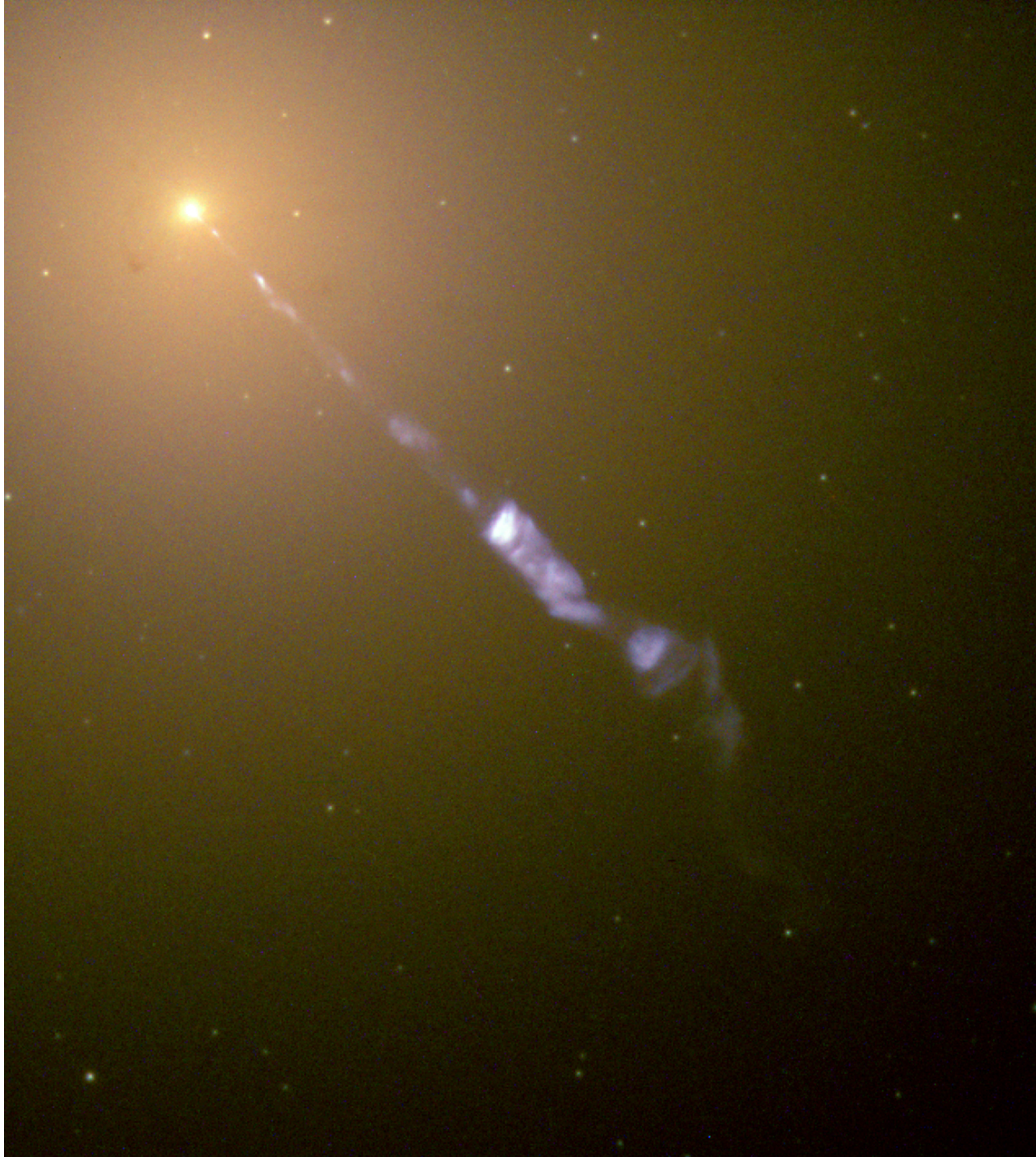
Lecture XVII.

Astrophysical particle acceleration

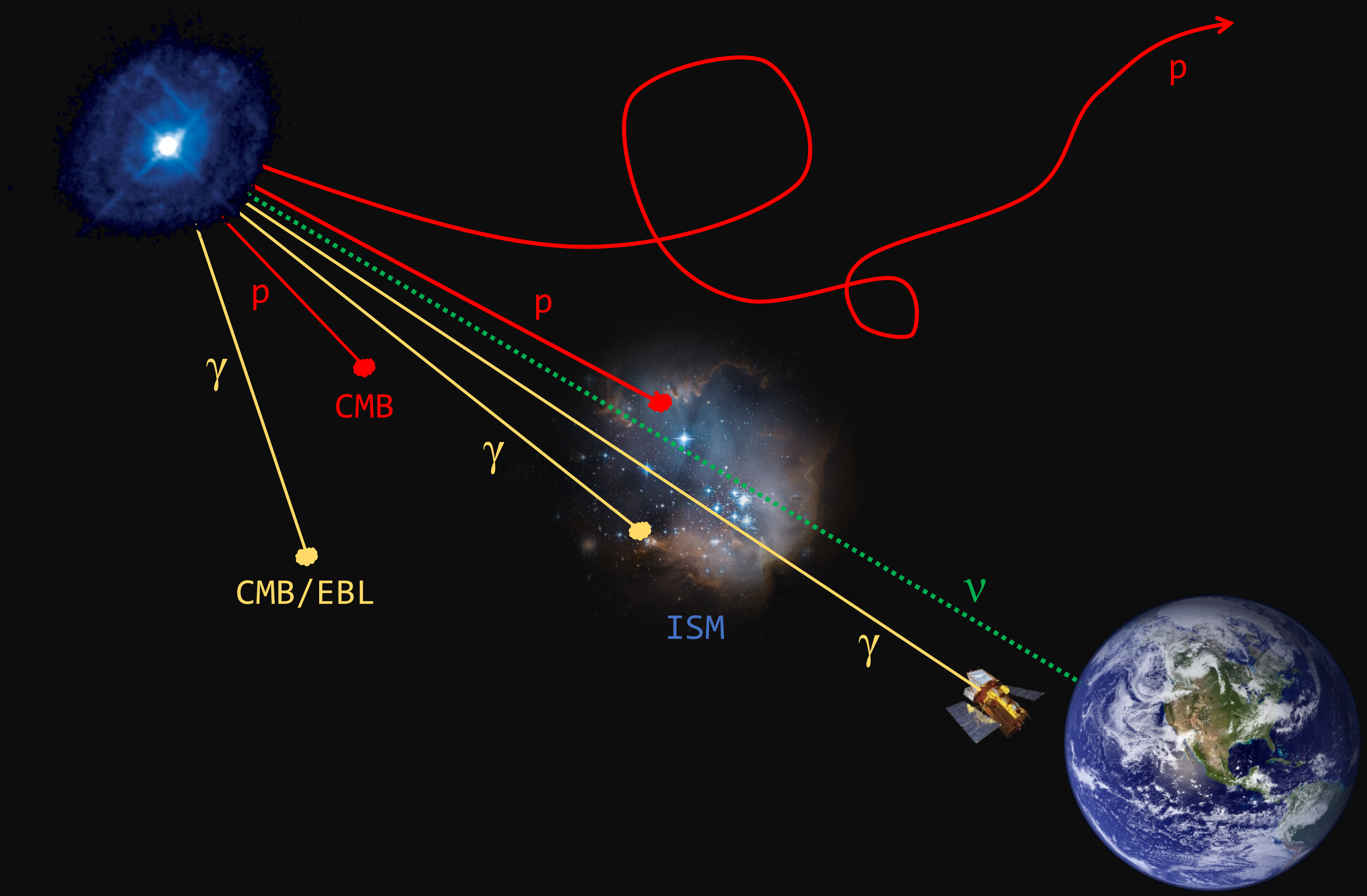
UF | UNIVERSITY of FLORIDA

Imre Bartos | Fall 2019



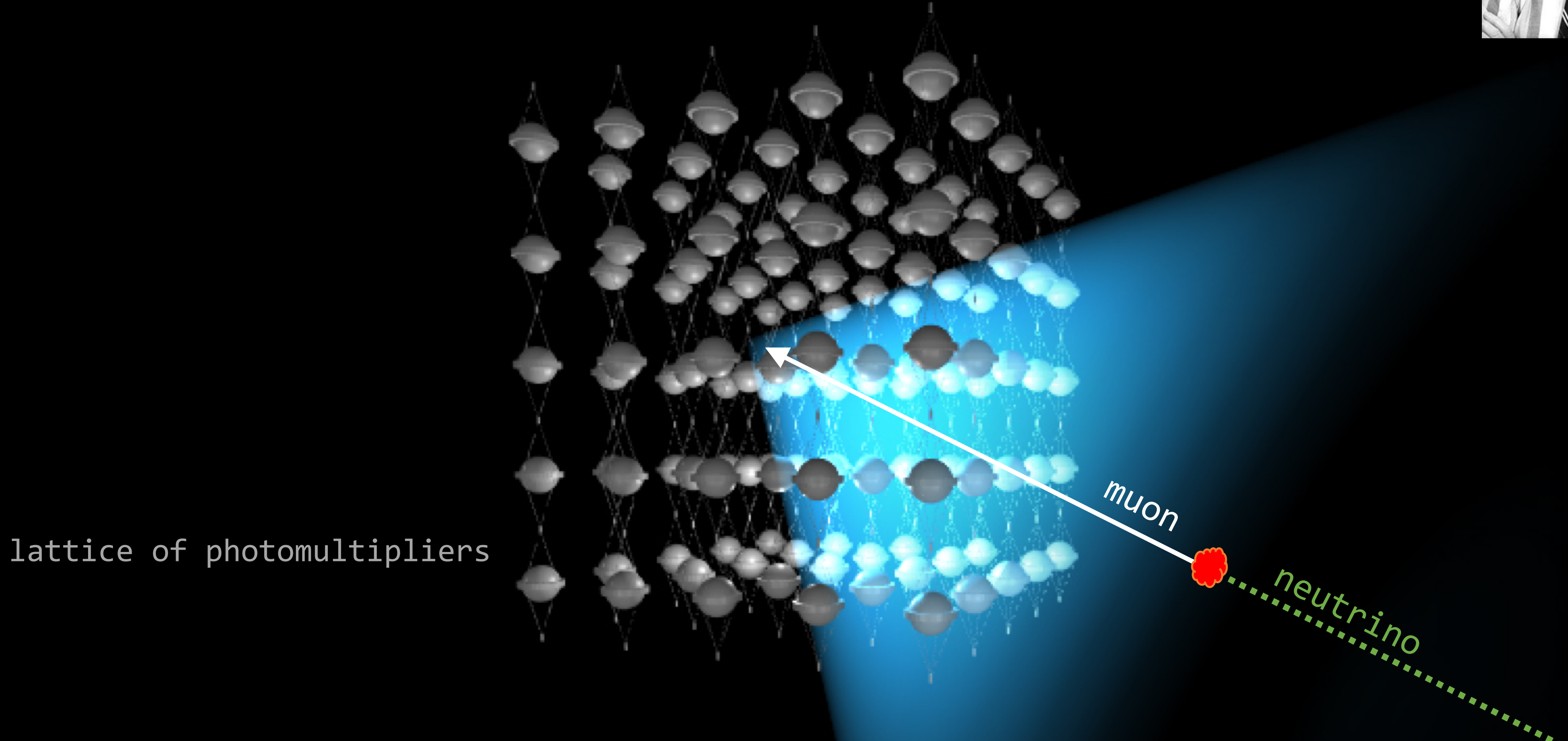
cosmic rays

difficulty finding the origin

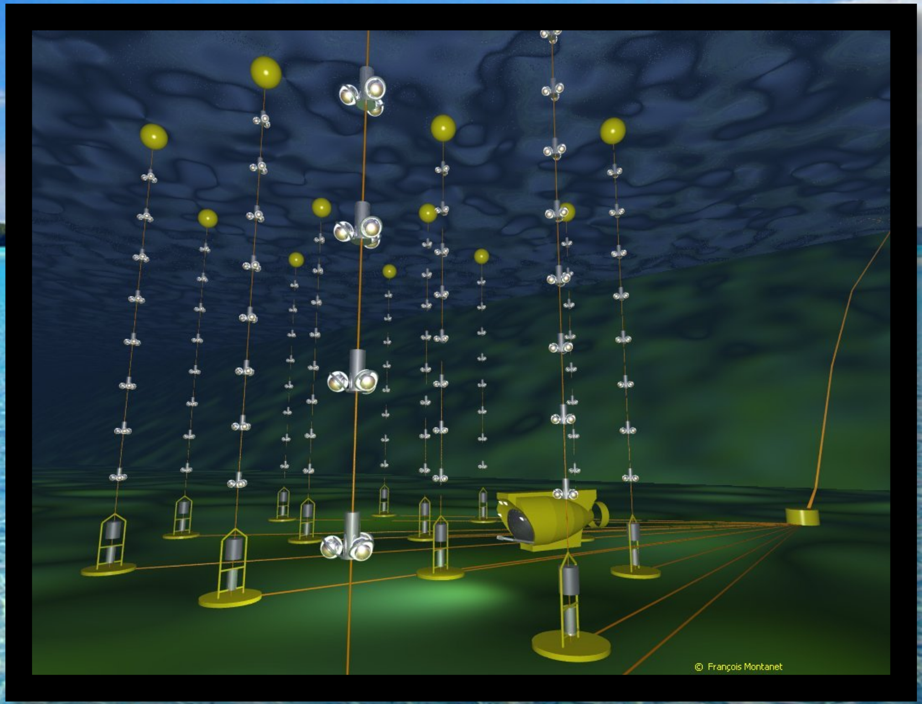


high-energy neutrino detection

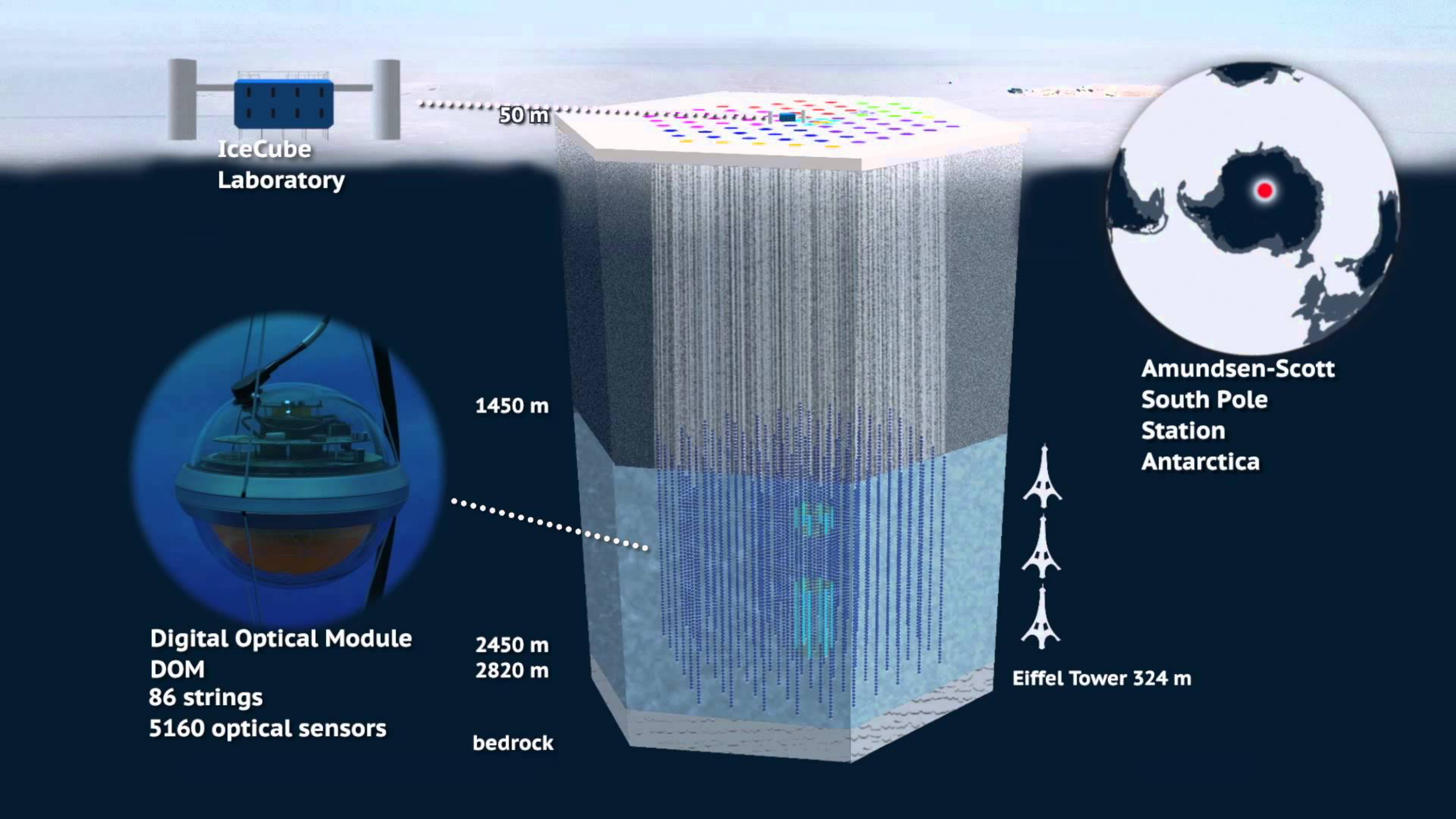
Moisey Markov (1960): we propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.



