EM Observations in the Multi-messenger Astronomy Era

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Non-EM Messengers

- Gravitational Waves
  - High frequency (>1 Hz)
  - Low frequency (<1 Hz)
- Neutrinos
  - Very High energy
  - Nuclear energy (~MeV)
  - Low energy
- Cosmic Rays
  - Nucleons
  - Electrons
- Exotic Particles
  - WIMPs
  - Magnetic monopoles

Non-EM Observatories

	Facilities	When	Localization
High freq GW	LIGO, Virgo, Kagra	Now	△ ~10 deg
Low freq. GW	LISA, Decigo	>2030	◎?
HE neutrino	IceCube, ANTARES	Now	○ ~deg
Nucl. neutrino	SuperKamiokande	Now	△ ~10 deg
LE neutrino	?	?	?×
CR Nucleon	Auger, TA	Now	△ ~10 deg
CR Electron	CALET, Fermi	Now	△ ~10 deg
WIMP	Xenon100, XMASS, etc.	?	×
Monopole	?	?	×

Non-EM Sources

	Galactic	Local Universe	Cosmological
High freq GW	Supernova	Compact Merger	
Low freq. GW	Binary stars	BH binary	BH binary
HE neutrino	BH/NS with jets?	SMBH with jets?	GRB?
Nucl. neutrino	Supernova		
LE neutrino	?	?	?
CR Nucleon	Supernova remnant, BH/NS with jets?	Now	
CR Electron	Supernova Remnant, pulsars, BH/NS jets?	Now	
WIMP	?	?	primordial
Monopole	?	?	primordial

non-EM astrophysical sources

- Local (<10's of Mpc) or Galactic
- Rare and unpredictable
- Poor or moderate localization
- High-energy

- in low-z galaxy, maybe absorbed if Galatic
- long+high duty-cycle + large sky coverage
- Wide-field required for follow-up
- UV/X-/gamma-ray, all EM (non-thermal)

EM search consideration #1

- Local (<10's of Mpc) or Galactic

  ➔in low-z galaxy, maybe absorbed

- Small aperture may be okay
  - e.g. ASAS-SN
- Sensitive search (e.g. Subaru HSC) must be clever
  - spectroscopic follow-up difficult for too many faint transient sources
  - Huge data
  - need association with rare events
    - X-ray or radio source,
    - timing coincidence
- Radio, IR, X-/gamma-ray useful for Galactic

EM search consideration #2

- Rare and unpredictable

  ➔long+high duty-cycle + large sky coverage

- ground-based or satellite with long (>years) mission life
- Tiling has limitations
- Facilities with large sky coverage
  - LF radio: LOFAR etc
  - HF radio:
  - IR:
  - Optical: ASAS-SN, Evry, Pi of Sky, ...
  - UV:
  - Soft X-ray:
  - Hard X-ray: Swift BAT
  - LE gamma-ray: Fermi GBM
  - HE gamma-ray: Fermi LAT
  - VHE gamma-ray:

EM search consideration #3

- Poor or moderate localization

  ➔Wide-field required for follow-up

- Facilities
  - exsist? available?
    - wavelength coverage
- Sensitivity vs. field size
  - target to galaxies?
- latency
  - Human in the loop
  - Tiling
- Identification
  - Time variability – need repeated observation
  - Spectroscopy
    - Sensitivity
    - too many?

