Searching for Optical Counterparts for IceCube Neutrinos Using the Dark Energy Camera

Keith Bechtol
(LSST)
on behalf of the DES Collaboration

TeV Particle Astrophysics
17 August 2017

THE DARK ENERGY SURVEY

DES Y1Cosmology Results

Dark Energy Survey Year 1 Results: Photometric Data Set for Cosmology
Drlica-Wagner et al. 2017

Dark Energy Survey Year 1 Results: Redshift distributions of the weak lensing source galaxies
Hoyle et al. 2017

Dark Energy Survey Year 1 Results: Weak Lensing Shape Catalogues
Zuntz et al. 2017

Dark Energy Survey Year 1 Results: The Impact of Galaxy Neighbours on Weak Lensing Cosmology with im3shape
Samuroff et al. 2017

Dark Energy Survey Year 1 Results: Curved-Sky Weak Lensing Mass Map
Chang et al. 2017

Dark Energy Survey Year 1 Results: Galaxy-Galaxy Lensing
Prat et al. 2017

Dark Energy Survey Year 1 Results: Cosmological Constraints from Cosmic Shear
Troxel et al. 2017

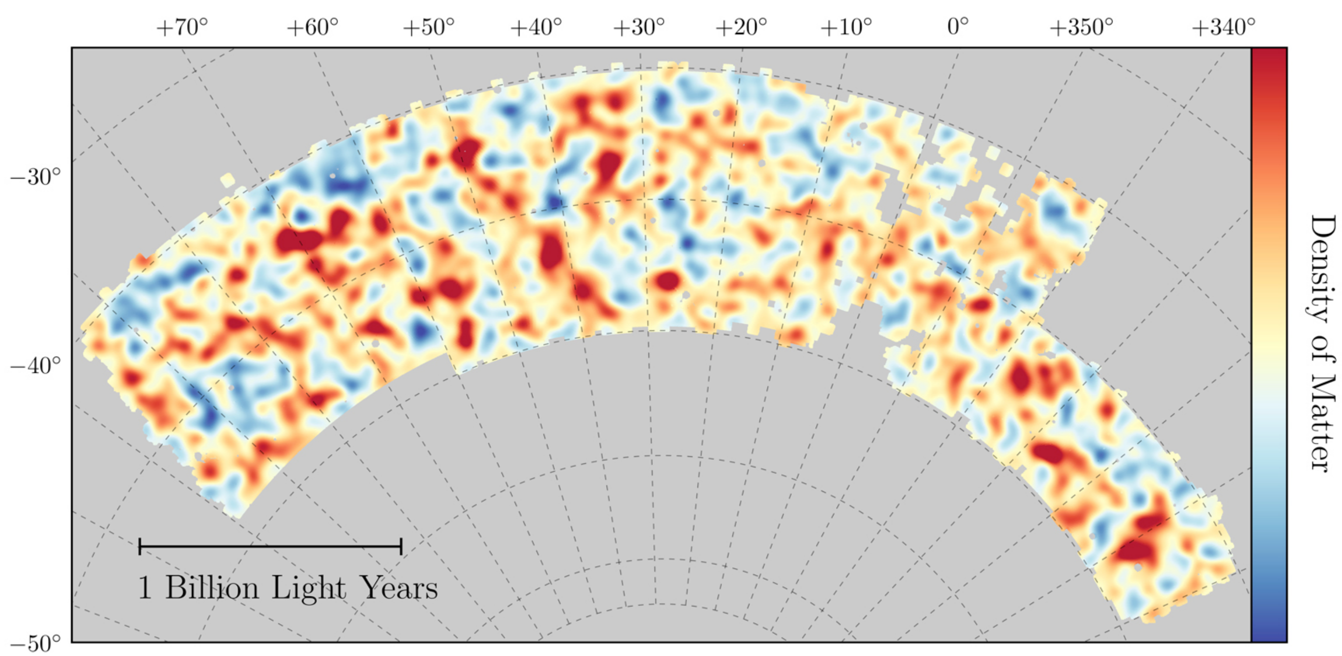
Dark Energy Survey Year 1 Results: Galaxy clustering for combined probes
Elvin-Poole et al. 2017

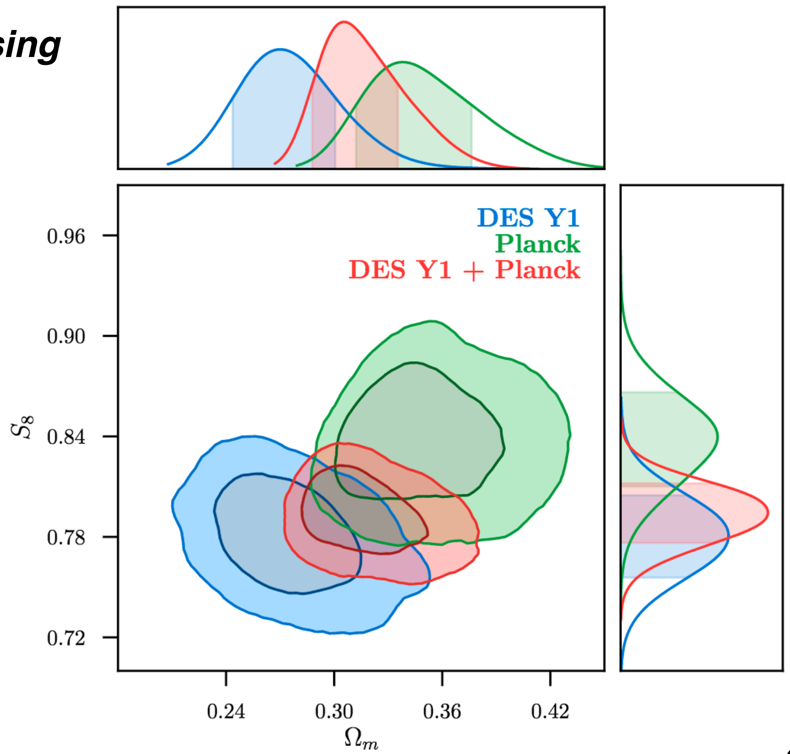
Dark Energy Survey Year 1 Results: Multi-Probe Methodology and Simulated Likelihood Analyses
Krause et al. 2017

Dark Energy Survey Year 1 Results: Cosmological Constraints from Galaxy Clustering and Weak Lensing
DES Collaboration 2017

See talk by Elisabeth Krause Wednesday morning

Onward!
5th DES observing season begins next week





Origin of Diffuse TeV-PeV Astrophysical Neutrino Flux??

THE DARK ENERGY SURVEY

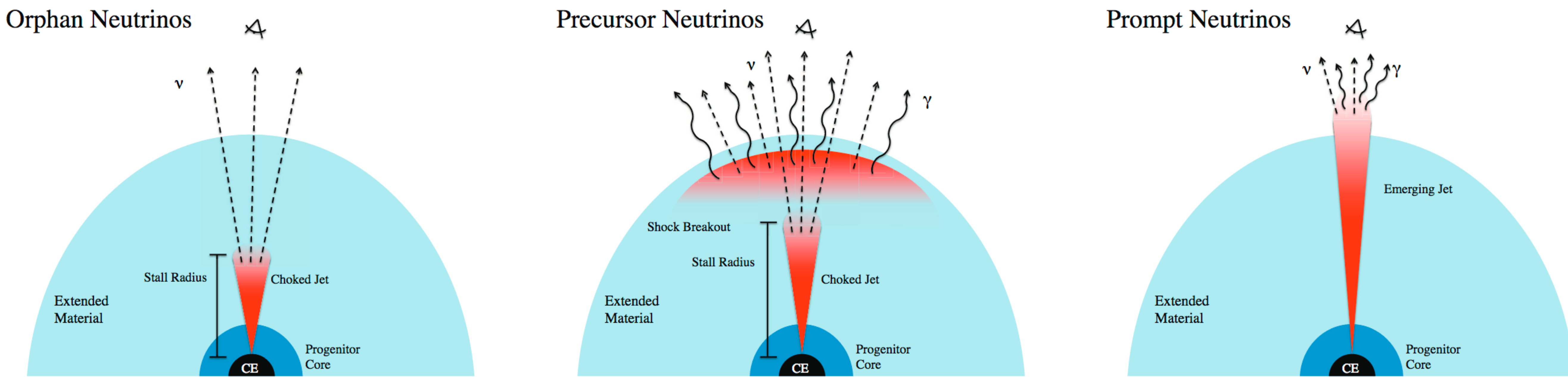
- ✓ Isotropy points to a **dominant extragalactic contribution**
- ✓ Lack of detected spatial and/or temporal structure implies that the sources are **numerous and individually faint / diffuse**
- ✓ Absence of correlation with gamma-ray source catalogs, together with high neutrino intensity relative to extragalactic gamma-ray background, suggests that the sources are **opaque to gamma-ray emission**
- ✓ Observed neutrino intensity requires **substantial non-thermal energy budget** for the source population(s)

This leaves a few interesting possibilities…

- Radio galaxies
- ***Core collapse supernovae*** → ***time-domain signature!***
- New "hidden" source class??

Explosive Optical Transients: Supernova-GRB Connection

Senno, Murase, & Meszaros 2016



Choked Jet | **Shock Breakout** | **GRB**

Choked Jet

Meszaros & Waxman 2001

Ando & Beacom 2005

Senno, Murase, & Meszaros 2016

Low luminosity GRB

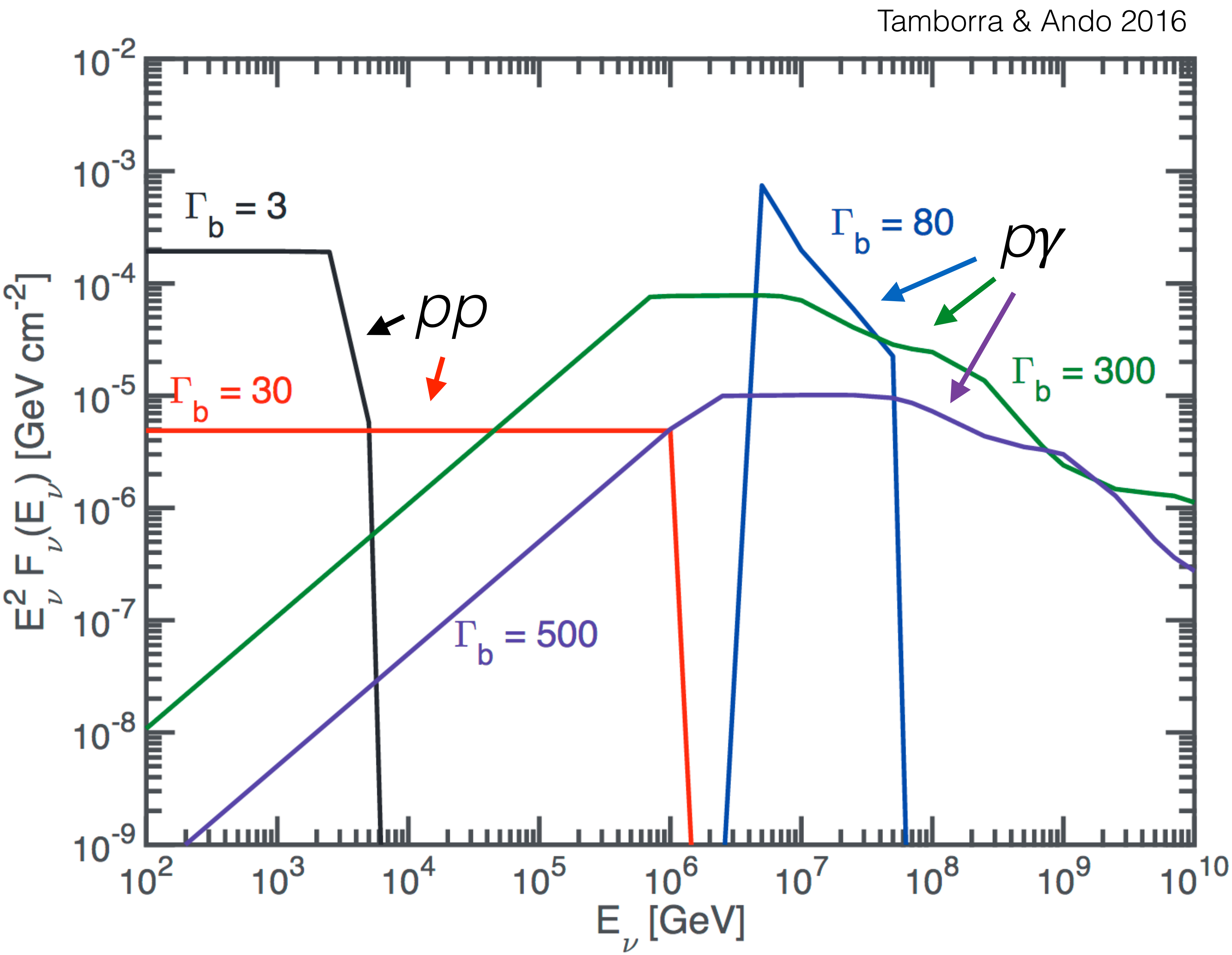
Murase et al. 2006

Murase & Ioka 2013

Tamborra & Ando 2016

Prompt Neutrino Emission
Directional
(1-100 sec)

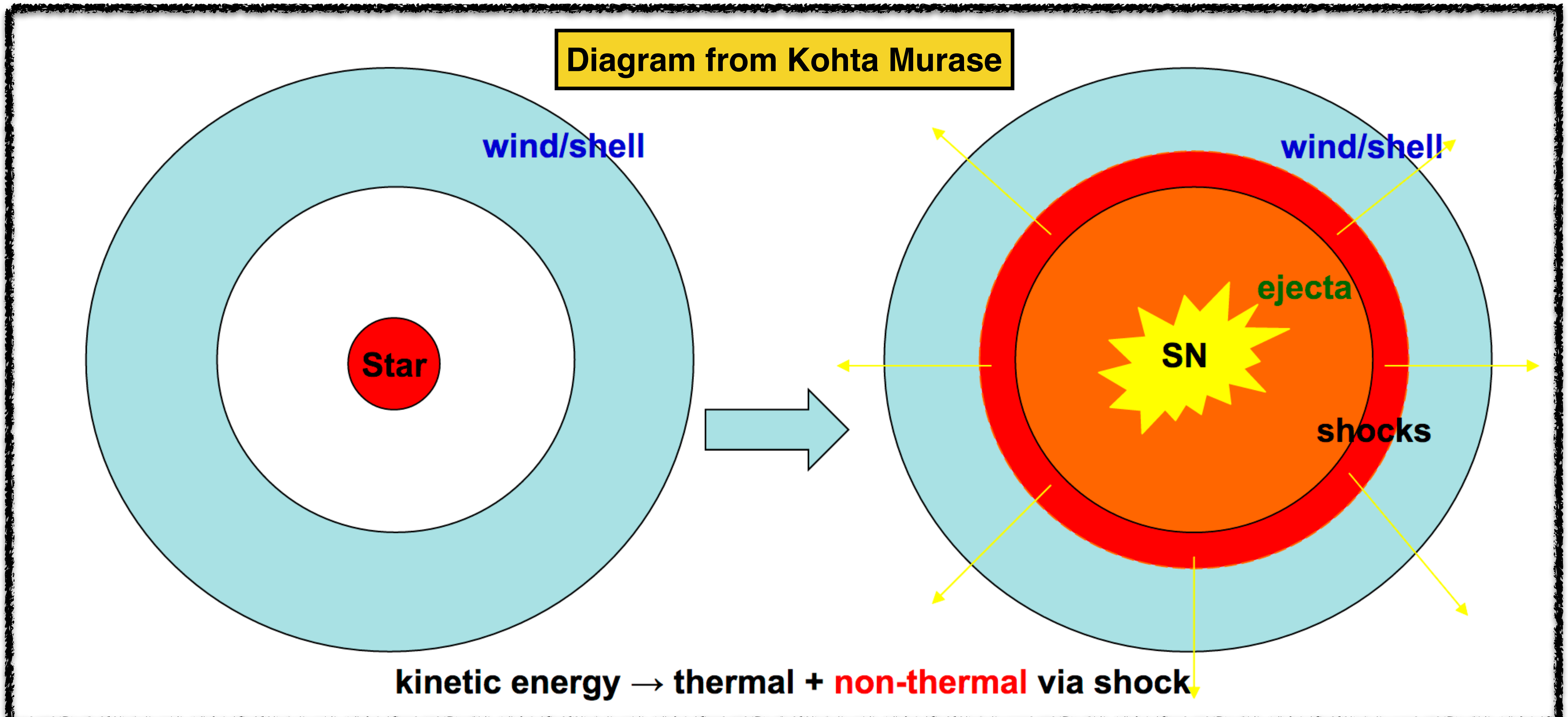
Explosive Optical Transients: Supernova-GRB Connection



