IceCube's Optical Follow-Up with the Palomar and Zwicky Transient Factory

Third AMON Workshop, DESY Zeuthen

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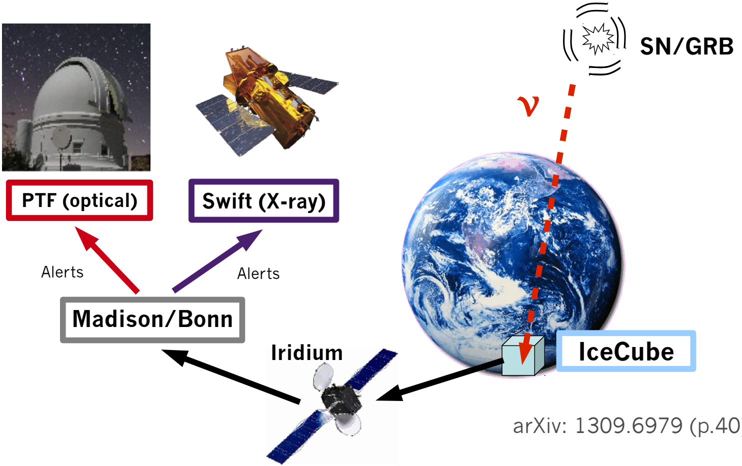
12th December 2014

PTF/ZTF



arXiv: 1309.6979 (p.40)

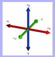
Palomar Transient Factory (PTF)

- Located in California
- Mainly discovering/observing SNe
- FoV: $2.3^\circ \times 3.5^\circ$
- 1.2 m telescope
- Lim. mag. of up to 21
- Can take spectra for interesting source candidates
- Follow-up since Aug. 2010
- $\sim$ 7 alerts per year

Selection	Level	neutrino purity
At least 8 coincident hits	Trigger Level $\sim 2000\,\mathrm{Hz}$	0.0001%
Basic muon event selection (tracks only)	Level 1 $\sim 35\,\mathrm{Hz}$	0.01%
Up-going tracks	Level 2 $\sim 2\,\mathrm{Hz}$	0.1%
Neutrino selection (BDT)	OFU Level $\sim 3\,\mathrm{mHz}$	90%

Neutrino multiplet ($\geq 2\nu$):

Time $< 100s$ Space $< 3.5^\circ$



PTF ← Calculate λ → Swift

$$\lambda = -2\ln\mathcal{L} = \frac{\Delta\Psi^2}{\sigma_q^2} + 2\ln(2\pi\sigma_q^2) - 2\ln\left(1 - e^{\frac{-\theta_A^2}{2\sigma_w^2}}\right) + 2\ln\left(\frac{\Delta T}{100\,\mathrm{s}}\right) \tag{1}$$

$\Delta\Psi$:	angular separation
σ_q^2, σ_w^2:	directional error
θ_A:	FoV radius
ΔT:	time difference

Space term: Small for close and well-reco neutrinos

Telesopce term: Small for events likely to be in FoV

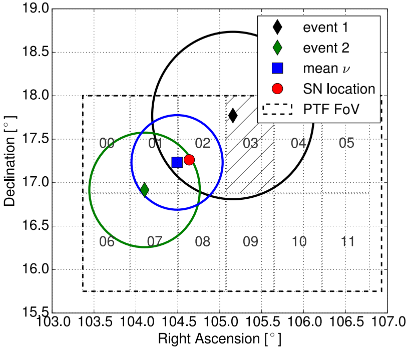
Time term: Small for events close in time

