High Energy Neutrinos and Transient Phenomena

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Outline

- High energy neutrinos
  - Why important?
  - How to produce?
  - Very quick overview of IceCube neutrinos
- High energy neutrinos from transient phenomena
  - Some general arguments about IceCube targets
  - What have been done so far
  - What “we” can do

High energy neutrinos

Multi-messenger astronomy

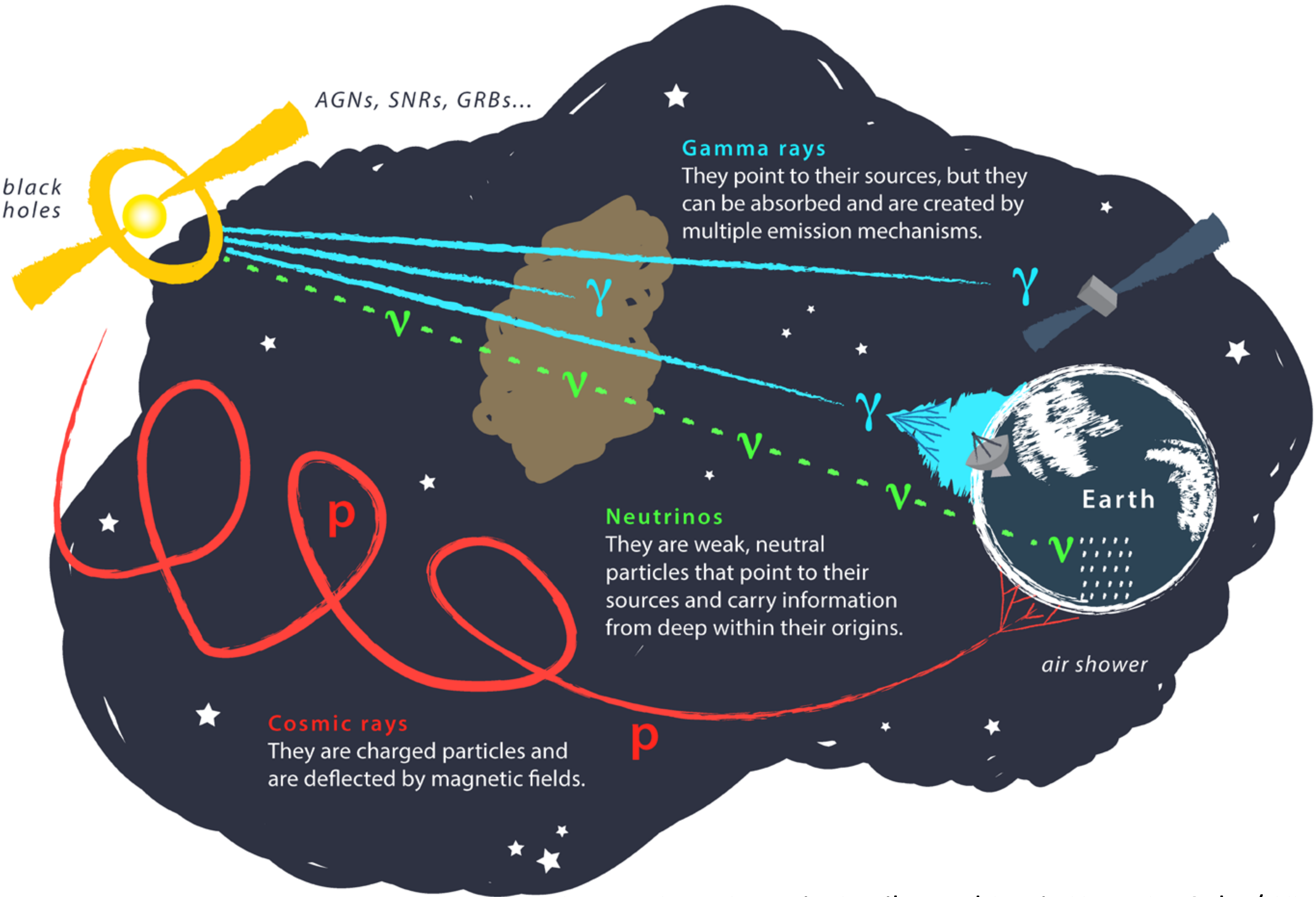
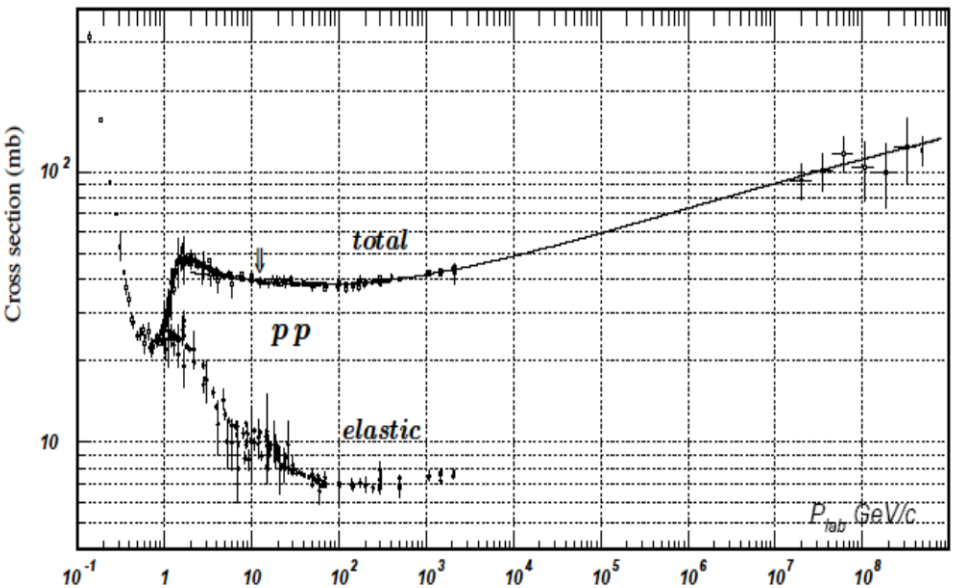


