Multi-Messenger Astrophysics with the IceCube Neutrino Observatory

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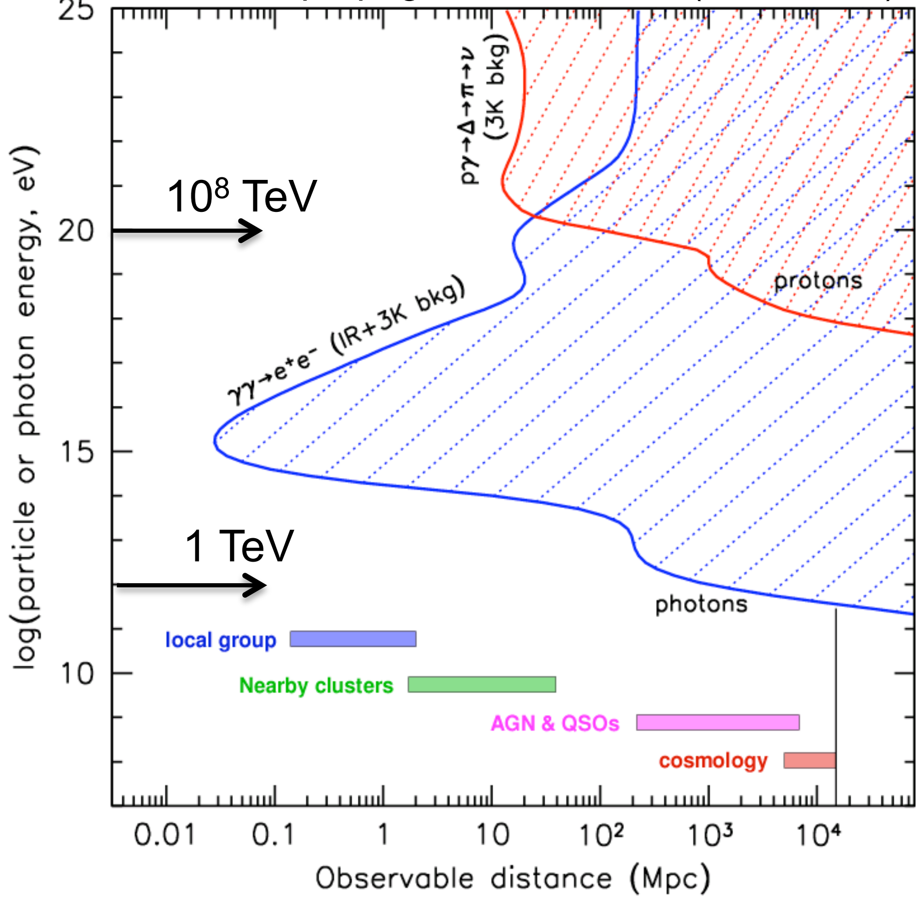
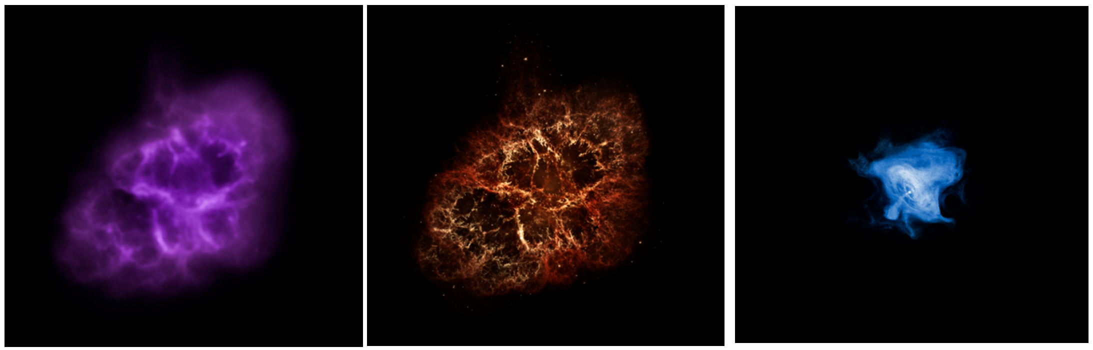
Why Multi-Messenger with Neutrinos?

Complementary messenger:

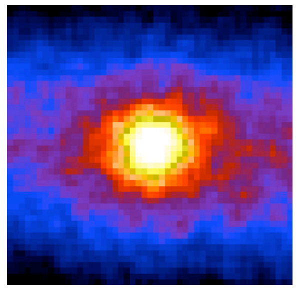
- Can disentangle leptonic vs. hadronic origins for photon observations
- Can be observed at energies where universe is opaque to photons (> 100 TeV)
- Travel at light speed; but can arrive from interior of source *before* photons arrive from surface
- Observations by neutrino telescopes are continuous and “all”-sky

Photon propagation distances (P. Gorham)



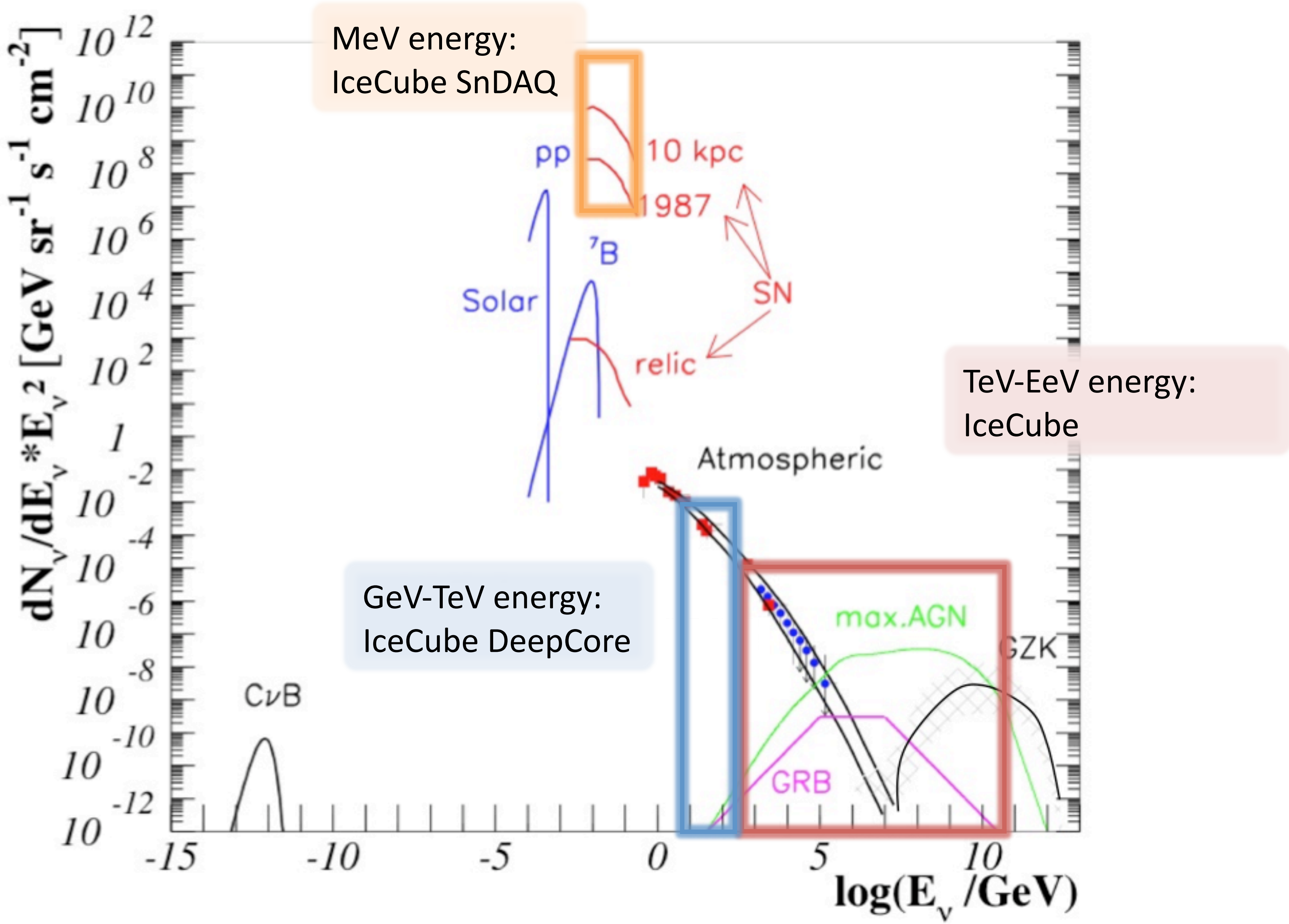


The Crab, in infrared (Spitzer), optical (Hubble), x-ray (Chandra)

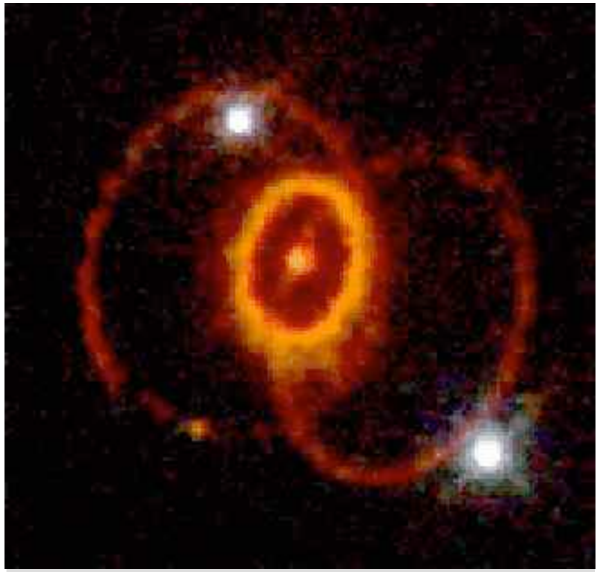


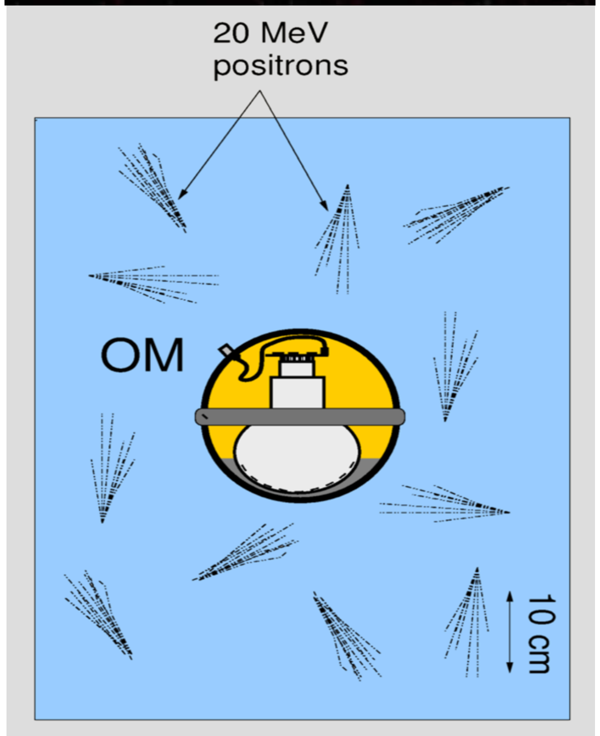
The sun, “seen” in MeV neutrinos by Super-Kamiokande

