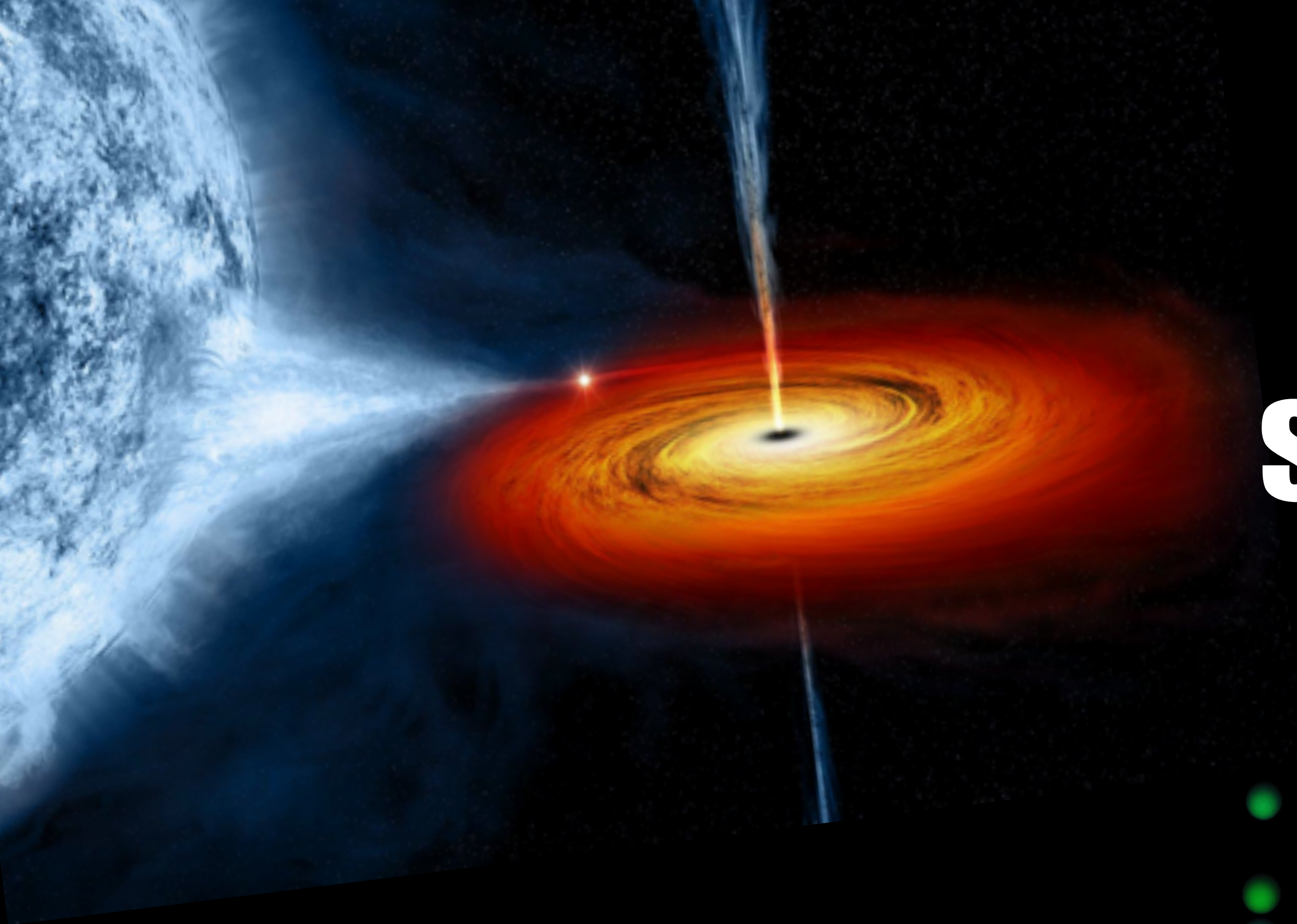
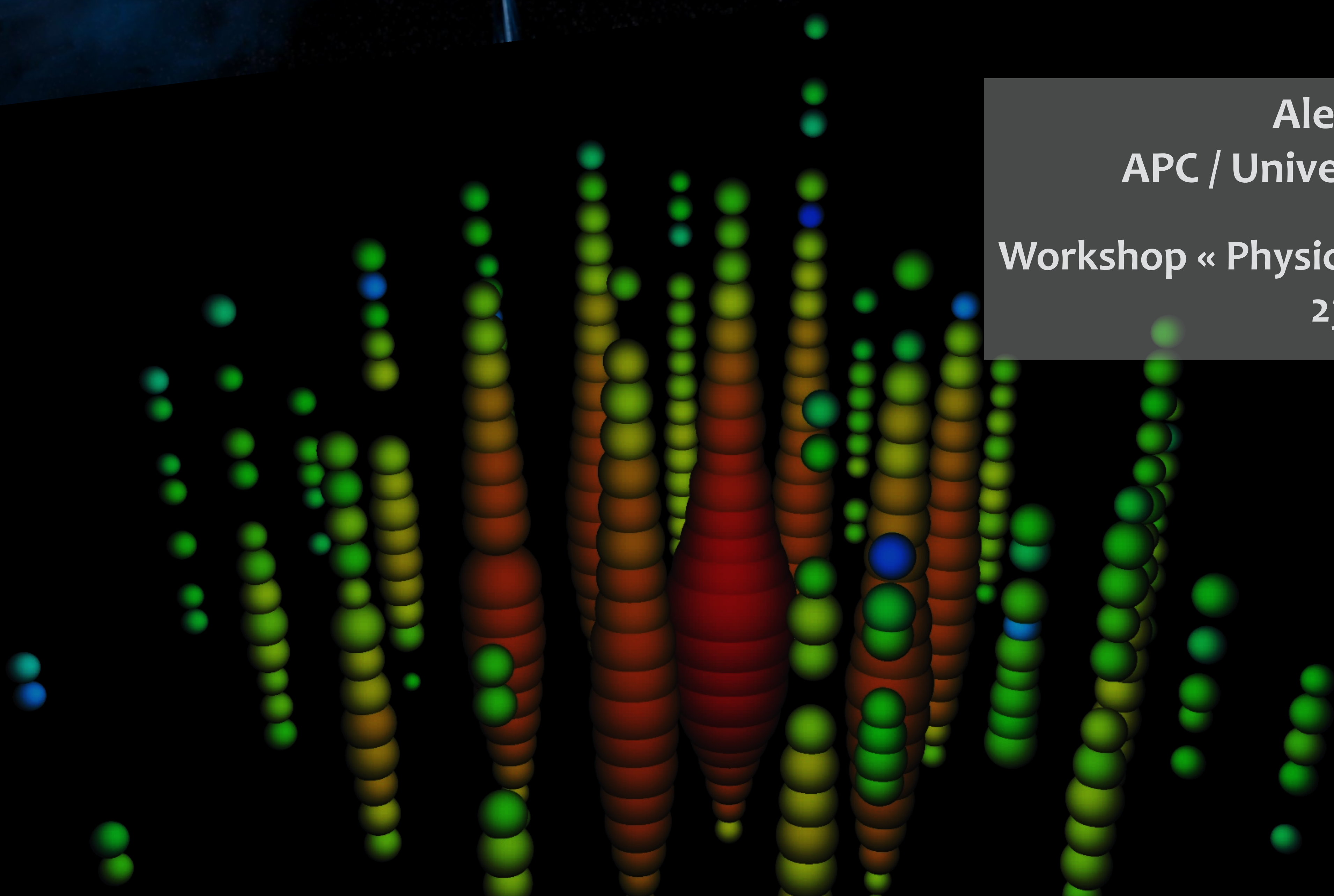


High-energy neutrino search from (galactic) transient sources

Alexis Coleiro
APC / Université Paris Diderot

Workshop « Physics of relativistic outflows »
23/03/2016



PARIS DIDEROT
PARIS 7

Outline

1 **I. Introduction**

> *Transient high-energy sources (microquasars and AGN)*
> *Particle acceleration mechanisms + observational constraints*

2 **II. Neutrino emission (theoretical models)**

> *p-p interactions*
> *p-gamma interactions*

3 **III. (First) observational constraints**

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1 Transient high-energy sources

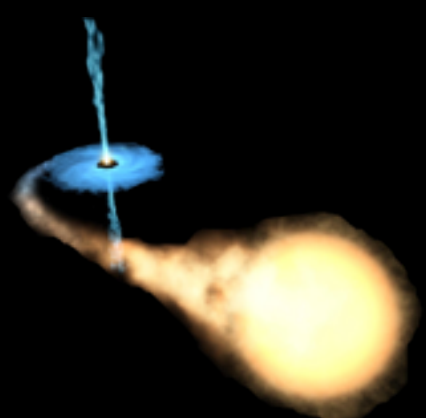

Merging compact objects


Supernovae

The unknown


AGN


Fast radio bursts


Accreting binaries


Magnetars Pulsars

Gamma-ray bursts

1 Transient high-energy sources

Merging compact objects

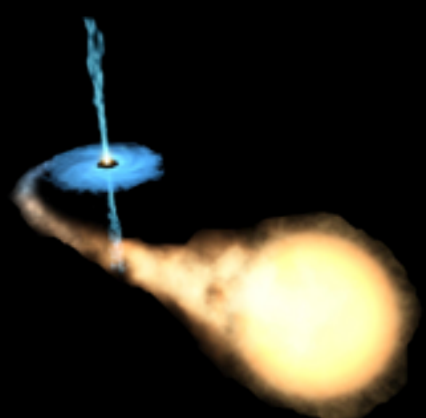
Supernovae

The unknown

AGN

Timescales: from the ms to the year

Fast radio bursts



Accreting binaries

Magnetars
Pulsars

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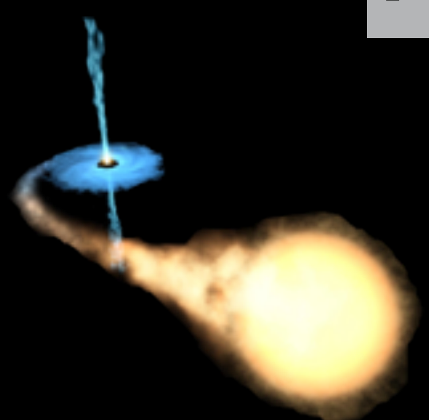
Timescales: from the ms to the year
Flaring all over the electromagnetic spectrum

Fast radio bursts



Accreting binaries

Magnetars Pulsars

Gamma-ray bursts

1 Transient high-energy sources

Merging compact objects

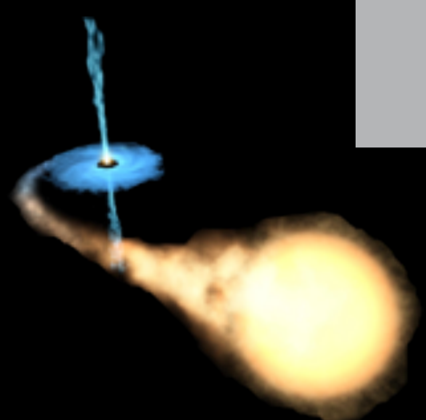
Supernovae

The unknown

AGN

Timescales: from the ms to the year
Flaring all over the electromagnetic spectrum
Multi-messenger emission (?)

Fast radio bursts

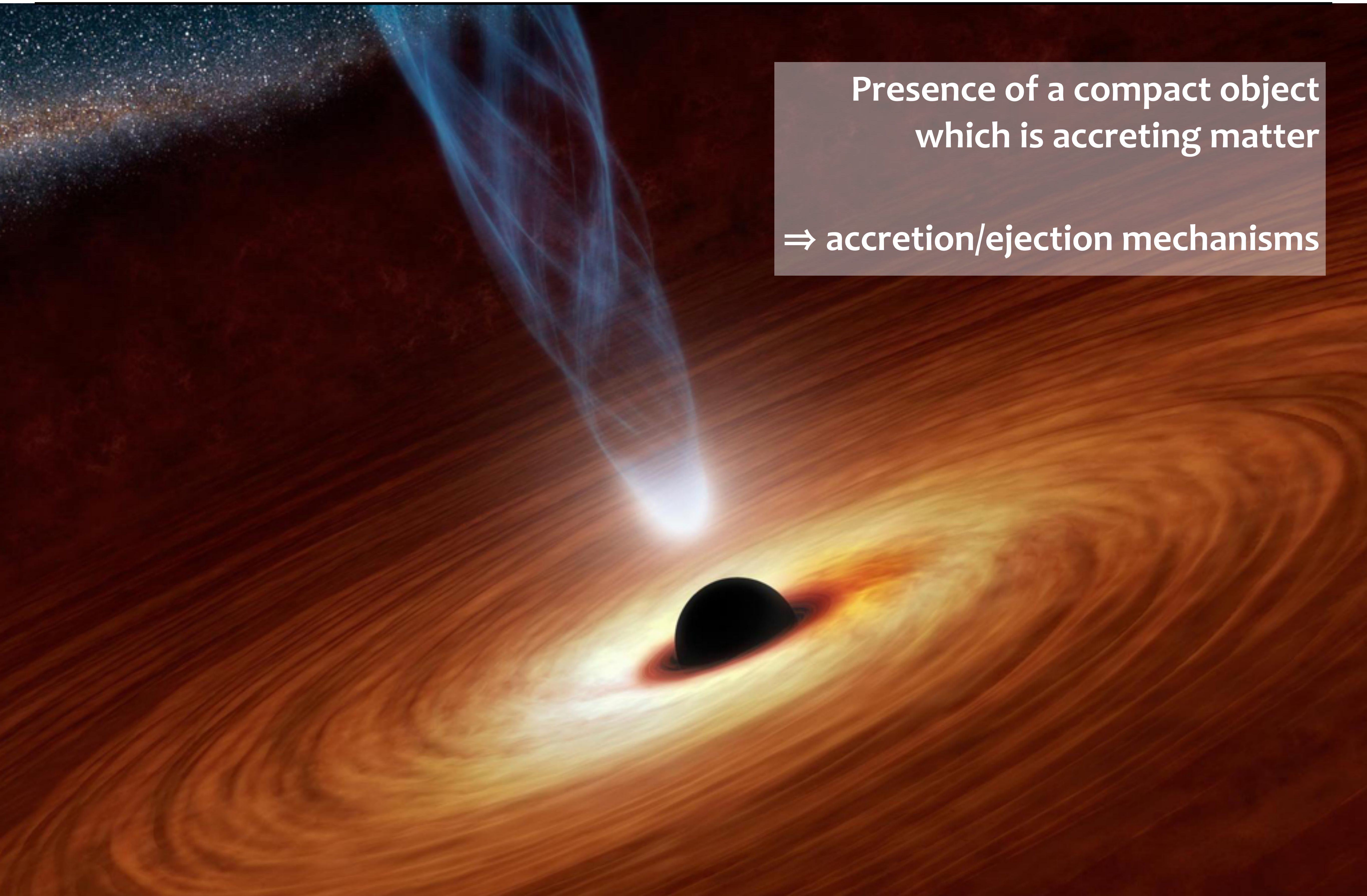


Accreting binaries

Magnetars
Pulsars

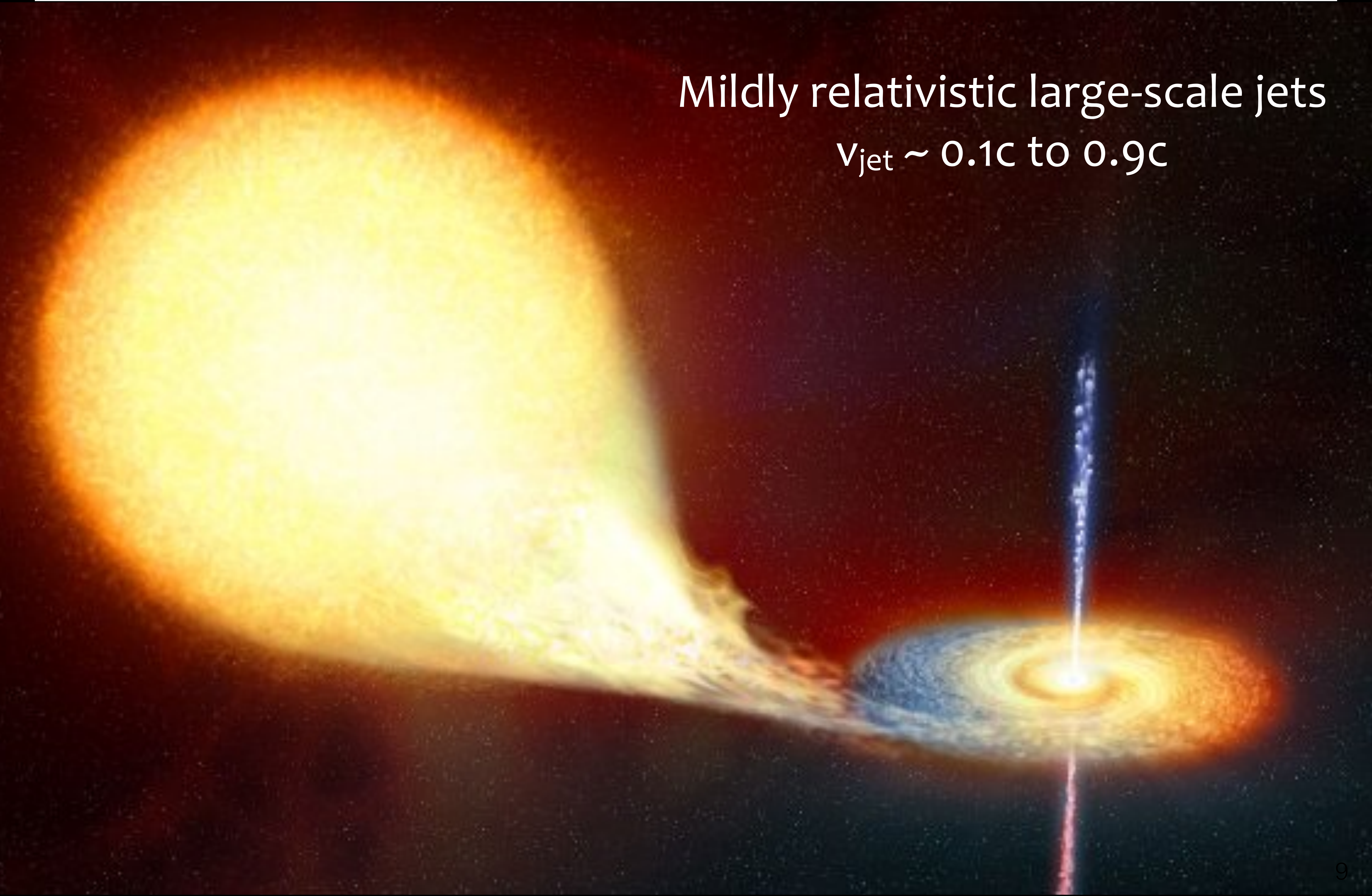
Gamma-ray bursts

1 Transient high-energy sources



1

Microquasars

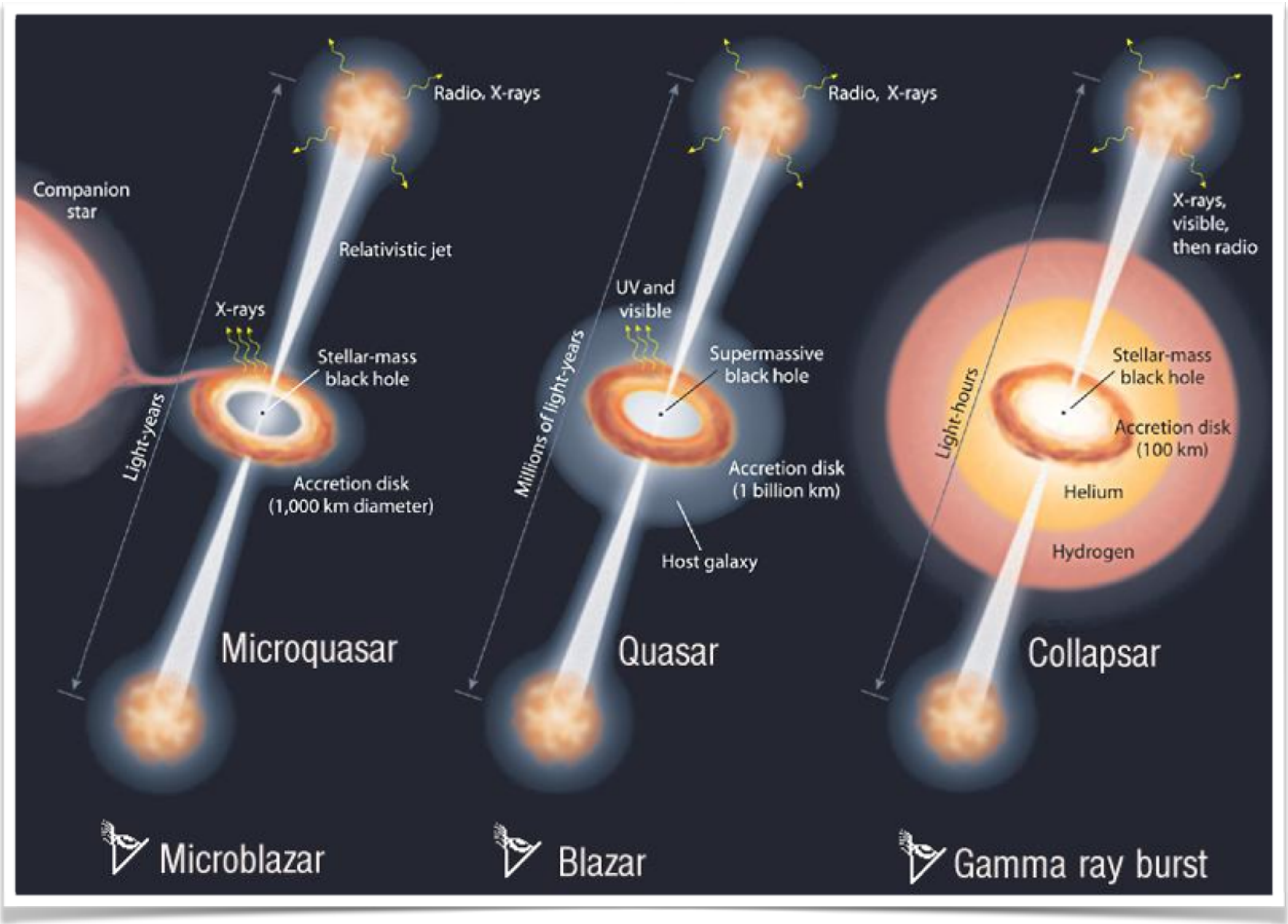


Mildly relativistic large-scale jets

$v_{jet} \sim 0.1c$ to $0.9c$

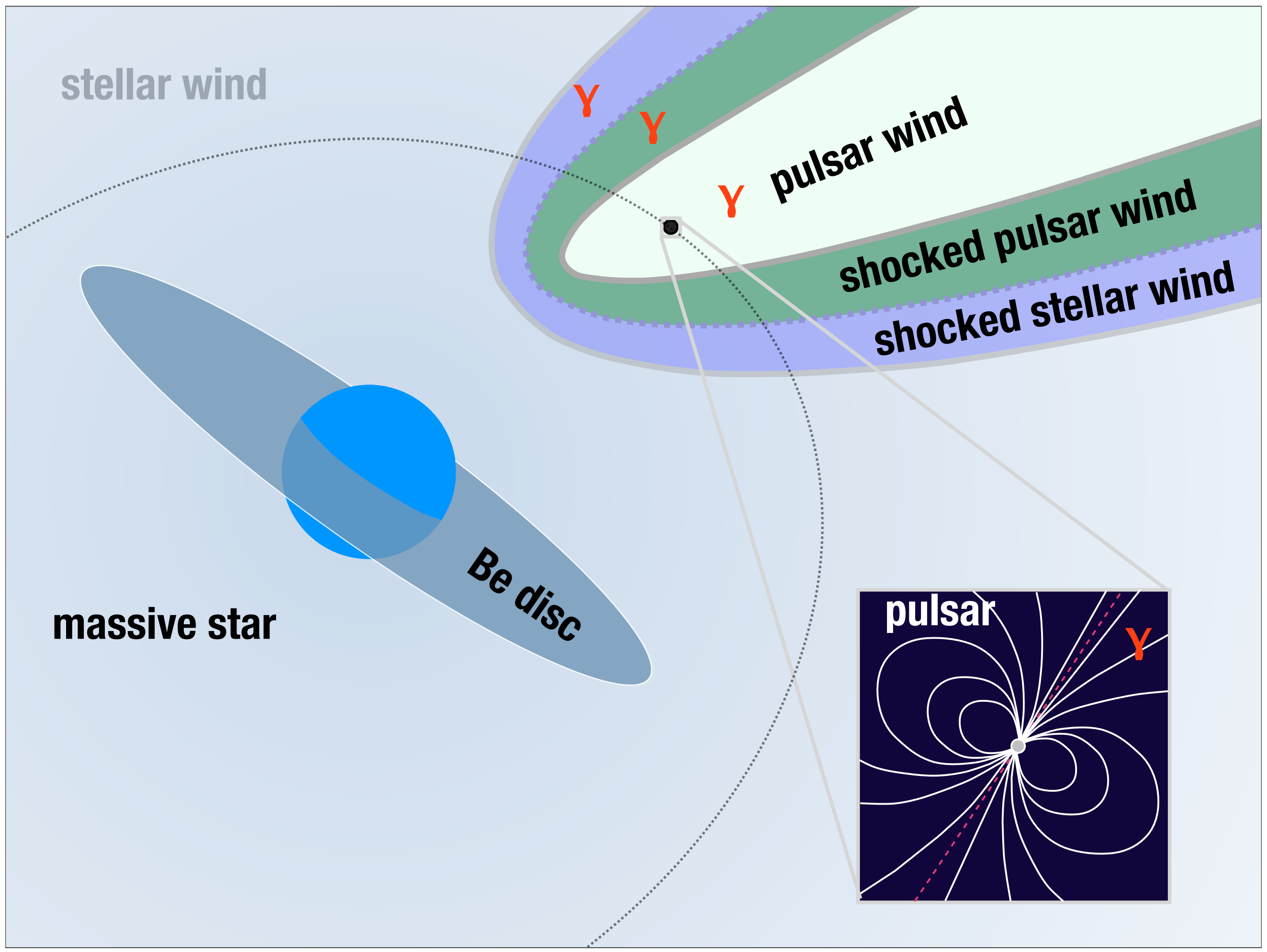
Microquasars

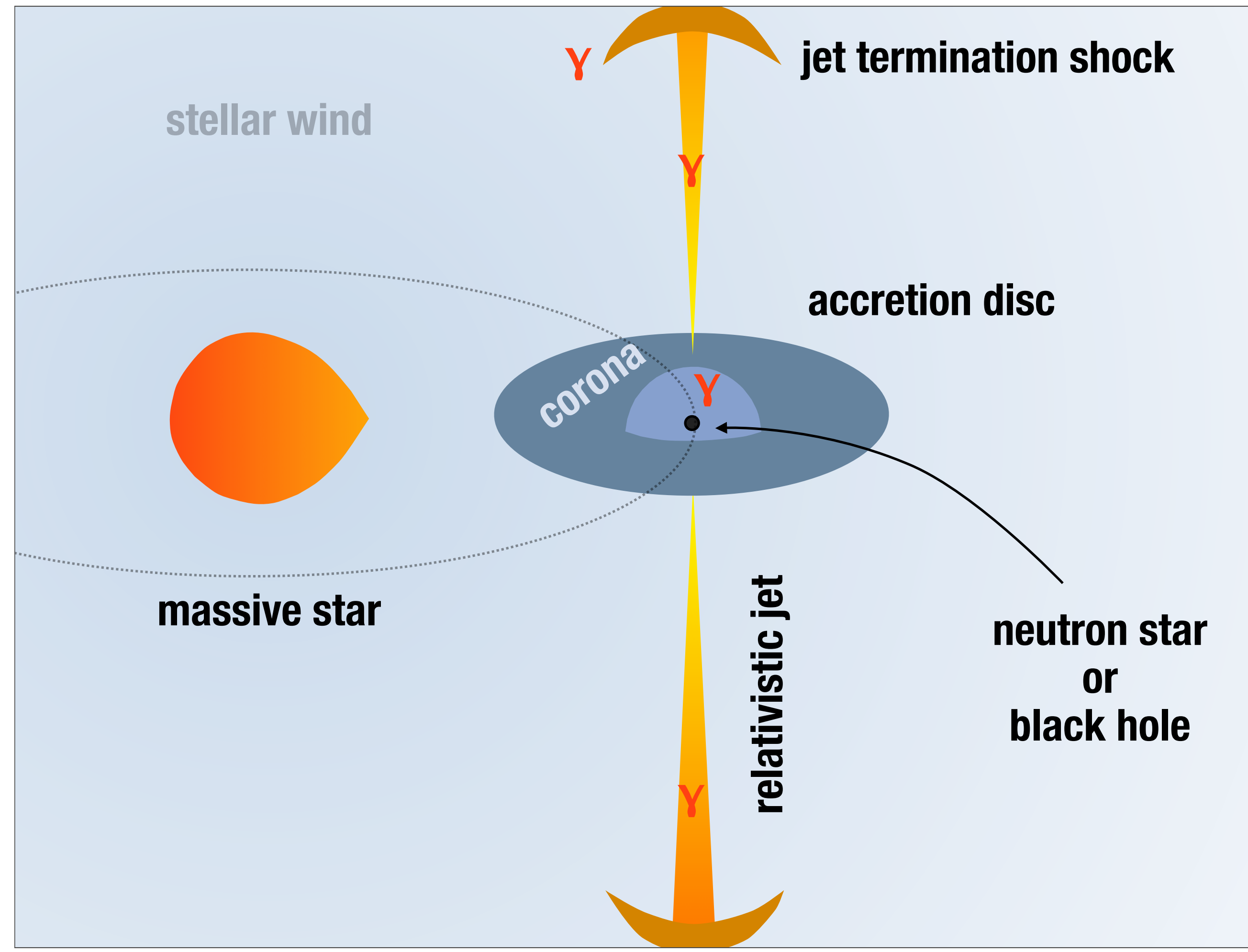
> to better understand particle acceleration and HE phenomena



