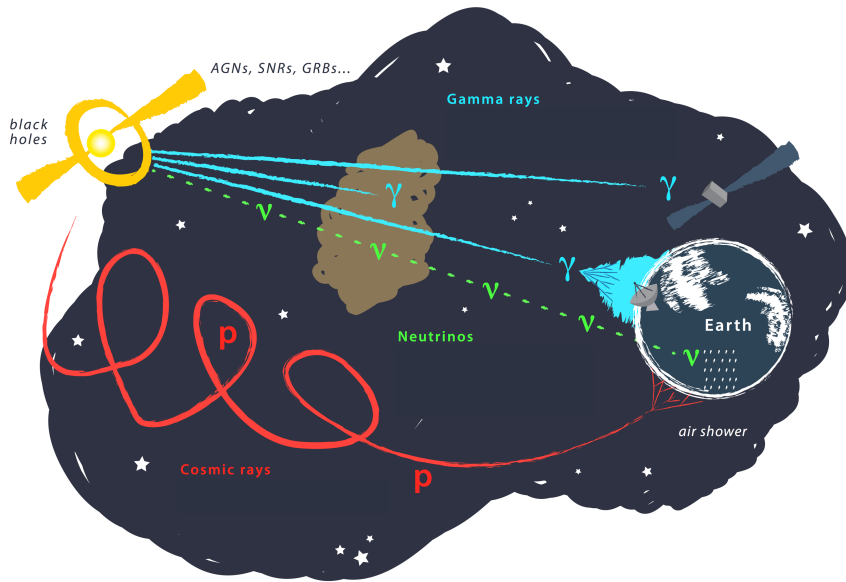


# Searching for Optical Counterparts to High-Energy Neutrino Sources with the Zwicky Transient Facility



Ludwig Rauch  
VLVnT 2018  
Dubna, 03.09.2018

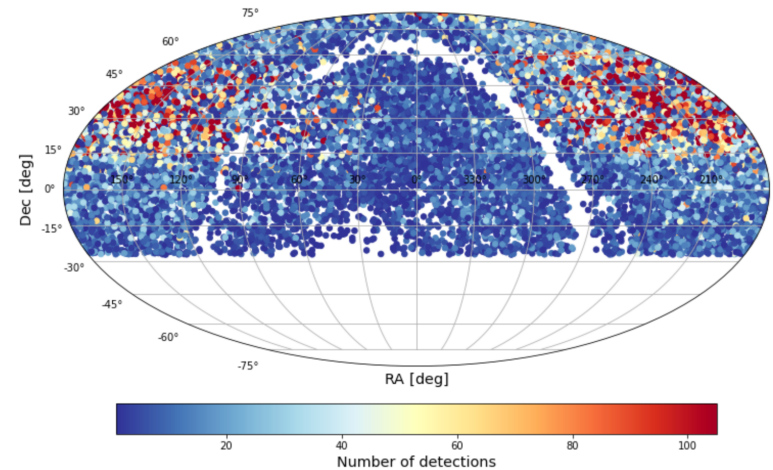
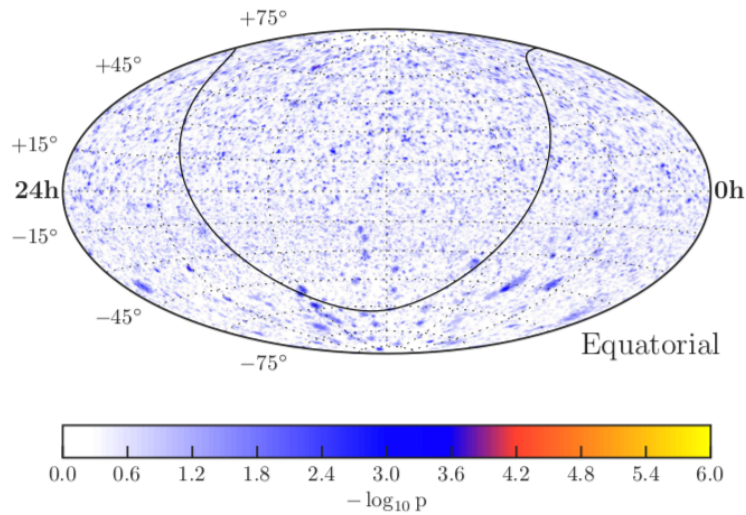
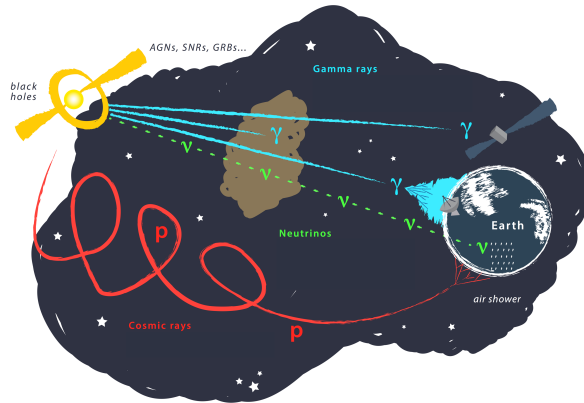
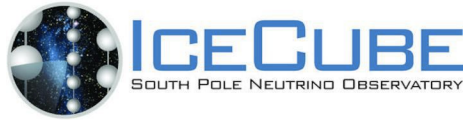
HELMHOLTZ  
Young Investigators



