The search for Electromagnetic Counterparts to GW sources

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Based partly on LIGO-G1602197

Outline

EMGW

AstroSat: Transients

AstroSat: Steady sources

GROWTH

Electromagnetic Counterparts

EM signatures

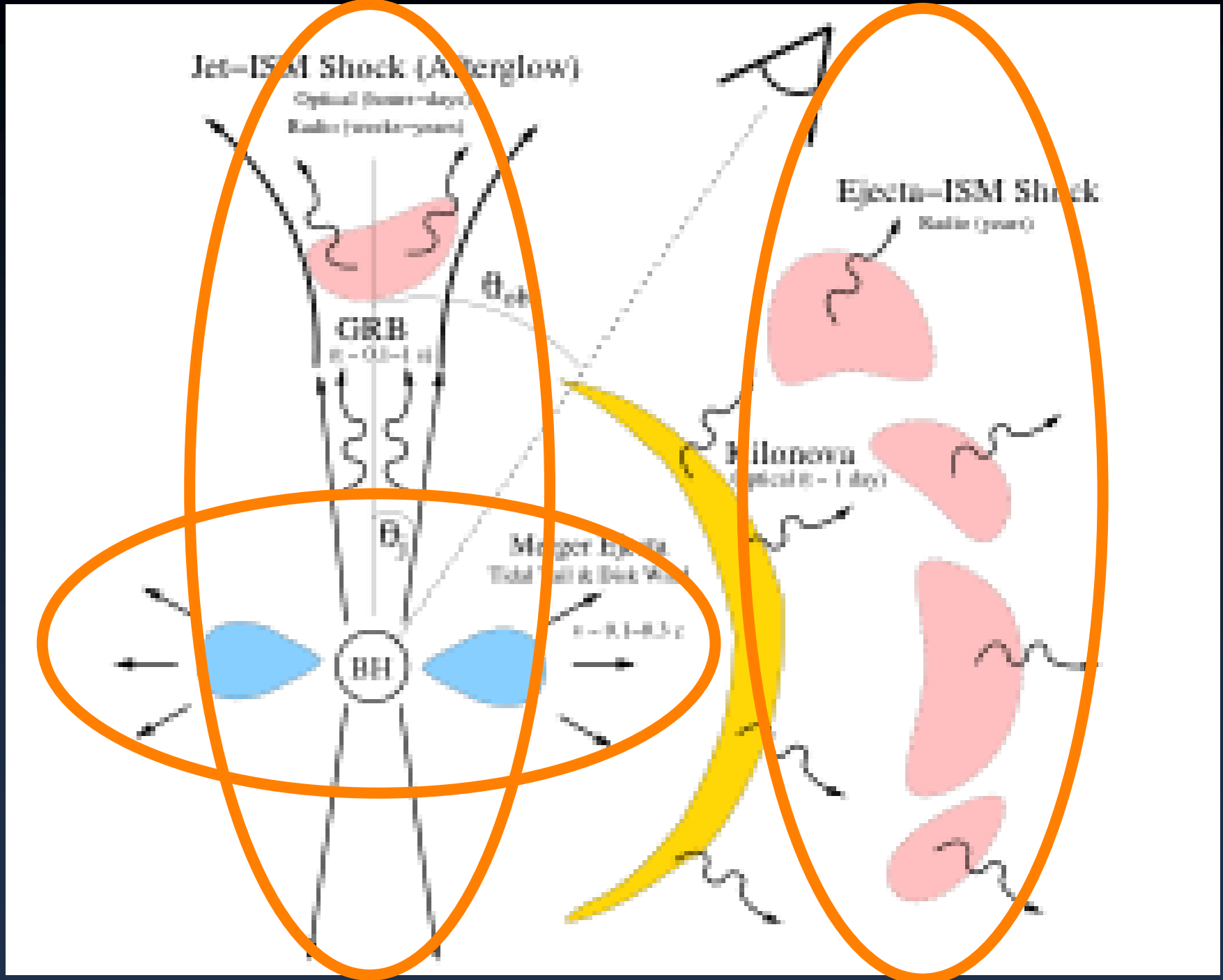
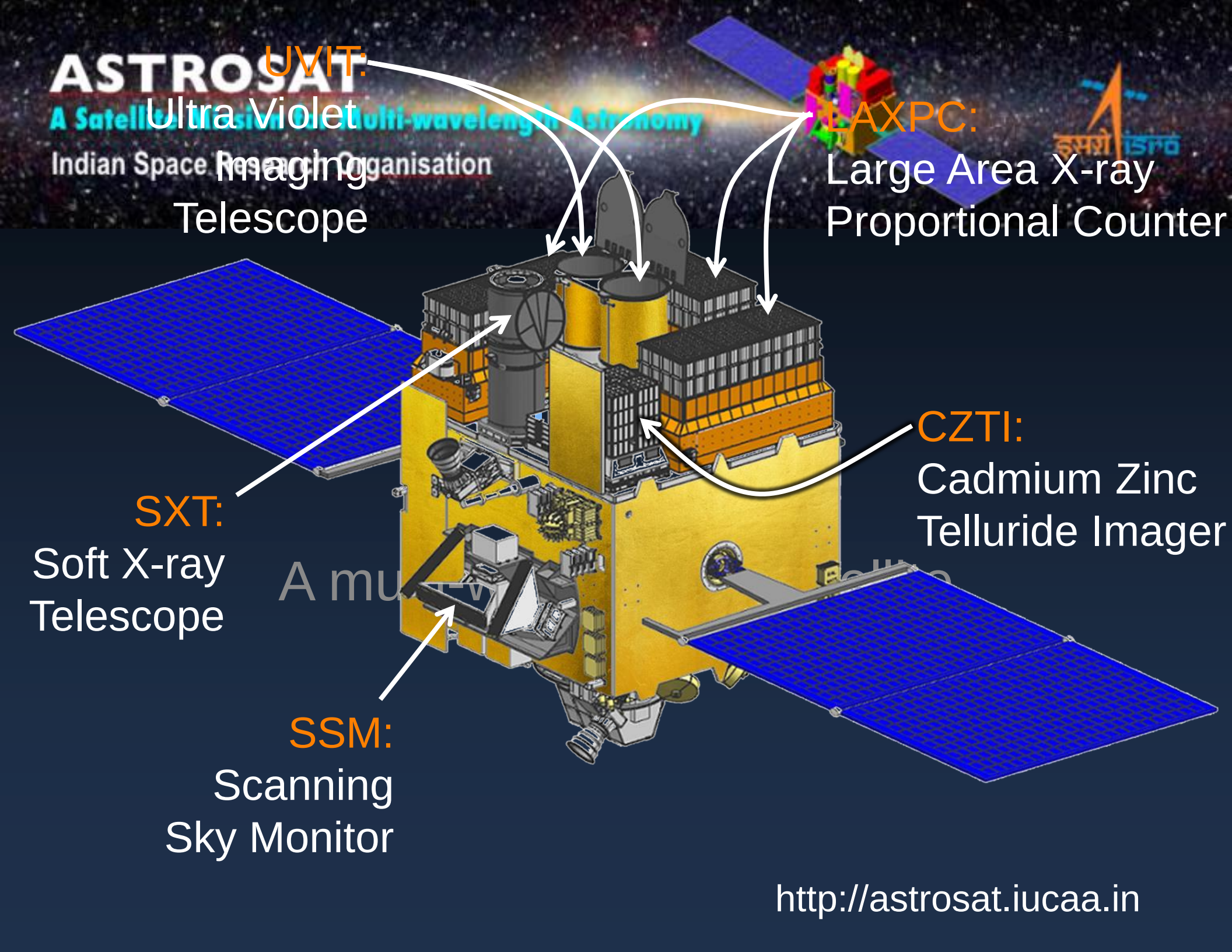


Figure from Metzger & Berger, 2012, ApJ, 746, 48

ASTROSAT

A multi-wavelength satellite

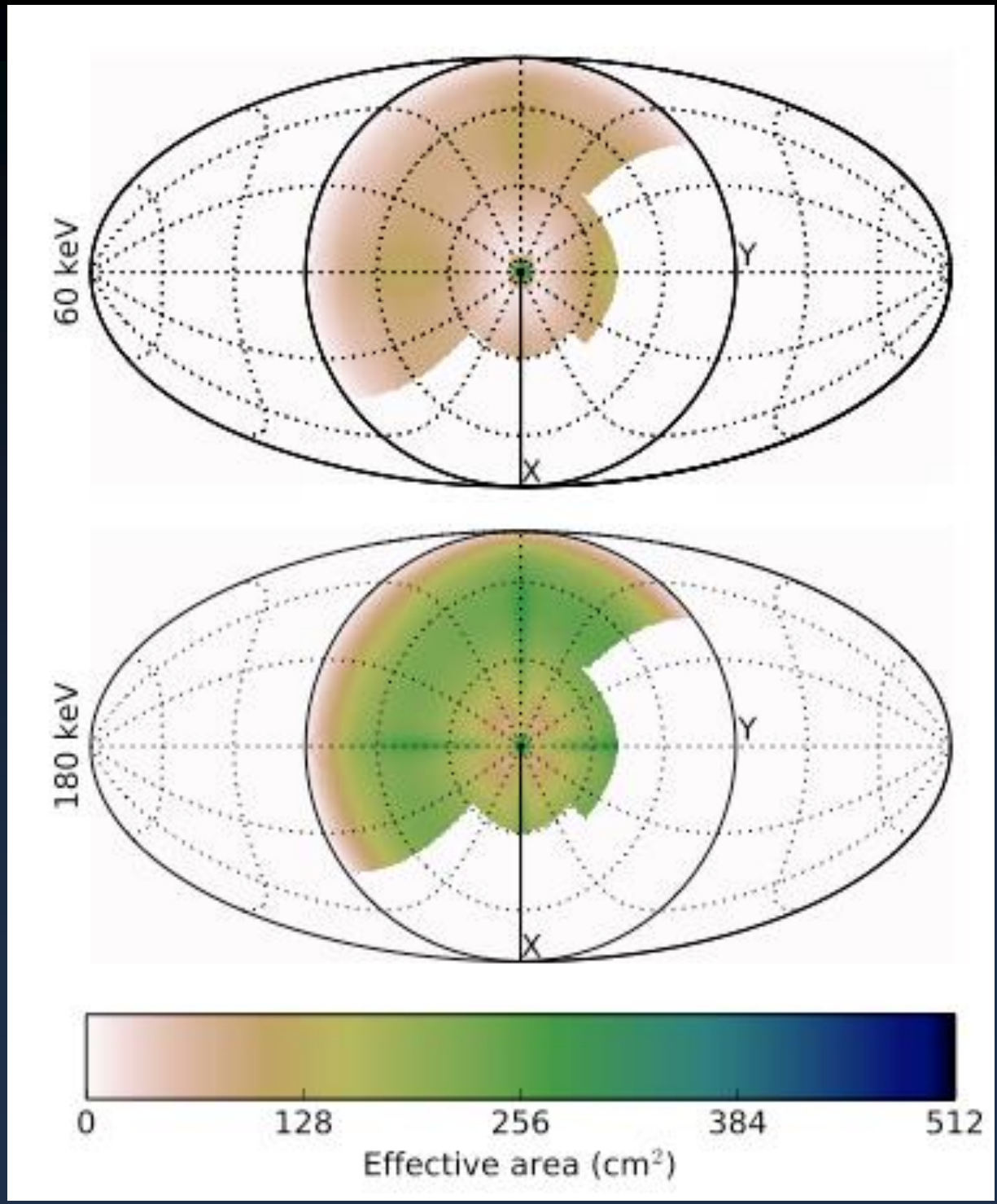

ASTROSAT
A Satellite Mission for Multi-wavelength Astronomy
Indian Space Research Organisation
UVIT:
Ultra Violet Imaging Telescope
LAXPC:
Large Area X-ray Proportional Counter
CZTI:
Cadmium Zinc Telluride Imager
SXT:
Soft X-ray Telescope
SSM:
Scanning Sky Monitor
http://astrosat.iucaa.in

CZTI field of view

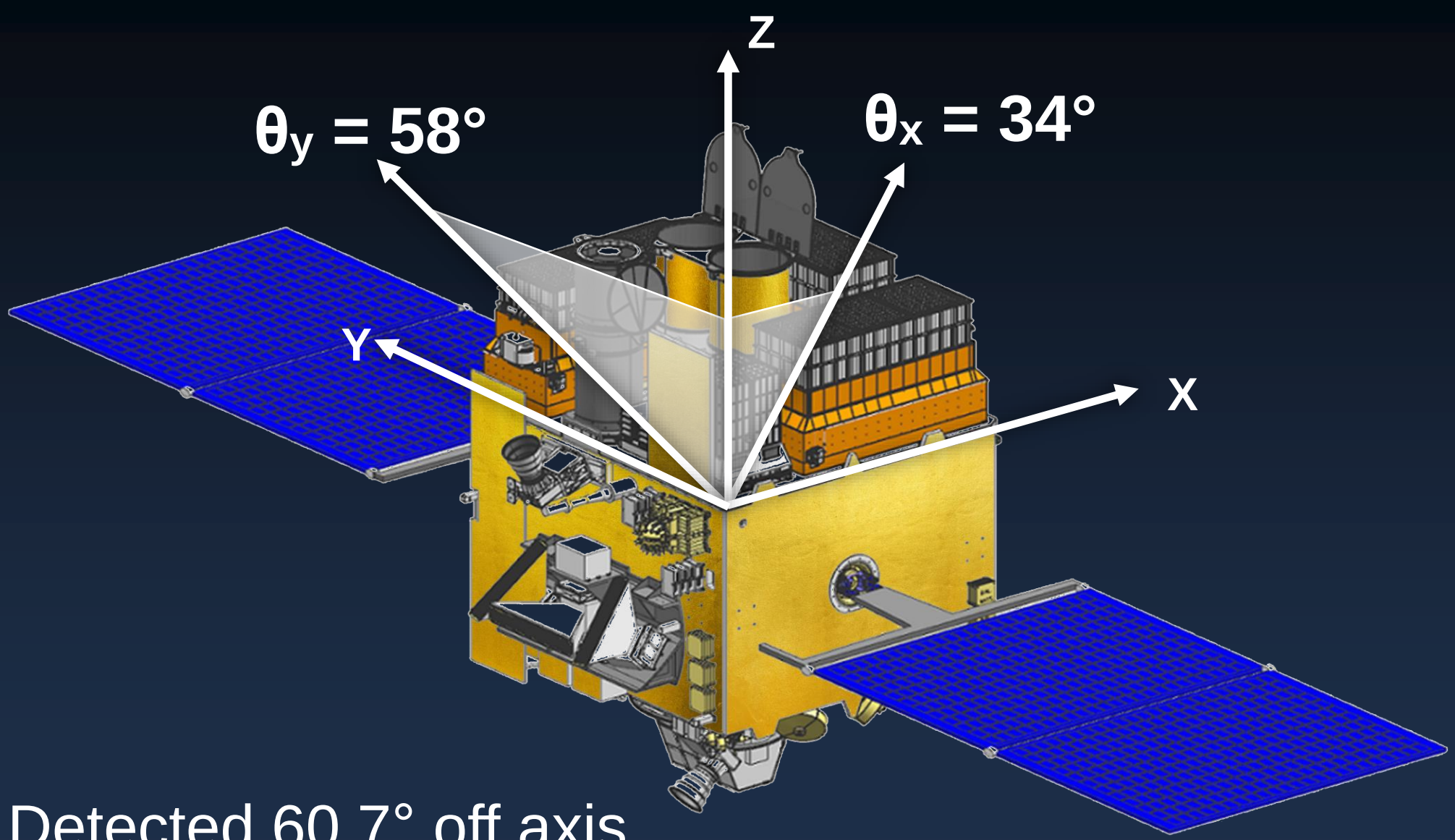
- Primary FoV: 4.5 degrees (FWHM)

