Optical follow-up of high-energy neutrinos detected by IceCube

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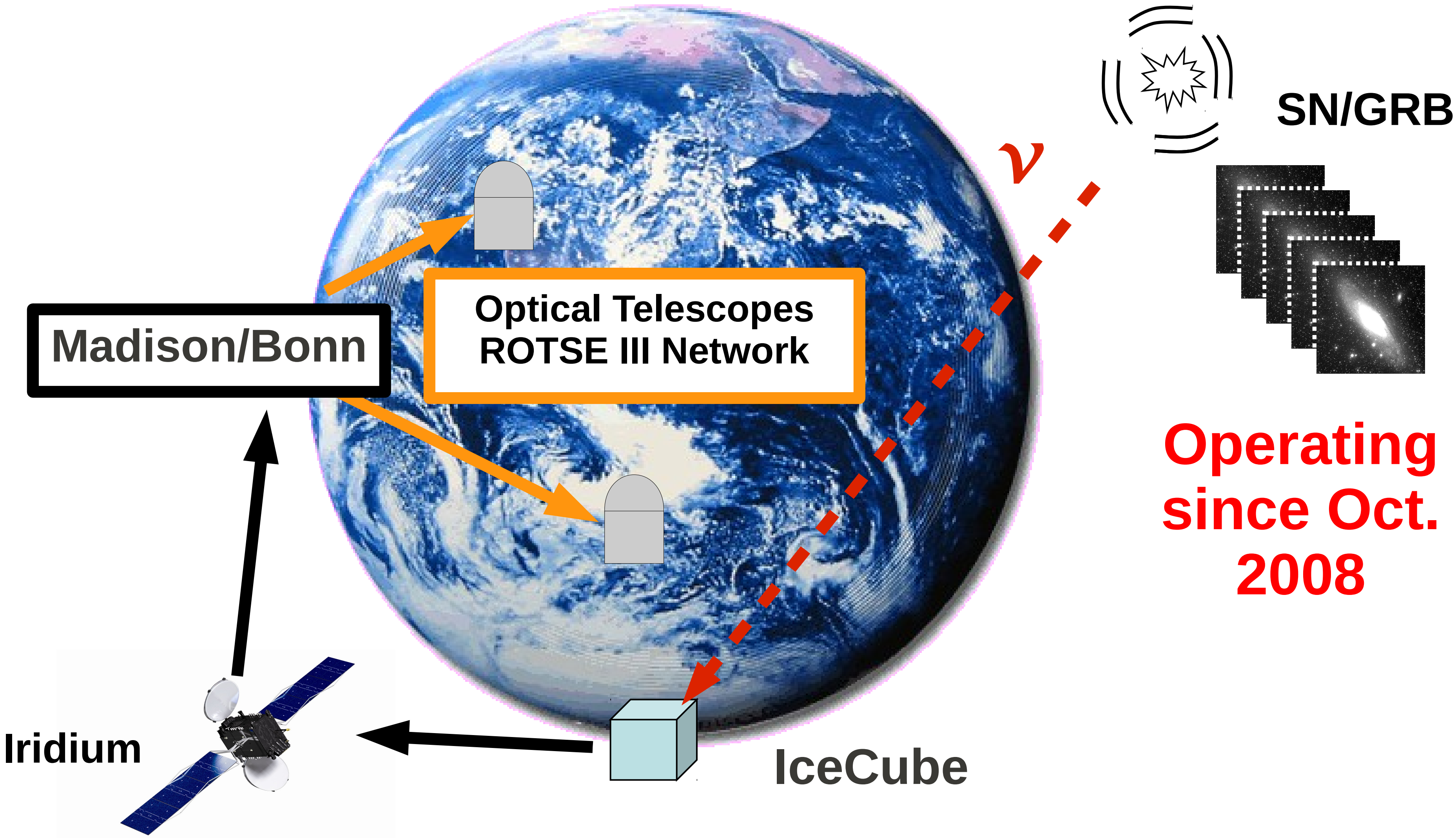
Content

- Concept of optical follow-up program
- IceCube Trigger and Performance
- Optical data Analysis (ROTSE)
- First Results (first year of data)
- Extensions

Concept of the optical follow-up



GRB neutrinos

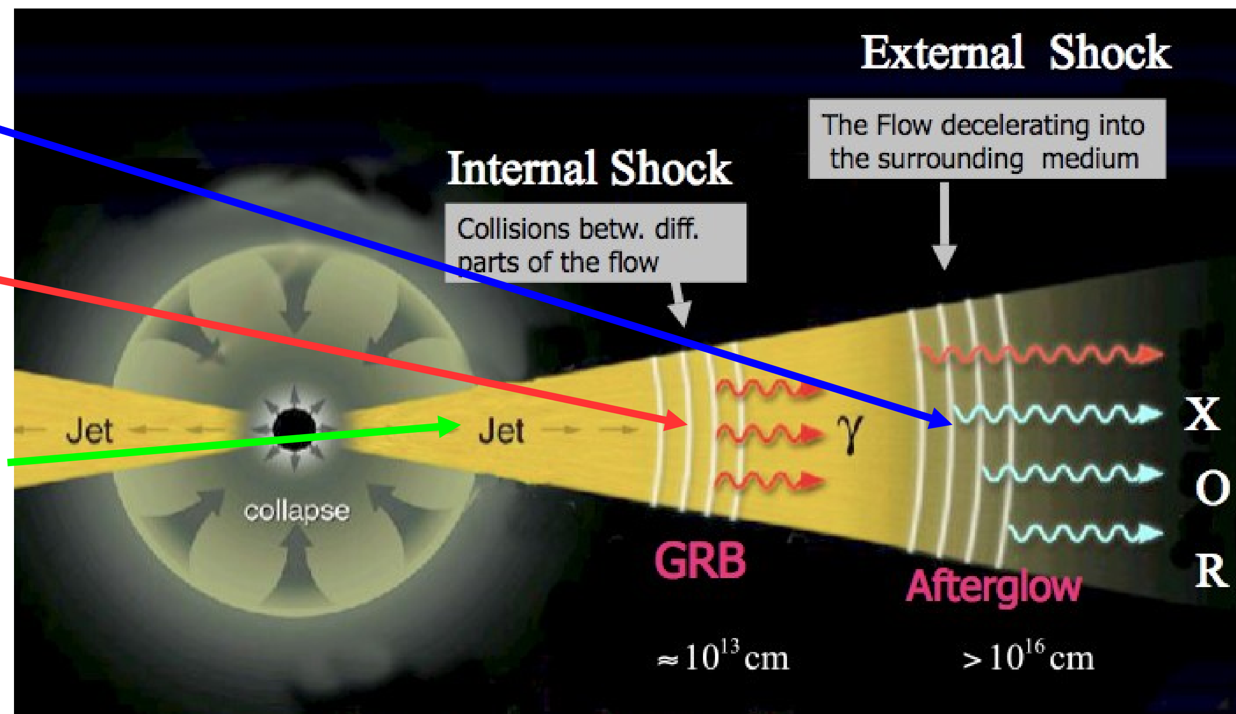
Fireball Shock Model (Meszaros, Rees 1994)

- Internal shocks: Collisions within jets → γ-radiation
- External shocks: Collision with interstellar medium → Afterglow (radio, X-ray, optical)

EeV Neutrinos from external Shocks (afterglow)
[Dermer 2001]
[Waxman & Bahcall, 2000]

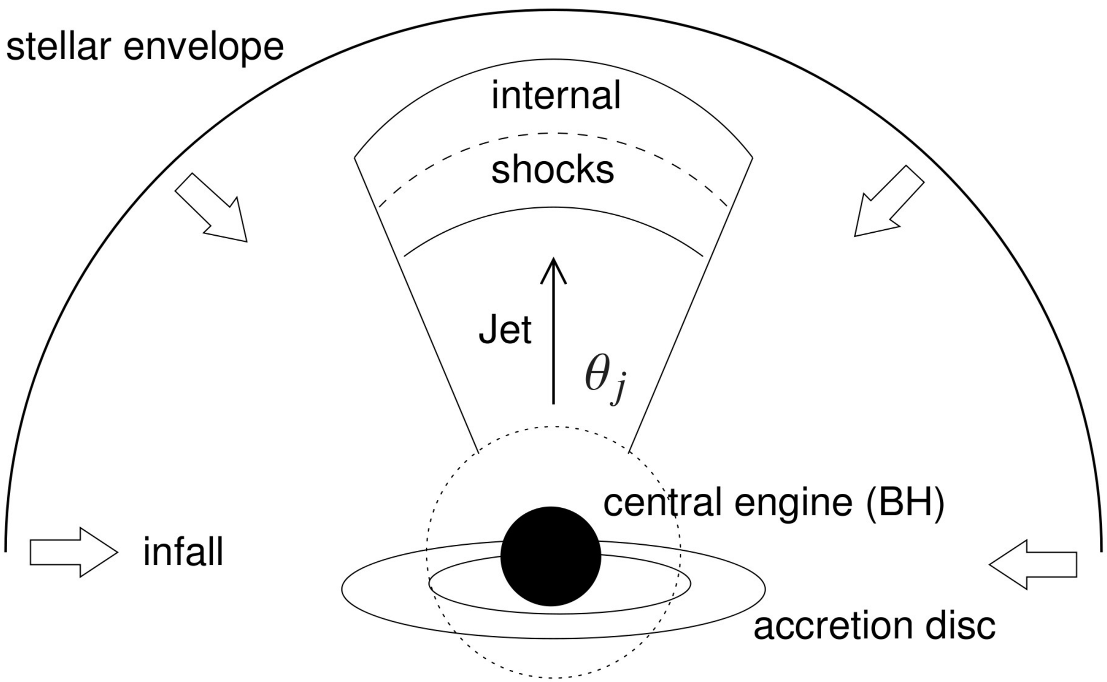
PeV Neutrinos from internal Shocks (prompt)
[Waxman & Bahcall 1997]
[Gupta & Zhang, 2006]
[Murase & Nagataki 2006]