EM search consideration #4

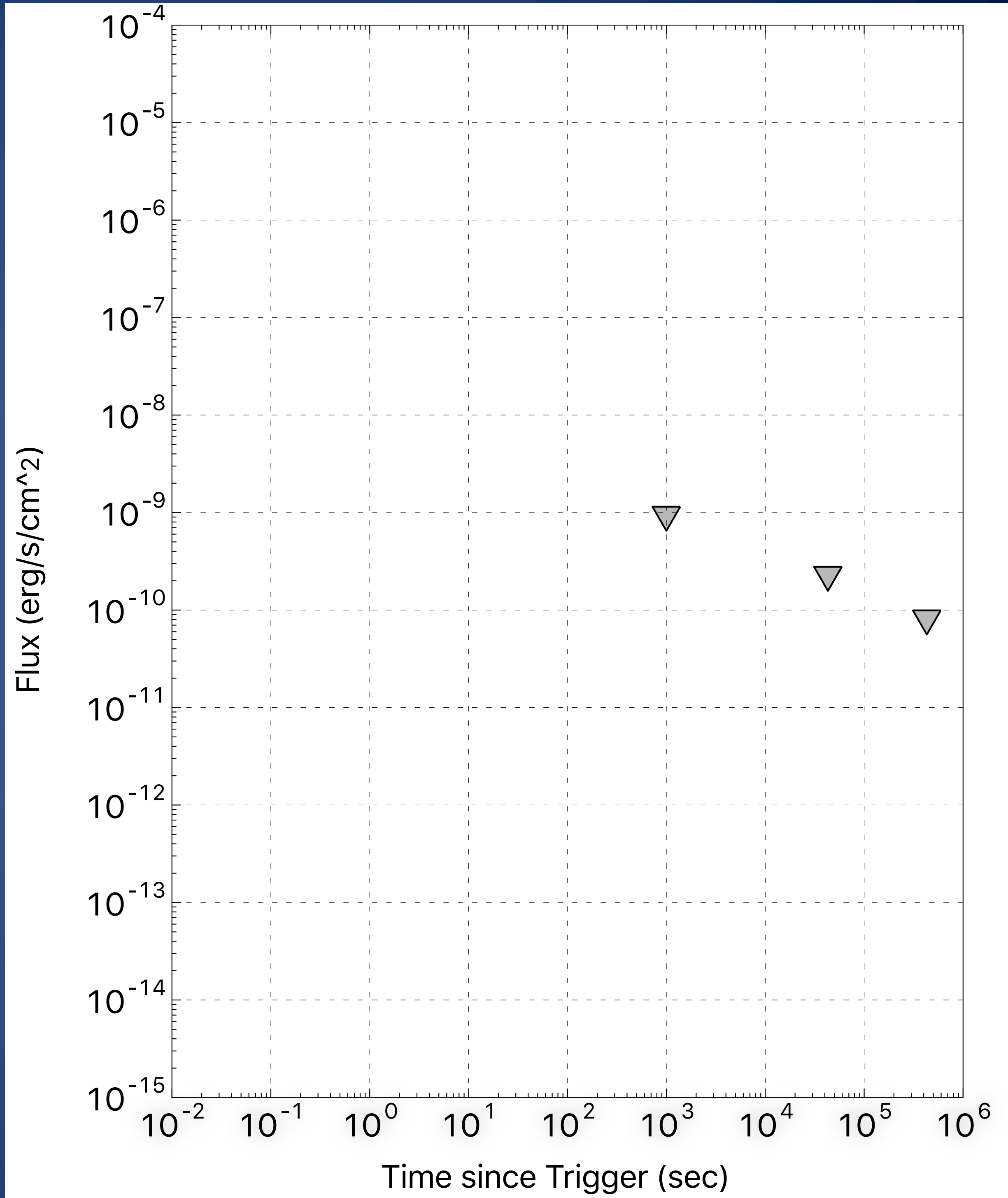
- High-energy

  ➔UV/X-/gamma-ray, all EM (non-thermal)

