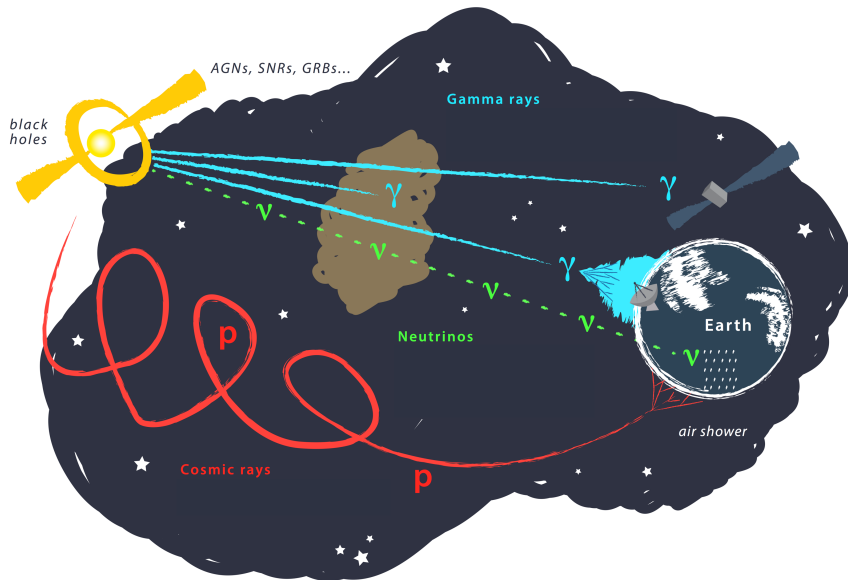


# Multi-Messenger Astronomy in the Era of the Zwicky Transient Facility (ZTF)

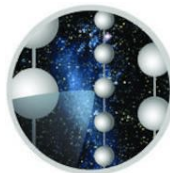


Ludwig Rauch

Monitoring the non-thermal Universe 2018

Cochem, 18.09.2018

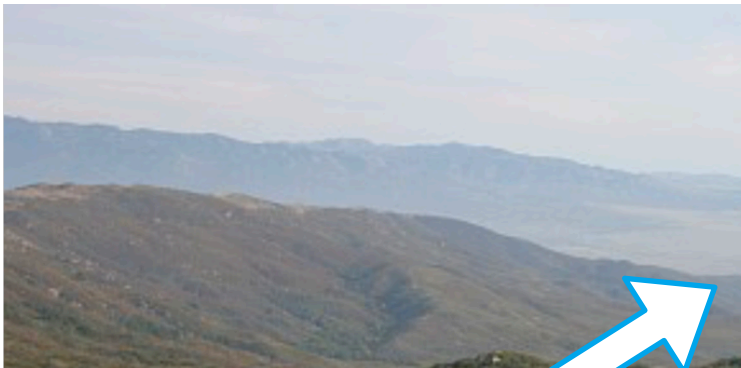
HELMHOLTZ  
Young Investigators



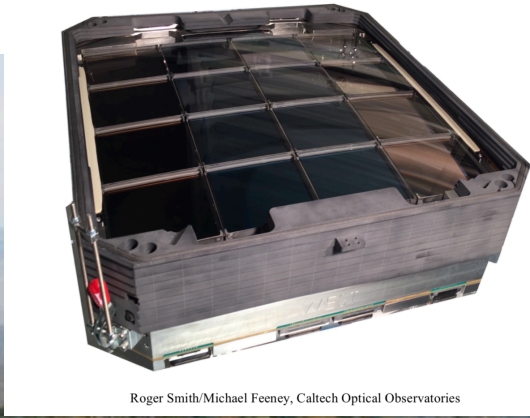
ICECUBE  
SOUTH POLE NEUTRINO OBSERVATORY



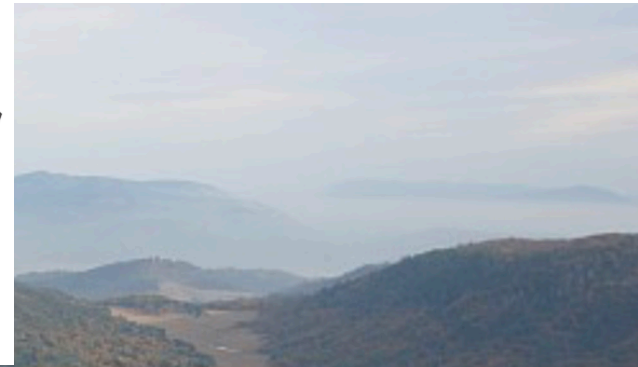
# Zwicky Transient Facility (ZTF)