- Overall sensitivity: >29% of the sky

- Median effective area at 180 keV = 190 sq cm ≈ 40% of peak



GRB151006A

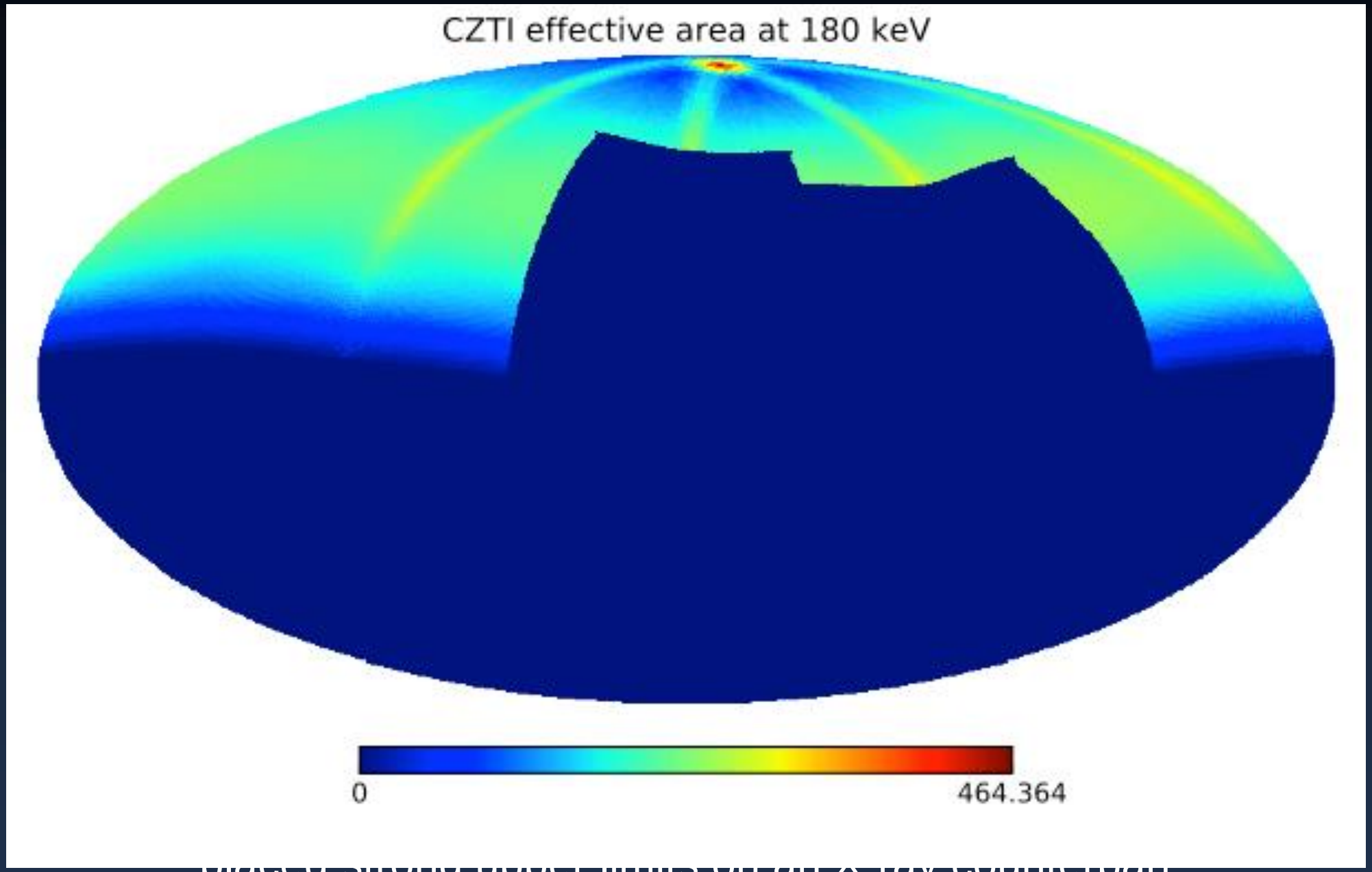


Detected 60.7° off axis

Bhalerao et al., 2015, GCN 18422

Coverage for GW150914

Coverage for GW151226



placed strong upper limits on an X-ray counterpart

Skymap plotted using data provided by LSC.

GRB detections

Continuous wave sources

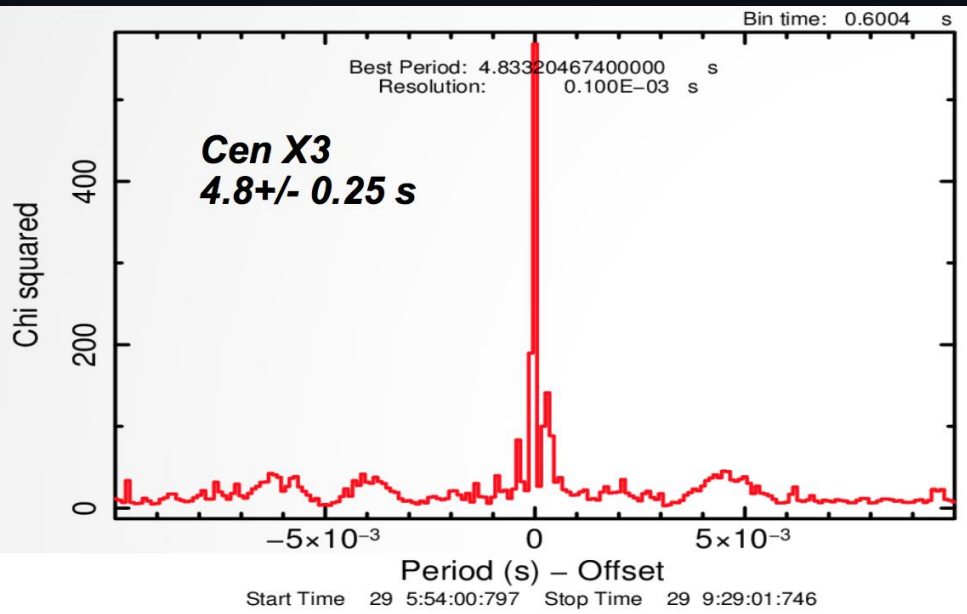
- Accreting NS: continuous wave sources
- Need accurate period throughout LIGO observing run
- AstroSat observations: LAXPC, SSM

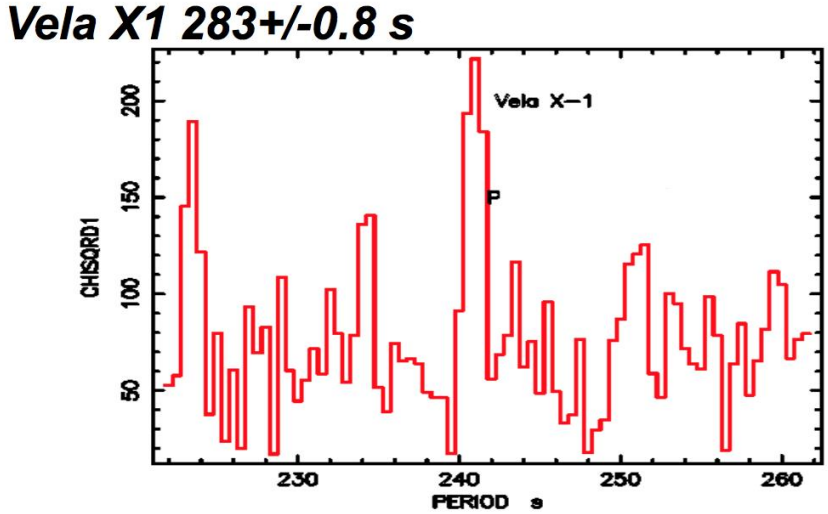
Large Area X-ray Proportional Counter

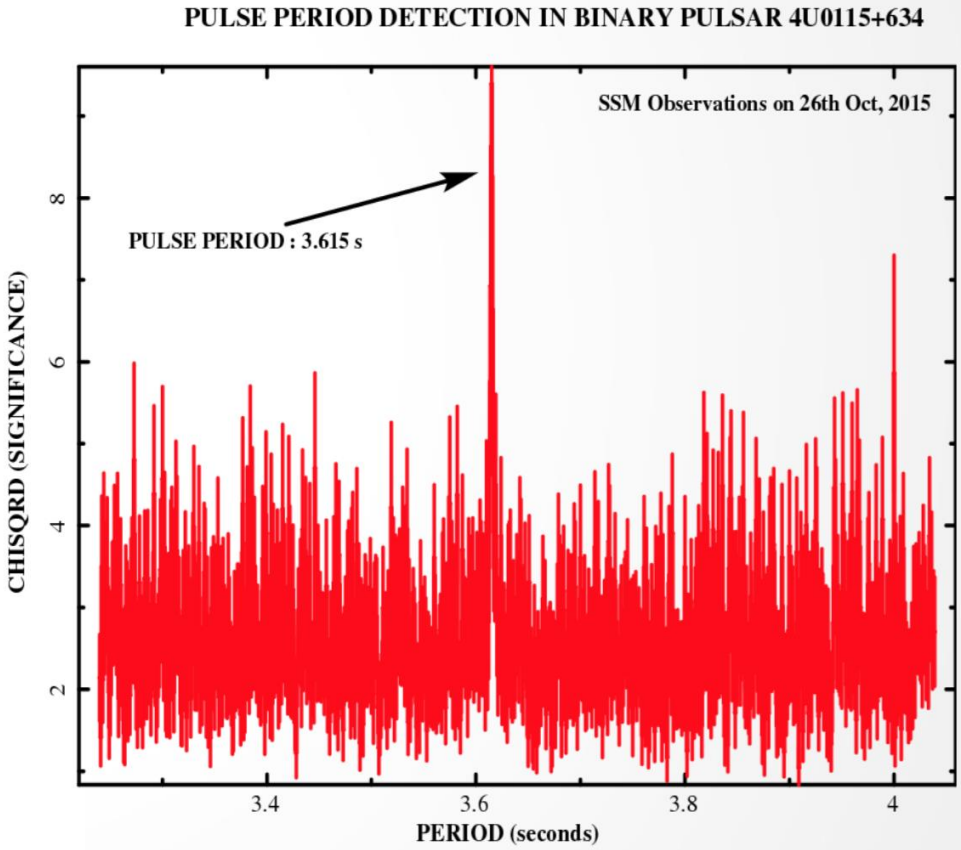
- Energy Range:
  - 2-80 keV
  - Resolution: 12-15% (at 22 keV)
- Effective area:
  - ~ 6000 cm^2
- Field of view:
  - FOV: 1°
  - Resolution: 5’ in scan mode
- Timing resolution:
  - 20 μs

http://www.iucaa.ernet.in/~astrosat/laxpc_specs.html

Scanning Sky Monitor





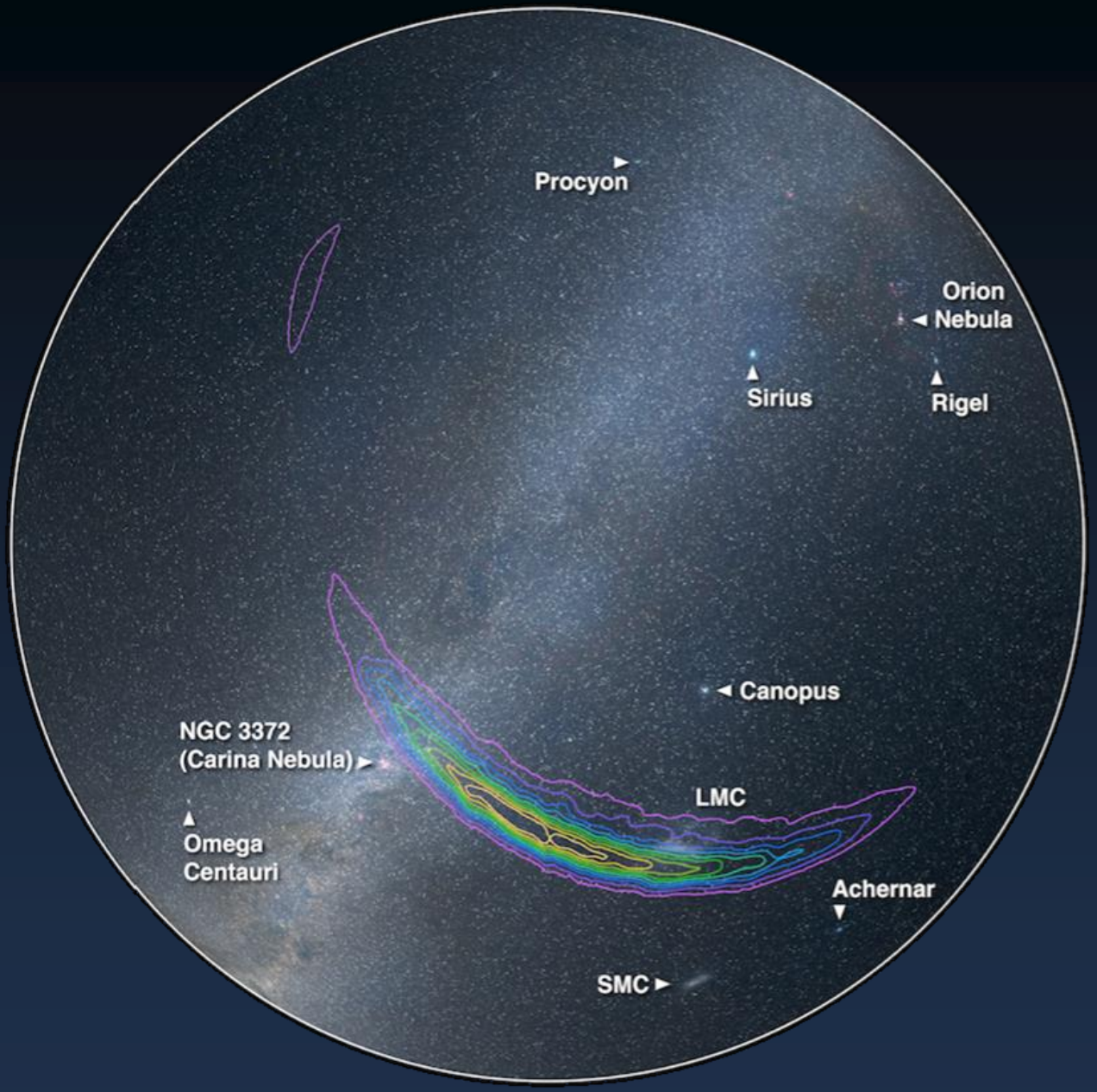


Slide courtesy M.C. Ramadevi / SSM Team

Large positional uncertainty

GW150914:
90% containment region spans
630 square degrees

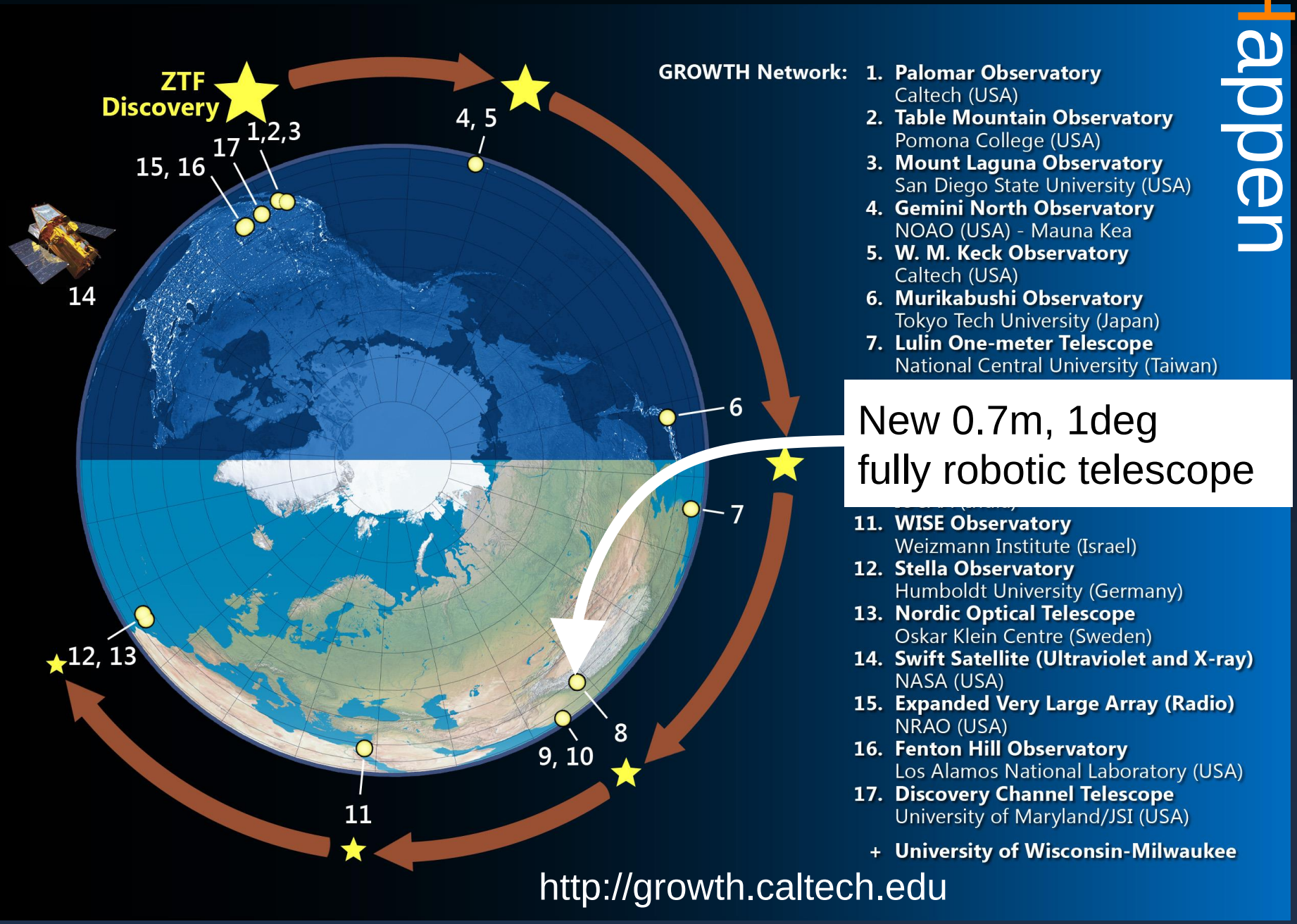
(arXiv:1602.08492, Abott et al.)



