Transient Sky in the Era of Time-Domain Astronomy

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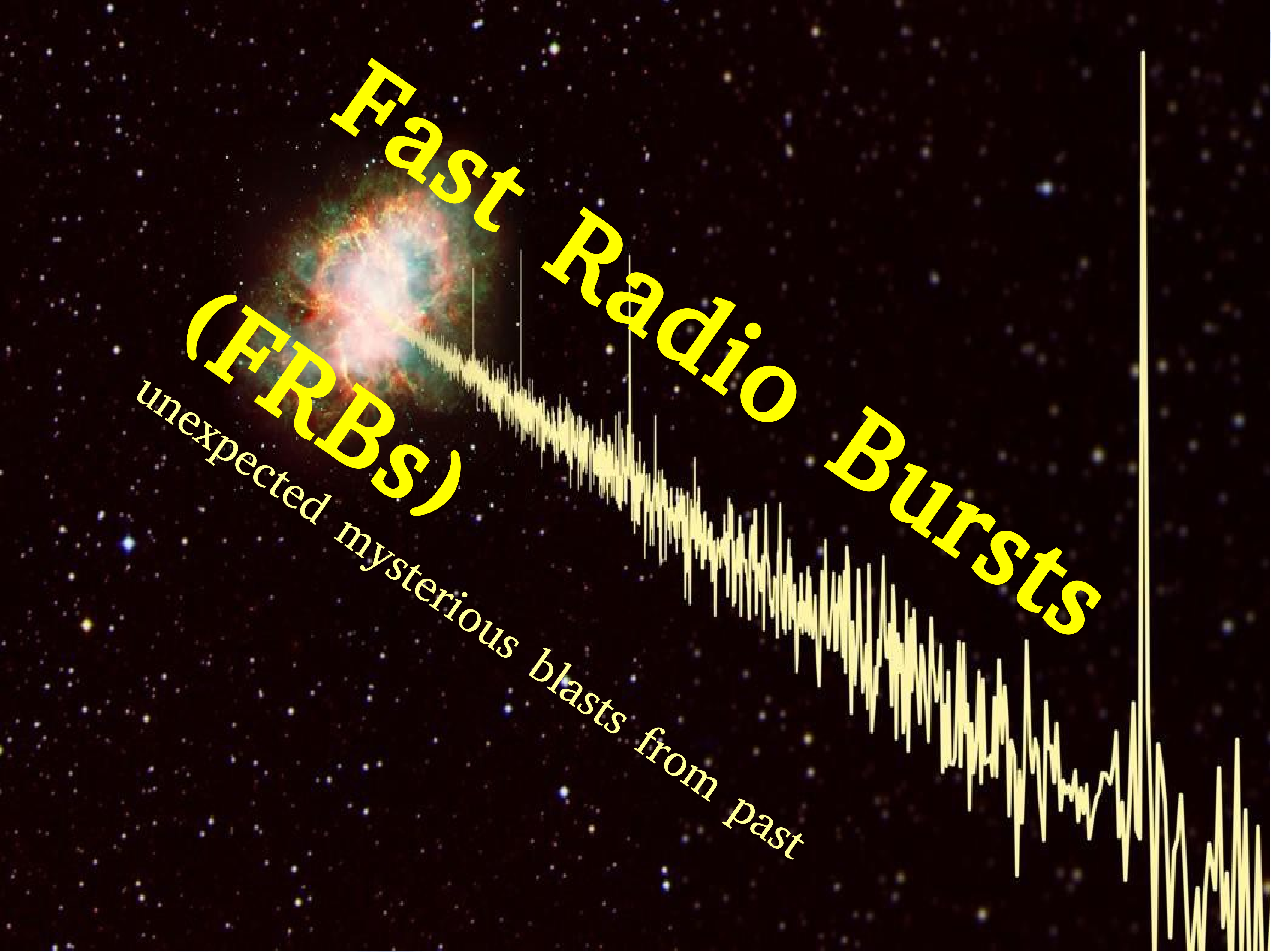
Lecture 2

UNIVERSITÀ DEGLI STUDI DI FERRARA
1391
EX LABORE FRUCTUS

Overview

- Fast Radio Bursts (FRBs)
- Review of some **current** synoptic surveys
- move on to **future** facilities
- Highlights on the **multi-wavelength and multi-messenger** character of future followup activities
- **Strategy, coordination** of followup observations.
- **Data mining**: development of clever code to cope with massive data sets


Fast Radio Bursts
(FRBs)
unexpected mysterious blasts from past

Basic properties

- Only 9 found so far (as of mid Dec 2014)
- All observed in 21 cm waveband
- Observed at different locations on sky
- No repetition
- Positional uncertainty
- Fluxes: 0.35-30 Jy [1Jy = 10^{-26} W m^{-2} Hz^{-1}]
- Durations: a few ms
- Very high dispersion measure:

  DM = 375 – 1629 pc cm^{-3}

$$DM = \int_0^d n_e \, dl$$

Dispersion

Plasma frequencies in astrophysics are usually around a few kHz, so in the radio band at 100 MHz −1 GHz the group velocity can be approximately written as

$$v_g = c\sqrt{1-\left(\frac{\omega_p}{\omega}\right)^2} \simeq c\left[1-\frac{1}{2}\left(\frac{\nu_p}{\nu}\right)^2\right]$$

Suppose a pulse of radio waves is emitted at t = 0 from a pulsar at distance l from Earth. The arrival time ta is then

$$t_a = \int_0^l \frac{dl}{v_g} \simeq \int_0^l \frac{dl}{c}\left[1+\frac{1}{2}\left(\frac{\nu_p}{\nu}\right)^2\right] = \frac{l}{c} + \frac{e^2}{2\pi m c \nu^2}\int_0^l n\,dl$$

$$\Delta t_a = \frac{e^2}{2\pi m c}\frac{D}{\nu^2}$$

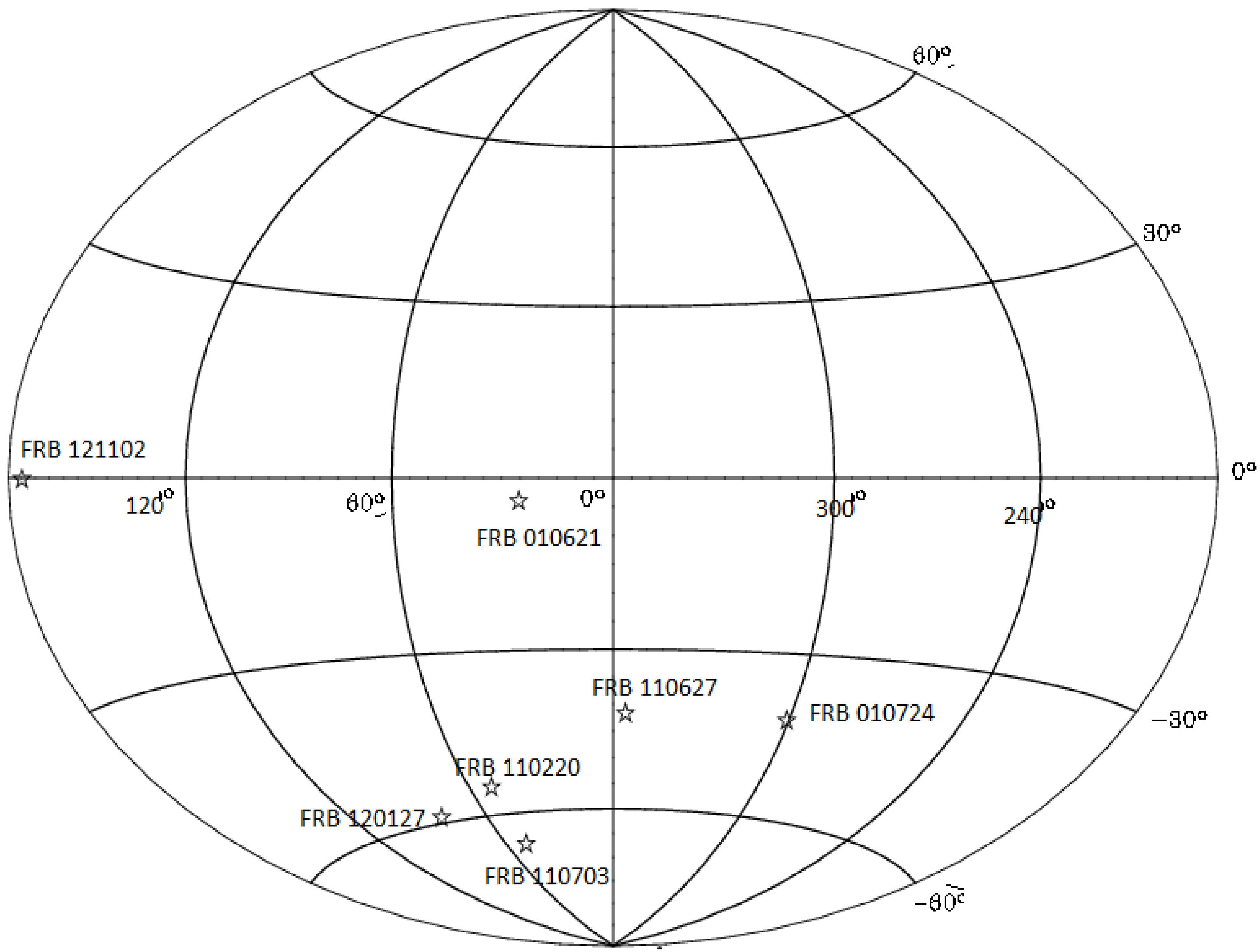
$$D := \int_0^l n\,dl$$ **DISPERSION (or DM)**