Gamma-ray binaries

Two main models:





Gamma-ray binaries

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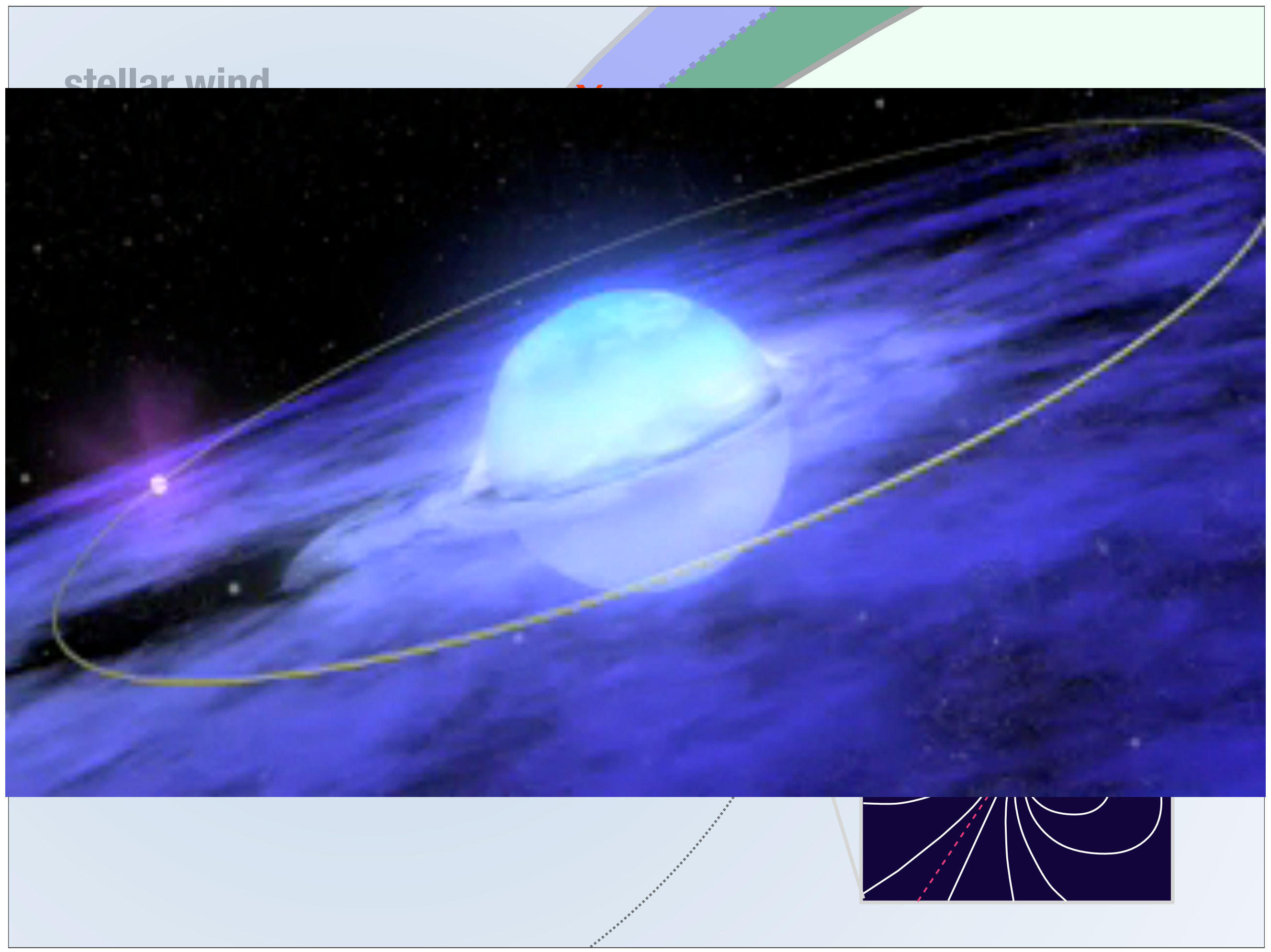
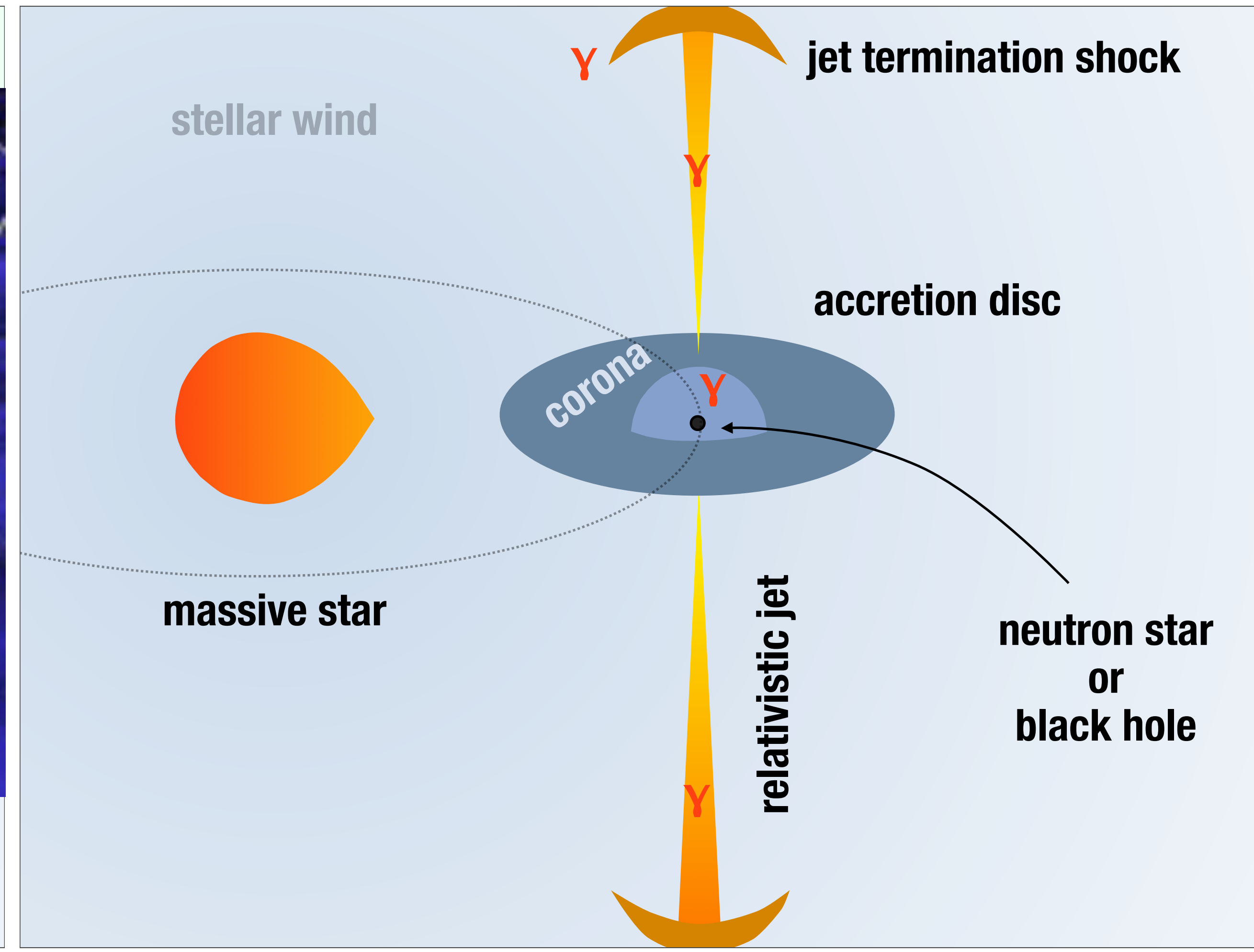




1 Jet formation mechanisms

Energy source to power the jet ?

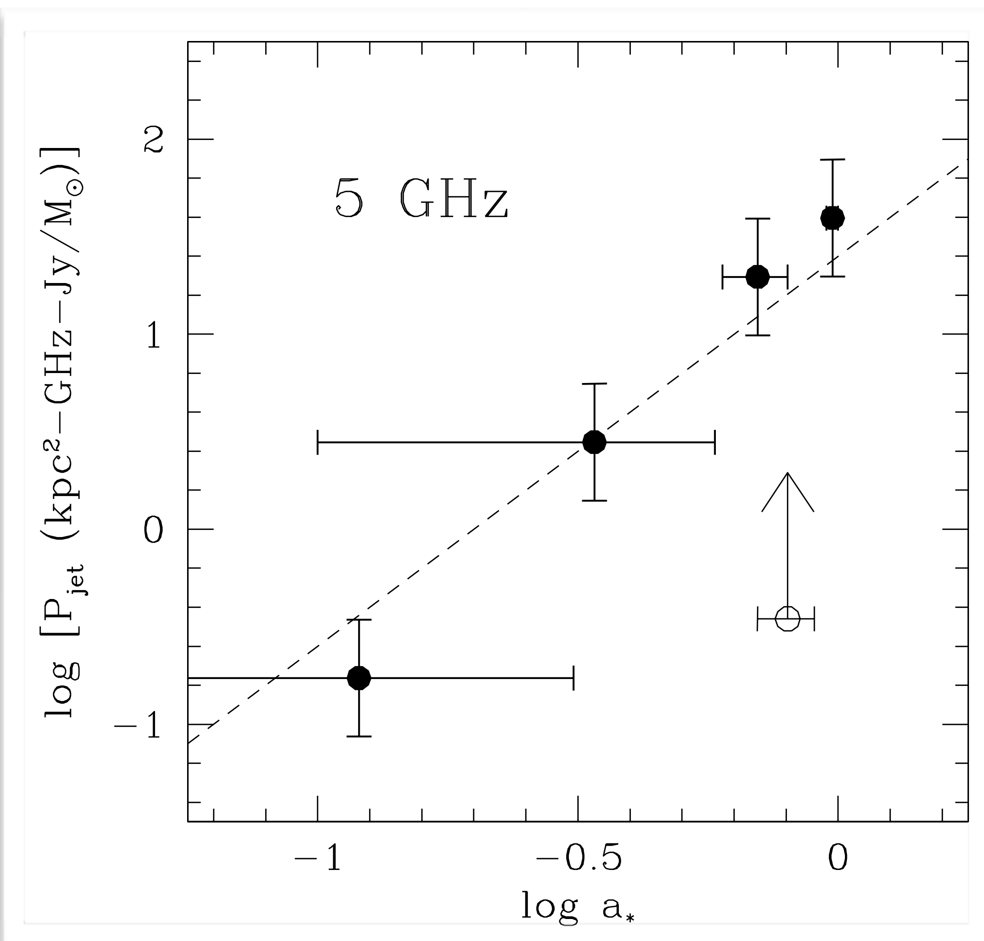
- Accretion disk: $L_{acc} \propto \dot{M}_{acc} c^2$
- Spinning black hole: $L_{spin} \propto a_s^2 B^2$

➜ but still need another mechanism to explain the acceleration to relativistic velocities

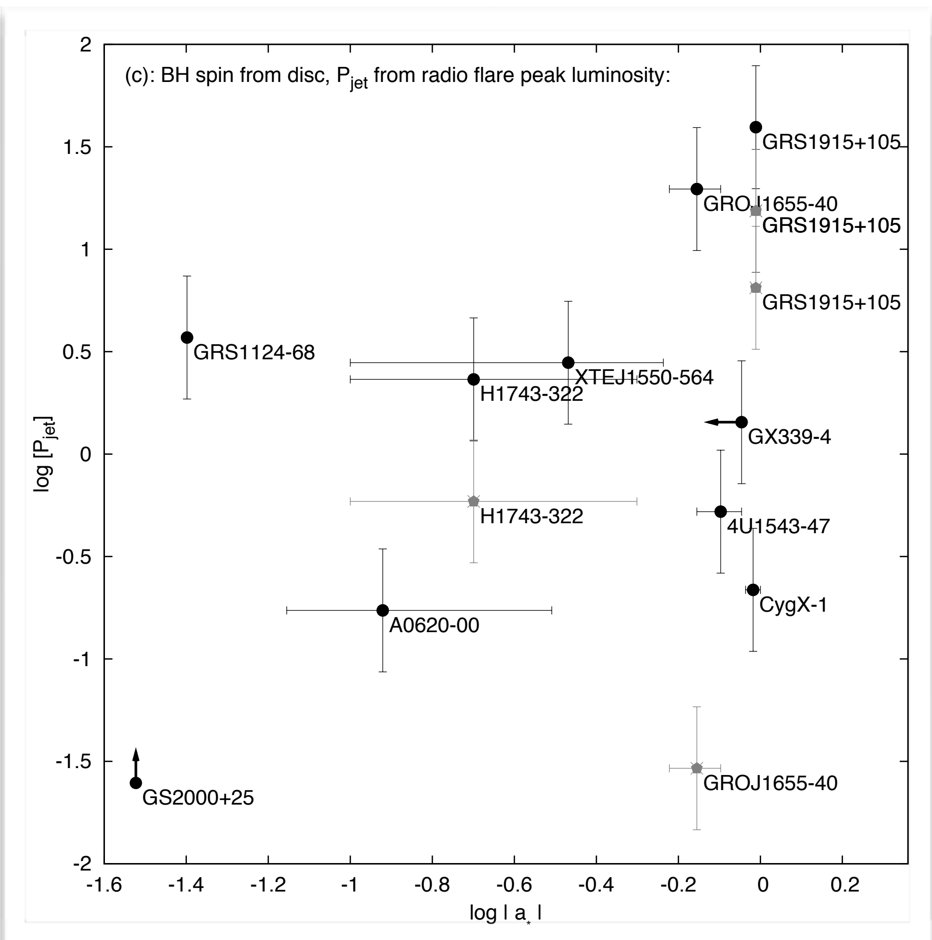
Jet formation mechanisms

Jet formation mechanism not established yet
Find observational signatures to distinguish between:

-accretion disc rotation model (Blandford & Payne 1982) : **hadronic jets (?)**
-black hole spin model (Blandford & Znajek 1977) : based on the birth of a dense, relativistic pair plasma in a strongly magnetized region : **leptonic jets**



Narayan & McClintock, 2012



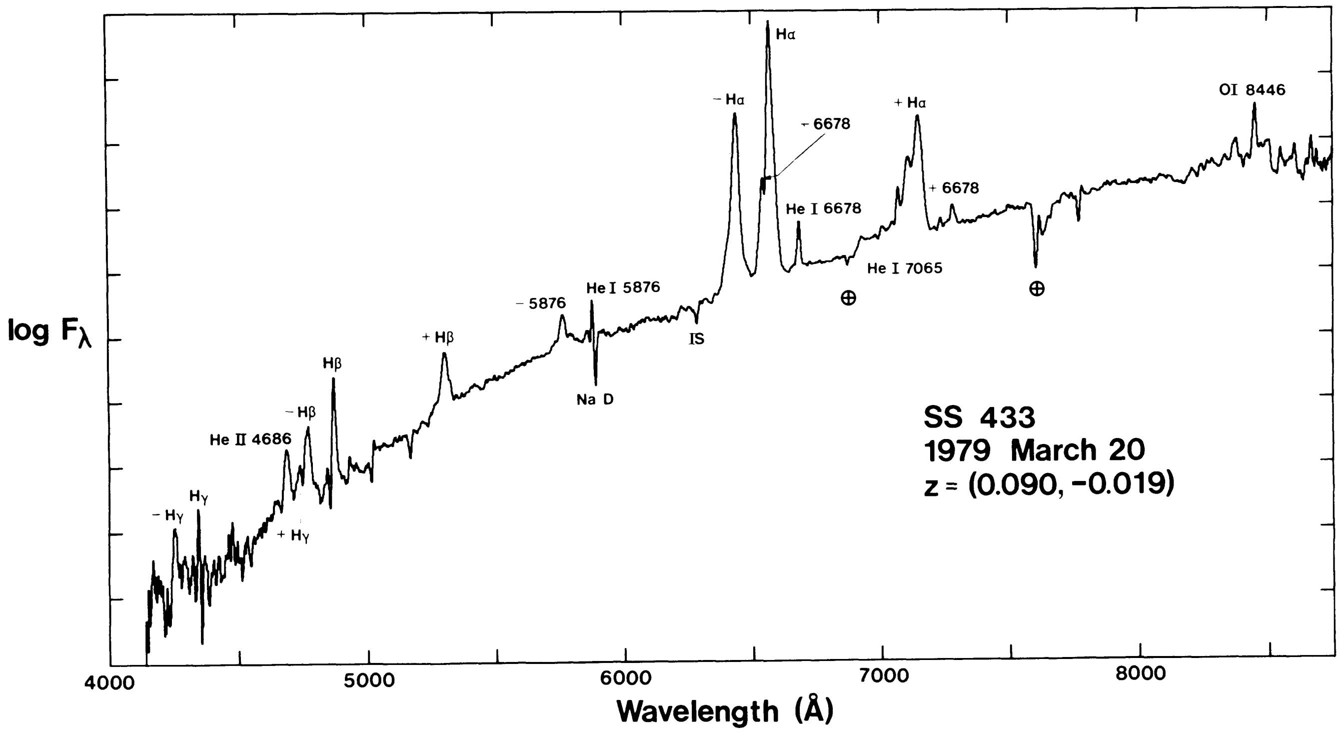
Russell et al., 2013

Jet composition

1

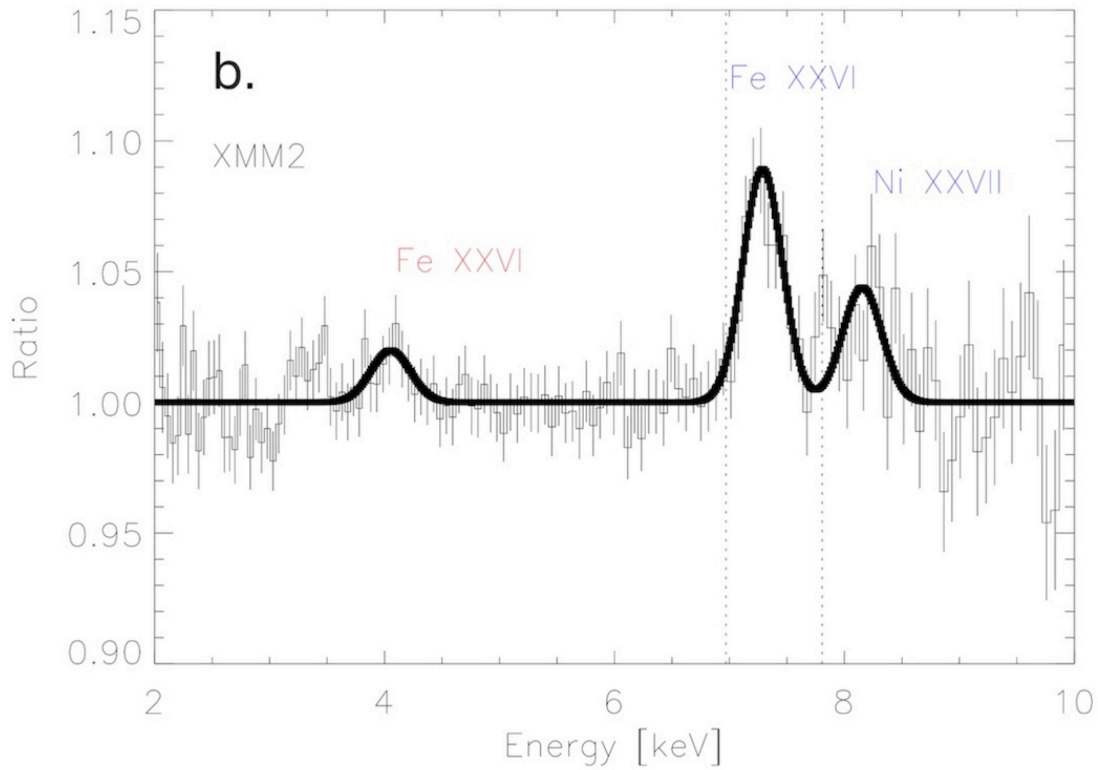
- One of the most important uncertainty: **jet composition** !
- In nearly all cases: jet radiation = synchrotron (only requires leptons)
  ⇒ not clear whether the jets are composed of e^+/e^- or p/e^-
- **Two exceptions: SS 433 and 4U 1630-47 (?):**

Doppler-shifted emission lines in SS 433 jets at ~0.25c



Margon et al., 1979

Doppler-shifted emission lines in gas moving at ~0.7c coincident with radio emission !



Diaz-Trigo et al., 2013

BUT detection of such "smoking gun" lines from jets having Lorentz factors well in excess of unity may be far more difficult than in SS 433, as the lines are anticipated to be very broad…

Jet composition

1

- One of the most important uncertainty: **jet composition** !
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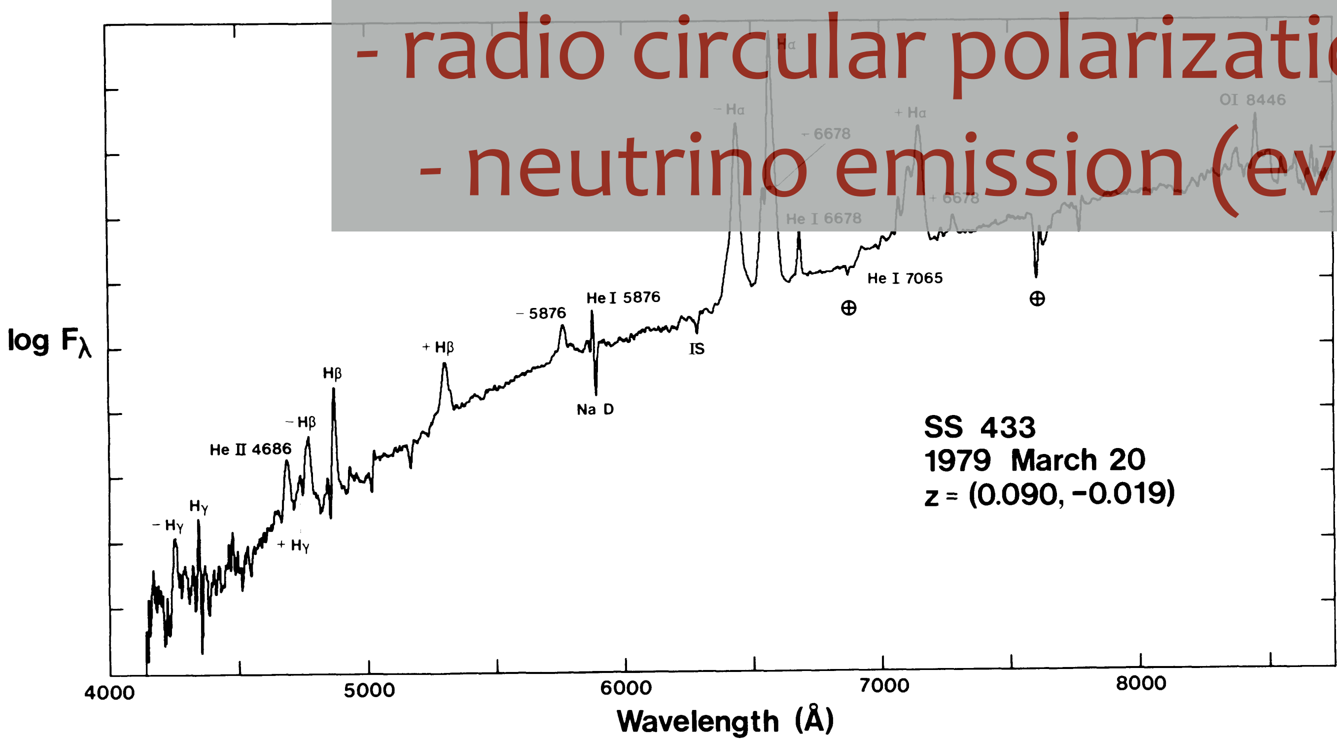
- **<u>Two exceptions: SS 433 and 4U 1630-47 (?):</u>**

Doppler-shifted emission lines in SS 433 jets at ~0.26c



Margon et al., 1979

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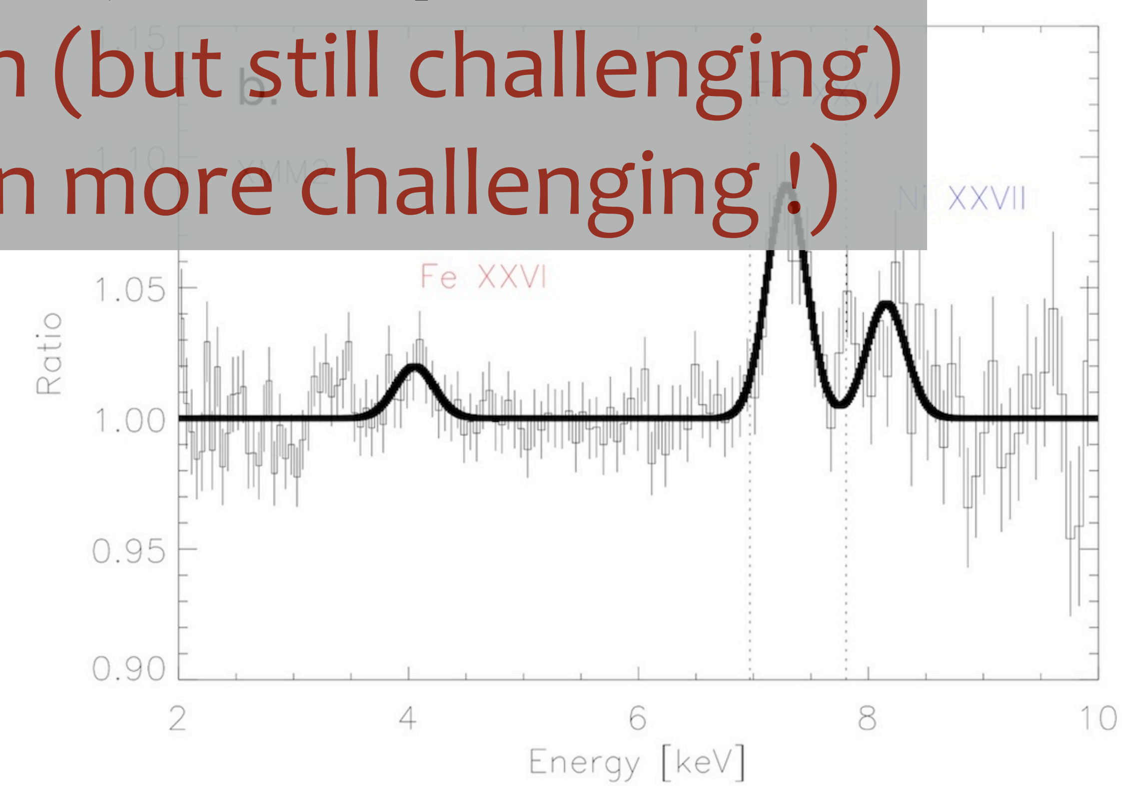

Diaz-Trigo et al., 2013

How to further constrain jet composition ?
- radio circular polarization (but still challenging)
- neutrino emission (even more challenging !)