Image: Juan Antonio Aguilar and Jamie Yang. IceCube/WIPAC

High-E neutrino production ; *pp* & *pγ*

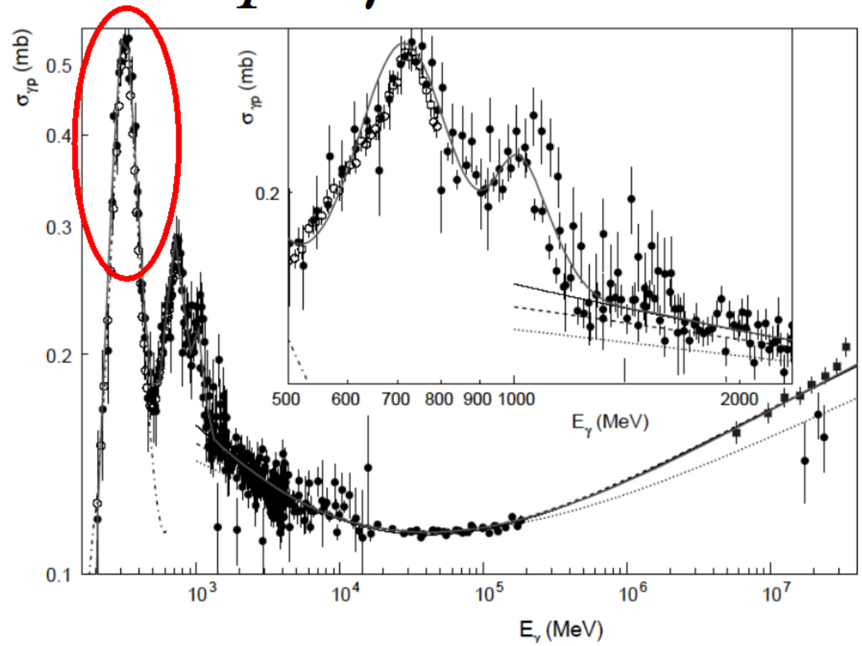
$$p+p \rightarrow N\pi + X$$



$$\sigma_{pp} \sim 1/m_\pi^2 \sim 30 \text{ mb}$$

$$\pi^\pm : \pi^0 \sim 2:1$$

Δ-resonance $$p+\gamma \rightarrow N\pi + X$$



$$\sigma_{p\gamma} \sim \alpha\sigma_{pp} \sim 0.5 \text{ mb} \quad \pi^\pm : \pi^0 \sim 1:1$$

$$\varepsilon'_p \varepsilon'_\gamma \sim (0.34 \text{ GeV})(m_p/2) \sim 0.16 \text{ GeV}^2$$

$$\pi^\pm \rightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e(\bar{\nu}_e) + e^\pm \qquad \pi^0 \rightarrow 2\gamma$$

$E_\nu \sim 0.04\, E_p$ → PeV neutrinos ⇔ a few 10 PeV protons

The Waxman-Bahcall bound

$$\varepsilon_\nu^2 \Phi_\nu = \frac{c}{4\pi} \int dz \left| \frac{dt}{dz} \right| \varepsilon_\nu^2 q_\nu(\varepsilon_\nu) F(z) \quad \Rightarrow \quad \varepsilon_\nu^2 \Phi_\nu \approx \frac{c t_H}{4\pi} \left[\frac{f_\pi}{4} \varepsilon_p^2 q_p(\varepsilon_p) \right] f_z$$

$f_\pi (< 1)$: meson production efficiency

$f_z (\sim 0.6\text{-}5)$: source redshift evolution

$\varepsilon_p^2 q_p(\varepsilon_p)$: cosmic-ray generation rate per volume

If CR injection rate is comparable to that of ultra-high energy cosmic rays;

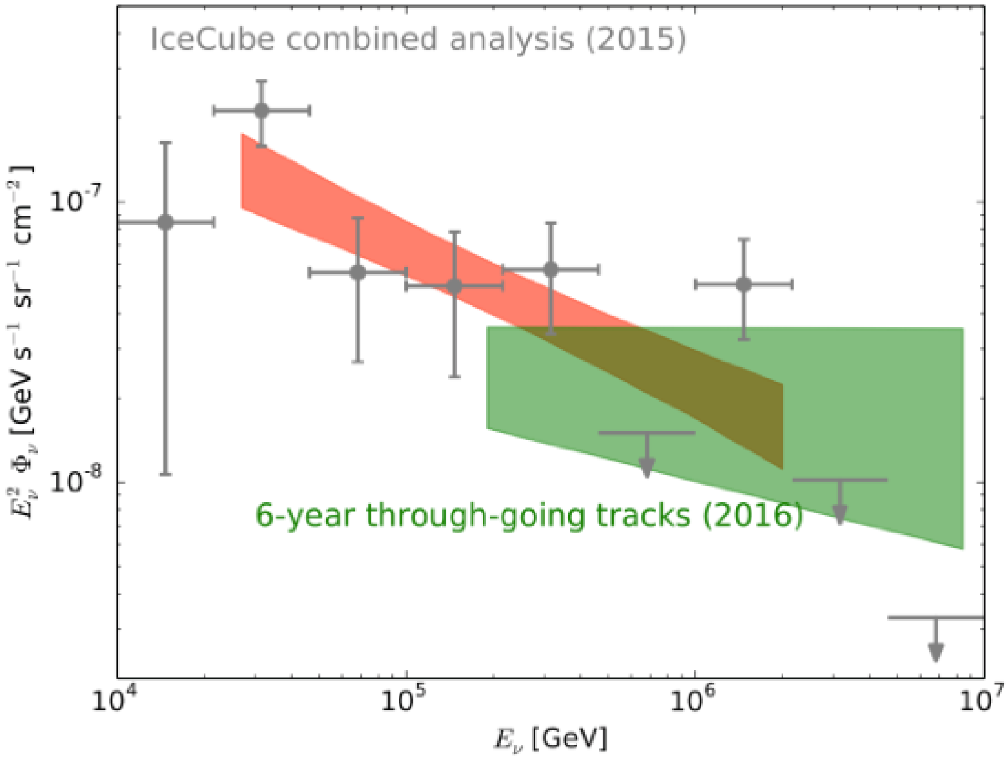
$$\varepsilon_p^2 q_p(\varepsilon_p) \sim 0.6 \times 10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1}$$

and the pion production is efficient, $f_\pi \sim 1$

$$\Rightarrow \quad \varepsilon_\nu^2 \Phi_\nu \sim f_z \times 10^{-8} \text{ GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$$

IceCube neutrinos

Aartsen+16



- ✓ The atm. background-only hypothesis is rejected at 3.6σ.
- ✓ The flux is comparable to the Waxman-Bahcall bound.
- ✓ Low energy excess at ~ 10 TeV?
- ✓ High energy cutoff at ~ PeV?

High energy neutrinos from transient phenomena

Some general arguments about IceCube targets

How many neutrinos per event?

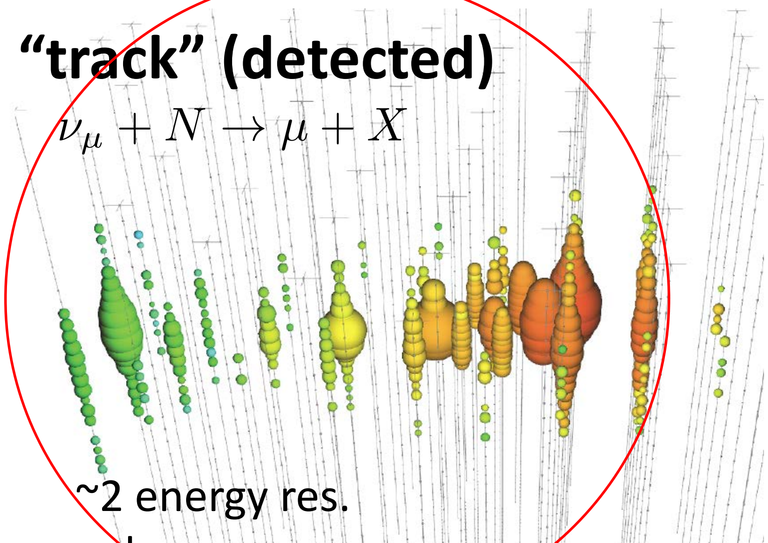
$$\mathcal{E}_{\rm exp} \xrightarrow[f_{\rm cr}]{} \mathcal{E}_{\rm cr} \xrightarrow[f_{pp,p\gamma}]{} \mathcal{E}_{\nu} \xrightarrow[\mathcal{B},\, \bar{E}_{\nu},\, d_{\rm L}]{} \bar{\mathcal{F}}_{\nu_\mu}$$

$$\sim 10^{-4}\ {\rm m}^{-2}\ \frac{\mathcal{E}_{\rm exp}}{10^{52}\ {\rm erg}} \frac{f_{\rm cr}}{0.1} \frac{f_{pp,p\gamma}}{1} \left(\frac{\mathcal{B}}{10}\right)^{-1} \left(\frac{\bar{E}_{\nu}}{100\ {\rm TeV}}\right)^{-1} \left(\frac{d_{\rm L}}{\rm Gpc}\right)^{-2}$$