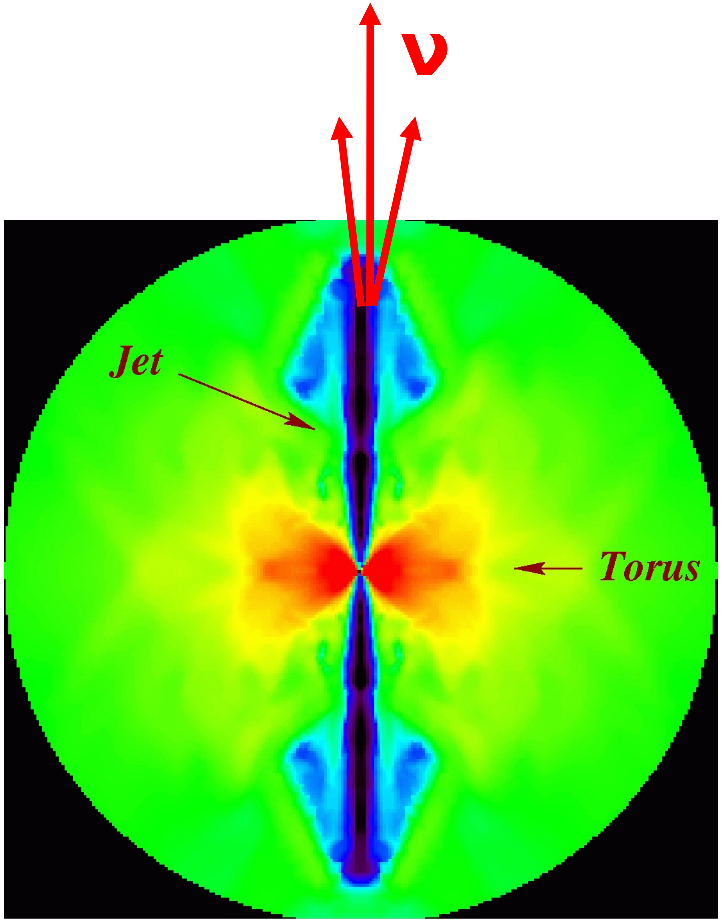
TeV neutrinos from inside the star (prescursor)
[Meszaros & Waxman, 2001]
[Razzaque et al. 2003]



High-energy SN neutrinos

- GRB-SN connection
- Core-collapse SN with soft relativistic jet





Razzaque, Meszaros, Waxman (Mod. Phys. Lett. A 20, 1998)
Ando, Beacom (Phys. Rev. Lett. 95, 2005)

Online Processing at South Pole

Trigger
~1600 Hz

general muon filter

Muon Filter
~35 Hz

well-reconstructed muon events

Online L2
~4 Hz

time consuming reconstructions

OFU Level
~2 mHz

almost neutrino level
Purity: 37% (IC40), 70% (IC59)

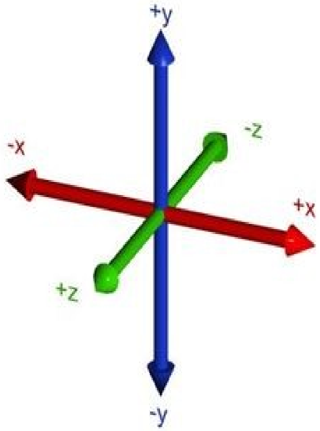
Latency:
6 hours in the past
Now: ~ 5 minutes

Multiplicity Trigger

Requirement: At least 2 neutrinos
→ Reject background of atmospheric neutrinos
→ 25 doublets per year

Neutrino Bursts from SN or GRB – Coincident in

time & **space**

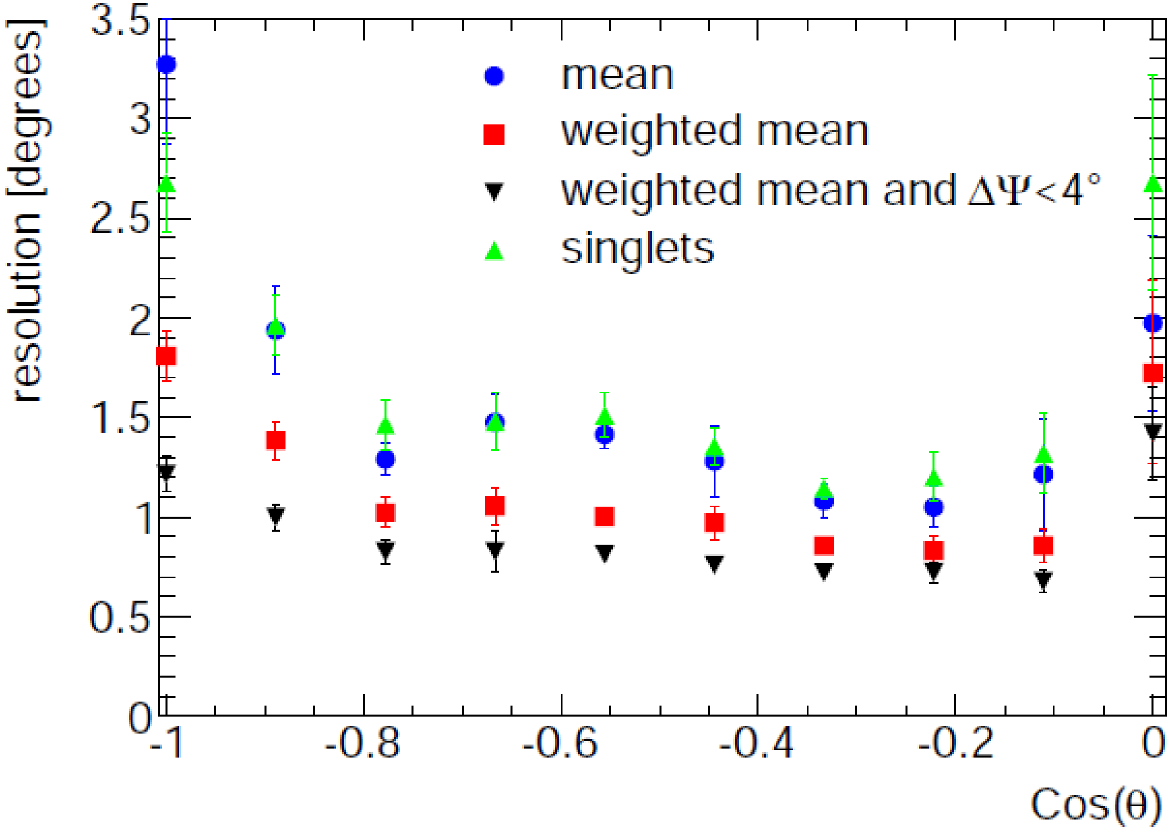


Time between events
ΔT<100 s

Angular Difference between reconstructed directions **$\Delta\Psi < 4°$**

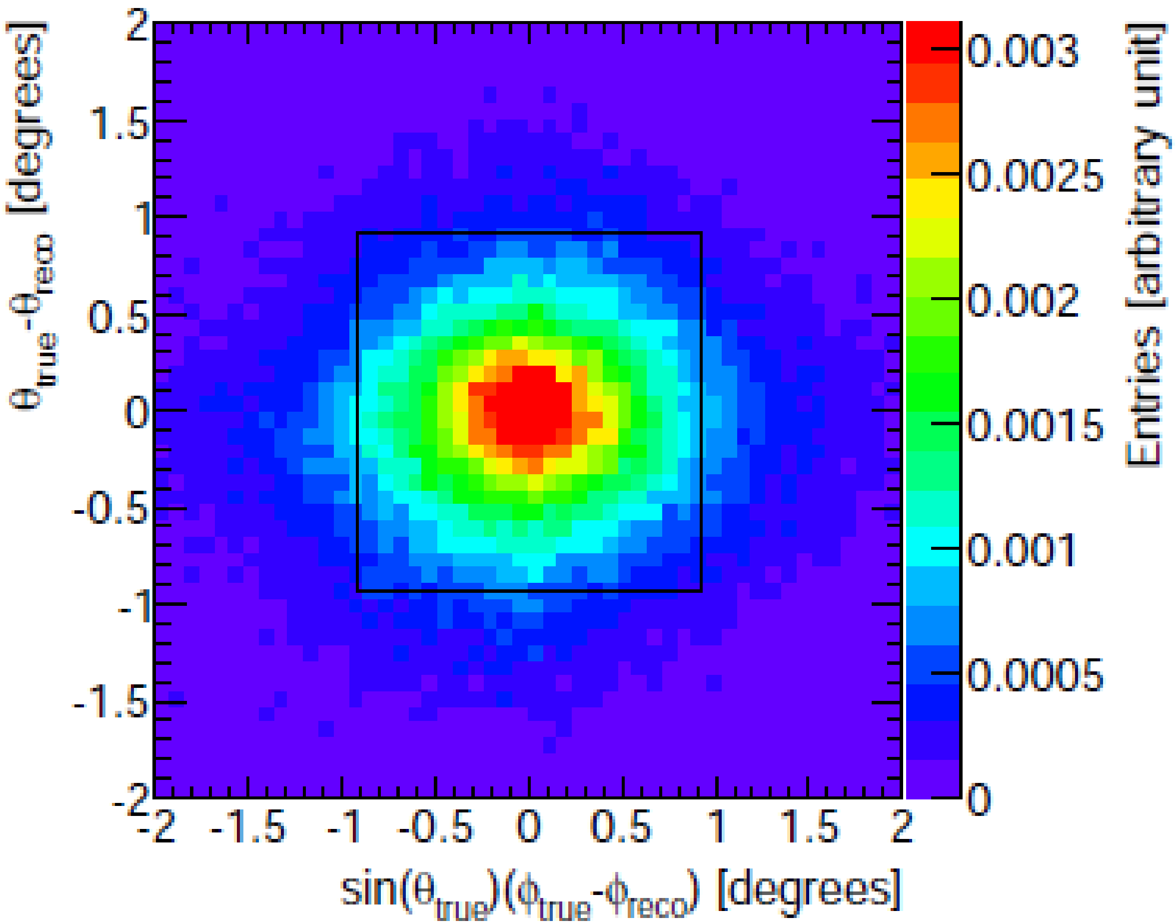
Doublet Resolution

Doublet direction: $\vec{\Psi}_{comb.} = \frac{\sum_i \frac{1}{\sigma_i^2}\vec{\Psi}_i}{|\sum_i \frac{1}{\sigma_i^2}\vec{\Psi}_i|}$, with $\sigma_i^2 = \frac{\sigma_{x,i}^2 + \sigma_{y,i}^2}{2}$