$$\Delta t_a \simeq \frac{4.15\times 10^{15}}{\nu^2} D \quad \text{s}$$

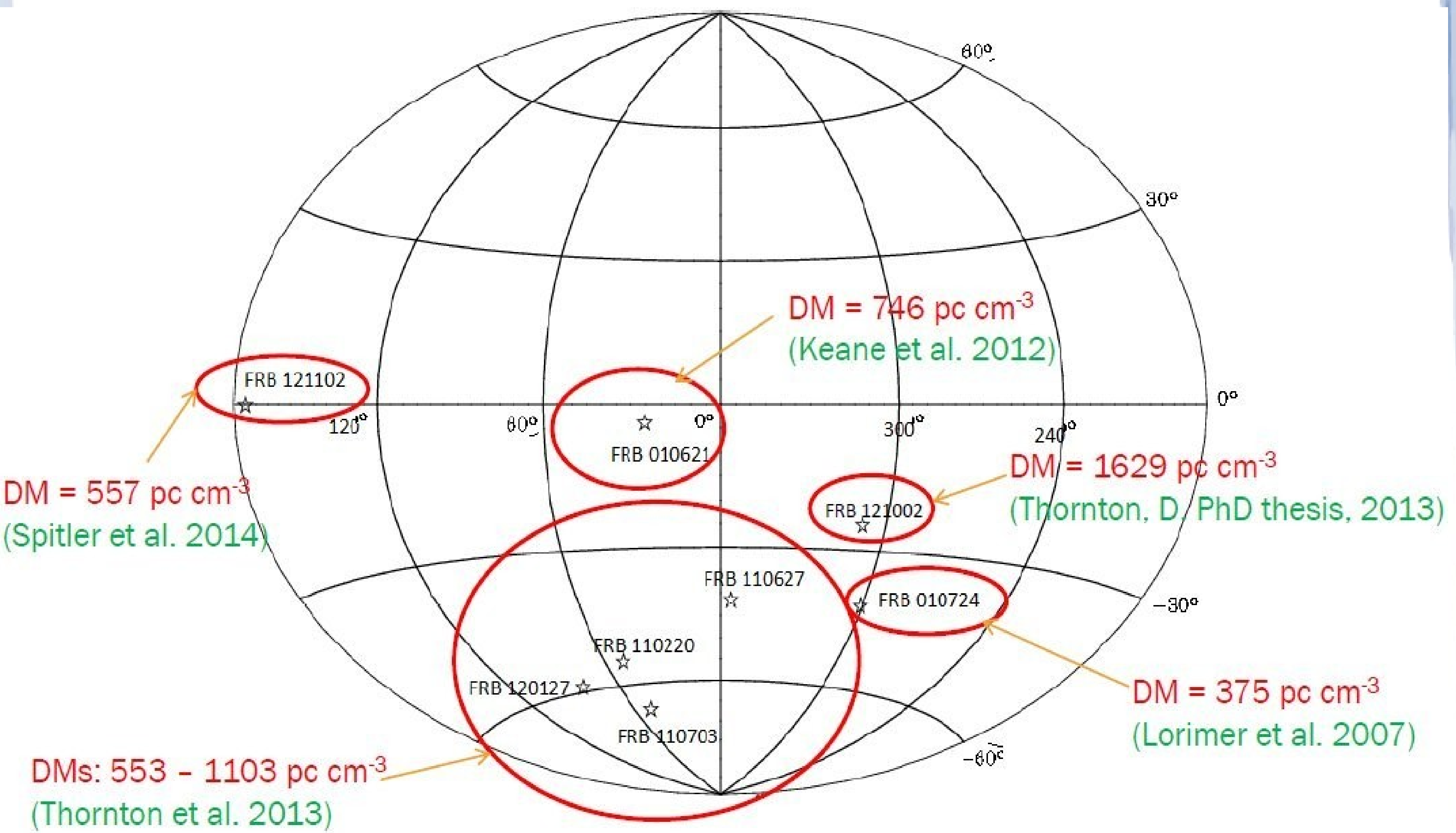
$$[D] = pc\,cm^{-3}$$

$$[\nu] = Hz$$

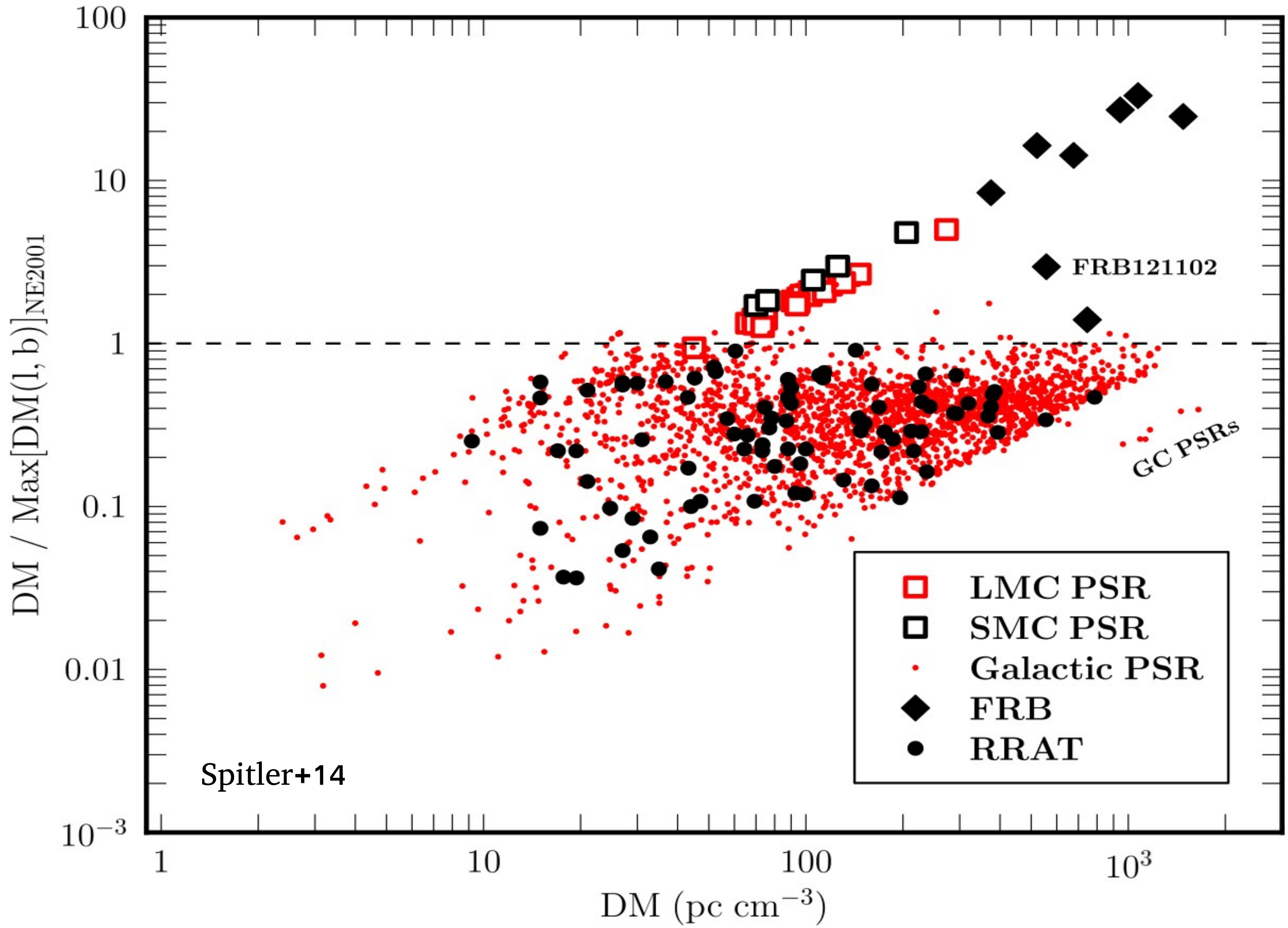
Distribution in Galactic coordinates



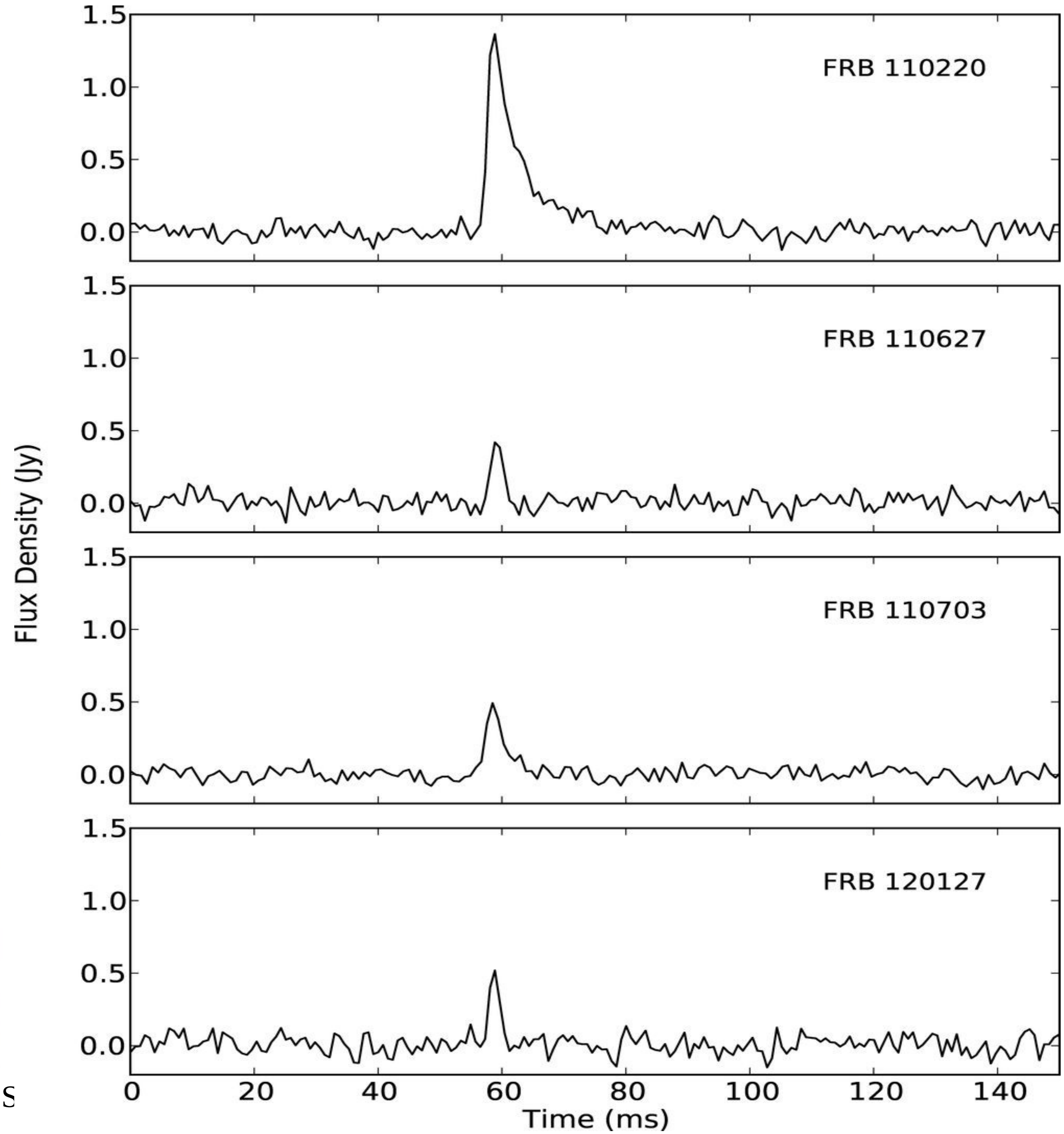
Distribution in Galactic coordinates



Comparison with galactic DM

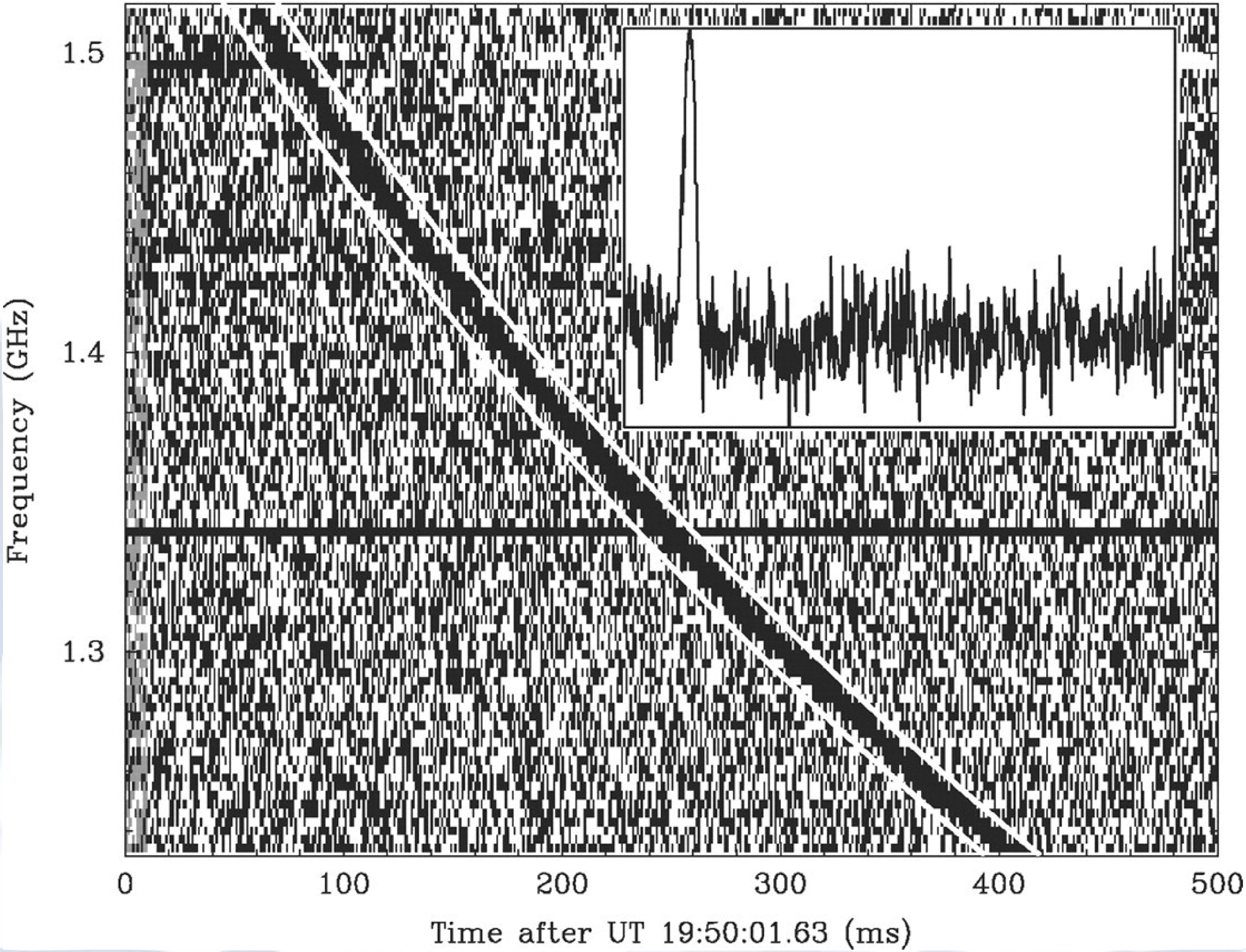


Pulse Time Profiles



Thornton+13

Dynamic Spectrum: intensity as a function of frequency



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Lorimer+07

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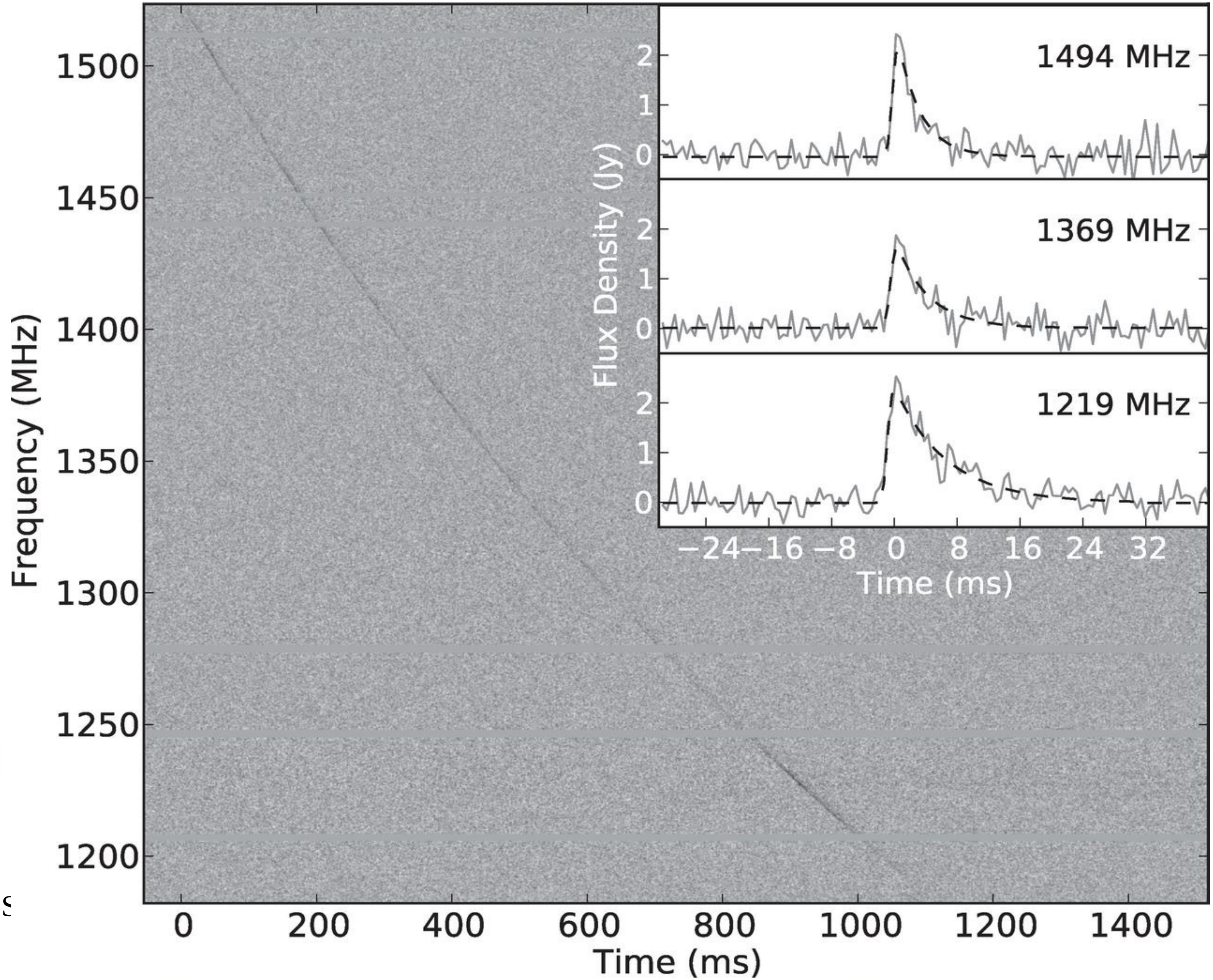
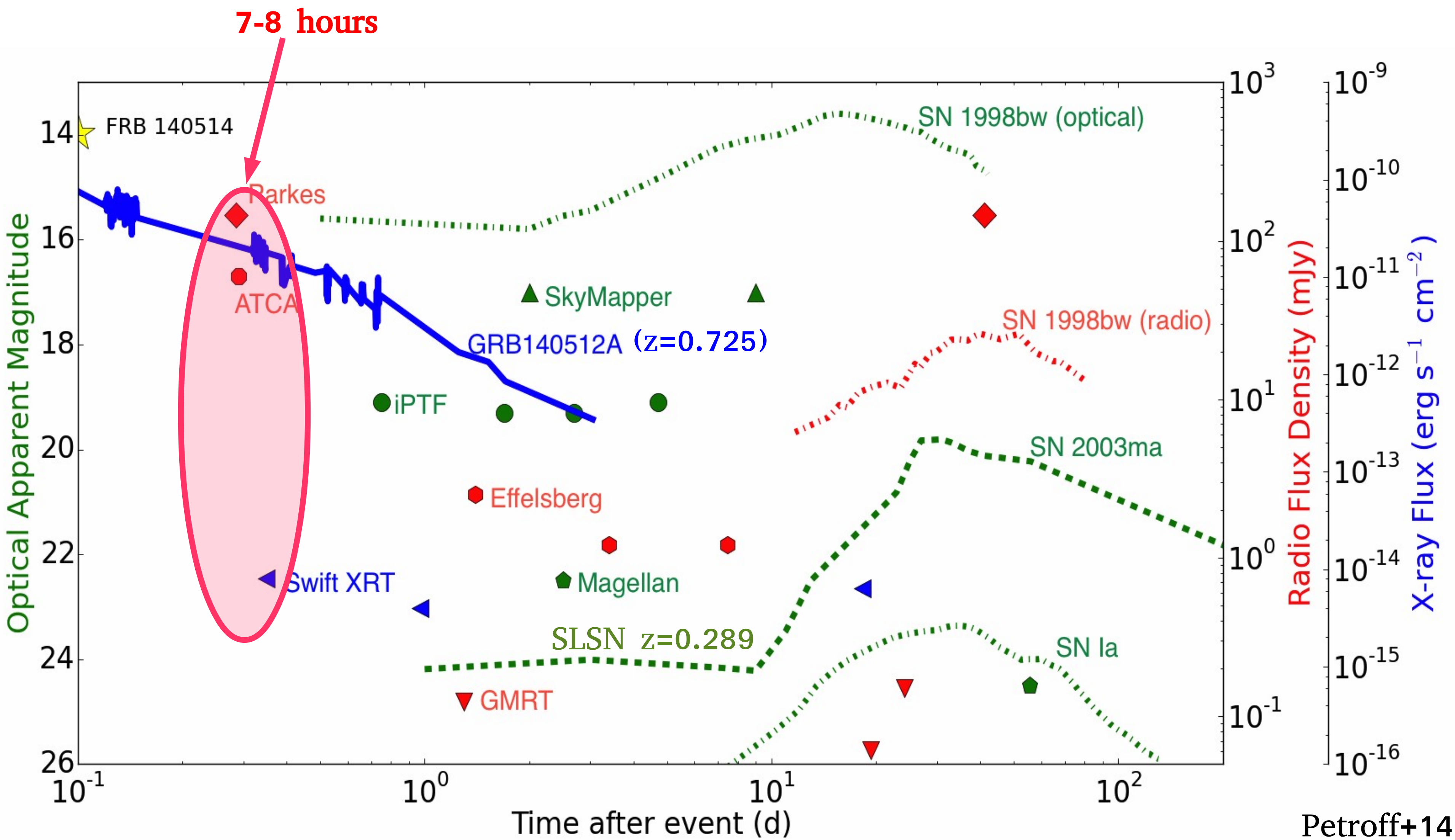


FRB110220

Thornton+13

FRB 140514: fast X-ray, optical, radio, upper limits



Petroff+14

Inferred FRB rates

Survey	Area	t_{obs}	FRBs found	Rate
	(deg^2)	(s)		(FRBs/day/sky)
HTRU	4078	270	4	$1.2^{+0.2}_{-0.3} \times 10^4$
PALFA	380	268	1	$3.6^{+5.8}_{-0.2} \times 10^4$
PH	3588	265	<1	$4.7^{+9.5}_{-1.0} \times 10^3$

Interpretations: almost everything…

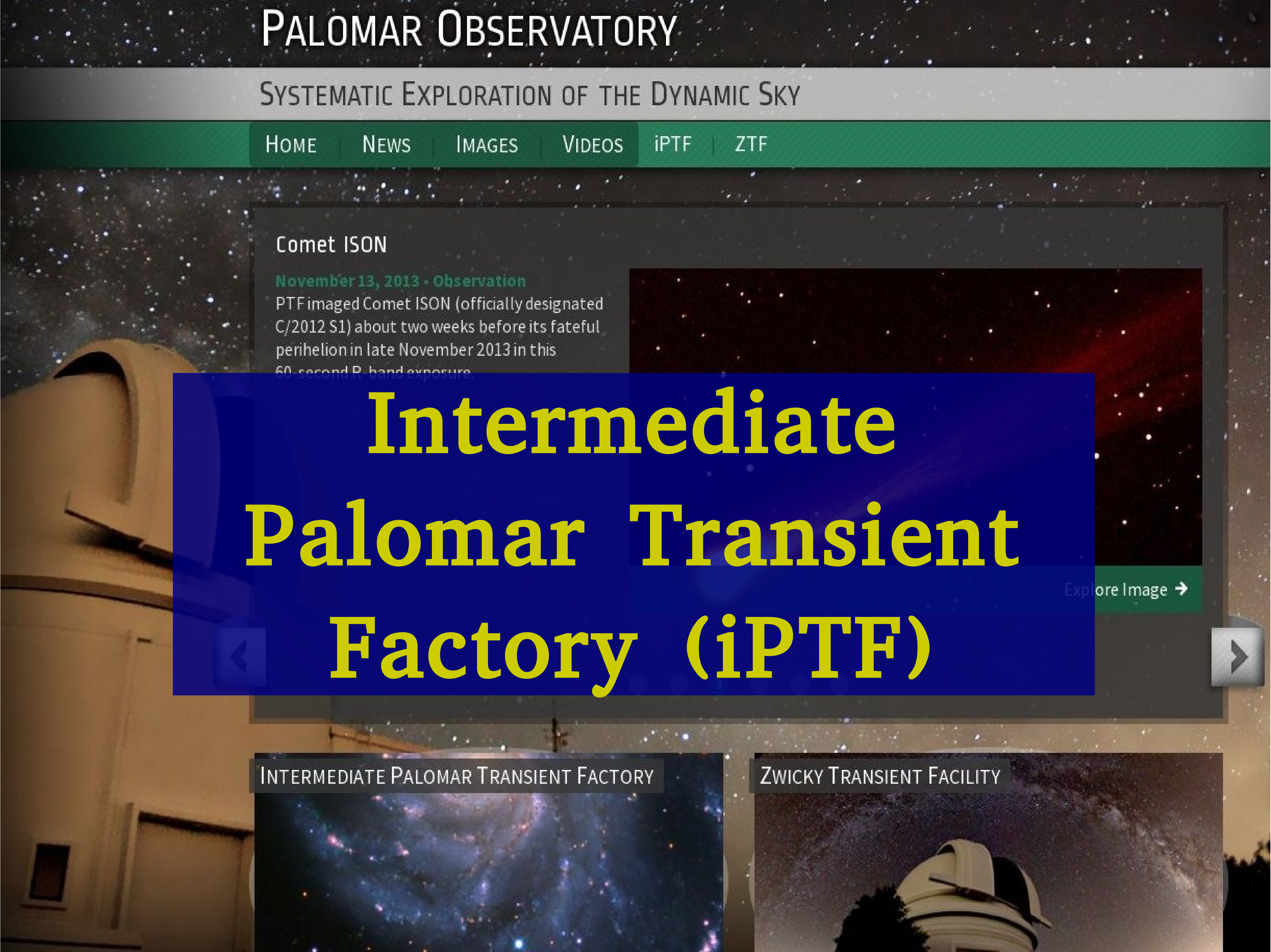
- Ascribing DM to host galaxies and IGM
  - $z \sim 0.5\text{-}1$, $L_{p,radio} \sim 10^{42\text{-}43}$ erg/s, $E \sim 10^{39\text{-}40}$ ergs

  ⇒ Hyperflares from magnetars, collapse of NS to BH, mergers of double NSs or binary WDs, connected with fraction of GRBs (Popov&Postnov07,Falcke&Rezzolla14,Totani13,Kashiyama13,Zhang14)
- Crab-like giant pulses or flares from local circumnuclear magnetars within nearby (< hundreds Mpc) galaxies (Pen+Connor15).
- Due to nearby (≤ 1 kpc) flaring stars? (Loeb+14; Maoz+15)

FRB: future developments

- Need to increase the sample
- Many unknowns (spectra, rate, distance, thus luminosities, origin...)
- If cosmological, FRBs can probe the ionized IGM
- Real-time detections and multi-wavelength followup (as it was the case with GRBs)
- FRBs are now science drivers on incoming telescopes (FAST, MeerKAT...)
- Potential for high-impact science


Currently
operational surveys



Palomar Observatory
Systematic Exploration of the Dynamic Sky
Home
News
Images
Videos
iPTF
ZTF
Comet ISON
November 13, 2013 • Observation
PTF imaged Comet ISON (officially designated C/2012 S1) about two weeks before its fateful perihelion in late November 2013 in this
Explore Image
Intermediate Palomar Transient Factory (iPTF)
Intermediate Palomar Transient Factory
Zwicky Transient Facility

PALOMAR OBSERVATORY

SYSTEMATIC EXPLORATION OF THE DYNAMIC SKY

- Built upon the legacy of Caltech-led PTF, which began in 2009
- Large field camera: 7.8 deg^2
- 11 active 2048x4096 pixel CCDs
- Telescope: 1.2m (48 inch) Samuel Oschin Telescope at Palomar Observatory (same used for photographic Palomar All-Sky Survey)
- Standard strategy: 60s exposures in R+g bands
    - R_{lim} = 20.5 mag @ 3σ
    - G_{lim} = 21 mag @ 3σ
    - Different cadences: from 90s to 5 days
- Real time transient search at Lawrence Berkeley National Lab
- 2017: iPTF will transition to the Zwicky Transient Factory (ZTF), which will be a direct lead-in to the LSST era.

INTERMEDIATE PALOMAR TRANSIENT FACTORY

ZWICKY TRANSIENT FACILITY

PALOMAR OBSERVATORY

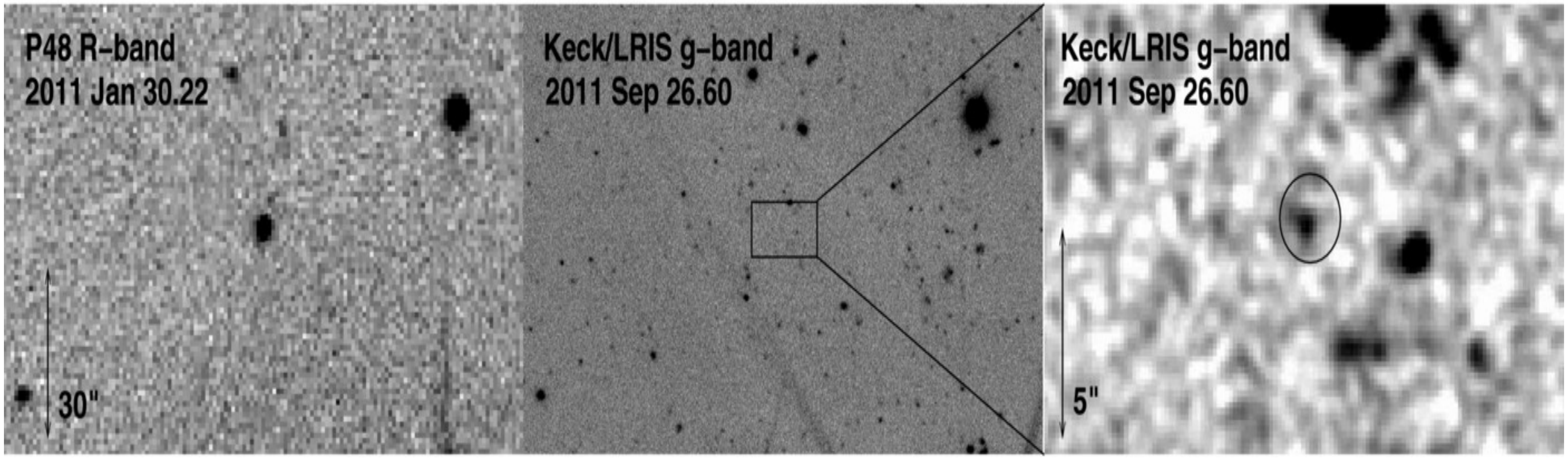
SYSTEMATIC EXPLORATION OF THE DYNAMIC SKY

Survey Operation

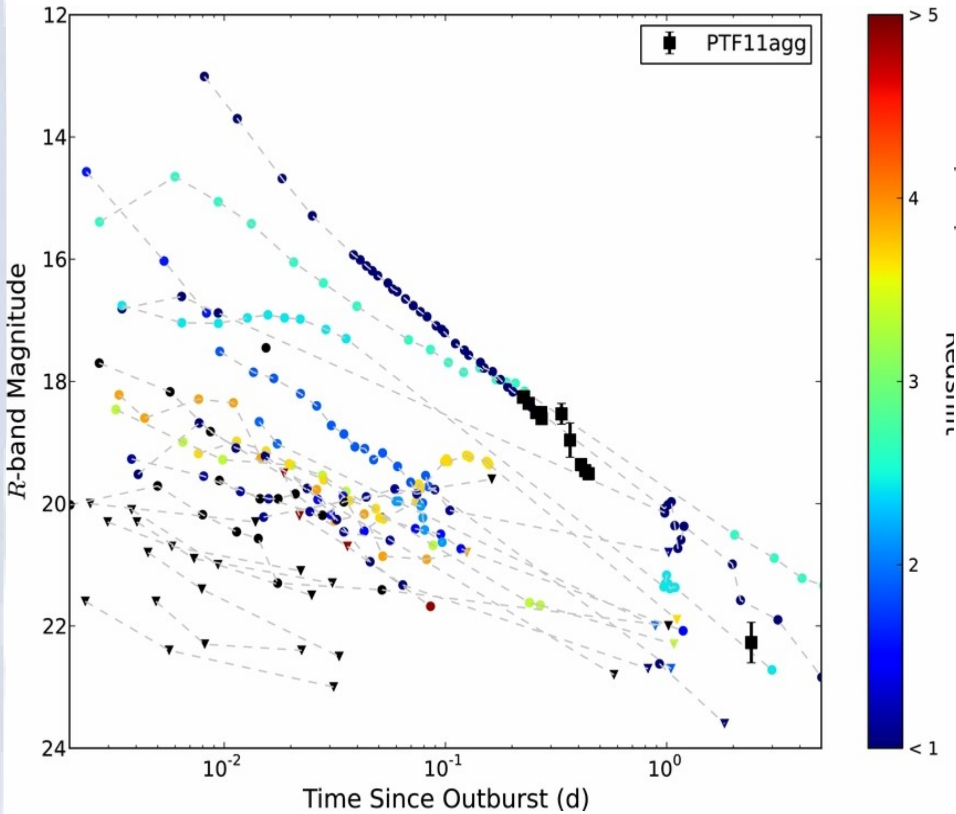
- Any interesting transient is followed up with many other facilities: P60, P200 for both imaging and spectroscopy
- P48 has robotic control system
- P60 is devoted to followup of interesting candidates of P48

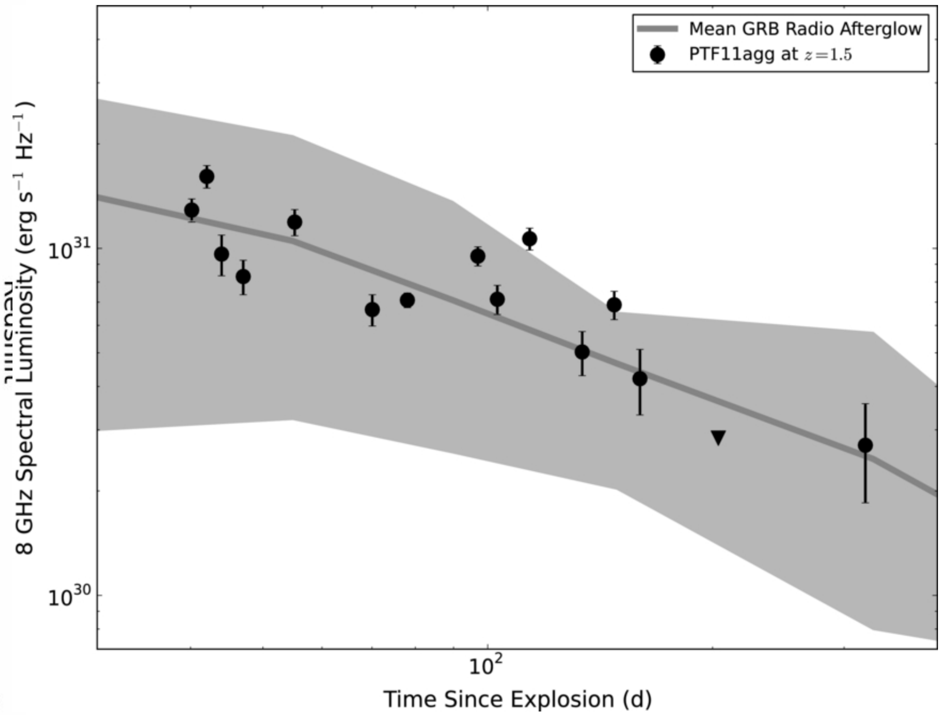
It works like a factory.

