IceCube Optical and X-ray Follow-up Program

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Realtime Astroparticle Physics
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Motivation

- Most transients unobserved by electromagnetic surveys
- Neutrino detector has ~98% livetime and 2π (4π) field of view
- Gather otherwise unavailable electromagnetic data
- Electromagnetic observation increases significance of neutrino event

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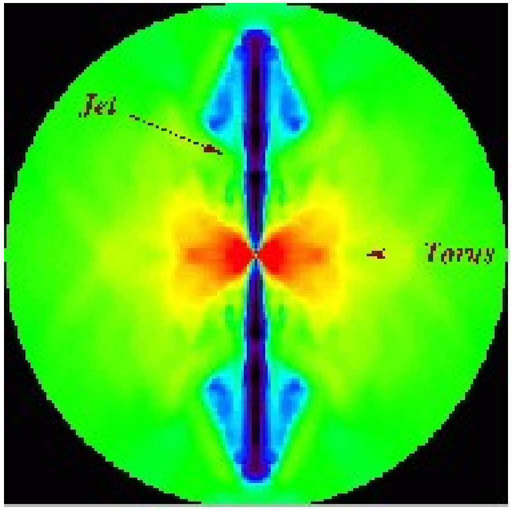
Motivation

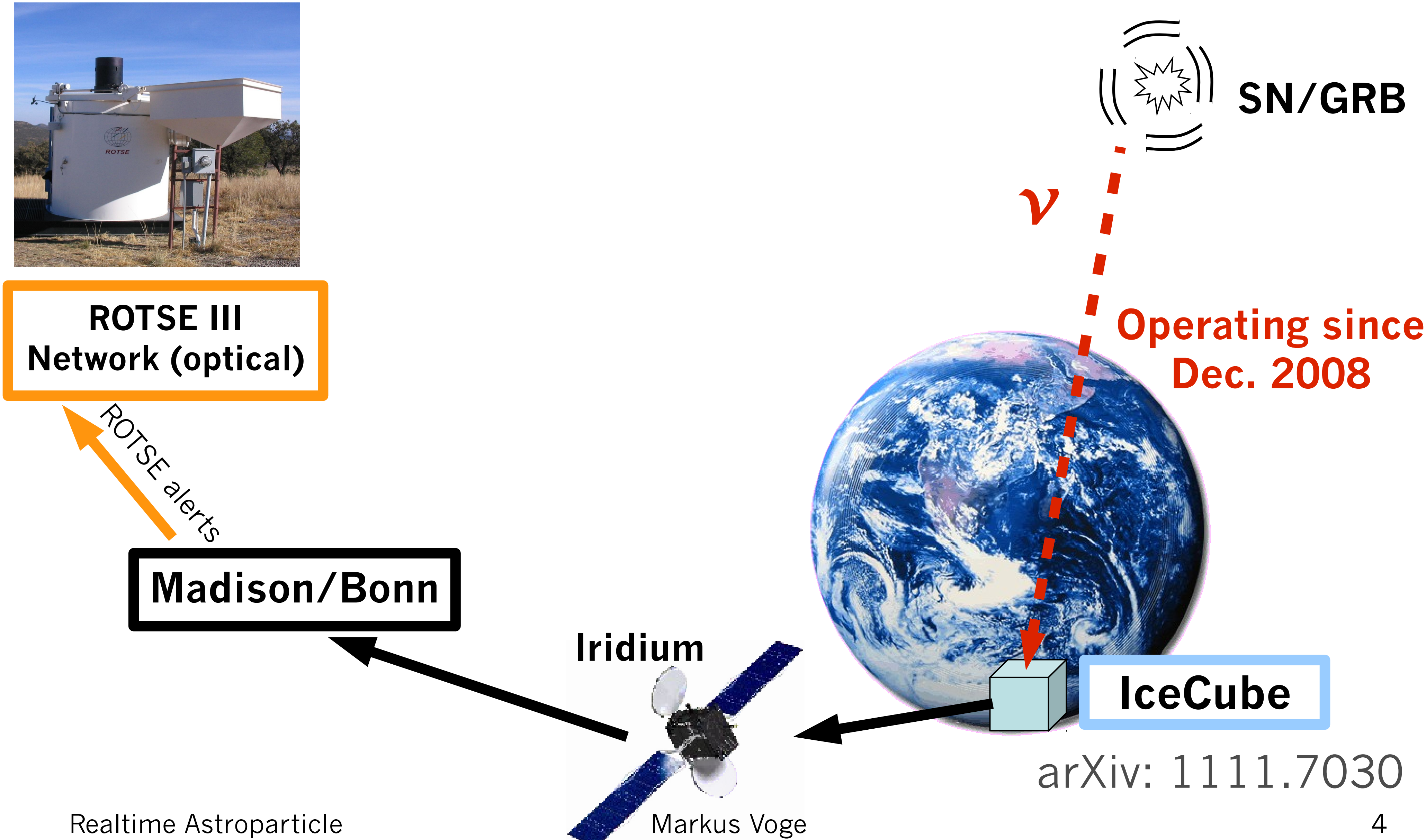
- Probe GRBs/SNe as source of high-energy neutrinos (and thus cosmic rays)
- One example physics model: Supernova-GRB connection (Ando, Beacom 2005)
  - Some core-collapse SNe might produce high-energy neutrinos similar to GRBs (Razzaque, Meszaros, Waxman 2005)
  - Mildly relativistic jets (slower than GRB jets) choked in stellar envelope

    → Detect neutrinos and find SNe in optical data



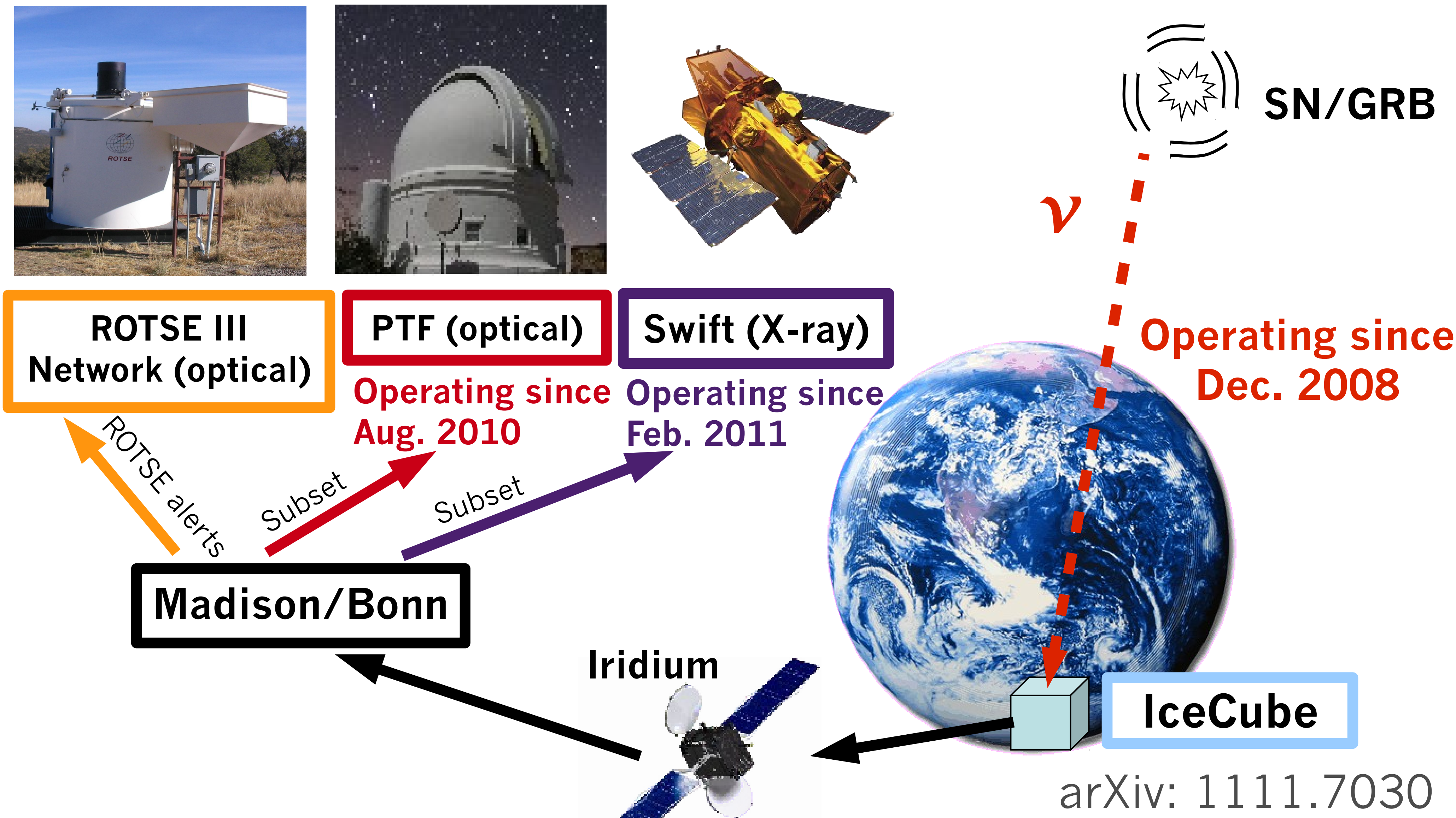
Simulation by MacFadyen (2000)

