Search for neutrino sources with optical telescopes

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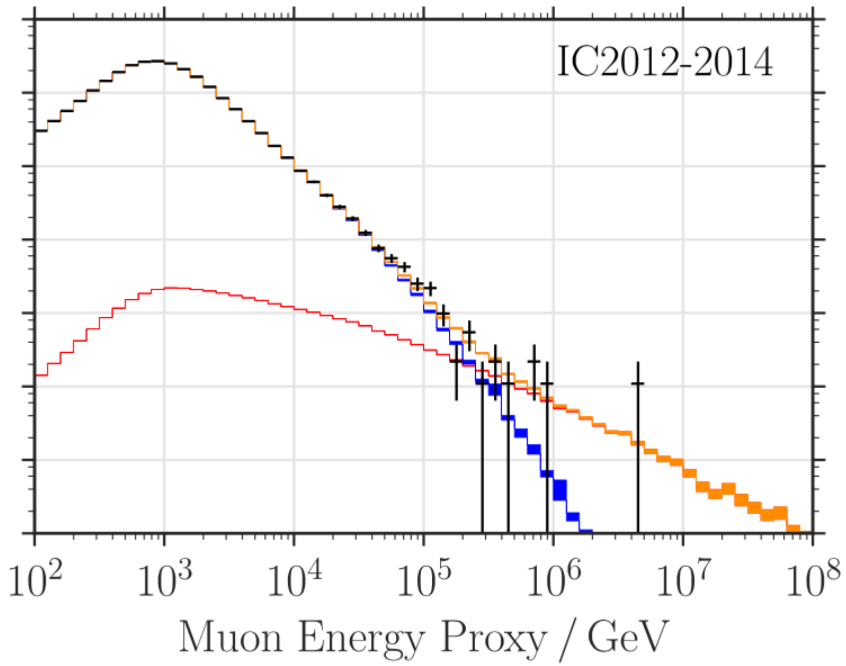
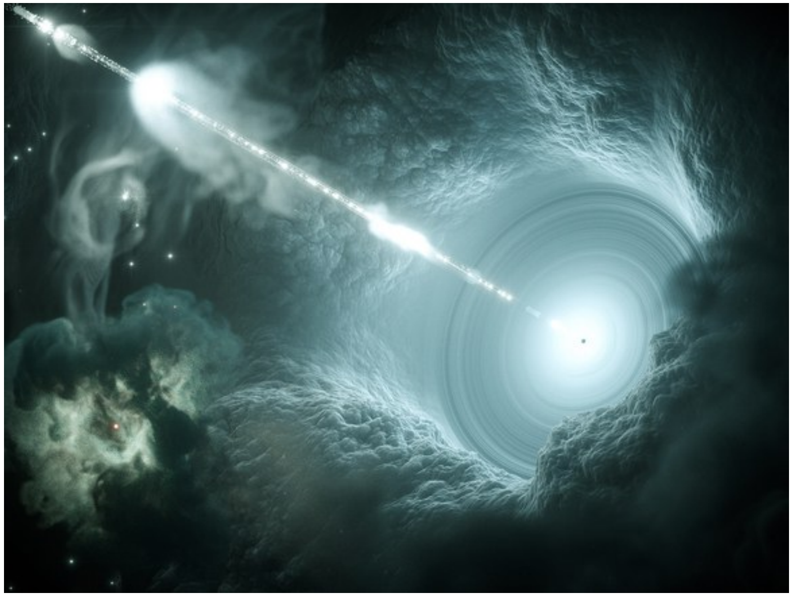
Amon workshop

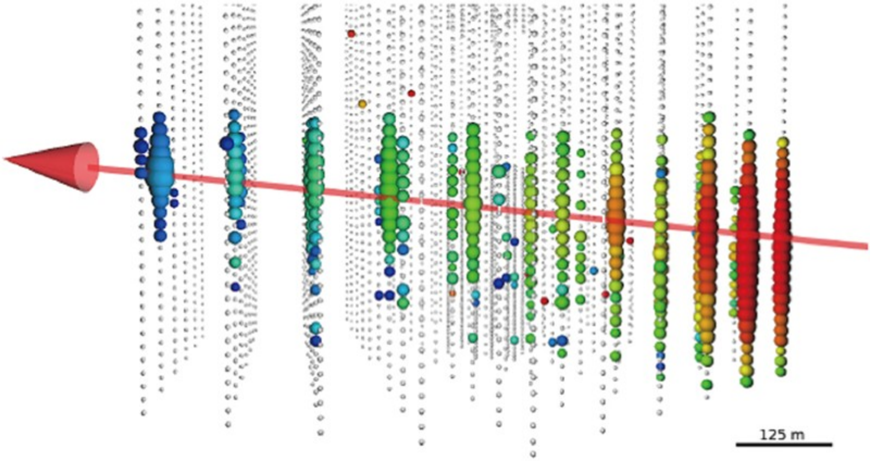
Chiba, May 2019

Strong evidence for extragalactic neutrino sources

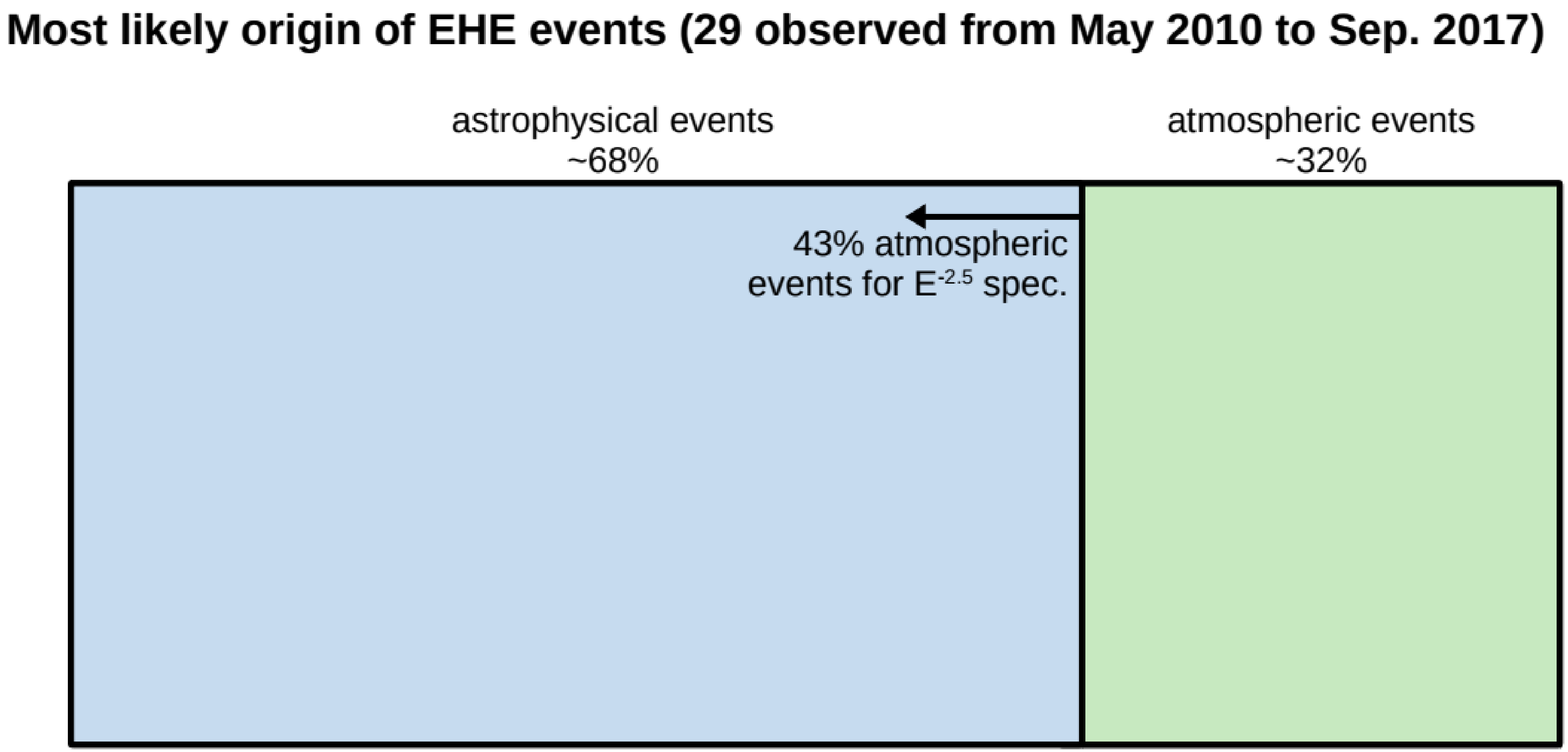
- diffuse astrophysical neutrino flux
- individual high-energy astrophysical events
- Fermi blazar TXS0506+056 identified as likely extragalactic neutrinos source