Energy Regimes for IceCube Detector



Supernova MeV Neutrino Detection in IceCube





Burst of low-energy (MeV) neutrinos
from core collapse supernovae

Neutrinos interact in the ice mostly by:

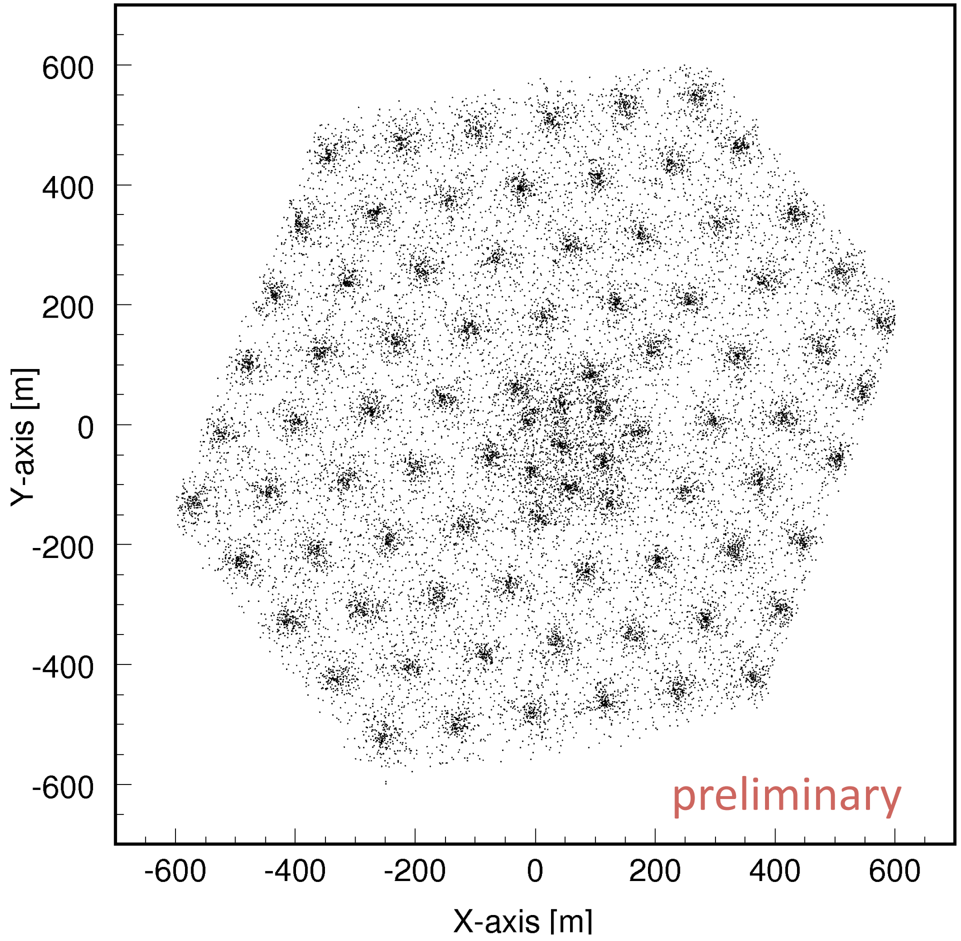
$$\bar{\nu}_e + p \rightarrow n + e^+$$

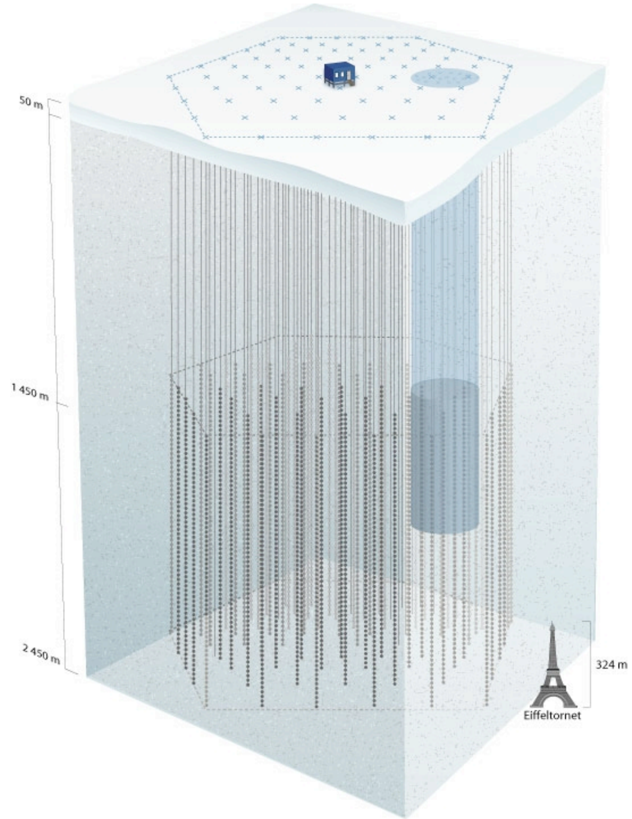
The produced positron is emitted almost isotropically

Short paths of ~25 MeV positrons do not create detectable "tracks." But their Cherenkov emission adds to the **noise rate**.

Supernova MeV Neutrino Detection in IceCube

Detected neutrino interaction vertices
(GEANT simulation)





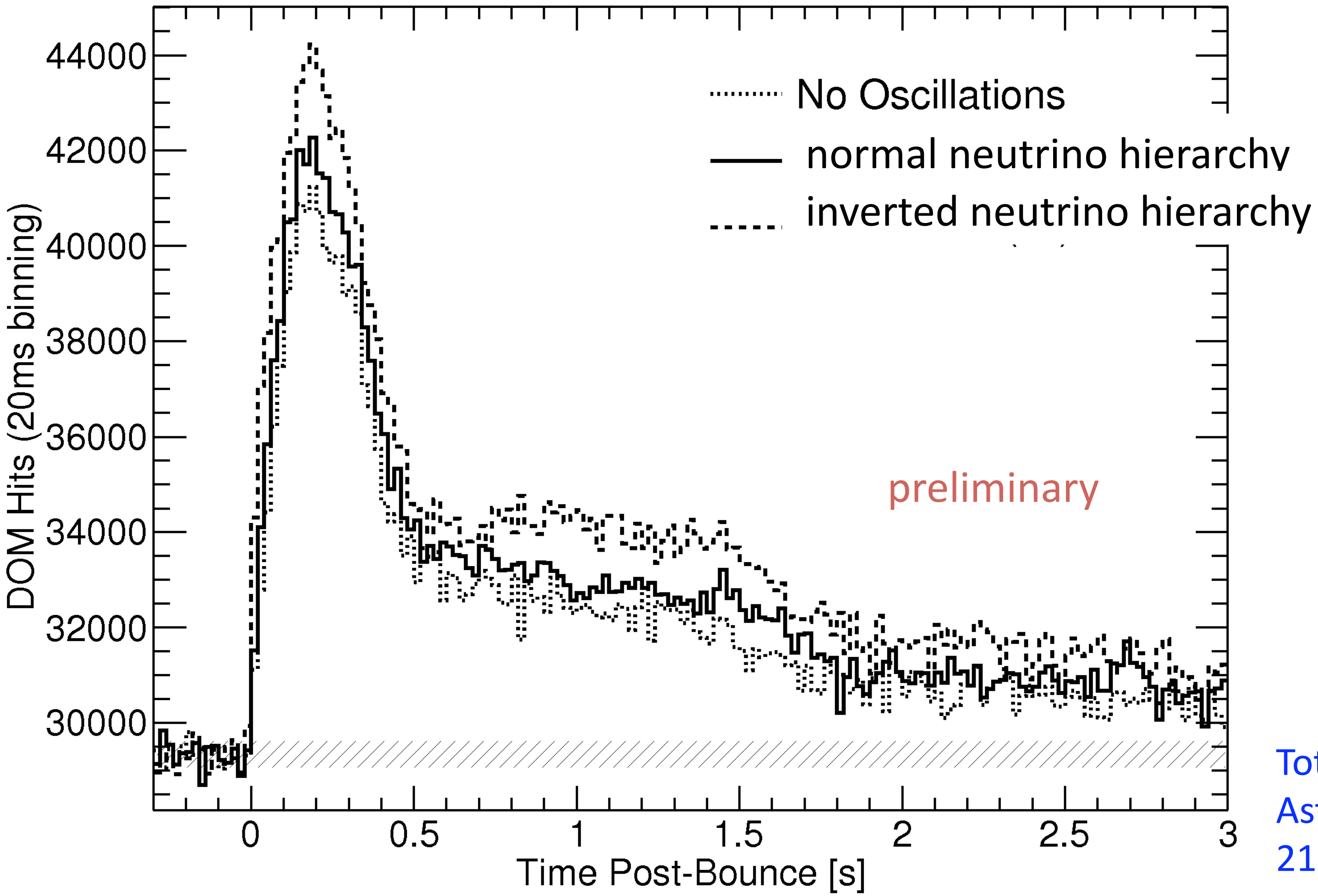
Supernova detection via increase of the dark noise rate globally throughout detector