A GRB orphan afterglow or…



Cenko+13



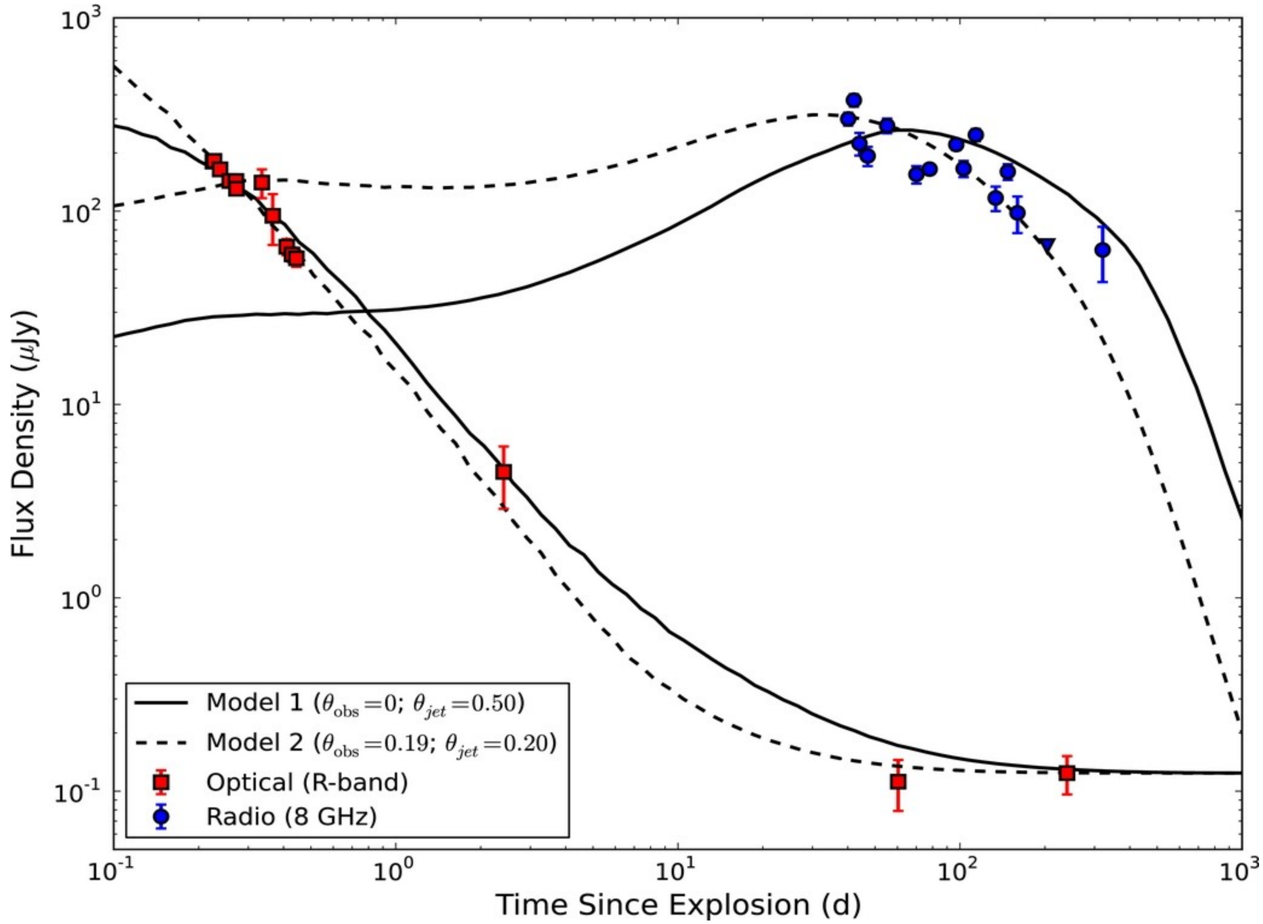


...or a new class of relativistic outbursts?

Optical+radio afterglow modelled with a jet as viewed close to the jet border or right on axis of a wider jet.

Basic question: **Why no associated GRB?**

Answer: **many possibilities.......**



Cenko+13

Pan-STARRS

Panoramic Survey Telescope And Rapid Response System


Home | Science Goals | Asteroid Threat | Design Features | Project Status | Internal Pages

Photograph by Rob Ratkowski for the PS1SC

Dangers from space

Learn about the threat to Earth from asteroids & comets and how the Pan-STARRS project is designed to help detect these NEOs. Learn more...

1,400,000,000 pixels

Pan-STARRS has the world's largest digital cameras.

Read about them here...

The PS1 Prototype

PS1 goes operational and begins science mission

PS1 Science Consortium formed...

PS1SC Blog

PS1 image gallery

Pan-STARRS

PS1 SCIENCE CONSORTIUM

Welcome to Pan-STARRS

Pan-STARRS -- the Panoramic Survey Telescope & Rapid Response System -- is an innovative design for a wide-field imaging facility developed at the University of Hawaii's Institute for Astronomy.

The combination of relatively small mirrors with very large digital cameras results in an economical observing system that can observe the entire available sky several times each month.

The prototype single-mirror telescope PS1 is now operational on Mount Haleakala; its scientific research program is being undertaken by the PS1 Science Consortium - a collaboration between ten research organizations in four countries,

PROJECT NEWS

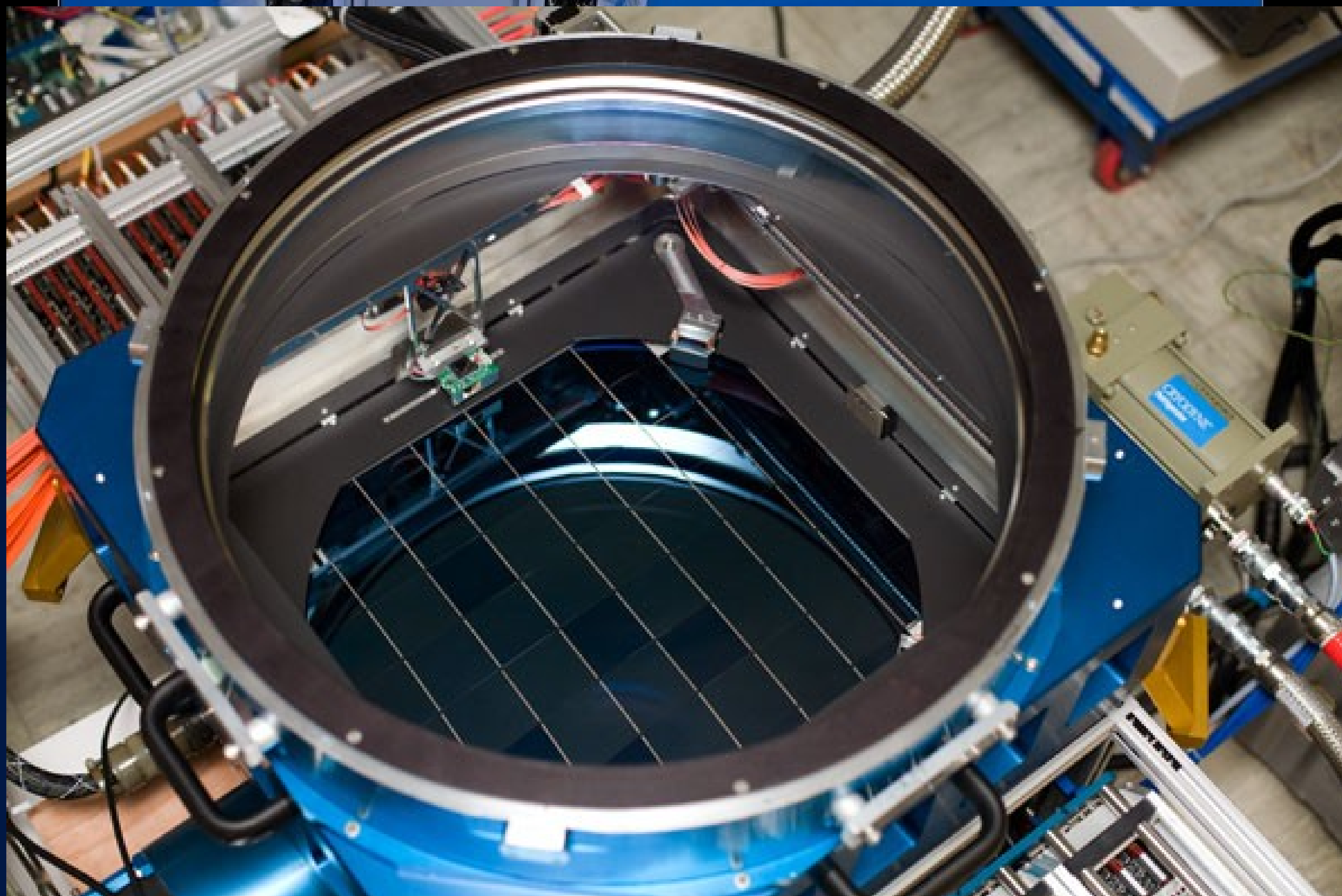
PS1 discovers 19 NEOs in one night

High School students from Texas and Germay join search for asteroids...

...and now Maui students as well

Home | Science Goals | Asteroid Threat | Design Features | Project Status | Internal Pages

- Relatively small mirrors with very large digital cameras
  - 64x64 array of CCDs, 600x600 pix each
  - Total 1.4 gigapixel

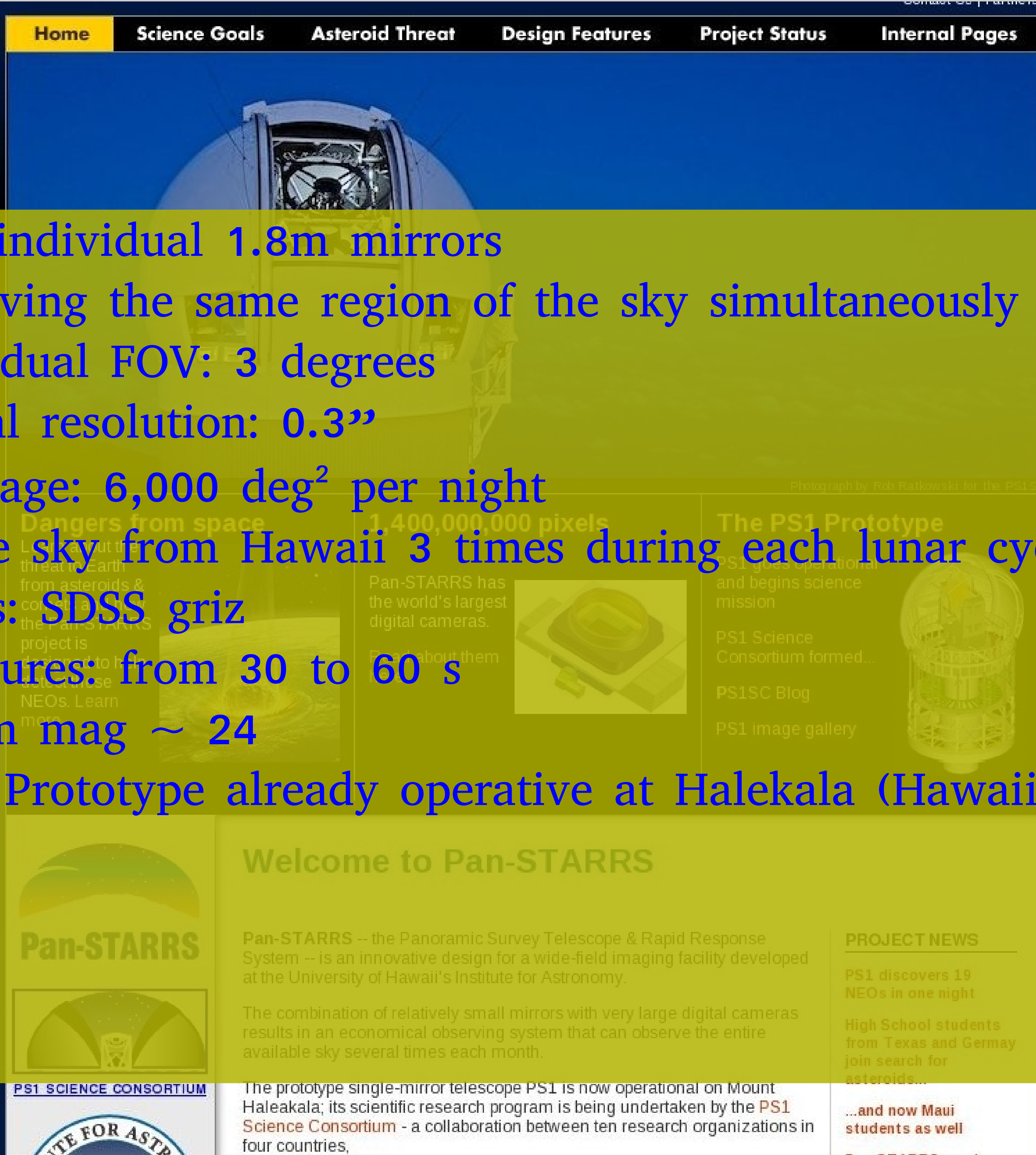


PS1 SCIENCE CONSORTIUM

The prototype single-mirror telescope PS1 is now operational on Mount Haleakala; its scientific research program is being undertaken by the PS1 Science Consortium - a collaboration between ten research organizations in four countries.

...and now Maui students as well

- Four individual 1.8m mirrors
- Observing the same region of the sky simultaneously
- Individual FOV: 3 degrees
- Spatial resolution: 0.3”
- Coverage: 6,000 deg^2 per night
- Whole sky from Hawaii 3 times during each lunar cycle
- Filters: SDSS griz
- Exposures: from 30 to 60 s
    - Lim mag ~ 24
- PS1 Prototype already operative at Halekala (Hawaii)




PS1 Dome


PS1+PS2

The PS1 Science Consortium:

University of Hawaii, Institute for Astronomy

Max Planck Society; institutes in Garching and in Heidelberg

The Johns Hopkins University, Dept. of Physics and Astronomy

Harvard-Smithsonian Center for Astrophysics

Las Cumbres Observatory

Durham University, Extragalactic Astronomy & Cosmology Research Group

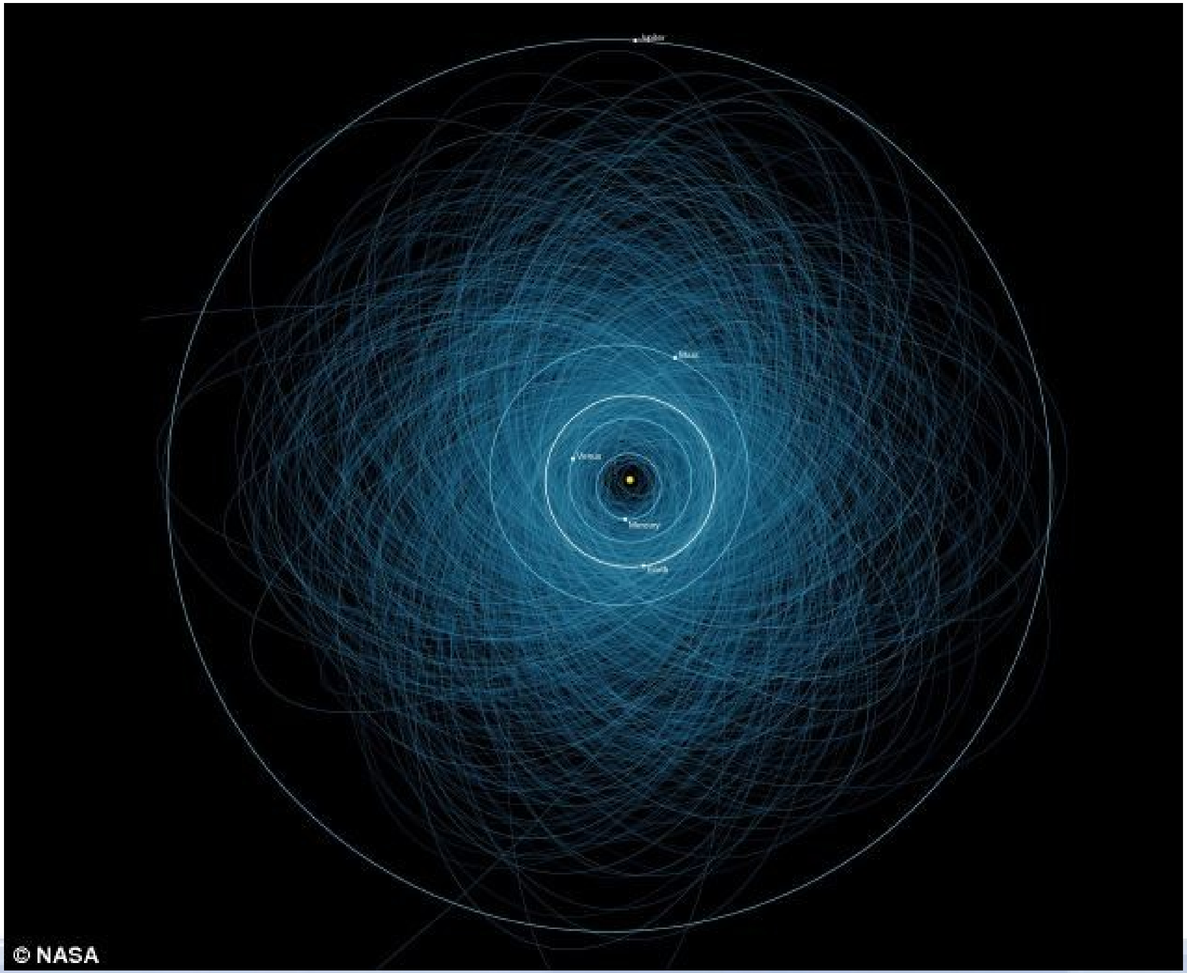
University of Edinburgh, Institute for Astronomy

Queen's University Belfast, Astrophysics Research Center

National Central University, Taiwan

Pan-STARRS Science Goals

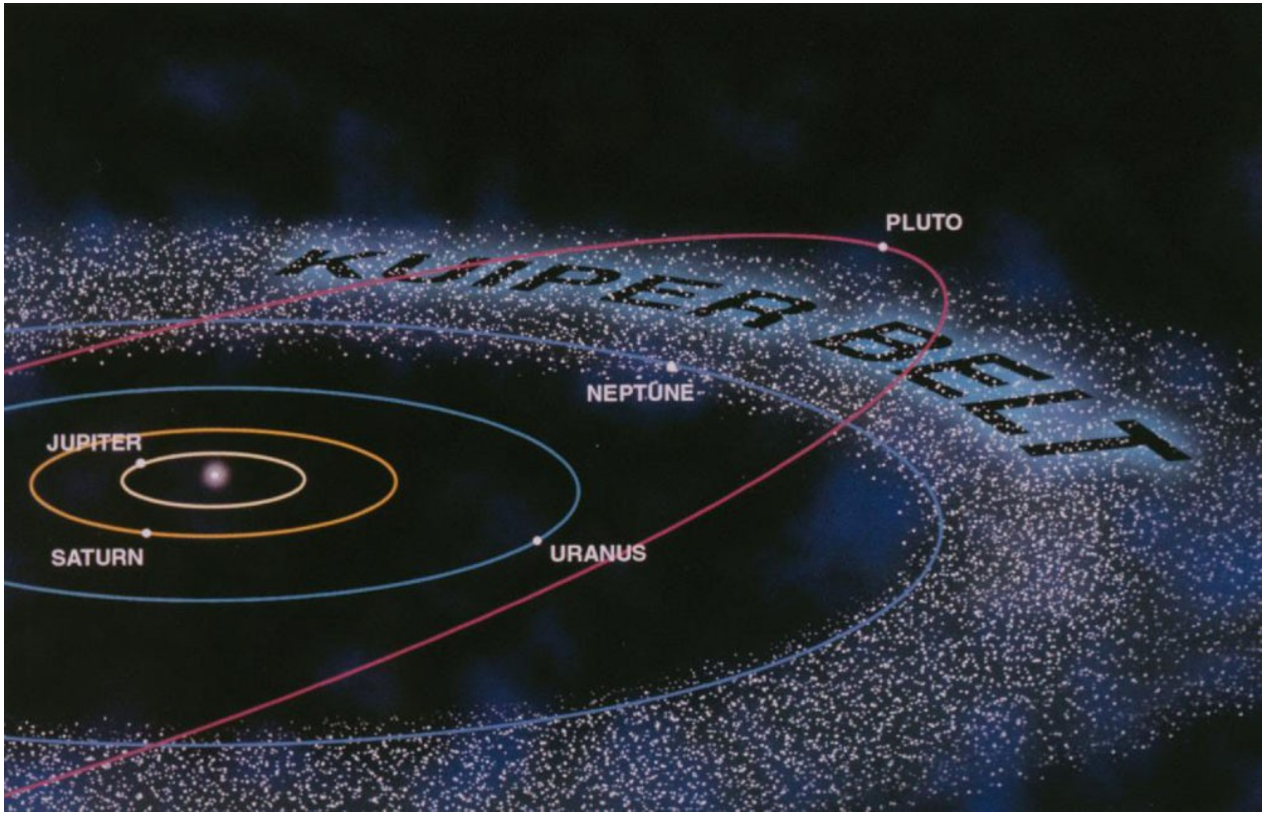
- Detection of near Earth objects (NEOs) and potentially hazardous objects (PHOs) in the Solar System
  - **1**-km diameter objects that pass close to the Earth and many of the **300**-m ones



