Gamma-ray bursts: a high-energy multi-messenger view

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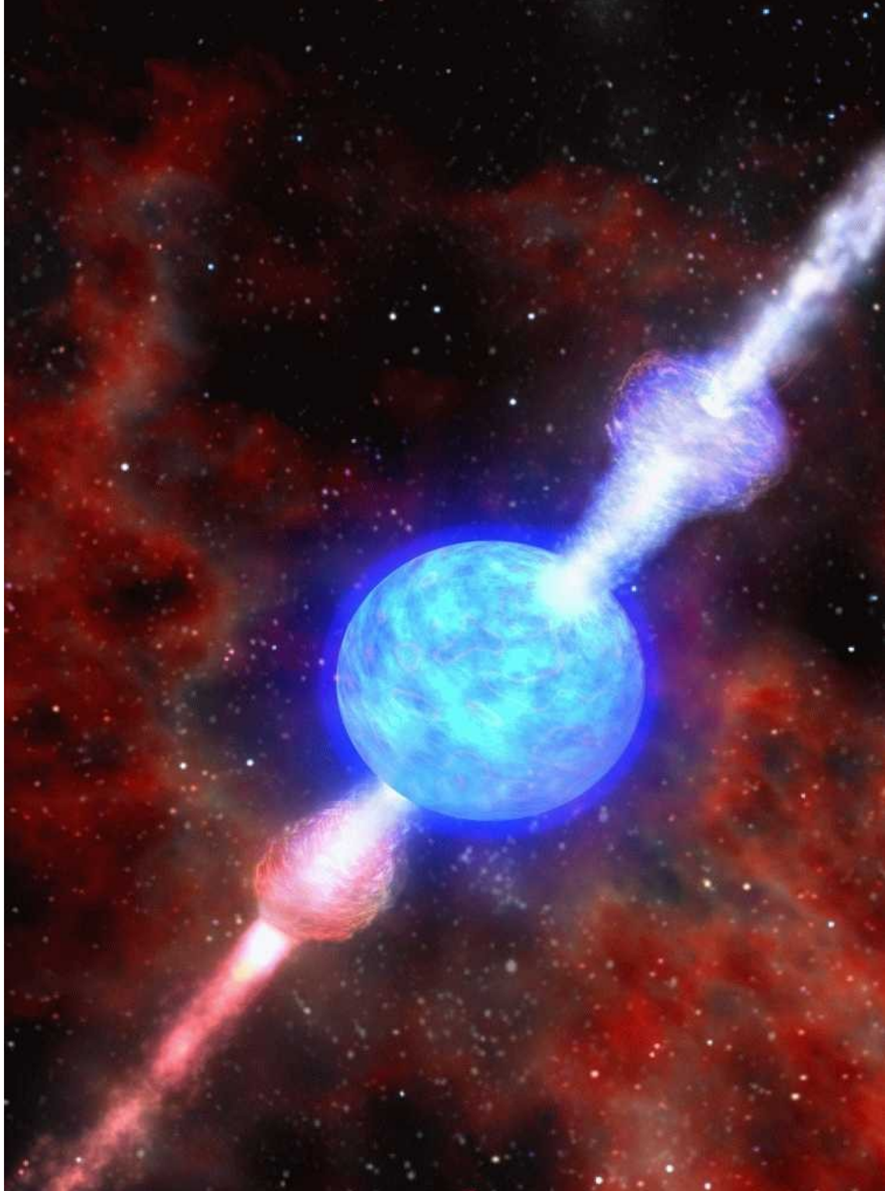
DARK Transient Tuesdays
May 28, 2019

VILLUM FONDEN

Gamma-ray bursts at a glance



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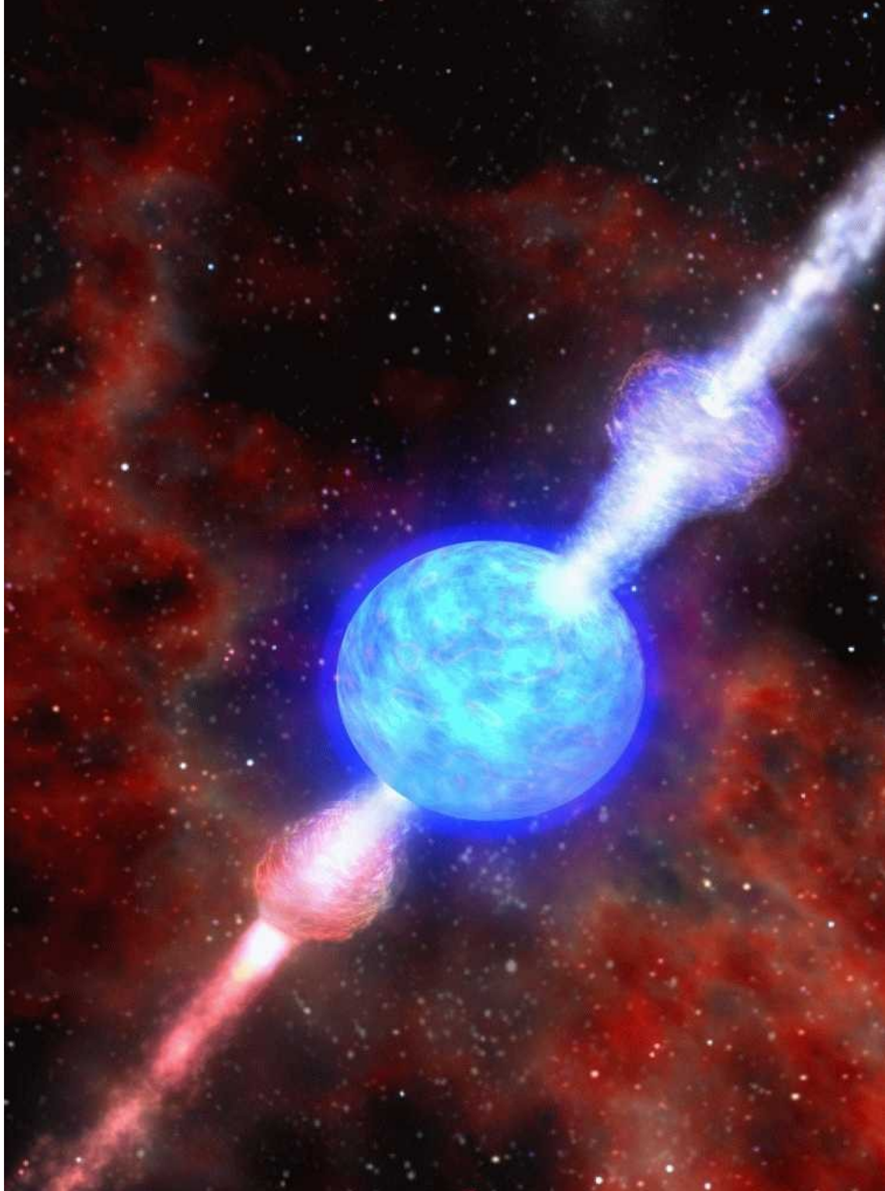
- Non-thermal gamma-ray transients



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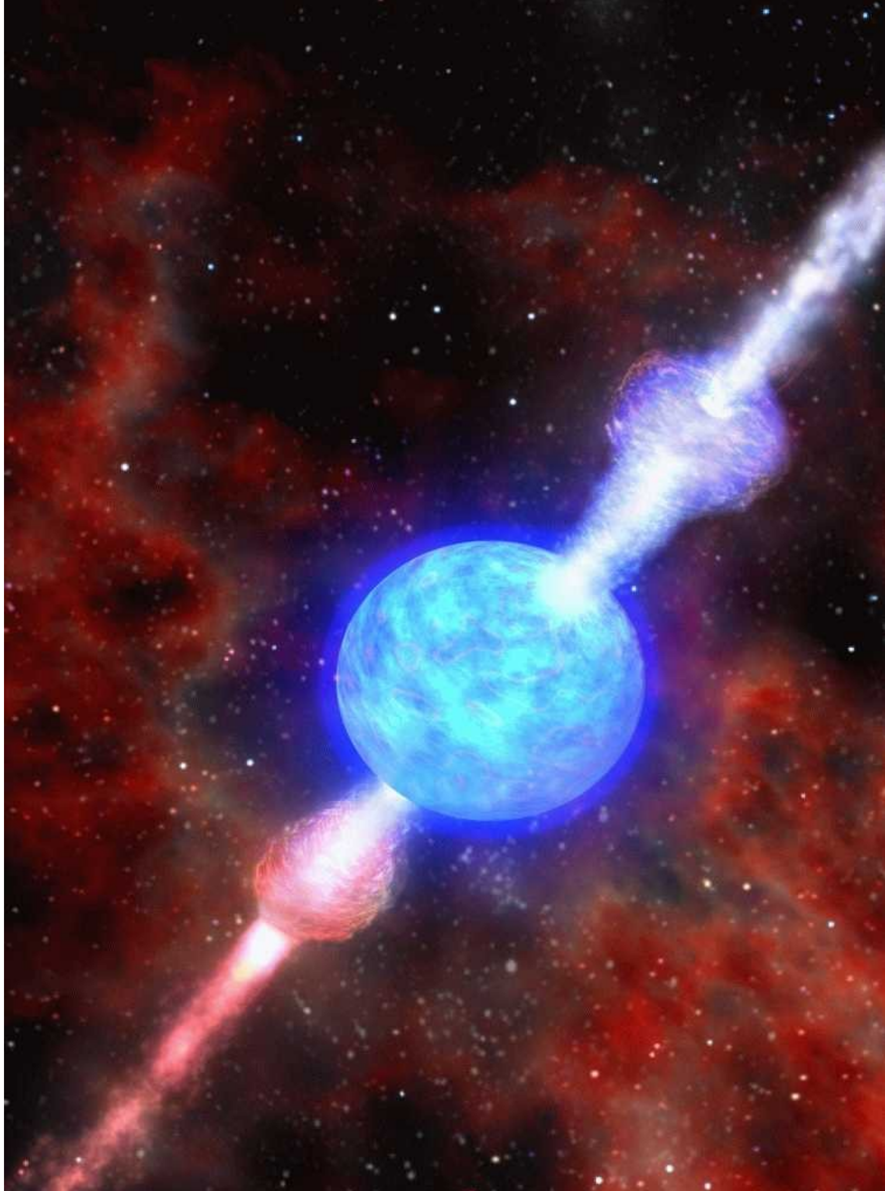

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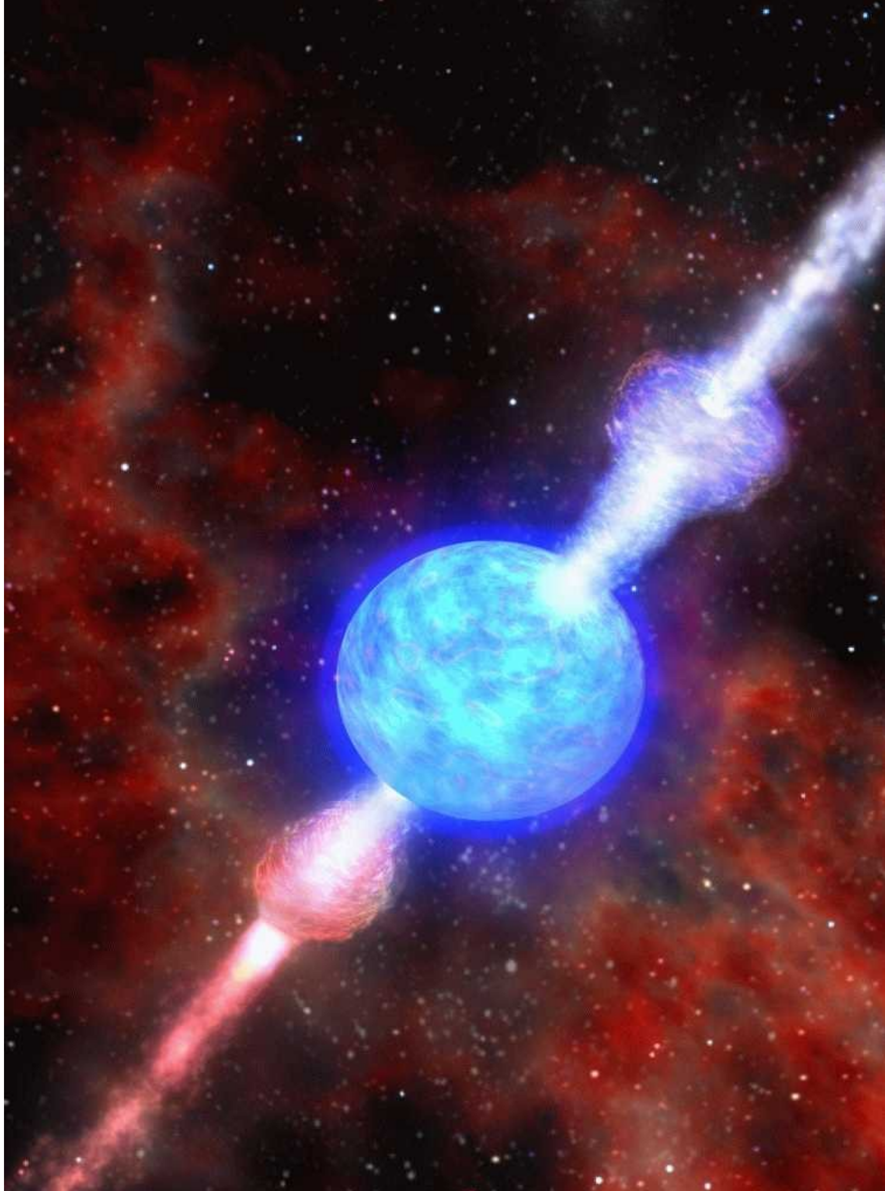

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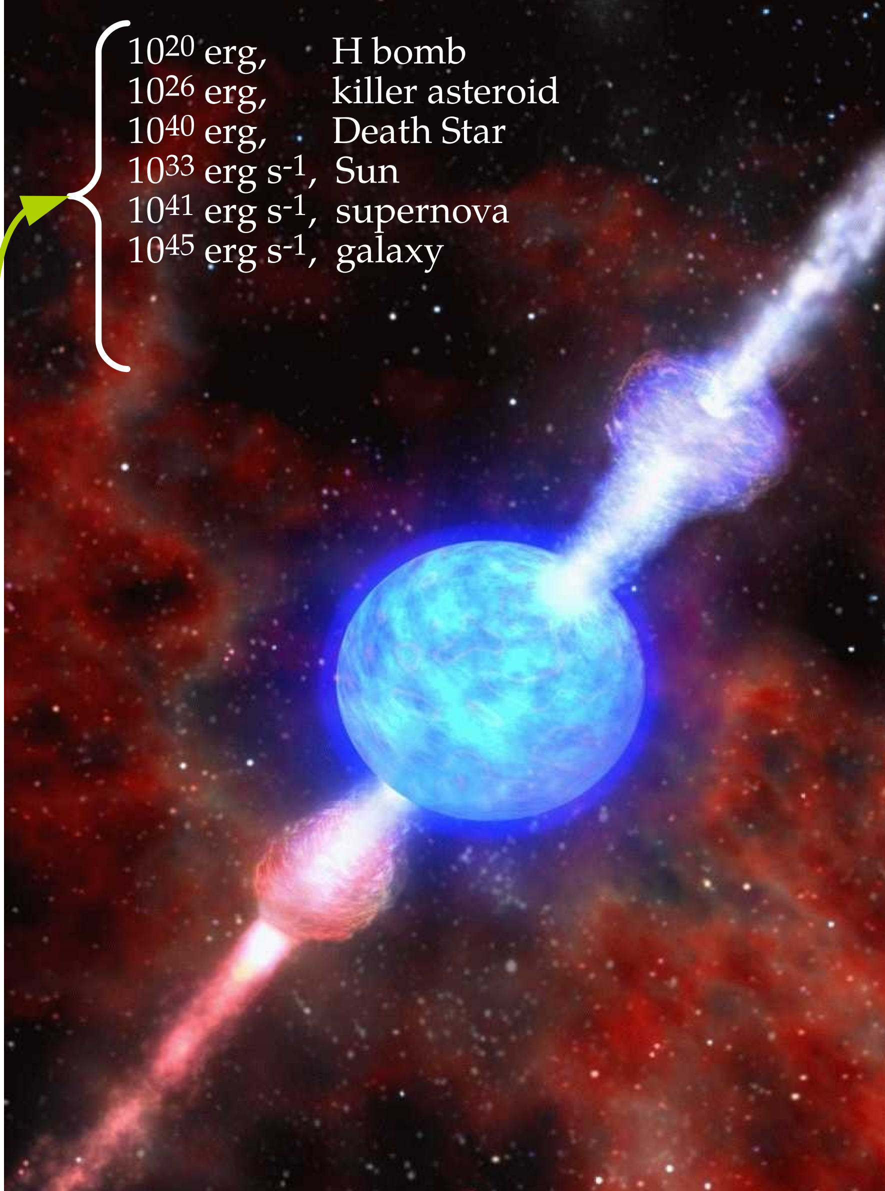

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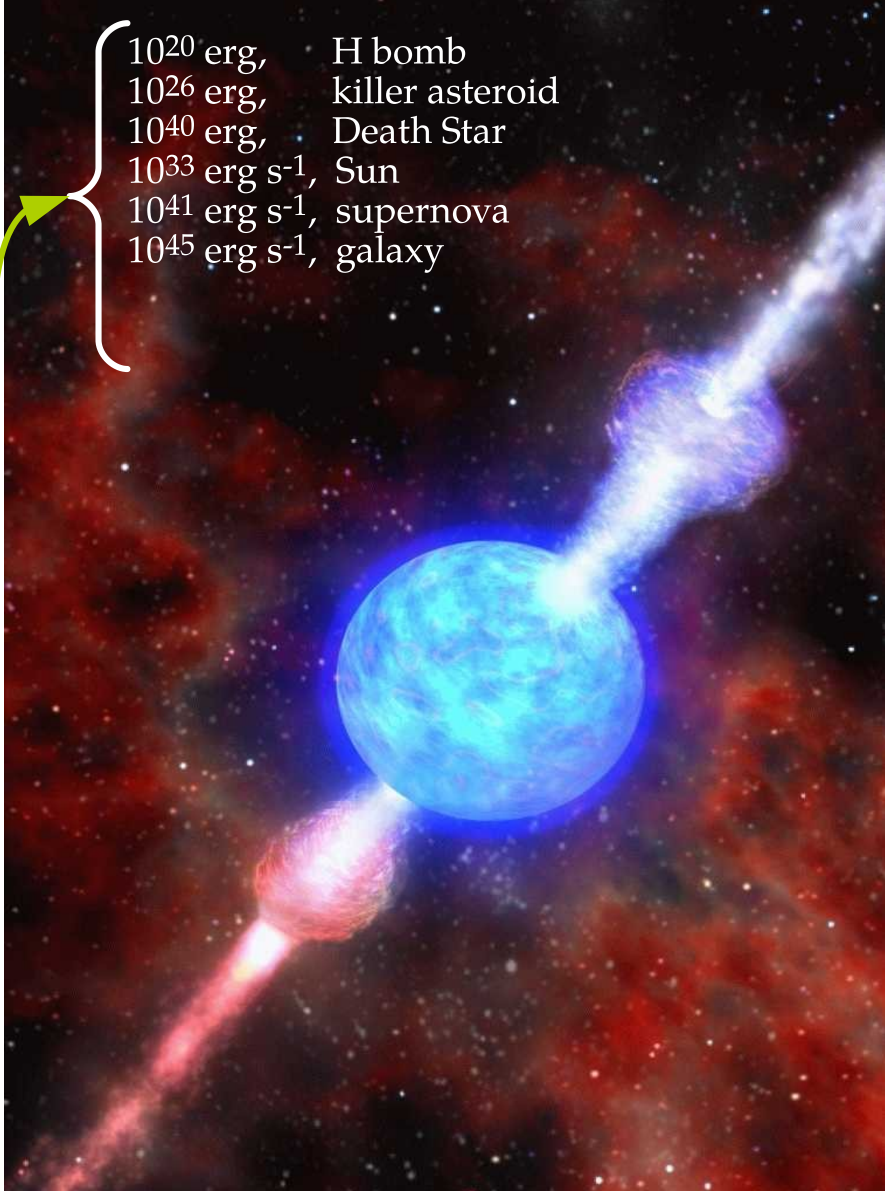

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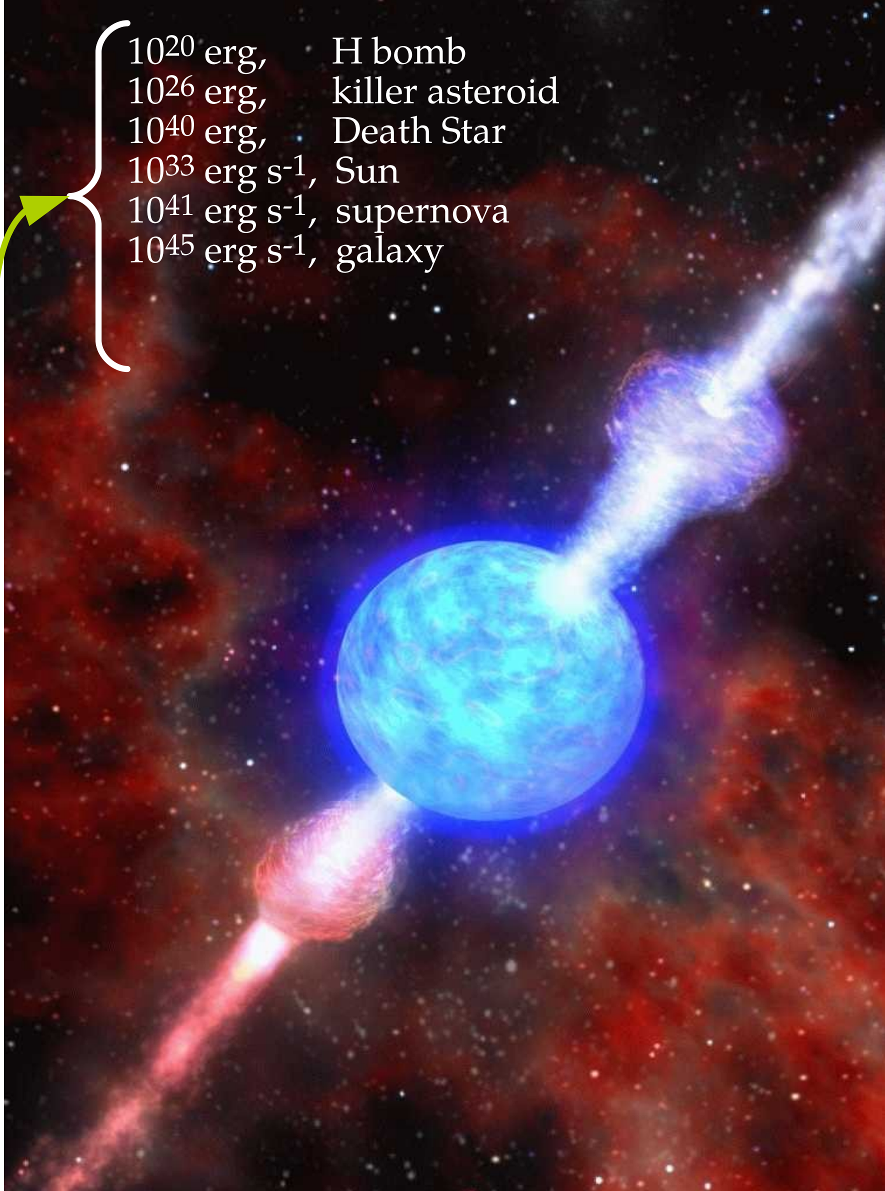

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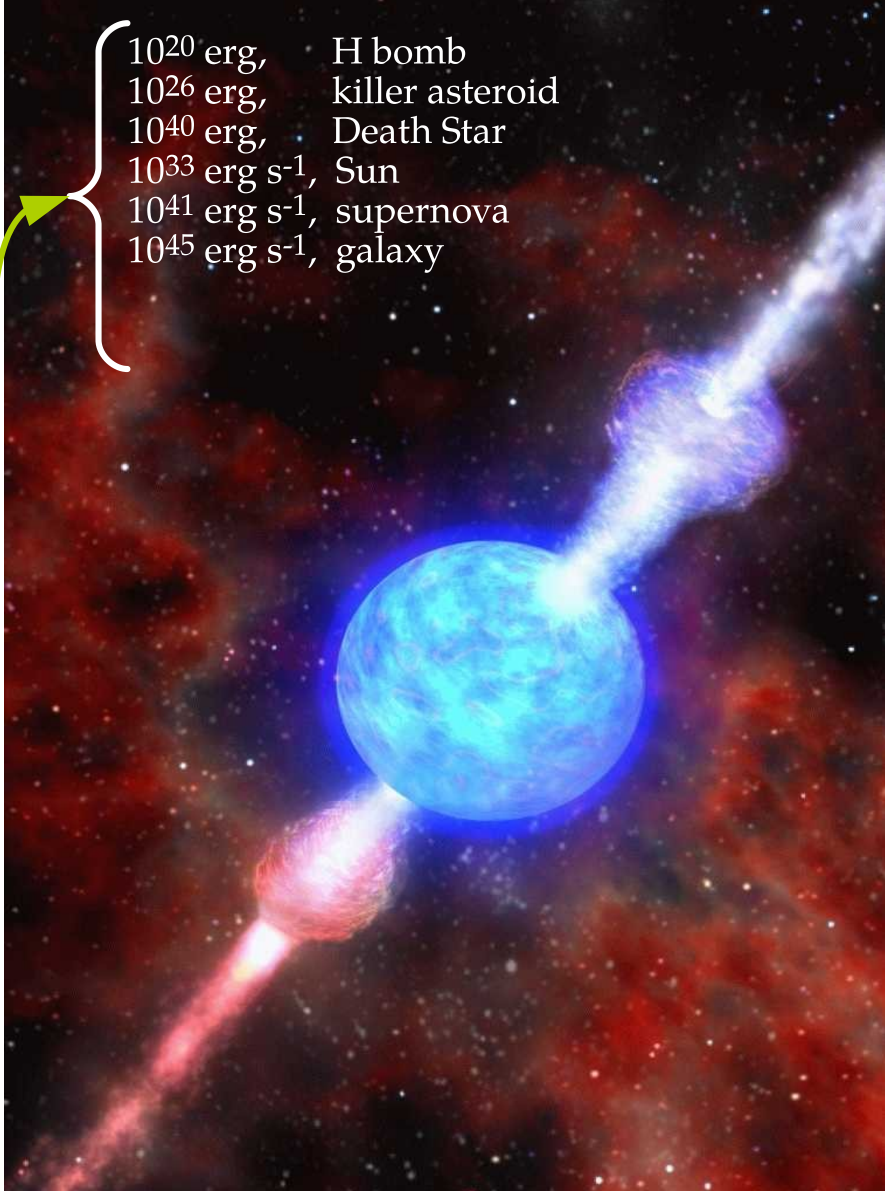

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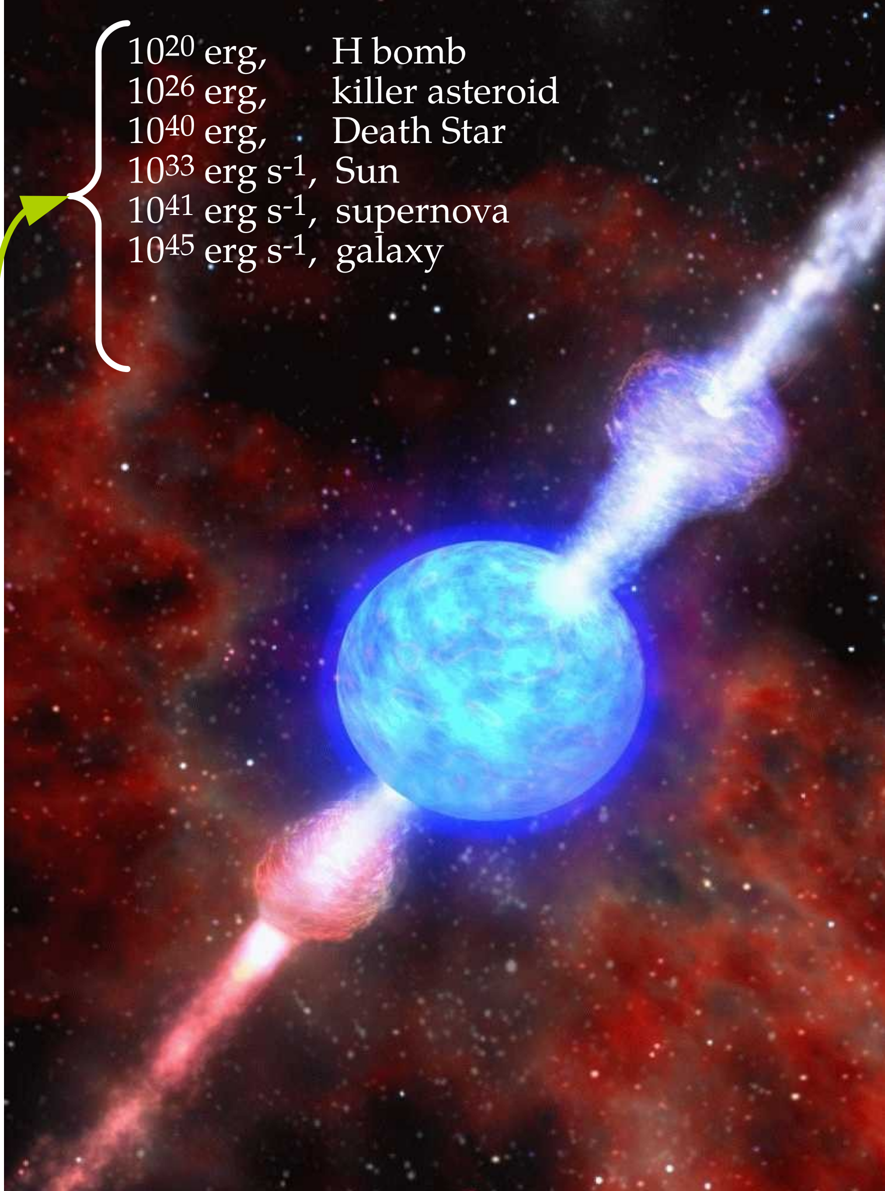

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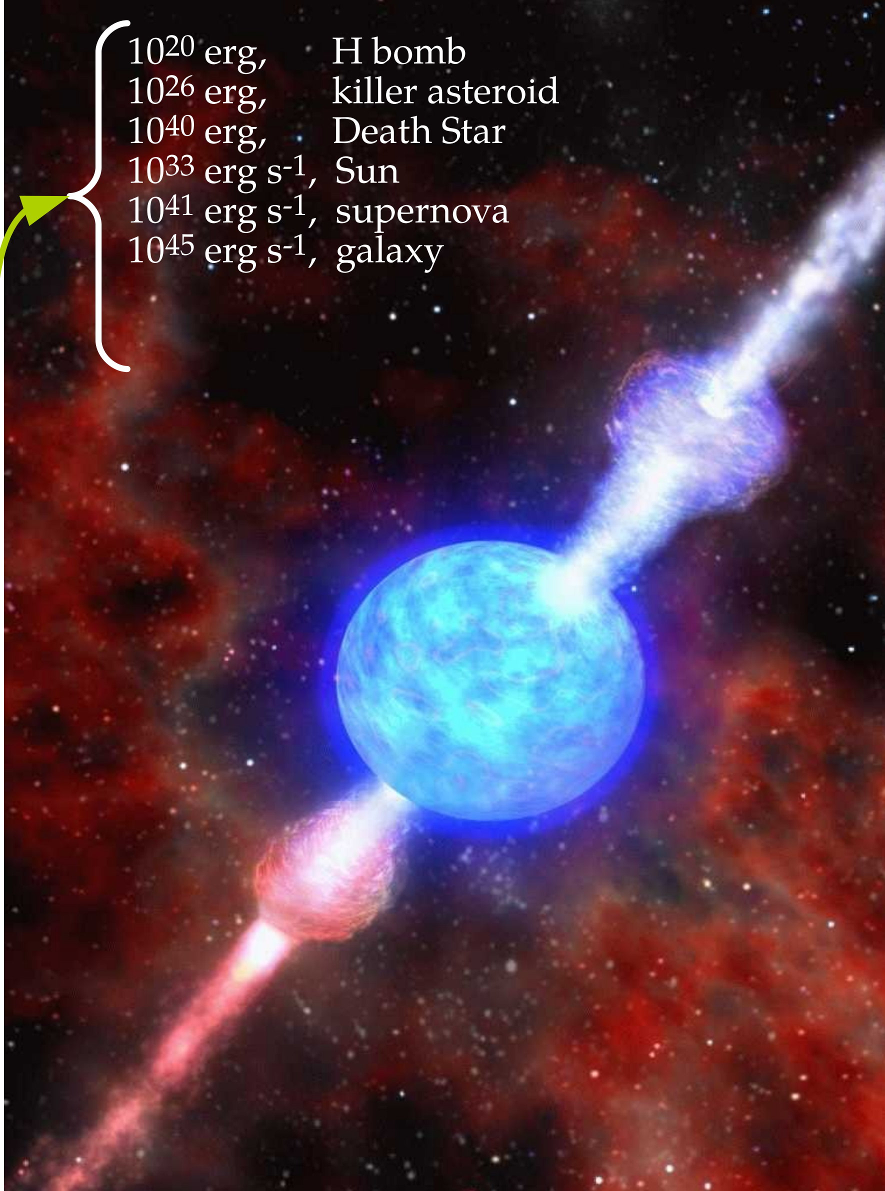

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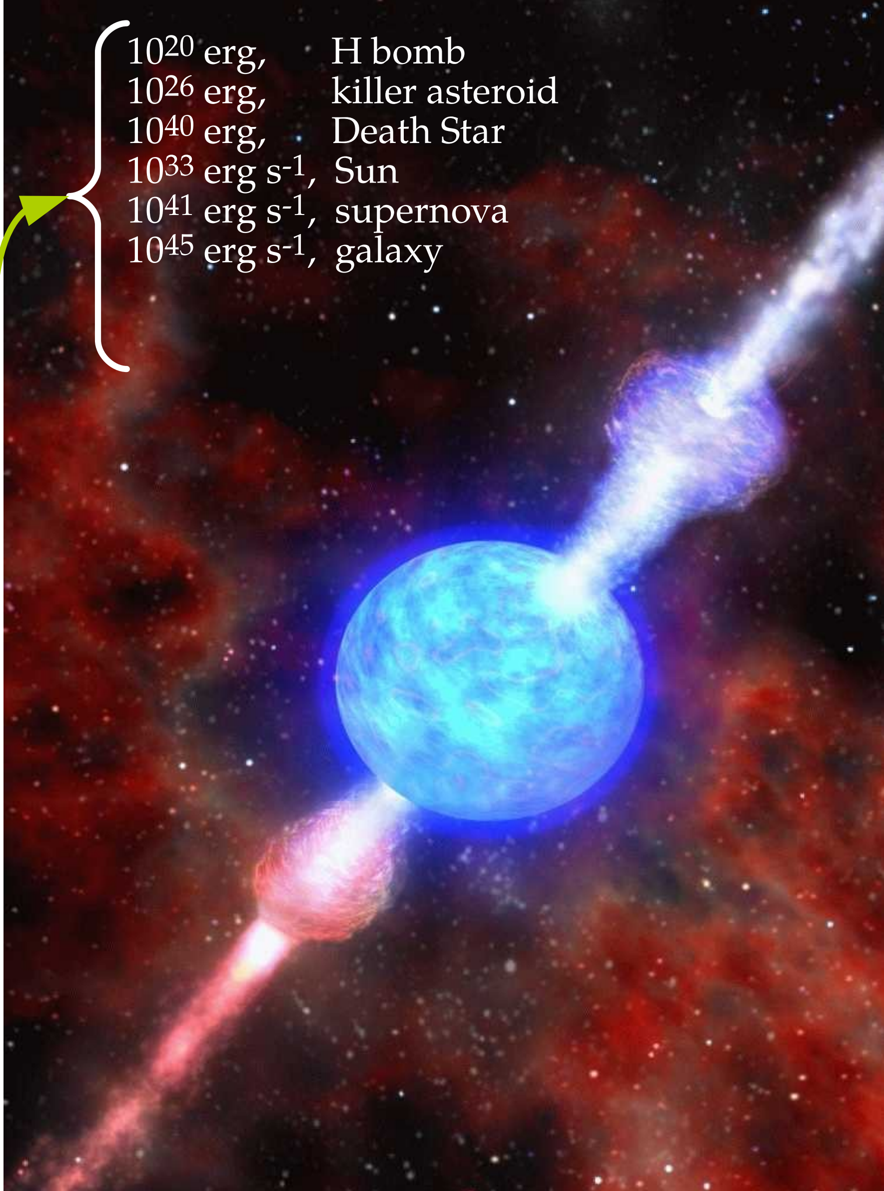
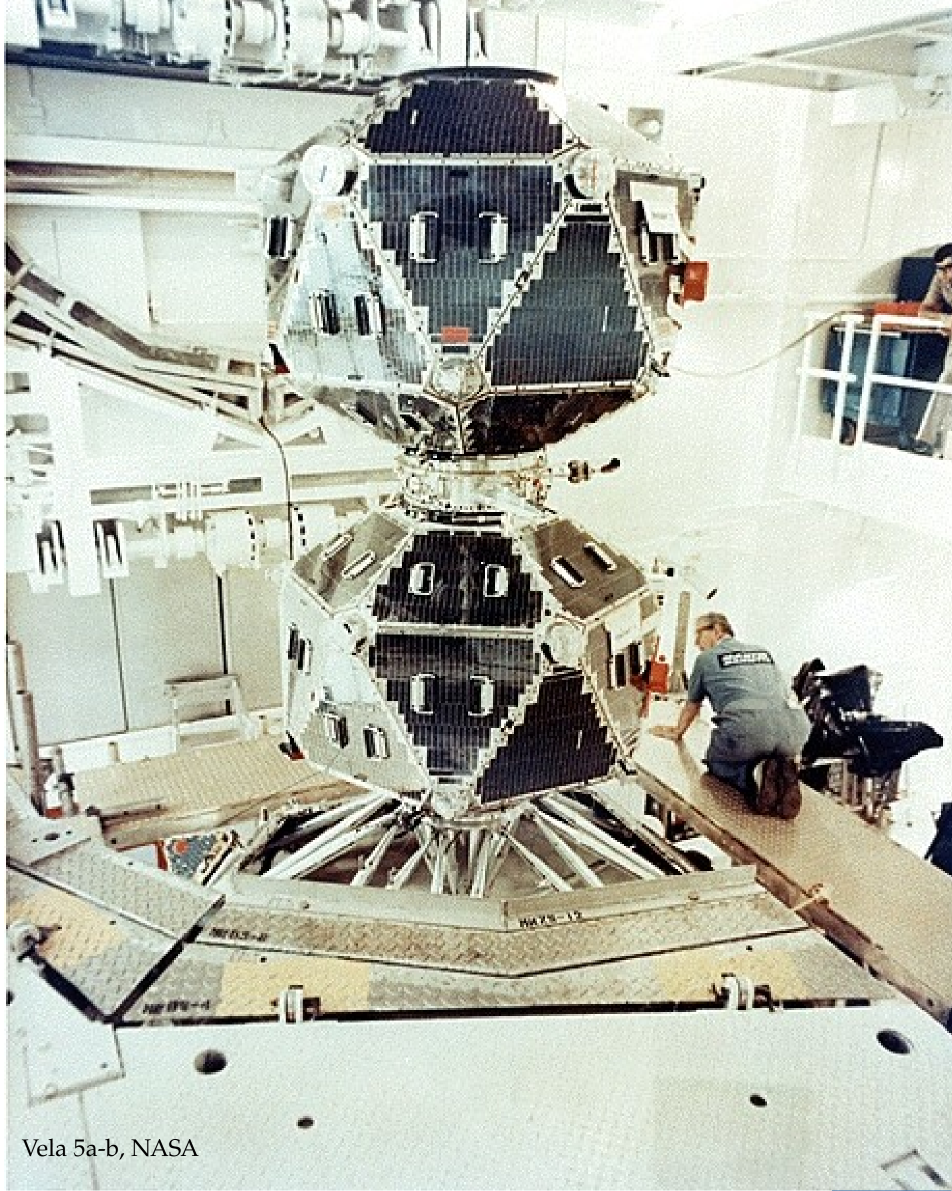
- Sources of high-energy ν & cosmic rays?



An accidental discovery

- 1963: Nuclear Test Ban Treaty
- Vela satellites launched to monitor it
- X-ray, gamma-ray, neutron detectors
- Gamma rays from nuclear tests: $< 1\ \mu s$
- Vela found longer emission, off-Earth



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THE ASTROPHYSICAL JOURNAL, **182**:L85–L88, 1973 June 1

OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

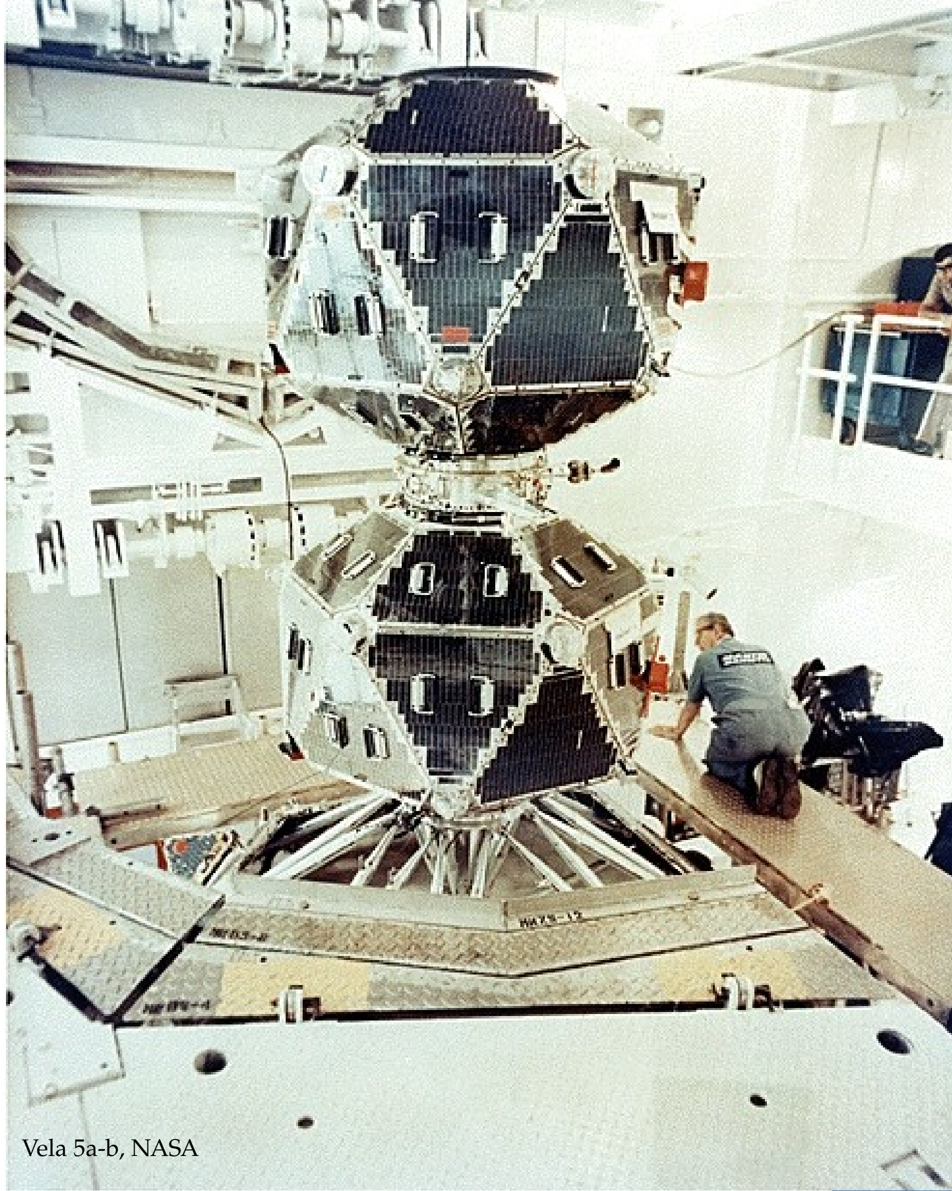
RAY W. KLEBESADEL, IAN B. STRONG, AND ROY A. OLSON

University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico
Received 1973 March 16; revised 1973 April 2

ABSTRACT

Sixteen short bursts of photons in the energy range 0.2–1.5 MeV have been observed between 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less than 0.1 s to ~30 s, and time-integrated flux densities from $\sim 10^{-5}$ ergs cm^{-2} to $\sim 2 \times 10^{-4}$ ergs cm^{-2} in the energy range given. Significant time structure within bursts was observed. Directional information eliminates the Earth and Sun as sources.