BUT detection of such "smoking gun" lines from jets having Lorentz factors well in excess of unity may be far more difficult than in SS 433, as the lines are anticipated to be very broad…

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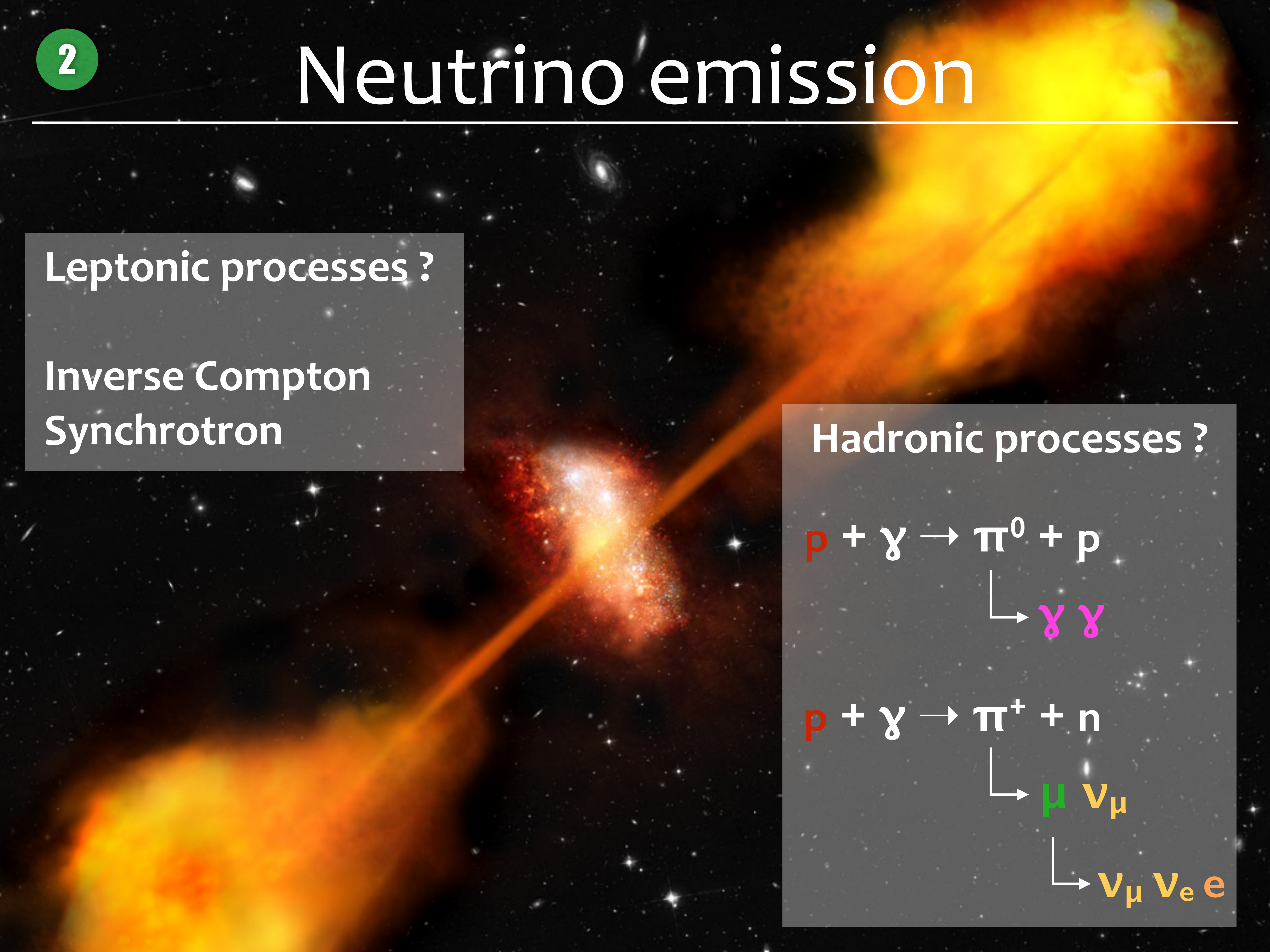
2

Neutrino emission



Leptonic processes ?

Inverse Compton
Synchrotron

Hadronic processes ?

$$p + \gamma \rightarrow \pi^0 + p$$
$$\hookrightarrow \gamma\ \gamma$$

$$p + \gamma \rightarrow \pi^+ + n$$
$$\hookrightarrow \mu\ \nu_\mu$$
$$\hookrightarrow \nu_\mu\ \nu_e\ e$$

2

Neutrino emission

Leptonic processes ?

Inverse Compton
Synchrotron

Hadronic processes ?

$$p + p \rightarrow p + p + \pi^0$$
$$\hookrightarrow \gamma\ \gamma$$

$$p + p \rightarrow \pi^+ + p + n$$
$$\hookrightarrow \mu\ \nu_\mu$$
$$\hookrightarrow \nu_\mu\ \nu_e\ e$$

2 X-ray binaries viewed by ANTARES

Several models describe neutrino emission from X-ray binaries:

p-p or p-ɣ interaction between jet and matter/radiation from the companion star or inside the jet directly:

see e.g. :

- Romero et al.: « **heavy jets » with dominant p+p collision : require large matter density (>10^{10} cm^{-3}) :**

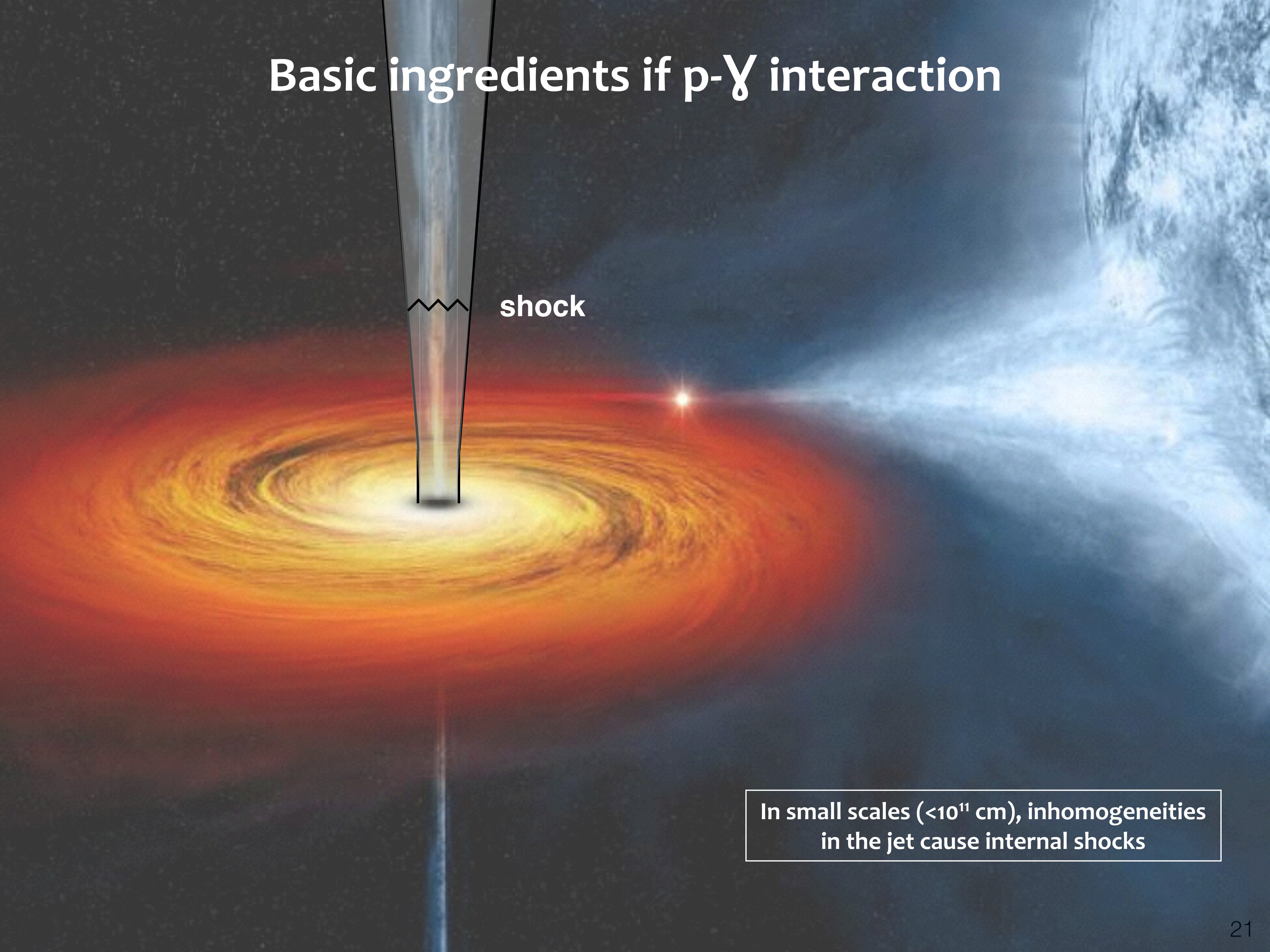
  may be valid for HMXB e.g. Cyg X-3 :

  stellar wind with mass loss rate 10^{-5} $M_{\odot}$/yr et v_{∞}=1000 km/s

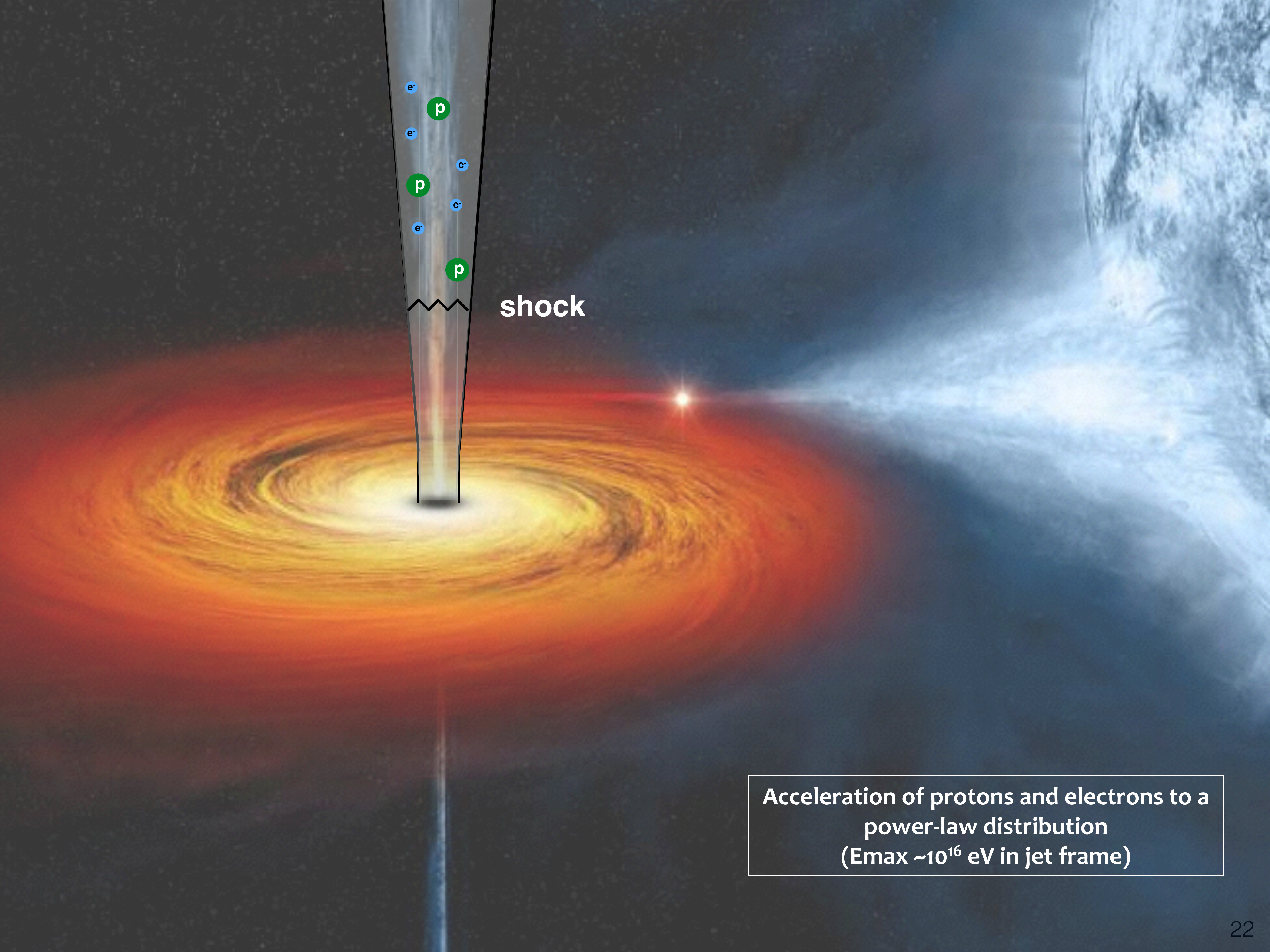
  → d>$10^{11}$$cm^{-3}$ at r=10^{12} cm from the star

- Levinson & Waxman; Aharonian et al.; Mannheim et al.: **relativistic jet interacting with dense photon field (LMXB): photohadronic models**

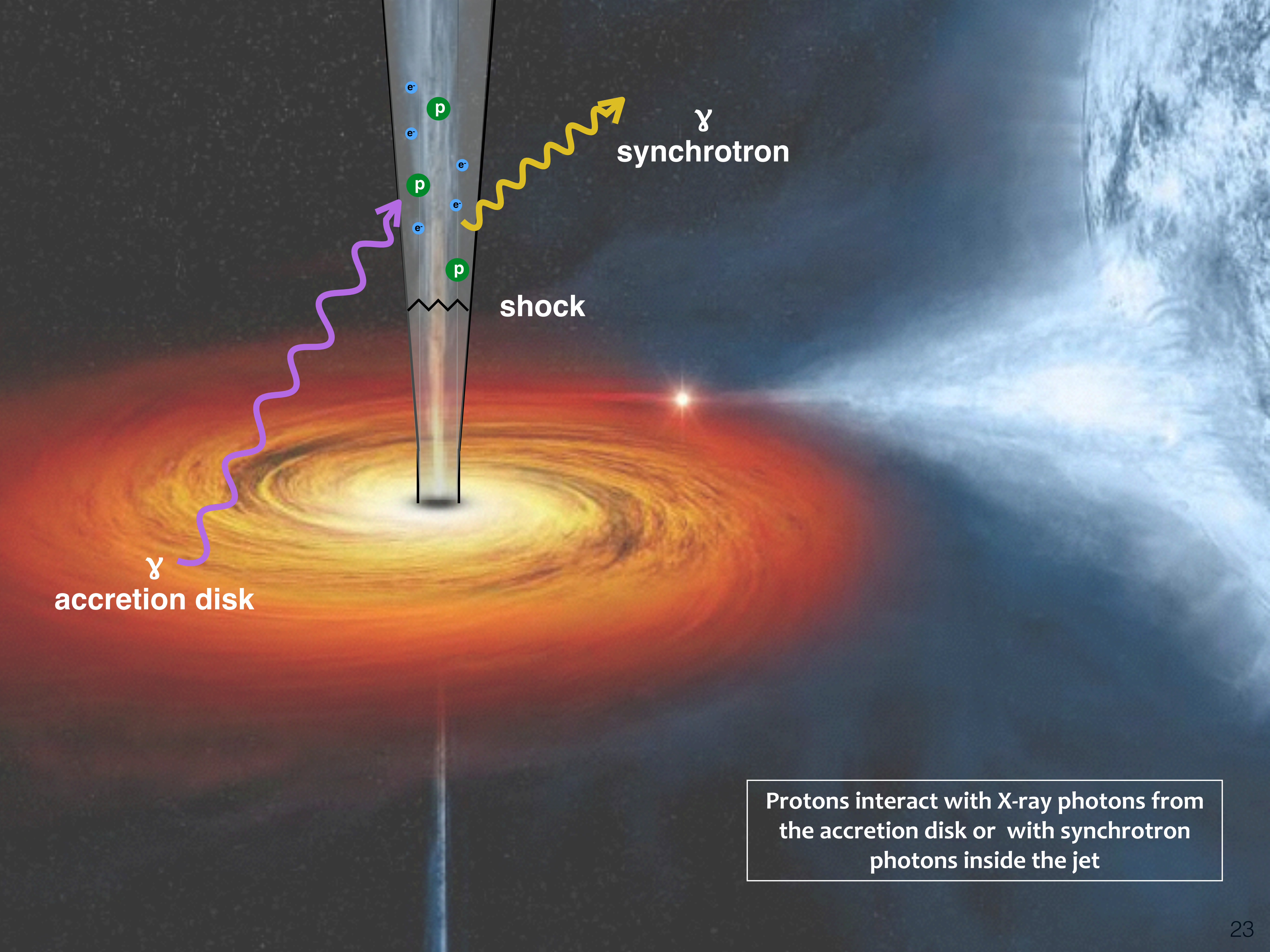
Basic ingredients if p-ɣ interaction



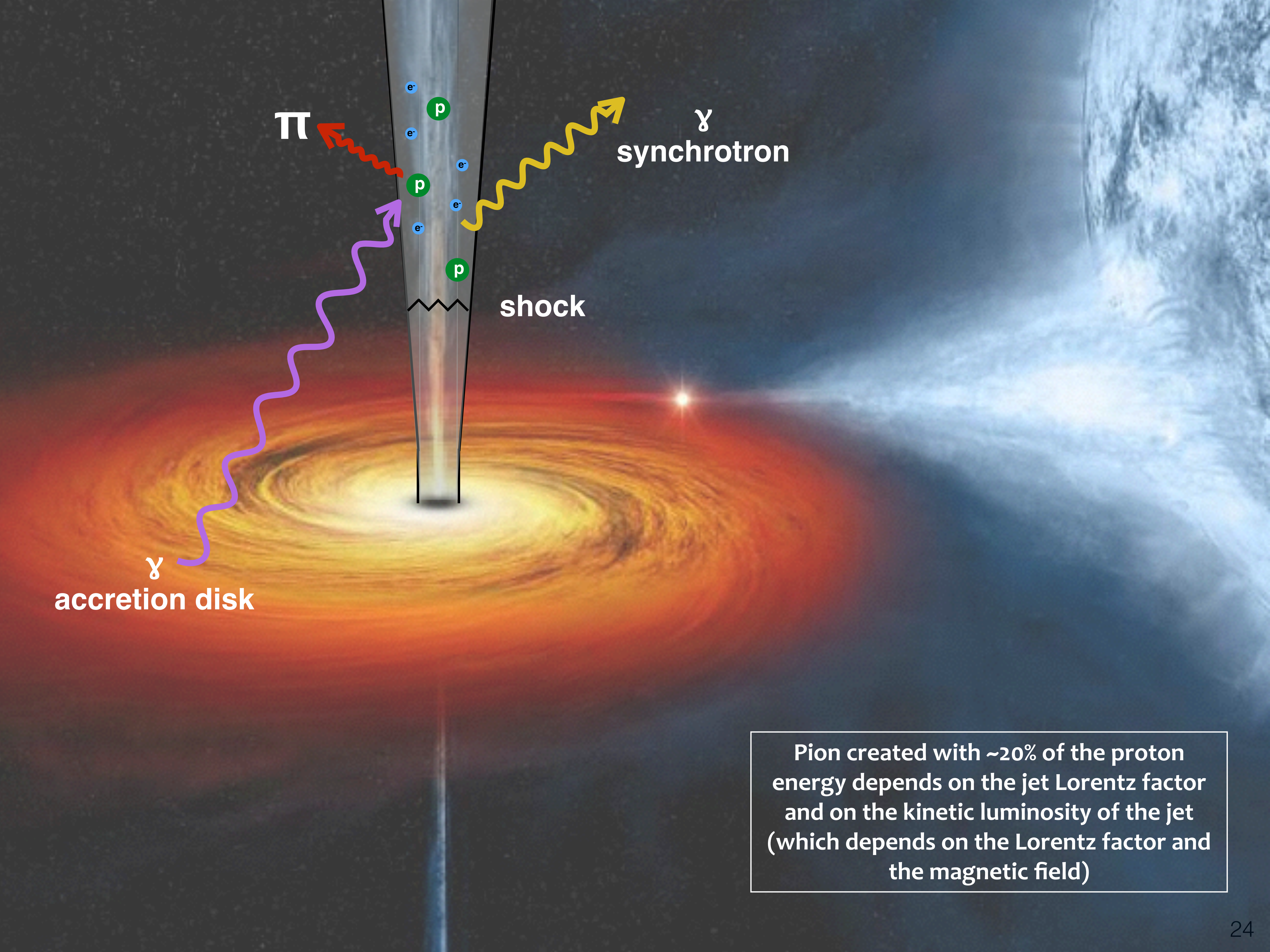
In small scales ($<10^{11}$ cm), inhomogeneities in the jet cause internal shocks



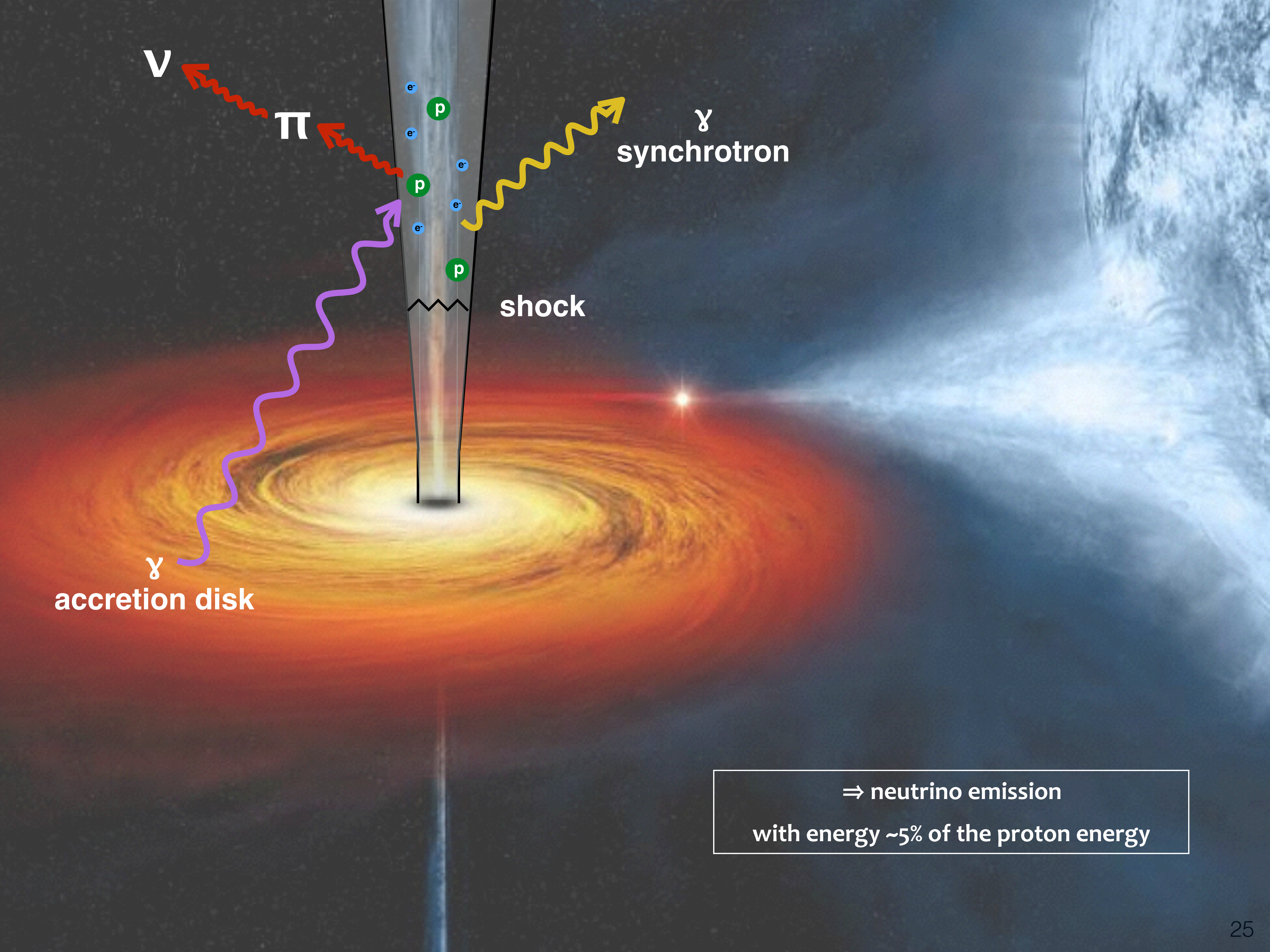
Acceleration of protons and electrons to a power-law distribution
(Emax ~10^{16} eV in jet frame)



Protons interact with X-ray photons from the accretion disk or with synchrotron photons inside the jet



Pion created with ~20% of the proton energy depends on the jet Lorentz factor and on the kinetic luminosity of the jet (which depends on the Lorentz factor and the magnetic field)



⇒ neutrino emission

with energy ~5% of the proton energy

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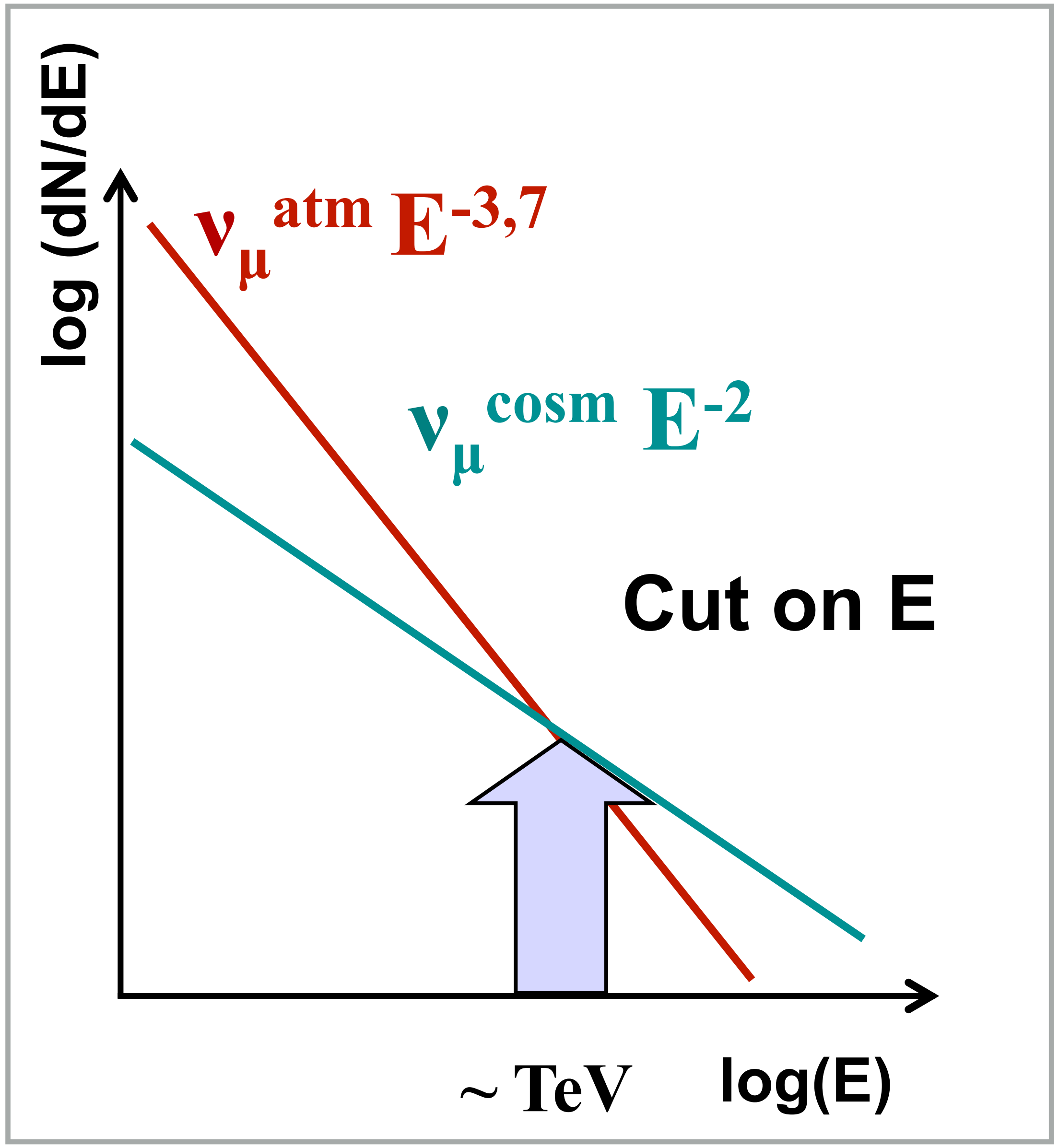
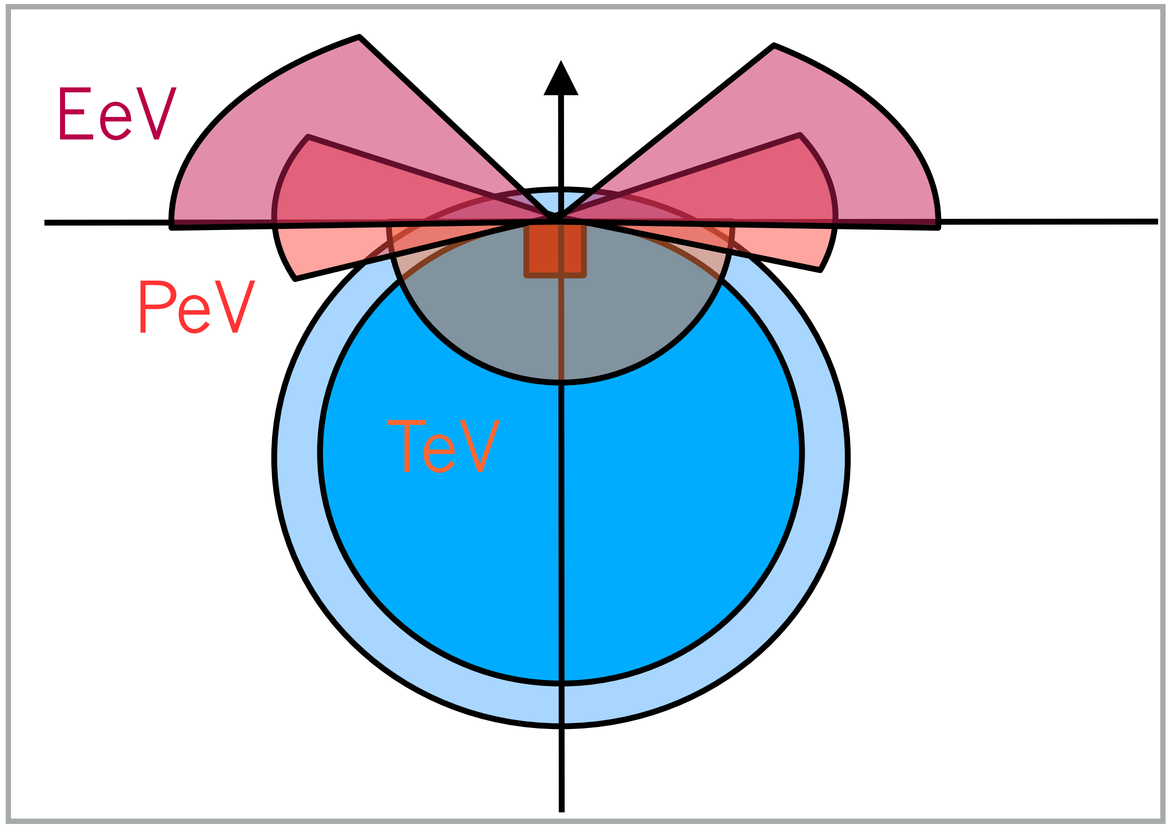
Neutrino astronomy in the Mediterranean