OFU and XFU Overview



arXiv: 1111.7030

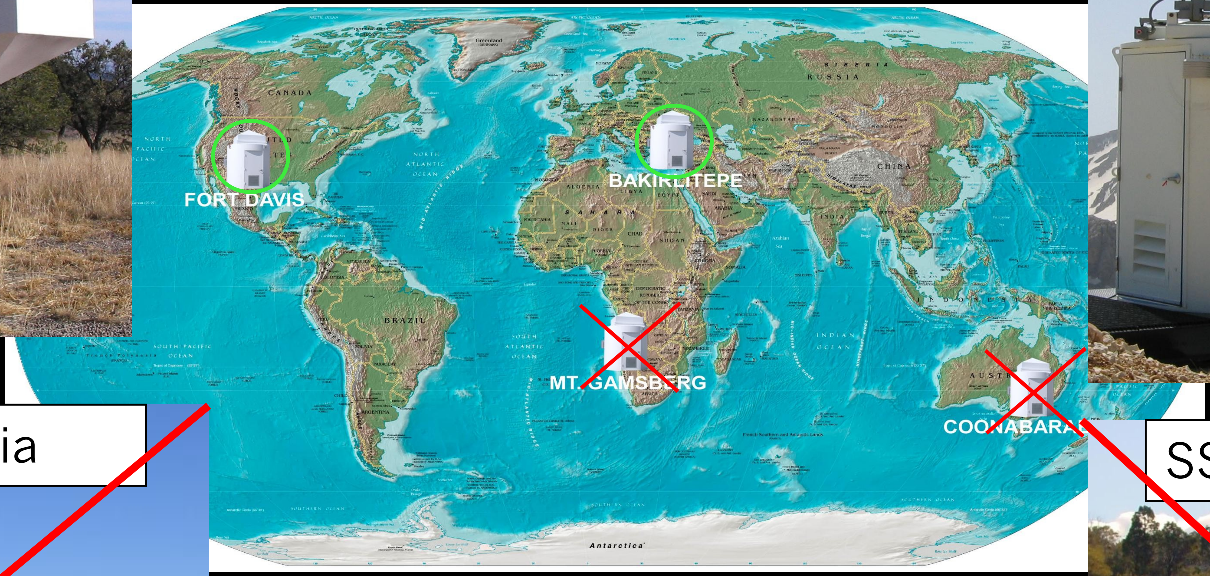
OFU and XFU Overview



ROTSE Overview

astro-ph/0210238

ROTSE =
Robotic Optical Transient
Search Experiment



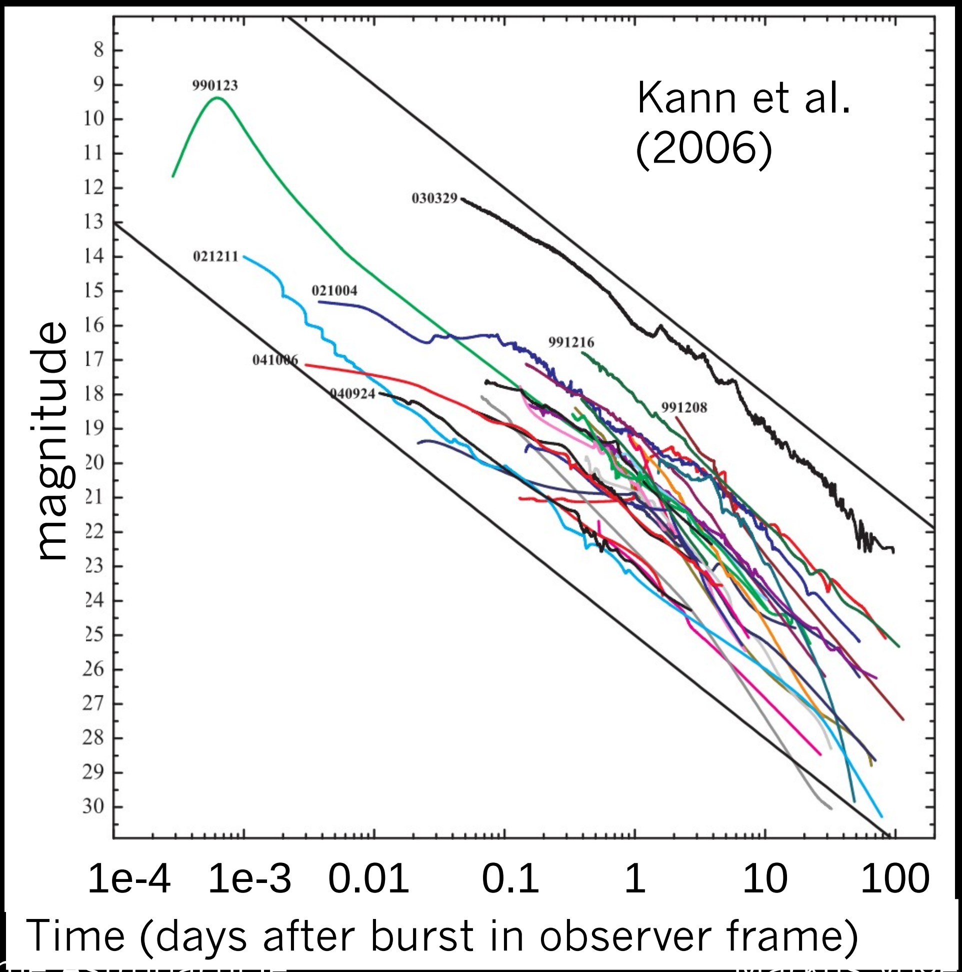
0.45m mirror

FoV: 1.85° x 1.85°

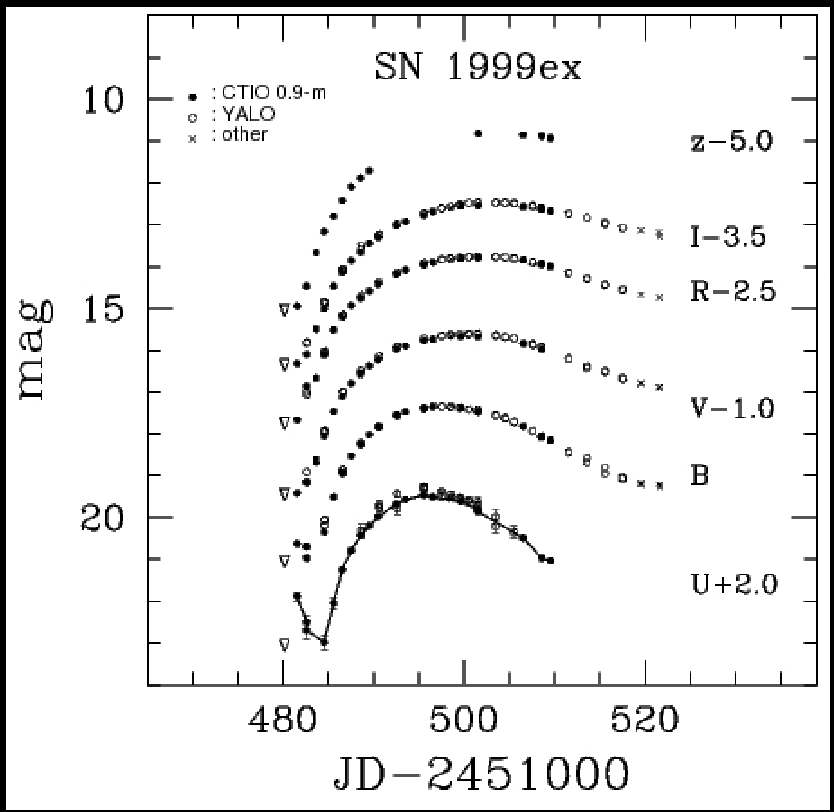
Entirely automatic
follow-up system

ROTSE Observation Schedule

- ~25 alerts per year sent to ROTSE, for each alert:
- First night: thirty 60 s exposures (for GRB afterglow)
- Following 24 nights: ten 60 s exposures (for SN light curve)



Strizinger et al. (2003)



PTF Overview

arXiv:0906.5350

- PTF = Palomar Transient Factory (located in California), mainly discovering/observing SNe
- 2.3° x 3.5° FoV (ROTSE: 1.85° x 1.85°)
- 1.2 m telescope (ROTSE: 0.45 m)
- Can take spectra for interesting alerts
- Follow-up since Aug. 2010
- ~10 Alerts per year

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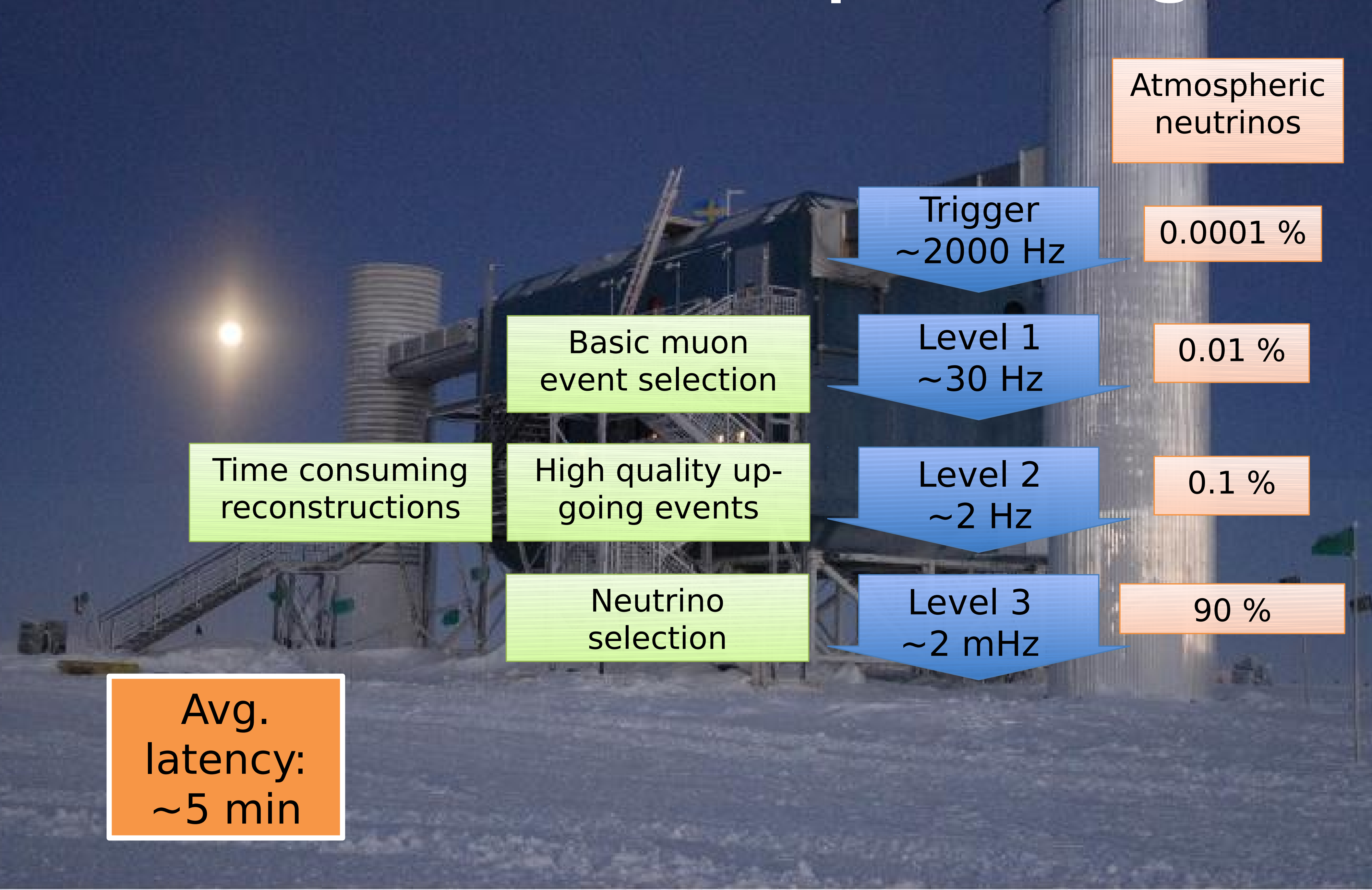
IceCube online data processing