Subject headings: gamma rays — X-rays — variable stars



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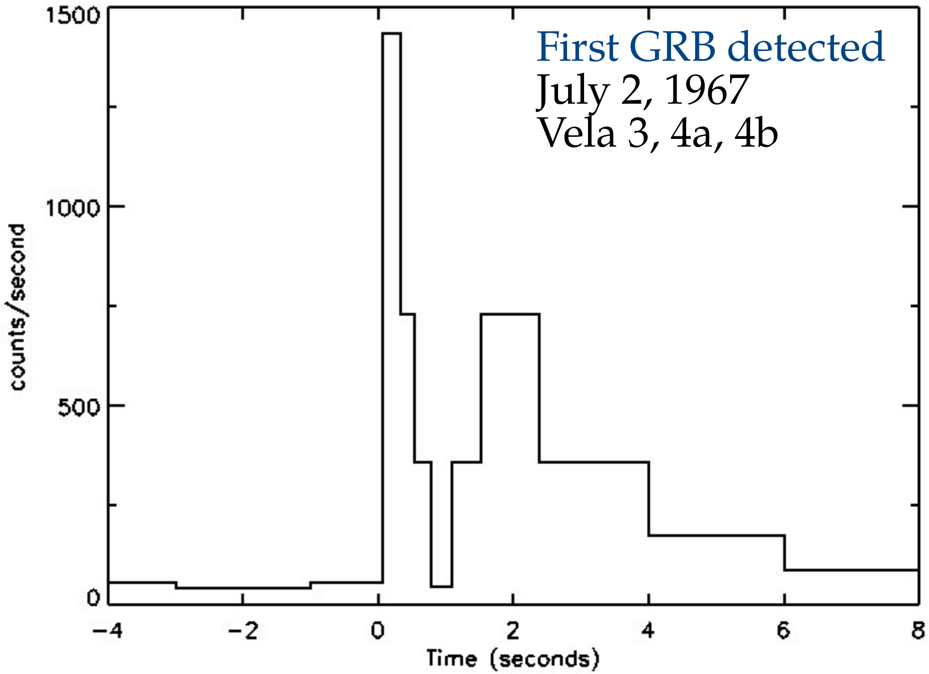

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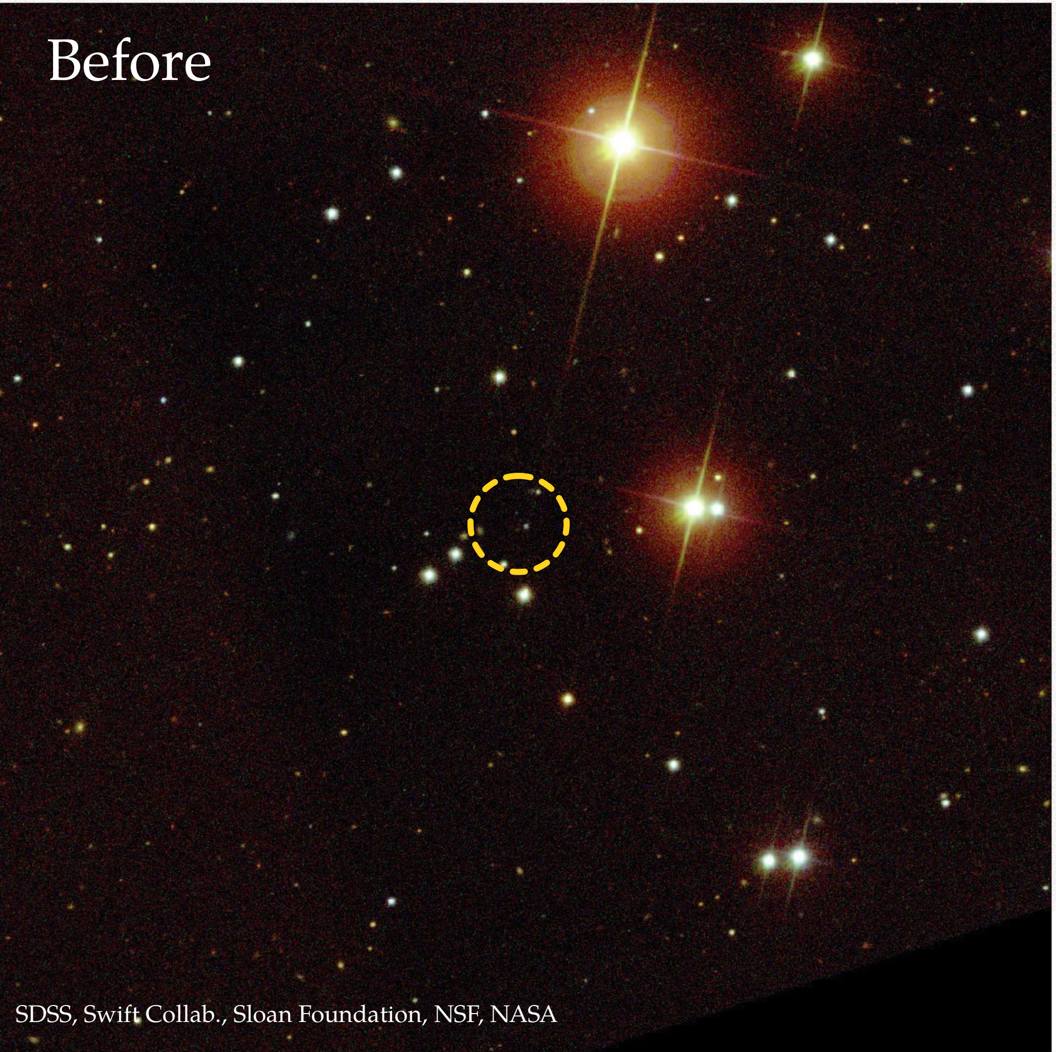

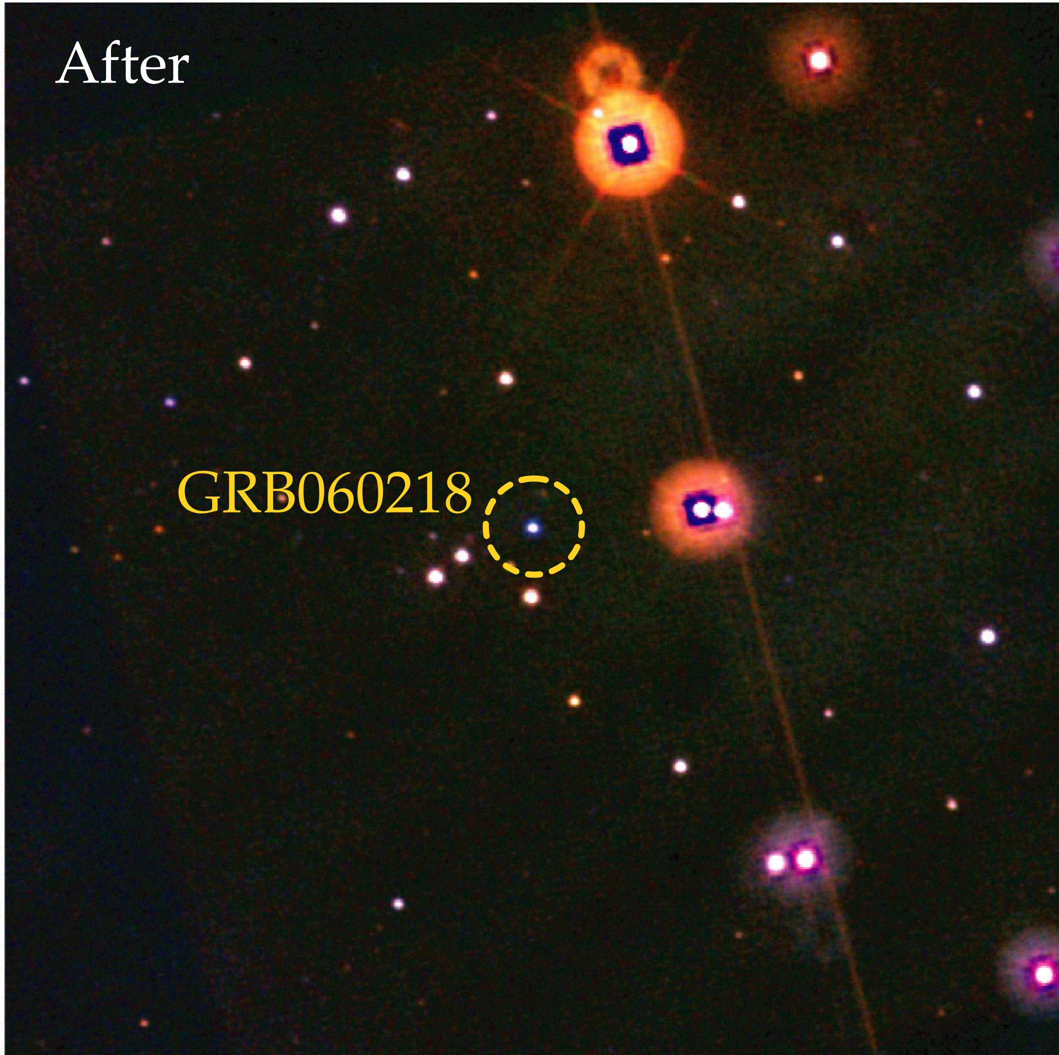

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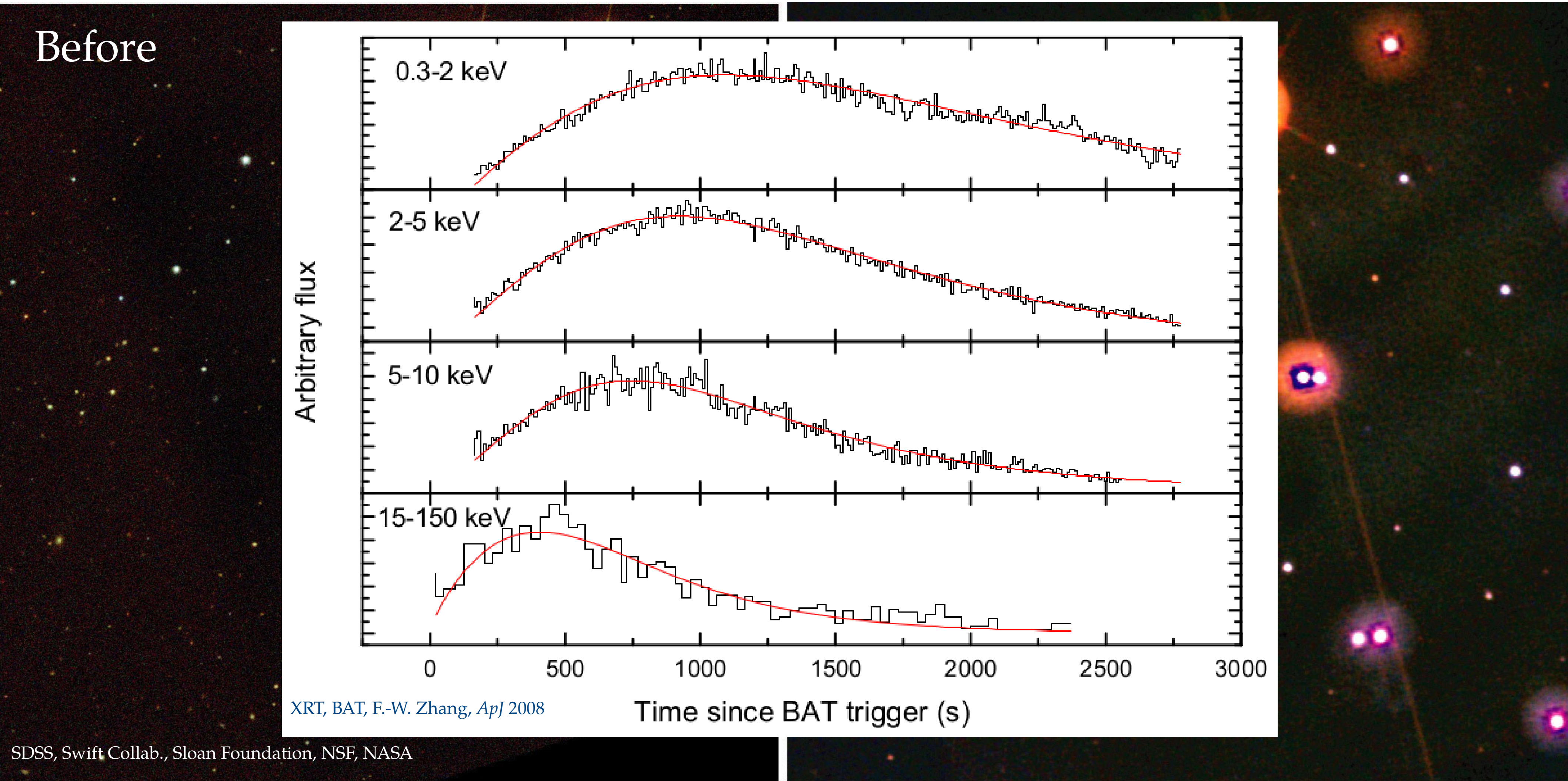
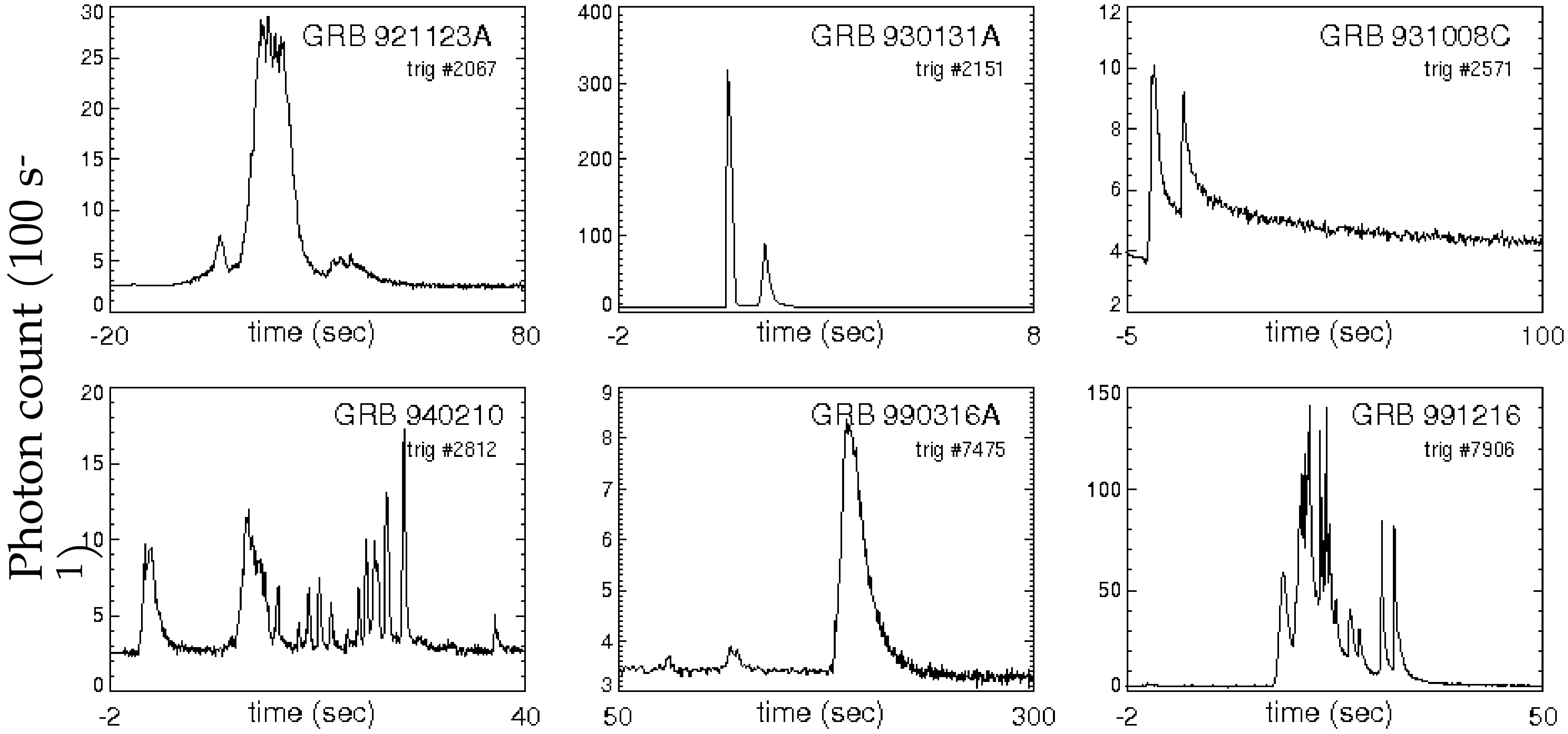


A zoo of GRB light curves



BATSE

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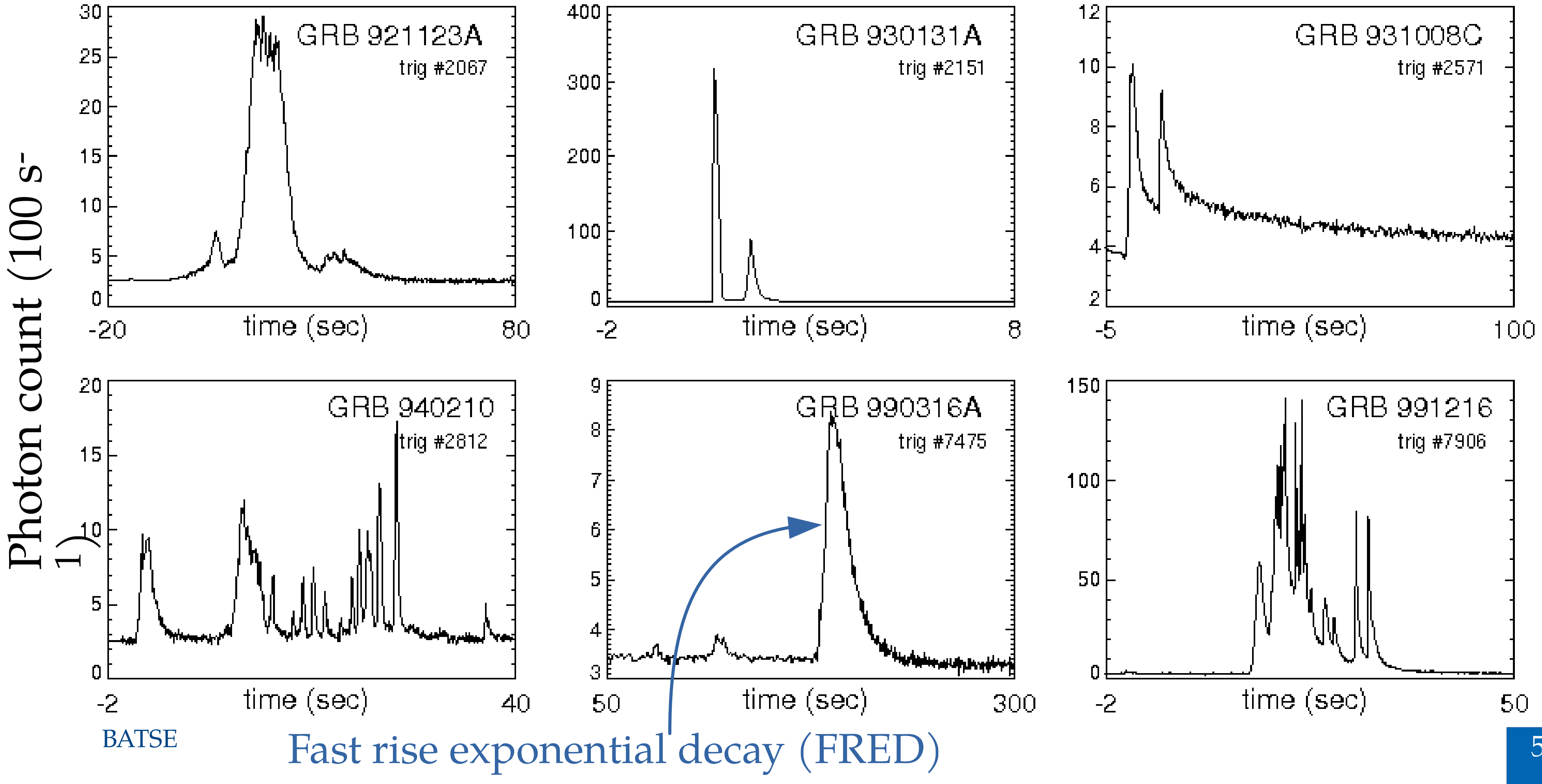

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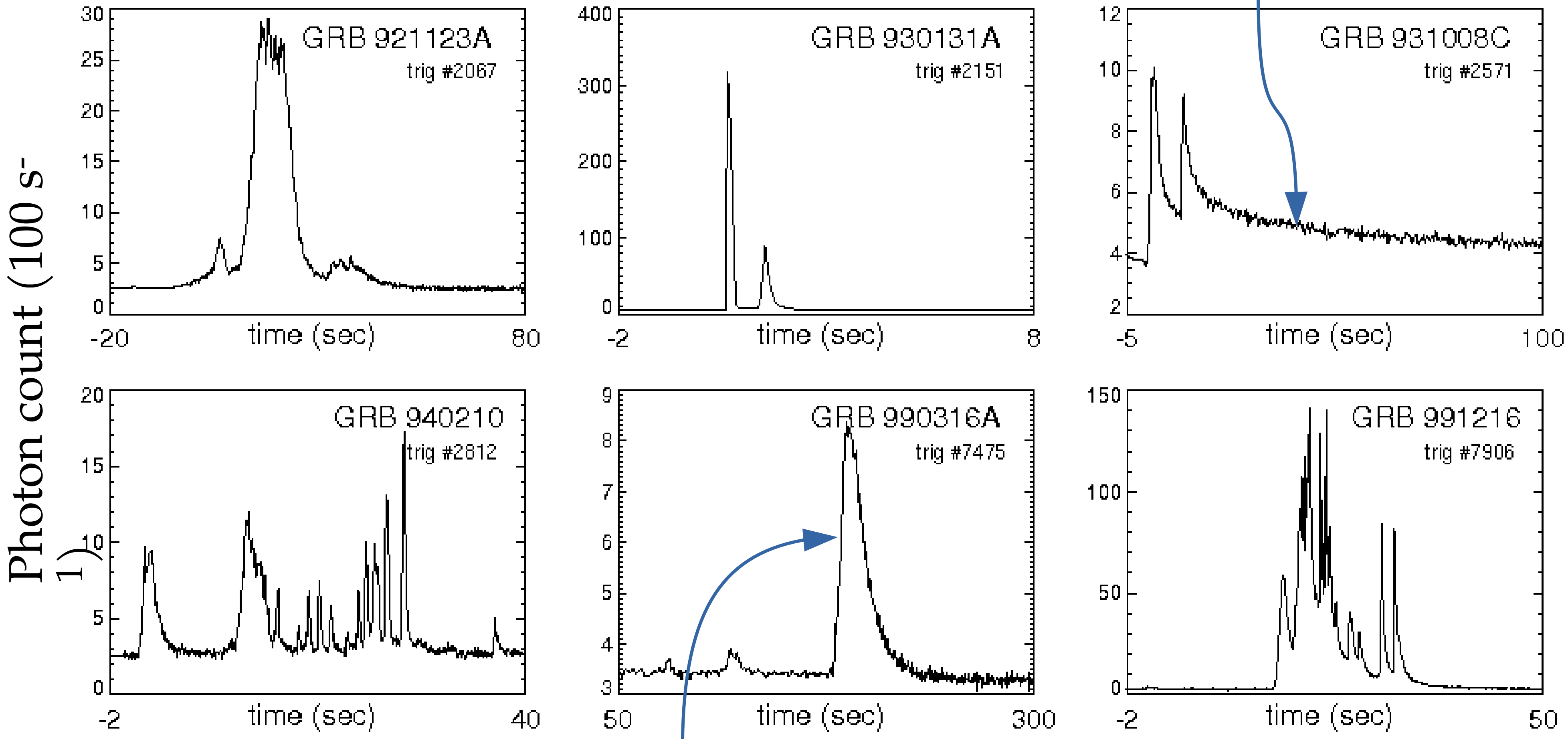
Variability time scale = width of pulses = 10s ms



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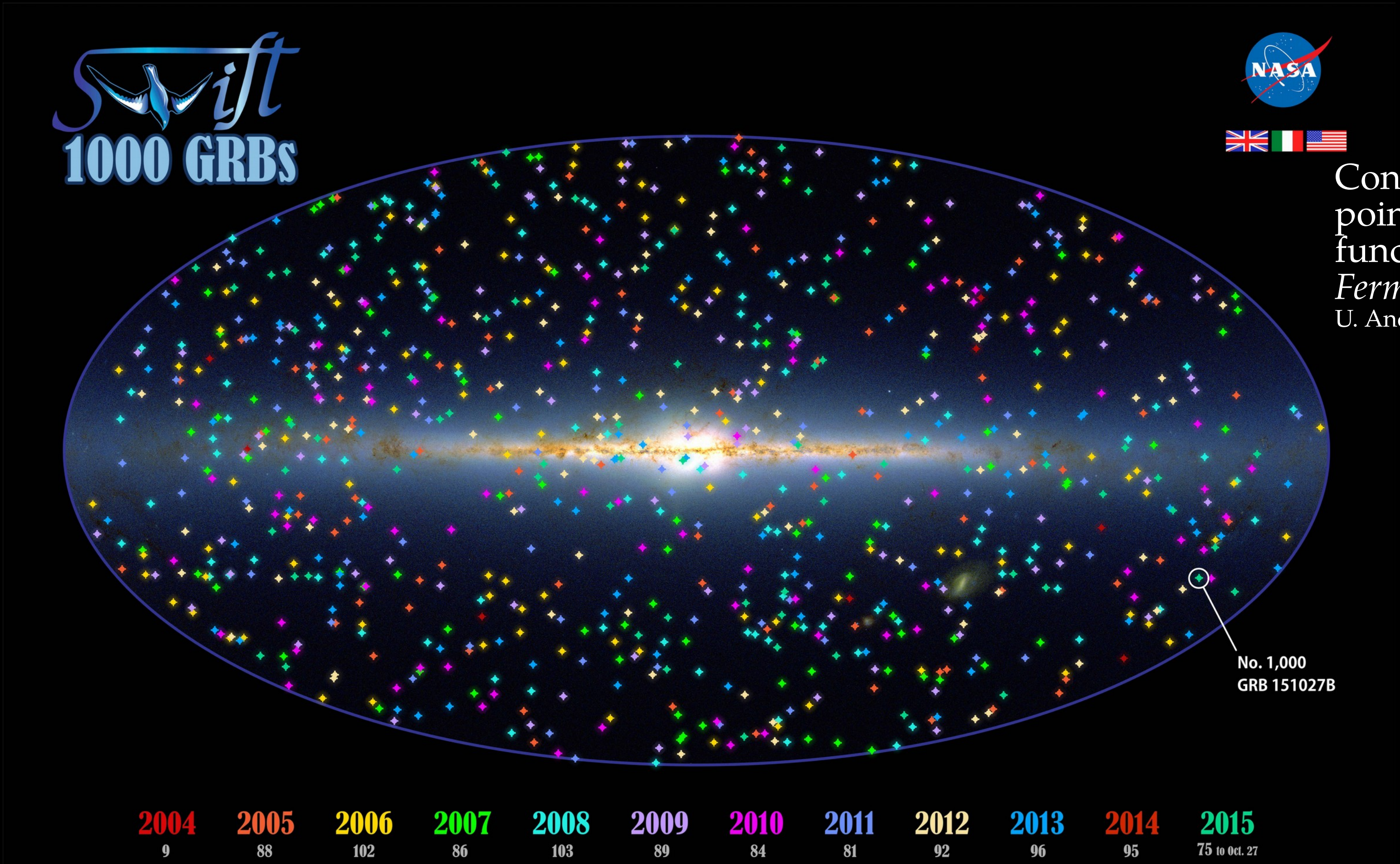
Fast rise exponential decay (FRED)

GRBs are distributed isotropically

… and this was the first indication that they are extragalactic

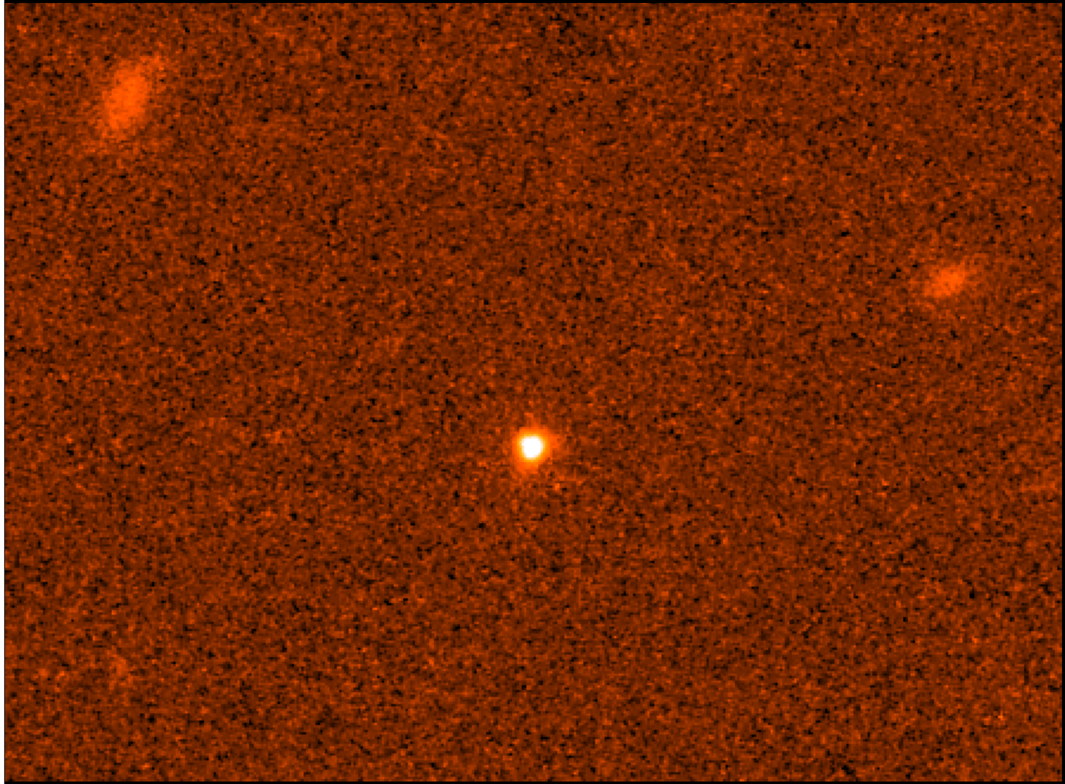


Confirmed by 2-point correlation function on 1634 *Fermi* GRBs
U. Andrade *et al.*, 1905.08864

See also: M. S. Briggs et al., *ApJ* 1993

GRBs are extragalactic

- ▸ First GRB with measured z
- ▸ 1997: BeppoSAX measures x-ray & optical afterglow
- ▸ Associated to host galaxy, $z = 0.835$
- ▸ Relatively few GRBs have known z
- ▸ Most GRBs are at $z \sim 1$ ($\sim$ Gpc)



HST / STScI/ NASA / June 1997

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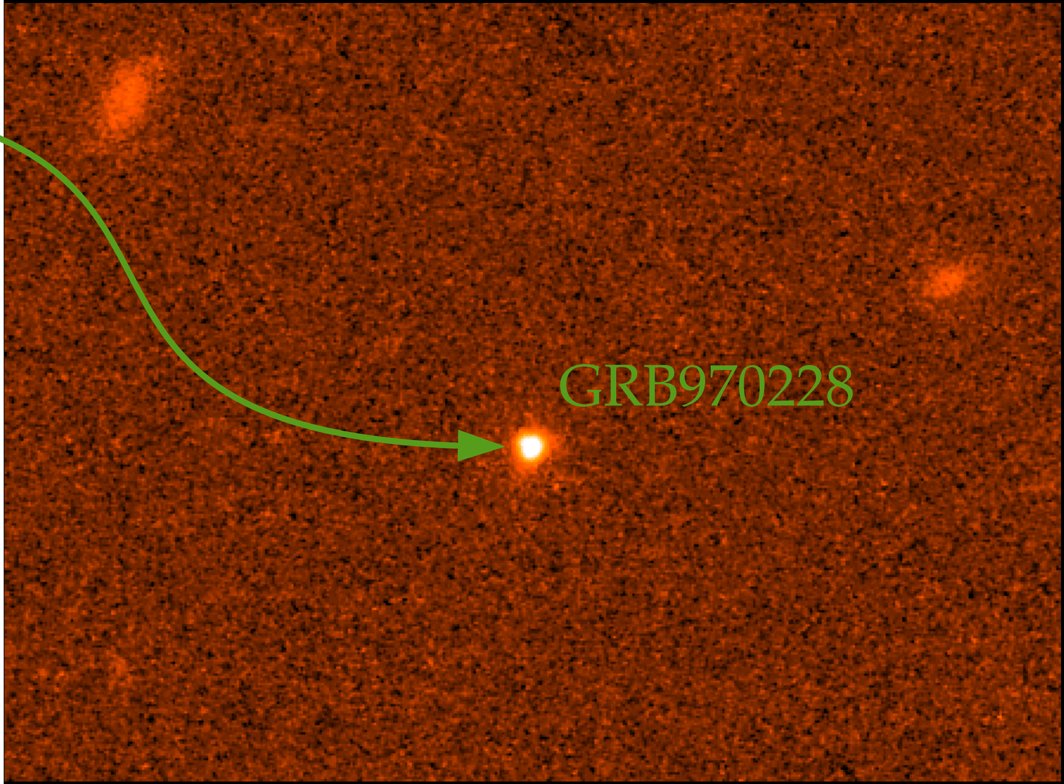

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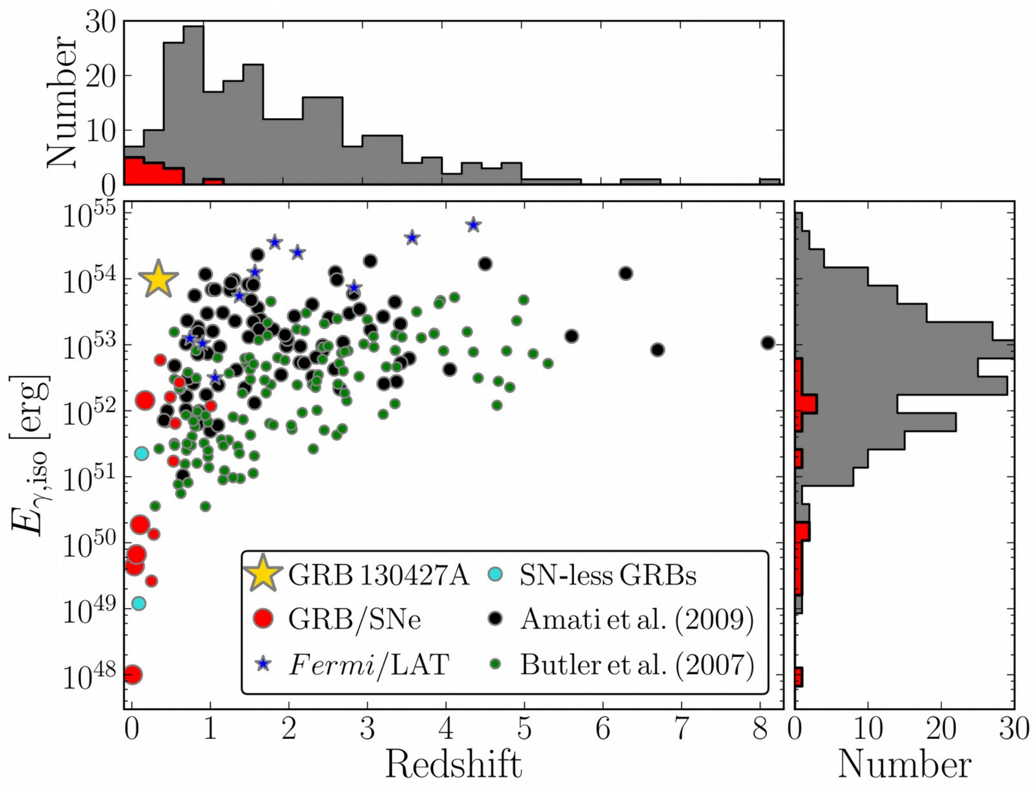

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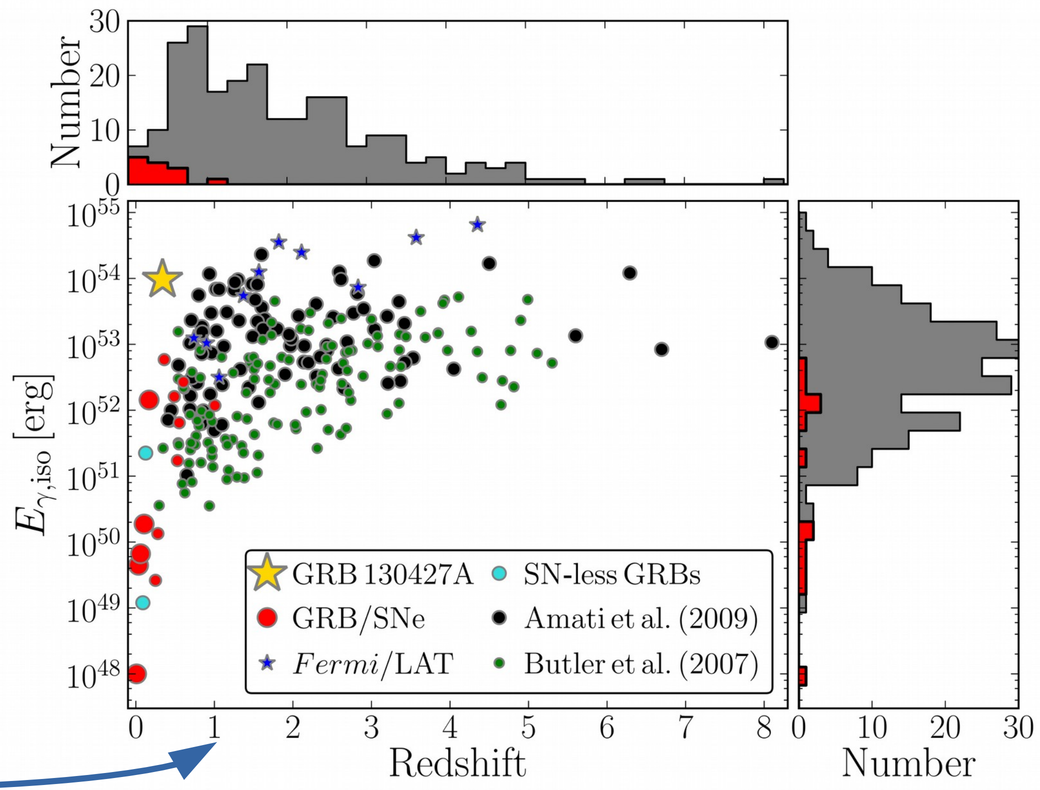

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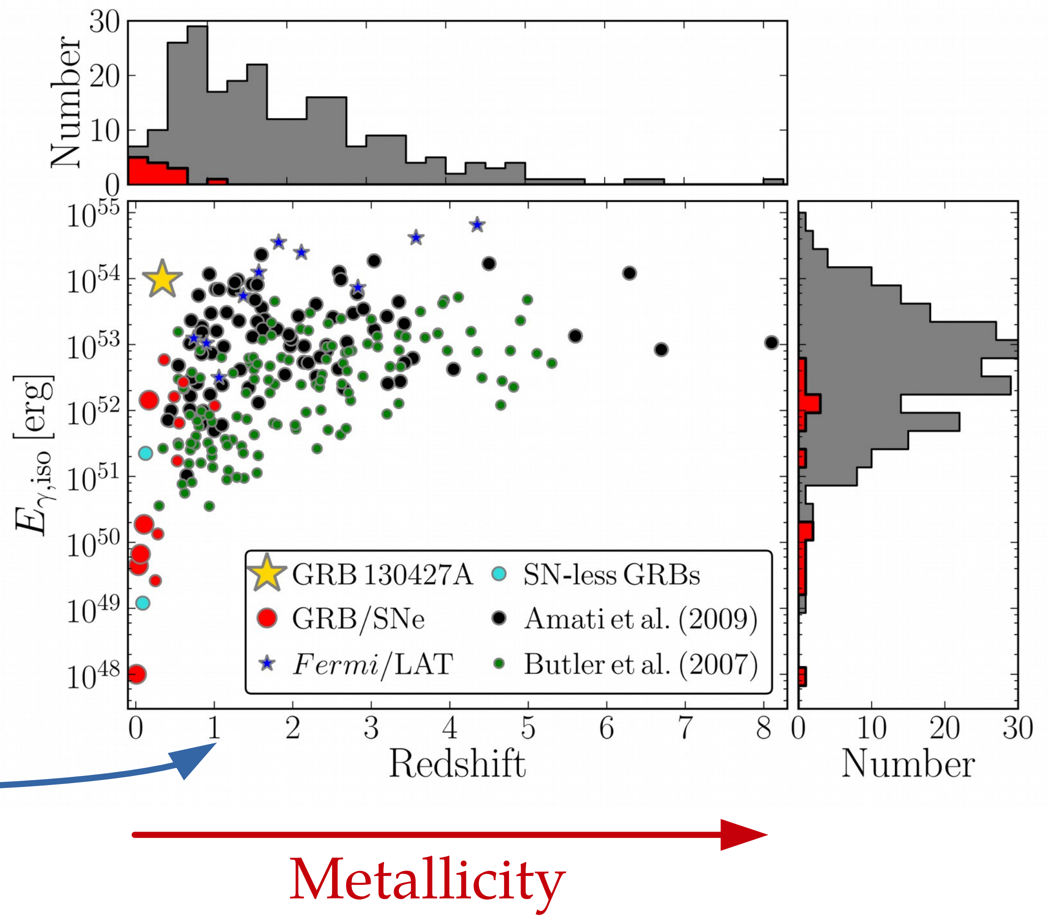

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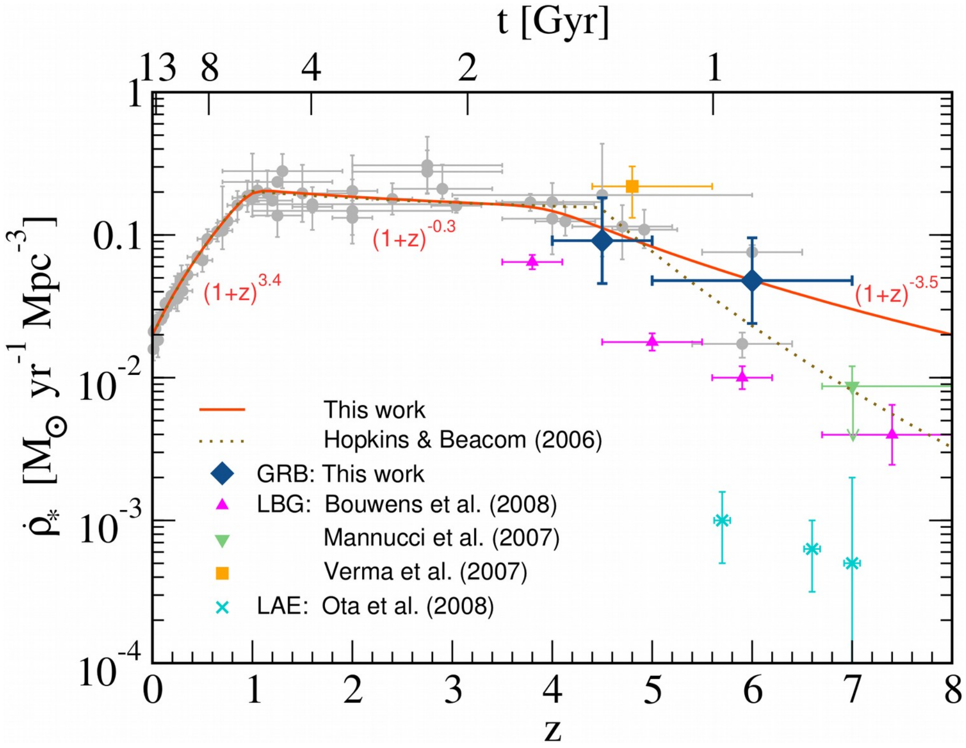
… But faraway can be useful

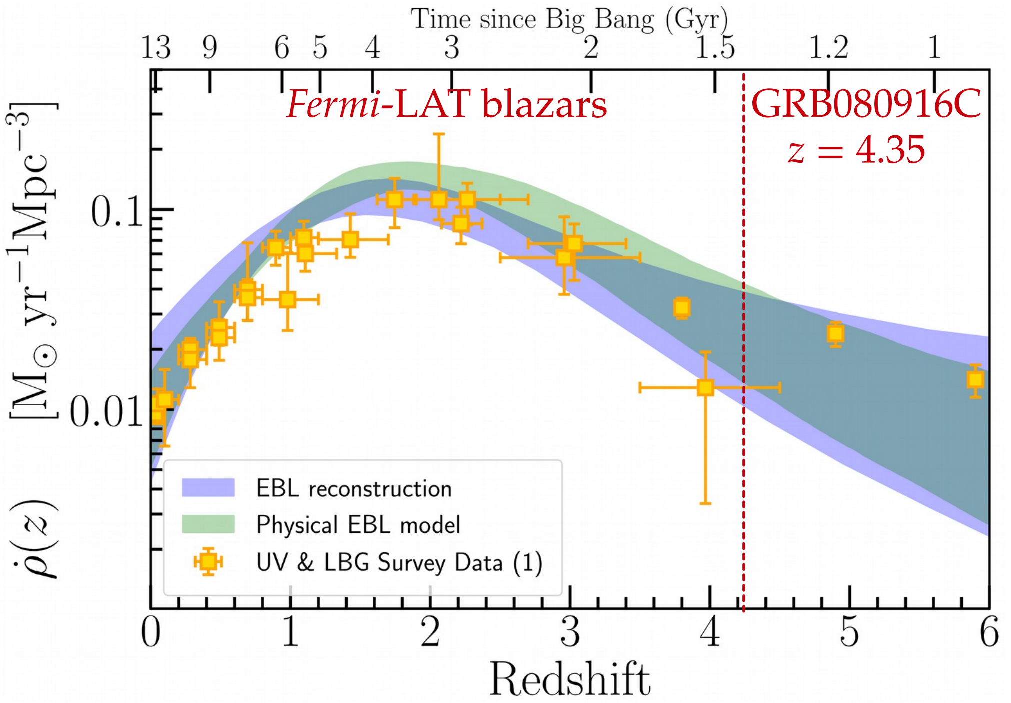
We can use GRBs to measure the star formation rate —

By counting them:



H. Yuksel *et al.*, *ApJ* 2008

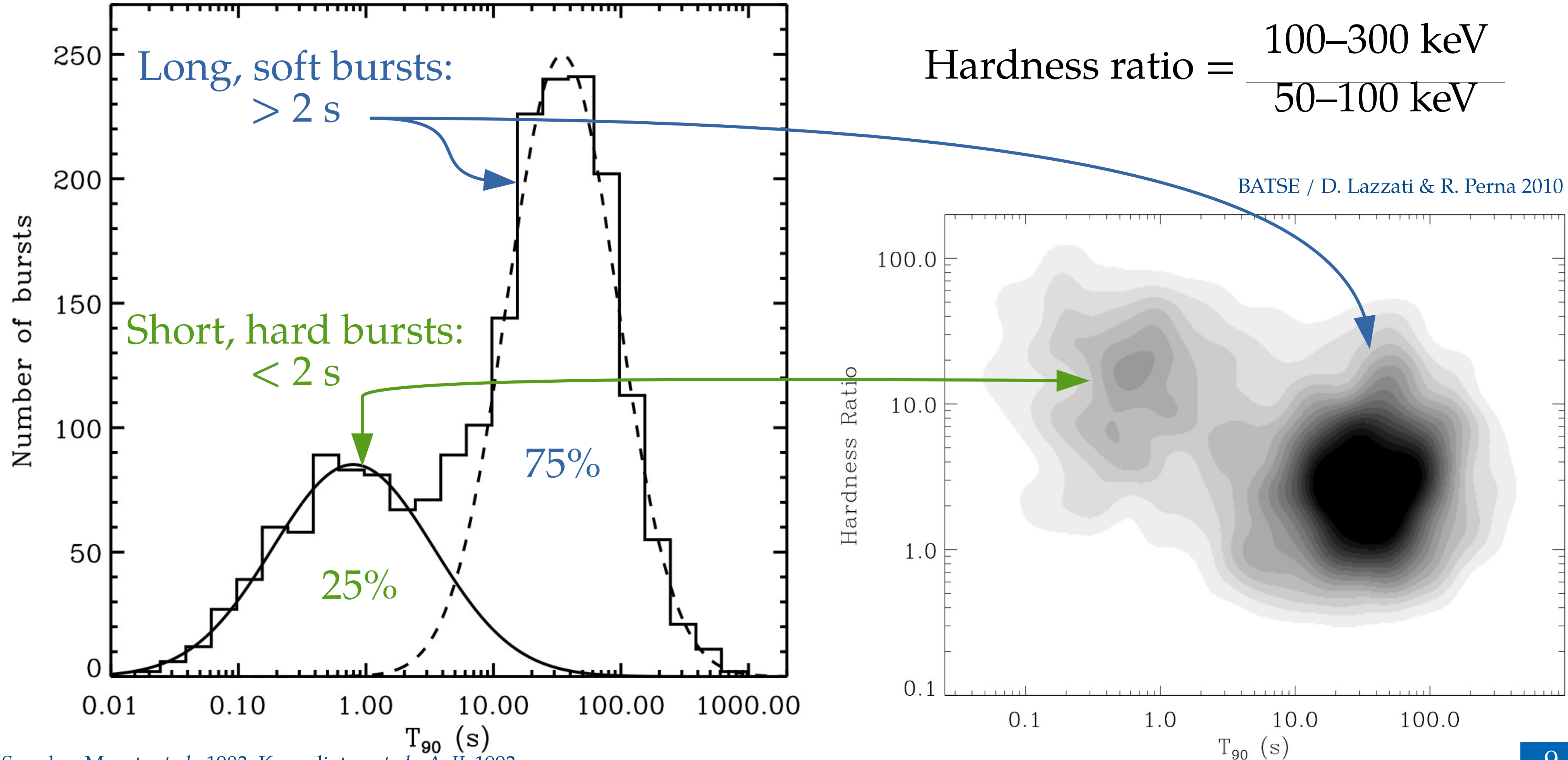
By seeing its dampening on the EBL:



Fermi-LAT Collab., *Science* 2018

Two (?) GRB populations

$$\text{Hardness ratio} = \frac{100\text{–}300\ \text{keV}}{50\text{–}100\ \text{keV}}$$



BATSE / D. Lazzati & R. Perna 2010

See also: Mazets *et al.*, 1983; Kouveliotou *et al.*, *ApJL* 1993

Short *vs.* long bursts: progenitors

Long bursts

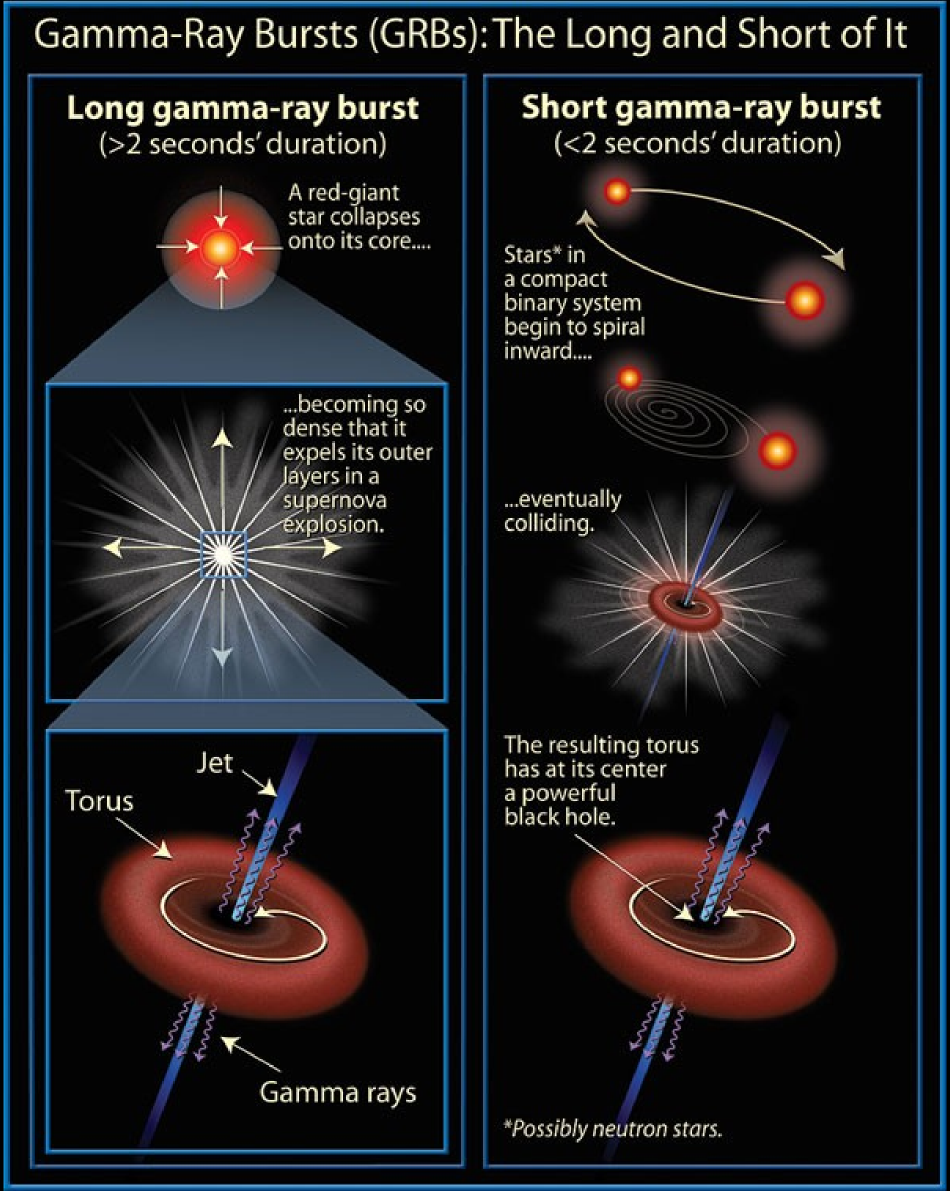
- Progenitor:
  - Massive star
  - Sub-solar metallicity
  - H- and He-depleted
  - Type-Ic supernova
- GRB980425 associated to SN 1998bw
- Associations exist only for low z
- <0.1% of stellar collapses make GRBs

T.J. Galama *et al.*, *ApJ* 2000; J. Horth *et al.*, *Nature* 2003;
A. Levan *et al.*, *Space Sci. Rev.* 2016

Short bursts

- Progenitor:
  - NS-NS merger
  - NS-BH merger
- GRB 170817A associated to LIGO NS-NS event GW170817
- Fainter than LGRBs
- Evidence: radioactively powered transient in light curve (kilonova)

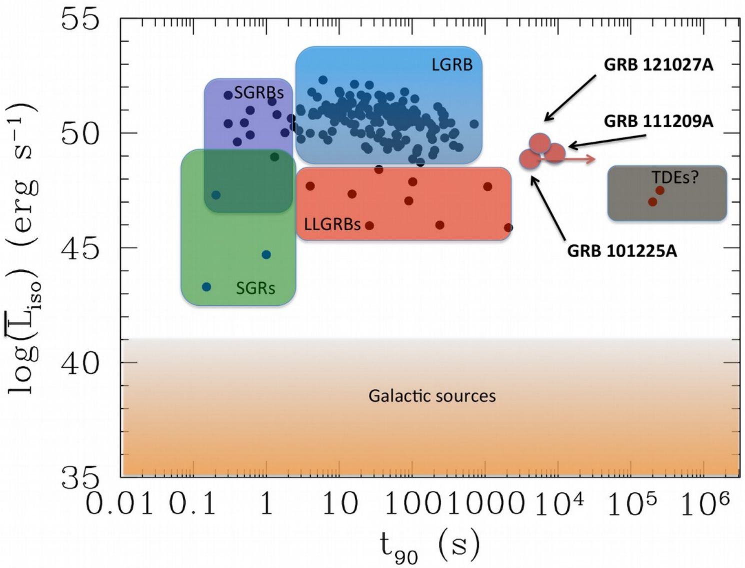
E.P. Mazets *et al.*, *Astrophys. Space Sci.* 1981, 1982
C. Kouveliotou *et al.*, *ApJL* 1993

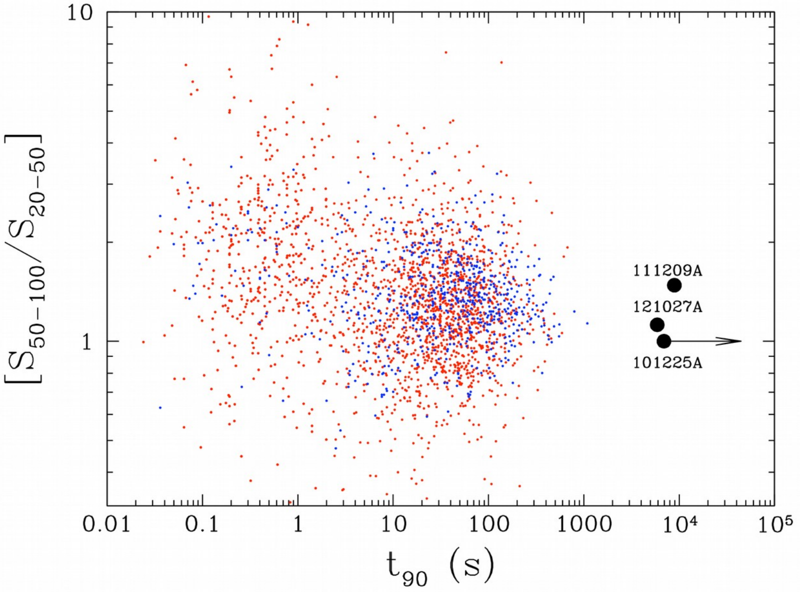

Gamma-Ray Bursts (GRBs): The Long and Short of It
Long gamma-ray burst
(>2 seconds' duration)
A red-giant star collapses onto its core....
...becoming so dense that it expels its outer layers in a supernova explosion.
Jet
Torus
Gamma rays
Short gamma-ray burst
(<2 seconds' duration)
Stars* in a compact binary system begin to spiral inward....
...eventually colliding.
The resulting torus has at its center a powerful black hole.
*Possibly neutron stars.