Pan-STARRS Science Goals

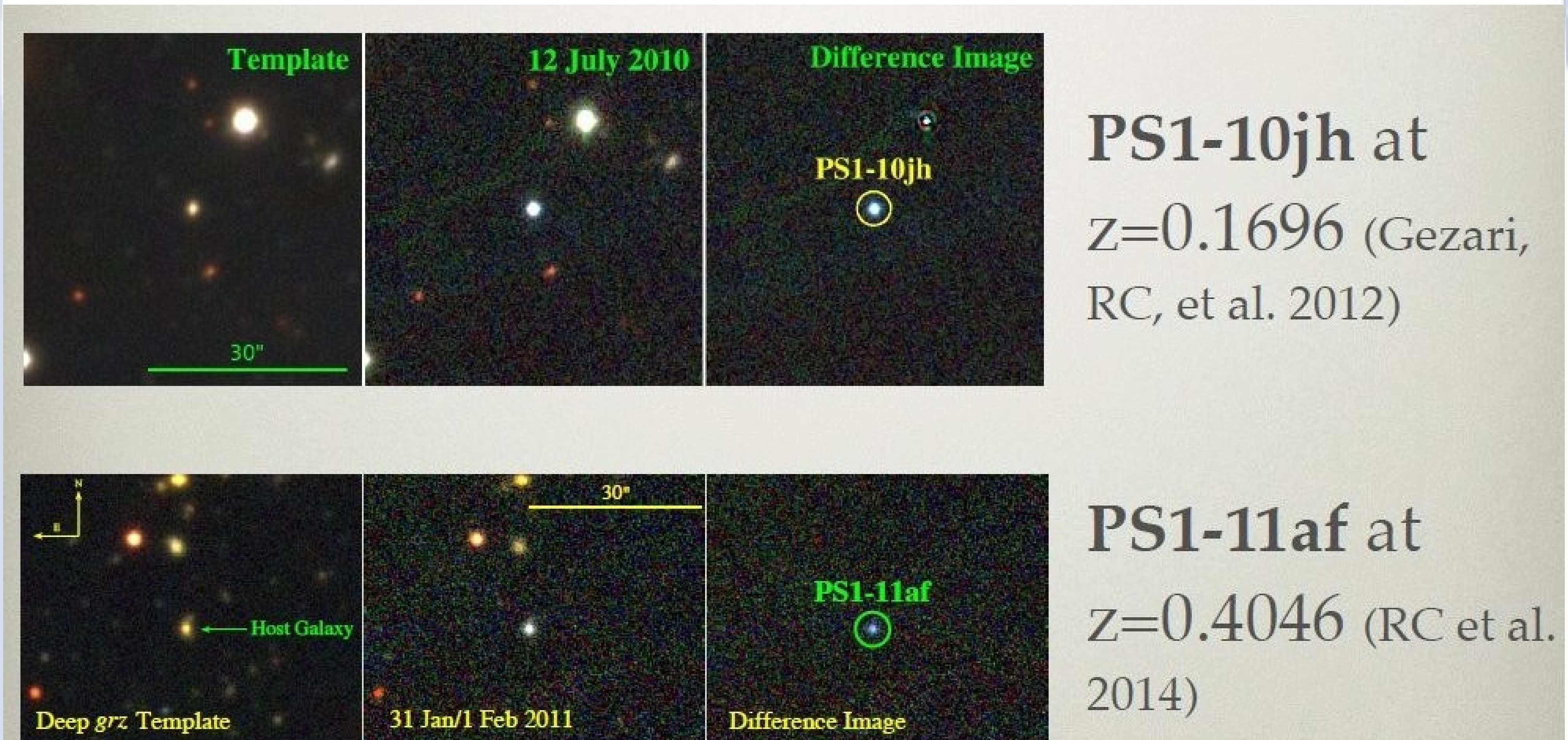
• Detection of main-belt asteroids (estimated number: 10,000,000) as potential source of NEOs

• Kuiper Belt objects (KBOs; outer Solar System). Some of these objects are as large as 1000 km in diameter. These objects are found in a region that starts near the orbit of Neptune and extends into the outer solar system well beyond the orbit of Pluto.



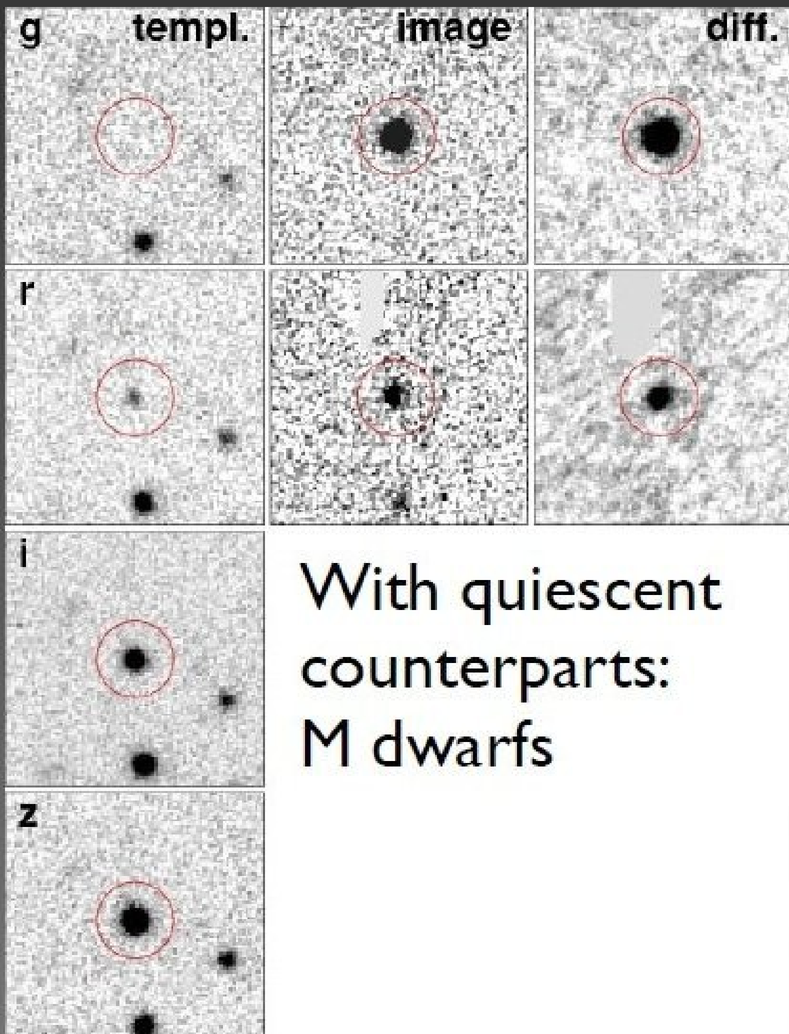
Pan-STARRS Science Goals

- Evolution and death of stars: SNe, GRBs, GRB orphan afterglows, CVs, microquasars, msec-pulsars...
- Young stellar objects
- Cepheids, RR Lyrae......and TDEs, of course:

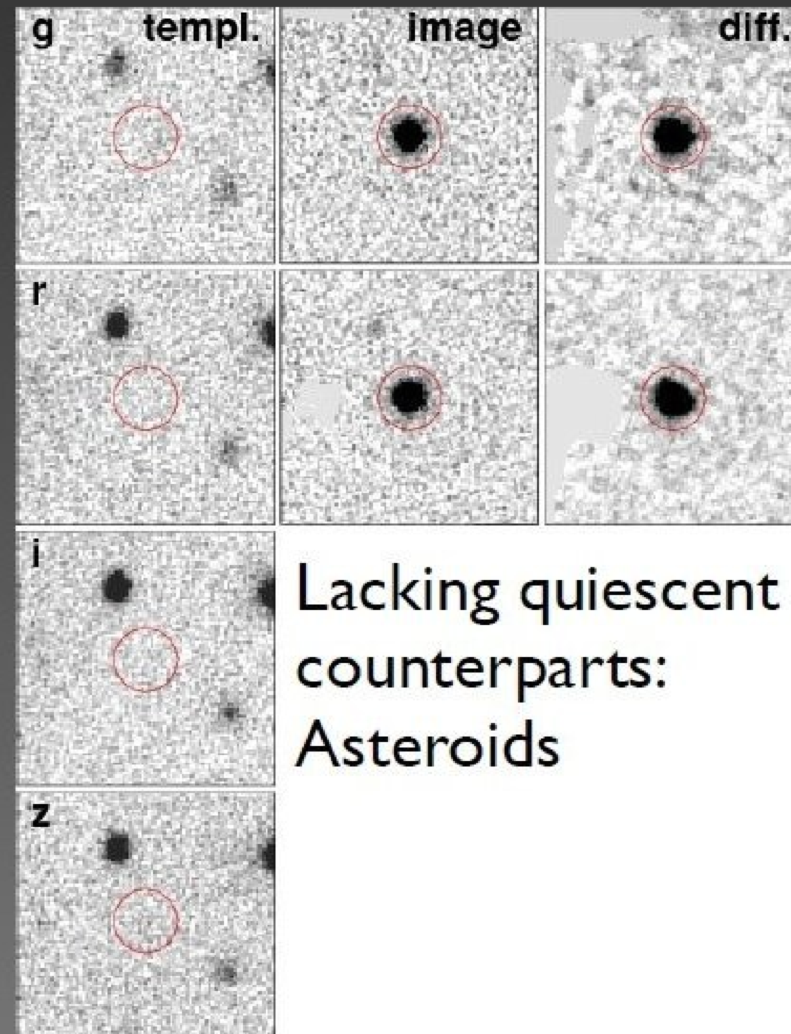


Fast Optical Transients

Search for transients with timescales of 0.5 hr to 1 day



With quiescent counterparts: M dwarfs



Lacking quiescent counterparts: Asteroids

Berger et al. 2013

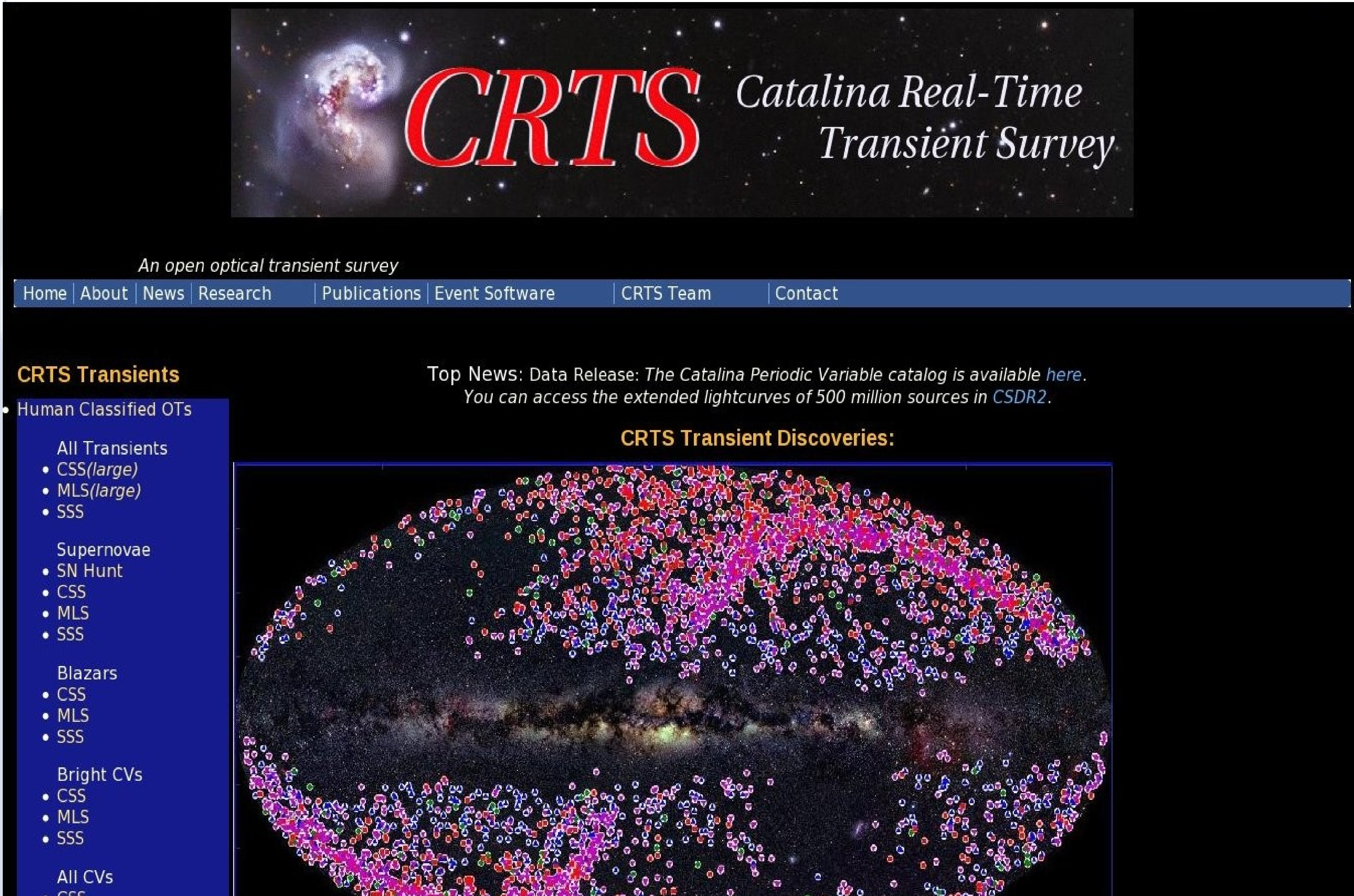
Lessons from Pan-STARRS

- PS1/MDS: Four seasons of griz(y) imaging to ~23.5 mag with a 3-day cadence in 70 deg^2 $\Longrightarrow$ ~150 transients per month.

- Spectroscopic follow-up (~150 nights on MMT, Magellan, Gemini) led to classification of ~650 transients; mainly SNe of known types (Ia/b/c, IIP/n). Key advantages are early discovery, high-quality light curves, broader redshift range.

- Only a few percent of classified events are outside of the normal SN classes: TDEs, ULSNe, Ibn, Iax, etc.

...and many other: CATALINA



...and many other: SkyMapper

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SkyMapper telescope

Overview | Collaboration policy

SkyMapper is a state-of-the-art automated wide-field survey telescope that represents a new vehicle for scientific discovery. It is sited under the dark skies of Siding Spring Observatory near Coonabarabran, in central NSW. SkyMapper's mission is to robotically create the first comprehensive digital survey of the entire southern sky. The result will be a massively detailed record of more than a billion stars and galaxies, to a sensitivity one million times fainter than the human eye can see. The survey's data set will be made freely available to the scientific and general community via the internet.

The SkyMapper telescope was constructed by EOS Australia. It has a modified cassegrain design, featuring:

- a 1.35m primary mirror,
- a 0.71m secondary (on 5 axis hexapod mount),
- a 0.56m aspheric corrector, and

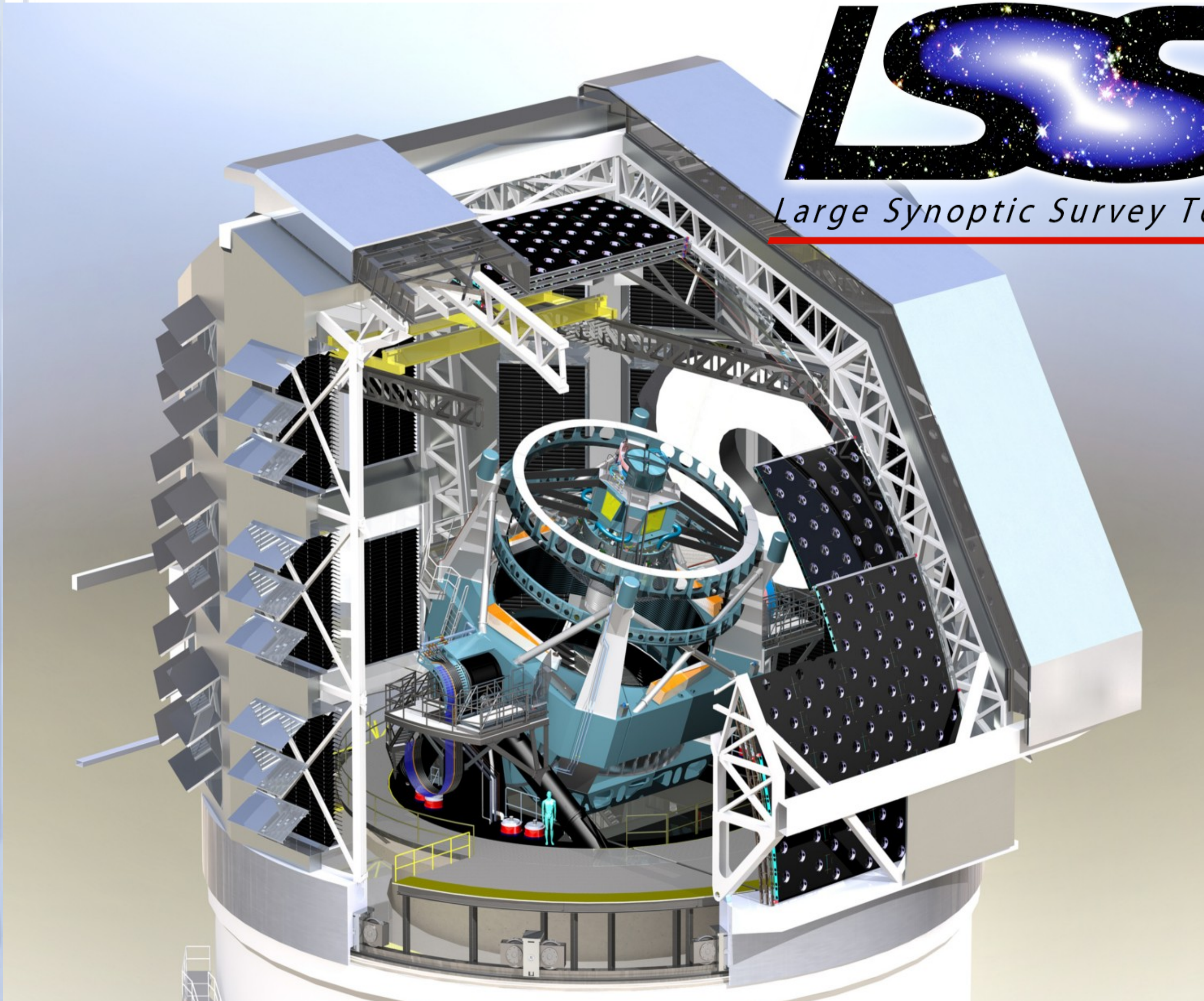
Related observatory

- Siding Spring Observatory

Active Instruments

- SkyMapper instrument


A revolution is
around the corner

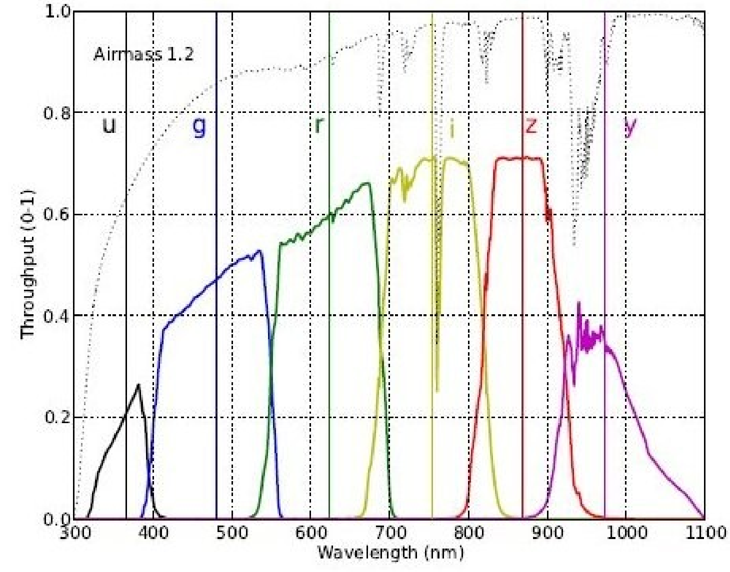


LSST

Large Synoptic Survey Telescope

LSST

Large Synoptic Survey Tele



8.4-m telescope in Cerro Pachon (Northern Chile)

From ~2020

FOV: 9.6 deg^2

Camera: 3.2 Gigapixel (largest in the world)

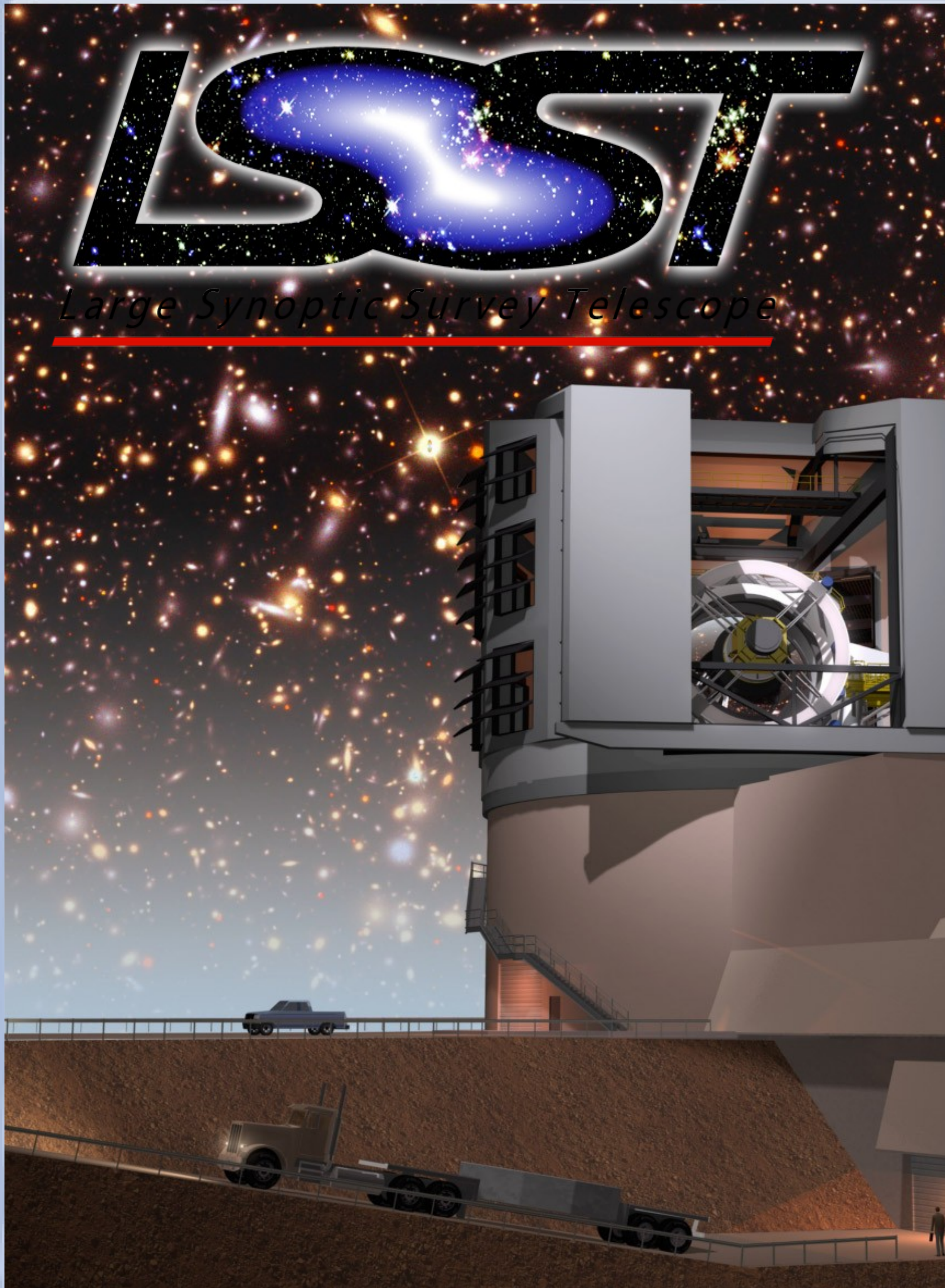
Sensitivity (5σ): r~24.5 mag (15 s exposure), 27 mag (stacked).