With IceCube – signal type

“track” (detected)

$$\nu_\mu + N \rightarrow \mu + X$$



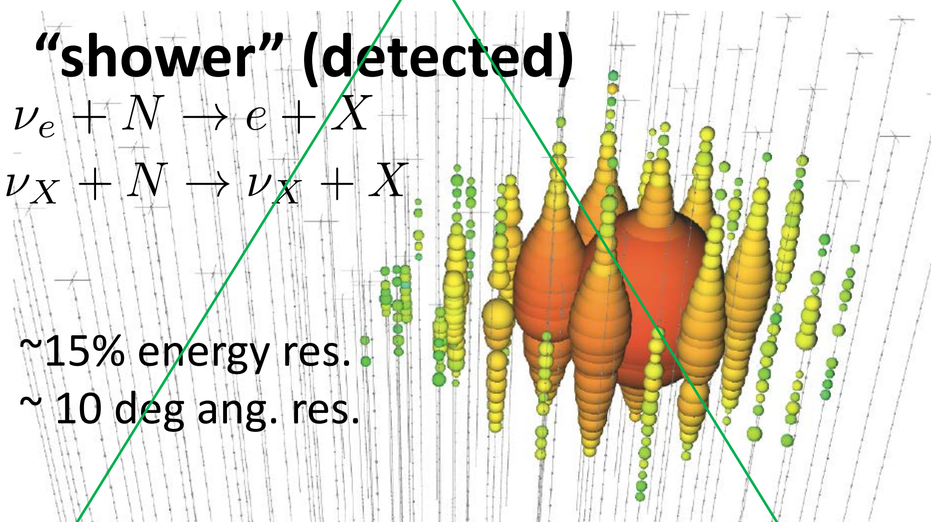
~2 energy res.

< deg ang. res.

“shower” (detected)

$$\nu_e + N \rightarrow e + X$$

$$\nu_X + N \rightarrow \nu_X + X$$

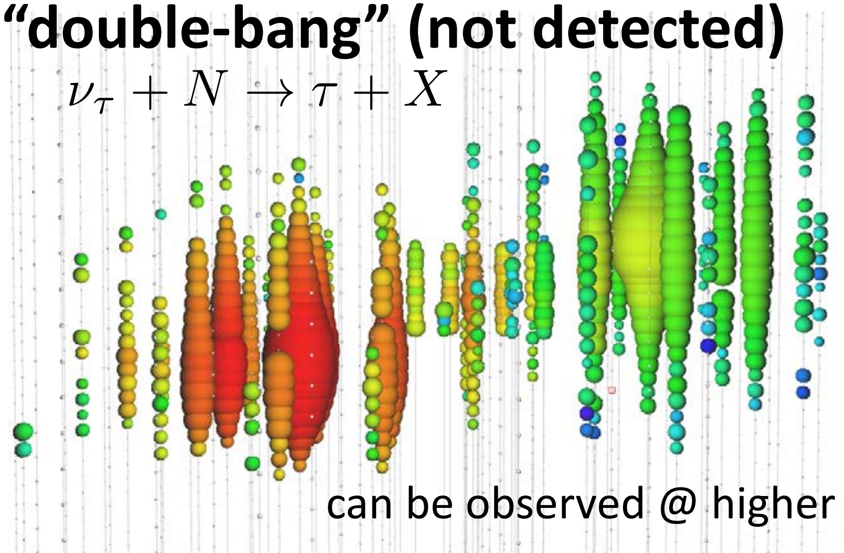


~15% energy res.

~ 10 deg ang. res.

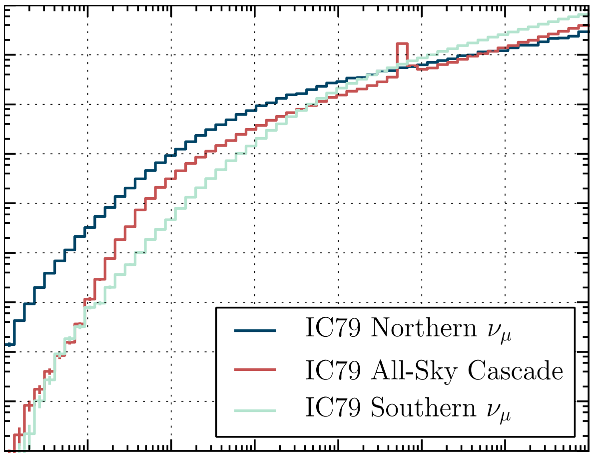
“double-bang” (not detected)

$$\nu_\tau + N \rightarrow \tau + X$$



can be observed @ higher energies

With IceCube – for detection, in general



Very roughly, $A_{\nu_\mu} \sim 100\ \mathrm{m}^2\ \frac{\bar{E}_{\nu_\mu}}{100\ \mathrm{TeV}}$

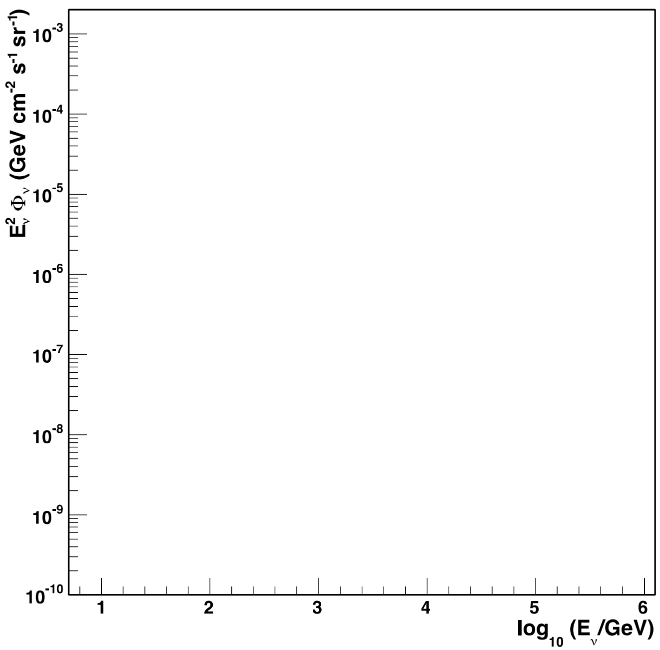
$$\longrightarrow\ N_{\nu_\mu} \sim \mathcal{F}_{\nu_\mu} A_{\nu_\mu} \sim 0.01\ \frac{\mathcal{E}_{\mathrm{exp}}}{10^{52}\ \mathrm{erg}} \frac{f_{\mathrm{cr}}}{0.1} \frac{f_{pp,p\gamma}}{1} \left(\frac{\mathcal{B}}{10}\right)^{-1} \left(\frac{d_{\mathrm{L}}}{\mathrm{Gpc}}\right)^{-2}$$