ICECUBE  
SOUTH POLE NEUTRINO OBSERVATORY



# The Idea in Short

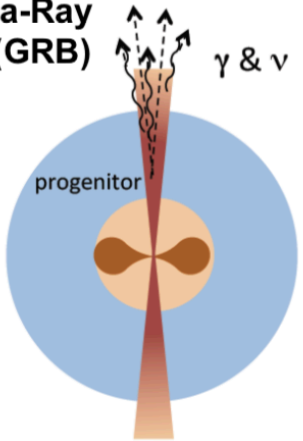


Combine two northern sky surveys in realtime

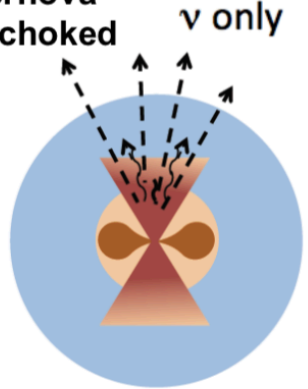


# Neutrino Source Candidates

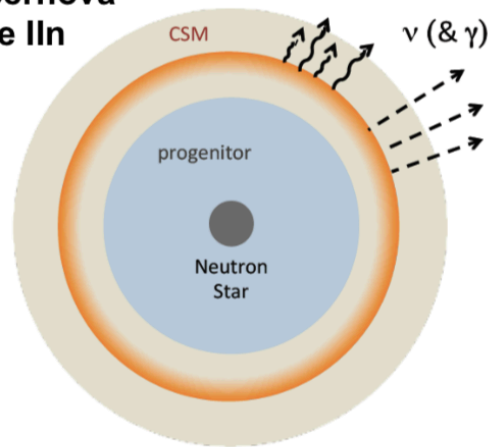
**Gamma-Ray Burst (GRB)**



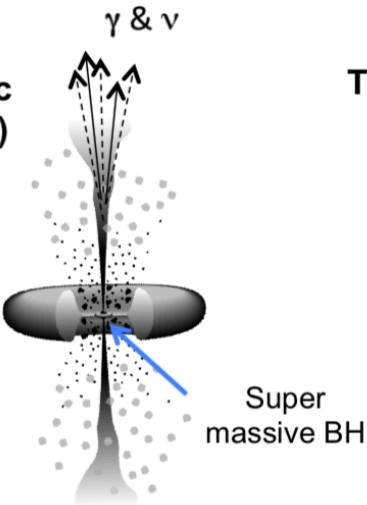
**Supernova with choked jets**



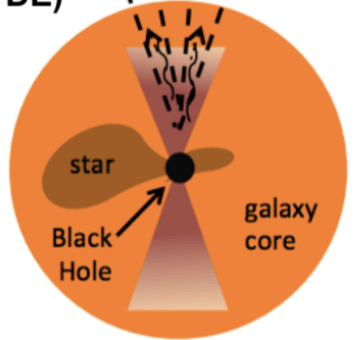
**Supernova Type II<sub>n</sub>**



**Active Galactic Nucleus (AGN)**

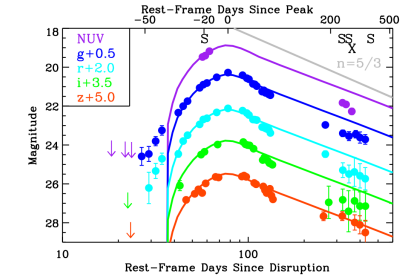
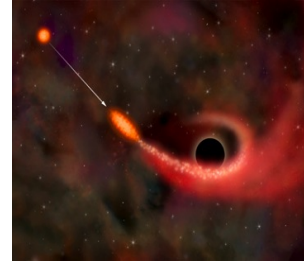