**P48**  
survey  
telescope



**P200**  
Spectroscopic  
follow-up



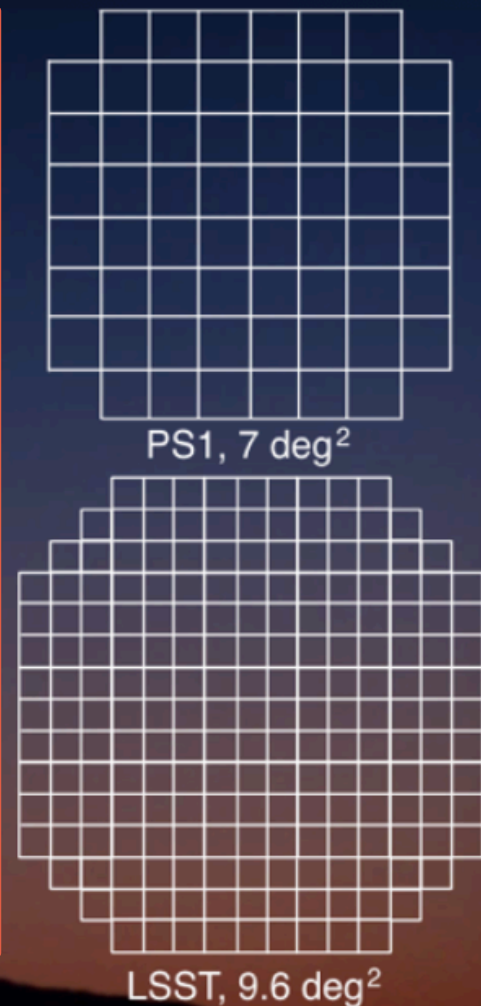
**P60**  
classification

Caltech (PI: Shri Kulkarni)  
University of Maryland  
University of Washington  
University of Wisconsin-Milwaukee  
Los Alamos National Lab

Lawrence Berkeley National Lab  
Oskar Klein Centre, Stockholm  
Humboldt-University Berlin/DESY  
Weizmann Institute, Israel  
TANGO Consortium, Taiwan

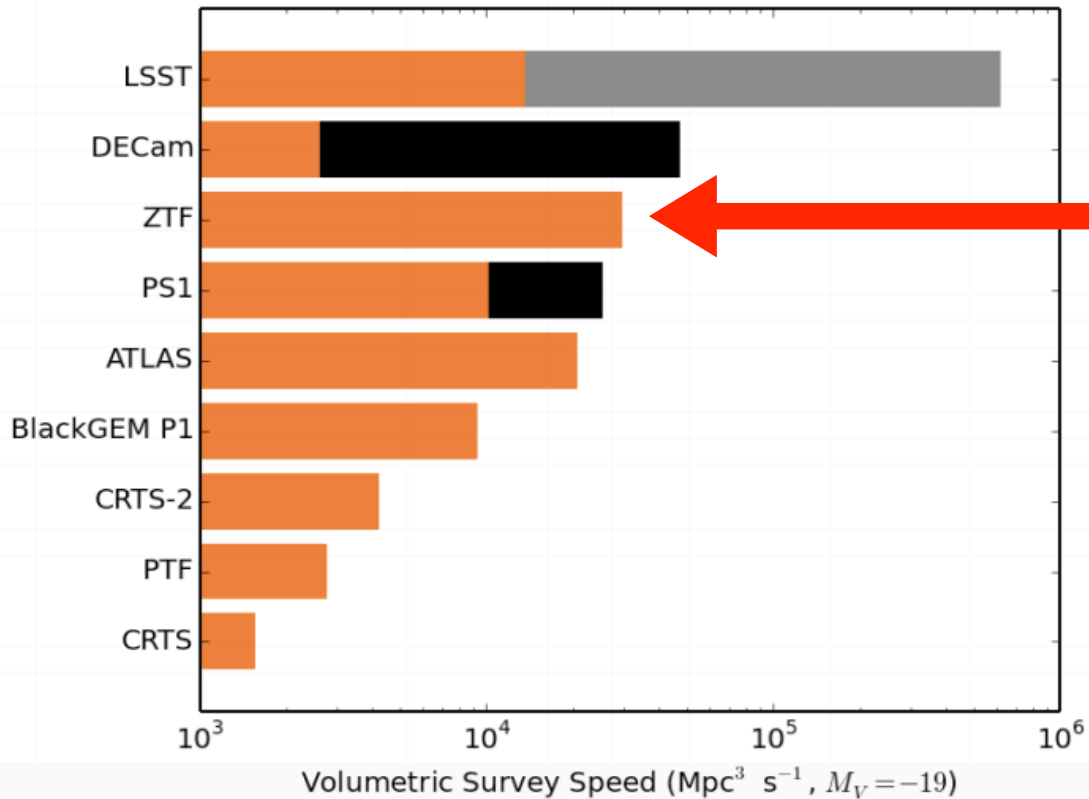
# Current / Future Optical Surveys

**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 ~20.5mag
- Complete set of lightcurves for source identification
- All-sky coverage ( $3\pi$  in 8h)
- Cadence approx. 3 days
- On site spectrograph (SED-machine)

 Spectroscopically-accessible



# ZTF Science Working Groups

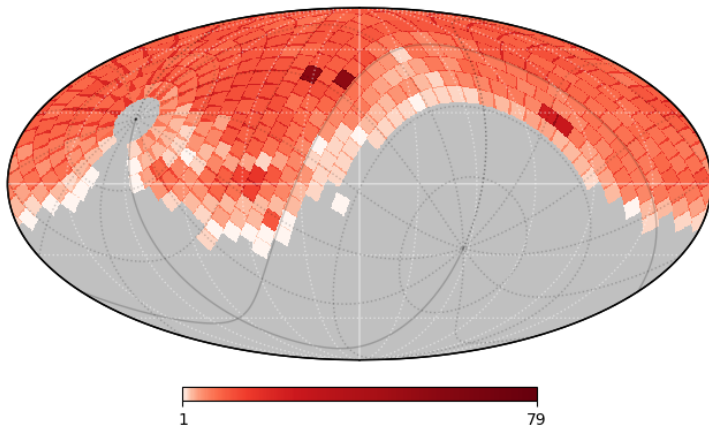
- Multi-messenger astronomy: Electromagnetic counterparts of gravitational waves, gamma rays and neutrino sources
- Active galactic nuclei & tidal disruption events
- Cosmology with supernovae and gravitational lensing
- Physics of supernovae and relativistic explosions
- Solar system bodies
- Stellar science
- .....