Credit: M. Zevin / Astrobites / LVC / arXiv:1602.03840

Global Relay of Observatories

Watching Transients Happen



GROWTH Network:

1. **Palomar Observatory**
   Caltech (USA)
2. **Table Mountain Observatory**
   Pomona College (USA)
3. **Mount Laguna Observatory**
   San Diego State University (USA)
4. **Gemini North Observatory**
   NOAO (USA) - Mauna Kea
5. **W. M. Keck Observatory**
   Caltech (USA)
6. **Murikabushi Observatory**
   Tokyo Tech University (Japan)
7. **Lulin One-meter Telescope**
   National Central University (Taiwan)

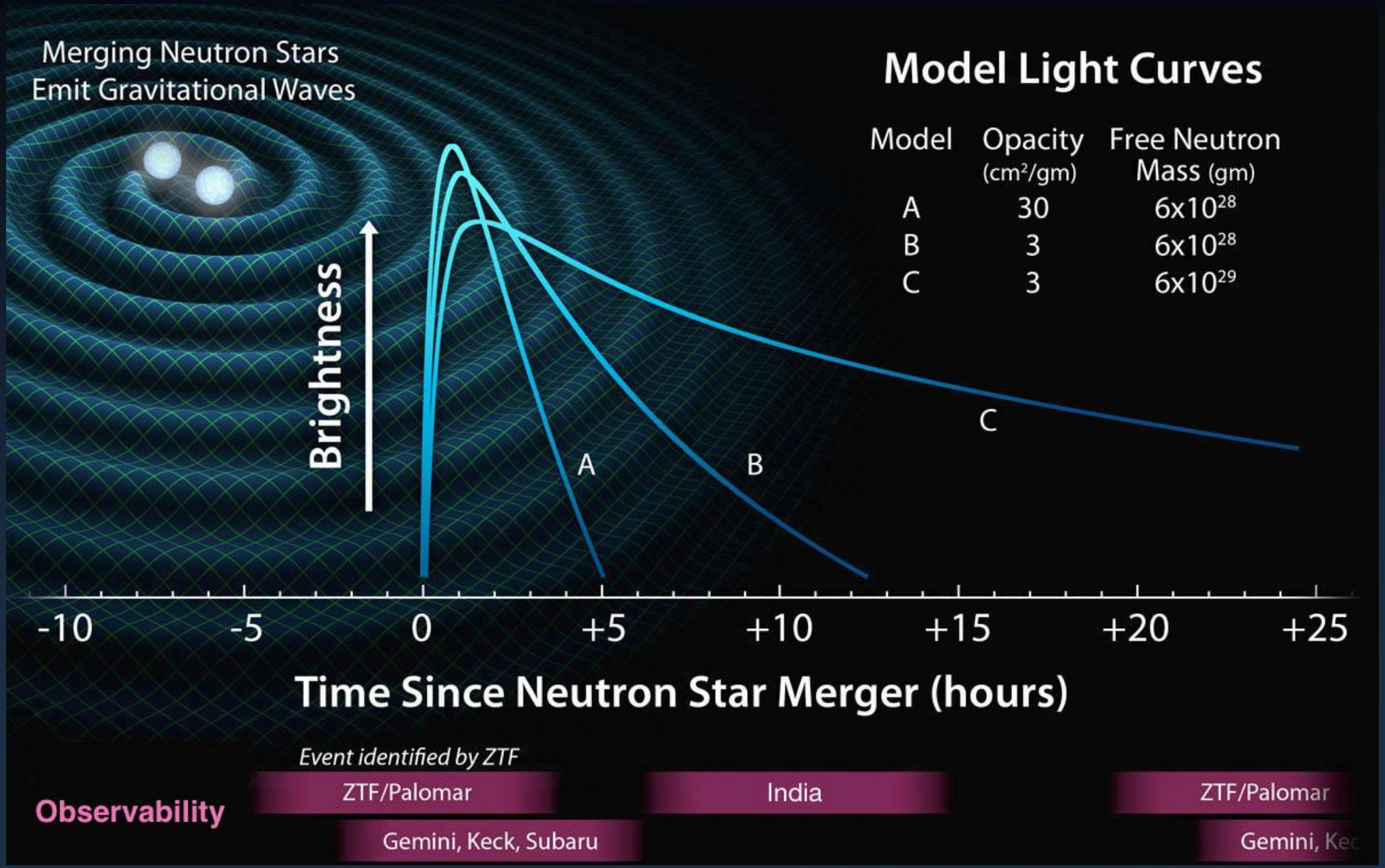
New 0.7m, 1deg fully robotic telescope

11. **WISE Observatory**
    Weizmann Institute (Israel)
12. **Stella Observatory**
    Humboldt University (Germany)
13. **Nordic Optical Telescope**
    Oskar Klein Centre (Sweden)
14. **Swift Satellite (Ultraviolet and X-ray)**
    NASA (USA)
15. **Expanded Very Large Array (Radio)**
    NRAO (USA)
16. **Fenton Hill Observatory**
    Los Alamos National Laboratory (USA)
17. **Discovery Channel Telescope**
    University of Maryland/JSI (USA)

\+ **University of Wisconsin-Milwaukee**

http://growth.caltech.edu

EM counterparts to GW sources



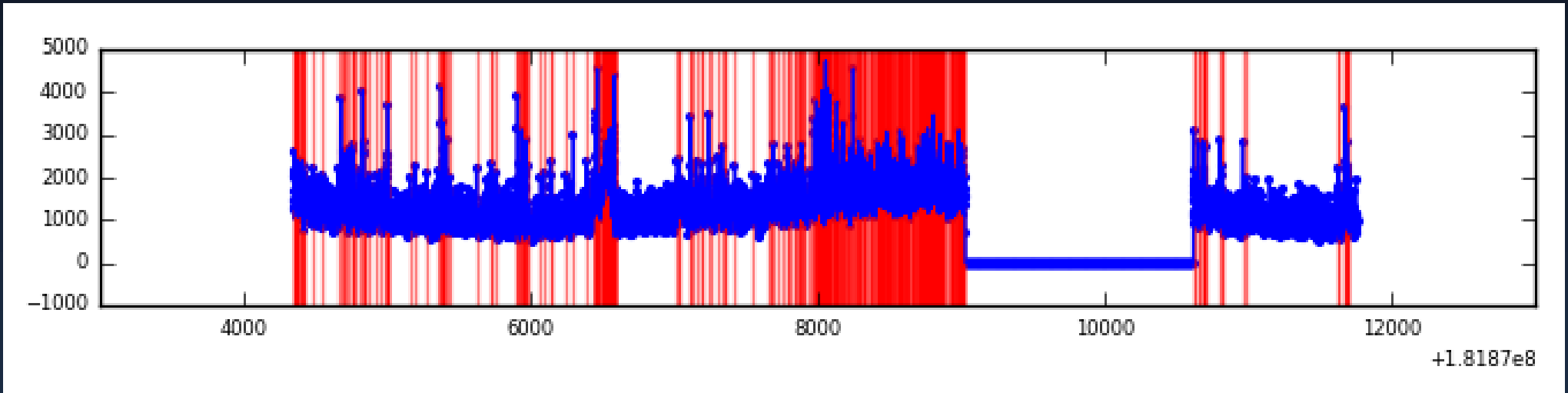
GROWTH India telescope

- 0.7 m aperture, 1 sq degree field of view
- Fully robotic telescope
  - » Interfacing developed and demonstrated at IUCAA
- Sensitivity: ~21 mag in 5 minutes
  - » 4k back-illuminated camera

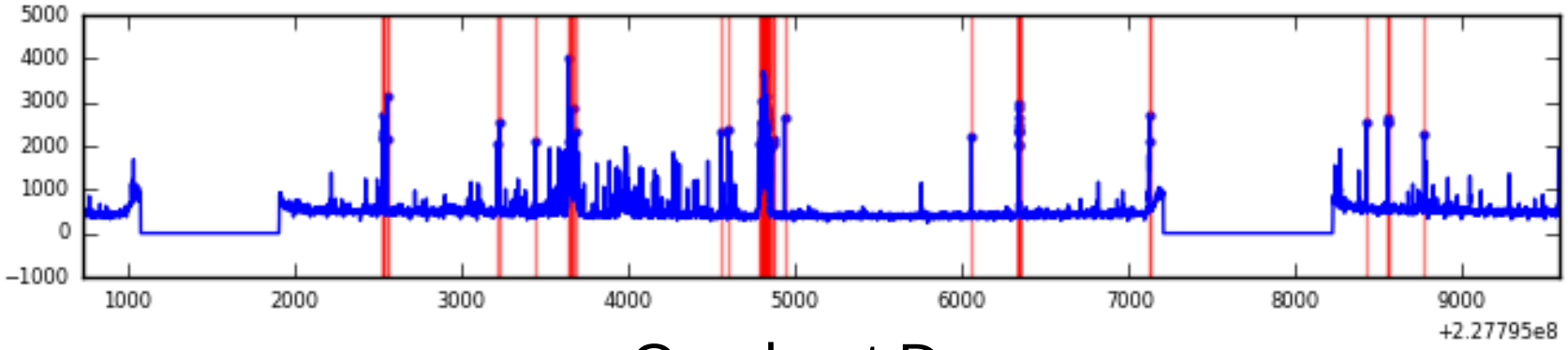
Challenge: finding X-ray transients

Raw-est data

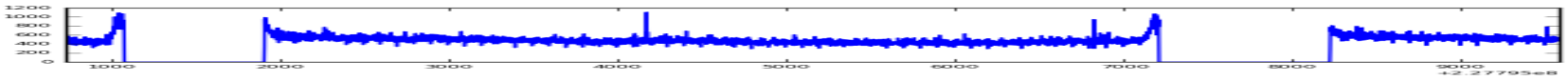
- “Bunches” with dozens of photons in 20-40 microseconds