Atmospheric neutrinos

		Atmospheric neutrinos
	Trigger ~2000 Hz	0.0001 %
Basic muon event selection	Level 1 ~30 Hz	0.01 %
Time consuming reconstructions; High quality up-going events	Level 2 ~2 Hz	0.1 %
Neutrino selection	Level 3 ~2 mHz	90 %

Avg. latency: ~5 min

Neutrino Multiplet Filter

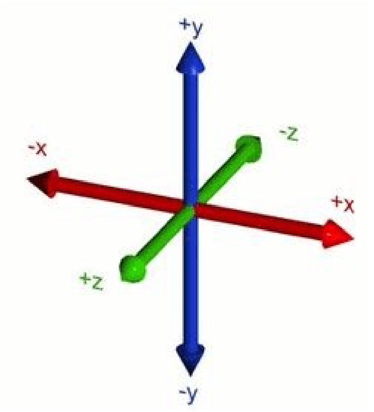
Require at least 2 neutrinos (doublet)
→ Reduce atmospheric ν-background to
~50 background doublets per year

Neutrino Burst from SN or GRB – events close in

Time

&

Direction



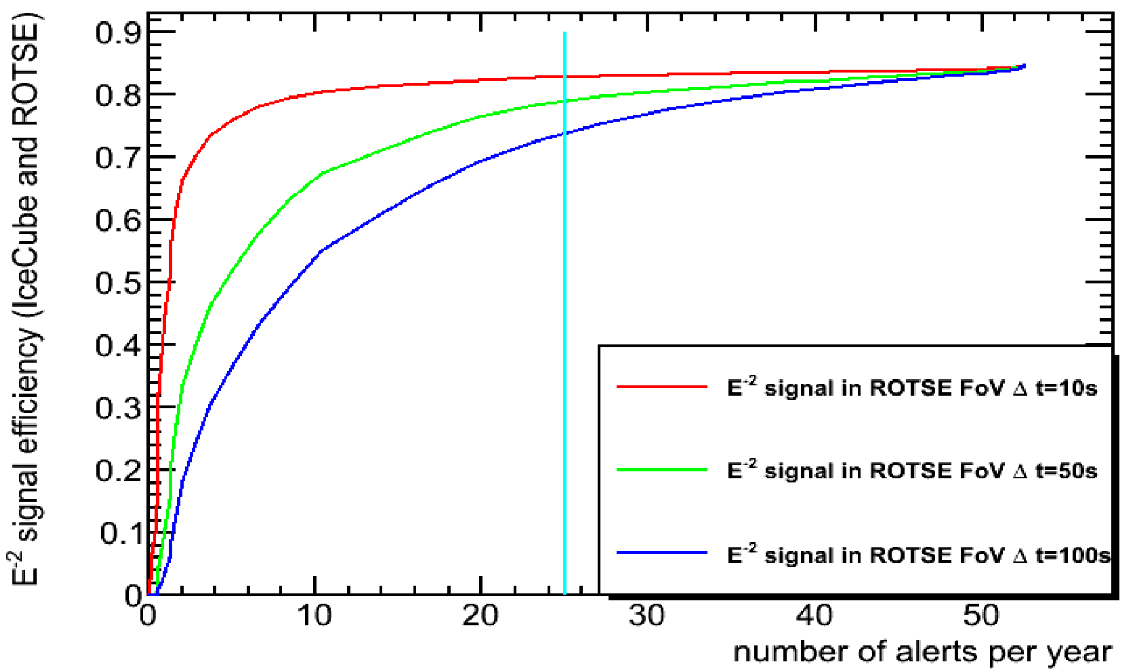
Time between events
ΔT<100 s

Angular distance between
reconstructed direction **ΔΨ<3.5°**

Likelihood to select alerts

- Multiplet condition fulfilled for ~50 alerts per year
- From this set of alerts, we select subsets to forward to the telescopes based on a likelihood function

ROTSE



- Cut on likelihood, so that
  - ~25 alerts/yr for ROTSE
  - ~10 alerts/yr for PTF
  - ~7 alerts/yr for Swift
- PTF and Swift alerts are subsets of ROTSE alerts

- So far: ~120 alerts sent to ROTSE, 23 to PTF, 14 to Swift

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Likelihood function

$$\ln L = \frac{\Psi^2}{\sigma_q^2} + 2\ln(2\pi\sigma_q^2) - 2\ln\left|1 - e^{\frac{-\Theta_A^2}{2\sigma_w^2}}\right| + 2\ln\left(\frac{\Delta T}{100\,s}\right) + const$$

Favors events with small angular separation Ψ, relative to reconstr. error σ	Punishes badly reconstructed events	Favors doublets within FoV of telescope	Favors neutrino pairs within small time interval

- Likelihood approach to select most interesting doublets
- Signal-like doublets tend to have smaller values

Image Analysis (ROTSE)

ROTSE takes images (30 in first night, 10 per night for 3 weeks)

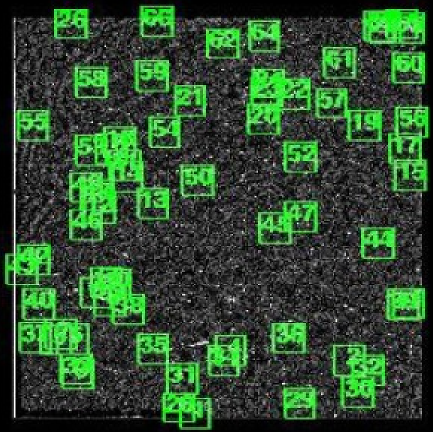
New Image

–

Reference Image

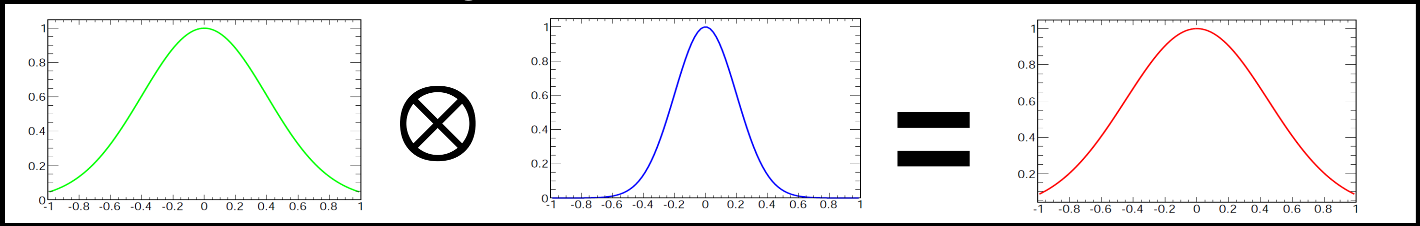
=

Subtracted Image



Cross-Convolution (Yuan, Akerlof 2008):

„Smearing“ of new and ref. image in order to match different point spread functions and allow for pixel by pixel subtraction



Results: IceCube side

		Multiplicity	Measured	Expected
2008/09	**IC 40**	Doublets	15	8.55
2008/09	**IC 40**	Triplets	0	0.003
2009/10	**IC 59a**	Doublets	19	15.66
2009/10	**IC 59a**	Triplets	0	0.004
2009/10	**IC 59b**	Doublets	10	10.32
2009/10	**IC 59b**	Triplets	0	0.004
10/11	**IC 79**	Doublets	22	32.2
10/11	**IC 79**	Triplets	0	0.008
11/12	**IC 86_1**	Doublets	24	19.59
11/12	**IC 86_1**	Triplets	0	0.005

PRELIMINARY

Upward fluctuation 2.1σ (IC 40 and IC 59a)