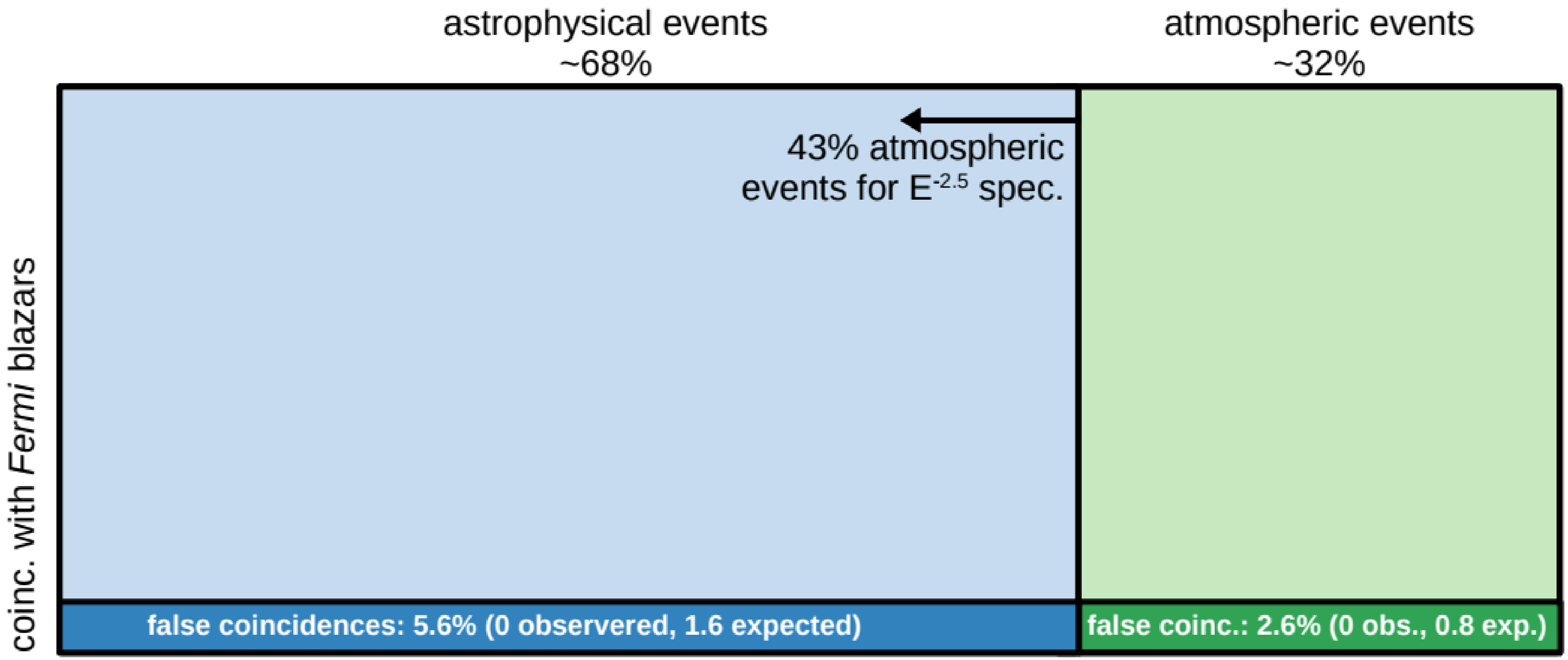
Back-of-the-envelope estimation



> ~60% of the extremely-high-energy (EHE) alerts are astrophysical

Back-of-the-envelope estimation

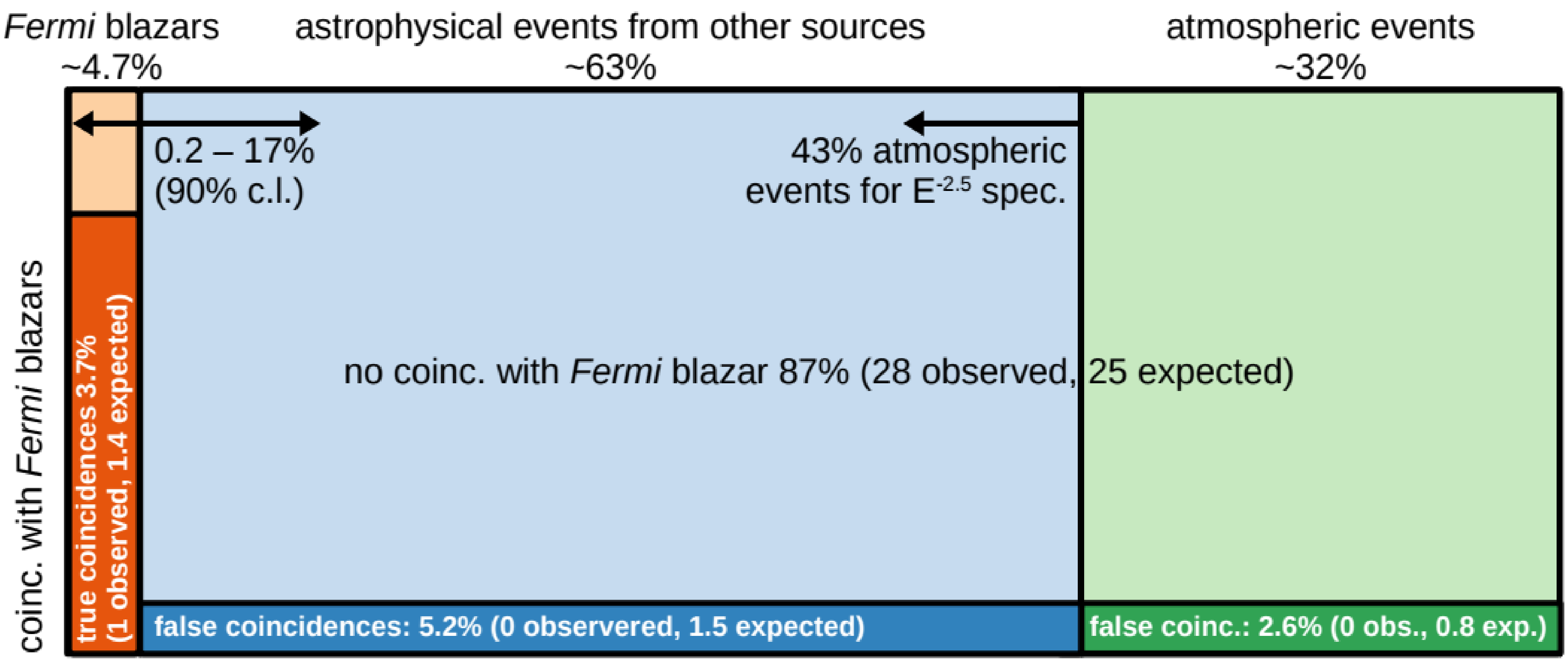
Most likely origin of EHE events (29 observed from May 2010 to Sep. 2017)



- average 90% error circle 1.75(°)^2 → 8% chance to find an unrelated Fermi blazar
- 2.4 chance coincidences expected (0 detected)

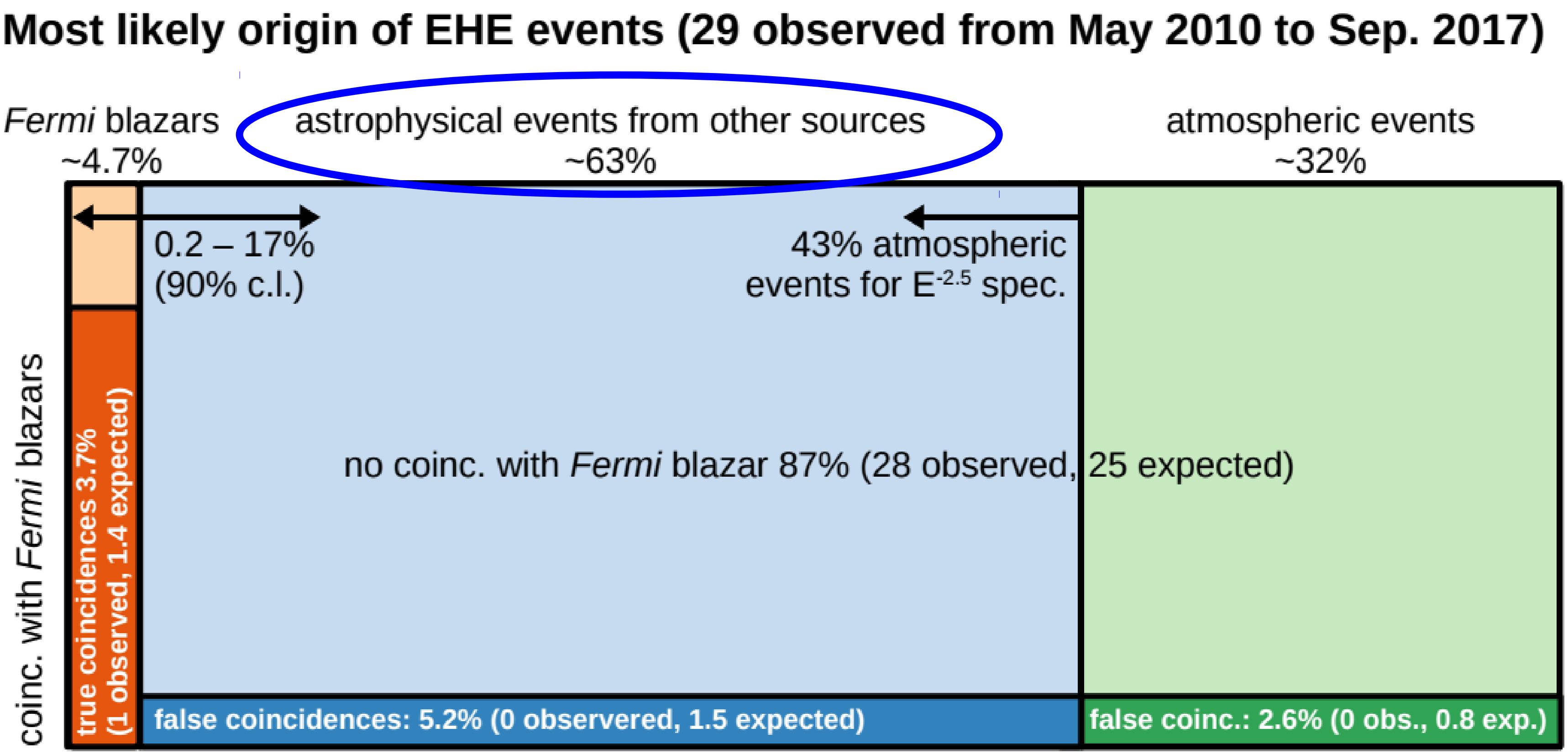
Back-of-the-envelope estimation

Most likely origin of EHE events (29 observed from May 2010 to Sep. 2017)



- assume that coincidence with TXS 0506+065 is real
- calculate allowed fraction of EHE events from resolved and unresolved Fermi blazars → 0.2 – 17%

Back of the envelope estimation



→ most EHE events come from so far unidentified astrophysical sources

Potential extragalactic neutrino sources

Explosions of massive stars

Accreting supermassive black holes

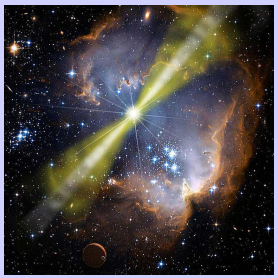
Calorimetric sources

seconds weeks months constant **livetime**

Potential extragalactic neutrino sources

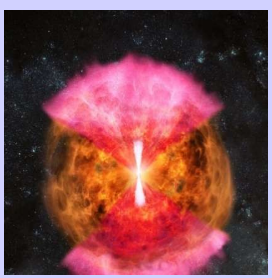
Explosions of massive stars

GRBs



seconds

weeks



choked-jet SN

type IIn supernovae

Accreting supermassive black holes

months

constant

Calorimetric sources

livetime

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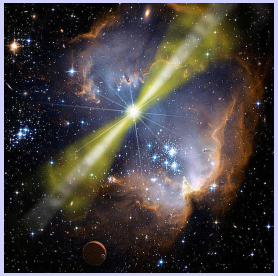
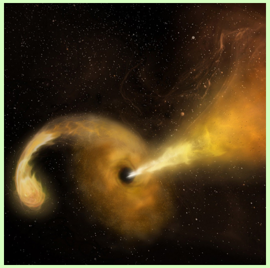
Explosions of massive stars

GRBs

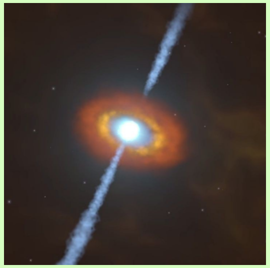


Accreting supermassive black holes

TDEs

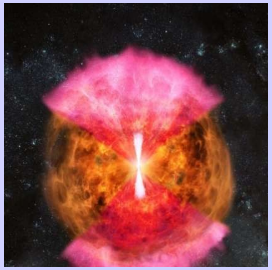


blazars



Calorimetric sources

seconds weeks months constant **livetime**



choked GRBs

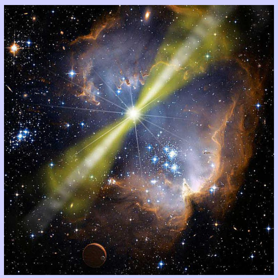
type IIn supernovae

others AGNs

Potential extragalactic neutrino sources

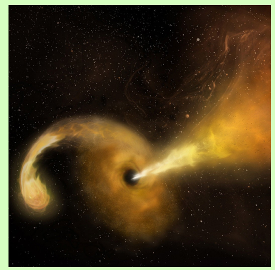
Explosions of massive stars

GRBs

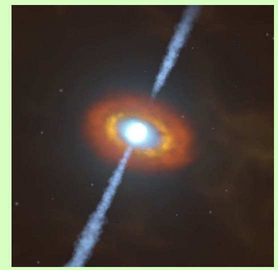


Accreting supermassive black holes

TDEs



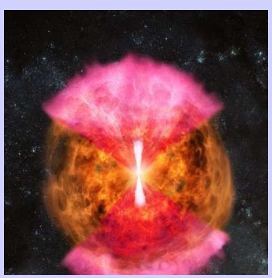
blazars



Calorimetric sources

starburst gal.