Opportunity to constrain bulk Lorentz factor

+ cosmic-ray energetics

Explosive Optical Transients: Interactions with Circumstellar Wind



Interactions with dense circumstellar wind (e.g., type IIn SN)

Murase et al. 2011
Katz, Sapir, & Waxman 2011
Zirakashvili & Ptuskin 2016
Petropolou et al. 2017

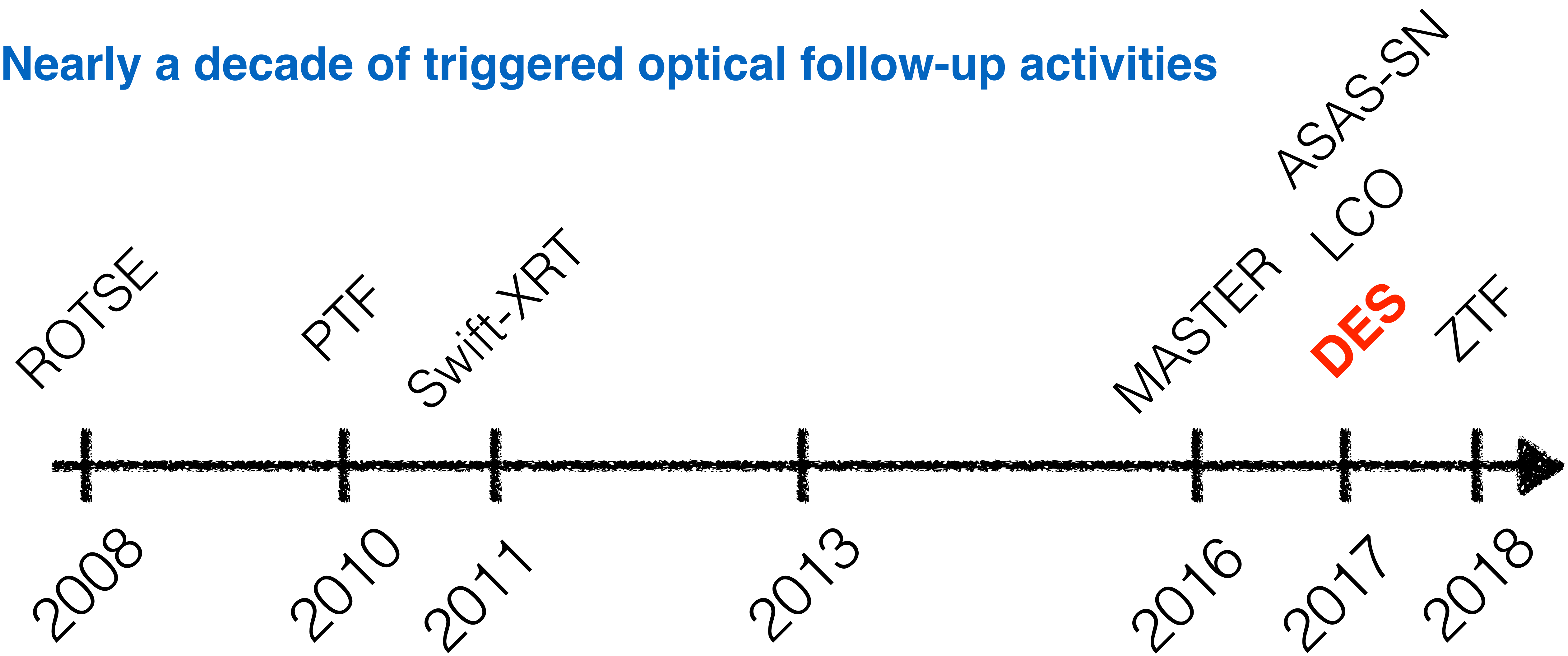
→ **Delayed Neutrino Emission**
Isotropic
(days to months)

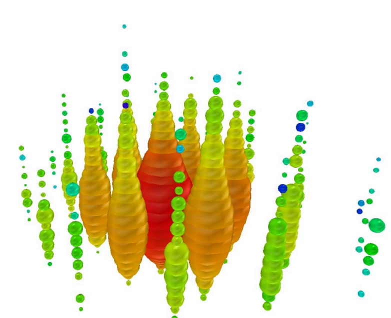
See talks by Raffaella Margutti, Kohta Murase, Maria Petropoulou

IceCube Realtime Alert System: Optical and X-ray Follow-up Partners

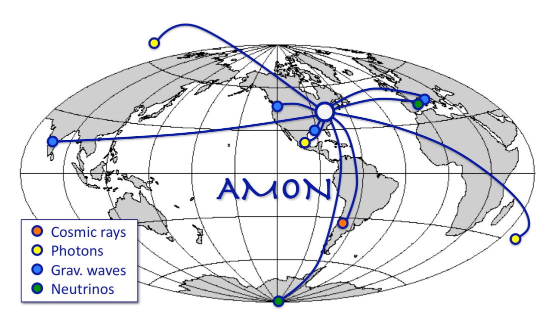
THE DARK ENERGY SURVEY

Nearly a decade of triggered optical follow-up activities





Astrophysical Neutrinos

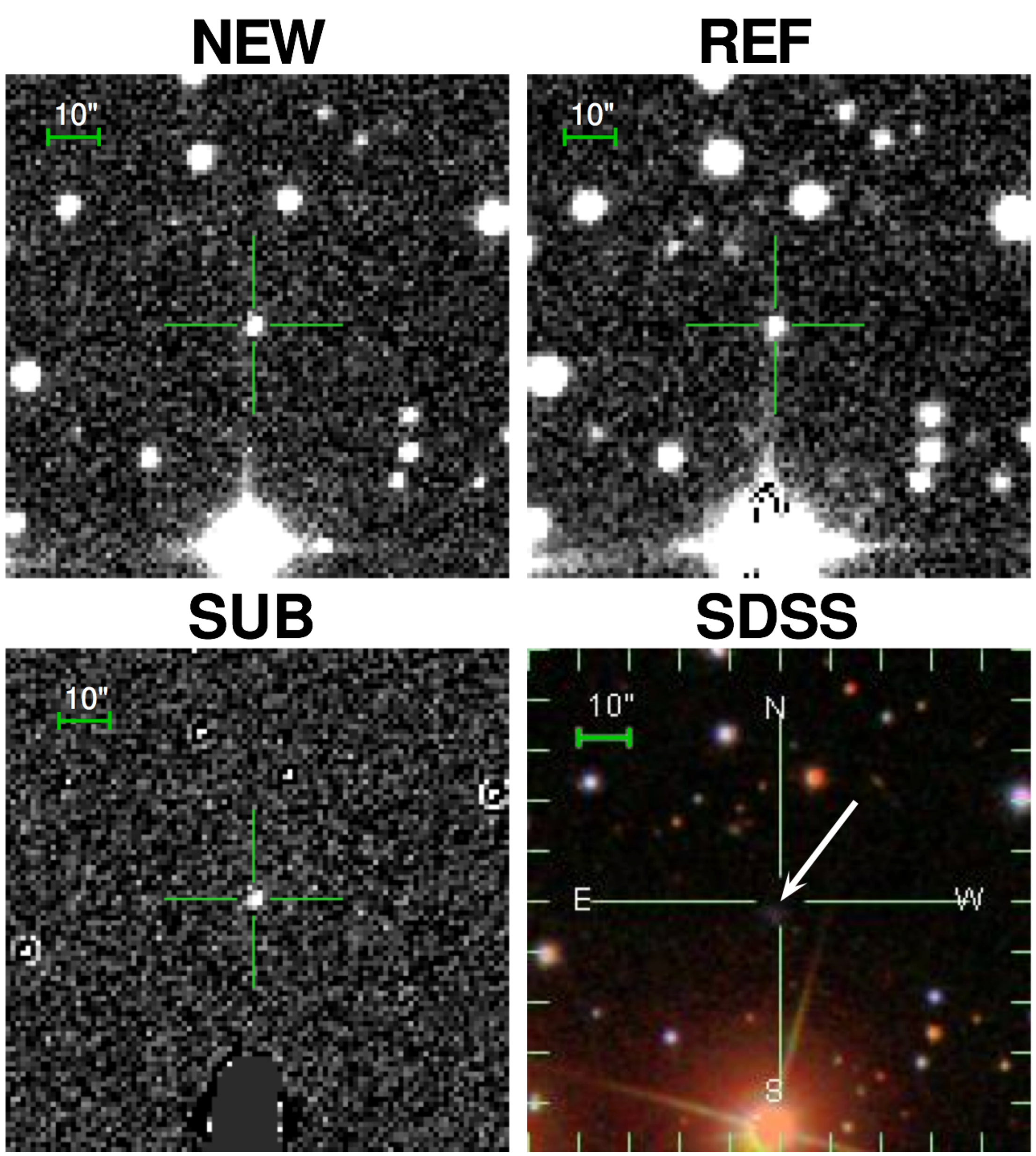


Public Realtime Alerts

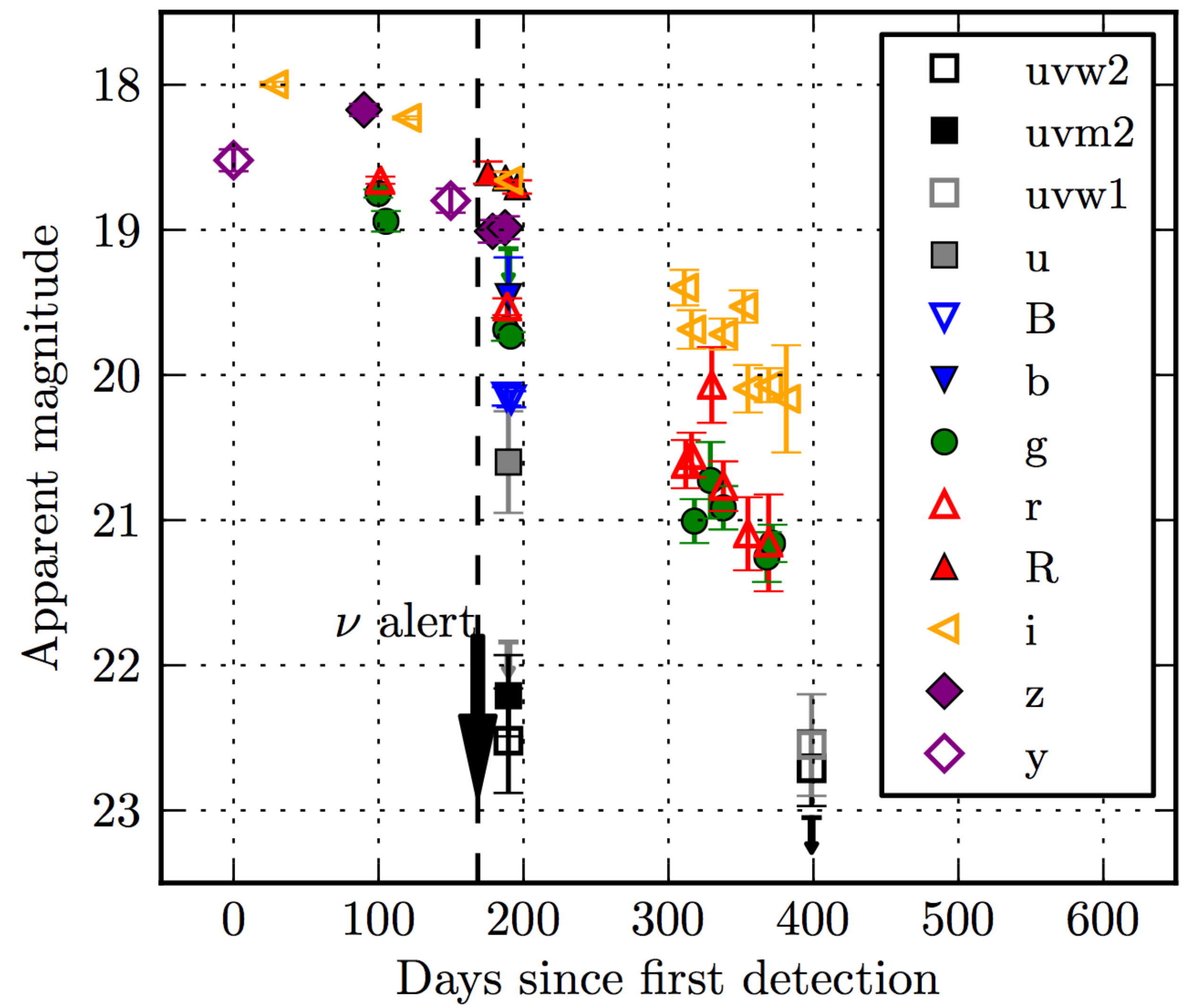
IceCube 2017
arXiv:1612.06028

Highlights from Previous Searches

Palomar Transient Factory (PTF) observations triggered by IceCube neutrino doublet



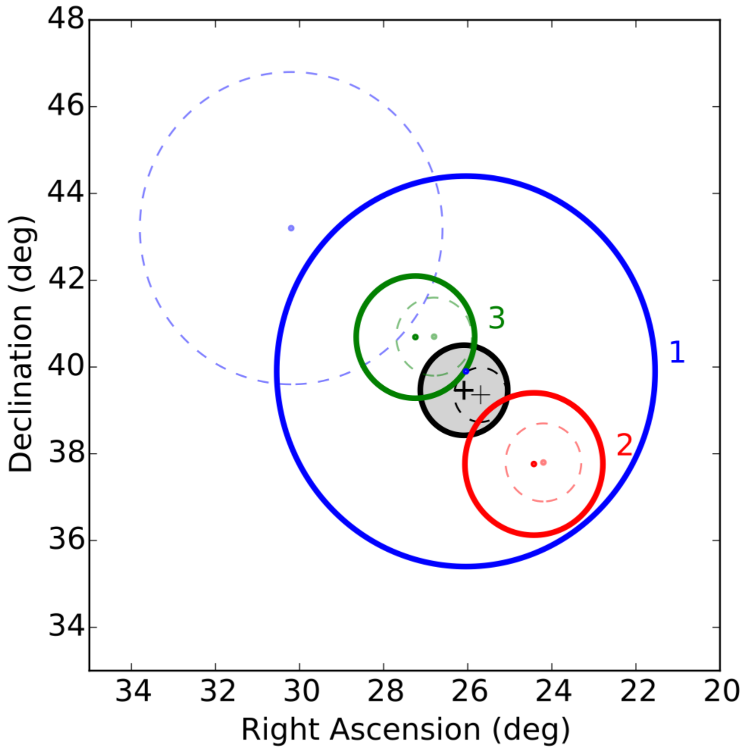
IceCube 2015
arXiv:1506.03115



Type IIn SN “PTF12csy” at z = 0.0684

…but explosion time at least 158 days prior to neutrino event based on detections in Pan-STARRS routine survey imaging