Weighted with soft SN spectrum

Doublet PSF



ROTSE's field of view: 1.85° x 1.85°

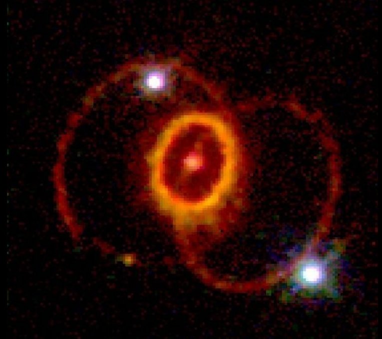
Passing rate dependent on model parameters (40-60%)

Results – IceCube

Data from 18.Dec 2008 until 31.Dec 2009

	Multiplicity	Measured	Expected (scrambling)
IC 40	Doublets	15	8.55
IC 40	Triplets	0	0.003
IC 59	Doublets	19	15.66
IC 59	Triplets	0	0.004

Only IC results:
deviation from expectation,
p-value 3.5%
significance 2.1σ

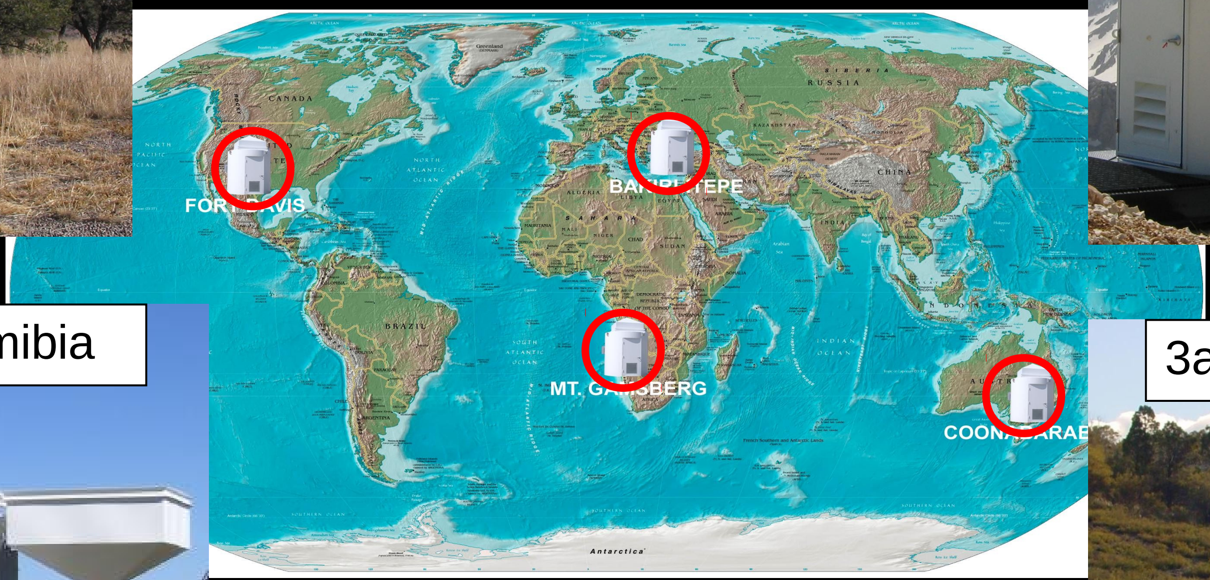


Searching for Optical Counterpart with ROTSE

3b, McDonald, Texas

3d, TUG, Turkey

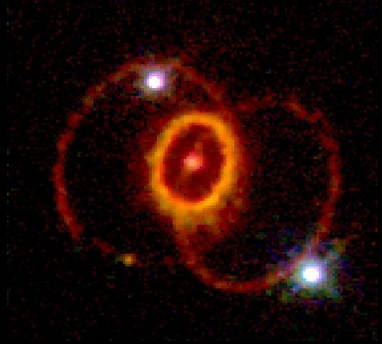
Robotic Optical Transient Search Experiment



3c, H.E.S.S., Namibia

3a, SSO, Australia

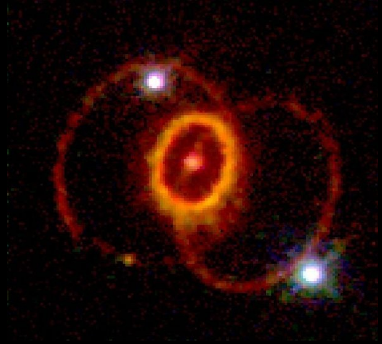
4 x 0.45m
FoV: 1.85° x 1.85°
fast follow-up
fully automated system



Optical Analysis

From 18.Dec 2008 until 31.Dec 2009:

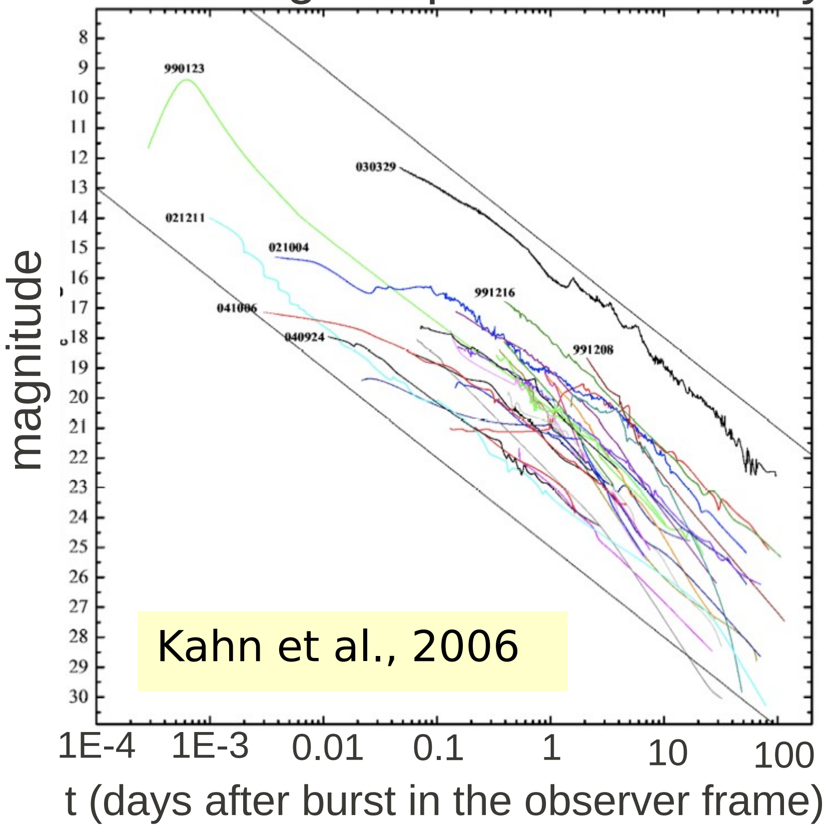
- 31 alerts with dec>0 forwarded to ROTSE
- 5 too close to sun
- 7 too close to galactic plane or too crowded
- 2 only have bad data
- **17 good alerts**



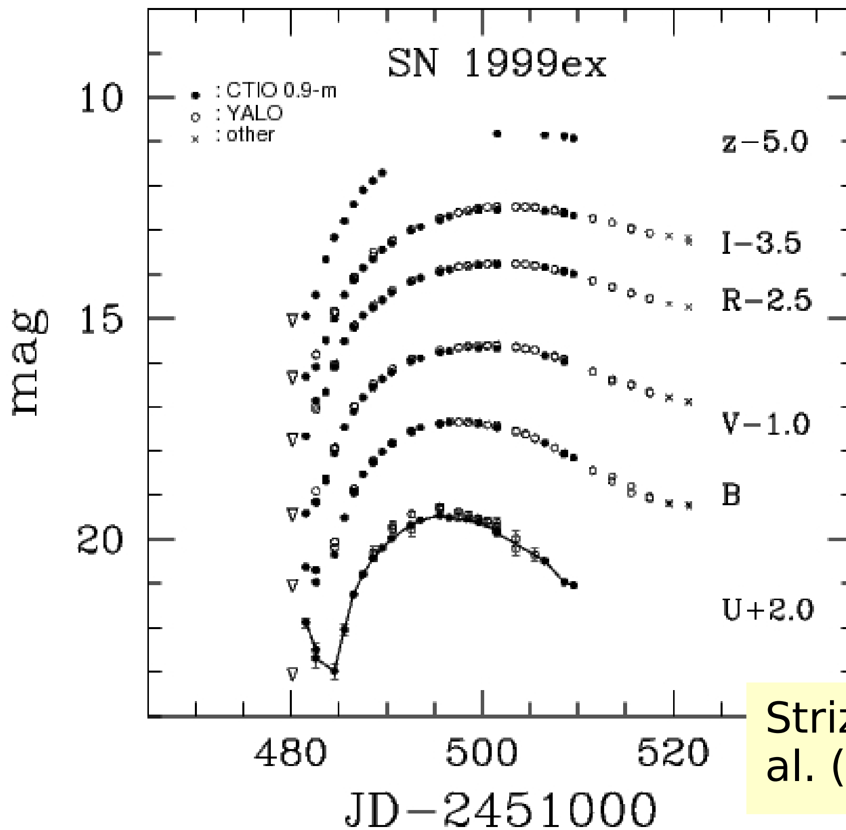
Observation Schedule of IceCube Follow-Up