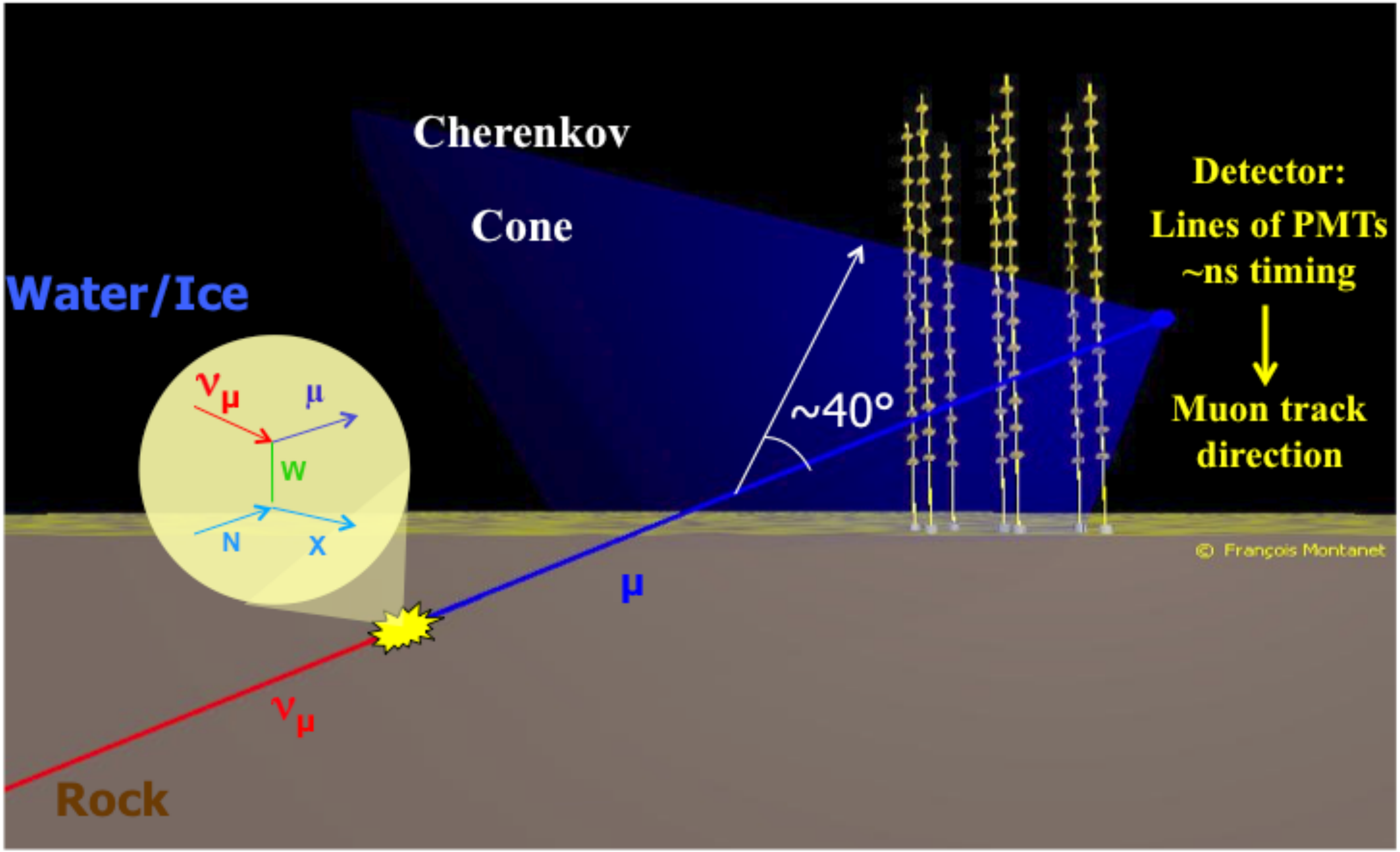
> Look at high energy events



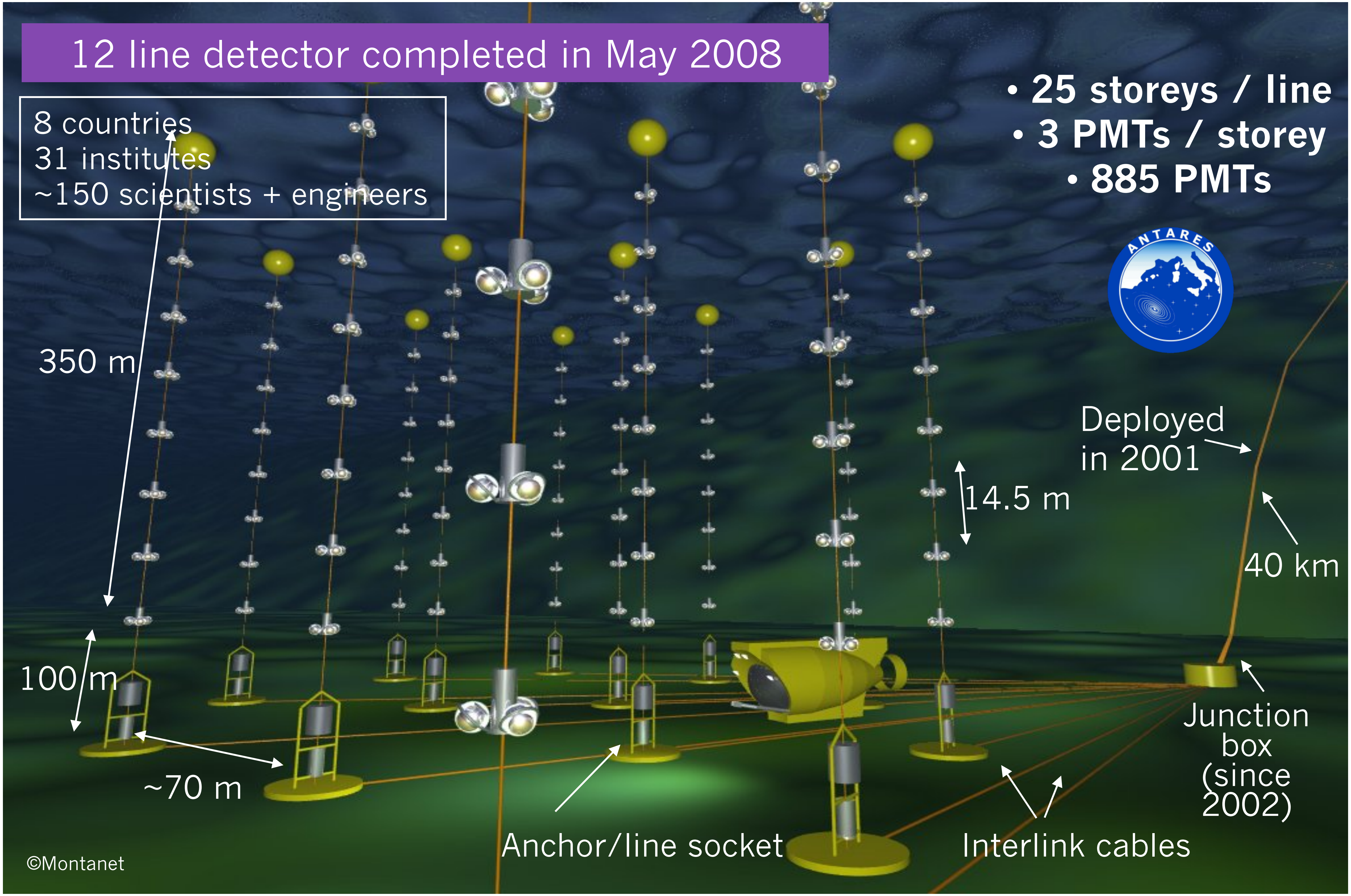


3

Neutrino astronomy



3 The ANTARES neutrino telescope

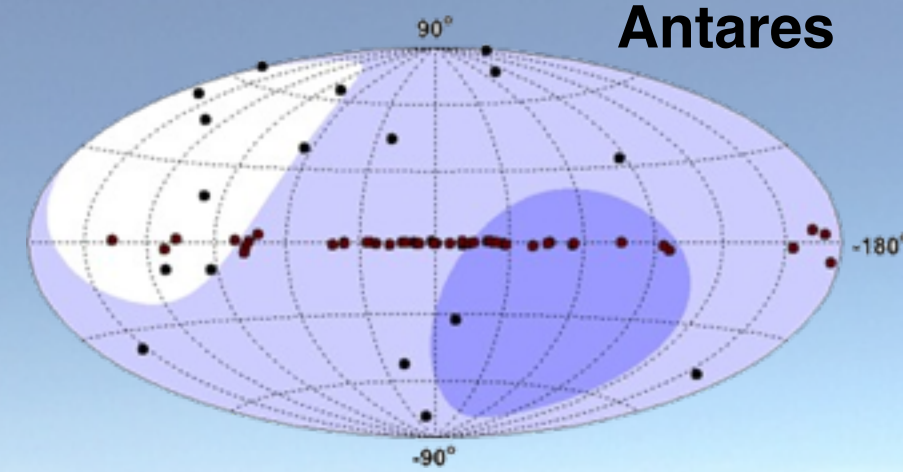


3 Neutrino astronomy in the Mediterranean

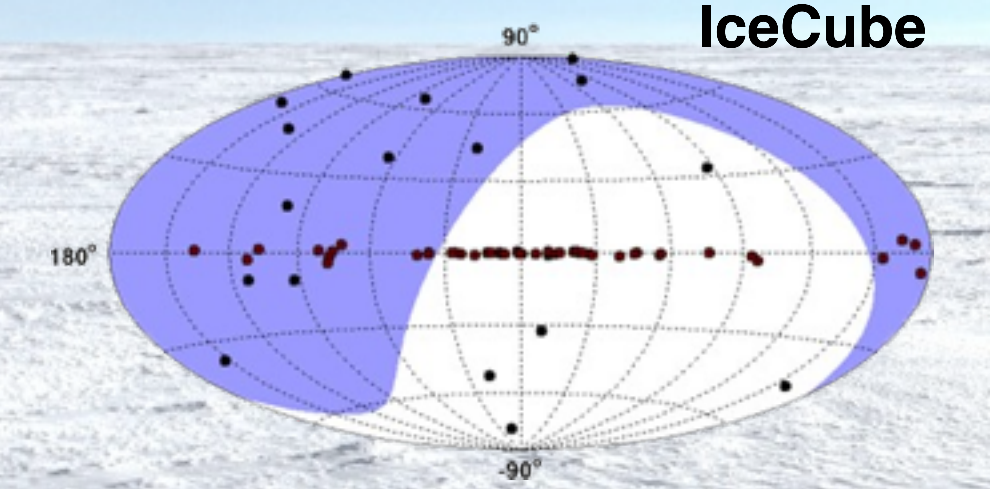
Mediterranean / South Pole

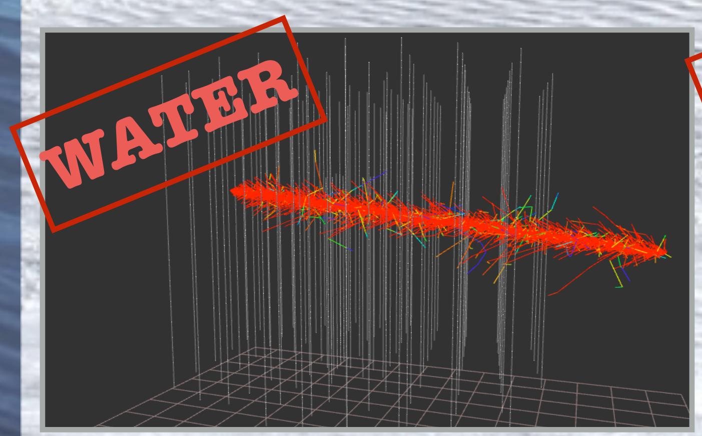
- **Complementary coverage:**
  - galactic center / extragalactic sources
- **Good pointing accuracy / Calorimetry**
- **Optical noise (biolum) + K40 / no noise**
- **Absorption / diffusion**
- **Mediterranean : logistically attractive**

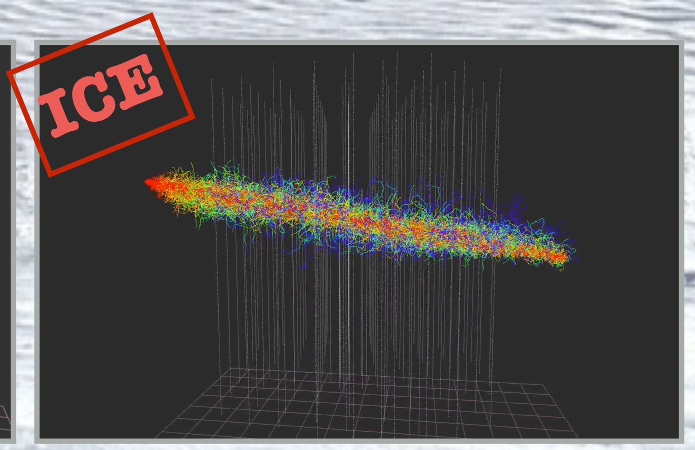
Antares



IceCube

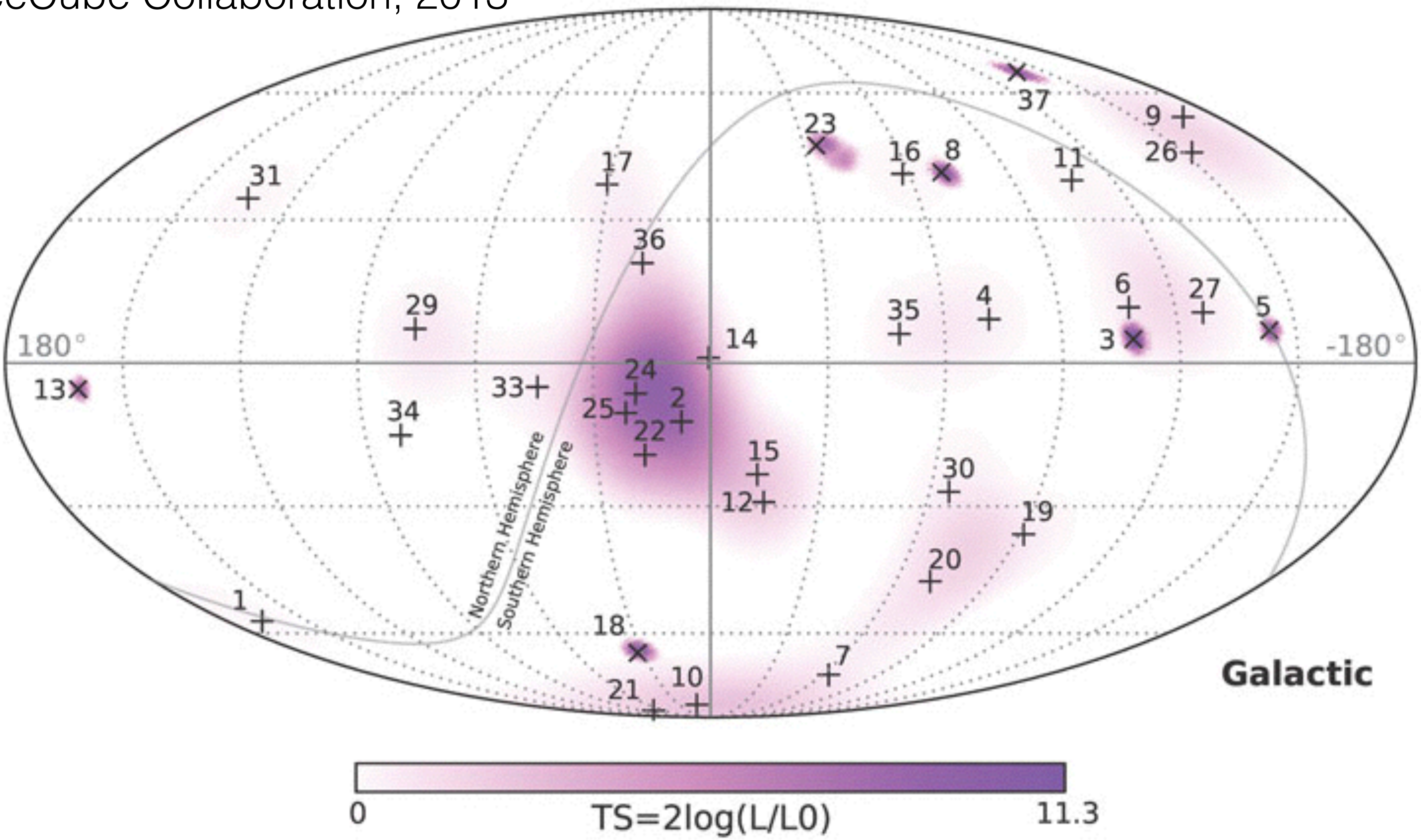






3 IceCube cosmic neutrino signal

IceCube Collaboration, 2013



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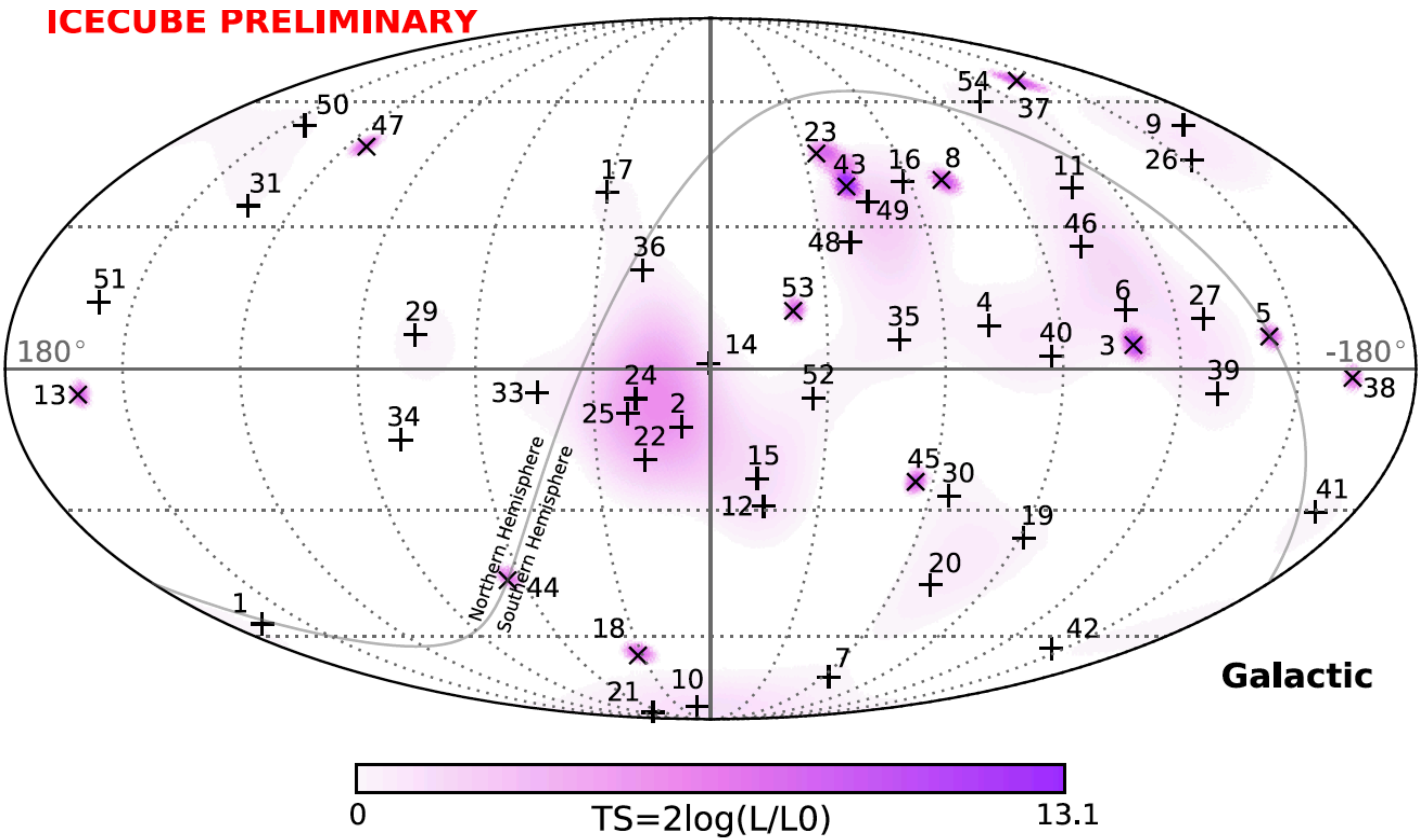
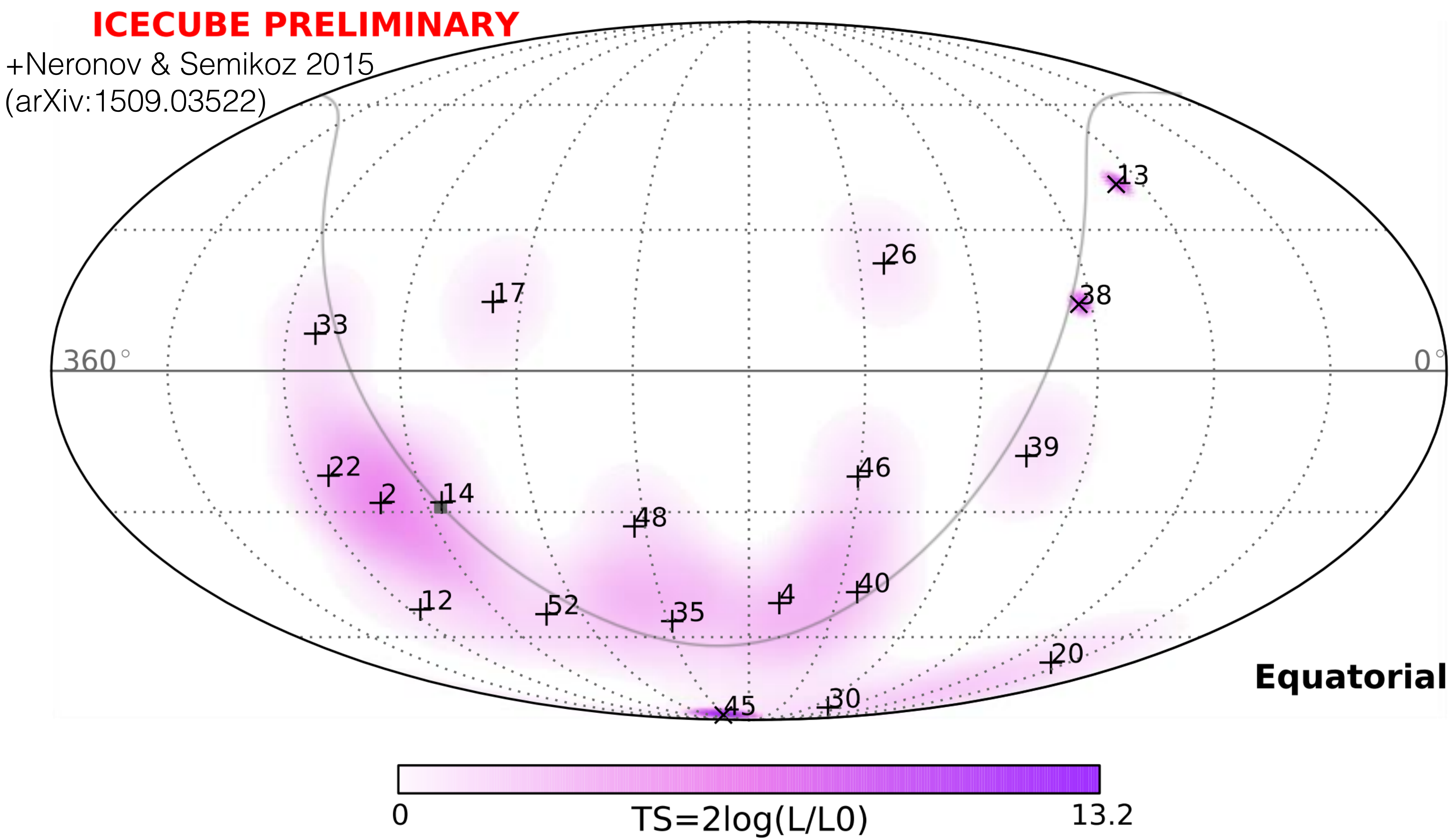
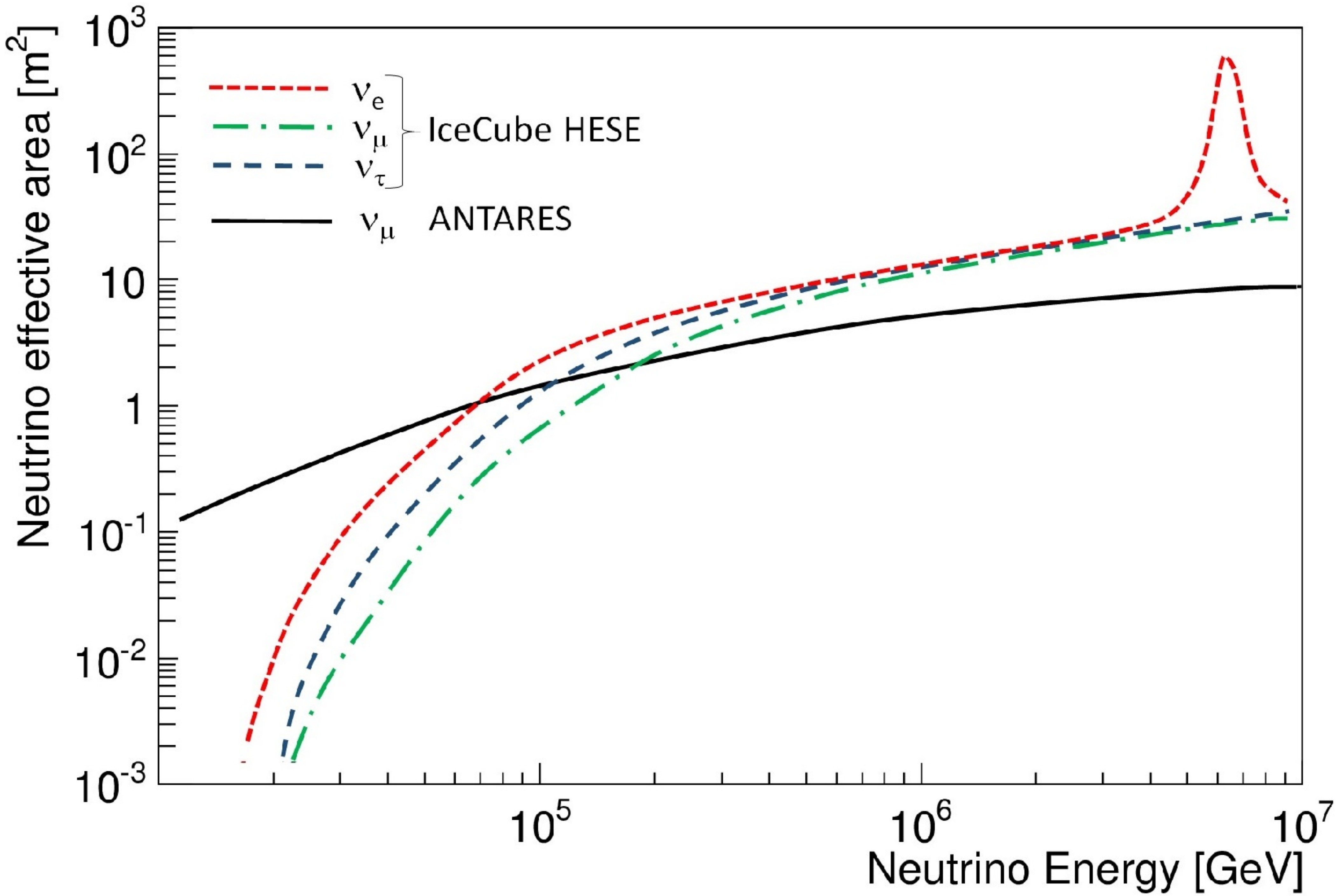


3 IceCube cosmic neutrino signal

Energy > 100 TeV (*a posteriori*)