NASA

Ultra-long bursts

- Duration: several thousand seconds
- First identified in 2013
- Long-lasting X-ray, optical light curves
- May be due to:
  - Blue supergiants
  - Newborn magnetars?
- New population or tail-end of long bursts?





A.J. Levan et al., *ApJ* 2013

What are the engines of GRBs?

Two requirements:

- High variability (~ms)
- Abundant available energy ($> 10^{51}$ erg)

C. Fryer *et al.*, 1904.10008

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Rotational energy:

$$E_{\rm rot} = 5 \cdot 10^{50} \left(\frac{\omega}{1\ \rm kHz}\right)^2\ \rm erg$$

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Potential energy released by accreting matter:

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Convert a fraction of this into jet energy

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Magnetic fields in GRBs

- Assuming gamma rays come from electron synchrotron:

$$B \approx \begin{cases} 10^5 \text{ G} & \text{in internal shocks } (10^8\text{–}10^{10} \text{ km}) \\ 1 \text{ G} & \text{in afterglow } (10^{11}\text{–}10^{13} \text{ km}) \end{cases}$$

A.M. Hillas, *Ann. Rev. Astron. Astrophys.* 1984; S. Hümmer *et al.*, *Astropart. Phys.* 2010
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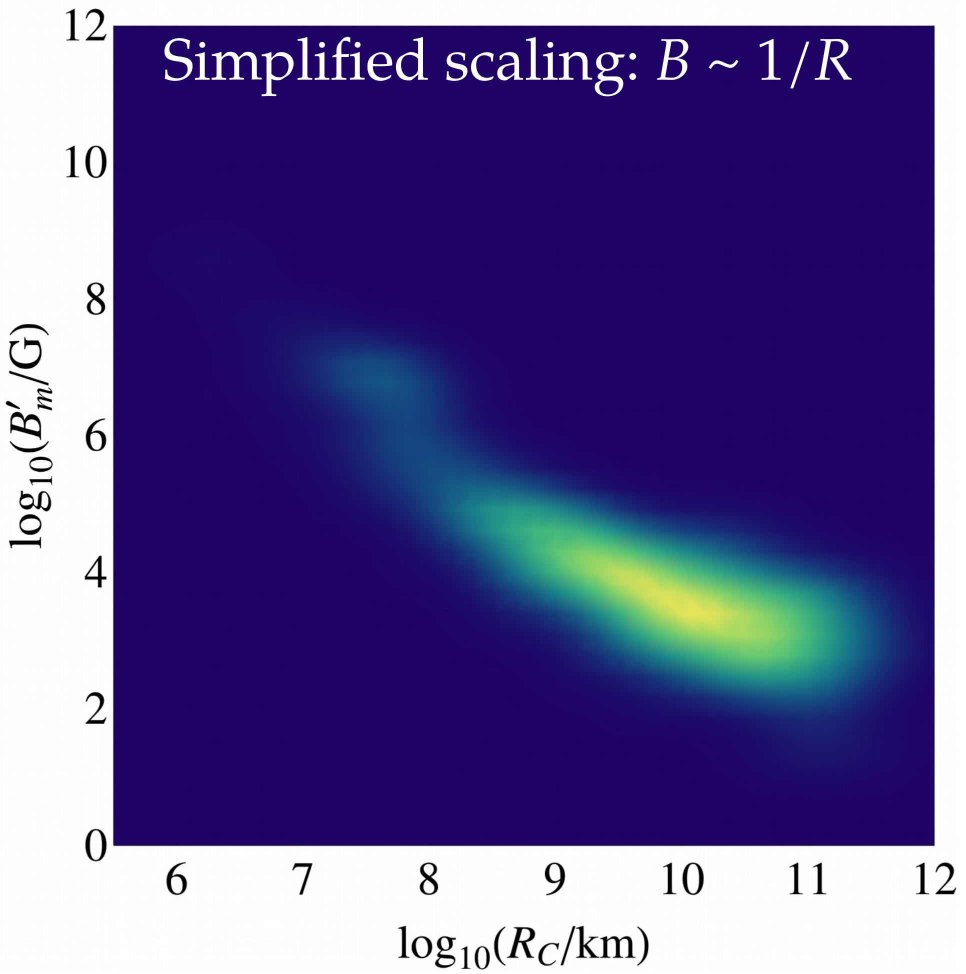

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- Hillas criterion:

Larmor radius < Acceleration region

- To accelerate protons to 10^{11} GeV:

$$B \gtrsim 3 \cdot 10^{12} \left(\frac{\text{km}}{R}\right) \text{ G}$$

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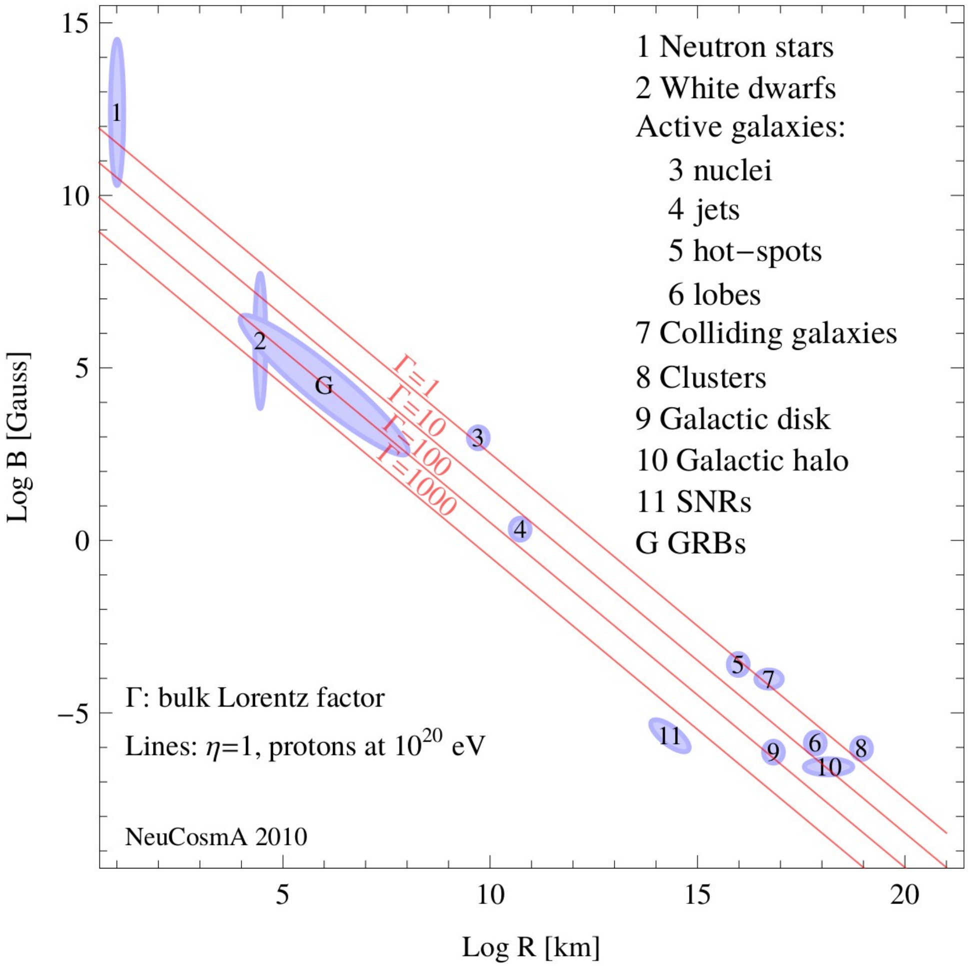

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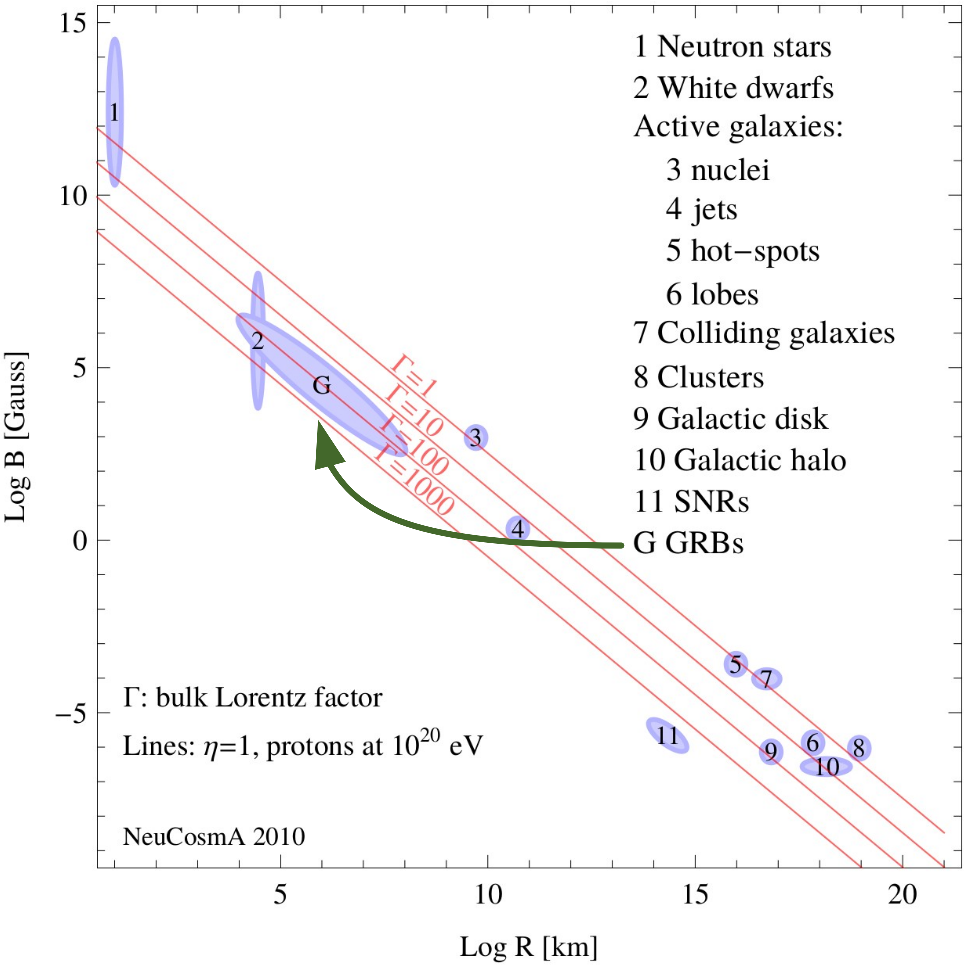

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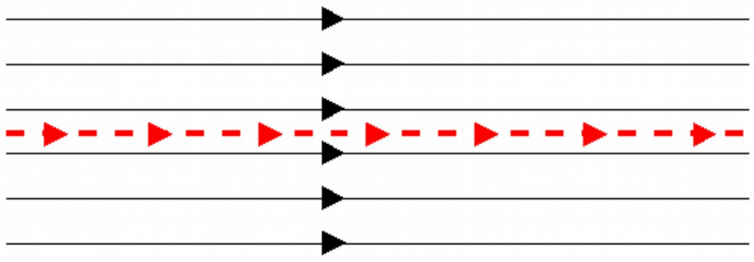
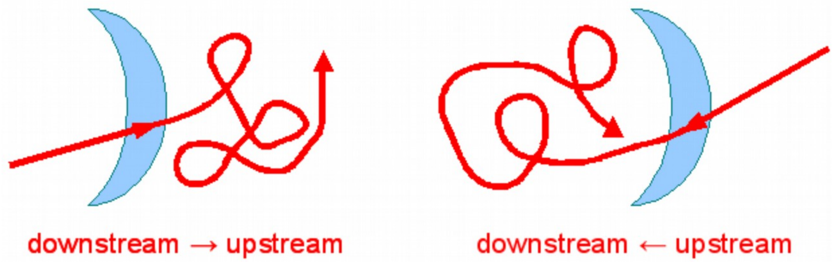
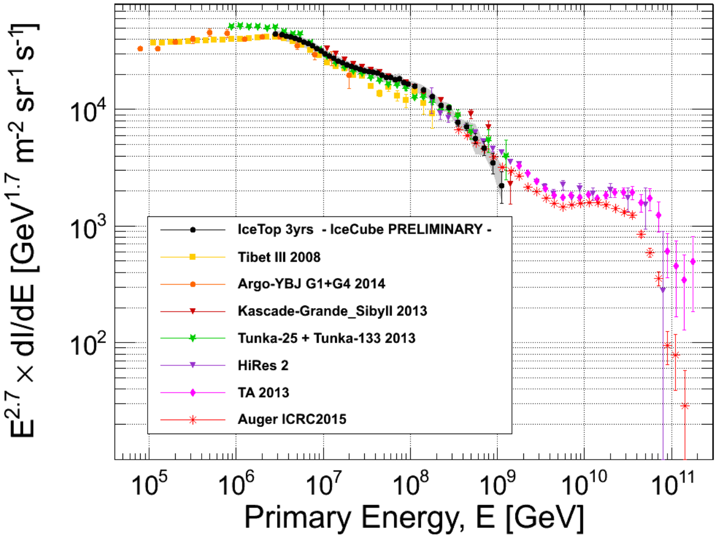
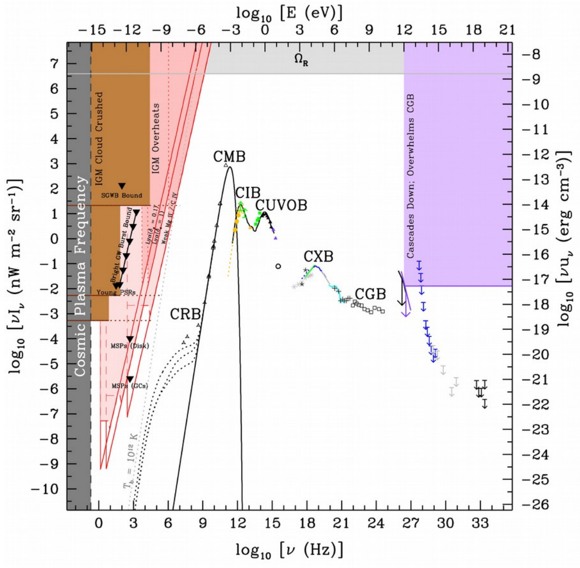
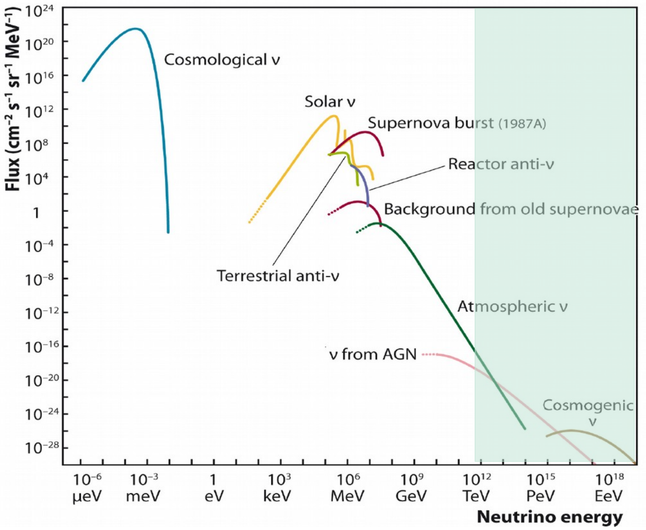
Luckily, UHECR Sources Should Be Wasteful…

	Man-made accelerators	Astrophysical accelerators
		
Acceleration	In vacuum	In a medium
E.m. fields	Ordered	Messy
Beam dumps	Precisely regulated	Fully unregulated

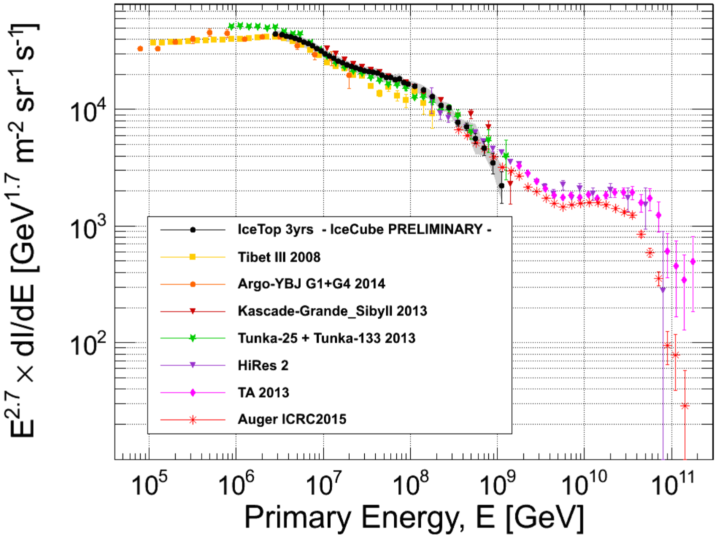
Astrophysical accelerators *inevitably* make high-energy secondaries

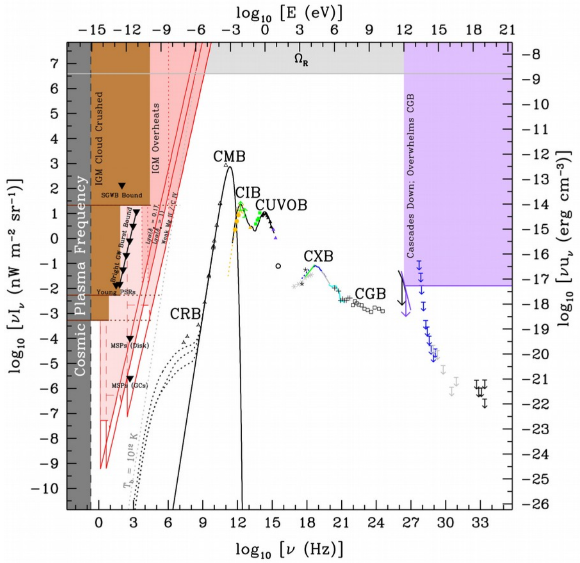


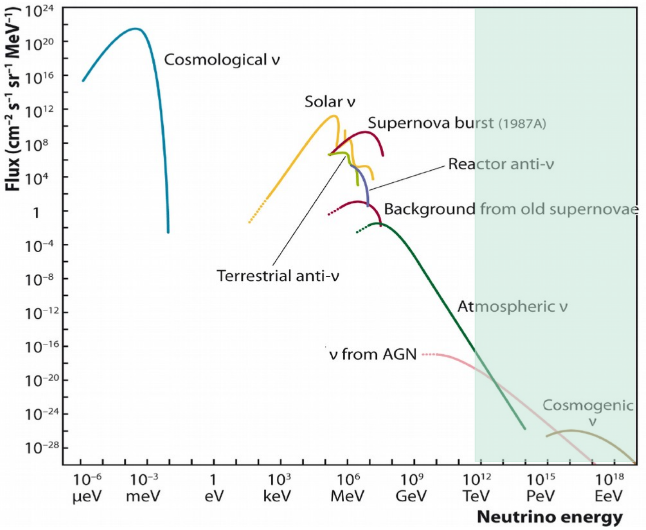




UHE cosmic rays + Photons → Neutrinos

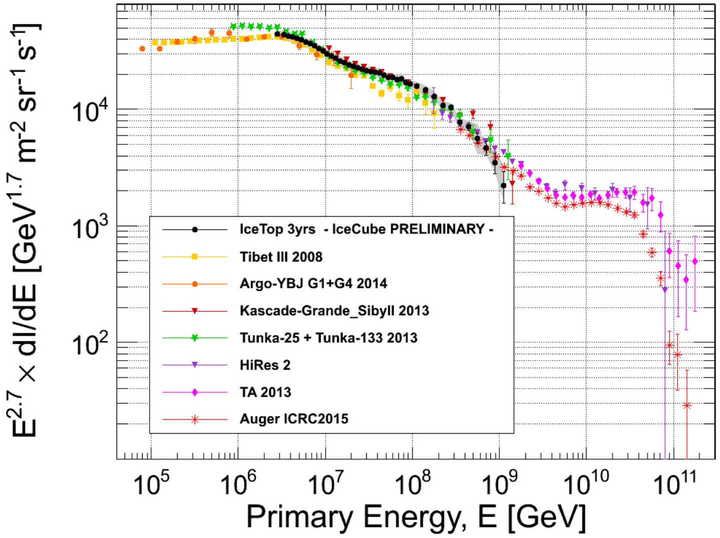


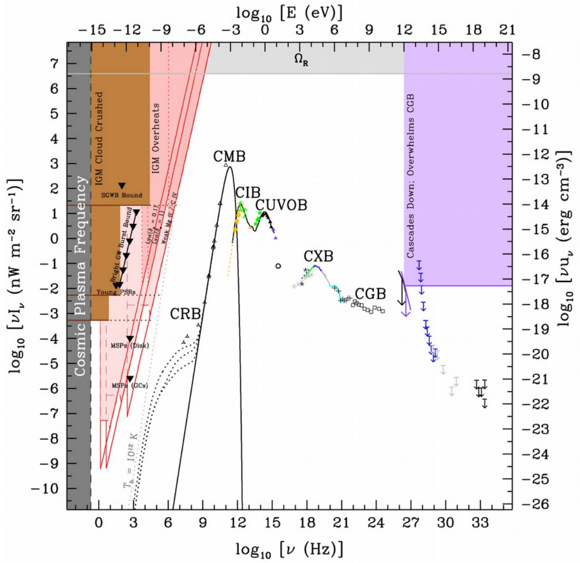


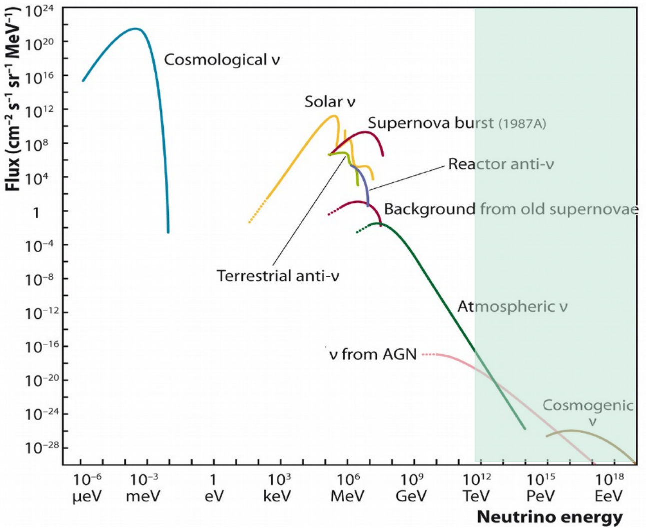


UHE cosmic rays + Photons → Neutrinos

UHE cosmic rays	Photons	Neutrinos
0.1–100 PeV	MeV	TeV–PeV
EeV–ZeV	meV	1–100 EeV







UHE cosmic rays + Photons → Neutrinos

UHE cosmic rays	Photons	Neutrinos	
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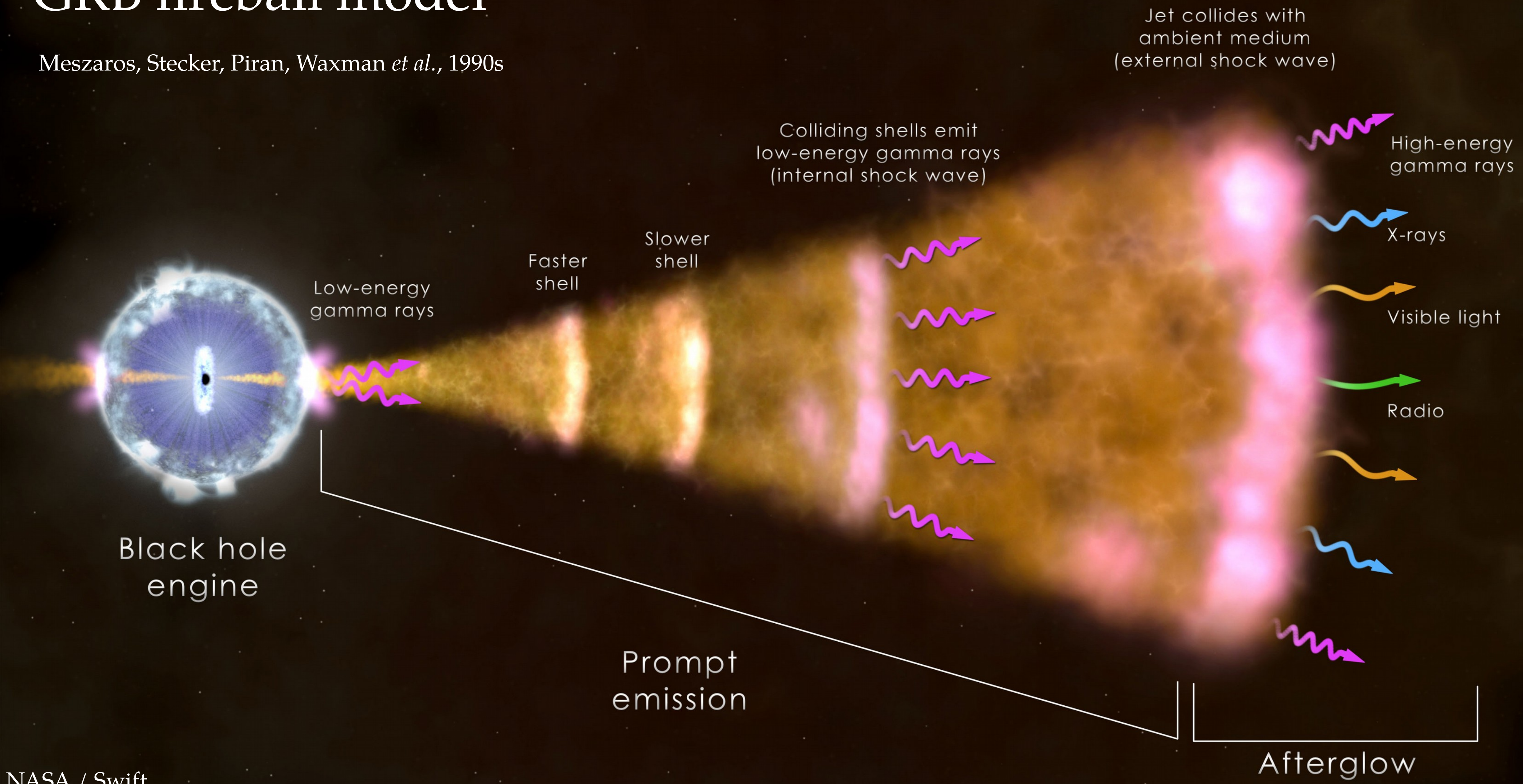
GRB fireball model

Meszaros, Stecker, Piran, Waxman *et al.*, 1990s



NASA / Swift

GRB fireball model

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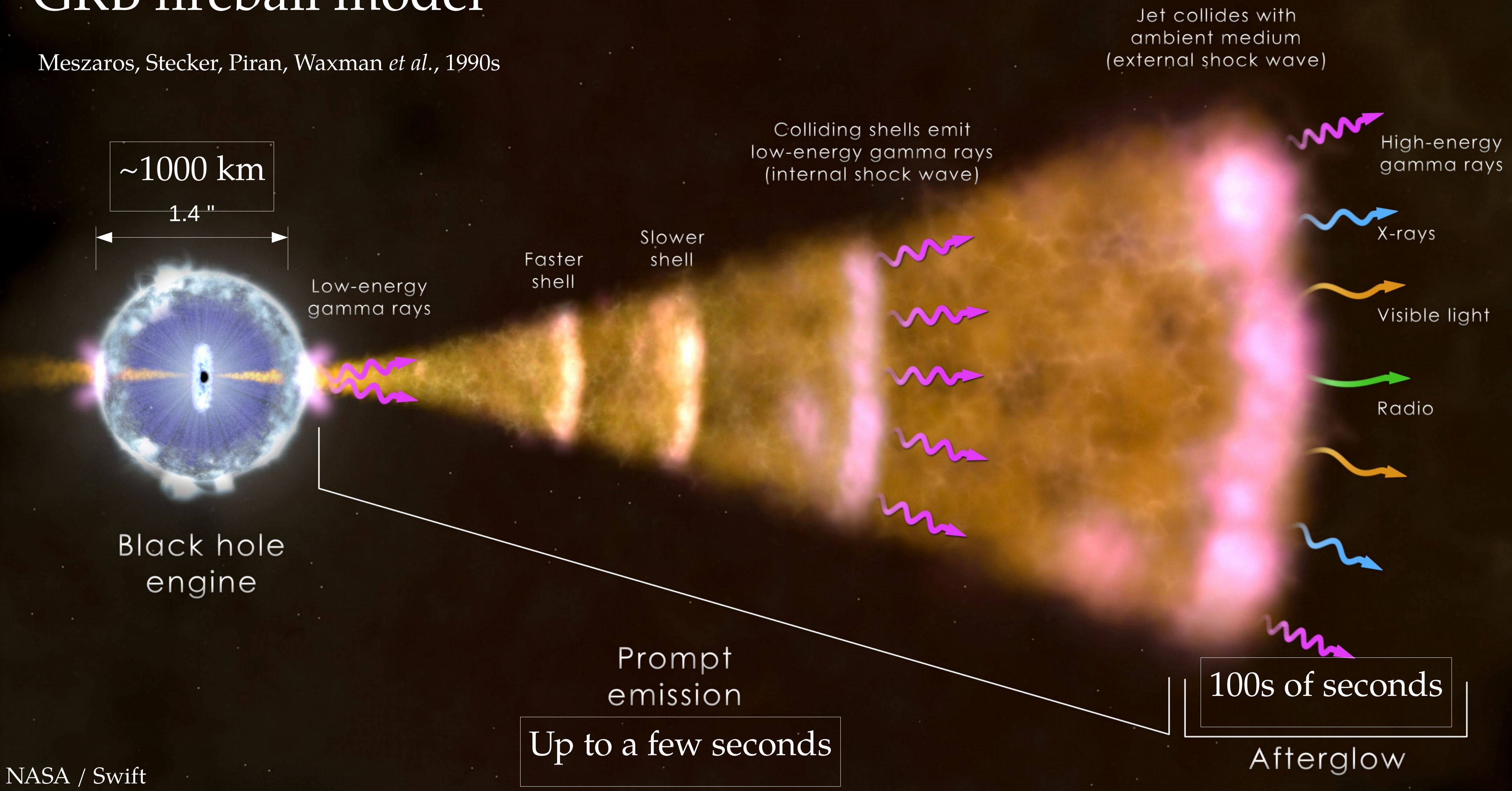

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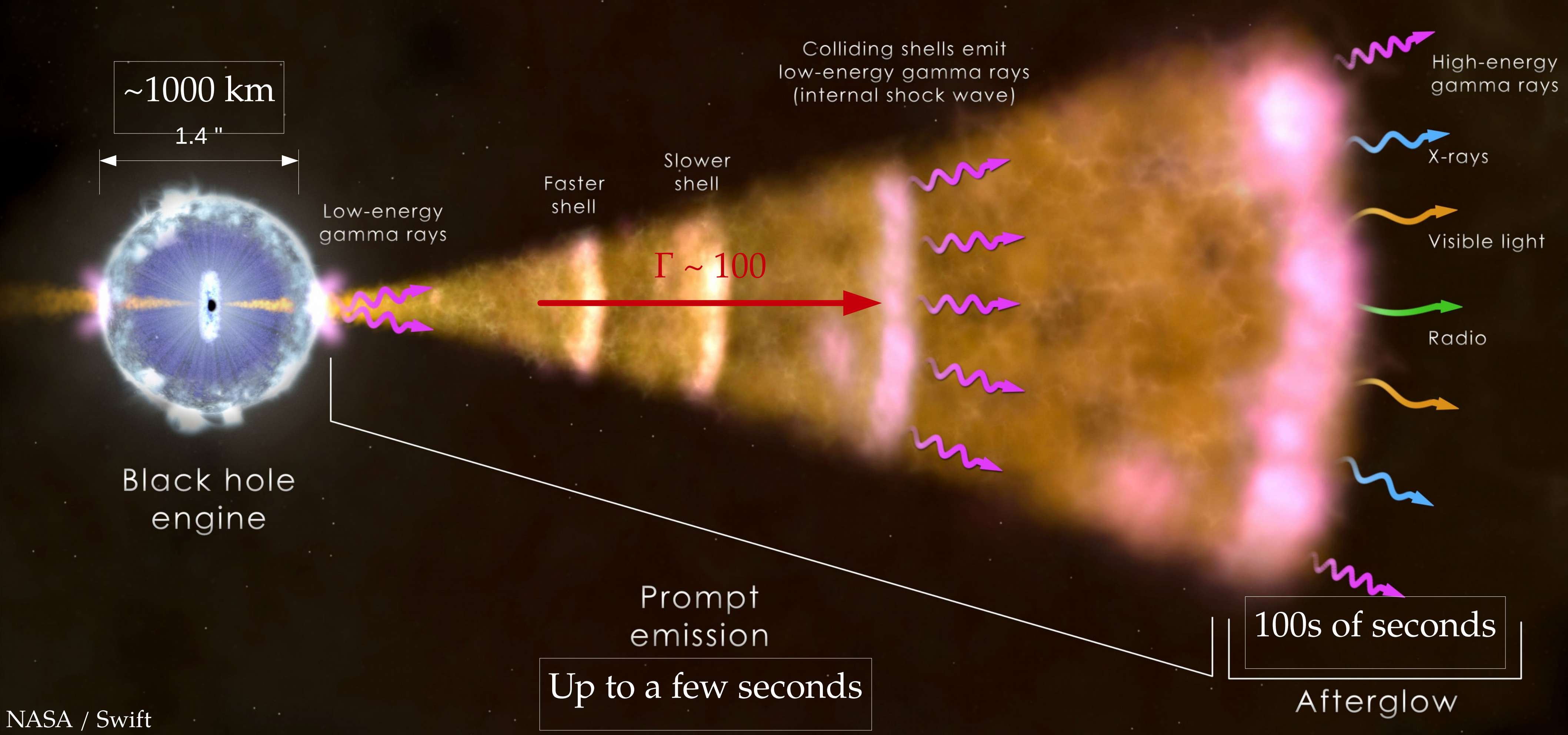
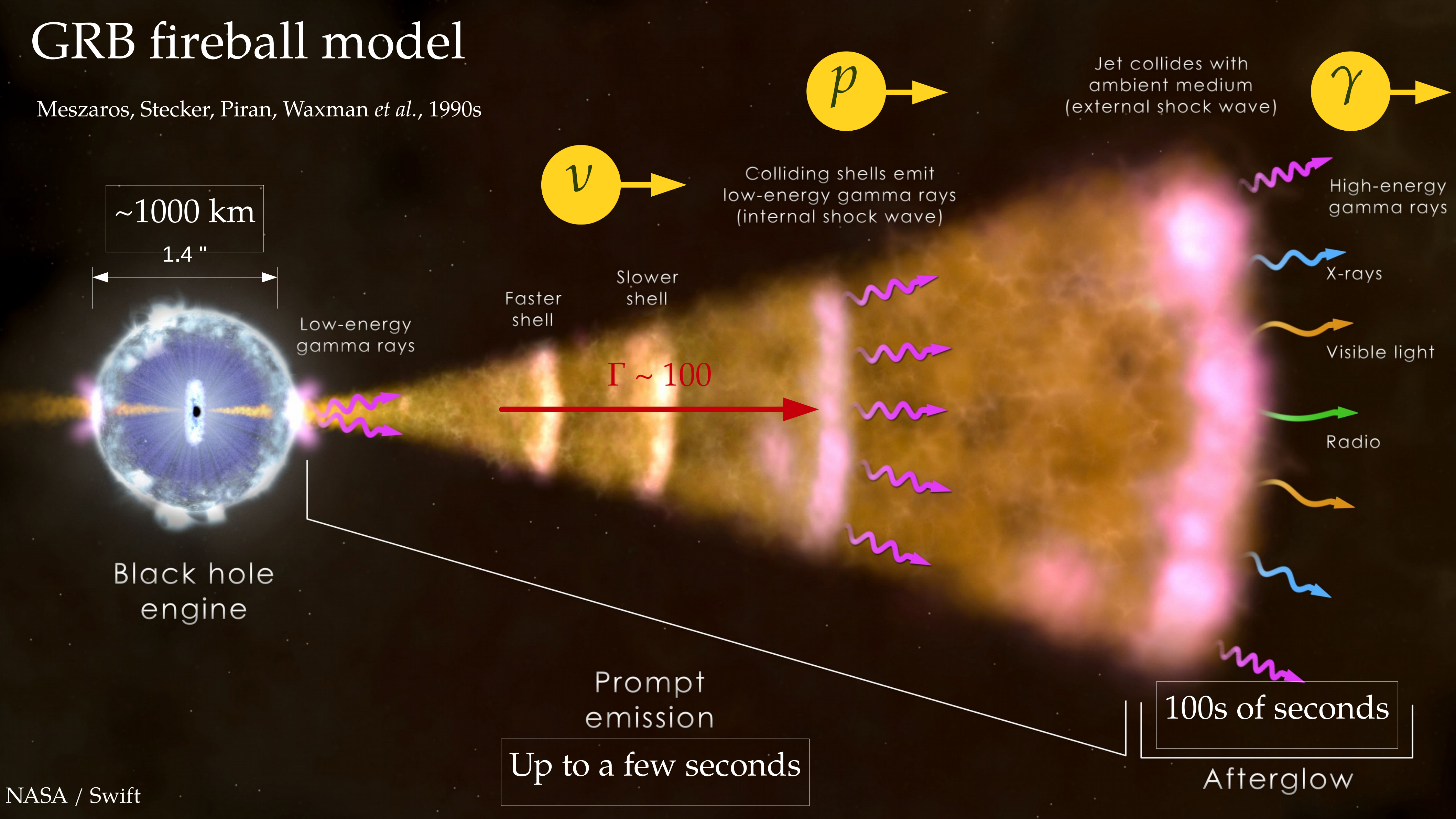
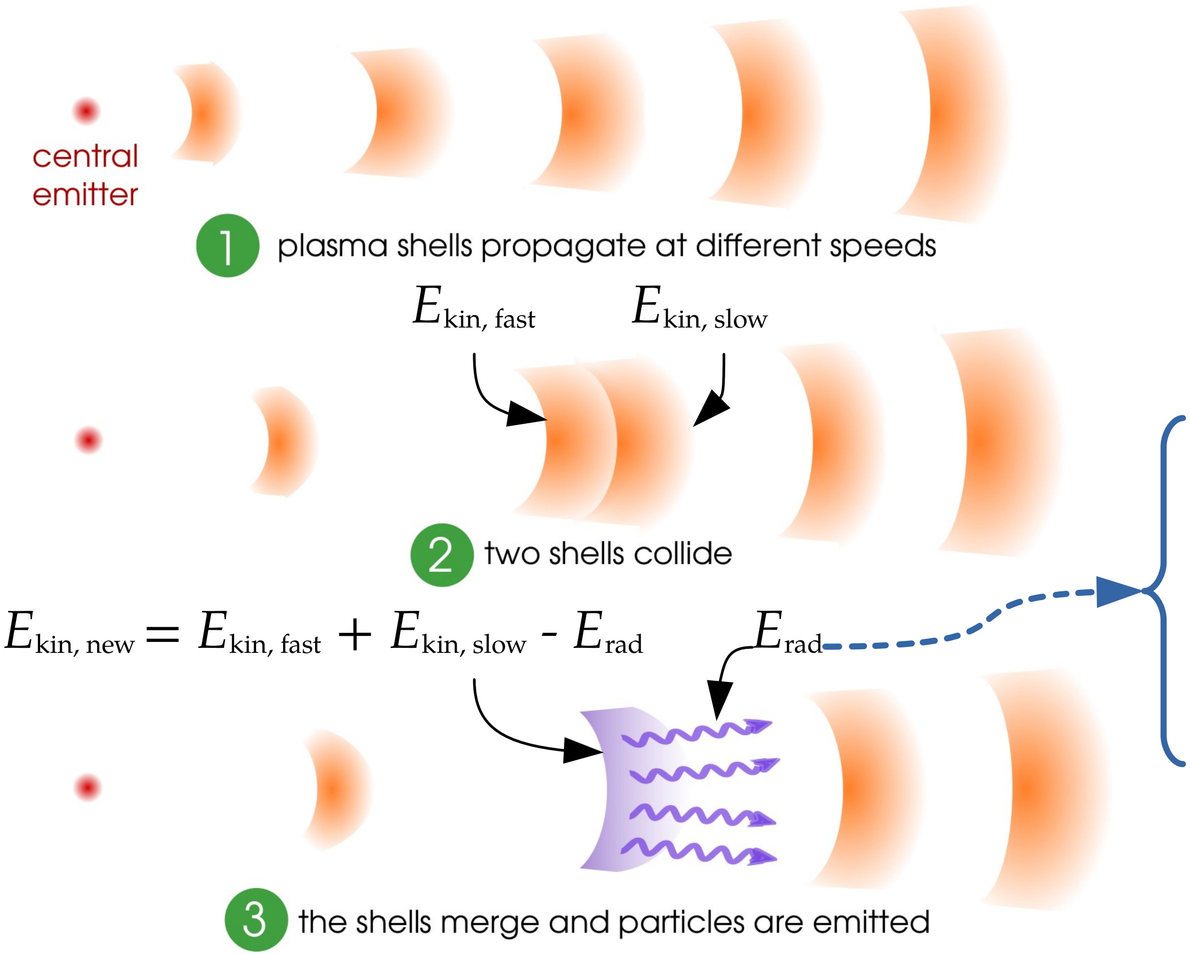


NASA / Swift


GRB fireball model
Meszaros, Stecker, Piran, Waxman et al., 1990s
ν
p
γ
Jet collides with ambient medium (external shock wave)
Colliding shells emit low-energy gamma rays (internal shock wave)
~1000 km
1.4 "
Low-energy gamma rays
Faster shell
Slower shell
Γ ~ 100
High-energy gamma rays
X-rays
Visible light
Radio
Black hole engine
Prompt emission
Up to a few seconds
100s of seconds
Afterglow
NASA / Swift

Internal collisions



Energy shared among:

- Electrons: $f_e \times E_{\text{rad}}$
- Protons: $f_p \times E_{\text{rad}}$
- Magnetic field: $f_B \times E_{\text{rad}}$

The multi-messenger connection

$$p + \gamma_{\text{target}} \to \Delta^+ \to \begin{cases} p + \pi^0, & \text{Br} = 2/3 \\ n + \pi^+, & \text{Br} = 1/3 \end{cases}$$

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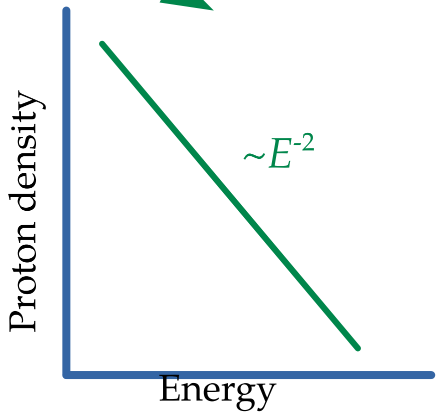

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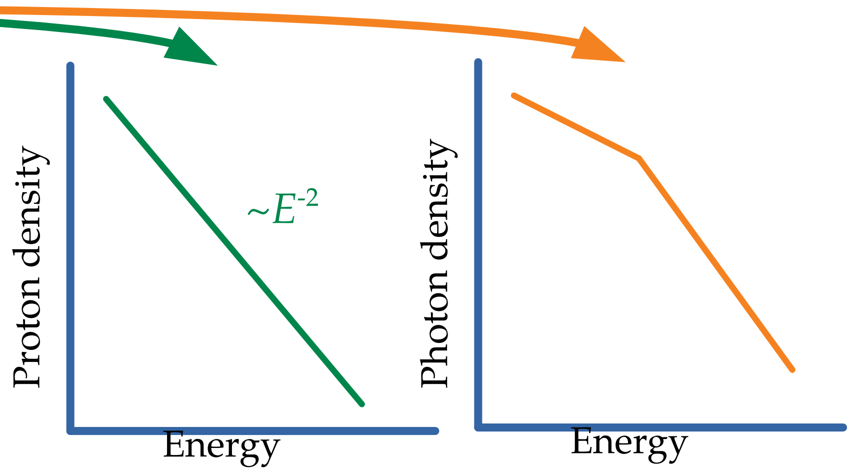

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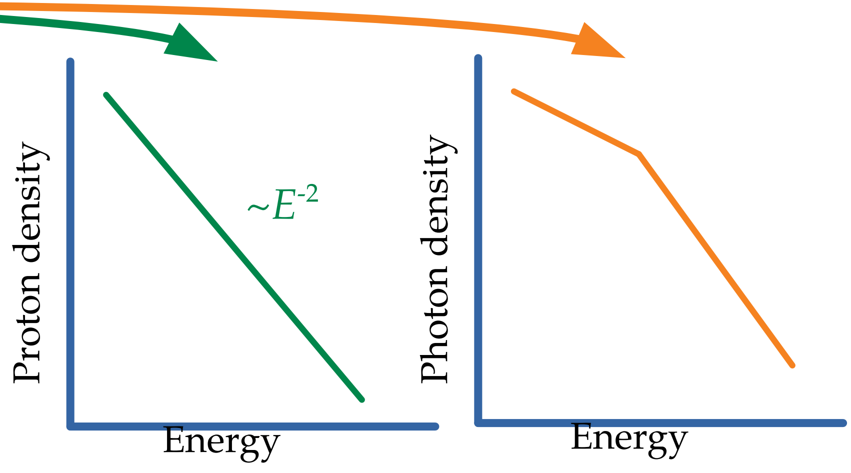
$$\pi^0 \rightarrow \gamma + \gamma$$

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

$$n \text{ (escapes)} \rightarrow p + e^- + \bar{\nu}_e$$



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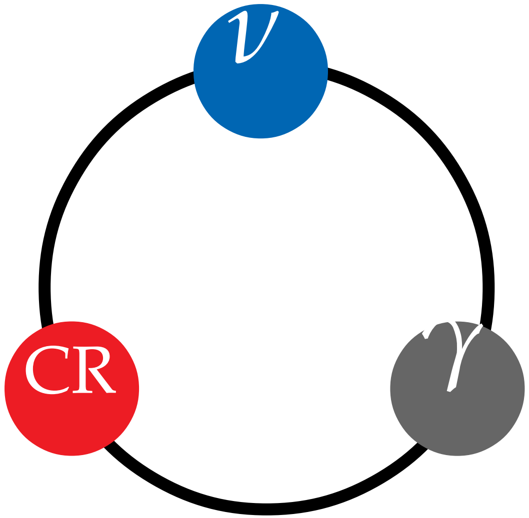

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

The multi-messenger connection

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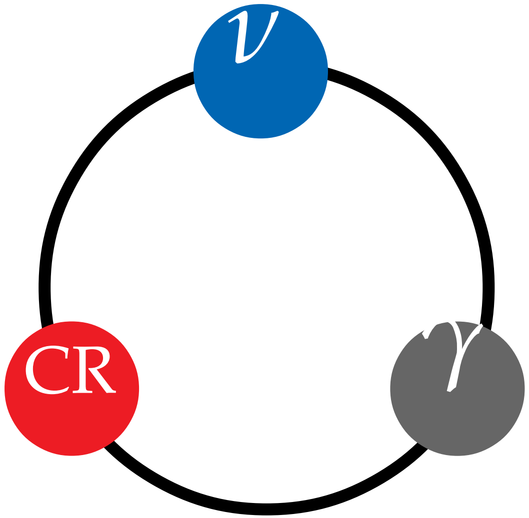

1 PeV 20 PeV

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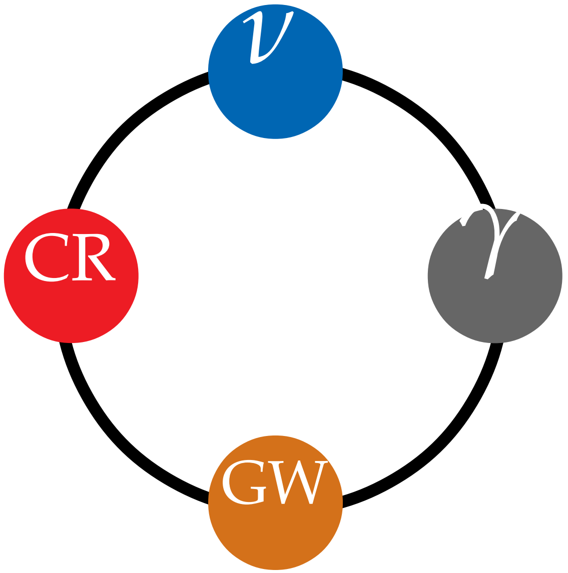

