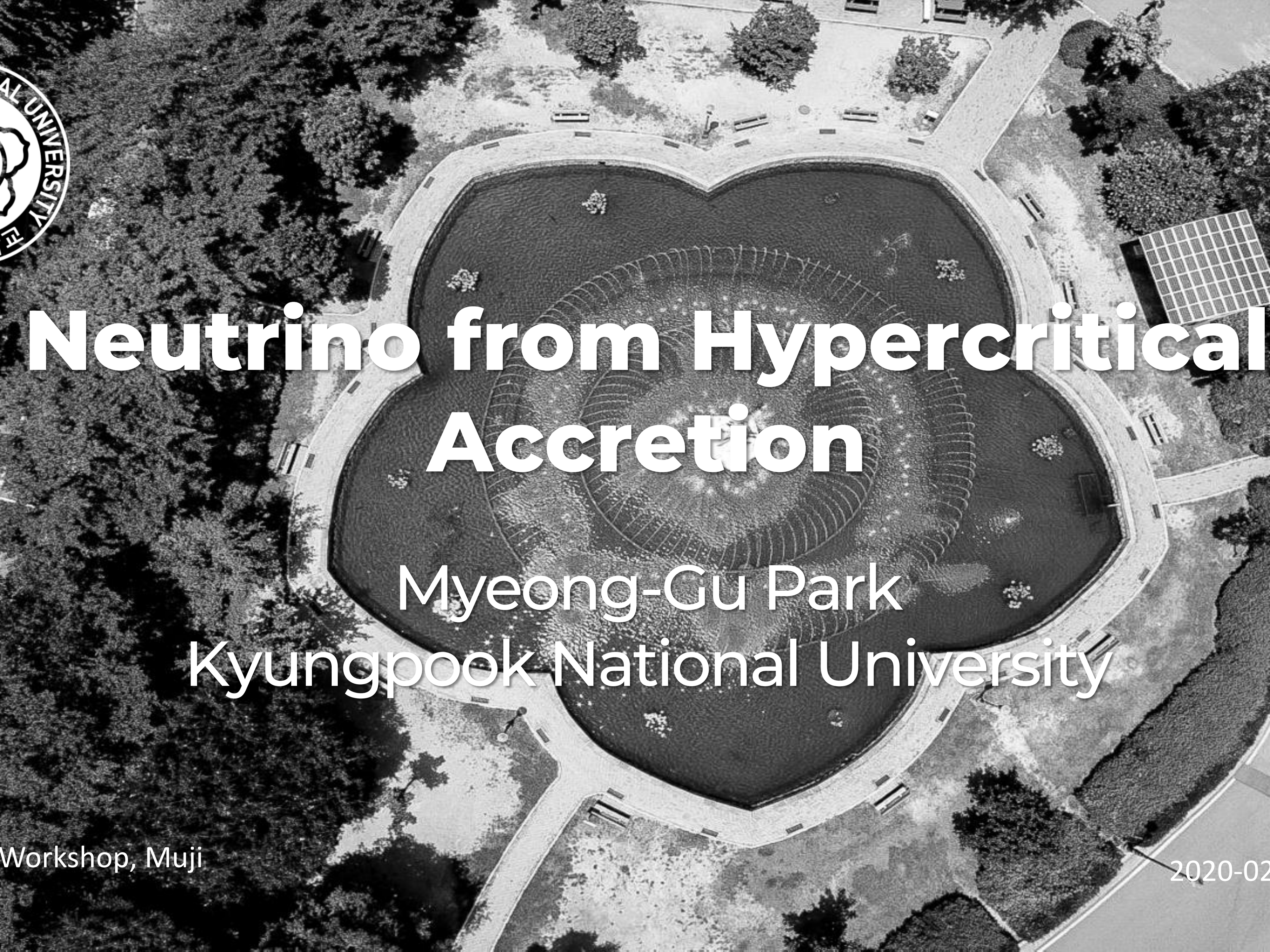


Neutrino from Hypercritical Accretion

Myeong-Gu Park
Kyungpook National University

Workshop, Muji

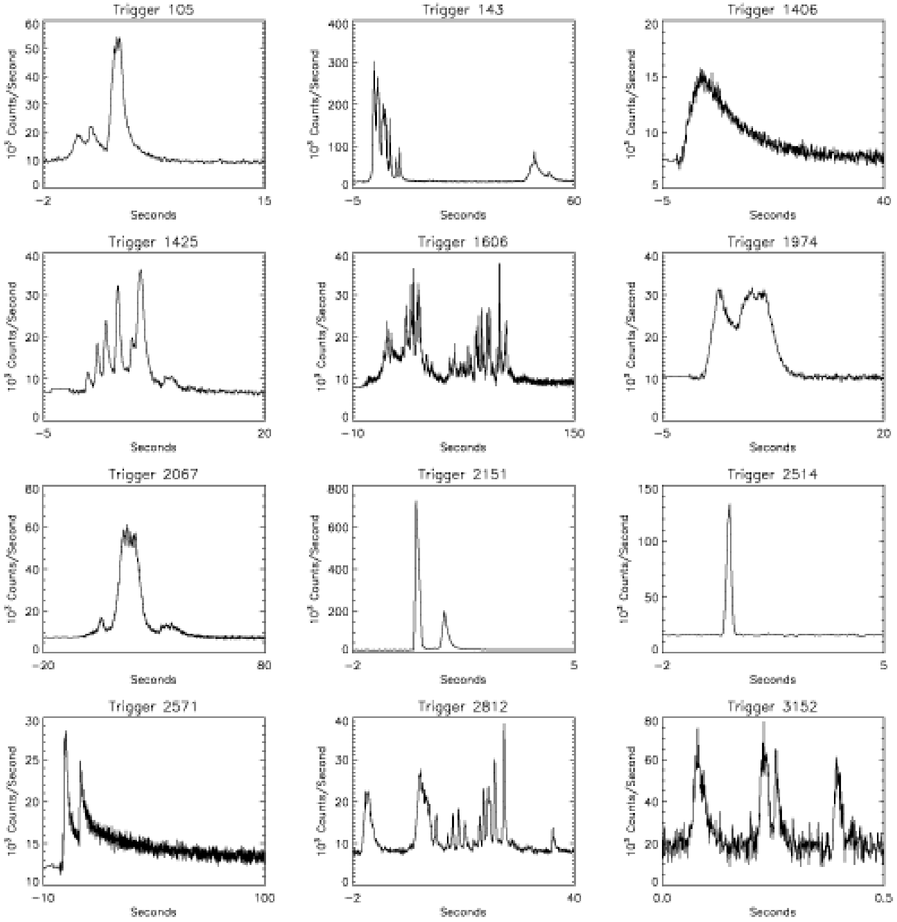
2020-02

Astrophysical neutrino burst events involving compact objects

- NS-NS/BH-NS mergers
  - GW events
  - Gamma-ray burst
  - EM afterglow
  - Neutrino burst
- AGNs
  - High energy neutrino
  - EM
- Supernovae
- Supernova fall back
- Hypercritical accretion

Gamma-Ray Bursts (GRBs)

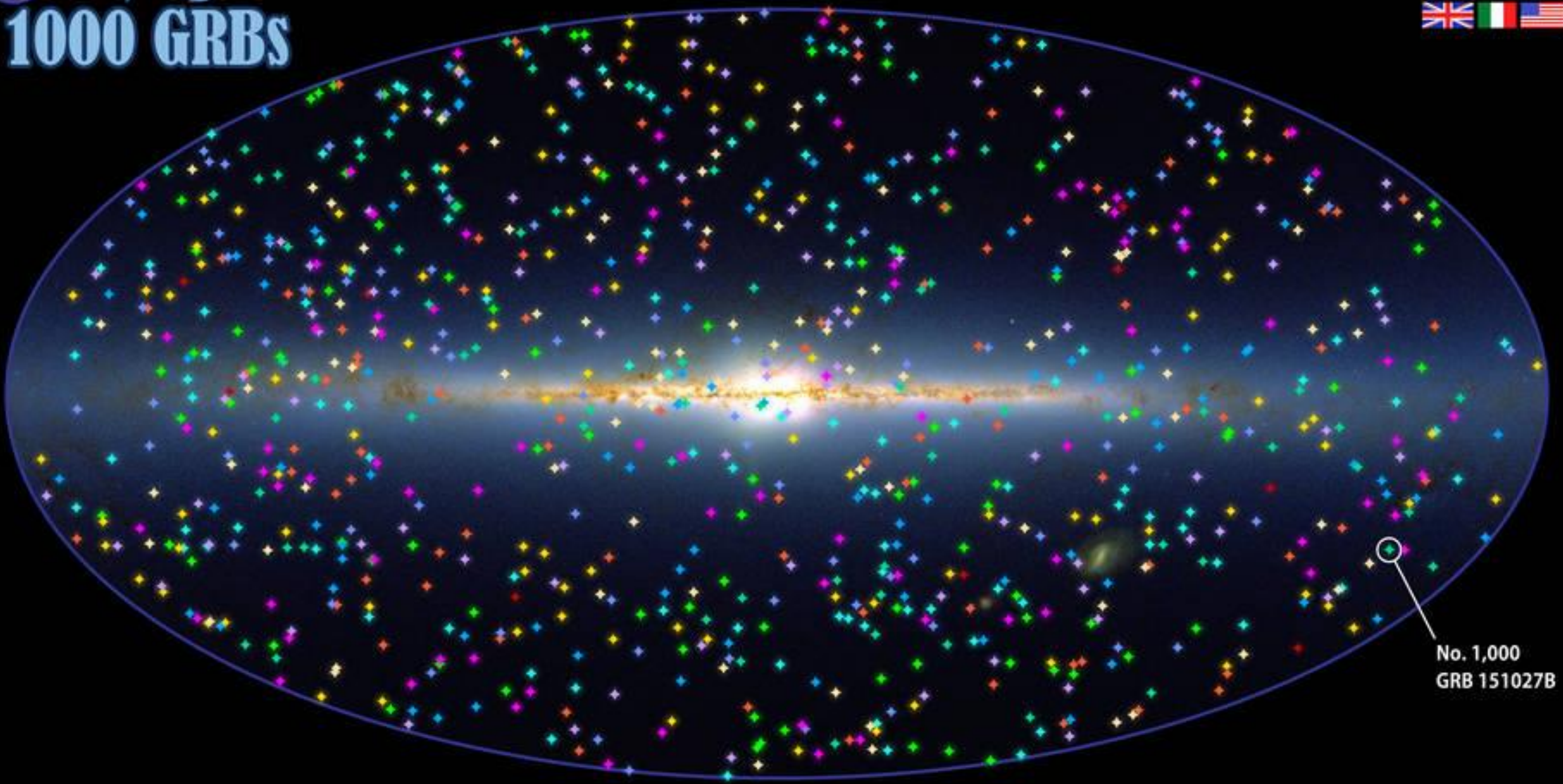
- Brief, bright flash of gamma-rays
- Vela 5 (1969~1979) detected 73 GRBs
- Timescales of 10 msec ~ hour
- Wide variation both in time-structure and duration
- As bright as the visible stars, some as bright as Venus
- Never repeat from the same source



Identification of GRBs

- Isotropic distribution in the sky
    - Local: Solar System, Galactic Halo?
    - Cosmological
    - 1973 ~ 1993
- Compton Gamma-Ray Observatory (1991~2000)
- BeppoSax (1996~2002)
    - Italian-Dutch X-ray mission
    - 0.1~200 keV, good energy resolution
    - Wide-field cameras
        - Capable of monitoring X-ray transient phenomena
    - 1 msec resolution from 60~600 keV