# ZTF Survey Plan

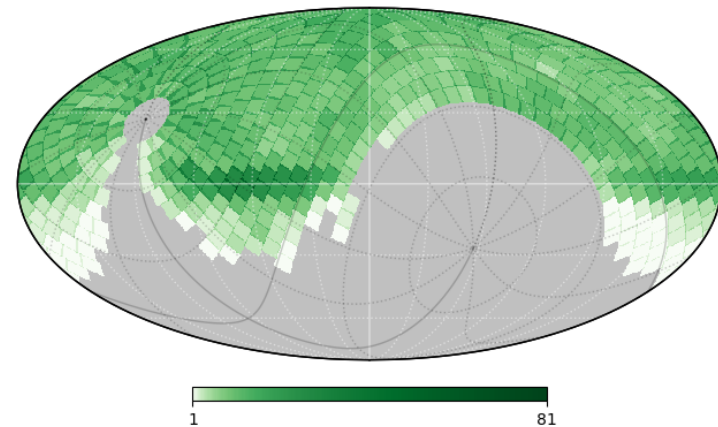
ZTF time shared between:

- 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: red filter



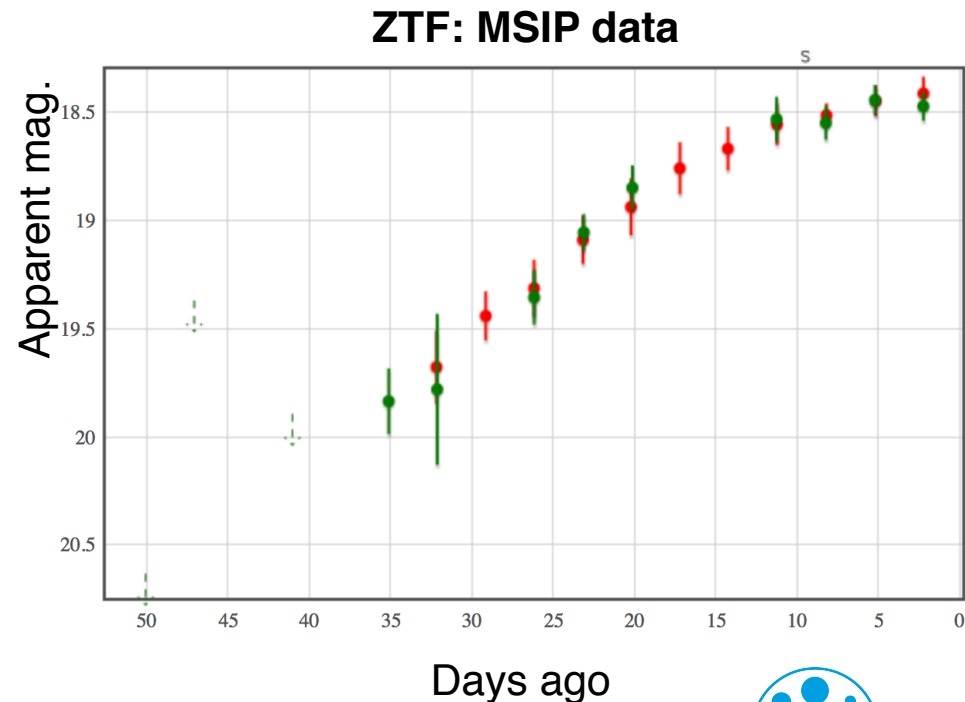
ZTF: green filter



# ZTF Example Lightcurve

- Large field-of-view is optimal for target-of-opportunity programs if localisation is challenging (e.g. gravitational waves)
- In addition: short overhead and exposure times optimal for high cadence observations
- Well sampled light curves in two bands (green, red)