seconds weeks months constant **livetime**



choked GRBs

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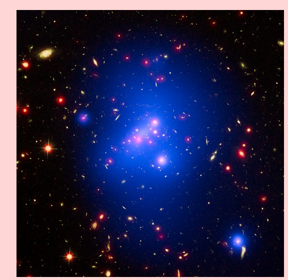
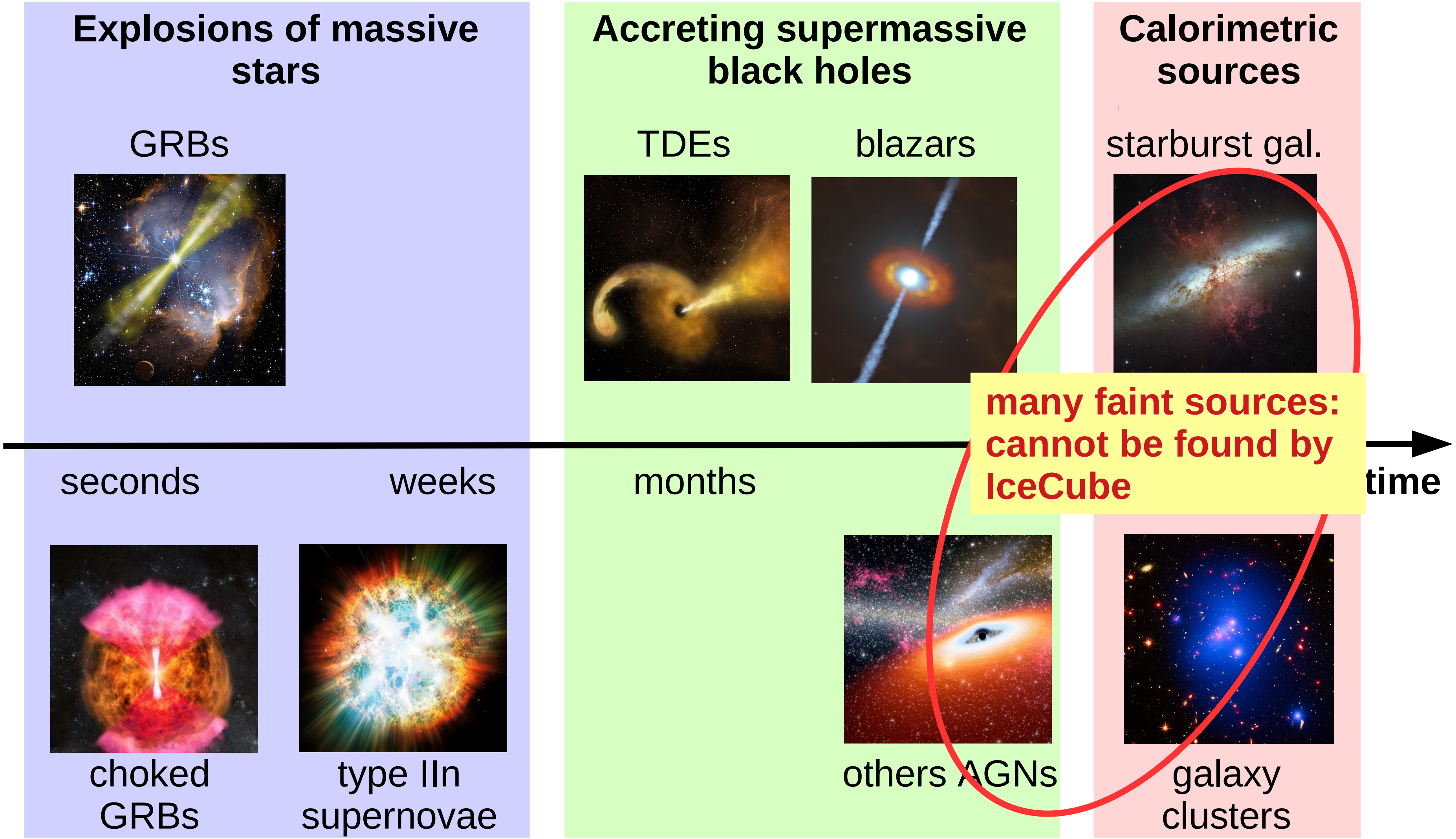
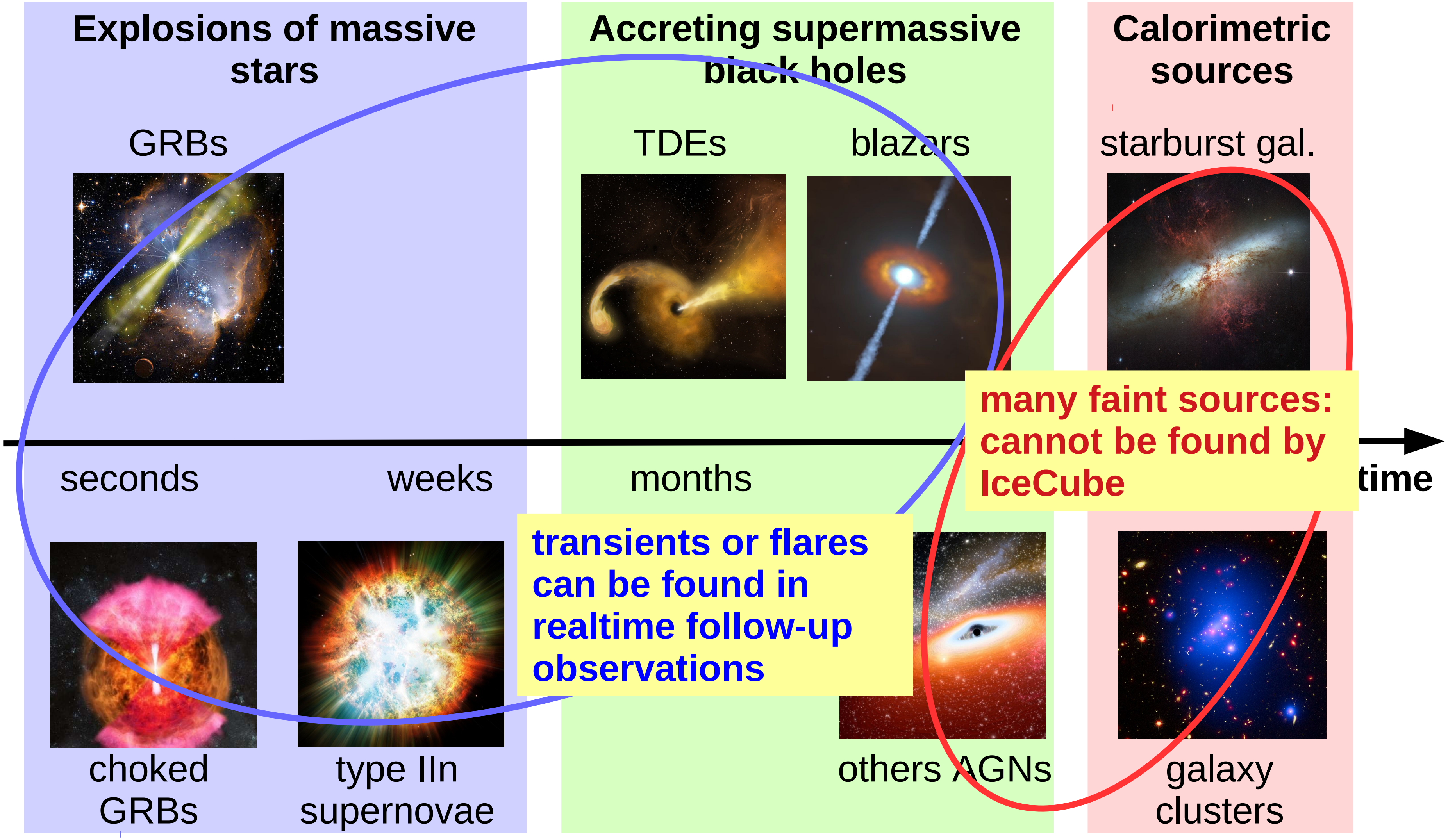


galaxy clusters

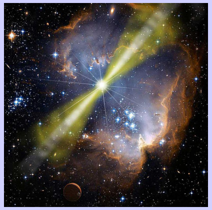
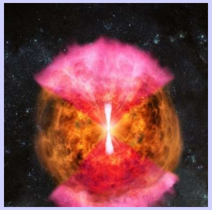
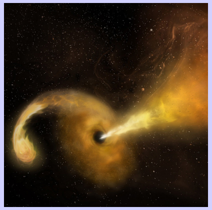
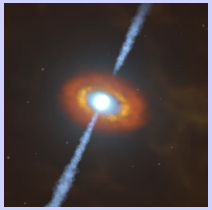
Potential extragalactic neutrino sources



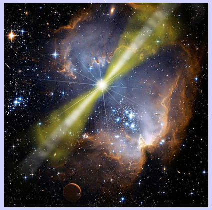
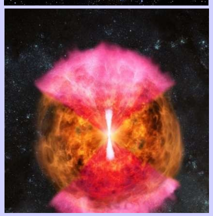
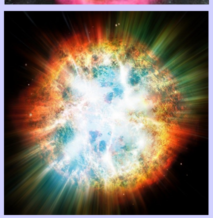
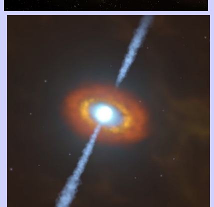
Potential extragalactic neutrino sources



Expected multiwavelength emission

		Expected emission:
GRBs		γ-rays, X-rays, UV, **optical**, radio rarely: VHE γ-rays
choked or ll-GRBs		**optical** maybe: γ-rays, X-rays, late radio
type IIn SNe		**optical** rarely: X-rays
jetted TDEs		**optical**, UV, X-rays
blazars		all wavelengths

Expected multiwavelength emission

		Expected emission:	Opt. peak mag.:	Duration:
GRBs		γ-rays, X-rays, UV, **optical** rarely: VHE γ-rays	-24th	~100 s
choked or II-GRBs		**optical** maybe: γ-rays, X-rays, late radio	SN: -19th	ν: ~100 s em.: ~30 d
type IIn SNe		**optical** rarely: γ-rays, X-rays	-18th (-21th if superl.)	~100 days
jetted TDEs		**optical**, UV, X-rays	-20th	~100 days
blazars		all wavelengths	-26th	minutes - months

Why look for optical emission?