Swift 1000 GRBs

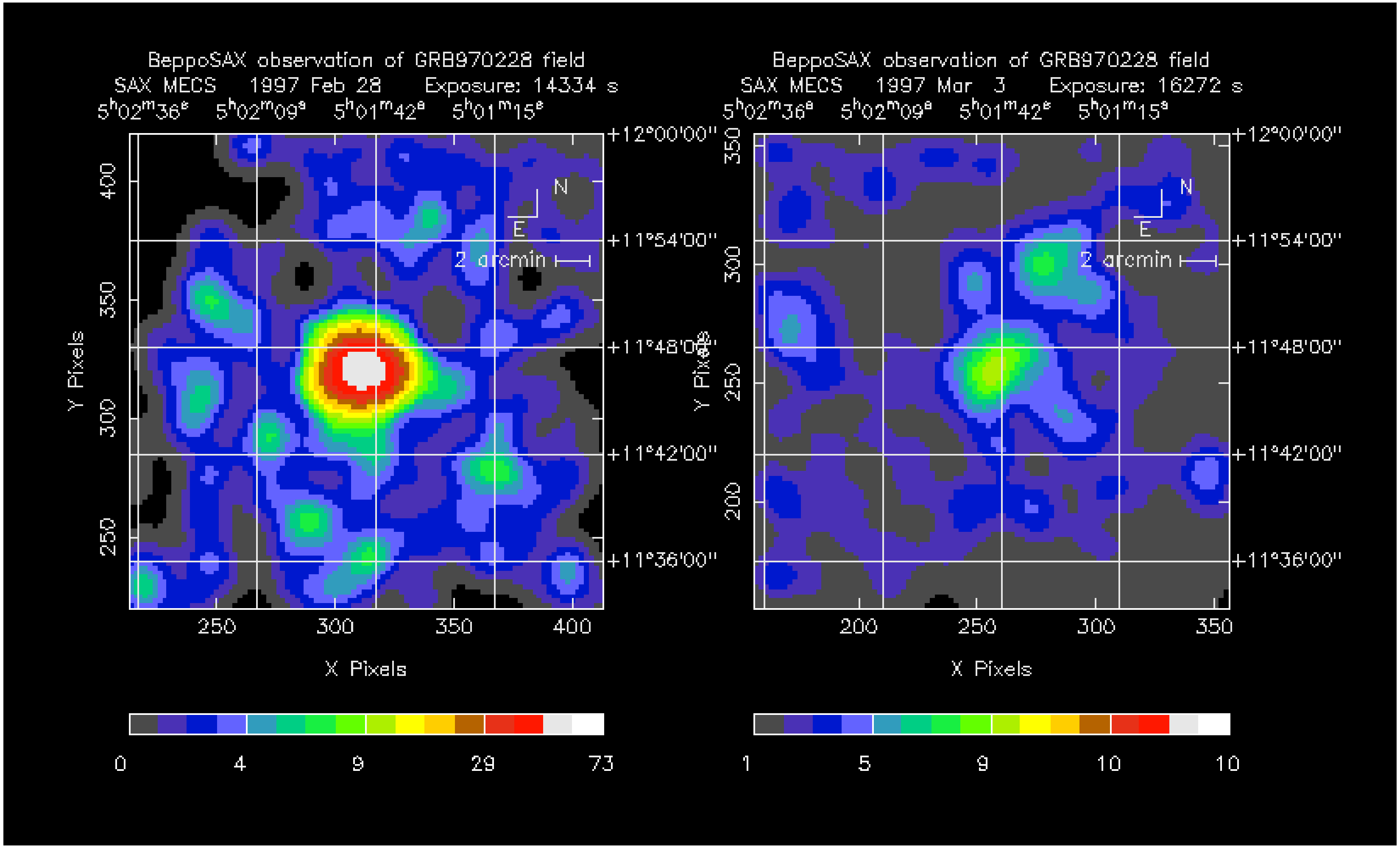


2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
9	88	102	86	103	89	84	81	92	96	95	75 to Oct. 27

BeppoSax GRB 970228 (discovered with WFC)

Feb 28, 1997 (8 hr after GRB using MECS)

March 3, 1997 (fainter by 20)



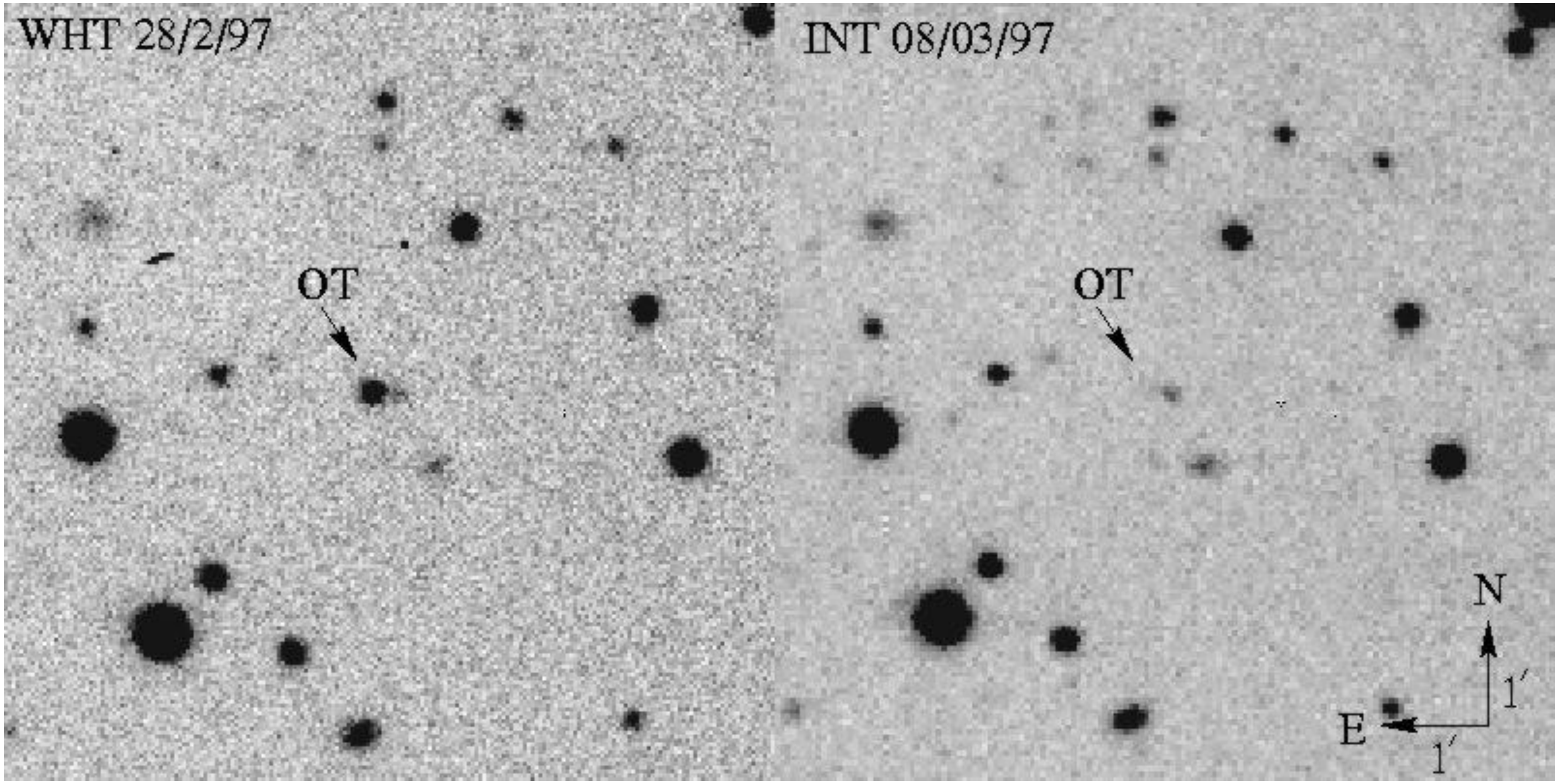
Each square is about 6 arc min

Woosley

GRB 970228

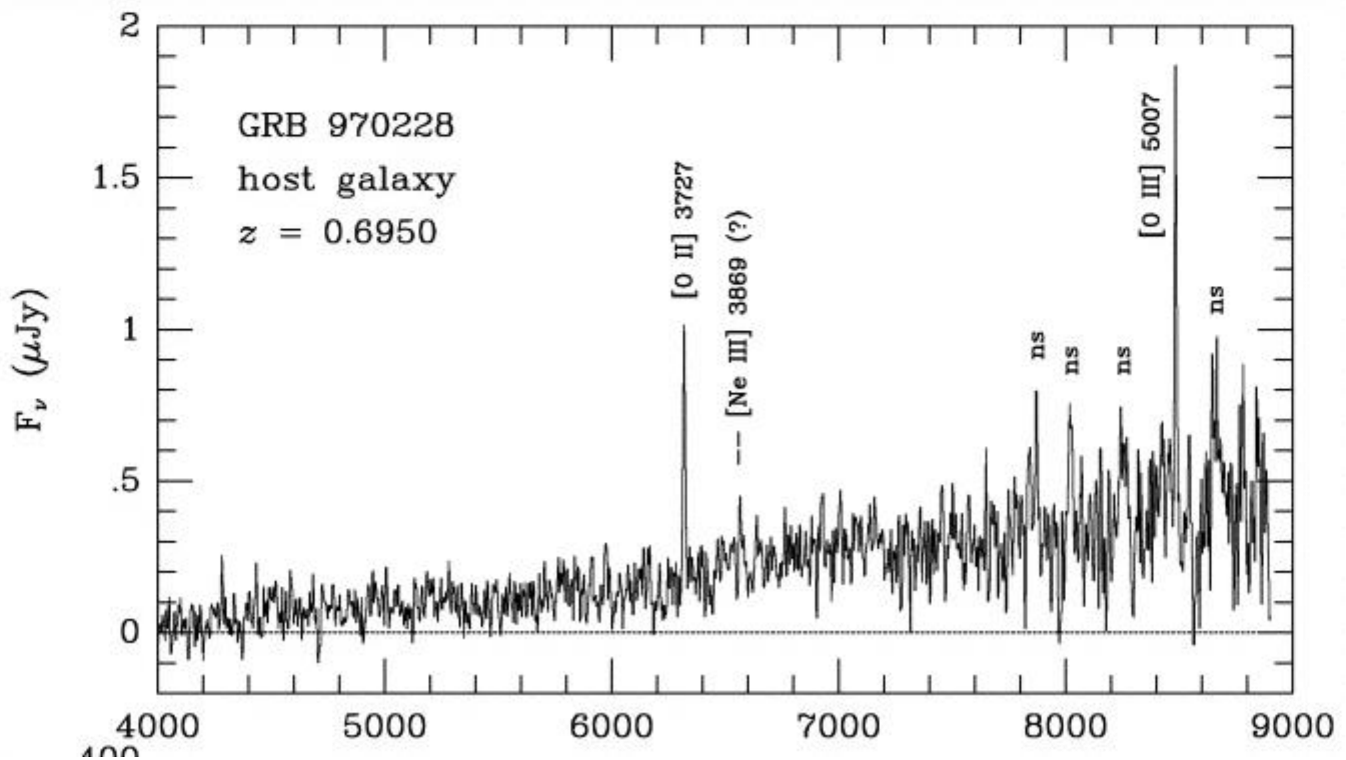
William Hershel Telescope

Isaac Newton Telescope



Groot, Galama, von Paradijs, et al IAUC 6584, March 12, 1997

Woosley



Spectrum of the host galaxy of GRB 970228 obtained at the Keck 2 Telescope. Prominent emission lines of oxygen and neon are indicated and show that the galaxy is located at a redshift of z = 0.695. (Bloom, Djorgovski, and Kulkarni (2001), ApJ, 554, 678. See also GCN 289, May 3, 1999.