DUMAND *(Deep Underwater Muon And Neutrino Detector)*

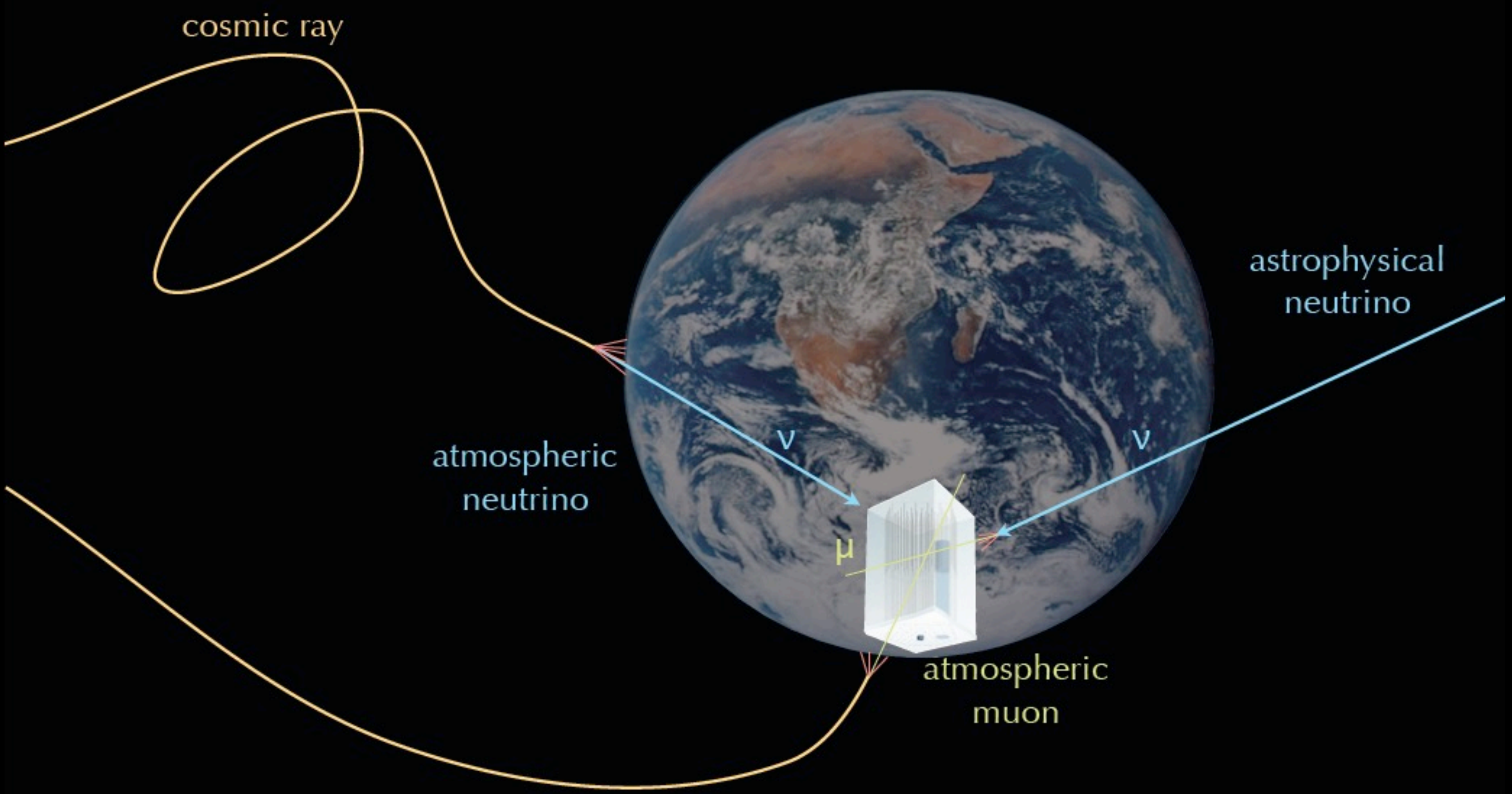


1976–1995

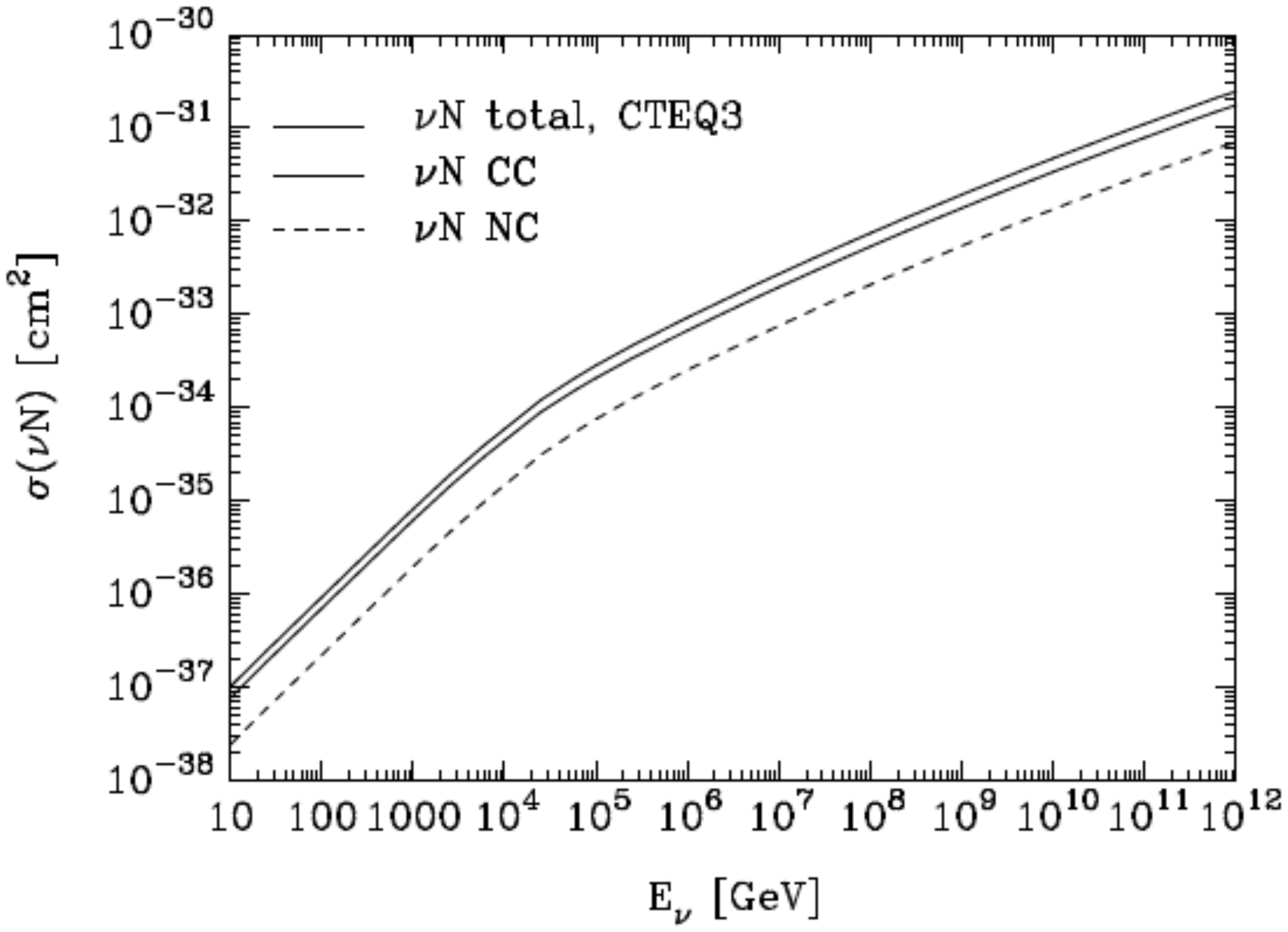


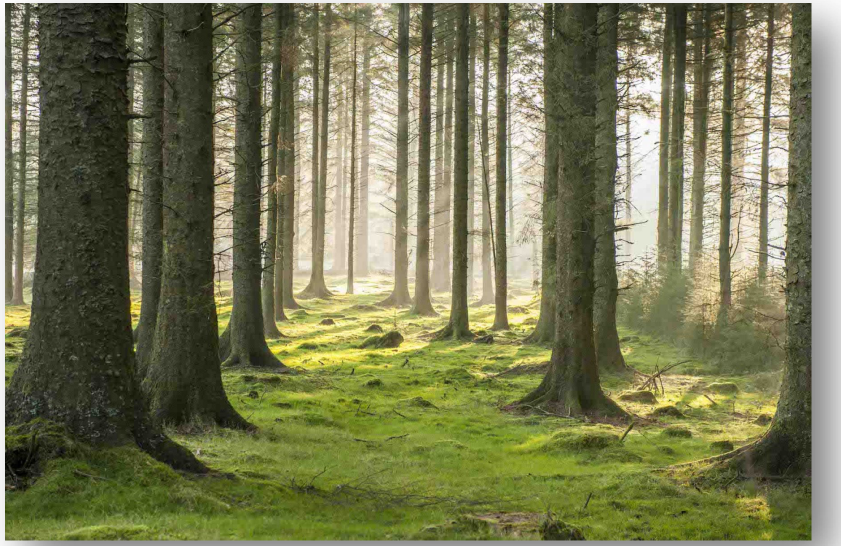
IceCube
Laboratory
50 m
1450 m
2450 m
2820 m
bedrock
Digital Optical Module
DOM
86 strings
5160 optical sensors
Amundsen-Scott
South Pole
Station
Antarctica
Eiffel Tower 324 m

Signals and Backgrounds



Neutrino cross section





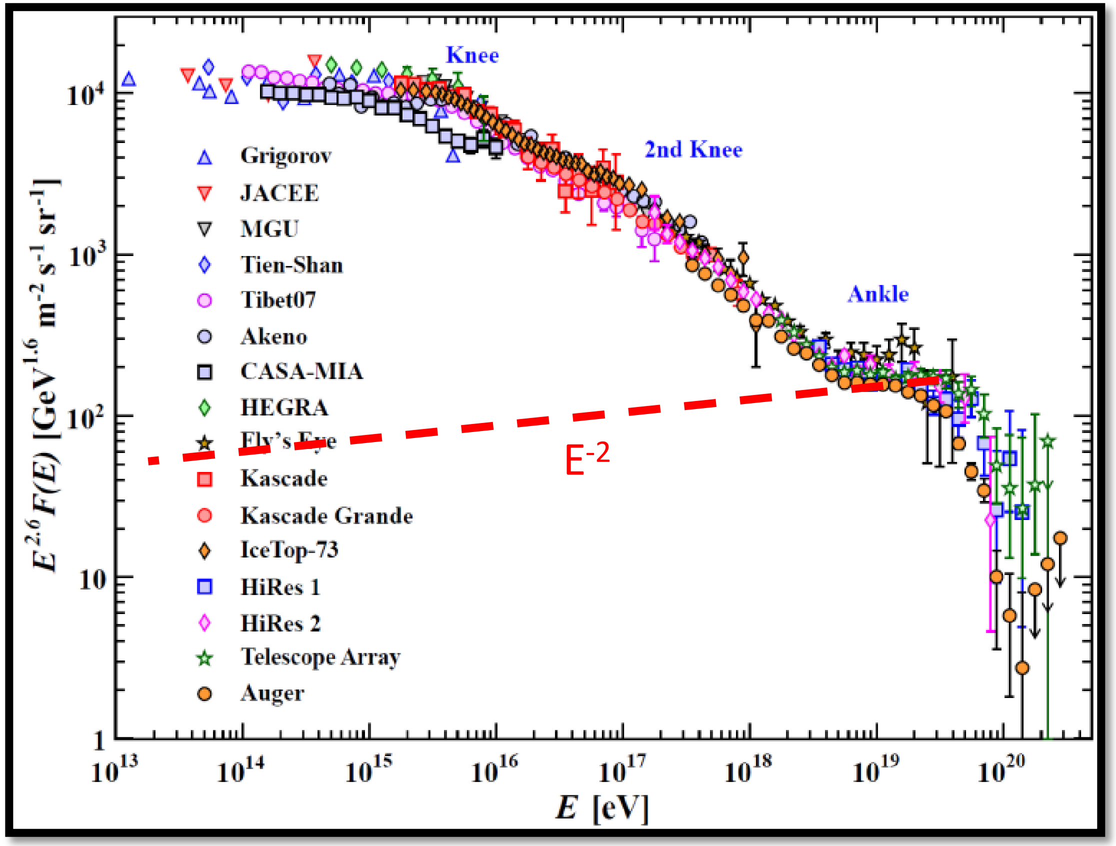
What fraction will cross the Earth at 10 TeV energy? (the energy of the LHC)

$$\frac{\mathrm{d}\Phi}{\mathrm{d}z} = -n\sigma\Phi$$

$$\Phi = \Phi_0 \mathrm{e}^{-n\sigma z}$$

(pp cross section at 10 TeV --- ~10^{-25} cm^2)

Neutrino flux upper bound



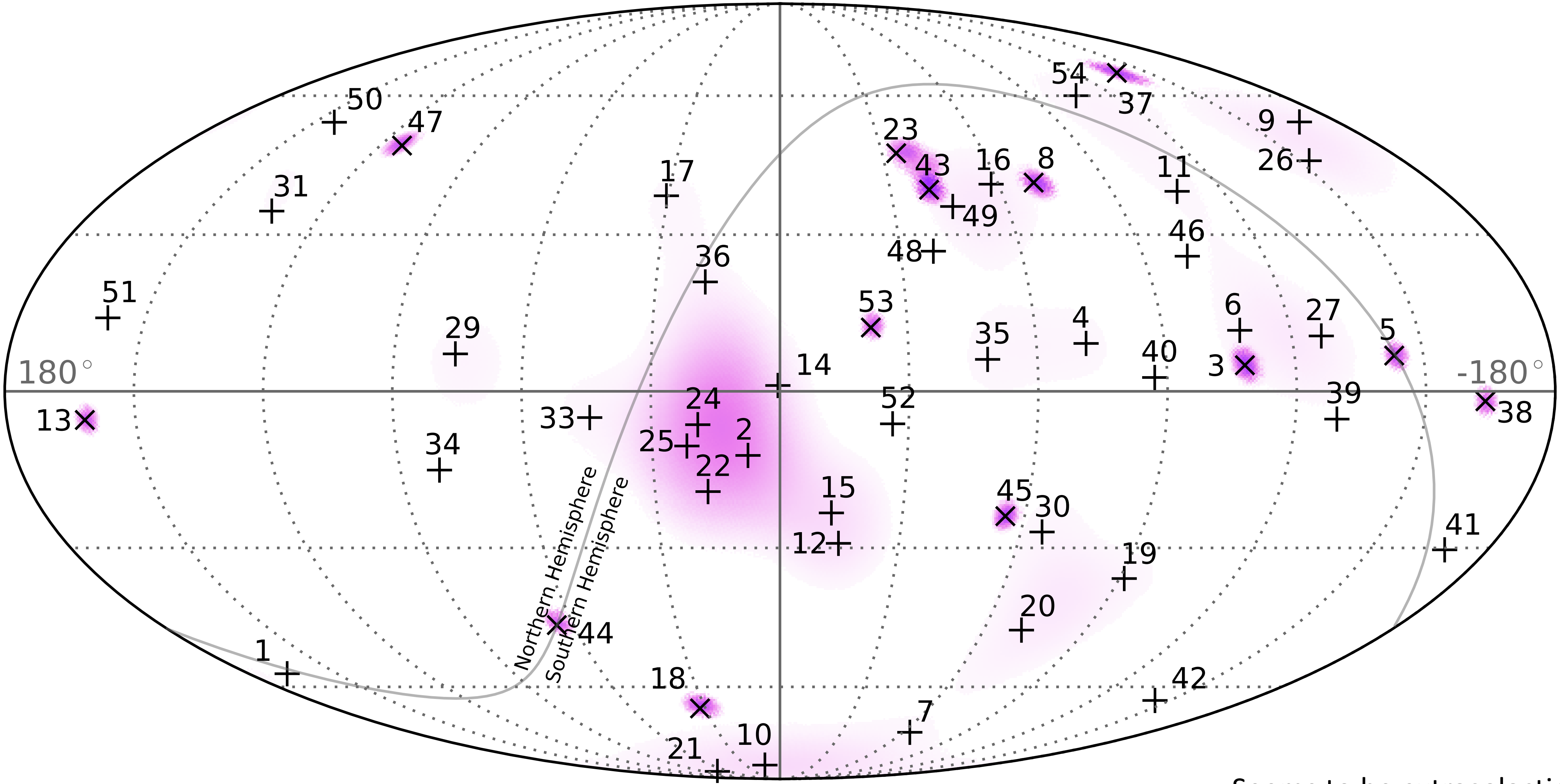
Extragalactic cosmic rays should eventually collide with gas and produce high energy neutrinos.
What will be the neutrino flux if the extragalactic flux

- follows a Fermi spectrum and
- continues down to lower energies?