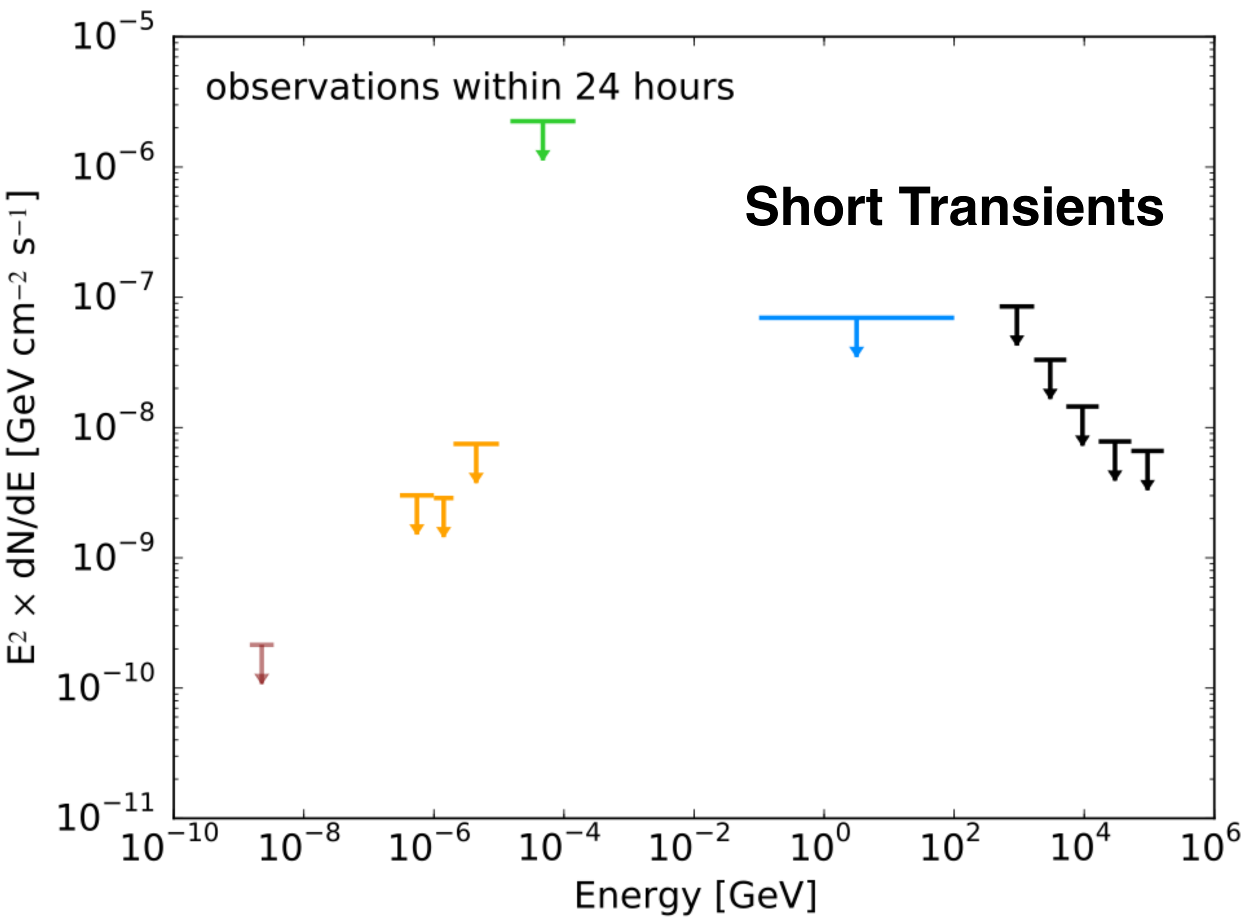
Highlights from Previous Searches

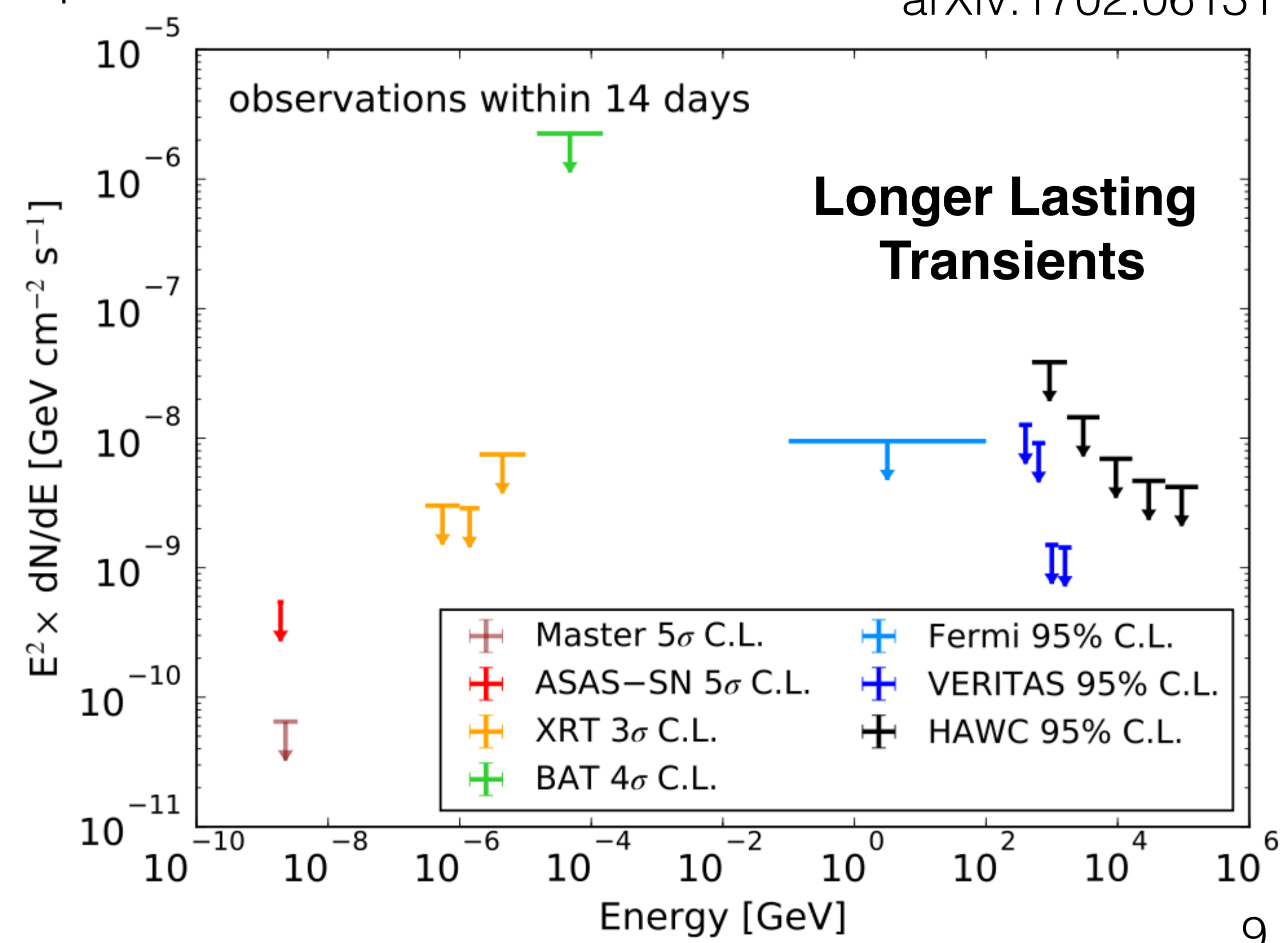


First IceCube trigger with **3 muon neutrino candidates arriving within 100 s** that are consistent with single point source origin
("False Alarm Rate" ~ 1 / 13.7 years)

Trigger electromagnetic follow-up

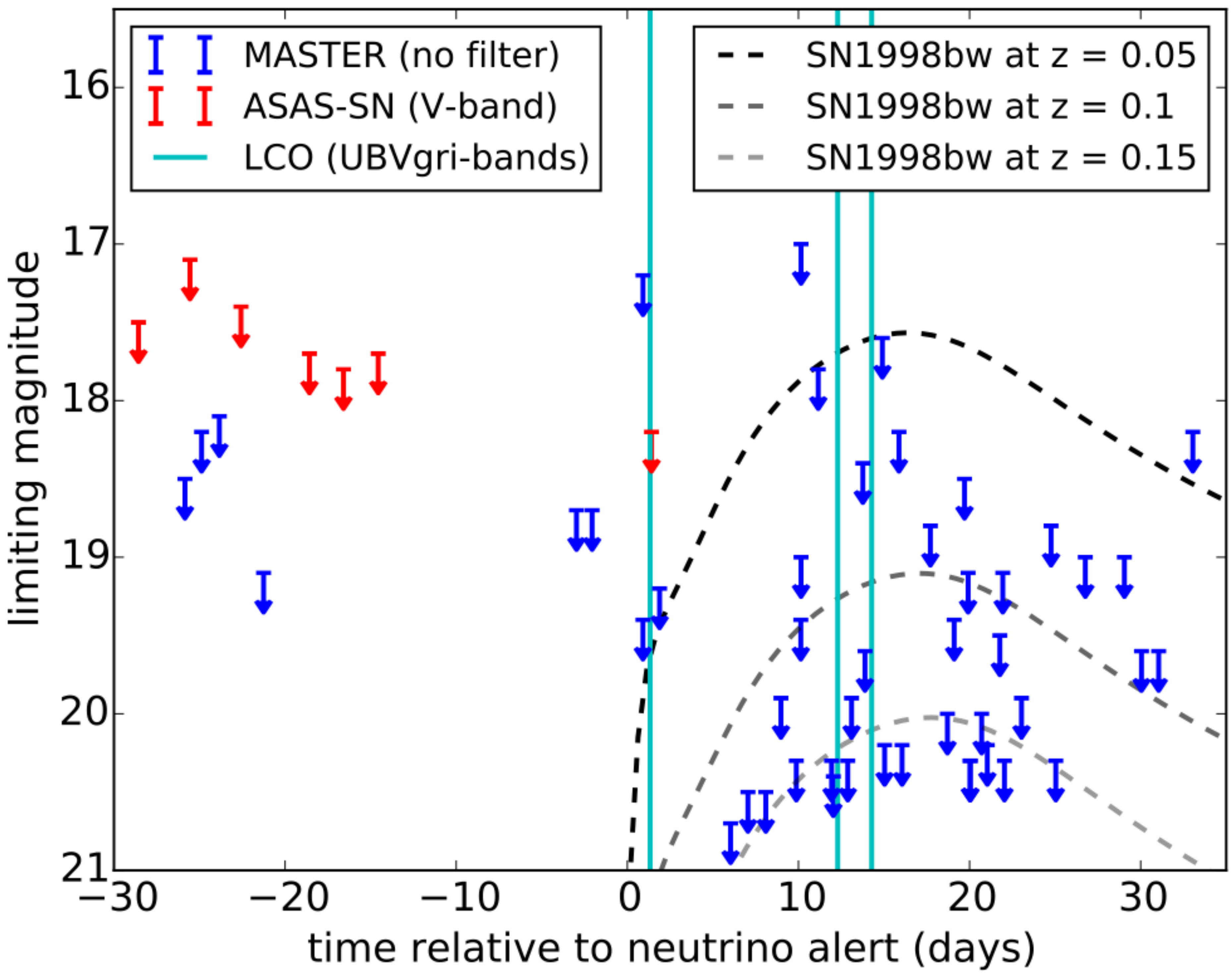
IceCube 2017
arXiv:1702.06131





Highlights from Previous Searches

No plausible transient optical counterpart identified



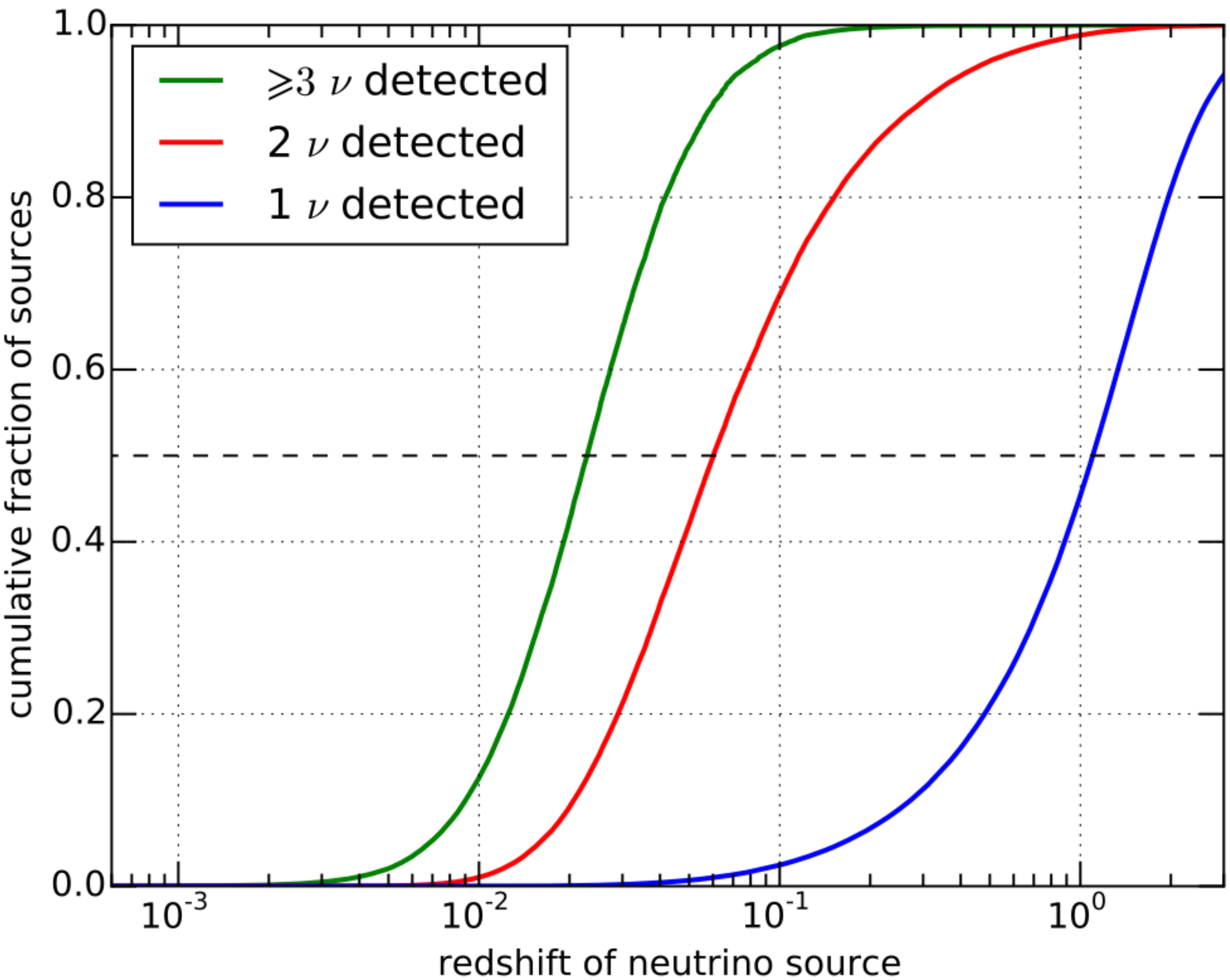
Type Ic broadlined SN 1998bw accompanied GRB 980425

IceCube 2017
arXiv:1702.06131

Highlights from Previous Searches

Coincident neutrino events can be used to estimate source redshift

(distinct feature from single-event triggers)



Assumed event rate density

= 4 x 10^{-6} Mpc-3 yr^{-1}

(1% of CC SN rate)