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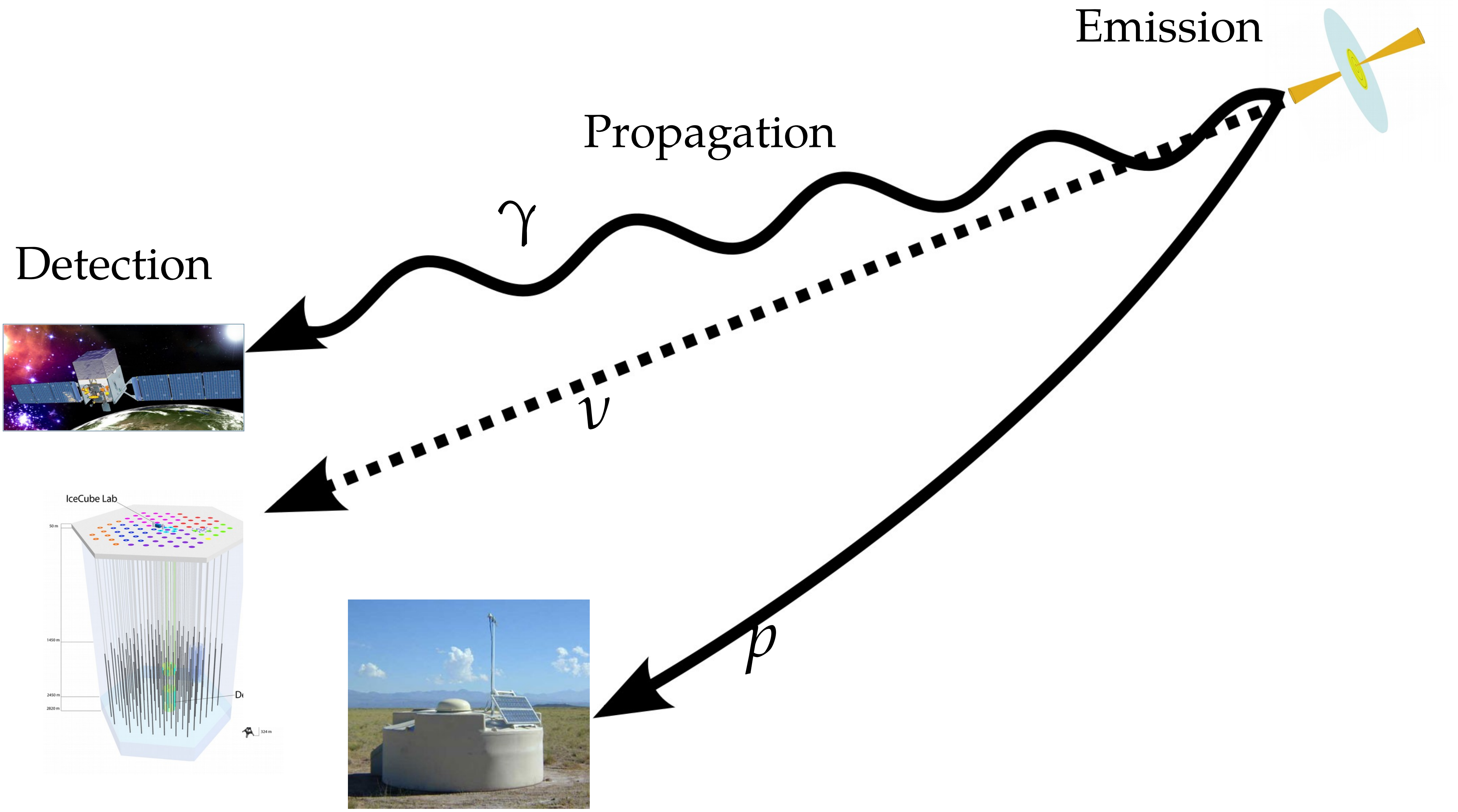
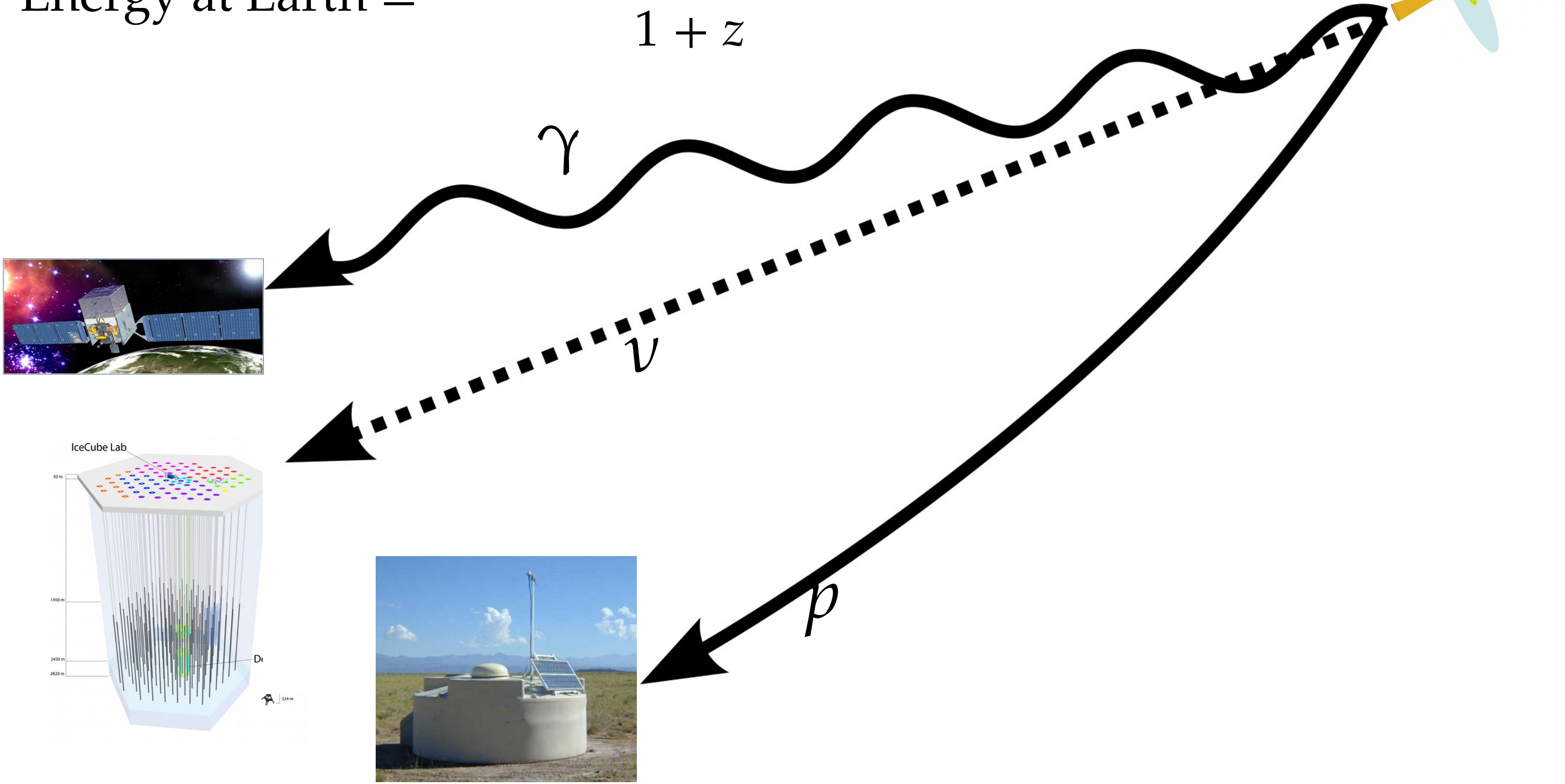

Emission
Propagation
γ
Detection
ν
p
IceCube Lab

$$\text{Energy at Earth} = \frac{\text{Energy at production}}{1+z}$$



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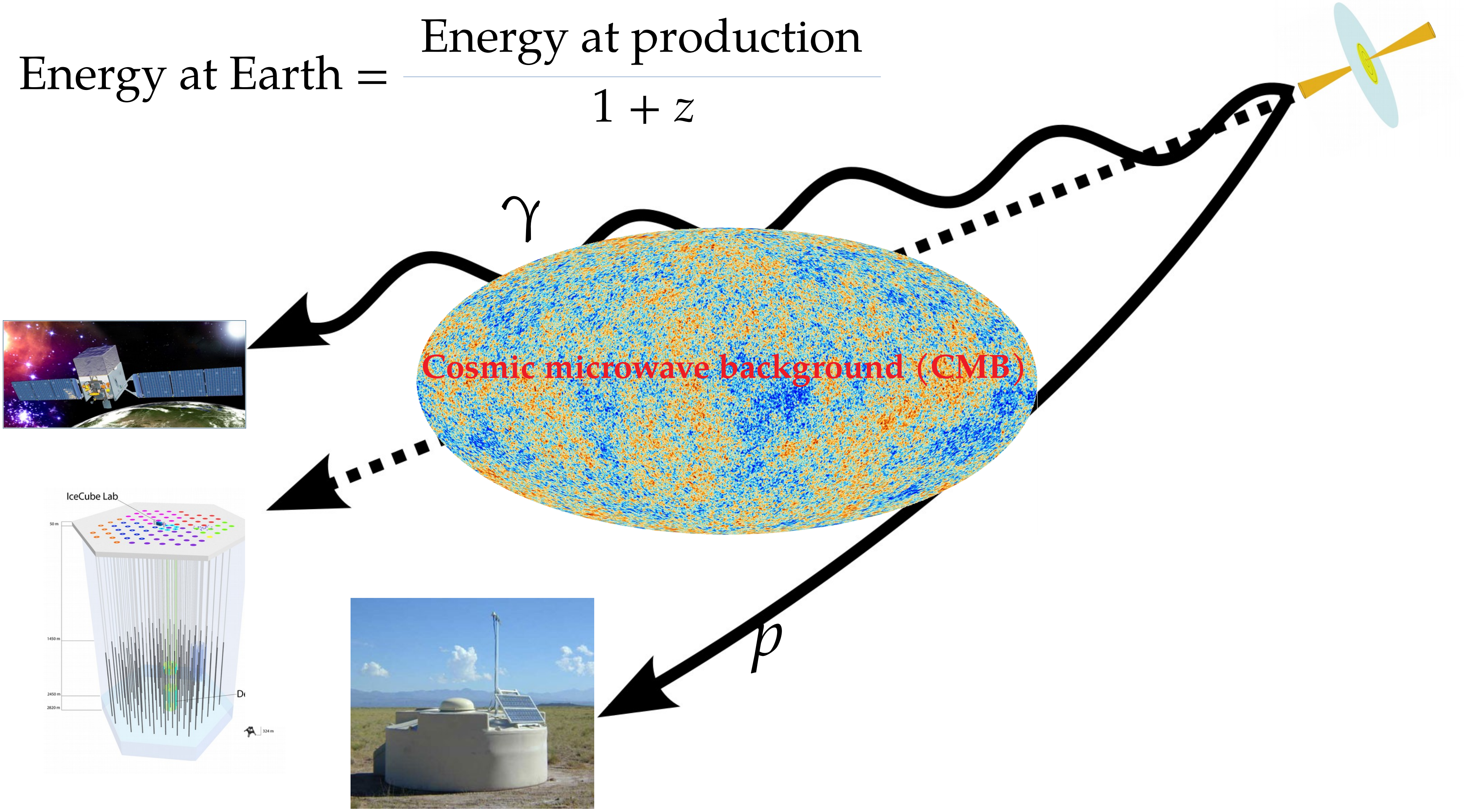
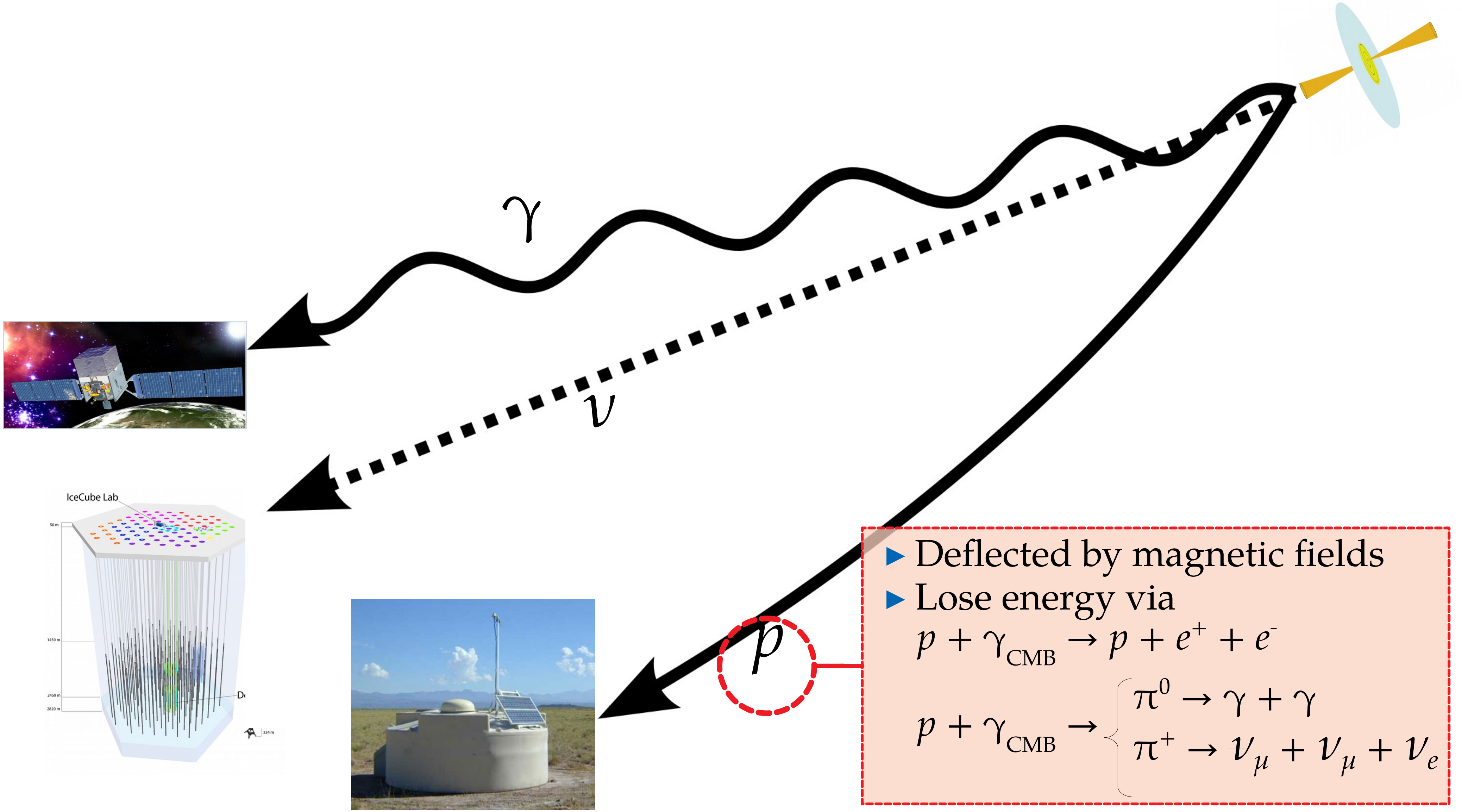
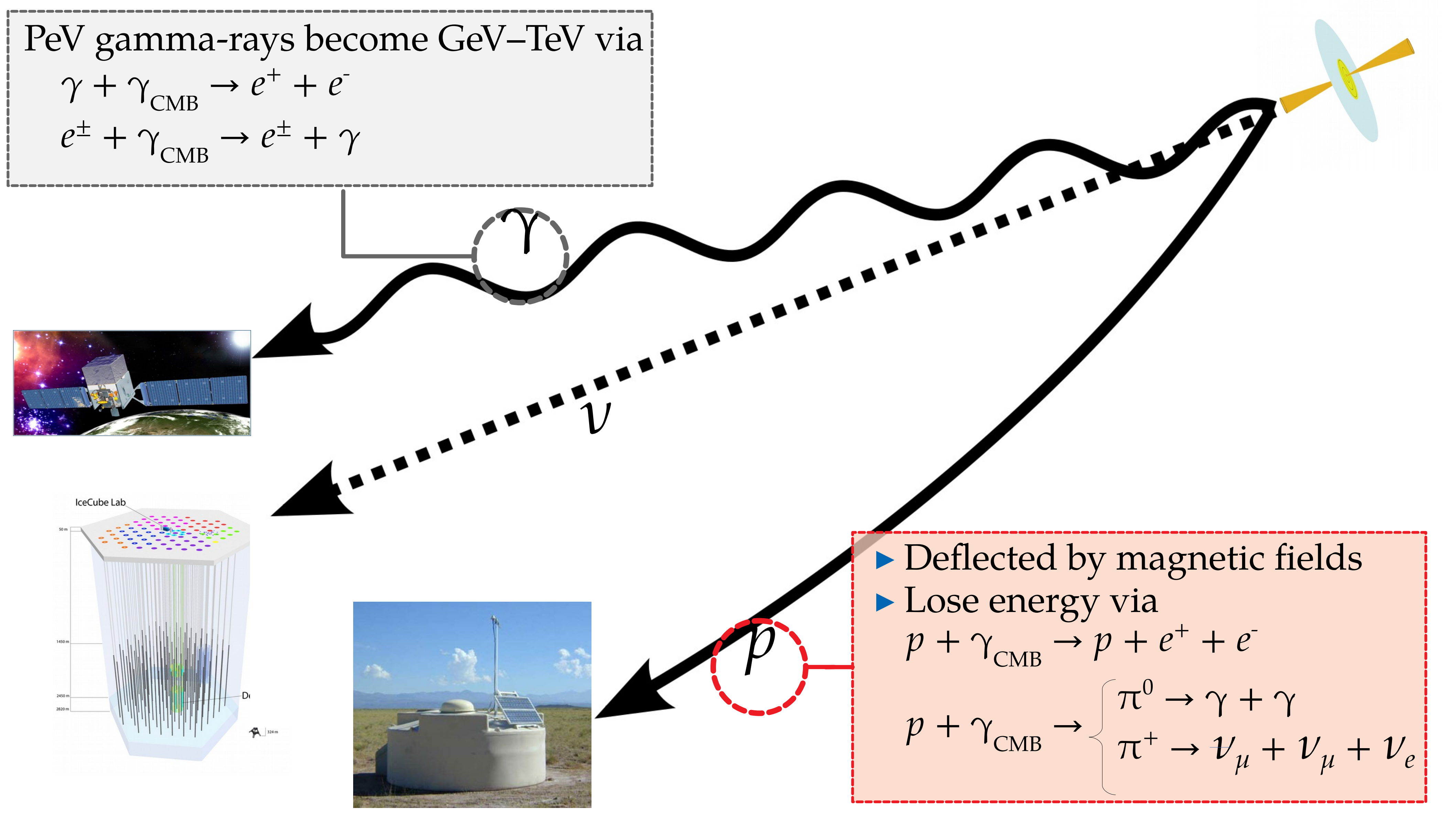




- Deflected by magnetic fields
- Lose energy via

$$p + \gamma_{\text{CMB}} \rightarrow p + e^{+} + e^{-}$$

$$p + \gamma_{\text{CMB}} \rightarrow \begin{cases} \pi^{0} \rightarrow \gamma + \gamma \\ \pi^{+} \rightarrow \nu_{\mu} + \nu_{\mu} + \nu_{e} \end{cases}$$


PeV gamma-rays become GeV–TeV via
$\gamma + \Upsilon_{CMB} \rightarrow e^{+} + e^{-}$
$e^{\pm} + \Upsilon_{CMB} \rightarrow e^{\pm} + \gamma$
Υ
ν
p
IceCube Lab
Deflected by magnetic fields
Lose energy via
$p + \Upsilon_{CMB} \rightarrow p + e^{+} + e^{-}$
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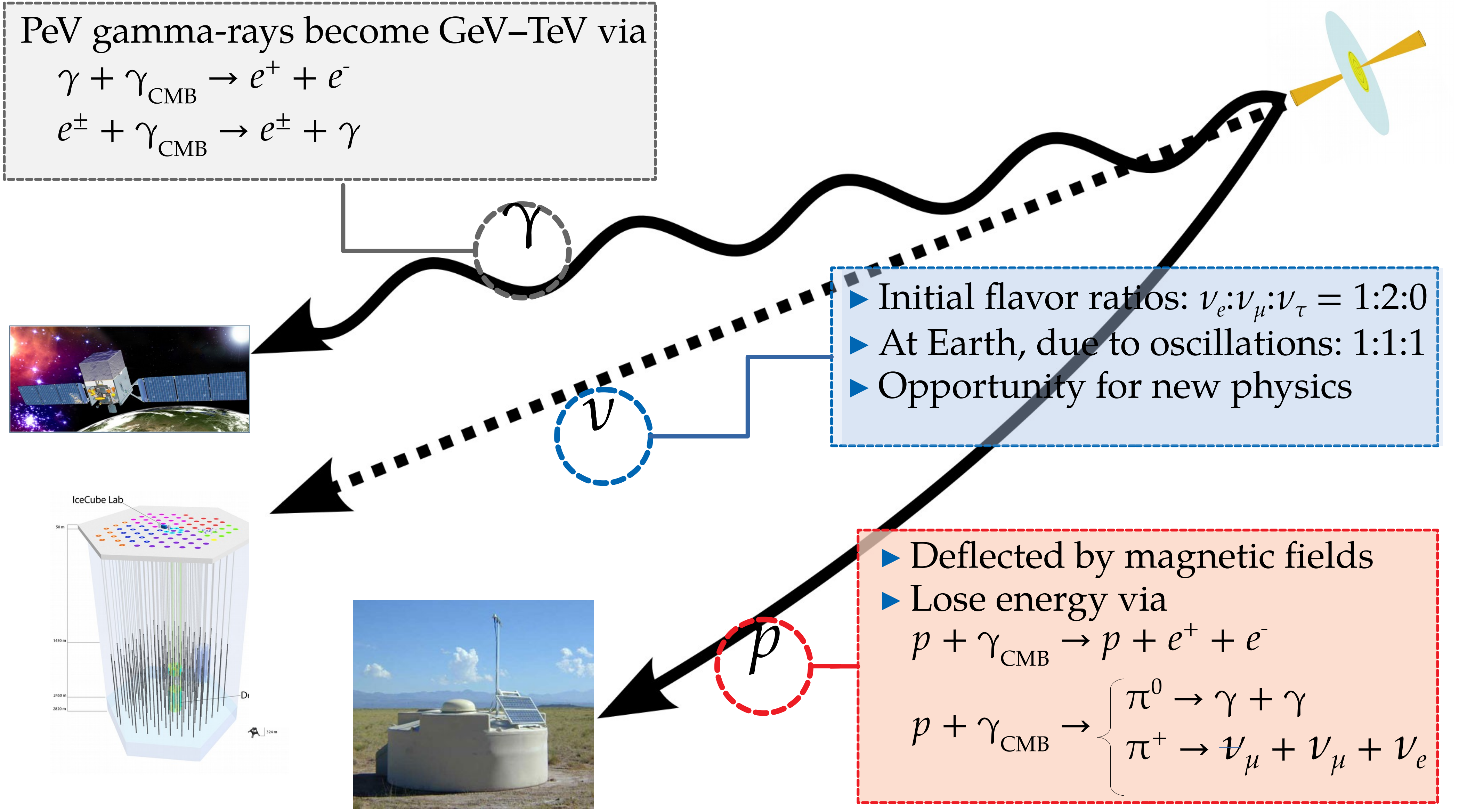
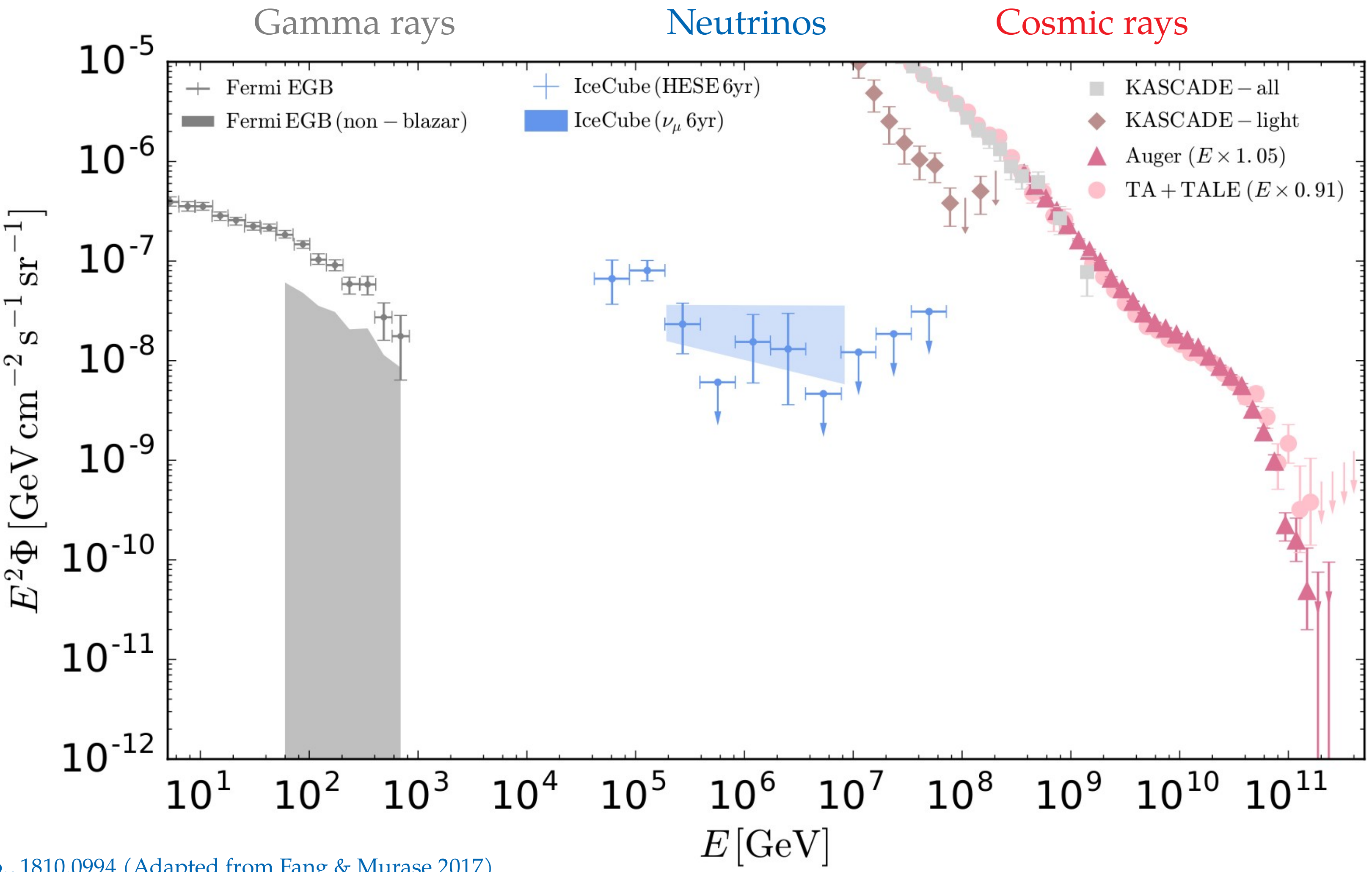
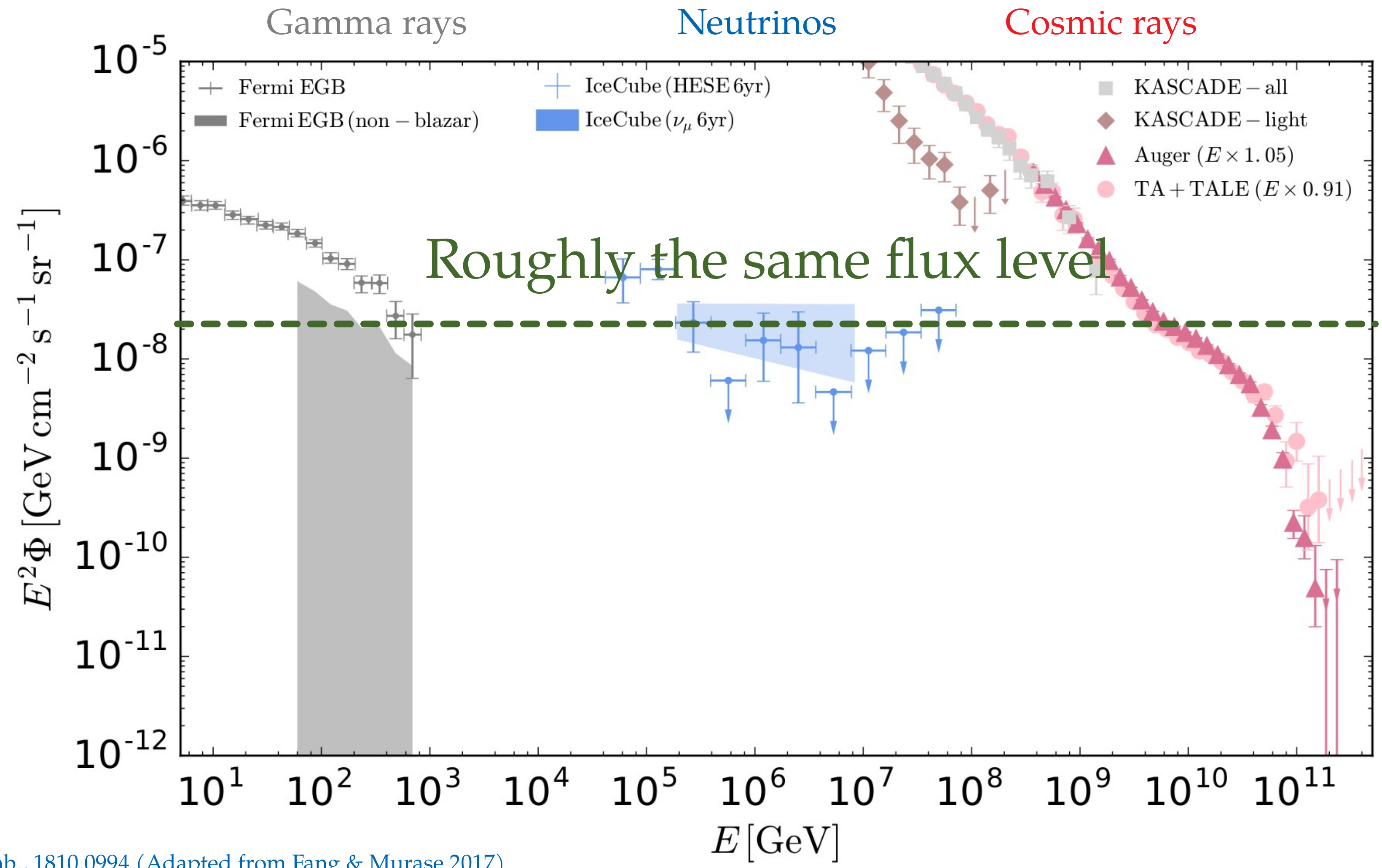

PeV gamma-rays become GeV–TeV via
$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$
$e^\pm + \gamma_{CMB} \rightarrow e^\pm + \gamma$
γ
ν
p
Initial flavor ratios: $\nu_e:\nu_\mu:\nu_\tau = 1:2:0$
At Earth, due to oscillations: 1:1:1
Opportunity for new physics
Deflected by magnetic fields
Lose energy via
$p + \gamma_{CMB} \rightarrow p + e^+ + e^-$
$p + \gamma_{CMB} \rightarrow \begin{cases} \pi^0 \rightarrow \gamma + \gamma \\ \pi^+ \rightarrow \nu_\mu + \nu_\mu + \nu_e \end{cases}$
IceCube Lab

Fluxes at Earth



GRAND Collab., 1810.0994 (Adapted from Fang & Murase 2017)

Fluxes at Earth



GRAND Collab., 1810.0994 (Adapted from Fang & Murase 2017)

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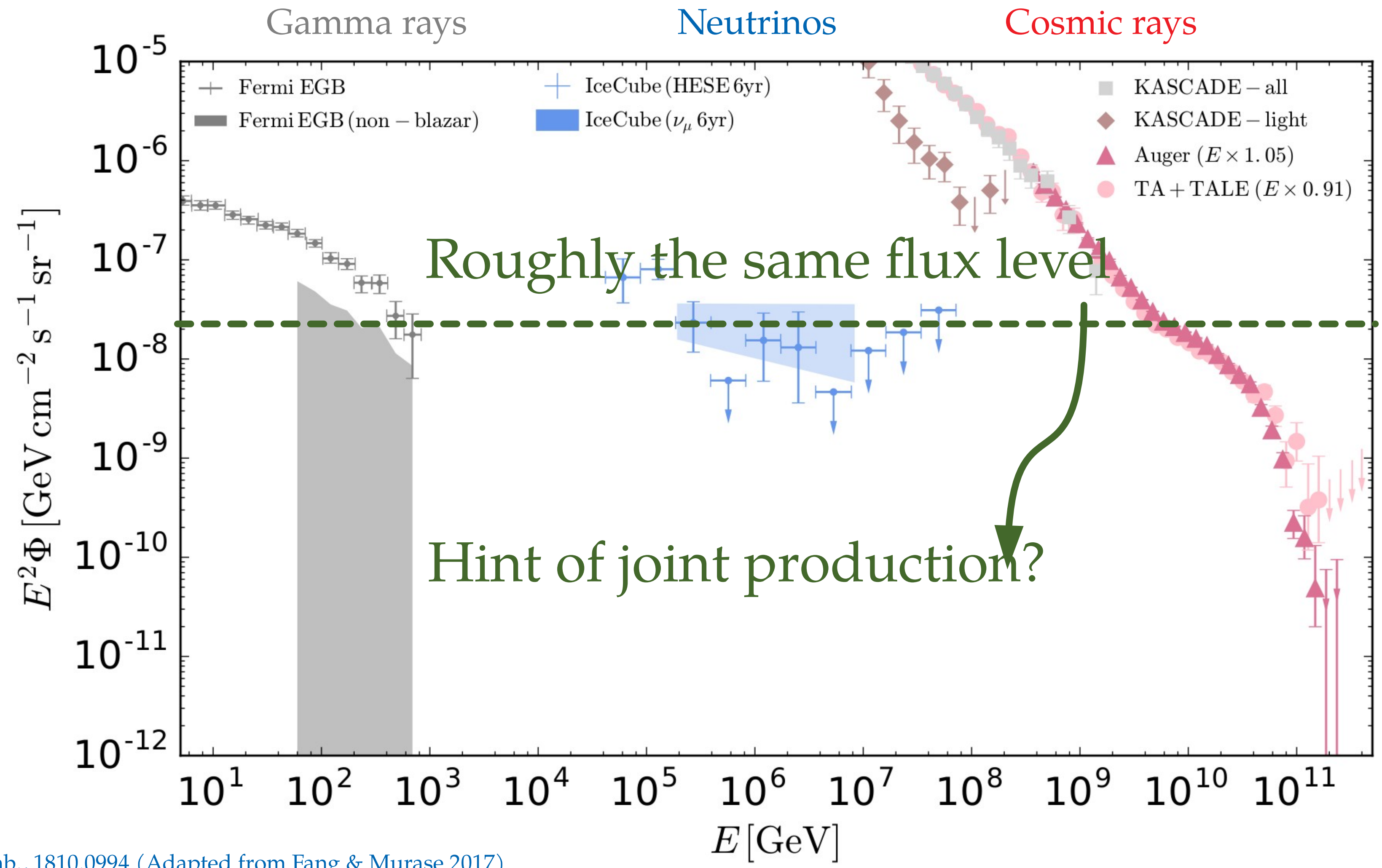

GRAND Collab., 1810.0994 (Adapted from Fang & Murase 2017)

Neutrinos – The Ultimate Smoking Gun

	Gamma rays	Neutrinos	UHE Cosmic rays
Point back at sources			
Size of horizon			
Energy degradation			
Relative ease to detect			

Note: This is a simplified view

Neutrinos – The Ultimate Smoking Gun

	Gamma rays	Neutrinos	UHE Cosmic rays
Point back at sources	Yes	Yes	No
Size of horizon			
Energy degradation			
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Note: This is a simplified view

Neutrinos – The Ultimate Smoking Gun

	Gamma rays	Neutrinos	UHE Cosmic rays
Point back at sources	Yes	Yes	No
Size of horizon	10 Mpc (at EeV)	Size of the Universe	100 Mpc (> 40 EeV)
Energy degradation			
Relative ease to detect			

Note: This is a simplified view

Neutrinos – The Ultimate Smoking Gun

	Gamma rays	Neutrinos	UHE Cosmic rays
Point back at sources	Yes	Yes	No
Size of horizon	10 Mpc (at EeV)	Size of the Universe	100 Mpc ($>$ 40 EeV)
Energy degradation	Severe	Tiny	Severe
Relative ease to detect			

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Size of horizon	10 Mpc (at EeV)	Size of the Universe	100 Mpc (> 40 EeV)
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Relative ease to detect	Easy	Hard	Easy

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Relative ease to detect	Easy	Hard	Easy

Note: This is a simplified view

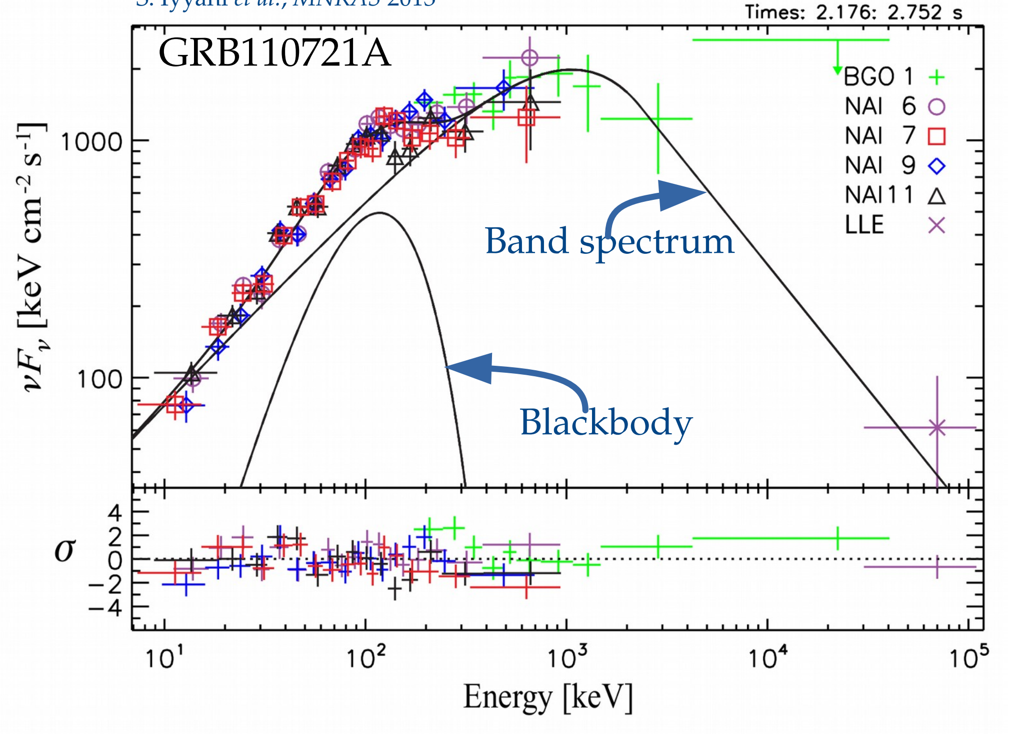
Gamma rays – spectrum basics

- Gamma-ray spectrum peaks at ~MeV
- Typically fitted by the Band function,

$$\nu F_\nu(E_\gamma) \propto \begin{cases} \left(\frac{E_\gamma}{100\ \mathrm{keV}}\right)^\alpha \exp(-E_\gamma/E_0) & , E_\gamma < (\alpha-\beta)E_0 \\ \left(\frac{E_\gamma}{100\ \mathrm{keV}}\right)^\beta & , E_\gamma \geq (\alpha-\beta)E_0 \end{cases}$$

- The spectrum evolves in time
- Some bursts are better fitted by a broken power law
- There might be multiple components

S. Iyyani *et al.*, *MNRAS* 2013



D. Band *et al.*, *ApJL* 1993

Gamma rays – spectrum basics

- Gamma-ray spectrum peaks at ~MeV
- Typically fitted by the Band function,

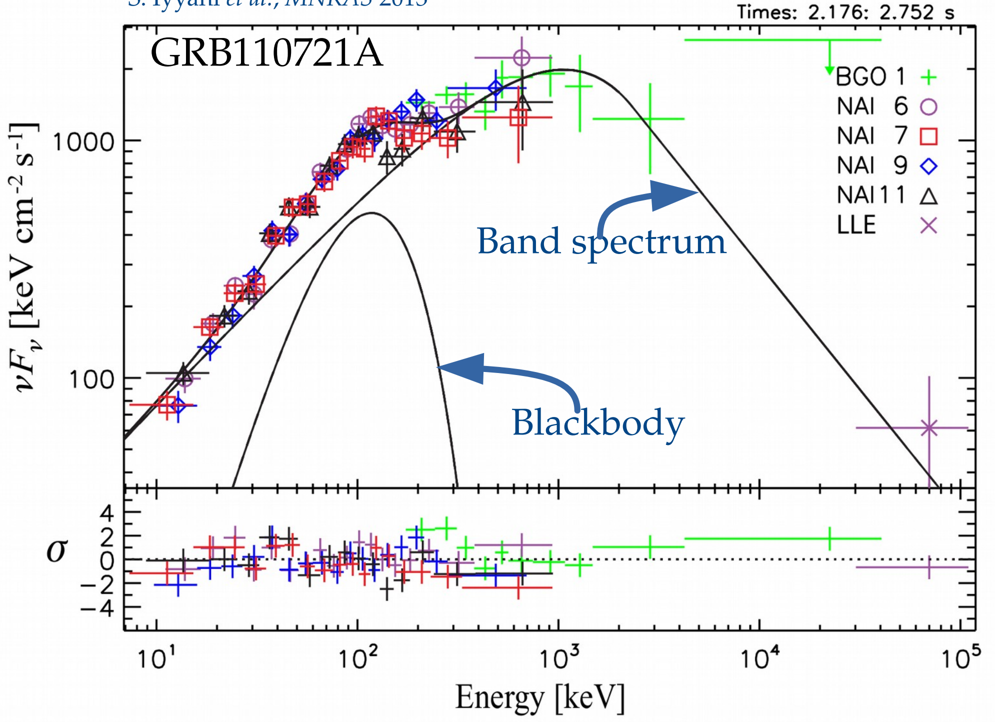
⟨α⟩ = -1

$$\nu F_\nu(E_\gamma) \propto \begin{cases} \left(\frac{E_\gamma}{100\ \mathrm{keV}}\right)^{\alpha} \exp(-E_\gamma/E_0) & , E_\gamma < (\alpha-\beta)E_0 \\ \left(\frac{E_\gamma}{100\ \mathrm{keV}}\right)^{\beta} & , E_\gamma \geq (\alpha-\beta)E_0 \end{cases}$$

⟨β⟩ = -2

- The spectrum evolves in time
- Some bursts are better fitted by a broken power law
- There might be multiple components

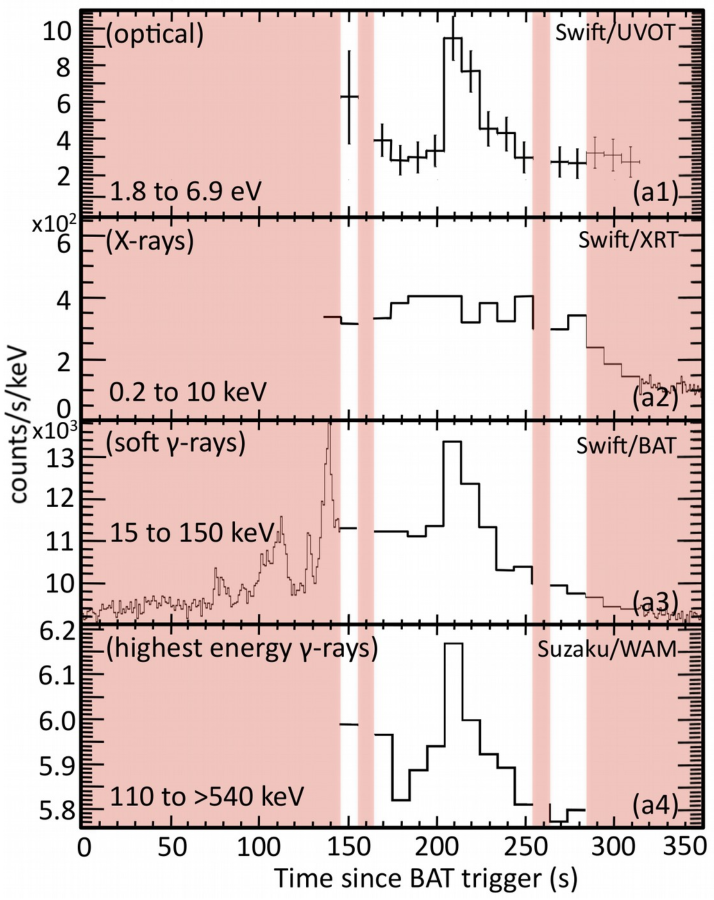
S. Iyyani *et al.*, *MNRAS* 2013



D. Band *et al.*, *ApJL* 1993

Multi-wavelength emission

Unified model from optical to gamma-ray emission —



S. Guiriec *et al.*, *ApJL* 2016

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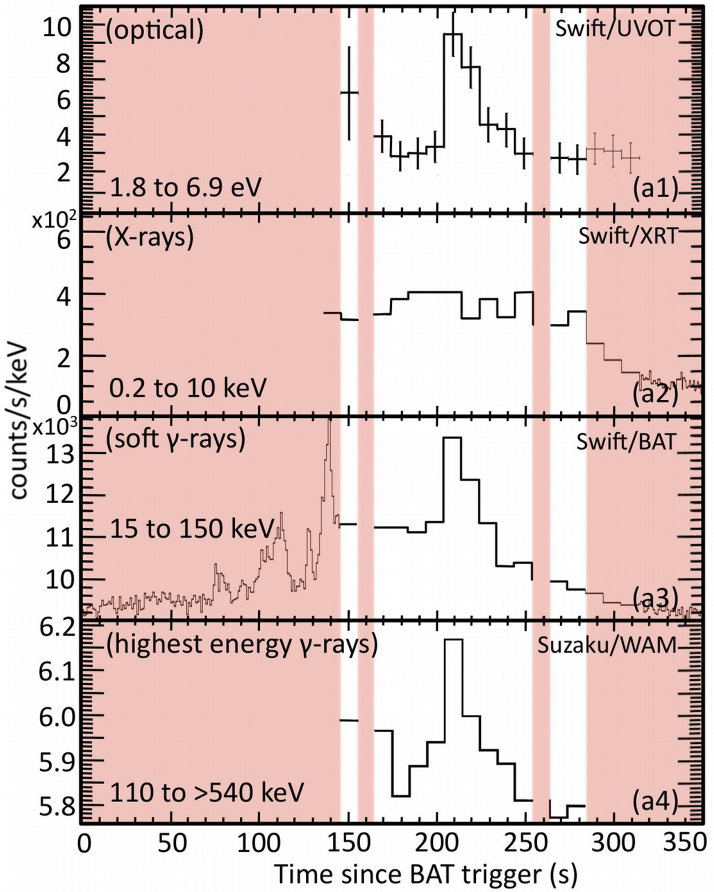

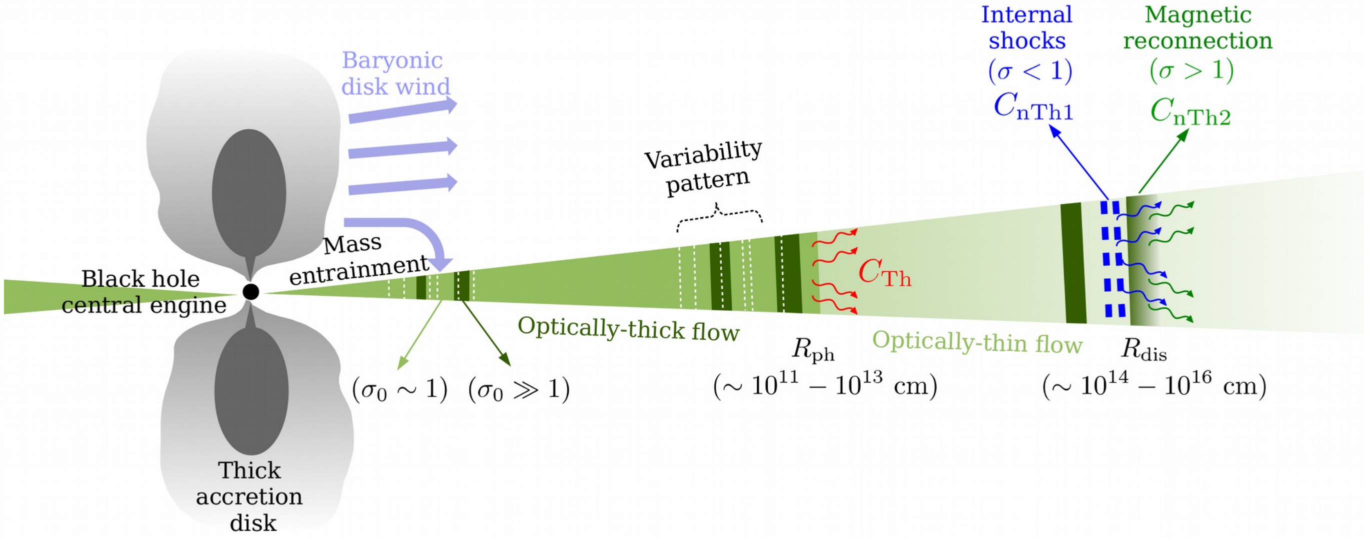

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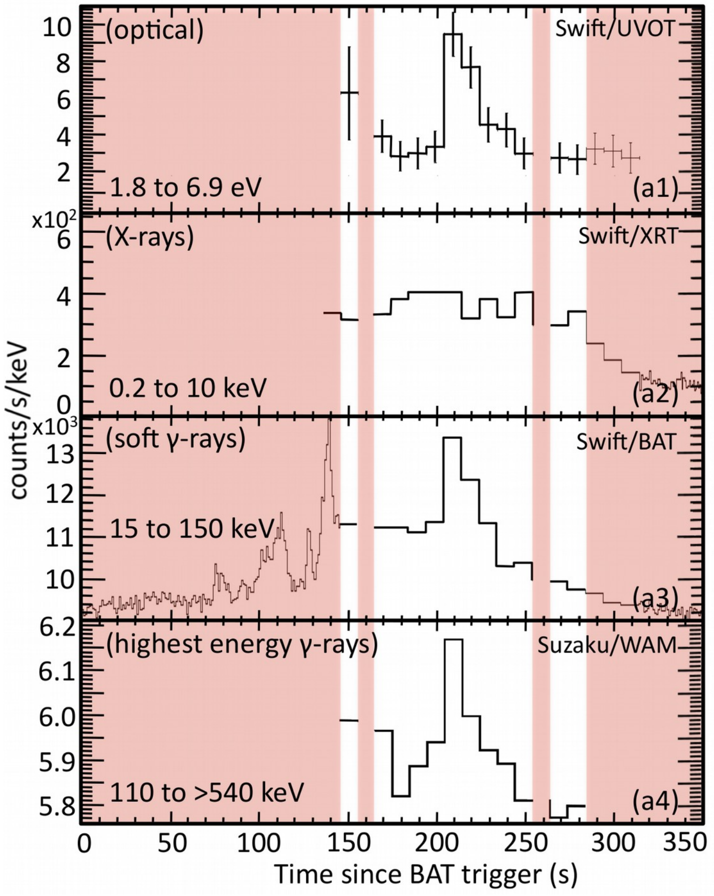
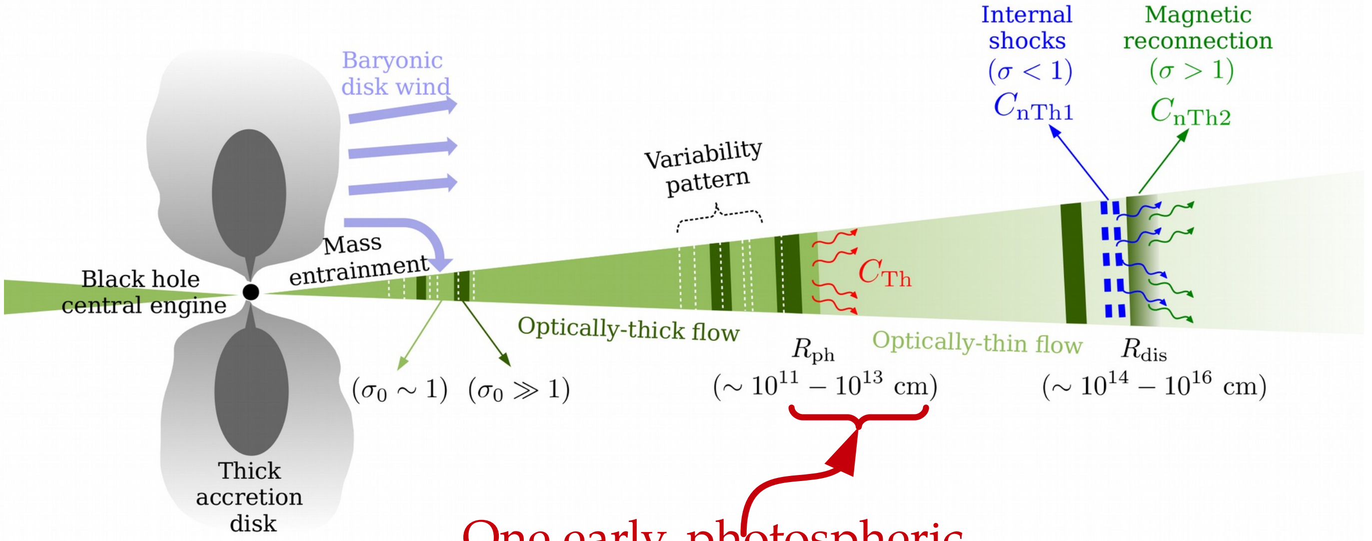