**Tidal Disruption event (TDE)**

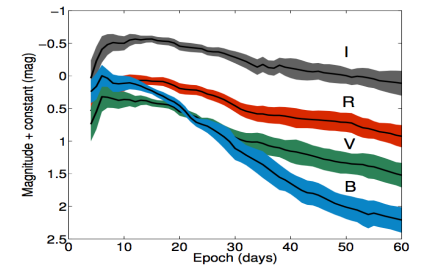


# Expected Time Scales of Transients

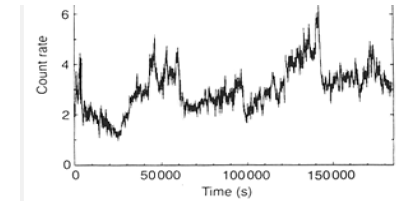
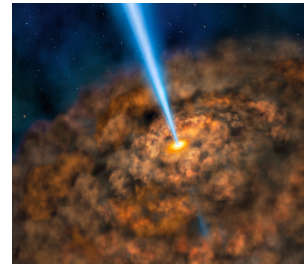
**Tidal disruption events** ~1d - 100d



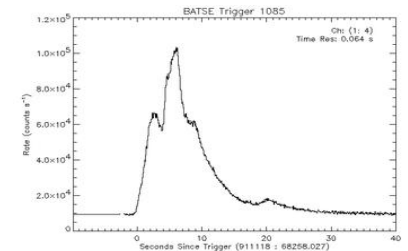
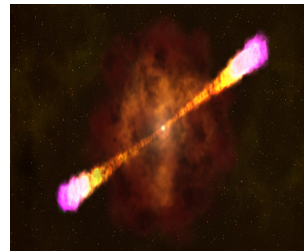
**Supernovae** ~100d