No directionality, but excellent time resolution and high significance signal

Example: SN MeV Neutrino Detection in IceCube

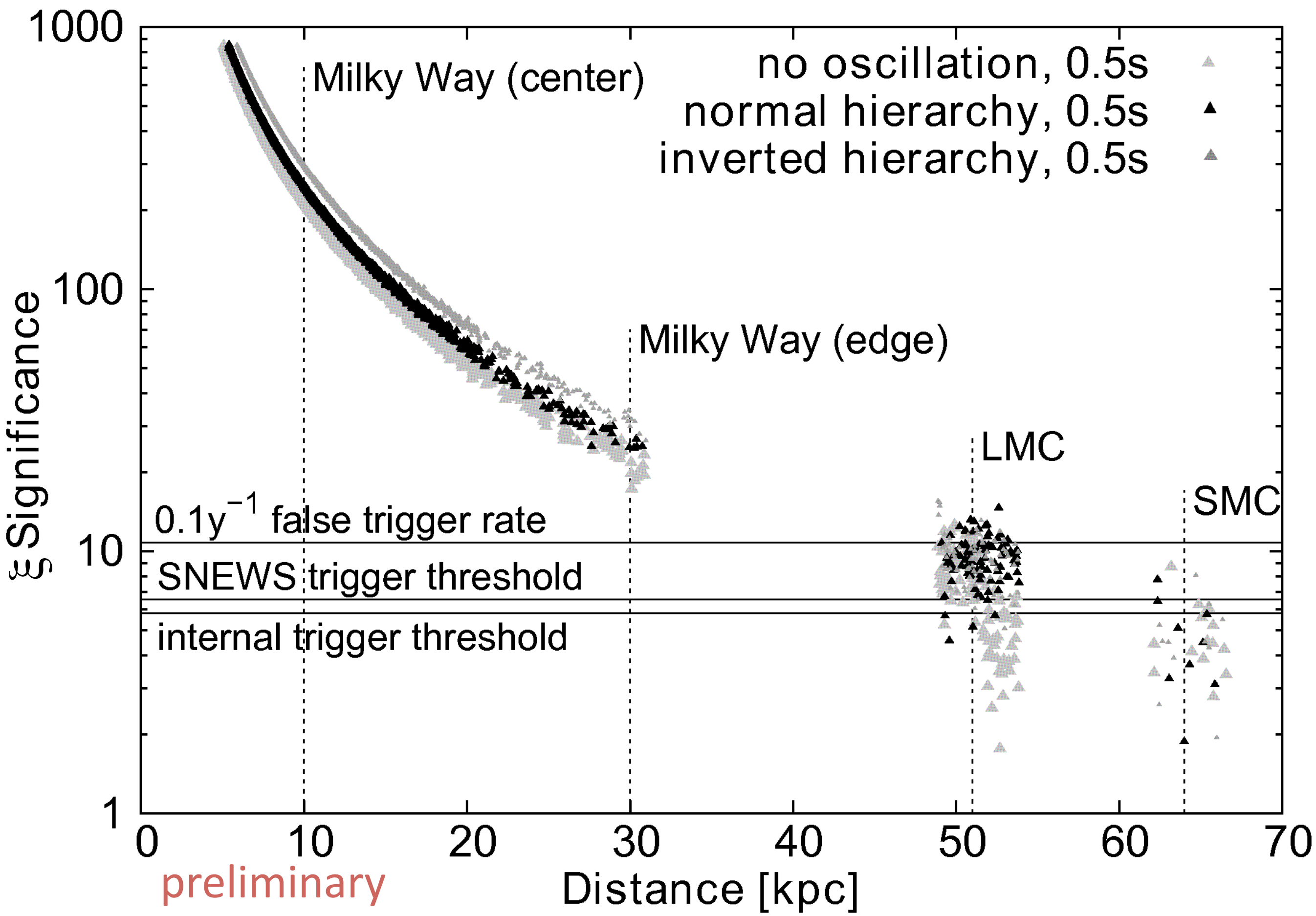
Lawrence Livermore model, 10 kpc distance (e.g. a SN at galactic center)

IceCube Monte Carlo with time-dependent energy spectra incorporated

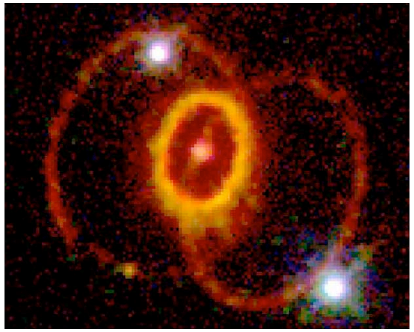


Totani et al. Astrop. Phys. 496, 216 (1998)

Sensitivity / Reach of SN Detection



ξ > 25 in Galaxy
ξ ~ 3-10 in Magellanic clouds



SN 1987A in Large Magellanic Cloud

Since 2009:
IceCube sending real-time datagrams to SNEWS SuperNova Early Warning System

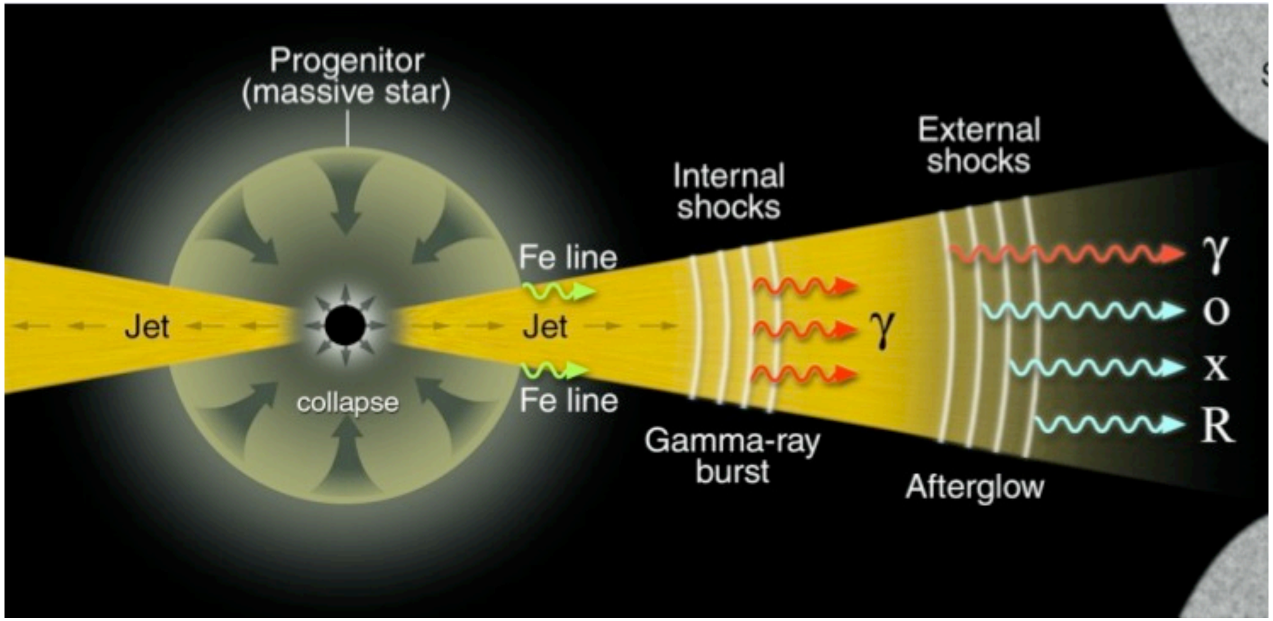
~ TeV Neutrinos from Supernovae ?

"Choked-GRB" proposed class between SN and GRB, with soft relativistic jets.

Soft jets fail to penetrate stellar envelope:

⇒ No gamma- or x-ray signature of jet

⇒ Neutrinos can escape, reveal hidden jet



	SN	Choked/LL GRB	GRB
Energy	10^{51} erg	10^{51} erg	10^{51} erg
Rate/gal	$\sim 10^{-2}$ yr^{-1}	10^{-5}–10^{-2} yr^{-1}	$\sim 10^{-5}$ yr^{-1}
Γ	~1	~3–100	~100–10^3