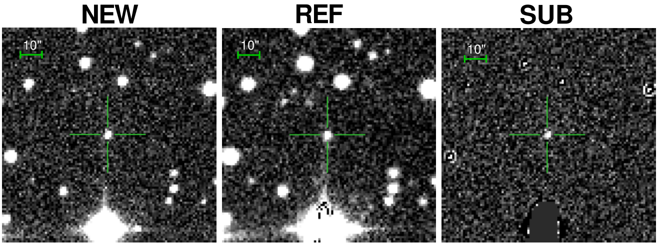
OFU/XFU: Measured multiplets and alerts

Season	PTF Alerts	Swift alerts
IC79 (10/11)	9	1
IC86-1 (11/12)	8 (5.9)	6 (5.4)
IC86-2 (12/13)	7 (8.3)	8 (7.5)
IC86-3 (13/14)	5 (5.3)	4 (4.7)
IC86-4 (14/15)	2	2
Sum	31	21

Table: Alerts of the Optical and X-ray Follow-Up (in brackets number of expected background alerts).

- Alert from 2012-03-30:
  - (still) most significant alert so far: $\Delta T = 1.8\,\mathrm{s}$, $\Delta\Psi = 1.3°$
  - SN **PTF12csy** found in PTF images, very close to neutrinos $(0.14°)$
  - Late-time IIn, $z = 0.068$, $\sim 300\,\mathrm{Mpc}$

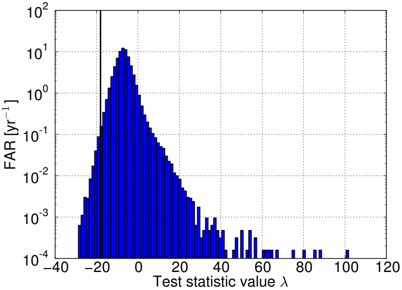




Significance of neutrino alert and SN detection

- Significance for IceCube alert from test-statistic distribution
- Integral to the left (signal region) gives false alarm rate (FAR) of $0.216\,\mathrm{yr}^{-1}$

$\Rightarrow$ **p = 12.7%** for IC86-1 season



- Calculate number of coincident (chance) core-collapse SN (CCSN) detections:

$$\overline{N}_{\mathrm{det}} = \Omega_{\mathrm{search}} \cdot \int_0^{300\,\mathrm{Mpc}} \frac{dN_{\mathrm{SN}}}{dt\; dV} \cdot T(m_{\mathrm{lim}}, \hat{M}, r) \cdot r^2\, dr \quad (2)$$

$\Rightarrow$ Poissonian probability of 1.6% to detect any CCSN within $300\,\mathrm{Mpc}$, within the alert error, by chance

- Combined p-value of IceCube alert and SN detection: **p = 1.4%** $= 2.4\,\sigma$

PTF12csy: Observations

- First follow-up observations on 3, 5, 7, 9 Apr 2012 (PTF)

⇒ SN PTF12csy found, looking several months old

- More observations by PTF, FTN, Pan-STARRS
- **Archival** Pan-STARRS data contains SN
- Description of instruments and photometric pipelines
- **Spectra** taken with Gemini North (17 Apr 2012) and Keck I (9 Feb 2013)
- Swift **UV/X-ray** observ. on 20 Apr 2012 and 15 Nov 2012

PTF12csy: Photometry

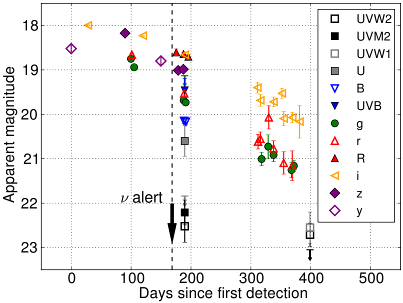


Figure: Raw light curve in apparent magnitudes

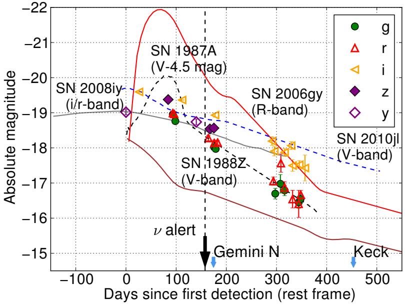
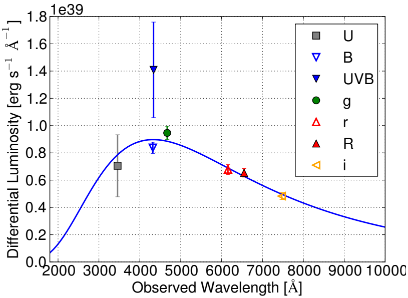