- Let us detect a nearby bigshot

$$N_{\nu_\mu} \gtrsim 1 \rightarrow d_{\mathrm{L}} \lesssim 300\ \mathrm{Mpc}\ \left(\frac{\mathcal{E}_{\mathrm{exp}}}{10^{52}\ \mathrm{erg}}\right)^{1/2} \left(\frac{f_{\mathrm{cr}}}{0.1}\right)^{1/2} \left(\frac{f_{pp,p\gamma}}{1}\right)^{1/2} \left(\frac{\mathcal{B}}{10}\right)^{-1/2}$$

- or we can also stack $1/N_{\nu_\mu} \sim 100\ \left(\frac{\mathcal{E}_{\mathrm{exp}}}{10^{52}\ \mathrm{erg}}\right)^{-1} \left(\frac{f_{\mathrm{cr}}}{0.1}\right)^{-1} \left(\frac{f_{pp,p\gamma}}{1}\right)^{-1} \frac{\mathcal{B}}{10} \left(\frac{d_{\mathrm{L}}}{\mathrm{Gpc}}\right)^{2}$ events

With IceCube – vs atm. background



Very roughly,

$$\Delta N_{\rm bg,\mu} \sim 1 \ \frac{\Delta\Omega}{1\ {\rm deg}^2}\frac{\Delta t_{\rm obs}}{1\ {\rm month}}\left(\frac{E_{\nu_\mu}}{1\ {\rm TeV}}\right)^{-3/2}$$

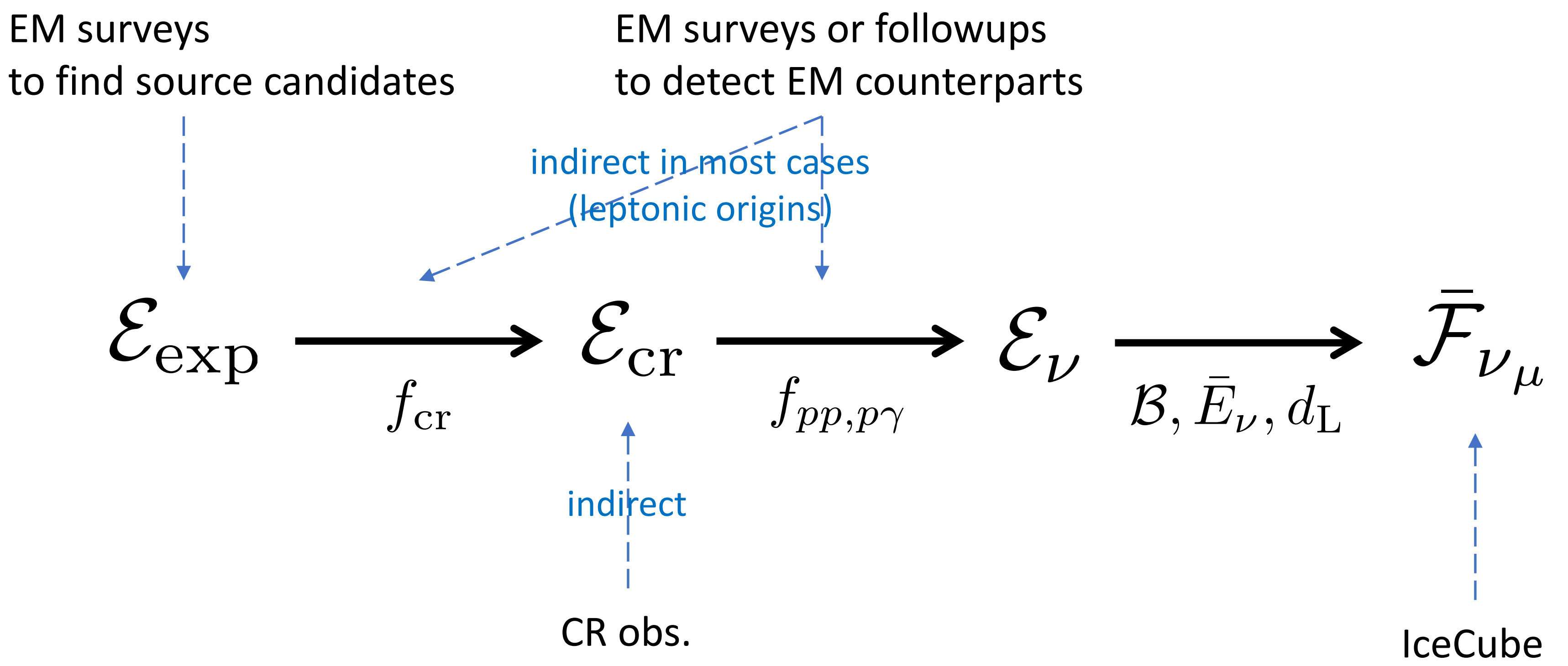
or $$\Delta t_{\rm obs,c} \sim 1\ {\rm month}\left(\frac{\Delta\Omega}{1\ {\rm deg}^2}\right)^{-1}\left(\frac{E_{\nu_\mu}}{1\ {\rm TeV}}\right)^{3/2}$$

- ✓ Less than ~ 1 % are expected to be of cosmic origin @ ~TeV.
- ✓ > 100 TeV → likely astrophysical

- For stacking,

$$\frac{\Delta t_\nu}{N_{\nu_\mu}} \lesssim \Delta t_{\rm obs,c} \rightarrow \Delta t_\nu \lesssim 8\ {\rm hrs}\ \frac{\mathcal{E}_{\rm exp}}{10^{52}\ {\rm erg}}\frac{f_{\rm cr}}{0.1}\frac{f_{pp,p\gamma}}{1}\left(\frac{\mathcal{B}}{10}\right)^{-1}\left(\frac{d_{\rm L}}{\rm Gpc}\right)^{-2}\left(\frac{\Delta\Omega}{1\ {\rm deg}^2}\right)^{-1}\left(\frac{E_{\nu_\mu}}{1\ {\rm TeV}}\right)^{3/2}$$

What we can learn, in general



(non-)detections of neutrinos $\longrightarrow$ $f_{\rm cr}, f_{p\gamma}, f_{pp}, \cdots$

origins of IceCube neutrinos,
origins of cosmic rays,
acceleration and emission mechanism, …