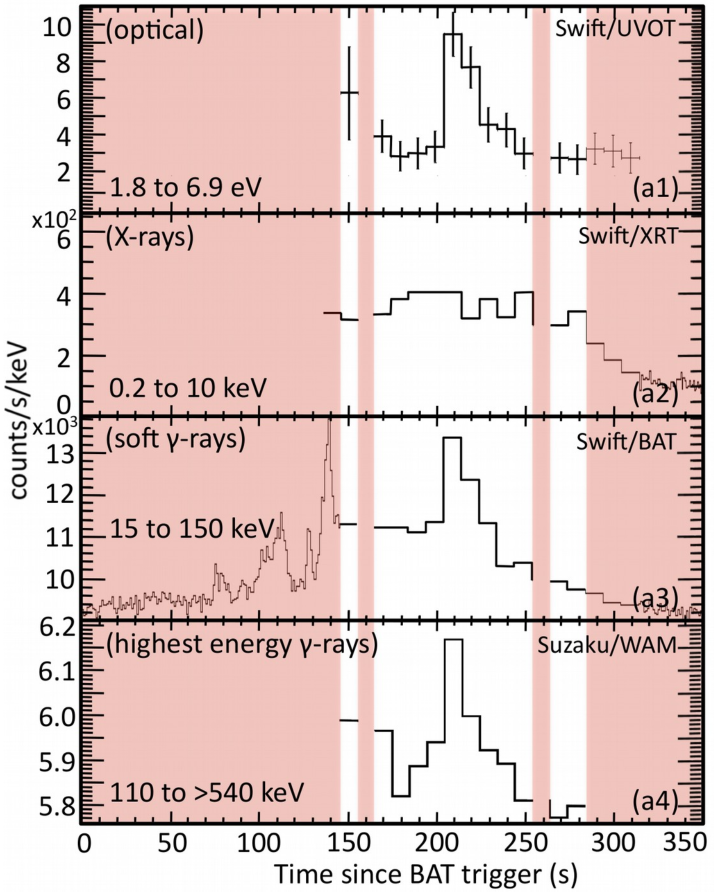


One early, photospheric thermal component

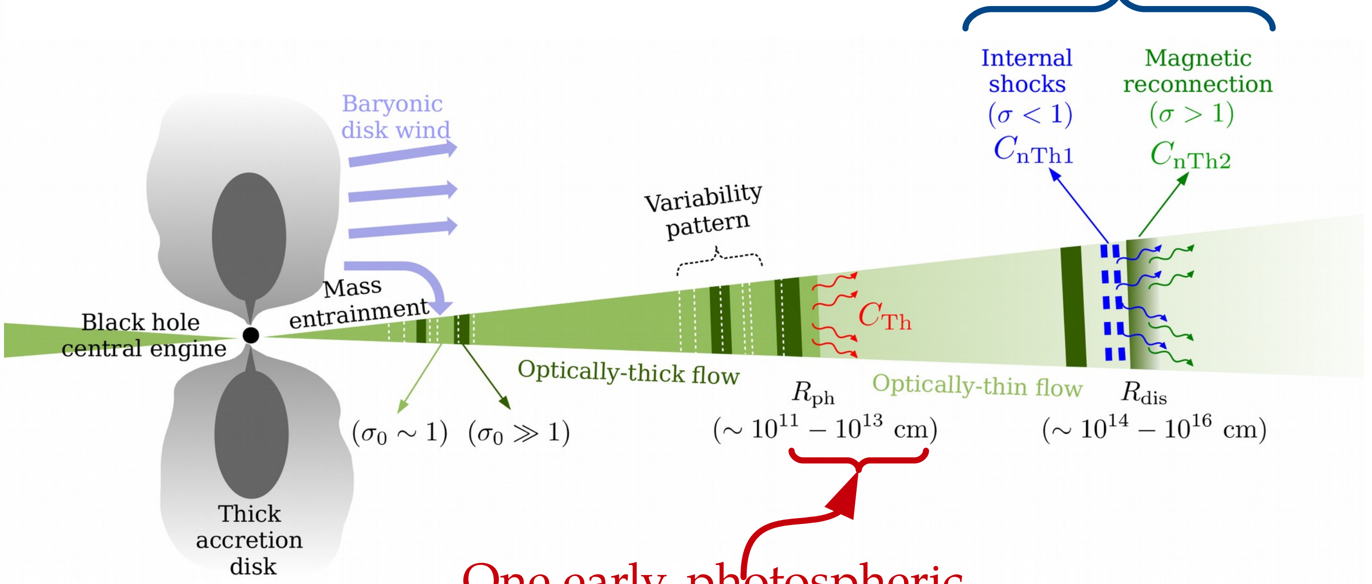
S. Guiriec *et al.*, *ApJL* 2016

Multi-wavelength emission

Unified model from optical to gamma-ray emission —



Two late non-thermal components

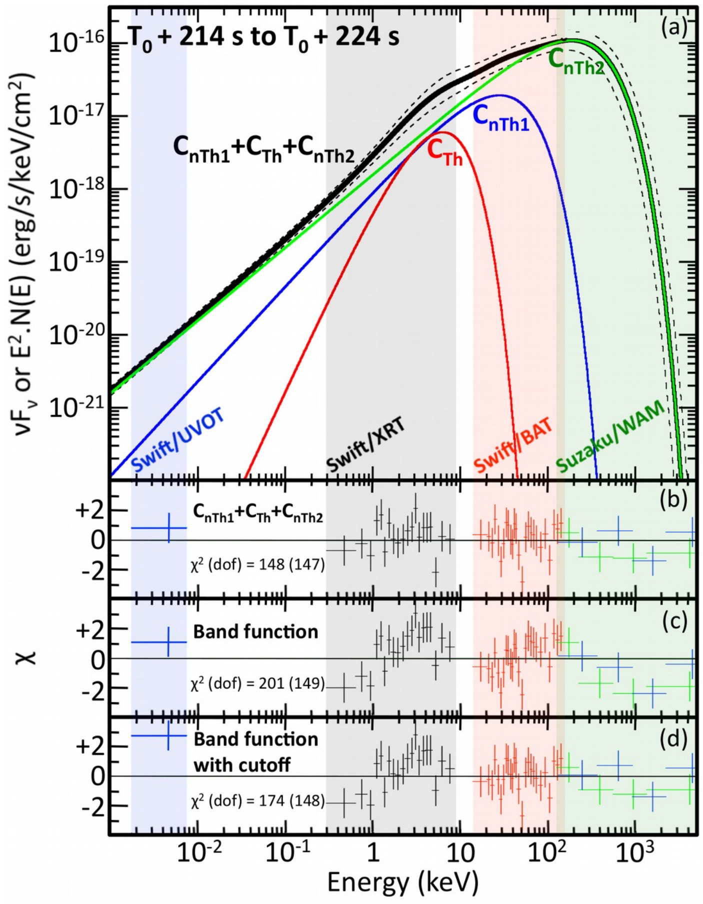


One early, photospheric thermal component

S. Guiriec *et al.*, *ApJL* 2016

Multi-wavelength emission

Unified model from optical to gamma-ray emission —



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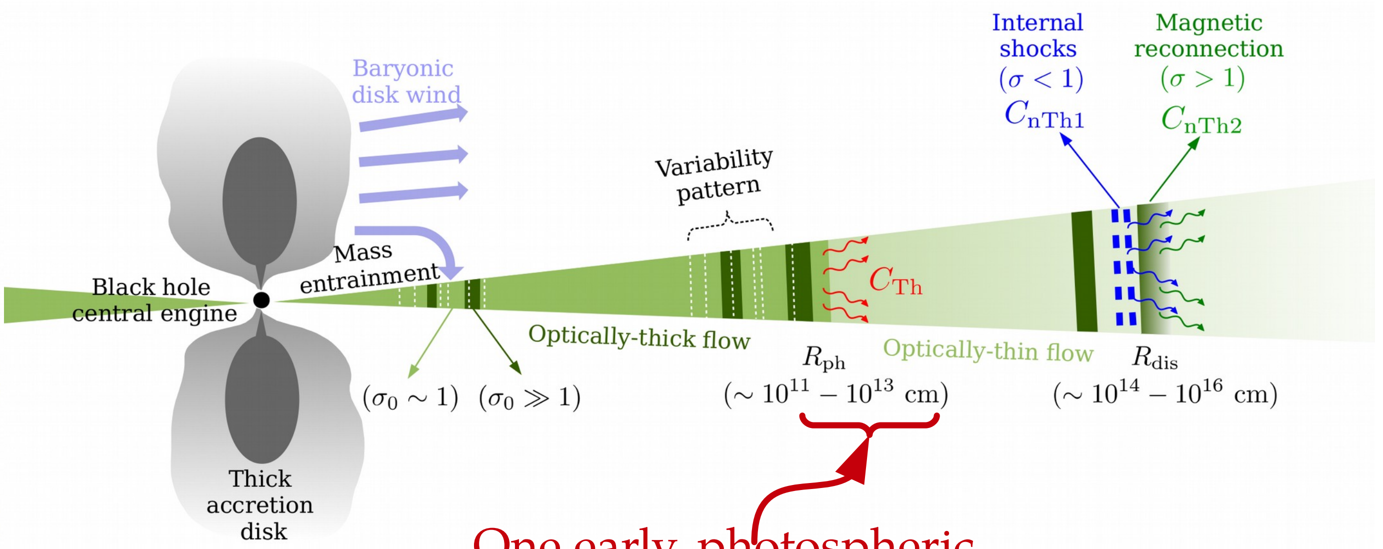
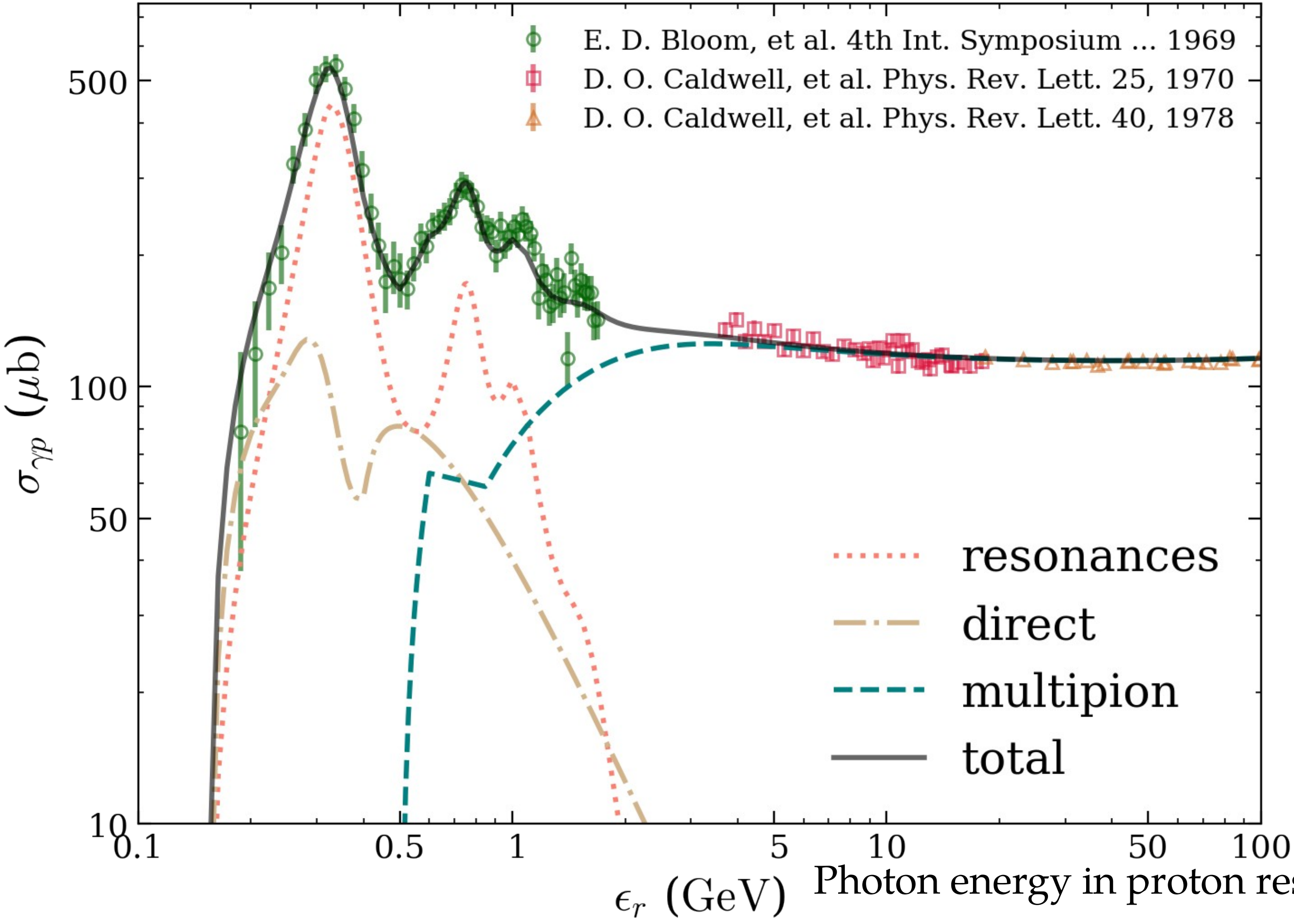


One early, photospheric thermal component

S. Guiriec *et al.*, *ApJL* 2016

High-energy neutrinos from $p\gamma$ interactions

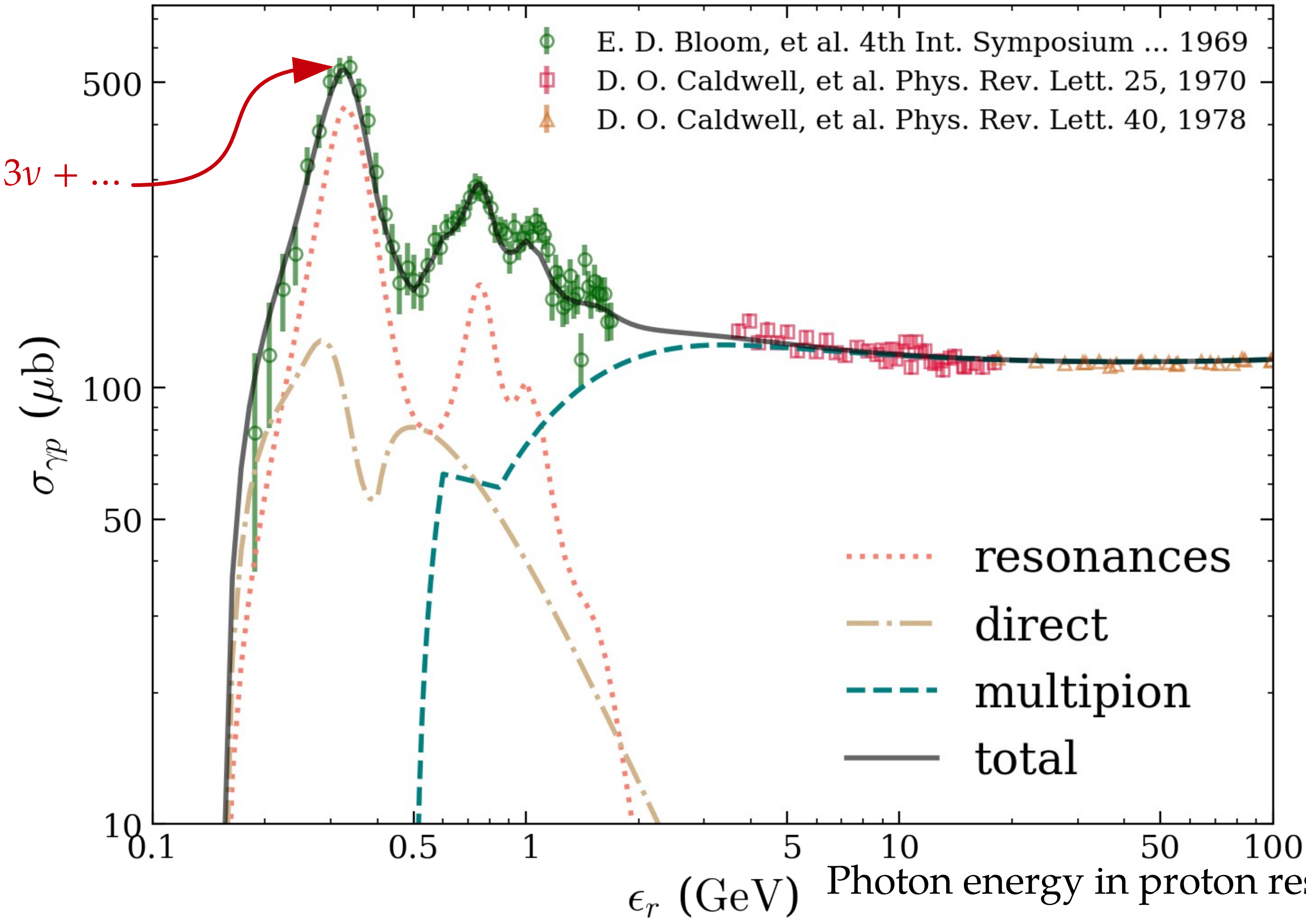


Photon energy in proton rest frame

L. Morejón *et al.*, 1904.07999

High-energy neutrinos from $p\gamma$ interactions

Delta resonance:
$p + \gamma \rightarrow \Delta \rightarrow \pi^+ \rightarrow 3\nu + \ldots$



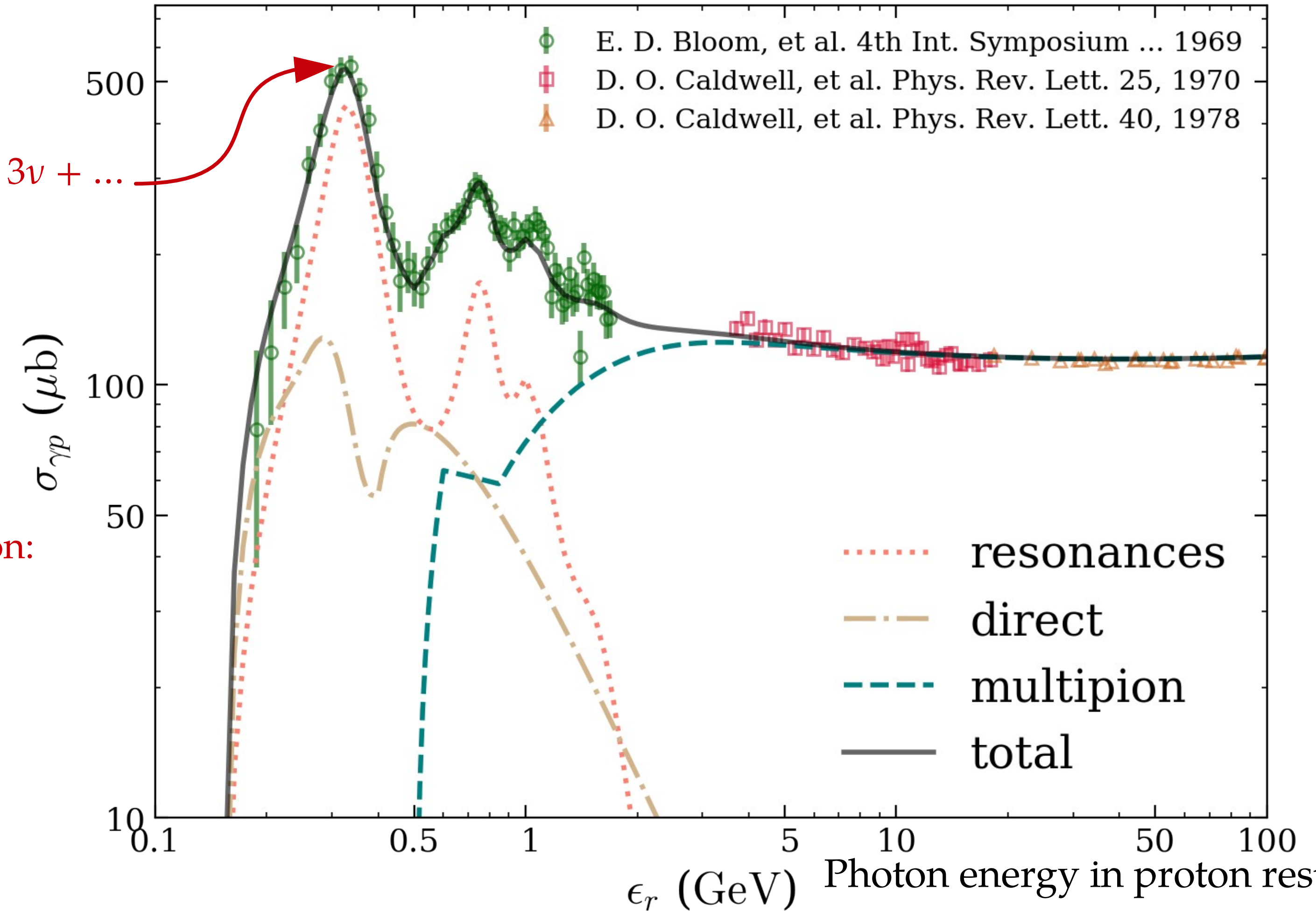
Photon energy in proton rest frame

L. Morejón *et al.*, 1904.07999

High-energy neutrinos from $p\gamma$ interactions

Delta resonance:
$p + \gamma \rightarrow \Delta \rightarrow \pi^+ \rightarrow 3\nu + \ldots$

Resonance condition:
$E_p \times E_\nu \sim 0.2\ \mathrm{GeV}^2$



Photon energy in proton rest frame

L. Morejón *et al.*, 1904.07999

Cooking up prompt neutrinos from GRBs

Energy in neutrinos $\propto$ energy in gamma rays

All the details are in the proportionality constant

Ingredients:

▸ Gamma-ray luminosity (erg s^{-1})	Measured
▸ Variability time scale (s)	Measured
▸ Shape of photon spectrum	Measured
▸ Redshift	Measured (sometimes)
▸ Bulk Lorentz factor of jet	Estimated
▸ Energy partition into *e*, *p*, magnetic field	Estimated (if not guessed)

The fine print

Energy in neutrinos $\propto$ energy in gamma rays

$$\int_0^\infty \mathrm{d}E_\nu E_\nu F_\nu(E_\nu) = \frac{1}{8}\left[1 - \left(1 - \langle x_{p\to\pi}\rangle\right)^{\tau_{p\gamma}}\right] \frac{f_p}{f_e} \int_{1\ \mathrm{keV}}^{10\ \mathrm{MeV}} \mathrm{d}E_\gamma E_\gamma F_\gamma(E_\gamma)$$

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Fraction of total p energy given to pions

Baryonic loading

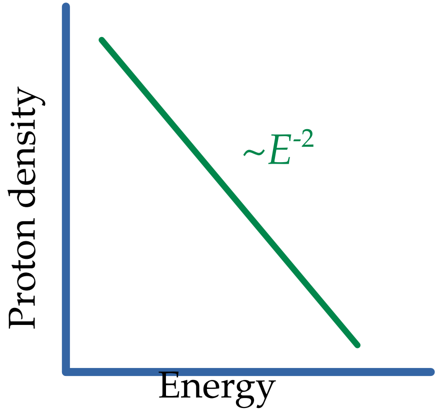
Optical depth to $p\gamma$:

$$\tau_{p\gamma} = \left(\frac{L_\gamma^{\mathrm{iso}}}{10^{52}\mathrm{erg\,s}^{-1}}\right)\left(\frac{0.01}{t_{\mathrm{v}}}\right)\left(\frac{300}{\Gamma}\right)^4\left(\frac{\mathrm{MeV}}{\epsilon_{\gamma,\mathrm{break}}}\right)$$

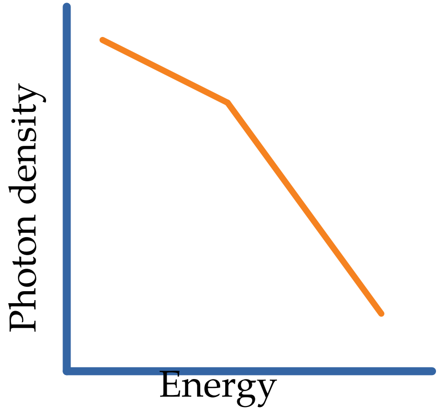
E. Waxman & J. Bahcall, *PRL* 1997
D. Guetta *et al.*, *Astropart. Phys.* 2004

The prompt neutrino fluence from one GRB

Protons



Photons



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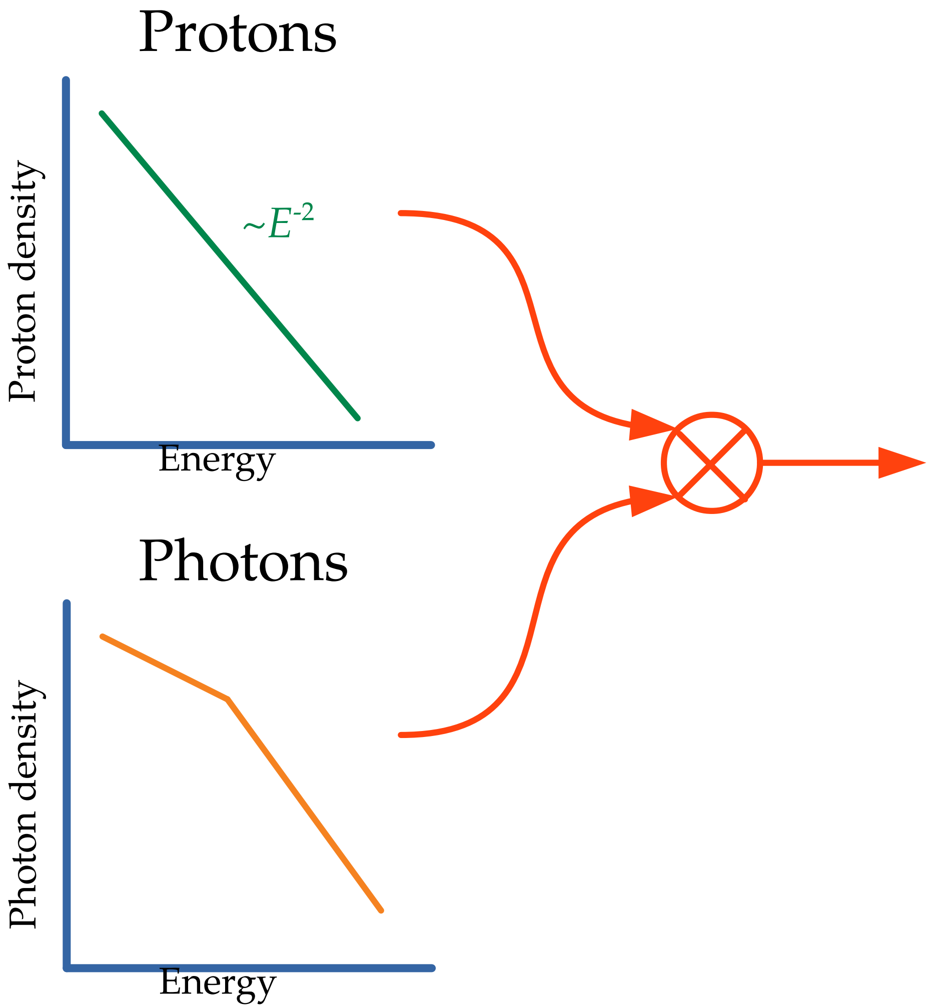

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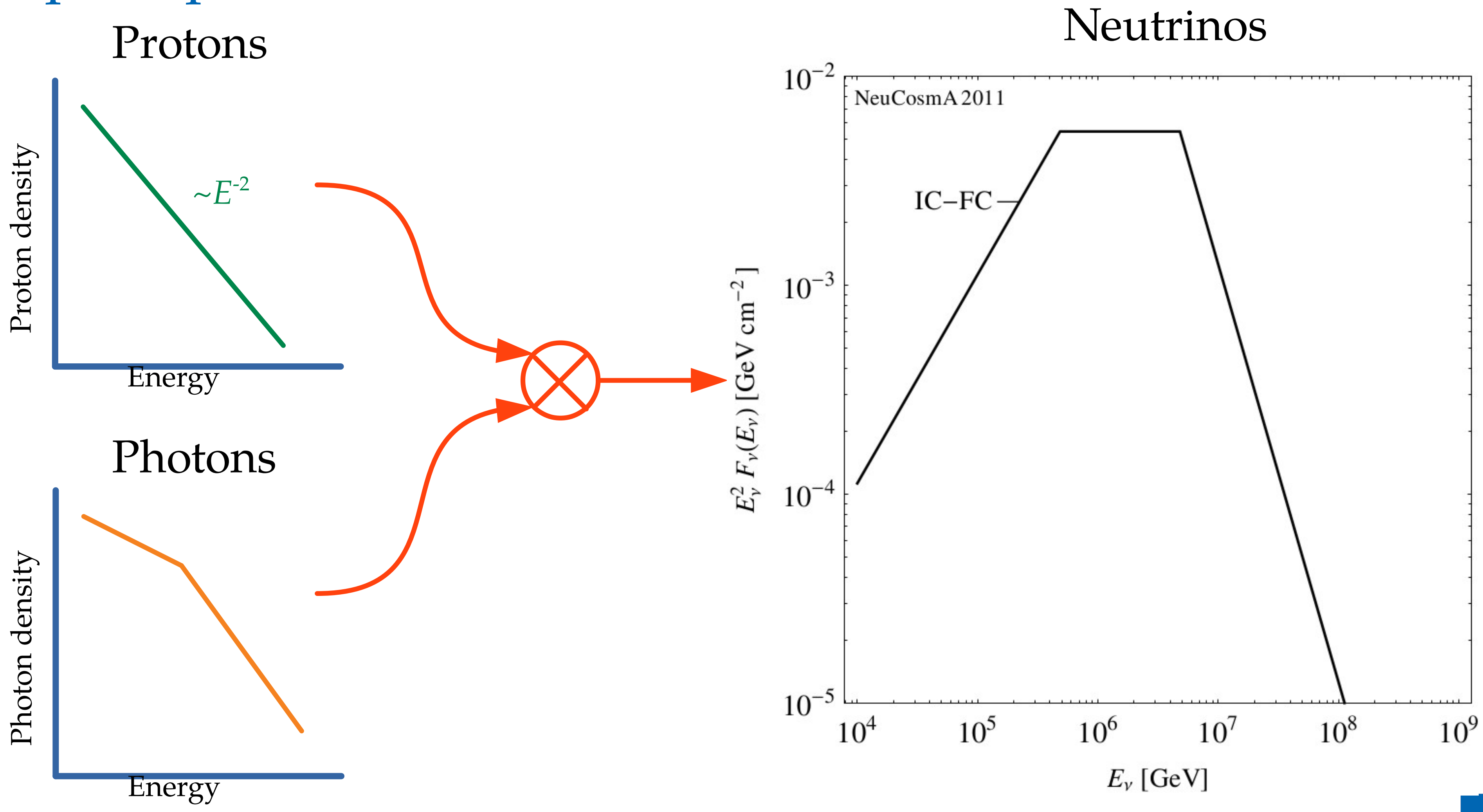

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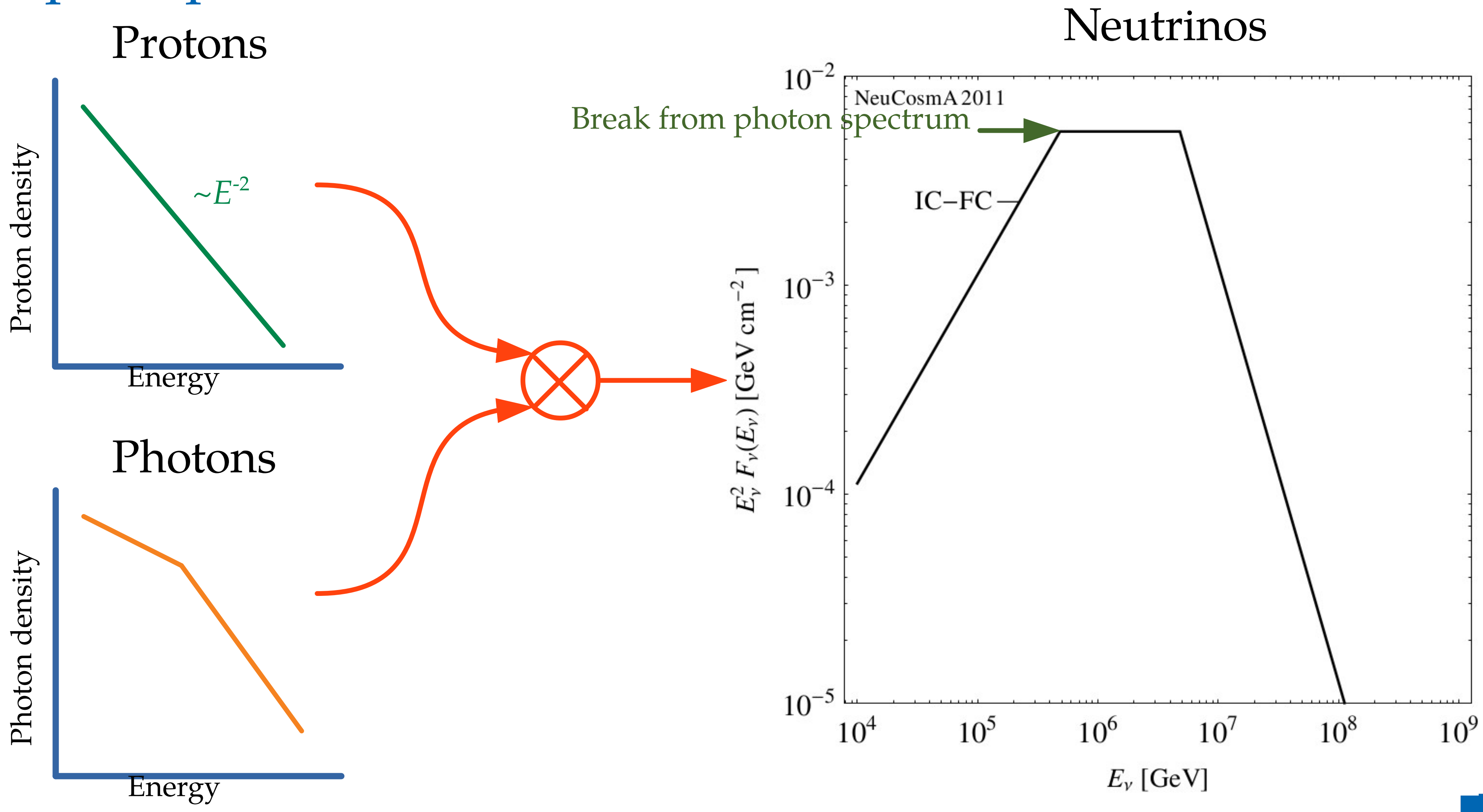

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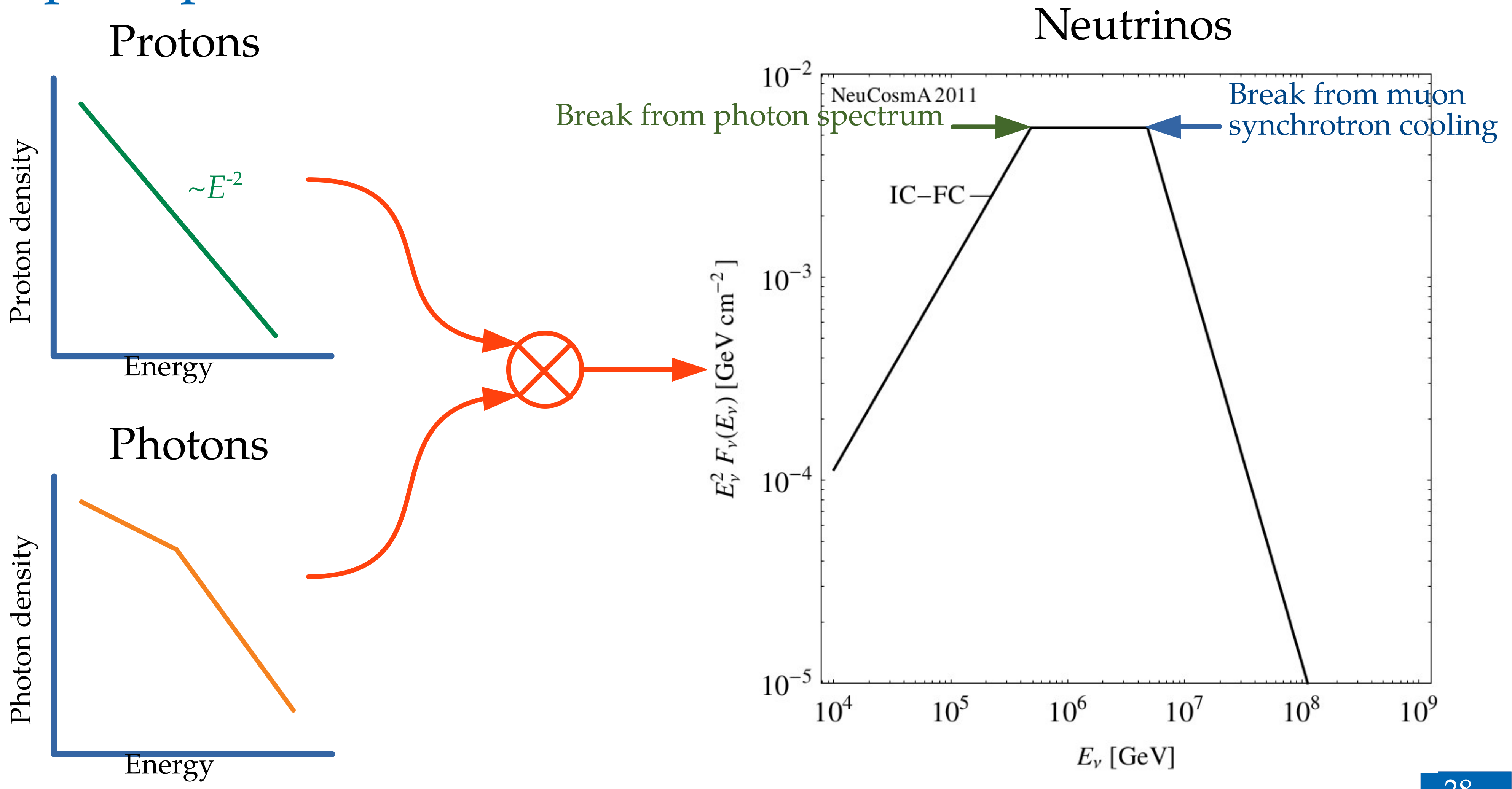


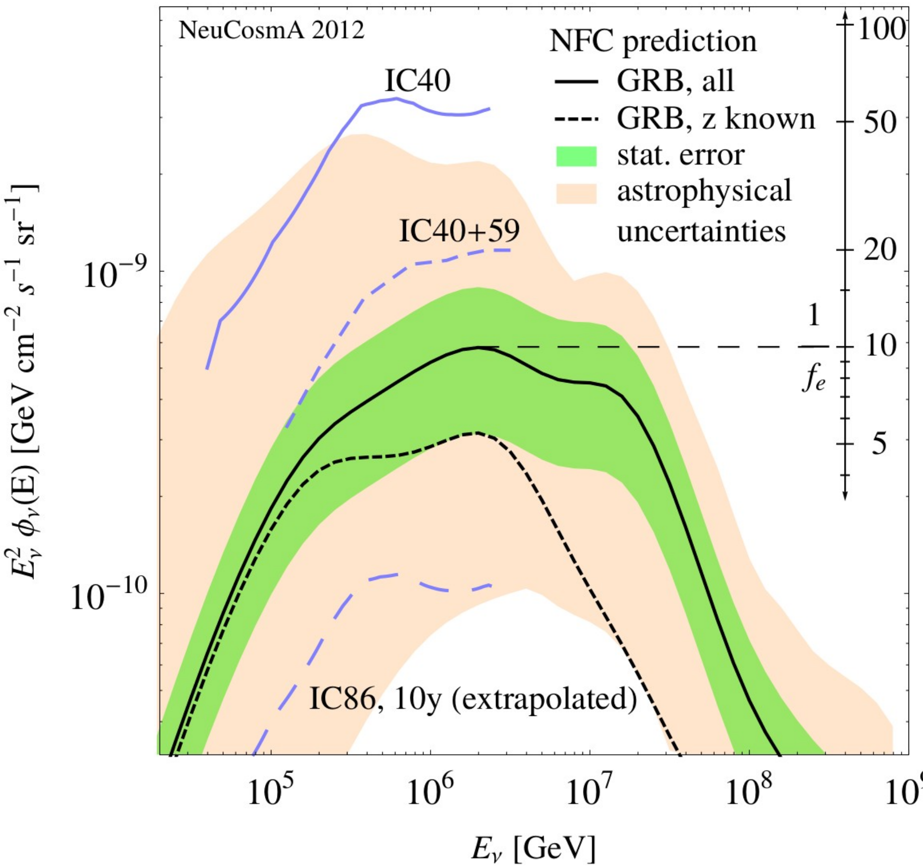
Diffuse flux of neutrinos from GRBs

- How do we estimate it?
- Compute the expected ν fluence from a sample of N_{obs} observed GRBs
- Stack the fluences to obtain the total F_ν
- Quasi diffuse flux:

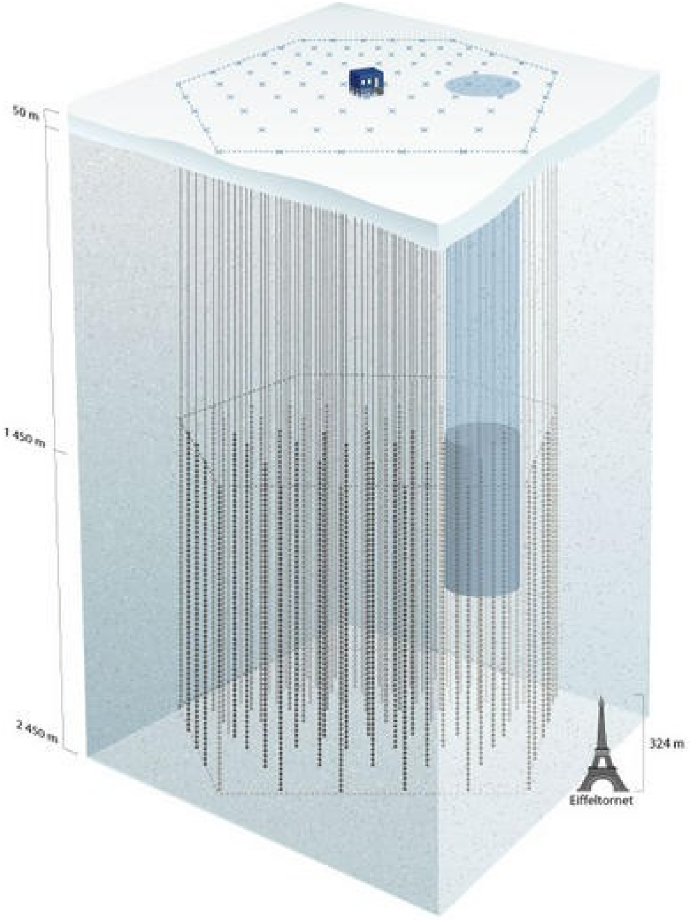
$$\phi_\nu(E_\nu) = F_\nu(E_\nu)\,\frac{1}{4\pi}\,\frac{1}{N_{\mathrm{obs}}}\,\frac{667\ \mathrm{bursts}}{\mathrm{yr}}$$

($N_{\mathrm{obs}} = 117$ in the plot)

S. Hümmer, P. Baerwald, & W. Winter, *PRL* 2012



IceCube – What is it?



- Km^3 in-ice Cherenkov detector in Antarctica
- >5000 PMTs at 1.5–2.5 km of depth
- Sensitive to neutrino energies > 10 GeV

How does IceCube see neutrinos?

Two types of fundamental interactions …

Charged-current (CC)

$\nu_l + N \to l + \text{hadrons}$

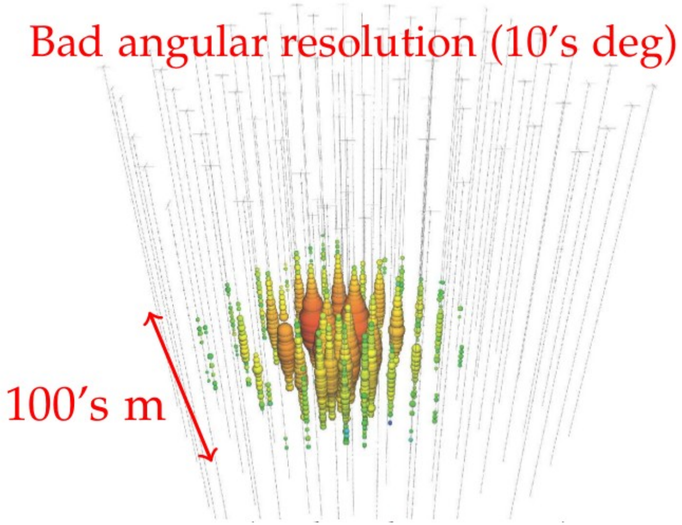
Neutral-current (NC)

$\nu_l + N \to \nu_l + \text{hadrons}$

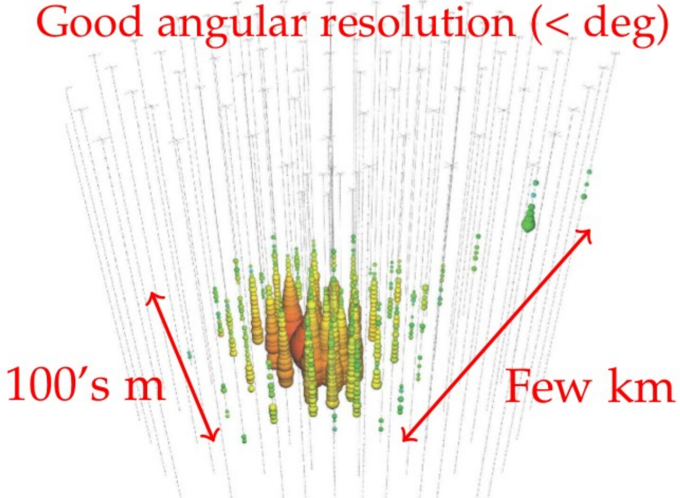
These shower and make light

… create two event topologies …

Showers — From CC ν_e or ν_τ, or NC ν_x



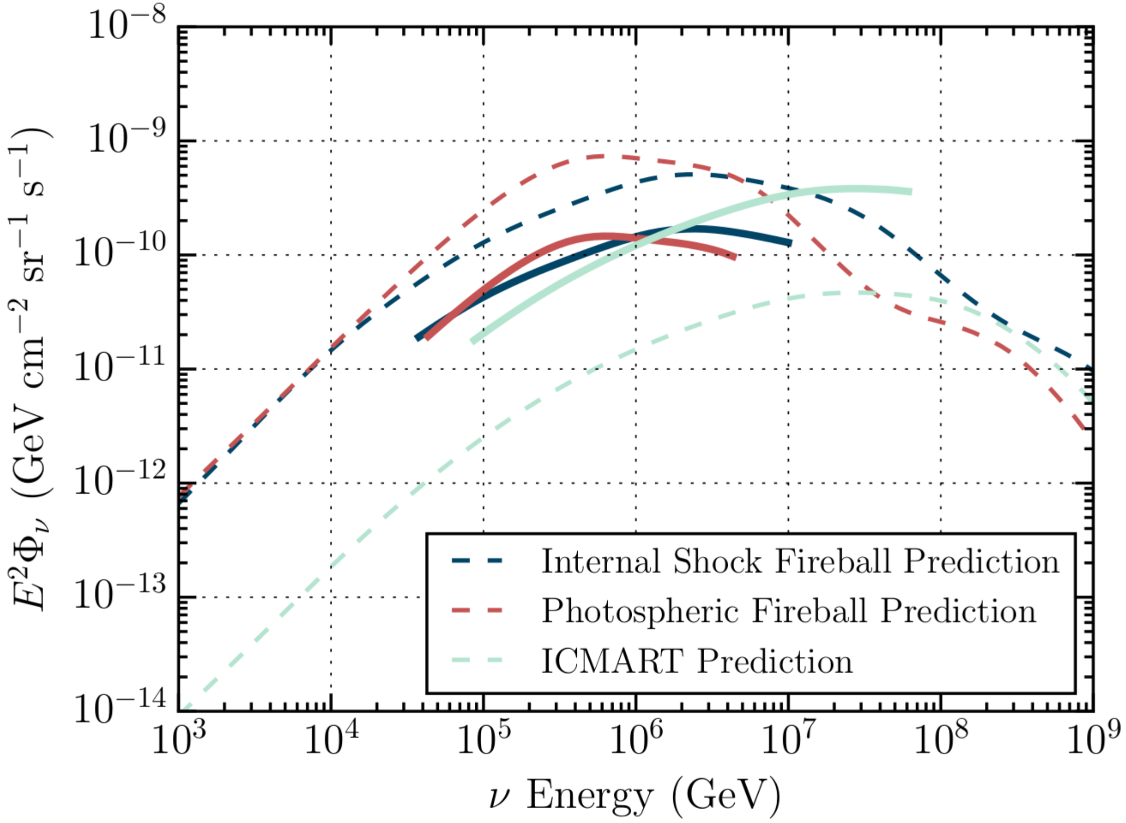
Tracks — From CC ν_μ mainly



Prompt GRB neutrino limits

- Catalog of 1172 GRBs
- No correlation found
- < 1% of the IceCube TeV–PeV flux is from (*bright*) GRBs
- What does this tell us?
  - Bright GRBs unlikely hadronic accelerators
  - More complex particle production models are needed
  - Consider low-luminosity or dark bursts

Dashed: quasi-diffuse flux prediction
Solid: 90% C.L. upper limit



IceCube Collab., *ApJ* 2017

So… why do we still look for neutrinos from GRBs?