Figure: Simplified, corrected light curve in absolute magnitudes, comparison with other SNe

PTF12csy: Spectral energy distribution (SED)

- Black-body fit to SED (reduced χ^2 of 1.6)
  - Temperature: $7156 \pm 214\,\mathrm{K}$
  - Bolometric lumin.: $(5.53 \pm 0.94) \times 10^{42}\,\mathrm{erg/s}$
  - Photometric radius: $(1.7 \pm 0.1) \times 10^{15}\,\mathrm{cm}$ (Stefan-Boltzmann law)



- SN is optically thick: we still see circumstellar material (CSM) shell at $t > 177$ days after explosion, $R_{\mathrm{ej}} < R_{\mathrm{phot}}$

⇒ Upper limit on ejecta velocity: $1125\,\mathrm{km/s}$

- After adding line luminosities to bol. lum., extrap. using light curve:

⇒ Total radiated energy: $2.1 \times 10^{50}\,\mathrm{erg}$ within 400 days after first detection (very sim. to SN 2008iy)

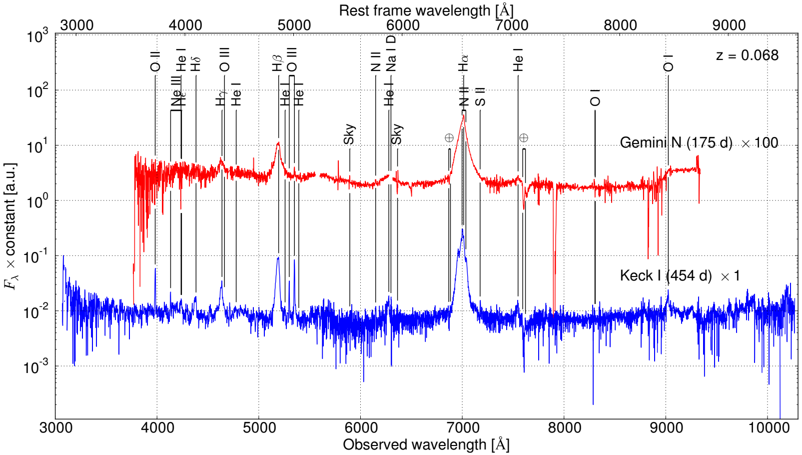


Figure: The two spectra from PTF12csy.

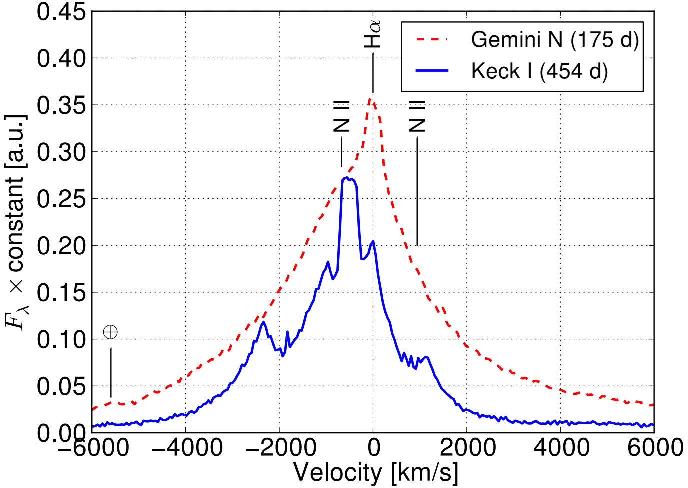
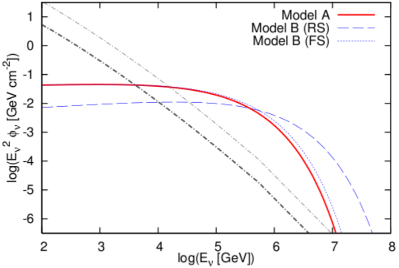


Figure: Close-up on the Hα line in both spectra.