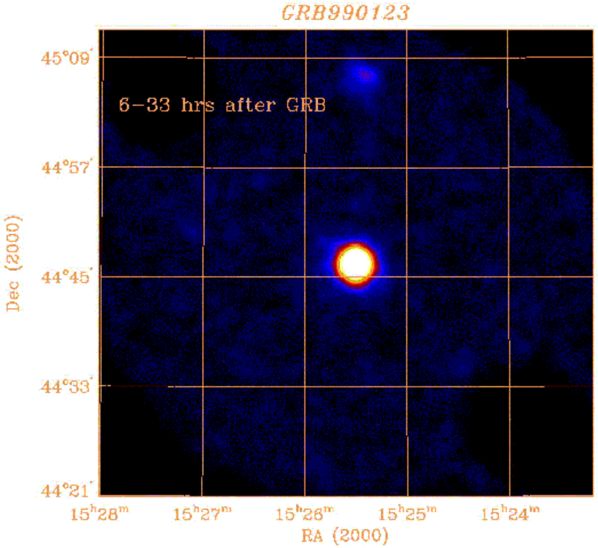
Energetics of GRB 970228

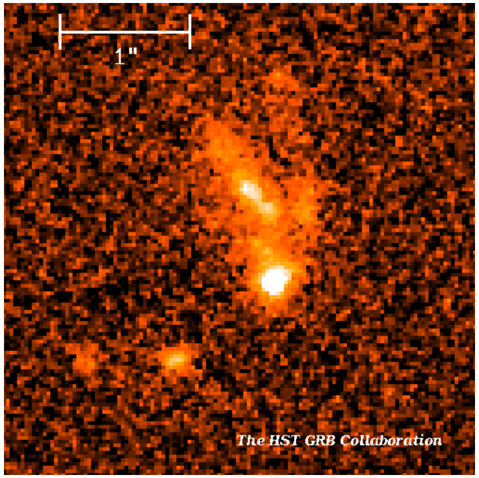
- Distance
  - z = 0.6950
  - Cosmological distance ~ 4.274 Gpc
- Brightness
  - 1.6 x 10^{52} erg in gamma-rays alone
  - ~ 2000 x L_{SN}
    - isotropic emission assumed

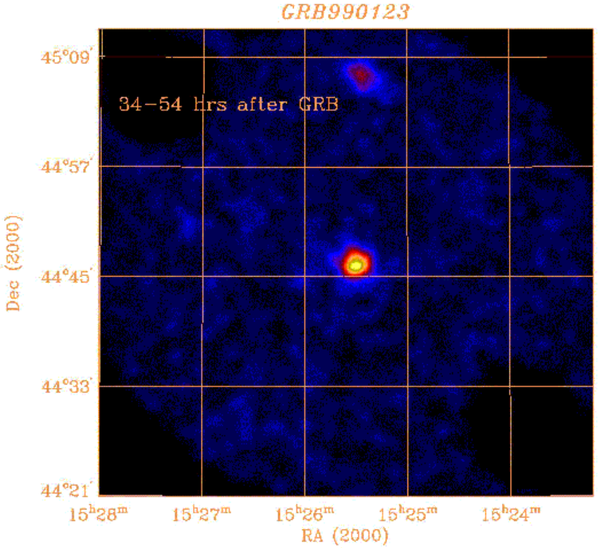
GRB 990123

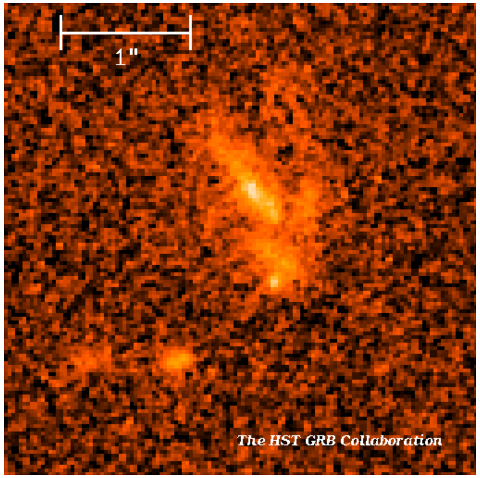
- $z = 1.61$
- $E \sim 10^{54}$ erg

- Typical GRBs
    - $z \sim 1$
    - $E \sim 10^{53}$ erg



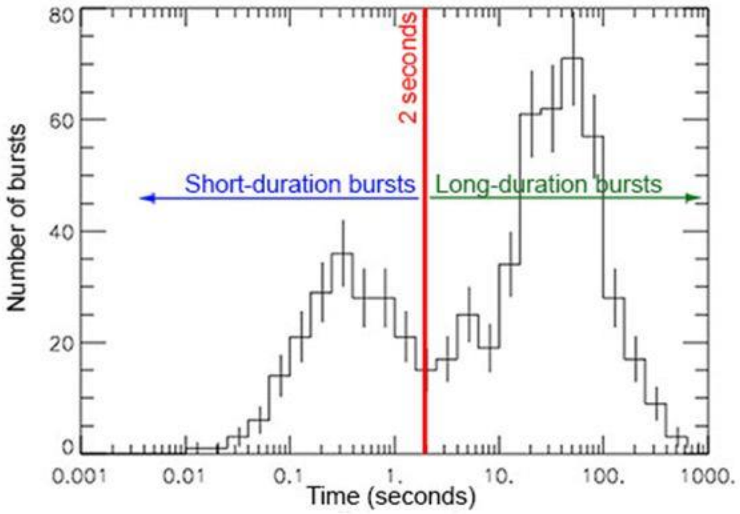






Short and Long GRBs

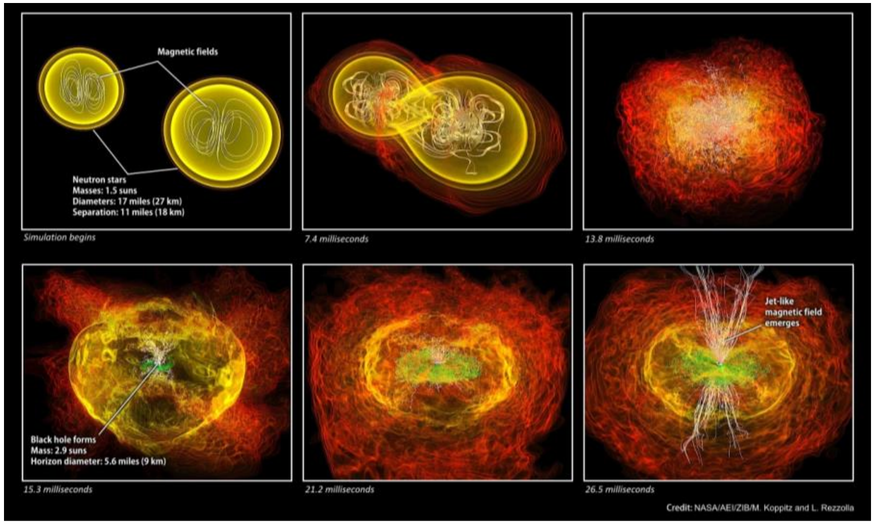
- Short vs Long GRBs
  - Short GRBs (SGRBs): t < 2 sec
  - Long GRBs (LGRBs): t > 2 sec
- LGRBs
  - ~ 70% of GRBs
  - Associated with star-forming regions
  - Many associated with a core-collapse supernova
- SGRBs
  - ~ 30% of GRBs
  - Not associated with star formation
  - Associated with elliptical galaxies, the central regions of large galaxy clusters



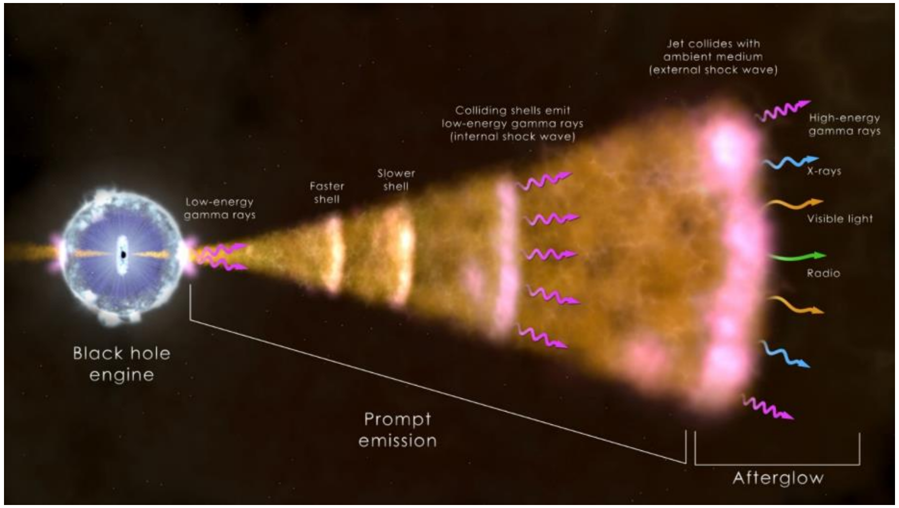
Graph of the time versus number of bursts for the gamma-ray bursts observed by the BATSE instrument on the Compton Gamma-ray Telescope.

GRB Engines

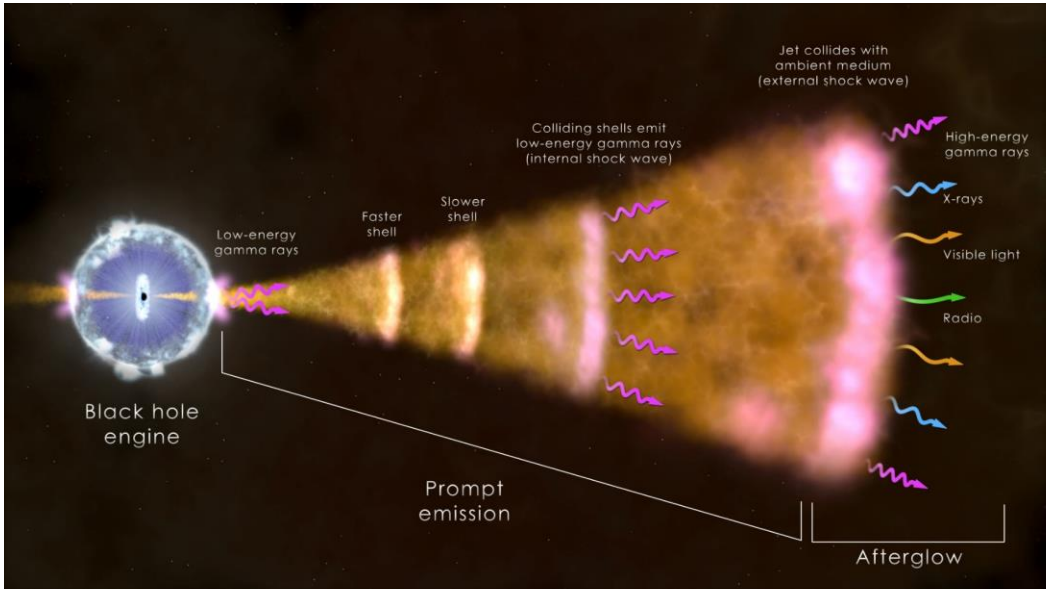
- Short GRBs
  - Compact GR emission region
  - NS-NS or BH-NS merger model
  - GW170817
    - GW signal
    - GRB 170817A – short GRB
    - Afterglow - kilonova