Cadence: twice/night (two 15-s exposures) every 3 nights.

Expected data output: 30 TB/night

Totale survey area: 3x10^4 deg^2, $\delta < +34.5$ deg

Wavelength coverage: 320-1050 nm (filters ugrizy)



Observation Strategy

- 90% time: deep-wide-fast survey mode

  18,000 deg^2 scanned 1000 times over all filters in 10 yr

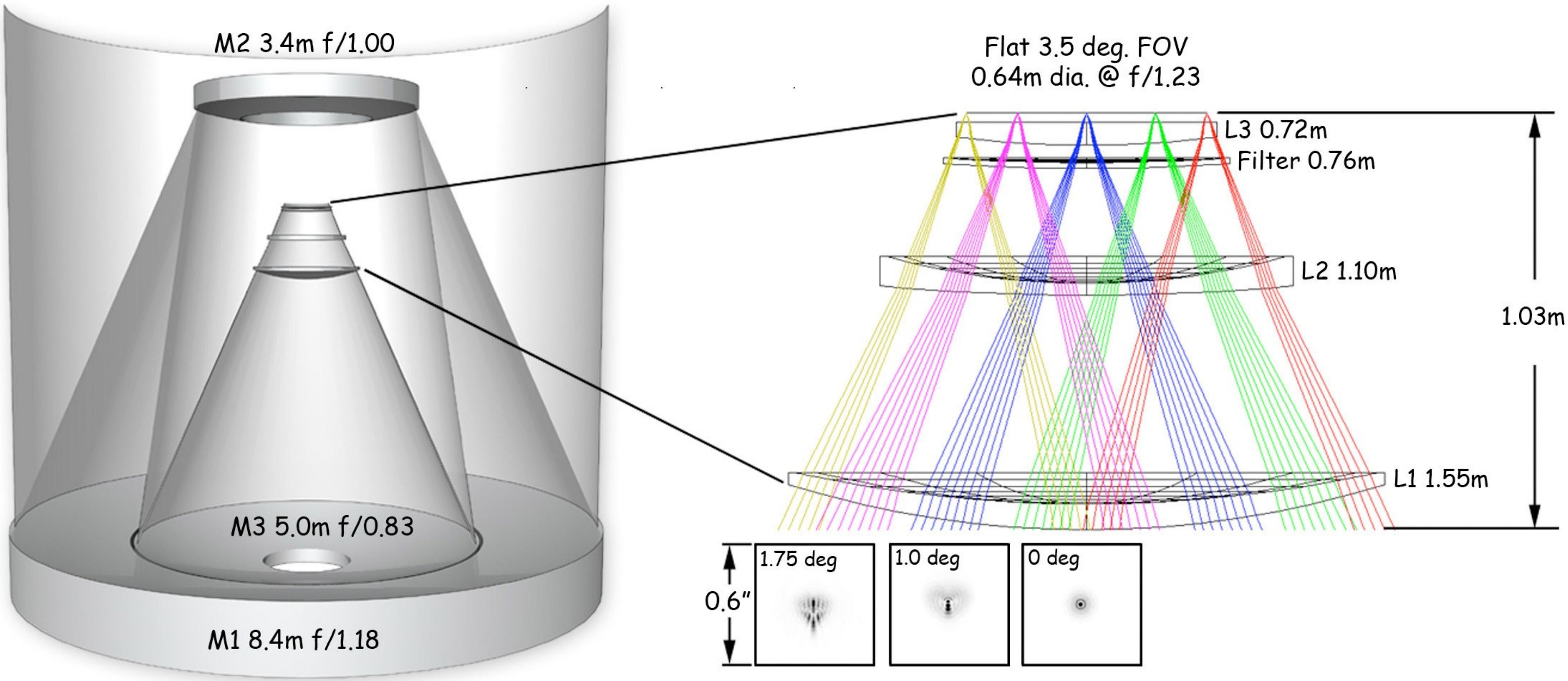
  Coadded map down to r~27.5 mag

  Catalogues of 10 billions galaxies and stars

- 10% time: special projects:

  Very Deep and Fast time domain survey

Data products publicly available and accessible.



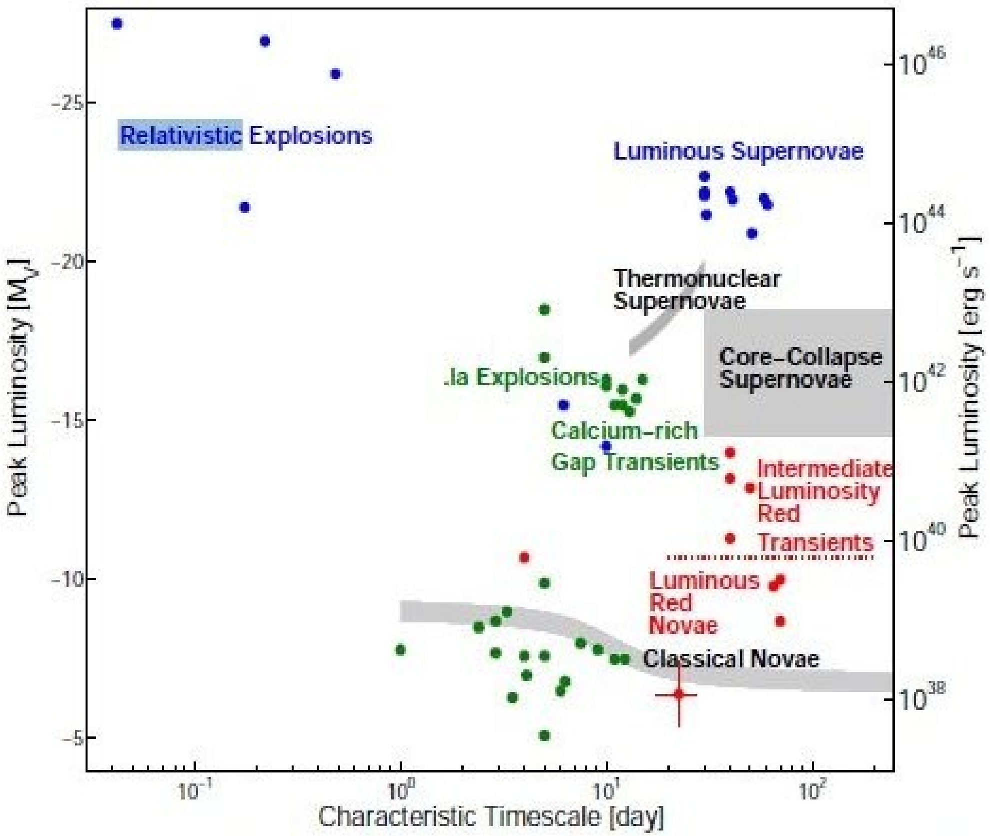
How is this possible?

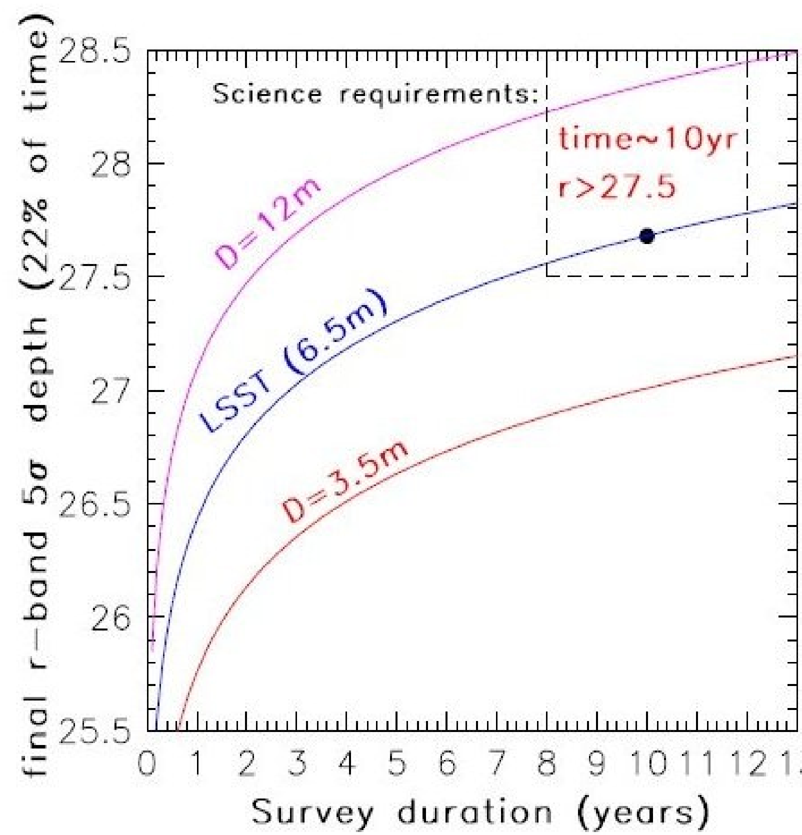
Confluence of several technological developments. New fabrication techniques for large optics developed for the most recent generation of large telescopes can be extended to novel optical designs which allow large fields of view. New detector technologies allow the construction of cameras which can capture these wide-angle images on focal planes paved with billions of high-sensitivity pixels (picture elements). Recent phenomenal advances in microelectronics and data storage technologies provide greatly enhanced facilities for digital computation, storage, and communication, and new software innovations enable fast and efficient searches of billions of megabytes of data.

Large Synoptic Survey Telescope

Science Drivers

- Probing Dark Energy and Dark Matter
- Taking an inventory of the Solar System
- *Exploring the Transient Optical Sky*
- Mapping out our own galaxy, the Milky Way





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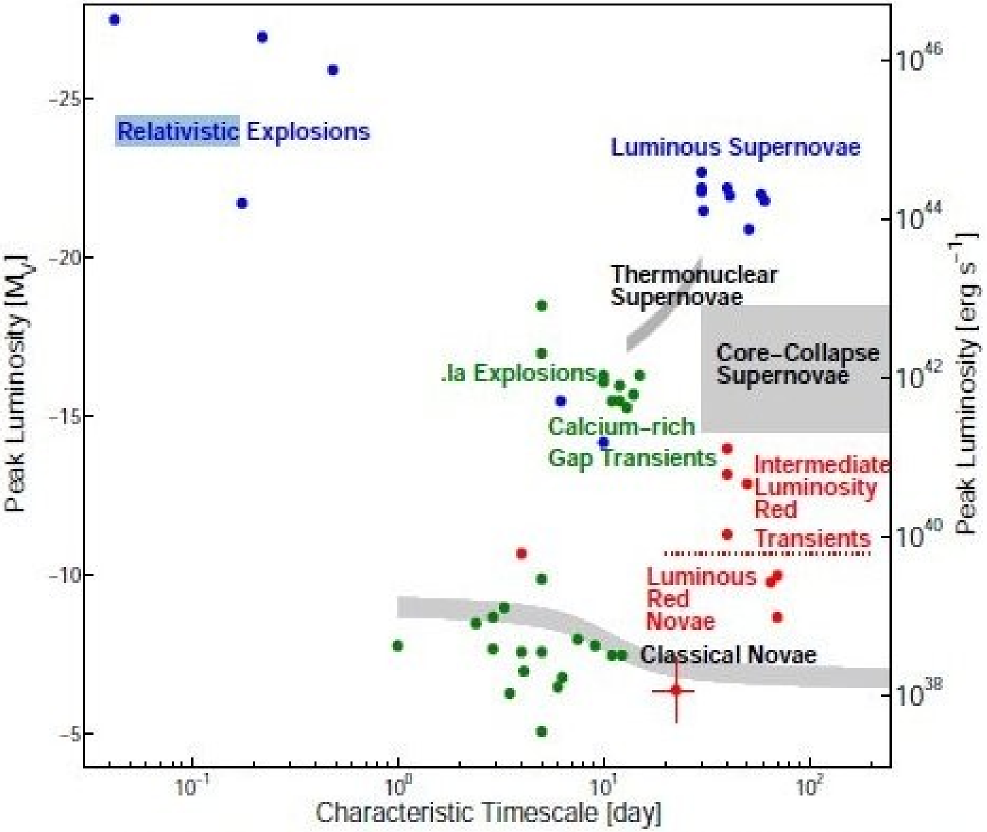
LSST and the Transient Sky

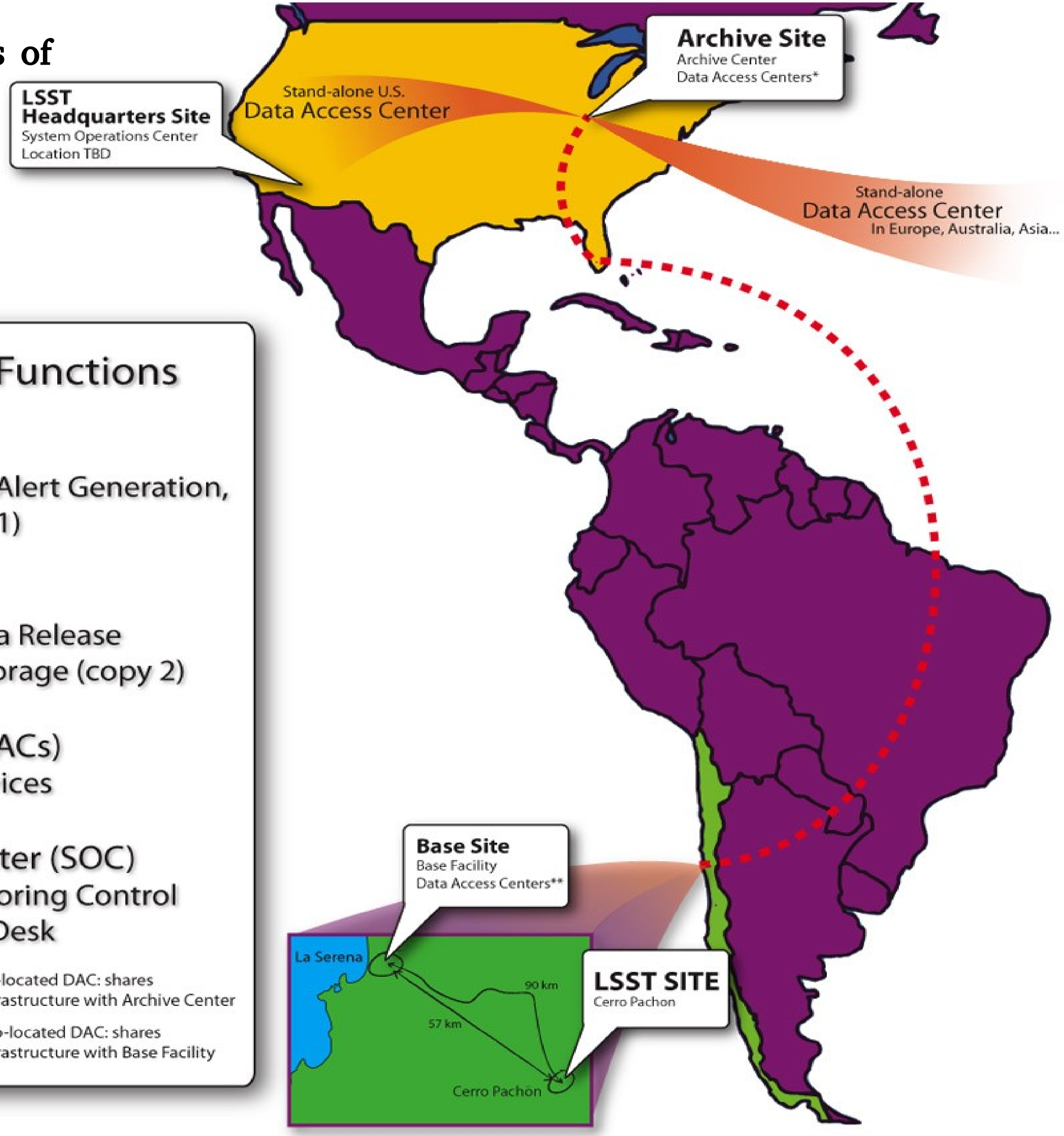
Large Synoptic Survey Telescope

- GRB afterglows and transients out to high z (z~7.5).
- Optical bursters (faster than 1mag/hr) down to r~25 mag.
- Microlensing in the Local Group
- Unusual SN population
- Dwarf Novae
- Deep search for Novae and SN progenitors
- Search for TDEs
- Exoplanets (hot Jupiters) via transits



- Accurate quasar variability
- Optical identification of transients found at other wavelengths, or GW, or neutrino

Real data process and alert generations for new sources of known ones caught in the act of varying



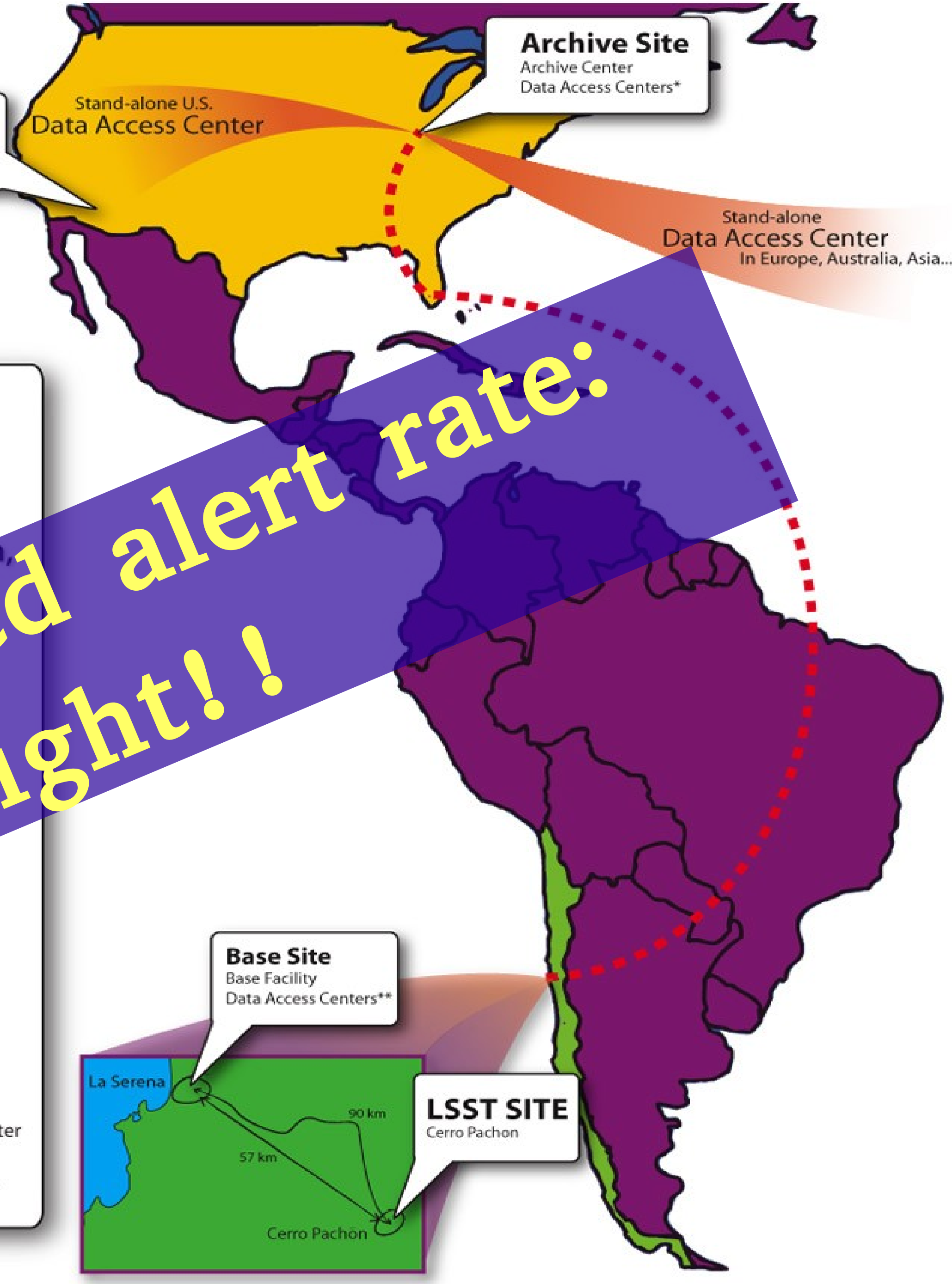
Site Roles and their Functions

- Base Facility
  Real-time Processing and Alert Generation, Long-term storage (copy 1)
- Archive Center
  Nightly Reprocessing, Data Release Processing, Long-term Storage (copy 2)
- Data Access Centers (DACs)
  Data Access and User Services
- System Operations Center (SOC)
  System Supervisory Monitoring Control & End User Support/Help Desk

* Co-located DAC: shares infrastructure with Archive Center

** Co-located DAC: shares infrastructure with Base Facility

Real data process and alert generations for new sources of known ones caught in the act of varying



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** Co-located DAC: shares infrastructure with Base Facility

Estimated alert rate: $\sim 10^6$/night!!