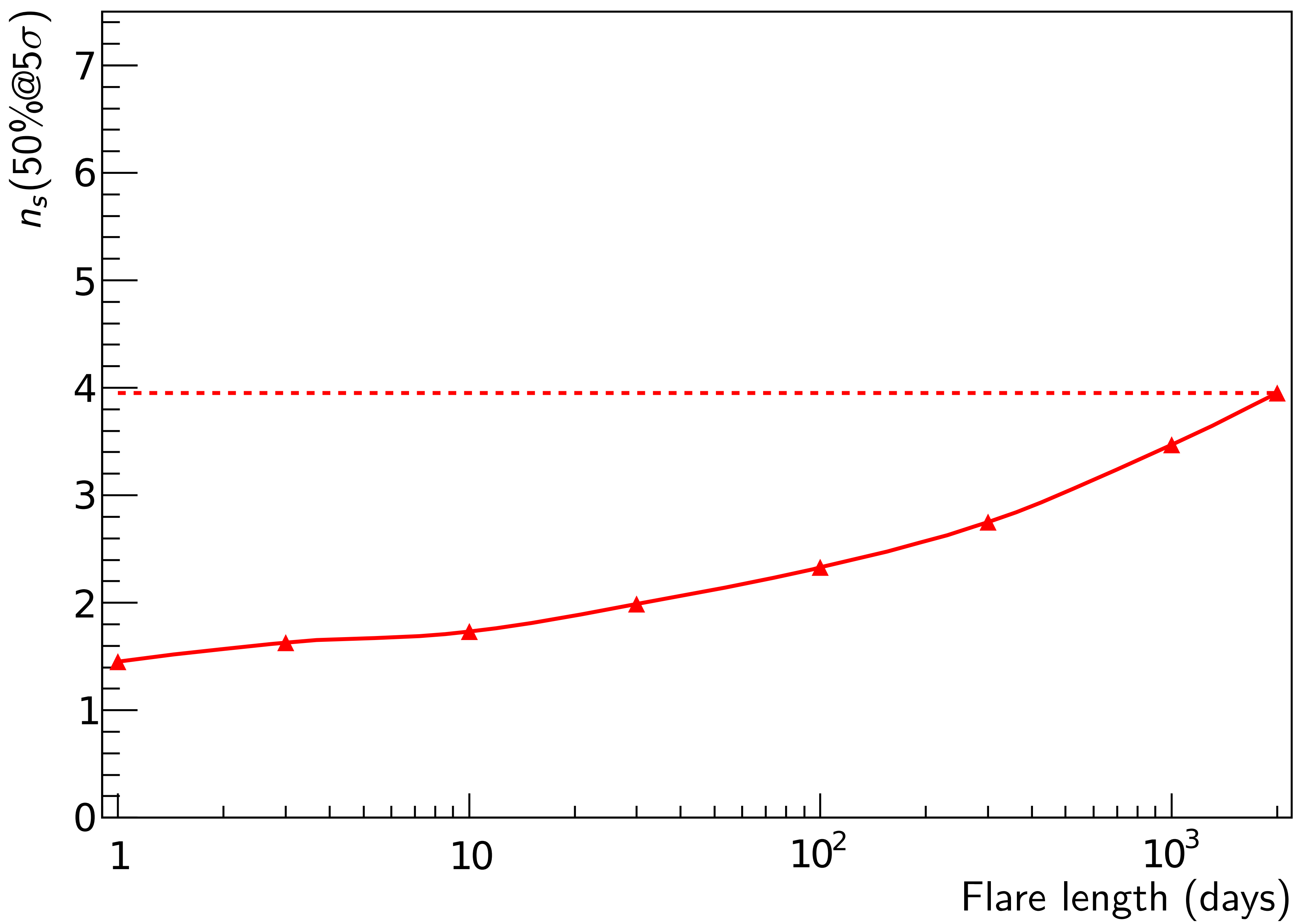
Neutrino emission in the Galactic plane region



Spurio, M. (2015)

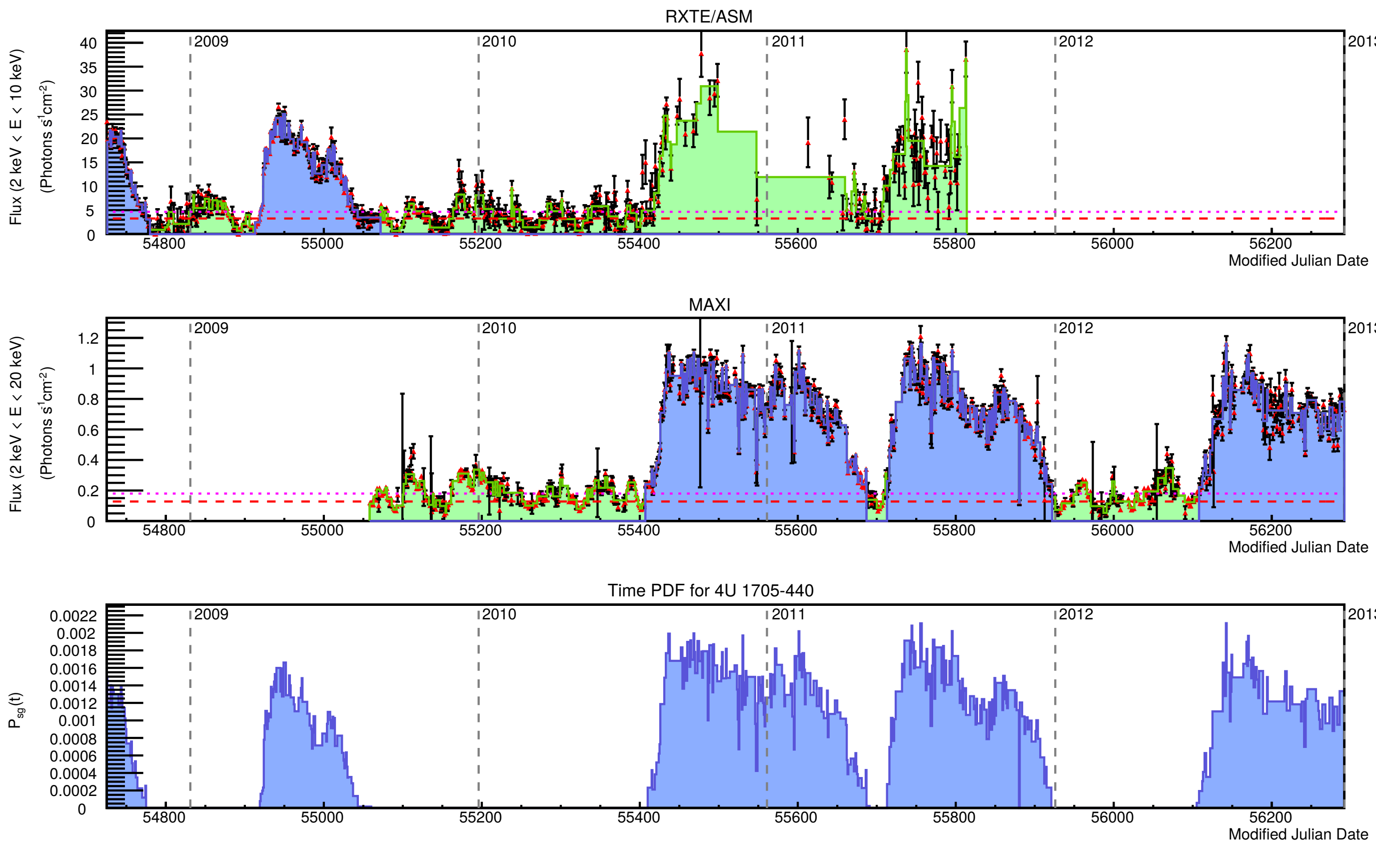
3 Transient neutrino emission

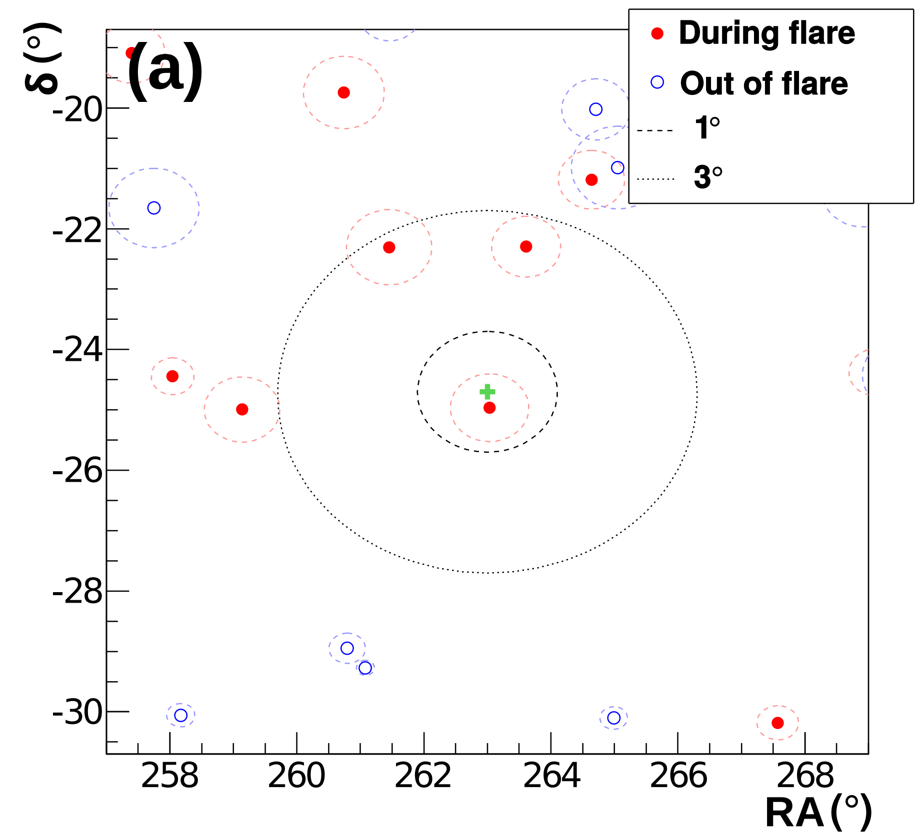
Number of events required for a 5σ discovery (50% probability)



ANTARES collab. (2015)

❸ X-ray binaries viewed by ANTARES

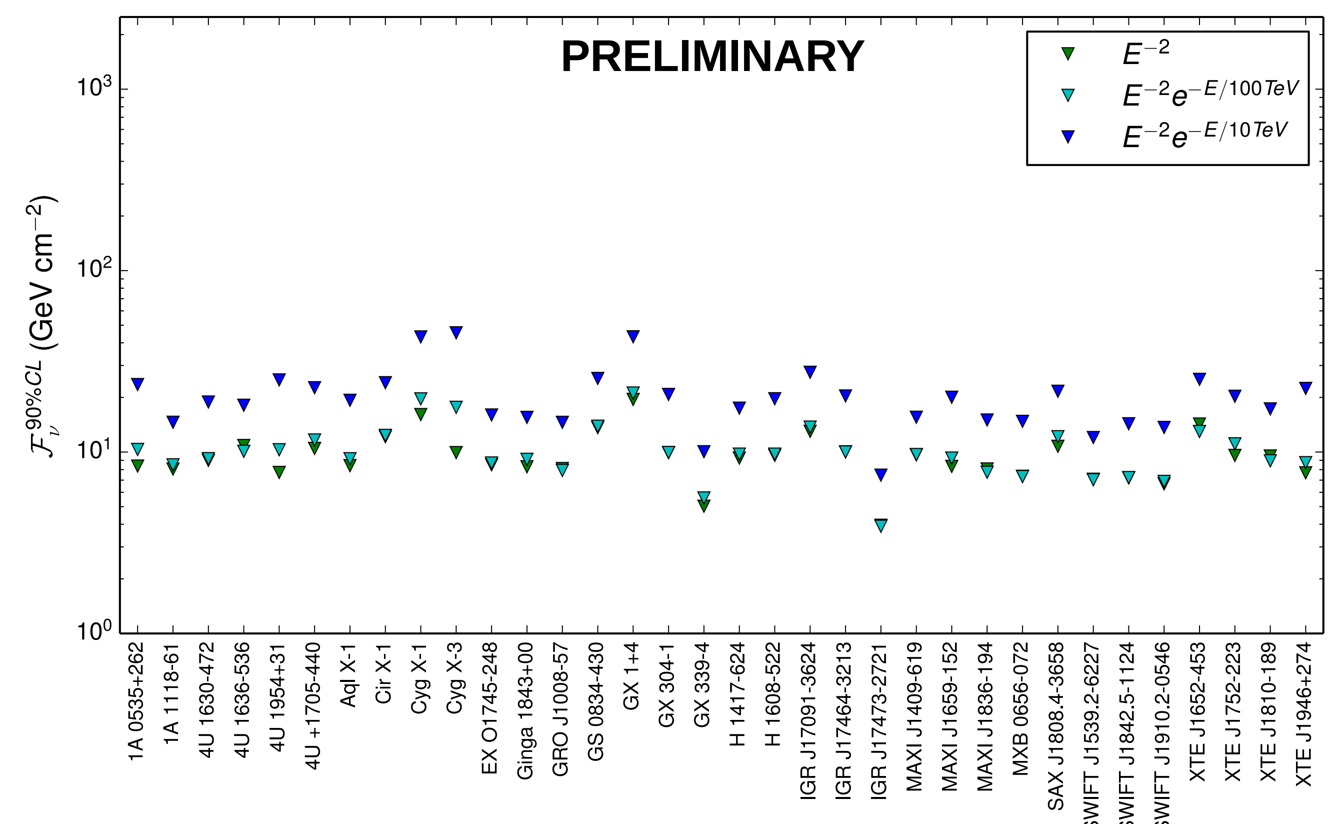




$$\ln \mathcal{L} = \left(\sum_{i=1}^{N} \ln[\mathcal{N}_{\rm S}\mathcal{S}_i + \mathcal{N}_{\rm B}\mathcal{B}_i] \right) - [\mathcal{N}_{\rm S} + \mathcal{N}_{\rm B}]$$

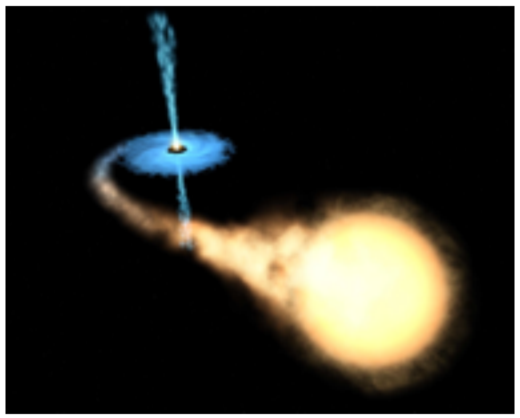
$$\mathcal{S}_i = \mathcal{S}^{\rm space}(\Psi_i(\alpha_s, \delta_s)) \cdot \mathcal{S}^{\rm energy}(dE/dX_i) \cdot \mathcal{S}^{\rm time}(t_i + lag)$$

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



3 X-ray binaries viewed by ANTARES

accretion disk + jet (expected)



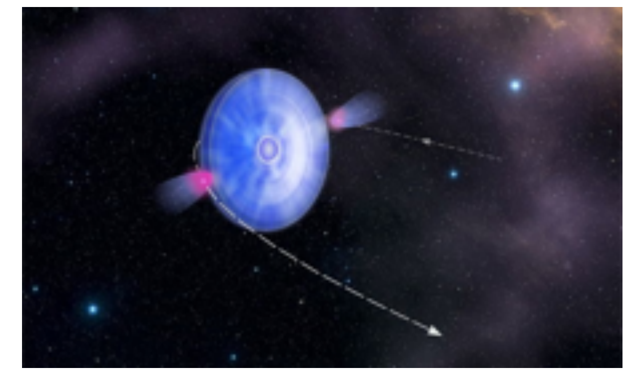
particle acceleration and neutrino production ?

-Distefano et al. 2002
-Romero et Orellana 2005 (HMXB)
-Bednarek 2005 (HMXB)
-Zhang et al. 2010 (LMXB)
-Pepe et al. 2015 (Cyg X-1)
-Vila et al. 2002 (GX 339-4)

Table 1. List of 33 X-ray binaries with significant flares selected for this analysis.

Name	Class	RA [°]	Dec [°]
Cyg X-1	HMXB (BH)	230.170	-57.167
1A 0535+262	HMXB (NS)	84.727	26.316
1A 1118-61	HMXB (NS)	170.238	-61.917
Ginga 1843+00	HMXB (NS)	281.404	0.863
GS 0834-430	HMXB (NS)	128.979	-43.185
GX 304-1	HMXB (NS)	195.321	-61.602
H 1417-624	HMXB (NS)	215.303	-62.698
MXB 0656-072	HMXB (NS)	104.572	-7.210
XTE J1946+274	HMXB (NS)	296.414	27.365
GX 1+4	HMXB (NS)	263.009	-24.746
MAXI J1409-619	HMXB (NS)	212.011	-61.984
GRO J1008-57	HMXB (NS)	152.433	-58.295
GX 339-4	LMXB (BHC)	255.706	-48.784
4U 1630-472	LMXB (BHC)	248.504	-47.393
IGR J17091-3624	LMXB (BHC)	257.282	-36.407
IGR J17464-3213	LMXB (BHC)	266.565	-32.234
MAXI J1659-152	LMXB (BHC)	254.757	-15.258
SWIFT J1910.2-0546	LMXB (BHC)	287.595	-5.799
XTE J1752-223	LMXB (BHC)	268.063	-22.342
SWIFT J1539.2-6227	LMXB (BHC)	234.800	-62.467
4U 1954+31	LMXB (NS)	298.926	32.097
Aql X-1	LMXB (NS)	287.817	0.585
Cir X-1	LMXB (NS)	230.170	-57.167
EX O1745-248	LMXB (NS)	267.022	-24.780
H 1608-522	LMXB (NS)	243.179	-52.423
SAX J1808.4-3658	LMXB (NS)	272.115	-36.977
XTE J1810-189	LMXB (NS)	272.586	-19.070
4U 1636-536	LMXB (NS)	250.231	-53.751
4U 1705-440	LMXB (NS)	257.225	-44.102
IGR J17473-2721	LMXB (NS)	266.825	-27.344
MAXI J1836-194	XRB (BHC)	278.931	-19.320
XTE J1652-453	XRB (BHC)	253.085	-45.344
SWIFT J1842.5-1124	XRB (BHC)	280.573	-11.418

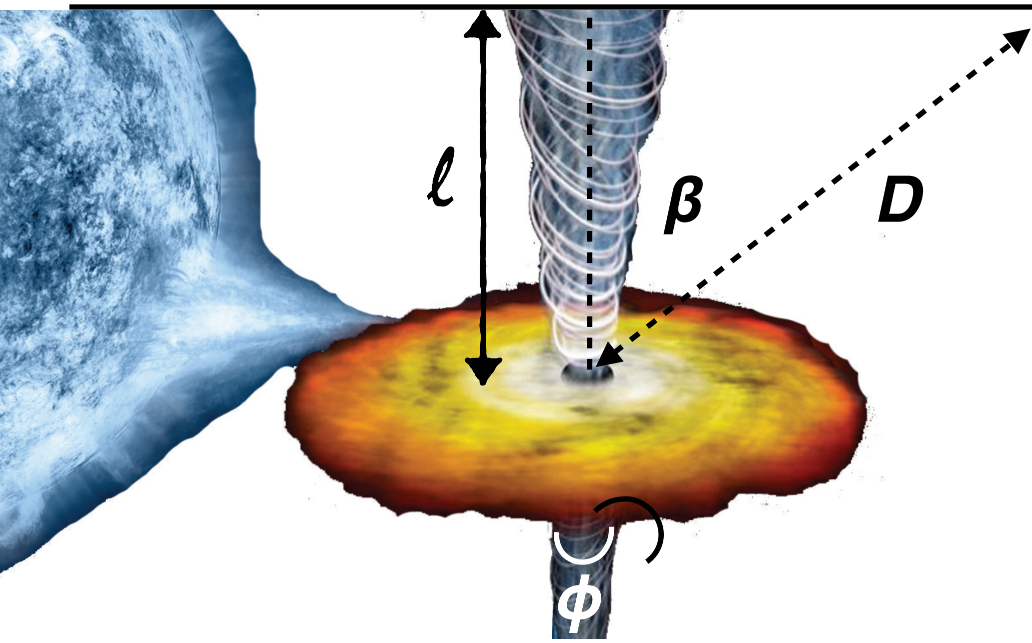
BeHMXB



particle acceleration and neutrino production ?

-Bartosik et al. 2003
-Anchordoqui et al. 2003
-Bednarek 2009
-Neronov & Ribordy 2009

3 Distefano et al. photohadronic model



Resolved microquasars :

Magnetic field:

$$B_* = 3.6\left[\ln\left(\frac{\gamma_{\max}}{\gamma_{\min}}\right)\frac{T_{B6}}{l_{15}}\right]^{2/7}\frac{\nu_9^{5/7}}{\delta}\,\mathrm{mG}$$

Jet luminosity:

$$L_{\rm jet} \geq \frac{7}{24}c\frac{(\Gamma l B_*)^2}{\eta_e}$$

Fraction of proton energy converted into pions:

$$f_{\pi,\,\rm peak} \simeq \min\left[1,\ 0.1\eta_{e,-1}^{1/2}\Gamma^{-2}\phi_{0.2}^{-1}L_{\rm jet,38}^{1/2}\right]$$

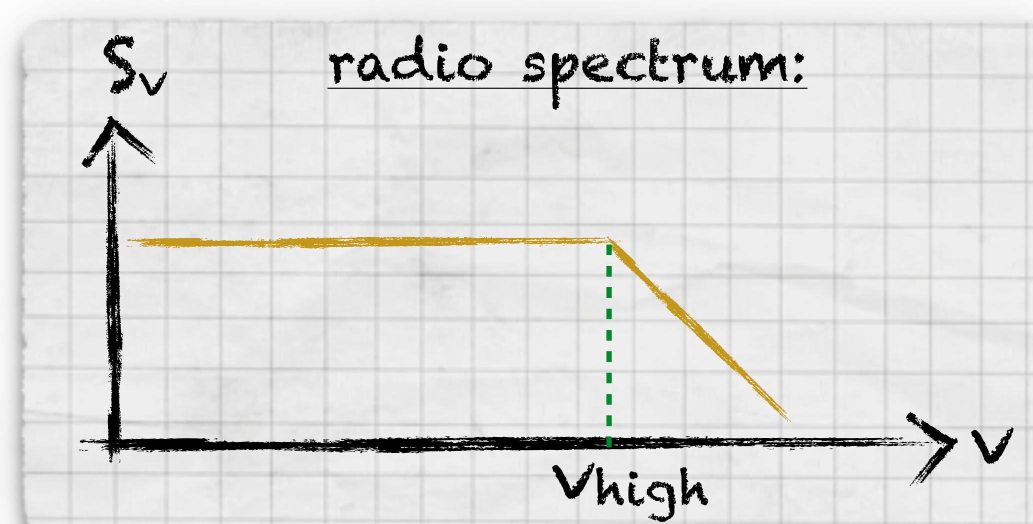
Neutrino flux:

$$f_{\nu_\mu} \simeq \frac{1}{2}\eta_p f_\pi \delta^4 \frac{L_{\rm jet}/8}{4\pi D^2}$$

Non-resolved microquasars :

$$L_{\rm syn} = 4\pi D^2 \frac{1}{1-\alpha_R} S_{\nu_{\rm high}}\nu_{\rm high} \quad \rightarrow \quad L_{\rm jet} = \eta_e^{-1}\eta_r^{-1}L_{\rm syn}$$

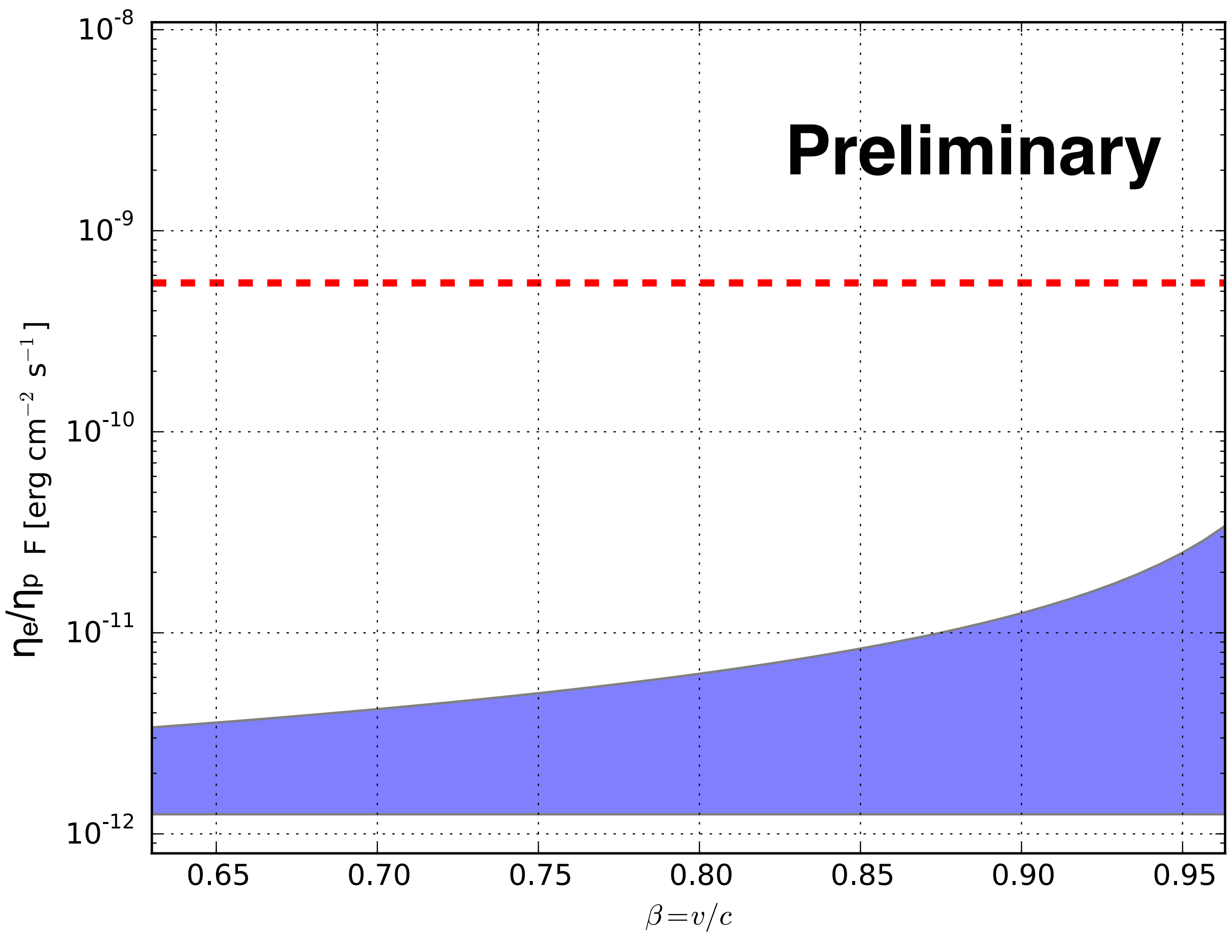
$$f_{\nu_\mu} = \frac{1}{2}f_\pi\eta_p\frac{L_{\rm jet}/8}{4\pi D^2} = \frac{1}{16(1-\alpha_R)}\frac{\eta_p}{\eta_e}f_\pi\eta_r^{-1}S_{\nu_{\rm high}}\nu_{\rm high}$$



Distefano et al. photohadronic model

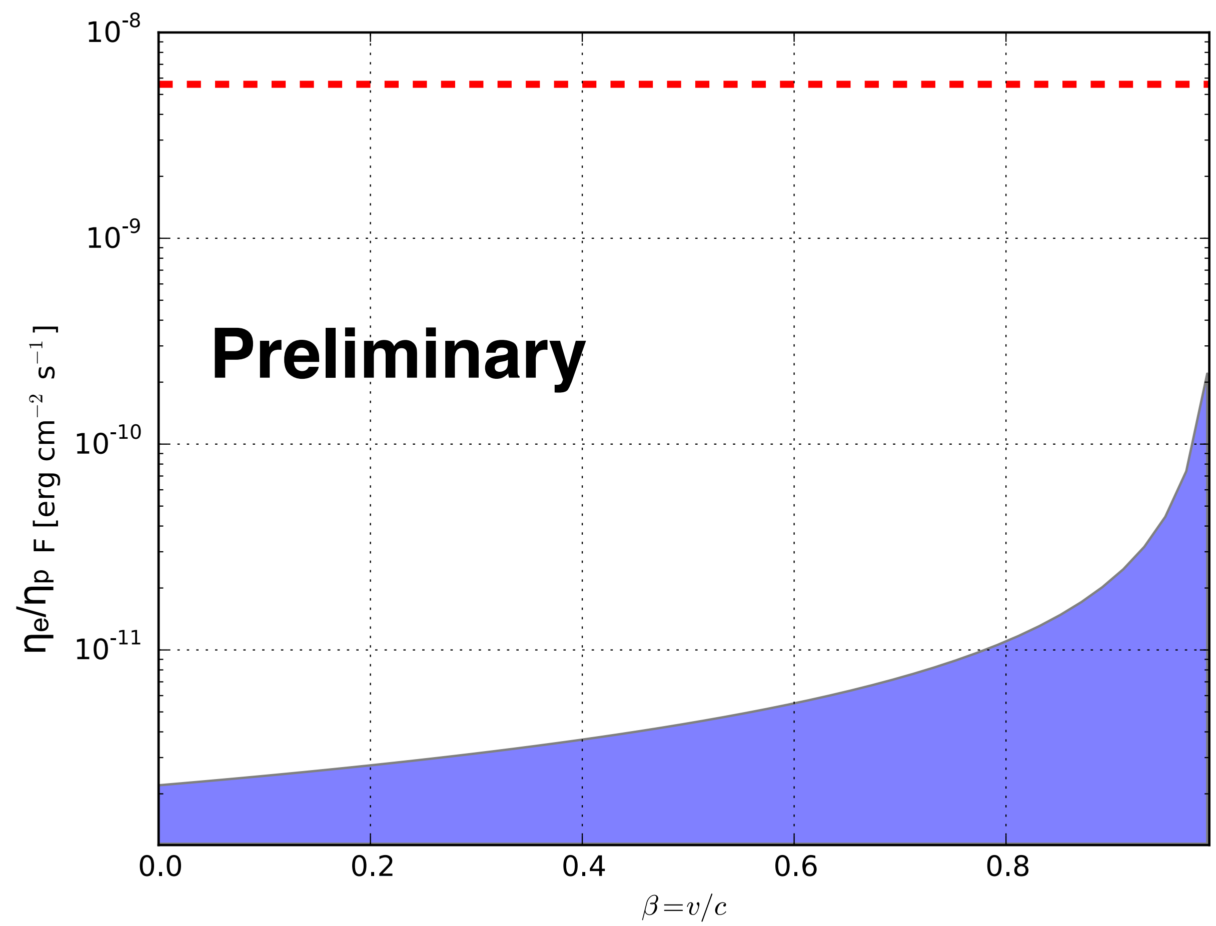
Comparison with model of Distefano et al., 2002
(takes into account jet parameters)