- First night: Following ROTSE scheme of afterglow detection: thirty 60 sec exposures
- Following 24 nights (14 initially): Ten 60s exposures

GRB afterglow: power-law decay

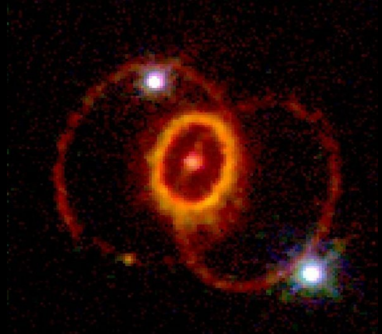


SN lightcurve: slowly rising



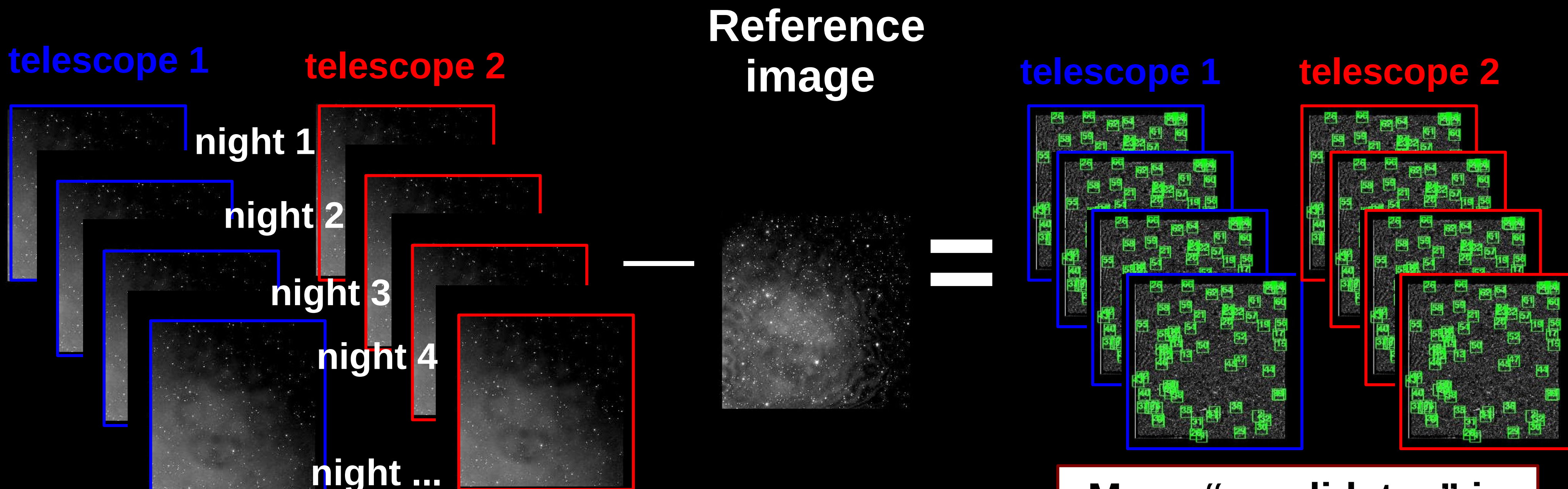
Strizinger et al. (2003)

Image Subtraction



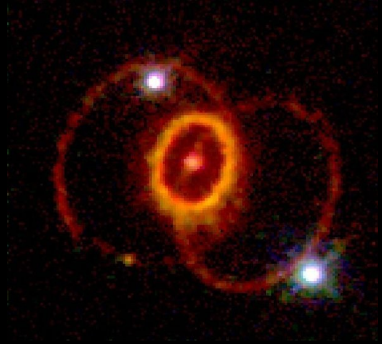
For each alert:
several nights of observations

Subtracted images for each night



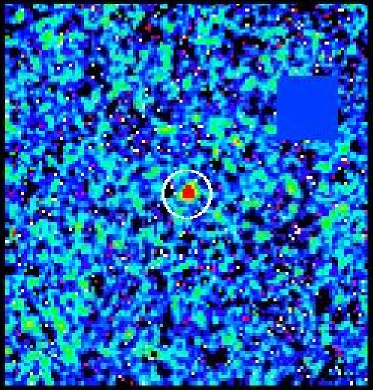
Many "candidates" in each night

Image subtraction algorithm (Yuan, Akerlof 2008)



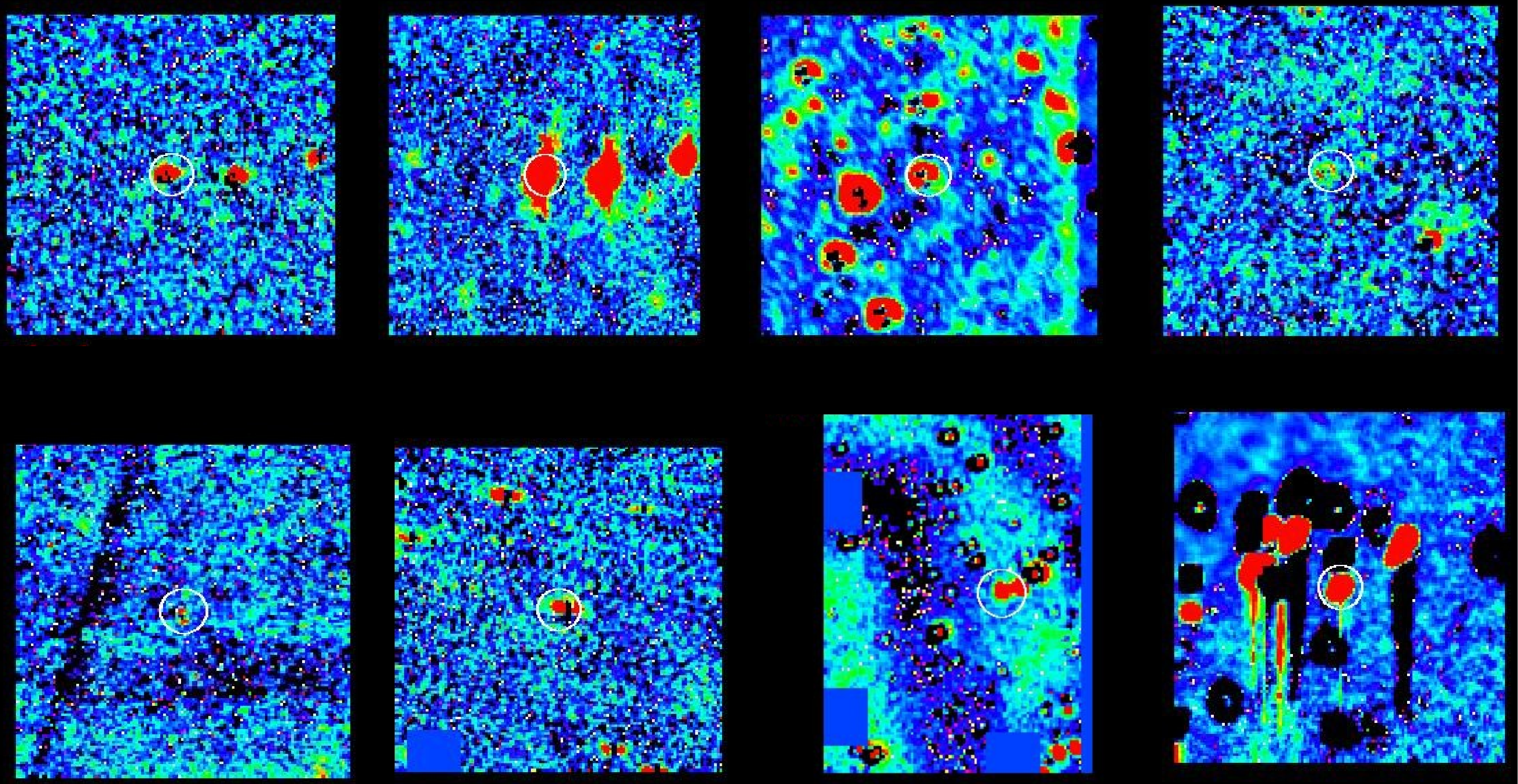
Reduce number of "candidates"

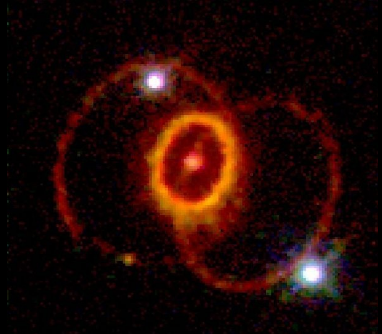
good!