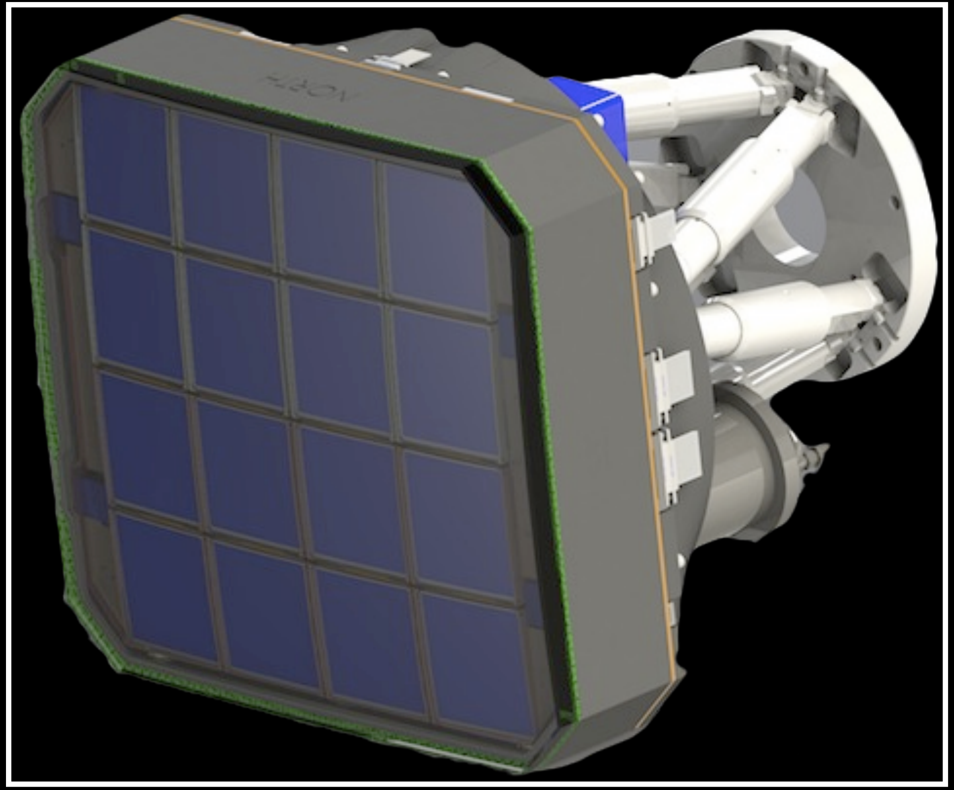
IceCube 2017

arXiv:1702.06131

Rapid Progress in Wide-field Time-Domain Optical Imaging Surveys

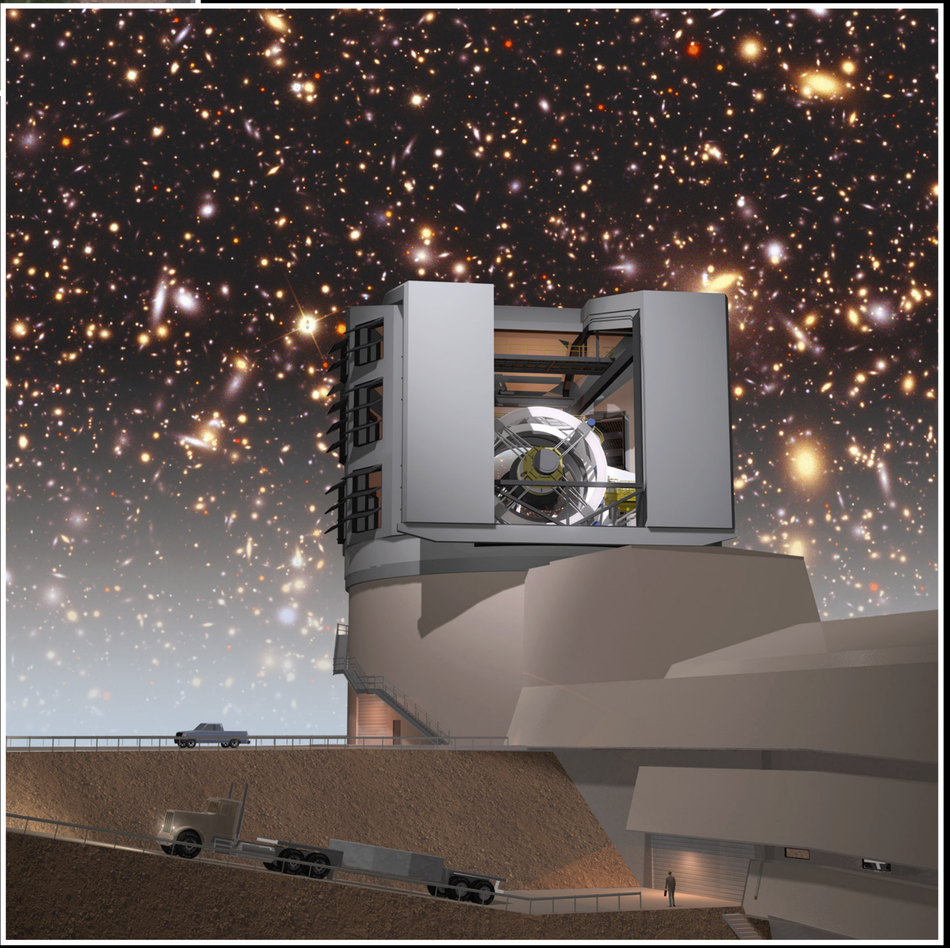
All-Sky Automated Survey for Supernovae
(ASAS-SN)

$r \sim 17$



Zwicky Transient Factory
(ZTF, 2018)

$r \sim 21$

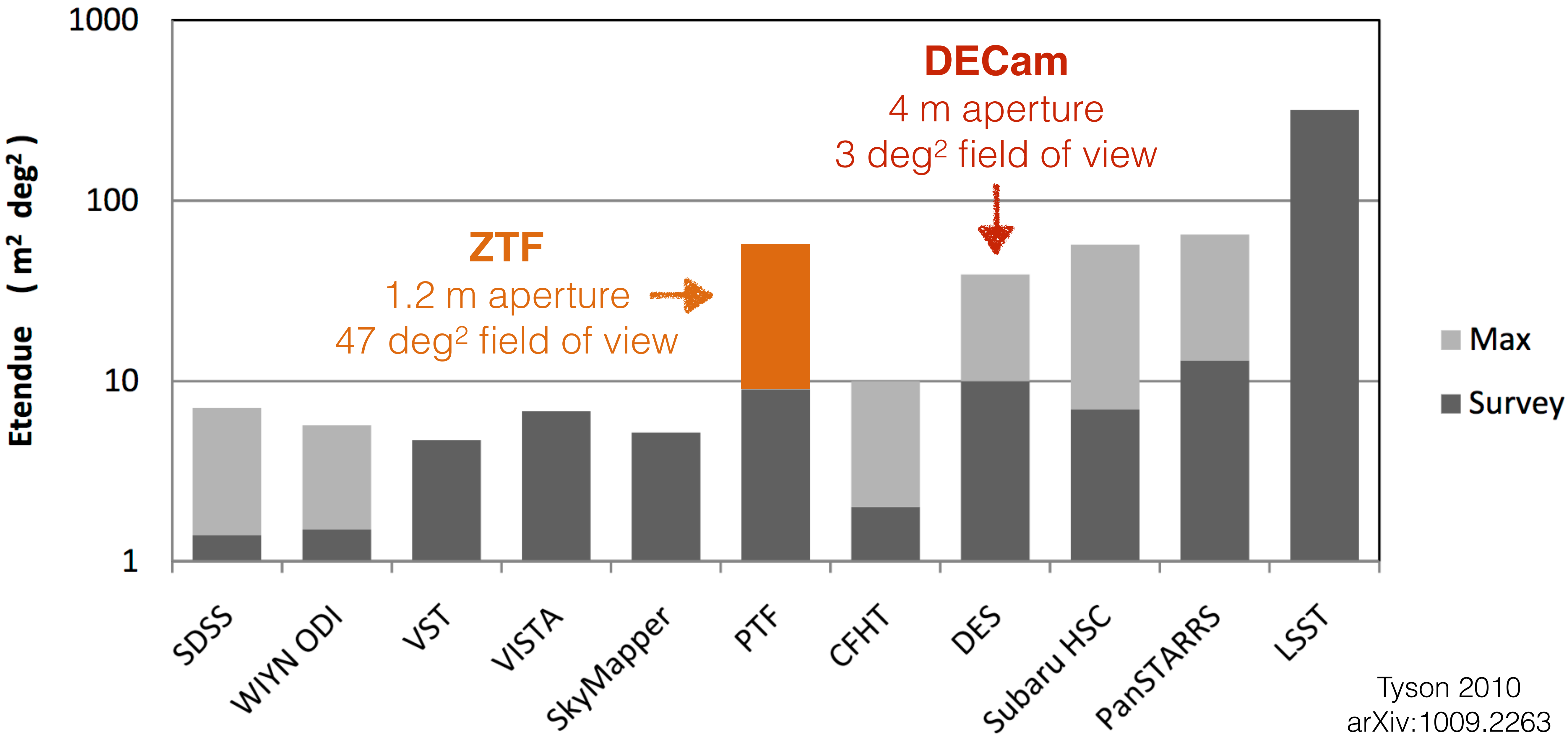


Large Synoptic Survey Telescope
(LSST, ~2022)

$r \sim 24$

Photon Collecting Power

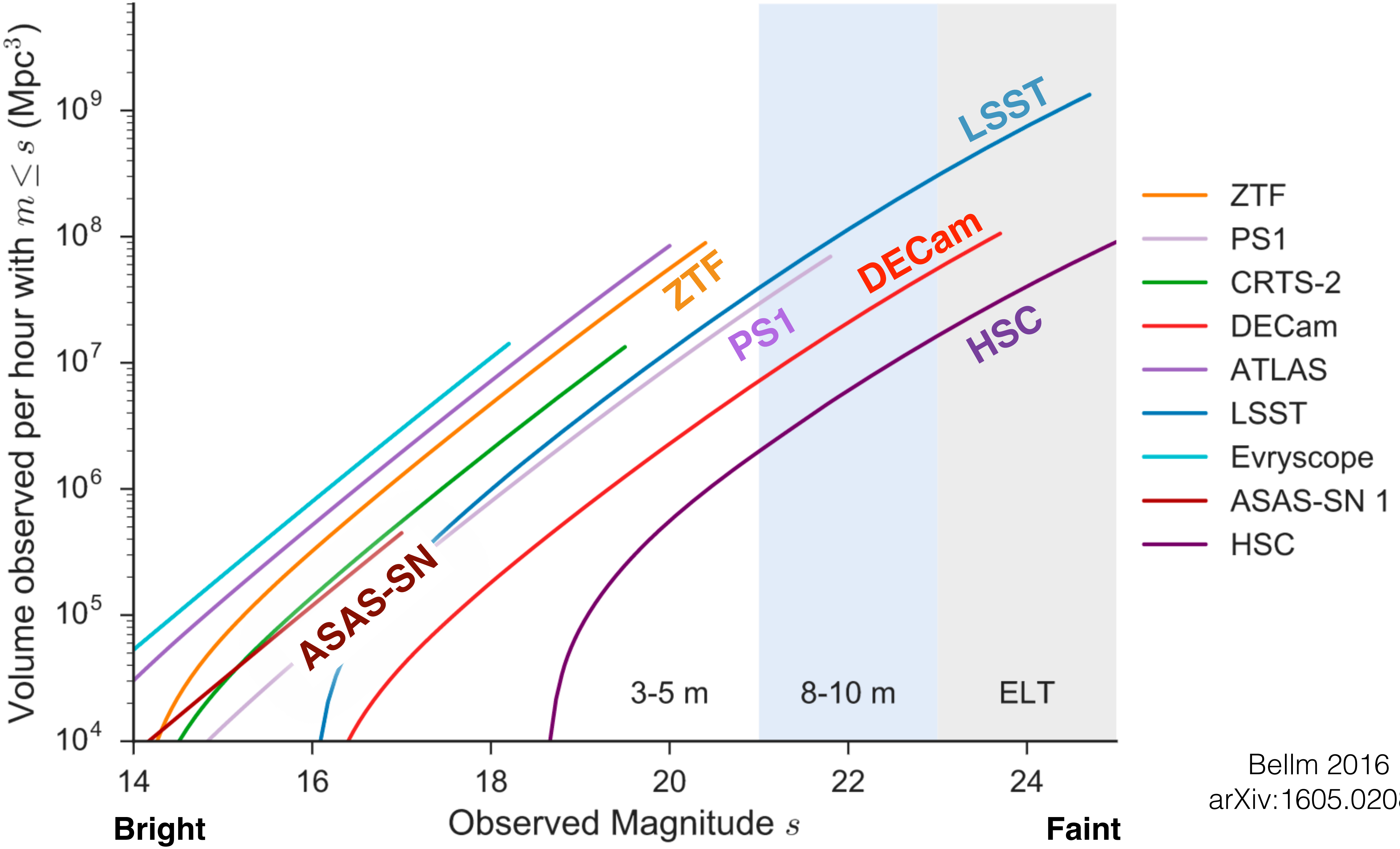
Etendue = Field of View × Effective Aperture (× Efficiency)



Tyson 2010
arXiv:1009.2263

Etendue measures to how fast a telescope + camera can map the sky

Volumetric Survey Speed



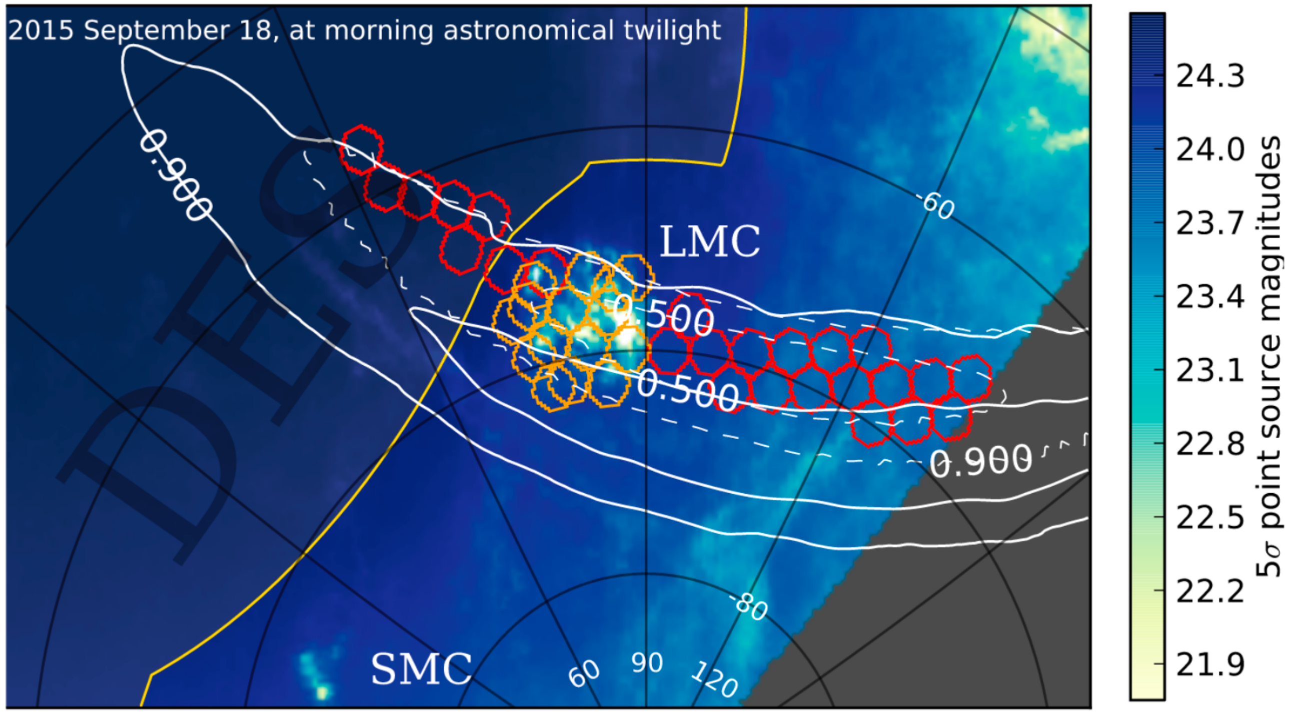
Bellm 2016
arXiv:1605.02081

Shaded regions indicate required telescope aperture for spectroscopic follow-up
(Example for luminosity M_V = 19 mag, typical of a type Ia SN)