HW: Should we be afraid of neutrinos when traveling to Mars?

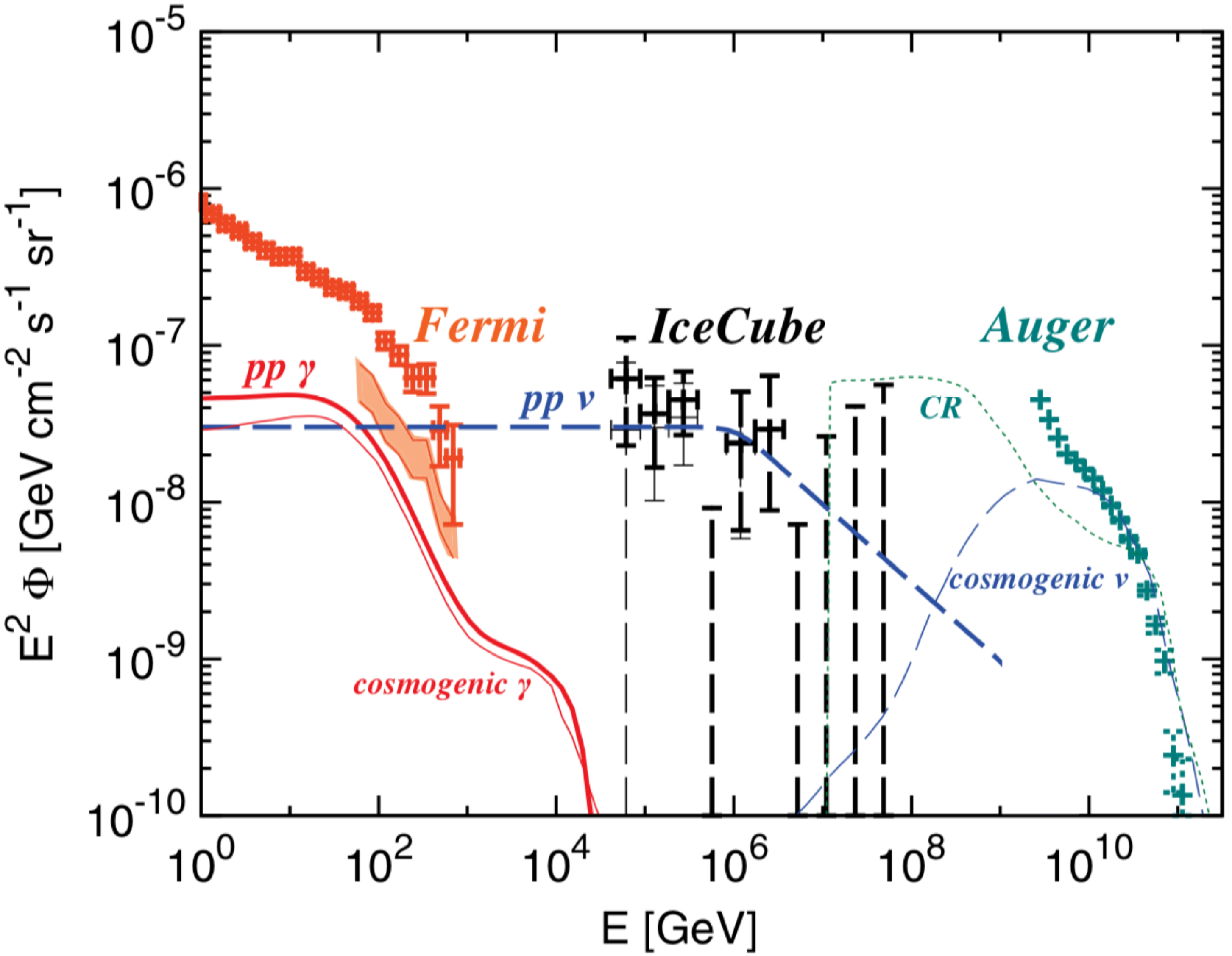
(calculate energy deposited in a human by neutrinos over the duration of the trip and compare to deposition from dangerous levels of radiation)

Detected high-energy neutrinos (>100 TeV)



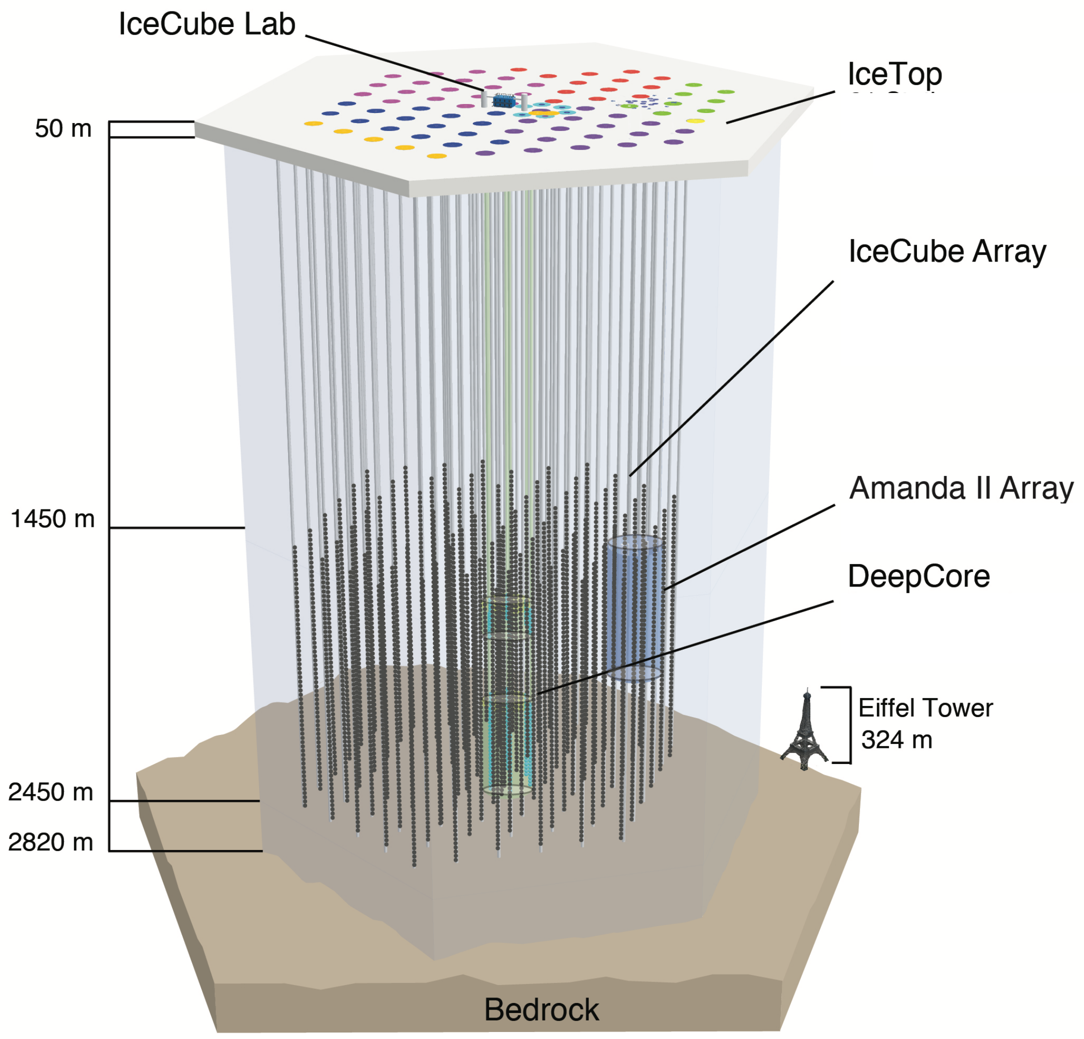
Seems to be extragalactic

The origin of ultrahigh-energy emission



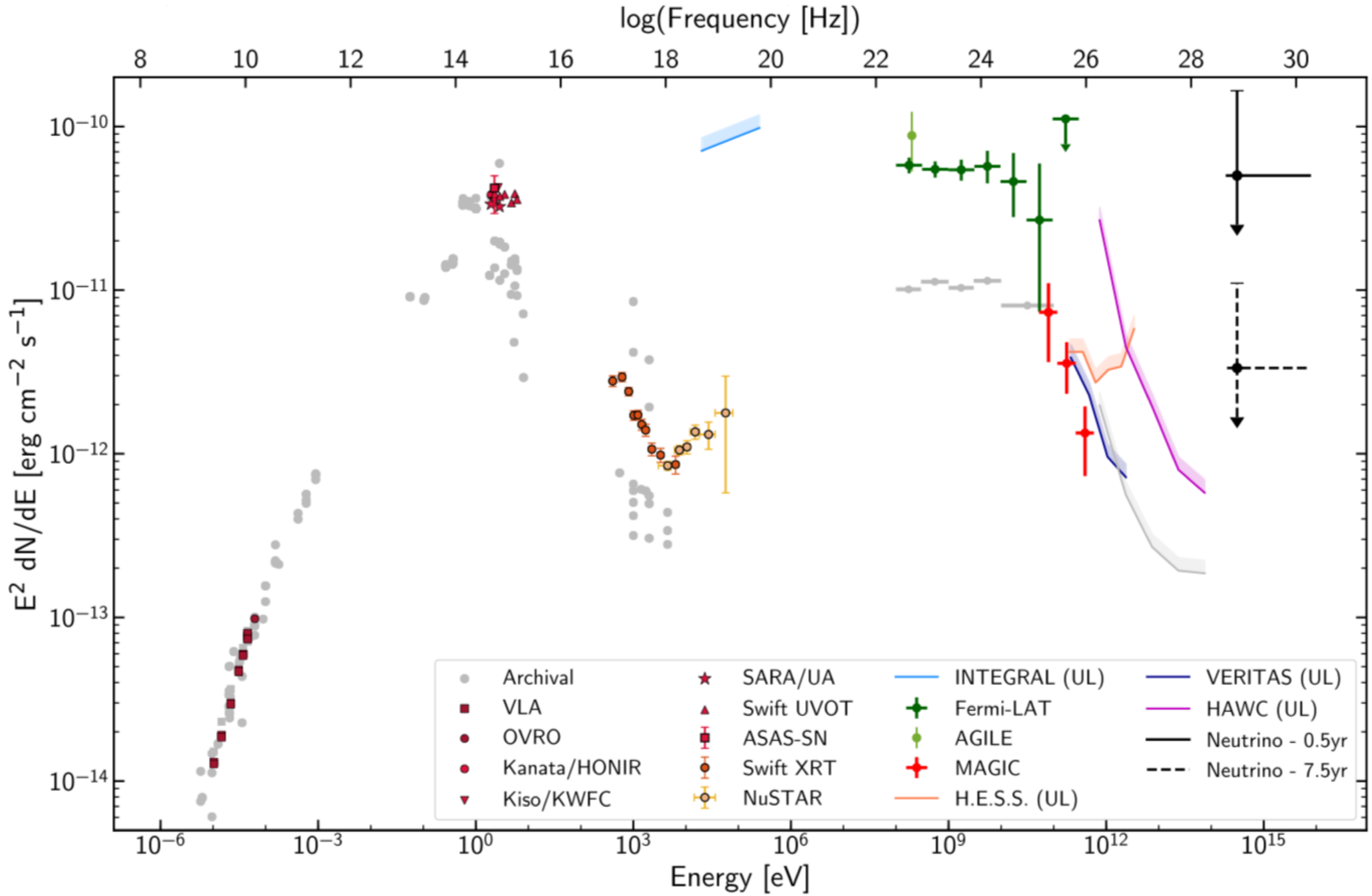
Murase & Waxman 2016

Interesting IceCube alert (IC180922)



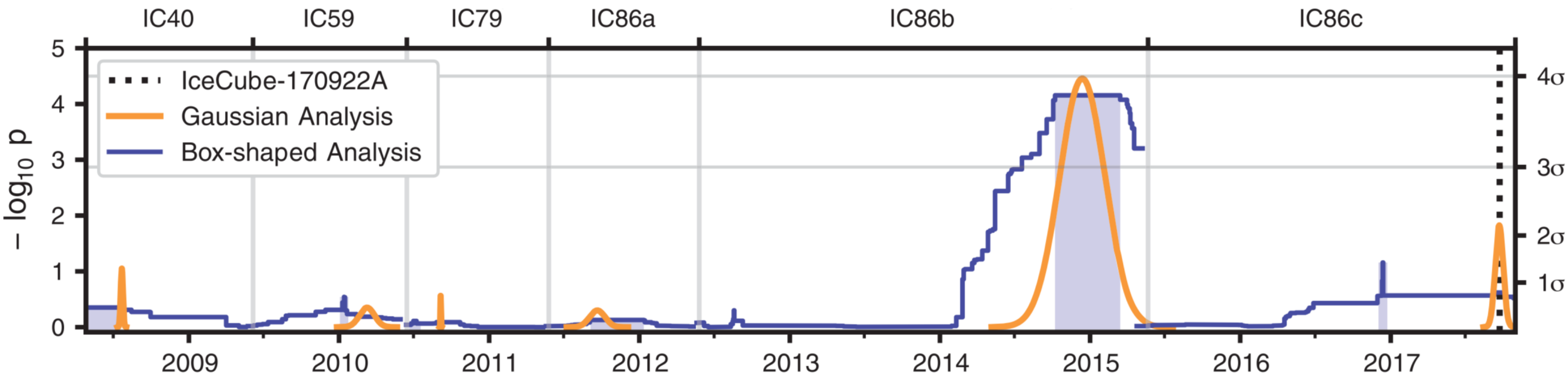
- Interesting neutrinos are sent out as alerts to astronomers.
- Sept 22, 2017 – TXS 0506+56 (290TeV)
- Fermi-LAT finds directionally coincident blazar.
- The blazar is flaring.
- MAGIC detected very high energy gamma rays up to 400 GeV.

