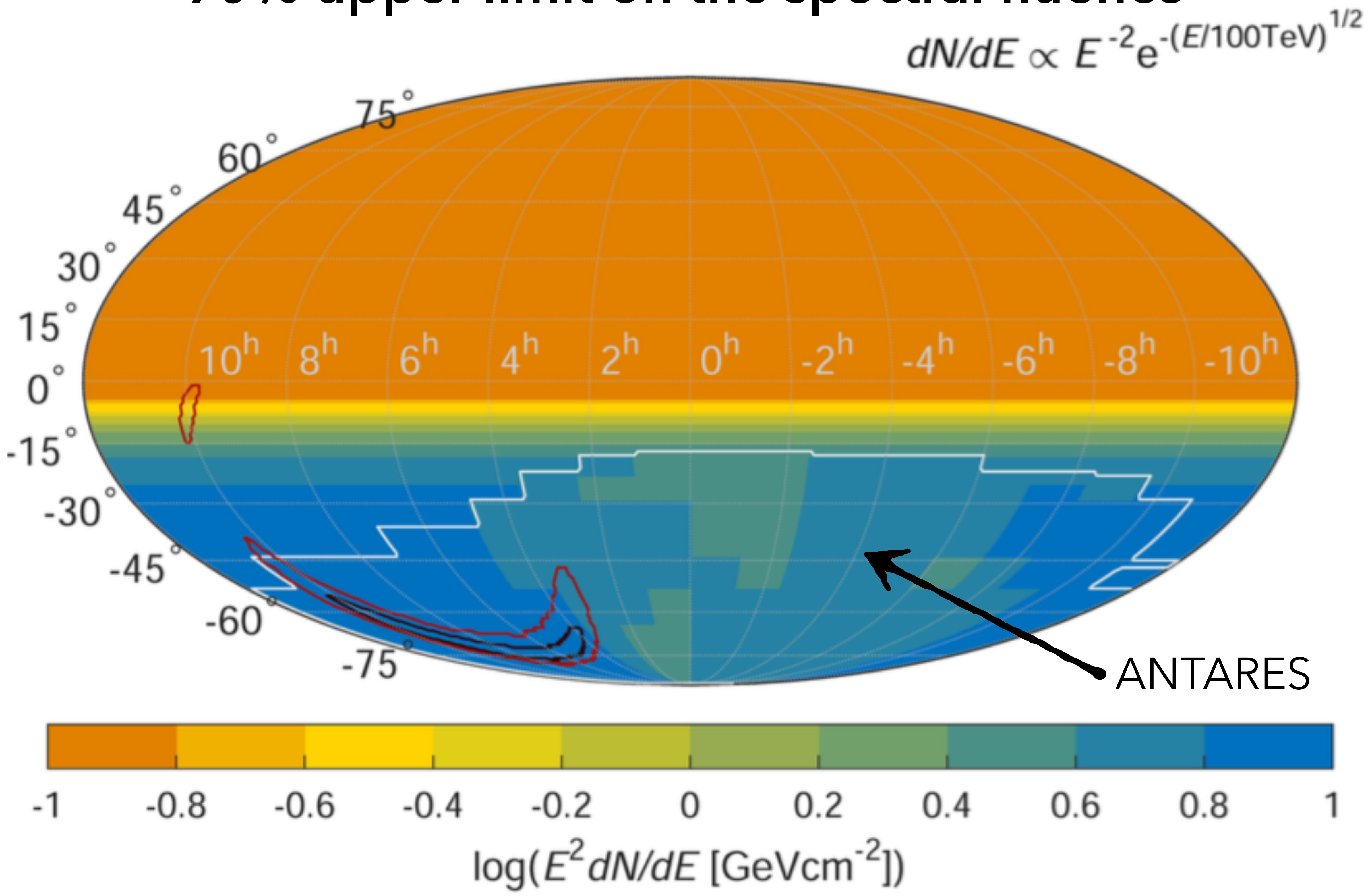

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# Neutrino follow-up

## Constraints on the total energy emitted in neutrinos

$$\boxed{\begin{aligned} \mathrm{E}^{\mathrm{ul}}_{\nu,\mathrm{tot}} &= 5.4 \times 10^{51} - 1.3 \times 10^{54}\,\mathrm{erg} \\ \mathrm{E}^{\mathrm{ul(cutoff)}}_{\nu,\mathrm{tot}} &= 6.6 \times 10^{51} - 3.7 \times 10^{54}\,\mathrm{erg} \end{aligned}}$$