DES Multimessenger Program

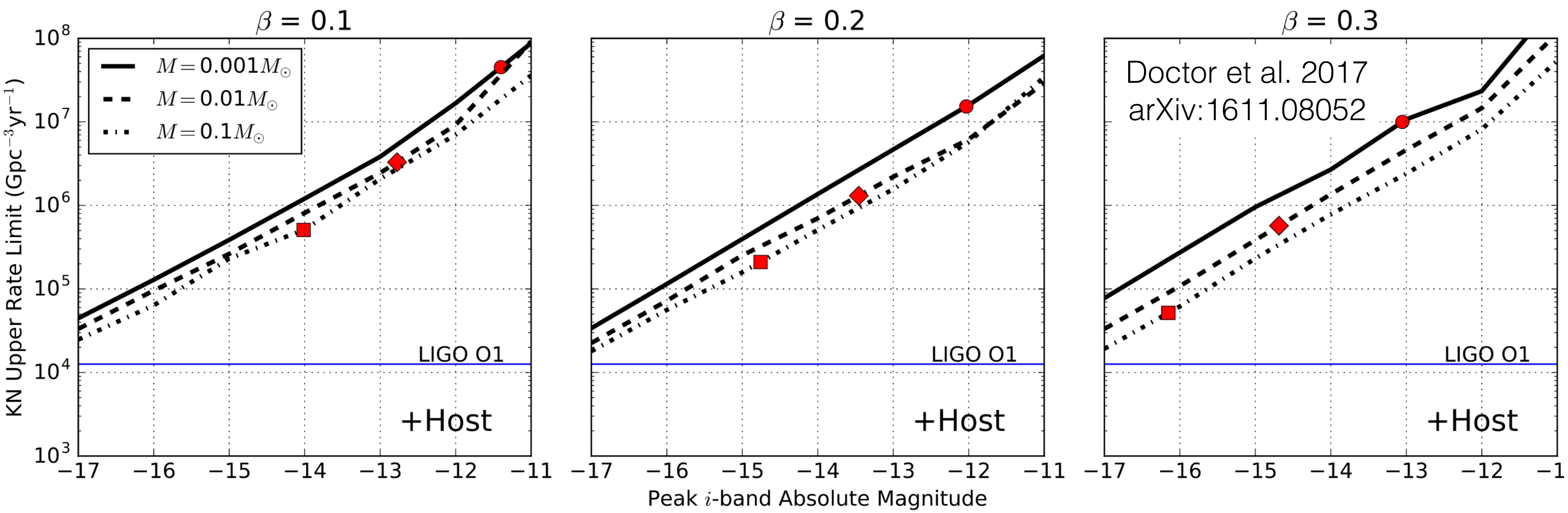
Search for optical counterparts to the first detected gravitational wave events

See also
Kessler et al. 2015, arXiv:1507.05137
Anis et al. 2016, arXiv:1602.04199
Cowperthwaite 2016, arXiv:1606.04538



Soares-Santos et al. 2016, arXiv:1602.04198

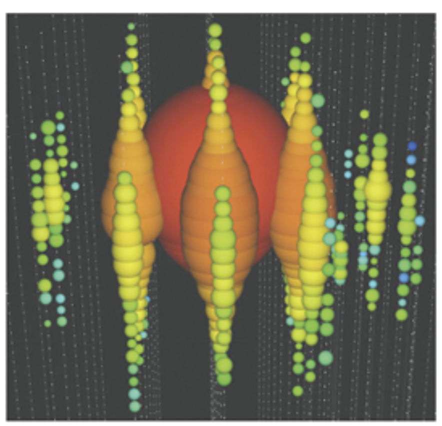
Upper bounds from an untriggered search for kilonovae in DES supernova fields



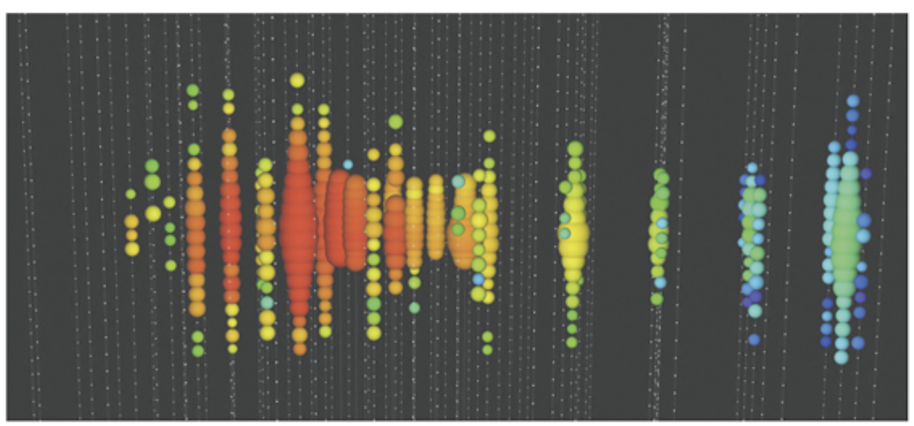
Search Strategy Considerations

- **Wide-field imaging matched to the angular resolution of track events**
- Imaging depth to efficiently detect sources at moderate redshifts
- All-sky coverage (+ template images)
- Observing cadence matched to optical emission timescale
- Control rate of unassociated optical transients passing selection

Cascade



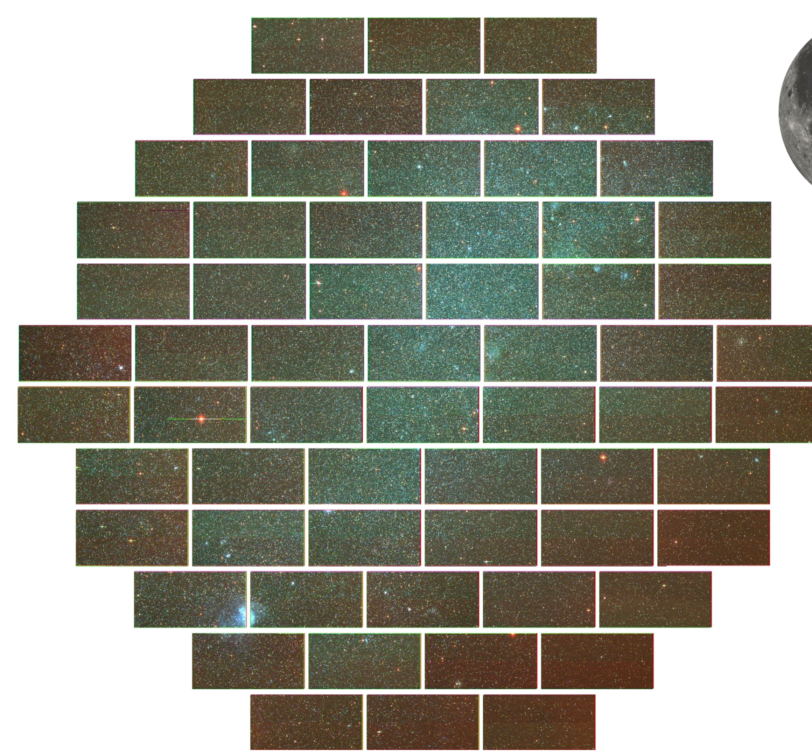
Track



IceCube 2014, arXiv:1406.6757

	Cascade	Track
Angular Resolution	~15 deg	~1 deg @ 1 TeV ~0.4 deg @ 100 TeV

Single DECam pointing



2.2 deg

Search Strategy Considerations

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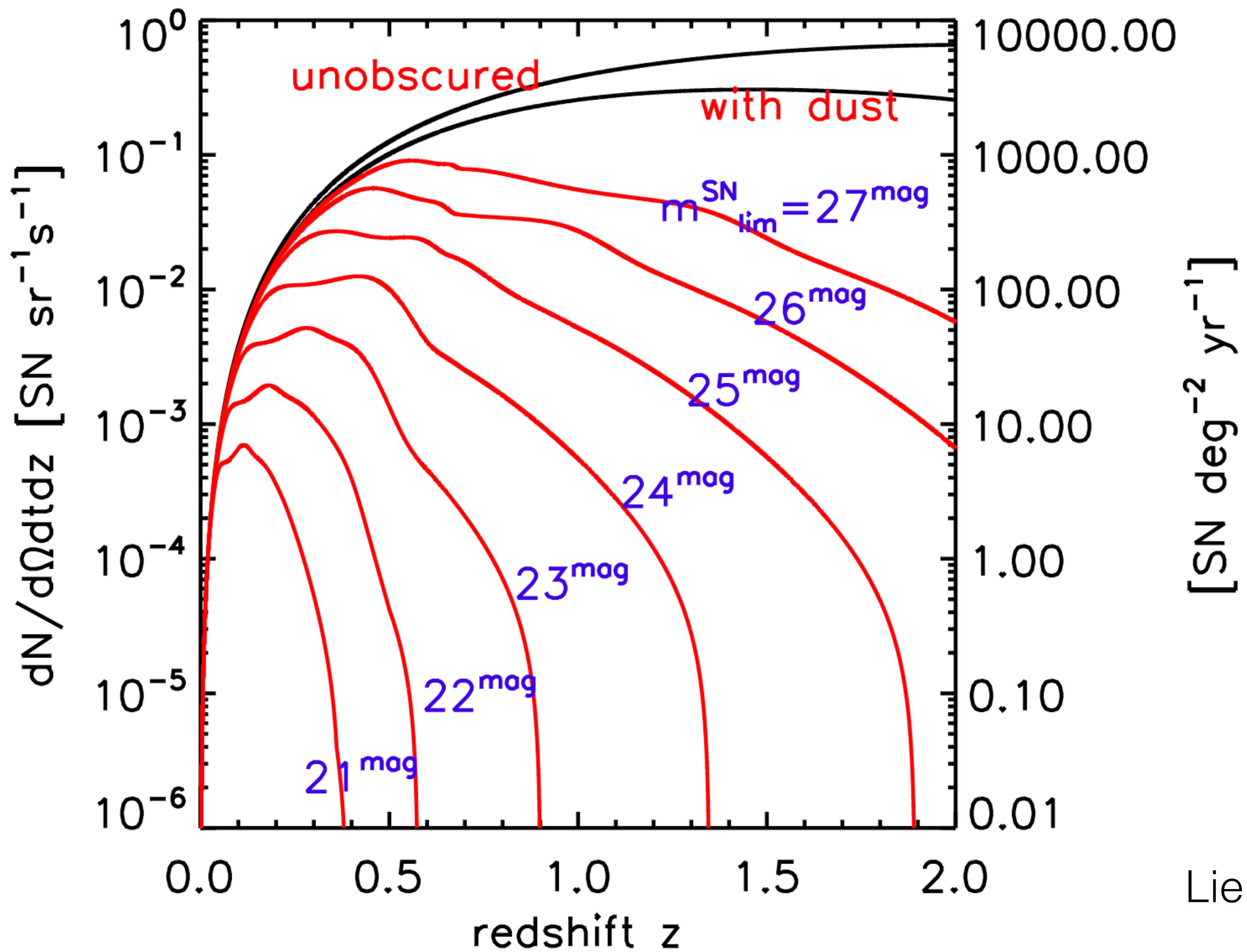

DECam can reach ~24th magnitude in each of the *g, r, i* bands in a total of 20 minutes

Lien & Fields 2009, arXiv:0902.0979

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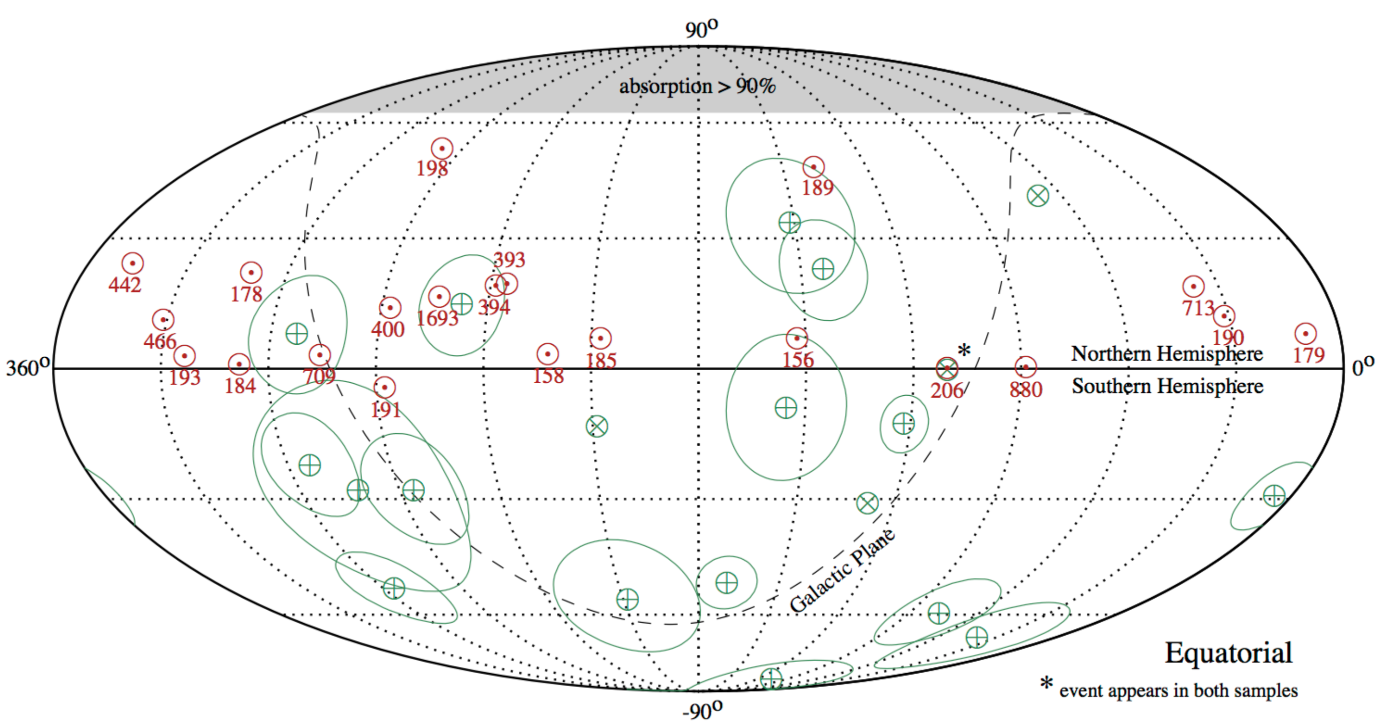
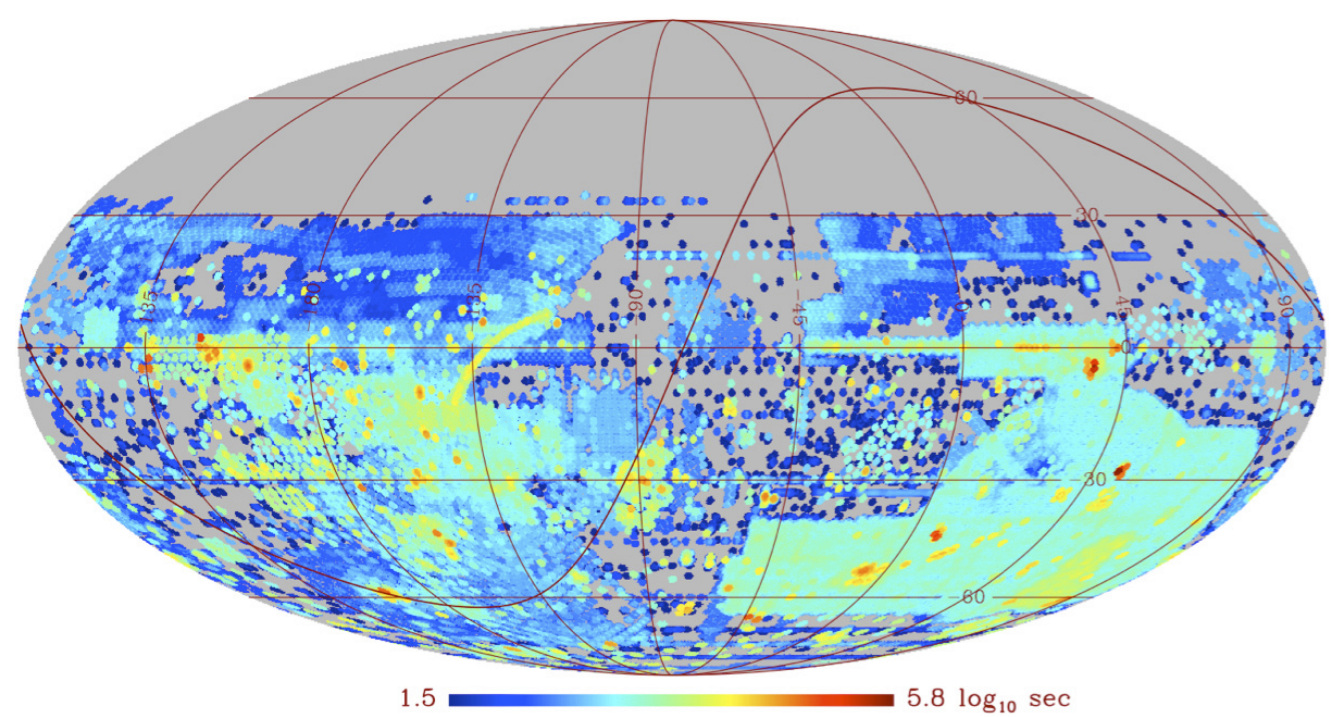
IceCube HESE (3yr) and NuMu (2y) Events