TXS 0506+56 blazar spectrum



IceCube+ 2018

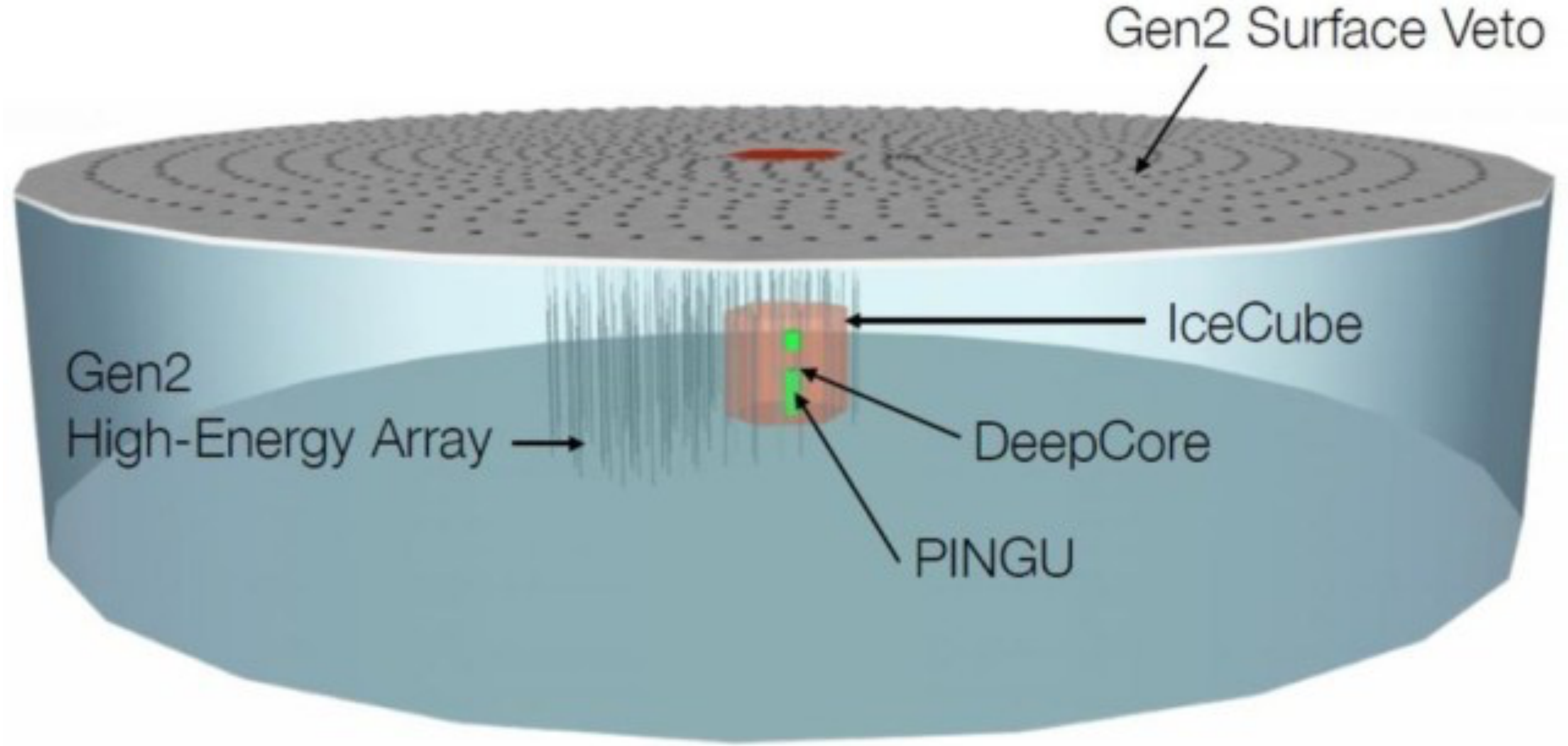
The blazar was also active in the past



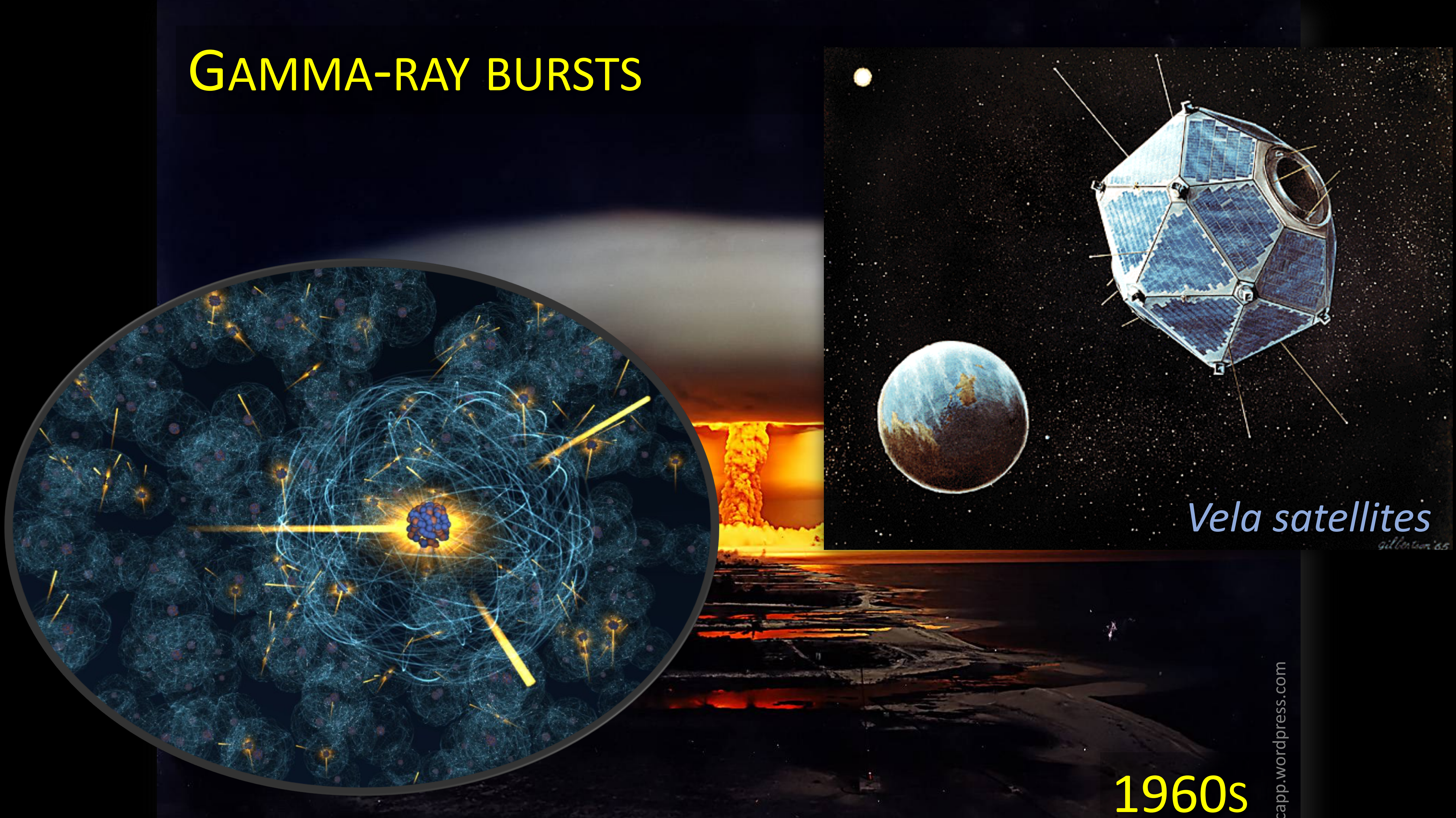
- An excess of 13 additional neutrinos.
- NOT coincident with flaring.

IceCube 2018

IceCube-Gen2



GAMMA-RAY BURSTS

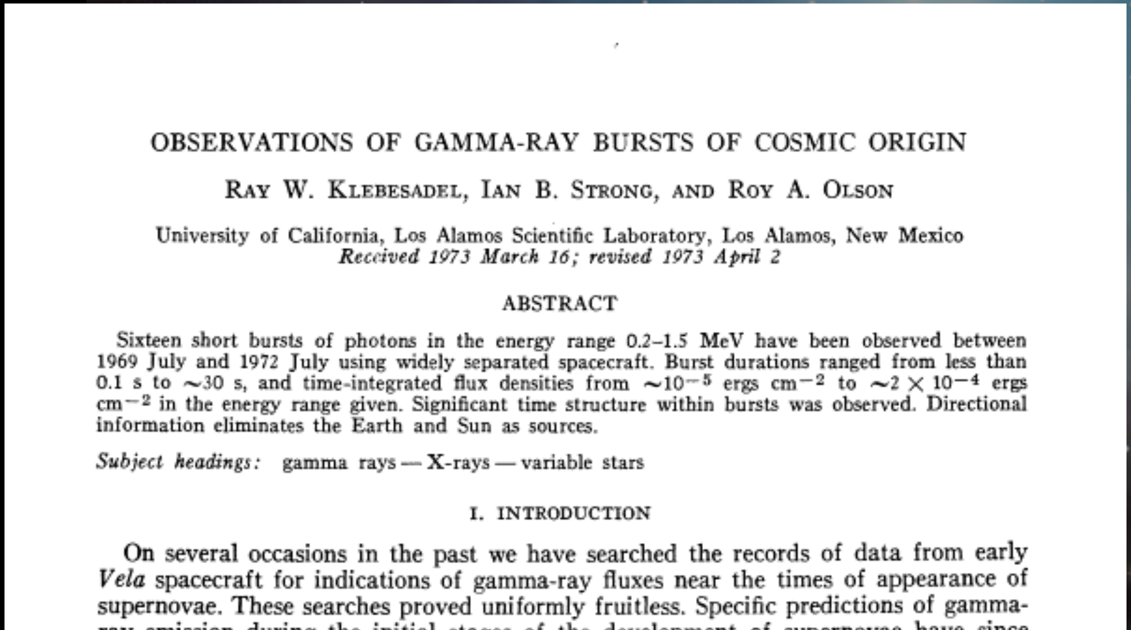


1960s

http://www.youtube.com/watch?v=LLCF7vPanrY

GAMMA-RAY BURSTS

?



OBSERVATIONS OF GAMMA-RAY BURSTS OF COSMIC ORIGIN

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Received 1973 March 16; revised 1973 April 2

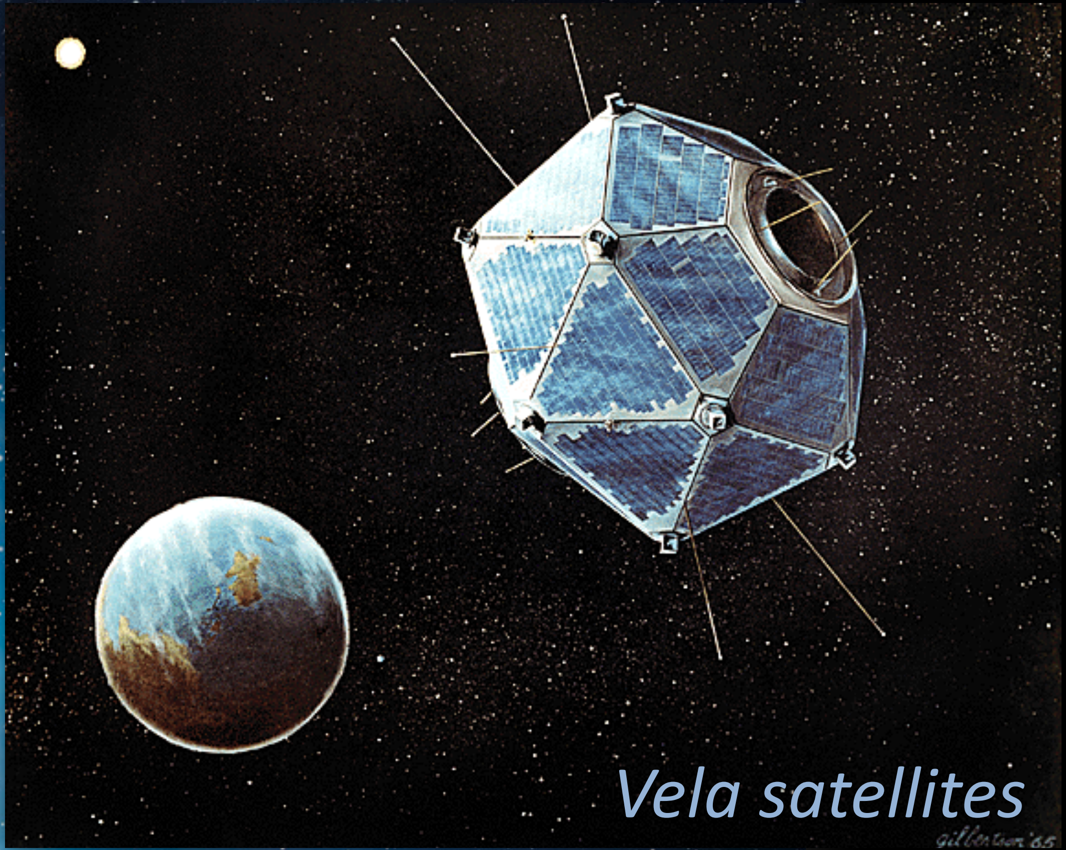
ABSTRACT

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

I. INTRODUCTION

On several occasions in the past we have searched the records of data from early *Vela* spacecraft for indications of gamma-ray fluxes near the times of appearance of supernovae. These searches proved uniformly fruitless. Specific predictions of gamma-



1960s

www.universetoday.com

GAMMA-RAY BURSTS

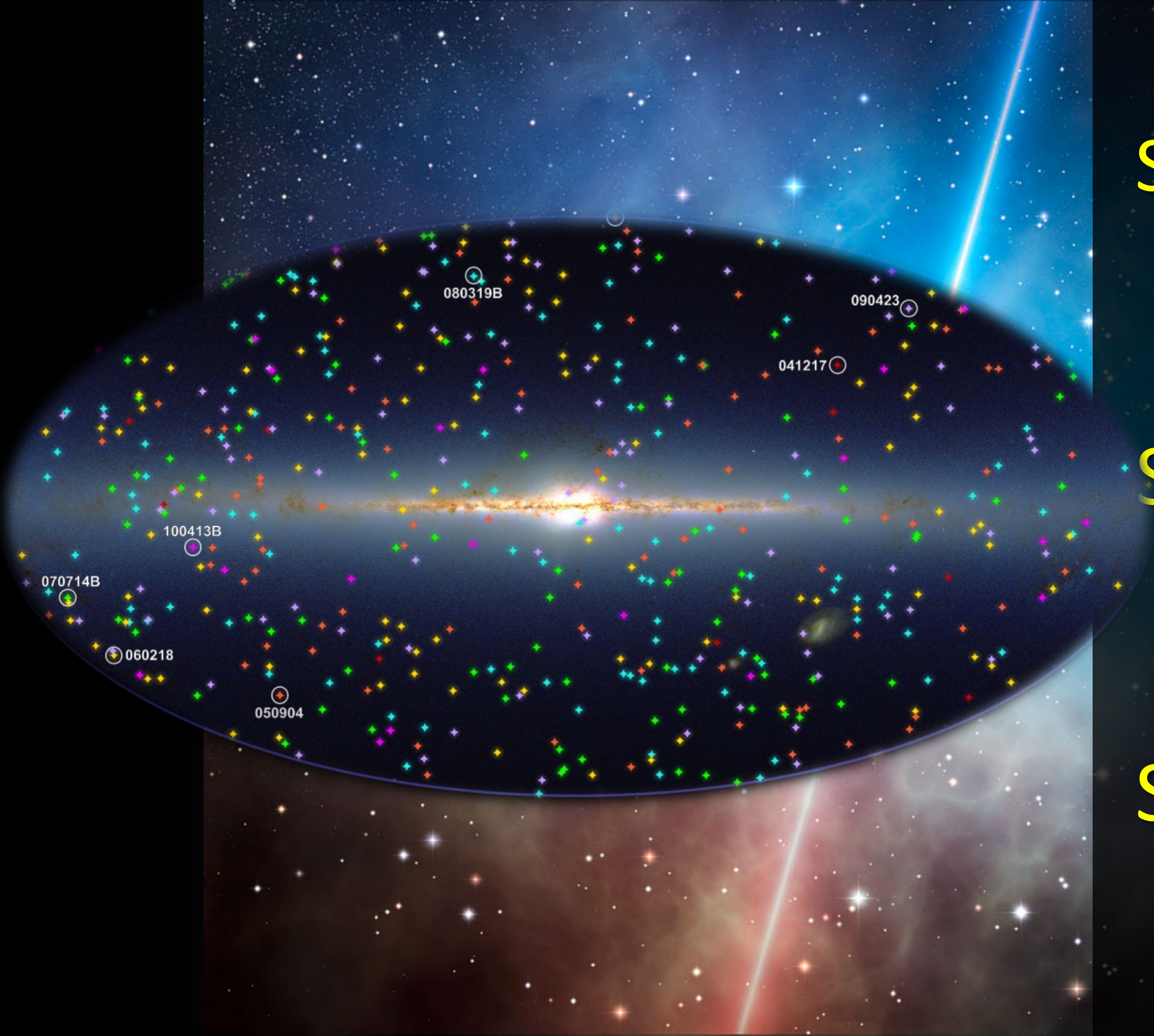
ORIGIN?