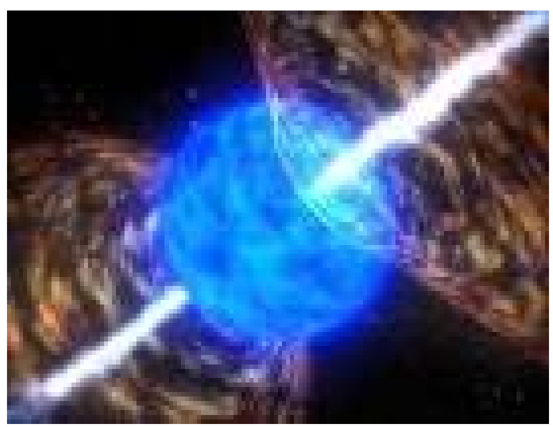
Target candidates

- $$N_{\nu_\mu} \sim \mathcal{F}_{\nu_\mu} A_{\nu_\mu} \sim 0.01 \; \frac{\mathcal{E}_{\rm exp}}{10^{52}\ {\rm erg}} \frac{f_{\rm cr}}{0.1} \frac{f_{pp,p\gamma}}{1} \left(\frac{\mathcal{B}}{10}\right)^{-1} \left(\frac{d_{\rm L}}{\rm Gpc}\right)^{-2}$$

$\mathcal{E}_{\rm exp}/d_{\rm L}^2 \uparrow$ Brighter transients

$f_{\rm cr} \uparrow$ with non-thermal signatures

$f_{pp}, f_{p\gamma} \uparrow$ in a “dense” environment

like  and their relatives

Multi-messenger obs. strategies

✓ For bigshot(s)

should not miss nearby events;
A wide field-of-view is more essential.

EM surveys ⇌ IceCube

ν alert quickly after the detection,
rapid EM followup

✓ For stacking

EM surveys ⟶ IceCube

Find as many as possible.

What have been done

Multi-messenger obs. strategies

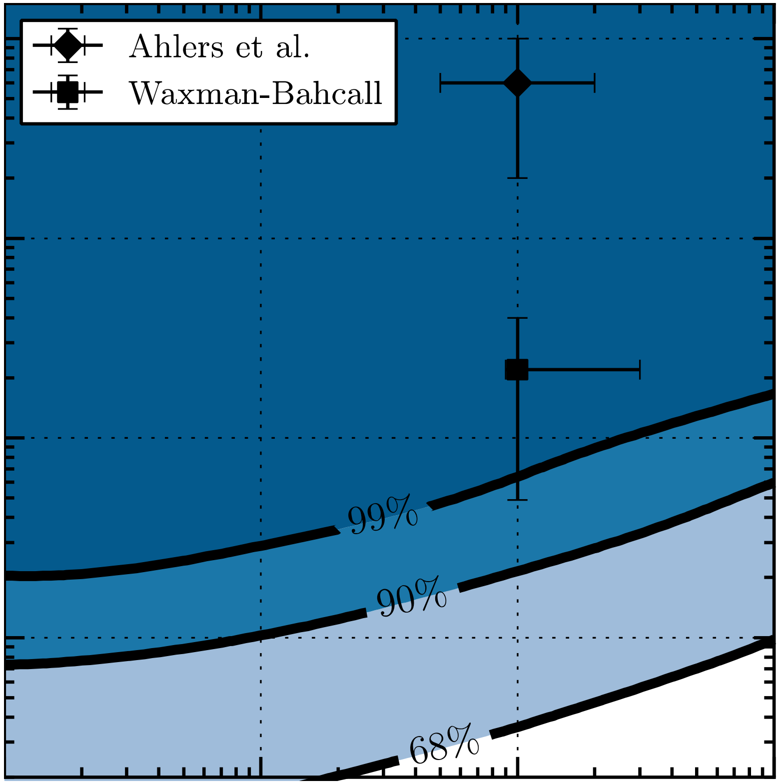
✓ For bigshot(s)

EM surveys $\rightleftharpoons$ IceCube

✓ For stacking

EM surveys $\longrightarrow$ IceCube

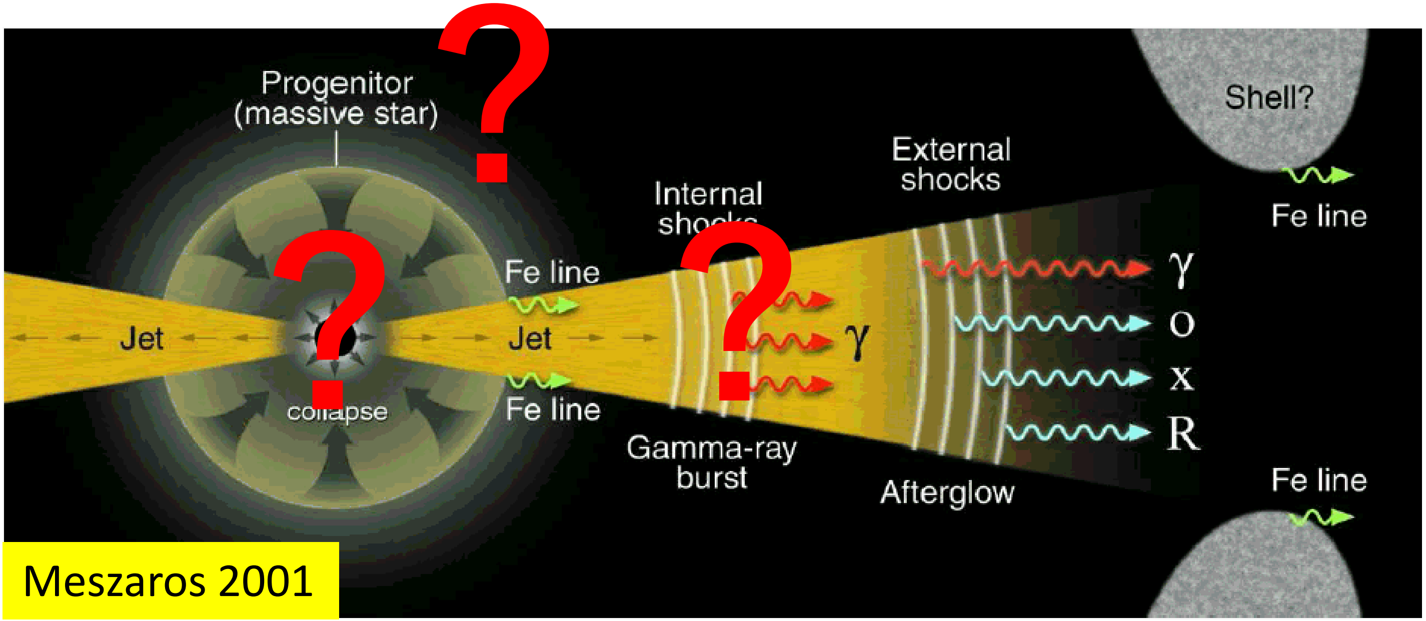
Stacking ~1000 GRBs



Exclude GRBs as the dominant source of the observed IceCube neutrinos.