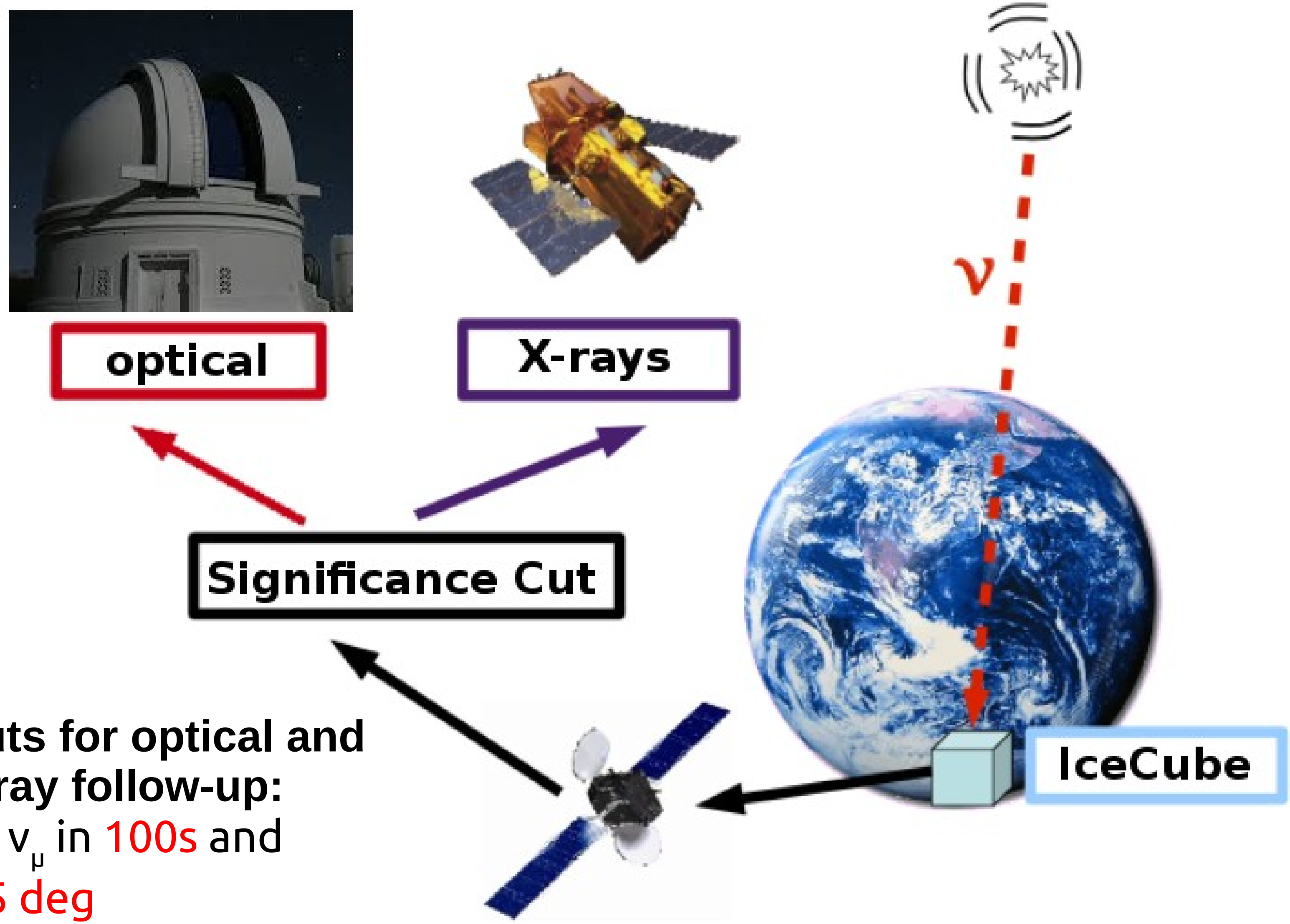
- all source classes emit in the optical
- telescopes can cover a large part of the sky
- most neutrino sources are not detected by current gamma-ray telescopes

Disadvantage:

- large number of counterpart candidates

→ a significant correlation is only expected for relatively rare sources

IceCube's optical and X-ray follow-up program

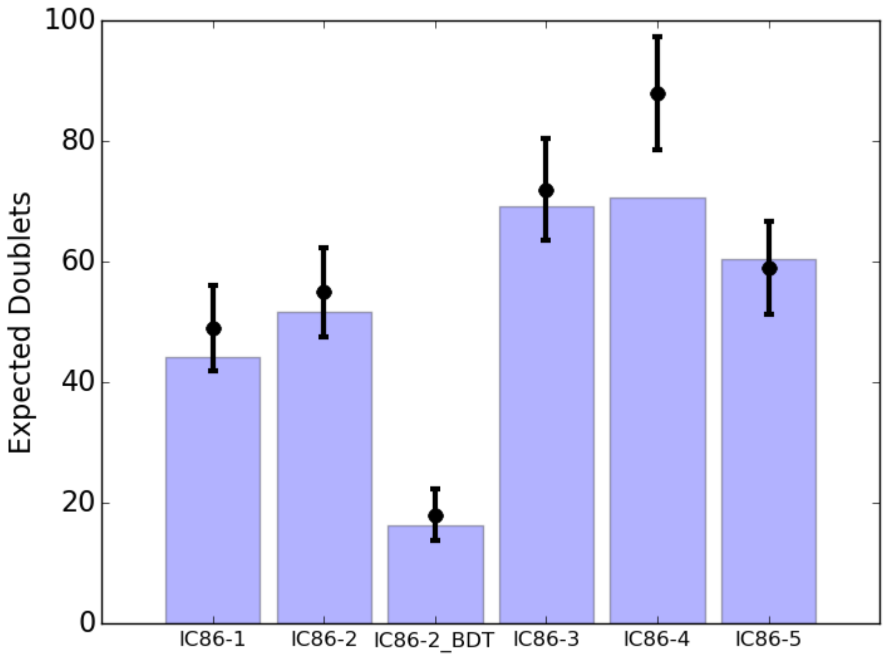


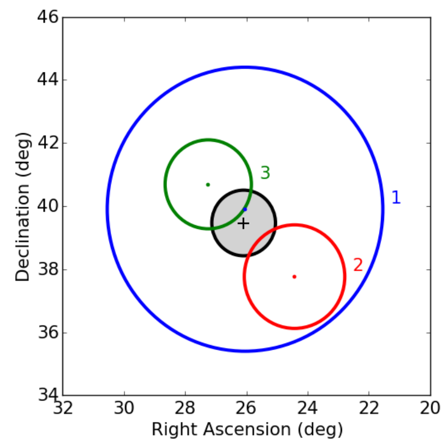
Cuts for optical and X-ray follow-up:
≥2 ν_μ in 100s and 3.5 deg

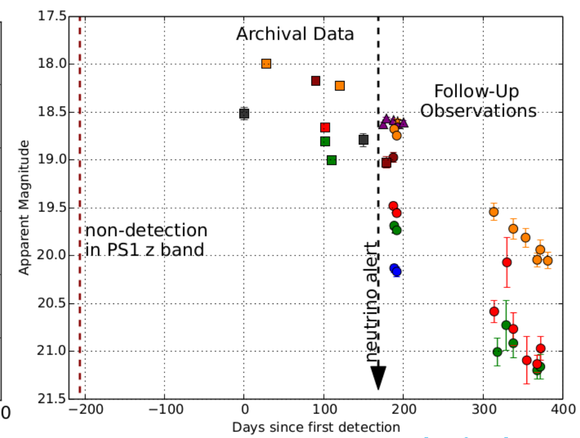
No likely counterparts detected

- alert rates consistent with expected number of chance coincidences [arxiv:1807.11492]
- most significant alerts consistent with background [arxiv:1506.03115, 1702.06131]
- no likely counterparts detected in optical or X-ray observations