- Offline PS analysis at position of SN
- Used Optical-Follow-Up dataset
- Part of SN IIn stacking analysis by Alexander Stasik



- Std. PS likelihood analysis with space and energy term:

$$\mathcal{L}(n_s) = \prod_i \frac{n_s}{N} S_i + (1 - \frac{n_s}{N}) B_i \quad (3)$$

- Model: Murase et al. 2011 (arXiv:1012.2834), ejecta-CSM interaction
- E^{-2} spectrum with cut-off at $\approx 70\,\mathrm{TeV}$ to $275\,\mathrm{TeV}$

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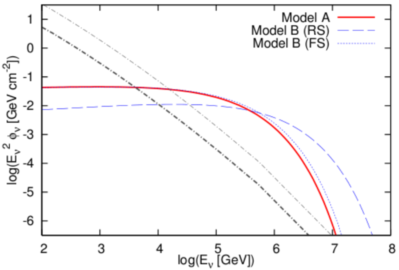

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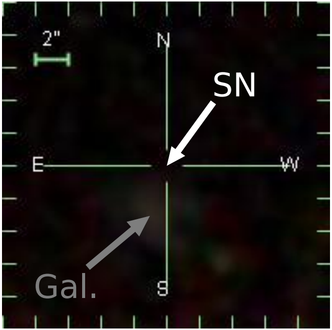
- Model: Murase et al. 2011 (arXiv:1012.2834), ejecta-CSM interaction
- E^{-2} spectrum with cut-off at $\approx 70\,\mathrm{TeV}$ to $275\,\mathrm{TeV}$
- Result:
  - Null-result: fitted n_s of 0
  - Upper limit: $> 1200 \times$ model fluence of $E^2\Phi \approx 4 \times 10^{-5}\,\mathrm{GeV\,cm^{-2}}$

PTF12csy: X-ray data

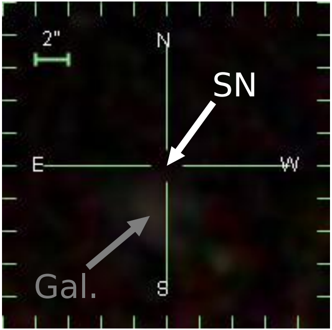
- Swift XRT observations with $4\,\mathrm{ks}$ exposures led to no detection
- $2\,\sigma$ upper limit on count rate is $\approx 0.001\,\mathrm{counts/s}$ ($0.2\,\mathrm{keV}$ to $10\,\mathrm{keV}$)
- Can be converted to unabsorbed luminosity upper limit of about $5 \times 10^{41}\,\mathrm{erg/s}$ to $6 \times 10^{41}\,\mathrm{erg/s}$
- Upper limit too high to exclude X-ray emission, e.g. $(2.4 \pm 0.8) \times 10^{41}\,\mathrm{erg/s}$ measured for other SN IIn



Source: SDSS DR10

- Host galaxy is faint dwarf galaxy
- Has absolute magnitude of $M_g \approx -16.2\,\mathrm{mag}$, slightly fainter than Small Magellanic Cloud ($M_V = -16.9\,\mathrm{mag}$)
- Faint host galaxies typical for bright IIn SNe (might be selection bias, might be physical)