1. They are arguably the best candidates for joint e.m.-neutrino emission
2. They are potential sources of UHE cosmic rays (more on this later)

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3. "Choked" GRBs might contribute sizeably to the TeV–PeV diffuse ν flux

E.g., P. Meszaros & E. Waxman, *PRL* 2001; I. Tamborra & S. Ando, *JCAP* 2015; N. Senno, K. Murase, & P. Meszaros, *PRD* 2016

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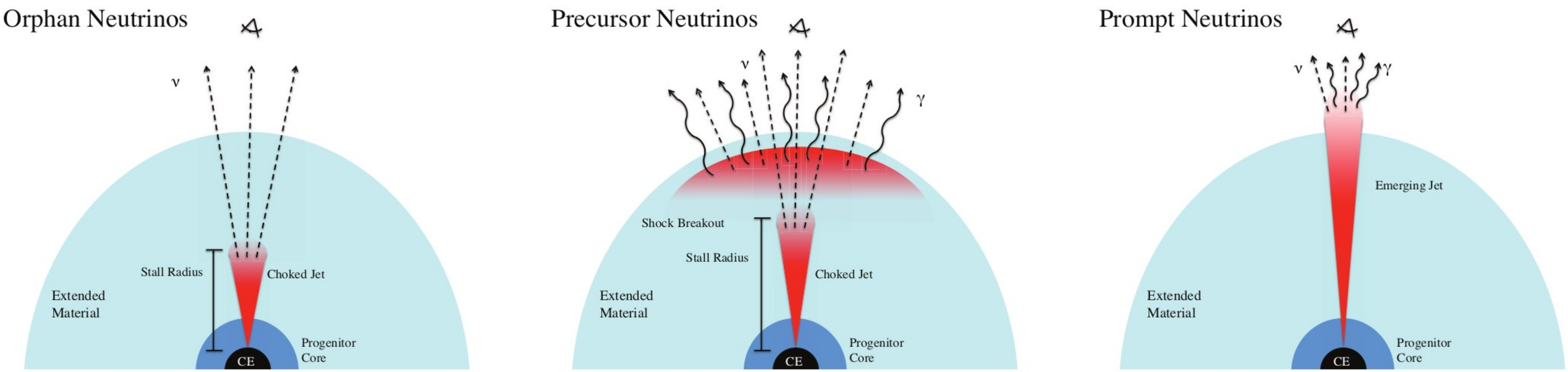
4. Neutrinos from GRB afterglows are expected at EeV

   E.g., K. Murase, *PRD* 2007; S. Horiuchi & S. Ando, *PRD* 2008; S. Razzaque & L. Yang, *PRD* 2015

Low-luminosity and dark GRBs

In jetted supernovae, the jet might be choked —



N. Senno, K. Murase, & P. Meszaros, *PRD* 2016

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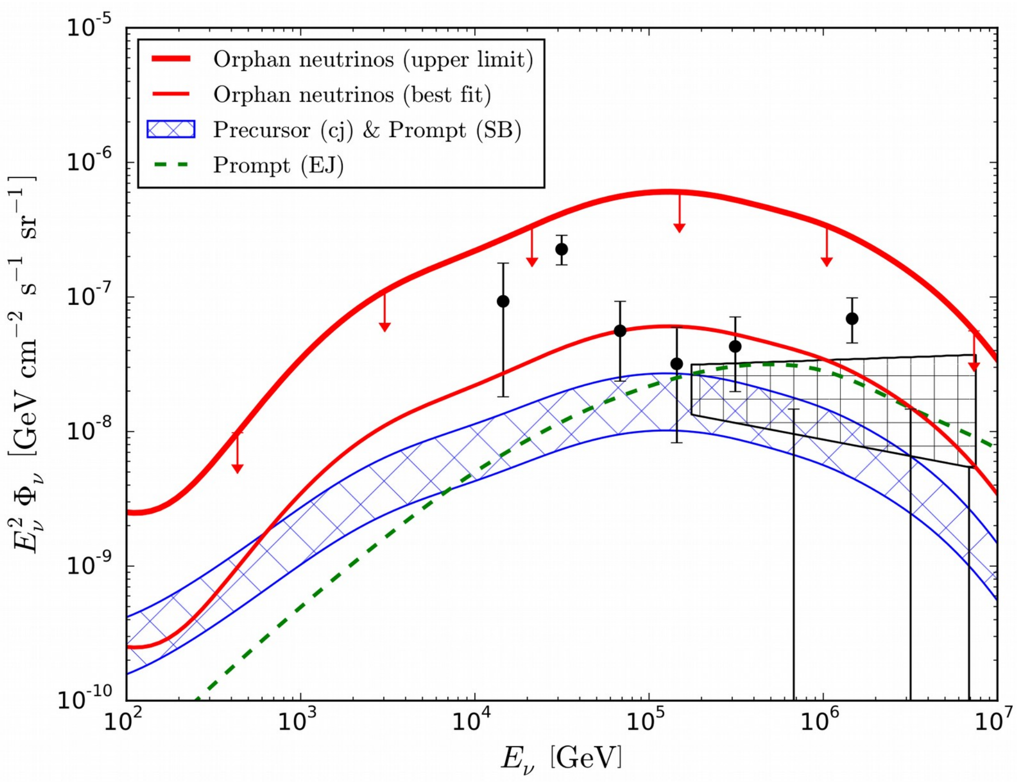

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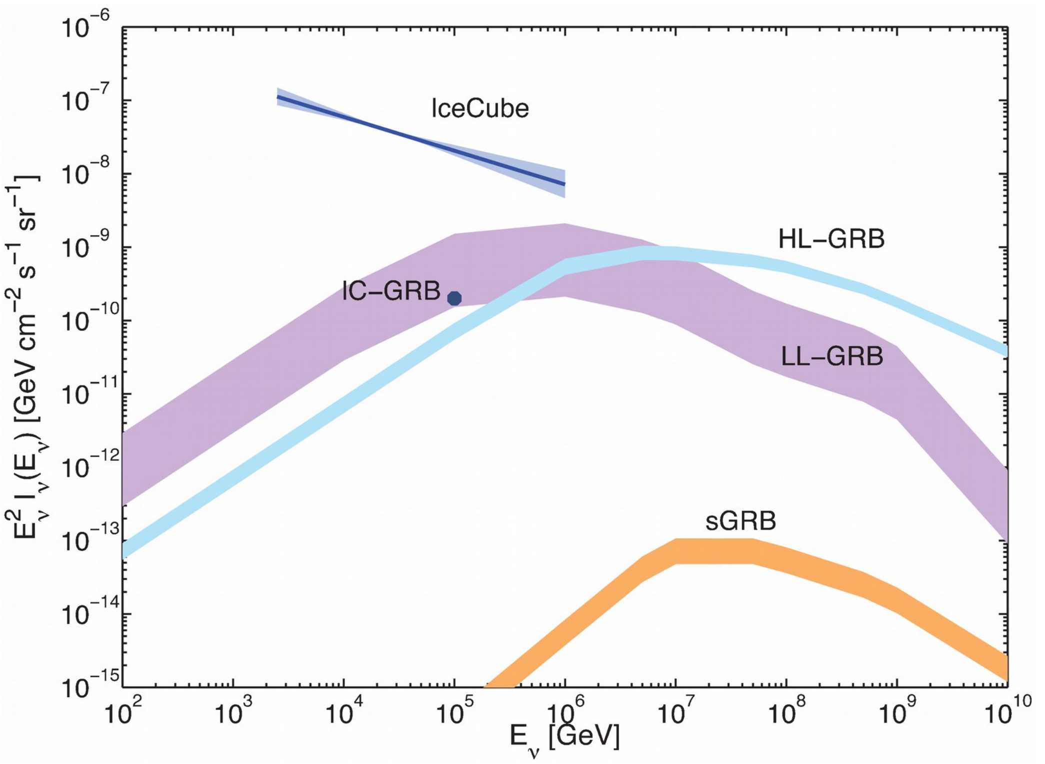
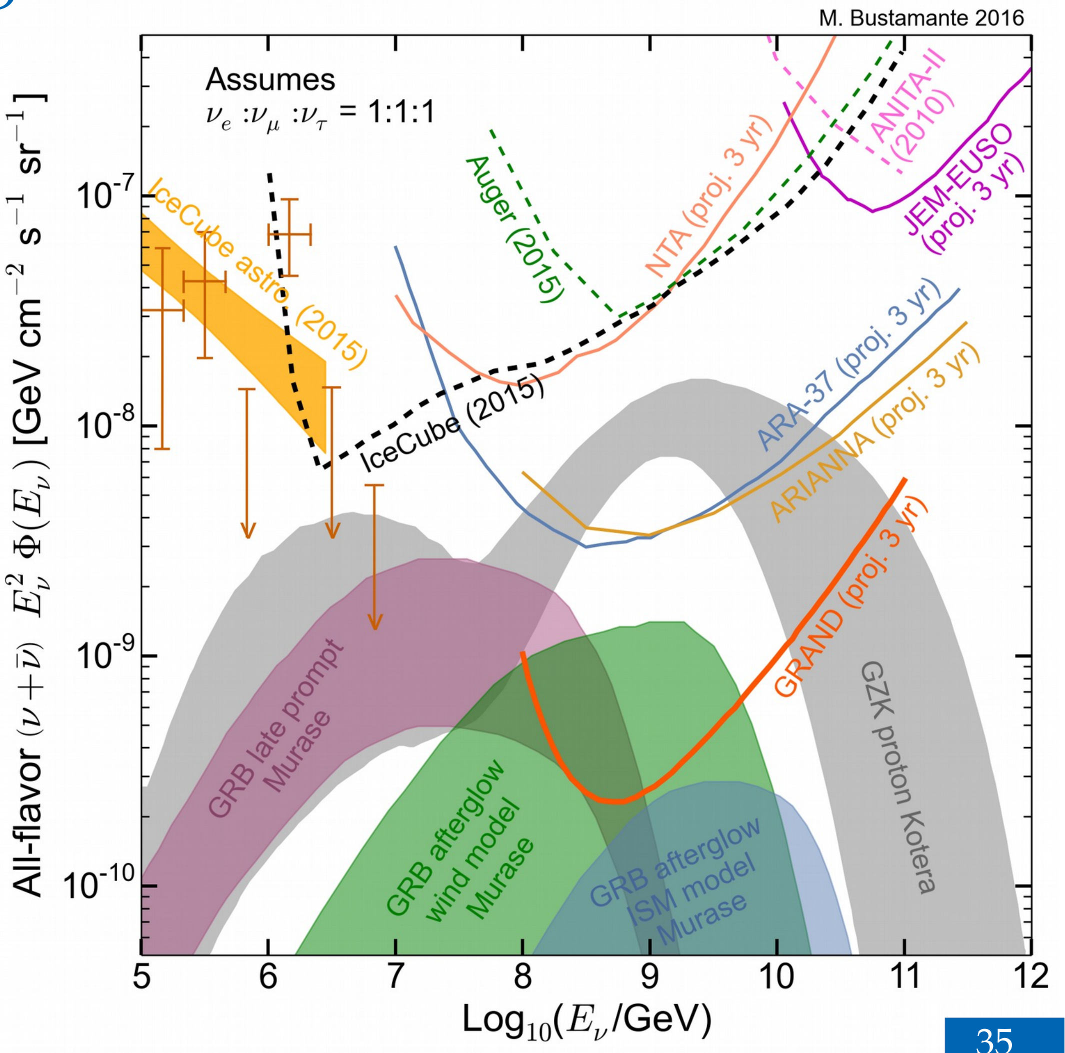


I. Tamborra & S. Ando, *JCAP* 2015

EeV neutrinos from GRB afterglows

- Neutrinos from $p\gamma$ interactions when the jet hits the ISM
- Lower-energy photons need higher-energy protons
- Neutrino flux peaks at ~EeV
- Probably need next-gen detectors to discover



Ultra-high-energy cosmic rays — The "neutron model"

$$p + \gamma_{\text{target}} \to \Delta^+ \to \begin{cases} p + \pi^0, & \text{Br} = 2/3 \\ n + \pi^+, & \text{Br} = 1/3 \end{cases}$$

$$\pi^0 \to \gamma + \gamma$$

$$\pi^+ \to \mu^+ + \nu_\mu \to \bar{\nu}_\mu + e^+ + \nu_e + \nu_\mu$$

$$n \text{ (escapes)} \to p + e^- + \bar{\nu}_e$$

Implicit assumptions:

- Protons are perfectly confined in the sources
- All protons interact in the sources and make neutrinos

After propagation to Earth, with flavor mixing, we expected

$\nu_e:\nu_\mu:\nu_\tau:p = 1:1:1:1$ ("one ν_μ per cosmic ray")

… but we found far fewer neutrinos

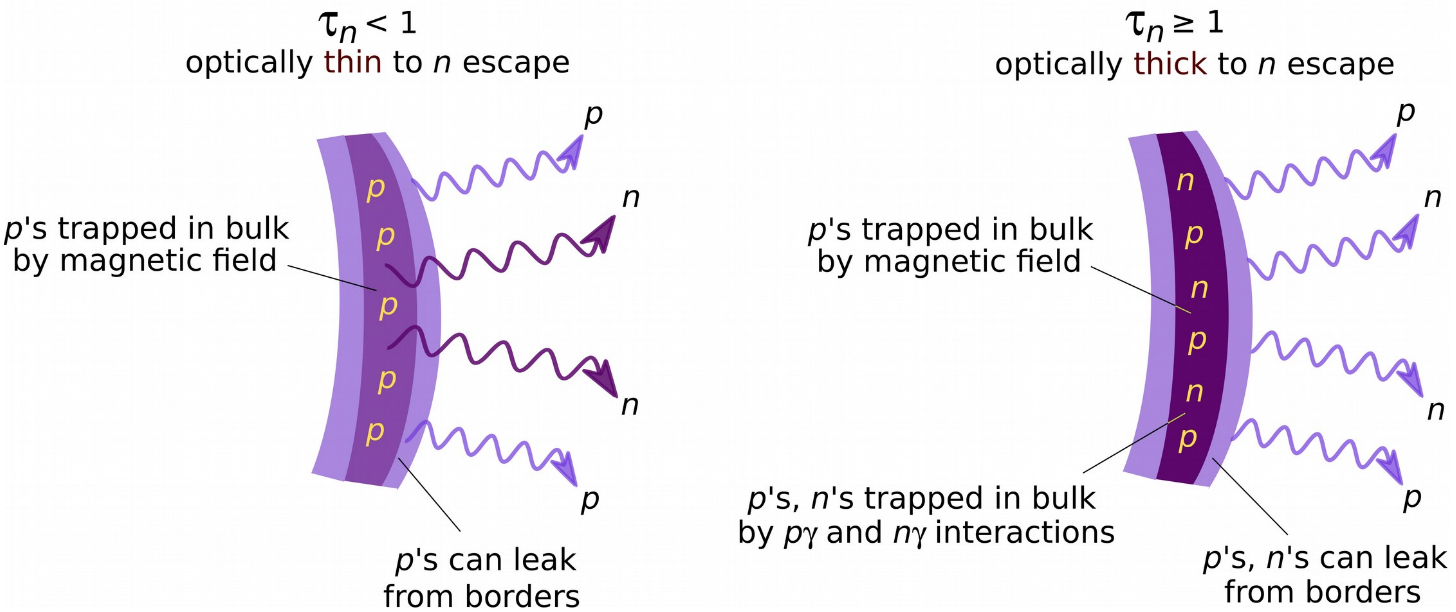
IceCube Collab., *Nature* 2012
M. Ahlers *et al.*, *Astropart. Phys.* 2011

UHECRs — Beyond the neutron model

Allow UHECRs to escape as either

- Neutrons, which decay into protons outside the source; or
- Protons that leak out without interacting in the source

Relative contribution determined by optical depth to $n\gamma$ interactions



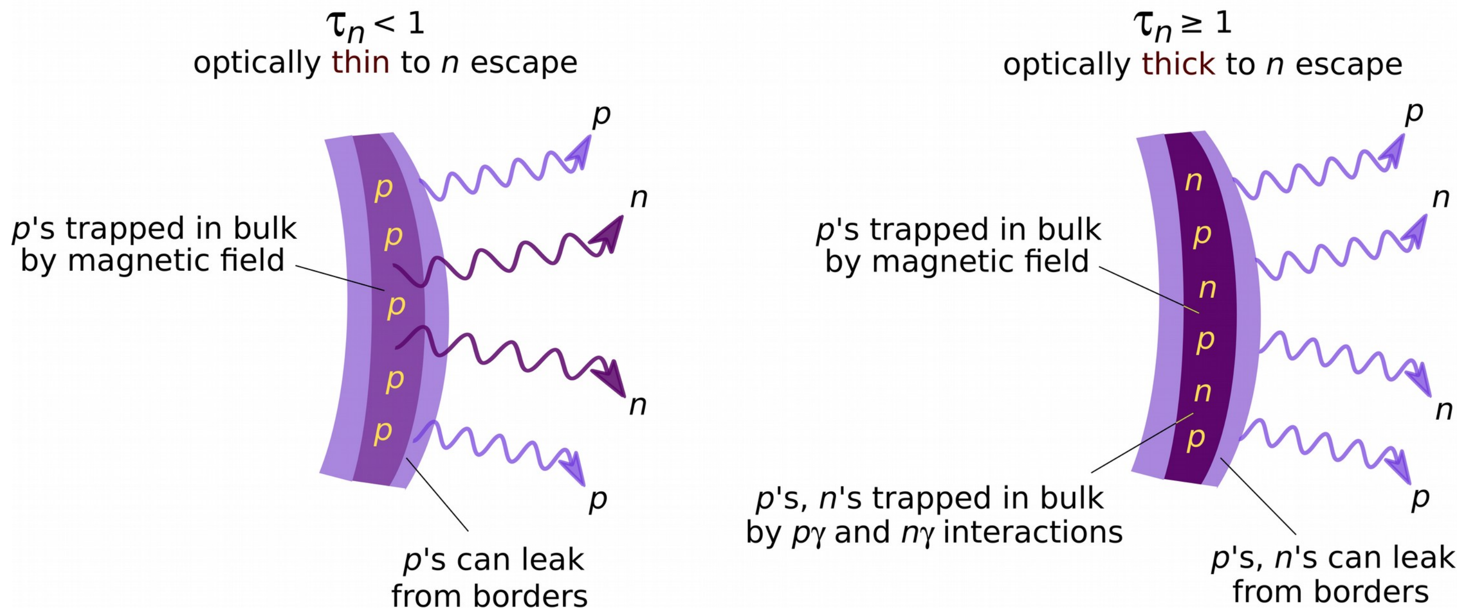
P. Baerwald, **MB**, & W Winter, *ApJ* 2013

UHECRs — Beyond the neutron model

Allow UHECRs to escape as either

- **Neutrons**, which decay into protons outside the source; or ← Neutrinos are made
- **Protons** that leak out without interacting in the source ← Neutrinos are *not* made

Relative contribution determined by optical depth to $n\gamma$ interactions

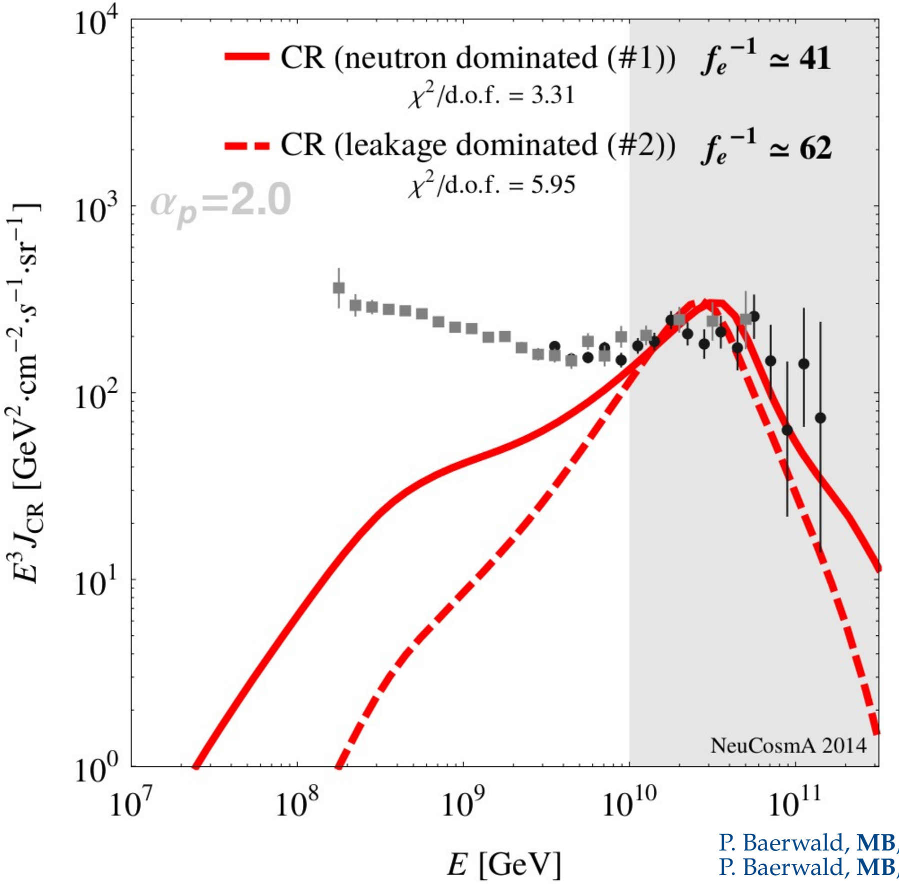


P. Baerwald, **MB**, & W Winter, *ApJ* 2013

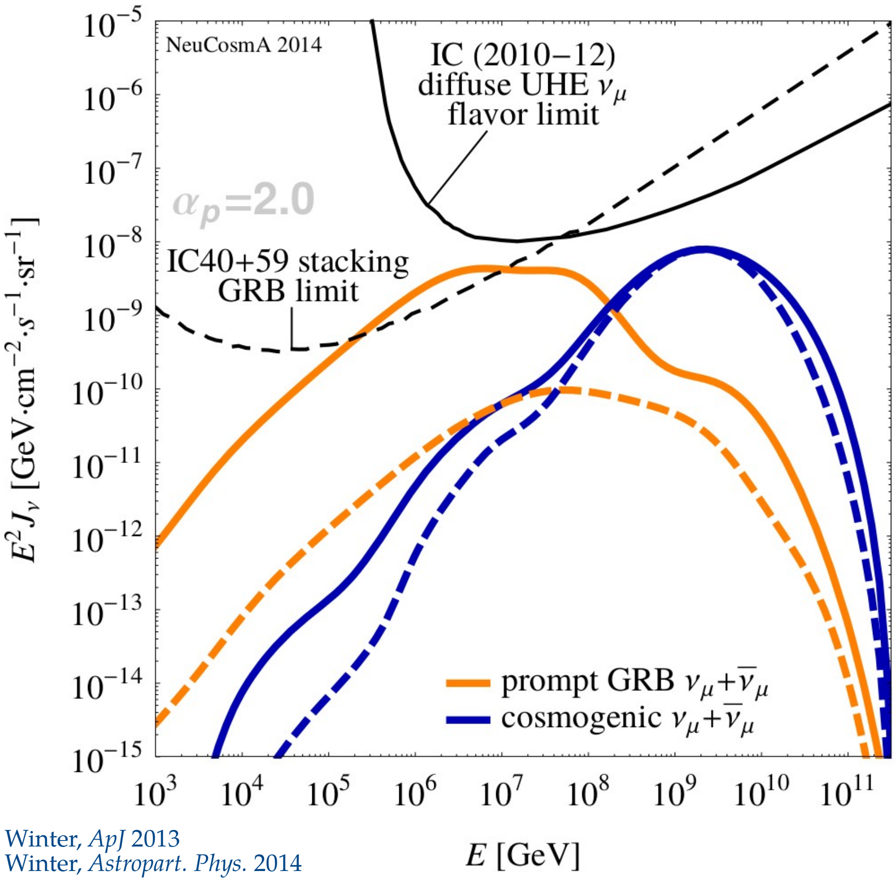
Diffuse GRB UHECR and neutrino fluxes at Earth

Neutron model *vs.* two-component model: prompt and cosmogenic neutrinos

Cosmic rays



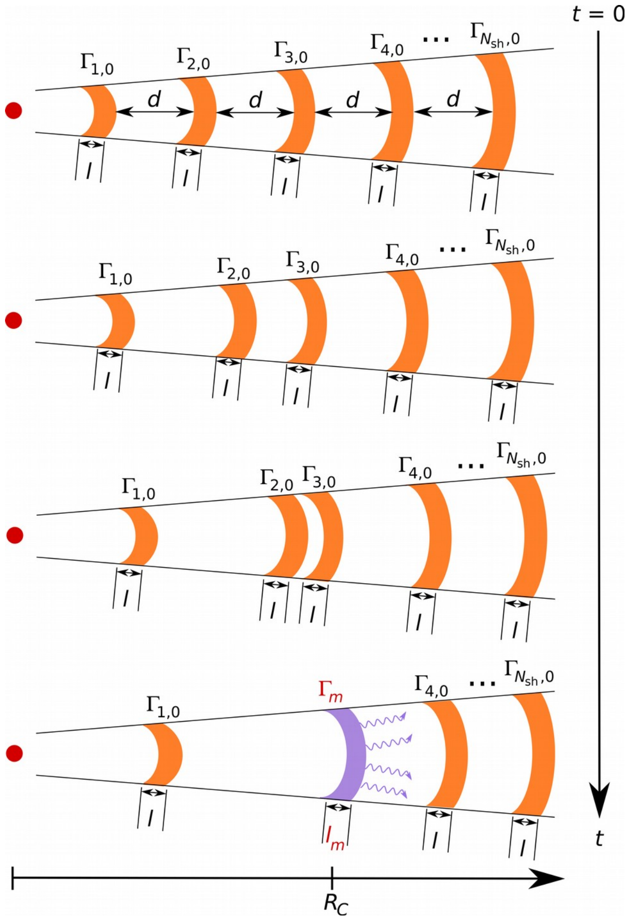
Neutrinos



P. Baerwald, **MB**, & W Winter, *ApJ* 2013
P. Baerwald, **MB**, & W Winter, *Astropart. Phys.* 2014

Emission from an evolving fireball

Simulate multiple, distinct internal collisions and their particle emission —



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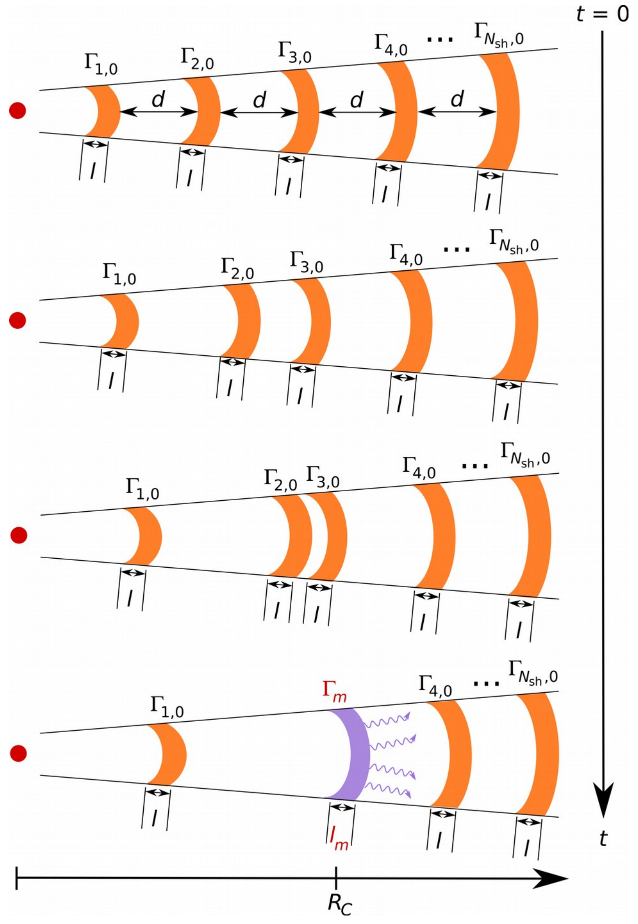

~1000 collisions

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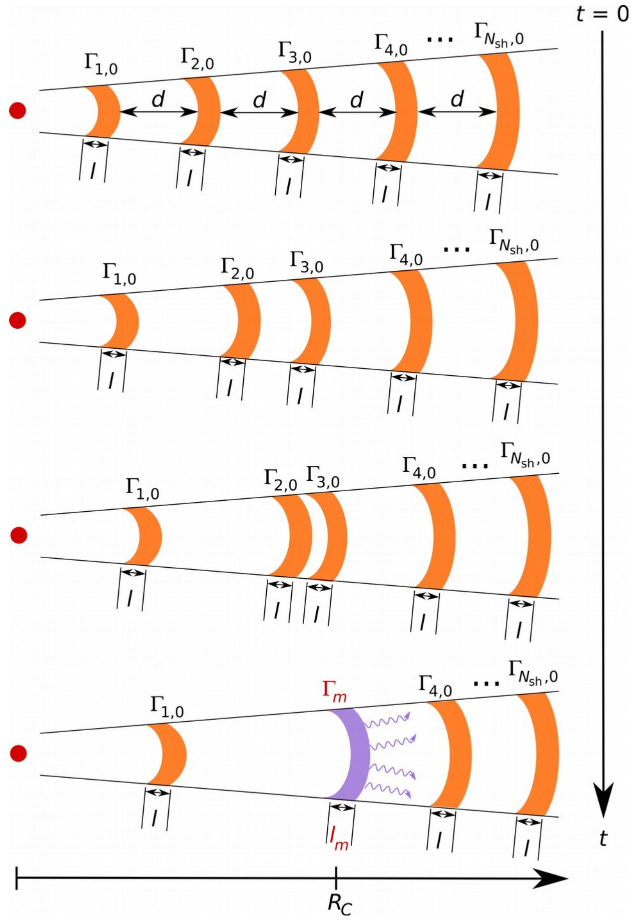
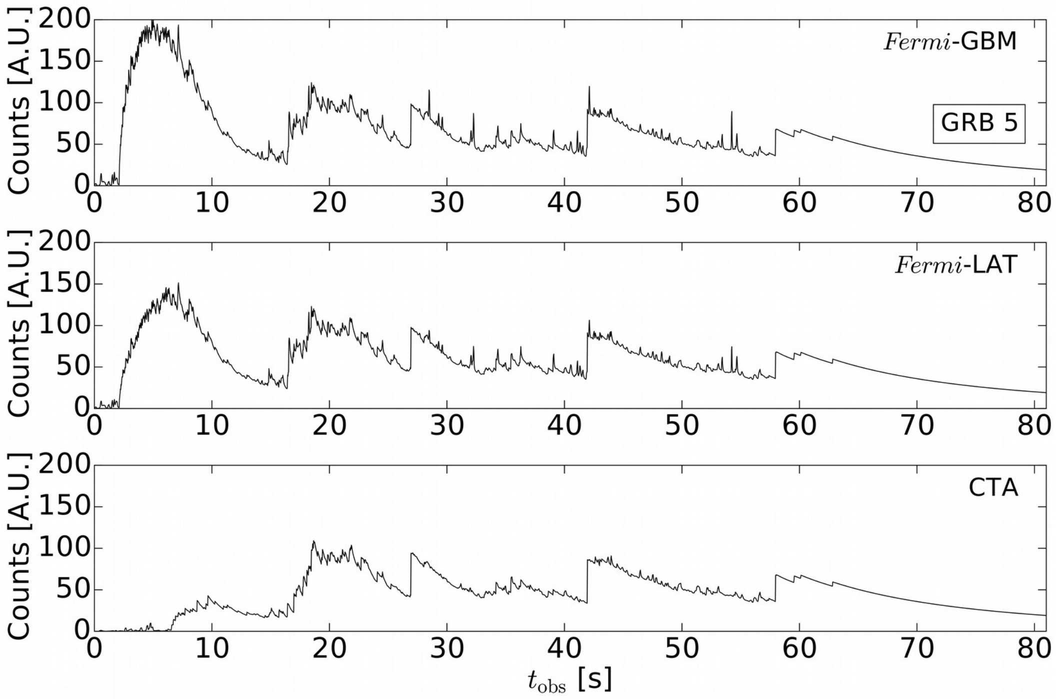


~1000 collisions

Synthetic light curves



MB *et al.*, *ApJ* 2017
MB, P. Baerwald, & W Winter, *Nature Commun.* 2015

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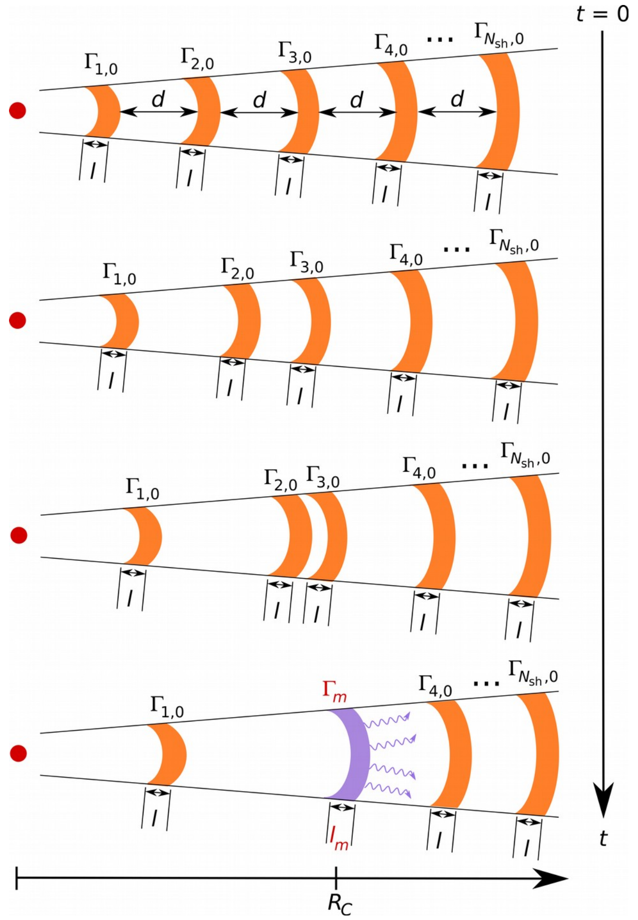

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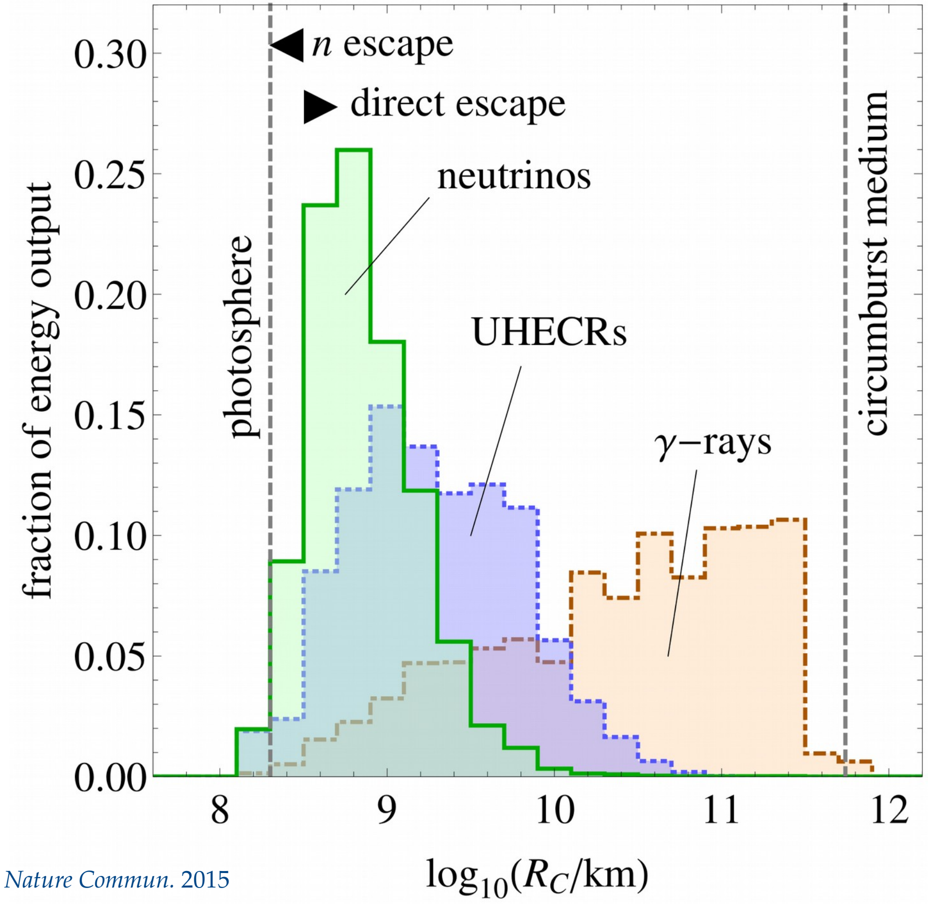

MB *et al.*, *ApJ* 2017
MB, P. Baerwald, & W Winter, *Nature Commun.* 2015

Are GRBs still good UHECR source candidates?

- High-luminosity bursts: Not so much
- Low-luminosity bursts: Yes!

	HL GRBs	LL GRBs
Luminosity (erg s^{-1})	$> 10^{49}$	$< 10^{49}$
Rate (Gpc^{-3} yr^{-1})	1	300 (predicted)
Survival of heavy nuclei in jet?	Unlikely	Likely
Can explain IceCube ν?	No	Yes

D. Boncioli, D. Biehl, & W. Winter, *ApJ* 2019; B.T. Zhang *et al.*, *PRD* 2018

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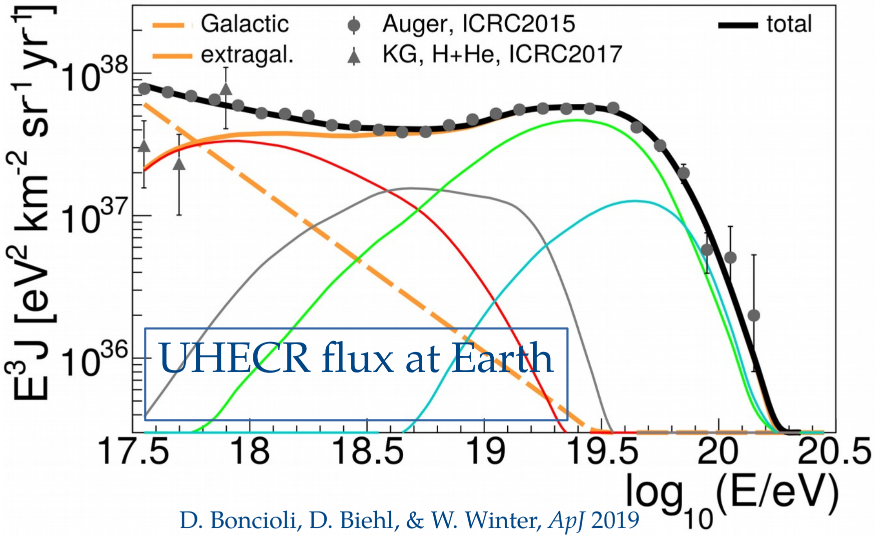

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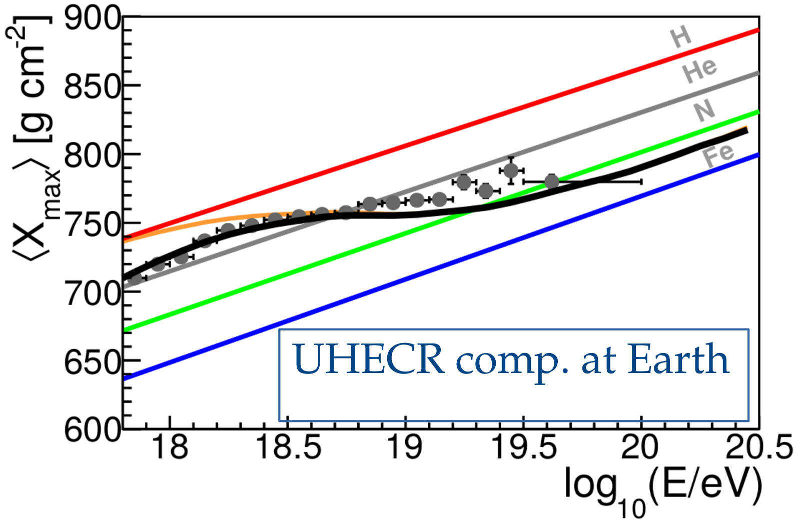

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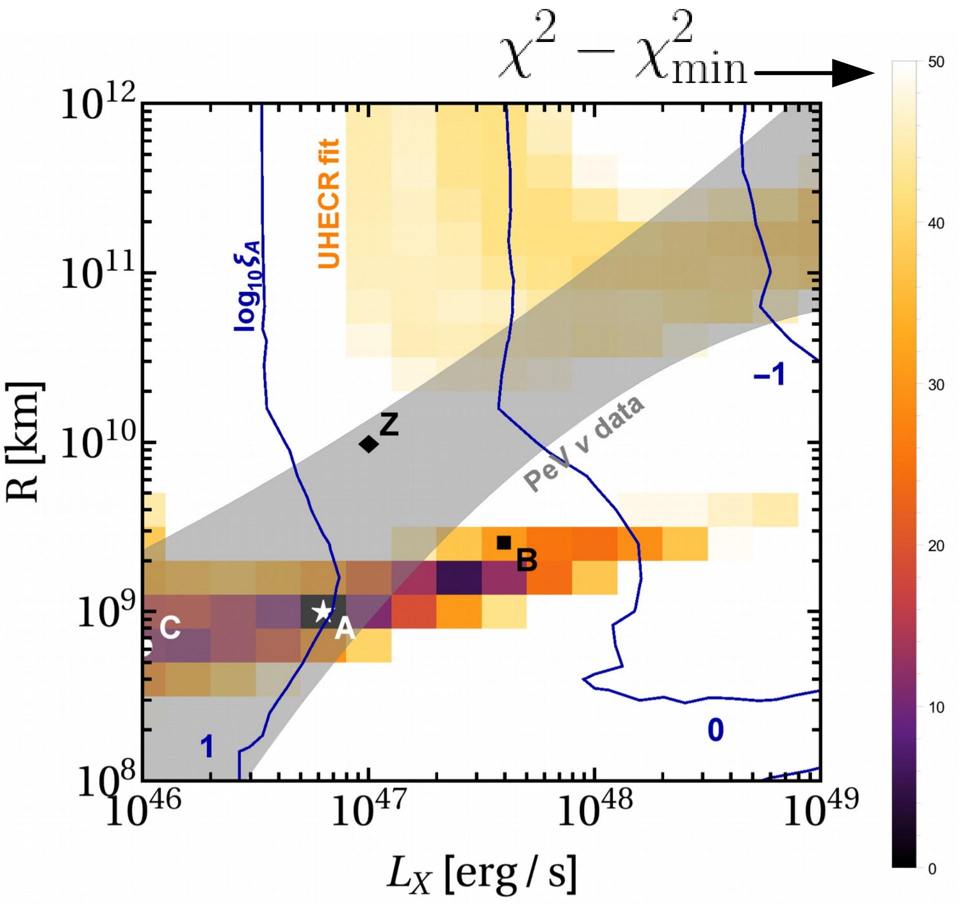
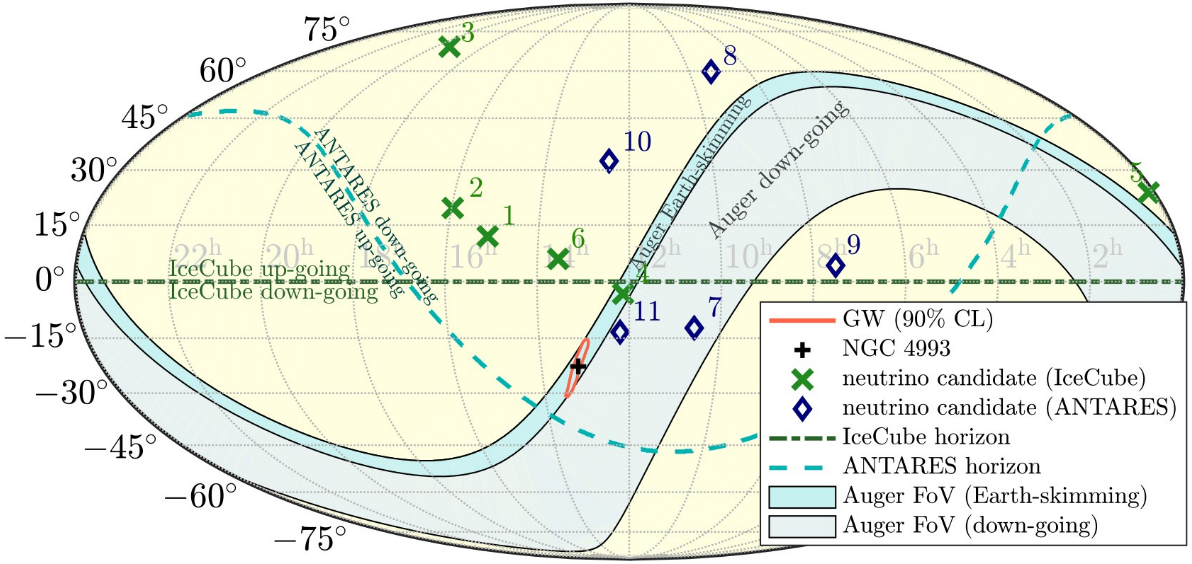
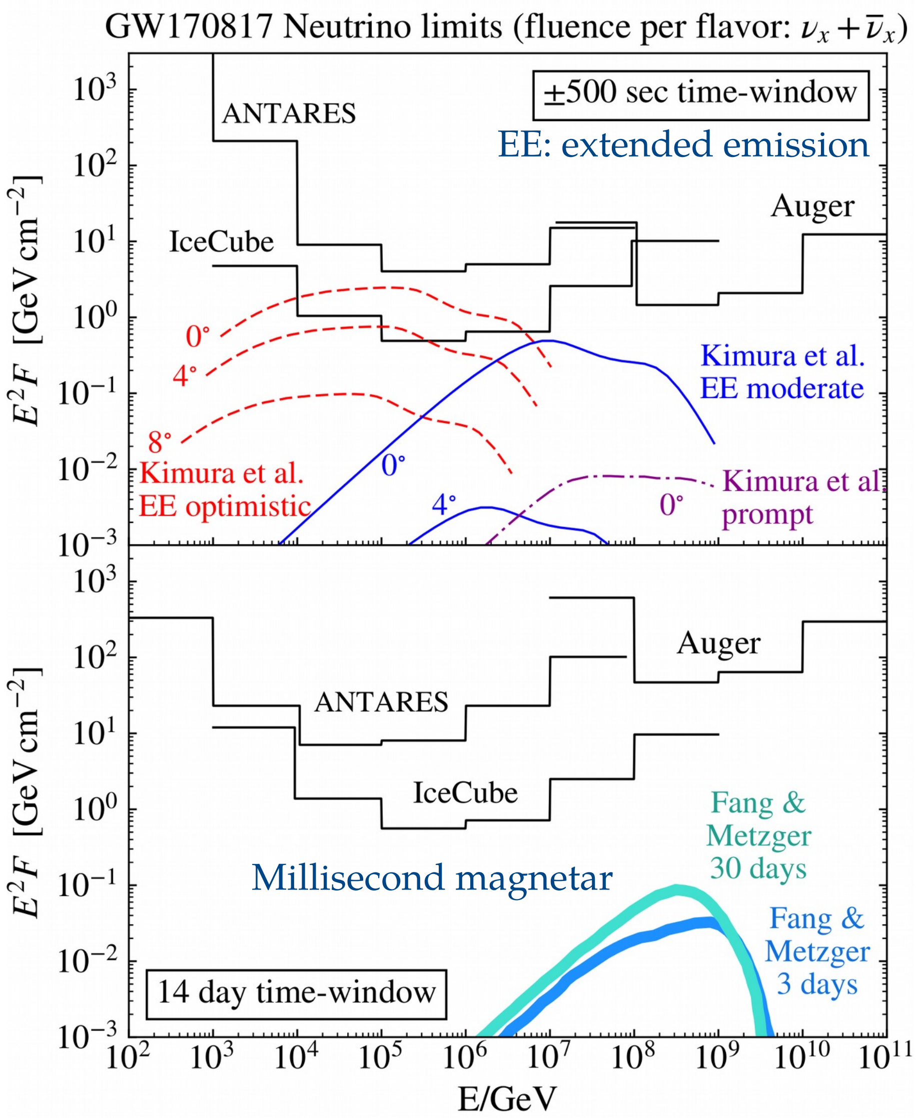


D. Boncioli, D. Biehl, & W. Winter, *ApJ* 2019; B.T. Zhang *et al.*, *PRD* 2018

GW170817 (NS-NS merger)

- Short GRB seen in *Fermi*-GBM, INTEGRAL
- Neutrino search by IceCube, ANTARES, and Auger
- MeV–EeV neutrinos, 14-day window
- Non-detection consistent with off-axis





ANTARES, IceCube, Pierre Auger Collab., *ApJL* 2017

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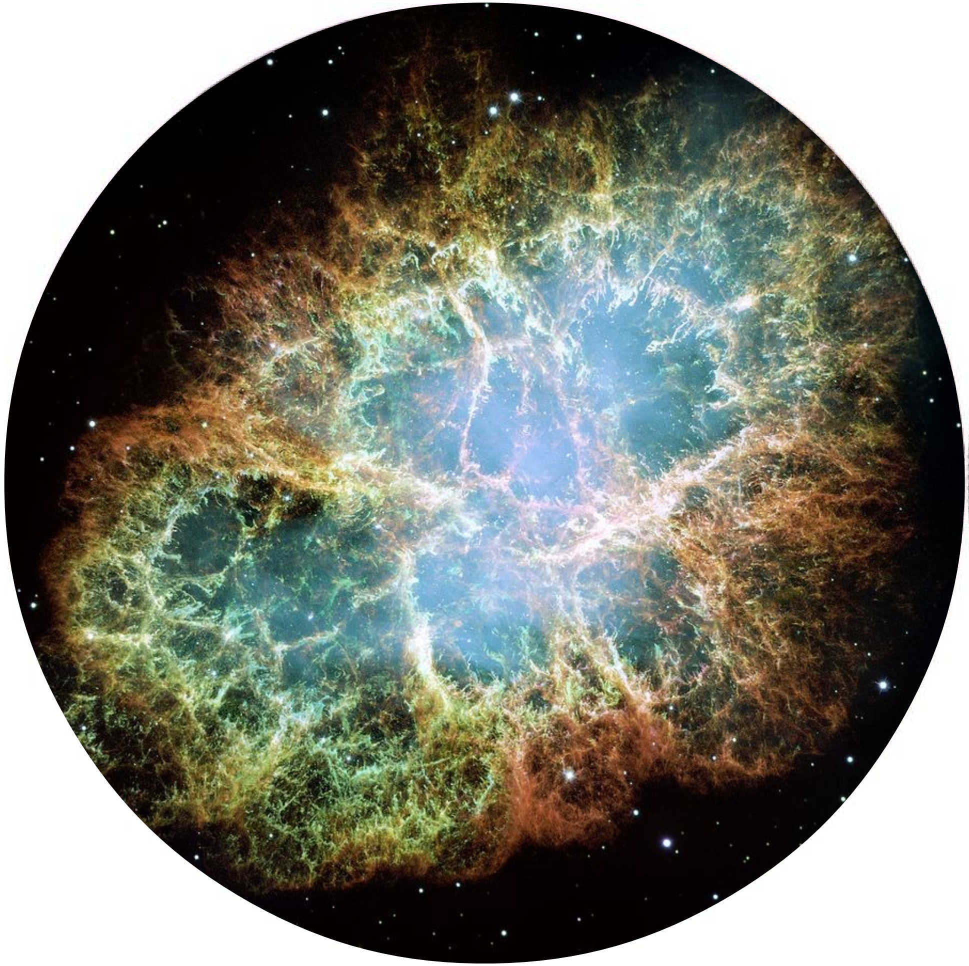

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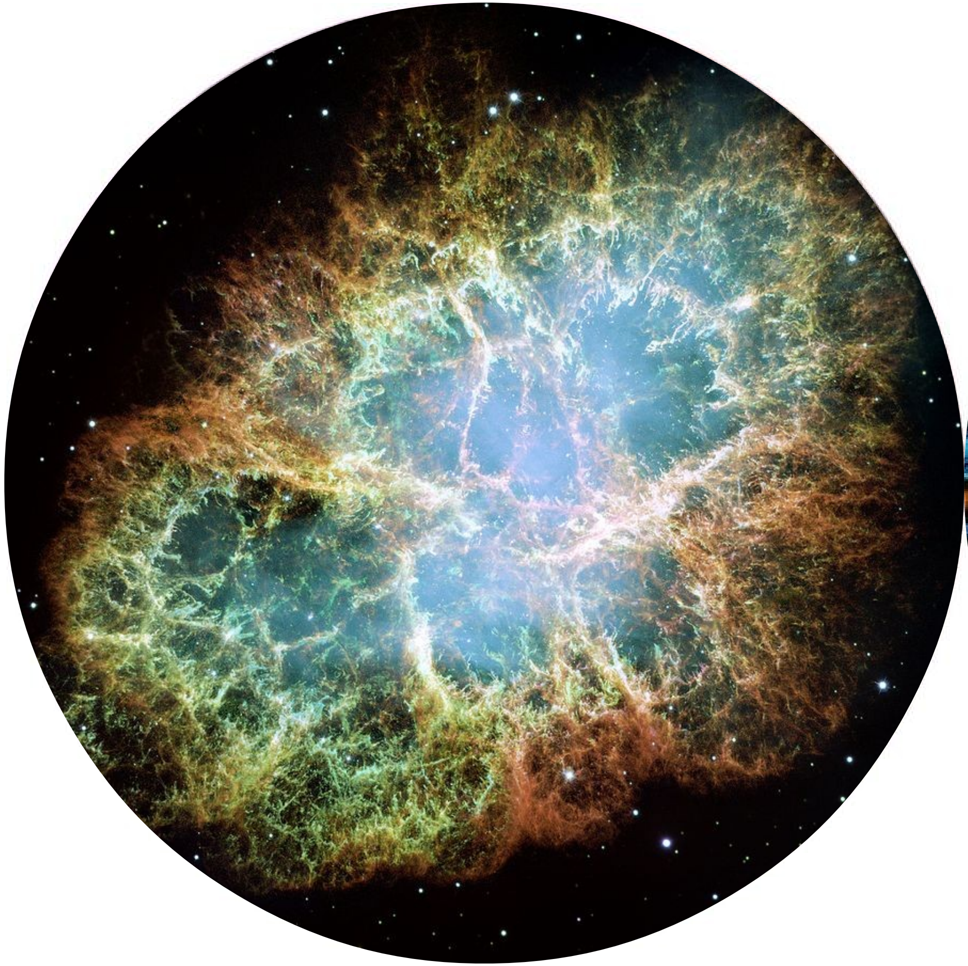

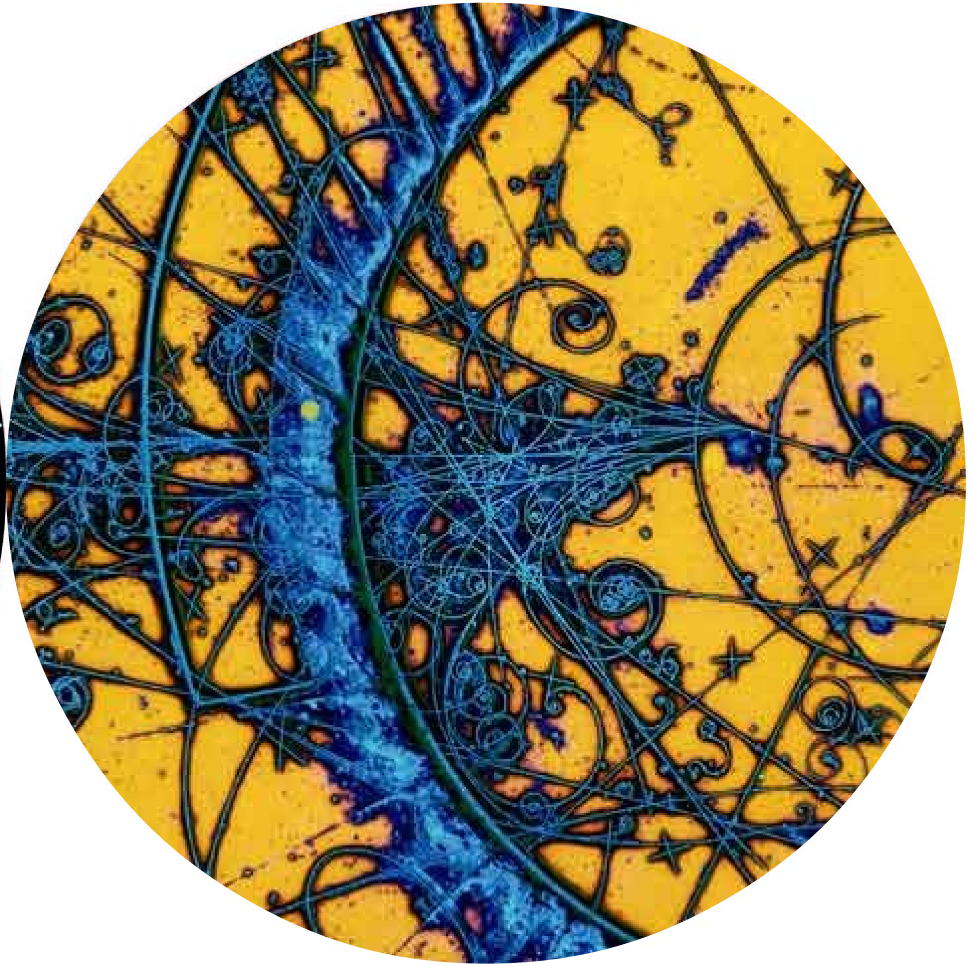

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Why study fundamental physics with GRBs?