(Long) Gamma-Ray Bursts

- A standard picture



- What we do not know
  - **Central engine?** → **BH and magnetar formation**
  - **Prompt emission?** → **Physics of the jet**
    Origin of UHECRs
  - **Progenitor?** → **GRB-SN connection**

Q. What is the GRB mechanism?

"Band" function
～ broken power law

✓ $\varepsilon_{peak} \sim 0.1\text{-}1\ \mathrm{MeV}$

✓ @ low energy $N_E \propto E^{\alpha}$

$$\alpha \sim -1$$

✓ @ high energy $N_E \propto E^{\beta}$

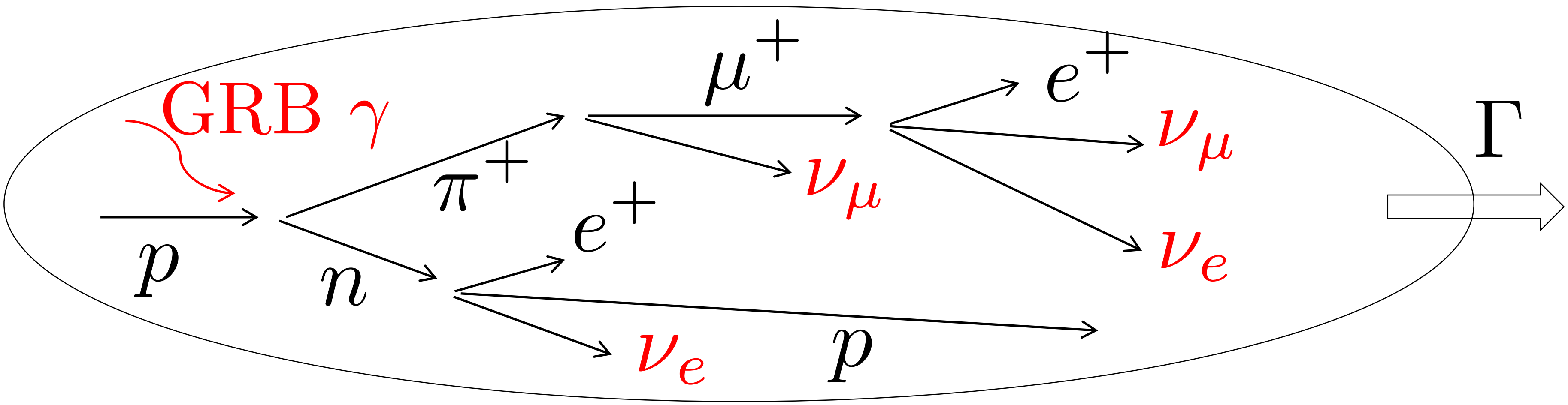
$$\beta \sim -(2\text{-}3)$$

Abdo+2010

✓ non-thermal features → particle acceleration?

✓ polarization? (e.g., Yonetoku+2012) → magnetic fields?

GRB prompt neutrinos



$$p + \gamma \rightarrow N\pi + X \text{ with } \sigma_{p\gamma} \sim \text{a few} \times 10^{-28}\ \text{cm}^2$$

✓@ Δ-resonance $\varepsilon'_p \times \varepsilon'_\gamma \sim 0.2\ \text{GeV}^2$

$$\varepsilon_{\nu,obs} \sim 0.05\ \varepsilon_{p,obs} \sim 0.01\ \Gamma^2 \varepsilon^{-1}_{\gamma,obs}\ \text{GeV}^2$$

$$\sim 1\ \text{PeV}\ \Gamma^2_{2.5} \varepsilon^{-1}_{\gamma,obs,\text{MeV}}$$

✓Meson production efficiency (large astrophysical uncertainties)

$$f_{p\gamma} \sim 0.2 n_\gamma \sigma_{p\gamma} (r/\Gamma) \propto r^{-1}\Gamma^{-2} \longrightarrow F_\nu \propto \eta_{\text{CR}} r^{-1} \Gamma^{-2}$$

The GRB-UHECR hypothesis

- If not only electrons but protons are accelerated,

$$\varepsilon_p < erB \sim 3 \times 10^{20}\ r_{14} B_4\ \mathrm{eV}$$

Waxman 1995

- If $E_{CR}^{iso} \sim E_{\gamma}^{iso} \sim 10^{53}$, erg

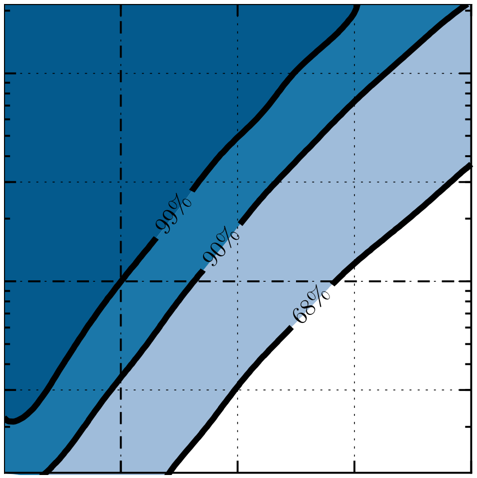
with $\rho_{GRB} \sim 1\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$

Wanderman & Piran 2003

$$\Longrightarrow \quad Q_{CR} \sim 10^{44}\ \mathrm{erg\ Mpc}^{-3}\ \mathrm{yr}^{-1}$$

Consistent with the UHECR observations

Stacking ~1000 GRBs



Emission mechanism, the GRB-UHECR hypothesis, and so on are being tested.

Way to go!

Multi-messenger obs. strategies

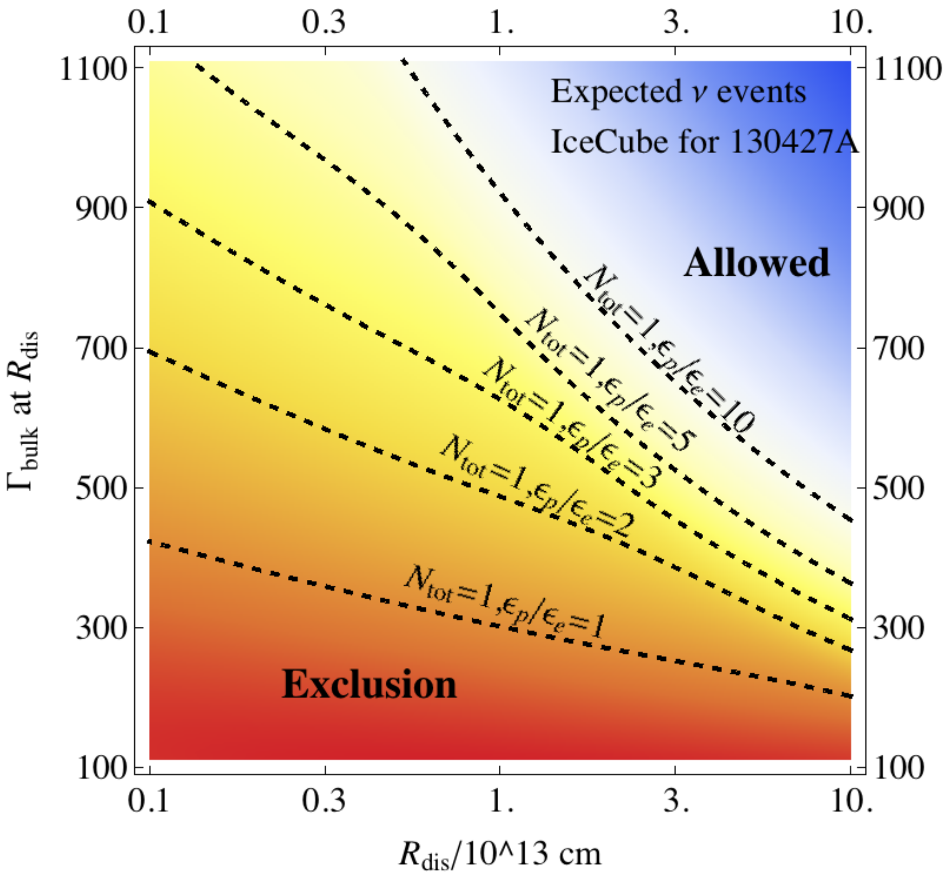
✓ For bigshot(s)