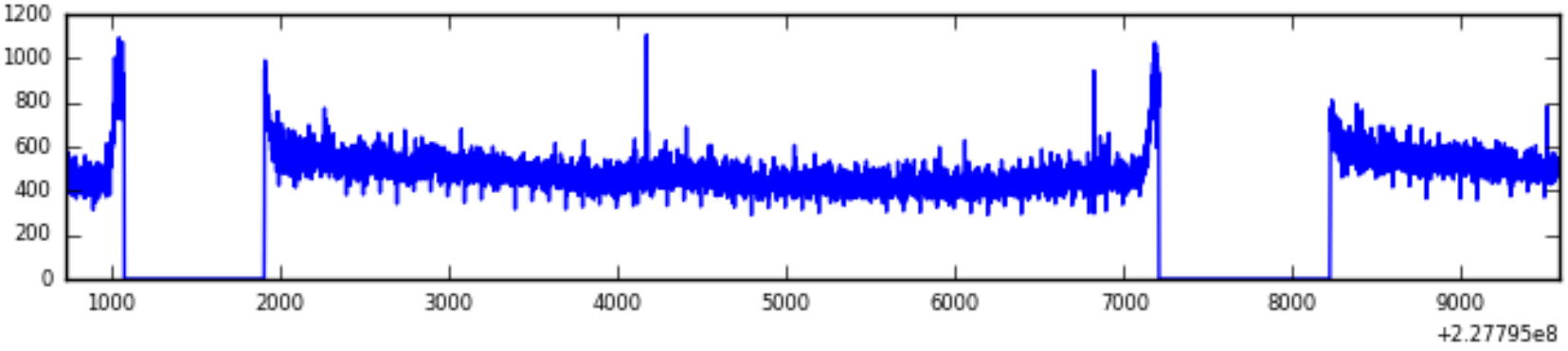


Raw data



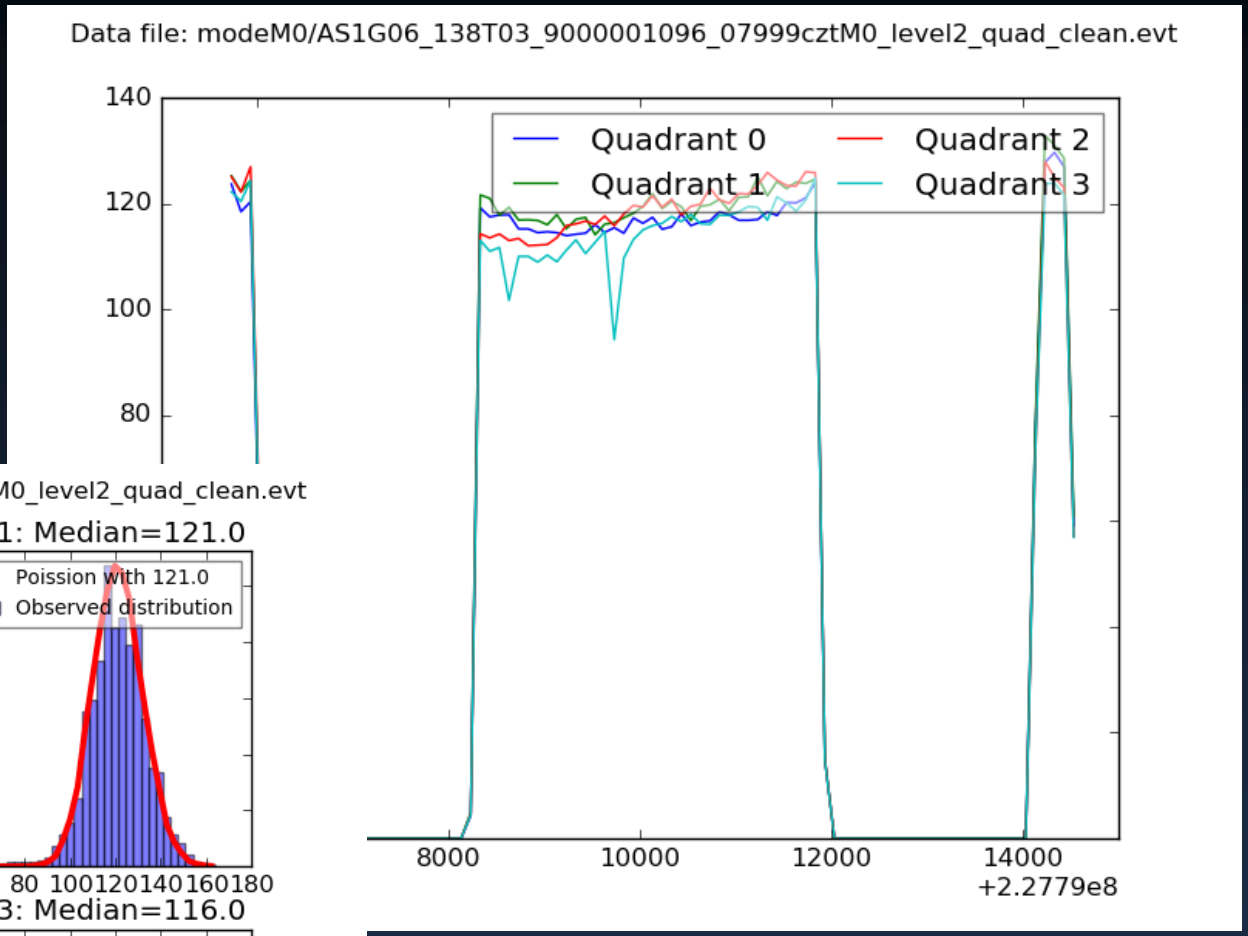
Quadrant D

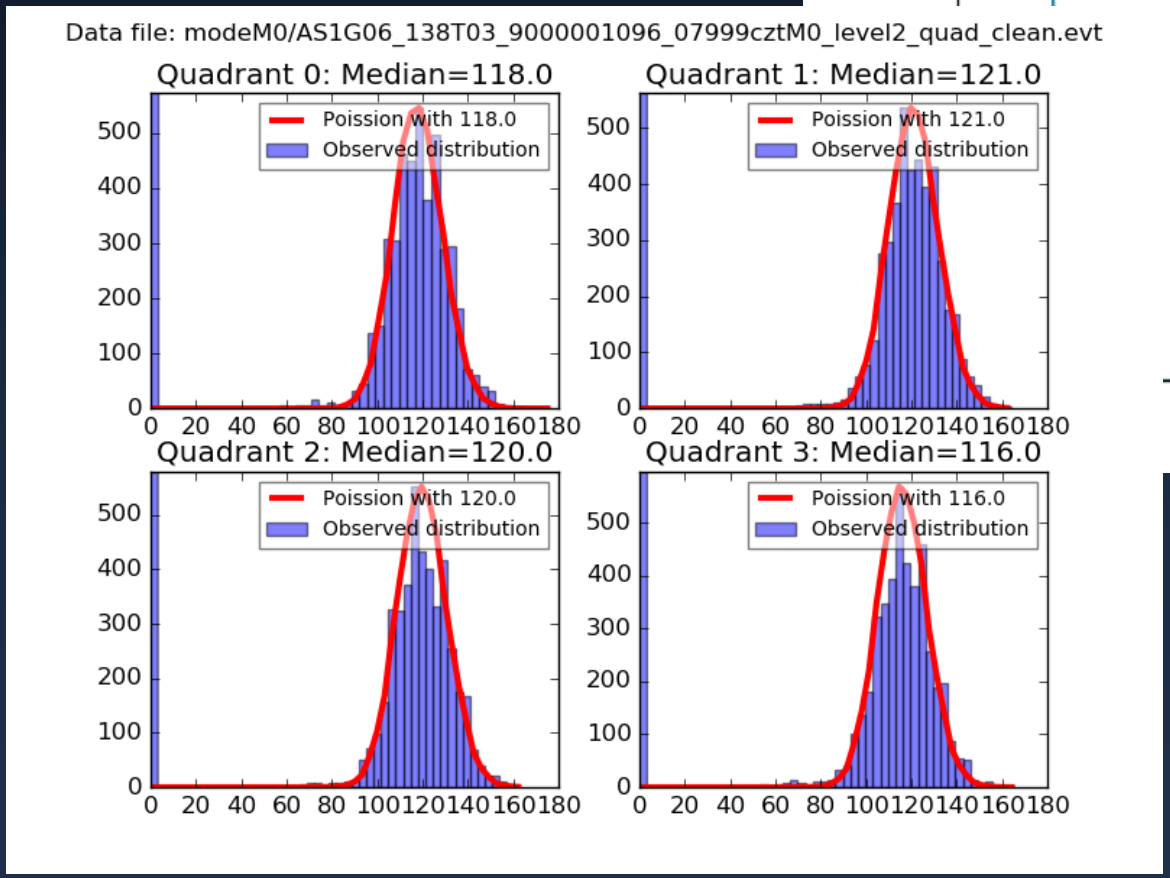




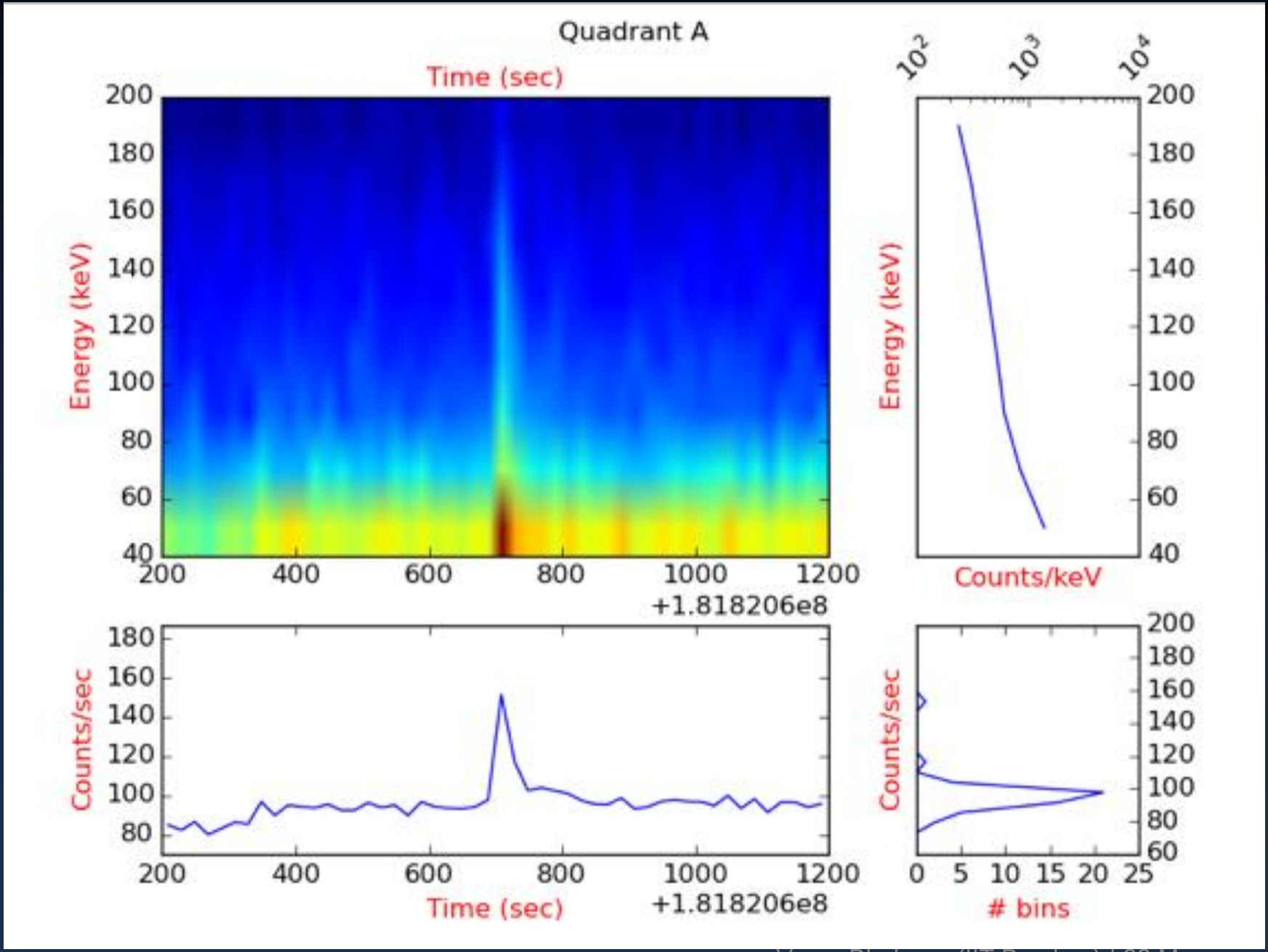
Quadrant C

Clean data

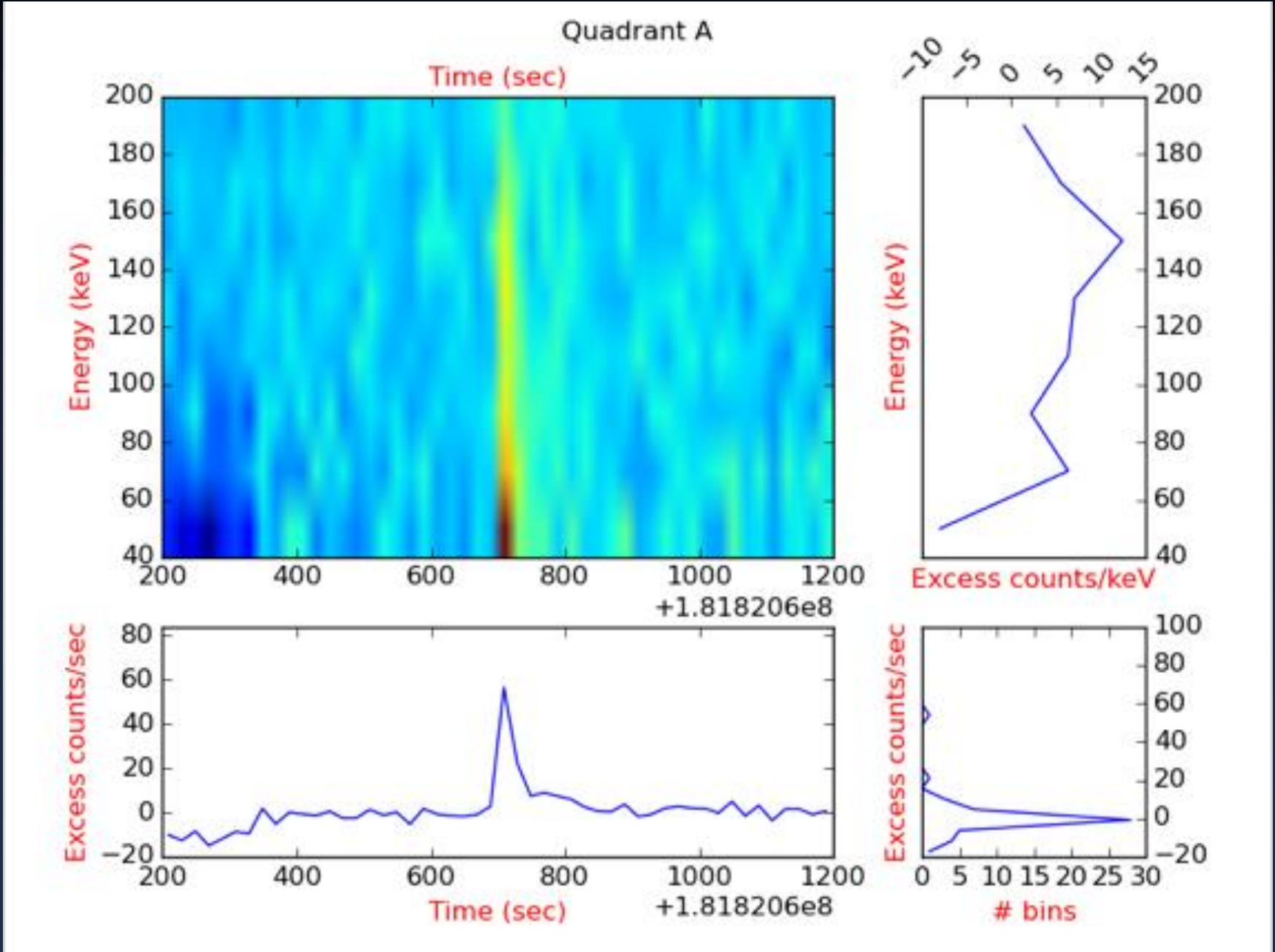

Data file: modeM0/AS1G06_138T03_9000001096_07999cztM0_level2_quad_clean.evt
Quadrant 0
Quadrant 1
Quadrant 2
Quadrant 3
140
120
100
80
8000
10000
12000
14000
+2.2779e8


Data file: modeM0/AS1G06_138T03_9000001096_07999cztM0_level2_quad_clean.evt
Quadrant 0: Median=118.0
Poission with 118.0
Observed distribution
Quadrant 1: Median=121.0
Poission with 121.0
Observed distribution
Quadrant 2: Median=120.0
Poission with 120.0
Observed distribution
Quadrant 3: Median=116.0
Poission with 116.0
Observed distribution

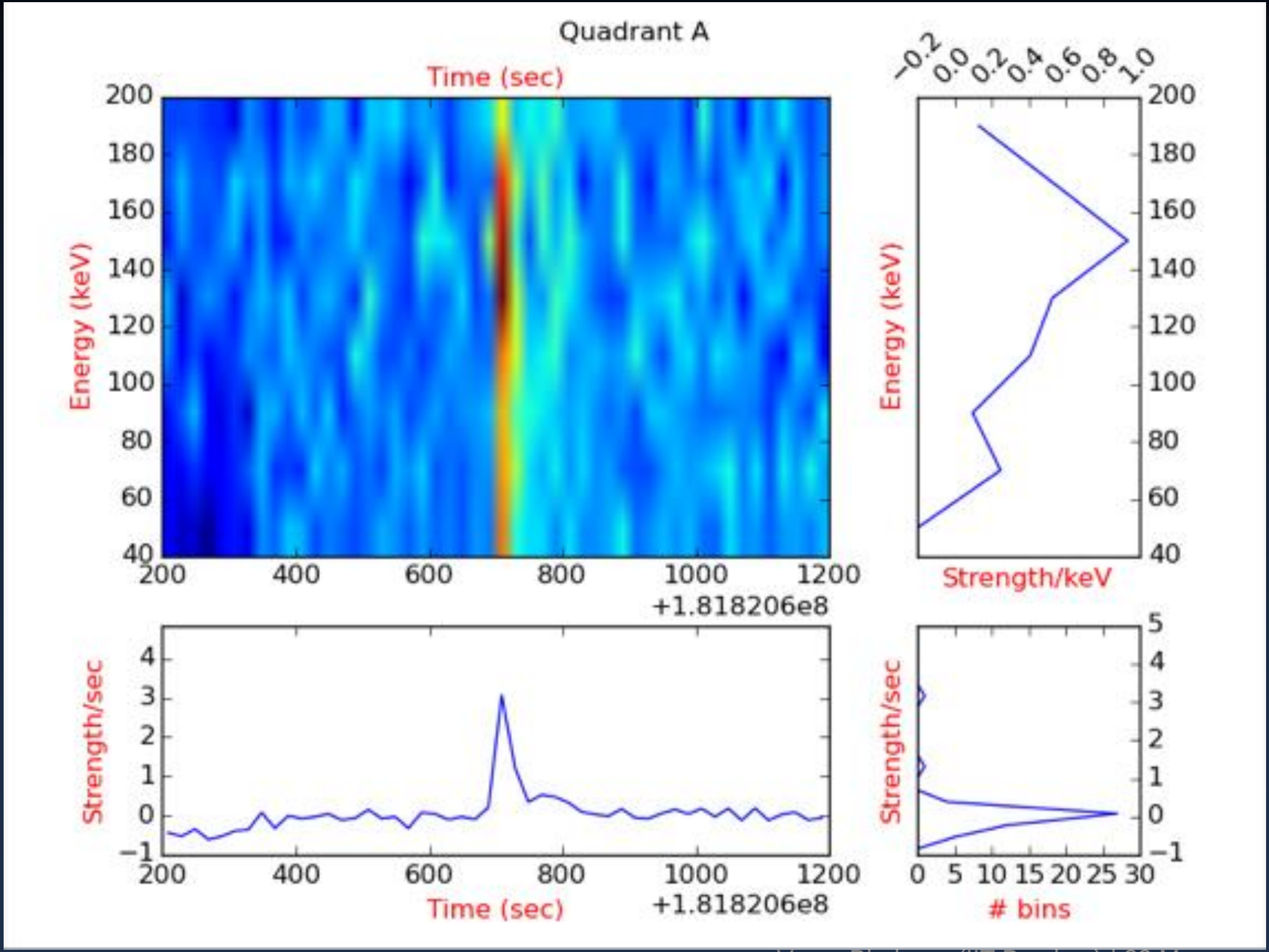
Time-Energy plots



Median subtracted



Median Sub + Sigma normalised



False alarm rates

- Require coincidence in multiple quadrants
- Estimate false alarm rate from de-trended data (collapsed over energy)

Questions?

AstroSat: Transients

AstroSat: Steady sources

GROWTH

Search for X-ray transients

Indian Eyes on Gravitational Wave Skies

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LIGO Document number LIGO-G1602197

Extra slides, these are…

Want to go here, you do not…

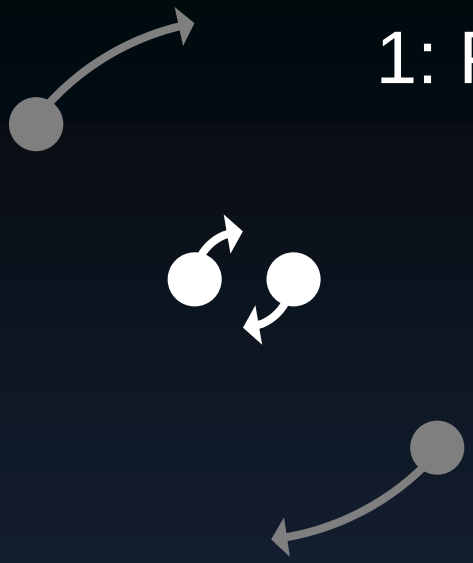
Introductory material

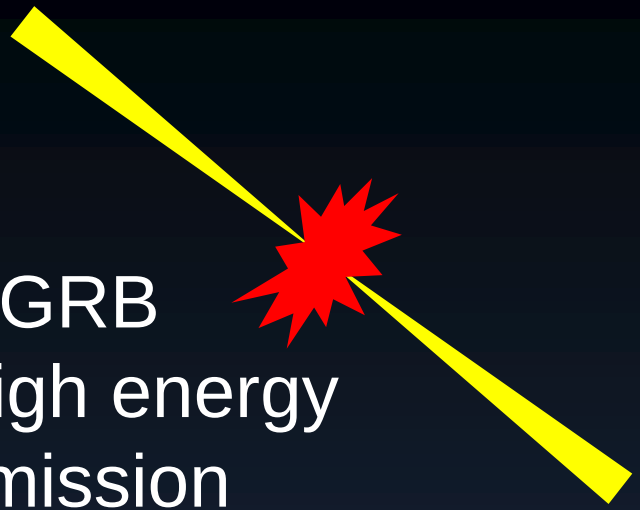
Transient sources of GW

- Binary systems:
  - » Black hole + Black hole
  - » Black hole + Neutron Star
  - » Neutron Star + Neutron Star
- Core collapse supernovae
  - » If asymmetric explosion
- Unknowns!