Downward fluctuation

Expectation from scrambling data ~6000 times

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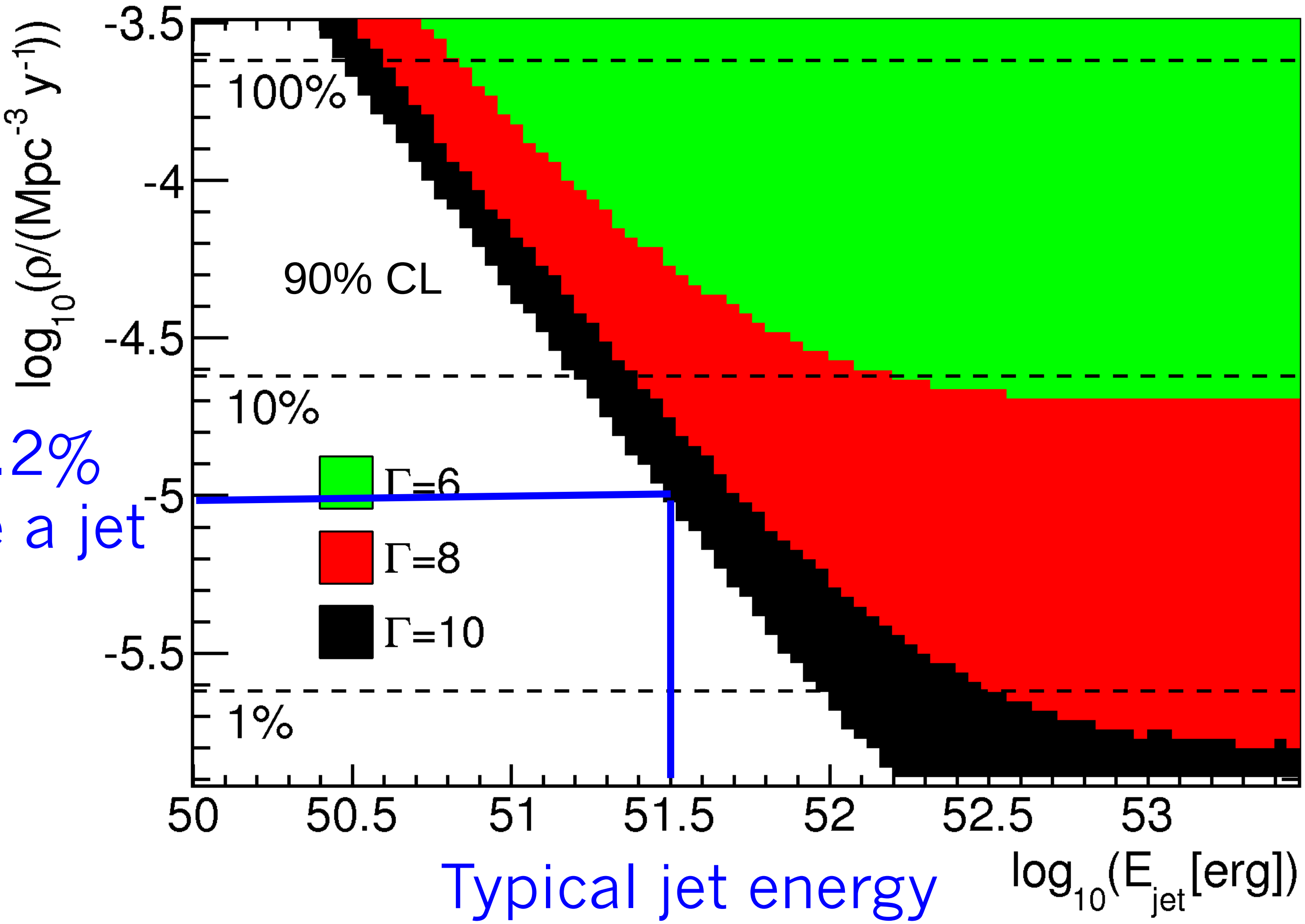
Results: ROTSE follow-up

Optical image analysis: no SN has been found in correlation with neutrino alert



Less than 4.2% of SNe have a jet with Γ>10

Typical jet energy

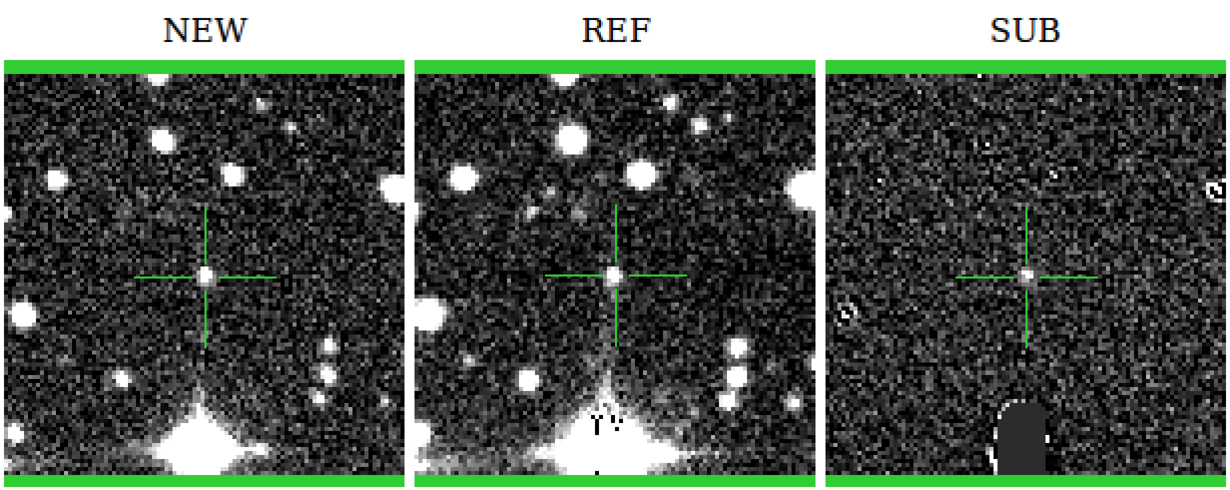
arXiv: 1111.7030

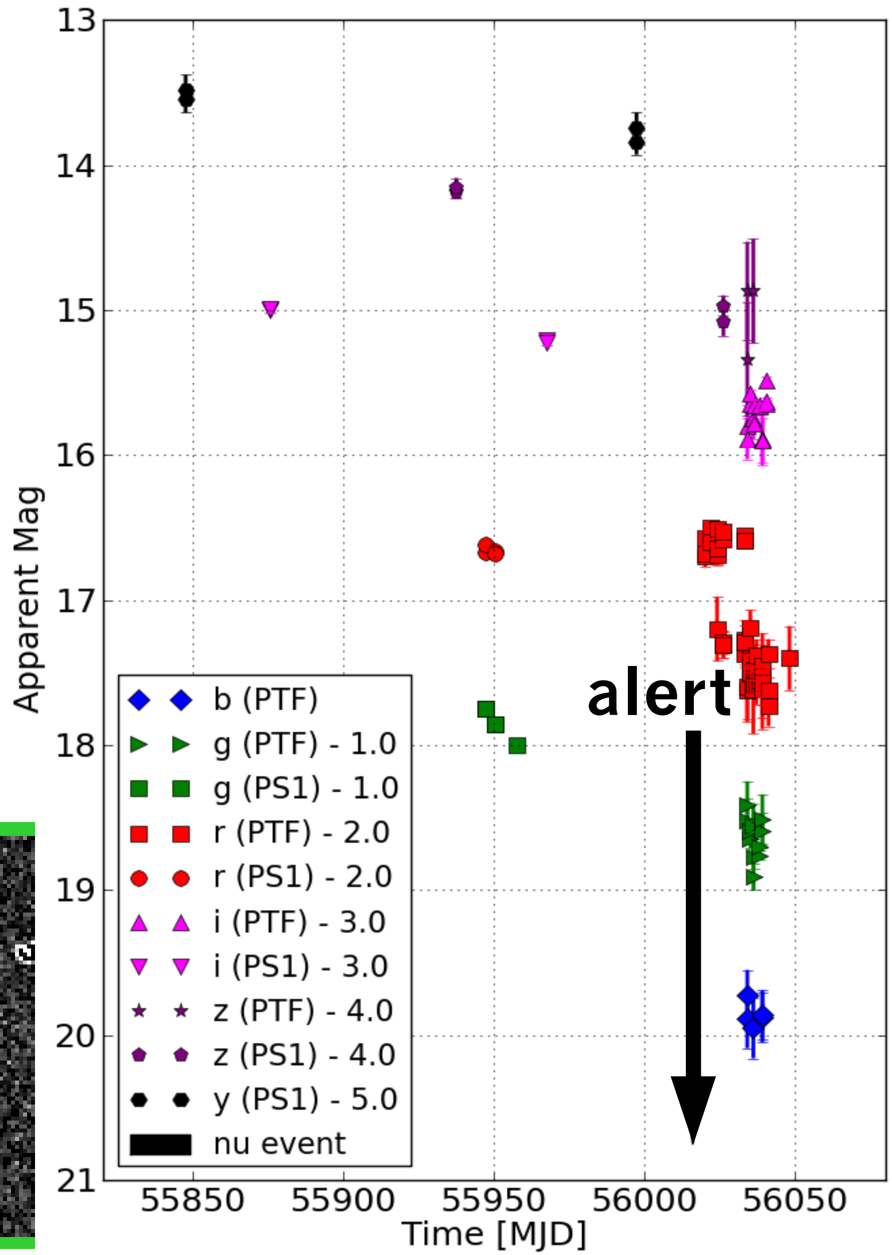
Limit on choked jet SN model, Ando & Beacom (2005)

Recent Results: Optical follow-up

Alert from 2012-03-30:

- One of most significant alerts
  - ΔT = 1.8 s, ΔΨ = 1.3°, rate of 0.25 / year
- **Type IIn supernova found** in PTF follow-up data, very close to neutrino direction! (0.14° separation)
- Spectrum also taken
- Archival data: was an old source, explosion many months before neutrino trigger
- **Very unlikely that neutrinos were correlated**