**Active galactic nuclei** ~1h - 10d

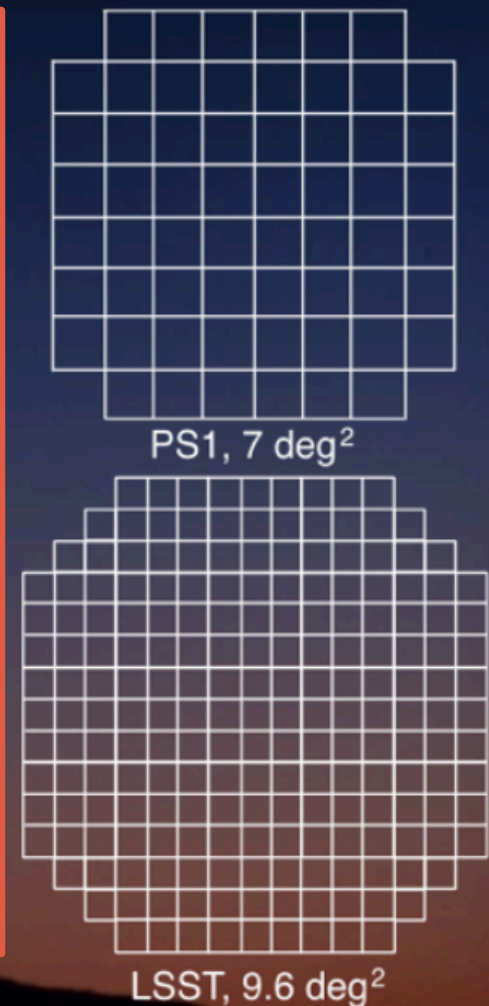


**Gamma ray bursts** ~10s - 100s



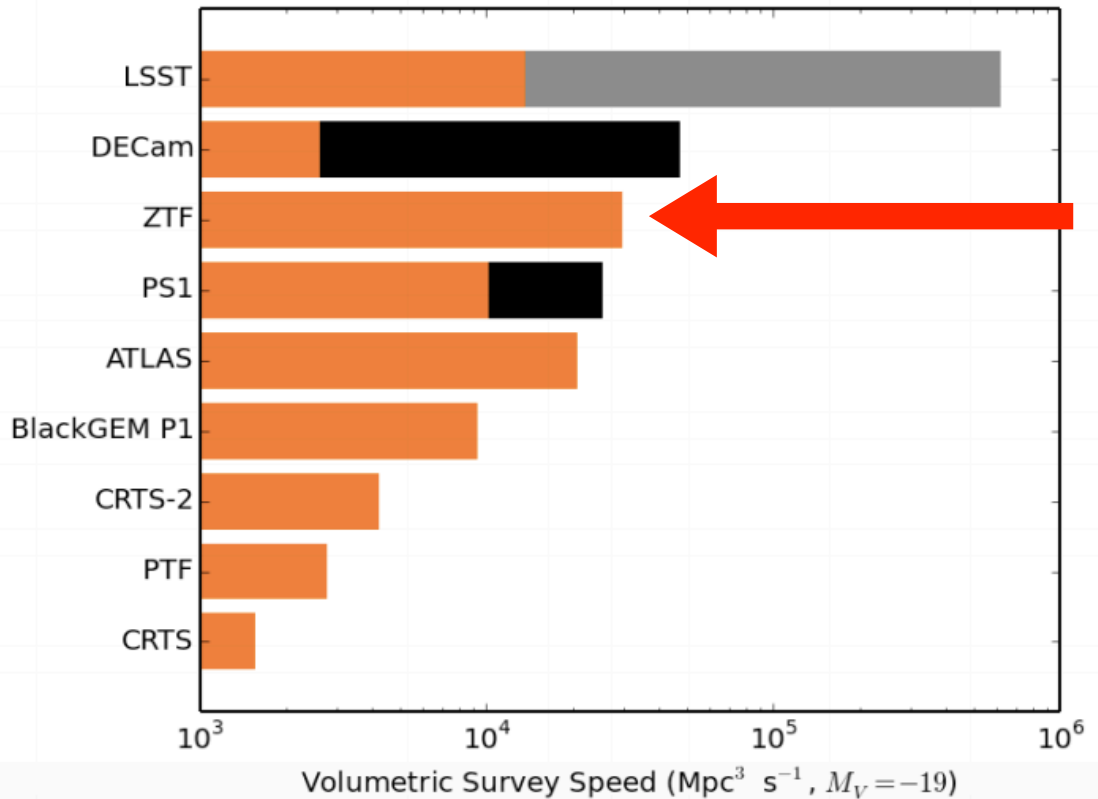
# Current / Future Optical Surveys

**ZTF can scan the entire Northern sky every night to 20.5 mag**



1 deg

# ZTF Spectroscopically-Accessible Transients



ZTF provides:

- Unprecedented catalogue of transients up to  $\sim 20.5$ mag
- Complete set of lightcurves for source identification
- All-sky coverage ( $3\pi$  in 8h)
- Cadence approx. 3 days
- On site spectrograph (SED-machine)
- Additional spectroscopic time available on other telescopes

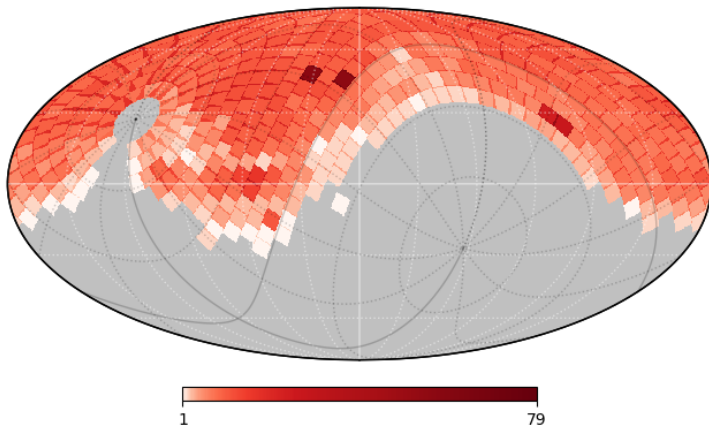
 Spectroscopically-accessible

# ZTF Survey Plan

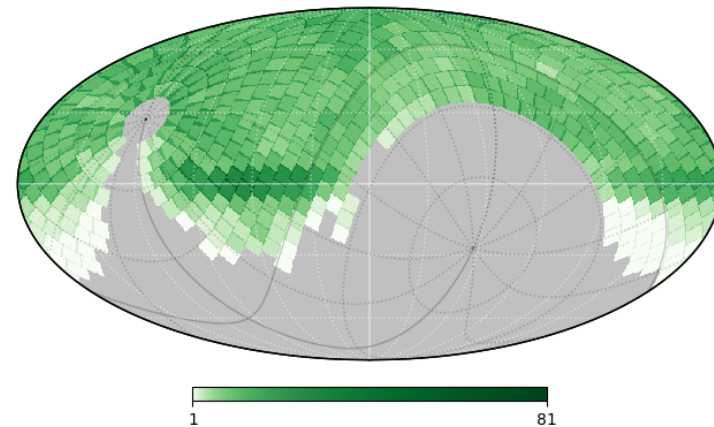
ZTF time shared between:

- Public survey (MSIP) 40 %: g & r band, all Northern sky every 3 days, sweep of Galactic plane
- Partnership 40% (first year) high-cadence observations of 1/10 of the Northern extragalactic sky, 5-6 visits/night + I-band survey with 4-day cadence of 0.5 sky
- Caltech private time 20%

ZTF: r-filter



ZTF: g-filter

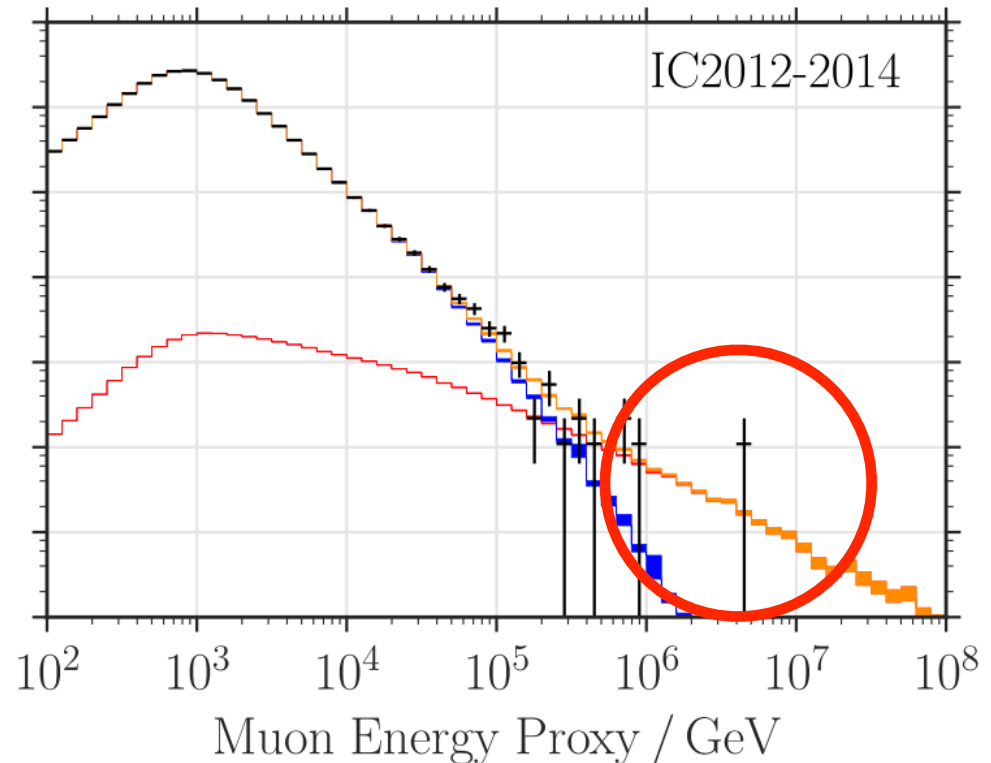




# Optical Follow-Up Program of High-Energy Neutrinos

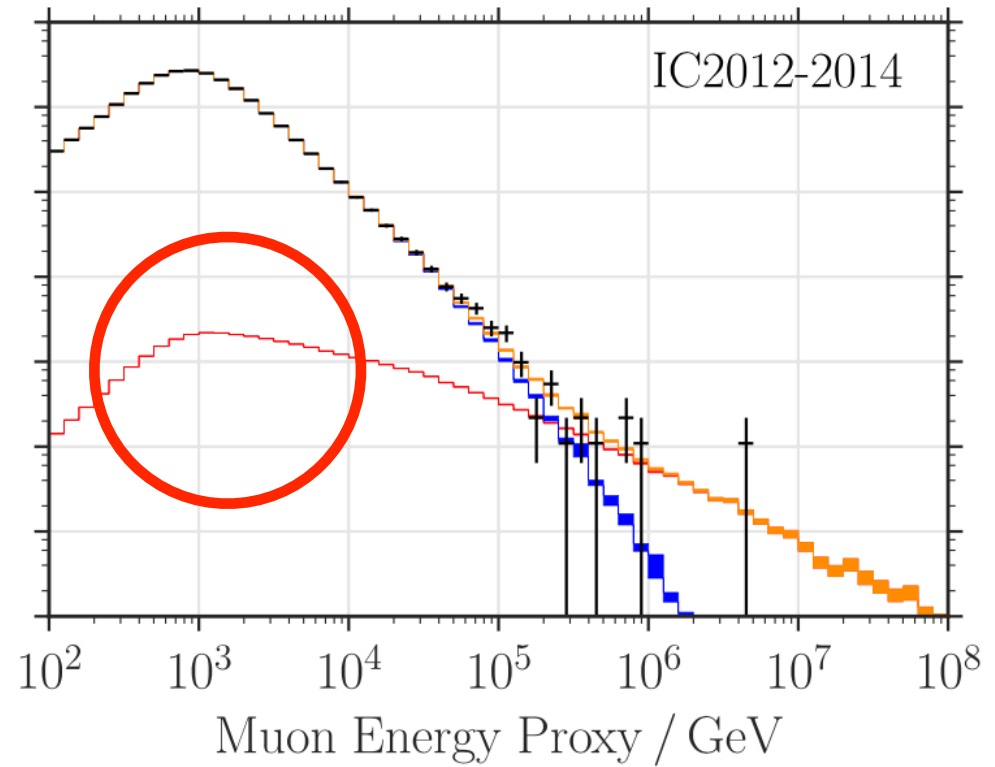
## Target of Opportunity

- Follow-up of high-energy neutrinos (TeV, PeV) for early time information of transient
- Track events: ( $\sim 1$  deg,  $\sim 10$ /year)
  - ~1 pointing of ZTF covers the neutrino error circle