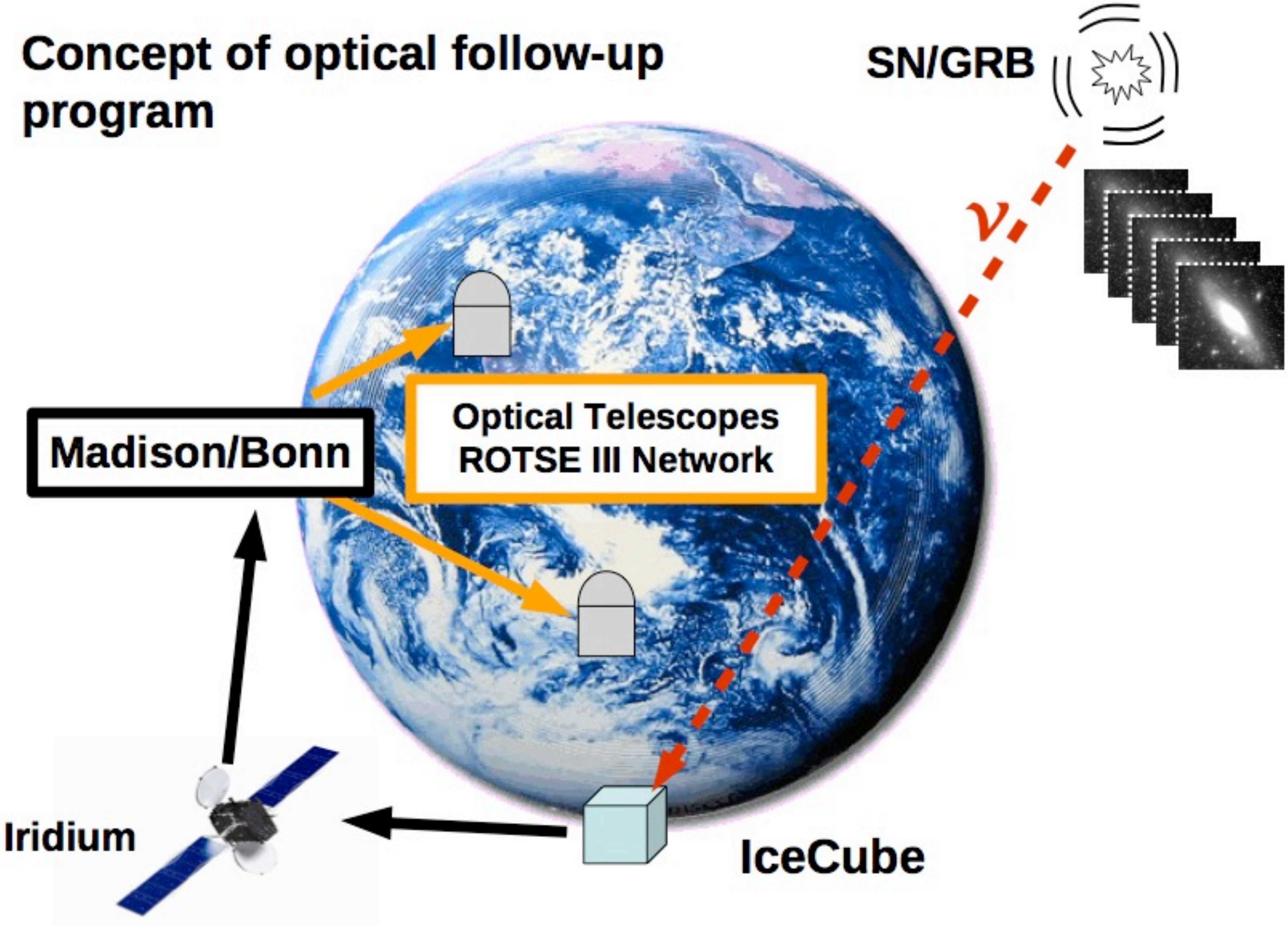
Barion rich
Nonrelativistic
Frequent

Baryon poor
Relativistic jets
Rare

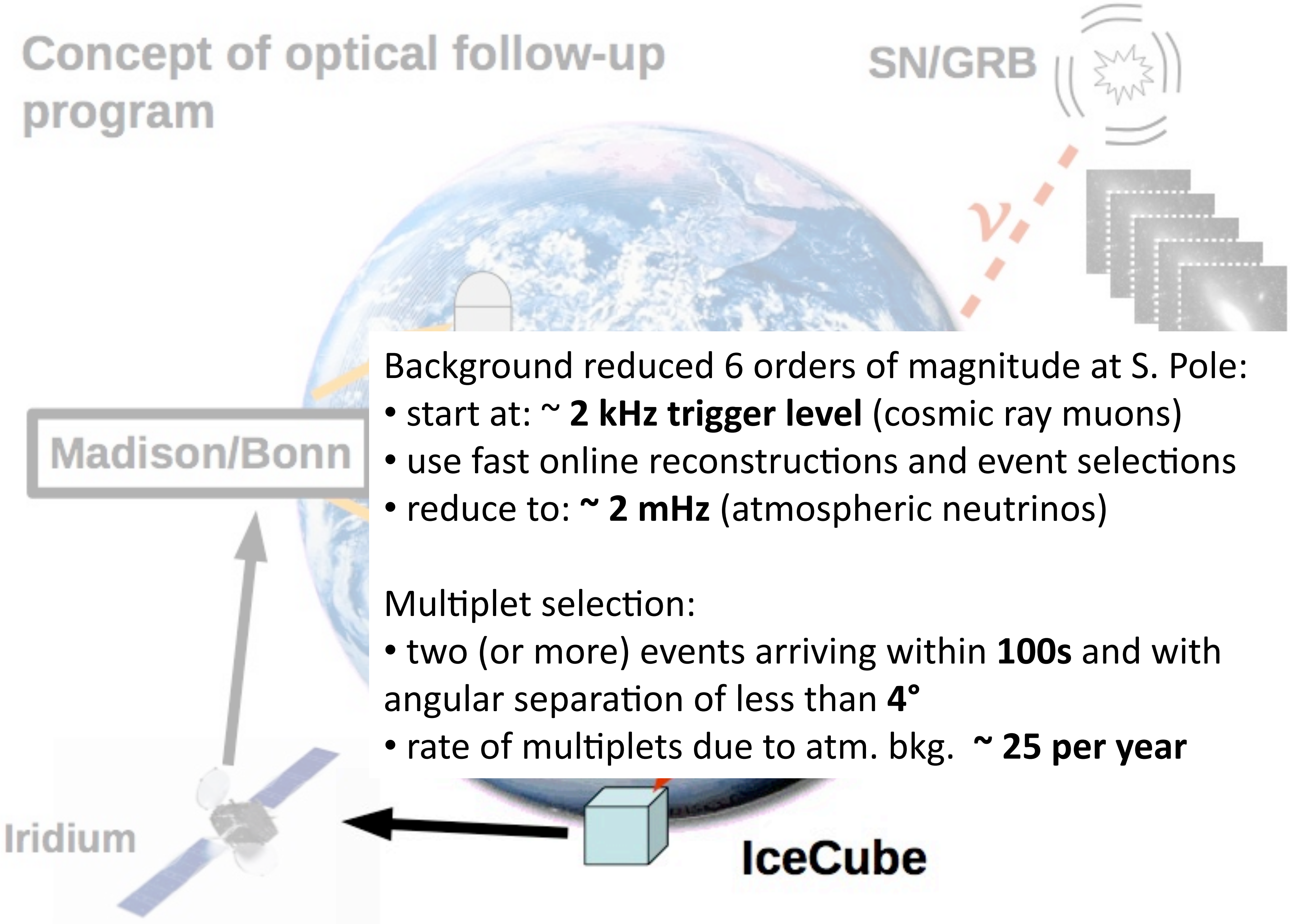
Similar kinetic energy

taken from Ando (2009)

IceCube Optical Follow-Up Program



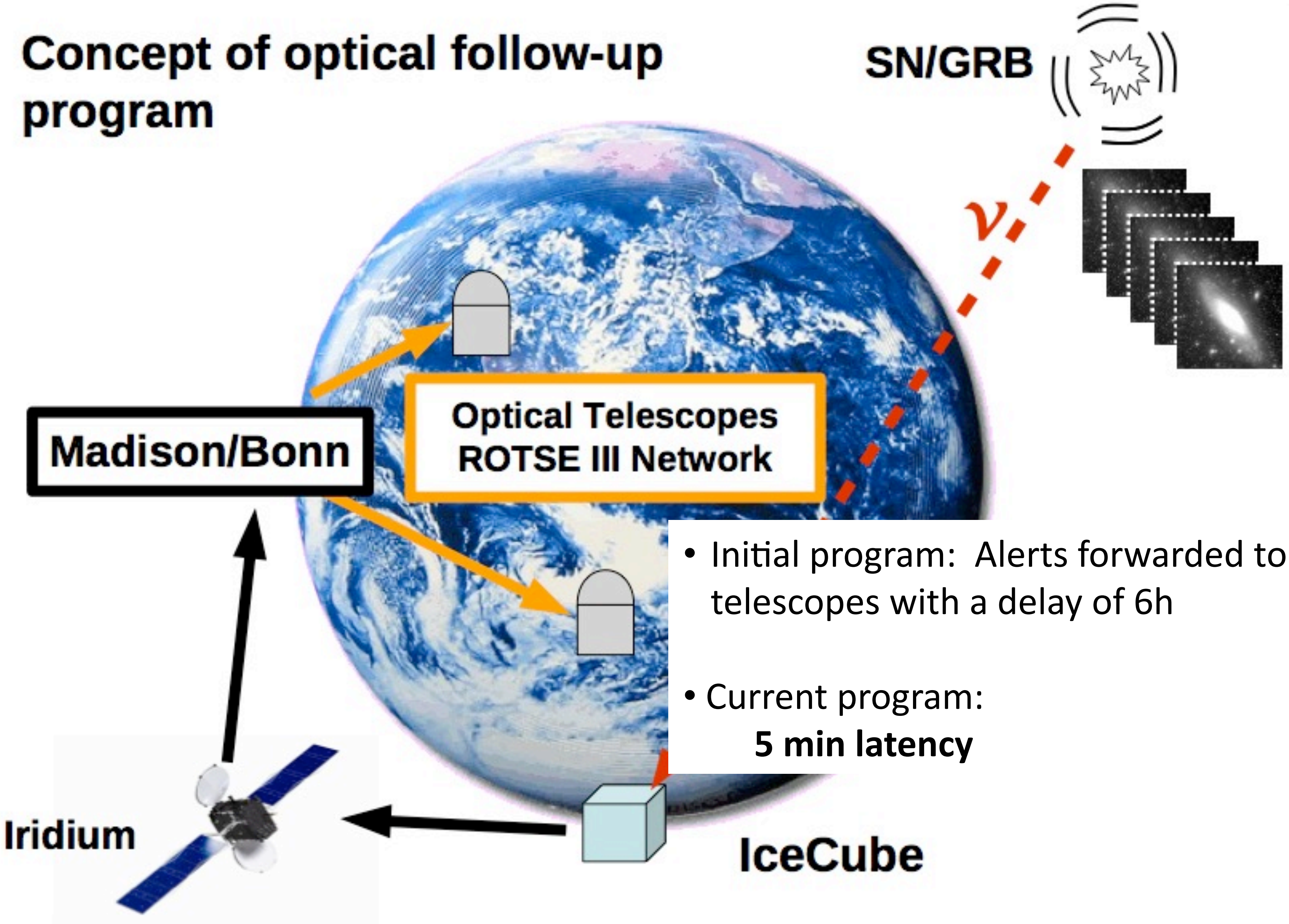
IceCube Optical Follow-Up Program



Background reduced 6 orders of magnitude at S. Pole:
- start at: ~ **2 kHz trigger level** (cosmic ray muons)
- use fast online reconstructions and event selections
- reduce to: **~ 2 mHz** (atmospheric neutrinos)