All kind of missubtractions … just some examples

bad

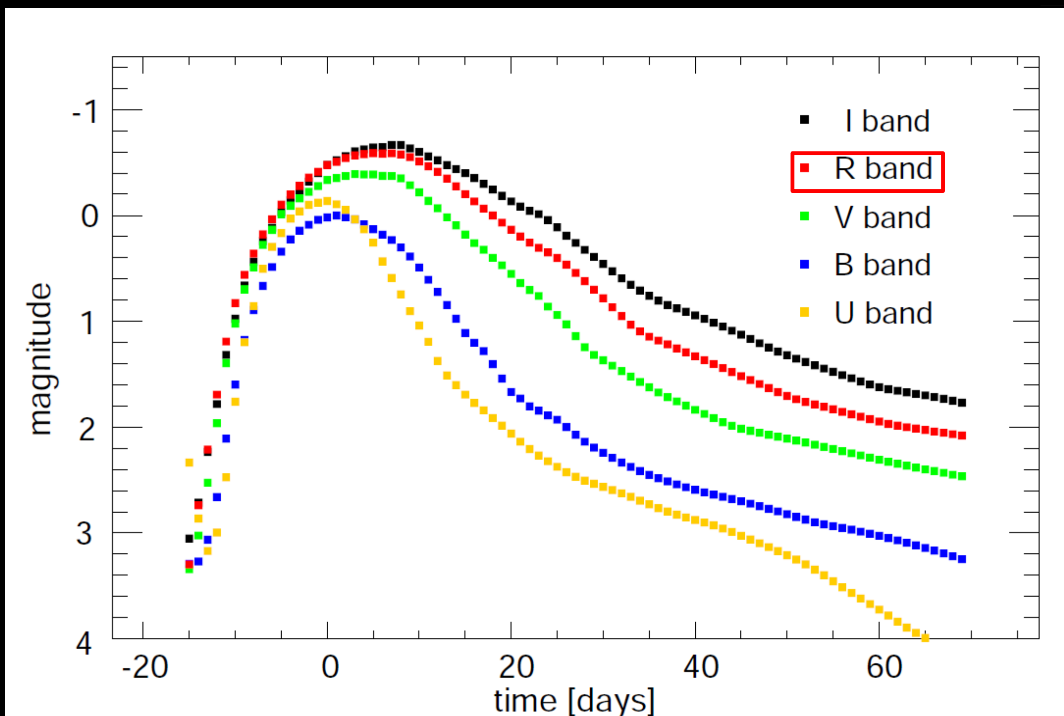




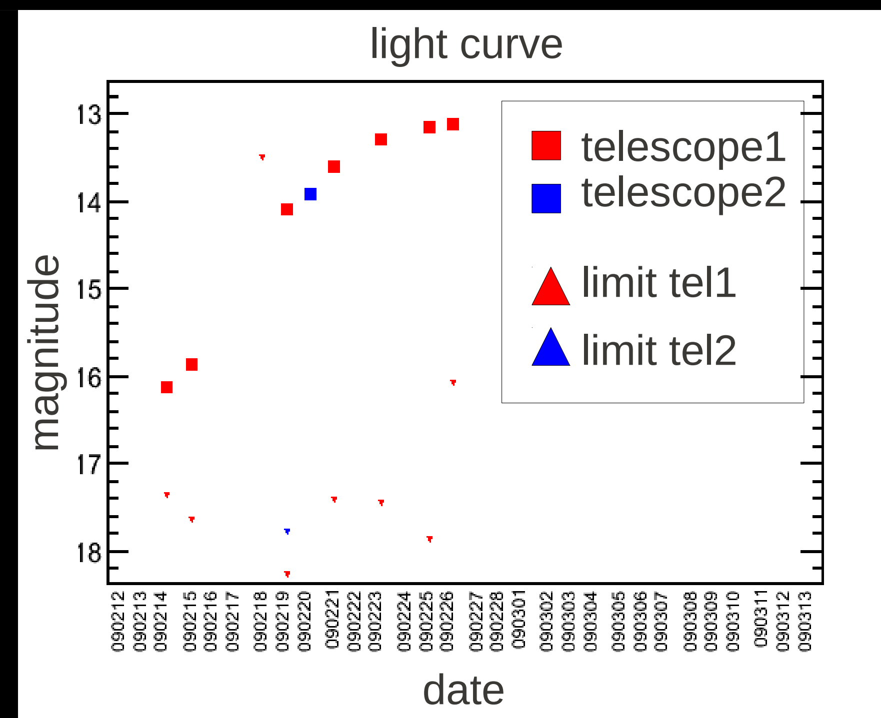
Optical SN Signal Simulation

Insert fake supernova to raw ROTSE images
Require candidate to be detected in at least two nights → light curve

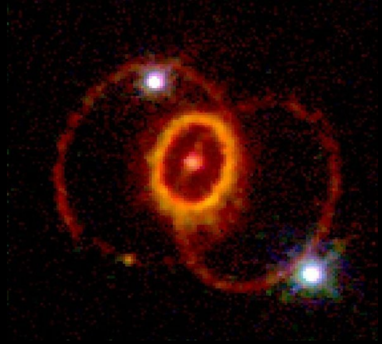
core-collapse SN template



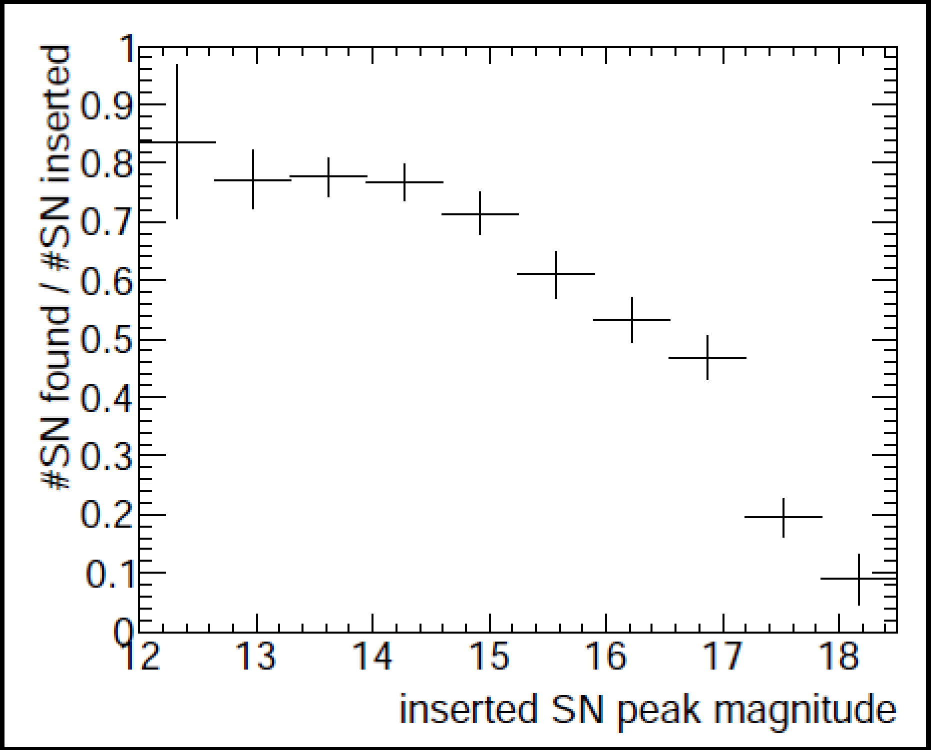
inserted template SN to ROTSE data

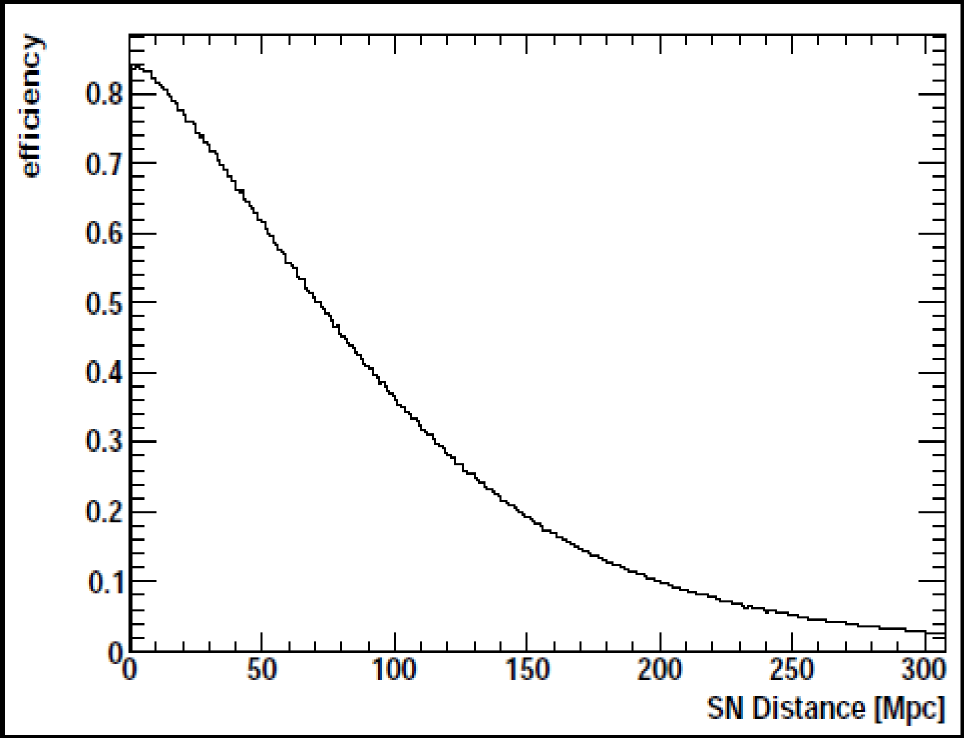


Trained BDT → Remove ~90% of bad candidates
Remaining candidates scanned „by eye“



Efficiency





Assuming absolut SN magnitude of -18 ±1

Results

Data from 18.Dec 2008 until 31.Dec 2009

	Multiplicity	Measured	Expected
IC 40	Doublets	15	8.55
IC 40	Triplets	0	0.003
IC 59	Doublets	19	15.66
IC 59	Triplets	0	0.004
Supernovae		0	0.074