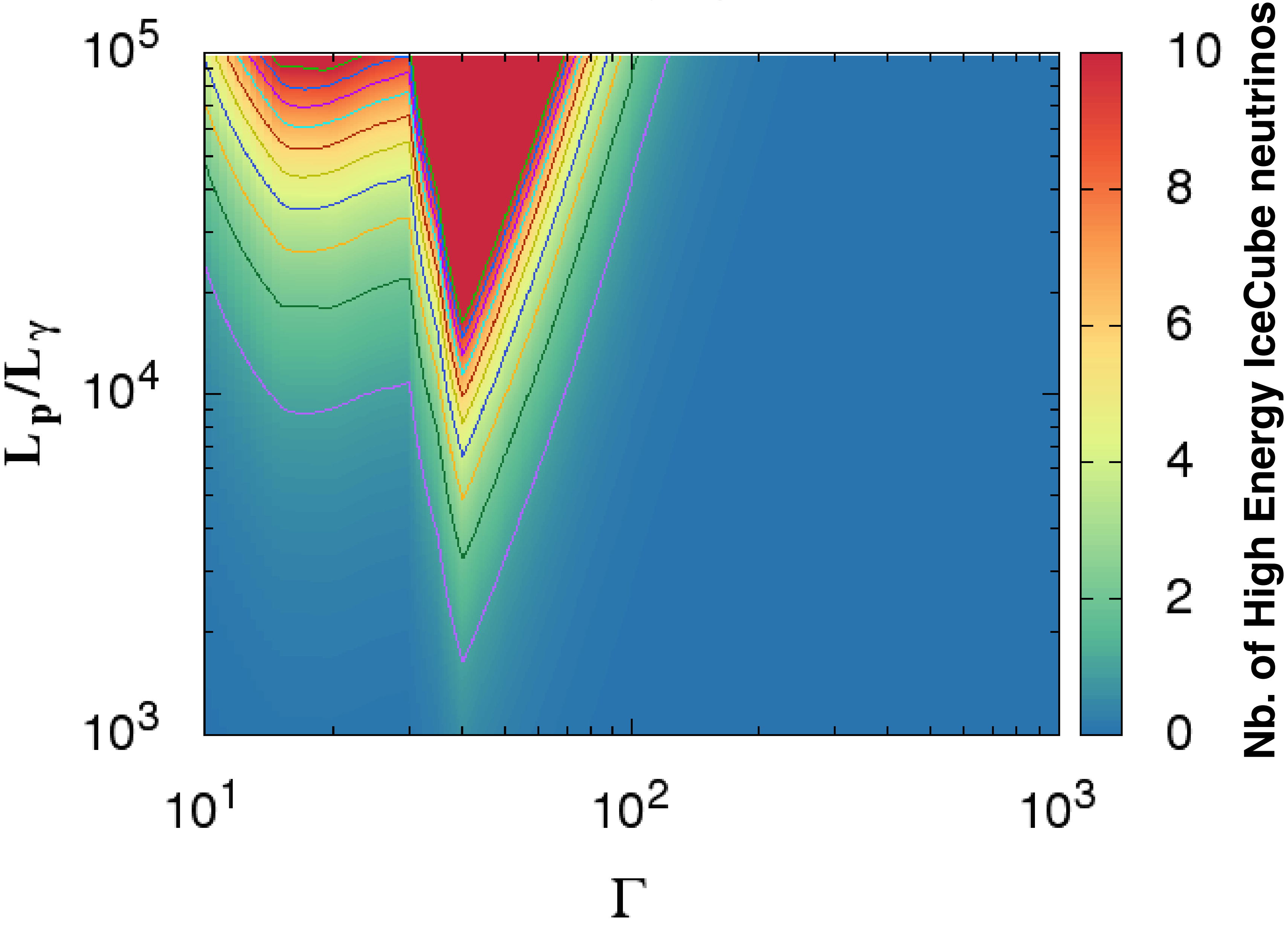
at $d=410^{+160}_{-180}$ Mpc

- Energy radiated in GW: ~5 x $10^{54}$ erg
- Typical short GRB isotropic-equivalent energies are ~$10^{49}$ erg
- May be similar to total energy radiated in neutrinos in GRBs *(Mészaros 2015; Bartos et al., 2013)*