STRENGTH

SIZE

SOURCE

GAMMA-RAY BURSTS



ORIGIN?

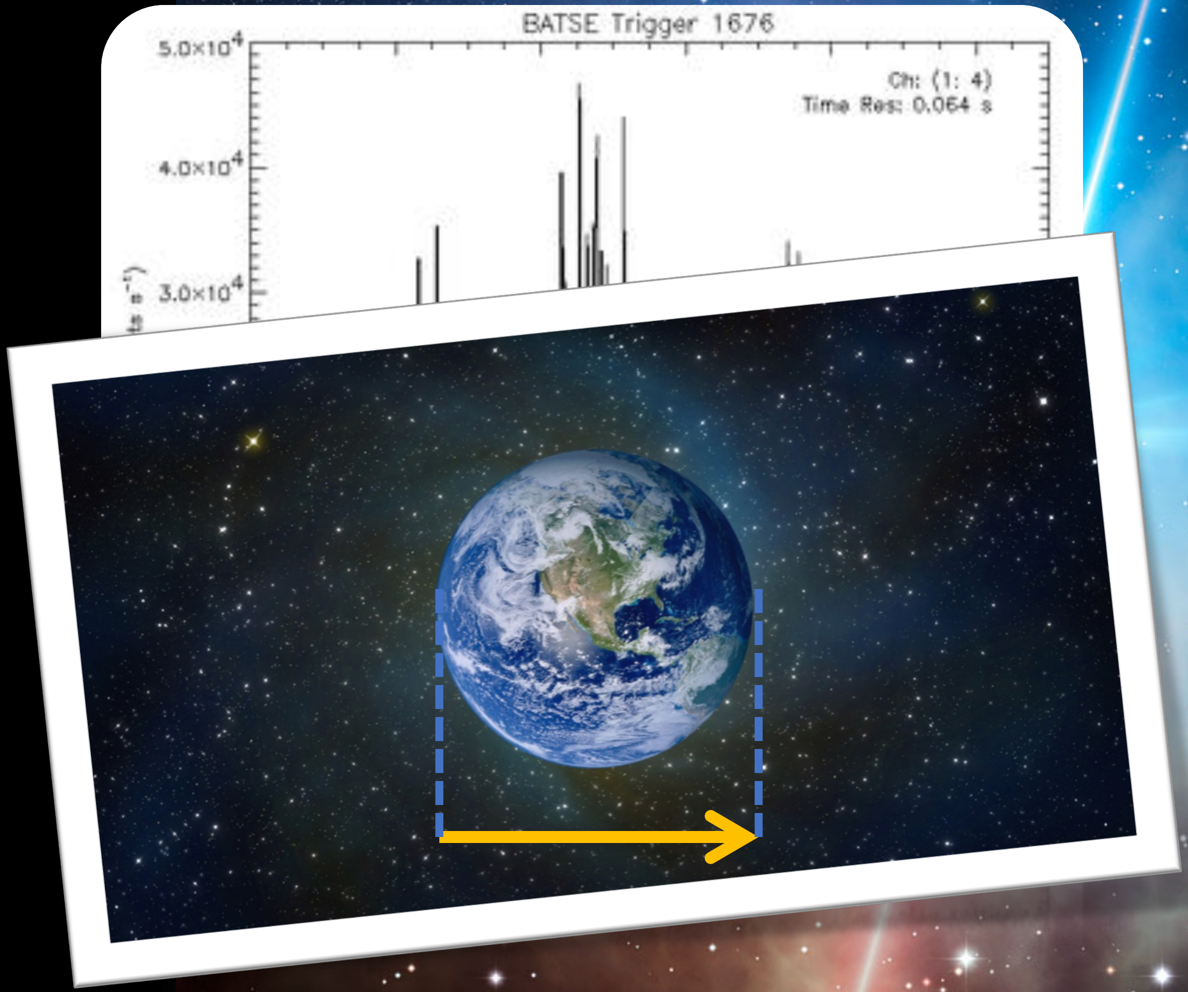
STRENGTH

EXTRAGALACTIC → ENERGETIC

SIZE

SOURCE

Gamma-ray bursts



Origin?

Strength — Extragalactic → energetic

Size — Small! (< Earth)

Source

Gamma-ray bursts

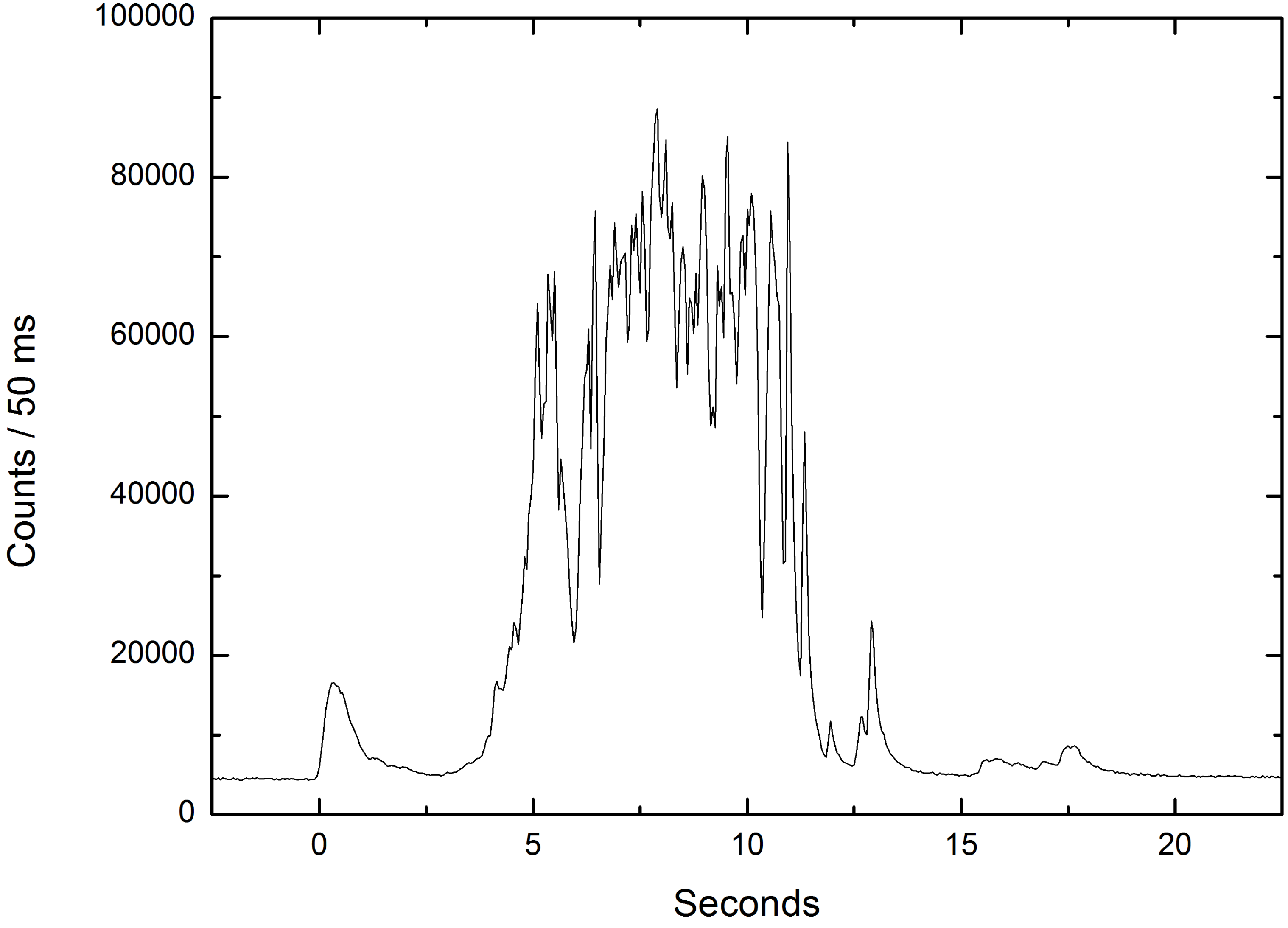
Origin?

Strength — Extragalactic → energetic

Size — Small! (< Earth)

Source
1. Massive stars
2. Binary mergers

Light curves

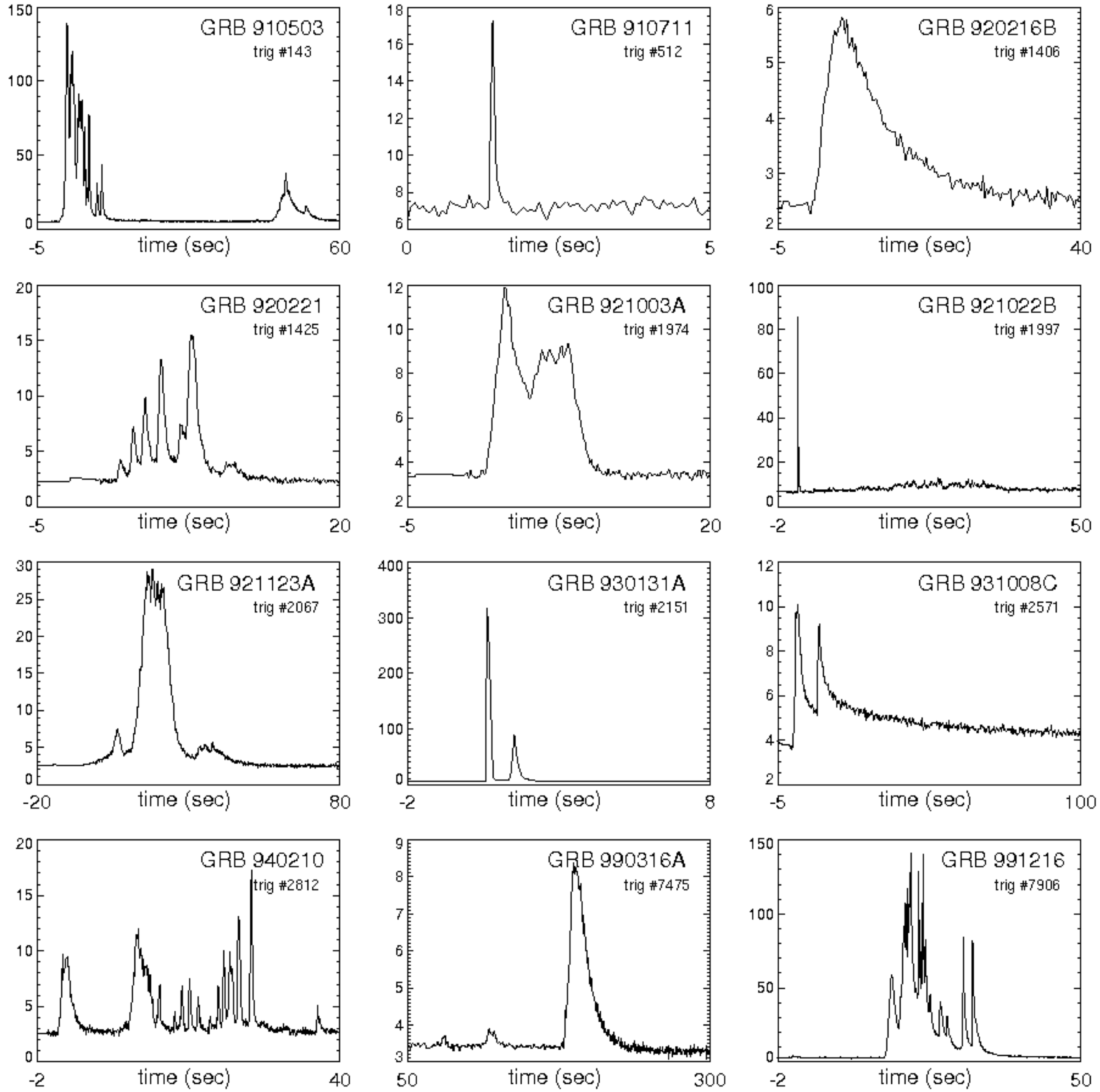


Light curves

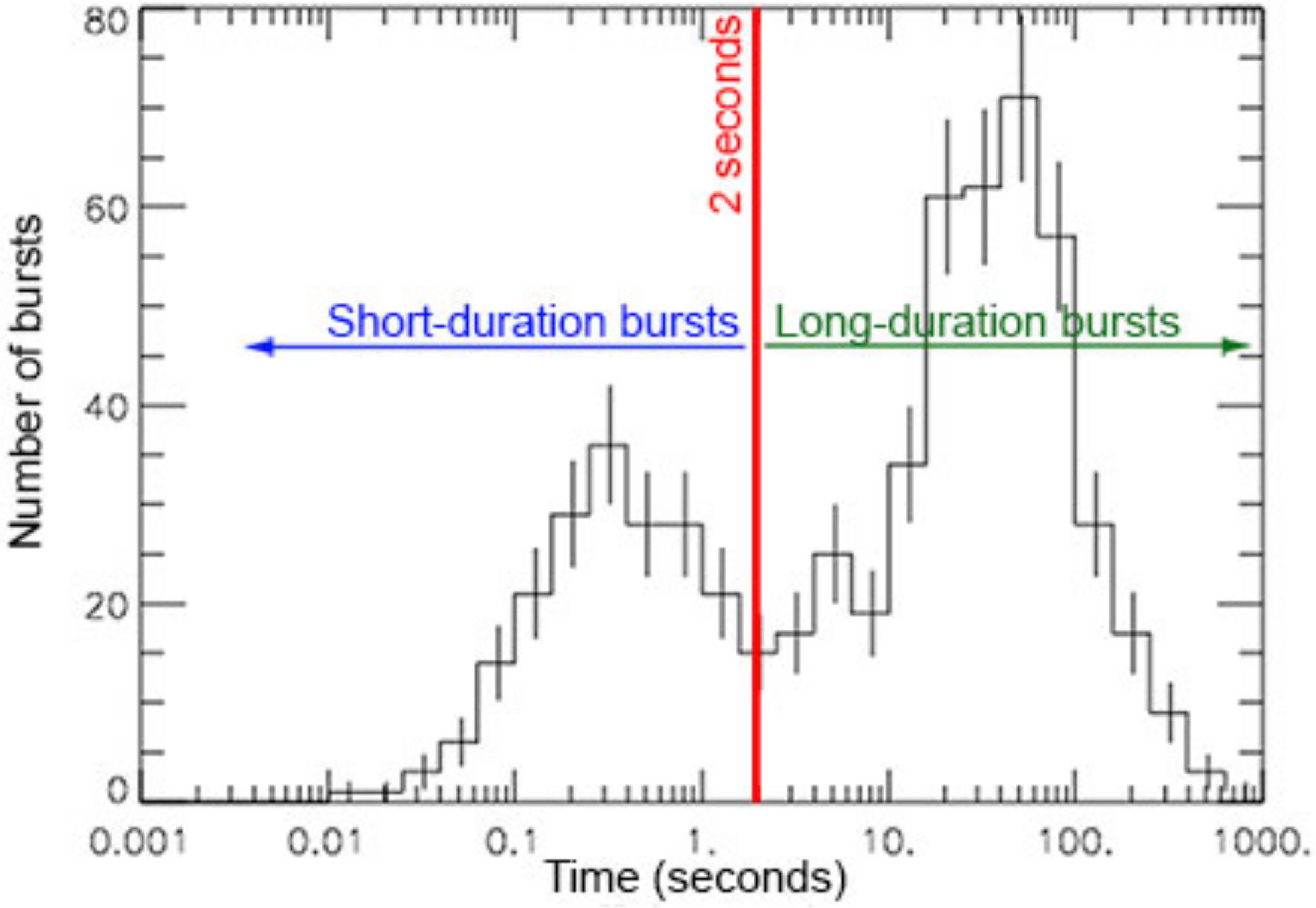
No two GRB light curves are identical.