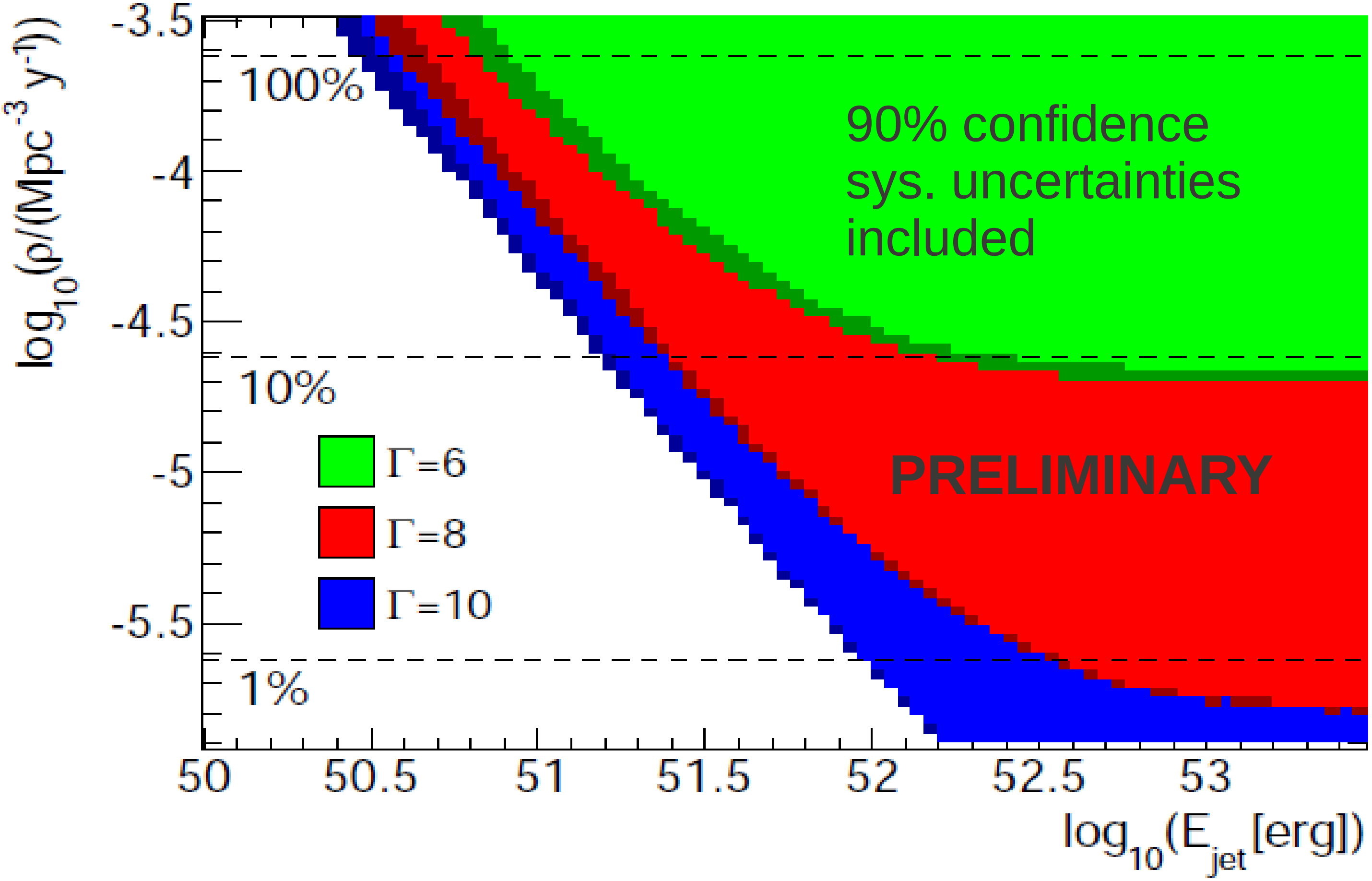
Only IC results: deviation from expectation, p-value 3.5% significance 2.1σ

Limit (one year)

Core-collapse SN with jets (Ando & Beacom)

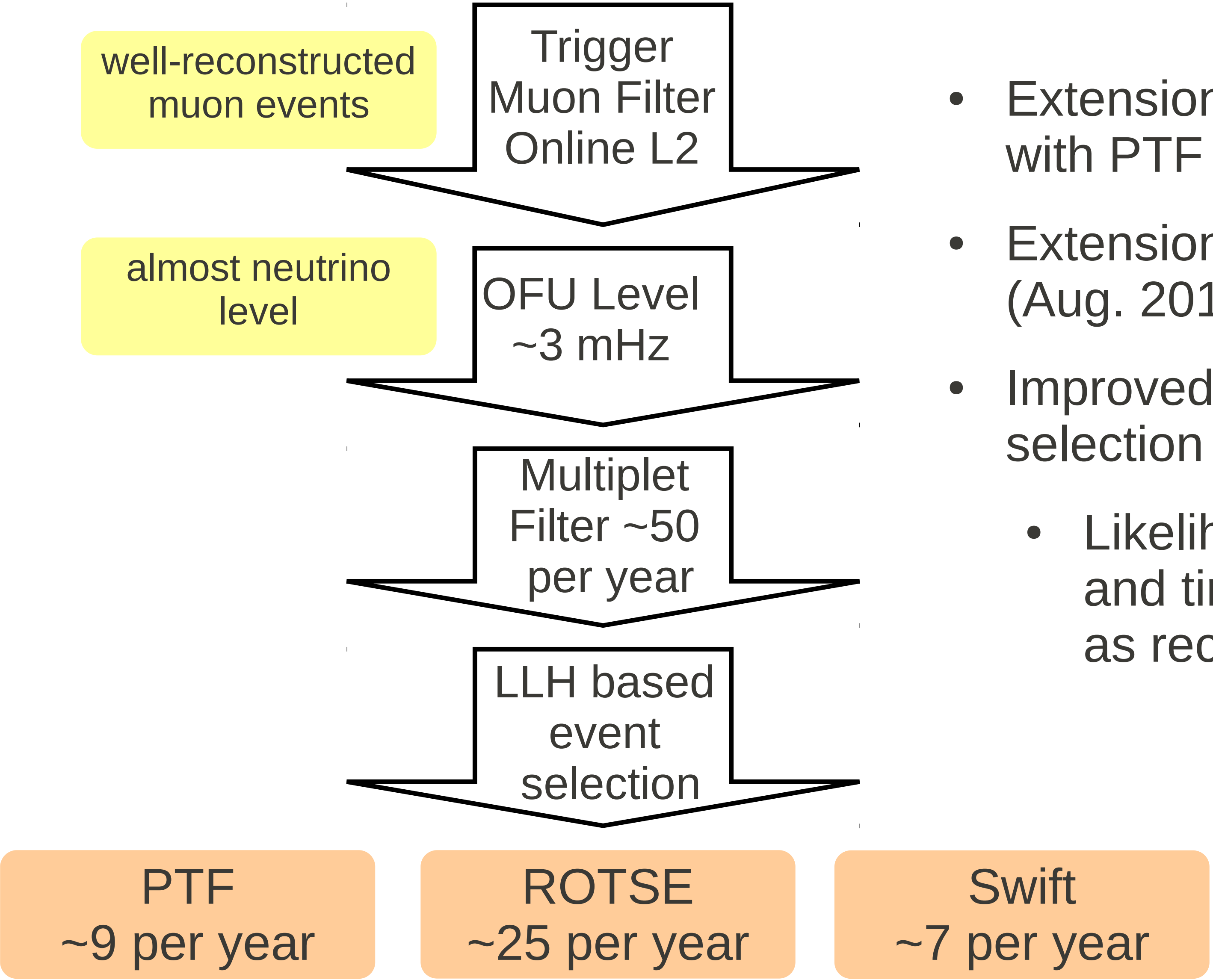
Model Parameters:

- Rate of core-collapse SN with jets, ρ
- Jet energy E_{jet}
- Lorentz boost factor, Γ



A sub-population of SN with typical values Γ = 10 and of E_{jet} = 3×10^{51}erg does not exceed 4.2% (submitted to A&A)

Extension



- Extension of optical follow up with PTF (Feb. 2011)
- Extension to X-rays with Swift (Aug. 2011)
- Improved neutrino event selection with test statistic
  - Likelihood based on angular and time difference as well as reconstruction quality

Summary

- Optical follow-up running
  - with ROTSE since Oct. 2008
  - with PTF since Aug. 2011
  - with Swift since Feb. 2011
- Results of first year ready to publish
- IC59, IC79 soon to follow