PTF12csy: Host galaxy



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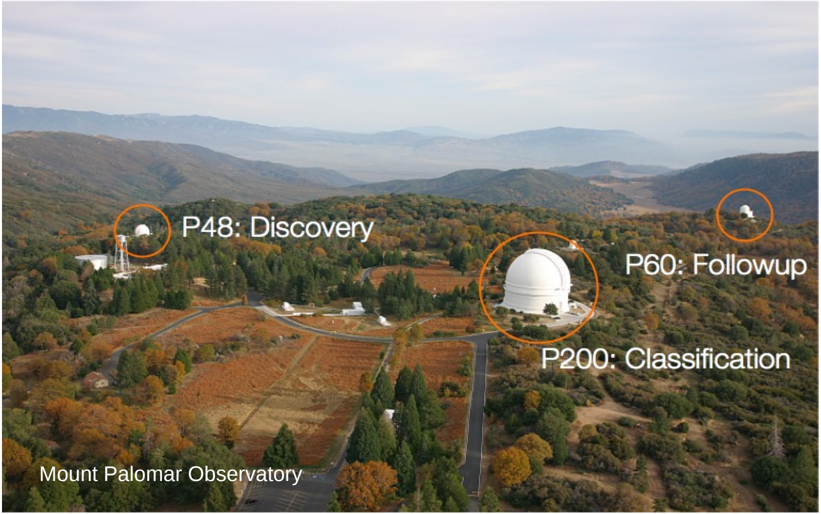
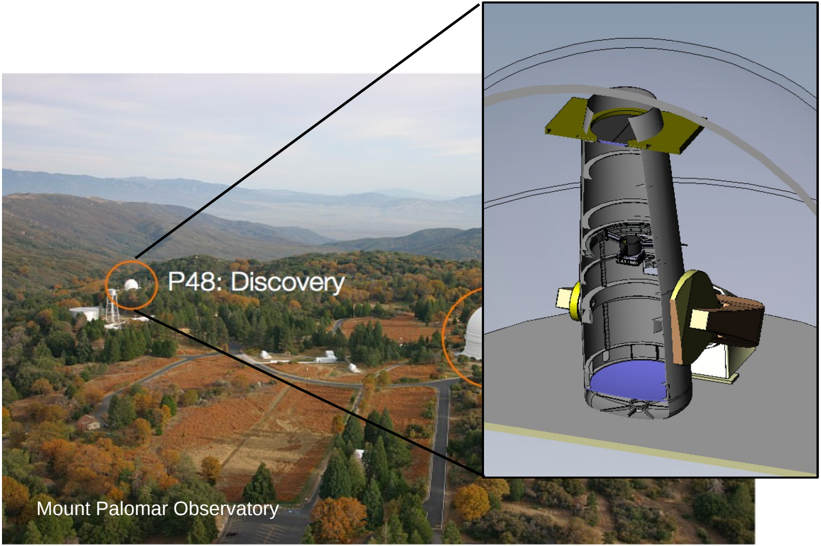
- Faint host galaxies typical for bright IIn SNe (might be selection bias, might be physical)
- Metallicity of $12 + \log \mathrm{O/H} \approx 8$ (from luminosity), i.e. quite metal-poor
- SN position about $4\,\mathrm{kpc}$ off-center, galaxy radius of $3.5\,\mathrm{kpc}$

$\Rightarrow$ SN environment probably different from average of host galaxy



Collaboration of Caltech, Oskar Klein Centre (Stockholm), Weizmann Insitute (Rehovot, Israel), DESY, University of Maryland



First light: beginning of 2017

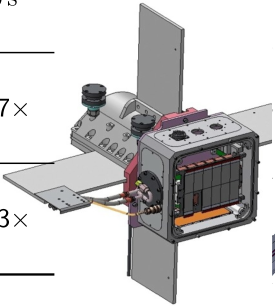
ZTF versus PTF

	PTF	ZTF
Active Area	$7.26\,\mathrm{deg}^2$	$47\,\mathrm{deg}^2$
Overhead Time	$46\,\mathrm{s}$	$< 15\,\mathrm{s}$
Optimal Exposure Time	$60\,\mathrm{s}$	$30\,\mathrm{s}$
Relative Areal Survey Rate	$1\times$	$14.7\times$
Relative Volumetric Survey Rate	$1\times$	$12.3\times$