- Public high-cadence data increases information about the late-time evolution of the lightcurve
- Spectroscopic typing of all selected transients possible





# Search for Low-Energy Neutrino Sources ?

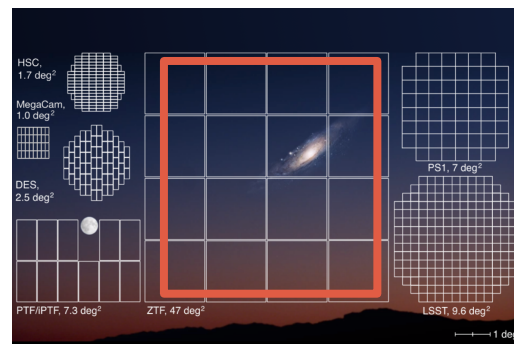


# Real-time Neutrino Correlation with IceCube

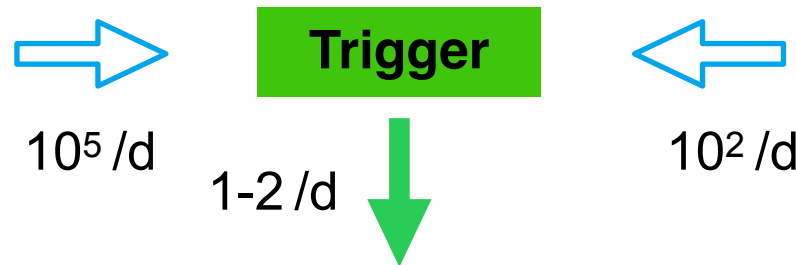
## Alert Management, Photometry and Evaluation of Lightcurves: AMPEL



Transient positions from ZTF



Novel realtime alert management and trigger software



Neutrino tracks from IceCube

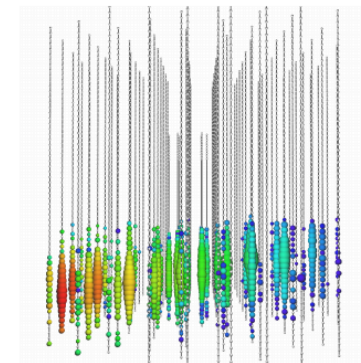
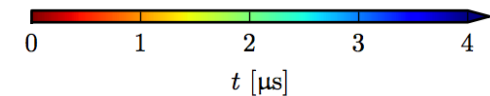
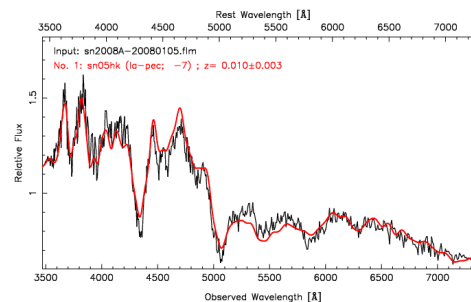