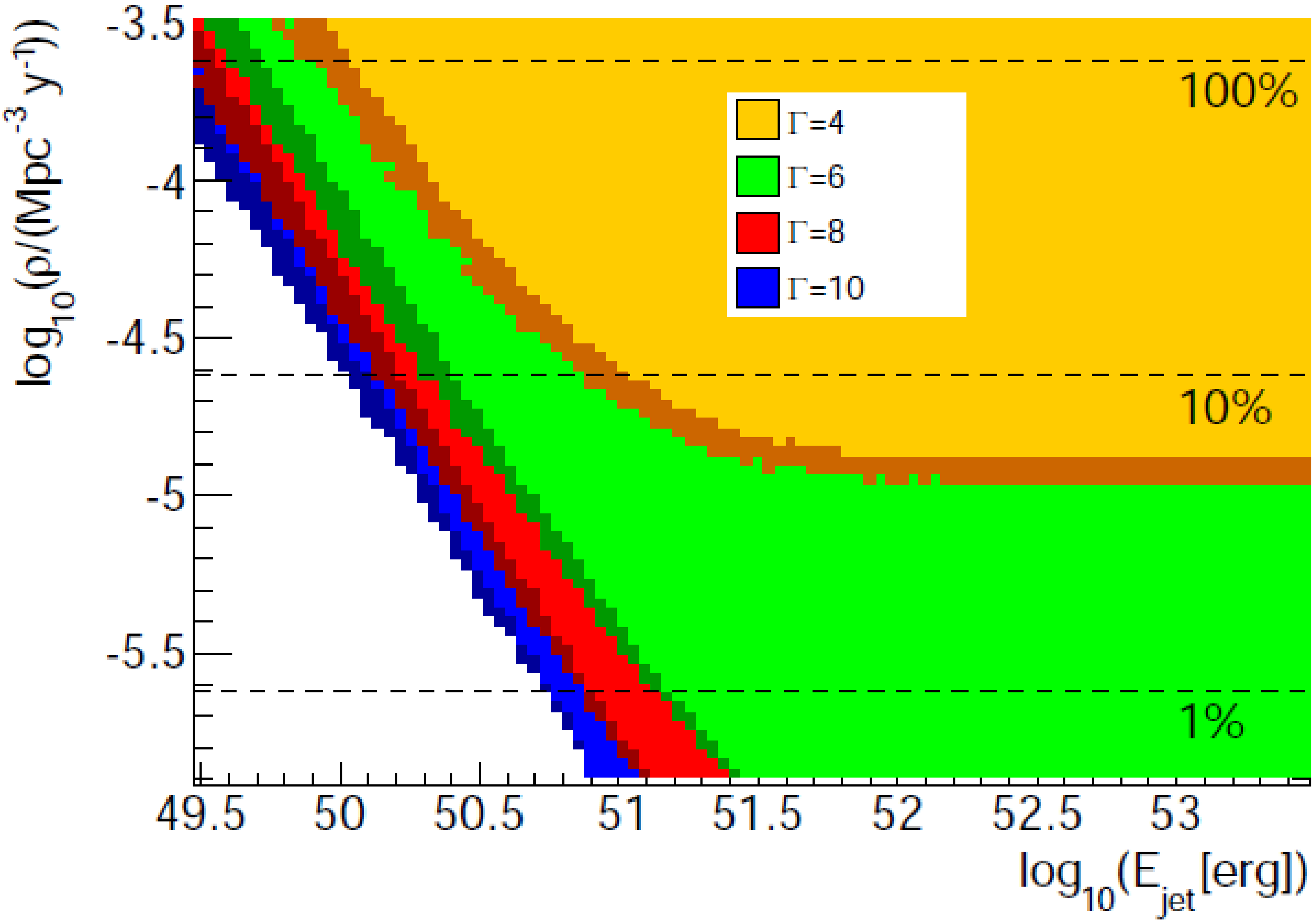
Back-Up

Future Limit (10 years)

10 years of IC86

Assuming measurement matches prediction

Assuming a telescope capable of detecting SN with peak magnitude 20.5



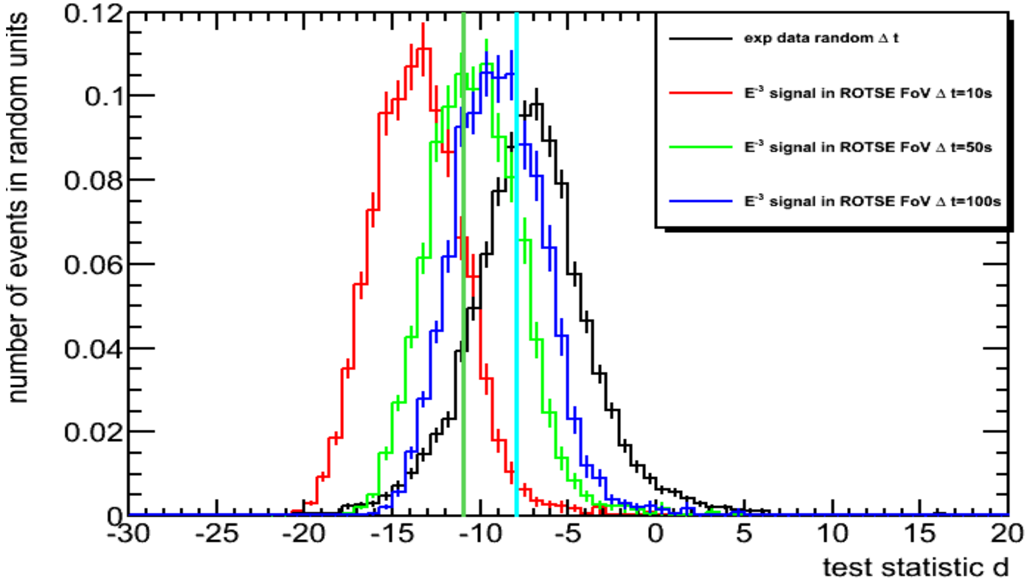
Test Statistic

Improved neutrino event selection with test statistic

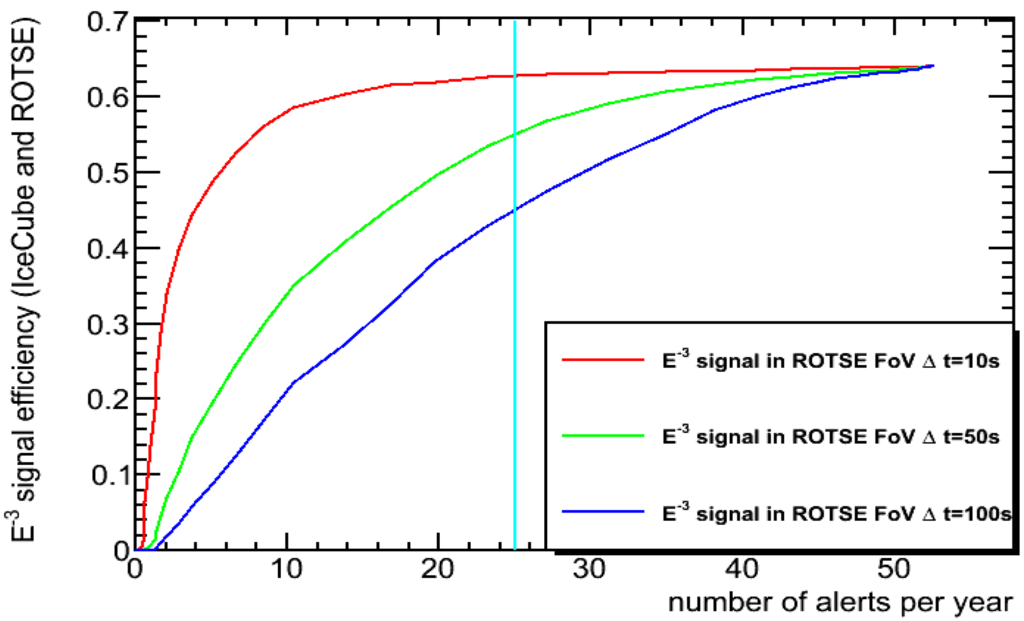
$$\ln L = \frac{\Psi^2}{\sigma_q^2} + 2\ln\left(2\pi\sigma_q^2\right) - 2\ln\left|1 - e^{\frac{-\Theta_A^2}{2\sigma_w^2}}\right| + 2\ln\left(\frac{\Delta T}{100\,s}\right) + const$$

Favors events with small angular difference Ψ. Controlled by recons-truction quality σ	Punishment for badly reconstructed events	Favors doublets that lie within the FoV Θ_A of ROTSE/Swift	Favors neutrino pairs within a small time window

Likelihood



ROTSE



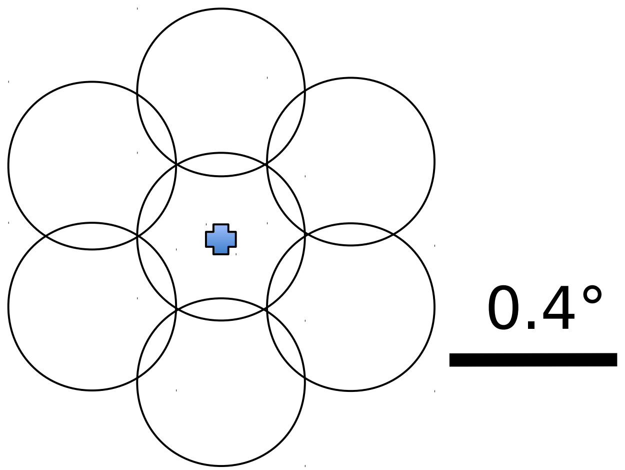
- LLH based on angular and time difference between events and on reconstruction quality
- Selects most signal like doublets
- Energy soon to be included