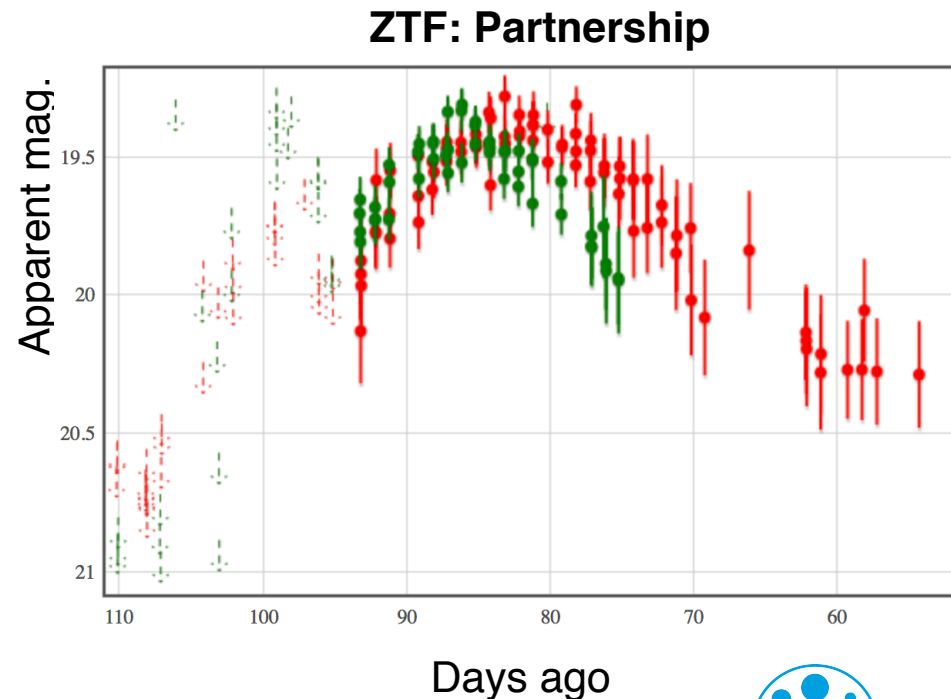
	PTF	ZTF
Active Area	7.26 deg <sup>2</sup>	47 deg <sup>2</sup>
Overhead Time	46 s	< 15 s
Optimal Exposure	60 s	30 s



# ZTF Example Lightcurve

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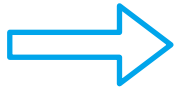
	PTF	ZTF
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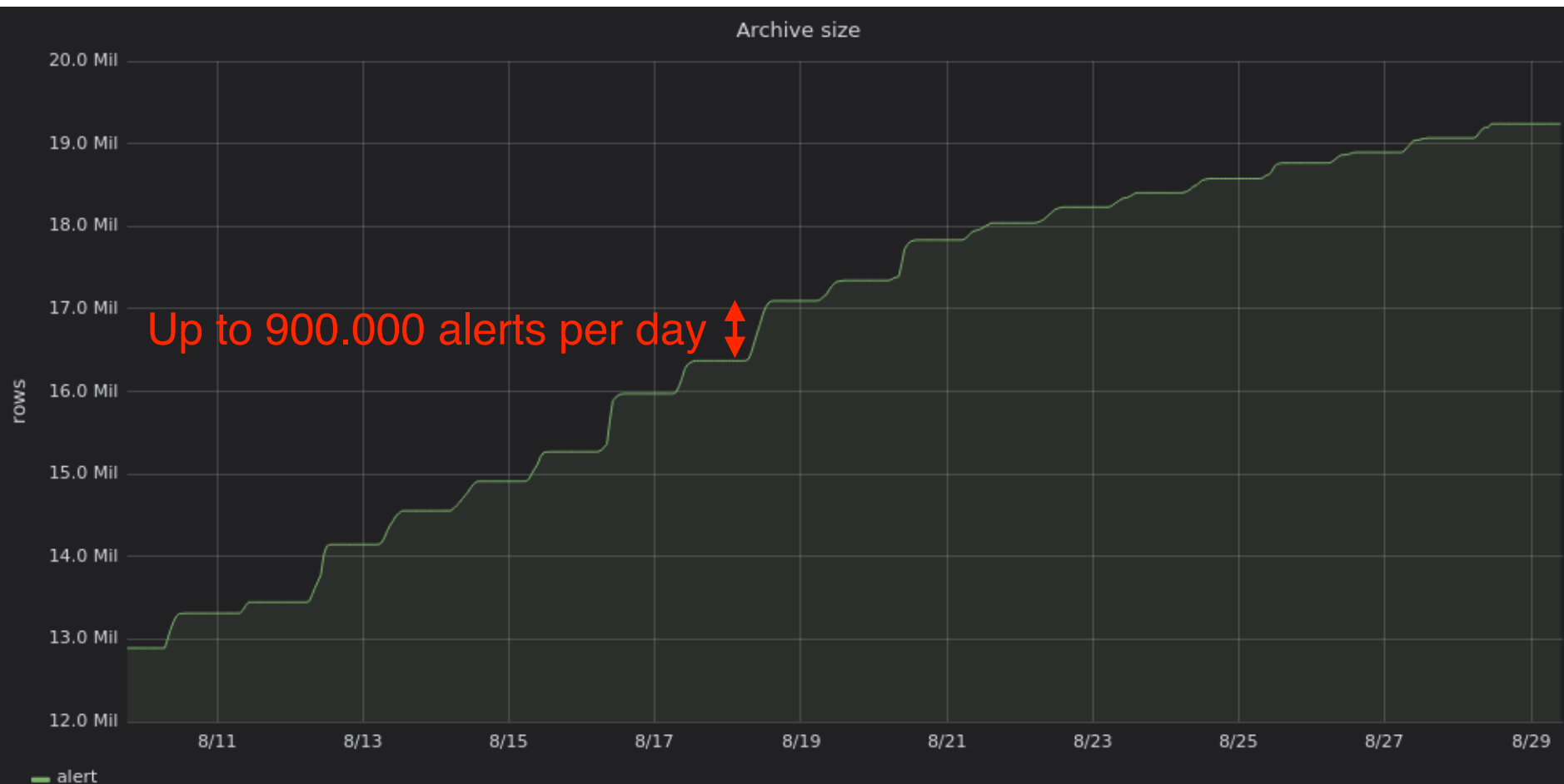