Illustration: Transient Spectrum



# Real-time Neutrino Correlation: Primary Transient Selection

## Short transients (GRB-like)

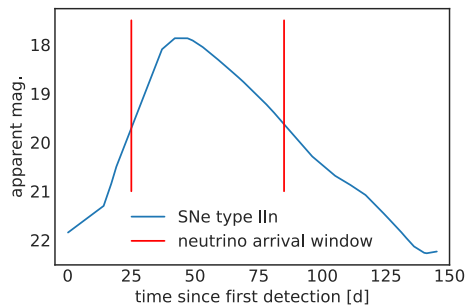
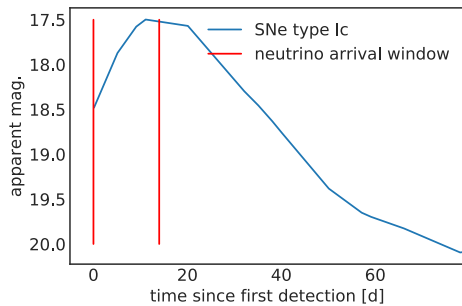
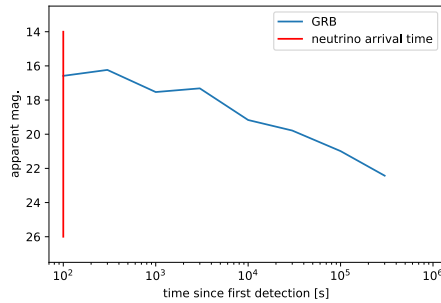
- More than 2 detections in  $< 12\text{h}$
- Falling lightcurve
- Realtime maximum likelihood calculation of test statistic

## Medium length transients (SN Ic, Kilonova)

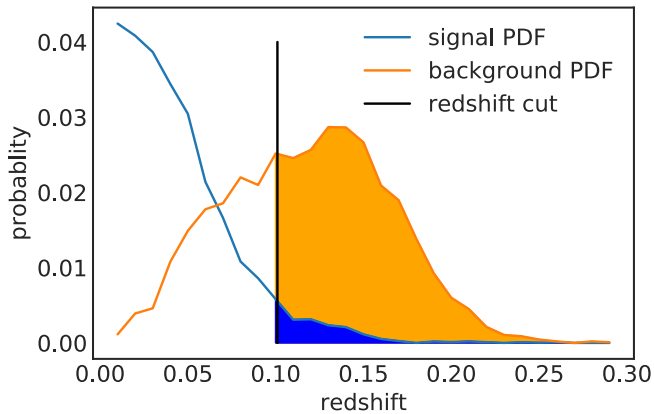
- Time window of 2 weeks
- More than 3 optical detections

## Long transients (SN IIn, SLSN, TDE, AGN)

- Time window of 8 weeks
- More than 5 optical detections



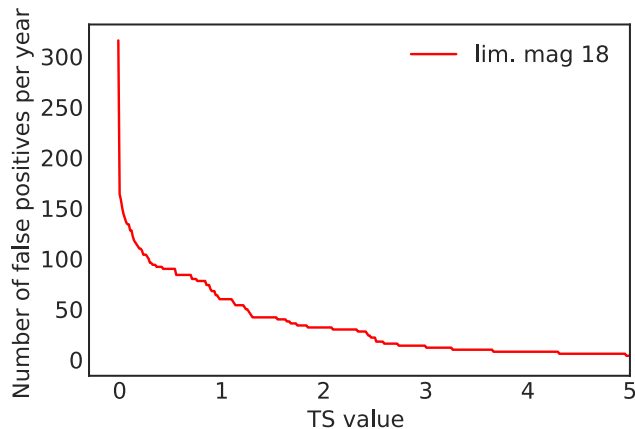
# Real-time Neutrino Correlation: Search for Counterparts



## Background discrimination:

- Trained neural network estimates redshift of host galaxy
- Neutrino counterparts (signal) show generally smaller redshifts

→ **Enables rejection of transients showing no significant neutrino emission (background)**



## Spectroscopic follow-up

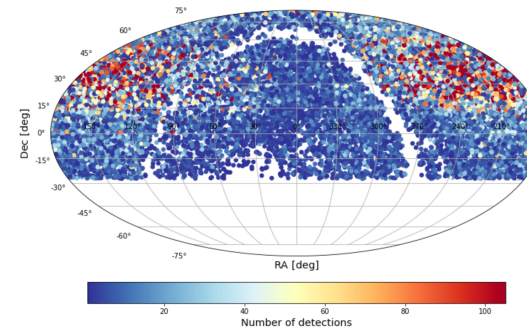
- Real-time maximum likelihood calculation
- Statistical excess between neutrino and optical counterpart will trigger spectroscopic follow-up
- Optimised on false positive rate of < 100 triggered spectra per year.