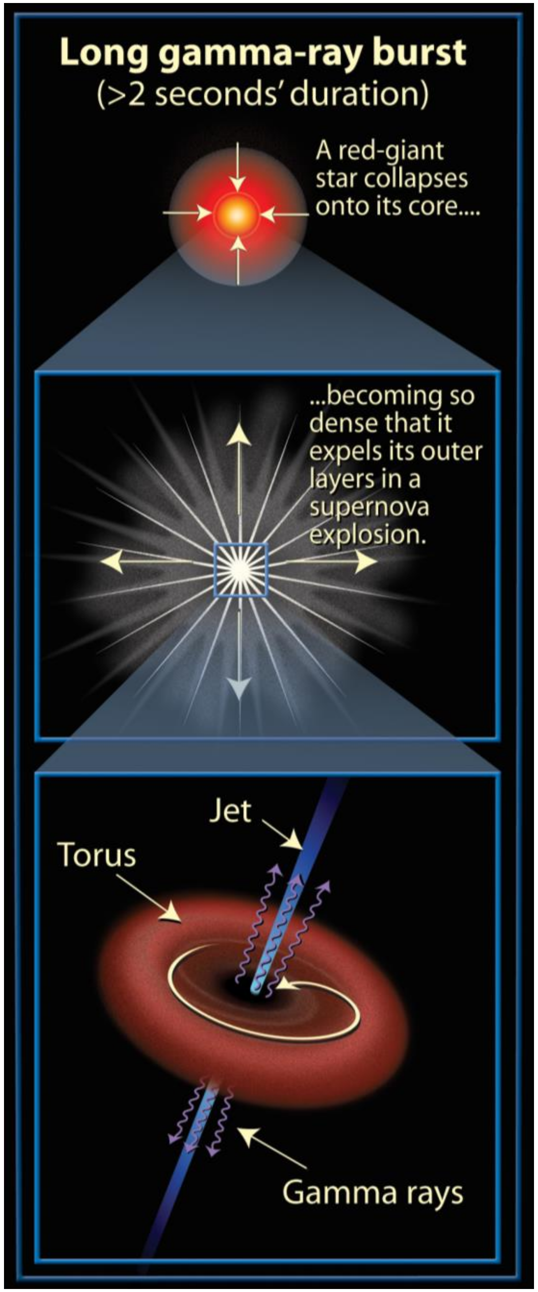


Credit: NASA/AEI/ZIB/M. Koppitz and L. Rezzolla



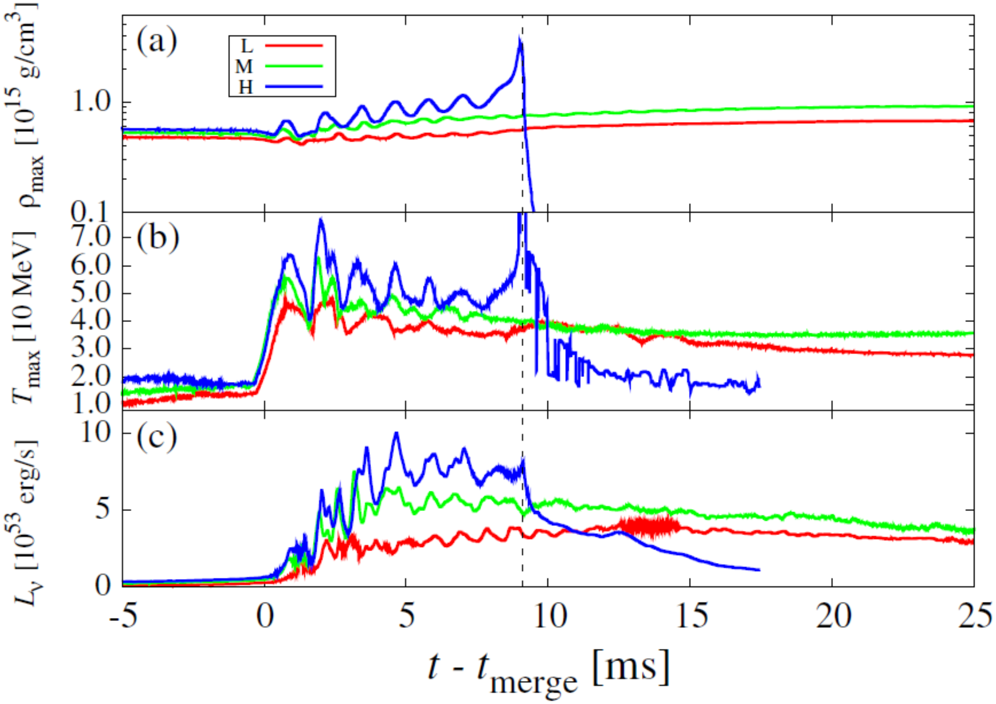
- Long GRBs
  - Collapsar model
    - Core of an extremely massive, low-metallicity, rapidly rotation star collapses into a black hole





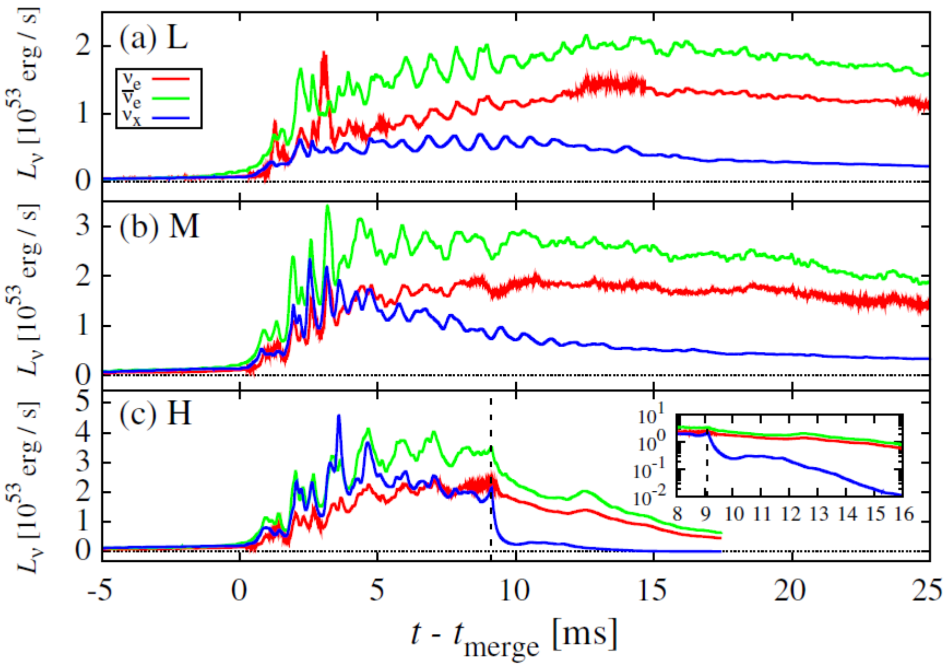
Thermal Neutrinos from NS-NS Merger

- Gravitational binding energy should be released as in supernovae
  - ~ 3 x 10^{53} erg
  - Released as thermal and kinetic energy
  - Some of these energy in the form of photons and neutrinos
- Relativistic radiation hydrodynamic simulations (Sekiguchi+ 2011)
  - ~ 3-8 x 10^{53} erg/s
  - 20-75 MeV neutrinos

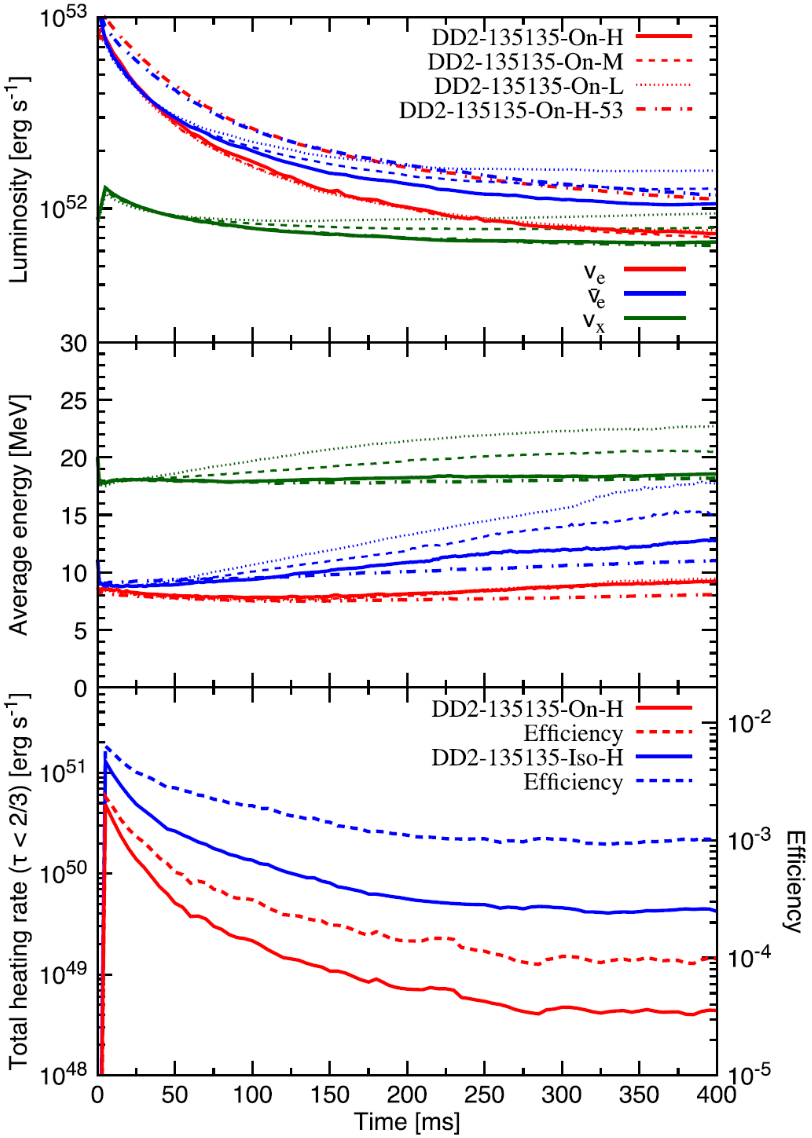


1.35, 1.5, 1.6 M_{sun}

- Neutrino luminosities for three flavors
- Expected detection number for 0.5 Mton HK + KNO
  - > 5 for distance < 5 Mpc in 2-3 sec for hyper-massive NS
  - GW or GRB detectors provide the precise time of the event



- GR axisymmetric neutrino radiation hydrodynamic simulations (Fujibayashi+ 2017)
  - A massive NS + torus
  - Neutrino-driven outflow
  - Neutrino radiation hydrodynamics
    - Radiation moment formalism (Thorne 1981)
    - Streaming + Trapped
    - M1 closure for streaming neutrinos



BNS Merger Rate

- BNS merger rate from aLIGO
  - R_{BNSM} ~ 250 - 2810 Gpc^{-3}/yr (arXiv2001.01761)
  - For $D_{\mathrm{eff}} = 200\ \mathrm{Mpc}$,

$$R \cdot \frac{4\pi}{3} D_{\mathrm{eff}}^{3} \sim 8.4 - 94 \text{ events/yr}$$

Neutrinos from GRBs

- Detailed models of GRBs still uncertain.
  - How does the central engine produce the fireball and launch the relativistic jet?
- Detection of neutrinos can confirm or reject many scenarios

Thermal Neutrinos from BNS Merger

- HK + KNO (Kyutoku-Kashiyama 2018)
  - Expected number of neutrino events

$$N_\nu = N_T \int_{t_i}^{t_f} \int_{E_{min}}^{E_{max}} \phi(E,t)\sigma(E)dEdt$$

  - Number of target protons

$$N_T \approx \frac{2}{18}\left(\frac{M_T}{m_p}\right) = 6.7 \times 10^{34}\left(\frac{M_T}{1\ \mathrm{Mt}}\right)$$

  - Cross section for proton

$$\sigma(E) = 9.5 \times 10^{-42}\ \mathrm{cm}\left(\frac{E - 1.3\ \mathrm{MeV}}{10\ \mathrm{MeV}}\right)^2\left(1 - \frac{7E}{m_p c^2}\right)$$

  - Expected number of neutrino events for a single merger

$$n \approx 0.5 \times 10^{-3} \times f_E f_{se} f_{osc}\left(\frac{M_T}{0.5\ \mathrm{Mt}}\right)\left(\frac{E_{\Delta t}}{3 \times 10^{52}\mathrm{erg}}\right)\left(\frac{\langle E\rangle}{10\ \mathrm{MeV}}\right)\left(\frac{D}{100\ \mathrm{Mpc}}\right)^{-2}$$

- Superposition (Kyutoku-Kashiyama 2018)
  - Superposition of many mergers
  - LIGO will tell the time of the events
  - Total number of neutrino detection

$$N = R_{BNSM} \cdot t_{obs} \cdot n$$

$$\sim 0.78 \times \left(\frac{M_T}{0.5\ \mathrm{Mt}}\right)\left(\frac{E_{\Delta t}}{3 \times 10^{52}\mathrm{erg}}\right)\left(\frac{\langle E_\nu \rangle}{10\ \mathrm{MeV}}\right)\left(\frac{D_{\mathrm{eff}}}{200\ \mathrm{Mpc}}\right)\left(\frac{t_{obs}}{30\ \mathrm{yr}}\right)$$

  - Noise control by using timing information from LIGO and using only $\Delta t_{obs} \approx 1$ sec

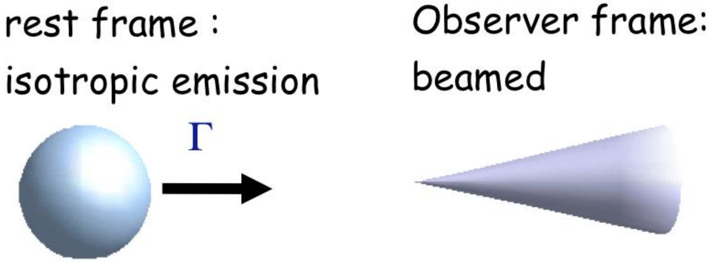
Relativistic Beaming?