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   ↦ Probe physics at new energy scales

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3. It comes *for free*

Open questions

Difficulty / payoff

Easy

- Are there two or three GRB populations?

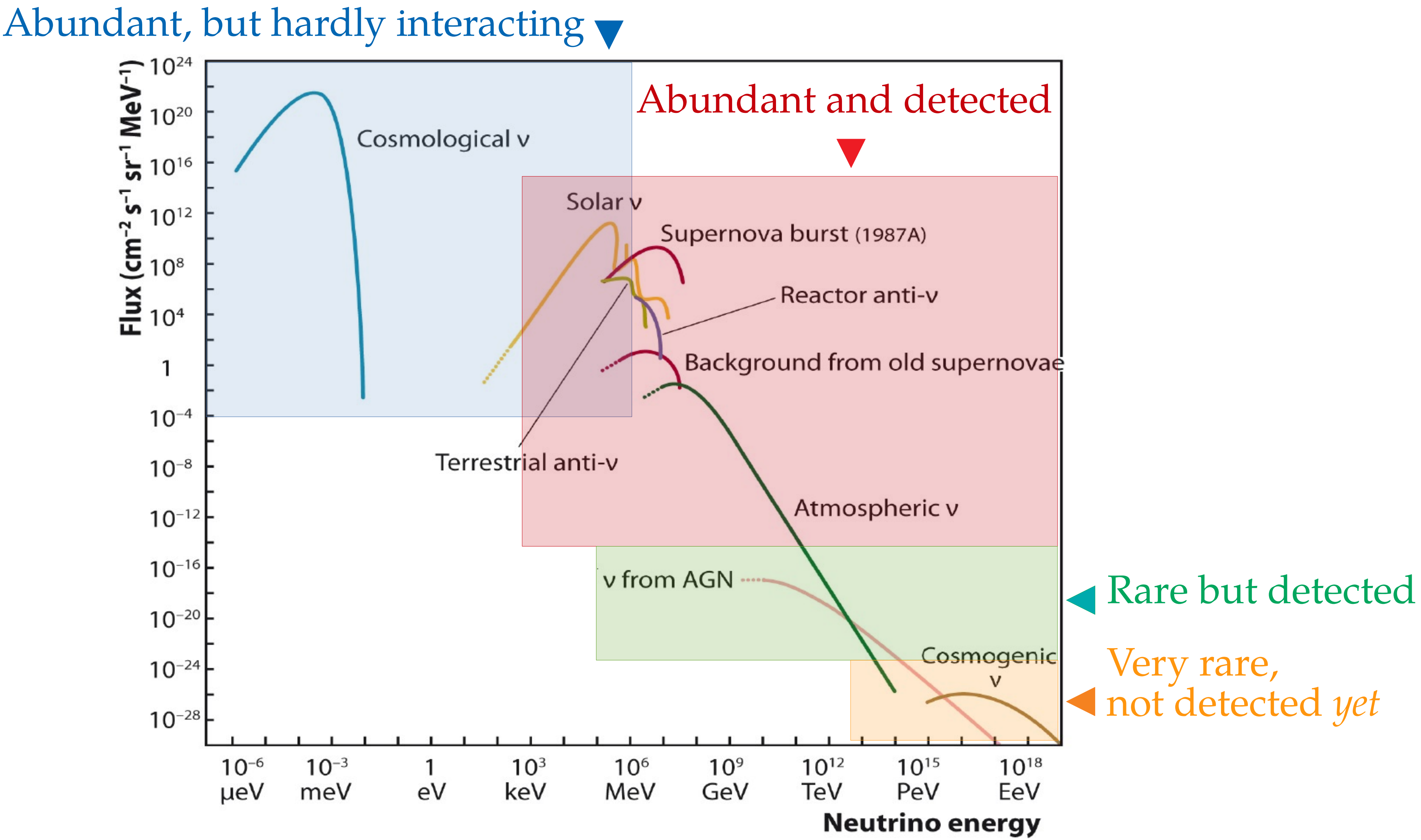
Medium

- How does the jet opening angle & direction affect our observations?
- Mass composition of the jet? How does it affect emission?
- Are jets structured?

Hard

- Can *e* synchrotron radiation explain the gamma-ray emission?
- Are GRBs – of any kind – high-energy hadronic accelerators?
- How are charged particles accelerated?
- Discovering dark bursts

Backup slides



Abundant, but hardly interacting
Abundant and detected
Rare but detected
Very rare,
not detected *yet*
Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Cosmogenic ν
10⁻⁶ μeV
10⁻³ meV
1 eV
10³ keV
10⁶ MeV
10⁹ GeV
10¹² TeV
10¹⁵ PeV
10¹⁸ EeV
Neutrino energy

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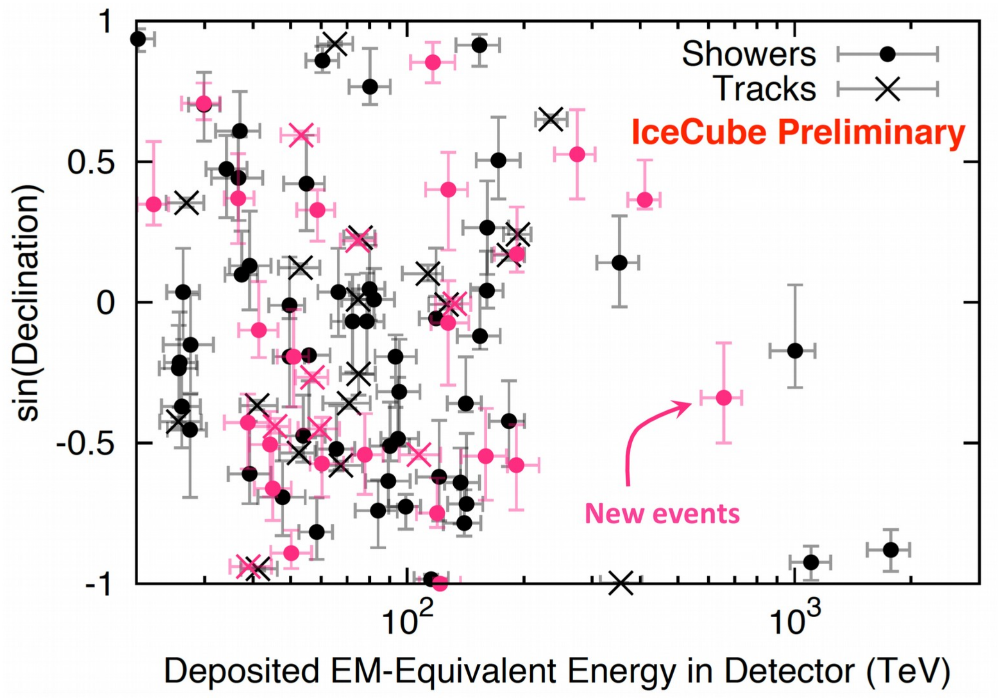
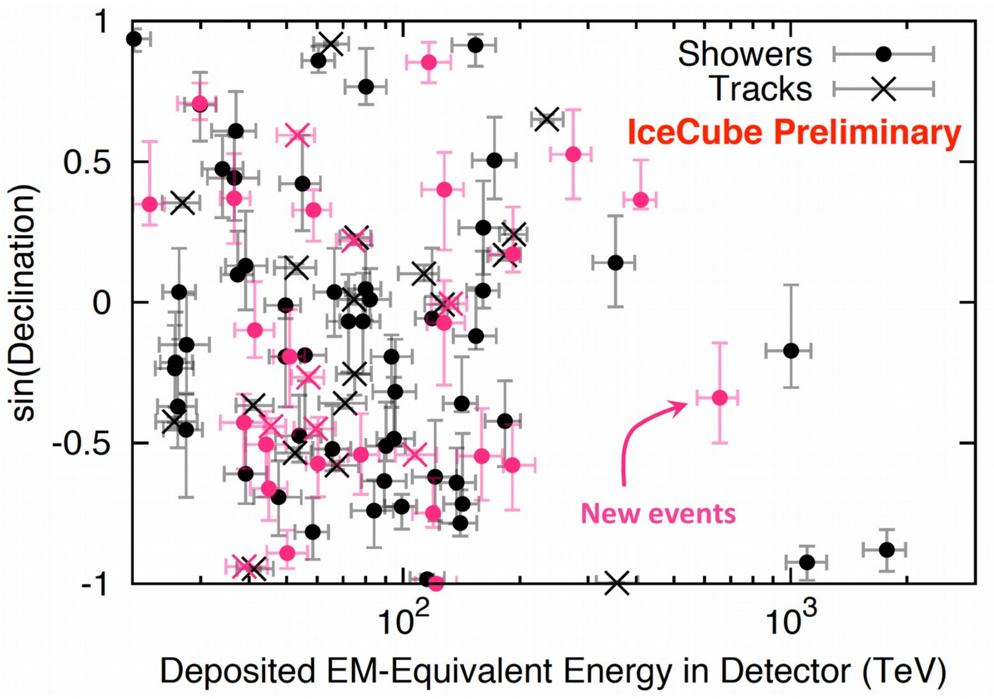
103 contained events between 15 TeV – 2 PeV



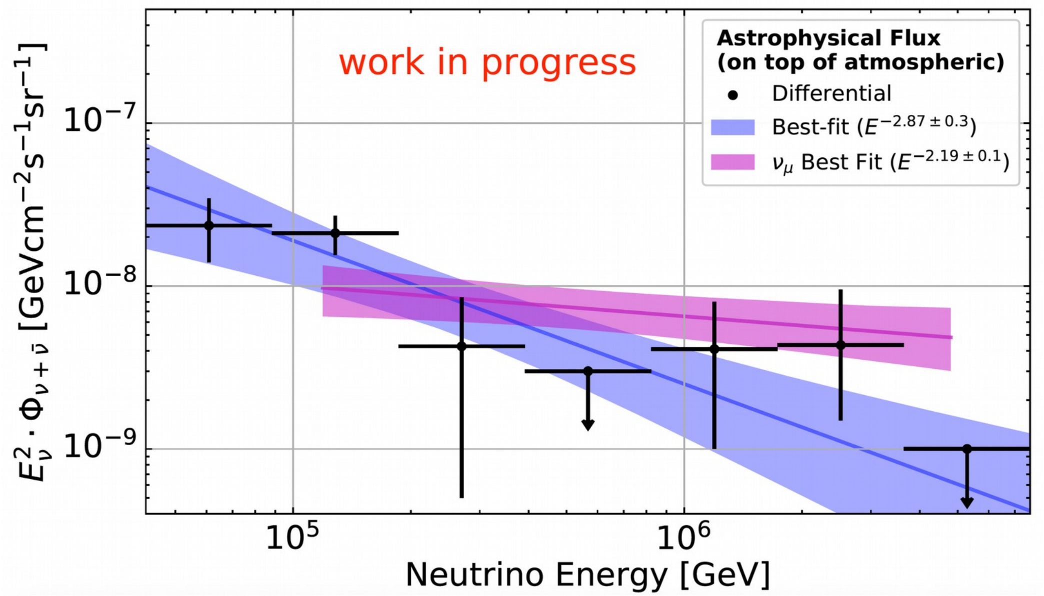
I. Taboada, Neutrino 2018

What has IceCube found so far (7.5 years)?

103 contained events between 15 TeV – 2 PeV



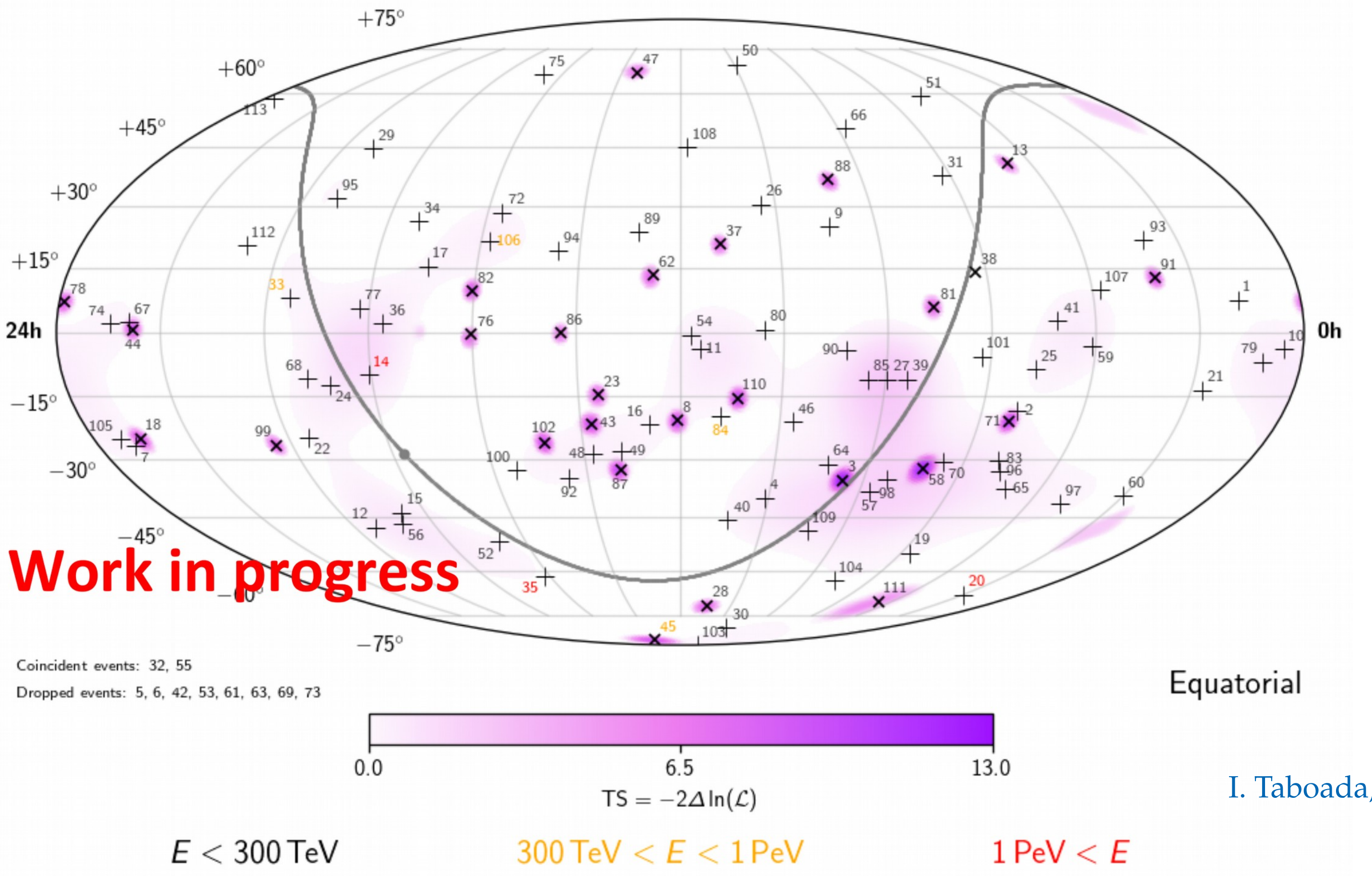
Astrophysical ν flux detected at $> 7\sigma$
(Normalization ok, but steep spectrum)



I. Taboada, Neutrino 2018

What has IceCube found so far (7.5 years)?

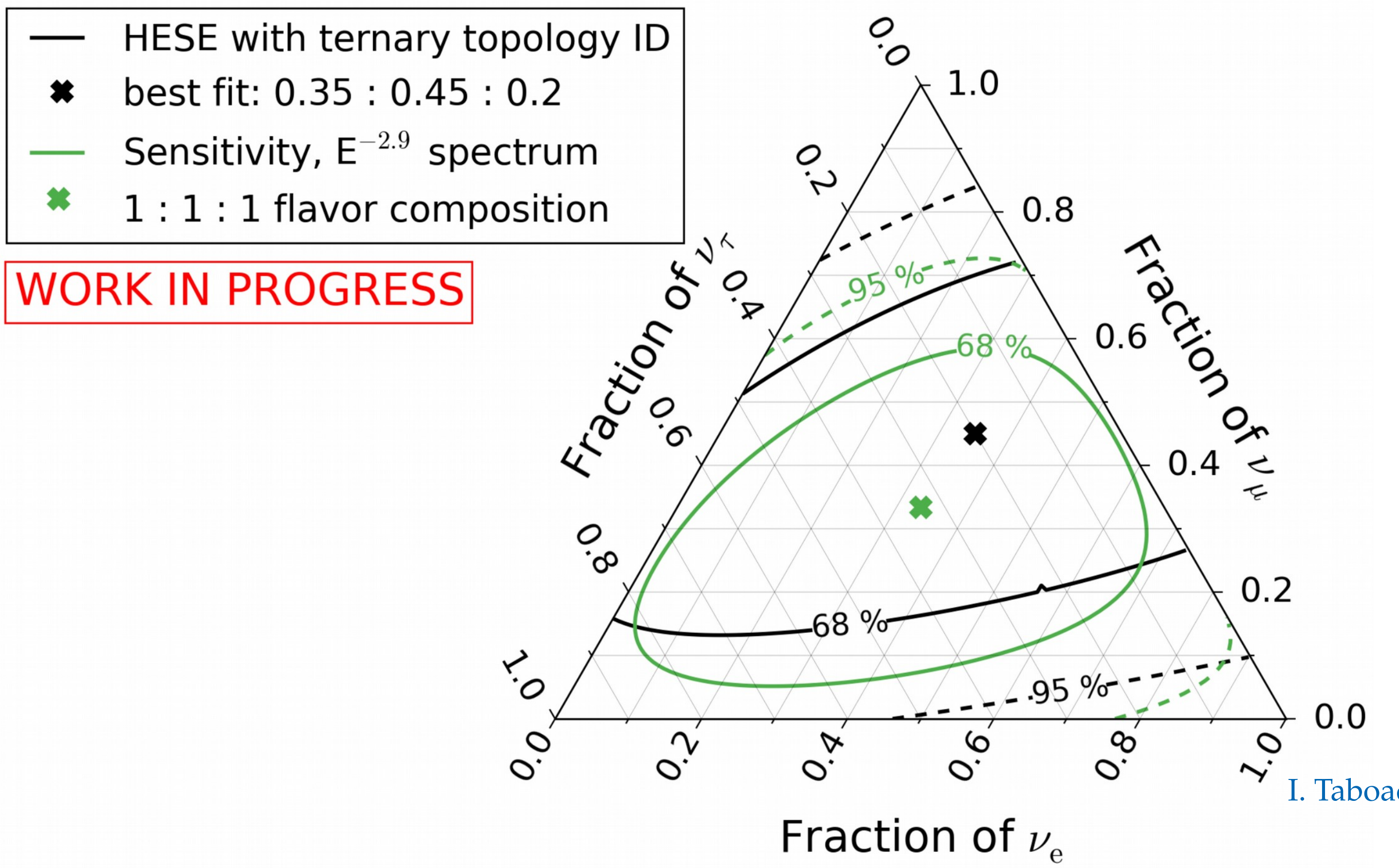
Arrival directions compatible with isotropy



I. Taboada, Neutrino 2018

What has IceCube found so far (7.5 years)?

Flavor composition compatible with equal proportion of each flavor



I. Taboada, Neutrino 2018

Fundamental physics with HE astrophysical neutrinos

- Numerous new-physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$
- So we can probe $\kappa_n \sim 4 \cdot 10^{-47}\ (E/\mathrm{PeV})^{-n}\ (L/\mathrm{Gpc})^{-1}\ \mathrm{PeV}^{1-n}$
- Improvement over current limits: $\kappa_0 < 10^{-29}$ PeV, $\kappa_1 < 10^{-33}$
- Fundamental physics can be extracted from:
  - Spectral shape
  - Angular distribution
  - Flavor information

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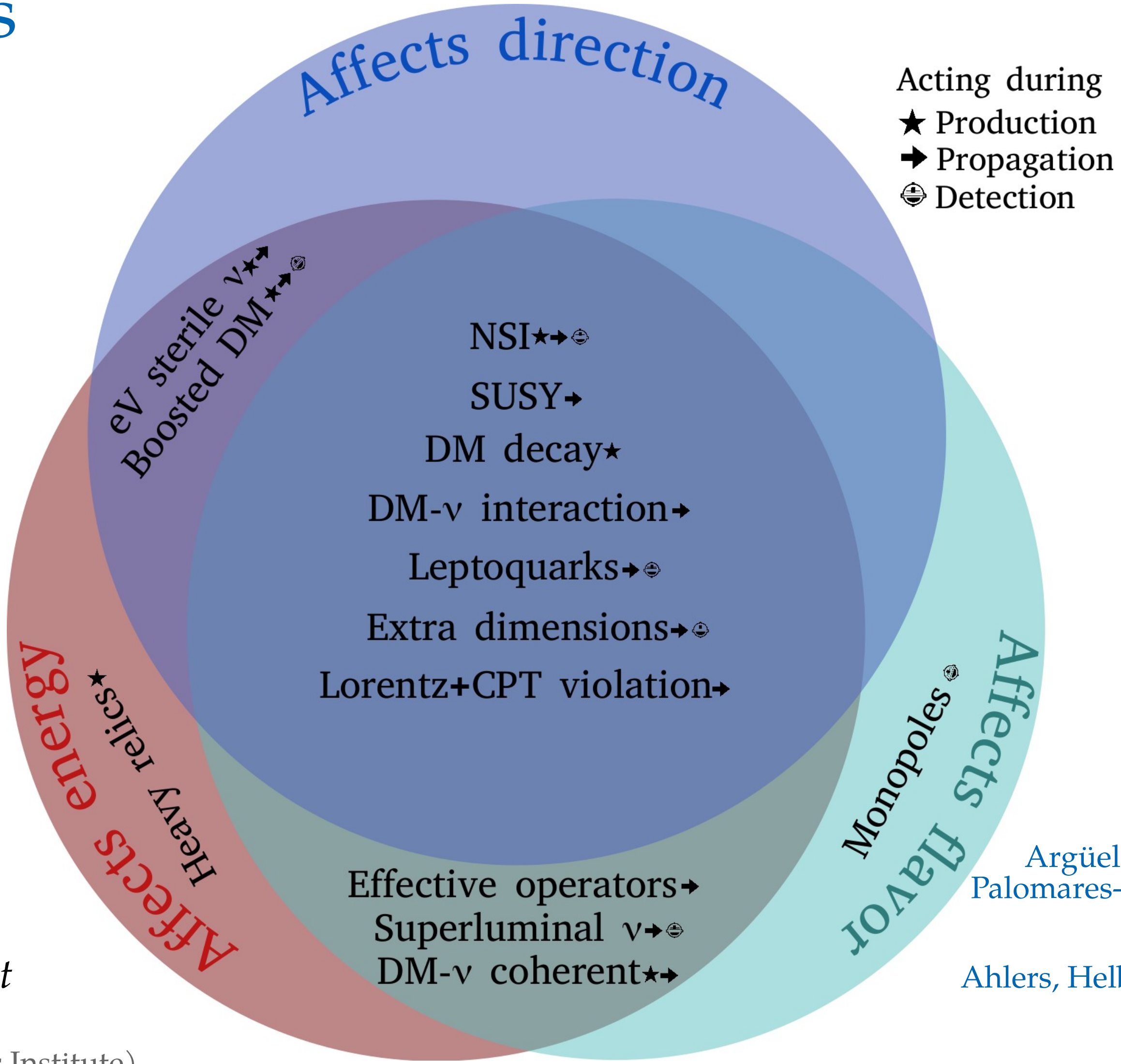
  - Angular distribution
  - Flavor information

In spite of
poor energy, angular, flavor reconstruction
& astrophysical unknowns

New ν physics

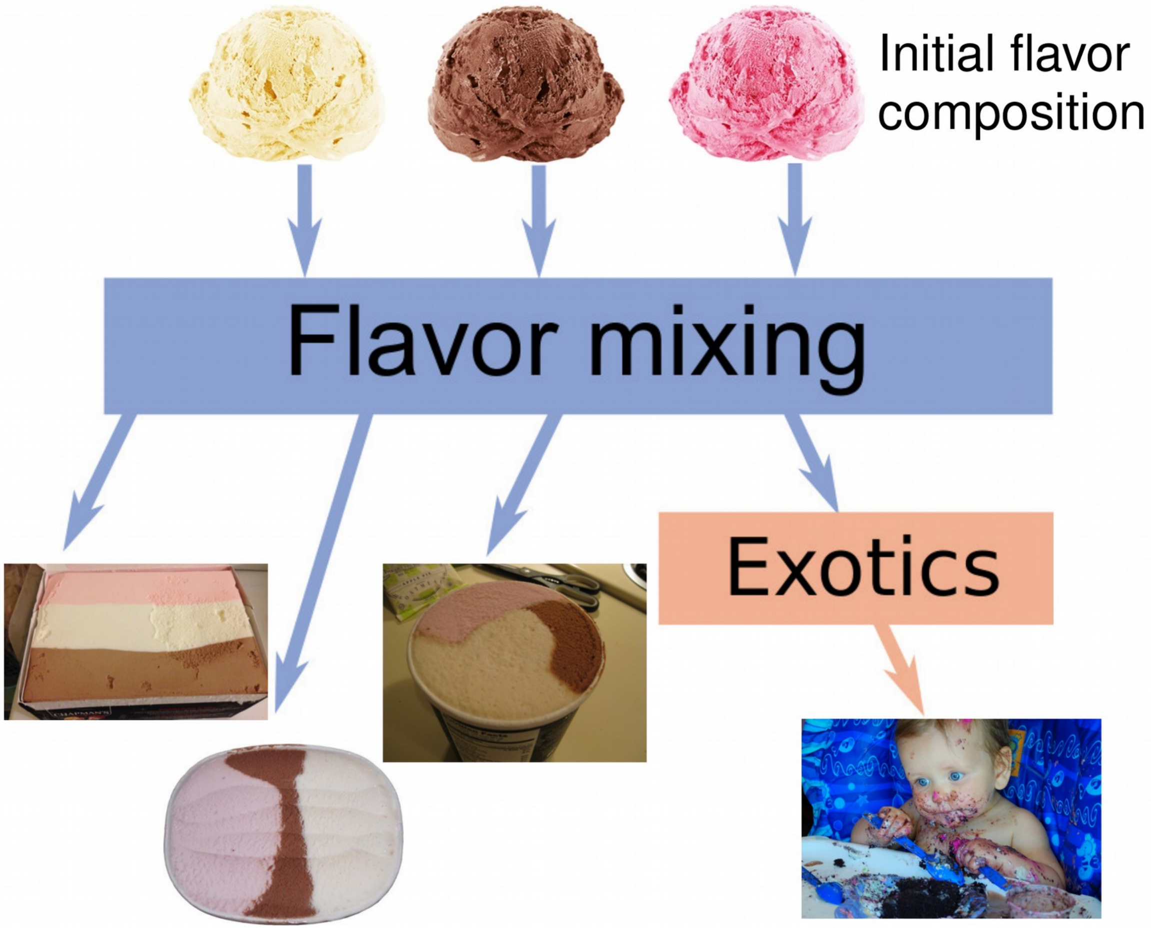


Note: Not an exhaustive list

Argüelles, **MB**, Conrad, Kheirandish, Palomares-Ruiz, Salvadó, Vincent, *In prep.*

See also:
Ahlers, Helbing, De los Heros, 1806.05696

New physics in the flavor composition



Why are flavor ratios useful?

- The normalization of the flux is uncertain – but it cancels out in flavor ratios:

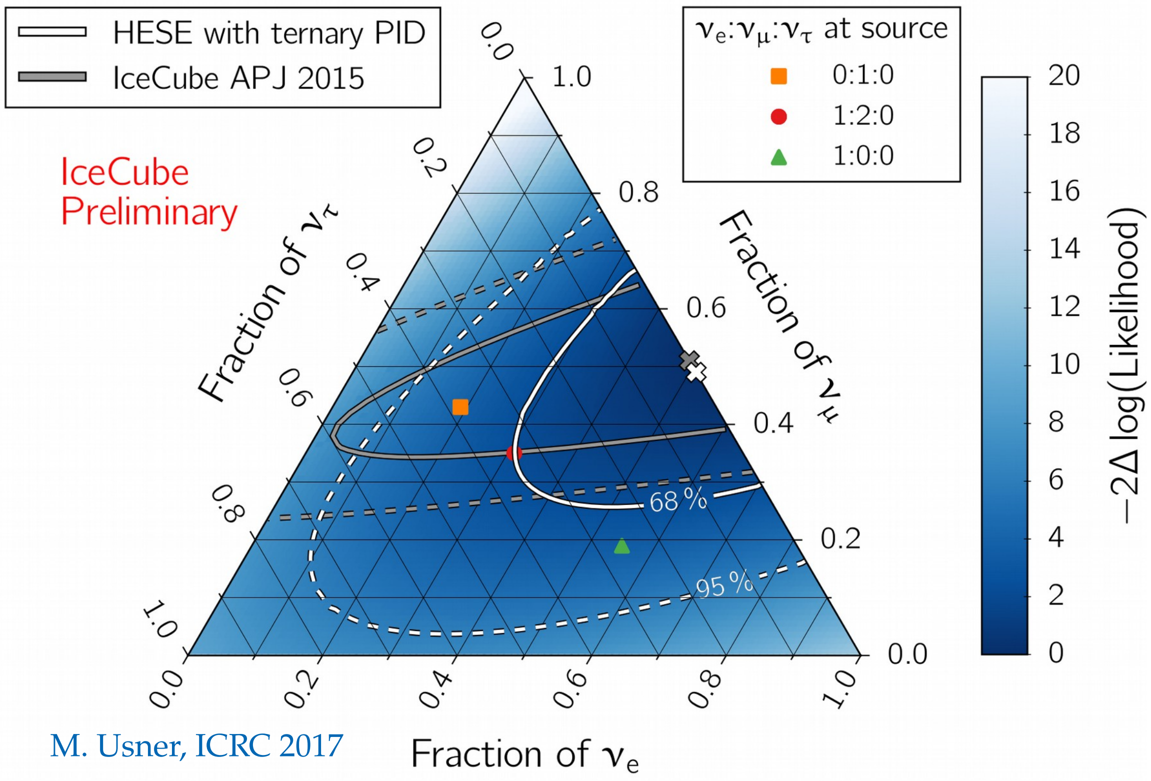
$$\alpha\text{-flavor ratio at Earth } (f_{\alpha,\oplus}) = \frac{\text{Flux at Earth of } \nu_\alpha \; (\alpha = e, \mu, \tau)}{\text{Sum of fluxes of all flavors}}$$

- Ratios remove systematic uncertainties common to all flavors

- Flavor ratios are useful in astrophysics and particle physics

Note: Ratios are for $\nu + \bar{\nu}$, since neutrino telescopes cannot tell them apart

IceCube flavor composition



M. Usner, ICRC 2017

- Compare number of tracks (ν_μ) *vs.* showers (all flavors)
- Best fit: $(f_e : f_\mu : f_\tau)_\oplus = (0.49 : 0.51 : 0)_\oplus$
- Compatible with standard source compositions
- Lots of room for improvement: more statistics, better flavor-tagging

Li, **MB**, Beacom 2016

Flavor – there and here

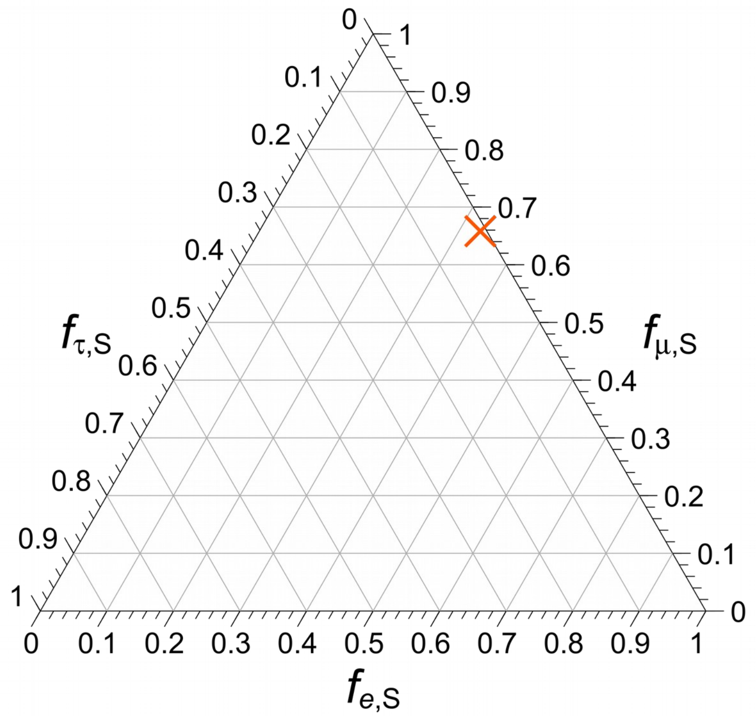
At the sources

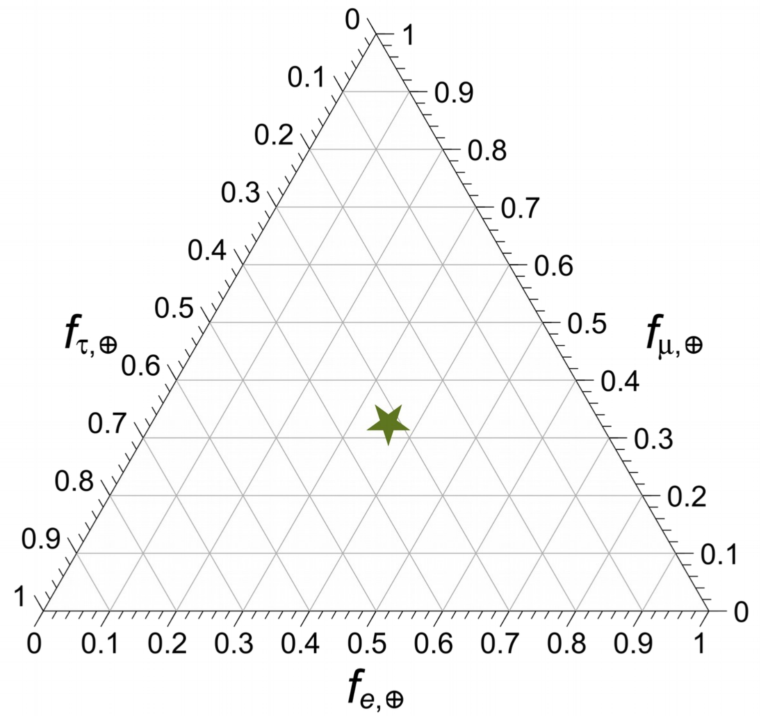
$(f_e:f_\mu:f_\tau)_S = (1/3 : 2/3 : 0)_S$

Neutrino oscillations

At Earth

$(0.36 : 0.32 : 0.32)_\oplus$





Flavor – there and here

$p + \gamma \rightarrow \nu_\mu + \nu_\mu + \nu_e$

At the sources

Neutrino oscillations

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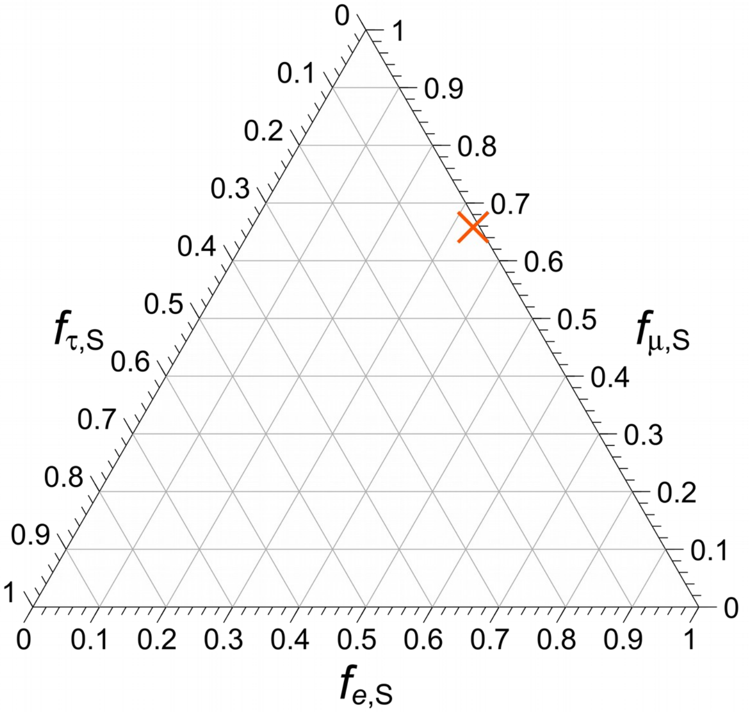

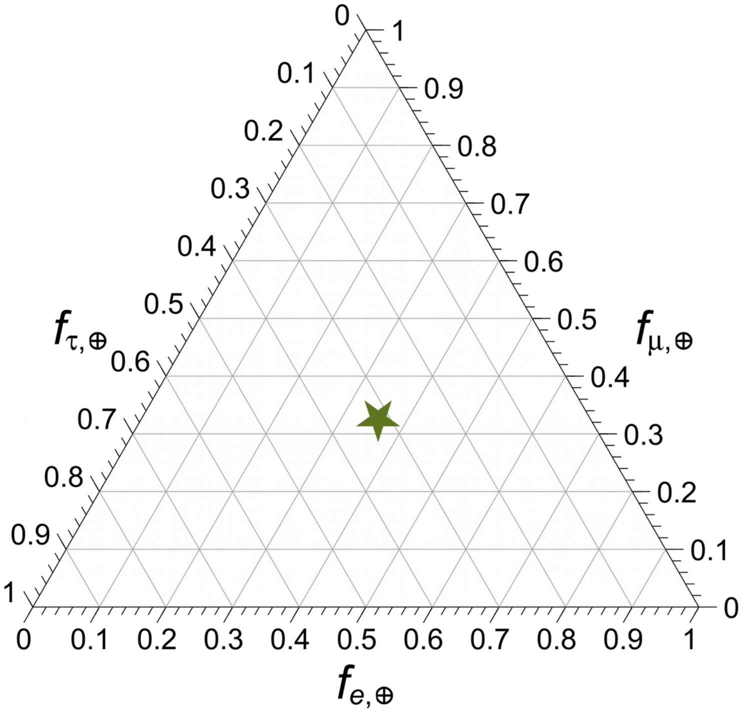

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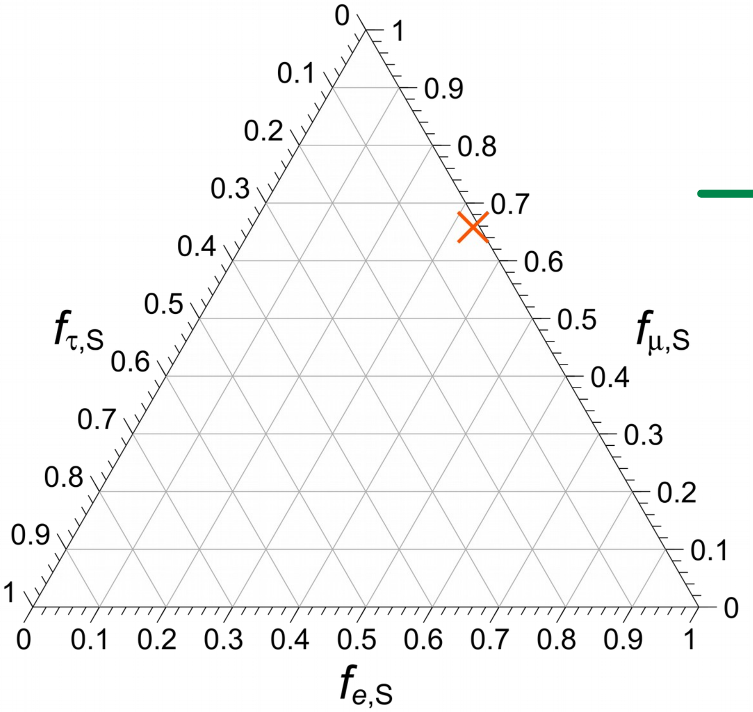
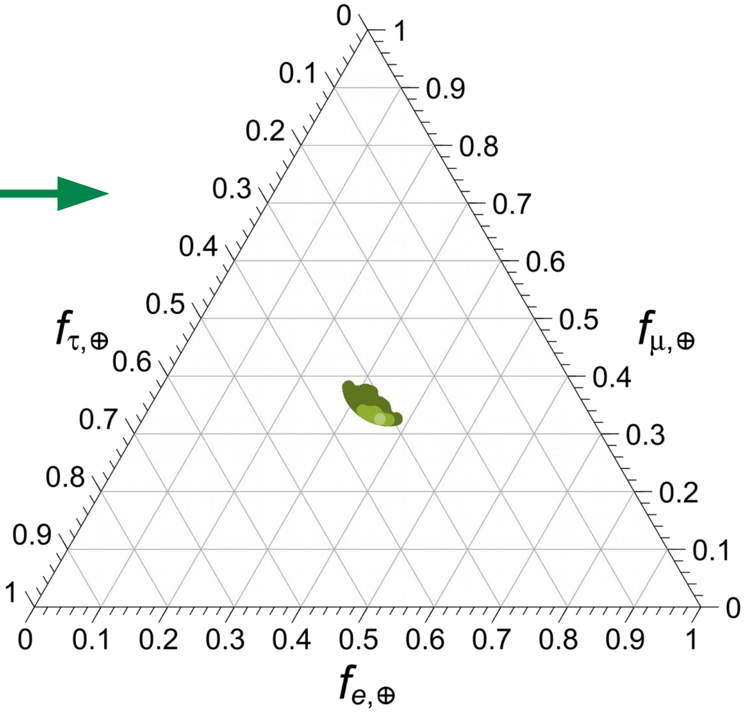


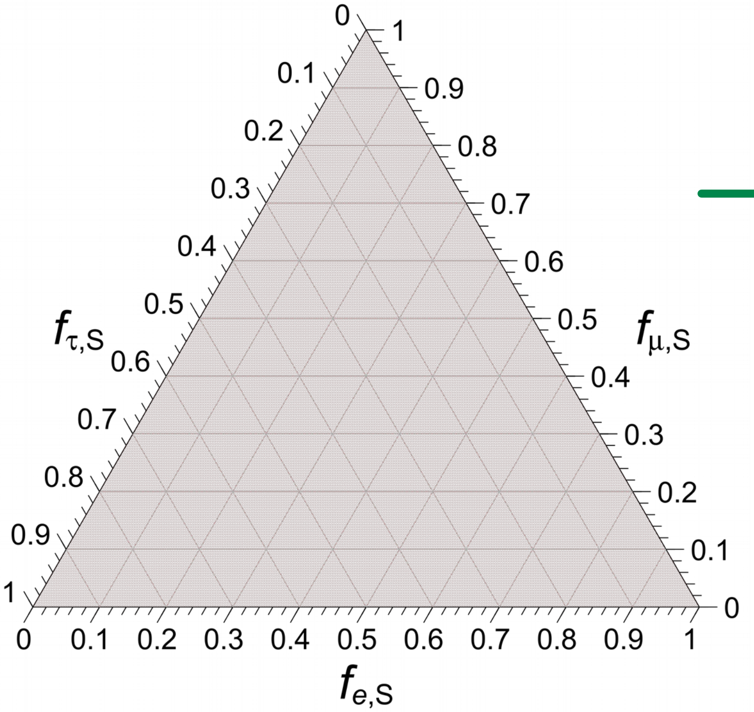
Uncertainties in values of mixing parameter (1σ, 3σ) →