Duration: milliseconds - minutes

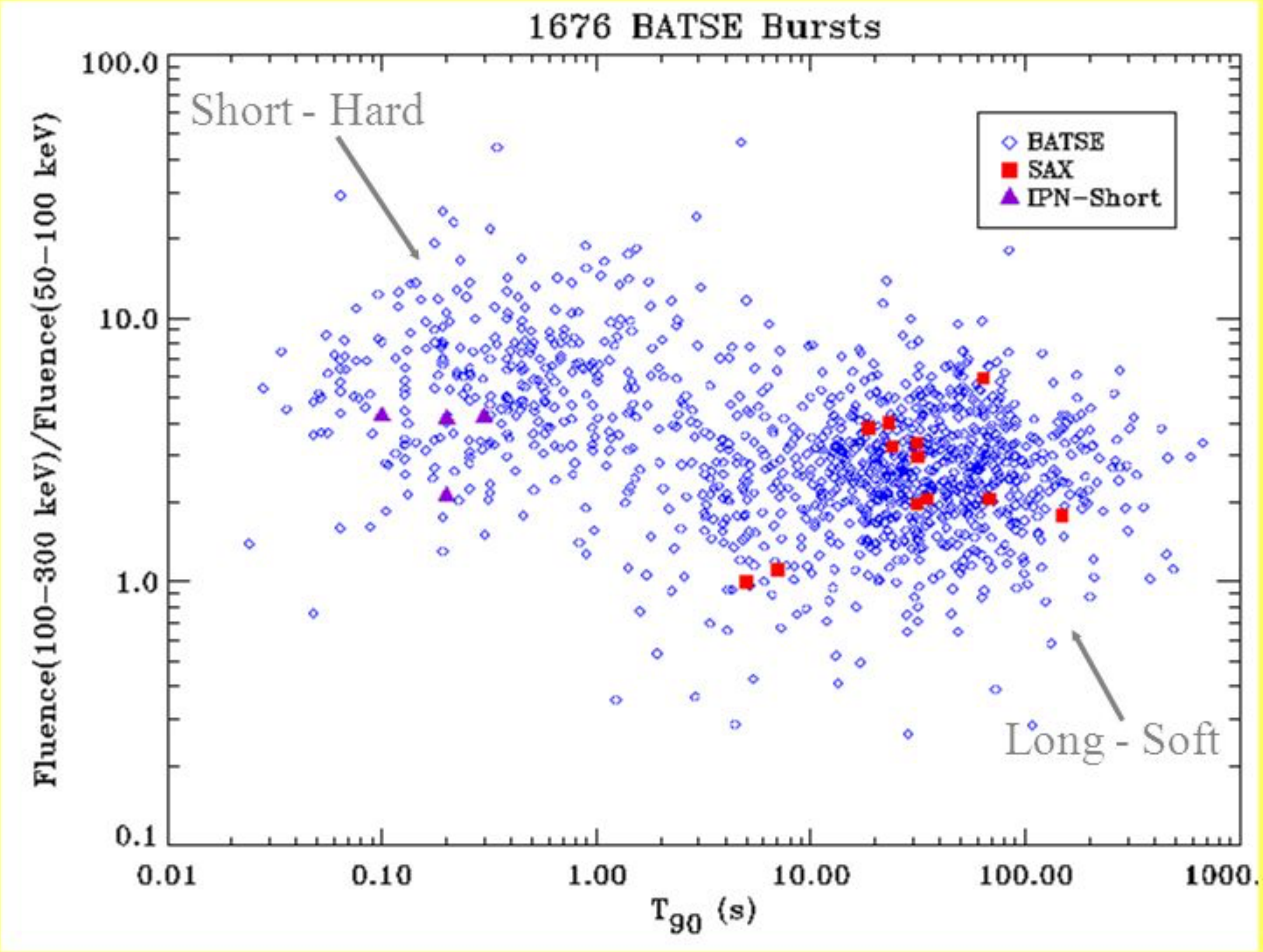
Some are not continuous (precursors).



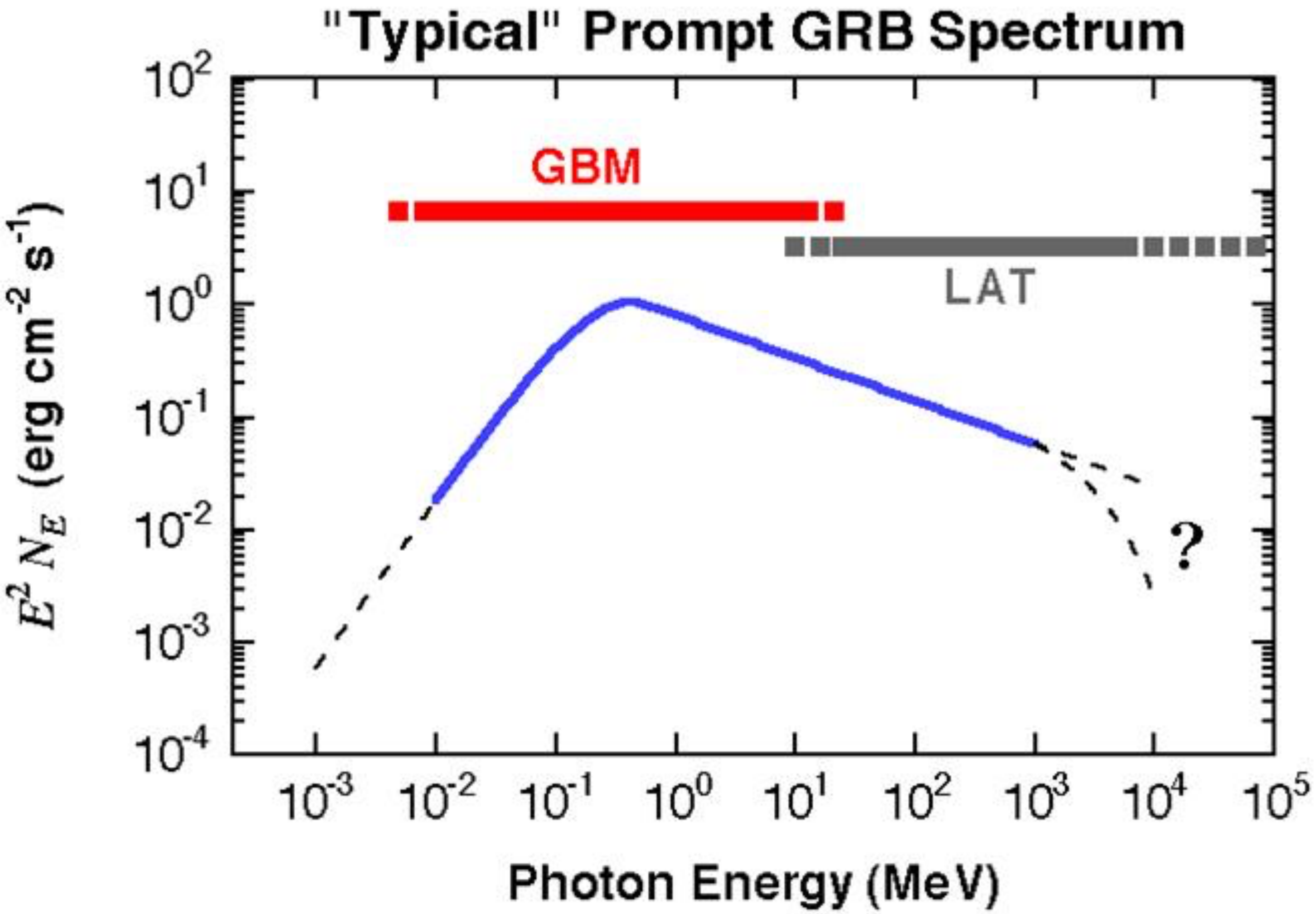
Long vs short GRBs



Two classes of GRBs



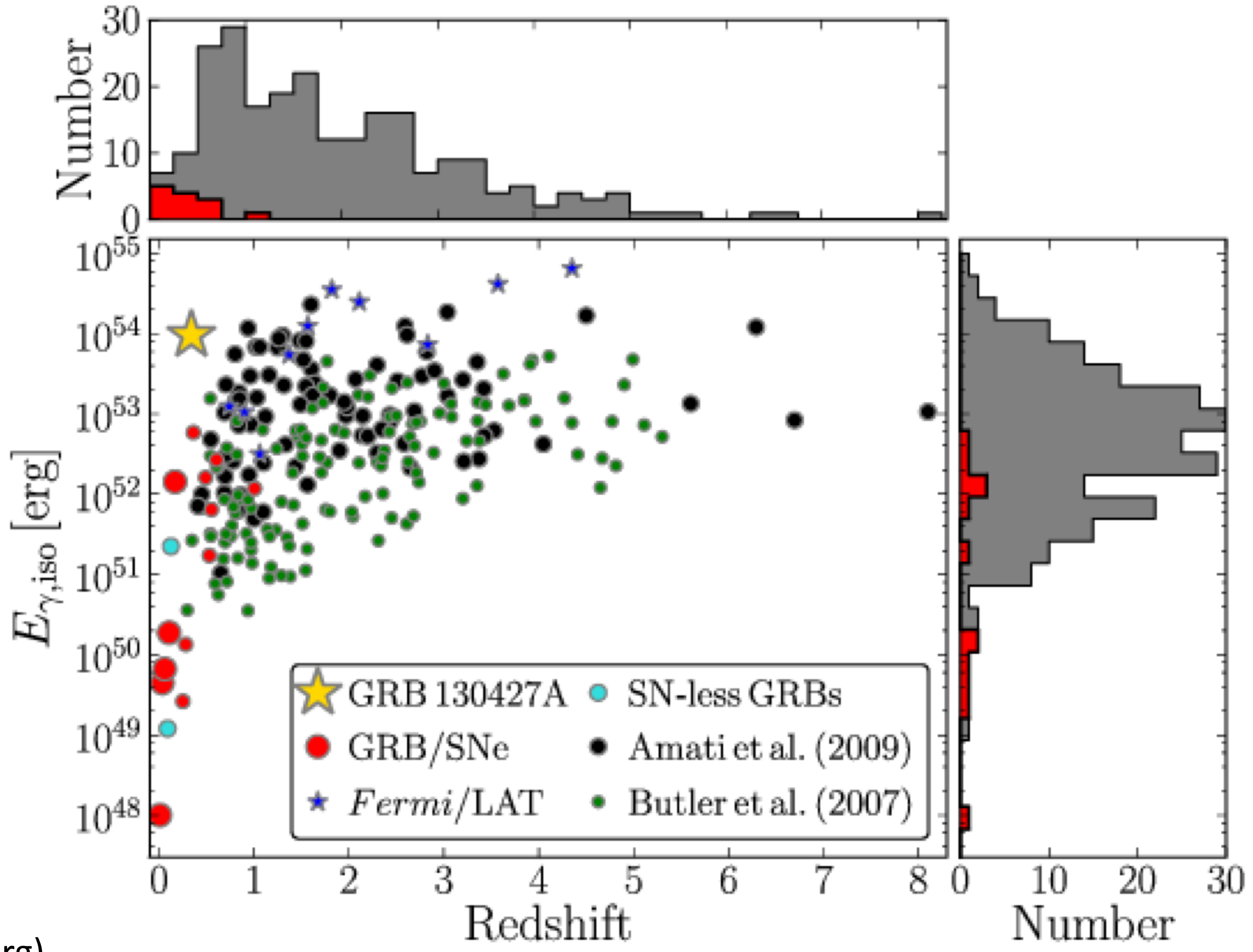
GRB spectrum



Band spectrum
(broken power-law)

$$N(E) = \begin{cases} N_0 \left(\dfrac{E}{100\ \mathrm{keV}}\right)^{\alpha} \exp\left[-\dfrac{E}{E_0}\right], & E \le E_b \\ N_0 \left(\dfrac{E_b}{100\ \mathrm{keV}}\right)^{\alpha-\beta} \exp[\beta-\alpha] \left(\dfrac{E}{100\ \mathrm{keV}}\right)^{\beta}, & E > E_b \end{cases} \quad (1)$$

Energetics



(solar mass = 1.8 x 10^{54} erg)

Fireball model

Luminosity is many orders of magnitude beyond the Eddington luminosity:

$$L_{\mathrm{E}} = 4\pi G M m_{\mathrm{p}} c/\sigma_{\mathrm{T}} = 1.25 \times 10^{38}\,(M/M_{\odot})\,\mathrm{erg\,s^{-1}}$$

So the high-temperature plasma expands → <u>outflow</u>.

For very high luminosities, the large density of gamma photons could make the fireball opaque to photons for energies above 0.5 MeV.

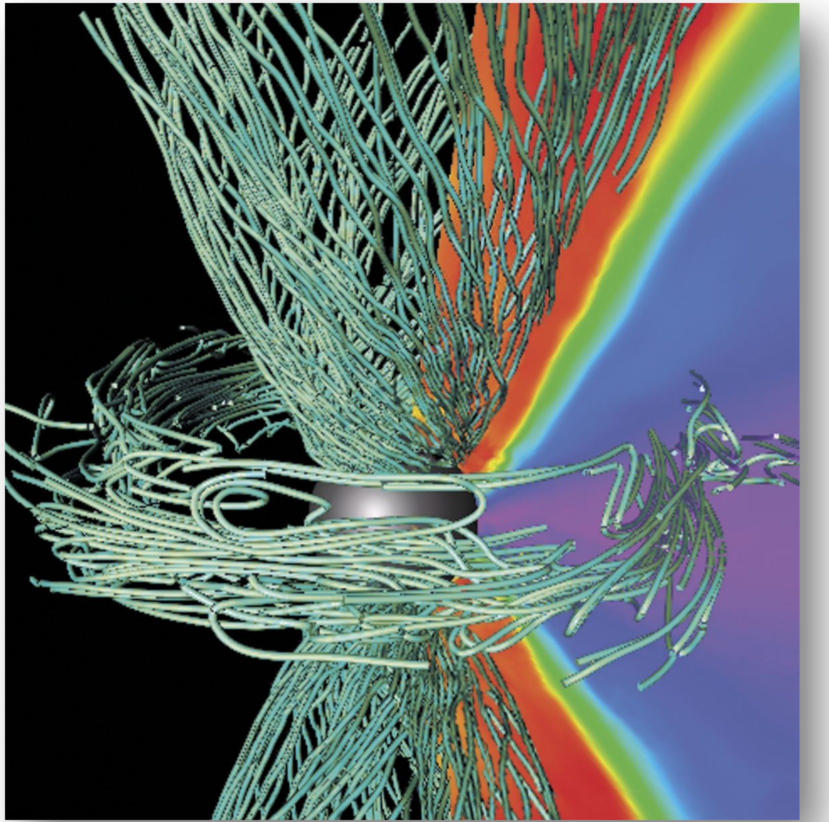
$$\gamma\gamma \rightarrow e^{\pm} \qquad\qquad m_{\mathrm{e}}c^2 = 0.511\,\mathrm{MeV}$$

But many GRB photons are >> 0.5 MeV → outflow needs to be <u>relativistic</u> (so it is less dense)

Total energy, as seen, is much more than what stellar core collapse and other events are thought to be able to produce → <u>beaming</u> (all the radiation is focused into some jet, so the total luminosity is not that high.)