- Particle energy is boosted by the bulk Lorentz factor Γ.

$$\langle E \rangle = \Gamma \, \langle E \rangle_0$$

- Number flux of particles is boosted by Γ^2.
  - Beam is focused into an angle of Γ^{-1}.

$$\frac{E}{D^2} = \Gamma^2 \left(\frac{E}{D^2} \right)_0$$



- Number of events observed decreases by Γ^{-2}.

$$R_{BNSM} = \Gamma^{-2} \, R^0_{BNSM}$$

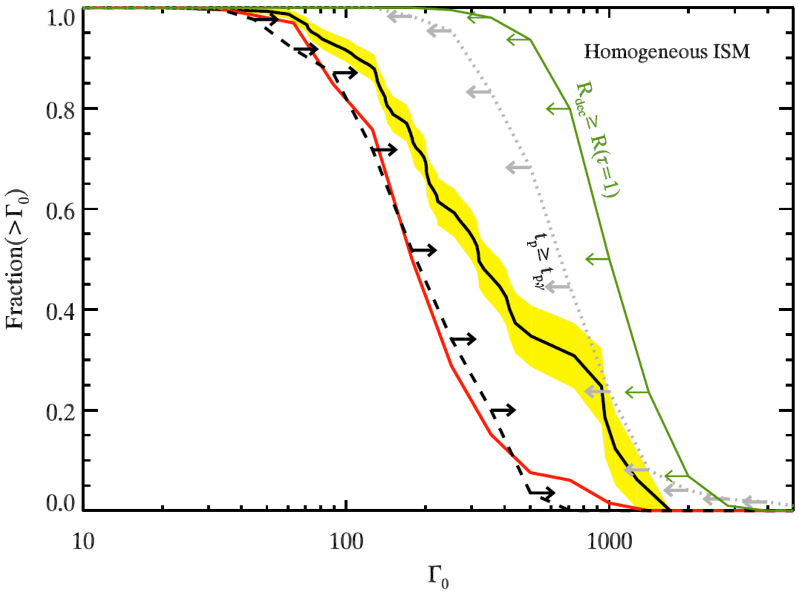
- Duration of burst shortened by Γ^{-1}.

- Total number of neutrino detection

$$N = \Gamma^{-2} R^0_{BNSM} \cdot t_{obs} \cdot \Gamma^3 n_0$$

$$\sim 7.8 \left(\frac{\Gamma}{300}\right)\left(\frac{M_T}{0.5\ \mathrm{Mt}}\right)\left(\frac{E^0_{\Delta t}}{3\times 10^{52}\mathrm{erg}}\right)\left(\frac{\langle E\rangle_0}{10\ \mathrm{MeV}}\right)\left(\frac{D_{\mathrm{eff}}}{200\ \mathrm{Mpc}}\right)\left(\frac{t_{obs}}{\mathrm{yr}}\right)$$

- Estimated Γ
  - $100 \le \Gamma \le 1000$ from observation + afterglow model (Ghirlanda+ 2018)

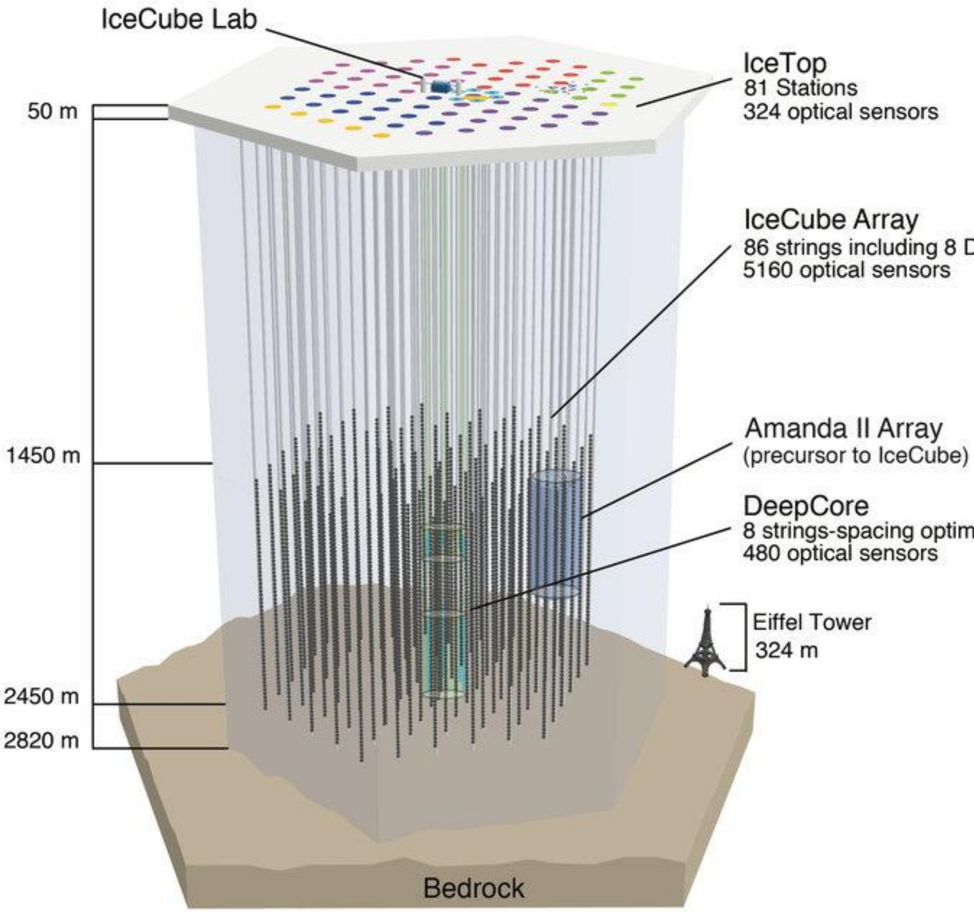


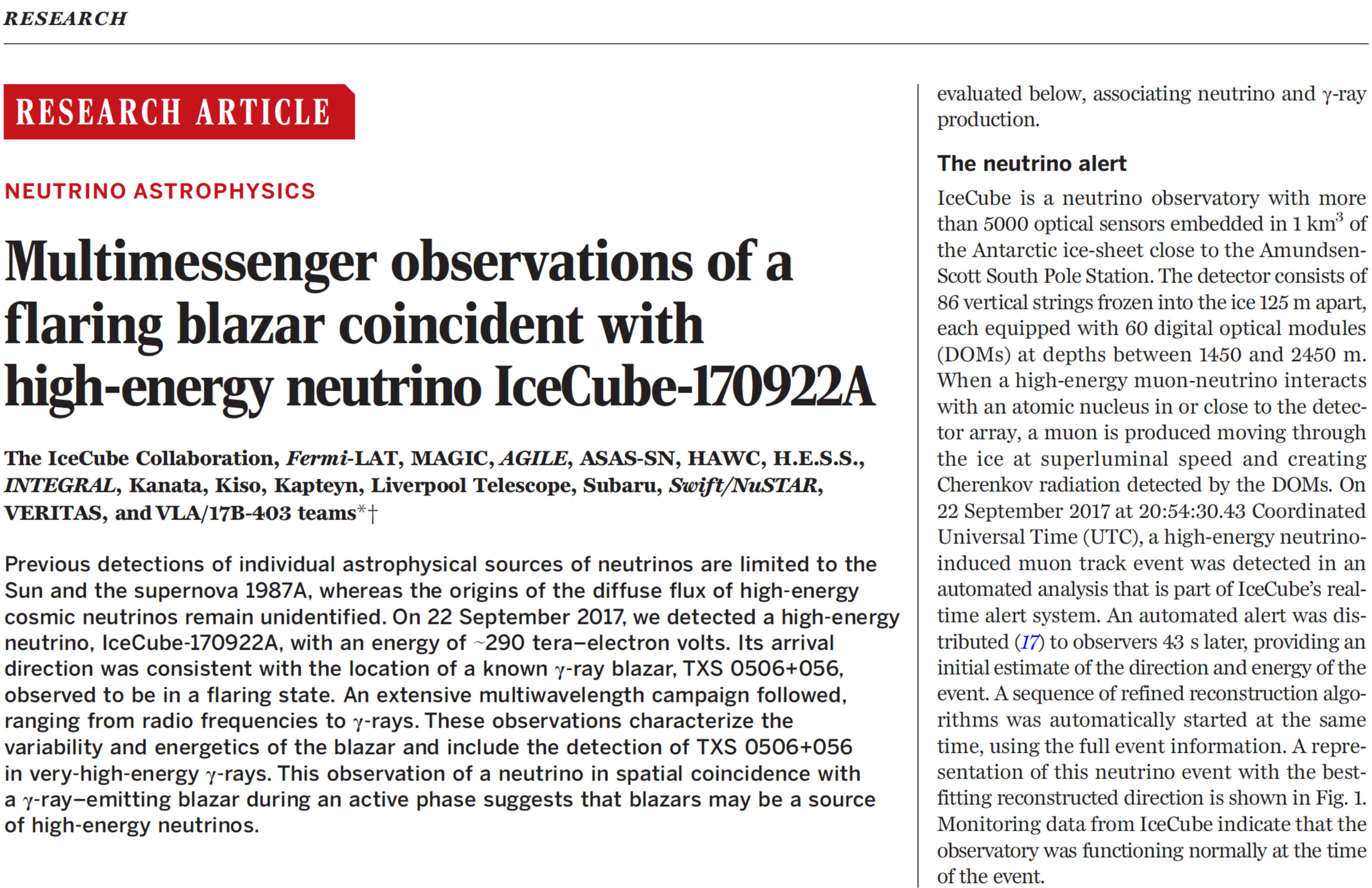
Non-thermal neutrinos from NS-NS/BH-NS mergers

- High-energy neutrinos from relativistic fireballs (Waxman & Bahcall 1997)
- Relativistic jet
- Blanford-Znajek process

Neutrinos from Blazar

- IceCube
  - Gigaton neutrino detector since Dec. 2010
  - 5160 Digital optical modules distributed over 86 strings
  - Cherenkov emission from secondary particles
- IceCube-170922A
  - ~ 290 TeV
  - Coincident with γ-ray (Fermi) flaring blazar TXS 0506+056





RESEARCH

RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†

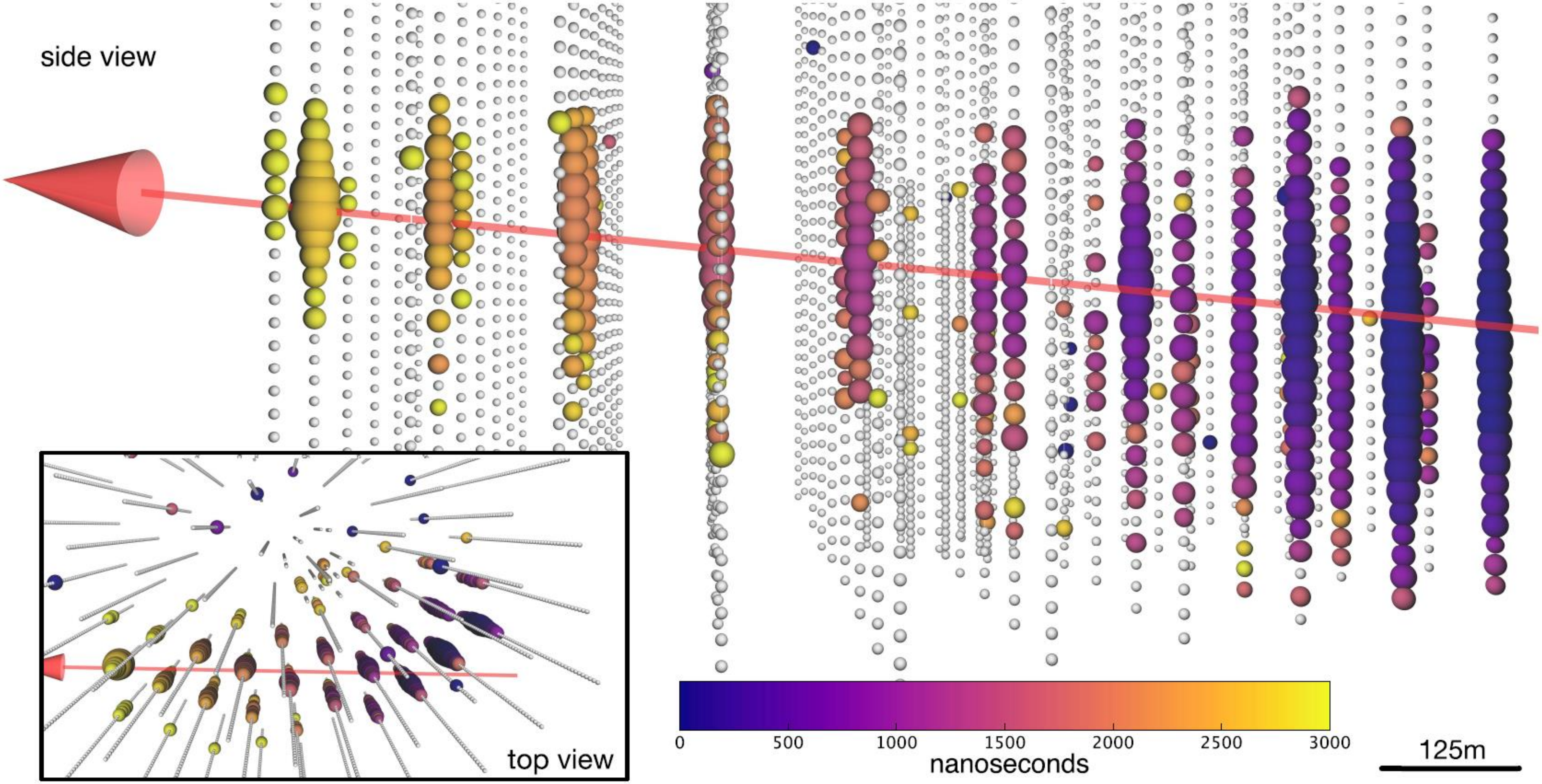
Previous detections of individual astrophysical sources of neutrinos are limited to the Sun and the supernova 1987A, whereas the origins of the diffuse flux of high-energy cosmic neutrinos remain unidentified. On 22 September 2017, we detected a high-energy neutrino, IceCube-170922A, with an energy of ~290 tera–electron volts. Its arrival direction was consistent with the location of a known γ-ray blazar, TXS 0506+056, observed to be in a flaring state. An extensive multiwavelength campaign followed, ranging from radio frequencies to γ-rays. These observations characterize the variability and energetics of the blazar and include the detection of TXS 0506+056 in very-high-energy γ-rays. This observation of a neutrino in spatial coincidence with a γ-ray–emitting blazar during an active phase suggests that blazars may be a source of high-energy neutrinos.