# ZTF Alert Stream

ZTF generates a stream of up to 900.000 alerts per day



Dedicates software necessary to analyse data

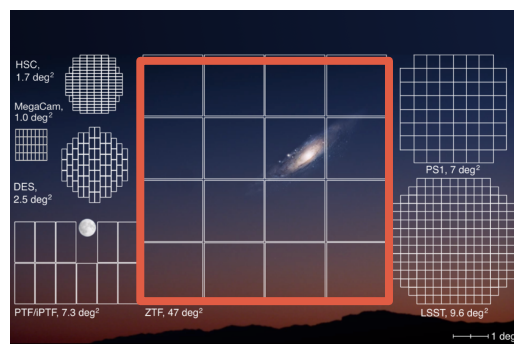


# Dedicated software development

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

- Software developed at DESY and HU-Berlin
- Real-time alert management of multiple alert streams
- Filtering of objects for dedicated science channel
- Real-time catalogue matching for selection/rejection
- Photometric redshift estimates, maximum likelihood matching, photometric typing, ...

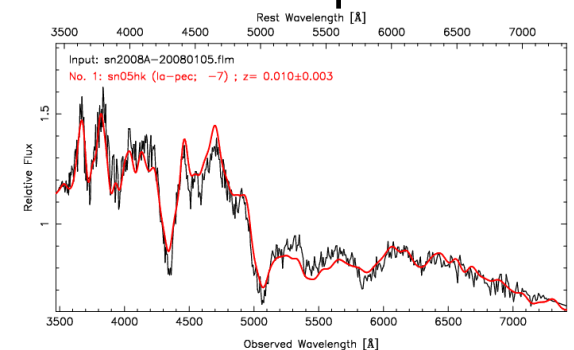
### Photometry from ZTF



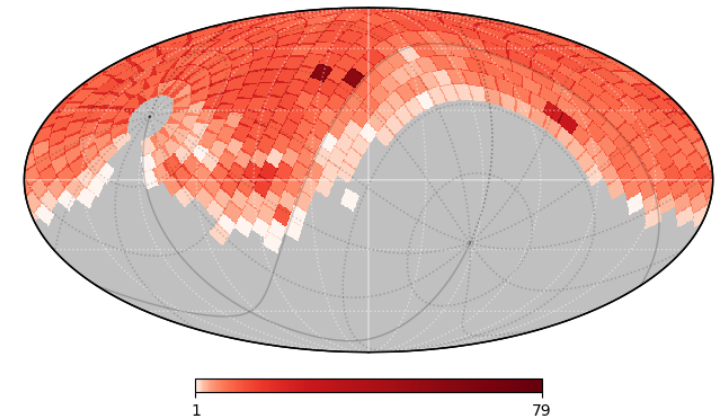
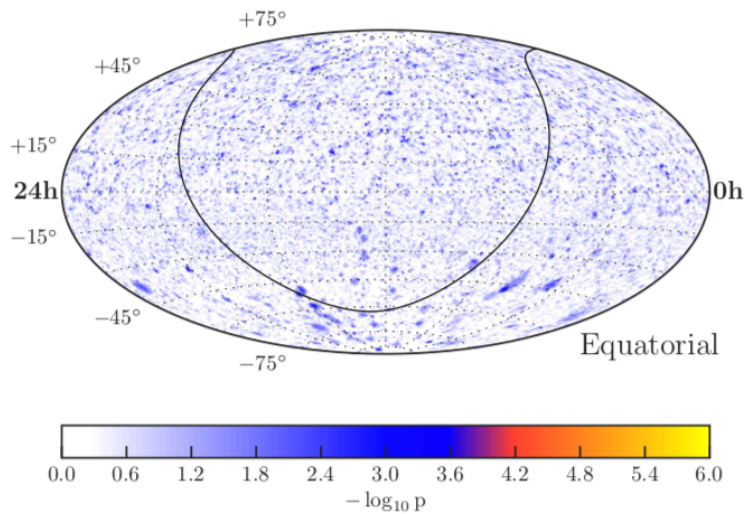
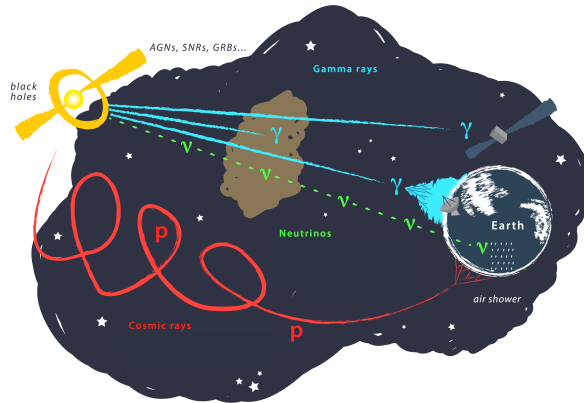
$10^5 / d$