Electromagnetic Counterparts

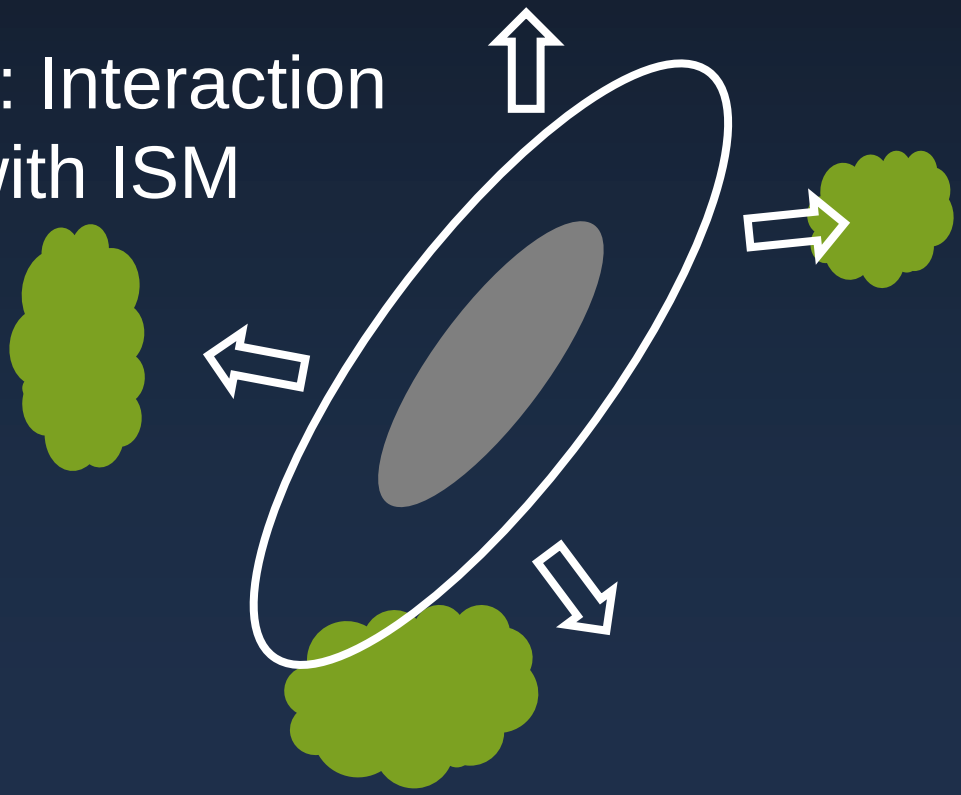
1: Pre-merger emission





2:GRB
High energy emission

4: Interaction with ISM



3: Kilonova
R-process nucleosynthesis

Complementary information

GW

- Masses
- Spins
- Geometric properties
  - » Position
  - » Distance
  - » Inclination angle…

EM

- Precise location
- Nucleosynthesis
- Ejecta properties
  - » Beaming
  - » Mass
  - » Velocity…
- Cosmology

Complete astrophysical picture

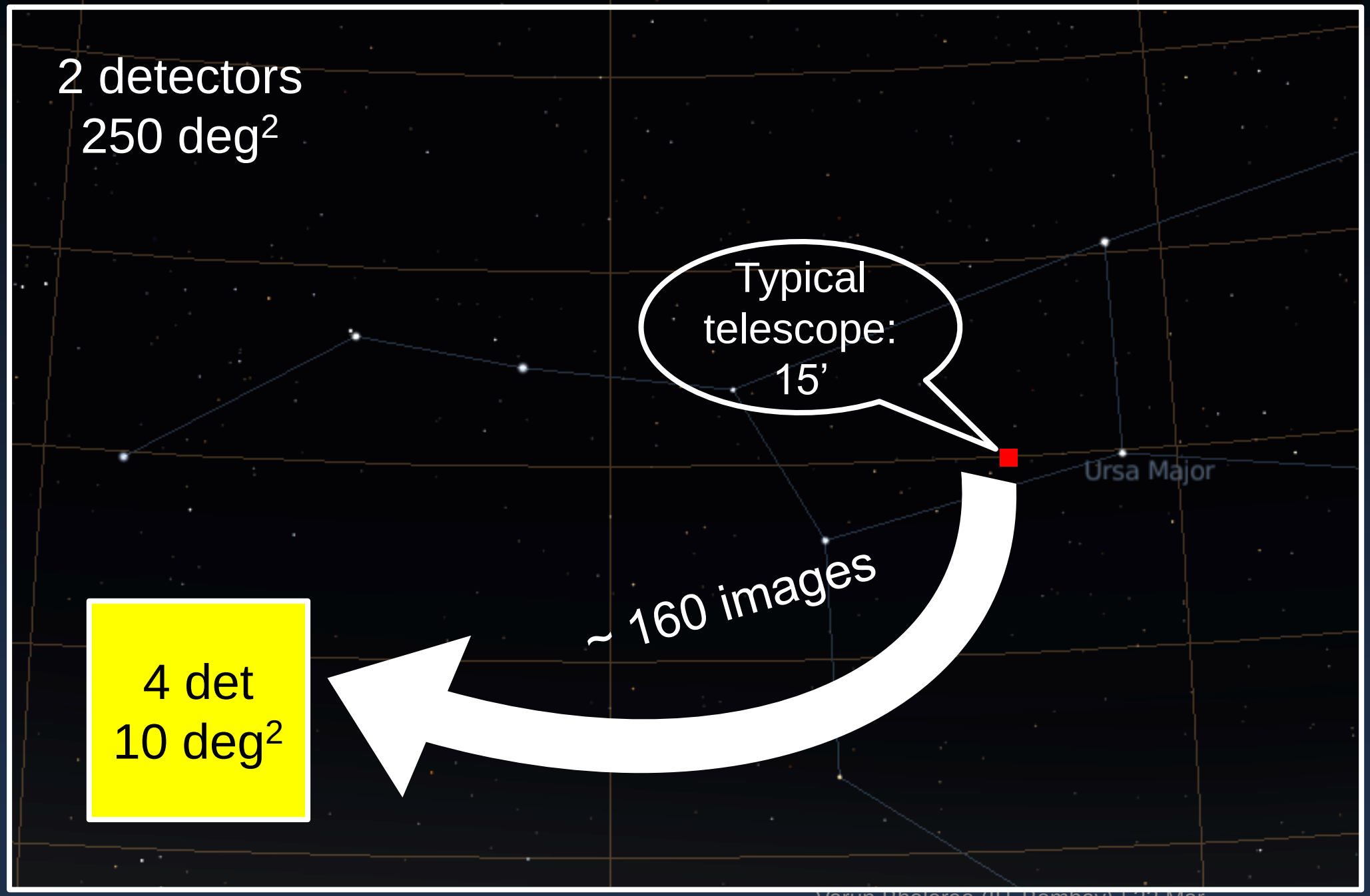
Significance of EM detection

- Better sky location – identify host galaxies
- Source environment

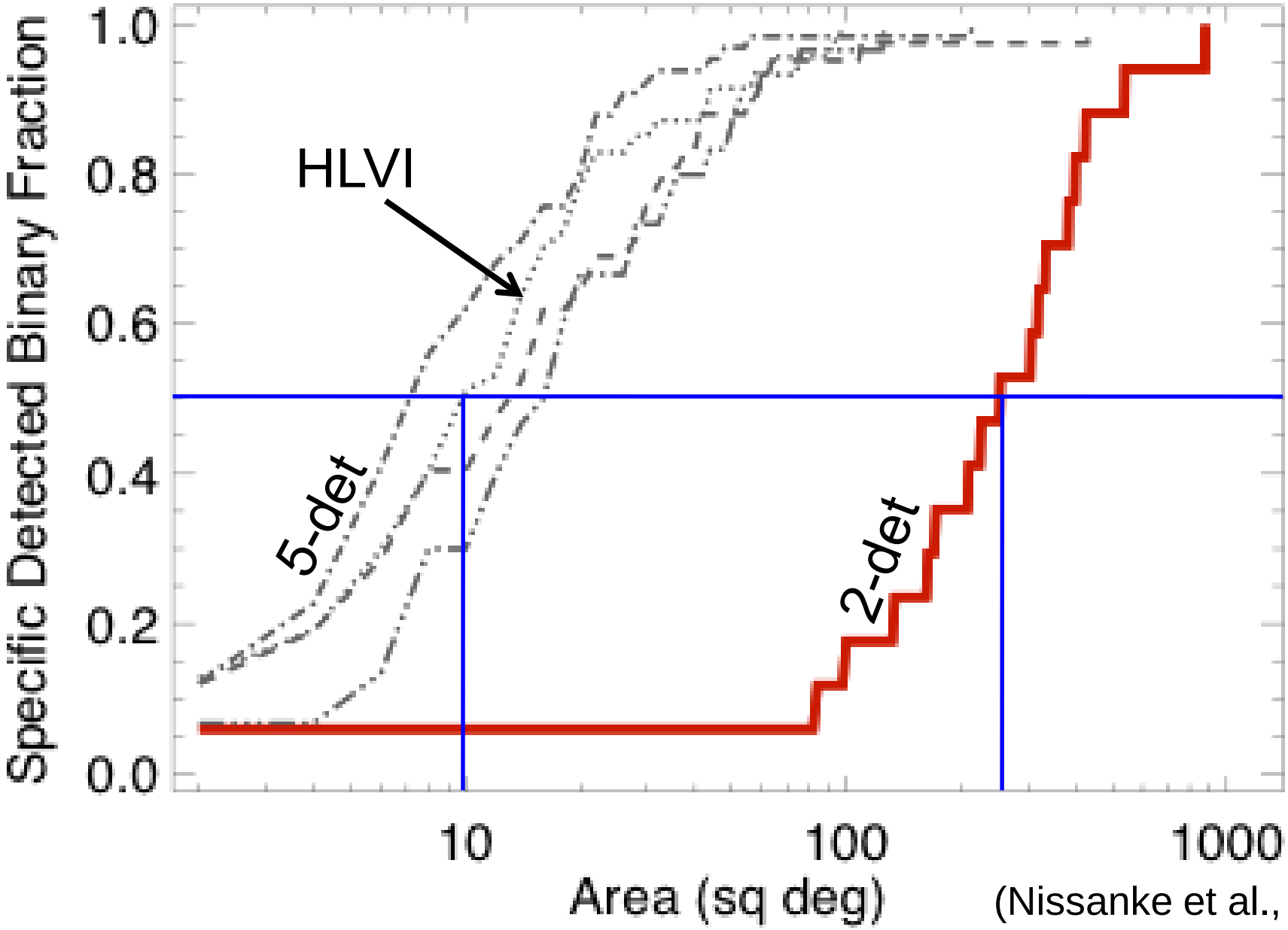
- Distance
- Standard sirens – independent cosmological measurements

- Properties of ejecta, nucleosynthesis, accretion

Localization



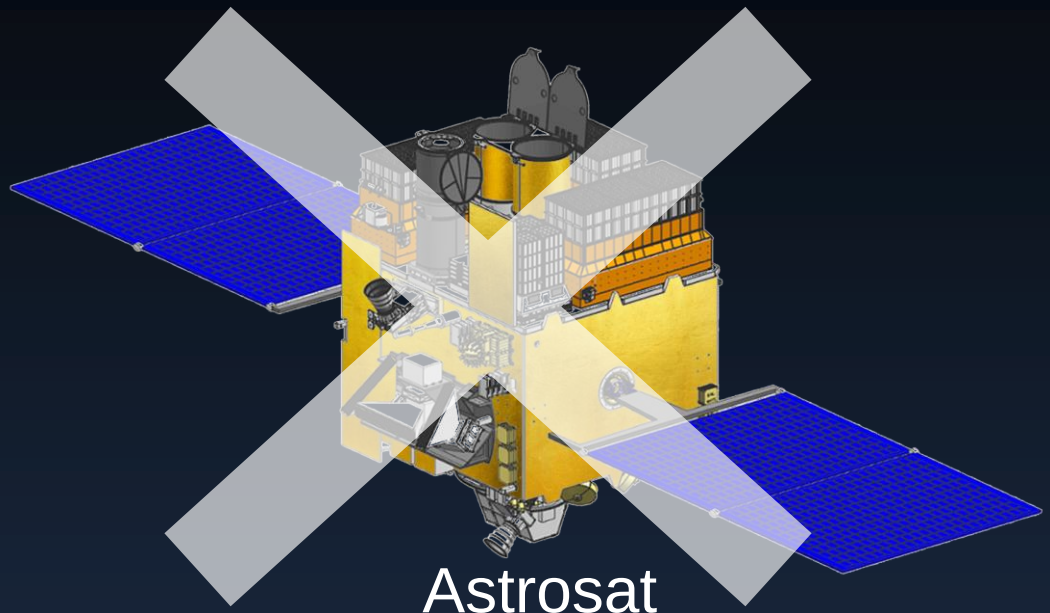
How large is the search region?



(Nissanke et al., 2012)

Followup

LVC + India MoUs for GW150914



Intermediate Palomar Transient Factory – 2 papers, 1 GCN

GW150914 – Follow-up contributions

- iPTF Search for an Optical Counterpart to Gravitational Wave Trigger GW150914
  arXiv:1602.08764
- Localization and broadband follow-up of the gravitational-wave transient GW150914
  arXiv:1602.08492
- LIGO/Virgo G184098: iPTF Optical Transient Candidates
  GCN 18337

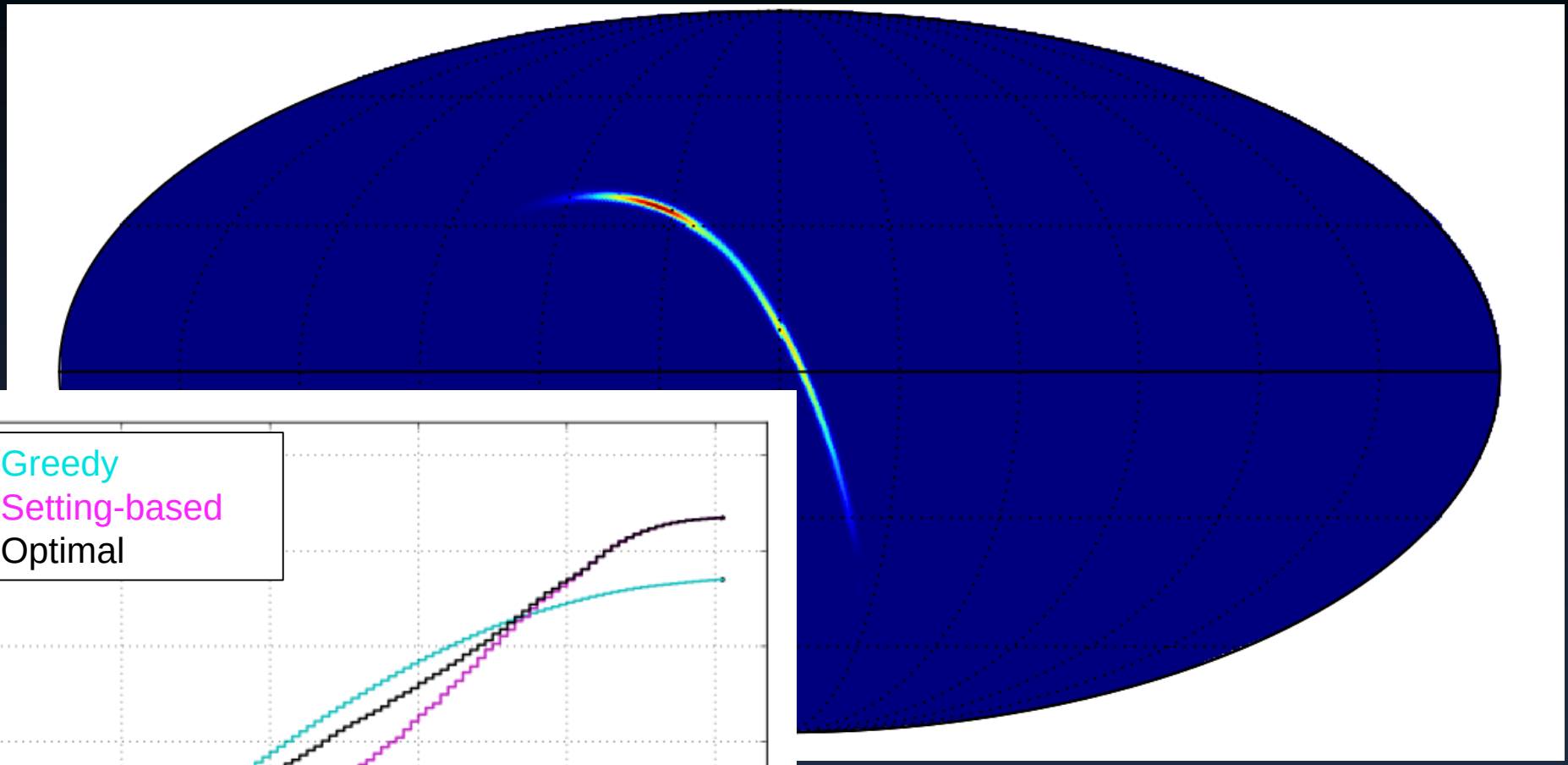
Scheduling

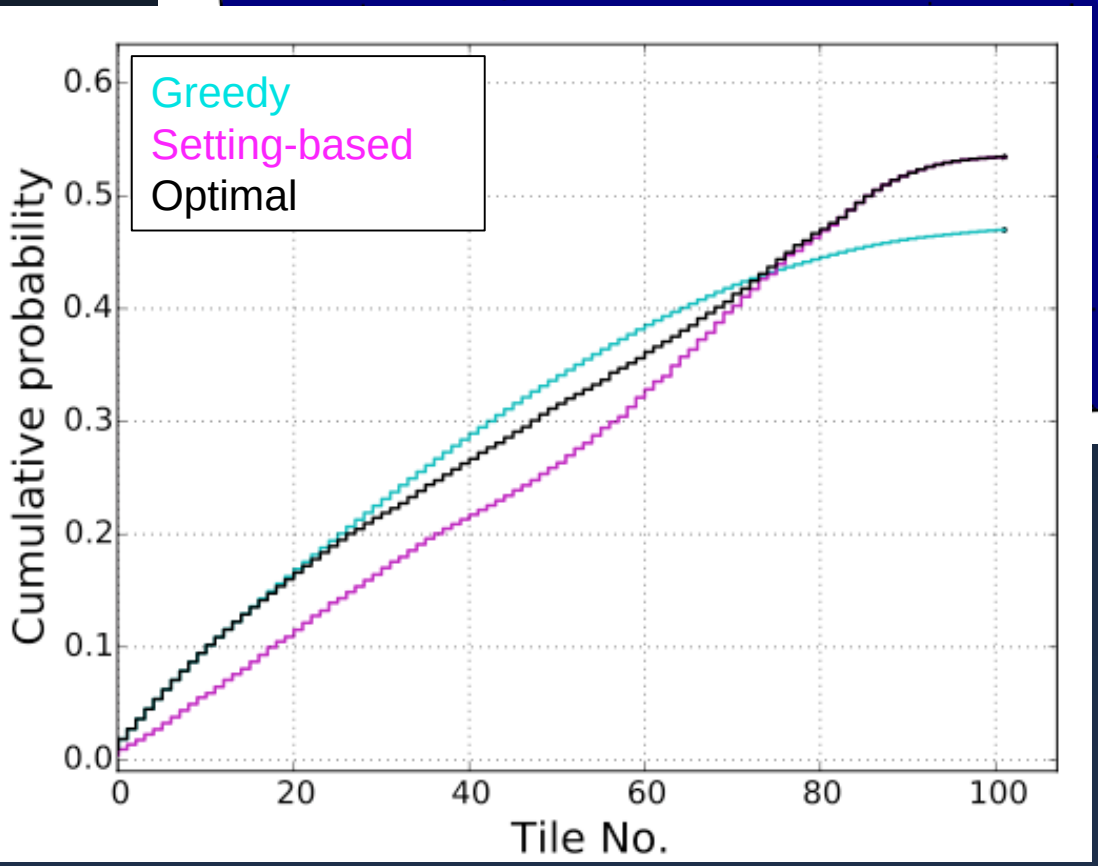
Better scheduling

- An enhanced method for scheduling observations of large sky error regions for finding optical counterparts to transients