Cyg X-1



$0.6<\boldsymbol{\beta}<0.97$, $\boldsymbol{\theta} = 40^\circ$, D=1.8 kpc
(Stirling et al., 2001)

MAXI 1659-152

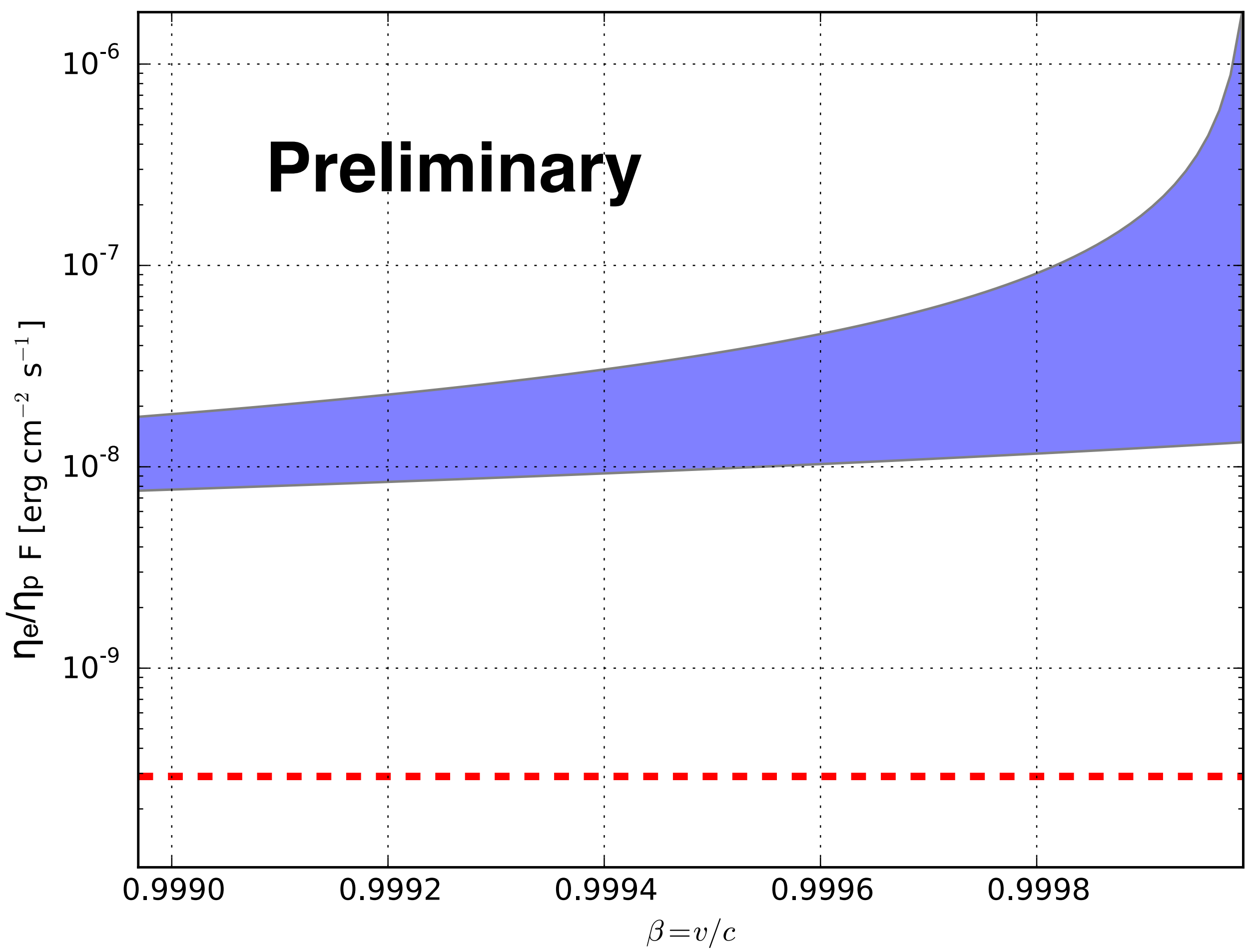


Γ=2, δ=1, D= 7±3 kpc

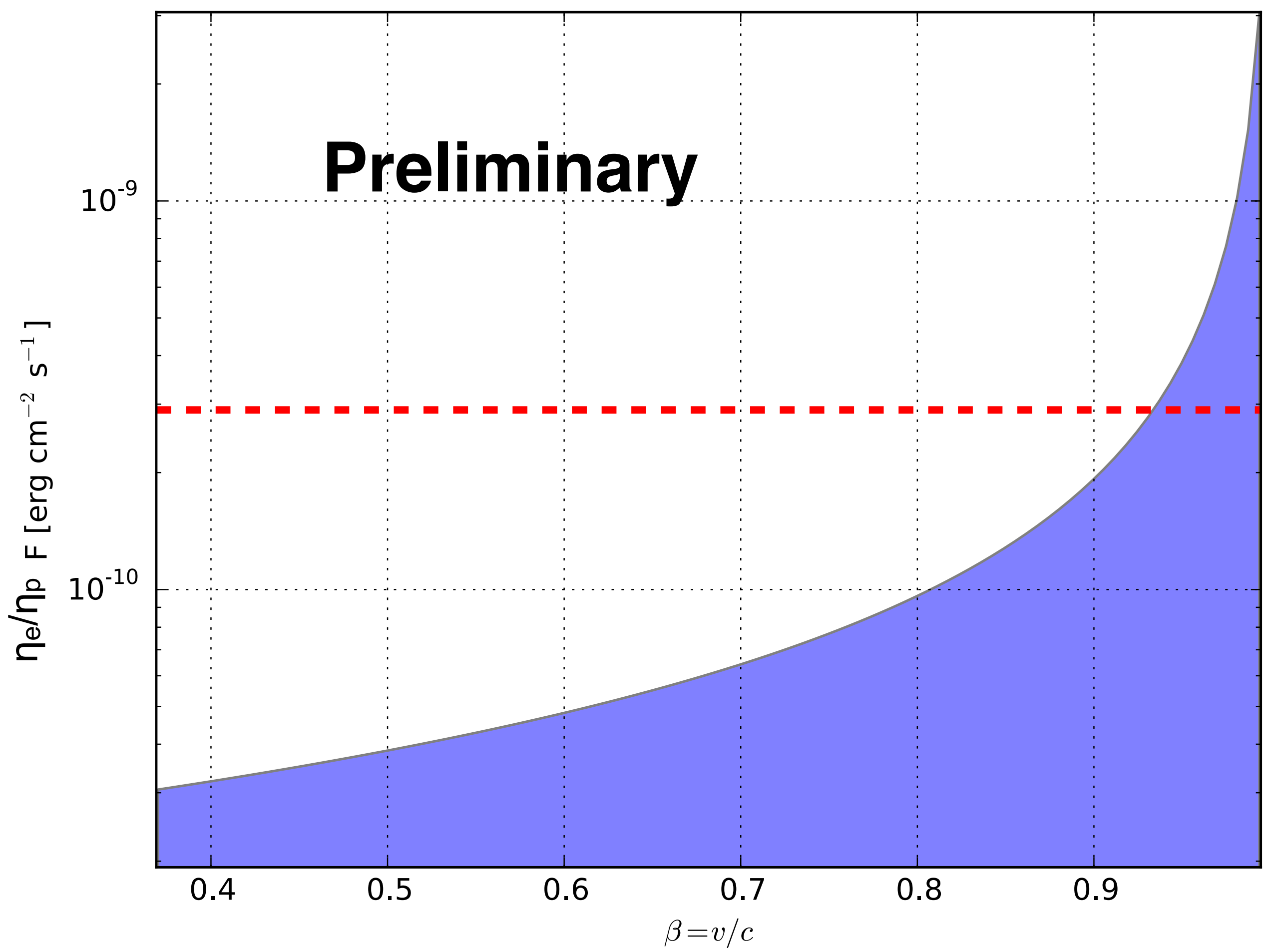
Distefano et al. photohadronic model

Comparison with model of Distefano et al., 2002
(takes into account jet parameters)

Circinus X-1 (neutron star + normal star)



$\Gamma > 22$, $\phi < 3°$, D=9.4 kpc
(Heinz et al., 2015)



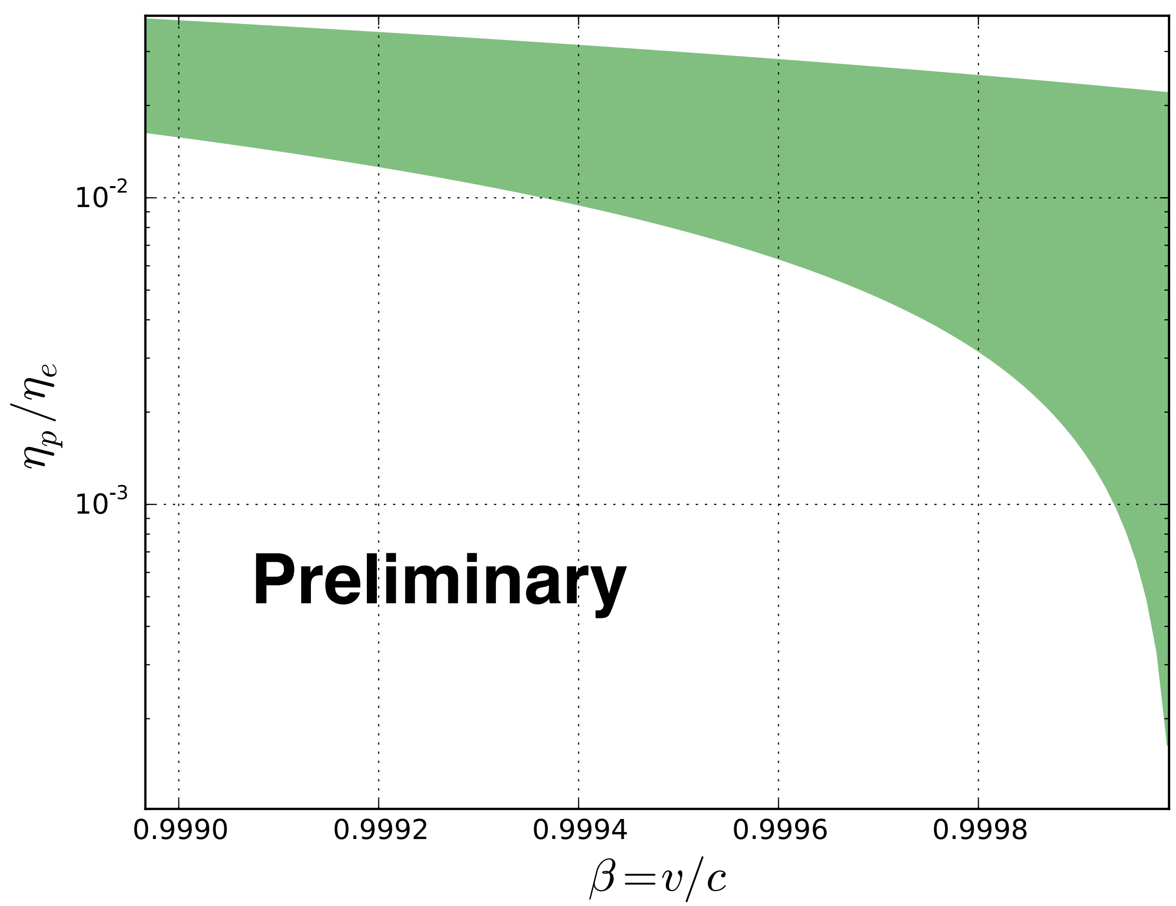
$1.076 < \Gamma < 5$, $\phi < 20°$, D=7.8 kpc
(Miller-Jones et al., 2012)

3 Distefano et al. photohadronic model

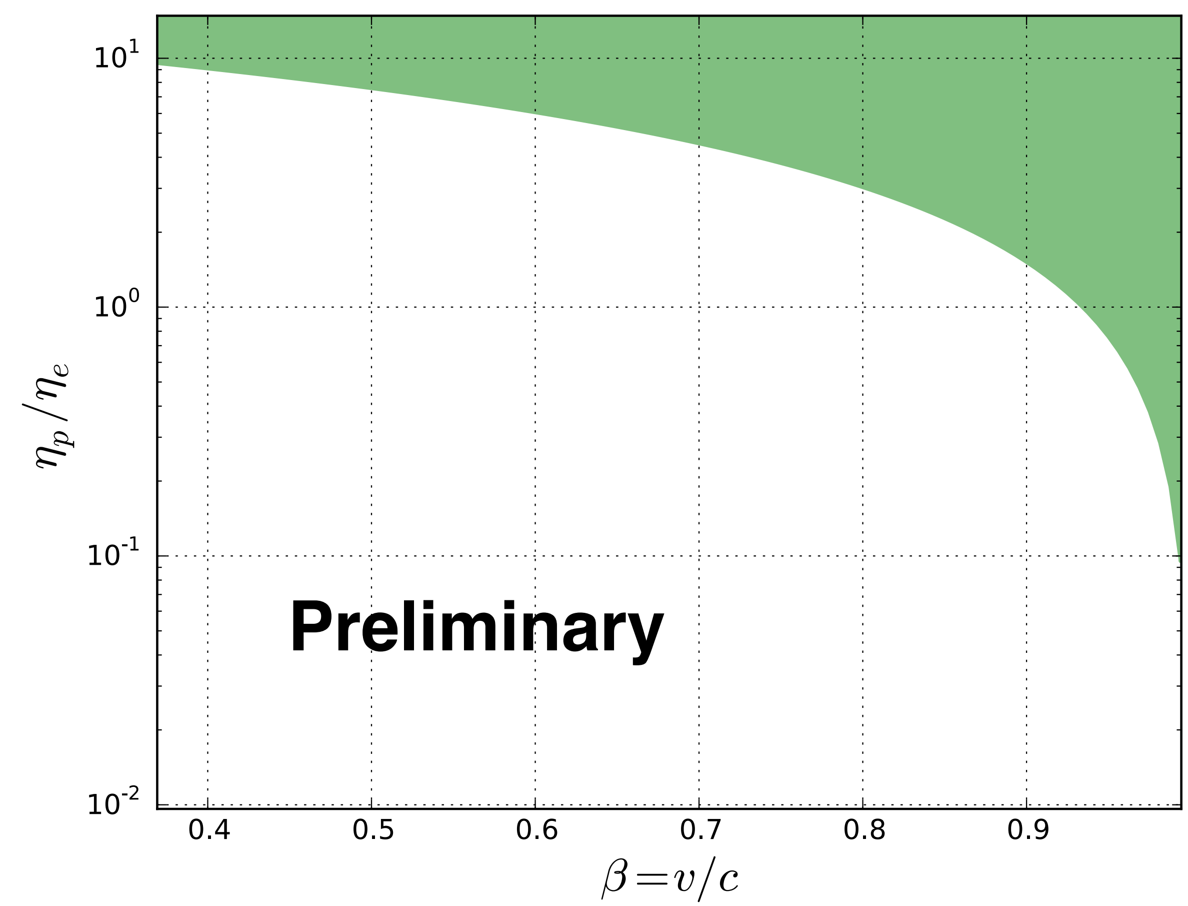
Comparison with model of Distefano et al., 2002

Enable to constrain η_p/η_e = ratio of jet energy fraction carried by accelerated protons and electrons

Upper limit on η_p/η_e for Circinus X-1 (neutron star + normal star)



$\Gamma > 22$, $\phi < 3°$, D=9.4 kpc
(Heinz et al., 2015)



$1.076 < \Gamma < 5$, $\phi < 20°$, D=7.8 kpc
(Miller-Jones et al., 2012)

Are the jet parameters similar for each burst ?… not sure at all !

Distefano et al. photohadronic model

but still some limitations…

cannot exclude that:

- protons lose smaller energies into pion decay
- lower Γ
- variable jet parameters vs time
- compact jets / discrete ejections
- magnetic field impact on neutrino emission (see Reynoso & Romero, 2009)
- microquasar activity signature: high-energy vs radio observations

- need high angular / high sensitivity / wide field of view radio observations

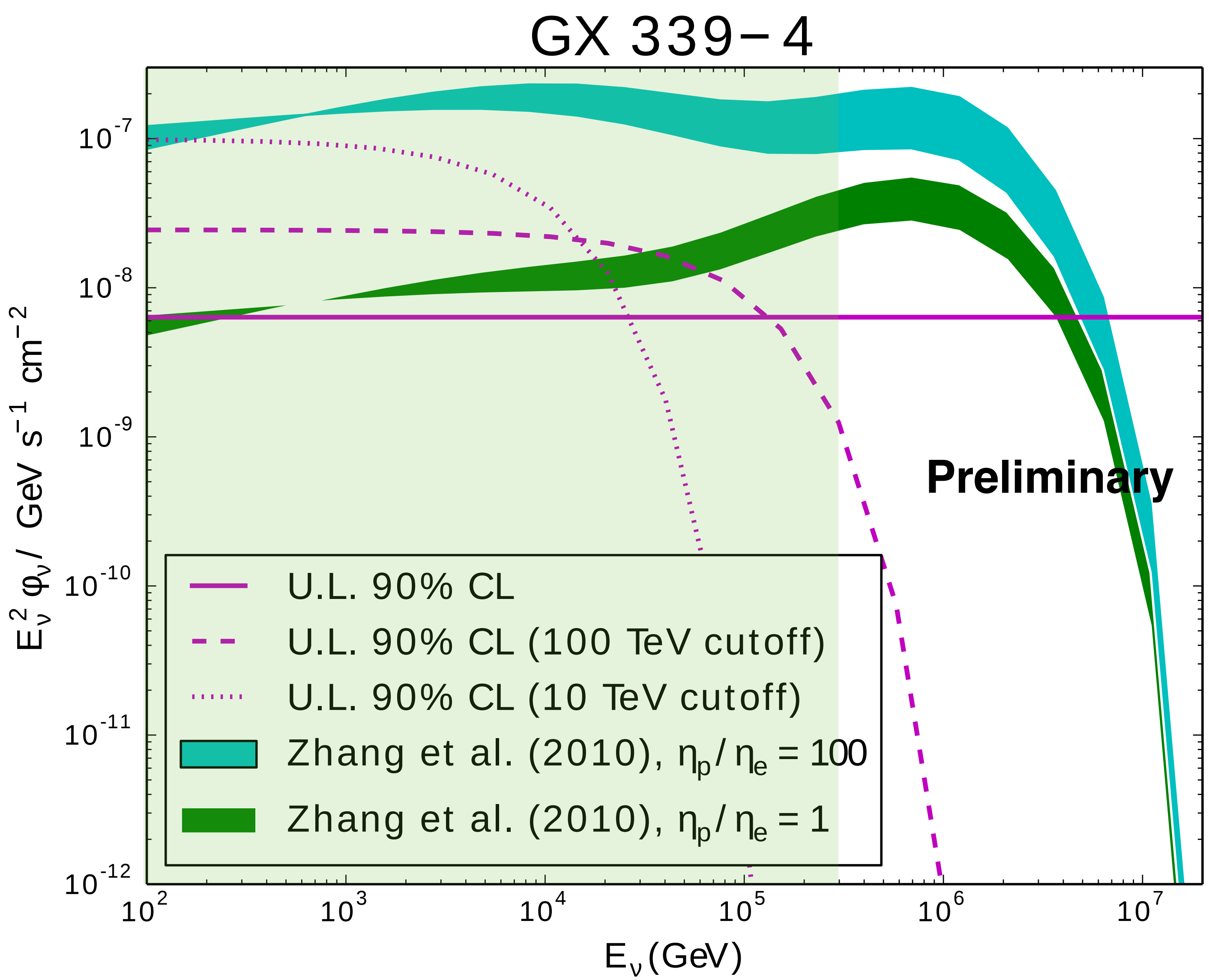
New / future radio (wide-field) instruments:

-estimation of β=v/c and θ (if distance is known)
+ spatial extension of the jet
+ polarization at different scales
+ proper motion (⇒ exact timing of ejection event)

X-ray binaries viewed by ANTARES

GX 339-4 (Zhang et al., 2010)

pp + p-gamma interactions



3 Gamma-ray binaries viewed by Antares

	PSR B1259-63★	LS 5039†	LS I +61°303•	HESS J0632+057◇	1FGL J1018.6-5856‡
P_{orb} (days)	1236.72432(2)	3.90603(8)	26.496(3)	315(5)	16.58(2)
e	0.8698872(9)	0.35(3)	0.54(3)	0.83(8)	-
ω (°)	138.6659(1)♯	212(5)	41(6)	129(17)	-
i (°)	19–31	13–64	10–60	47–80	-
d (kpc)	2.3(4)	2.9(8)	2.0(2)	1.6(2)	5.4
spectral type	O9.5Ve	O6.5V((f))	B0Ve	B0Vpe	O6V((f))
$M_\star$ ($M_\odot$)	31	23	12	16	31
$R_\star$ ($R_\odot$)	9.2	9.3	10	8	10.1
$T_\star$ (K)	33500	39000	22500	30000	38900
$d_{periastron}$ (AU)	0.94	0.09	0.19	0.40	(0.41)
$d_{apastron}$ (AU)	13.4	0.19	0.64	4.35	(0.41)
$\phi_{periastron}$	0	0	0.23	0.967	-
$\phi_{sup.\ conj.}$	0.995	0.080	0.036	0.063	-
$\phi_{inf.\ conj.}$	0.048	0.769	0.267	0.961	-

★ Wang et al. (2004); Moldón et al. (2011a); Negueruela et al. (2011)

† McSwain et al. (2004); Casares et al. (2005, 2011)

• Howarth (1983); Frail & Hjellming (1991); Martí & Paredes (1995); Gregory (2002); Aragona et al. (2009)

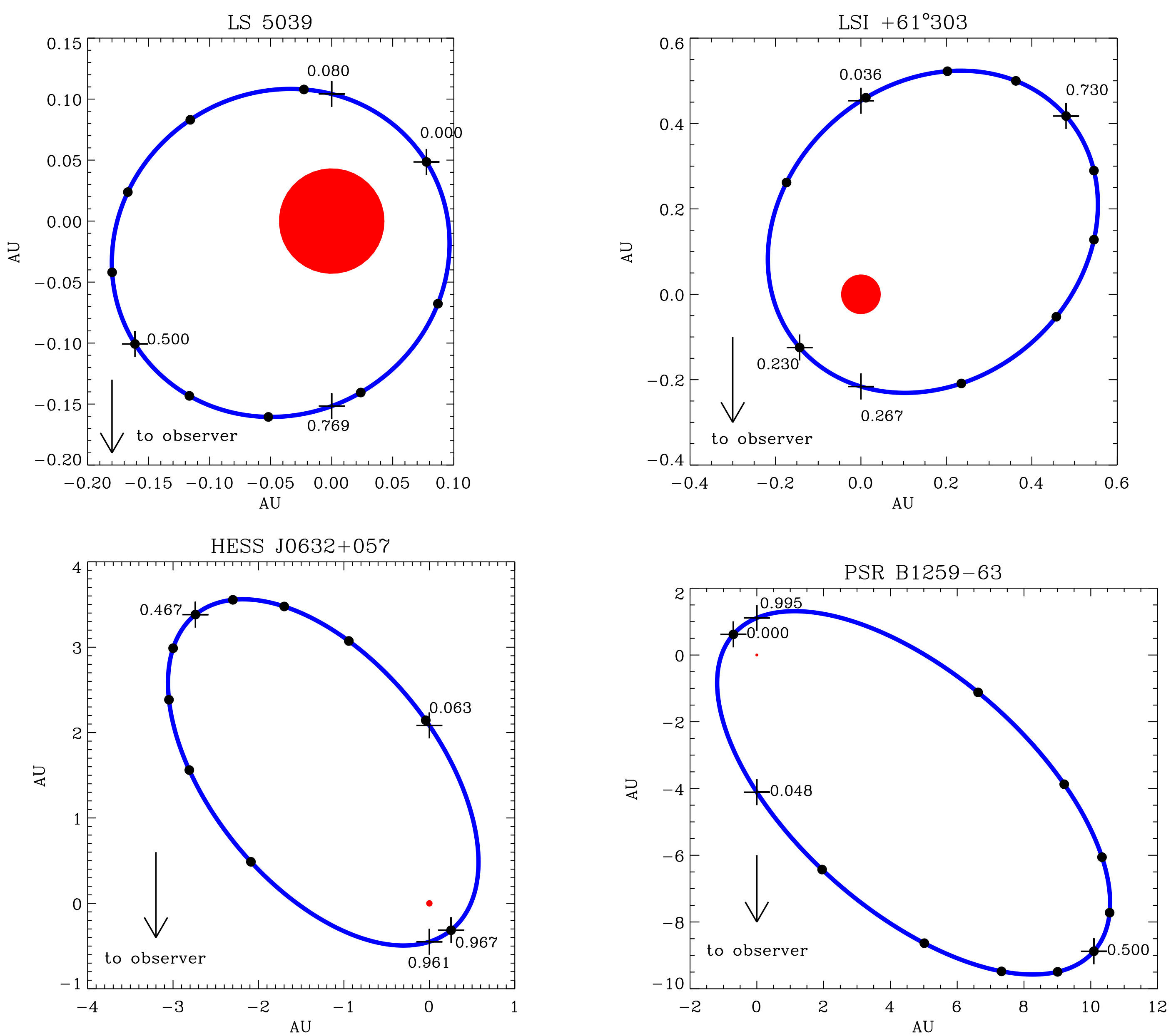
◇ Aragona et al. (2010); Casares et al. (2012); Bordas & Maier (2012)

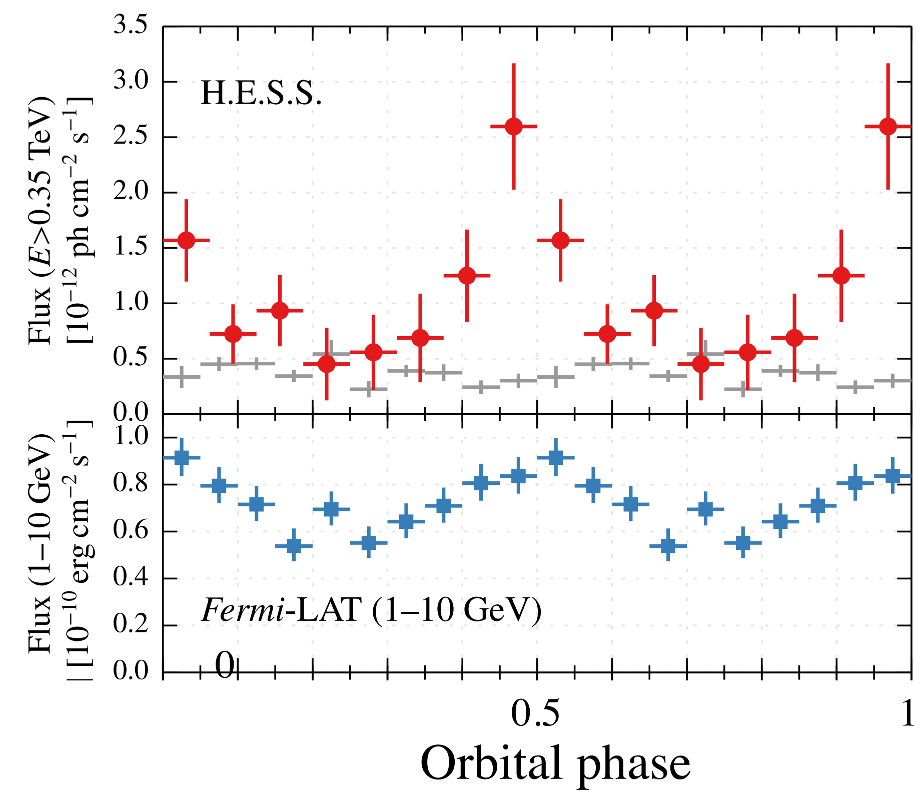
‡ *Fermi*/LAT collaboration et al. (2012b); Napoli et al. (2011)