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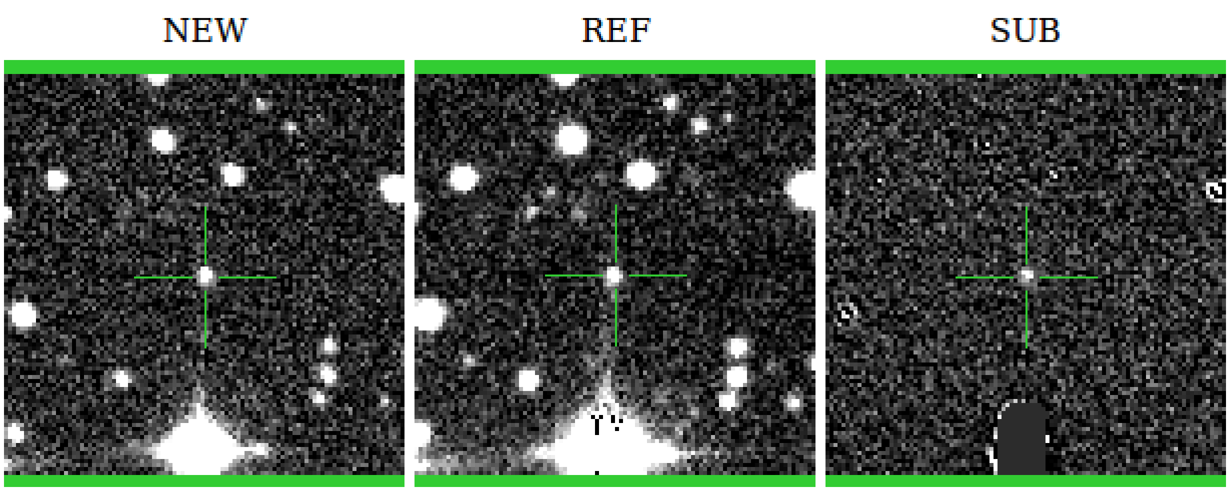
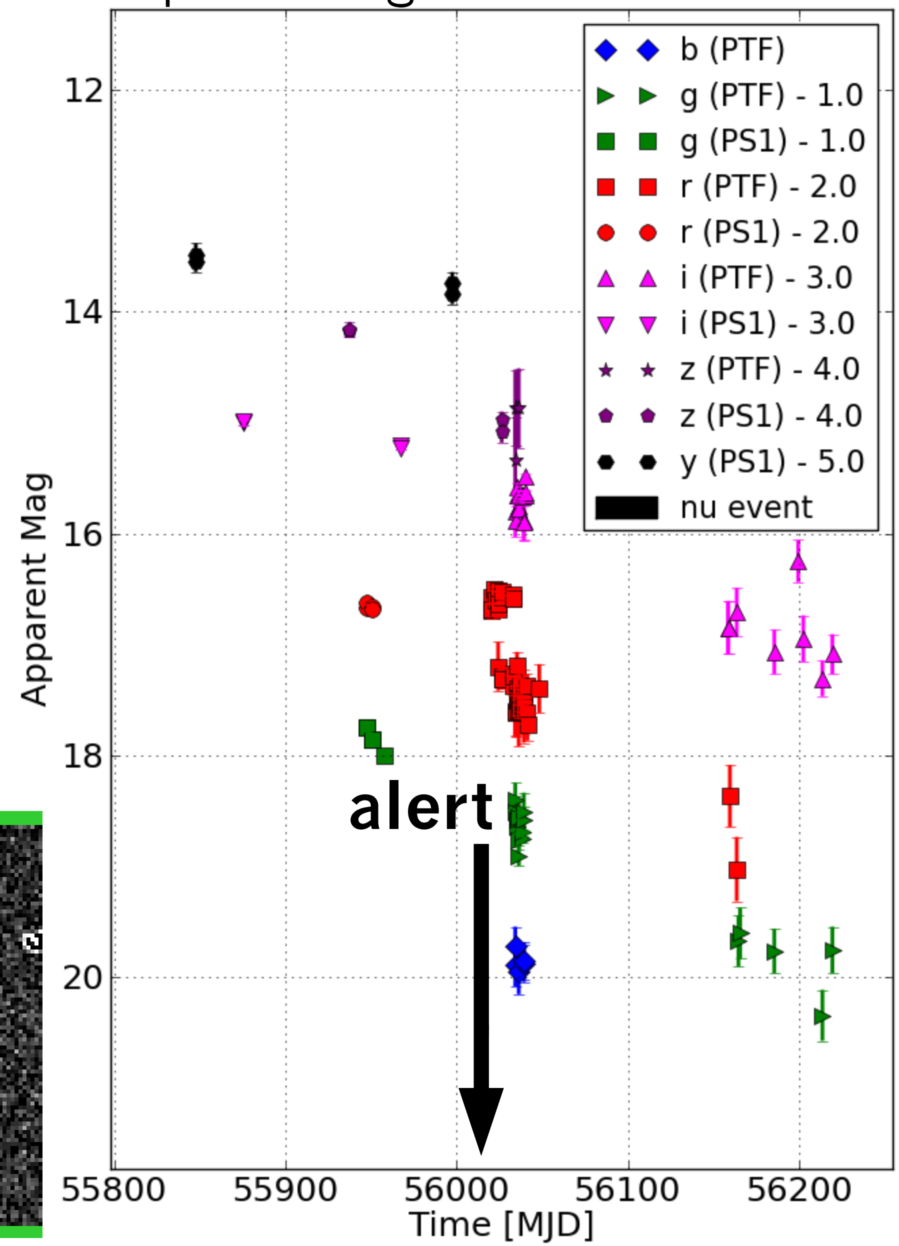


Updated light curve:



Summary

- IceCube's follow-up programs gathering unique data
- OFU running since Dec 2008
  - Nothing significant found: first limits published

arXiv: 1111.7030

- XFU running since Feb 2011
- Program has found exciting candidates leading to fast follow-up
- Majority of alerts still being analyzed

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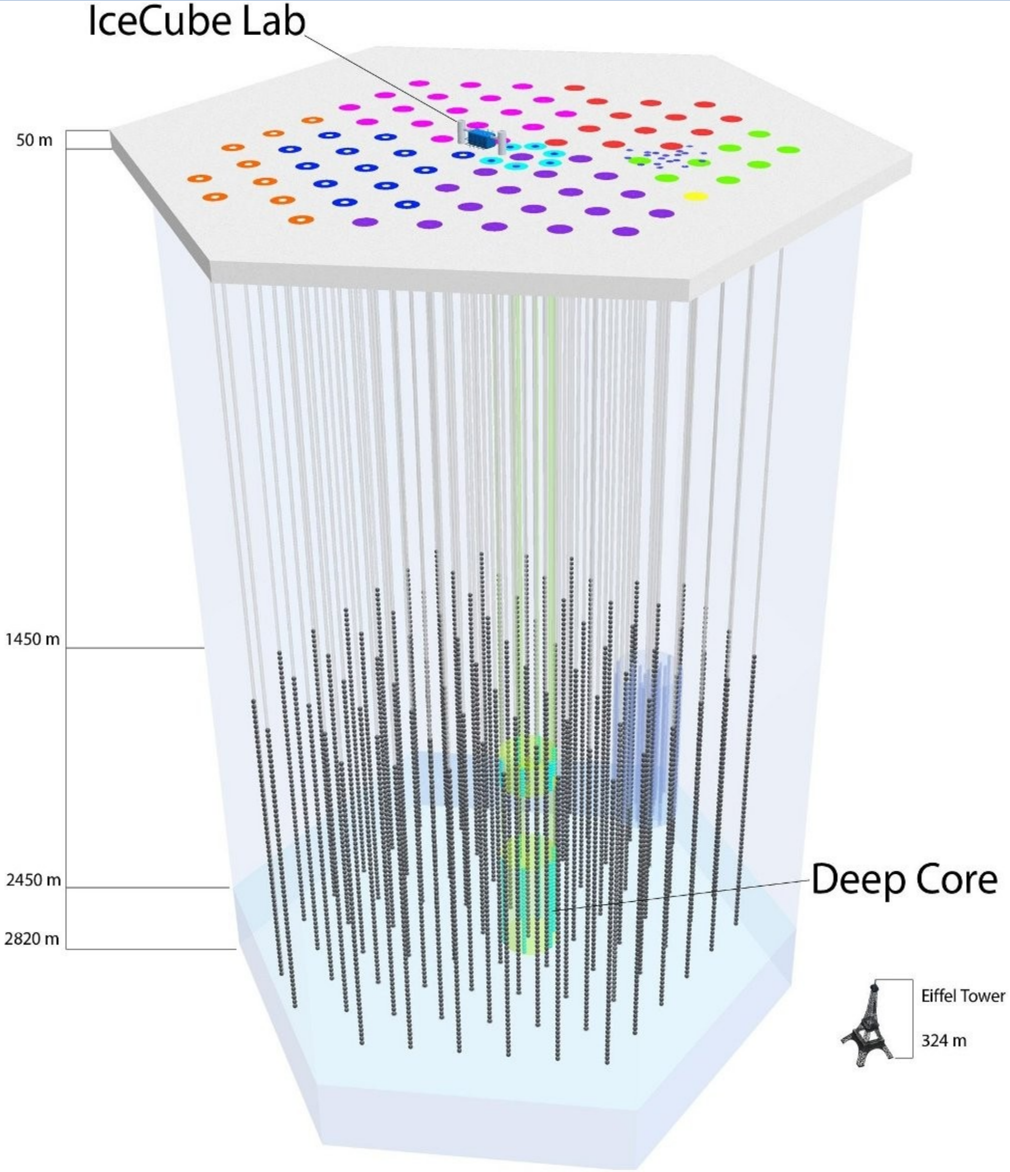
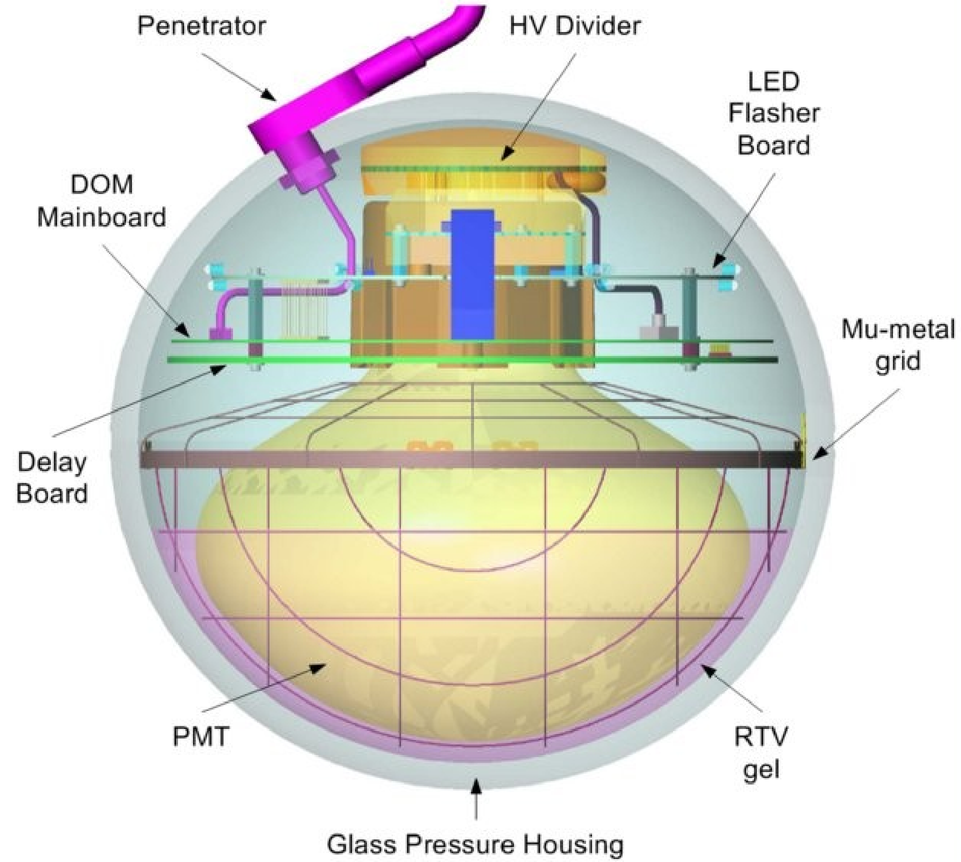
Backup slides