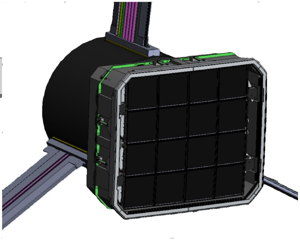
- $3750\,\mathrm{deg}^2/\mathrm{hour}$

$\Rightarrow$ 3π survey in 8 hours,
$>$ 250 observations/field/year
for uniform survey

Existing PTF camera
MOSAIC 12k



New ZTF camera:
16 6k x 6k e2v CCDs



Summary

- Optical Follow-Up of IceCube neutrino alerts with PTF:
  - Sent 31 alerts to PTF since 2010
  - Found interesting, rare type IIn SN **PTF12csy**
  - Most likely serendipitous detection (old age, far away, $2.4\,\sigma$)
  - High-energy neutrinos expected, but IceCube not sensitive
- Optical Follow-Up with ZTF:
  - Bright prospects for multi-wavelength programs
  - FoV so large that almost full sky observed regularly

Backup slides

Online Neutrino Analysis

- IceCube has measured astrophysical neutrino flux
- Best chance to identify sources: multi-messenger, i.e. correlation with other data, e.g. electromagnetic (esp. if sources are transient)
- Problem: Observations are sparse
- Hard to find fast transients
- Idea of (rapid) follow-up: Send alerts to observatories, triggered by IceCube

$\Rightarrow$ Need fast neutrino analysis, running "online"

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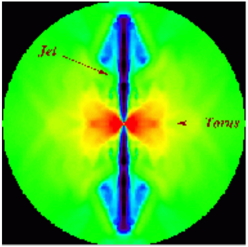
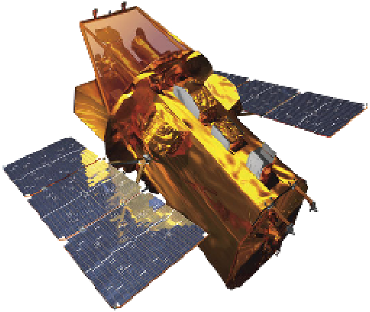
⇒ Need fast neutrino analysis, running "online"

- Look for transient sources ($< 100\,\mathrm{s}$) with low neutrino background:
  - GRBs (Waxman & Bahcall 1997, Murase & Nagataki 2006)
  - SNe with jets (Razzaque, Meszaros, Waxman 2005)
  - More exotic phenomena? (Fast Radio Bursts?) (Falcke & Rezzolla 2013)



- $10\,\mathrm{ks}$ exposure with XRT ($0.2\,\mathrm{keV}$ to $10\,\mathrm{keV}$), more intensive follow-up (up to 2 weeks) possible
- Need 'tiling' because of small FoV ($\sim 0.4^\circ$)
- Follow-up since February 2011
- $\sim$ 5 alerts per year

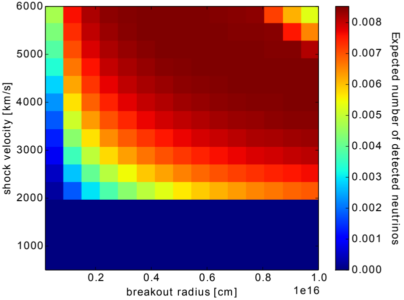


PTF12csy: Expected neutrino production

- Following a model by Murase (arXiv:1012.2834 and in prep.): ejecta-CSM interaction
- Parameters: total CR energy, break-out radius, v_{shock}
- Expect at most < 0.1 IC events within $\sim 100 - 1000$ days
- Not a neutrino doublet within $2\,\mathrm{s}$, $> 158\,\mathrm{days}$ (rest frame) after SN explosion

Work done by Nora Linn Strotjohann

Expected number of IceCube events:



- Very unlikely that neutrinos and SN were correlated (unless: blitzar (FRB)?)