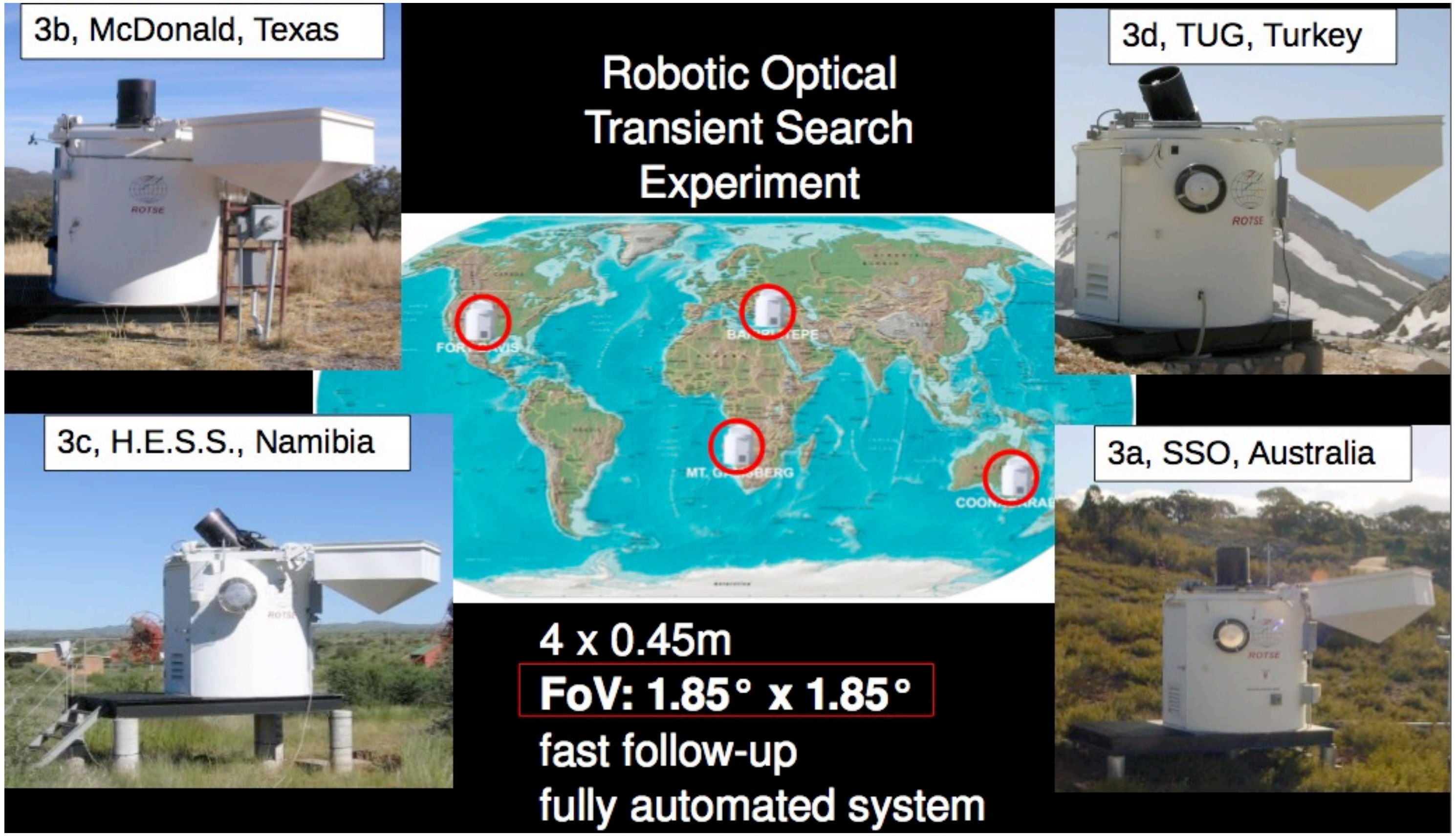
Multiplet selection:
- two (or more) events arriving within **100s** and with angular separation of less than **4°**
- rate of multiplets due to atm. bkg. **~ 25 per year**

IceCube Optical Follow-Up Program



- Initial program: Alerts forwarded to telescopes with a delay of 6h
- Current program:
  5 min latency

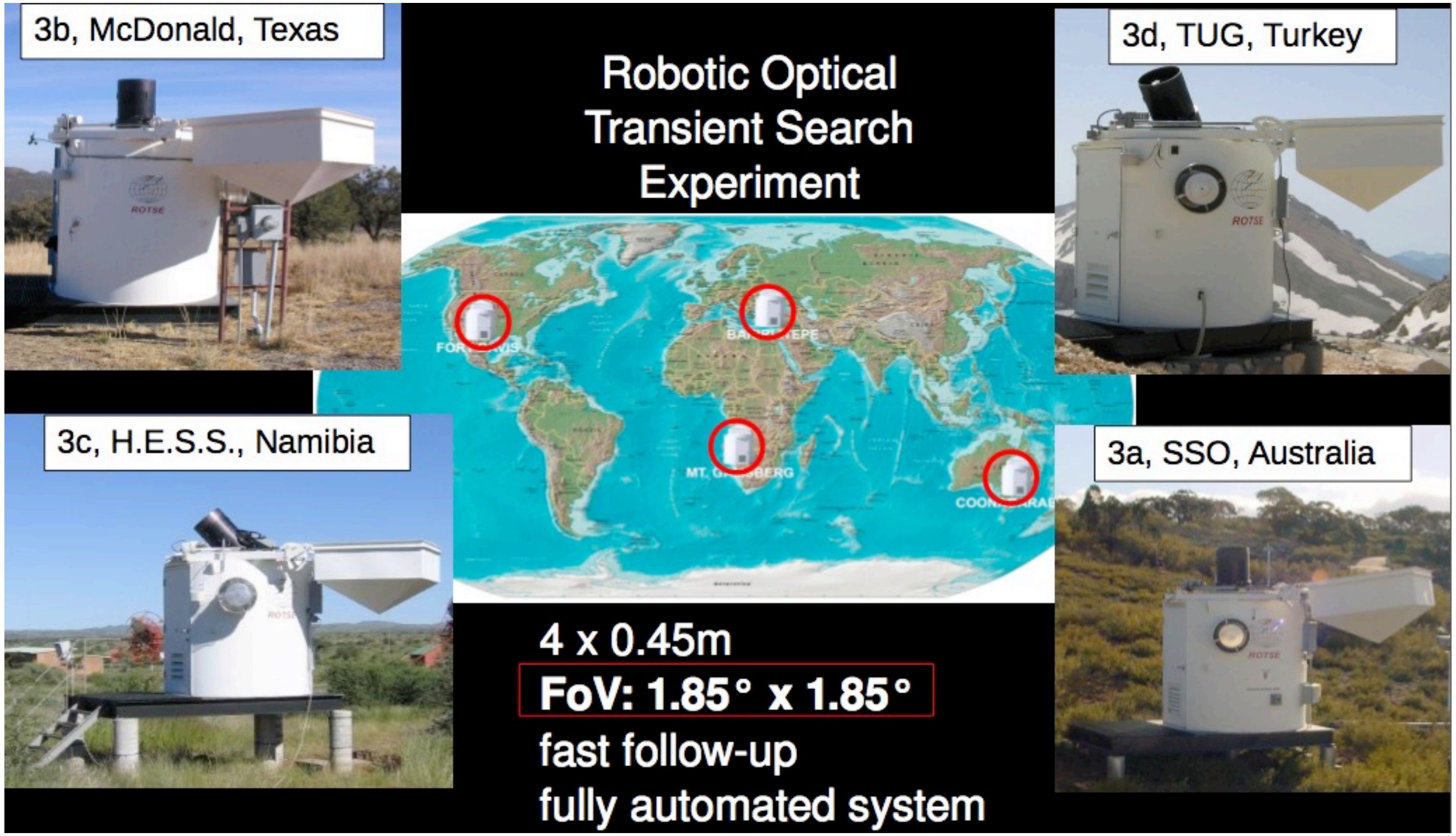
IceCube Optical Follow-Up Program



When ROTSE receives alert:
Prompt observation – thirty 60 sec exposures
Follow-up observations – each night for the next 14 to 24 nights

Analysis: Image subtraction to find optical SN counterpart
Automated source candidate selection, final candidates scanned by eye

IceCube Optical Follow-Up Program



2008 Dec. 16 – 2009 Dec. 31 (IceCube 40- and 59-string configurations)

<u>31 IceCube alerts forwarded to ROTSE</u>

-5 too close to sun

-7 too close to galactic plane

<u>-2 good data not collectable</u>

= 17 good optical follow-ups

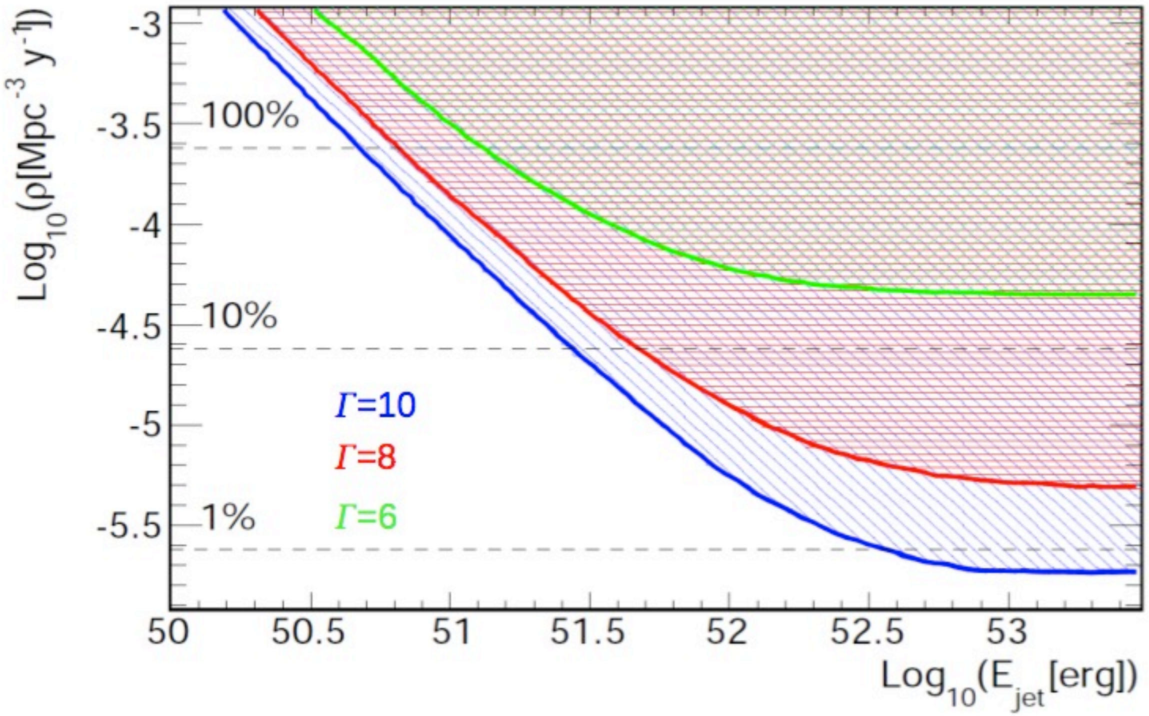
IceCube Optical Follow-Up Program

No optical counterpart observed.