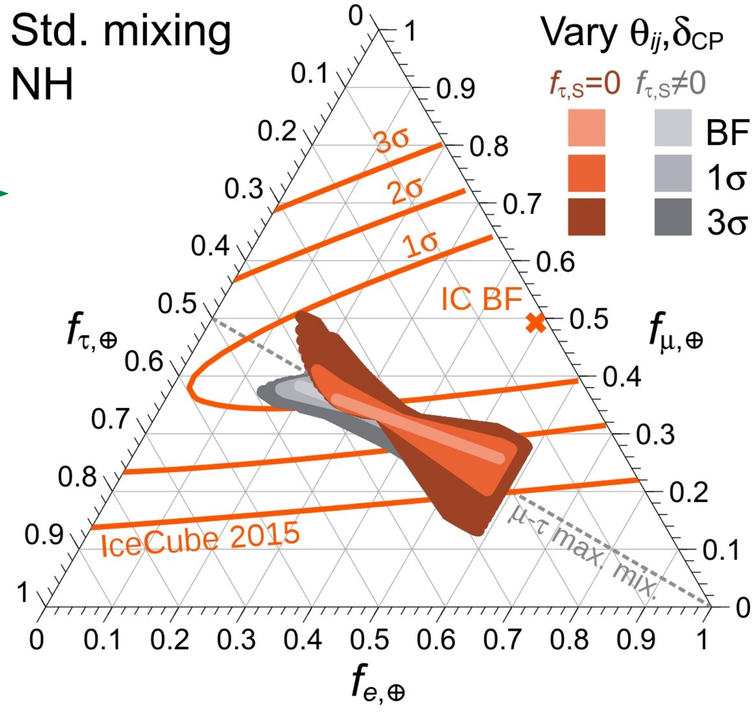
Flavor composition – Standard allowed region

At the sources

All possible flavor ratios



At Earth



MB, Beacom, Winter *PRL* 2015

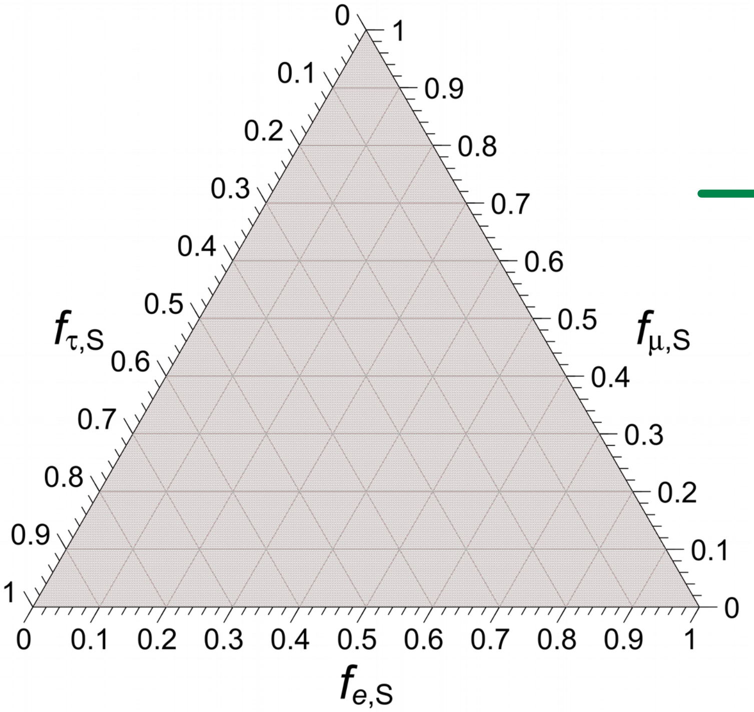
Flavor composition – Standard allowed region

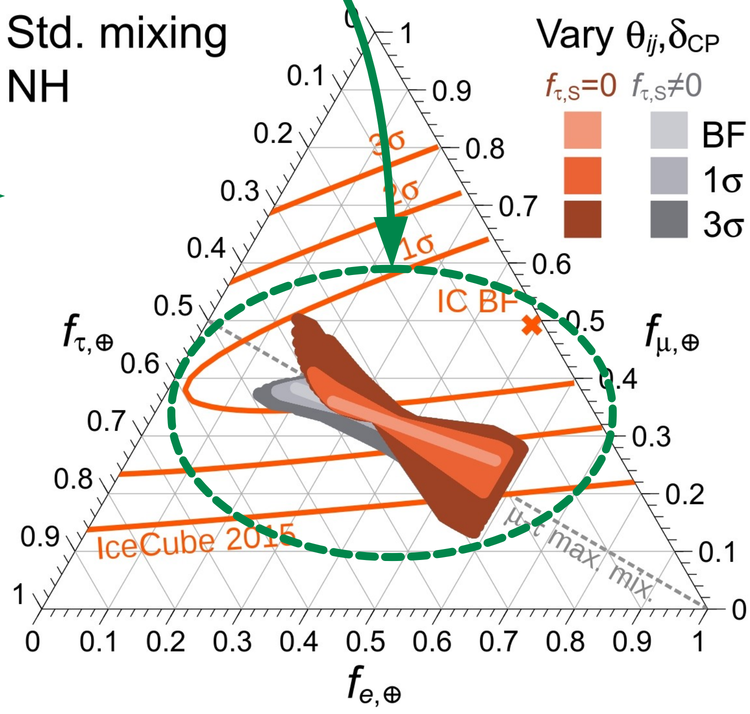
At the sources

At Earth

Only 10% of parameter space

All possible flavor ratios

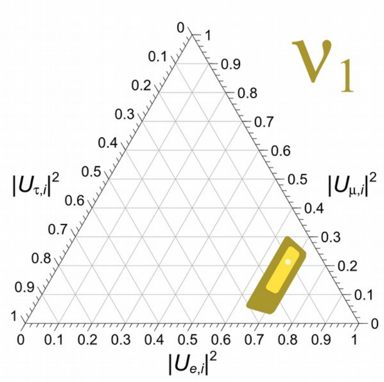


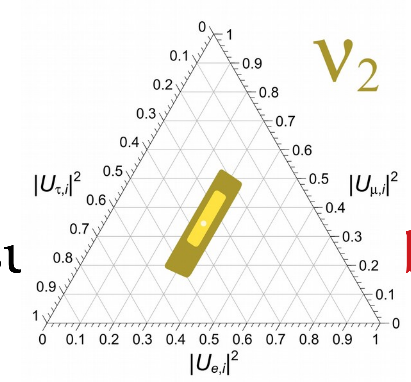


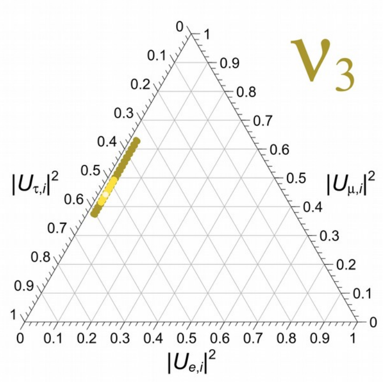
MB, Beacom, Winter *PRL* 2015

Two classes of new physics

- Neutrinos propagate as an incoherent mix of ν_1, ν_2, ν_3
- Each one has a different flavor content:







- Flavo… h are the resu… bination
- New …
  - Only reweigh the proportion of each ν_i reaching Earth (*e.g.*, ν decay)
  - Redefine the propagation states (*e.g.*, Lorentz-invariance violation)

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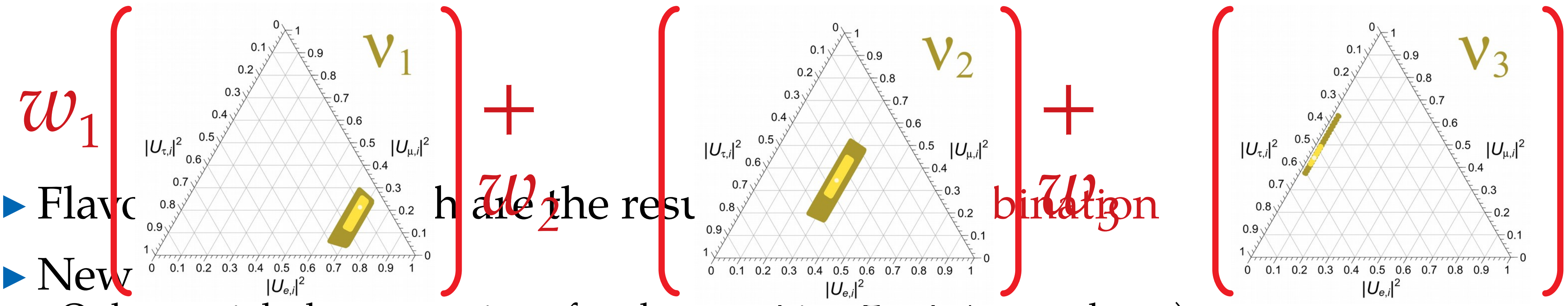

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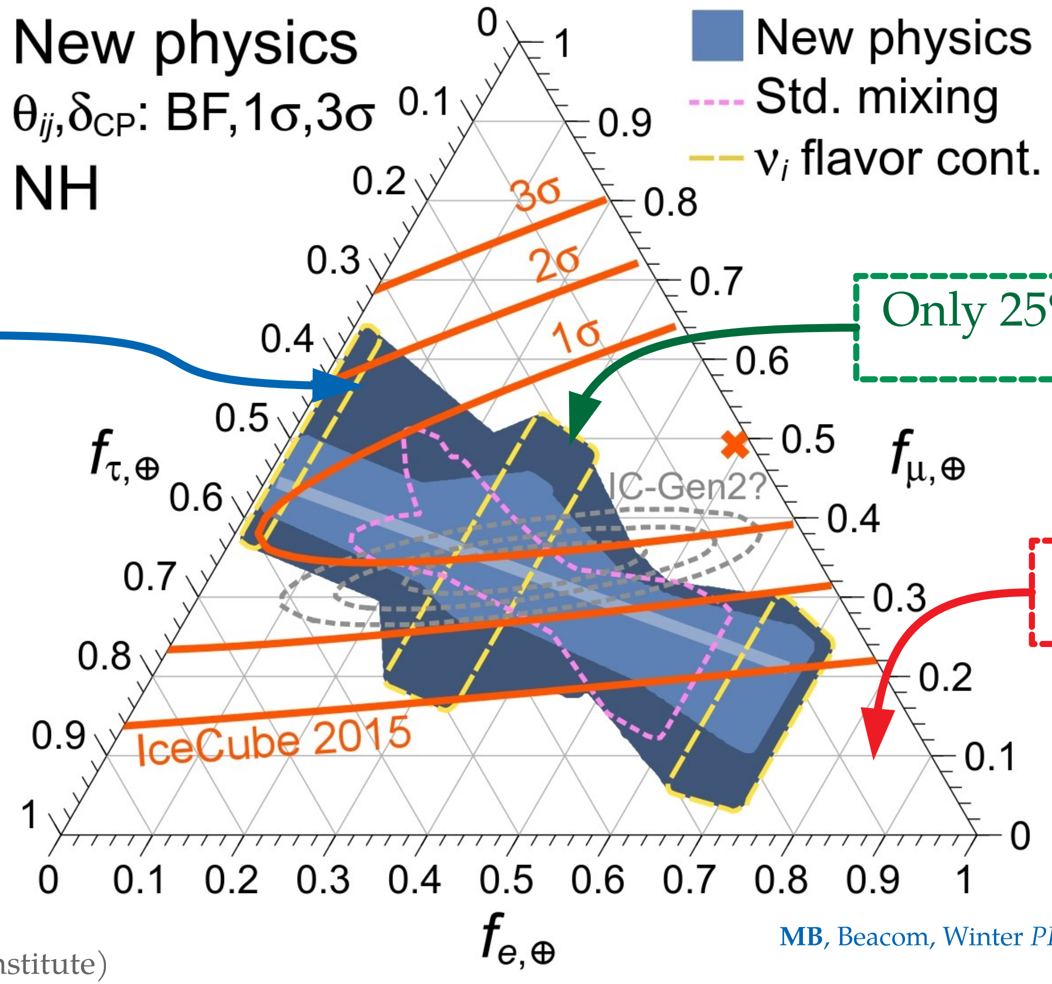
Flavor ratios accessible with decay-like physics



Region of all linear combinations of ν_1, ν_2, ν_3

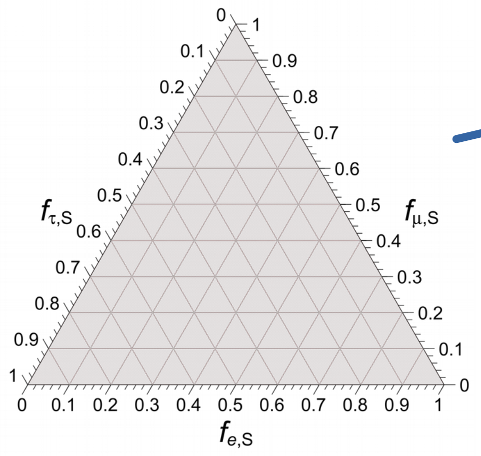
Only 25% of parameter space

What lies outside?

MB, Beacom, Winter *PRL* 2015

Measuring the neutrino lifetime

Sources



$\nu_2, \nu_3 \rightarrow \nu_1$

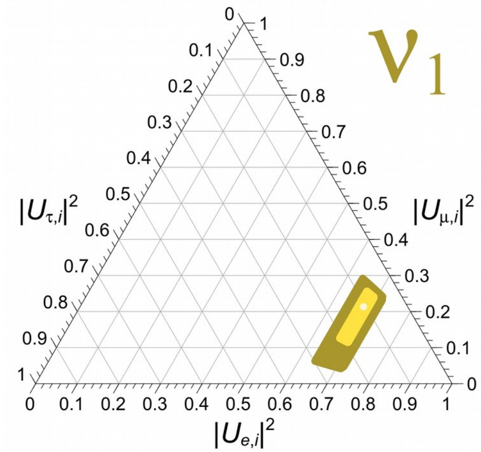
ν_1 lightest and stable

If all unstable neutrinos decay

$\nu_1, \nu_2 \rightarrow \nu_3$

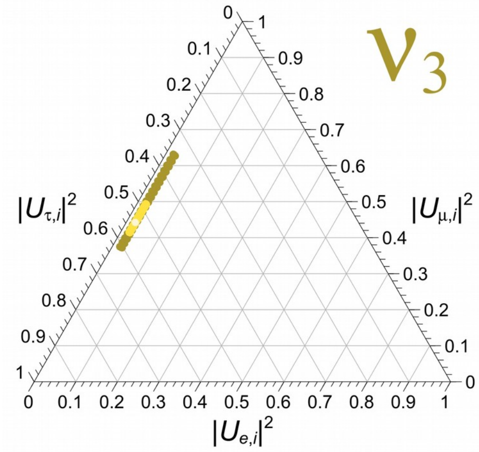
ν_3 lightest and stable

Earth



ν_1

$$f_{\alpha,\oplus} = |U_{\alpha 1}|^2$$



ν_3

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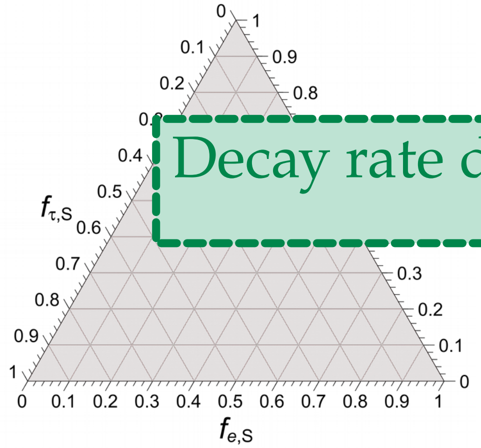
Measuring the neutrino lifetime

Sources



$\nu_2, \nu_3 \rightarrow \nu_1$

ν_1 lightest and stable

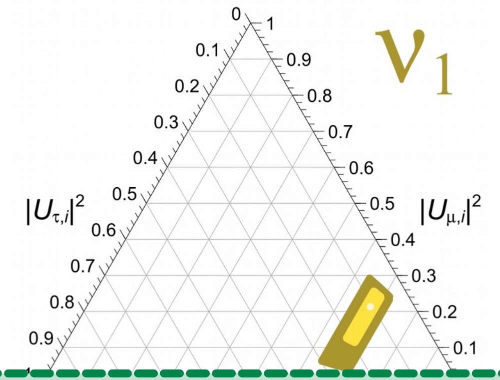
$\nu_1, \nu_2 \rightarrow \nu_3$

ν_3 lightest and stable

Decay rate depends on $\exp[- t \,/\, (\gamma\tau_i)] = \exp[- (L/E) \cdot (m_i/\tau_i)]$

Earth

ν_1



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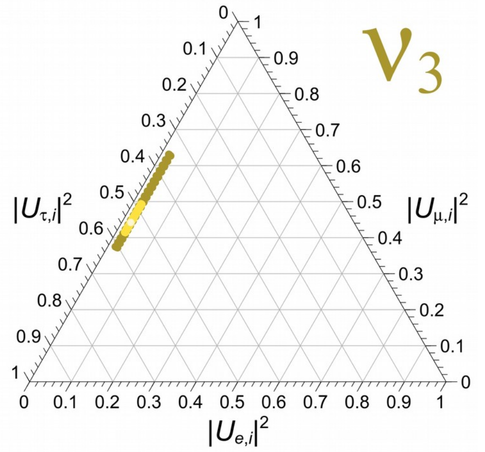
ν_3



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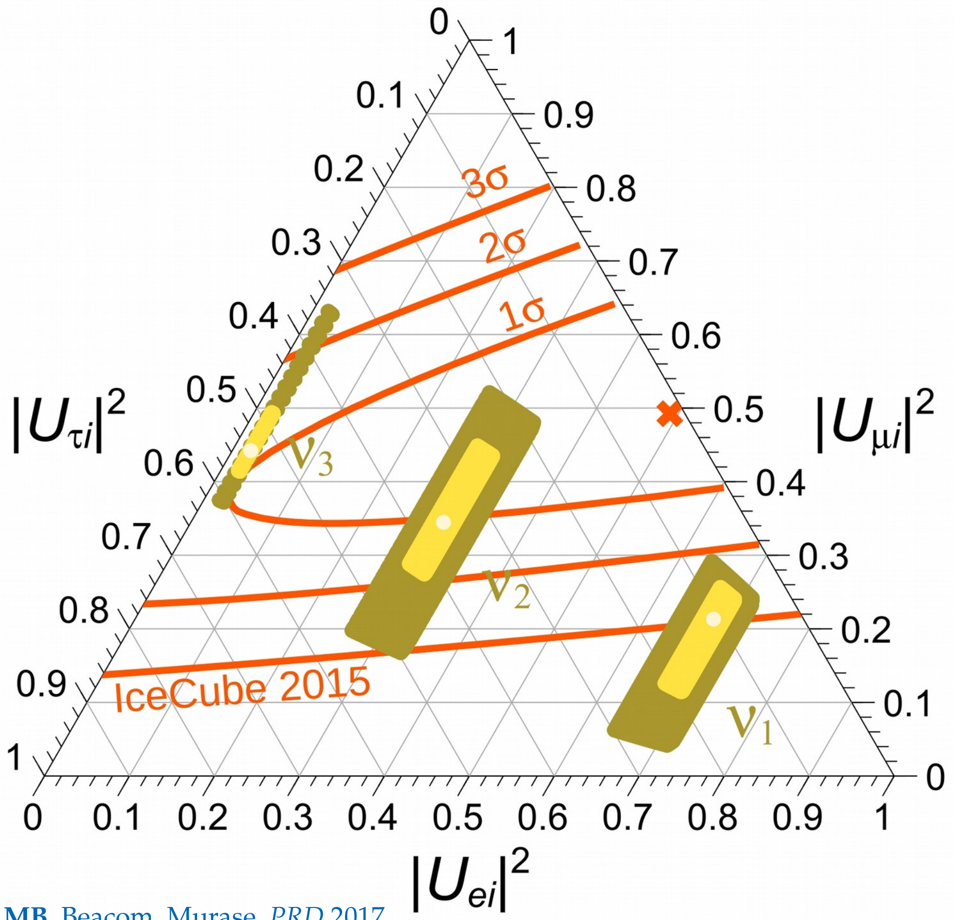
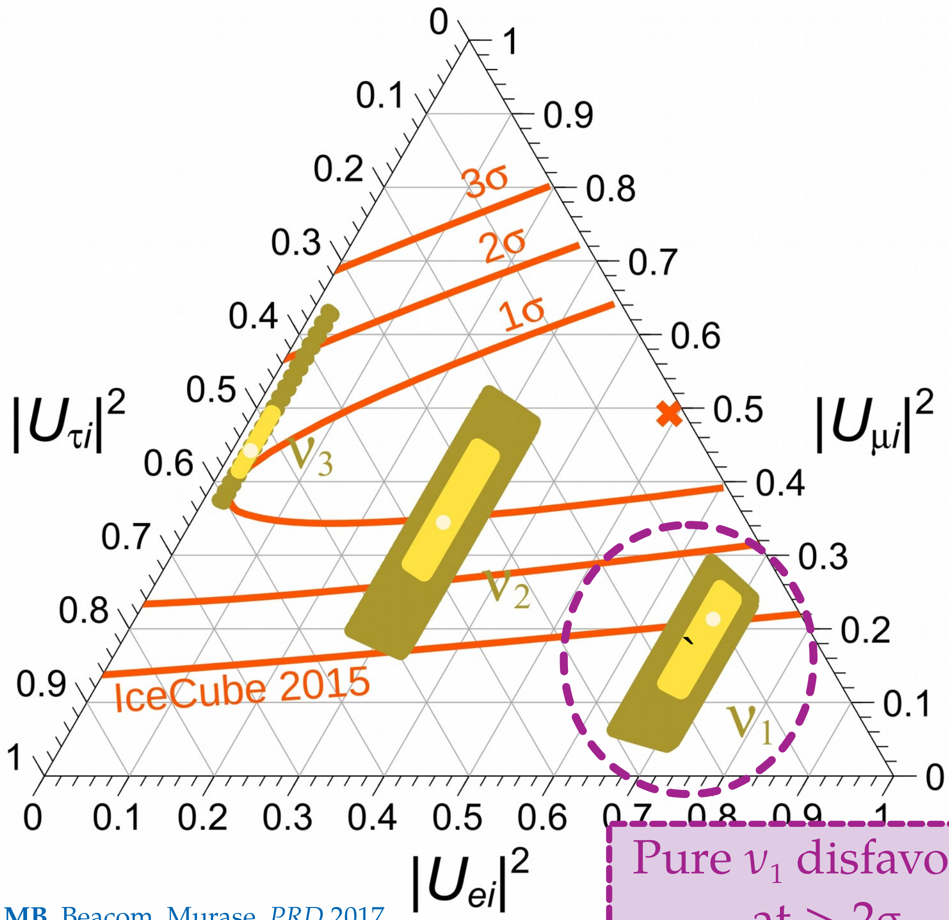


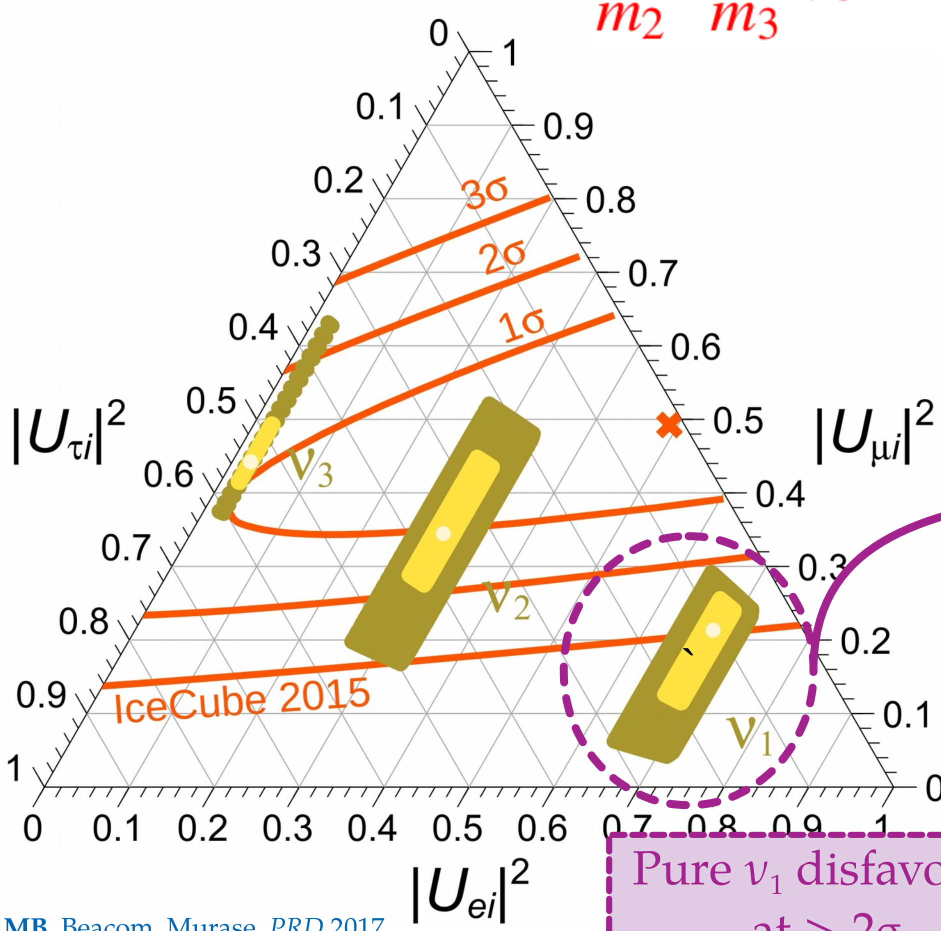
MB, Beacom, Murase, *PRD* 2017

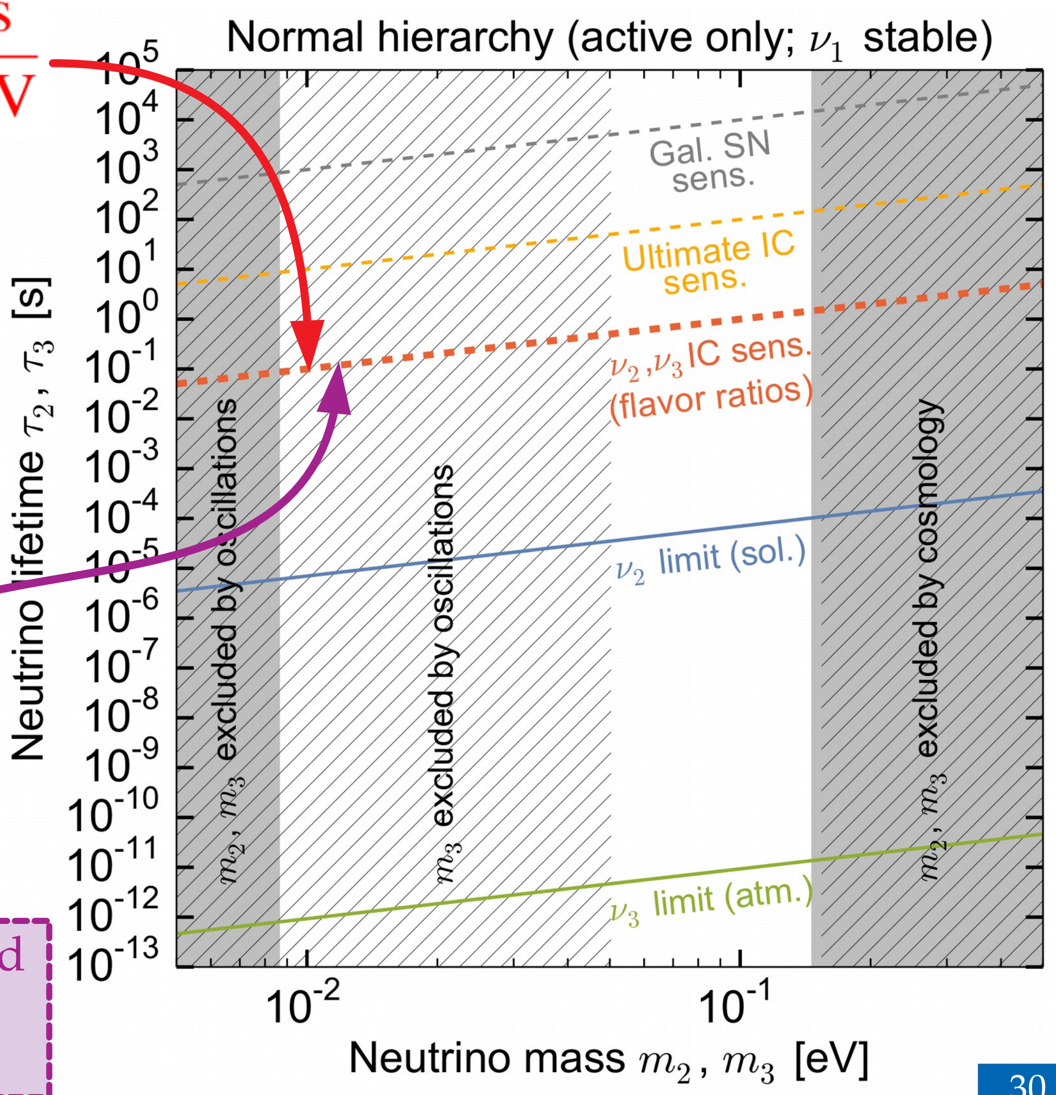


Pure ν_1 disfavored at > 2σ

MB, Beacom, Murase, *PRD* 2017

$$\frac{\tau_2}{m_2}, \frac{\tau_3}{m_3} \gtrsim 10\ \frac{\text{s}}{\text{eV}}$$





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MB, Beacom, Murase, *PRD* 2017

What lies beyond? *Take your pick*

- High-energy effective field theories
  - Violation of Lorentz and CPT invariance
    [Barenboim & Quigg, *PRD* 2003; **MB**, Gago, Peña-Garay, *JHEP* 2010; Kostelecky & Mewes 2004]
  - Violation of equivalence principle
    [Gasperini, *PRD* 1989; Glashow *et al.*, *PRD* 1997]
  - Coupling to a gravitational torsion field
    [De Sabbata & Gasperini, *Nuovo Cim.* 1981]
  - Renormalization-group-running of mixing parameters
    [**MB**, Gago, Jones, *JHEP* 2011]
- Active-sterile mixing
  [Aeikens *et al.*, *JCAP* 2015; V. Brdar, *JCAP* 2017]
- Flavor-violating physics
  - New $\nu\nu$ interactions
    [Ng & Beacom, *PRD* 2014; Cherry, Friedland, Shoemaker, 1411.1071; Blum, Hook, Murase, 1408.3799]
  - New neutrino-electron interactions
    [**MB** & Agarwalla, 1808.02042]
- …

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New physics – High-energy effects

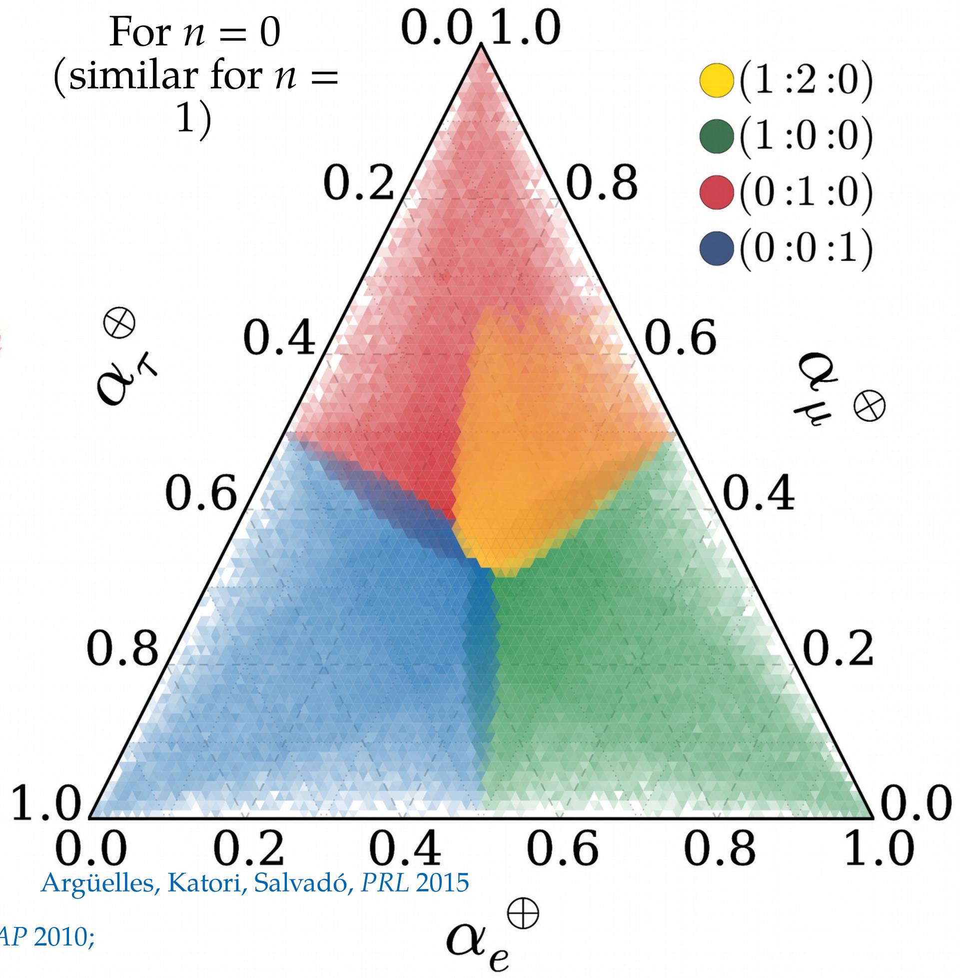
$$H_{\text{tot}} = H_{\text{std}} + H_{\text{NP}}$$

$$H_{\text{std}} = \frac{1}{2E} U^\dagger_{\text{PMNS}} \, \text{diag}\left(0, \Delta m^2_{21}, \Delta m^2_{31}\right) U_{\text{PMNS}}$$

$$H_{\text{NP}} = \sum_n \left(\frac{E}{\Lambda_n}\right)^n U_n^\dagger \, \text{diag}\left(O_{n,1}, O_{n,2}, O_{n,3}\right) U_n$$

This can populate *all* of the triangle –

- Use current atmospheric bounds on $O_{n,i}$:
  $O_0 < 10^{-23}$ GeV, $O_1/\Lambda_1 < 10^{-27}$ GeV
- Sample the unknown new mixing angles



Argüelles, Katori, Salvadó, *PRL* 2015

See also: Rasmusen *et al.*, *PRD* 2017; **MB**, Beacom, Winter *PRL* 2015; **MB**, Gago, Peña-Garay *JCAP* 2010; Bazo, **MB**, Gago, Miranda *IJMPA* 2009; + many others

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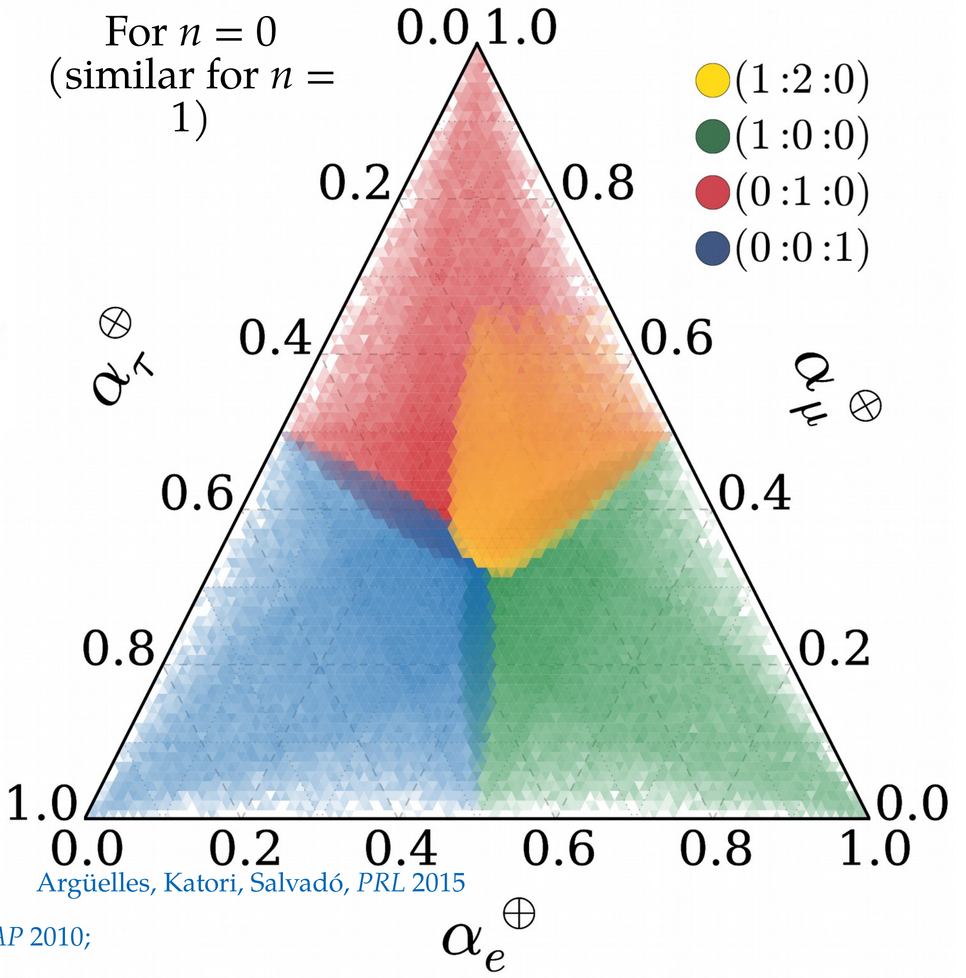

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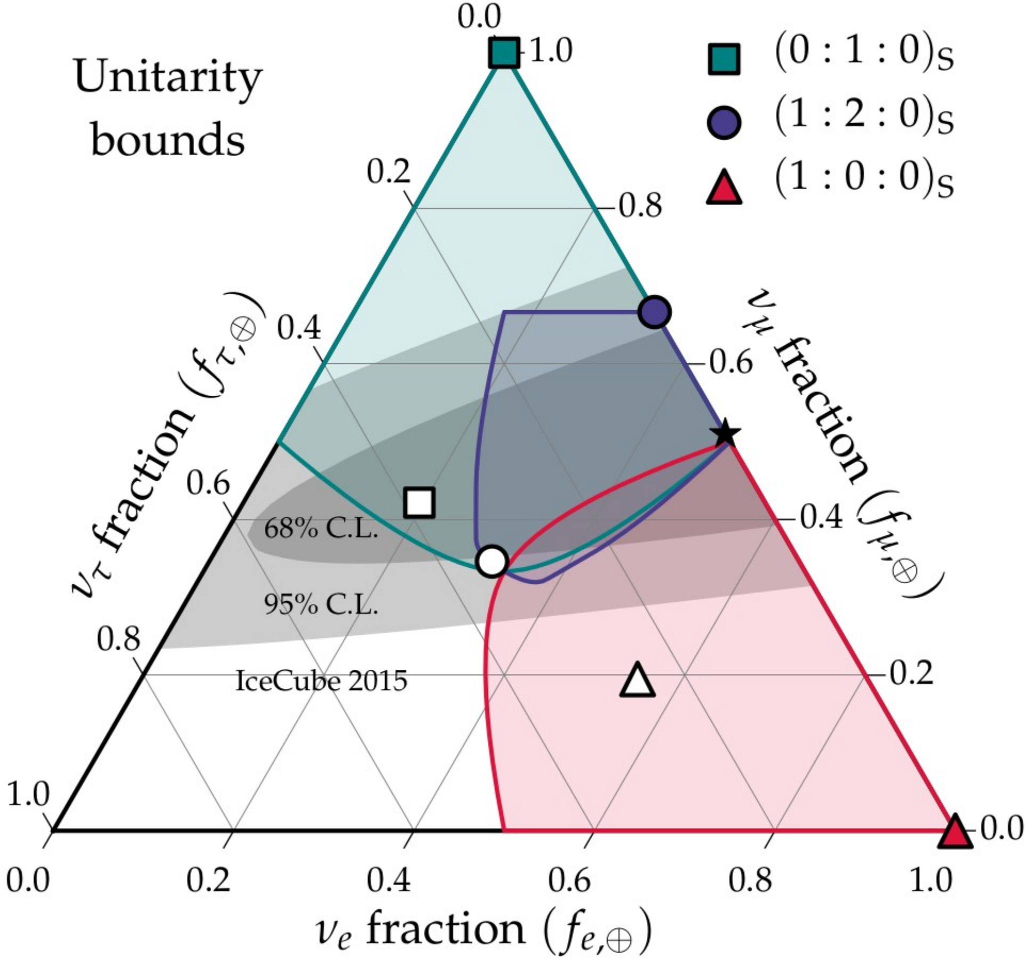
Using unitarity to constrain new physics

$$\mathrm{H}_{\mathrm{tot}} = \mathrm{H}_{\mathrm{std}} + \mathrm{H}_{\mathrm{NP}}$$

- New mixing angles unconstrained
- Use unitarity to bound all possible flavor ratios at Earth
- Can be used as prior in new-physics searches in IceCube



Ahlers, **MB**, Mu, 1810.00893

What are you taking home?

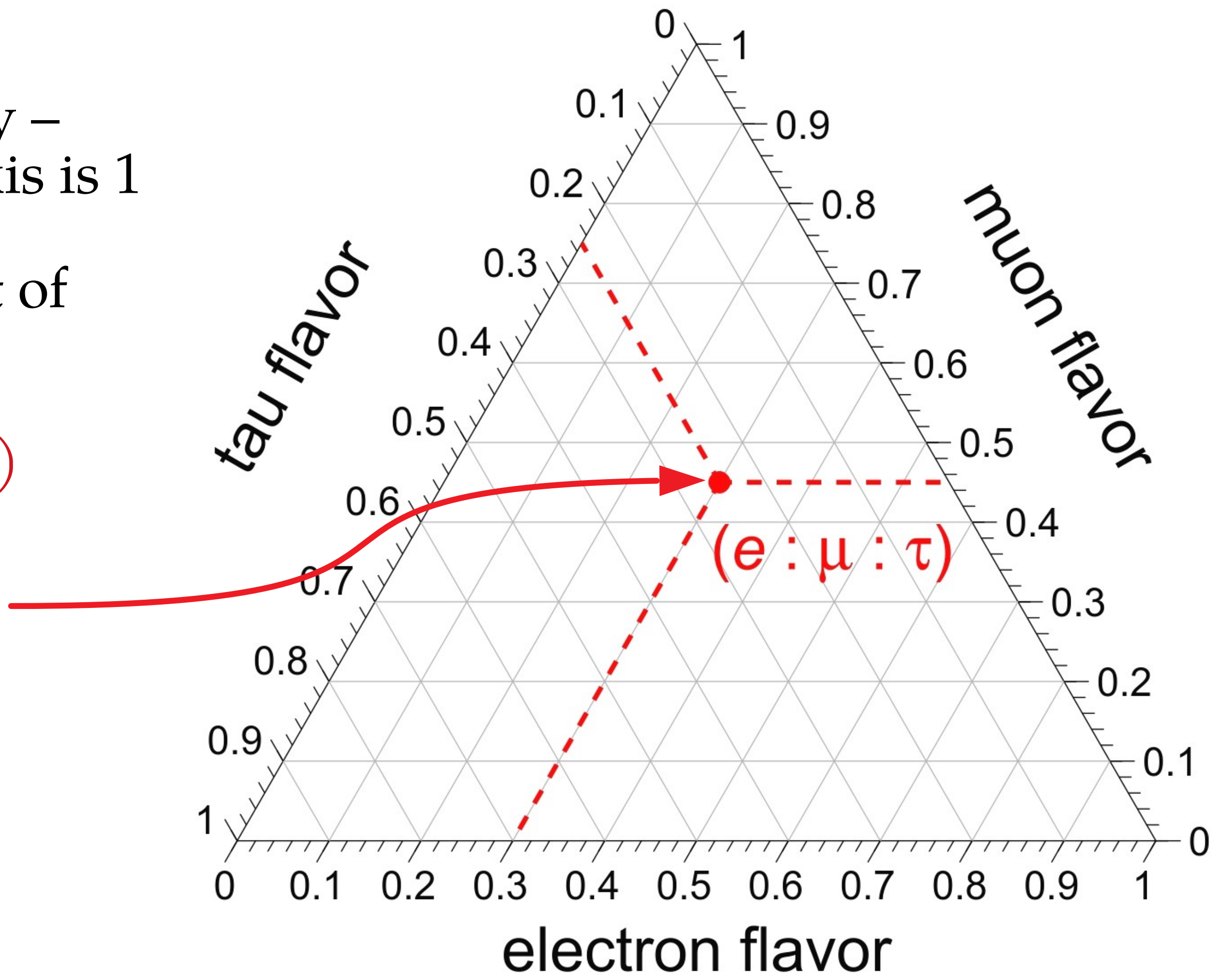
- Astrophysical neutrinos are the *only* feasible way to probe TeV–PeV physics
- New physics is possibly sub-dominant – so we need to be thorough
- We can extract TeV–PeV ν physics *now*, in spite of astrophysical unknowns
- Forthcoming improvements: statistics, better reconstruction, higher energies

Reading a ternary plot

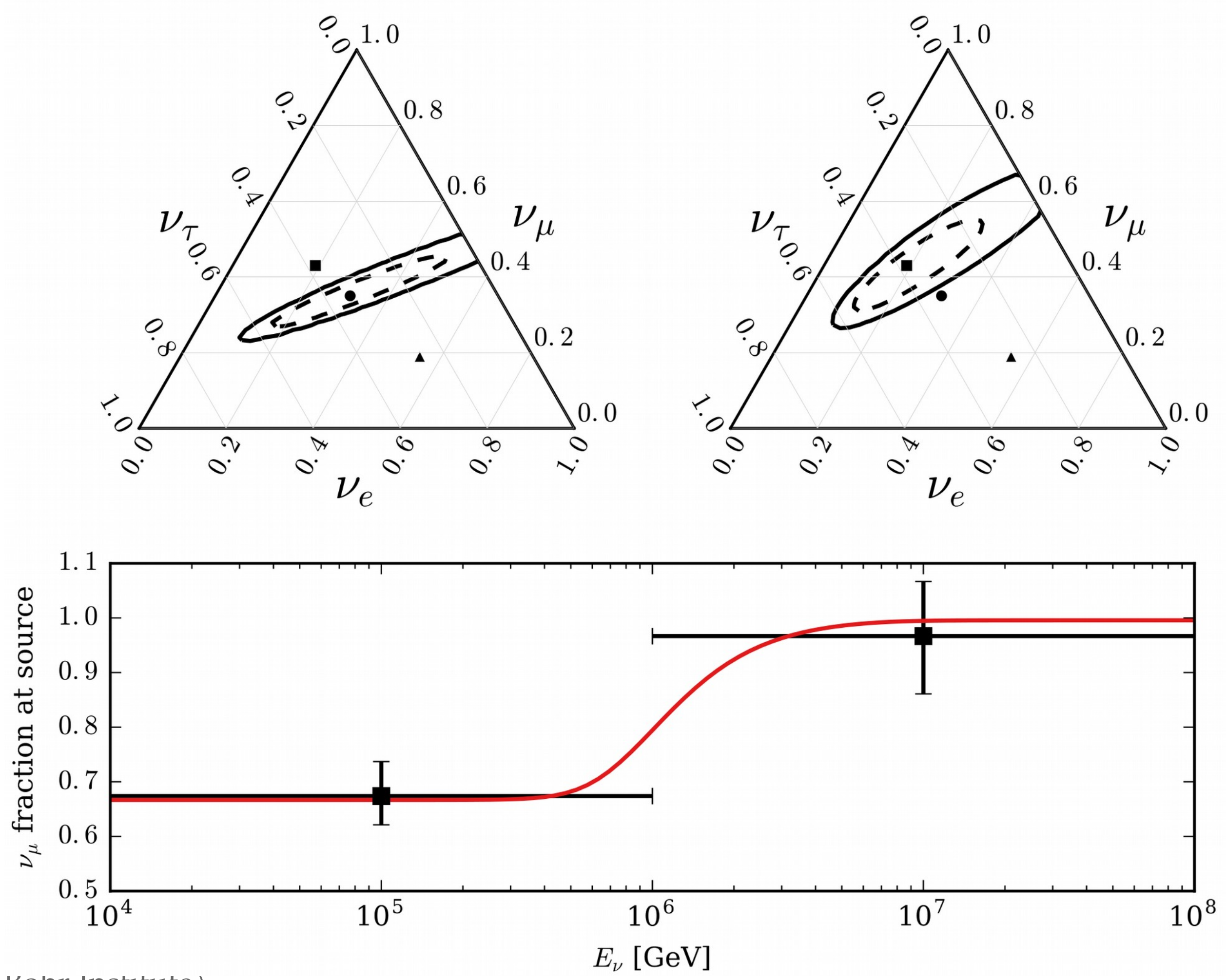
Assumes underlying unitarity – sum of projections on each axis is 1

How to read it: Follow the tilt of the tick marks, *e.g.*,

$$(e:\mu:\tau) = (0.30:0.45:0.25)$$



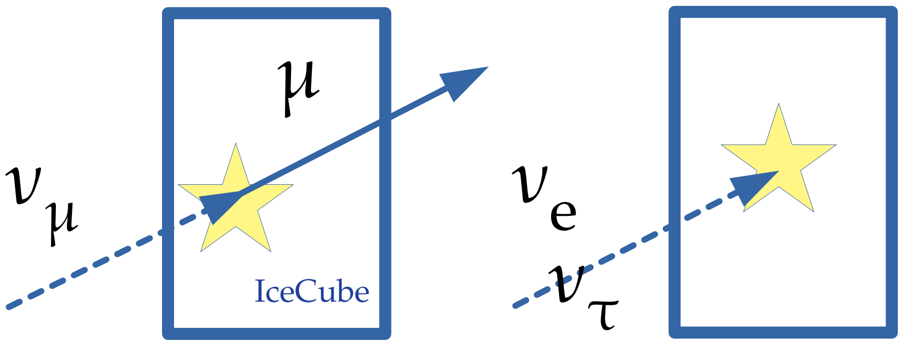
… Observable in IceCube-Gen2?



Borrowed from M. Kowalski

Contained *vs.* uncontained νN interactions

Contained events



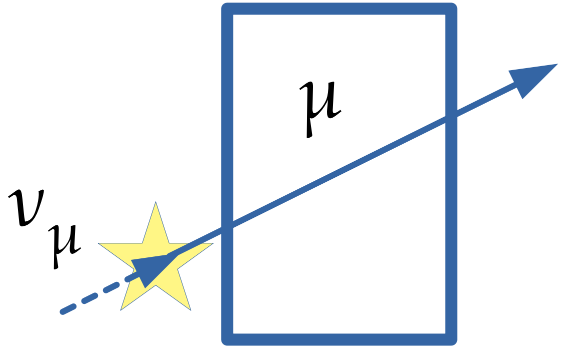
Starting track — Shower

Pro: Clean determination of E_ν

Con: Few events (<100)

Ref.: MB & A. Connolly, 1711.11043

Uncontained events



Through-going muon

Pro: Lots of events (~10k used)

Con: Uncertain estimates of E_ν

Ref.: IceCube, *Nature* 2017, 1711.08119

The new ν physics matrix

Where it happens

What it changes

	At source	**During propagation**	**At detection**
Energy	Matter effects	New interactions, sterile neutrinos	New resonances
Direction	DM decay / annihilation	New ν-N, ν-DM interactions	Anomalous ν magnetic moment
Topology / flavor	Matter effects	ν decay, sterile ν, new operators	Non-standard interactions
Time		Lorentz-invariance violation	

Argüelles, MB, Conrad, Kheirandish, Palomares-Ruiz, Salvadó, Vincent, *In prep.*