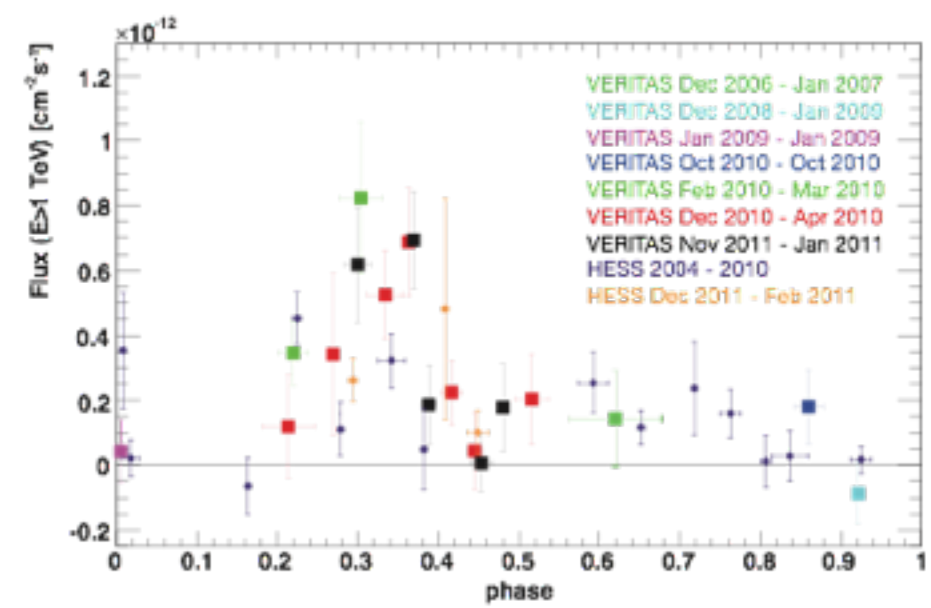
♯ argument of periastron of the pulsar orbit (massive star for the others systems)

3 Gamma-ray binaries viewed by Antares

Looking for a potential neutrino transient emission in time coincidence with TeV gamma-rays: work in progress…

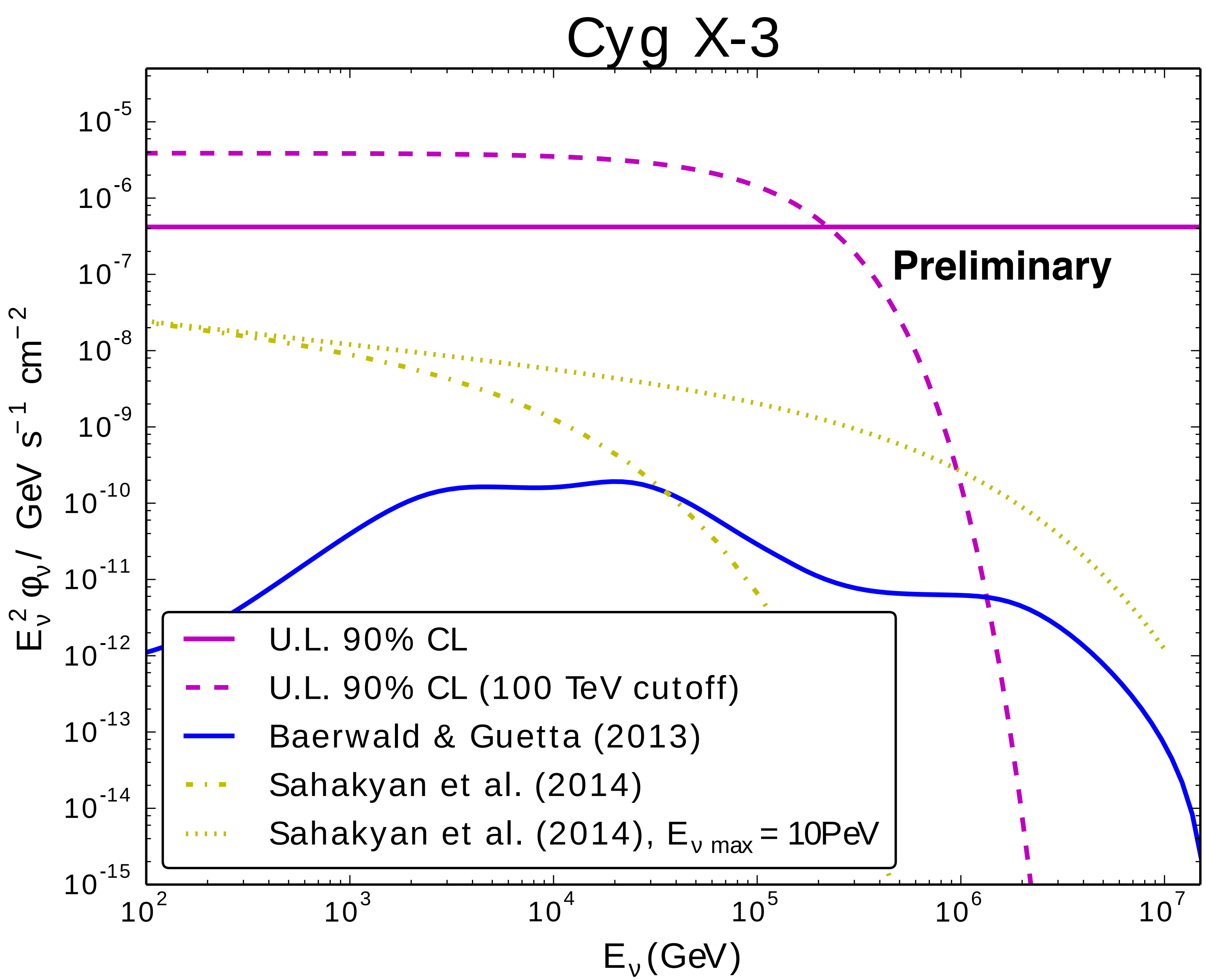






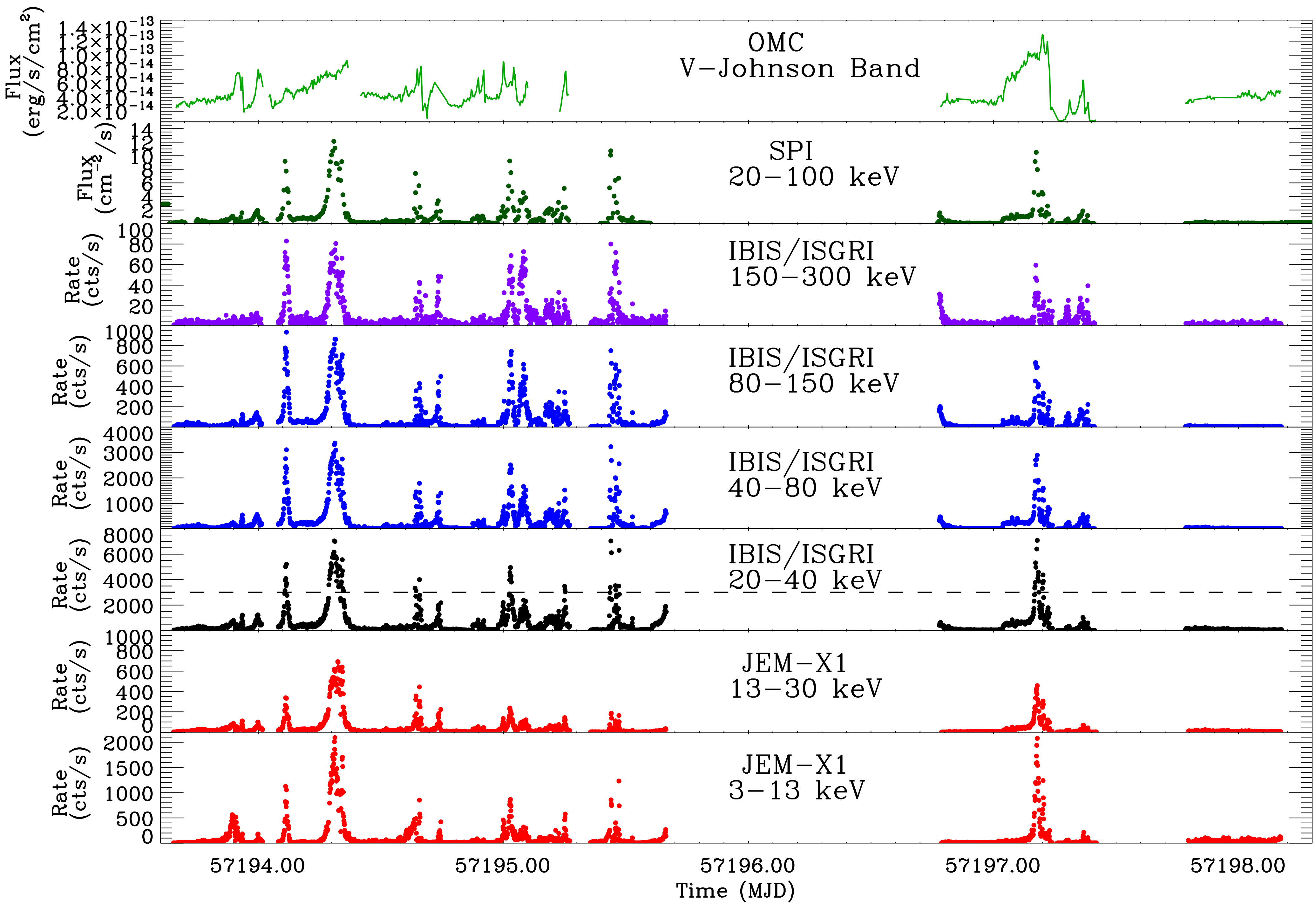
X-ray binaries viewed by ANTARES

Cyg X-3 (Baerwald & Guetta, 2013 - Sahakyan et al., 2014)



V404 Cygni

Looking for a potential neutrino transient emission in time coincidence with 2015 flaring period of V404 Cygni

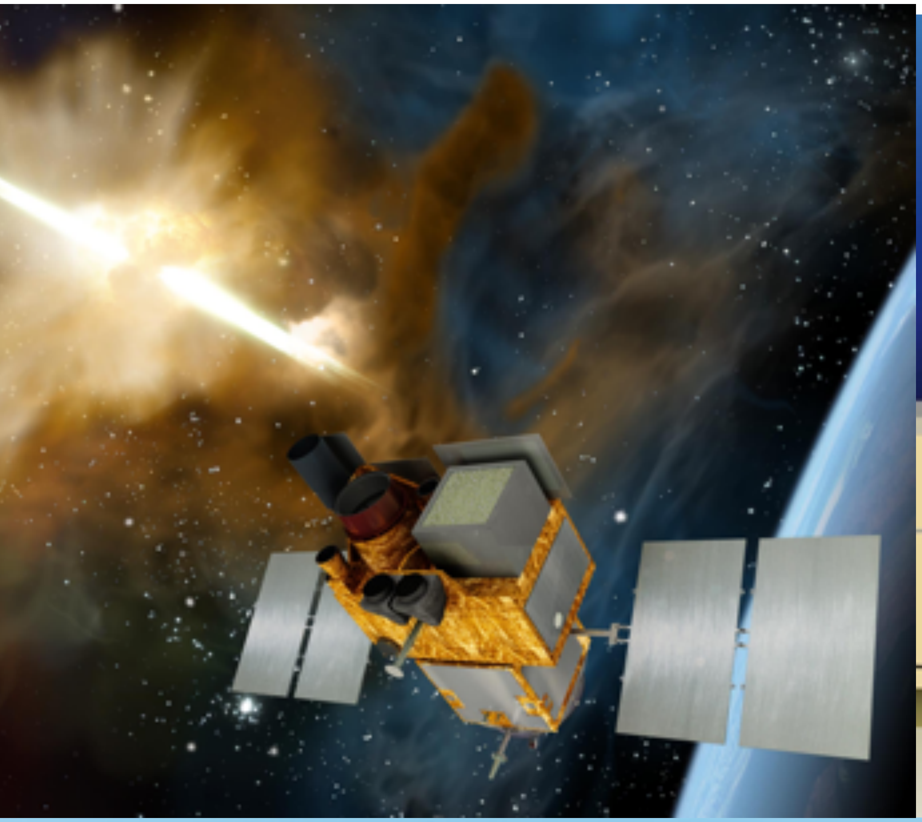


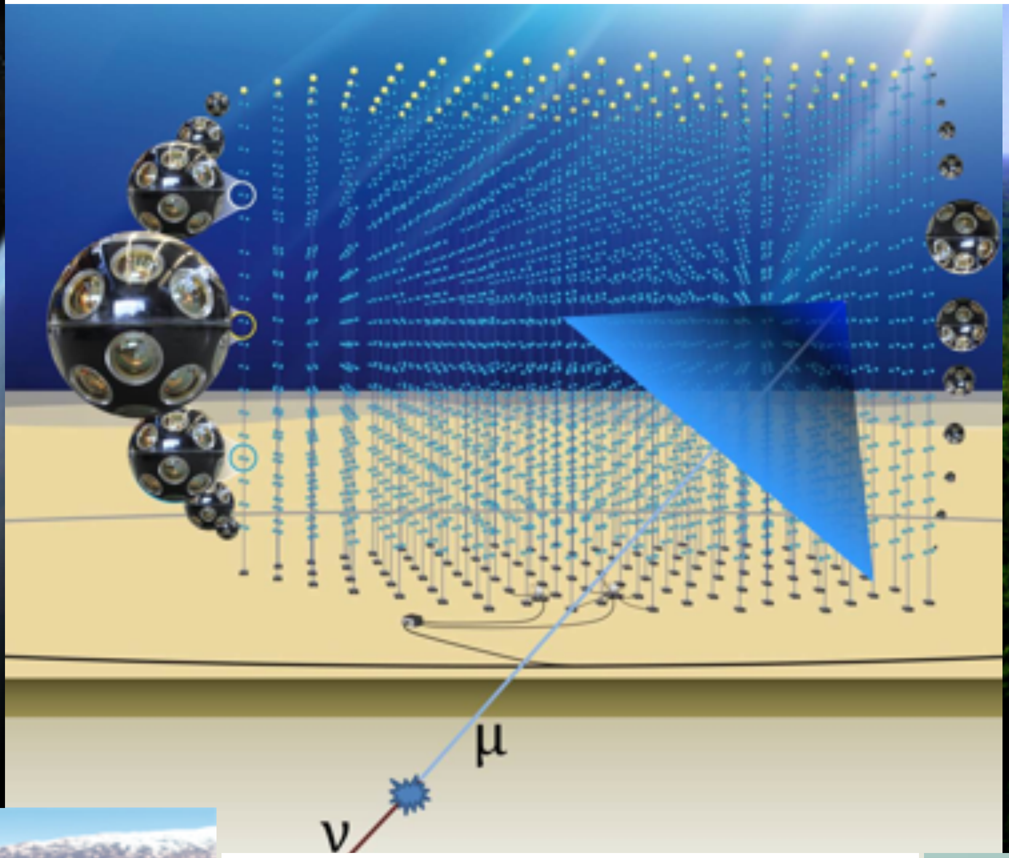
Rodriguez et al. (2015)

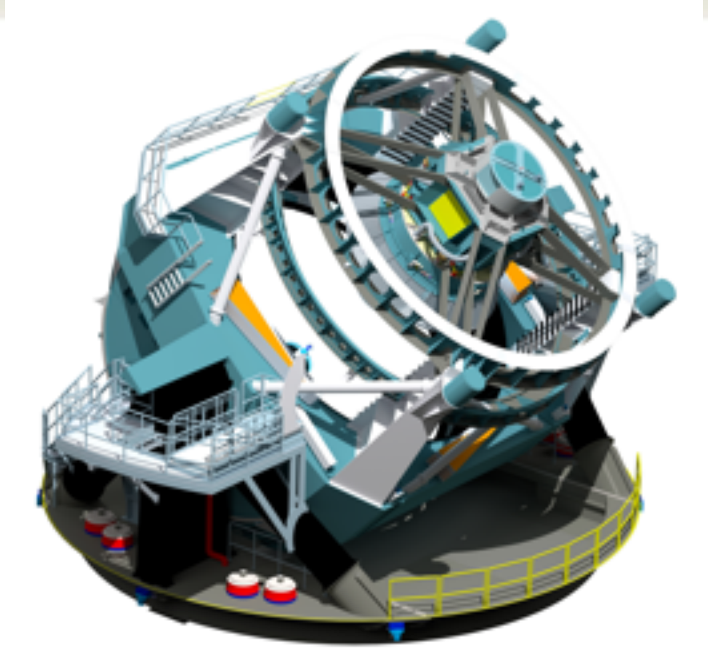
3

Multi-messenger era

> the next future

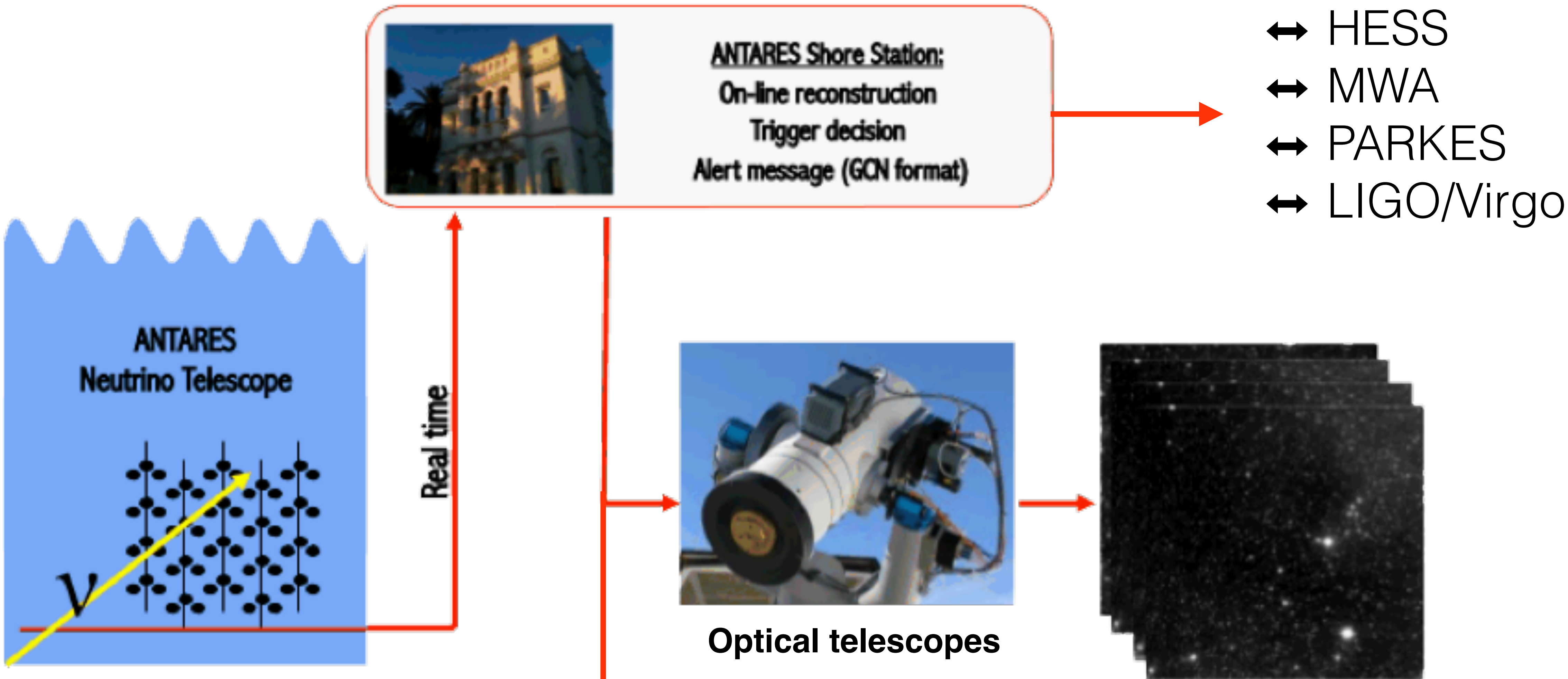


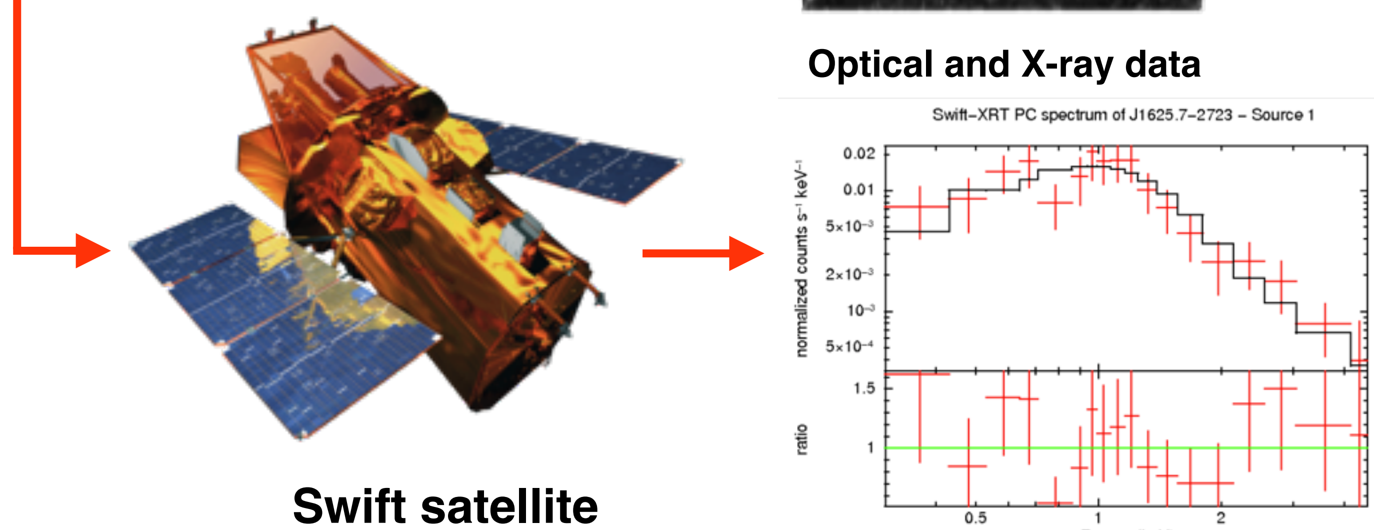




Multi-messenger era

> online follow-up





Triggers:

-direction (local galaxy)

-high energy (E > 5-10 TeV)

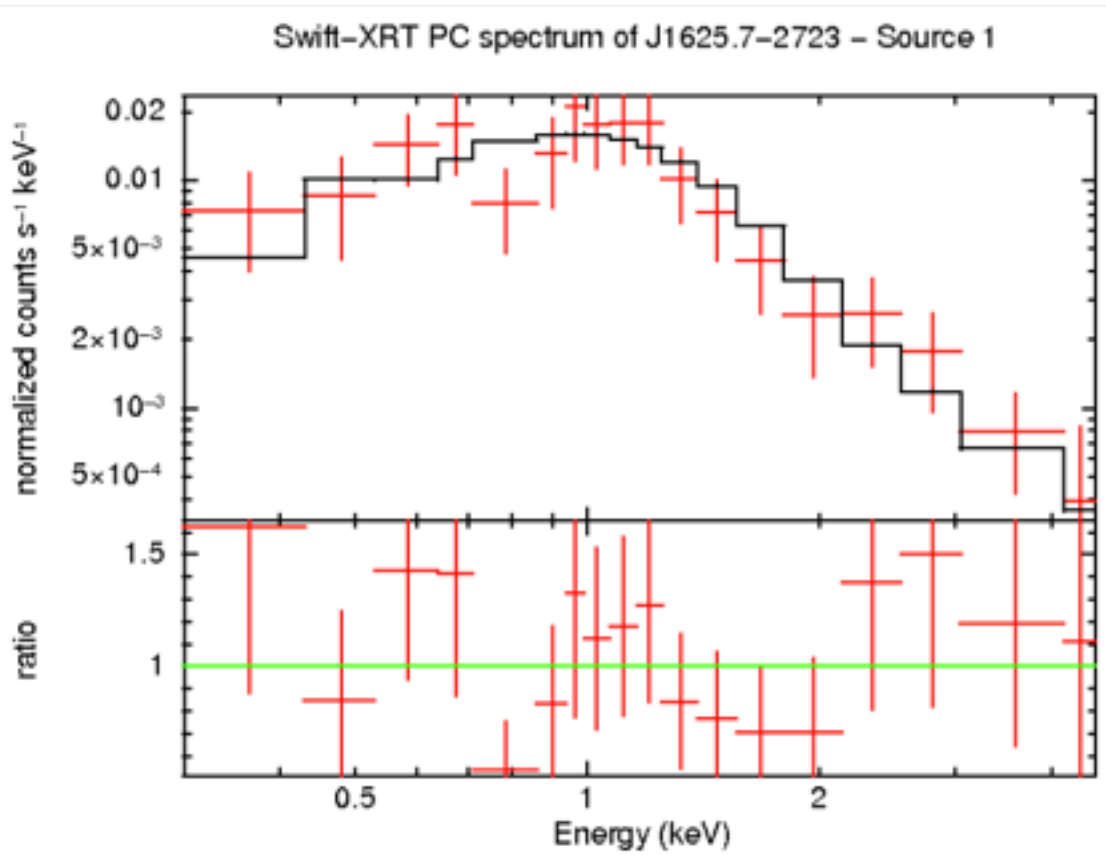
-doublet: 2 neutrinos within 3° and 15 min

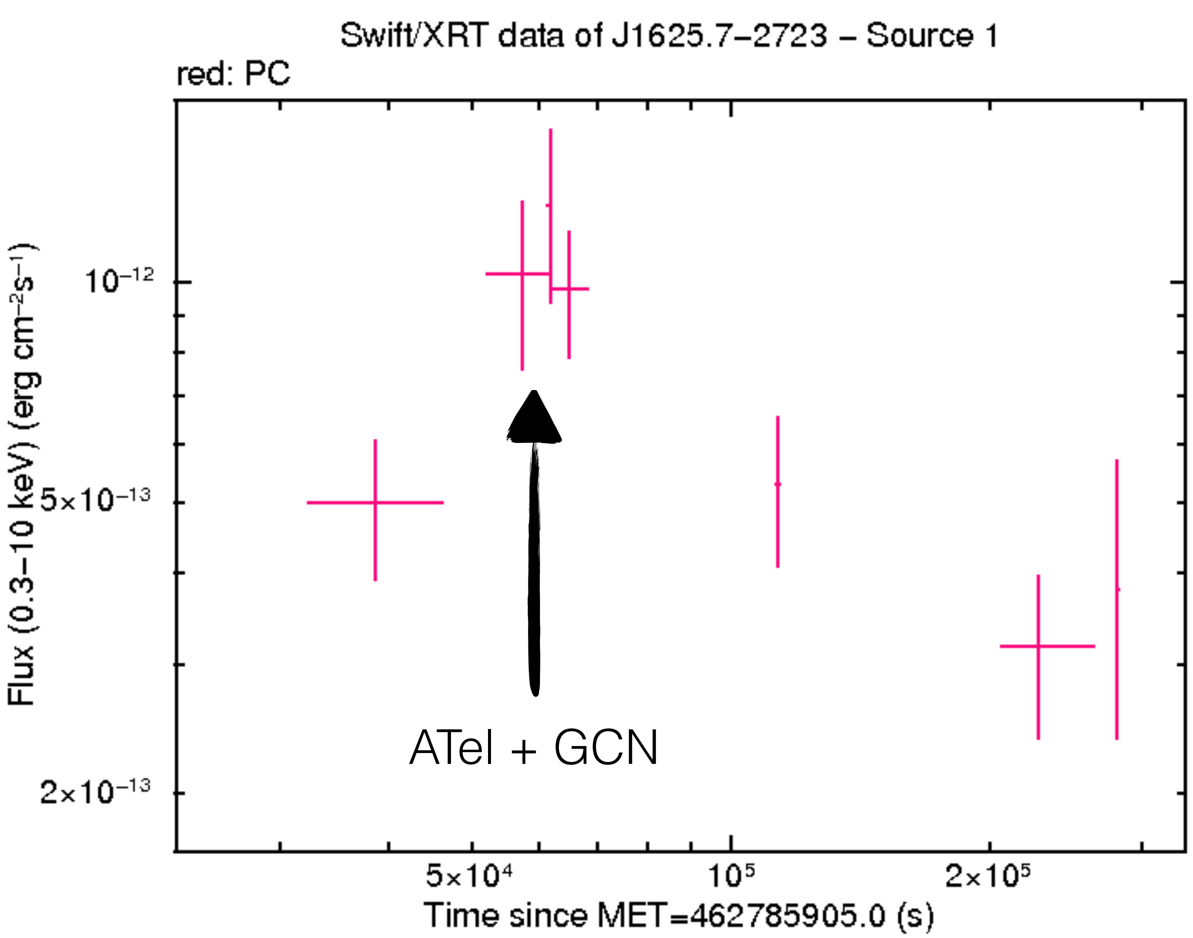
Multi-messenger era

> The ANT091501A alert

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

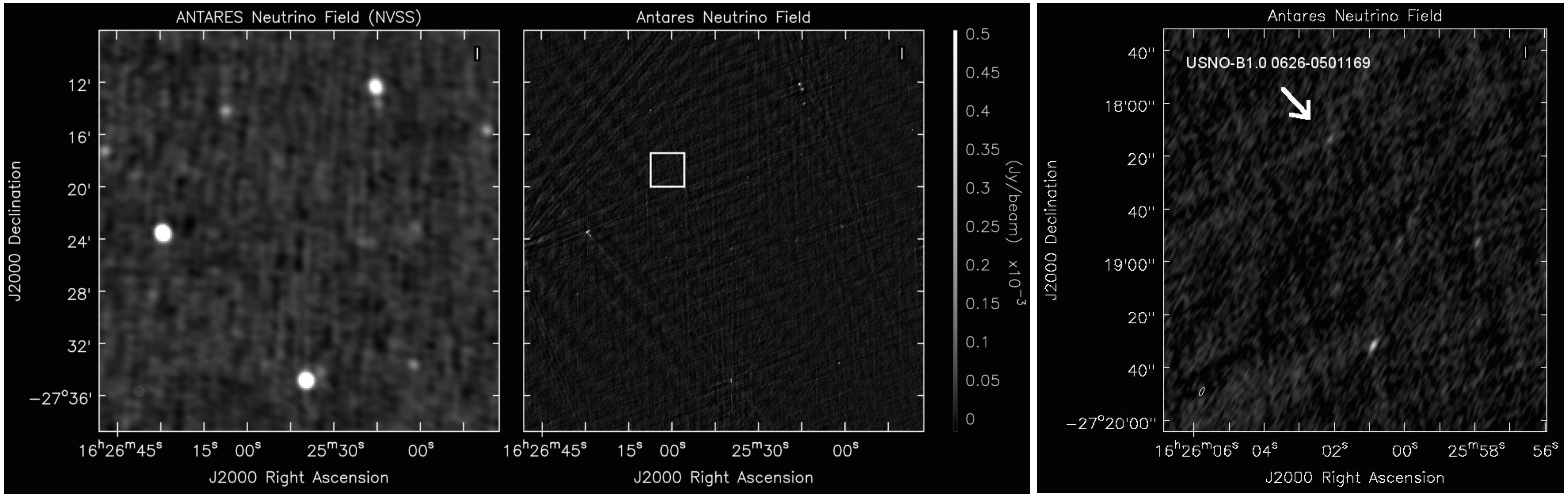
- **Swift**: uncatalogued and variable X-ray source within 8 arcmin
- **Optical**: Bright star at Swift counterpart location