All DECam exposures up to June 2016



Search Strategy Considerations

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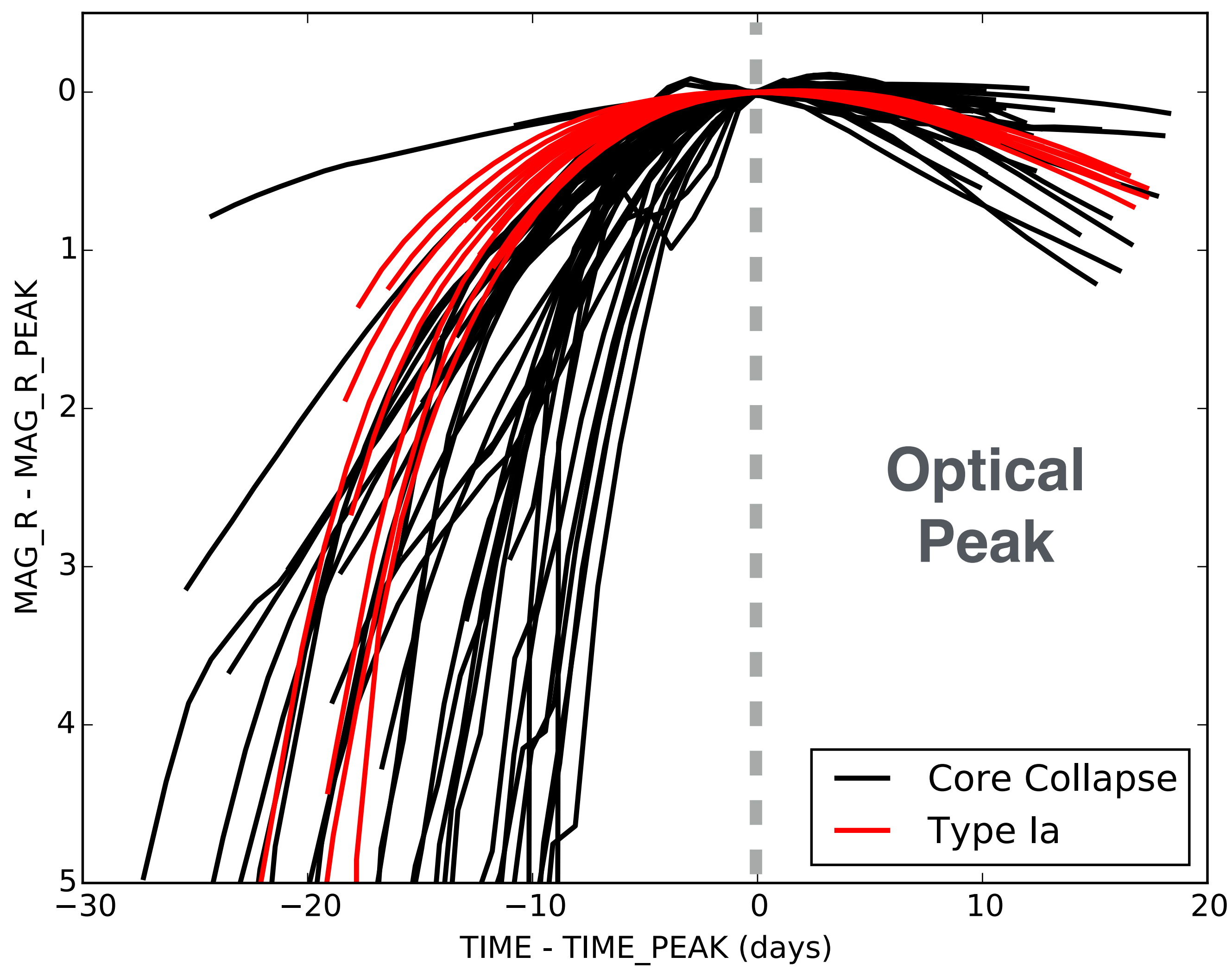

Peak of optical emission occurs a few days to a few weeks after initial explosion

Planning 6 epochs per alert = 2 hrs total DECam time

Search Strategy Considerations

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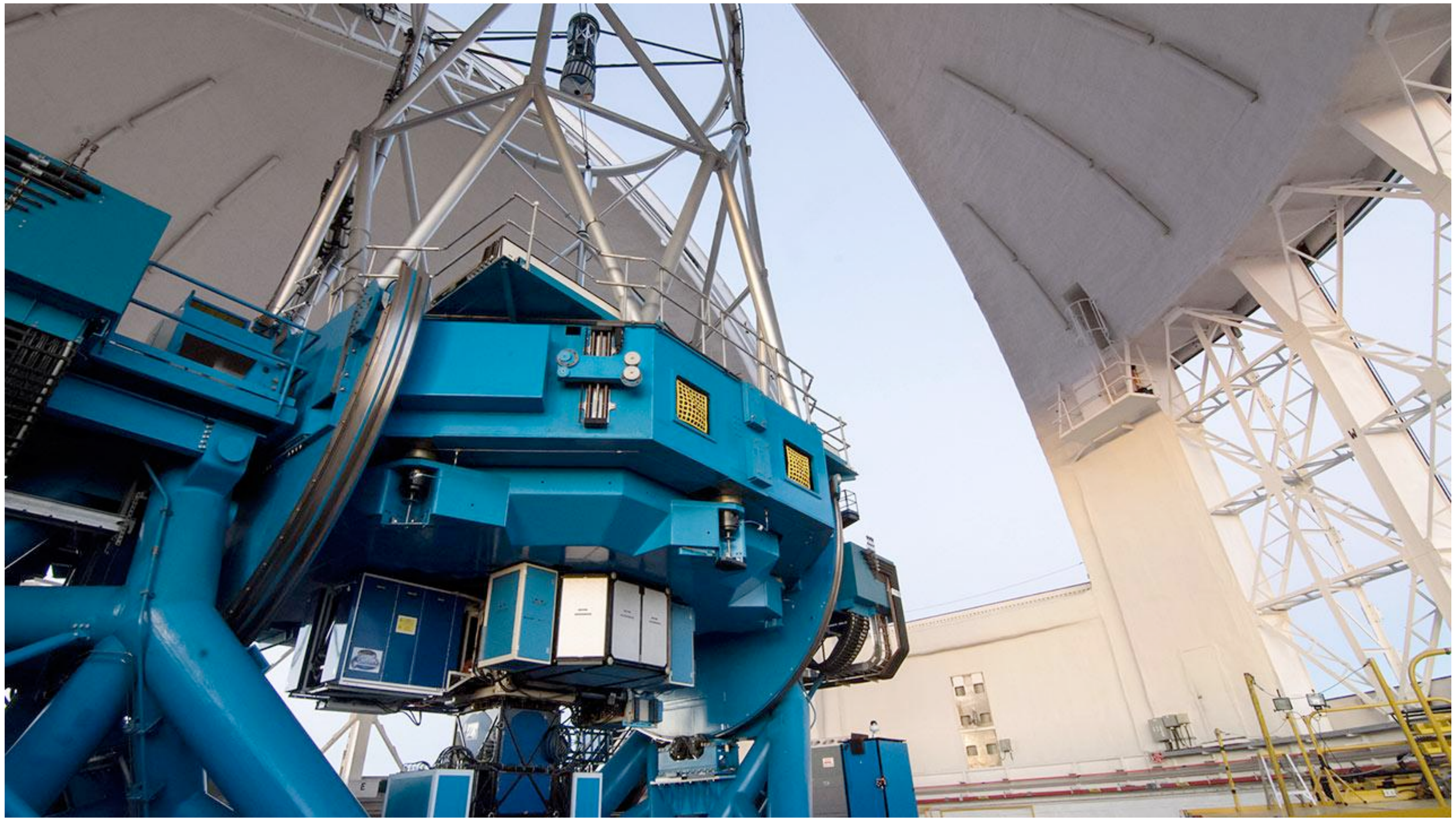
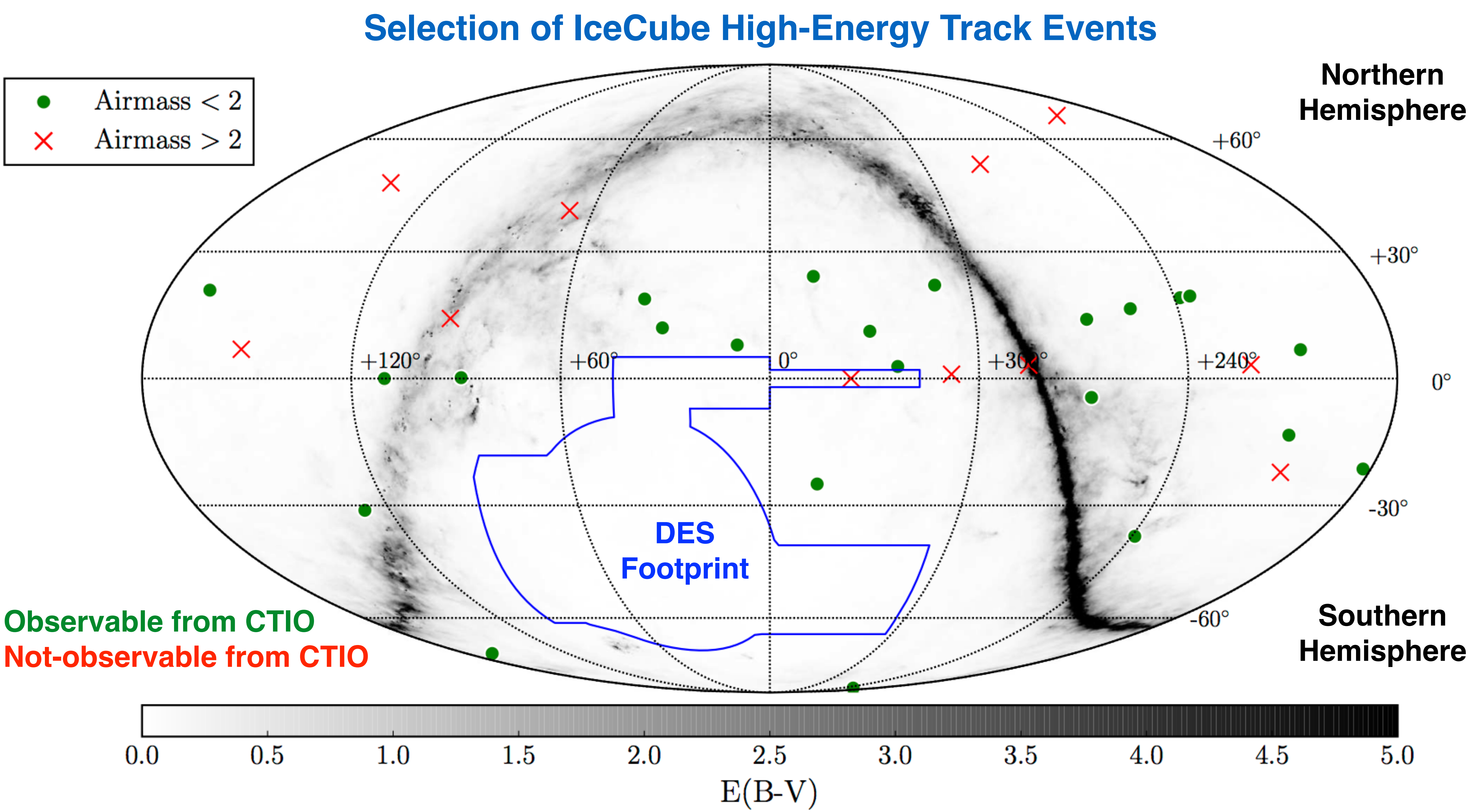


Triggered target-of-opportunity observations with spectroscopic instruments to classify and determine redshift of candidates (e.g., Gemini/GMOS-S)