First limits on hadronic jet production in core-collapse SNe jet derived.

Limit on core collapse supernova (CCSN) jet model (90% confidence level) depending on:

- jet energy E_{jet}
- Lorentz boost factor Γ
- rate of CCSN with jets ρ

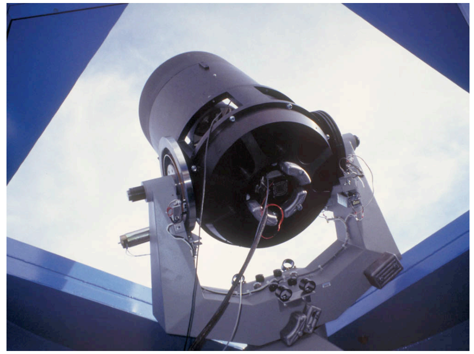


Stringent limits for higher boost factors in soft jet model:

< 7.8% of all SNe have a jet with Γ=10 and a typical jet energy of E =$3\cdot10^{51}$ erg.

Status of IceCube "Burst" Follow-Up Programs

Telescope	Approx. Alert Rate	IceCube Triggered since
ROTSE	**30 alerts / yr**	**Dec. 2008**
Palomar Transient Factory	**10 alerts / yr**	**Jul. 2010**
Swift XRT	**7 alerts / yr**	**Feb. 2011**



ROTSE — **30 alerts / yr** — **Dec. 2008**

FoV: 1.85° x 1.85°

Limiting Magnitude: 18.5

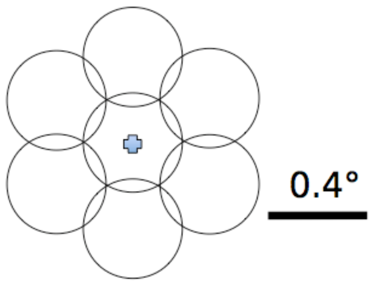
Palomar Transient Factory — **10 alerts / yr** — **Jul. 2010**

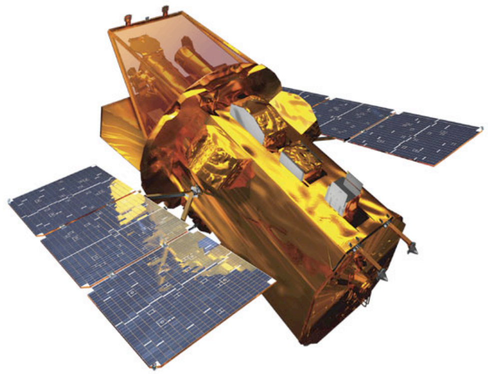
FoV: 3.5° x 2.3°

Limiting Magnitude: 20.6

Swift XRT — **7 alerts / yr** — **Feb. 2011**

Tiled observations to match IceCube PSF





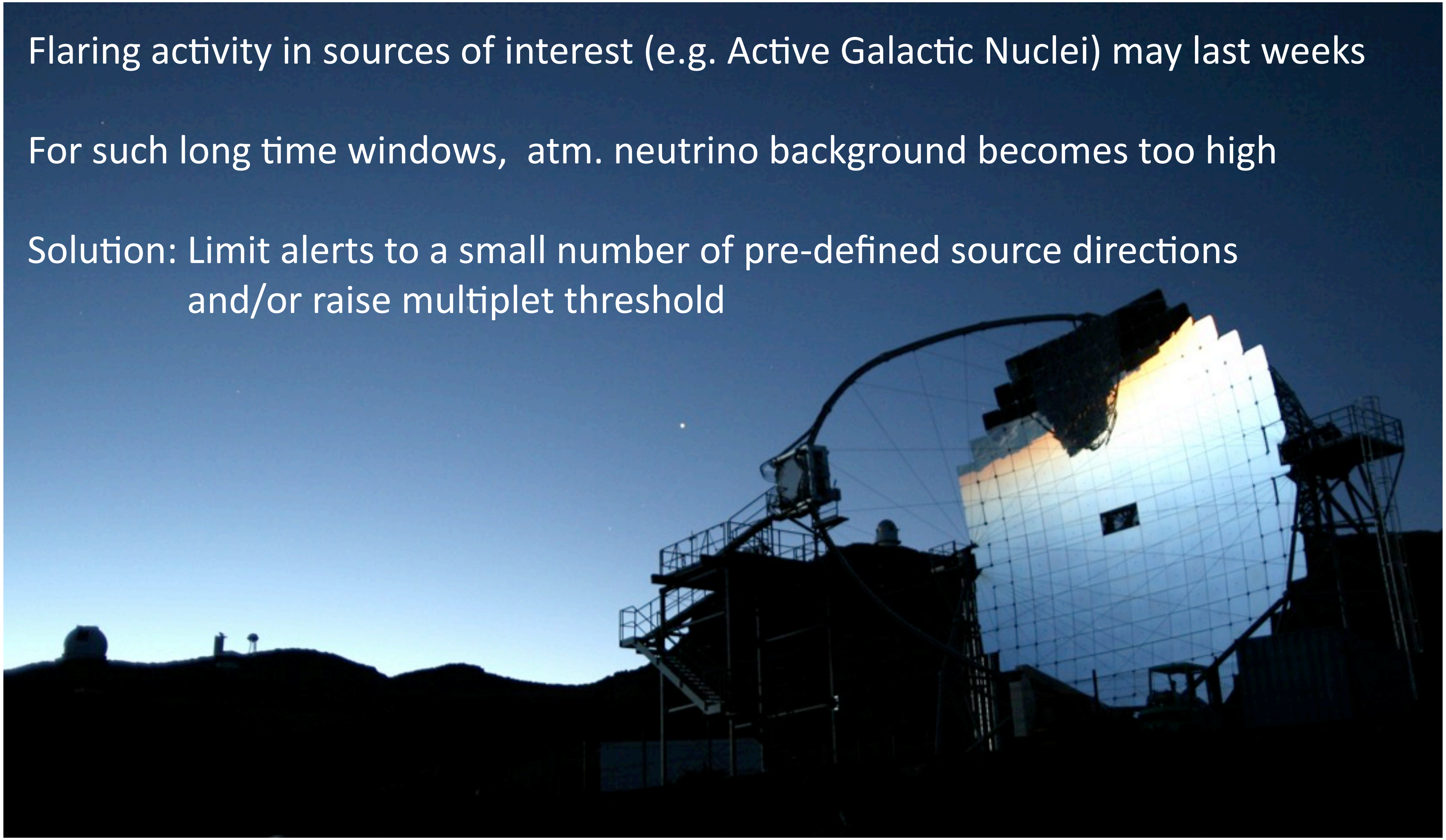
Neutrino-Triggered Target of Opportunity Program

Modify strategy for <u>Imaging Atmospheric Cherenkov Telescopes:</u>

Flaring activity in sources of interest (e.g. Active Galactic Nuclei) may last weeks

For such long time windows, atm. neutrino background becomes too high

Solution: Limit alerts to a small number of pre-defined source directions
and/or raise multiplet threshold



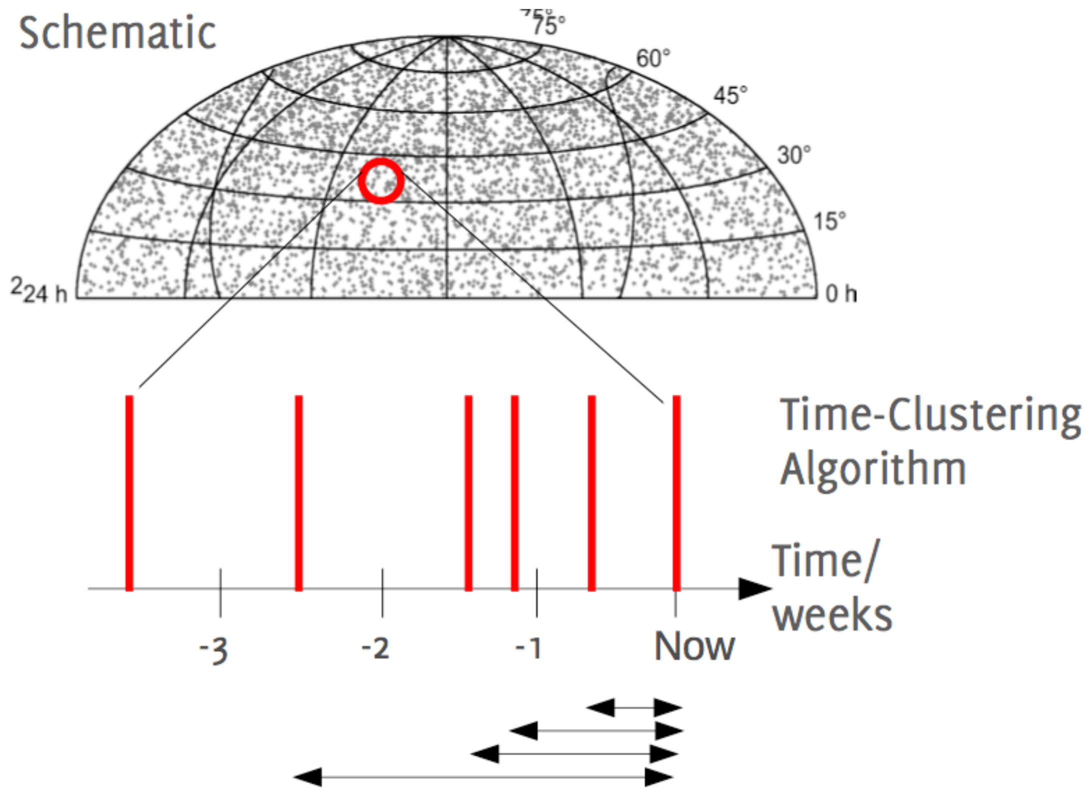
Neutrino-Triggered Target of Opportunity Program

Similar to optical follow-up, use online reconstructions and event selection at the south pole to reach ~ 1 mHz rate (atmospheric neutrinos)

When new event occurs near pre-defined source location:

Evaluate significance of this plus previous events up to three weeks earlier

Send alert if significance crosses pre-defined threshold



Neutrino-Triggered Target of Opportunity Program

First tests conducted with **MAGIC** from **2011 March 21 to May 13** using IceCube 79-string.