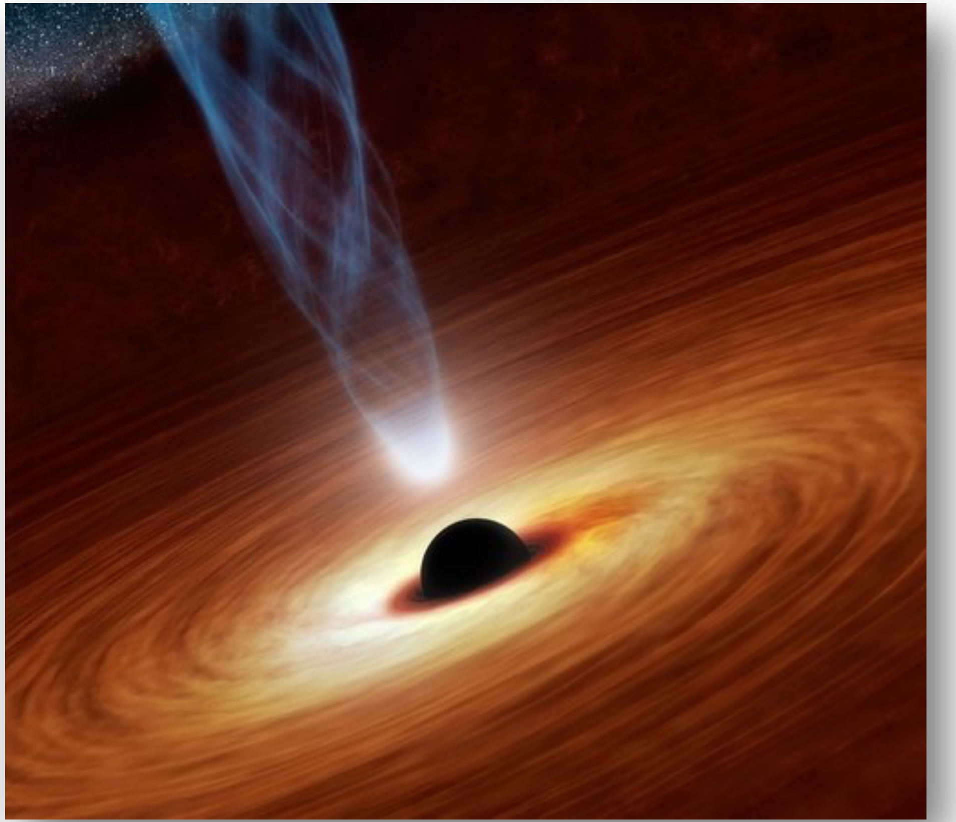
Meszaros RPP 2006

Relativistic outflow

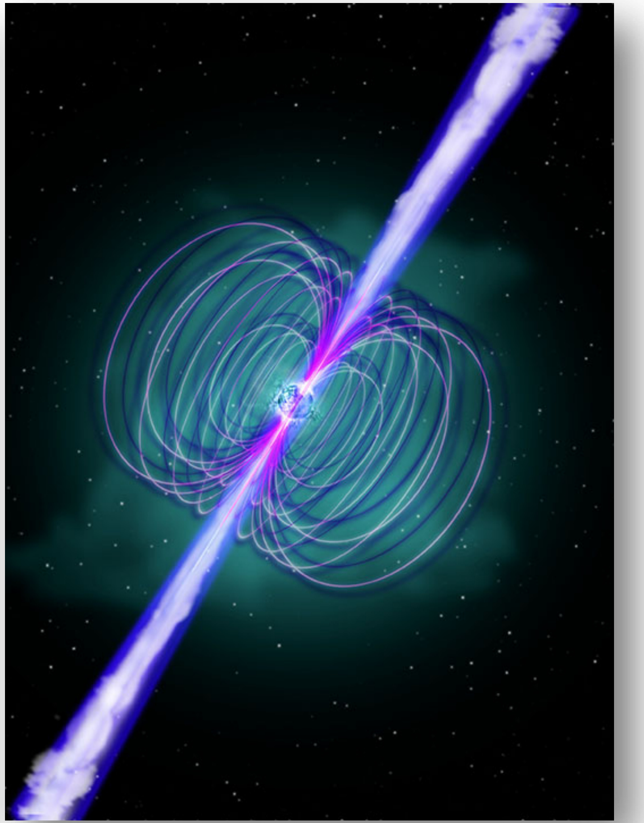


Magnetic field lines should be important (but we don't really know)

http://sites.krieger.jhu.edu/astronomy/numerical-simulations/



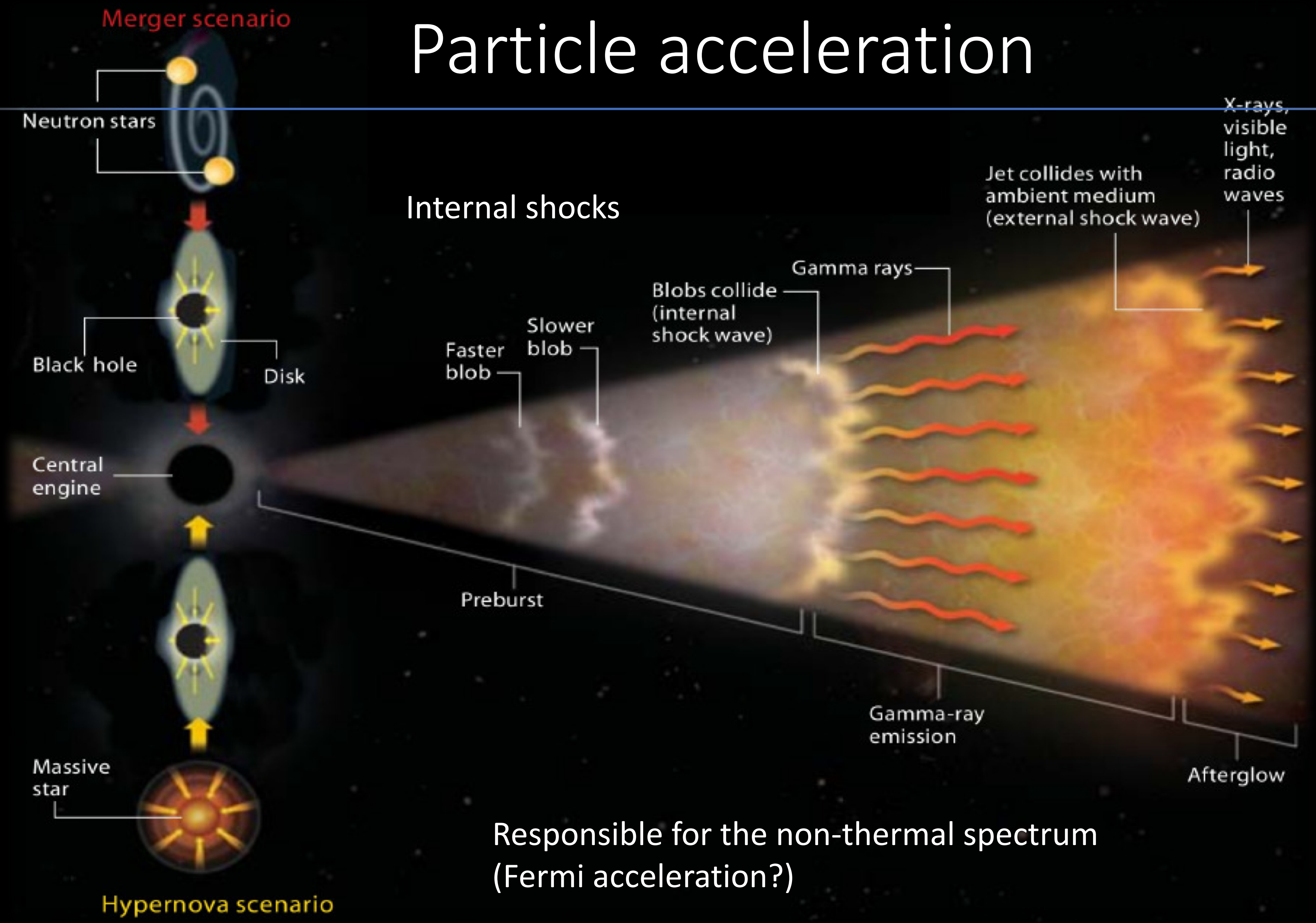
Accreting black hole



Magnetar
(neutron star with strong magnetic fields)

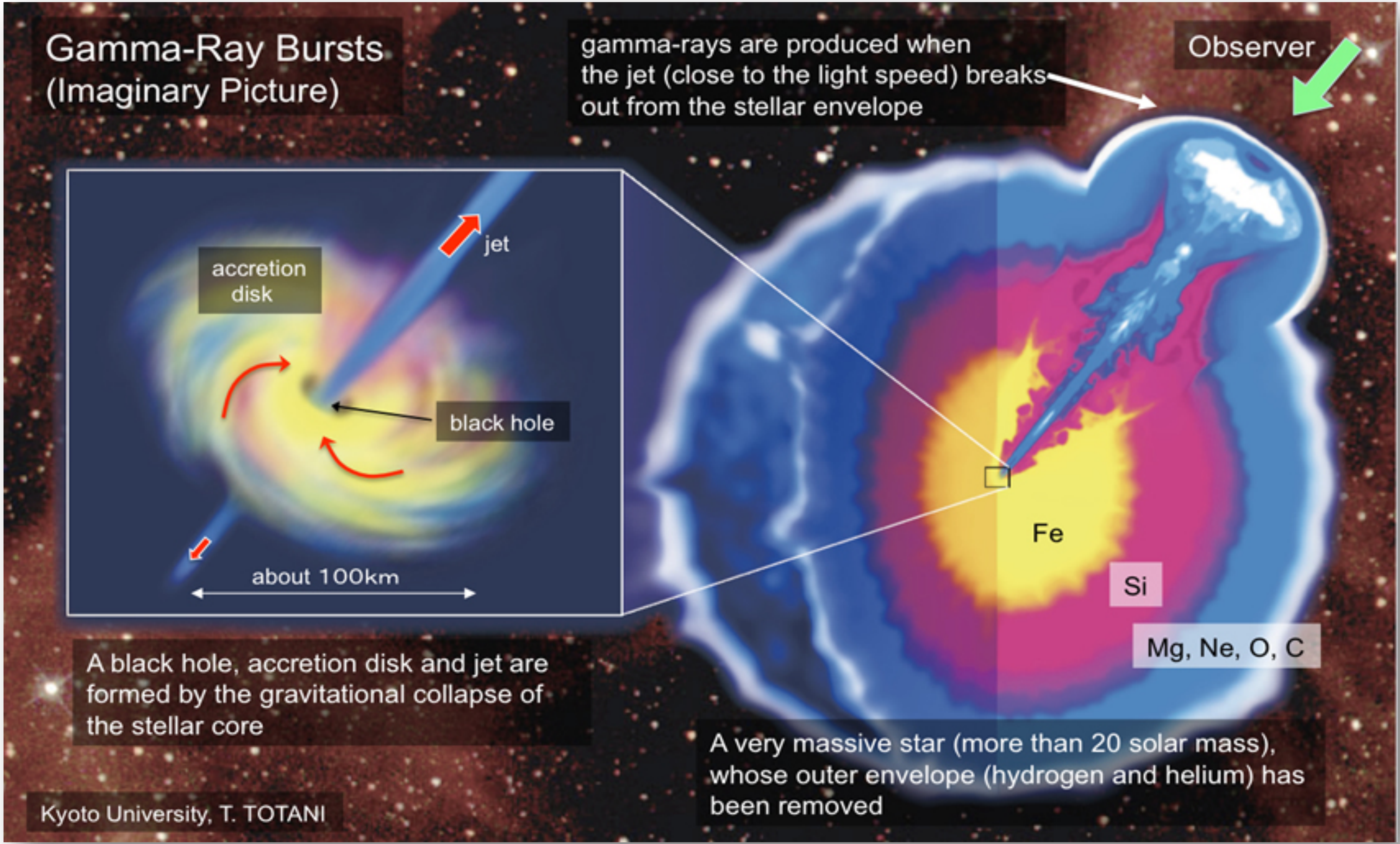
Particle acceleration

Internal shocks

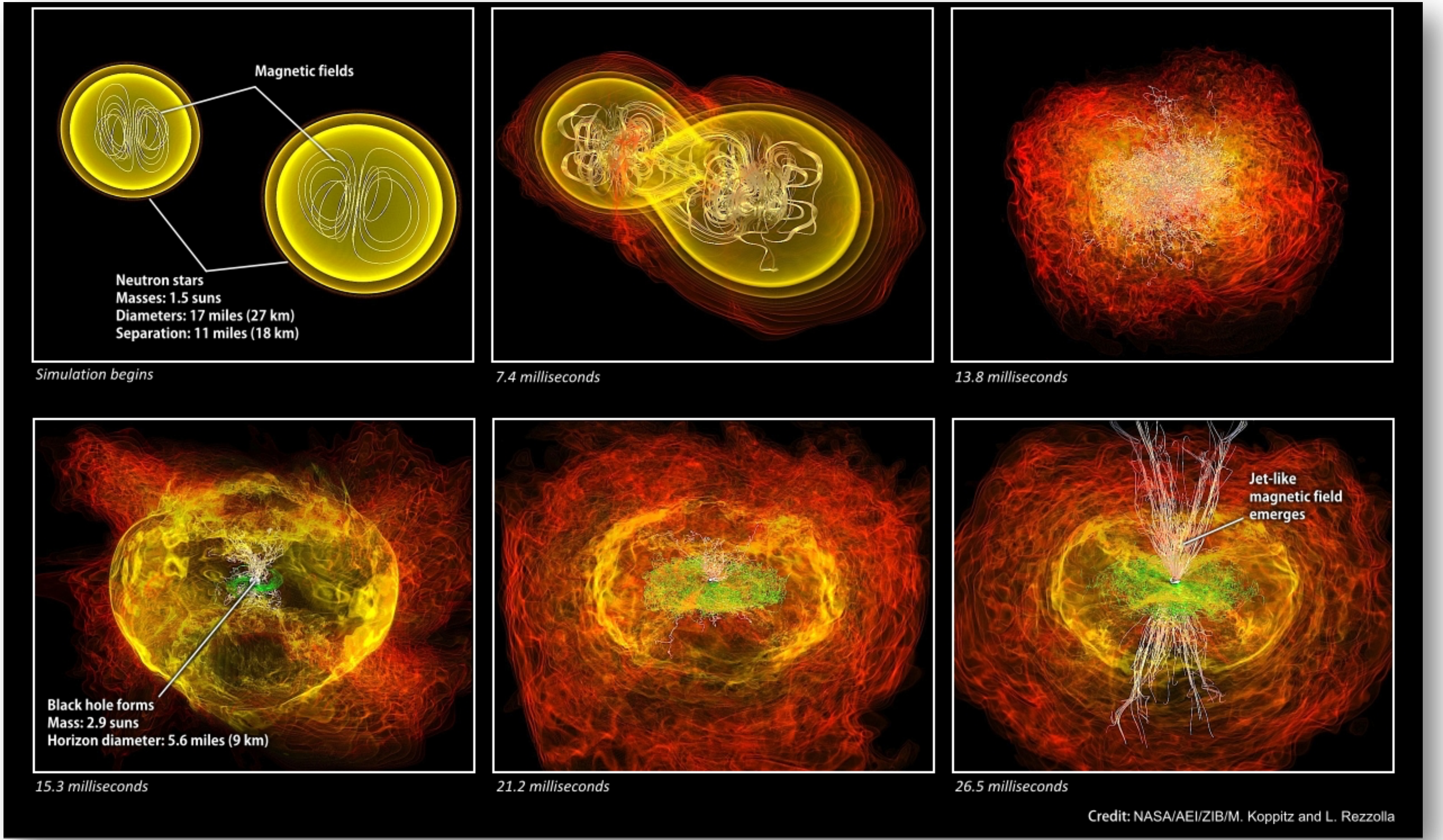


Responsible for the non-thermal spectrum
(Fermi acceleration?)