Observability from CTIO



Dark Energy Camera (DECam)
at CTIO in Chile at latitude = 30 deg south

Simulated Nightly Light Curves

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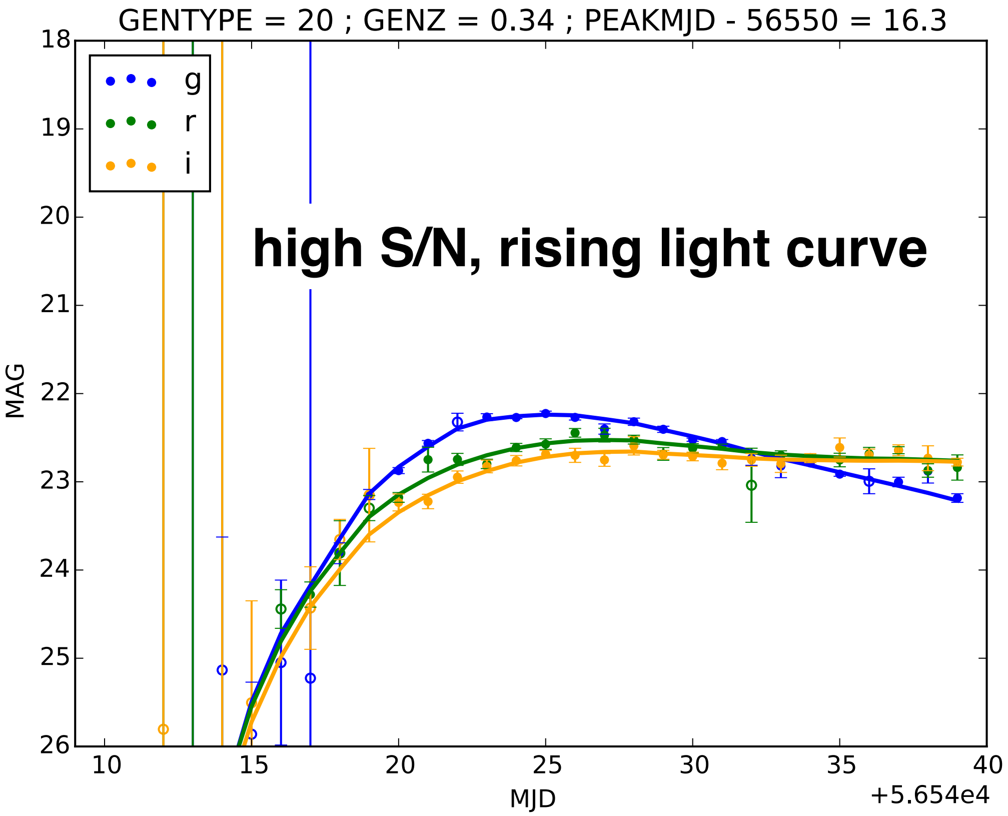
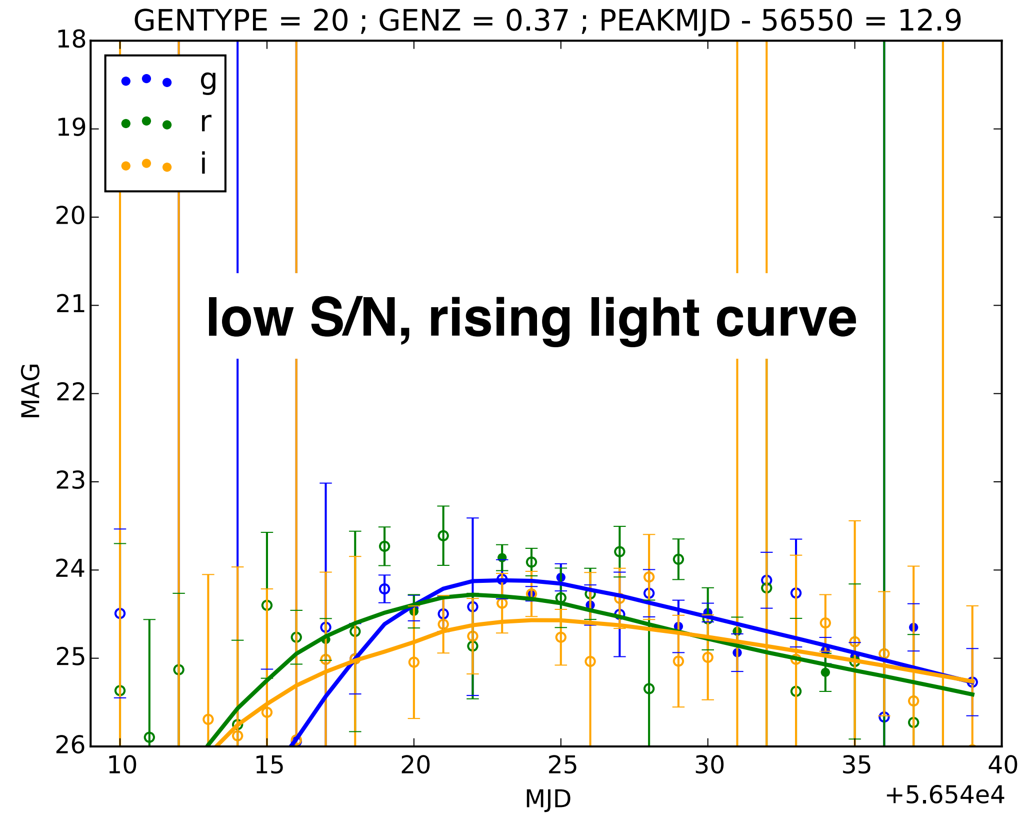
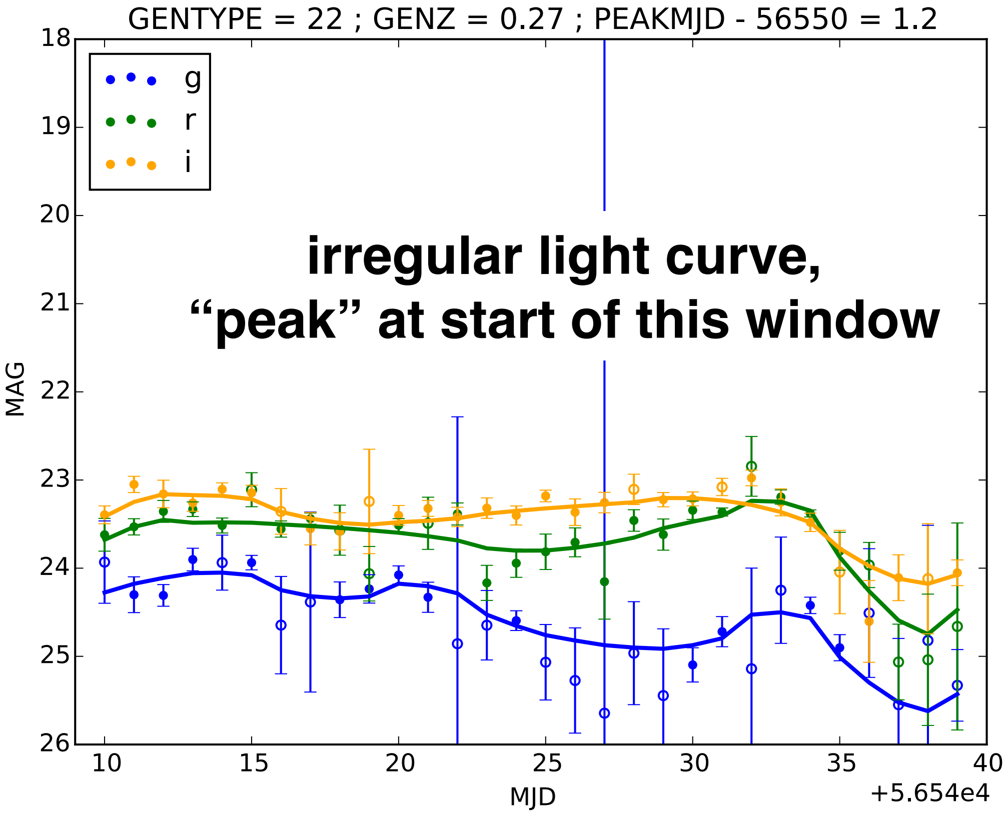
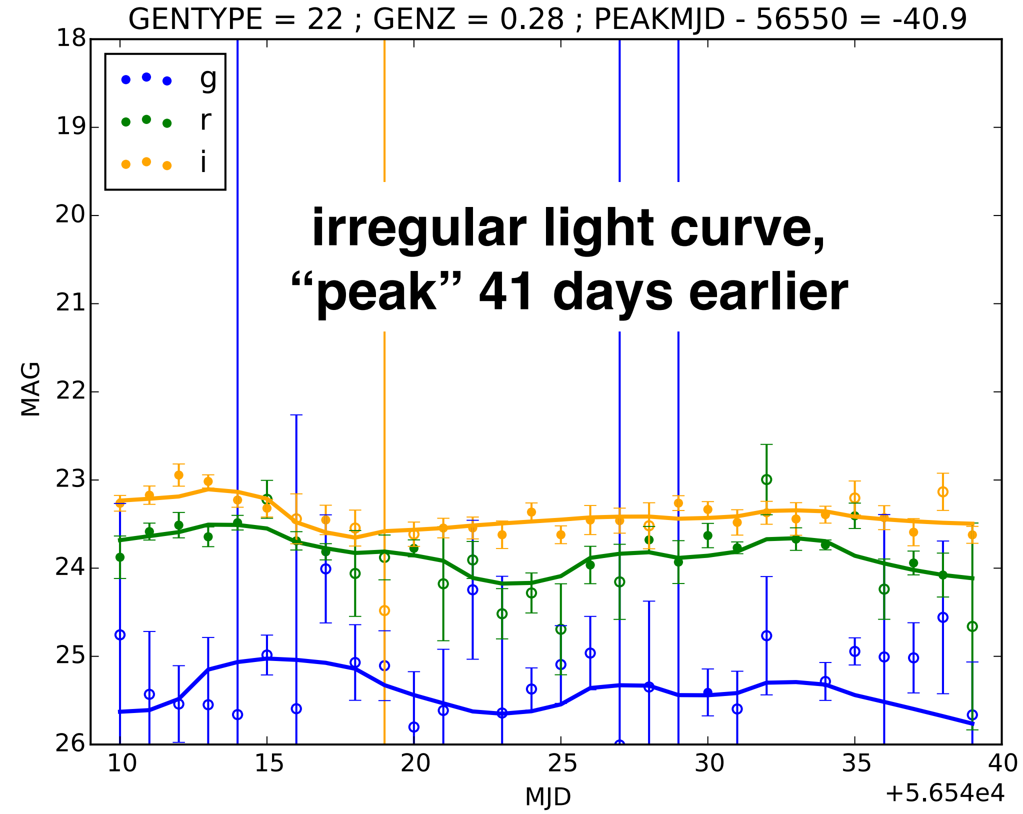