Software: the soul of the machine

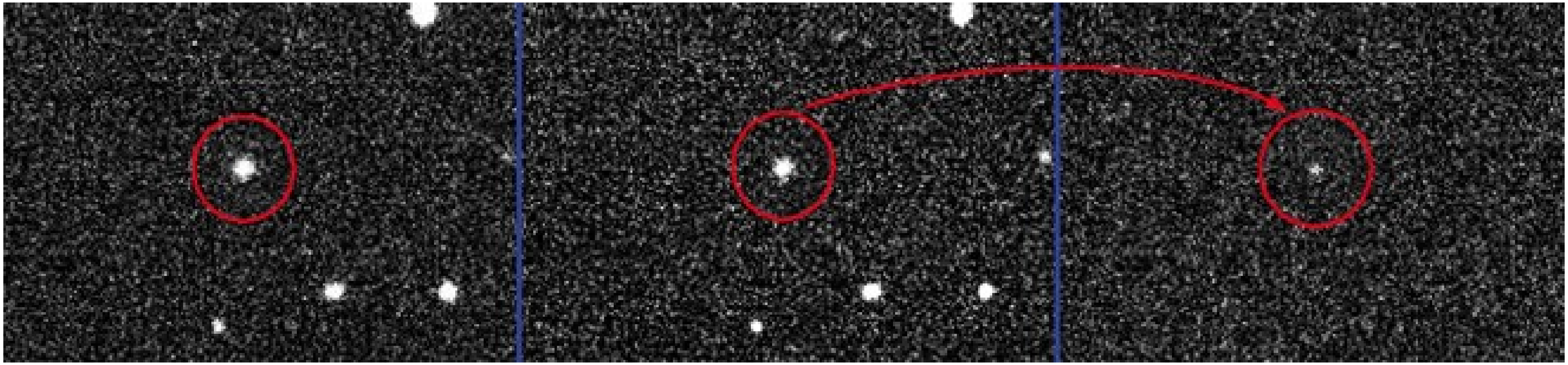
• Pairs of 15-s exposures, 2-s readout, moves to next while reading out the 2nd frame.

--> <u>330 MB/s Huge data rate</u>

• Data analysed in the minute before new pair of frames is taken.

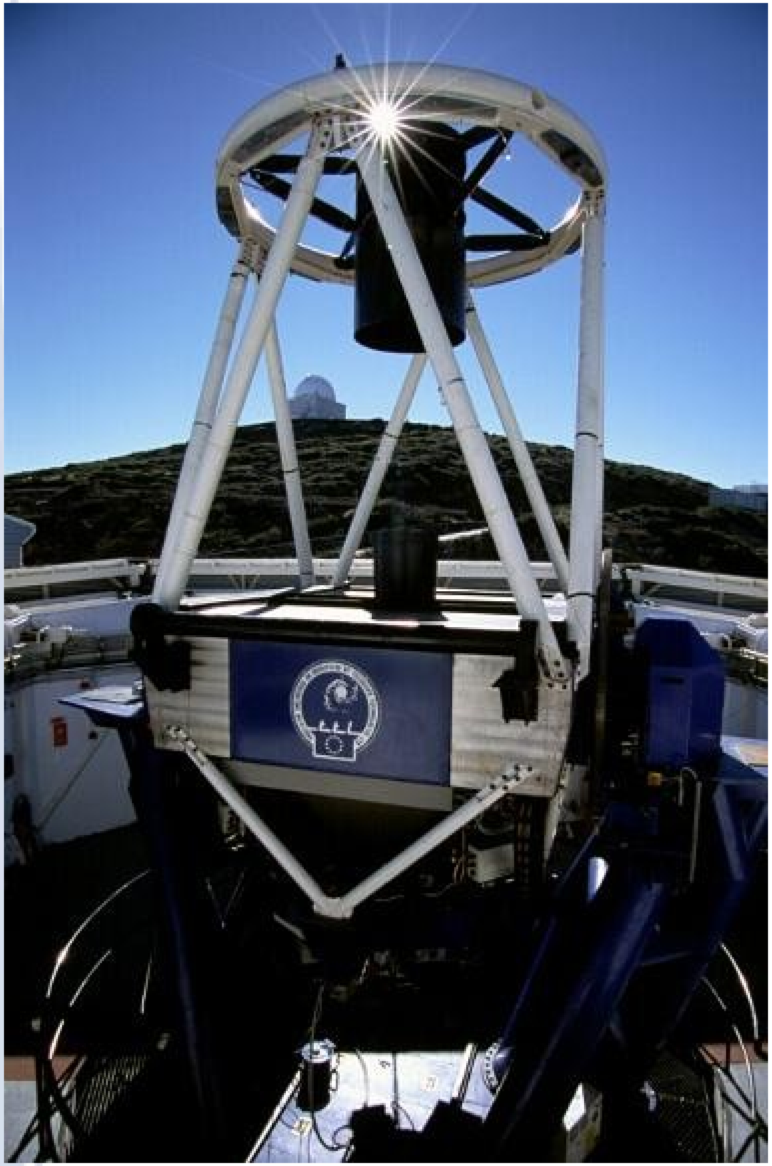
• Schedule changed whenever rapidly varying objects are found and alerts sent to other facilities and space satellites.

Image subtraction



Two images of a cluster of galaxies, taken three weeks apart, are subtracted to reveal that a supernova has exploded in one of the galaxies. All of the persistent information in the two images is removed by the subtraction. LSST will detect events as faint as 24th magnitude in ten seconds and equivalent to the brightness of a golf ball at the distance of the Moon.

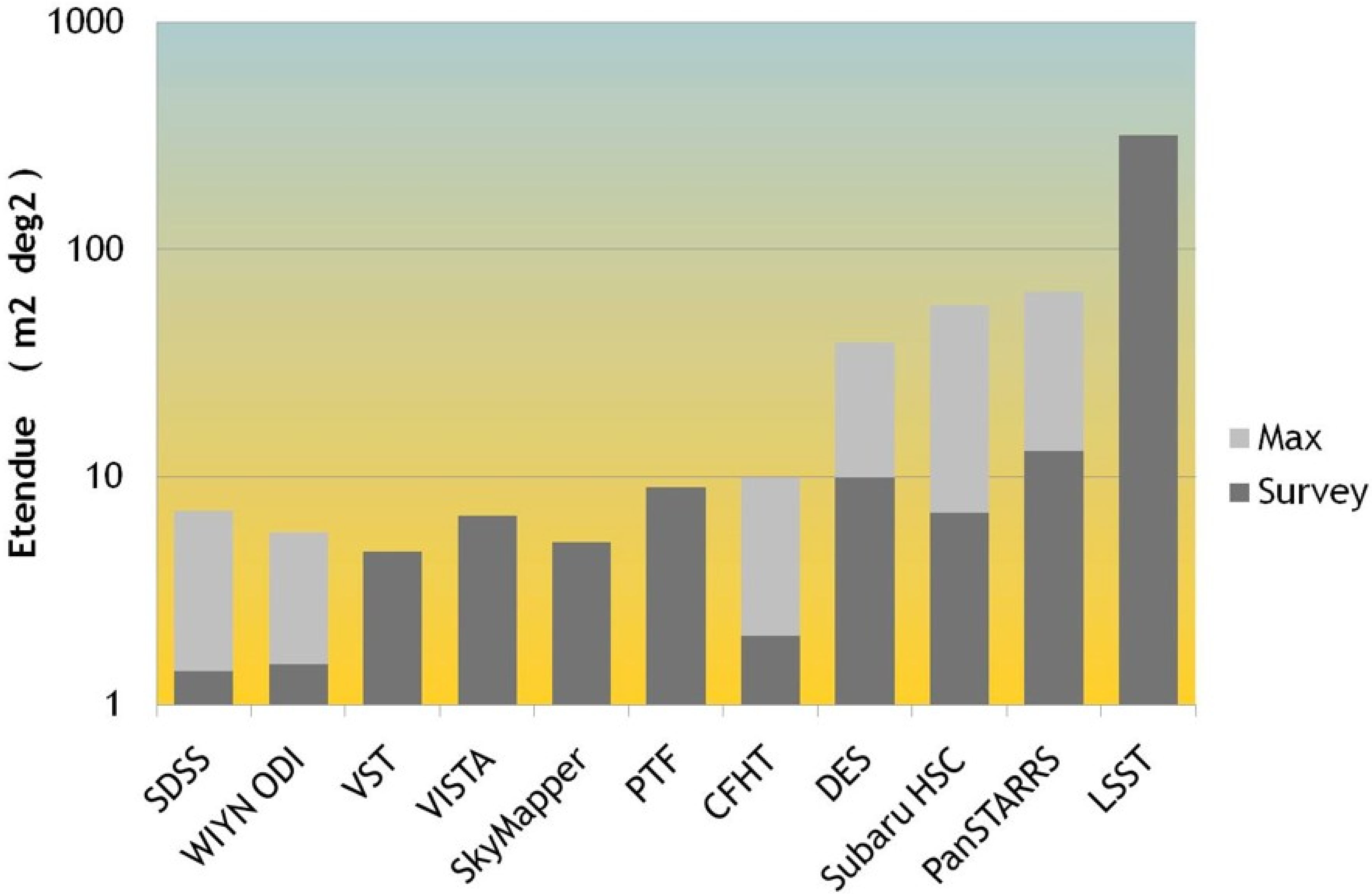
Many facilities are planned to followup the LSST transients: The Liverpool Telescope 2



2-m robotic Liverpool Telescope

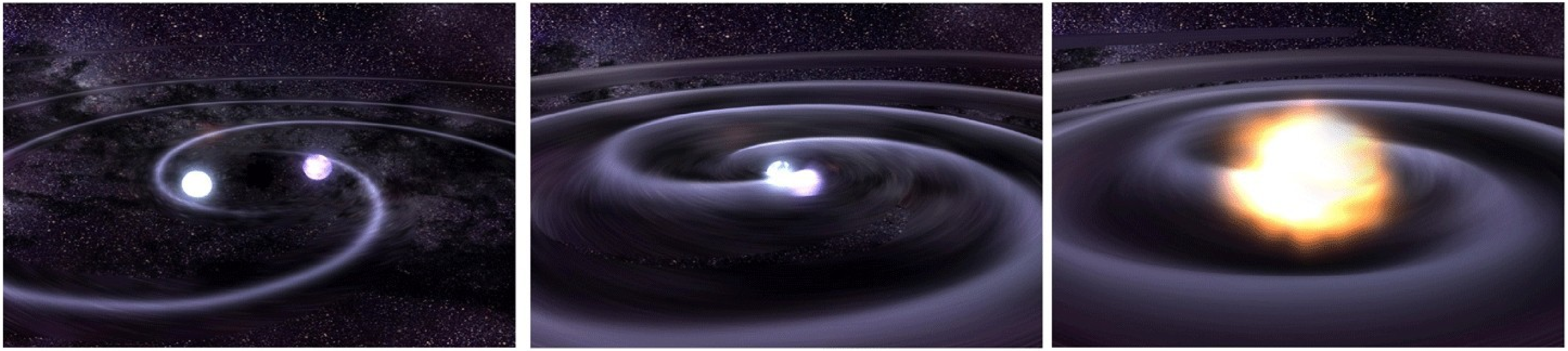
- 4-m robotic telescope
- Planned for 2020
- Based on experience of LT (2-m)
- Data taking start 30 sec of the receipt of transient alerts

A measure of survey power is etendue = collecting area x FOV



Often equated with “discovery rate” or “survey potential”

Electromagnetic Follow-up of Gravitational Wave Candidates



LIGO Scientific Collaboration

VIRGO

Transient GW & EM Sources

<u>Compact Binary Merger</u>

- Binary systems comprising of Neutron Stars and/or Black Holes.
- Possible Short GRB source.

<u>Single Neutron Stars</u>

- Magnetars, pulsars – rapidly rotating; strong magnetic fields.
- Crust realignment can cause EM bursts – e.g. SGRs

<u>Core Collapse Supernova</u>

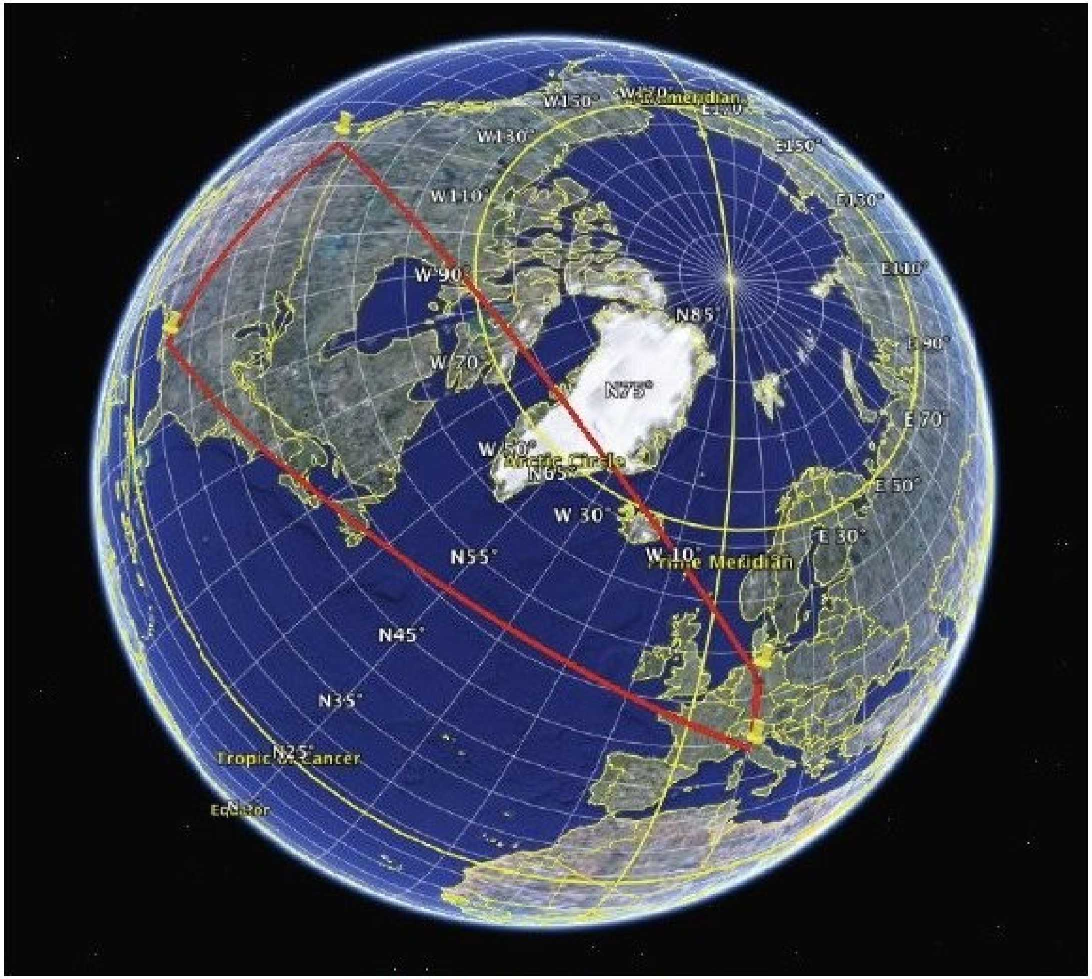
- Large enough non-spherical explosion can produce GWs.
- Known EM sources, possible sources of Long GRBs.

<u>*"The Unknown"*</u>

LSC LIGO Scientific Collaboration VIRGO

Electromagnetic Follow Up

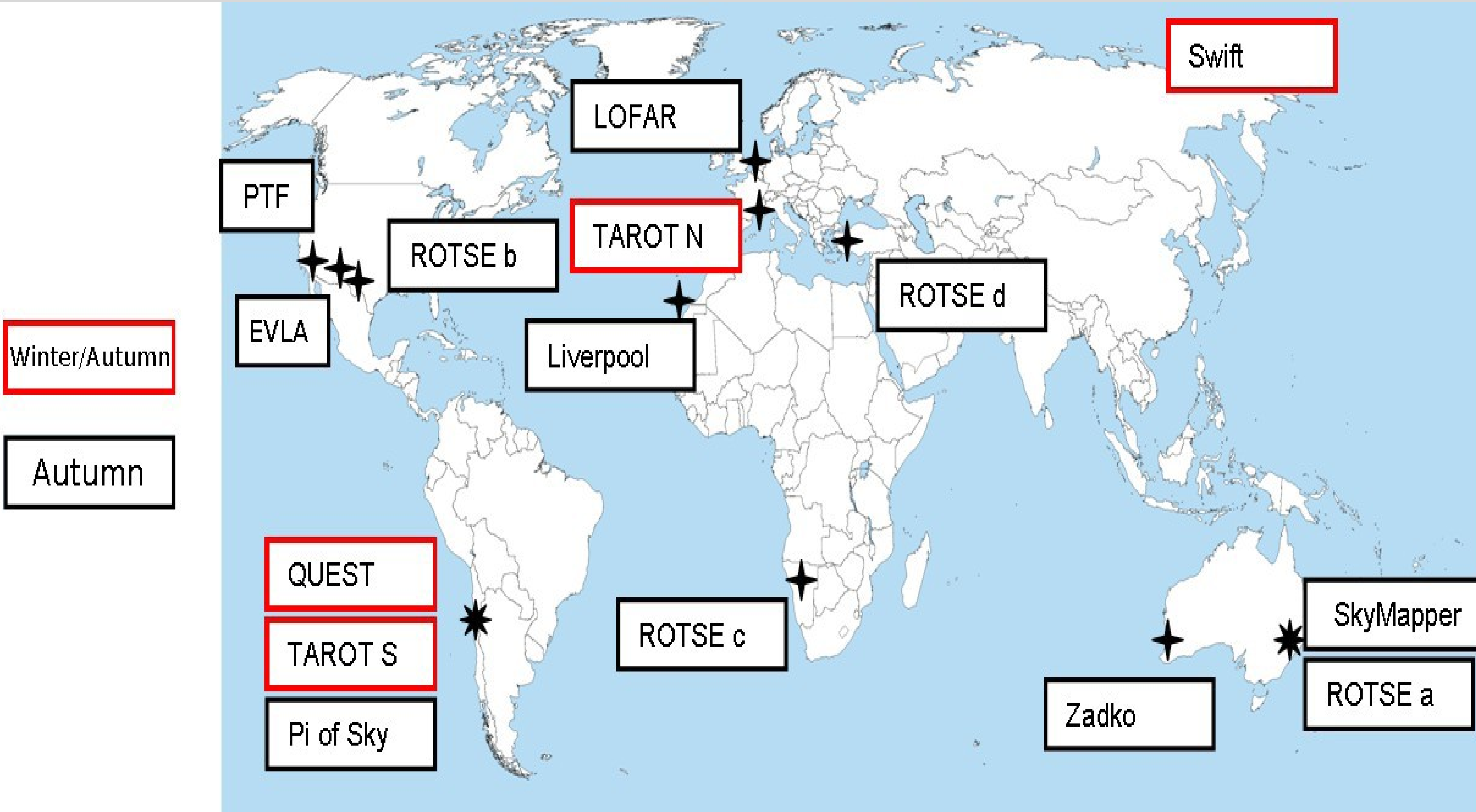
- Network of a minimum of 3 gravitational wave (GW) detectors allows us to triangulate possible source sky location.
- Many transient sources of GWs expected to provide electro-magnetic counterparts (GRBs, Supernovae, SGRs etc)
- The EM follow up campaign during the most recent science run ("S6") was aimed at imaging these potential source regions as quickly and thoroughly as possible.



Map taken from Google Earth

LSC LIGO Scientific Collaboration VIRGO

GW Partner Telescopes



Radio Joins the Synoptic Revolution

- Large investments in SKA-prototypes
- Focal-plane array technology to give
  - FoV 8 deg^2 for WSRT/Apertif
  - FoV 30 deg^2 for ASKAP.
- LNSD design for MeerKAT
- Optimized for 1.4 GHz
- Time domain is Key Science program