EM surveys $\rightleftharpoons$ IceCube

✓ For stacking

EM surveys $\longrightarrow$ IceCube

“The brightest GRB ever since 2010”



Shan, KK, Meszaros 2013

Multi-messenger obs. strategies

- ✓ For bigshot(s)

EM surveys ⇌ IceCube

- ✓ For stacking

EM surveys ⟶ IceCube

Alerts from IceCube

✓ Not to be ”cry wolf too often” …

$$\Delta N_{\mathrm{bg},\mu} \sim 1 \, \frac{\Delta\Omega}{1\ \mathrm{deg}^2} \frac{\Delta t_{\mathrm{obs}}}{1\ \mathrm{month}} \left(\frac{E_{\nu_\mu}}{1\ \mathrm{TeV}}\right)^{-3/2}$$

1. High energy events

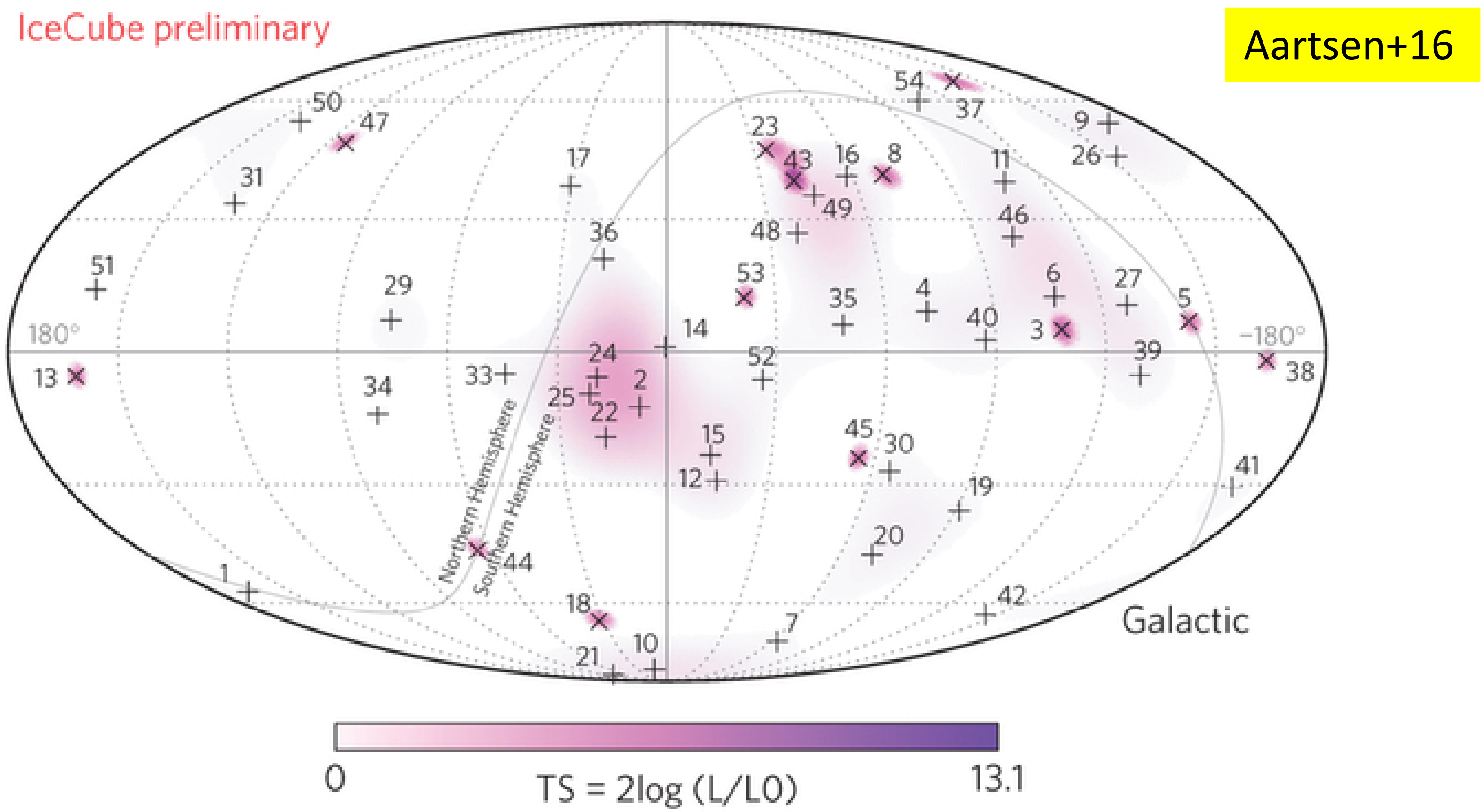
2. Multiplets

i.e. two or more neutrinos from the same direction within 100 s

✓ The real-time search

“In case of automatic forwarding,
the median latency for triggering follow-up observatories is ~ 1 min. ”

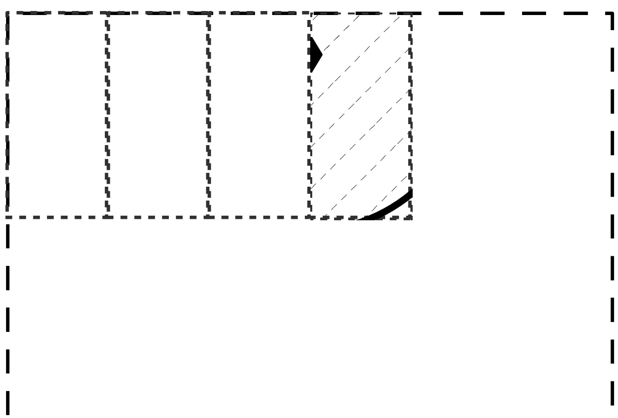
High energy events



So far no association with any transient source reported, but only one single association means huge, keep on going!