# Implications

*Moharana et al., 2016*

- Calculate HEN flux from a short GRB
- Non-detection of neutrino event can constrain jet parameters



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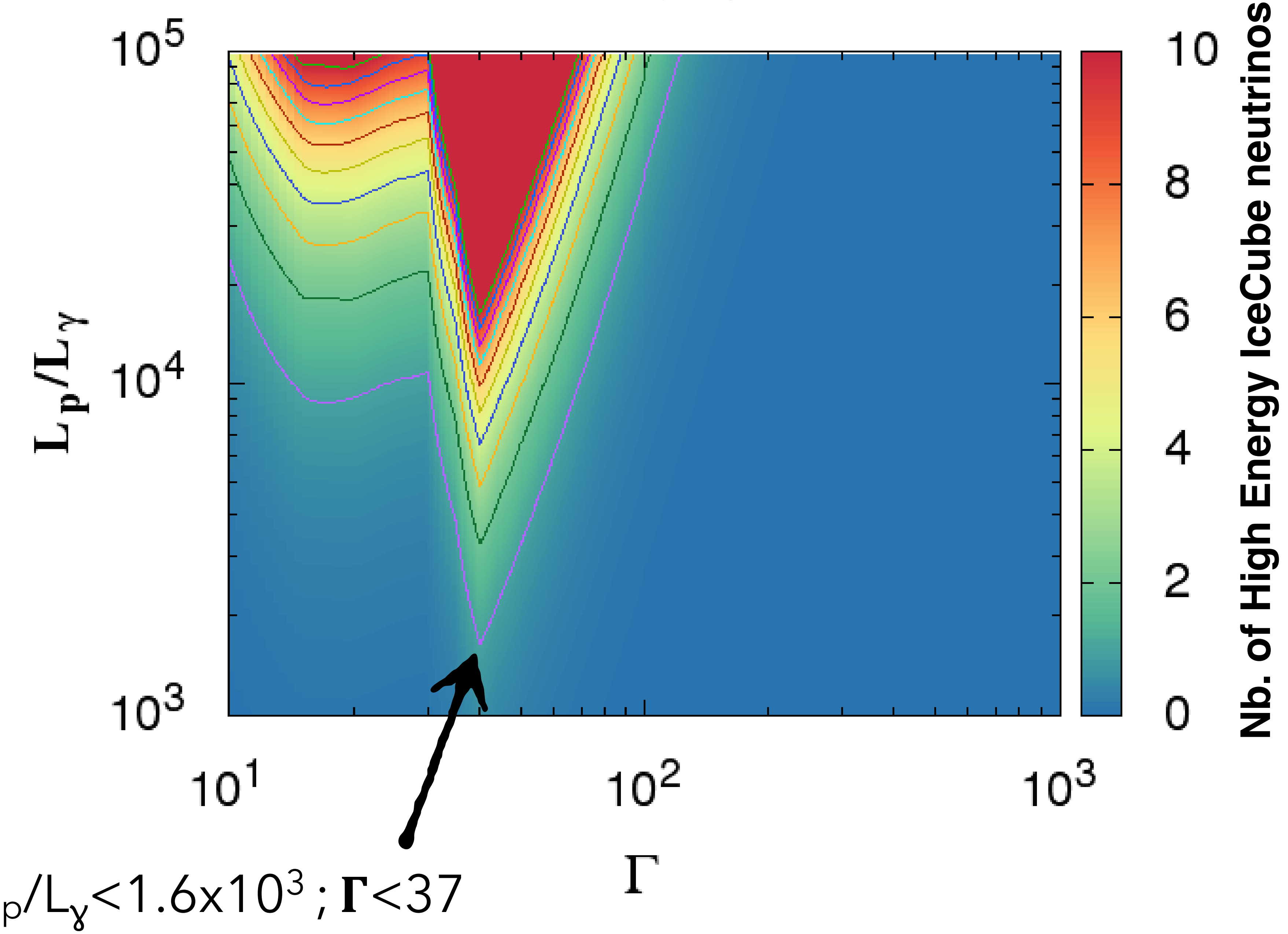