Criteria for source list resulted in 22 sources (1 galactic, 3 FSRQs, and 18 BL Lac objects) in northern hemisphere.

Will now start program with MAGIC using completed IceCube-86 detector.

Memorandum of Understanding signed recently with **VERITAS** and will also join N-ToO.

For a test run of this program we used selection criteria based on FERMI measurements [5]. For the galactic sources we choose sources that were observed in TeV and had a FERMI variability index > 15. Blazars were chosen according to the following criteria:

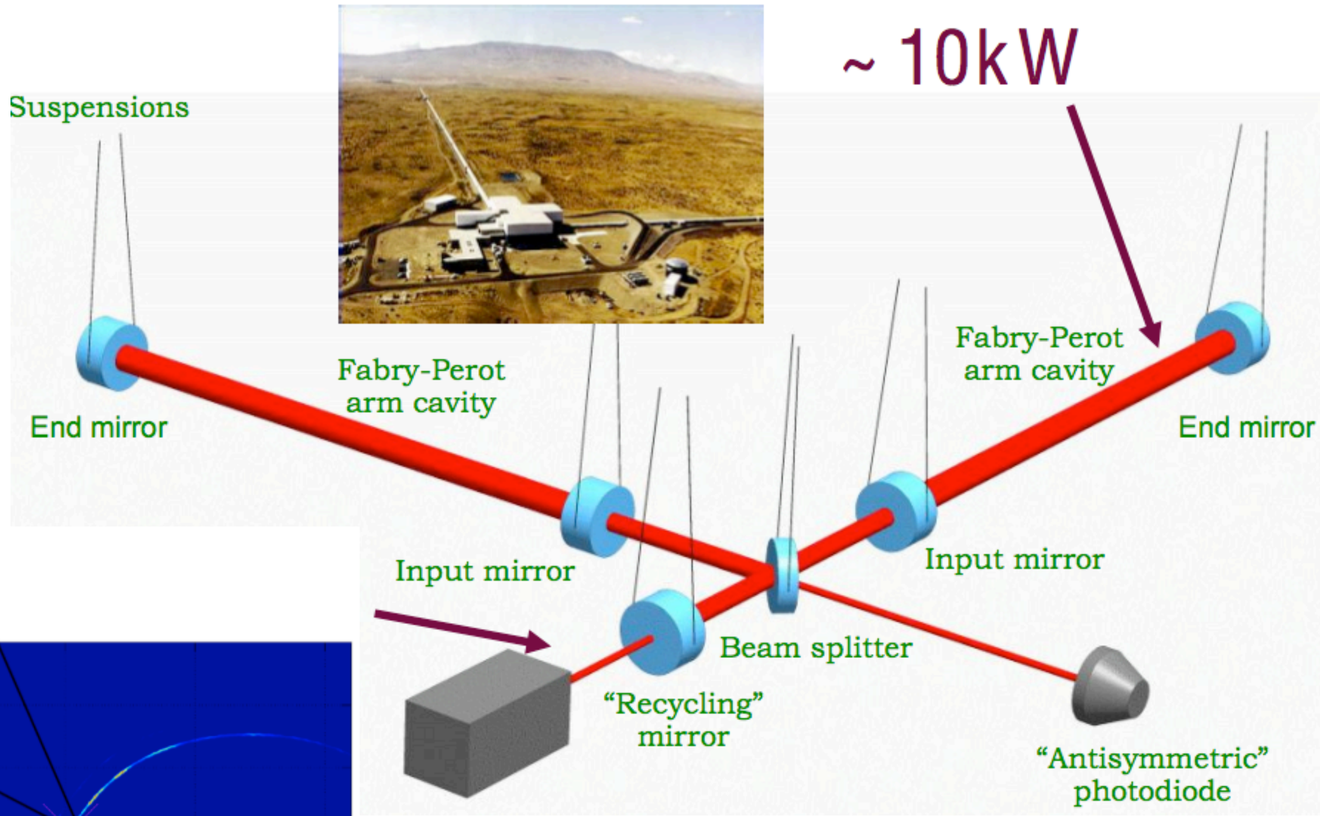
- Redshift < 0.6
- Fermi variability index > 15
- Spectral index as observed with FERMI < 2.4 (BL Lacs only)
- FERMI flux $1 - 100$ GeV $> 1 \cdot 10^{-9}$ph cm^{-2} s^{-1} (BL Lacs only)
- FERMI flux $0.1 - 1$ GeV $> 0.7 \cdot 10^{-7}$ph cm^{-2} s^{-1} (FSRQs only)

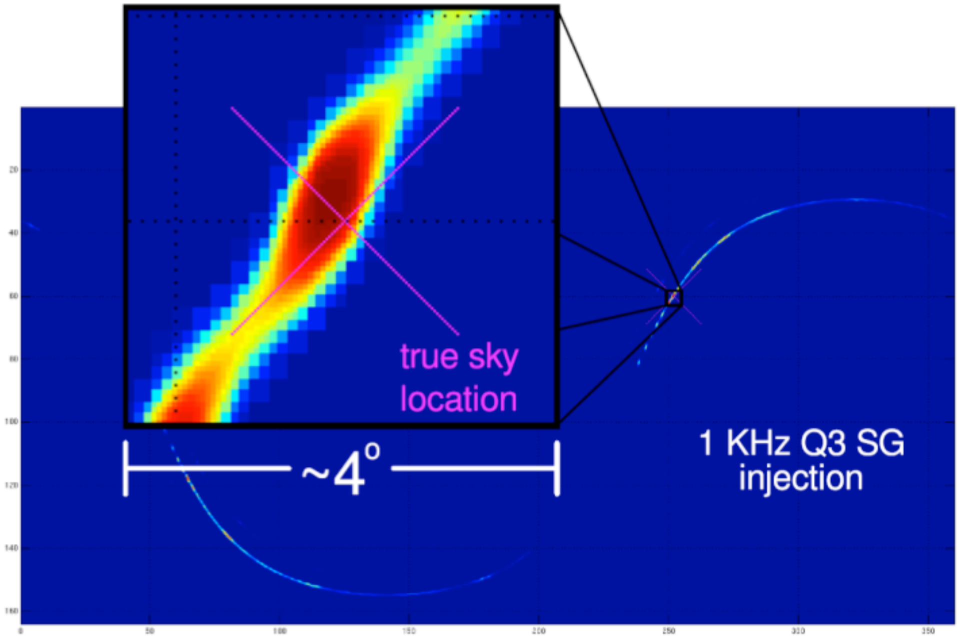
Gravitational Wave + High Energy Neutrino (GWHEN)

Single interferometer can detect passing GW, but without directional information.

Triangulation with **network** of GW detectors around Earth can localize direction:

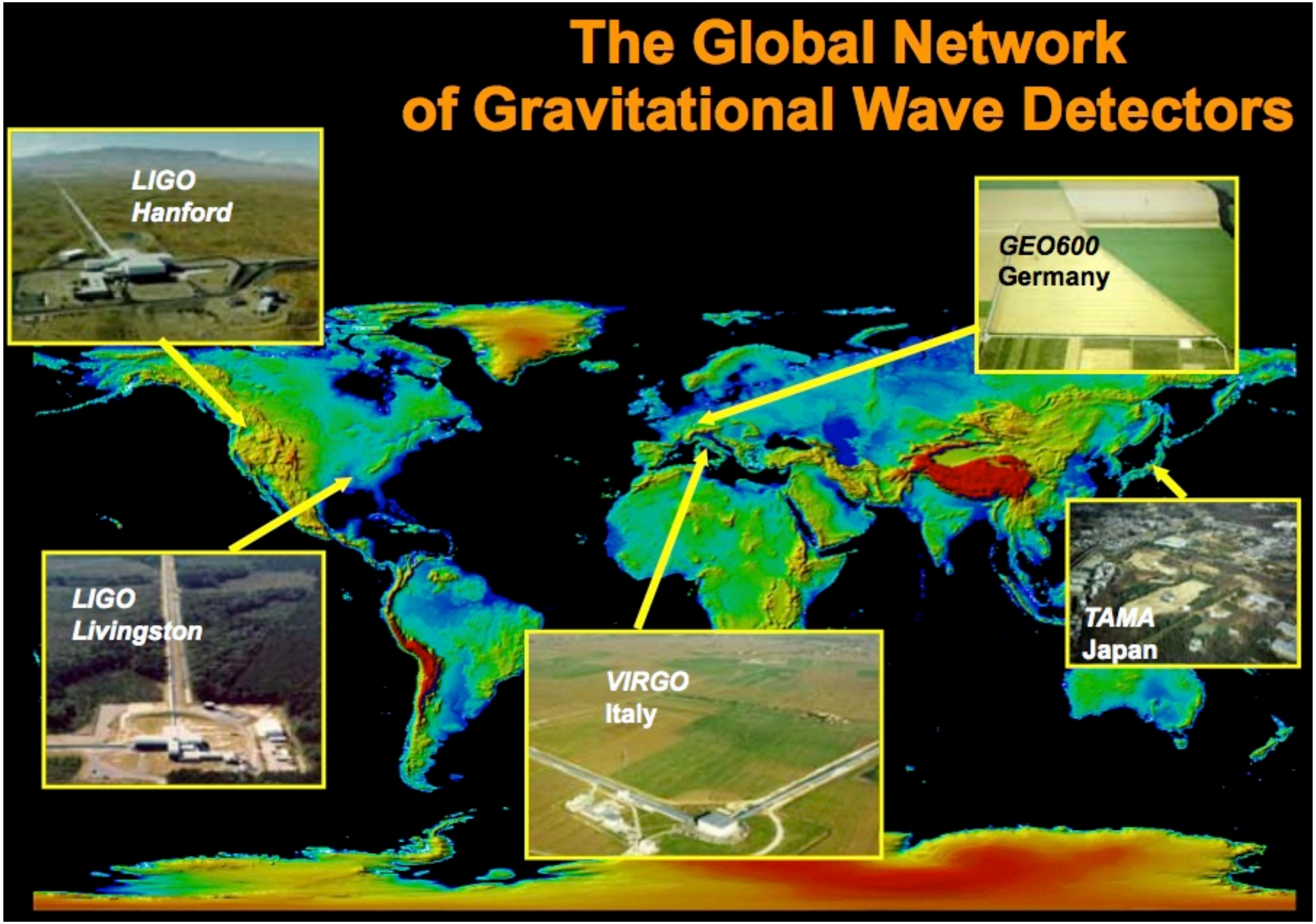
INITIAL LIGO OPTICAL LAYOUT (NOT TO SCALE)