  → no bright (>2 events) 100s long transients



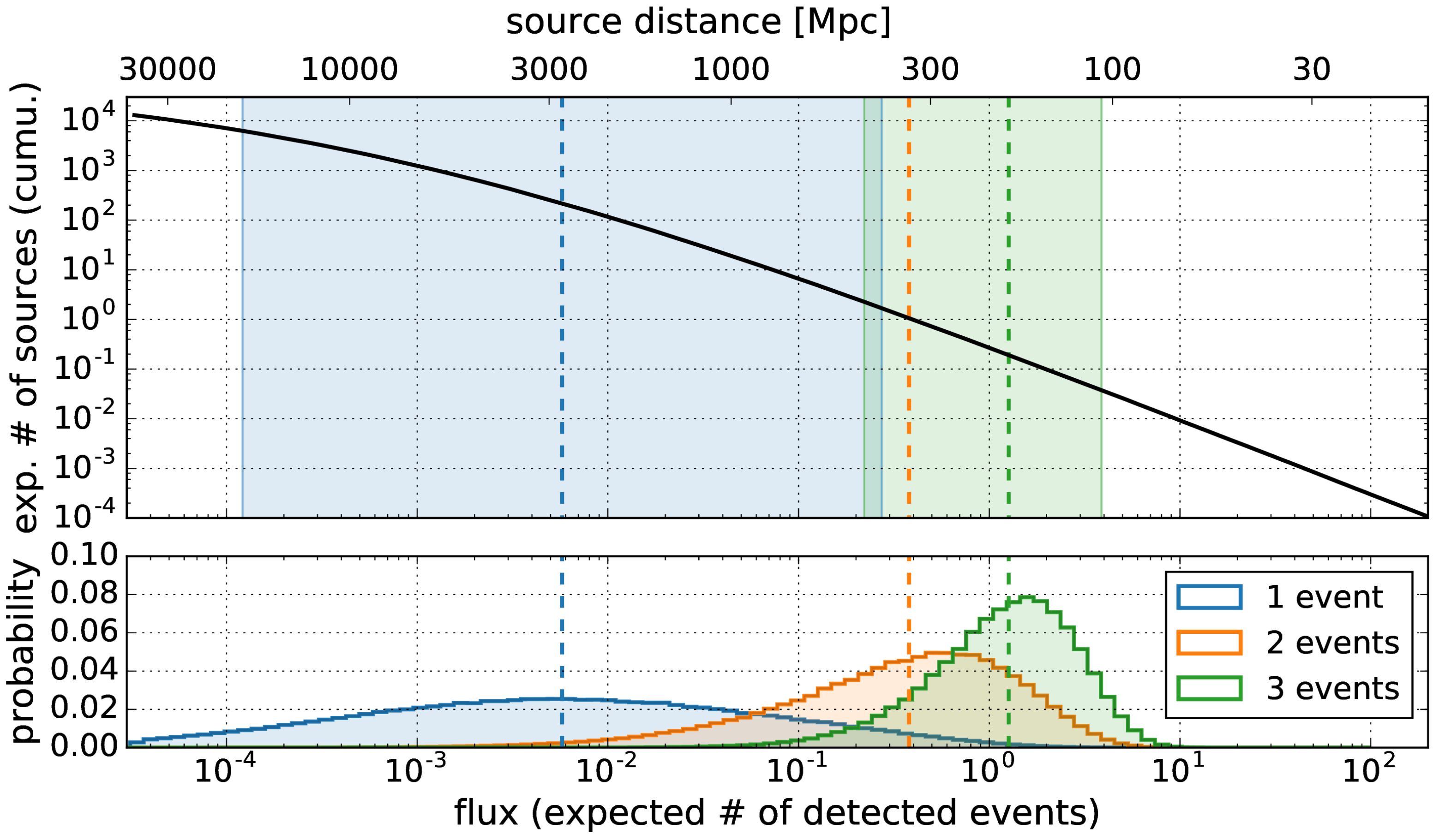




Distance of a neutrino source

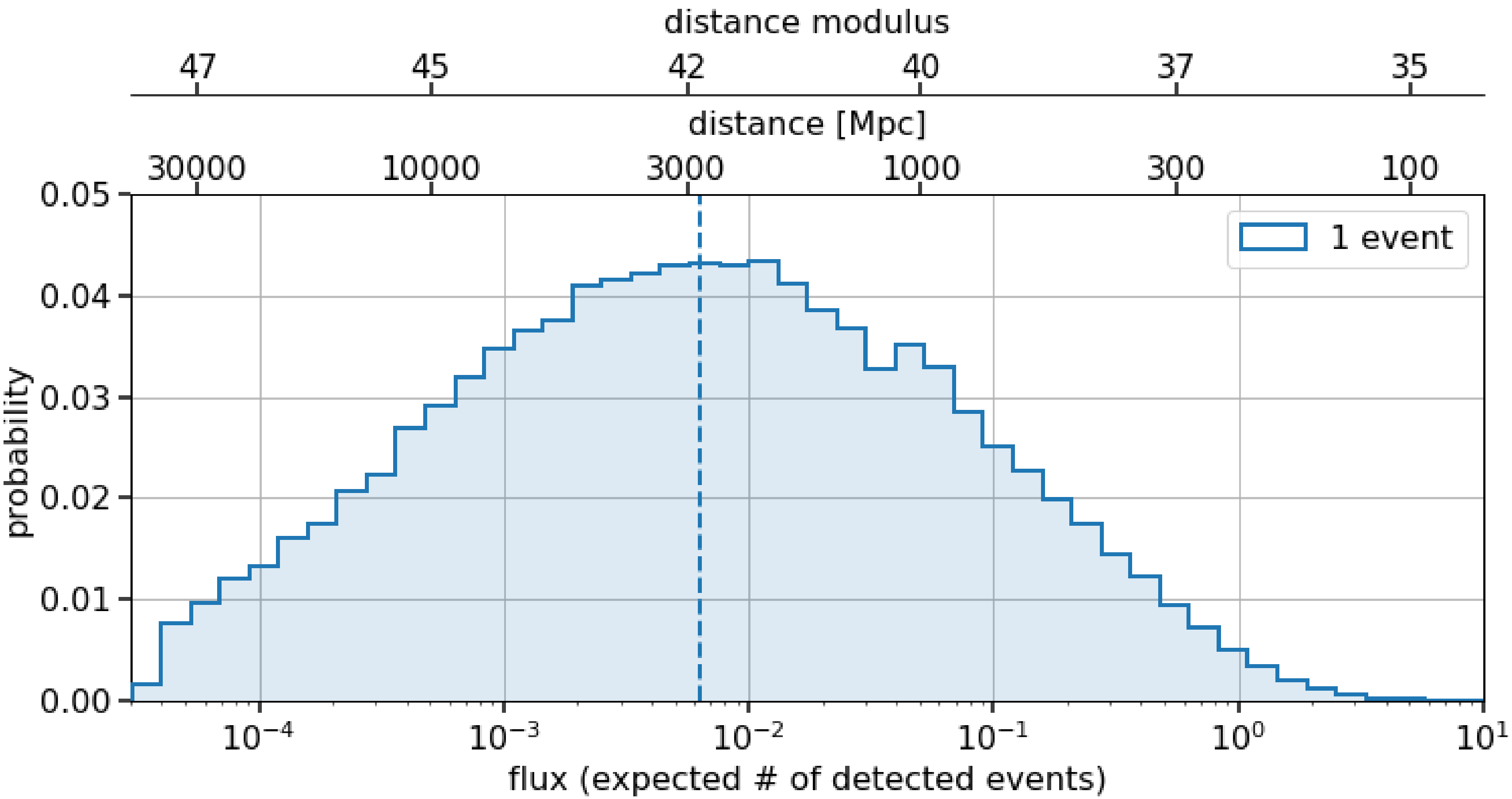
> simulate cosmic population of neutrino sources (here no evolution): calculate which of them are detected with 1, 2, or 3 events

→ single events are most likely detected from distant sources



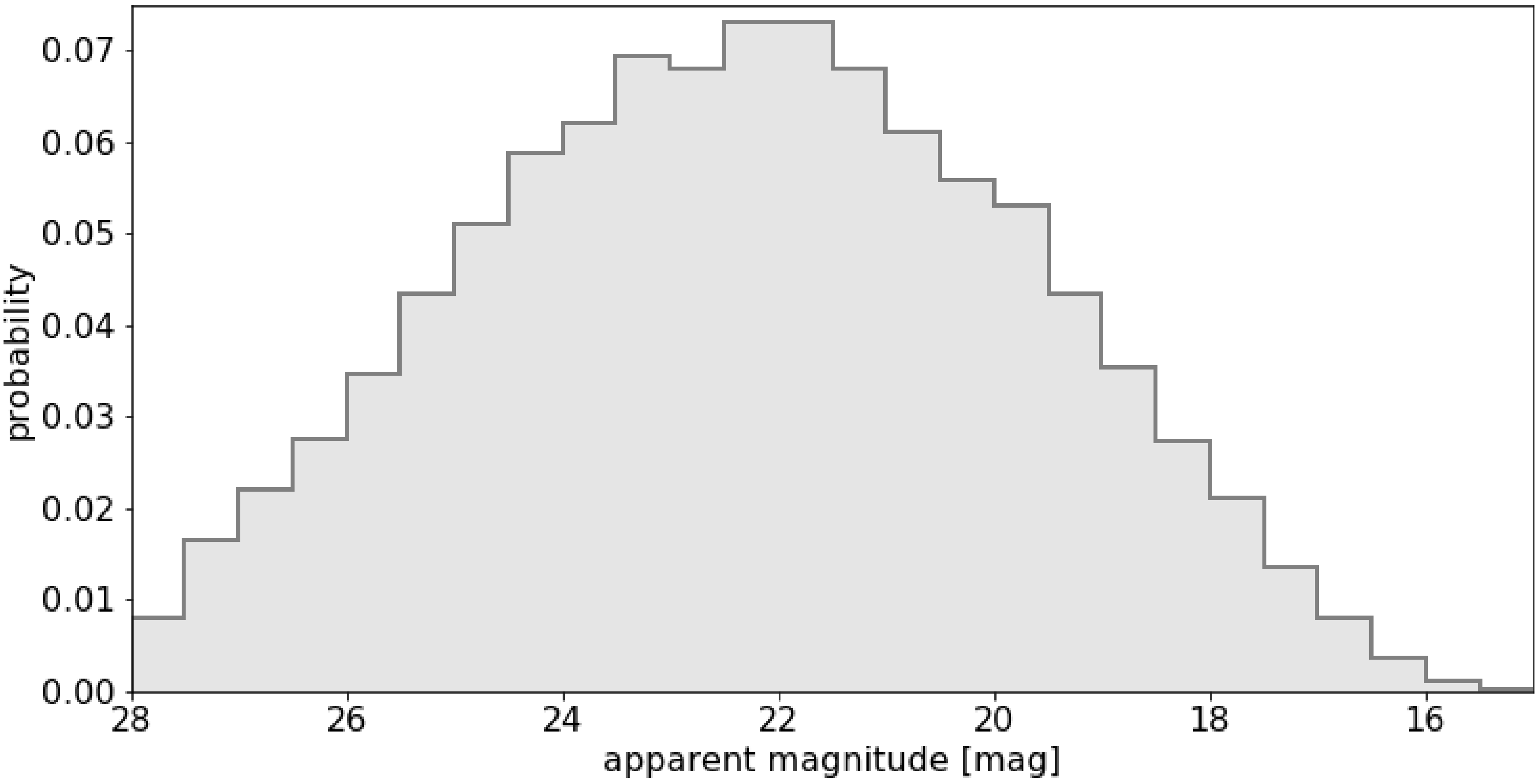
Fluxes and distances of sources detected with one event

- median distance is 3 Gpc or distance modulus of 42 (for no-evolution scenario)



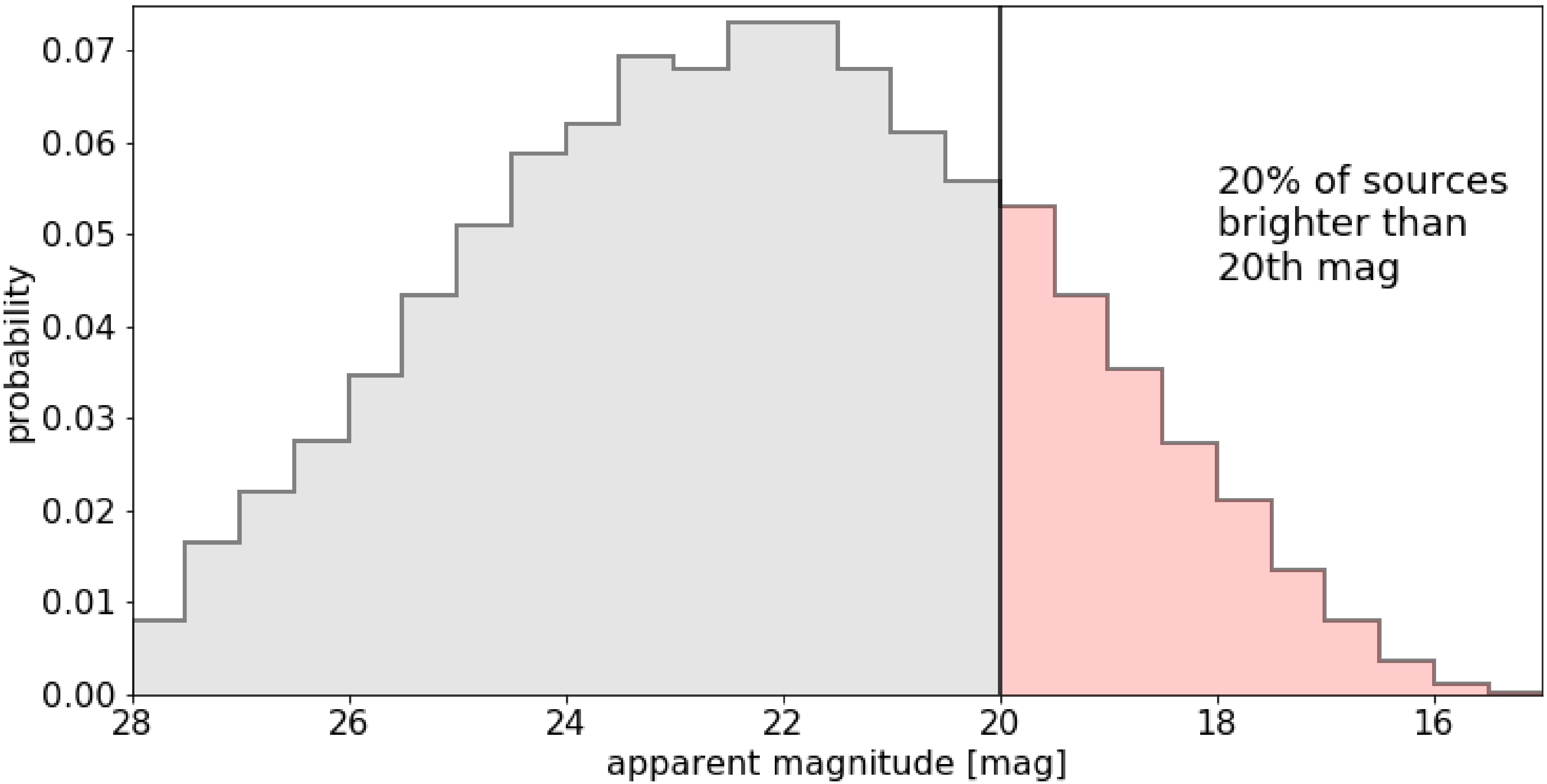
Magnitudes of sources detected with one event