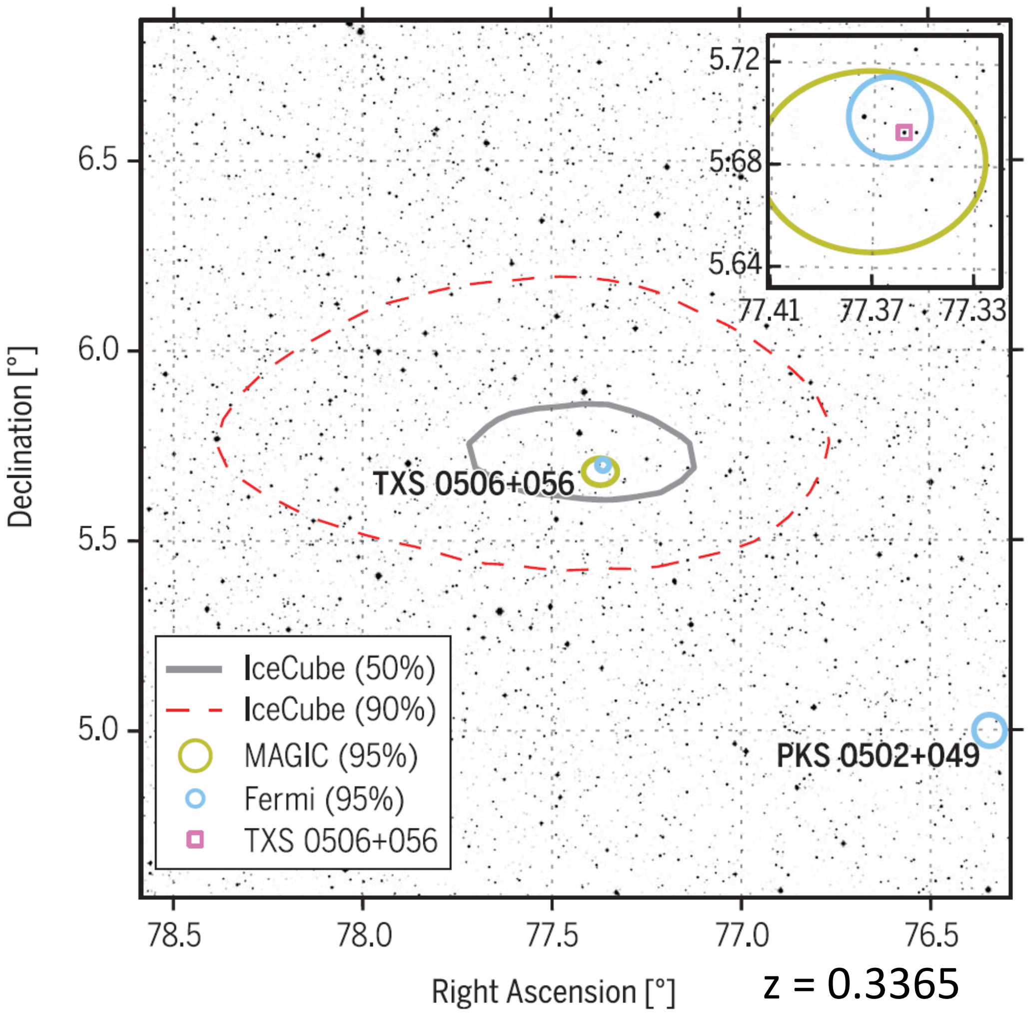
evaluated below, associating neutrino and γ-ray production.

The neutrino alert

IceCube is a neutrino observatory with more than 5000 optical sensors embedded in 1 km^3 of the Antarctic ice-sheet close to the Amundsen-Scott South Pole Station. The detector consists of 86 vertical strings frozen into the ice 125 m apart, each equipped with 60 digital optical modules (DOMs) at depths between 1450 and 2450 m. When a high-energy muon-neutrino interacts with an atomic nucleus in or close to the detector array, a muon is produced moving through the ice at superluminal speed and creating Cherenkov radiation detected by the DOMs. On 22 September 2017 at 20:54:30.43 Coordinated Universal Time (UTC), a high-energy neutrino-induced muon track event was detected in an automated analysis that is part of IceCube's real-time alert system. An automated alert was distributed (*17*) to observers 43 s later, providing an initial estimate of the direction and energy of the event. A sequence of refined reconstruction algorithms was automatically started at the same time, using the full event information. A representation of this neutrino event with the best-fitting reconstructed direction is shown in Fig. 1. Monitoring data from IceCube indicate that the observatory was functioning normally at the time of the event.

Science, 13 July 2018

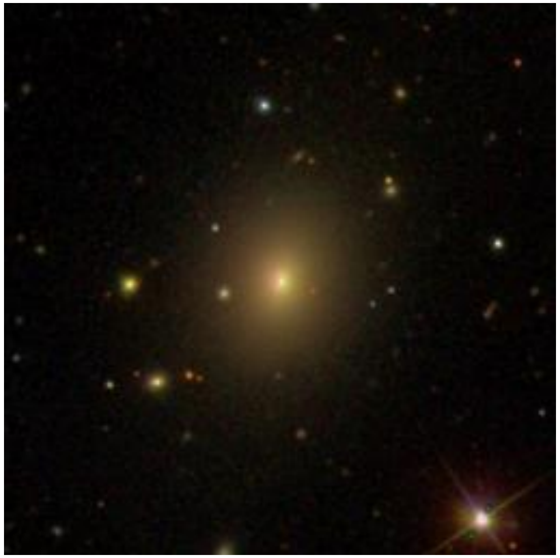

side view
top view
0
500
1000
1500
2000
2500
3000
nanoseconds
125m


5.72
5.68
5.64
77.41
77.37
77.33
6.5
6.0
5.5
5.0
Declination [°]
TXS 0506+056
PKS 0502+049
IceCube (50%)
IceCube (90%)
MAGIC (95%)
Fermi (95%)
TXS 0506+056
78.5
78.0
77.5
77.0
76.5
Right Ascension [°]

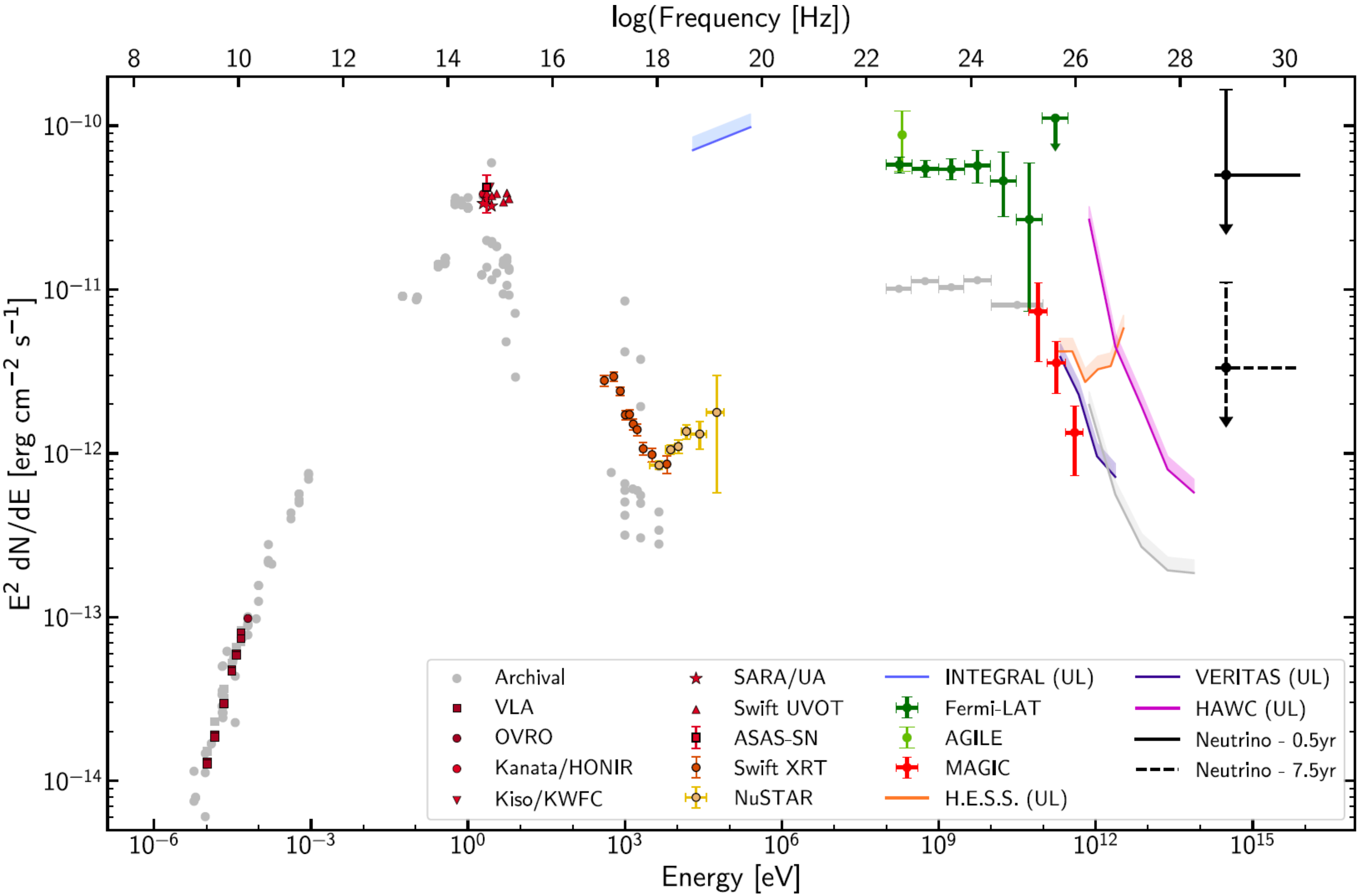
z = 0.3365

Blazar

- Highly variable Active Galactic Nucleus
  - hours to days
- Emission across the EM spectrum
  - Source of high-energy gamma ray
- Some show superluminal motion
- Theoretical model
  - AGN with a relativistic jet, directed very nearly toward Earth
  - Relativistic beaming: $\Gamma \leq 10$
- Classification
  - BL Lac objects: low-power radio galaxies
  - Optically Violently Variable (OVV) Quasars: radio-loud quasars