Besides triangulation, each additional GW detector in the **network** reduces the effective background (due to local noise at each site), improving sensitivity

Gravitational Wave + High Energy Neutrino (GWHEN)



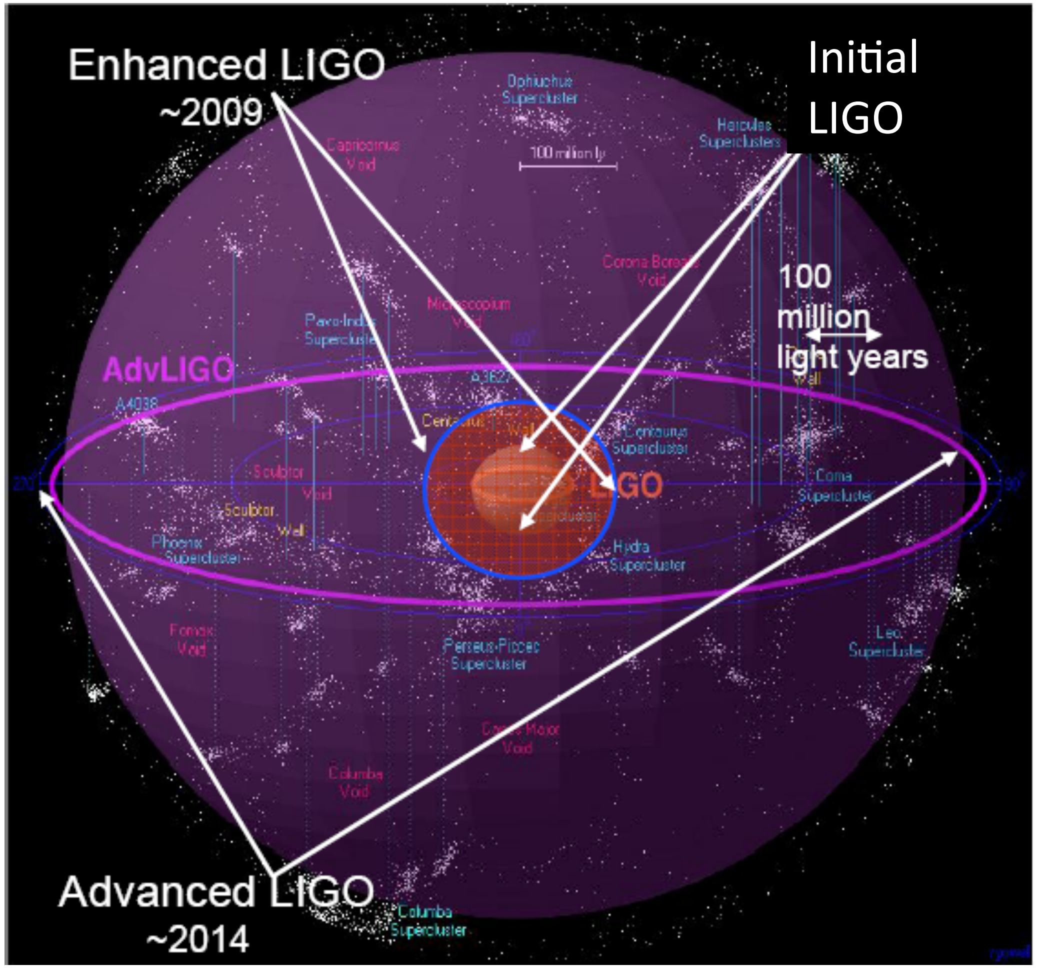
Gravitational Wave + High Energy Neutrino (GWHEN)

Initial analysis aim:

Cross-correlate GW data stream with High energy neutrino events
⇒ Offline analysis

When Advanced LIGO starts, can also operate as a joint trigger
⇒ **Online analysis**
⇒ lower threshold on each side (e.g. single neutrino)

LIGO data stream can also be cross-correlated with **IceCube Supernova DAQ stream**
⇒Offline analysis, lower threshold
⇒Online analysis, e.g. SNEWS



Advanced LIGO: x10 better sensitivity to GW amplitude

⇒probed volume x1000 = $(\text{reach})^3$

Summary

Wide variety of neutrino triggers and multi-messenger observations under way:

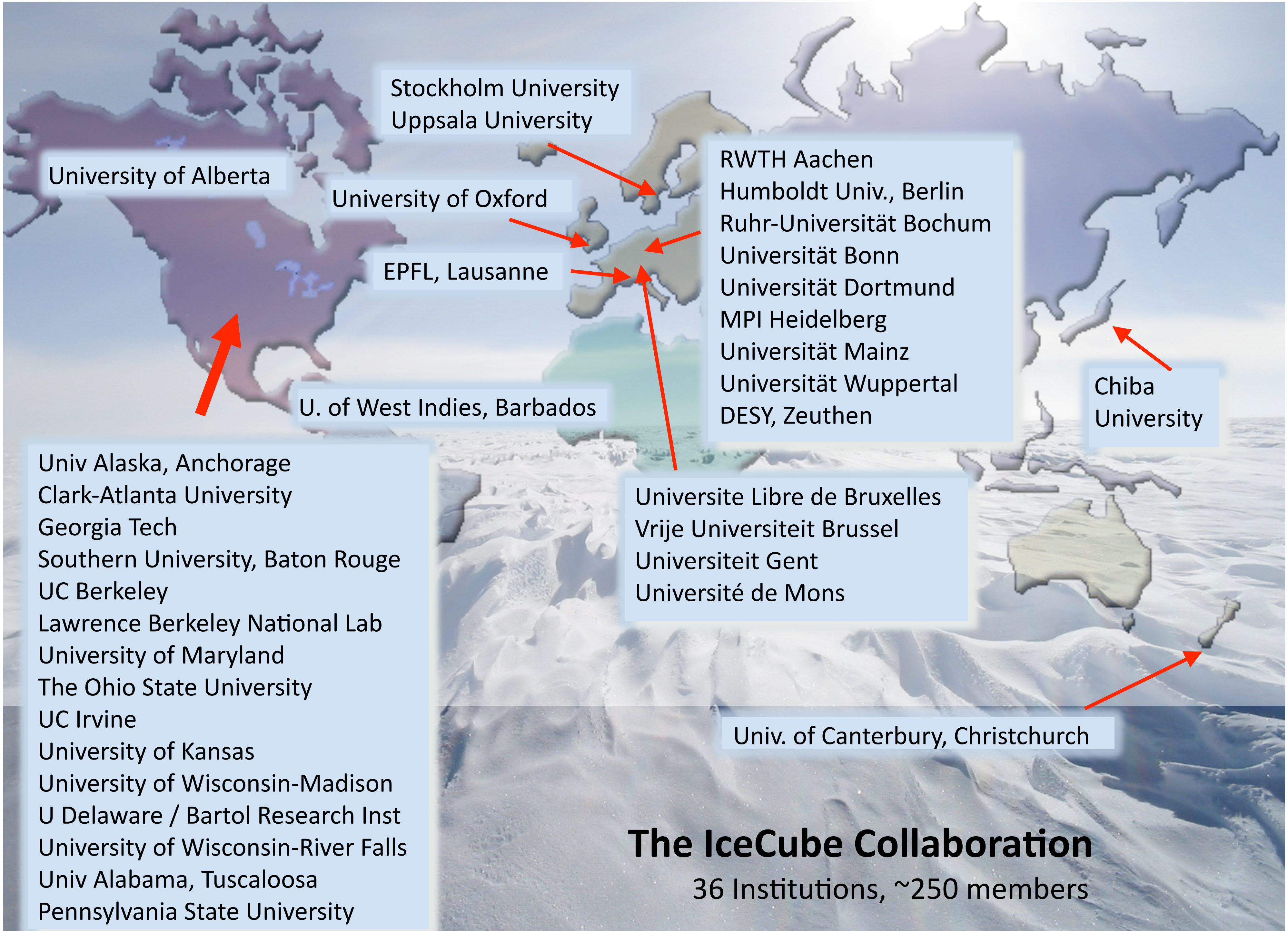
- HE neutrino optical follow-up
- HE neutrino X-ray follow-up
- HE neutrino gamma-ray follow-up
- MeV neutrino + Supernova alert
- HE neutrino + gravitational wave
- MeV neutrino + gravitational wave

Improve chance of discovery by effectively reducing backgrounds

Better physics insight with multi-messenger observations

Many more opportunities for joint observations and analyses with full IceCube coming online

There are *guaranteed* discoverable sources, and hopefully unexpected ones,
in the observation programs above… we only don't know how long is the wait!



The IceCube Collaboration

36 Institutions, ~250 members