> here for an absolute optical magnitude of -20



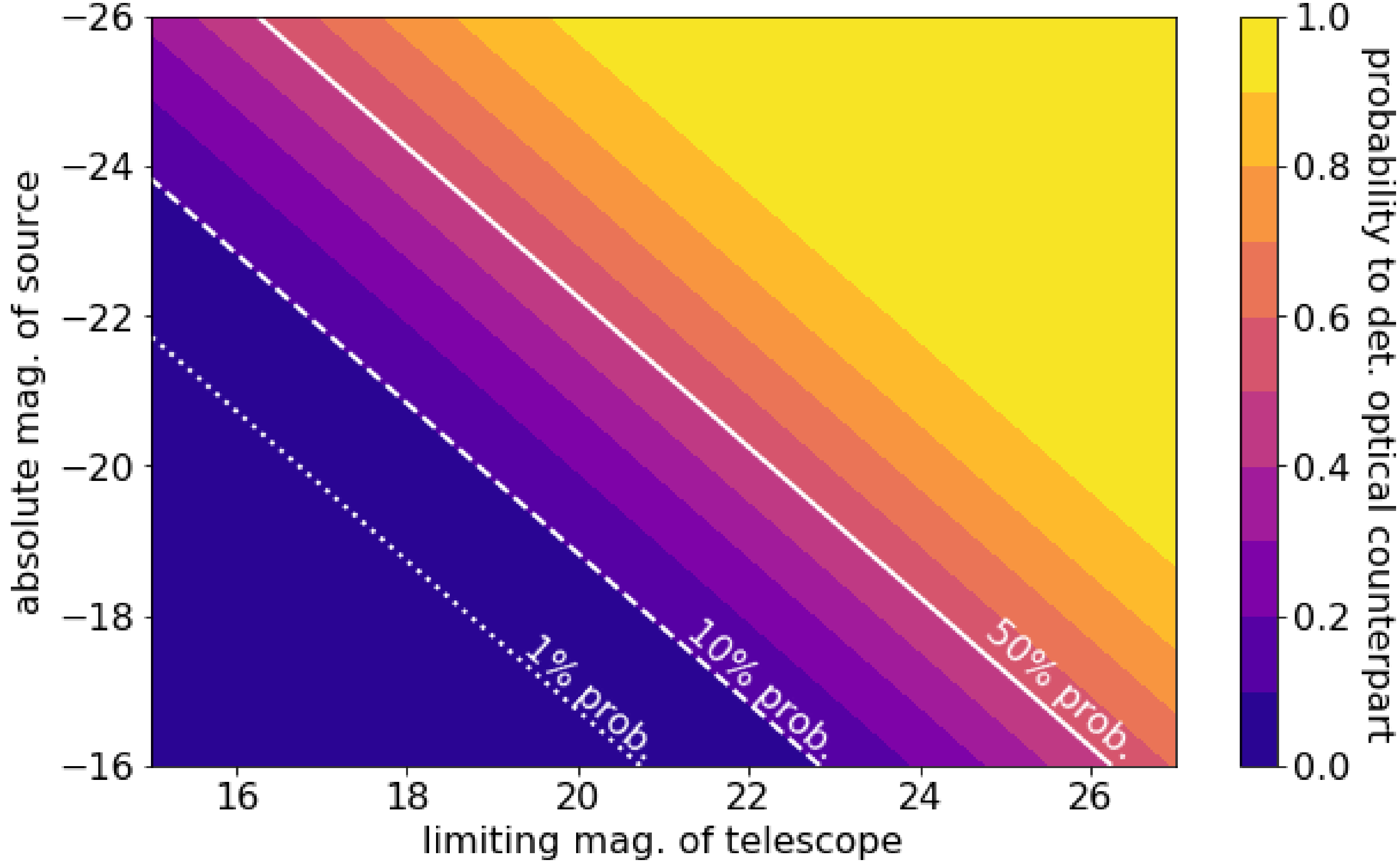
Magnitudes of sources detected with one event

- here for an absolute optical magnitude of -20
- most counterparts are close to the detection limit of a typical telescope



Probability to detect optical counterpart of EHE event

- probability that counterpart is detectable >>1 for typical telescope and moderately bright source



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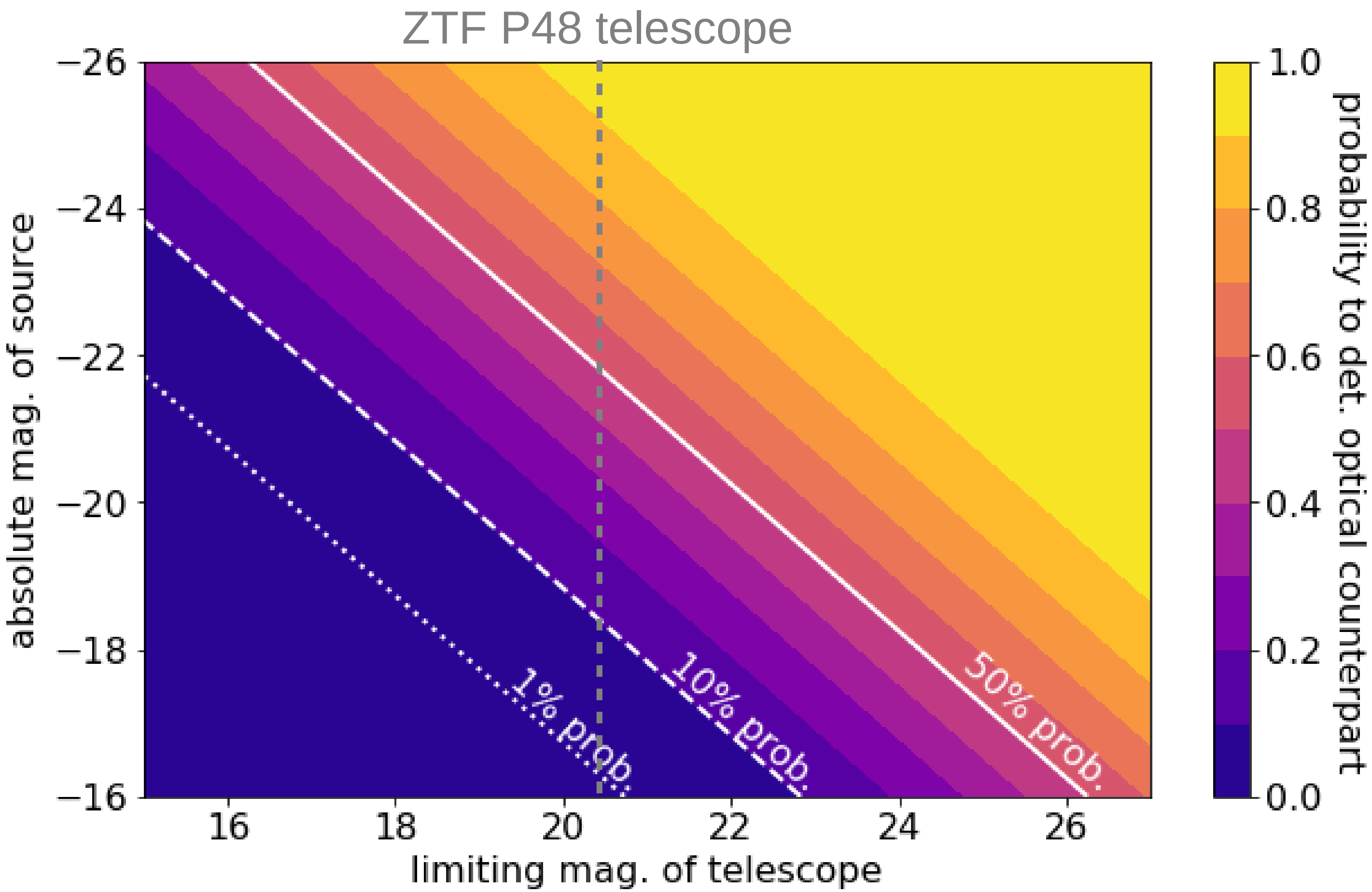
  - → observe many alerts to increase chances of detection



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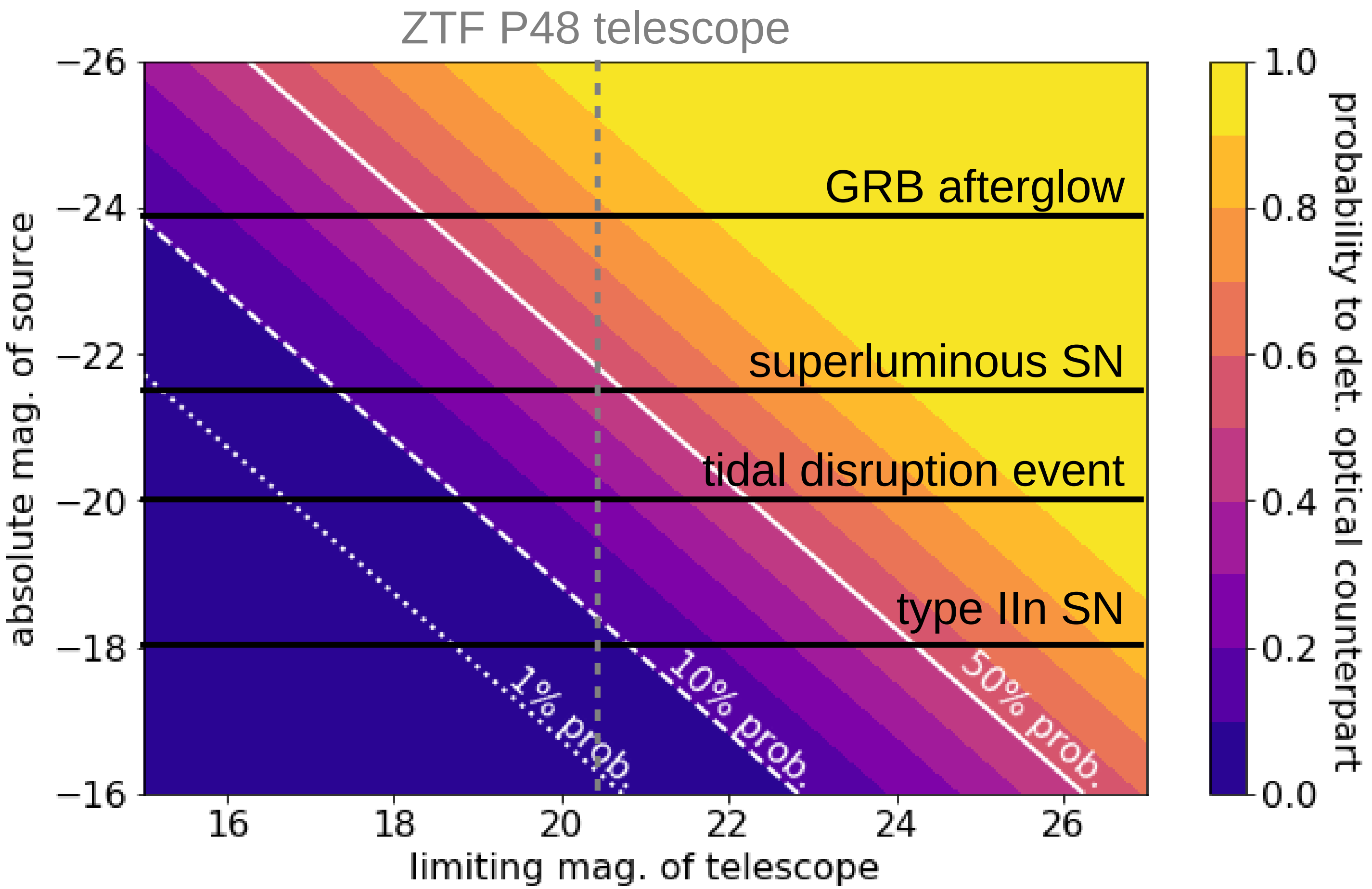
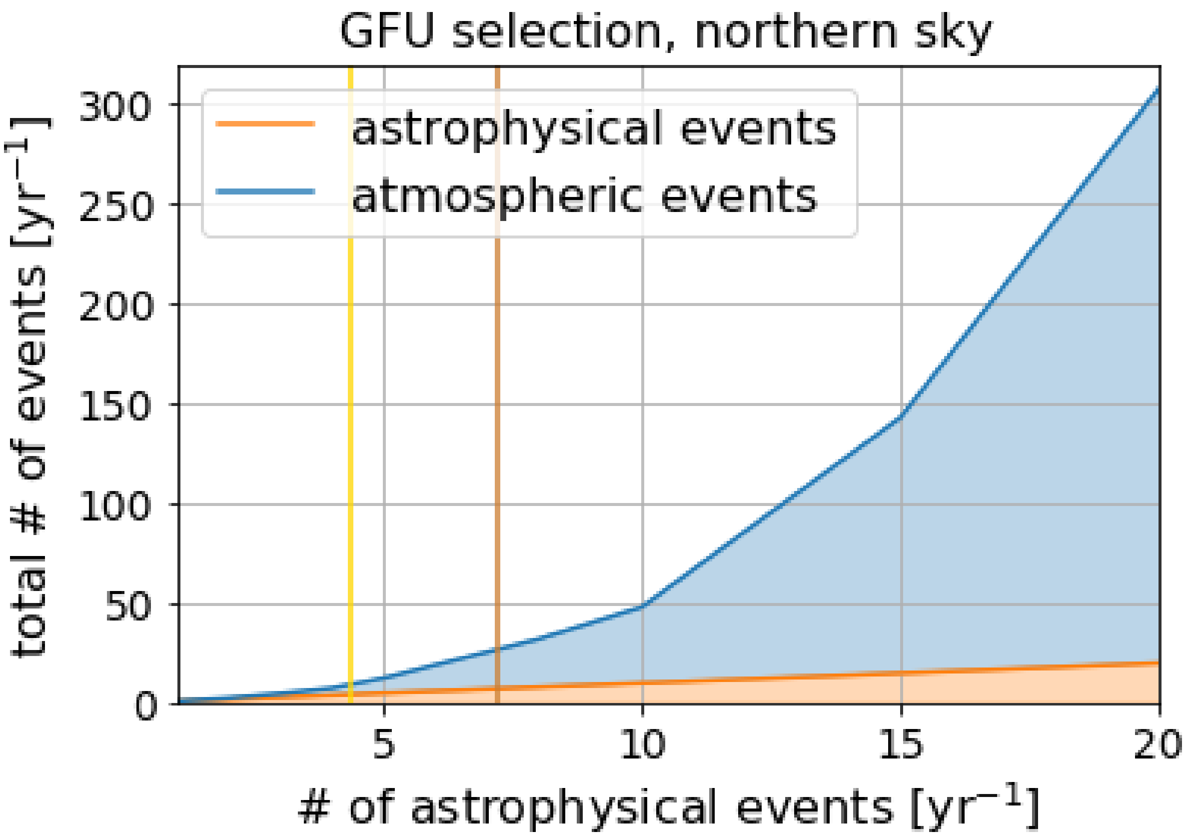