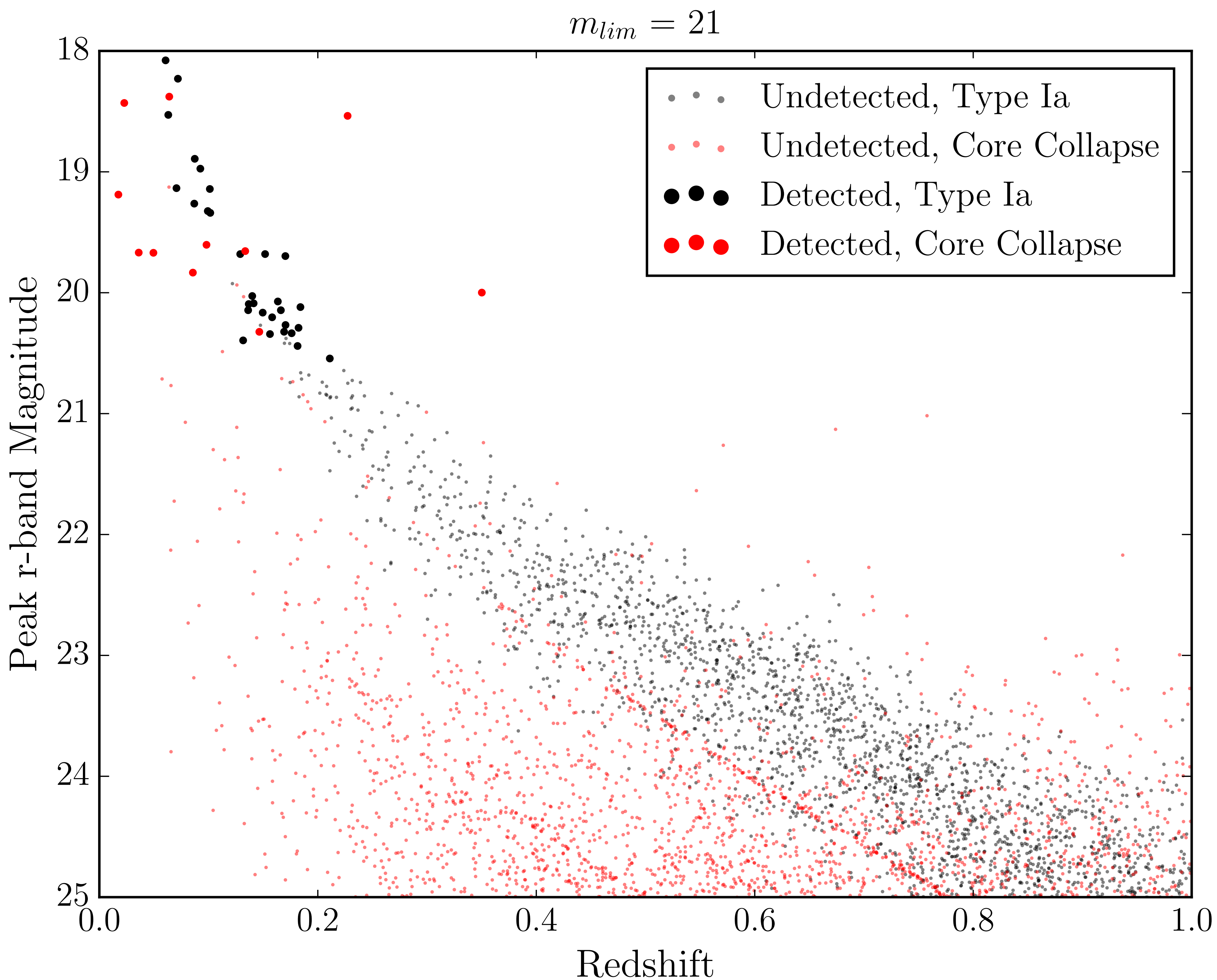




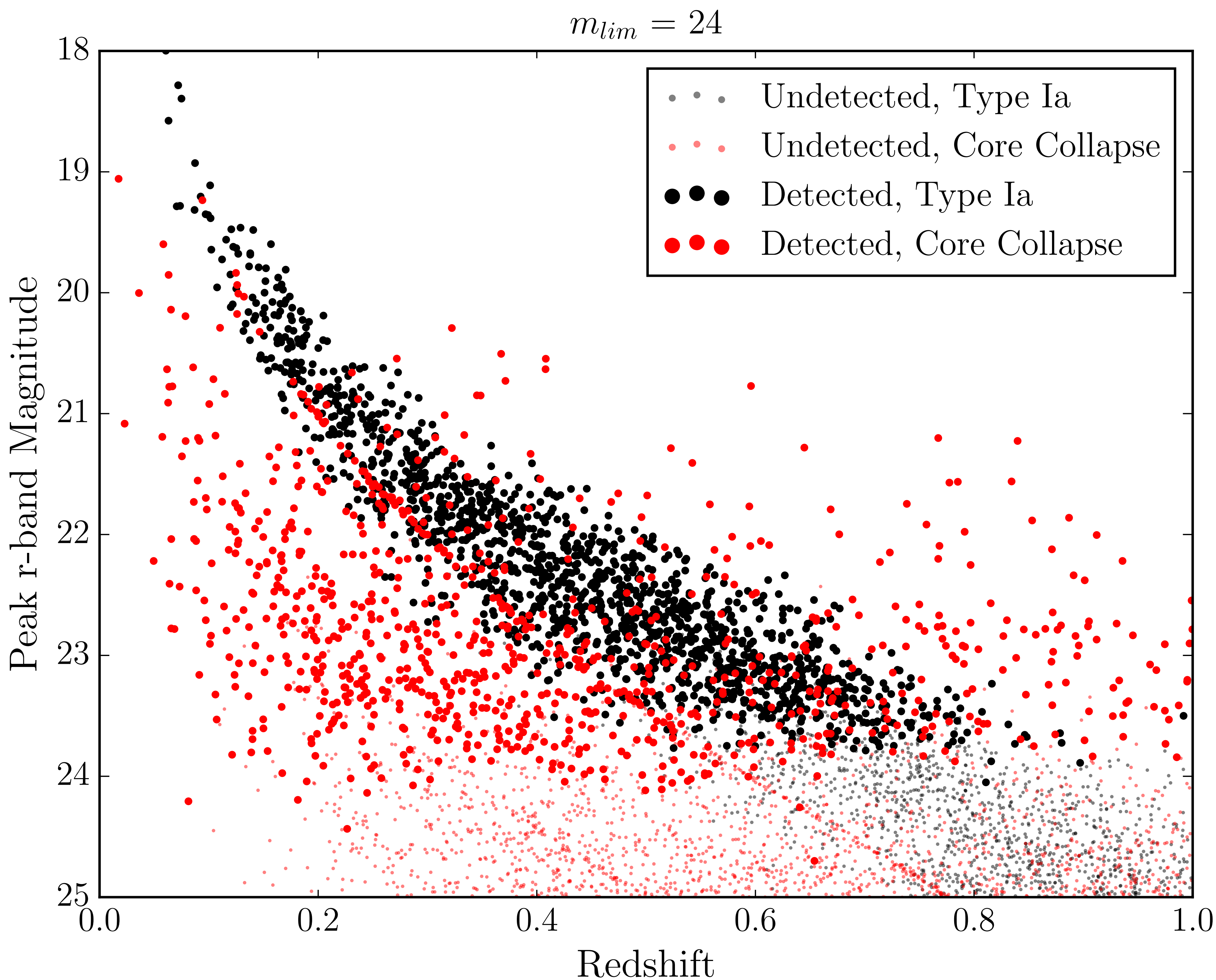


SNANA simulations package

Detection Efficiency: Pan-STARRS, PTF/ZTF, MASTER



Detection Efficiency: Planned DECam Trigged Follow-up

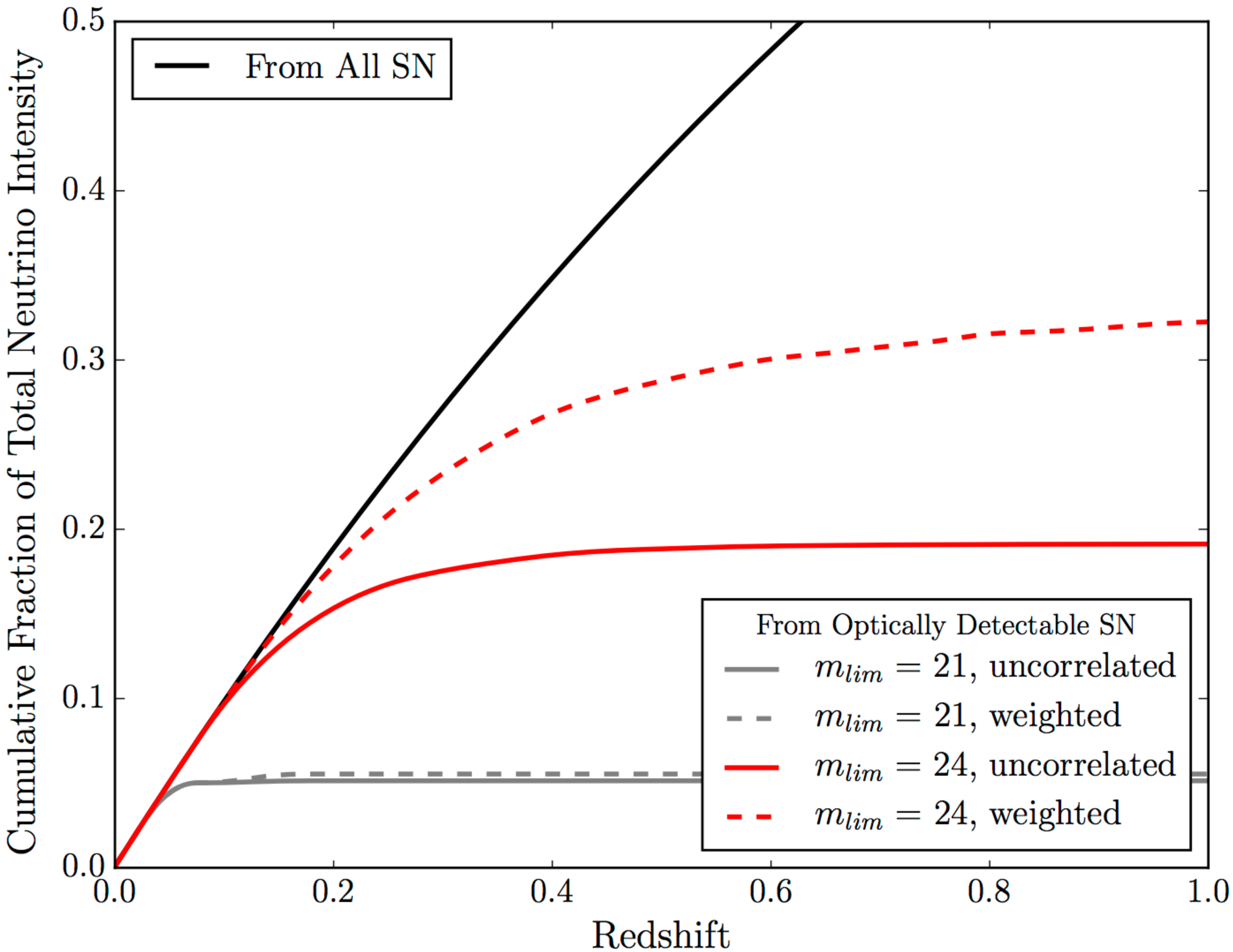


Redshift Integral

Volume Element — Neutrino Spectrum — SN Rate

$$\frac{dN_\nu(E_\nu)}{dE_\nu d\Omega dt_{\rm obs} dA} = \int_0^{z_{\rm max}} \frac{dV}{dz d\Omega} \frac{1}{4\pi D_L^2} \frac{dN_\nu(E_\nu(1+z))}{dE_\nu} \frac{1}{1+z} \mathcal{R}(z) dz$$

Luminosity Distance — Time Dilation



Illustrate 2 bracketing scenarios:

1. Neutrino luminosity **uncorrelated** with optical luminosity (conservative)
2. Neutrino luminosity **proportional** to optical luminosity (optimistic)

Rate of Unassociated Coincident Supernovae (i.e., “Background”)

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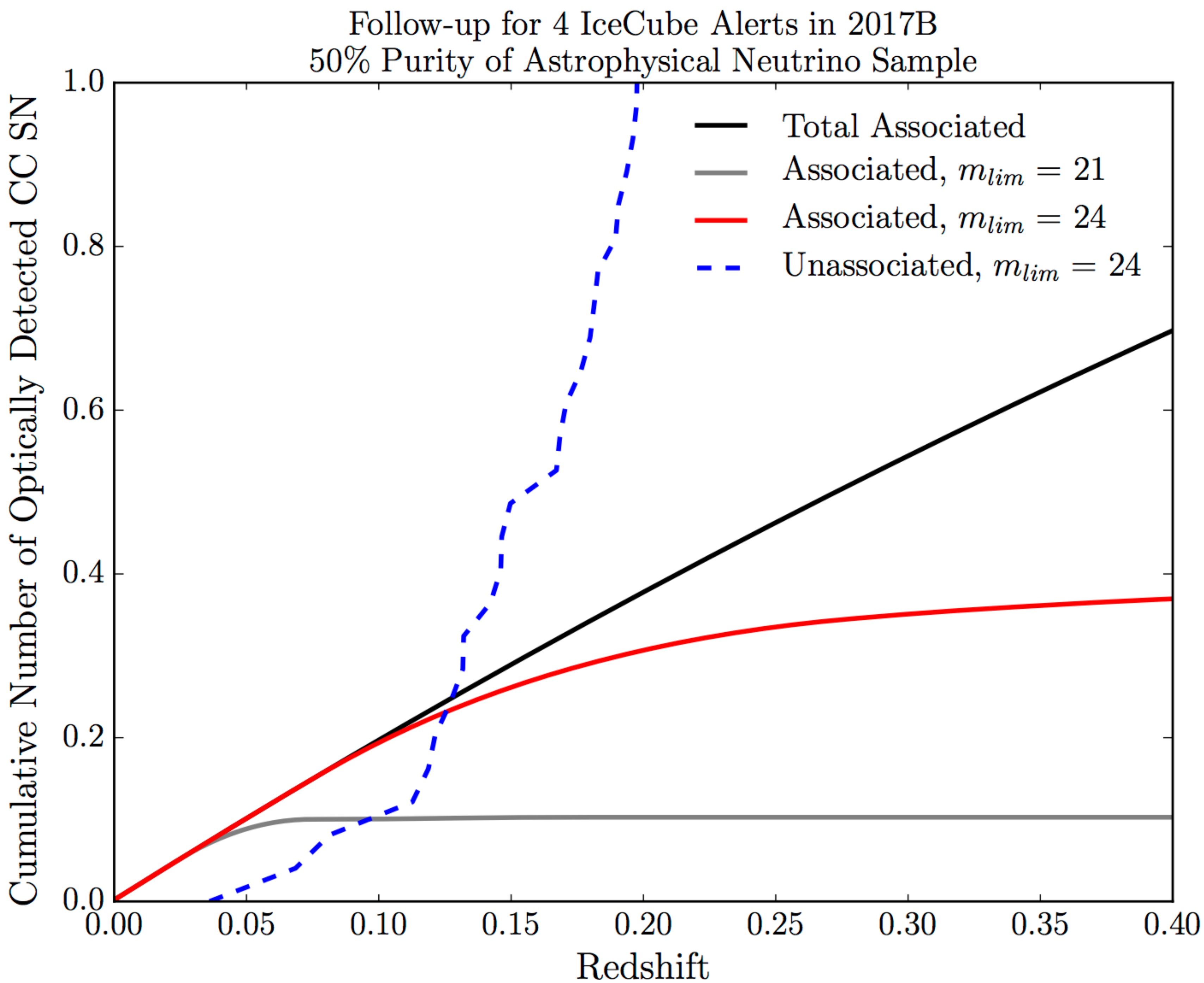
False positive rates for a variety of selections designed to remove unassociated transients

Cut	Background rate per neutrino event (Full DECam FOV)	Background rate per neutrino event (0.5 deg resolution)
30-day window	13.0	3.4
10-day window,	4.7	1.2
10-day window, CC only	1.5	0.4
10-day window, z < 0.4	1.5	0.4
10-day window, z < 0.4, CC only	0.8	0.2
10-day window, z < 0.2, CC only	0.3	0.07

Expected Rates of Associated and Unassociated Supernovae



Proposed follow-up of 4 IceCube alerts in 2017B w/ DECam

m_{lim} ~ 24 achieved in
~300 sec w/ DECam (3 deg^2)
~30 sec w/ LSST (10 deg^2)

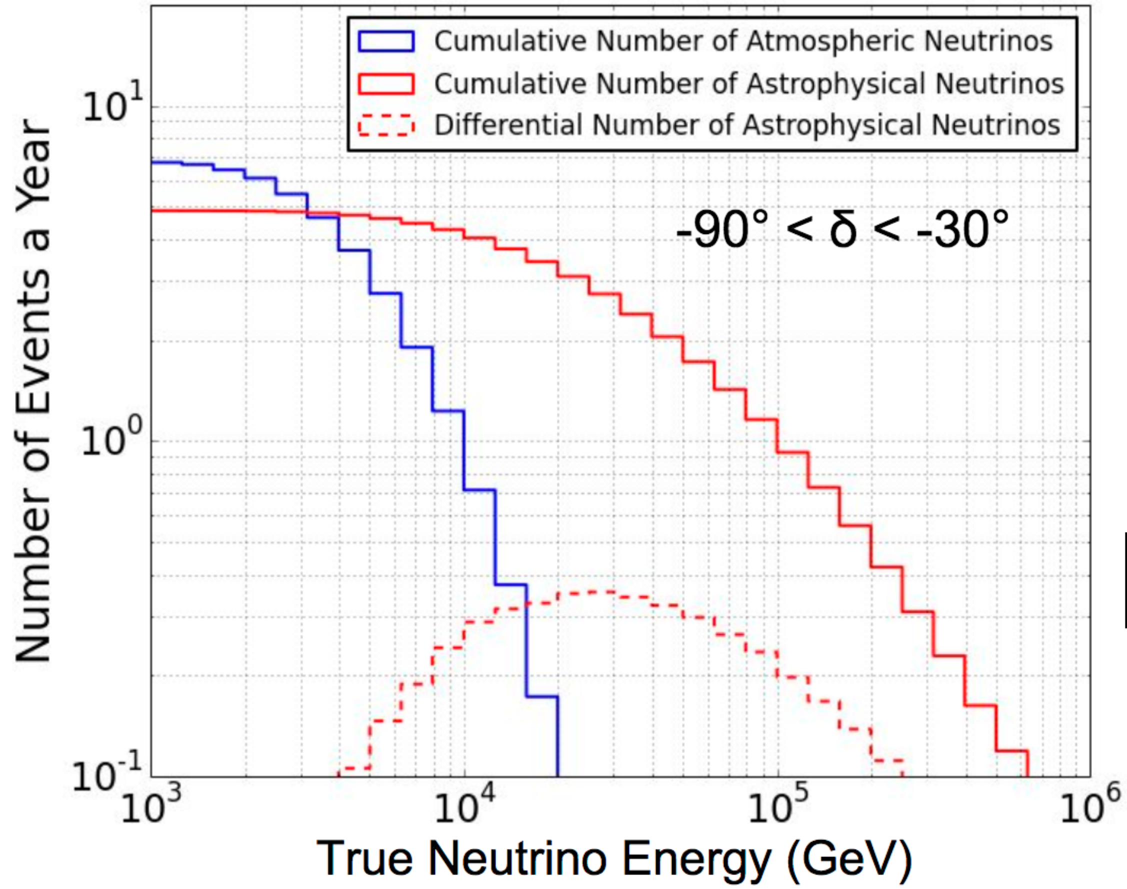
Baseline Pan-STARRS / ZTF

Estimate coincidence rate of unassociated CC SN in full DECam field of view (3 deg^2) using a 10 day window centered on neutrino event

Near-Term Opportunities

2017B Semester:

- DES: Granted 8 hrs of DECam time + 7 hours of Gemini/GMOS-S time for triggered follow-up of ~4 IceCube alerts
- IceCube implementing ESTReS realtime alert stream for high-purity selection of starting track events in southern sky



See talk by Sarah Mancina

Early 2018:

- ZTF begins public surveys, including survey of the full northern sky visible from Palomar Observatory with 3-day cadence

Longer-Term Opportunities

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Testing an association between TeV-PeV neutrinos and explosive optical transients appears feasible with a modest but *sustained* follow-up campaign

Neutrino observatories:

- KM3NeT, IceCube Gen-2

Optical Surveys, e.g., Large Synoptic Survey Telescope (LSST, ~2022):

- Samples of ~10^5 CC SN yr^{-1} over 18,000 deg^2 of the southern hemisphere
- Evolving modes of observatory scheduling / operation in LSST era

Extras

Summary of Current and Future Optical Survey Instrument Capabilities

Survey Camera	D (m)	$\Omega_{\rm fov}$ (deg^2)	Etendue (m^2 deg^2)	Pixels ($''$)	$t_{\rm exp}$ (sec)	$t_{\rm OH}$ (sec)	$m_{\rm lim}$	$\dot{\Omega}$ (deg^2 hr^{-1})	$N_{\rm obs}$ (yr^{-1})	$\dot{V}_{-19}$ (Mpc^3/s)	$f_{\rm spec}$
Evryscope	0.06(27×)	8660	26.5	13.3	120	4	16.4	251419	19279	1.1×10^4	1.00
ASAS-SN 1	0.14(4×)	73	1.1	7.8	180	23	17	1294	99	1.2×10^2	1.00
ATLAS	0.5(2×)	60	11.8	1.9	30	8	20.0	5684	435	2.3×10^4	1.00
CRTS	0.7	8.0	3.1	2.5	30	18	19.5	600	46	1.4×10^3	1.00
CRTS-2	0.7	19.0	7.3	1.5	30	12	19.5	1628	124	3.7×10^3	1.00
LSQ	1.0	8.7	6.8	0.9	60	40	20.5	313	24	2.3×10^3	1.00
PTF	1.2	7.3	8.2	1.0	60	46	20.7	246	18	2.3×10^3	1.00
Skymapper	1.3	5.7	7.5	0.5	110	20	21.6	157	12	3.9×10^3	0.52
PS1 3π	1.8	7.0	17.8	0.3	30	10	21.8	630	48	1.9×10^4	0.42
SST	2.9	6.0	39.6	0.9	1	6	20.7	3085	236	2.7×10^4	1.00
MegaCam	3.6	1.0	10.2	0.2	300	40	22.8	10	0.8	8.8×10^2	0.16
DECam	4.0	3.0	37.7	0.3	50	20	23.7	154	11	2.9×10^4	0.07
HSC	8.2	1.7	89.8	0.2	60	20	24.6	76	5	3.1×10^4	0.03
BlackGEM*	0.6(4×)	2(4×)	11.3	0.6	30	5	20.7	822	63	7.6×10^3	1.00
ZTF*	1.2	47	53.1	1.0	30	15	20.4	3760	288	2.5×10^4	1.00
LSST*	6.7	9.6	319.5	0.2	30	11	24.7	842	64	3.7×10^5	0.03

Bellm 2016
arXiv:1605.02081