$1-2 / d$

### Illustration: Transient Spectrum



# Example: Neutrino Astronomy with ZTF



Combine two northern sky surveys in real-time



# Real-time Neutrino Correlation with IceCube

Transient positions from ZTF

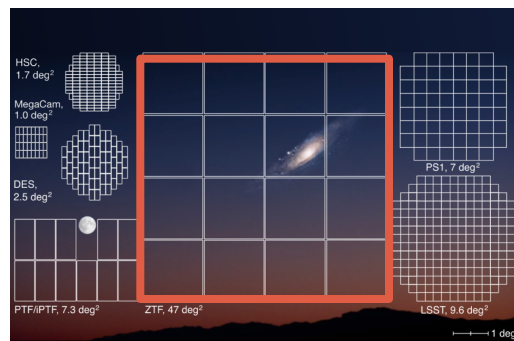
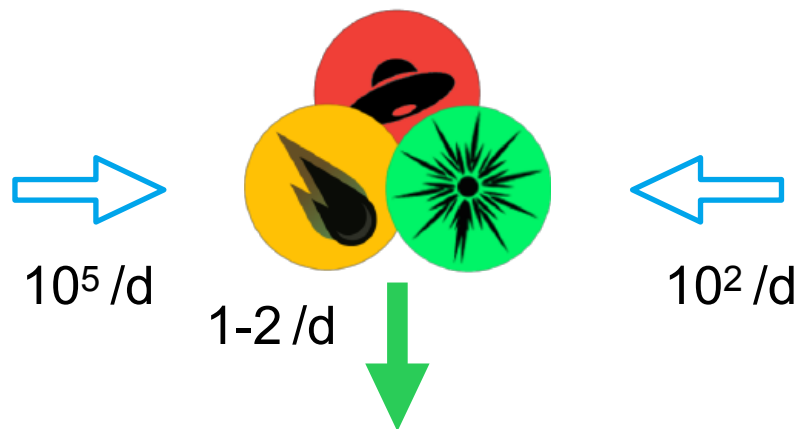


Illustration:  
Transient Spectrum

## AMPEL

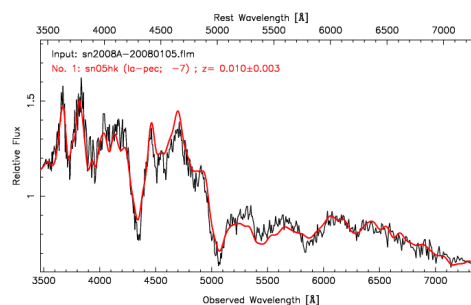
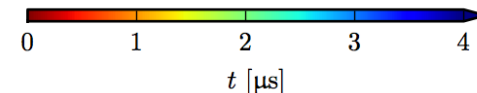
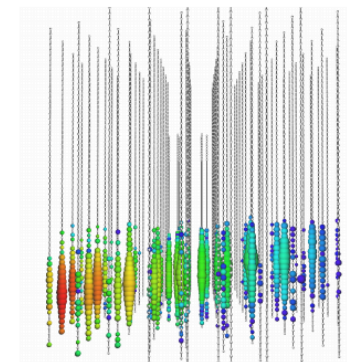