$L_p/L_\gamma < 1.6\times10^3$ ; $\Gamma < 37$

and $L_p \sim 3\times10^{52}$ erg/s if $L_\gamma \sim 10^{49}$ erg/s

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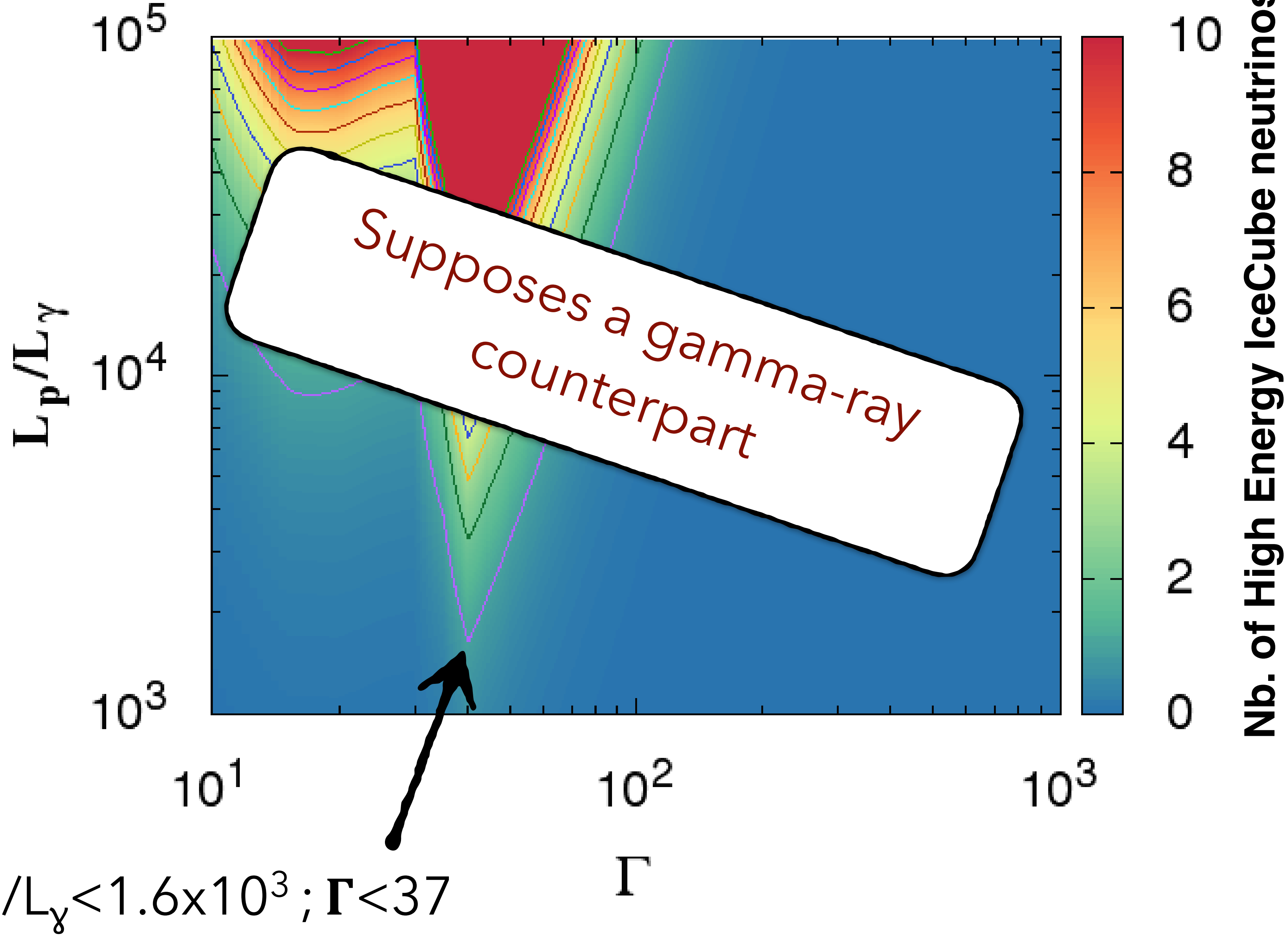