# Real-time Neutrino Correlation: Goal

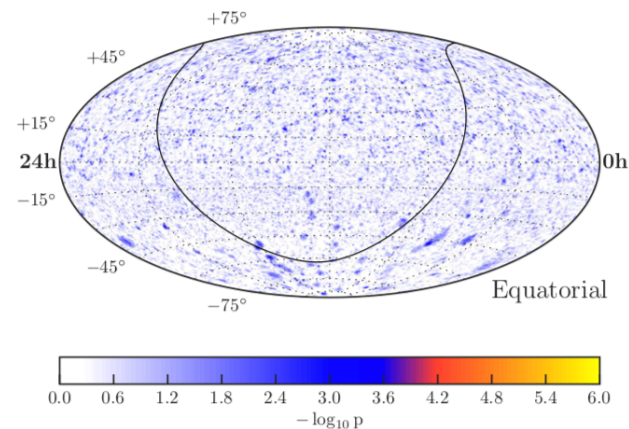
## Offline Stacking Analysis

- ZTF transient catalogue:
  - Complete (magnitude-limited) catalogue
  - Fast-fading transients can be detected
  - Well-sampled lightcurves
  - Spectroscopical classification available
- IceCube neutrino sky map
  - Large statistics of high-energy neutrino events

## ZTF transient catalogue



## IceCube neutrino sky map



# Current Status: Commissioning

## Current status:

- ZTF camera and alert stream online
- Software for online correlation and alert management (AMPEL)
- Spectrograph at Palomar Observatory (SED-m)



## ToO Program:

- ToO: First successful follow-up

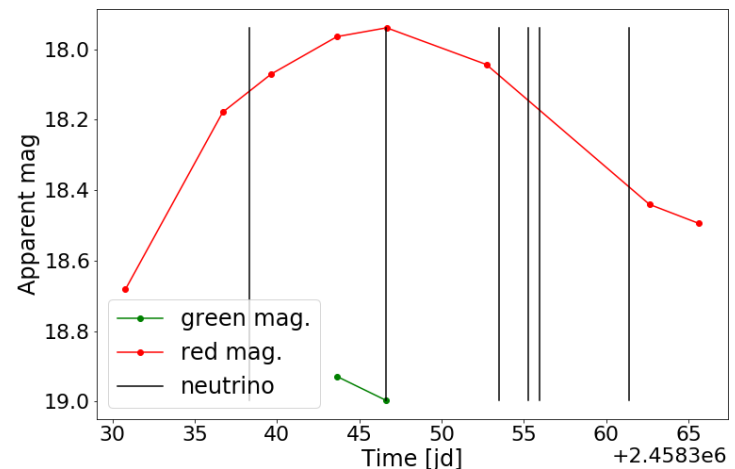
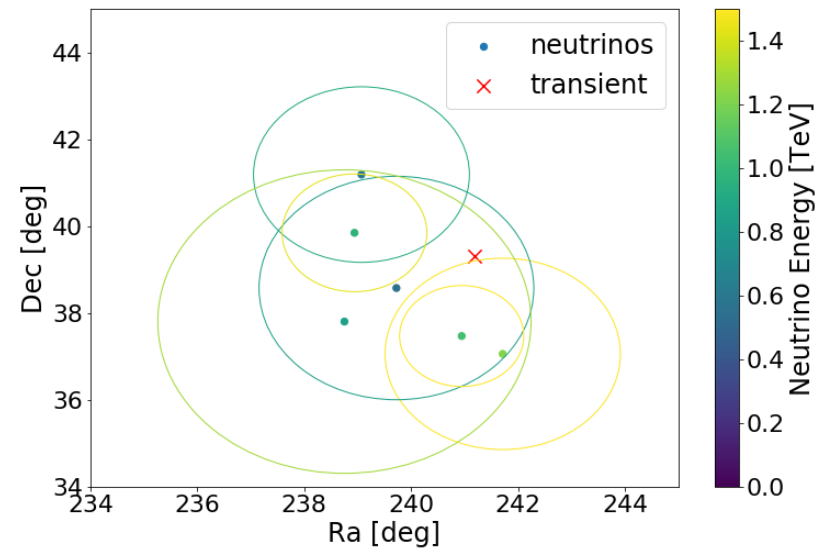


## Real-time neutrino correlation:

- IceCube neutrino stream
- Commissioning: validation of transient selection via maximum likelihood estimation
- Start of neutrino science data acquisition with ZTF



## Illustration: Transient selection via likelihood ratio



# Summary

ZTF transient catalogues and ToO program allows for improved and novel analyses

## Target of Opportunity

- Low rate of high-energy neutrinos
- High cadence of ZTF (3 days) allows to search for fast fading transients
- Spectroscopic classification available
- Large field of view to consider full error circles

## Stacking Analysis

- High rate of low-energy neutrinos
- Complete and magnitude limited transient catalogue