Markarian 501



log(Frequency [Hz])
8
10
12
14
16
18
20
22
24
26
28
30
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
E^2 dN/dE [erg cm^{-2} s^{-1}]
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
10^{9}
10^{12}
10^{15}
Energy [eV]
Archival
VLA
OVRO
Kanata/HONIR
Kiso/KWFC
SARA/UA
Swift UVOT
ASAS-SN
Swift XRT
NuSTAR
INTEGRAL (UL)
Fermi-LAT
AGILE
MAGIC
H.E.S.S. (UL)
VERITAS (UL)
HAWC (UL)
Neutrino - 0.5yr
Neutrino - 7.5yr

Multi-messenger Observation

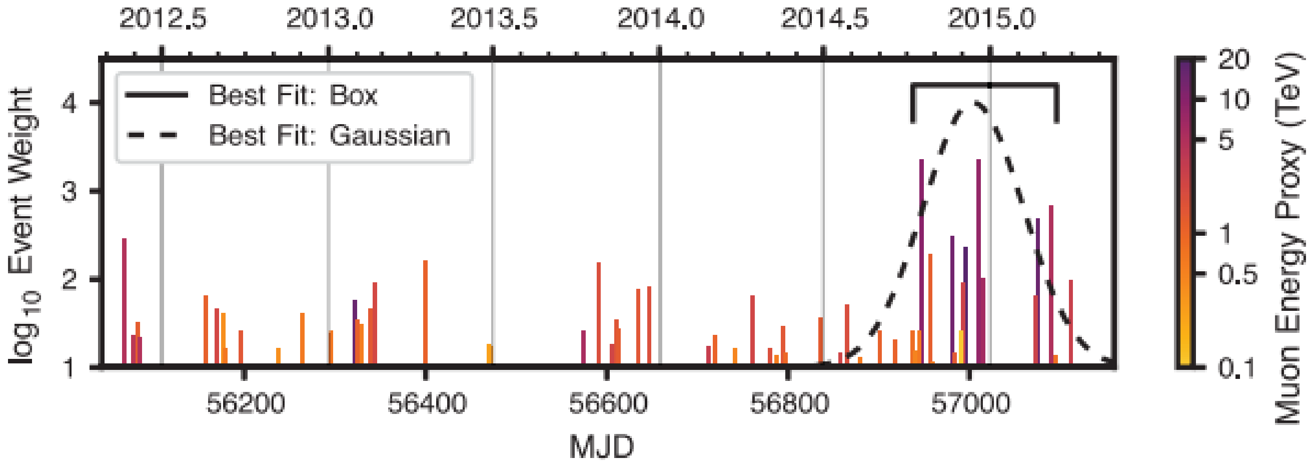
- Neutrino luminosity

  $\langle L_{iso}^{\mu} \rangle \sim 7.2 \times 10^{46}$ erg/s in 6 months period

  $E_{iso}^{\mu} \sim 1.1 \times 10^{54}$ erg
- Gamma-ray luminosity
  - $L_{iso}^{\gamma} \sim 1.3$ x 10^{47} erg/s (0.1 – 100 GeV) within two weeks of IceCube-170922A

Blazars as neutrino sources

- Neutrinos prior to IceCube-170922A



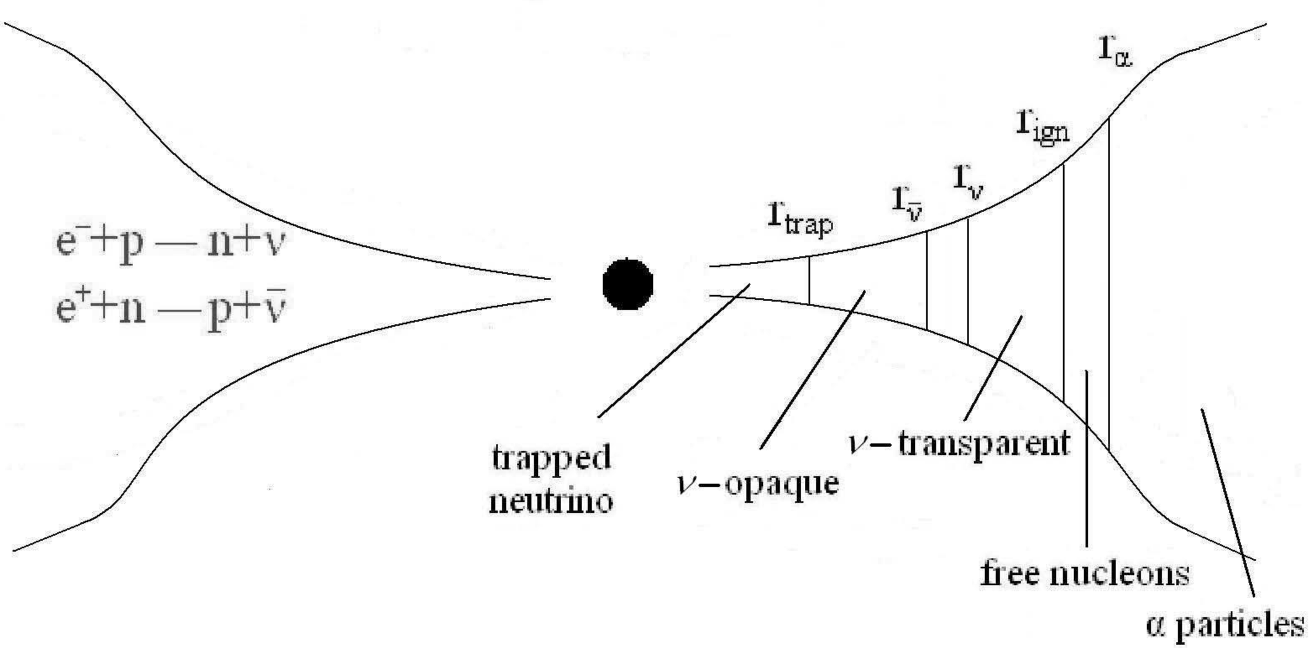
- All-flavor neutrino fluence: 4.2 x 10^{-3} erg/cm^2 (32 TeV ~ 3.6 PeV)
- $L_{\nu,iso}$ = 1.2 x 10^{47} erg/s > L_γ = 0.28 x 10^{47} erg/s

- Emission mechanism
    - Accelerated protons interact with ambient lower-energy photons
    - Production of gammas and neutrinos
        - Neutral pions – decay to gamma rays
        - Charged pions – decay to neutrinos and leptons
    - Luminosity and spectrum of lower-energy neutrinos?

Hypercritical Accretion

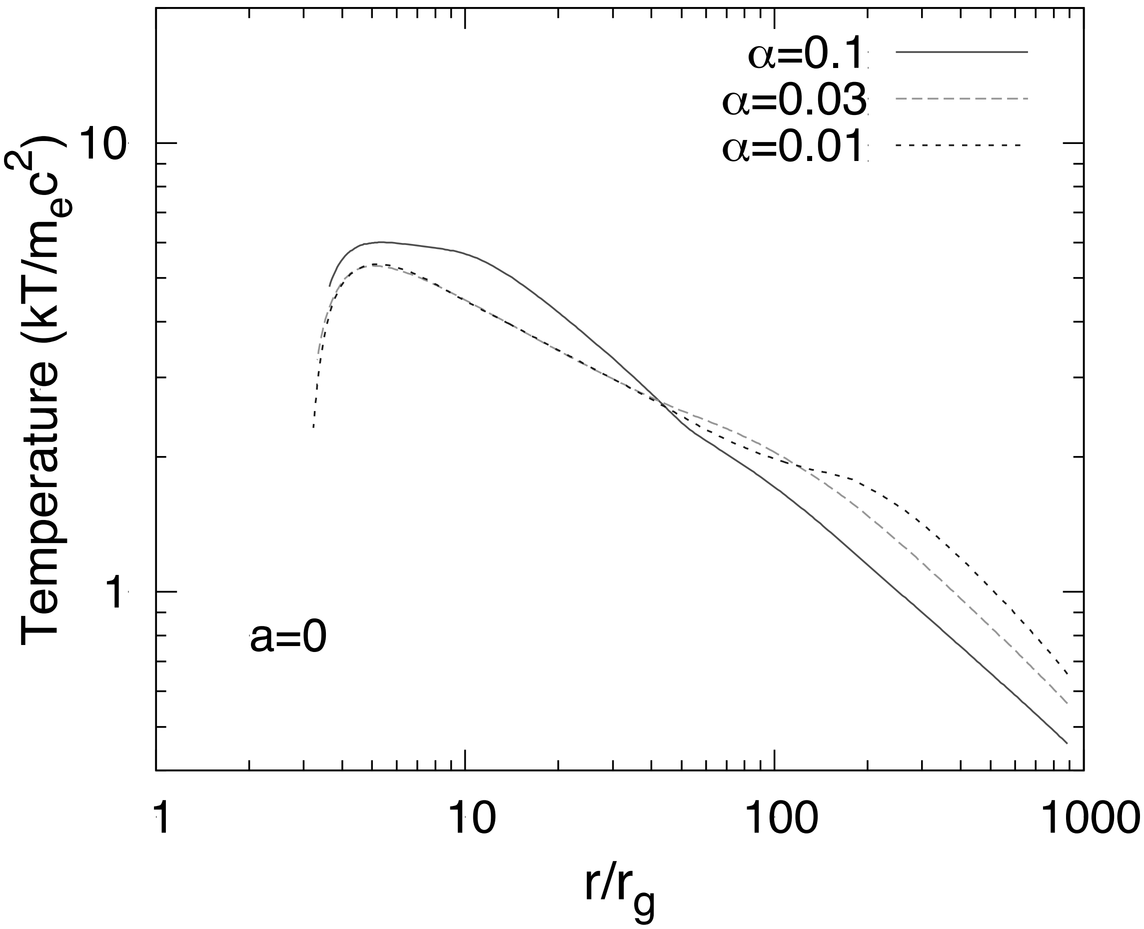
- $\dot{M} \gg \dot{M}_E$
- Optical depth $\tau_{es} \gg 1$
- Radiations are trapped.
- Torus or thick disk, quasi-spherical
- Cooled by neutrinos

- Condition for neutrino cooling domination
  - $\dot{M} > 3 \times 10^{-4}$ M_{sun}/yr for spherical infall onto NS (Chevalier 1989)
  - $\dot{M} > 3 \times 10^{4}$ M_{sun}/yr for disk around rotating BH (Chen & Beloborodov 2007)
  - $\dot{M} \sim 10^{7}$ M_{sun}/yr for disk around BH (Caballero et al. 2016)
- Possible scenario
  - NS-NS or BH-NS mergers
  - Collapsar
  - SN fallback
  - Tidal disruption of stars by SMBH

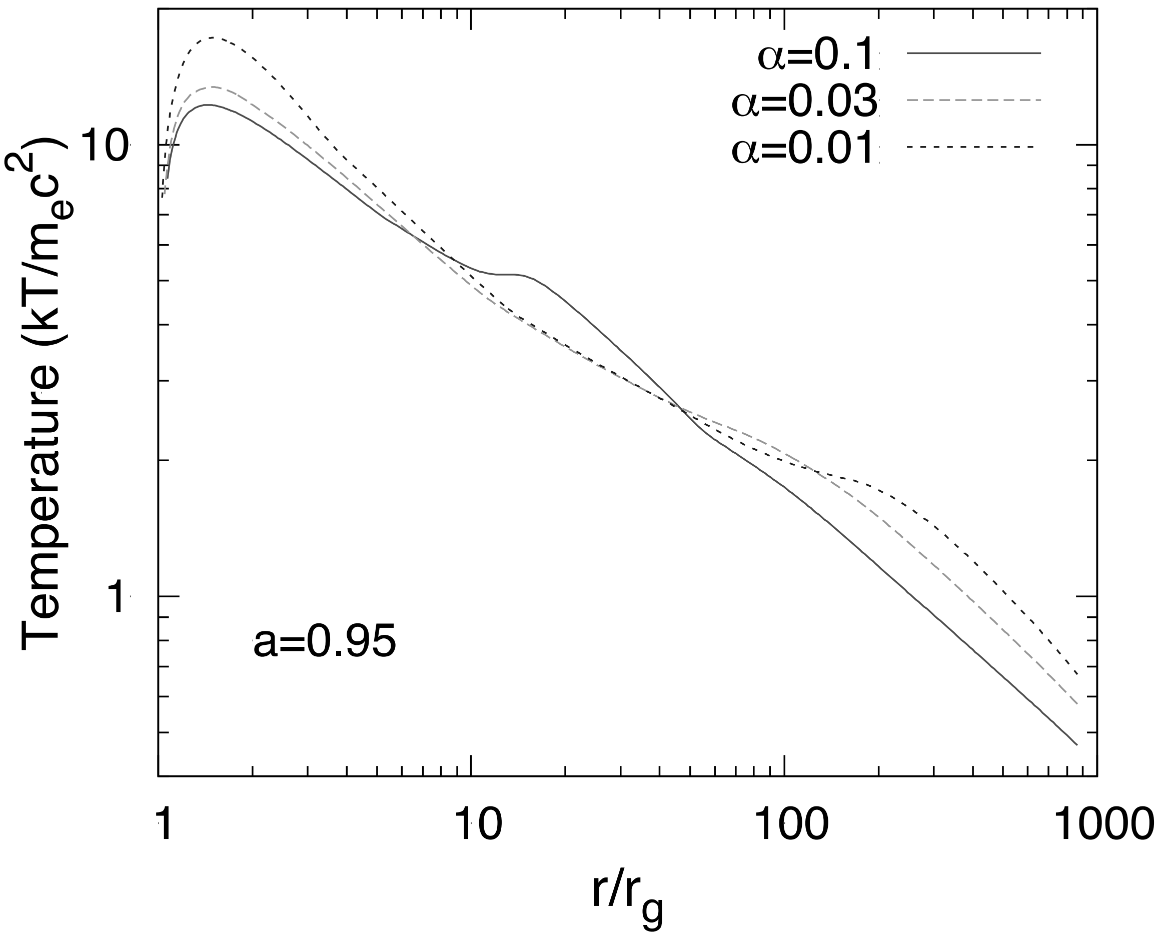


Caballero et al. 2016

- Temperature profile (Caballero et al. 2016)