Number of alerts vs. signal to background ratio

- lowering the energy threshold increases number of signal alerts
- future IceCube alerts: golden 50% signal & bronze 30% signal
- angular resolution also drops (not considered here)



catalog search:

few hundreds to 1000 signal events per year

10^5 background events per year

Required number of neutrino alerts for a detection

- number of events per year for which the detection of 1 true counterpart is expected
- number of astrophysical alerts in parentheses

	GRB (-24 mag)	**TDE** (-20 mag)	**SN Ic** (-19 mag)	**SN IIn** (-18 mag)
Panstarrs (lim. mag. 22.5)	1.2 (1.1)	2.6 (2)	4 (2.5)	7.4 (4)
ZTF (lim. mag. 20.5)	1.4 (1.3)	6.5 (3.7)	32 (8.3)	300 (20)
ASAS-SN (lim. mag. 18)	4 (2.5)	~1000 (33)	~10^4 (100)	>10^4 (>100)

- green: IceCube golden alerts, yellow: bronze alerts, red: larger sample required or do catalog search
- losses due to bad weather, engineering etc. not considered

DESY

Search strategies for different optical telescopes

global network of small telescopes:

- focus on <u>quick follow-up</u>
- search for GRB-like afterglows or other quickly fading transients

medium-size telescopes:

- distribute observation time over <u>many neutrino alerts</u>
- search for peculiar source (jetted TDE) or produce catalog for likelihood search

large telescopes:

- <u>deep observations</u> for alerts with highest energy and best angular reconstruction
- search for fainter sources (like CCSNe)
- indepth analysis of counterpart candidates

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Important for all follow-up observations:

> large enough field of view: ca. 1 deg diameter

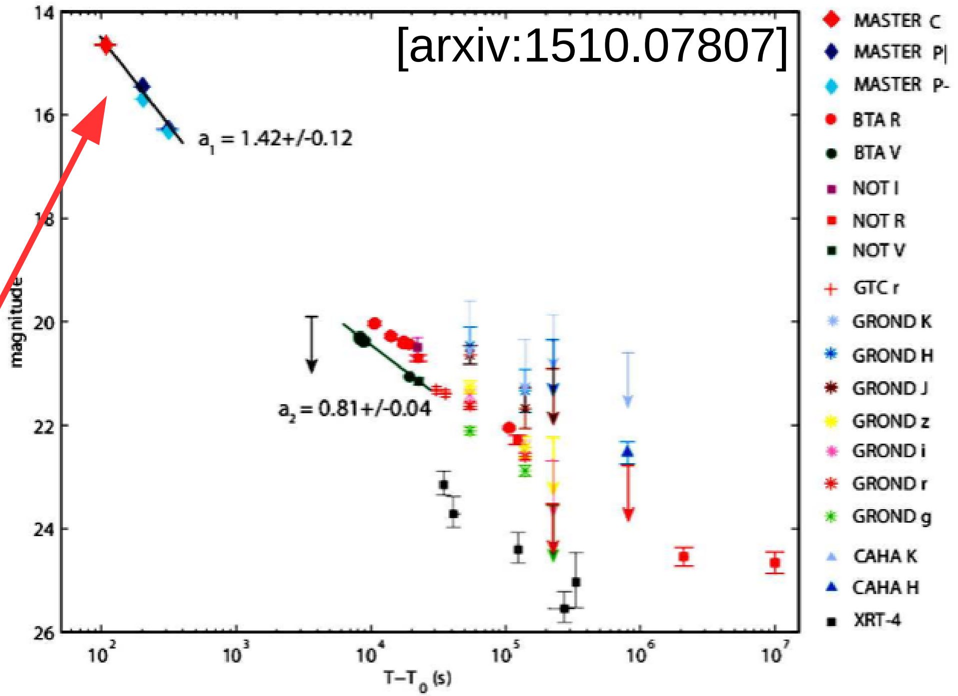
> if neutrinos expected at explosion: significance proportional to uncertainty on explosion date → quick observations

> sufficient spectroscopic time to confirm/rule out faint candidates (~80% of detected SNe are of type Ia)

MASTER global net

global network of small telescopes

- 9 telescopes around the globe → quick observations nearly always possible



example of GRB140801A:

- observations started automatically triggered by Fermi GCN
- afterglow detected 53s after GCN notice (99s after Fermi detection)
- other telescopes catch up 1h later: source has faded by 5 mag

- IceCube has strong limits on gamma-ray bright GRBs, but not on low-luminosity, orphan or “dirty fireball” GRBs

Zwicky Transient Facility

medium-size telescopes

- 48-inch (120cm) aperture
- can monitor entire northern sky in one night out to 20.5th mag
- large field of view: 47 square degrees
- Desy is ZTF and IceCube member: dedicated neutrino follow-up program

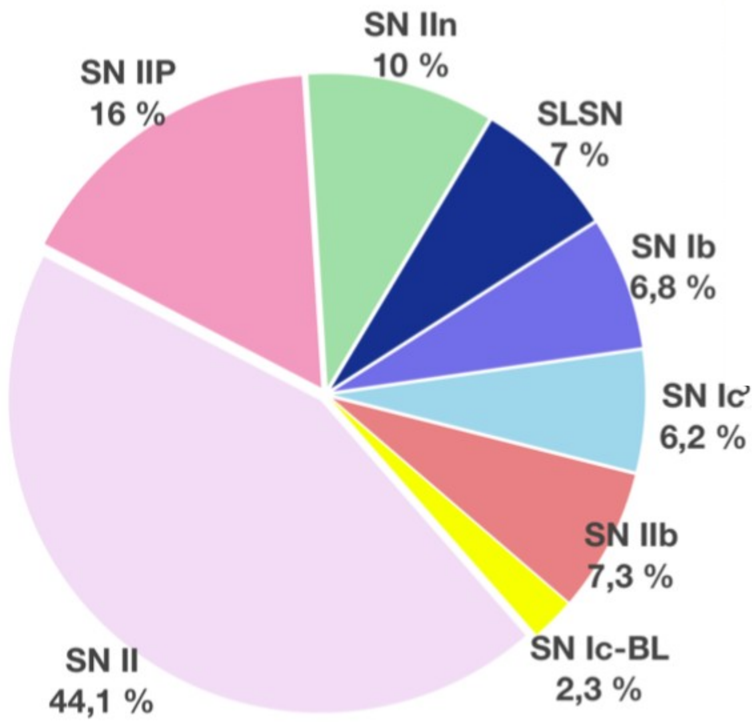
- should be able to observe 50-75% of IceCube alerts
- very unlucky since survey start in 2018:

Type	date	RA	Dec	Error	Comments
Doublet	2018-06-11 23:36:04.87	255.63	13.32	0.90	observed
EHE	2018-09-08 19:59:31.84	145.77	-2.52	0.34	Sun distance 22.68 deg
HESE	2018-10-14 11:52:19.07	225.18	-34.79	1.22	Sun distance 35.73 deg
EHE	2018-10-23 16:37:32.65	269.84	-8.89	0.29	camera down
HESE	2018-10-31 02:02:51.41	182.79	-68.39	1.22	retracted
HESE	2019-01-24 03:44:35	307.19	-32.29	1.23	Sun distance 13 deg
HESE	2019-03-31 06:55:43	337.79	-21.08	2.624	Sun too close

Zwicky Transient Facility

medium-size telescopes

- 2nd strategy: produce catalog for stacked search
- ZTF “redshift completeness factor” survey: obtain spectra for all objects brighter than 18.5th magnitude
- until March 2019: 662 SNe classified, 177 of them are CCSNe



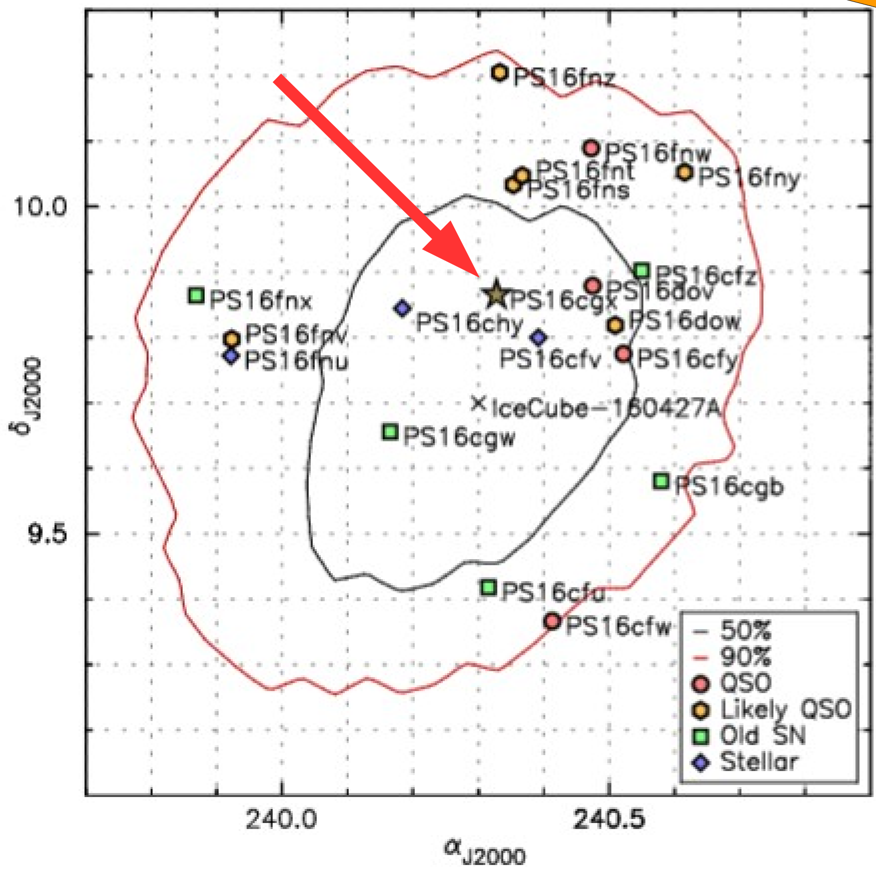
- likelihood analysis to search for neutrino emission from choked-jet and interacting SNe:
  ~250 CCSNe and 10^5 ν per year (up to 1000 astro. ν)
- trigger spectroscopic classification based on neutrino alerts?
  → would produce biased SN catalog