LOFAR

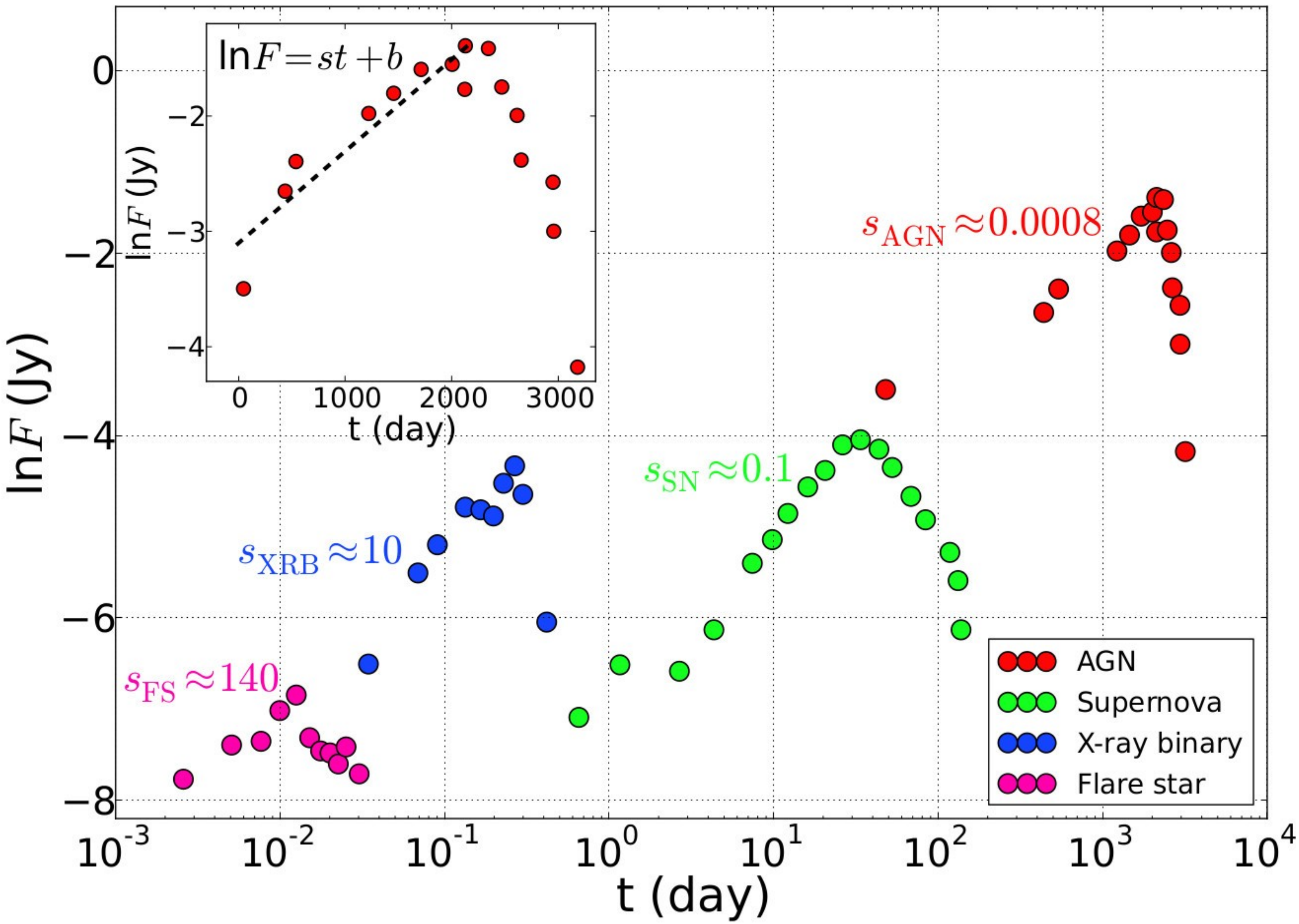

ASKAP


WSRT-Apertif


LWA


MeerKAT

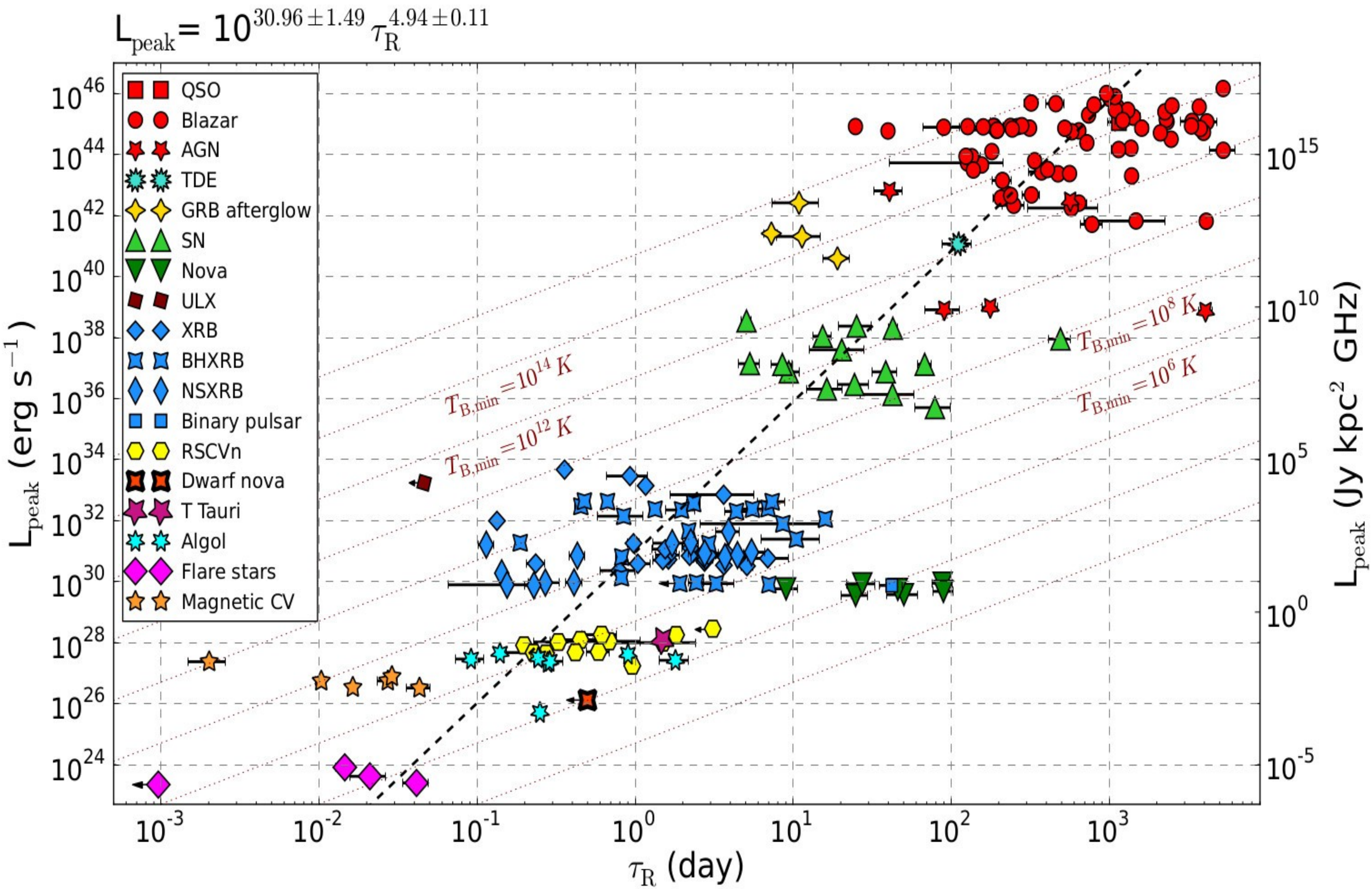
Radio Transient Timescales



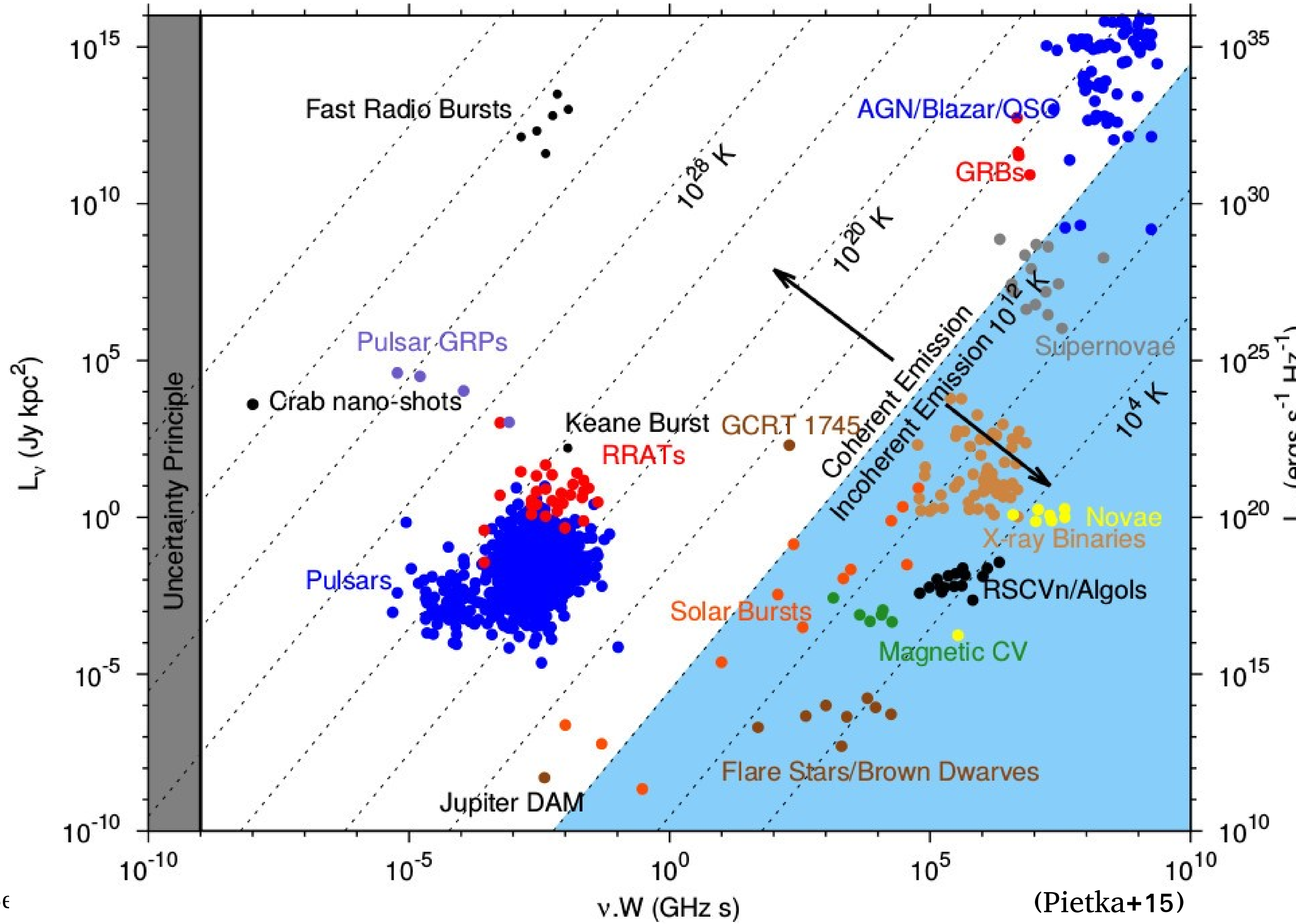
Sep

(Pietka+15)

Radio Transient Lum vs. Timescales

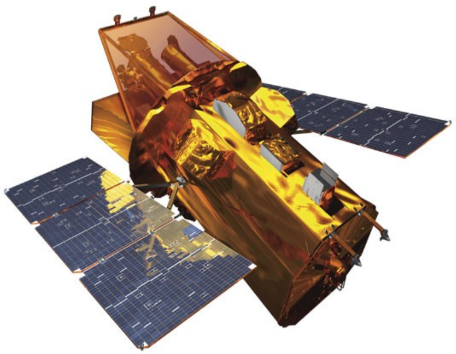


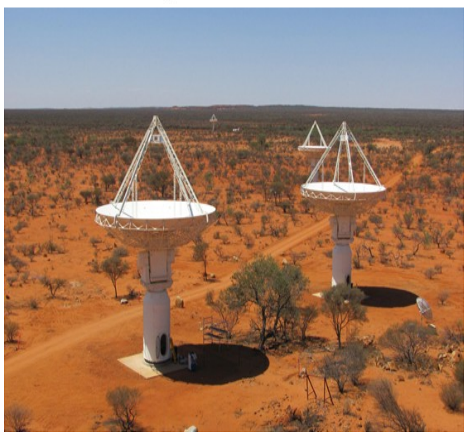
Radio Transient Phase Space

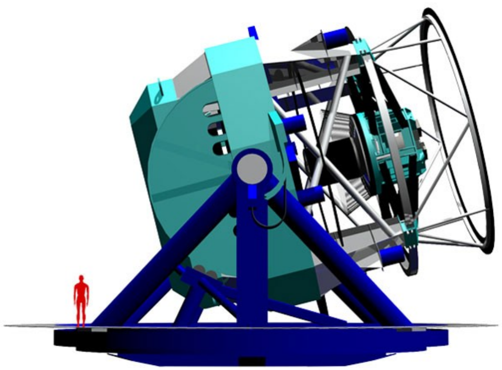


(Pietka+15)

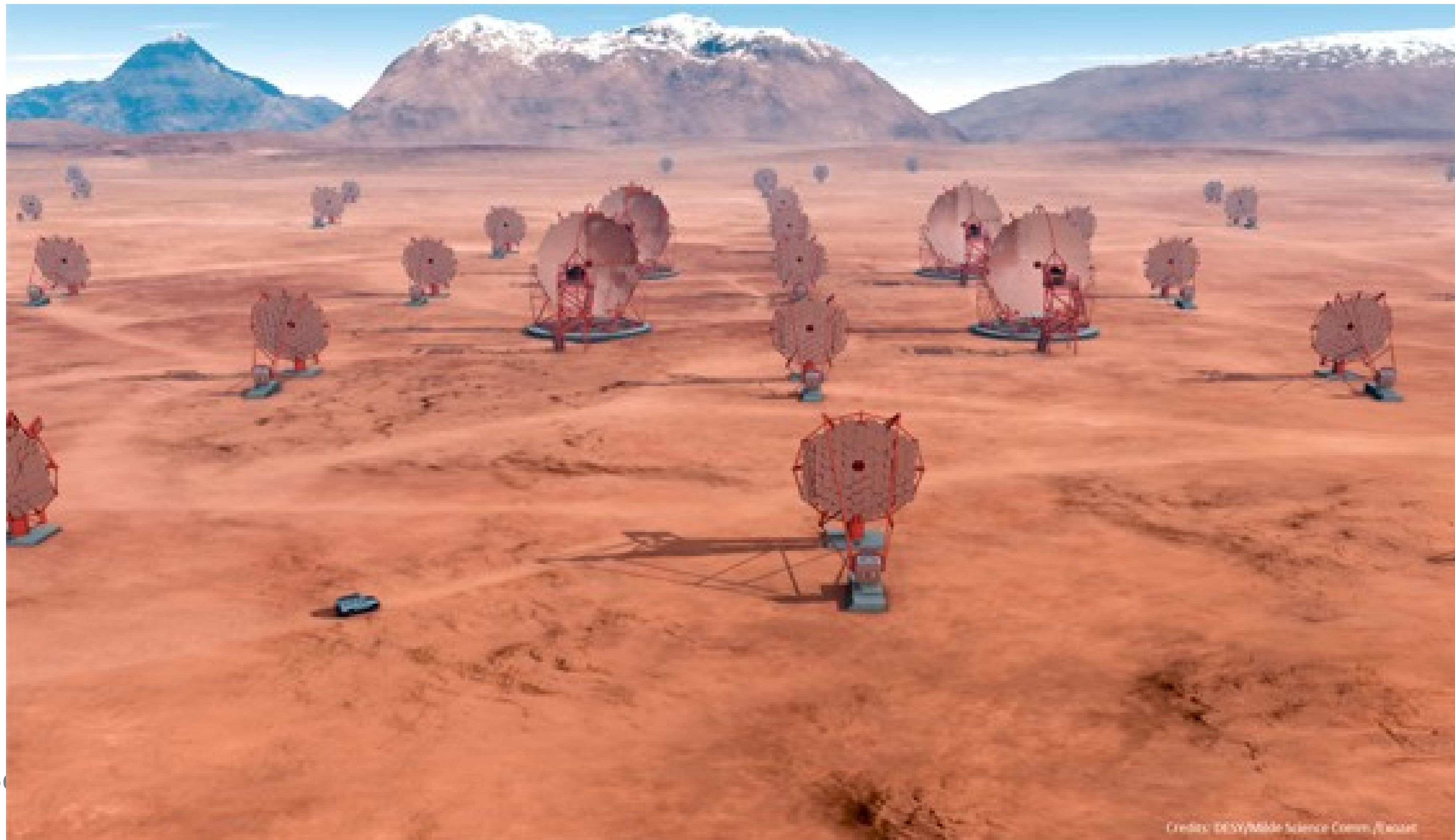
Follow-up: A biased but rewarding approach





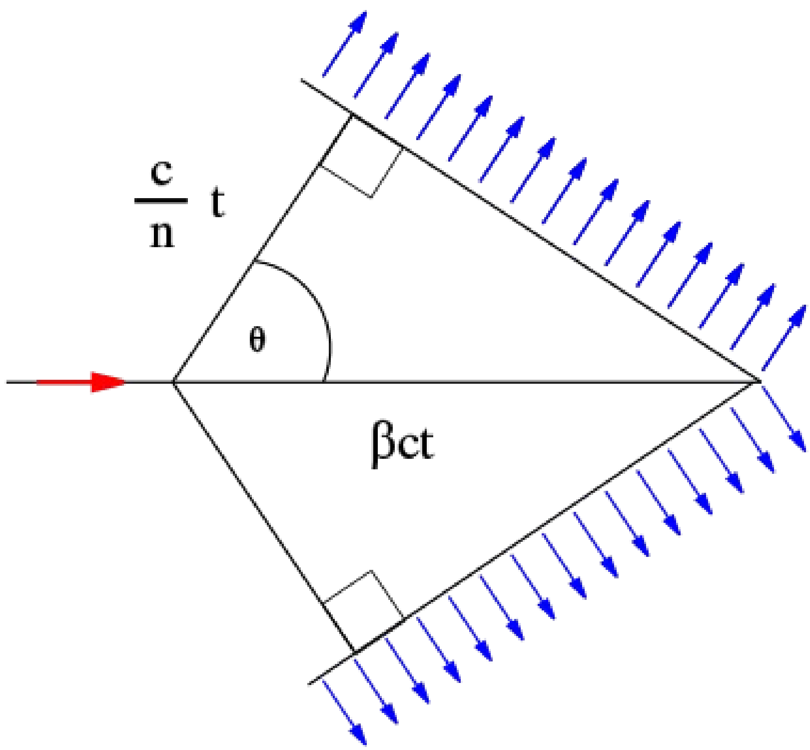


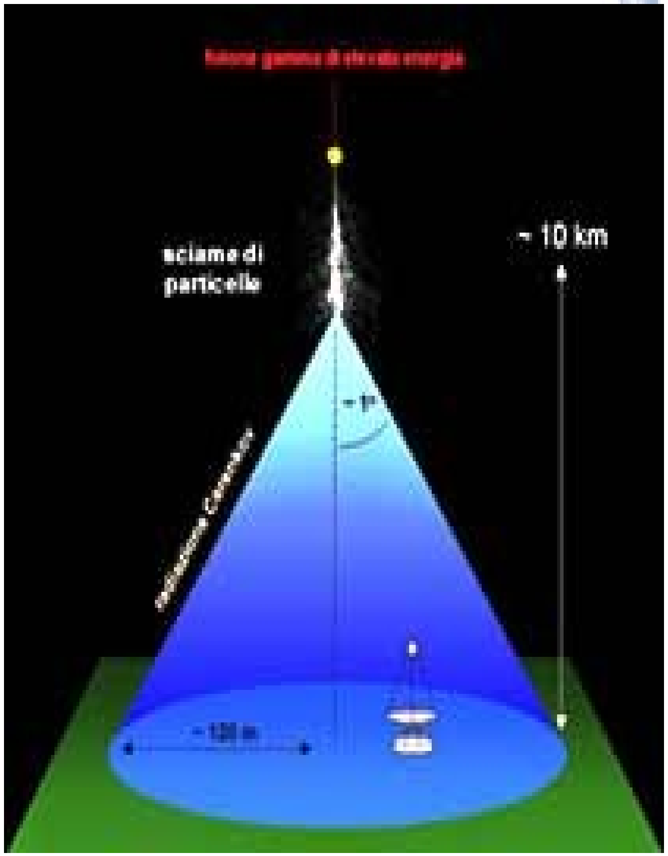
Cherenkov Telescope Array:
a forthcoming revolution in the very high energy gamma-ray (E>10 GeV)



Cherenkov Telescope

A gamma-ray interacting with atmospheric atoms gives rise to a high-energy particle cascade, which move at v>c_n (speed of light in medium). Cherenkov radiation is then produced and a blue-ish light is released as a consequence (nsec flashes).





CTA Science

Galactic Gamma-Ray Sources

- Supernova Remnants
- Pulsar Wind Nebulae
- Pulsar Physics
- Star-Formation Regions
- The Galactic Centre
- X-Ray Binaries & Microquasars
- Surveying the Sky with CTA

Extragalactic Gamma-Ray Sources

- Active Galactic Nuclei
- Extragalactic Background Light
- Gamma-Ray Bursts
- Galaxy Clusters

Fundamental Physics

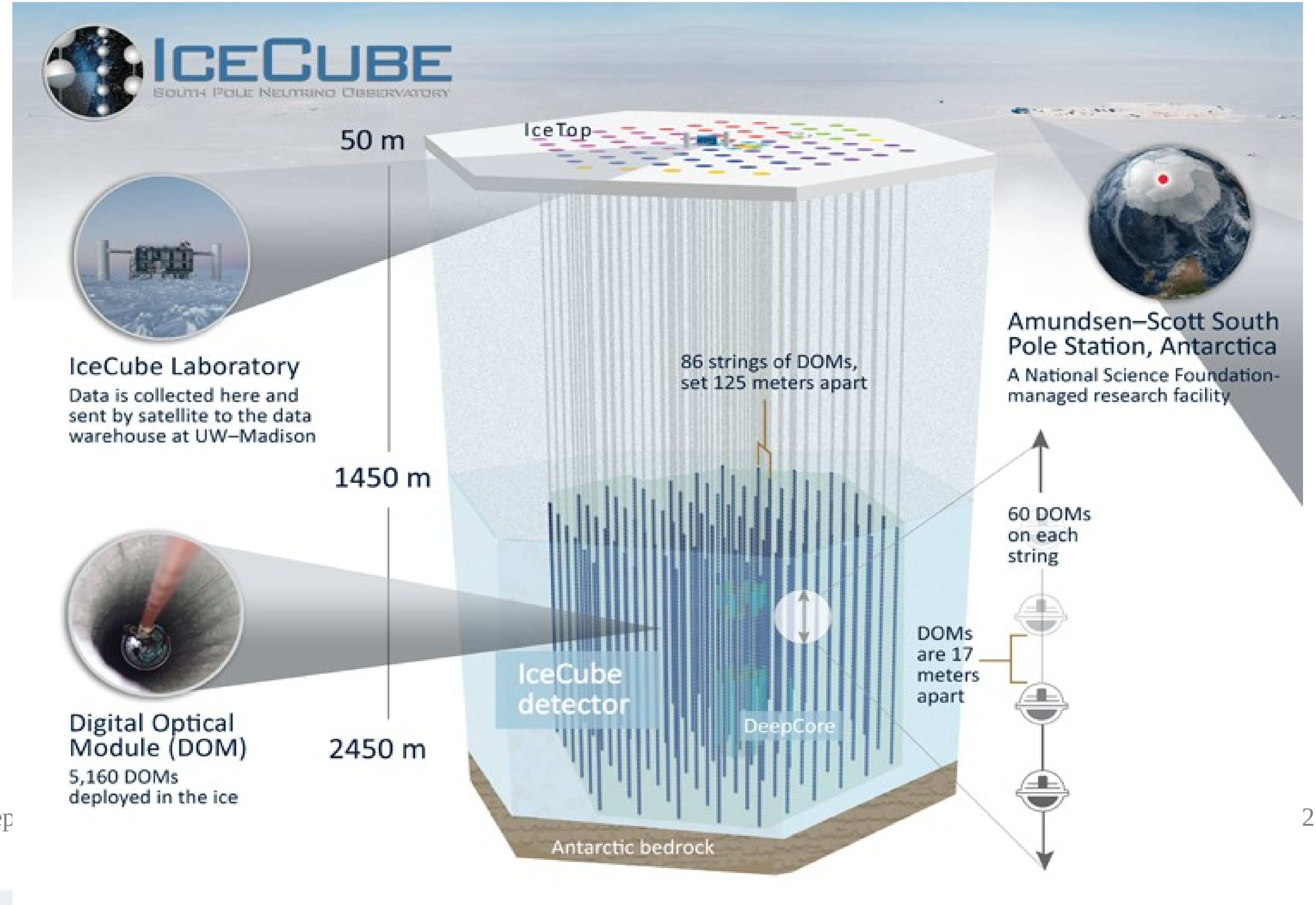
- Dark Matter
- Quantum Gravity
- Charged Cosmic Rays