Supposes a gamma-ray counterpart

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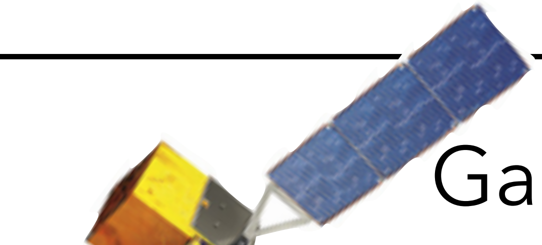
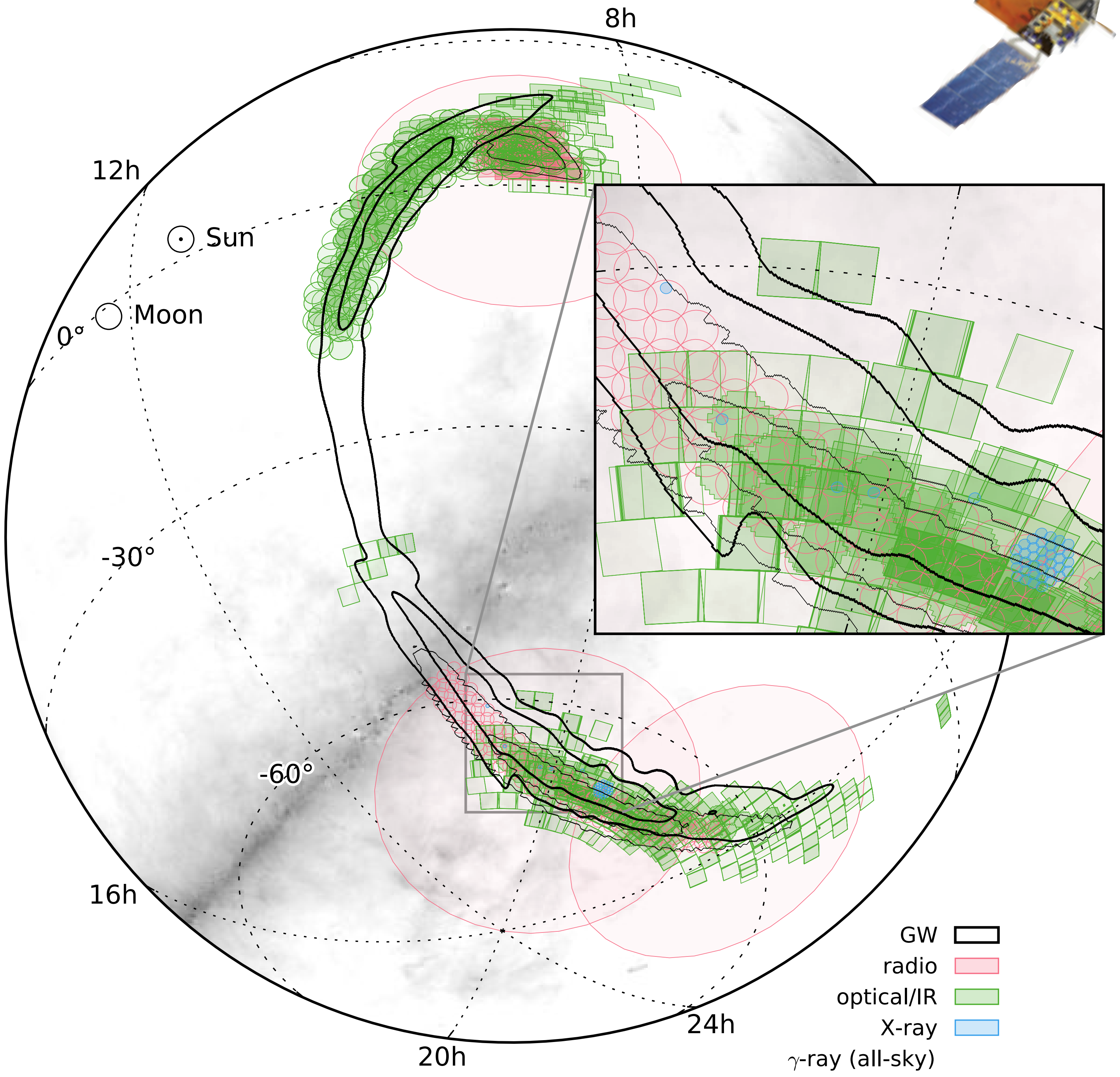
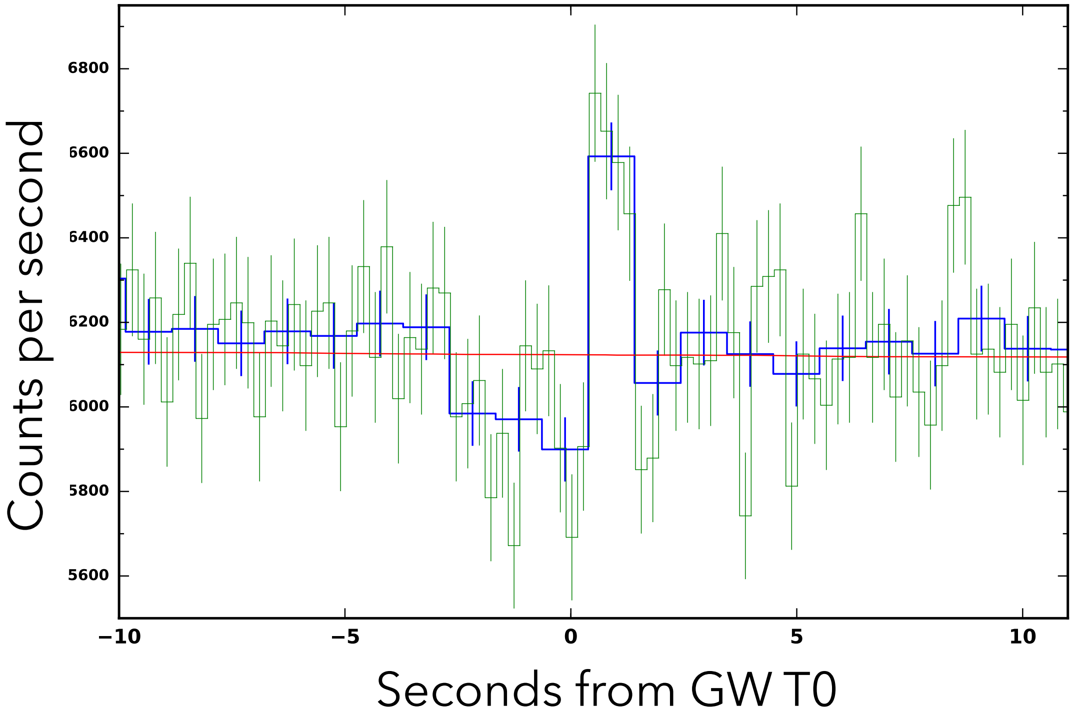
# Electromagnetic follow-up