$10^5 / d$

$1-2 / d$

$10^2 / d$

Neutrino tracks from IceCube



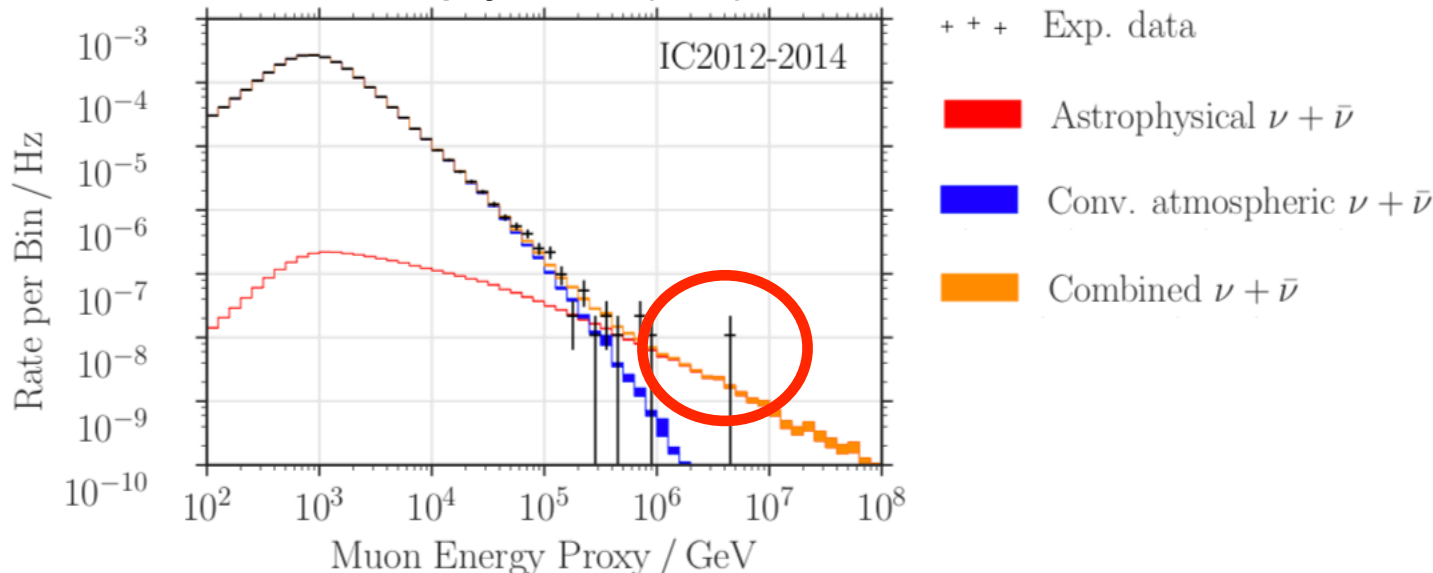


# Optical Follow-Up Program of High-Energy Neutrinos

## 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)
  - $\sim 1$  pointing of ZTF covers the neutrino error circle

Astrophys.J. 833 (2016) no.1, 3



# Optical Follow-Up Program of High-Energy Neutrinos

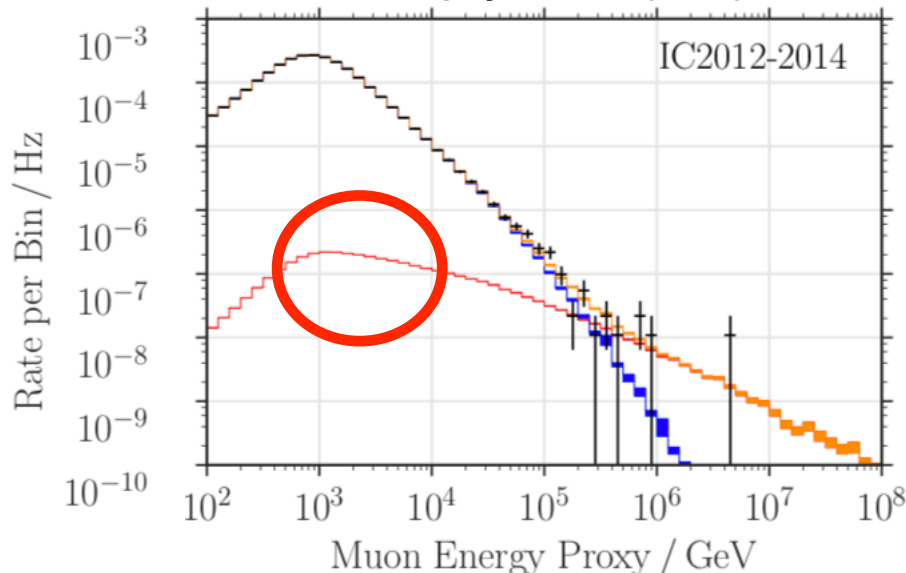
## Target of Opportunity

- Follow-up of high-energy neutrinos (TeV, PeV) for early time information of transient
- Track events: ( $\sim 1$  deg,  $\sim 10$ /year)  
 $\sim 1$  pointing of ZTF covers the neutrino error circle

## Real Time Trigger

- Use stream of IceCube muon track neutrinos with energies of several 100 GeV
- Matching algorithm will consider:
  - Position and error circle of candidates
  - Neutrino Energy

Astrophys.J. 833 (2016) no.1, 3



+ + + Exp. data

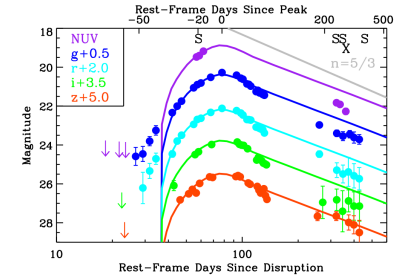
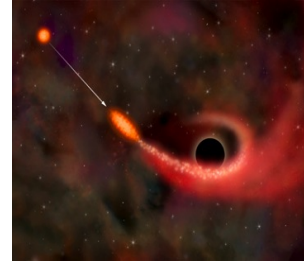
■ Astrophysical  $\nu + \bar{\nu}$

■ Conv. atmospheric  $\nu + \bar{\nu}$

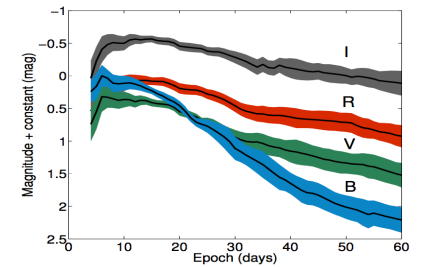
■ Combined  $\nu + \bar{\nu}$

# Expected Time Scales of Transients

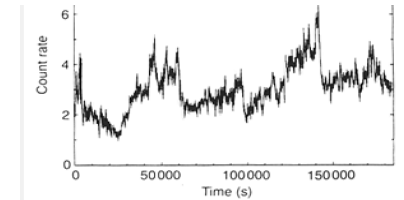
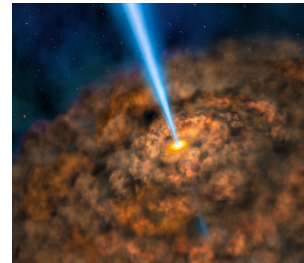
Tidal disruption events ~1d - 100d