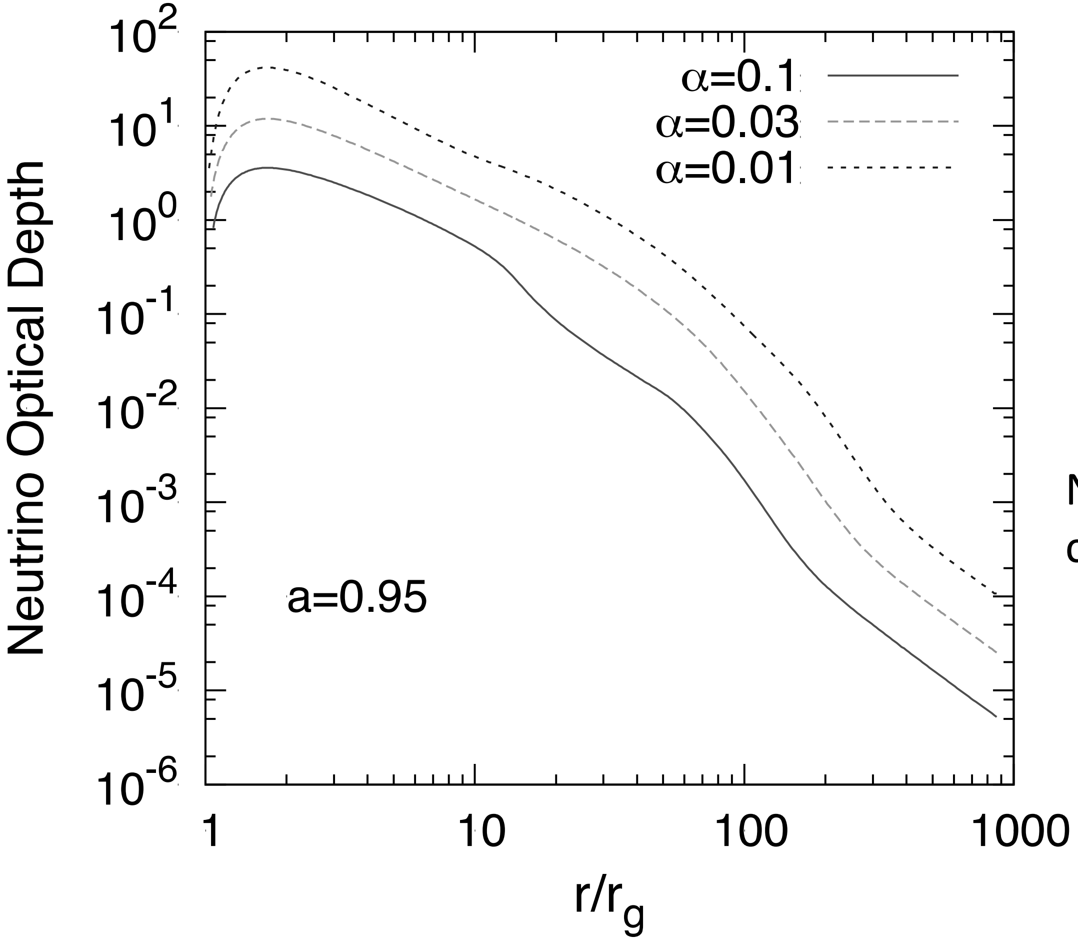


non-rotating BH


Temperature (kT/m_ec^2)
10
1
1
10
100
1000
r/r_g
α=0.1
α=0.03
α=0.01
a=0.95

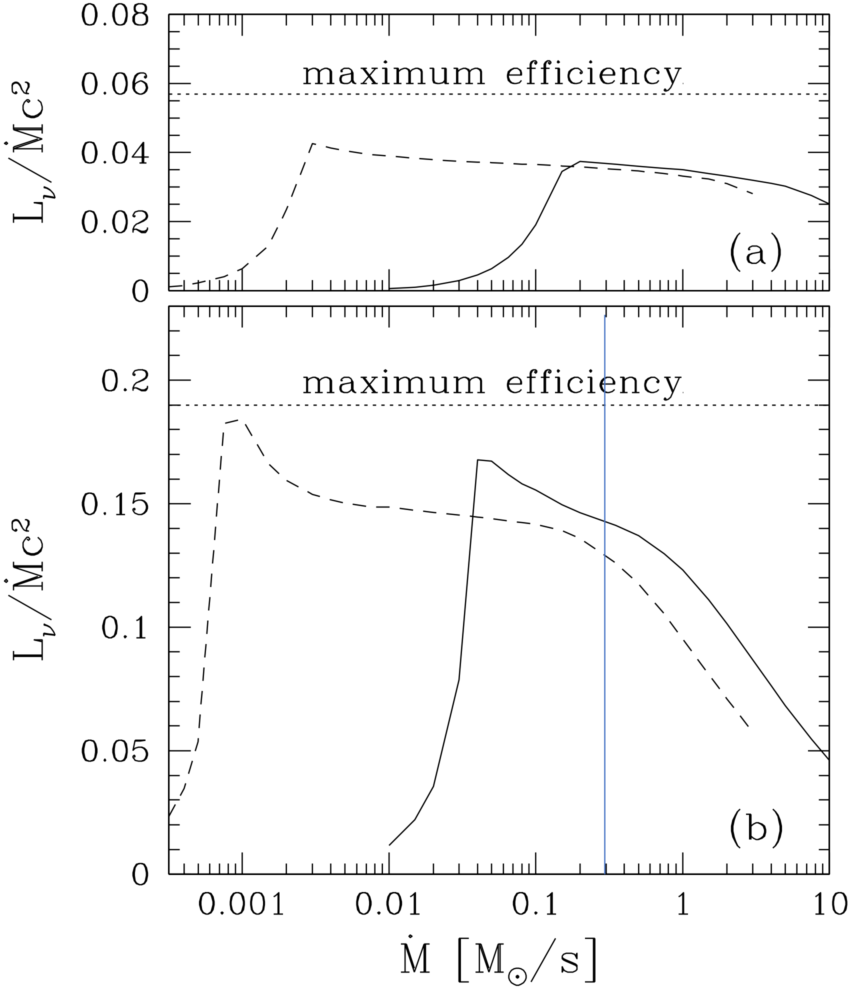
rotating BH

- Neutrino optical depth



Neutrino trapping can also occur.

- Luminosity/Radiation Efficiency



For $\dot{M}\sim 10^7$ M_{sun}/yr,
$L_\nu \sim 8 \times 10^{52}$ ergs/s

Radiation + Neutrino Hydrodynamics

- Radiation and neutrino driven (momentum & energy) hydrodynamics are important in highly dense accretion flow

Mixed-frame Radiation Moment Formalism

- Interaction between radiation and matter can exchange energy and momentum to each other.
  - Details can change the dynamics significantly
  - Full relativistic description required
  - Diffusion approximation is not accurate enough
  - Radiation(neutrino) trapping is actually complicated
- Radiation moment formalism (Park 2006)
  - Use frequency integrated radiation energy (scalar), momentum (vector), and pressure (tensor) to describe the radiation field
  - Covariant description
  - Straightforward application to any given spacetime
  - Valid for any optical depth regime
  - Closure relation required

Schwarzschild spacetime (Park 2006)

- Euler equation

$$
\begin{aligned}
r: \quad & \omega_g U^t \frac{\partial U^r}{\partial t} + \omega_g U^i \frac{\partial U^r}{\partial x^i} + \omega_g \frac{m}{r^2}\left[\Gamma^2 (U^t)^2 - \Gamma^{-2}(U^r)^2\right] \\
- \quad & \omega_g \frac{\Gamma^2}{r}\left[(rU^\theta)^2 + (r\sin\theta U^\phi)^2\right] \\
+ \quad & U^r U^t \frac{\partial P_g}{\partial t} + \Gamma^2 \frac{\partial P_g}{\partial r} + U^r U^i \frac{\partial P_g}{\partial x^i} \\
= \quad & -yU^r G^t + [1 + \Gamma^{-2}(U^r)^2] G^r + r^2 U^r U^\theta G^\theta \\
+ \quad & r^2 \sin^2\theta U^r U^\phi G^\phi + f^r + U^r U_\alpha f^\alpha
\end{aligned}
$$

* Spherically symmetric case without external force:

$$
\frac{y}{\Gamma}\frac{\partial U^r}{\partial t} + \frac{1}{2}\frac{\partial (U^r)^2}{\partial r} + \frac{m}{r^2} + \frac{y}{\Gamma}\frac{U^r}{\omega_g}\frac{\partial P_g}{\partial t} + \frac{y^2}{\omega_g}\frac{\partial P_g}{\partial r}
$$

$$
= \frac{y}{\omega_g} G^{\hat{r}}_{co} = \frac{y}{\omega_g} \bar{\chi}_{co} F^r_{co}
$$

- Kerr spacetime (Takahashi 2007)
  - Euler Equation (R. Takahashi 2007)

$$
\begin{aligned}
& \rho_0 h u^t \frac{\partial u^r}{\partial t} + \rho_0 h u^i \frac{\partial u^r}{\partial x^i} \\
+ \quad & \frac{\rho_0 h}{2} \left[(\ln \gamma_{rr})_{,r} (u^r)^2 + 2 (\ln \gamma_{rr})_{,\theta} u^r u^\theta - (\ln \gamma_{\theta\theta})_{,r} \frac{\gamma_{\theta\theta}}{\gamma_{rr}} (u^\theta)^2 \right] \\
- \quad & \frac{\rho_0 h}{2} \frac{(u^t)^2}{\gamma_{rr}} \left[\gamma_{\phi\phi} (\ln \gamma_{\phi\phi})_{,r} (\Omega + \beta^\phi)^2 + 2 \gamma_{\phi\phi} \beta^\phi_{,r} (\Omega + \beta^\phi) \right. \\
- \quad & \left. 2 \alpha^2 (\ln \alpha)_{,r} \right] \\
+ \quad & \frac{1}{\gamma_{rr}} \frac{\partial P_g}{\partial r} + u^r \left(u^t \frac{\partial P_g}{\partial t} + u^i \frac{\partial P_g}{\partial x^i} \right) \\
= \quad & -\alpha^2 u^t u^r G^t + [1 + \gamma_{rr} (u^r)^2] G^r \\
+ \quad & \gamma_{\theta\theta} u^r u^\theta G^\theta + \gamma_{\phi\phi} (\Omega + \beta^\phi)(G^\phi + \beta^\phi G^t) u^t u^r
\end{aligned}
$$

- Radiation + Neutrino Moment Formalism
  - Moment formalism for neutrinos
  - Extension to multi-component
  - Extension to varying geometry?
    - If tetrads can be defined at any time, moment formalism can be applied