Long GRBs – stellar core collapse

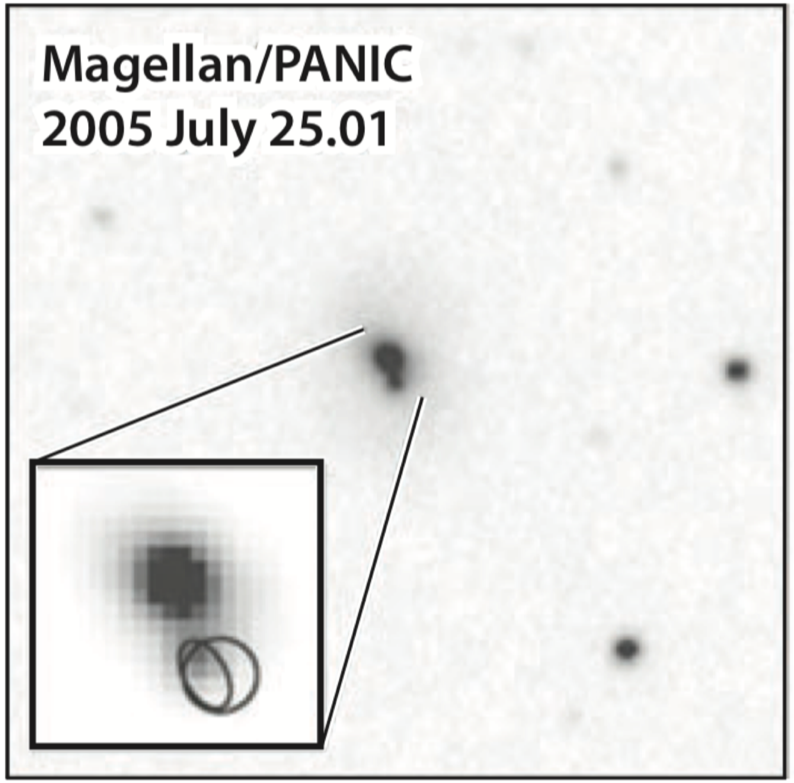


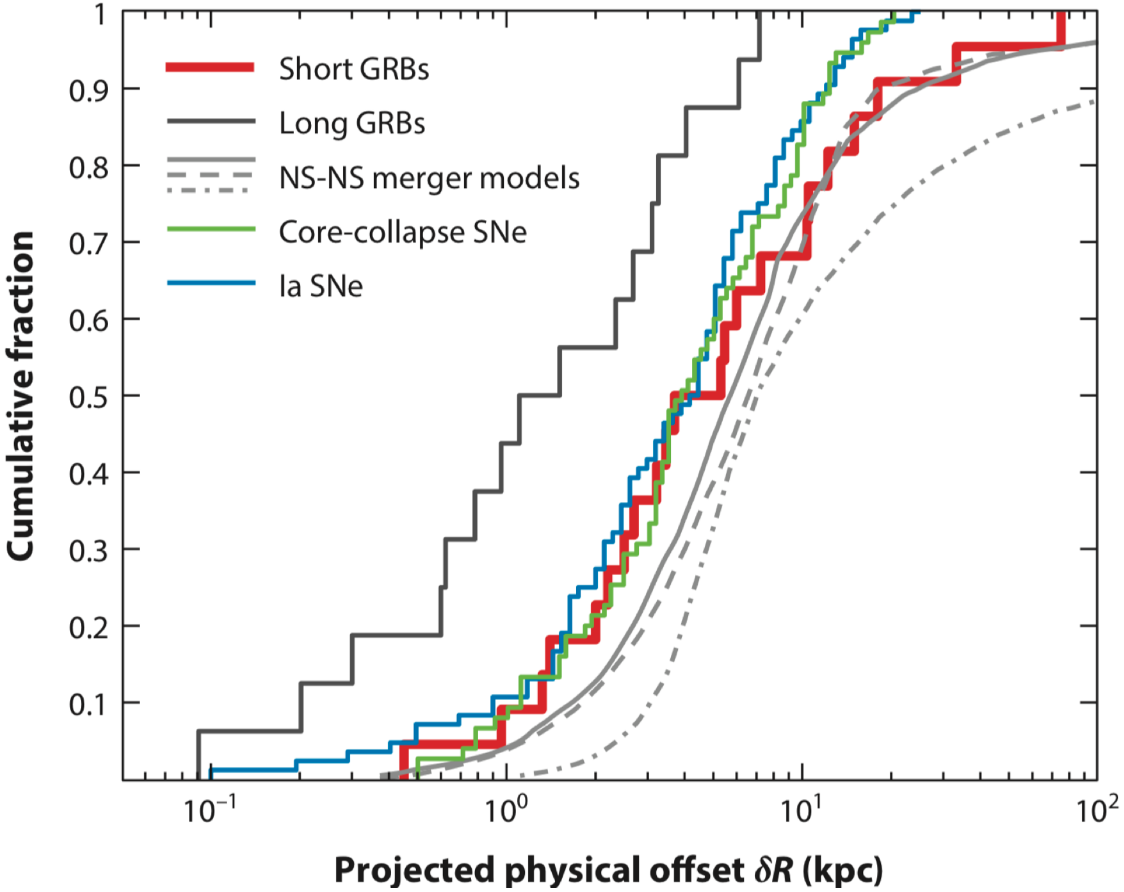
Short GRBs – binary mergers



Fallback time

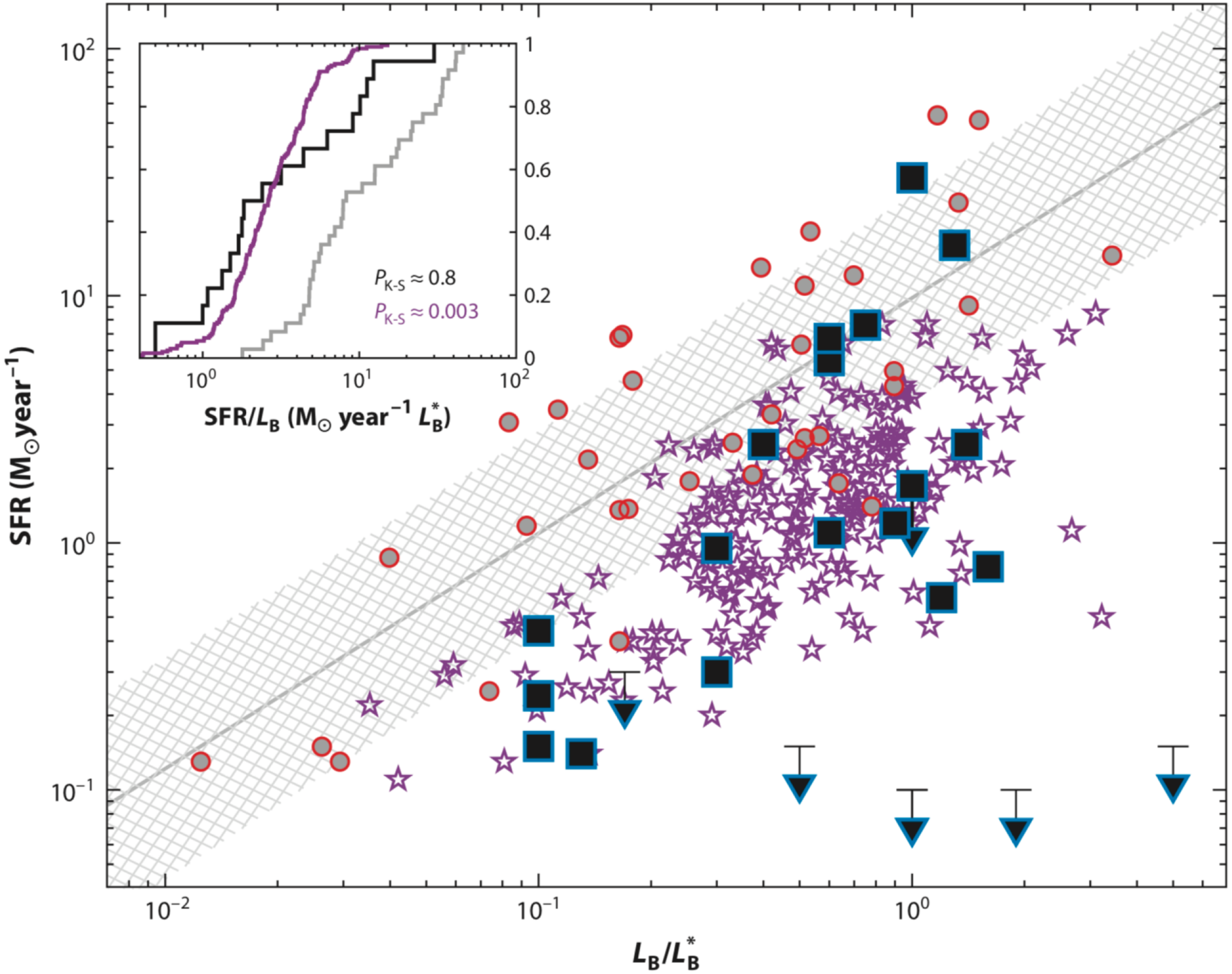
Kicks – short GRBs are often outside the host galaxy





Berger 2014

Star formation in host galaxies

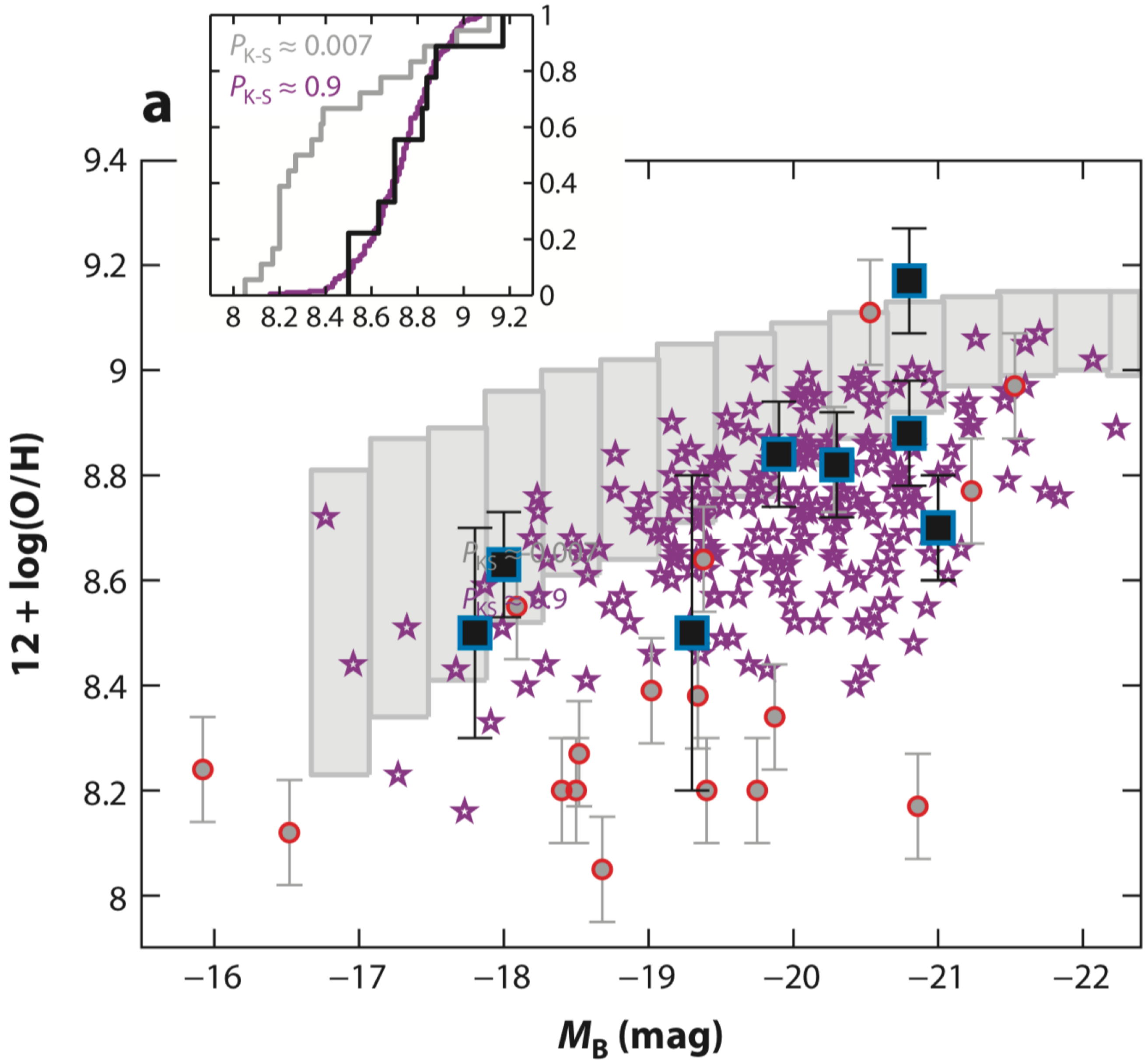


Star-formation rate (SFR) as a function of rest-frame B-band luminosity for the host galaxies of short GRBs (*squares*), long GRBs (*circles*), and field star-forming galaxies at similar redshifts to short GRB hosts (*stars*; Kobulnicky & Kewley 2004).

Low star formation indicates that the binary formed a long time ago.

Berger 2014

Metallicity of host galaxy

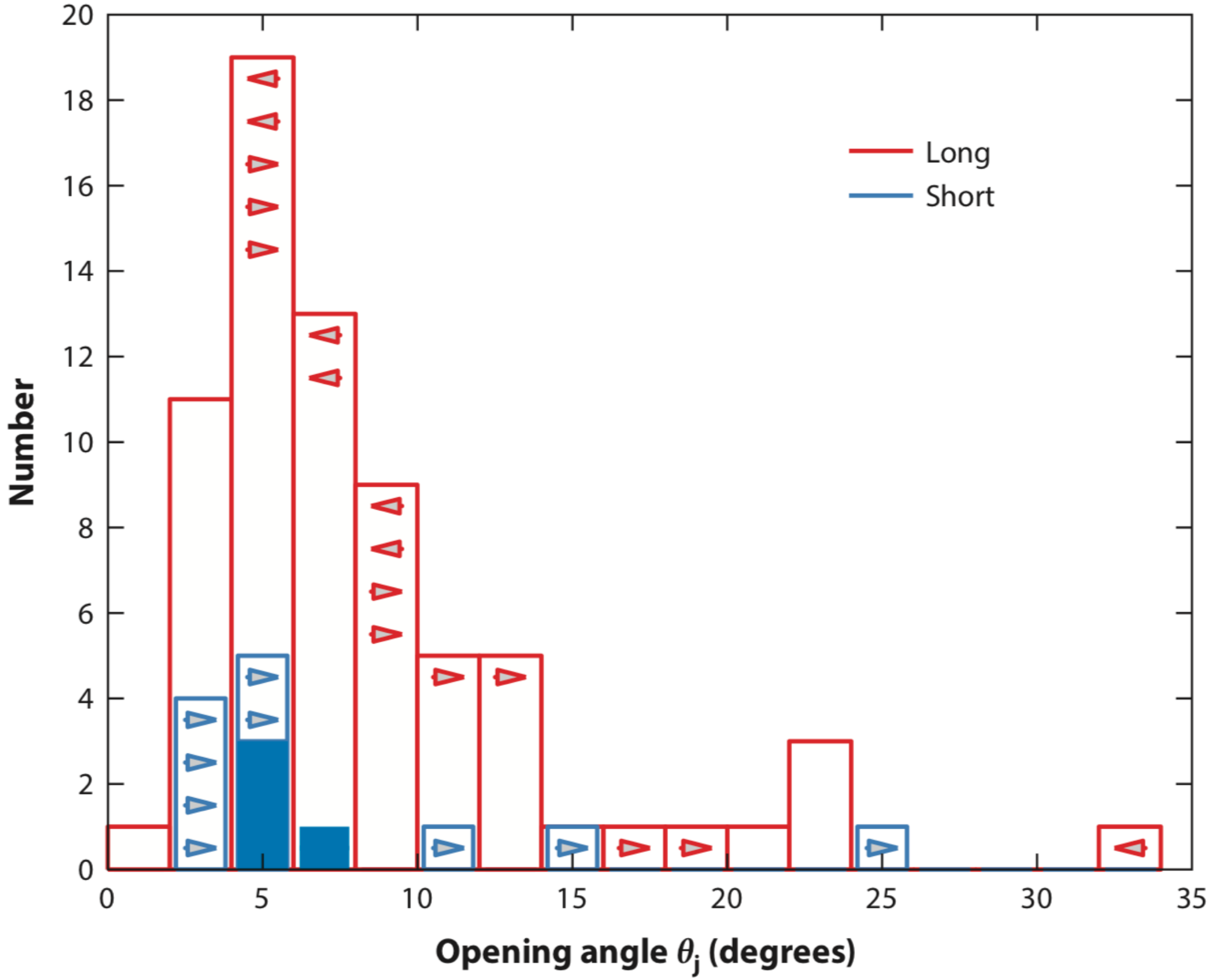


Metallicity as a function of host-galaxy rest-frame B-band luminosity for short GRBs (*squares*), long GRBs (*circles*), field galaxies at similar redshifts to short GRB hosts (*stars*; Kobulnicky & Kewley 2004), and the Sloan Digital Sky Survey luminosity-metallicity relation (Tremonti et al. 2004). Short GRB host galaxies have higher metallicities than long GRB hosts, but they closely track the luminosity-metallicity relation for the field galaxy population (*inset*).

Long GRBs prefer low-metallicity environments --- favorable for massive stellar explosions

Berger 2014

Opening angles



Berger 2014