- J. Rana, A. Singhal, B. Gadre, V. Bhalerao, S. Bose (IUCAA)
- arXiv:1603.01689
- LIGO-P1600007

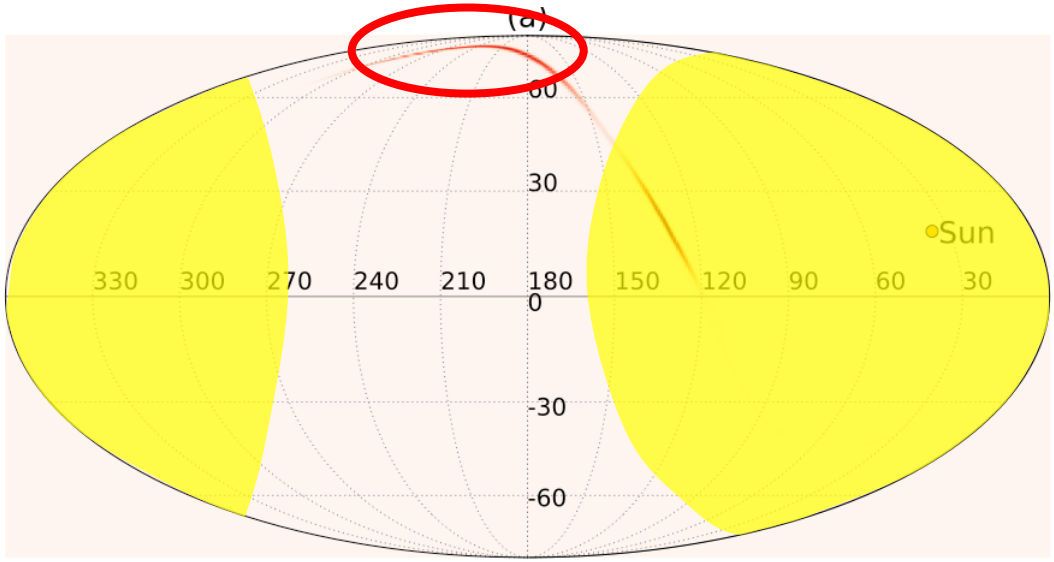
Better scheduling

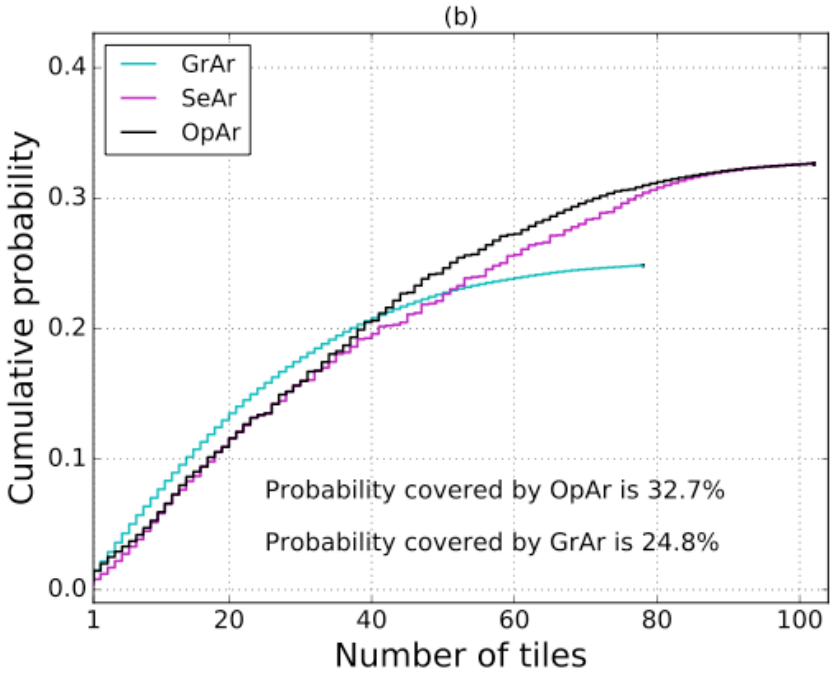


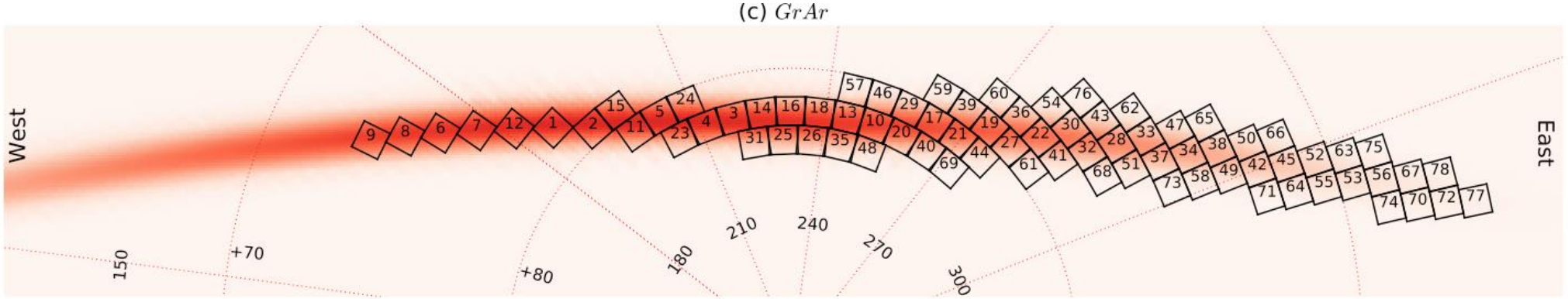


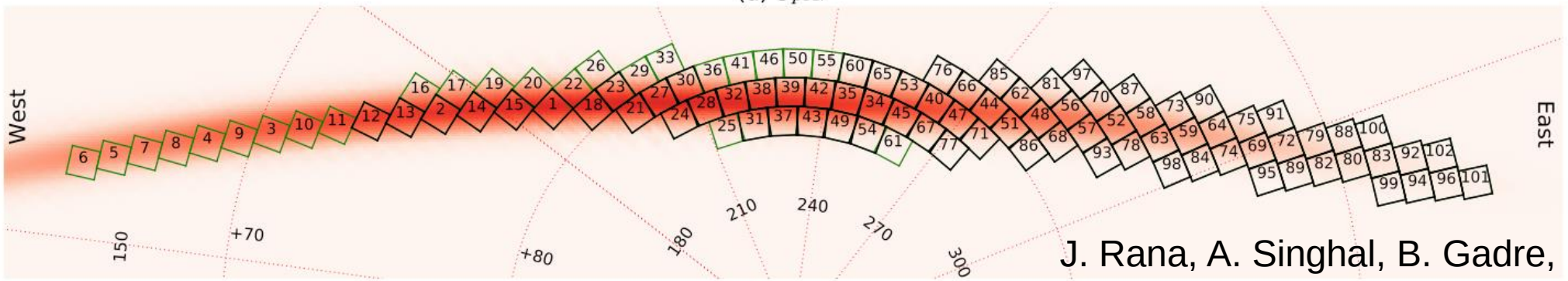
95% containment region: 313 sq. deg.

J. Rana, A. Singhal, B. Gadre,
V. Bhalerao, S. Bose, arXiv:1603.01689







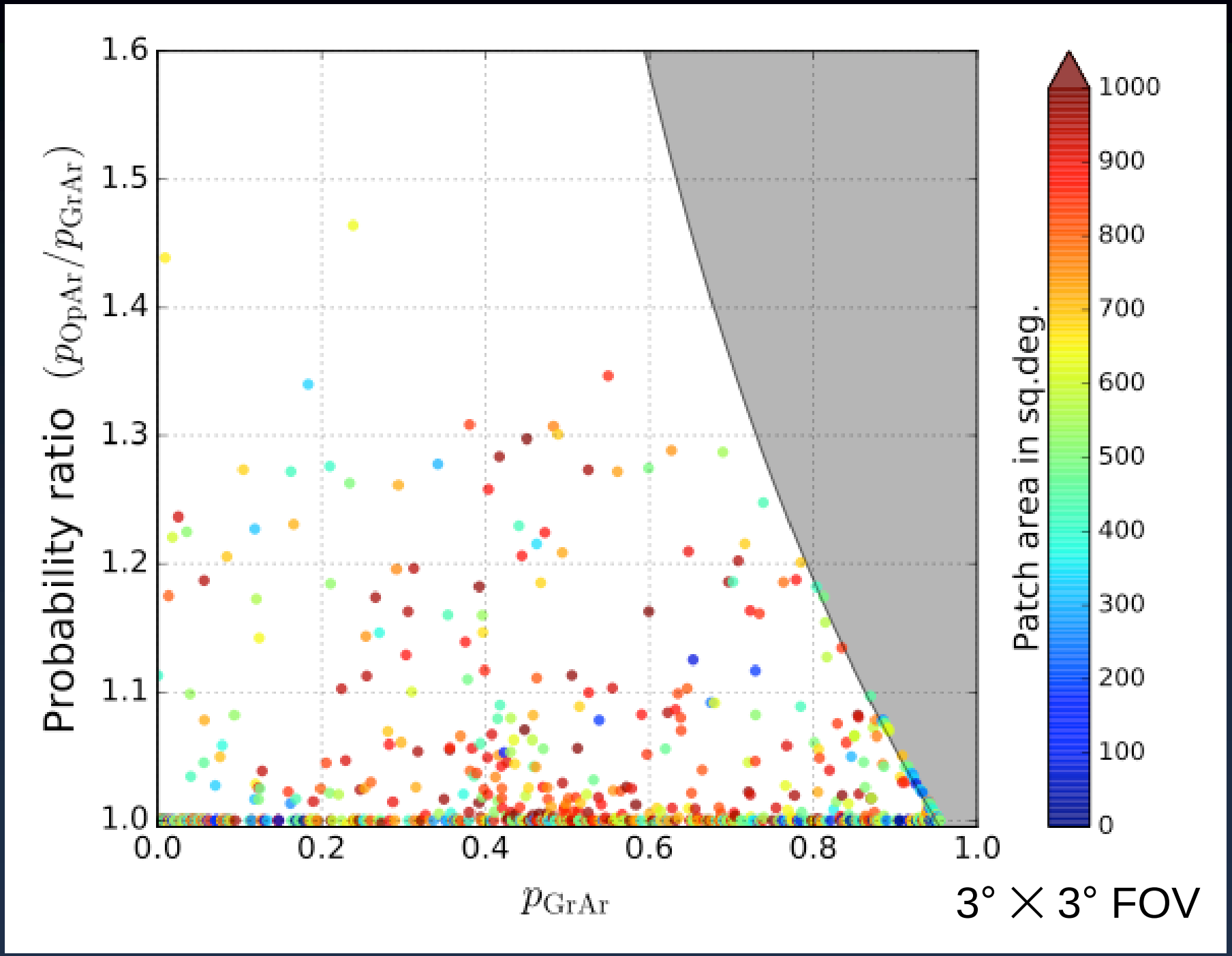


J. Rana, A. Singhal, B. Gadre, V. Bhalerao, S. Bose, arXiv:1603.01689

Better scheduling of observations

See Rana et al., arXiv: 20161603.01689. (LIGO-P1600007) Animation by Javed Rana

Optimized Array



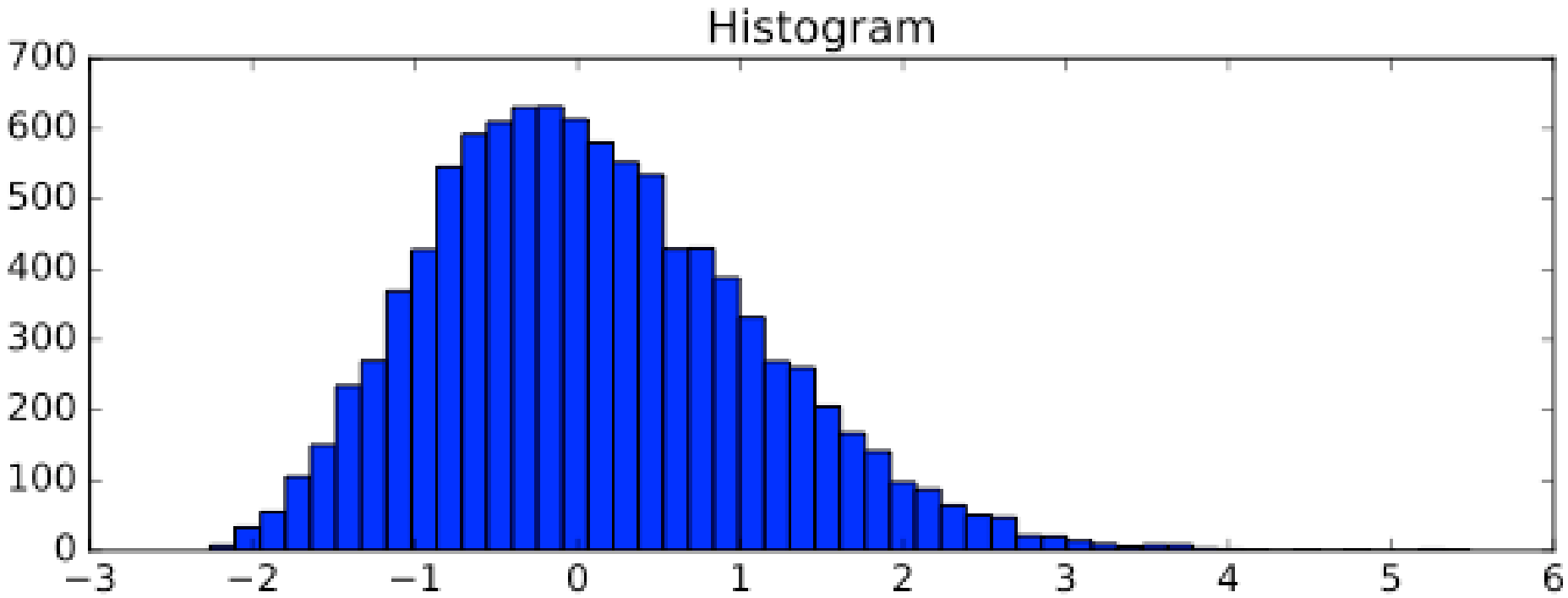
J. Rana, A. Singhal, B. Gadre, V. Bhalerao, S. Bose, arXiv:1603.01689

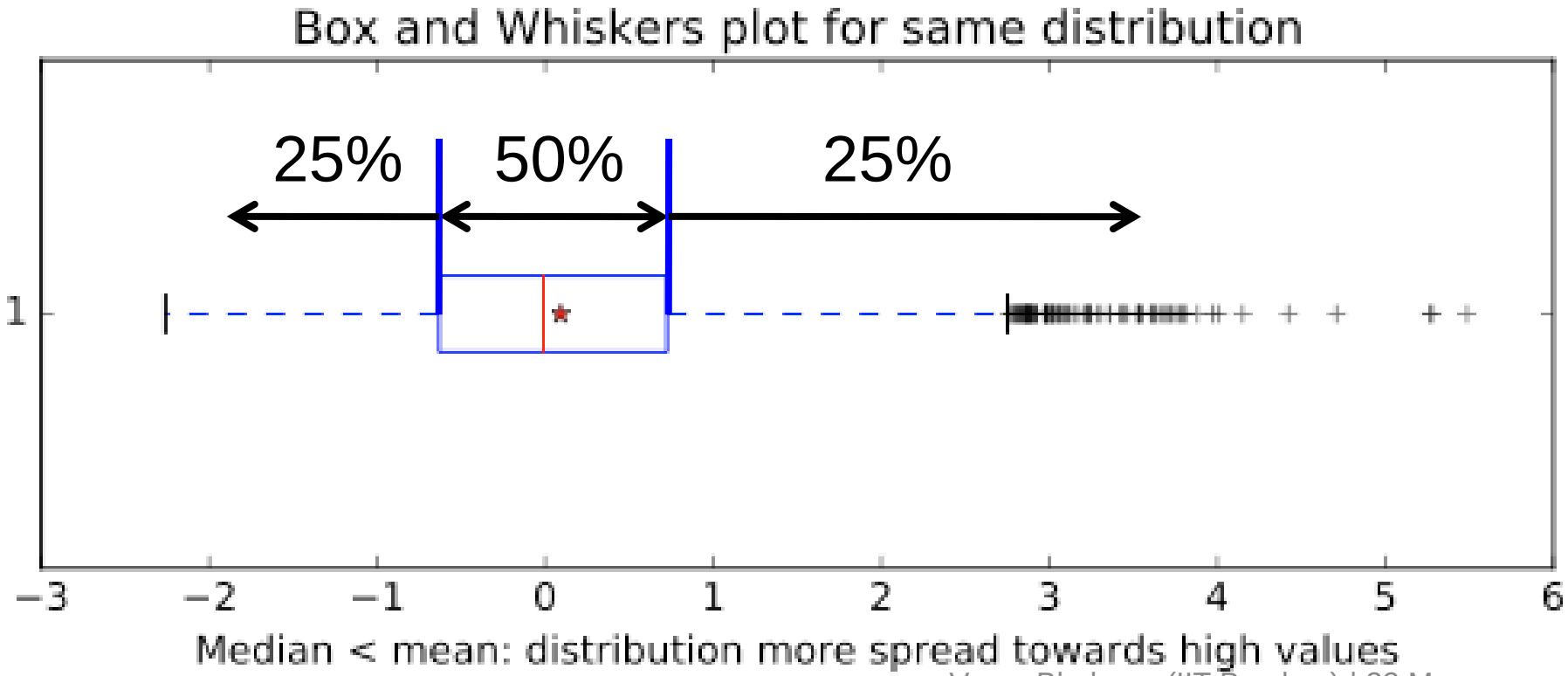
Geographic dependence

What's the best place to be?