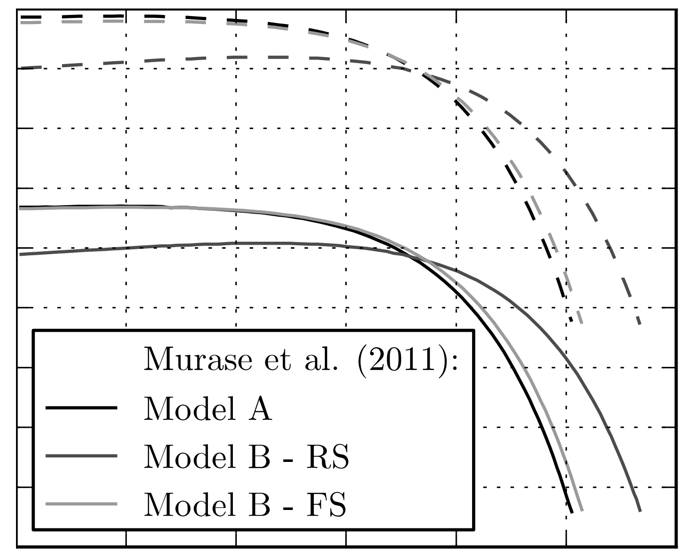
Follow-up of a neutrino multiplet

A ~ TeV ν doublet
+ SN IIn (~160 days after exp.)



Let's see…

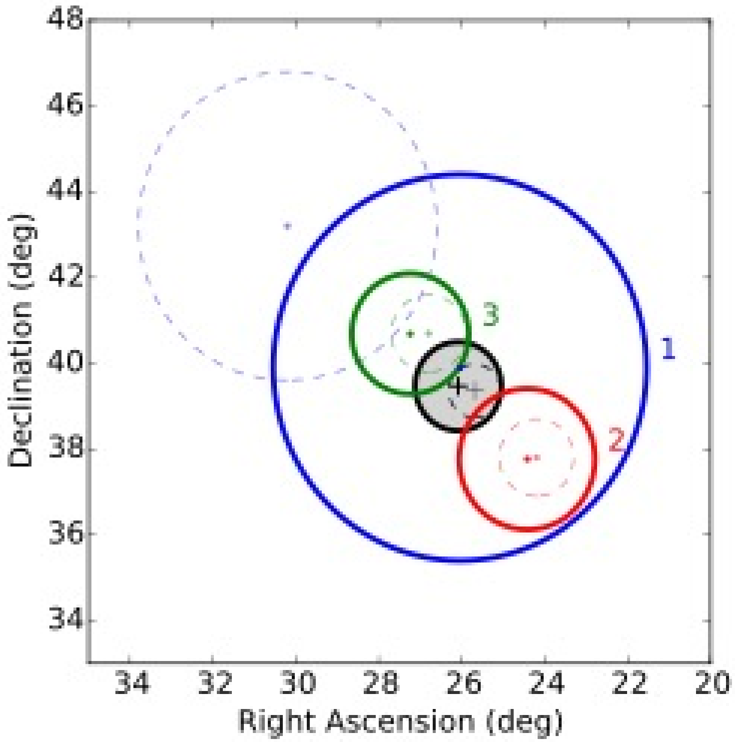
"Too ν bright to be true"



The significance of the chance detection is 2.2σ

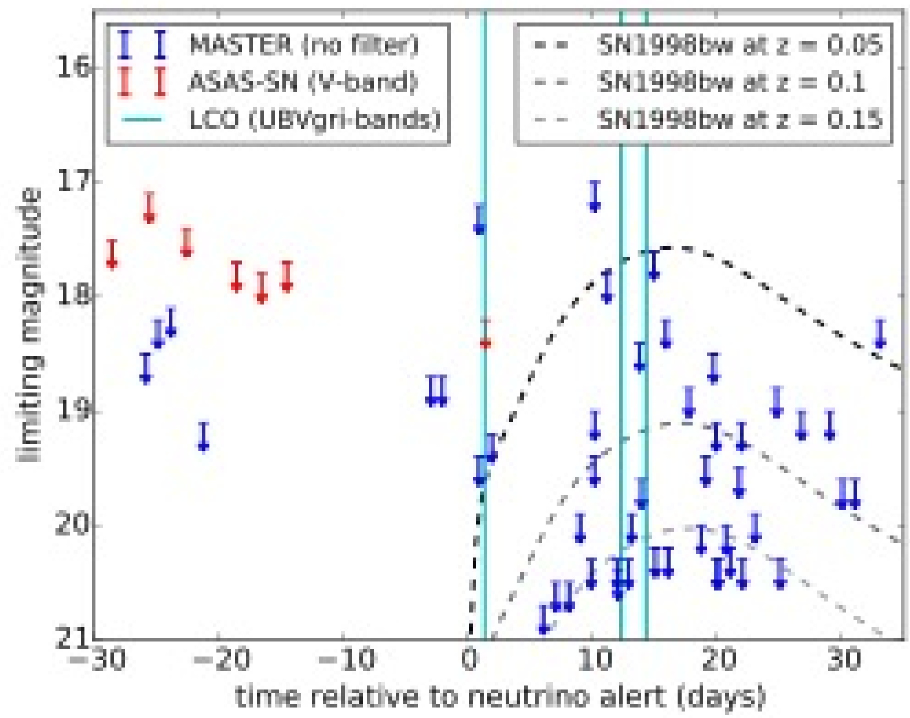
Follow-up of a neutrino multiplet

A ~TeV ν triplet candidate



Let's see…

No EM counterpart detected



The probability to detect one triplet from atm. backgrounds is 32%.

Stringent constraint on nearby energetic explosions

HE ν & transients so far (my personal view)

What “we” can do

(or what have not been done)

- GRB stacking is working very well.

  They are rare but EM bright and detected efficiently thanks to e.g., Swift and Fermi.

- Next target will be relatively dim in the γ-ray bands but still energetic or abundant transients, e.g.,
  - Low luminosity GRBs
  - Failed GRBs or choked jet events
  - Pulsar-driven supernovae
  - Interaction-powered supernovae
  - Tidal disruption events
  - …

- For stacking, EM survey strategies including target selection can be optimized based on the ν modeling and source distribution of each transient.

- EM followup of high energy ν events is useful.
  - ✓ So far in vain, but one single association means huge.
  - ✓ Rapid and followup of ~1 deg^2 and ~10 deg^2 fields for truck and shower events, respectively
  - ✓ The primary target is nearby bigshots.
- HSC can give a unique contribution. (Tanaka-san's talk)
  - ✓ Even for track events(?)
  - ✓ When HSC follows up the ~ 1 deg^2 field for ~30 mins, there always ~ 10 CCSNe at z ~< 0.4.
  - ✓ Only a minor fraction (~ 30 min/month ~ 1/1000) explode just after the trigger.
  - ✓ Effective especially for relatively rare, EM dim (so that not to be detected by other surveys), but ν bright ones (e.g., choked jet HNe)

- EM followup of ν multiplets is also interesting.
  It is even more biased to nearby bright sources.
  Relatively shallow surveys e.g., by ASAS-SN suffice?
  No need for HSC?
- There may be very ν-bright but EM-dim transients. (It's fun to think about it …)
  - ✓ how about failed SNe with choked jets, resulting in massive BH formation?
  - ✓ motivated by GW astronomy
  - ✓ Theoretical challenge:
    possible to make them "very ν-bright but EM-dim"
  - ✓ Observational challenge:
    not much info about the low luminosity end of SNe
    → H!S!C!