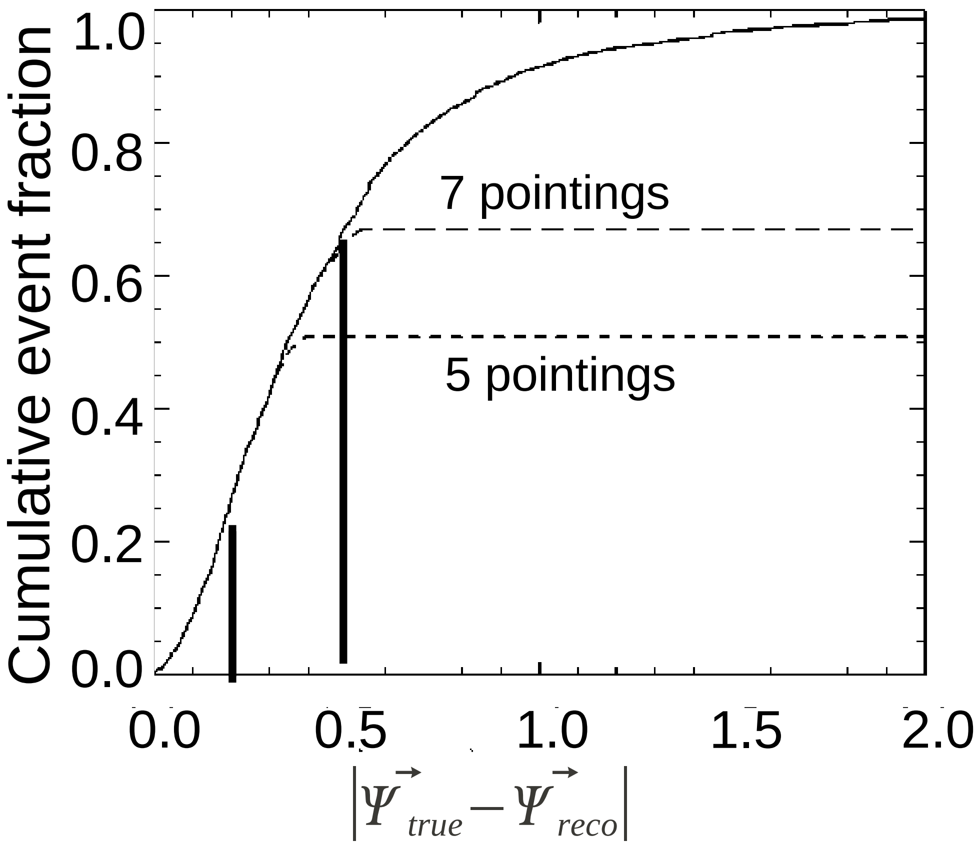
Rough comparison to version without LLH

$$P_{tot} = P^2_{singlet} \cdot P_{FoV} \cdot P_{LLH}$$

	$P_{Singlet}$	P_{FoV}	P_{LLH}	P_{tot}	Gain [%]
2 mHz	0.6	0.64	1	0.23	
100 s	0.7	0.64	0.7	0.22	- 4
50 s	0.7	0.64	0.86	0.27	17
10 s	0.7	0.64	0.97	0.3	30

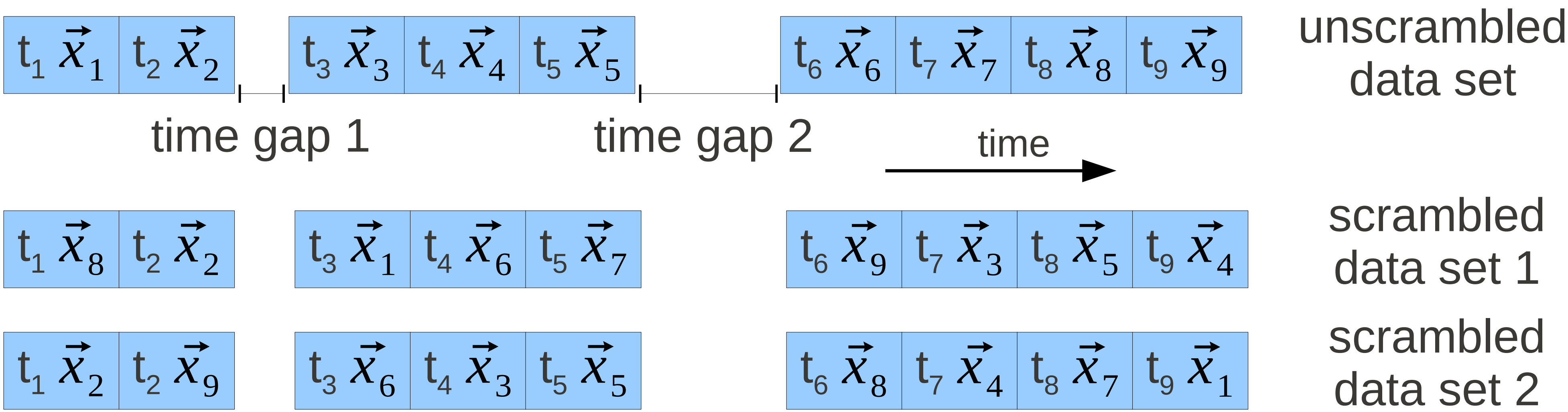
Swift





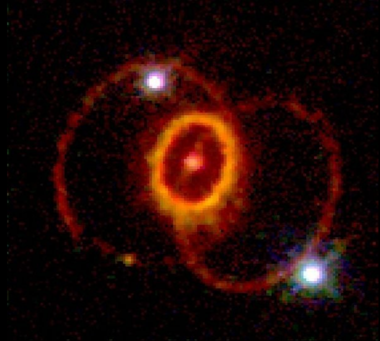
- Tiling needed due to small FoV of Swift
- Currently: One field per orbit
- Plan: 7 fields per orbit
- Swift team is debugging code: test should be one of these days

BG Estimation by Scrambling



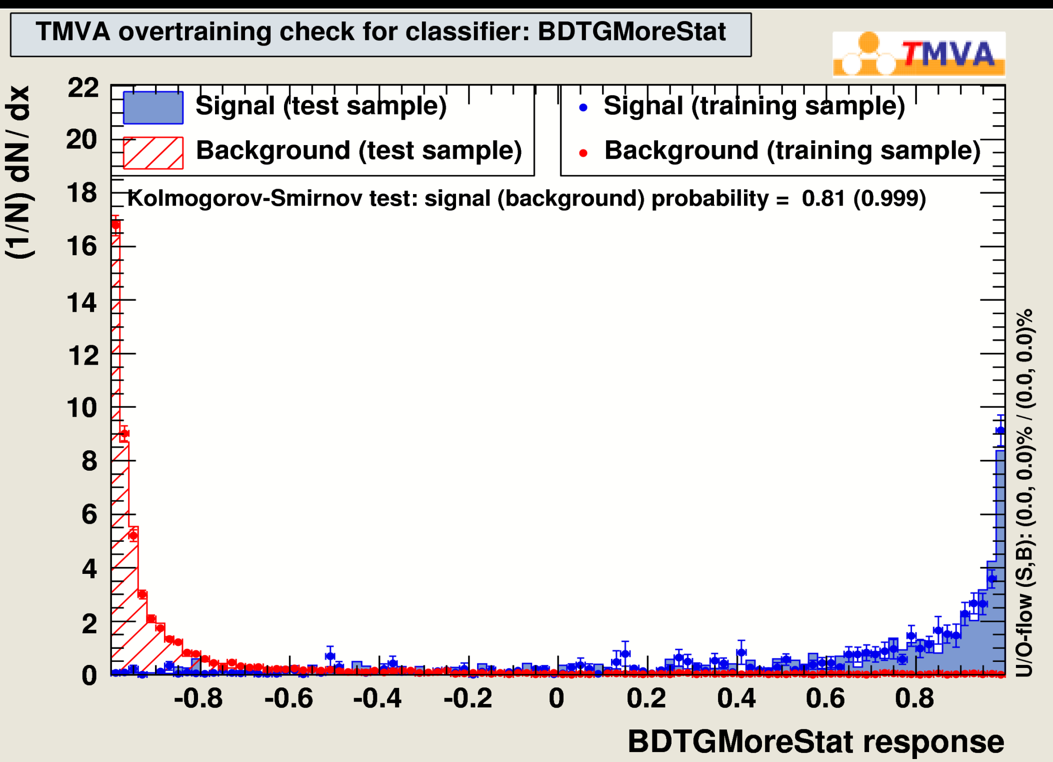
Exclude all bad runs

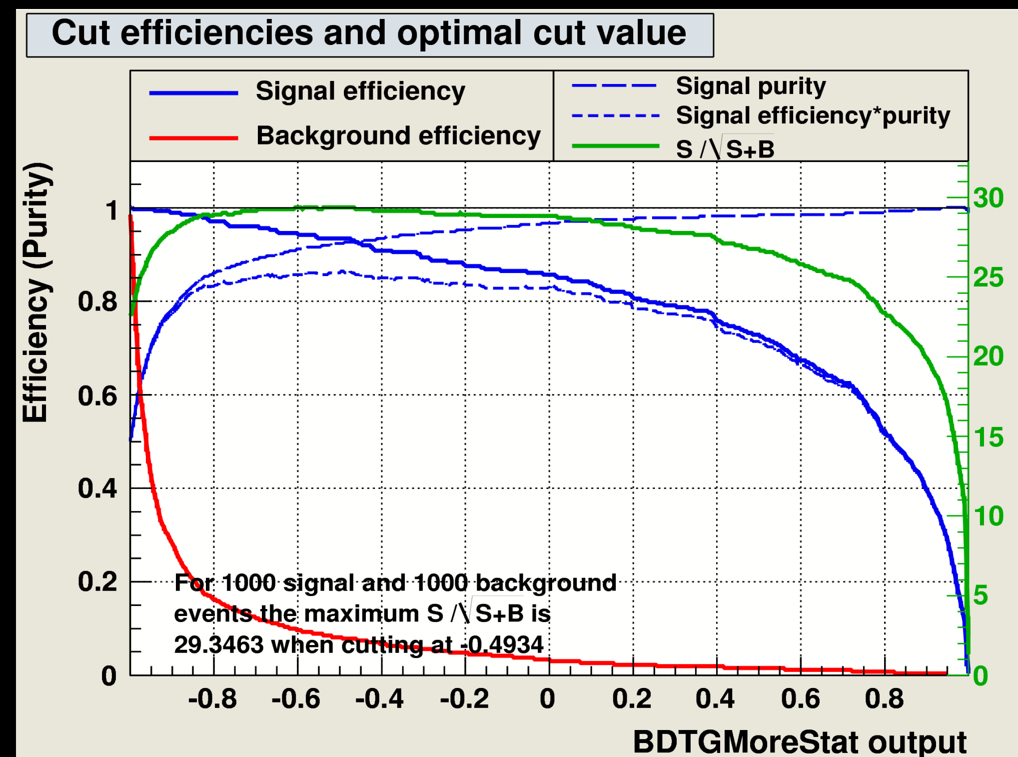
Calculate angular difference between two events using detector coordinates



Train BDT

Use signal over noise and geometric parameters (e.g. ellipticity) to train BDT





Remove candidates with BDT value < -0.5

Number of bad candidates decreases a lot, but still some left to be scanned by eye