Telescopes that followed up GW150914.

Geographic dependence of followup: IUCAA + ICTS project


Histogram
700
600
500
400
300
200
100
0
−3
−2
−1
0
1
2
3
4
5
6

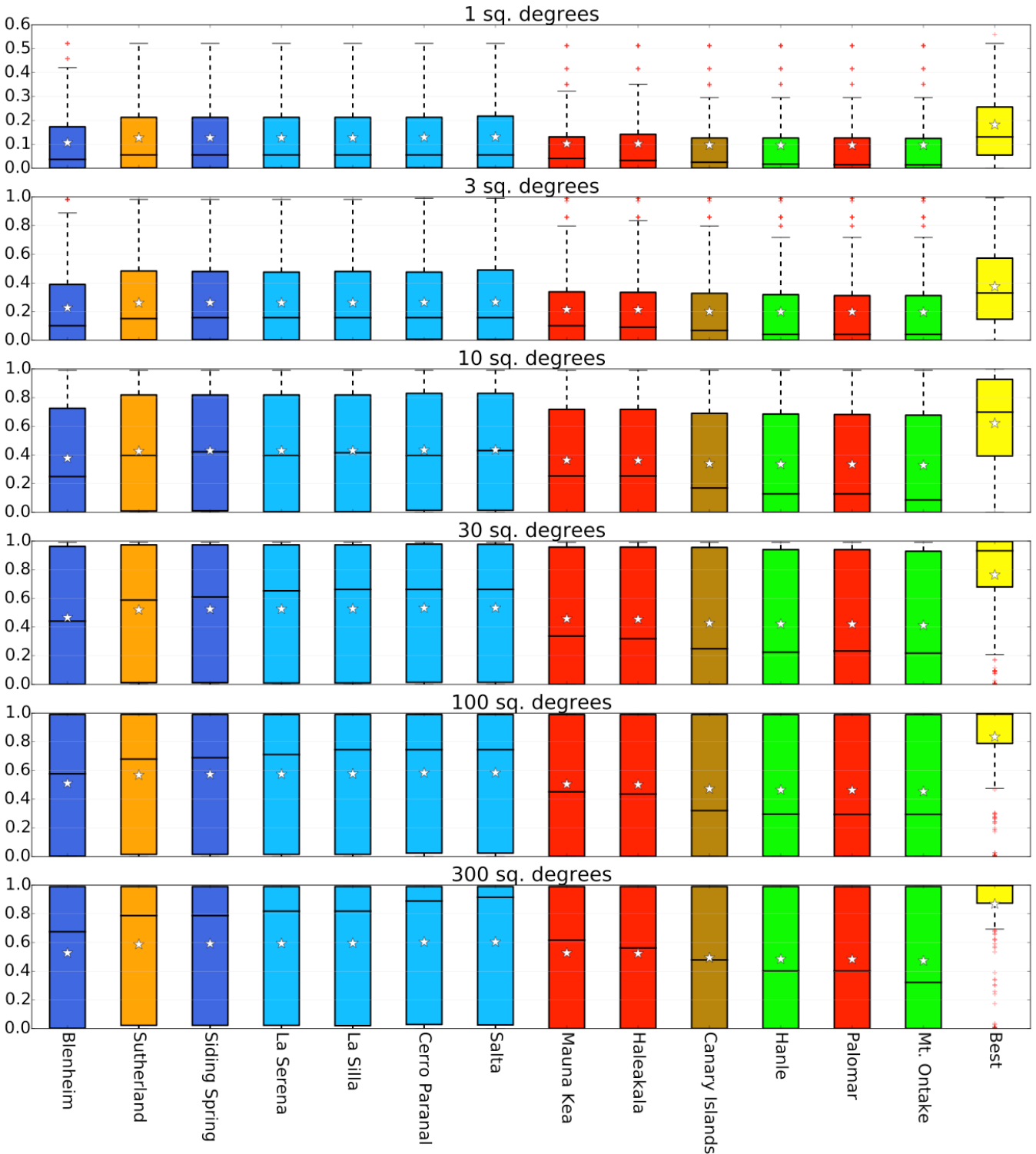

Box and Whiskers plot for same distribution
25%
50%
25%
1
−3
−2
−1
0
1
2
3
4
5
6
Median < mean: distribution more spread towards high values

Geographic and seasonal influences on optical followup of gravitational wave events

Srivastava et al.
arXiv:1610.07154

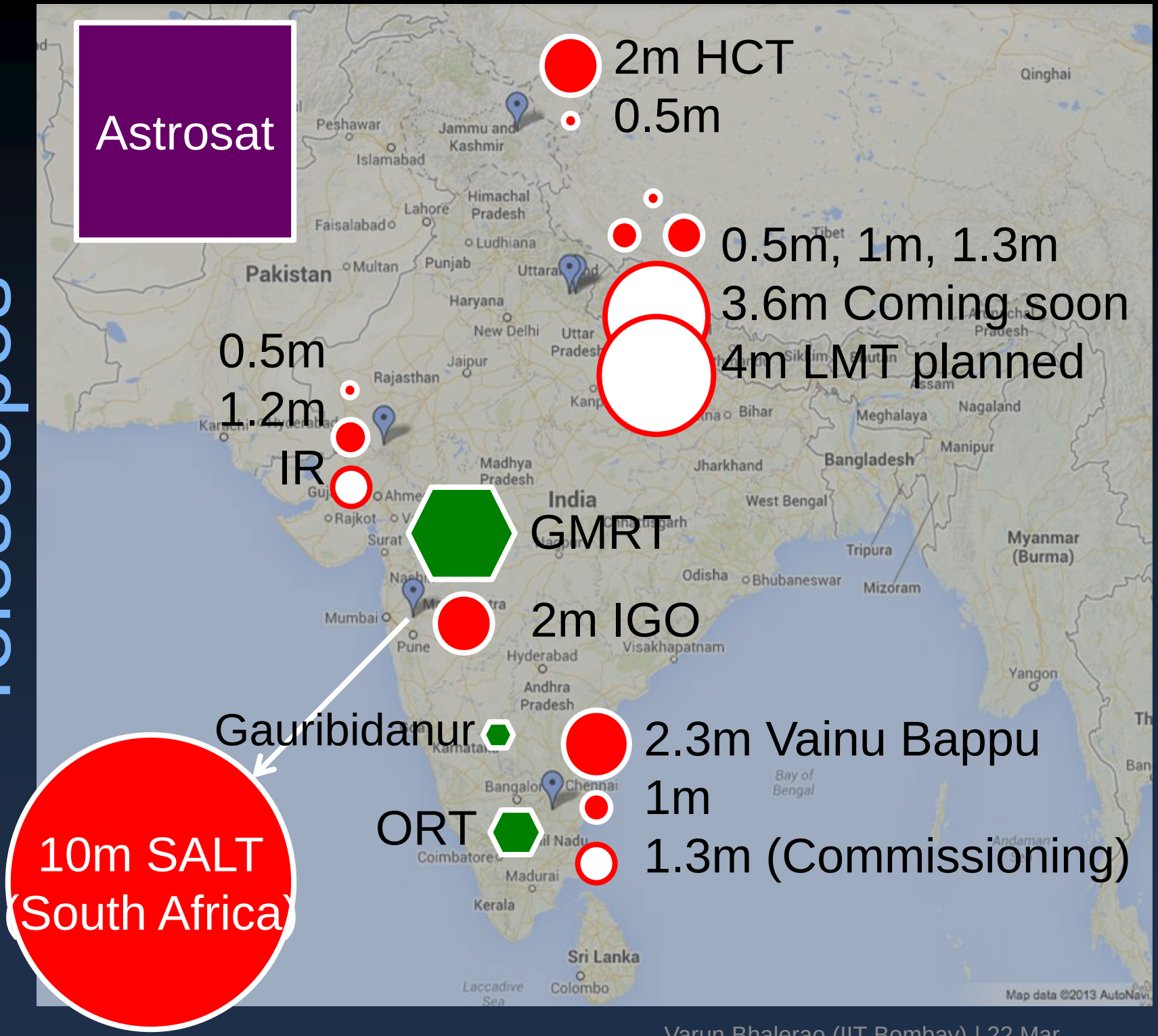
Simulations for events detected by 3 GW detectors in O2

Some locations confer slight advantages
(Simulations used data from arxiv:1404.5623)