IceCube Overview



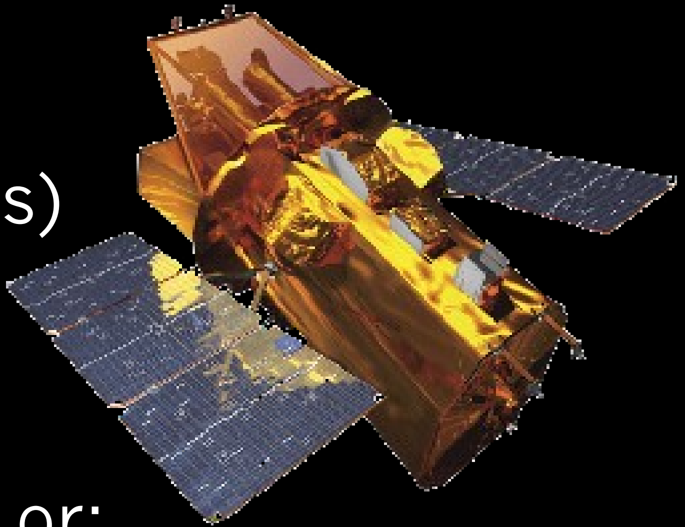


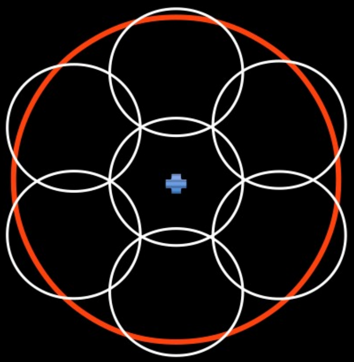
DOM = Digital Optical Module

Since May 2011: Taking data with full detector
86 strings (6 dense DeepCore strings)
5160 DOMs in the ice

Swift Overview

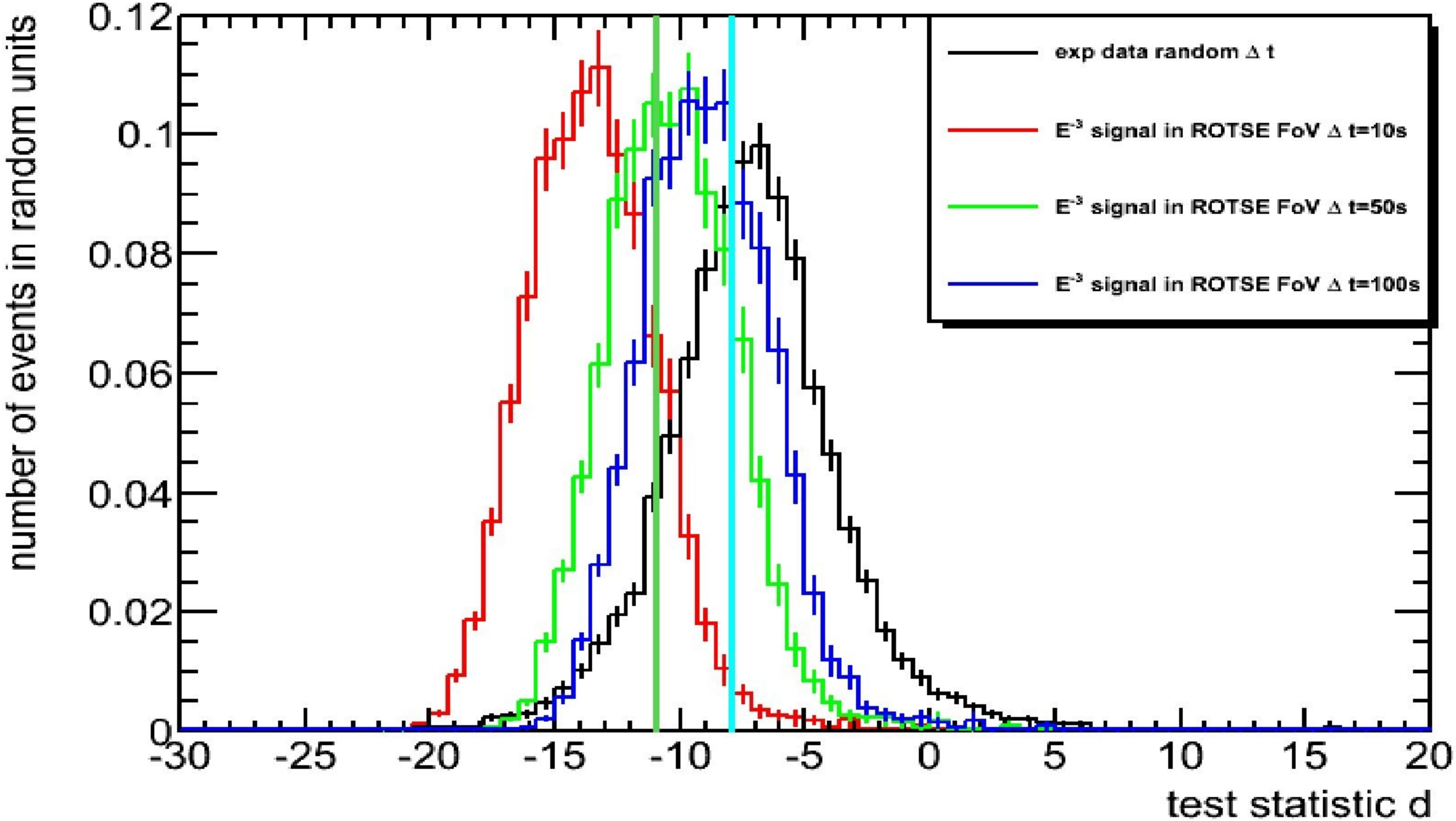
- 10,000 s exposure with XRT, more intensive follow-up (up to 2 weeks) possible, depending on:
  - Flux
  - Source not found in source catalog, or:
  - Brightening of known source (galaxy)
- Need 'tiling' because FoV too small (0.4°)
- Follow-up since Feb. 2011
- ~7 Alerts per year





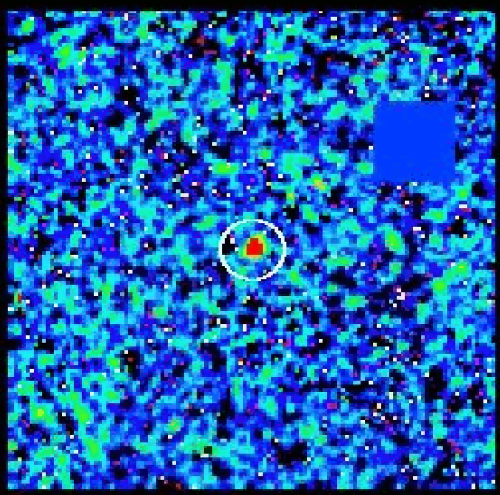
Likelihood function

$$\ln L = \frac{\Psi^2}{\sigma_q^2} + 2\ln(2\pi\sigma_q^2) - 2\ln\left(1 - e^{\frac{-\Theta_A^2}{2\sigma_w^2}}\right) + 2\ln\left(\frac{\Delta T}{100\,s}\right) + const$$



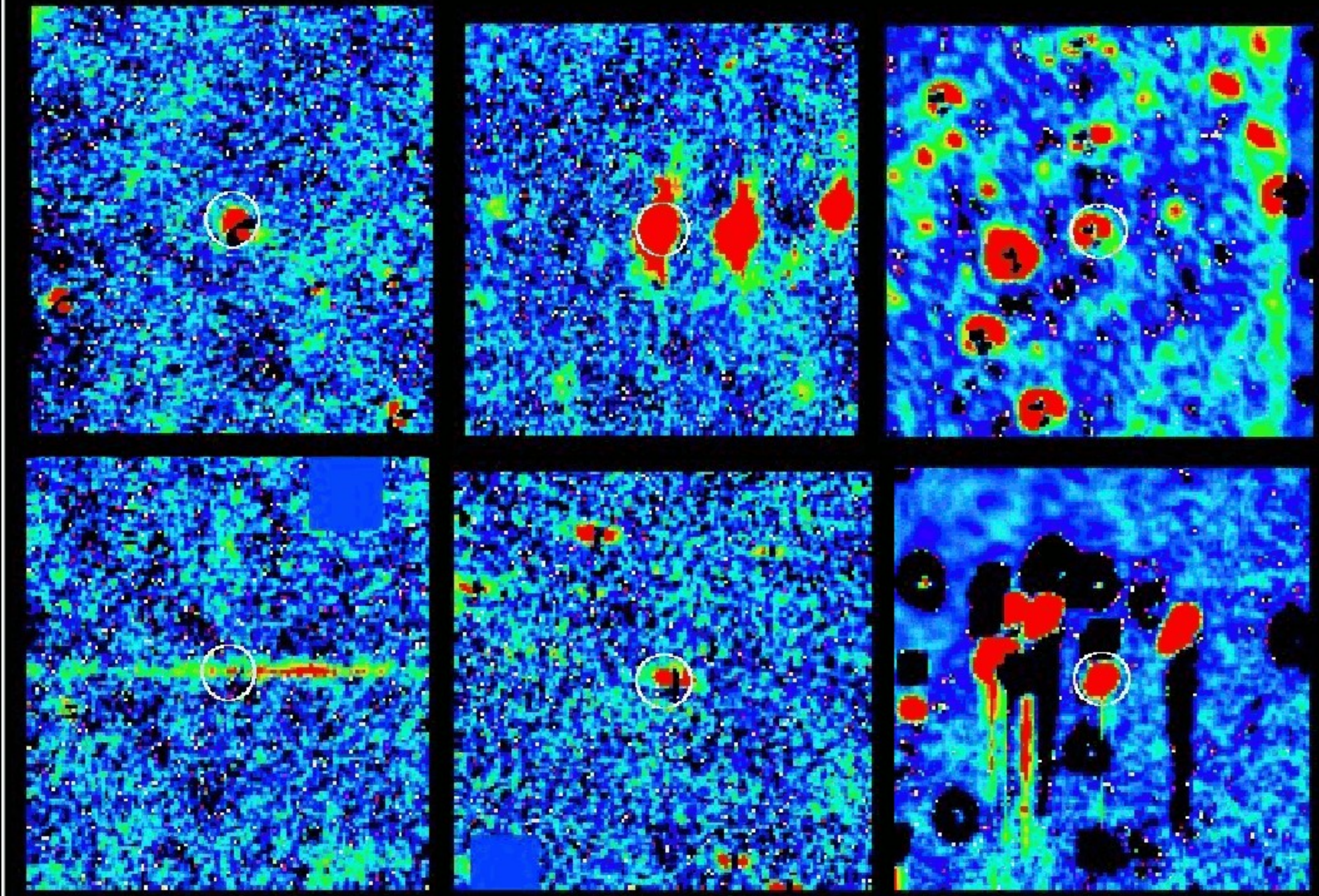
Rea
Phy

Image Analysis (ROTSE)



good

Many mis-subtractions:



bad (and ugly)