## Gamma-ray counterpart ?



*Abbott et al., 2016*



*Connaughton et al., 2016*

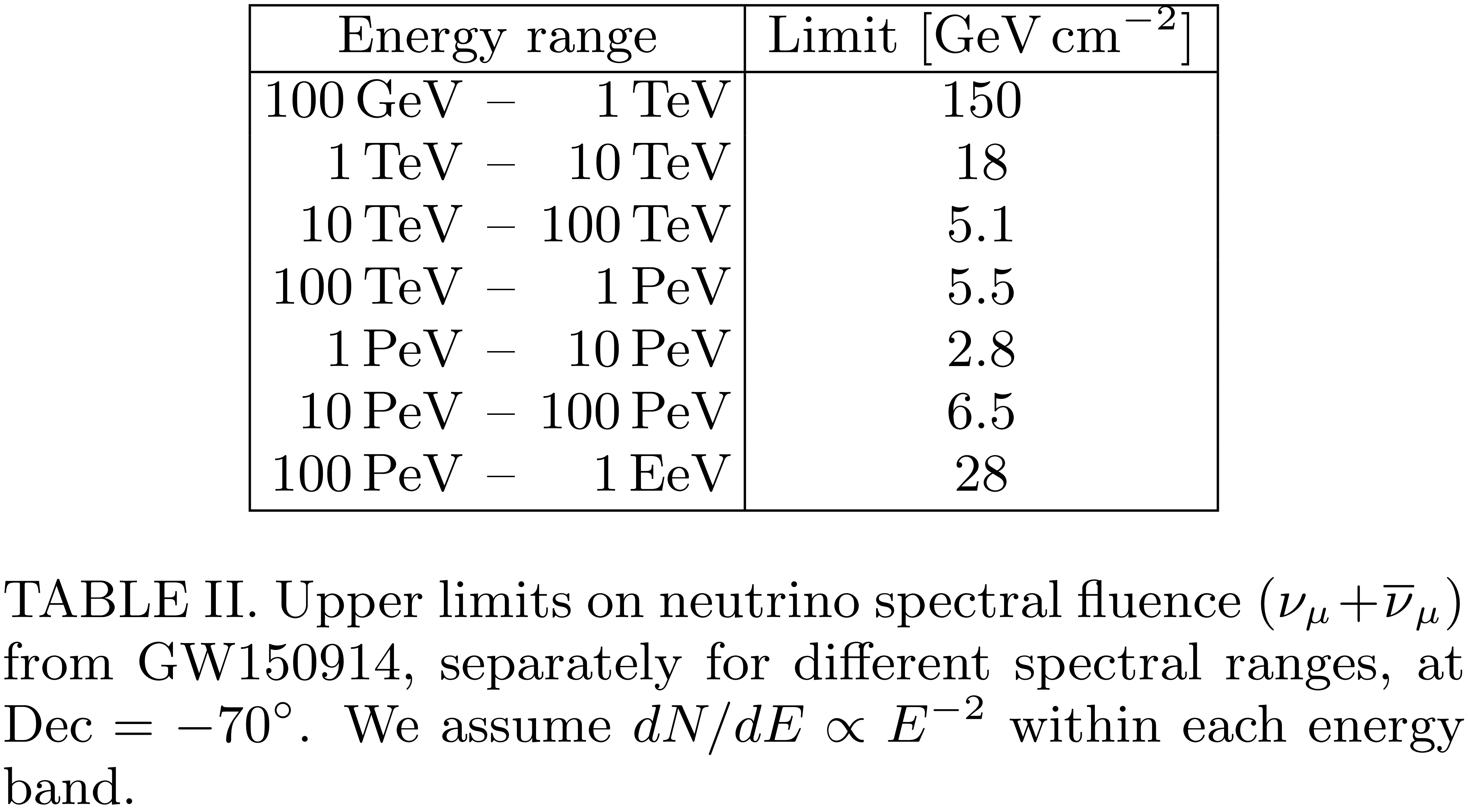
**Neutrino angular error : <0.5°²**
**GW angular error : ~100°²**

**⇒ Neutrino counterpart could constrain the position of the GW event on the sky !**

# What’s next ?

- First neutrino follow-up
- Thanks to previous GW+ HEN studies (e.g. ANTARES/LIGO-Virgo 2013)
- O2 LIGO+Virgo about to start (next summer)
- Expected detection rate ~2–400 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$
- Coincident neutrino/GW detection ?
- Can significantly constrain the GW source position
- Would open a new era

# Spectral fluence U.L.



| Energy range | Limit $[\mathrm{GeV\,cm^{-2}}]$ |
|---|---|
| 100 GeV – 1 TeV | 150 |
| 1 TeV – 10 TeV | 18 |
| 10 TeV – 100 TeV | 5.1 |
| 100 TeV – 1 PeV | 5.5 |
| 1 PeV – 10 PeV | 2.8 |
| 10 PeV – 100 PeV | 6.5 |
| 100 PeV – 1 EeV | 28 |

TABLE II. Upper limits on neutrino spectral fluence $(\nu_\mu+\overline{\nu}_\mu)$ from GW150914, separately for different spectral ranges, at Dec $= -70°$. We assume $dN/dE \propto E^{-2}$ within each energy band.

# IceCube candidate neutrinos

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## 1) p-value of observing 3 background events when expecting 4.4 :

$$1 - F_{\text{pois}}(N_{\text{observed}} \leq 2, N_{\text{expected}} = 4.4) = 0.81$$

## 2) Most significant event :

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proba. that at least one candidate (out of 3) has an energy high enough to make it appear even less background-like : $1 - (1 - 0.125)^3 \approx 0.33$

## 3) Position in the sky :

$\Omega_{\text{gw}} = 590\,\text{deg}^2$ (90% C.L. skymap) and then : $\Omega_{\text{gw}}/\Omega_{\text{all}} \approx 0.014$

proba. that at least one of the 3 candidates has a position consistent with 90% C.L. skymap :

$1 - (1 - 0.014)^3 \approx 0.04$