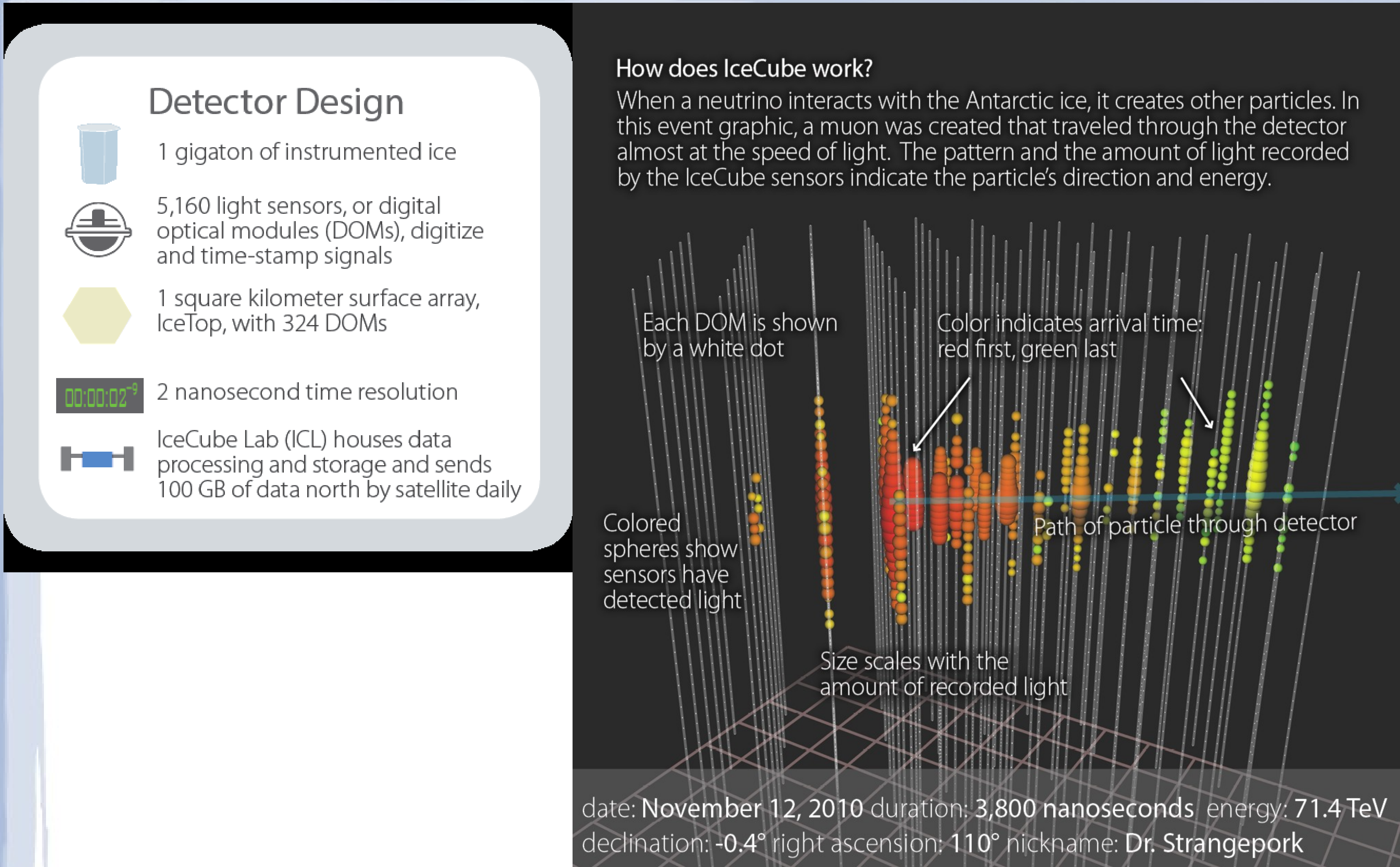
Optical Interferometry

- Optical Images of Stellar Surfaces

CTA will outperform currently operational HESS, Magic, VERITAS by a factor of 10 in sensitivity

Astrophysical neutrino detections

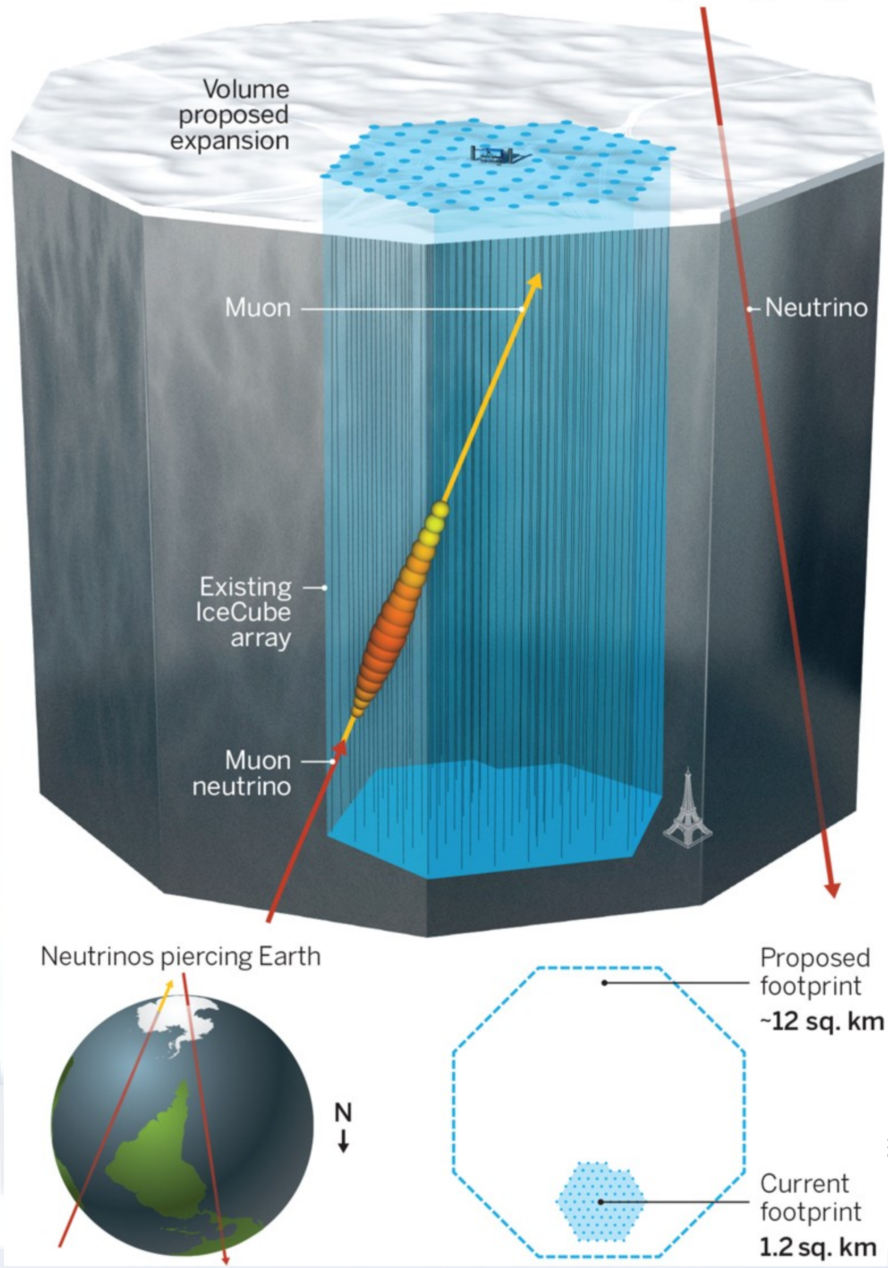




Detector Design
1 gigaton of instrumented ice
5,160 light sensors, or digital optical modules (DOMs), digitize and time-stamp signals
1 square kilometer surface array, IceTop, with 324 DOMs
00:00:02^{-9}
2 nanosecond time resolution
IceCube Lab (ICL) houses data processing and storage and sends 100 GB of data north by satellite daily
How does IceCube work?
When a neutrino interacts with the Antarctic ice, it creates other particles. In this event graphic, a muon was created that traveled through the detector almost at the speed of light. The pattern and the amount of light recorded by the IceCube sensors indicate the particle's direction and energy.
Each DOM is shown by a white dot
Color indicates arrival time: red first, green last
Colored spheres show sensors have detected light
Path of particle through detector
Size scales with the amount of recorded light
date: November 12, 2010 duration: 3,800 nanoseconds energy: 71.4 TeV
declination: -0.4° right ascension: 110° nickname: Dr. Strangepork

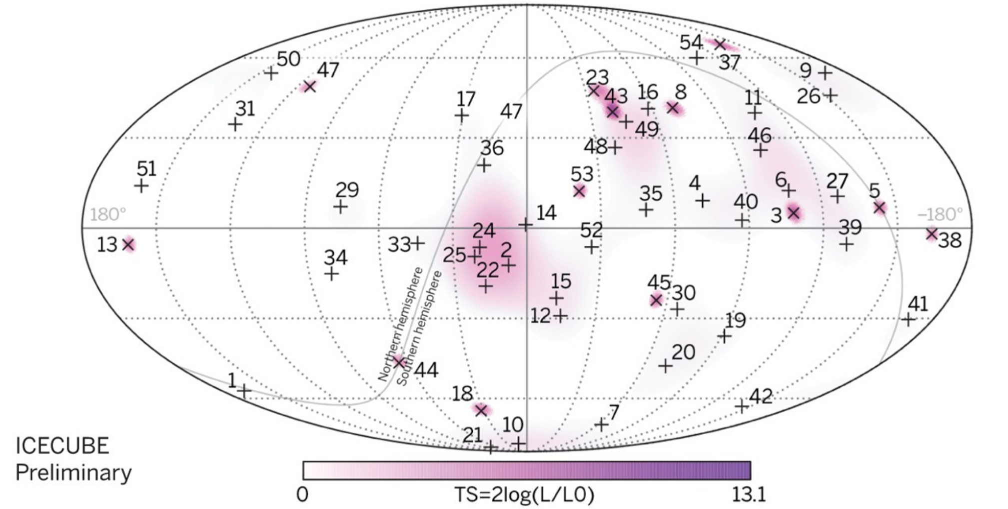
The big chill

IceCube's 2500-meter-long detector strings watch for light triggered when a neutrino strikes a nucleus in the ice, kicking out other particles such as muons. Researchers want to increase its volume 10-fold by adding strings.



Scattershot data

The 54 likely cosmic neutrinos that IceCube has seen come from all over the sky and show no obvious sources or correlation with the galactic plane (horizontal line).



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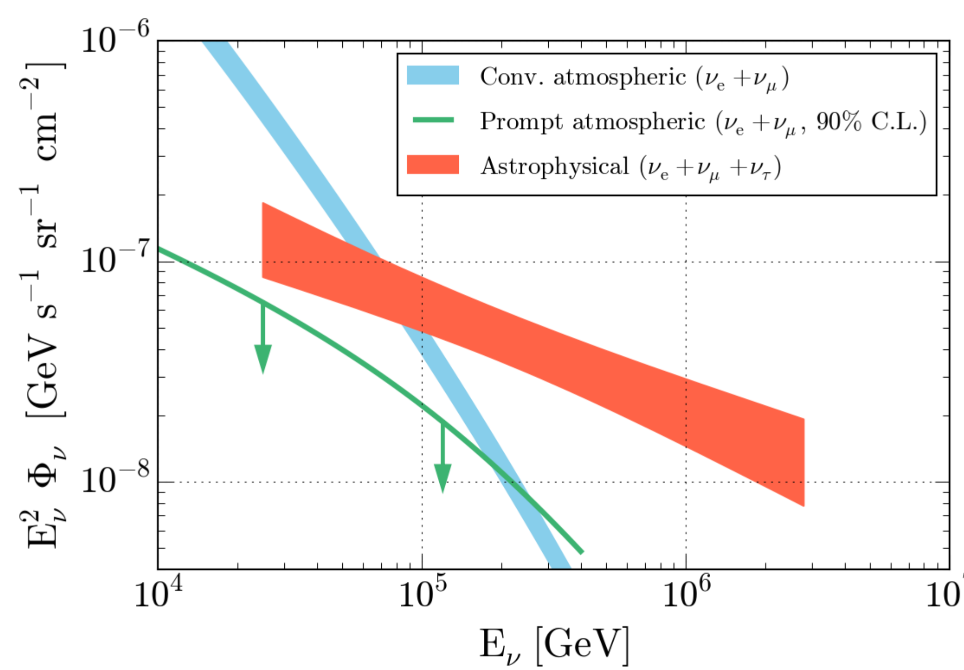
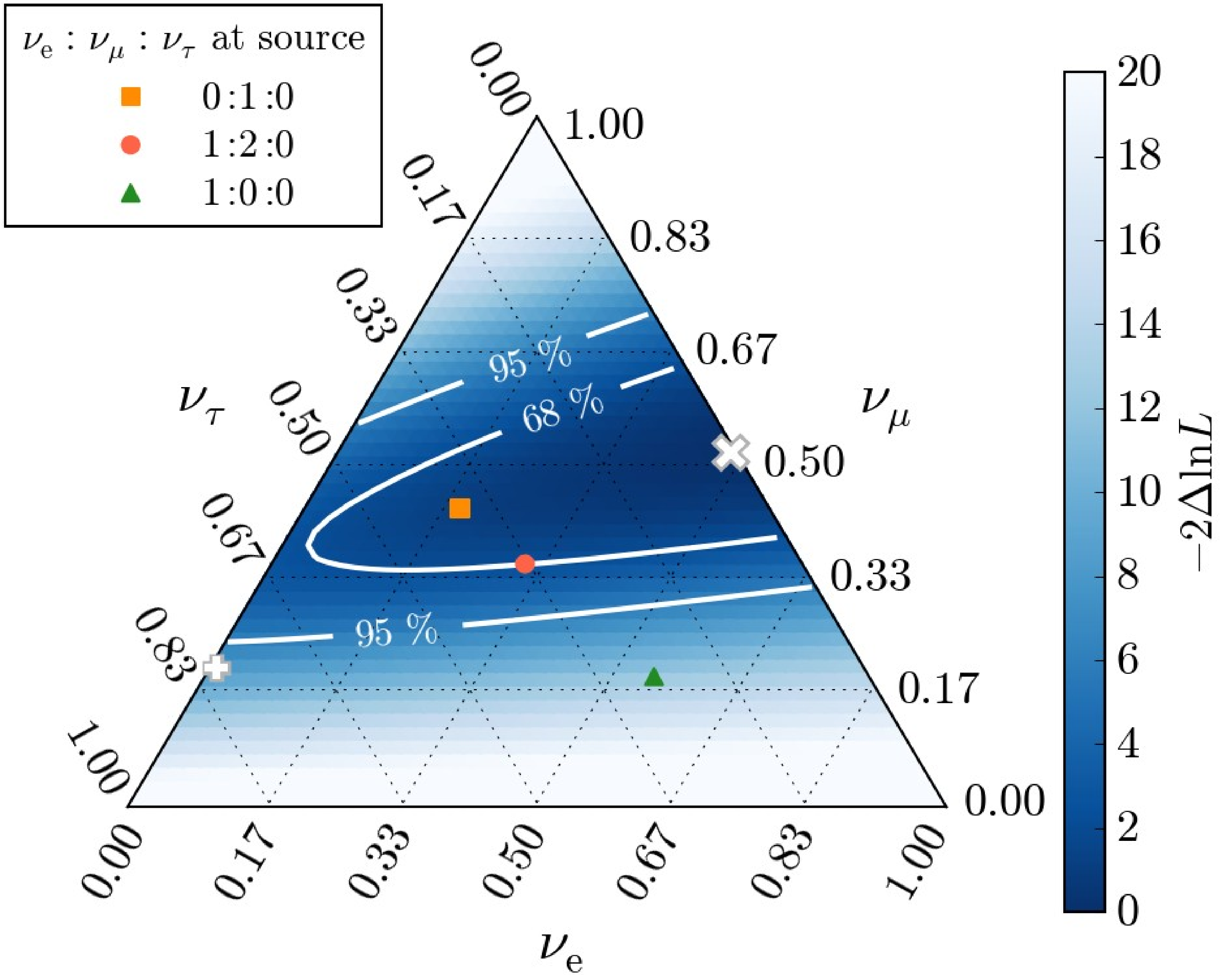


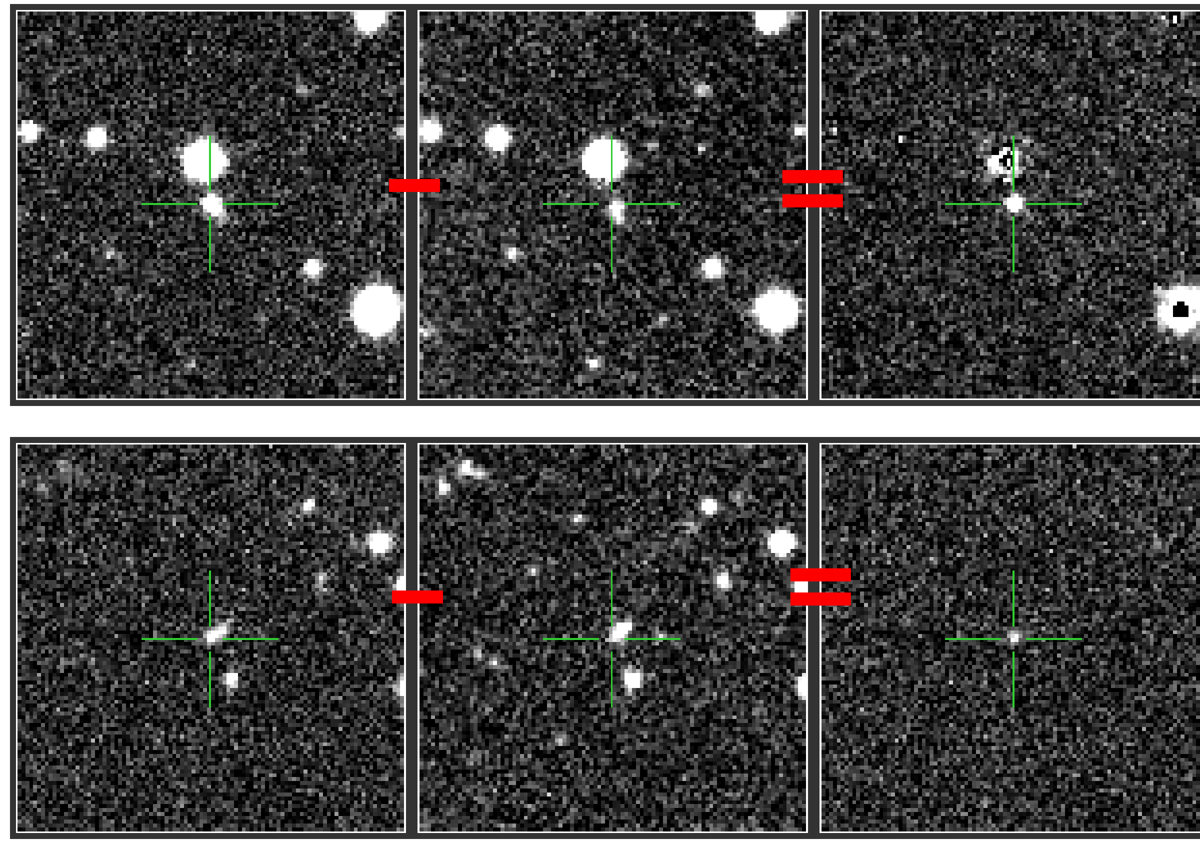

$\nu_e : \nu_\mu : \nu_\tau$ at source
0 : 1 : 0
1 : 2 : 0
1 : 0 : 0
95 %
68 %
95 %
ν_τ
ν_μ
ν_e
$-2\Delta \ln L$
0.00
0.17
0.33
0.50
0.67
0.83
1.00
0
2
4
6
8
10
12
14
16
18
20

CITIZEN SCIENCE

DAS UNTERSCHÄTZTE WISSEN DER LAIEN

Surveys generate thousands of transient candidates

Searching through them efficiently is demanding

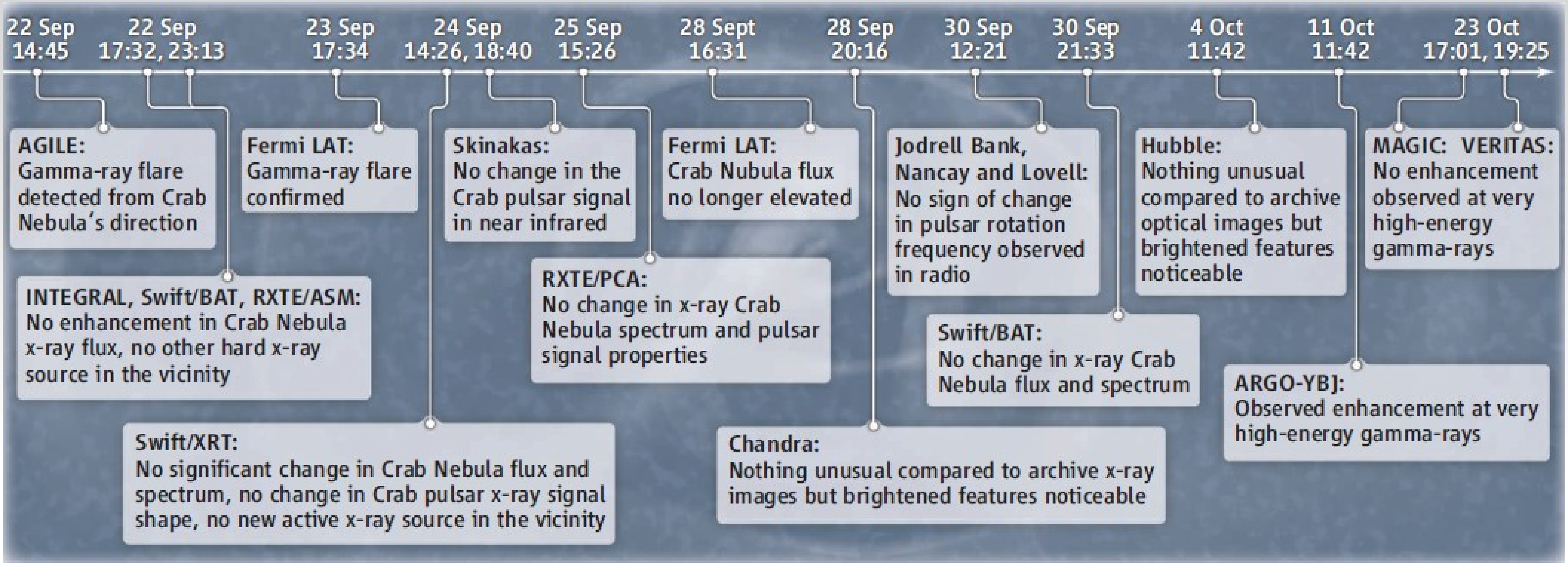


Use the public to identify the best objects

Guided by decision tree

Candidates must be clean, have positive pixels, not be elongated or diffuse, etc.

Crab flare coverage



Summary

- We just entered the multi-messenger astronomy era
- We just began discovering new classes of transient phenomena and exploring new territories in the time-luminosity phase space
- The impressive rate of transient alerts that forthcoming large synoptic surveys, multi-wavelength and non e.m. messsenger telescopes will provide require:
  - Effective algorithms for automatic selection/identification
  - Effective joint strategies and communication

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The End