Panstarrs detection of the SN PS16cgx

large telescopes

- follow-up of HESE event:

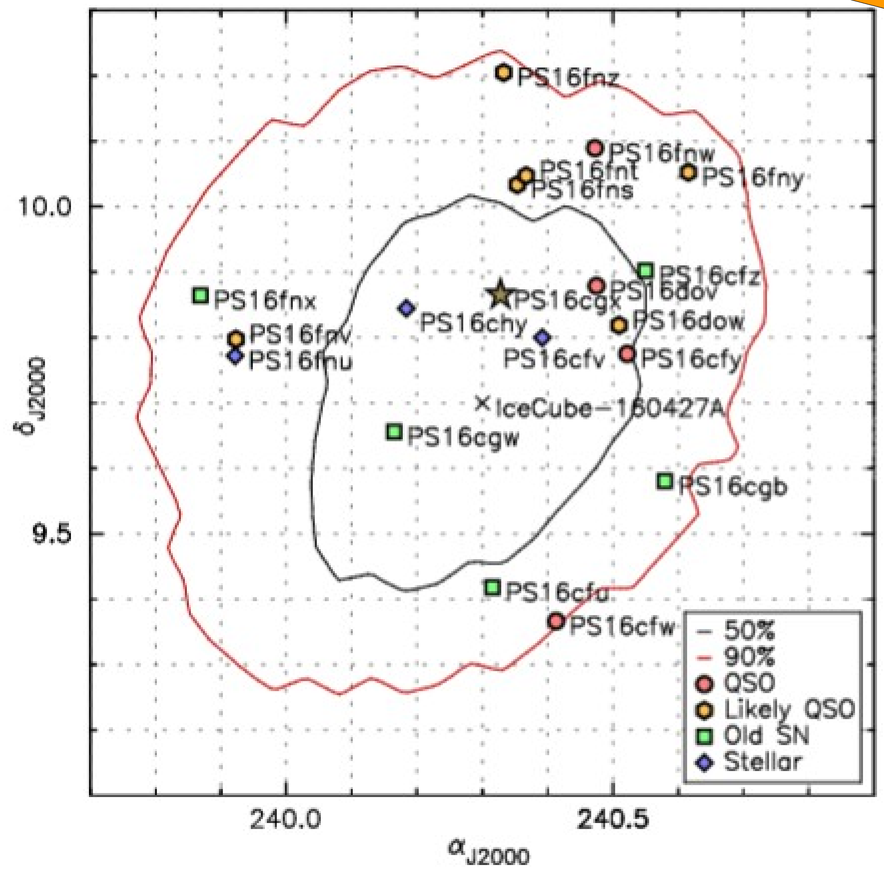
  E>130 TeV, error circle 0.77(°)^2
- typically 10-20 extragalactic transients with m_i<22.5
- quick initial follow-up observations:
  - rule out old candidates
  - rule out candidates that are not yet present
- need spectroscopic time to verify nature of faint counterpart candidates



Panstarrs detection of the SN PS16cgx

large telescopes

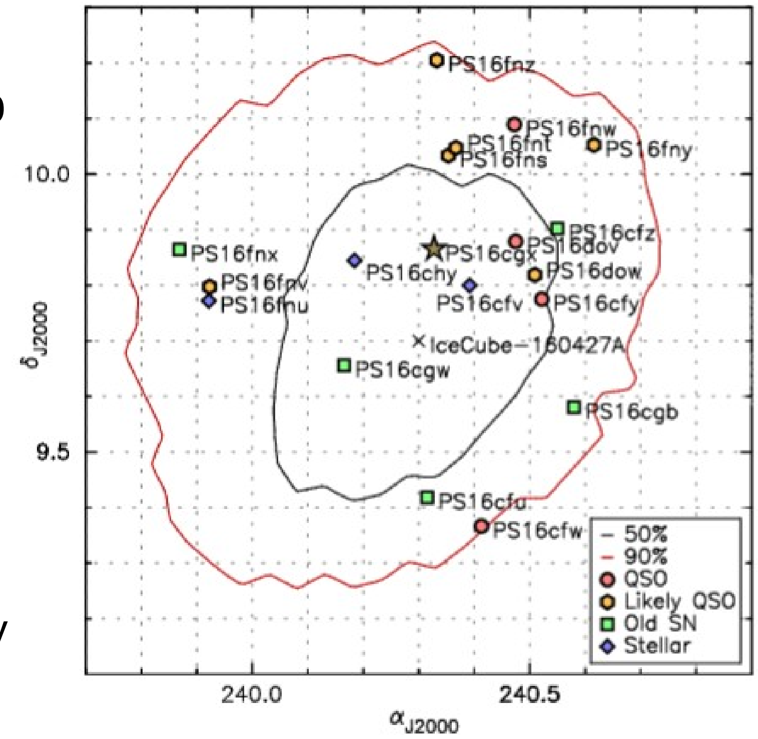
- 19 candidates within 90% error circle:
  - 10 likely QSOs
  - 5 old SNe
  - 3 stars
  - 1 young SN
- potential type Ic broad-line SN (associated with GRBs, could have choked jet)



- two spectra and multiband light curve are consistent with either a SN Ic broadline or a type Ia SN
- SNe Ia are ~20 times more frequent → likely a chance coincidence

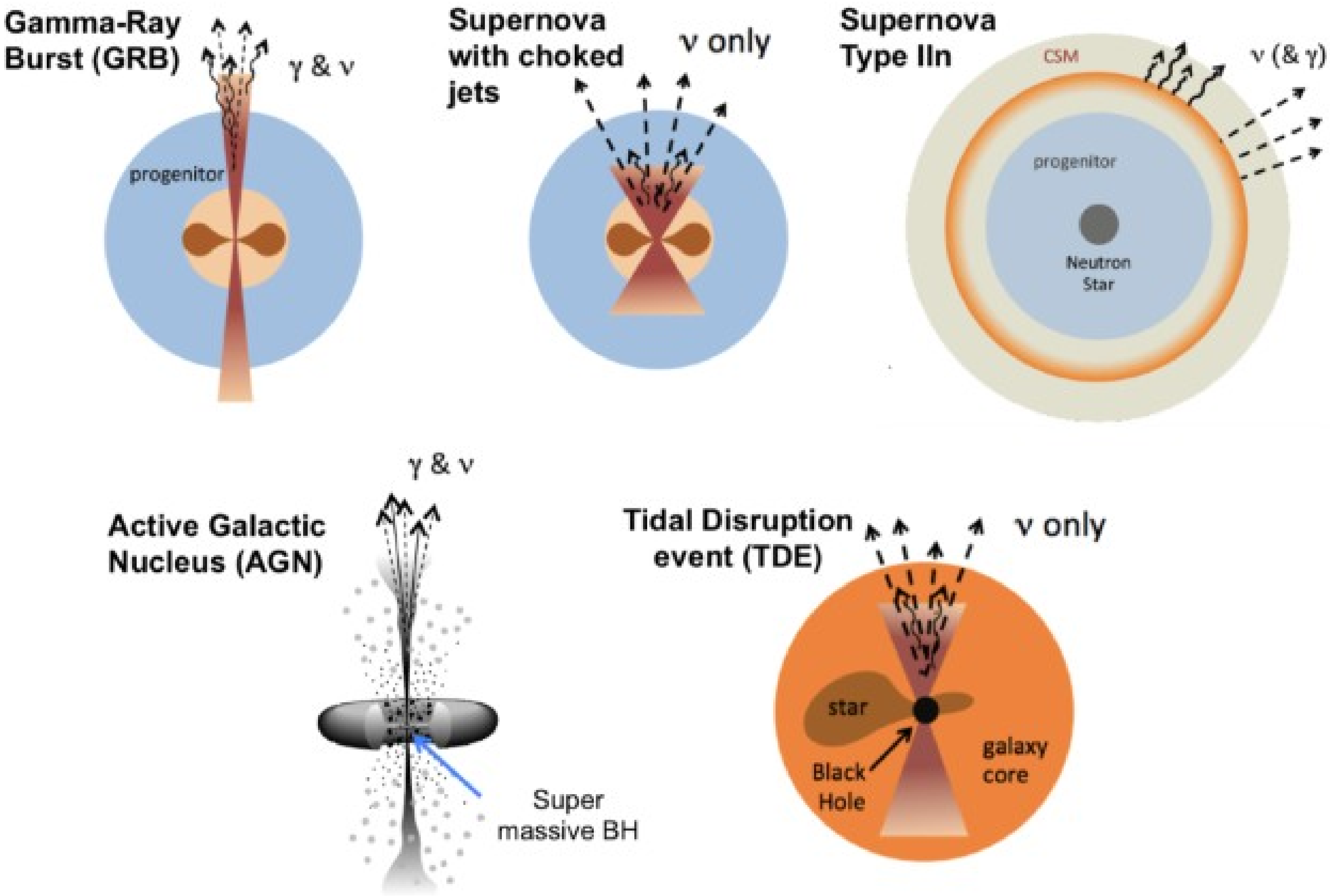
Summary

- most high-energy astrophysical neutrinos come from unknown sources
- the average source of a single neutrino is distant (at a few Gpc)
- observing many alerts improves the chances of a detection
- different strategies for telescope classes:
  - telescope network: rapid follow-up
  - medium-size telescopes: observed many alerts or stacked search
  - large telescopes: high-quality observations of most significant alerts



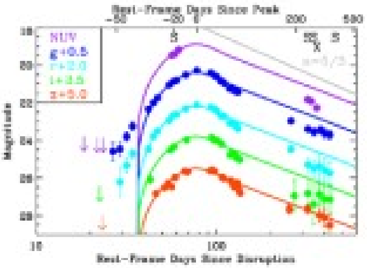
- photometric detection of a counterpart is not sufficient: need spectroscopy, a well sampled light curve and for some source classes a precise explosion date

Potential neutrino sources

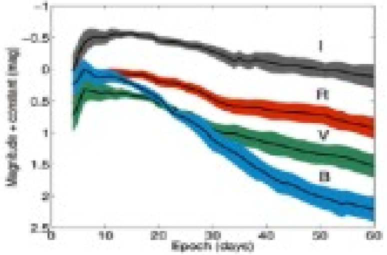


Emission time scales

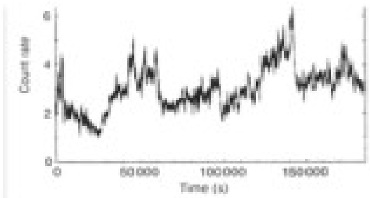
Tidal disruption events ~1d - 100d



Supernovae ~100d



Active galactic nuclei ~1h - 10d



Gramma ray bursts ~10s -100s