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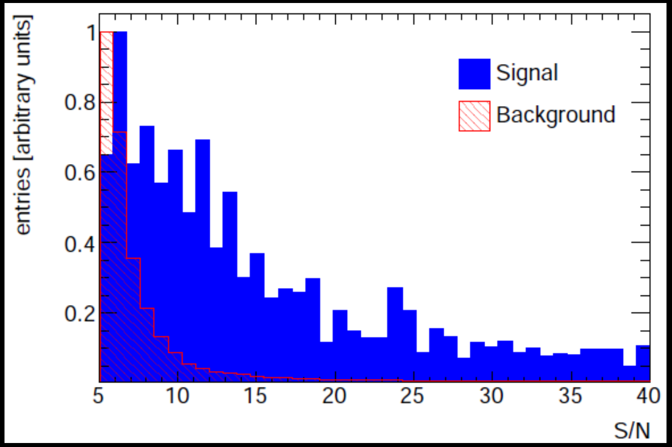
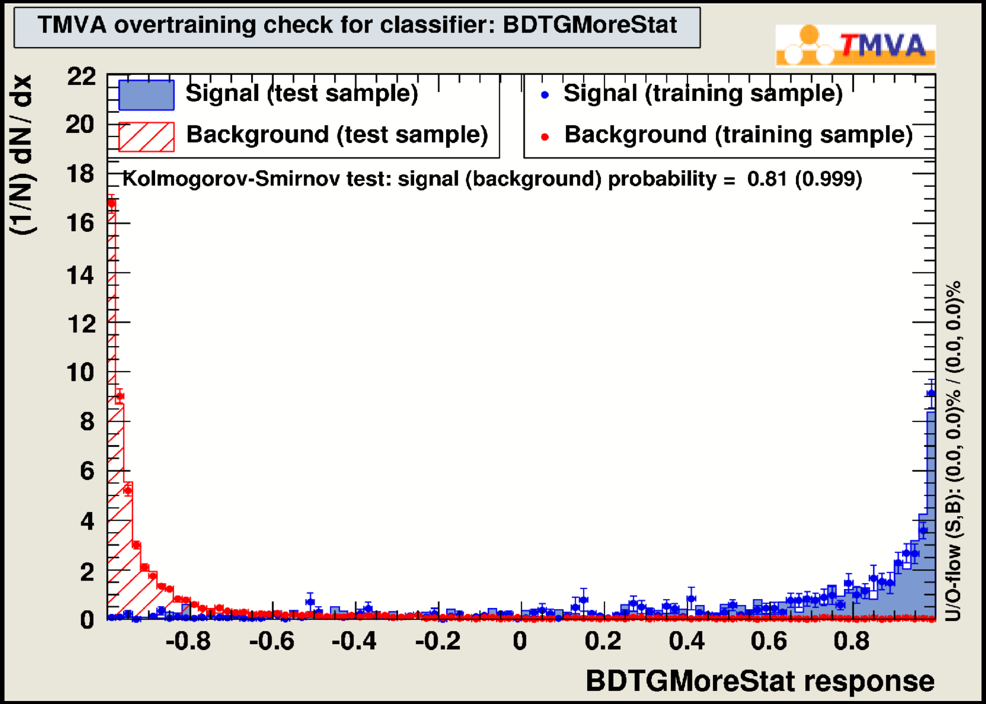
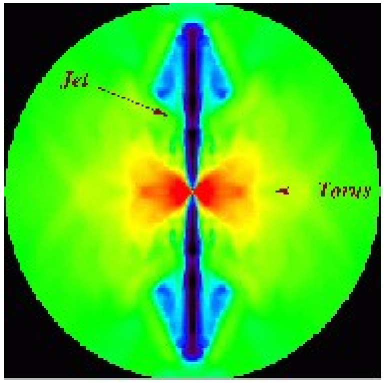
Image Analysis (ROTSE)

- Need to separate real candidates from mis-subtractions
- Useful separation variables:
  - Geometry:
    - Ellipticity
    - Semi-minor axis
    - Negative pixels
    - FWHM
    - Isophotal area
  - Variability of the object:
    - Change with respect to reference image
    - S/N
- Train boosted decision tree

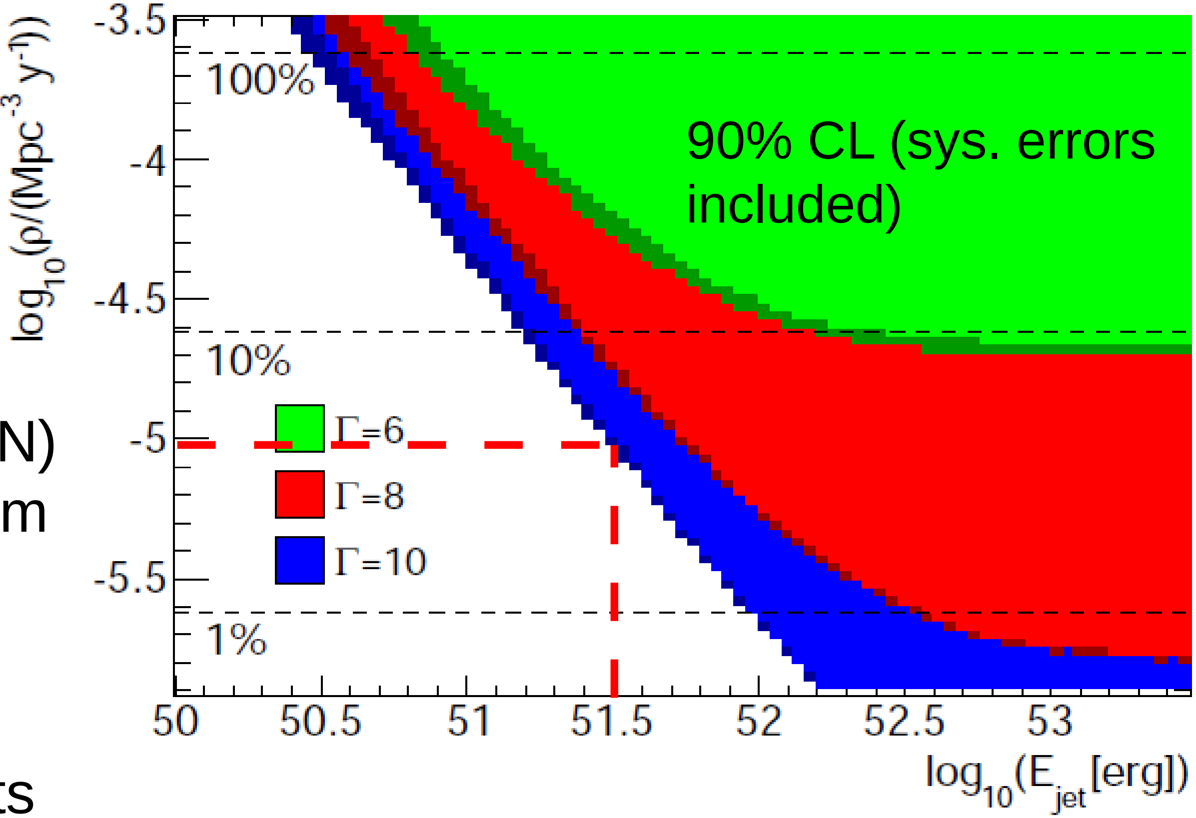




Results: Optical follow-up



Corecollapse-SNe (CCSN) with Jets (Ando & Beacom 2005)



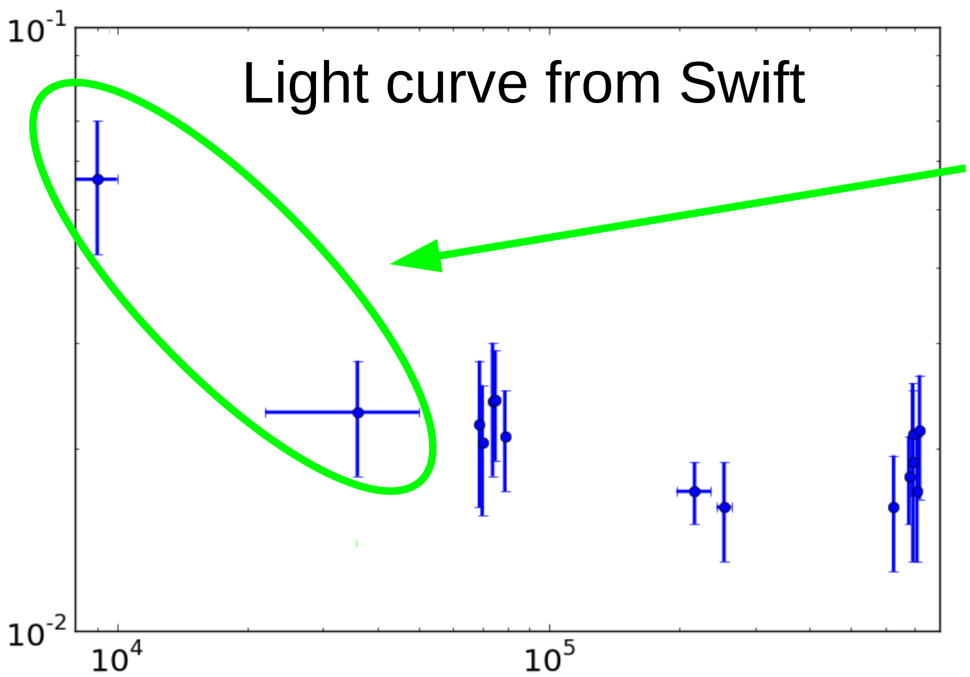
Model parameters:

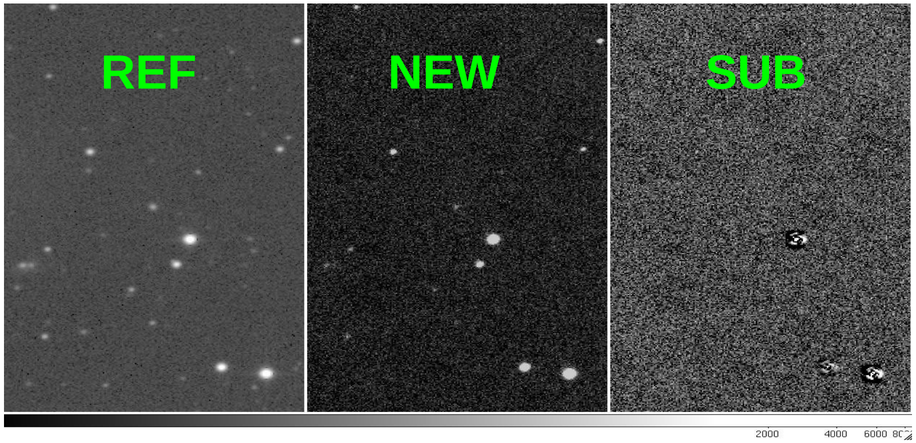
- Rate ρ of CCSN with jets
- Jet energy Ejet
- Lorentz boost factor Γ

Less than 4.2% of all CCSN host a jet with typical values of Γ= 10 and Ejet = 3×10^{51}erg

arXiv: 1111.7030

Recent Results: X-ray follow-up





Alert from 2012-03-03:

- First observations: **Fast fading source found**
- Just below Swift threshold for intensive follow-up
- Swift decision: More observations
- Later observations: **Fast decay not confirmed**
- IceCube: Everything ok, but nothing extraordinary
- Alert was also sent to PTF (lower image): no transient source found
- Result: One more observation with Swift shows slow fading/variability. **Probably background AGN**

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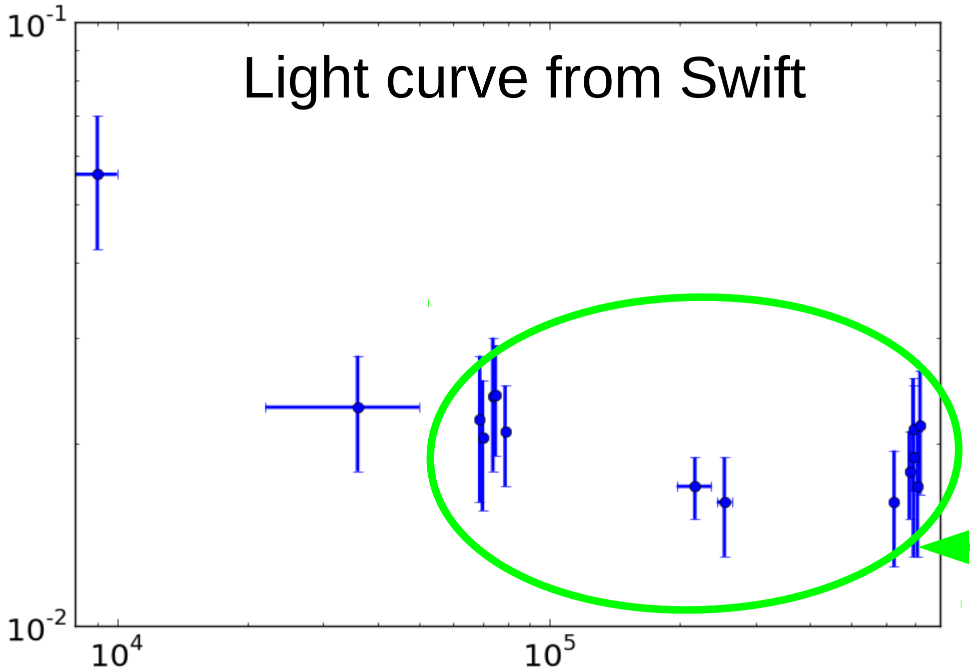

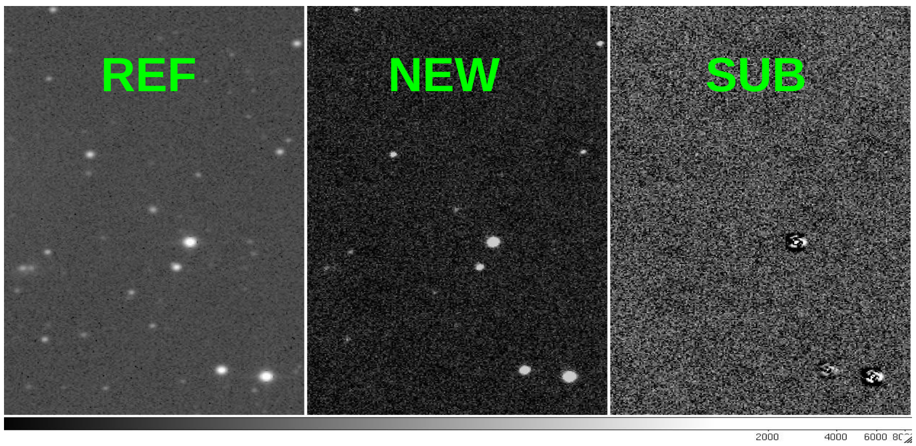

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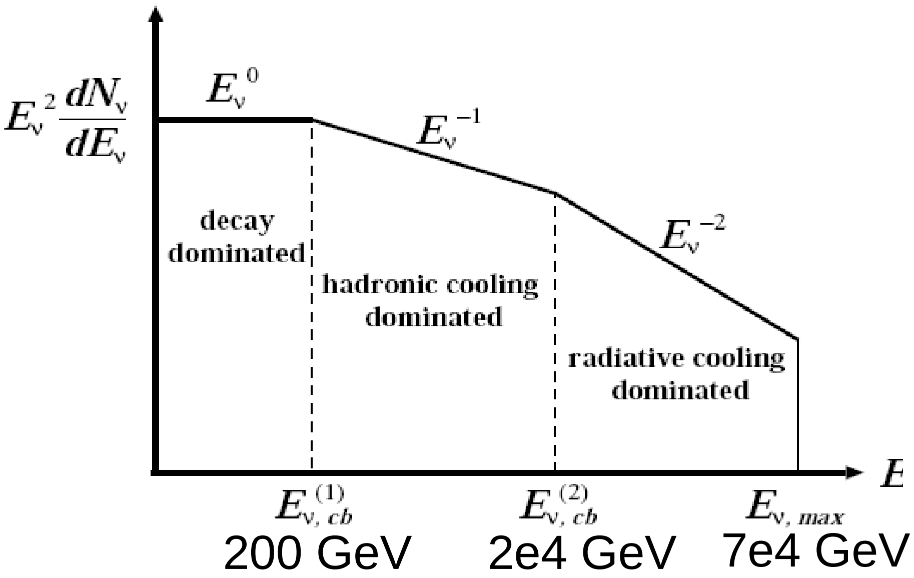
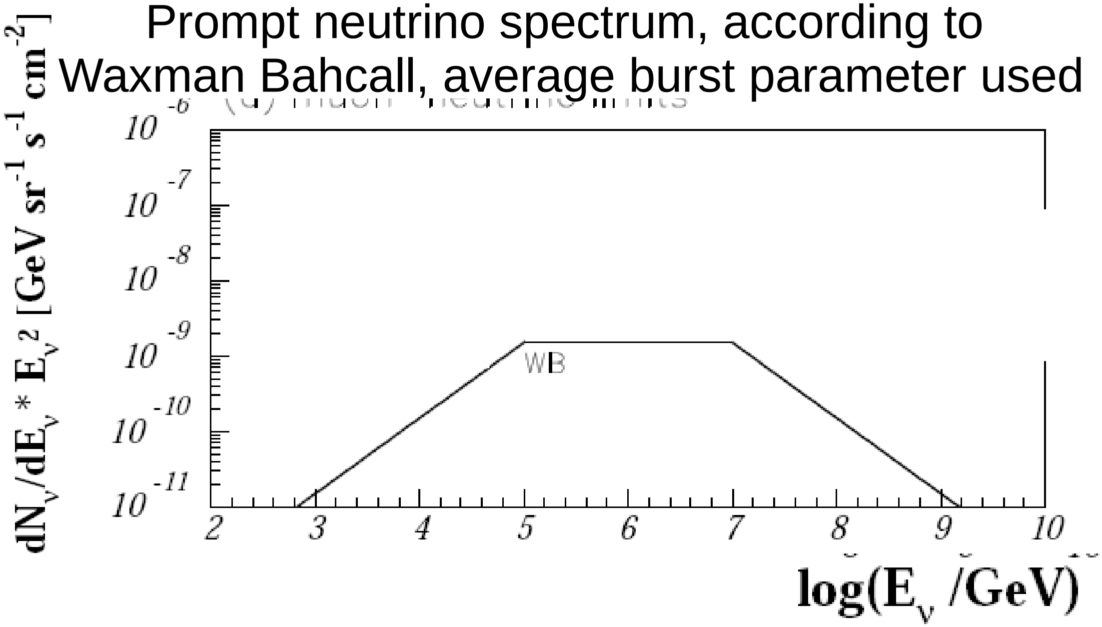
Soon: Development of new high energy singlet stream





Prompt neutrino spectrum, according to Waxman Bahcall, average burst parameter used

- OFU started by looking for SN Jets (Ando&Beacom). Multiplets needed due to low energy atmospheric neutino background.
- Low background of high energy events for GRB search
- Search for high energy neutrino singlets:
  - Low GRB neutrino flux: Probability to see one neutrino much higher than to see two.
  - Initial estimates: Sensitivity increase of factor 10 should be possible (the filter needs to be developed for exact numbers)