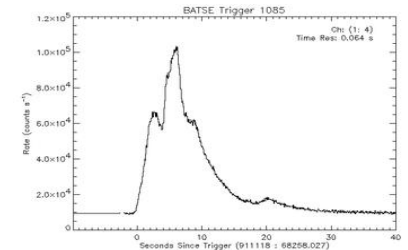
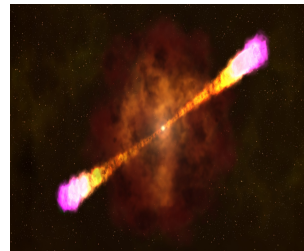
Supernovae ~100d



Active galactic nuclei ~1h - 10d



Gamma ray bursts ~10s -100s



# Real-time Neutrino Correlation: Primary Transient Selection

## Short transients (GRB-like)

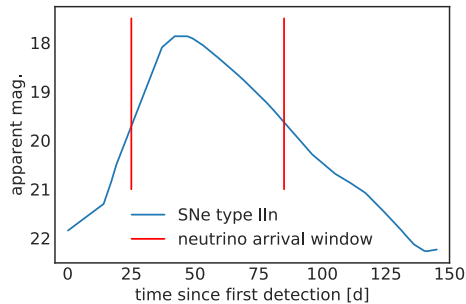
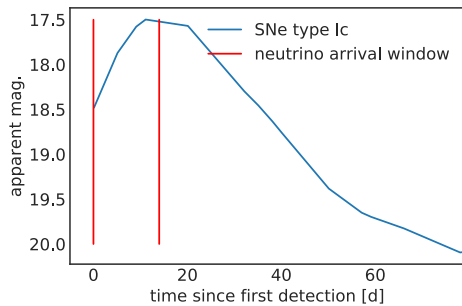
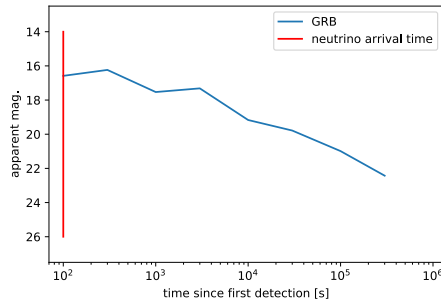
- More than 2 detections in  $< 12\text{h}$
- Falling lightcurve
- Realtime maximum likelihood calculation of test statistic

## Medium length transients (SN Ic, Kilonova)

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

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

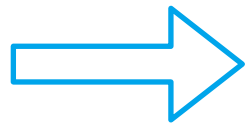
- Time window of 8 weeks
- More than 5 optical detections





# Summary

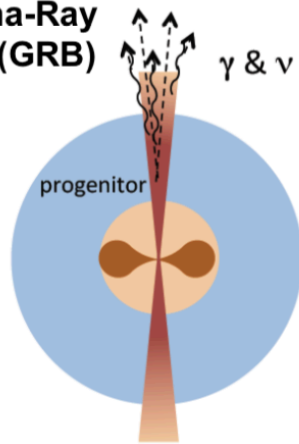
- ZTF features a 47 deg<sup>2</sup> field-of-view and high-cadence observations
- High classification capabilities with onsite spectrograph
- AMPEL: Software developed to manage large data streams and real-time analysis framework



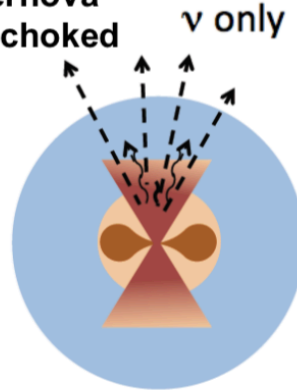
**ZTF starts a new era for real-time multi-messenger astronomy**

# Backup: Neutrino Source Candidates

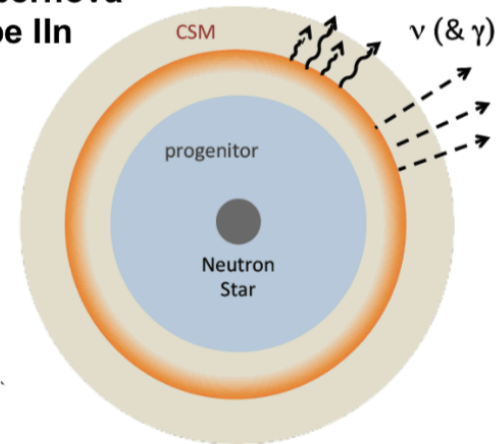
**Gamma-Ray Burst (GRB)**



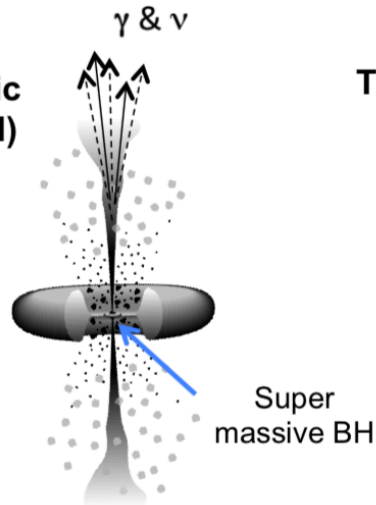
**Supernova with choked jets**



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



**Active Galactic Nucleus (AGN)**



**Tidal Disruption event (TDE)**