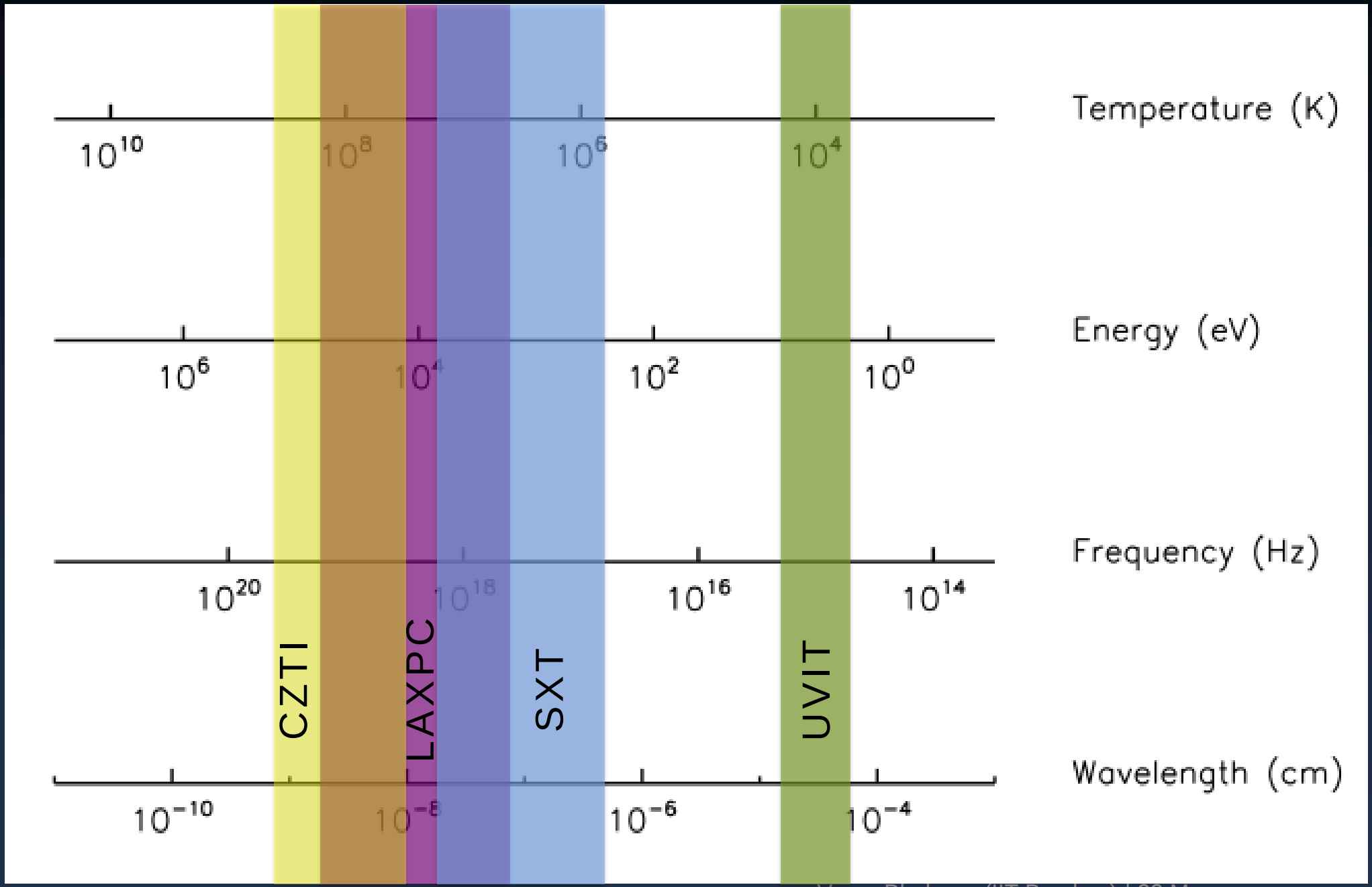
Follow-up telescopes

Large Indian Telescopes

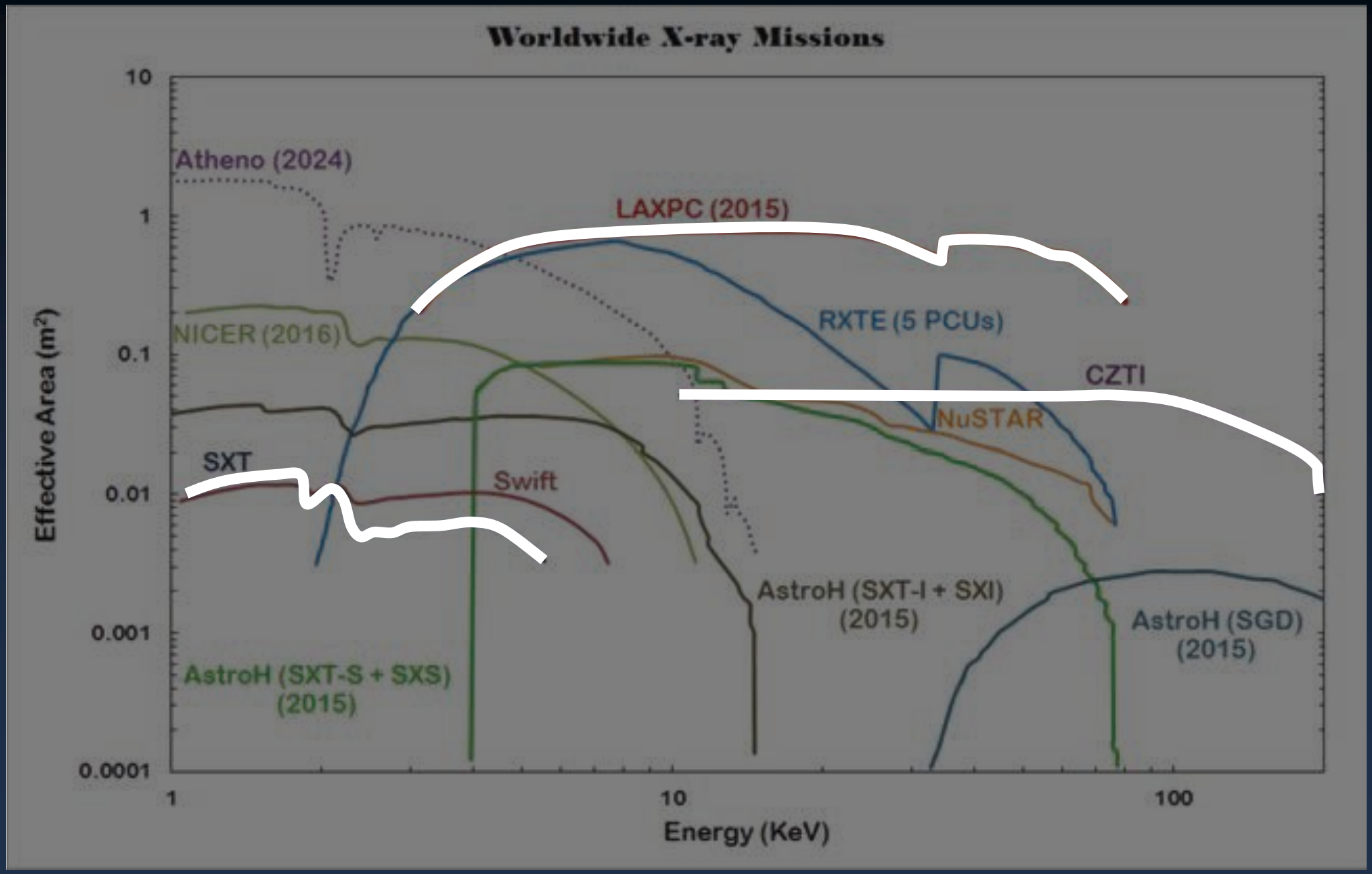


AstroSat

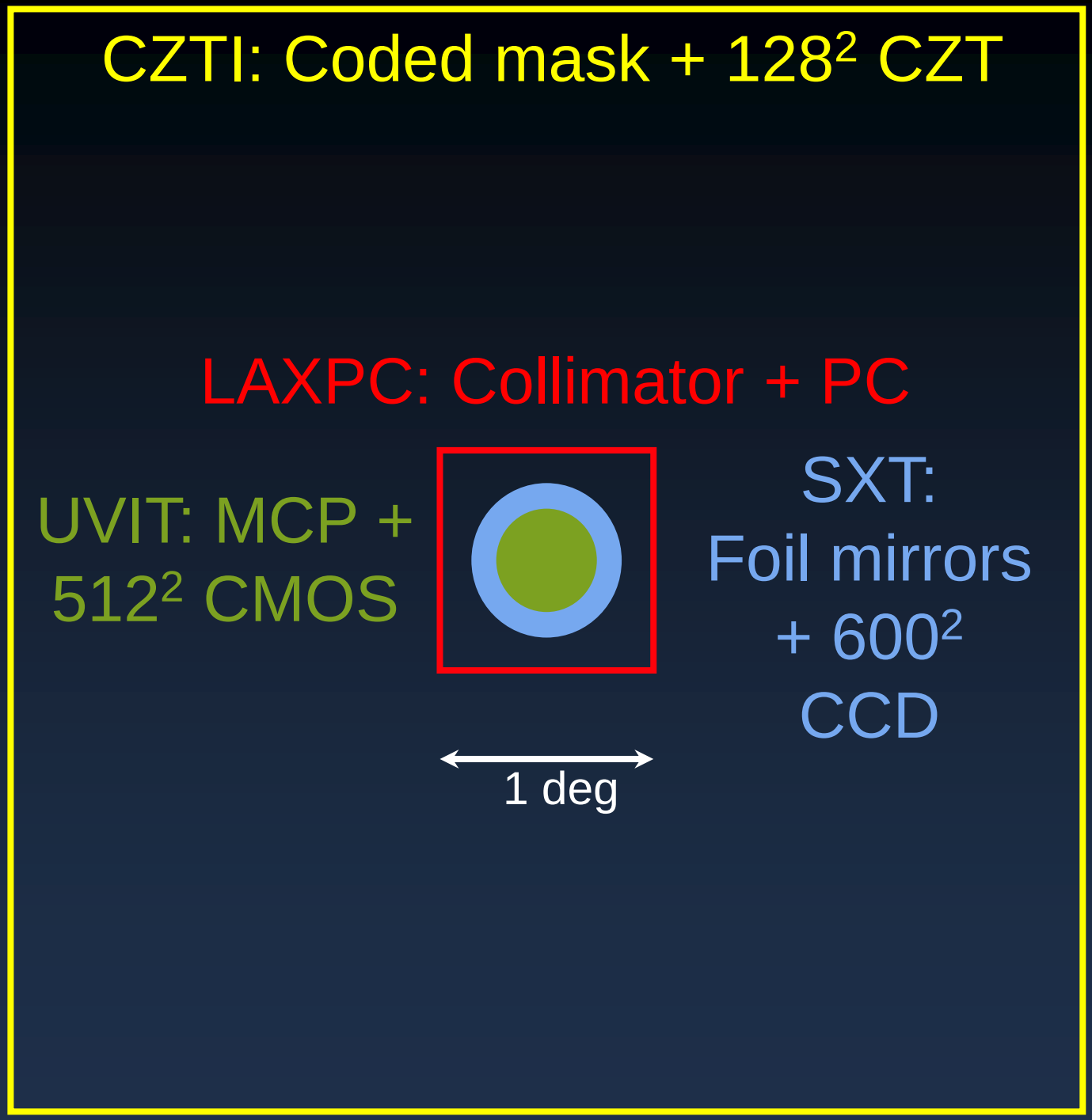
Spectral coverage



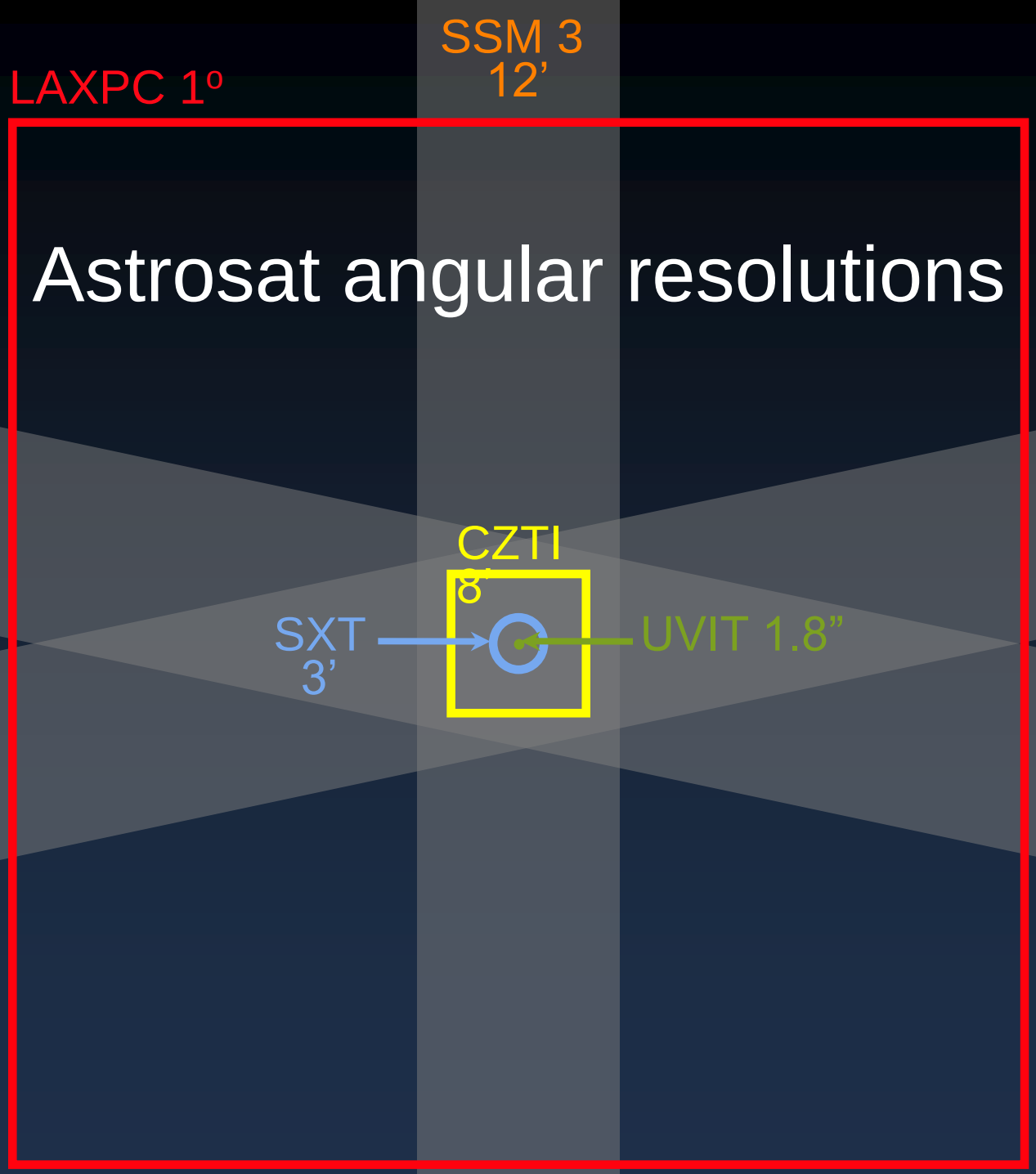
AstroSat specs



Astrosat Co-pointed FOVs

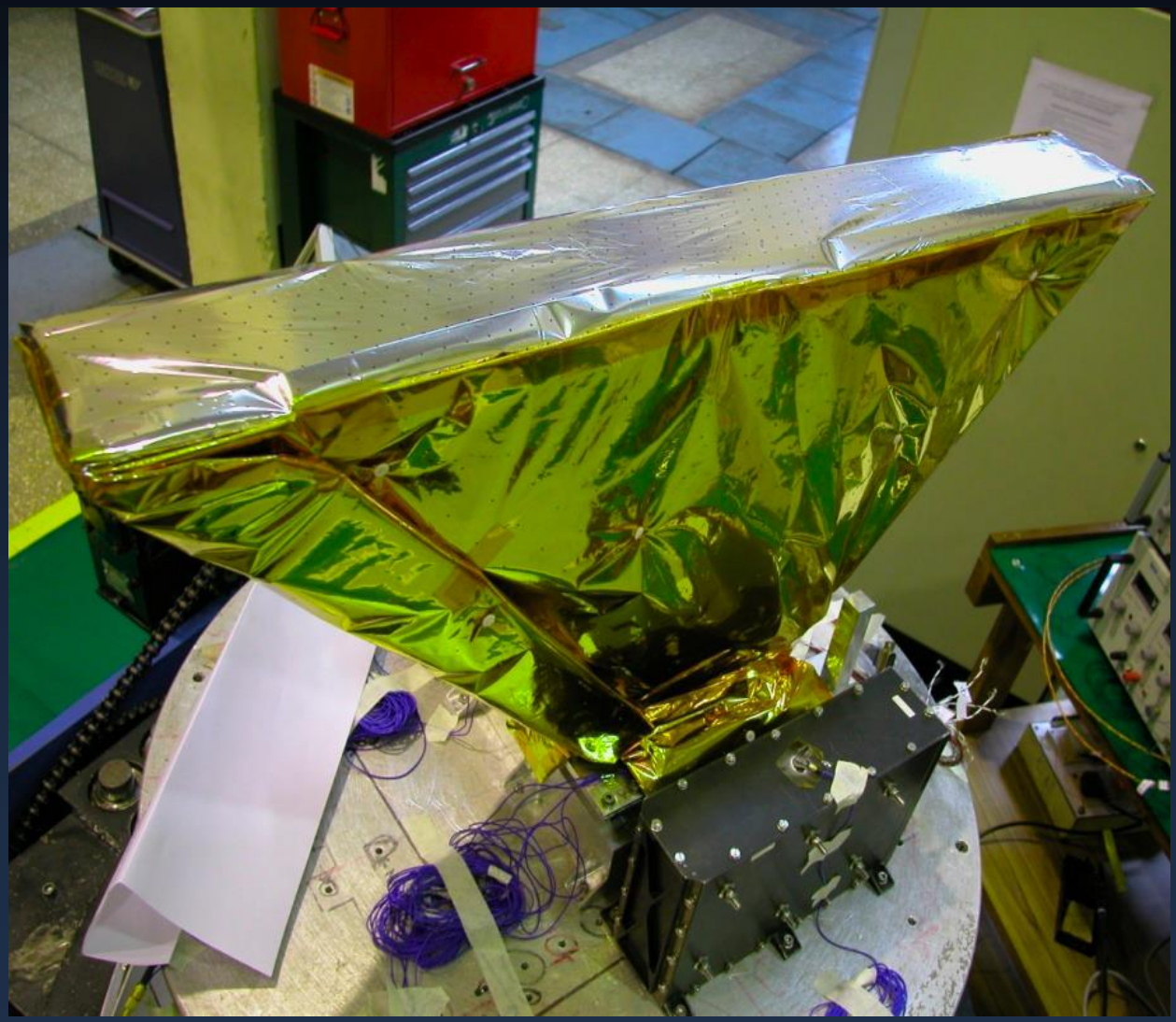


Astrosat angular resolutions



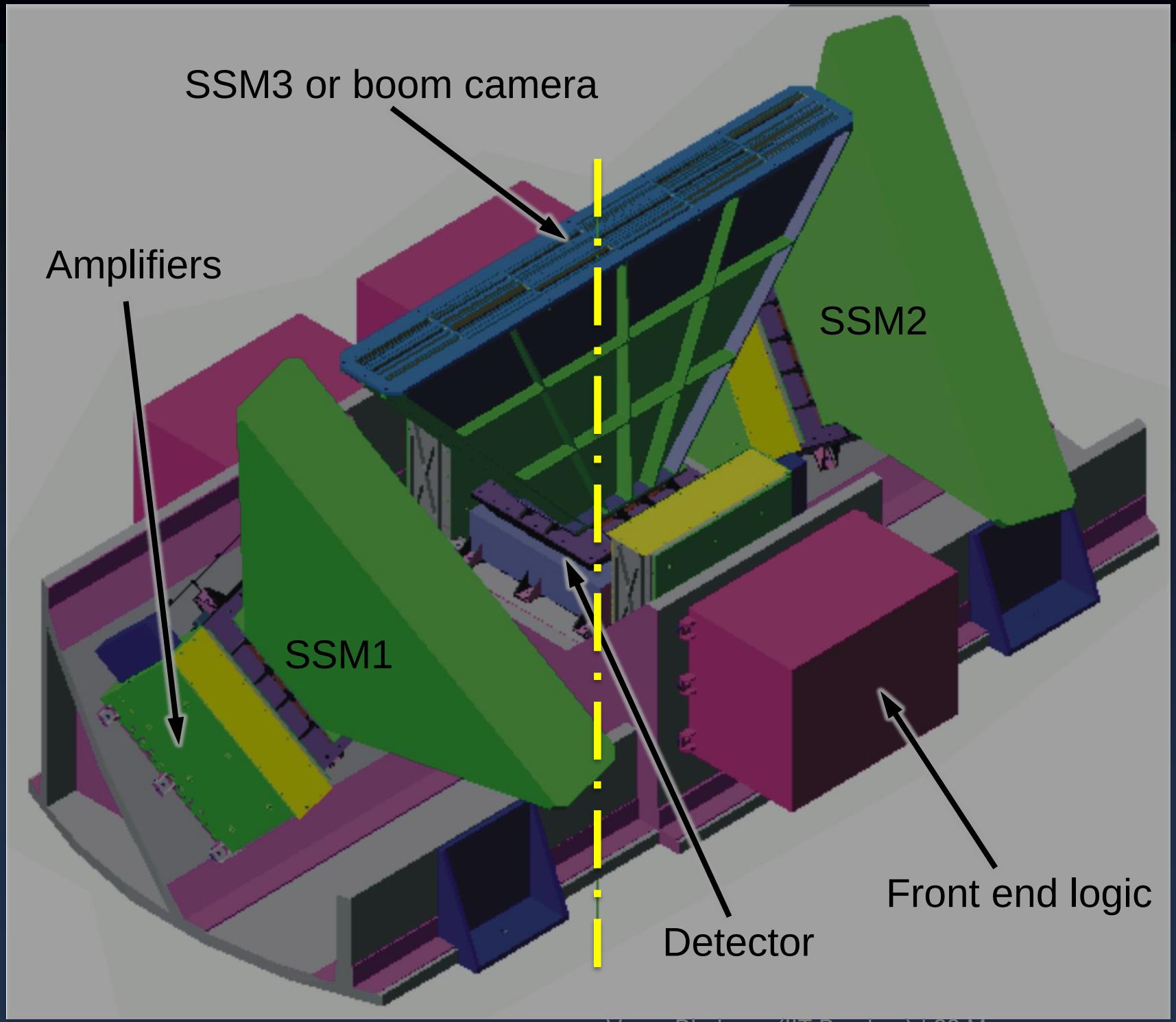
SSM

- Energy Range:
  - 2-10 keV
  - Resolution: 18% at 6 keV
- Effective area:
  - 80 cm^2 × 3
- Field of view:
  - 90° × 13° each
  - Resolution 10’
- Timing resolution:
  - 1 ms



http://www.iucaa.in/~astrosat/ssm_specs.html

SSM: 90° x 13° each



Cadmium Zinc Telluride Imager

- Energy Range:
  - 10-150 keV
- Effective area:
  - ~ 500 cm^2
- Field of view:
  - FOV 4.5° (FWHM)
  - Resolution 2’
- Timing resolution:
  - 20 μs precision

MOU signed!

http://www.iucaa.in/~astrosat/czti_specs.html