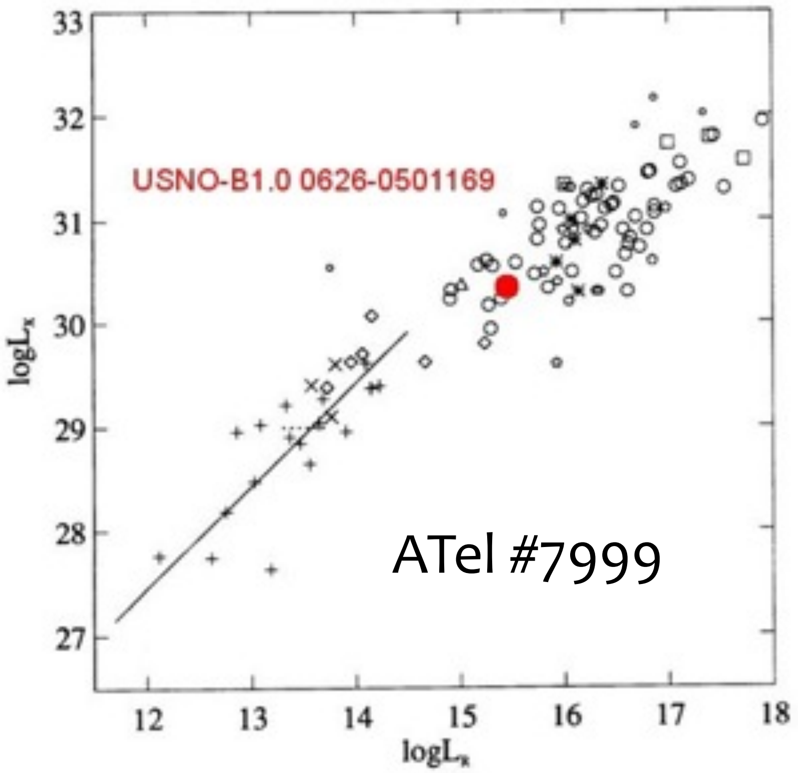


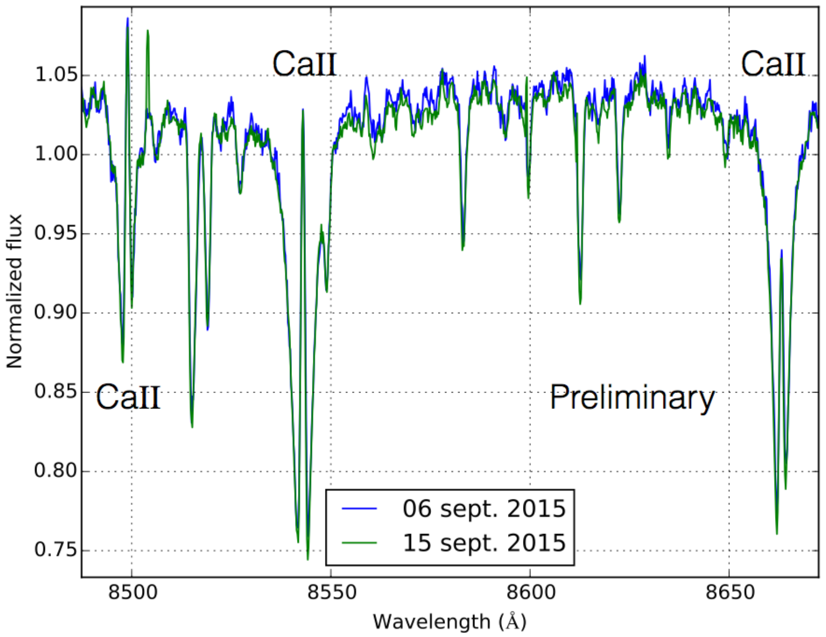


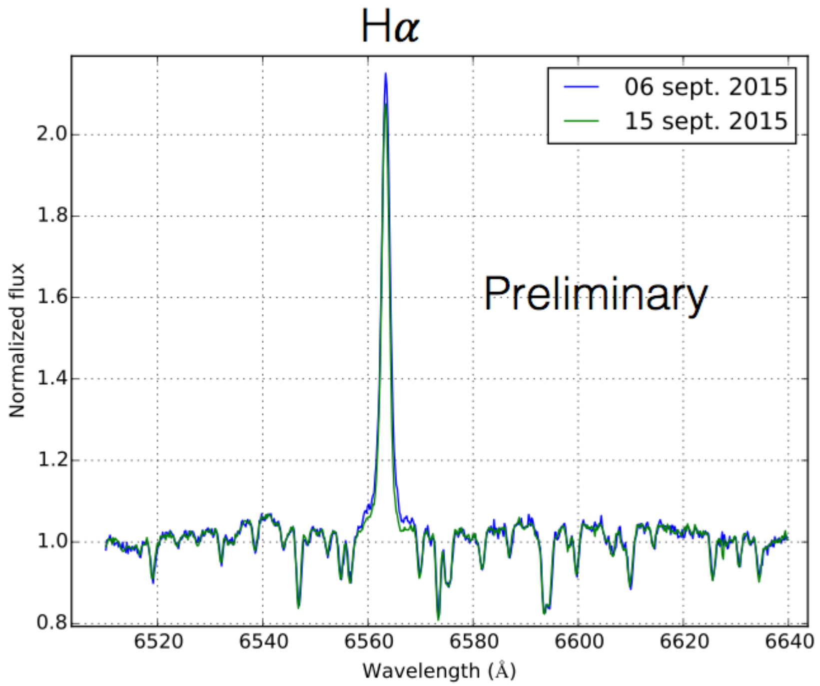
Multi-messenger era

> The ANT091501A alert







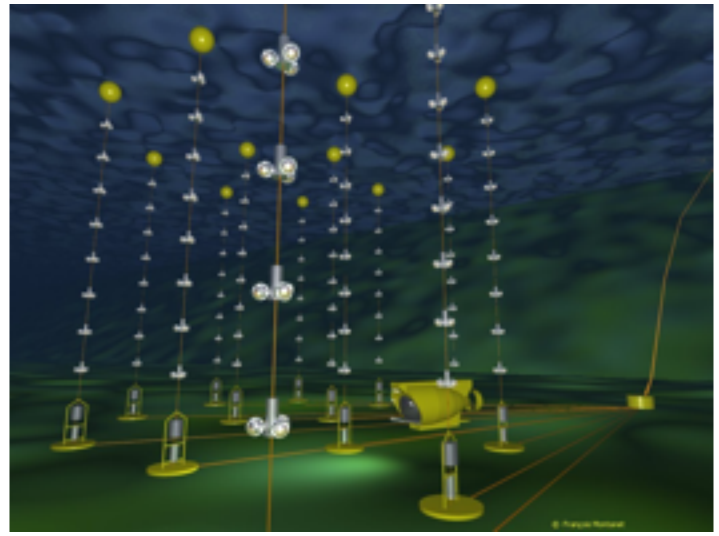


Coleiro et al., in prep.

Multi-messenger era

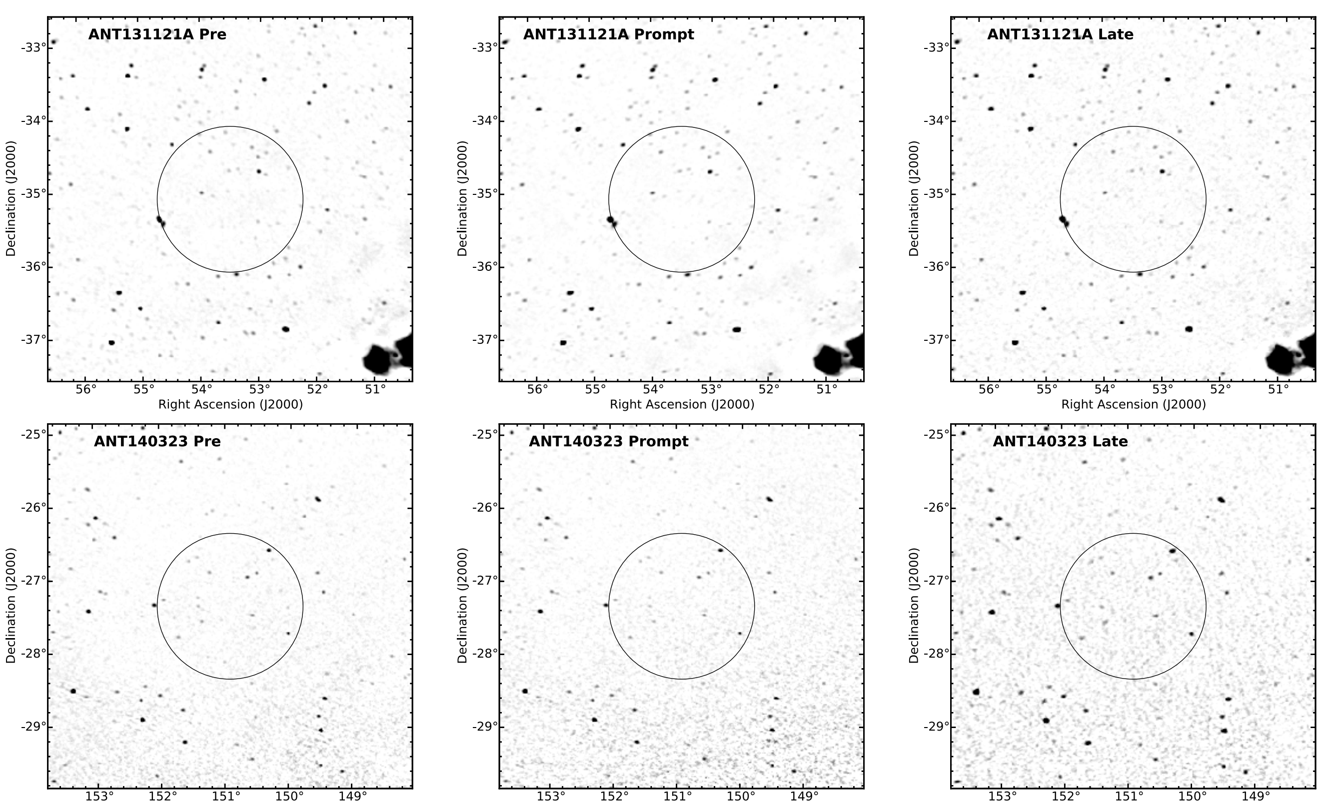
> MWA / ANTARES first follow-up

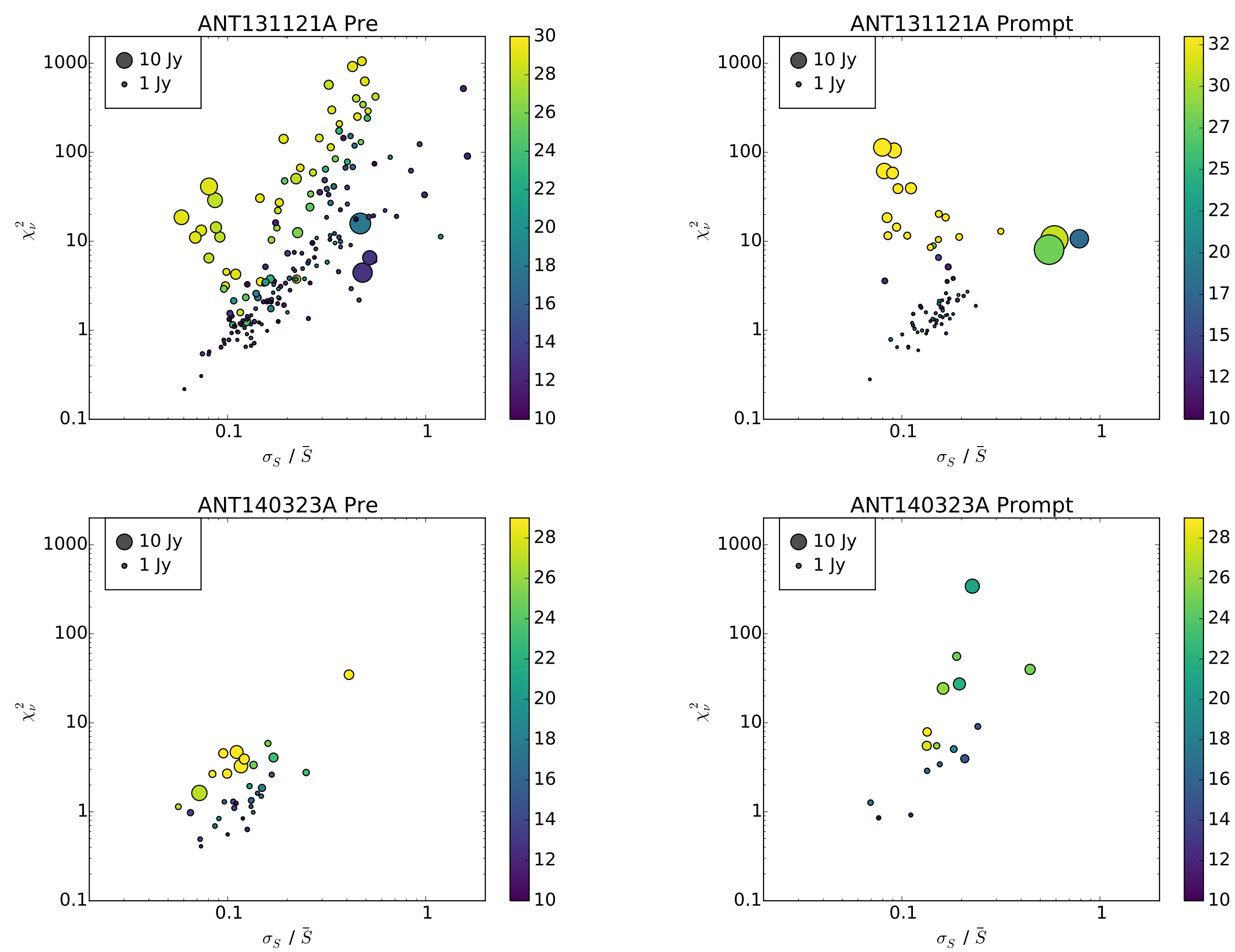
118-182 MHz



Low-freq. radio telescopes with large field of view → enable follow-up (of neutrino events)

First joint study: MWA / ANTARES (ApJ in press)

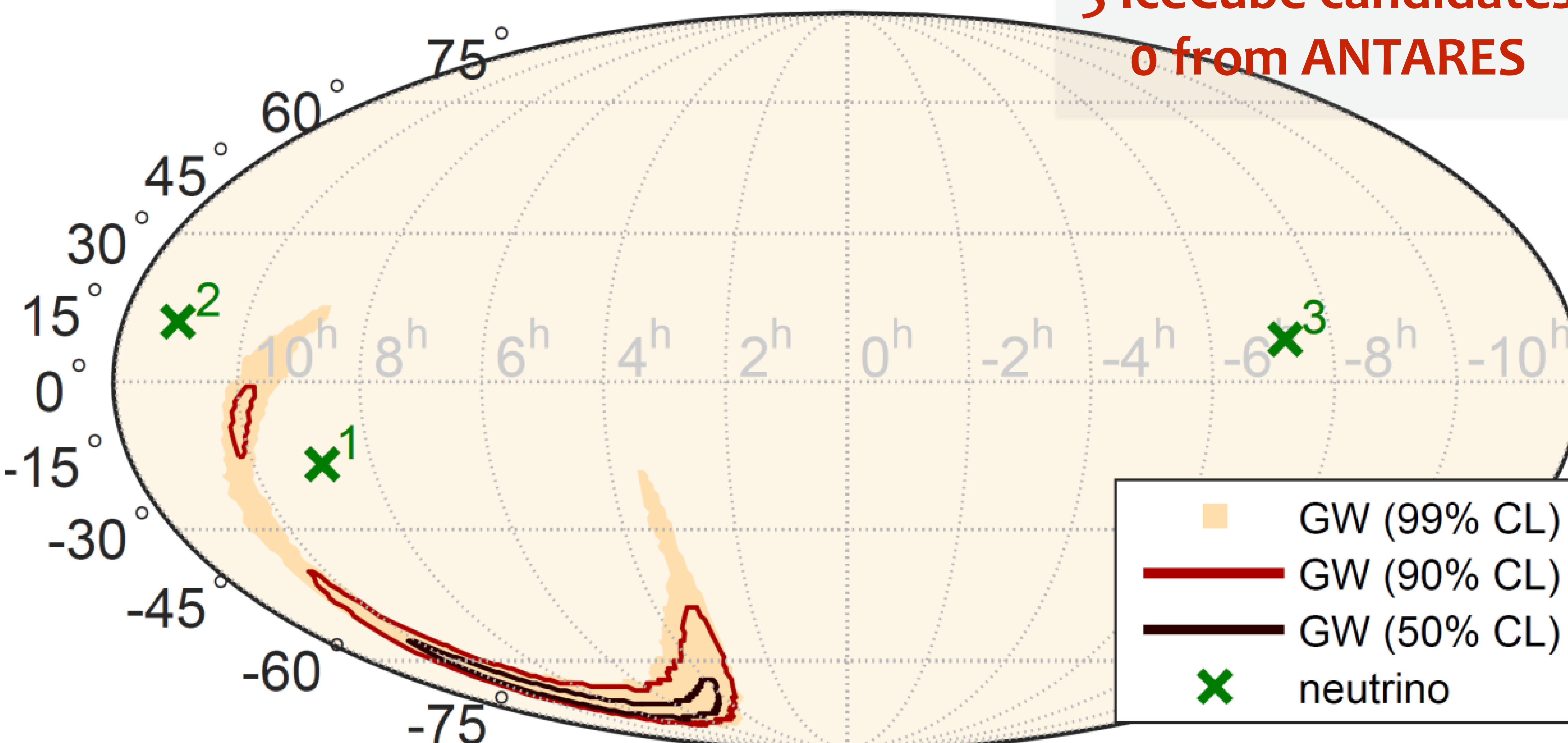




3 GW150914 neutrino follow-up

Within ±500 s from GW alert

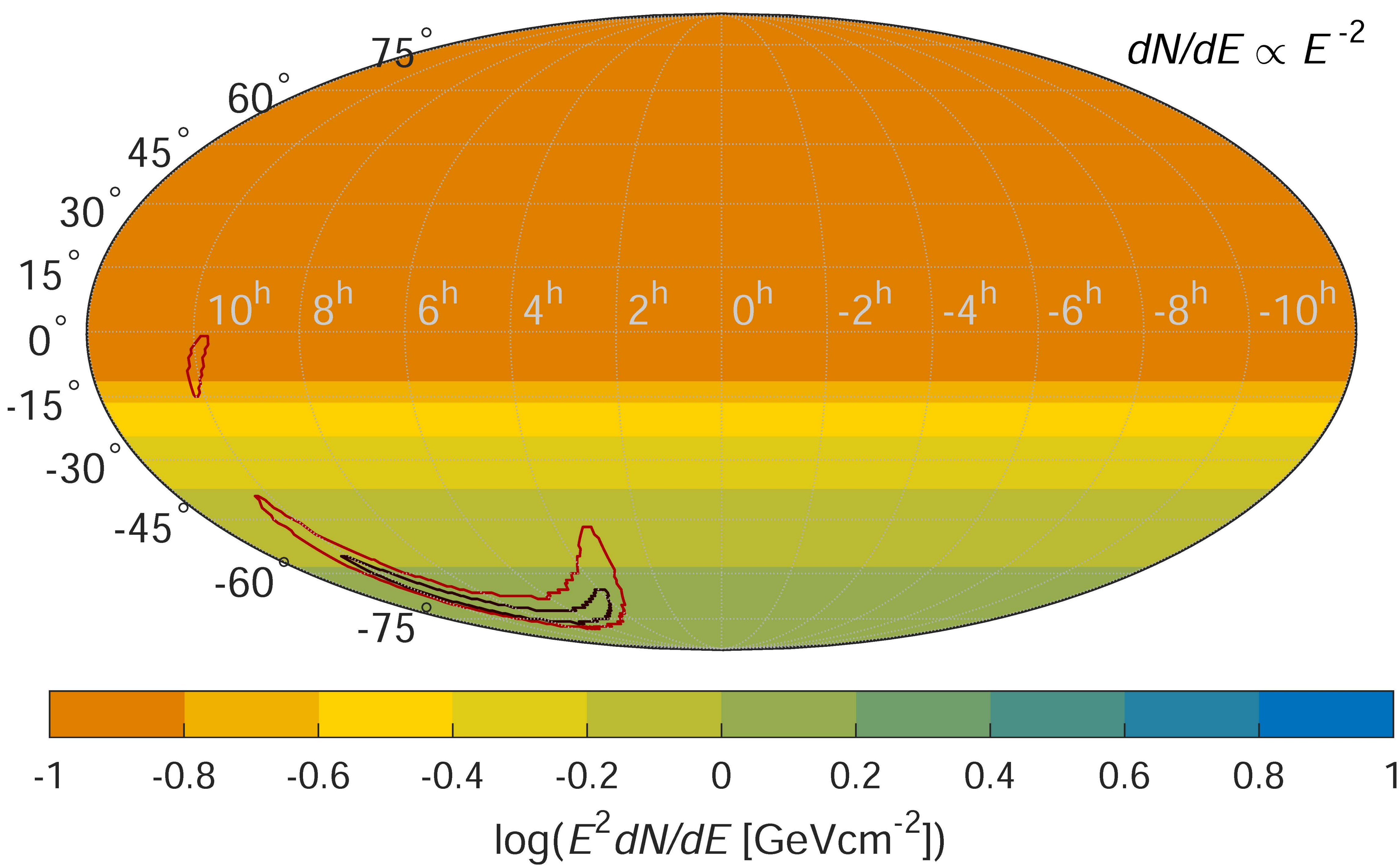
3 IceCube candidates
0 from ANTARES



online ANTARES and IceCube data
➜ Consistent with the background expectations

3 GW150914 neutrino follow-up

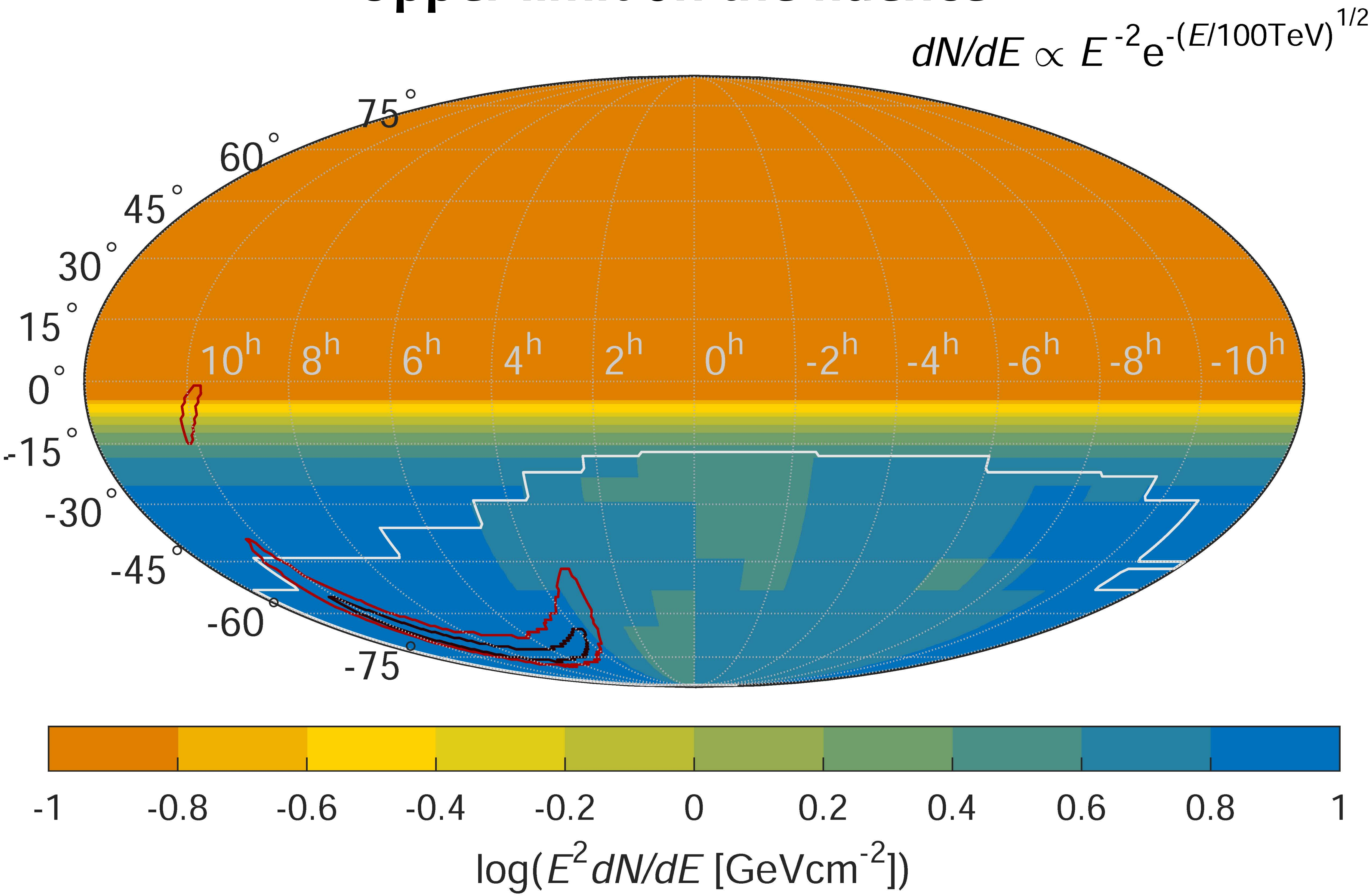
Upper limit on the fluence



http://arxiv.org/abs/1602.05411 (Submitted to PRD)

3 GW150914 neutrino follow-up

Upper limit on the fluence



http://arxiv.org/abs/1602.05411 (*Submitted to PRD*)

3 GW150914 neutrino follow-up

Constraints on the total energy emitted in neutrinos

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

- ≲ 1/100 of the energy radiated in GW: ~5 x 10^{54} erg
- Joint GW and neutrino searches ➜ improve the efficiency of electromagnetic follow-up:
  - neutrino direction accuracy: <0.5deg^2 for ANTARES
  - GWs direction reconstruction: ≳ 100deg^2

➜ joint candidate provides greatly reduced sky area for follow-up !!
(event filtering delay: ~3-5 s for ANTARES and ~1 min for LIGO-Virgo)

Conclusions

- ANTARES and IceCube start to rule out some (photo-)hadronic interactions
- KM3NeT more sensitive than IceCube to the Galactic plan region ! (ANTARES is already competitive in this part of the sky)
- Multi-wavelength/**multi-messenger** approach crucial to identify the sources/further constrain hadronic/leptonic mechanisms

Thank you for your attention !