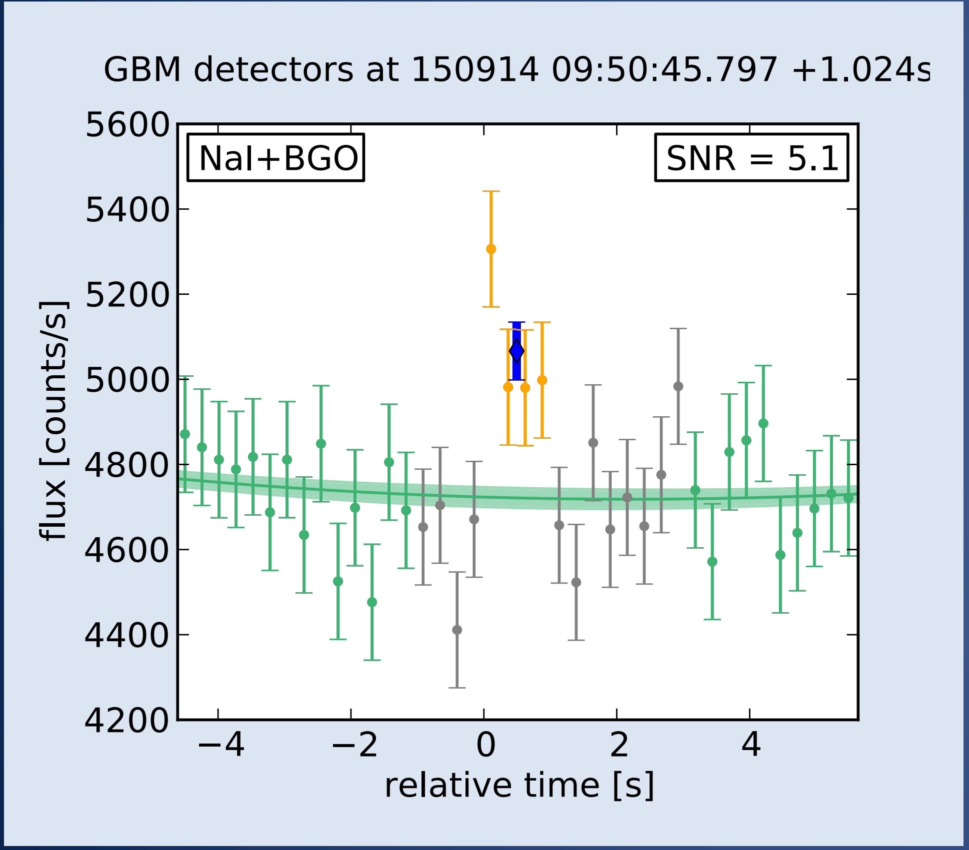
- Facilities with large sky coverage
  - LF radio: LOFAR etc
  - HF radio:
  - IR:
  - Optical: ASAS-SN, Evry, Pi of Sky, ...
  - UV:
  - Soft X-ray:
  - Hard X-ray: Swift BAT
  - LE gamma-ray: Fermi GBM
  - HE gamma-ray: Fermi LAT
  - VHE gamma-ray:

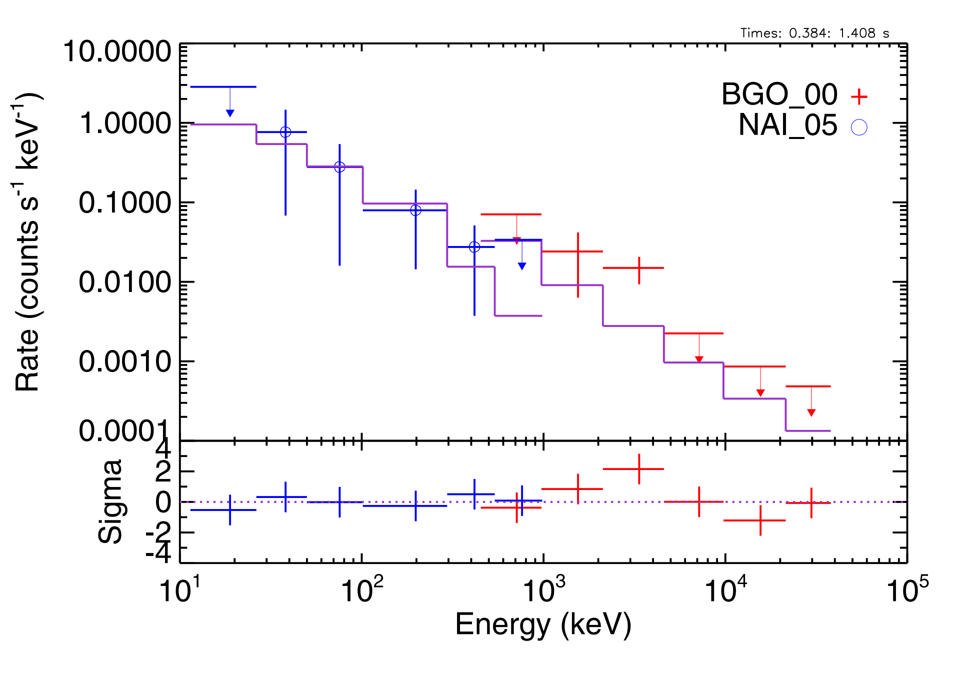
Soft X-ray mission

MAXI on GW150914



Possible detection of gamma-ray emission by Fermi GBM



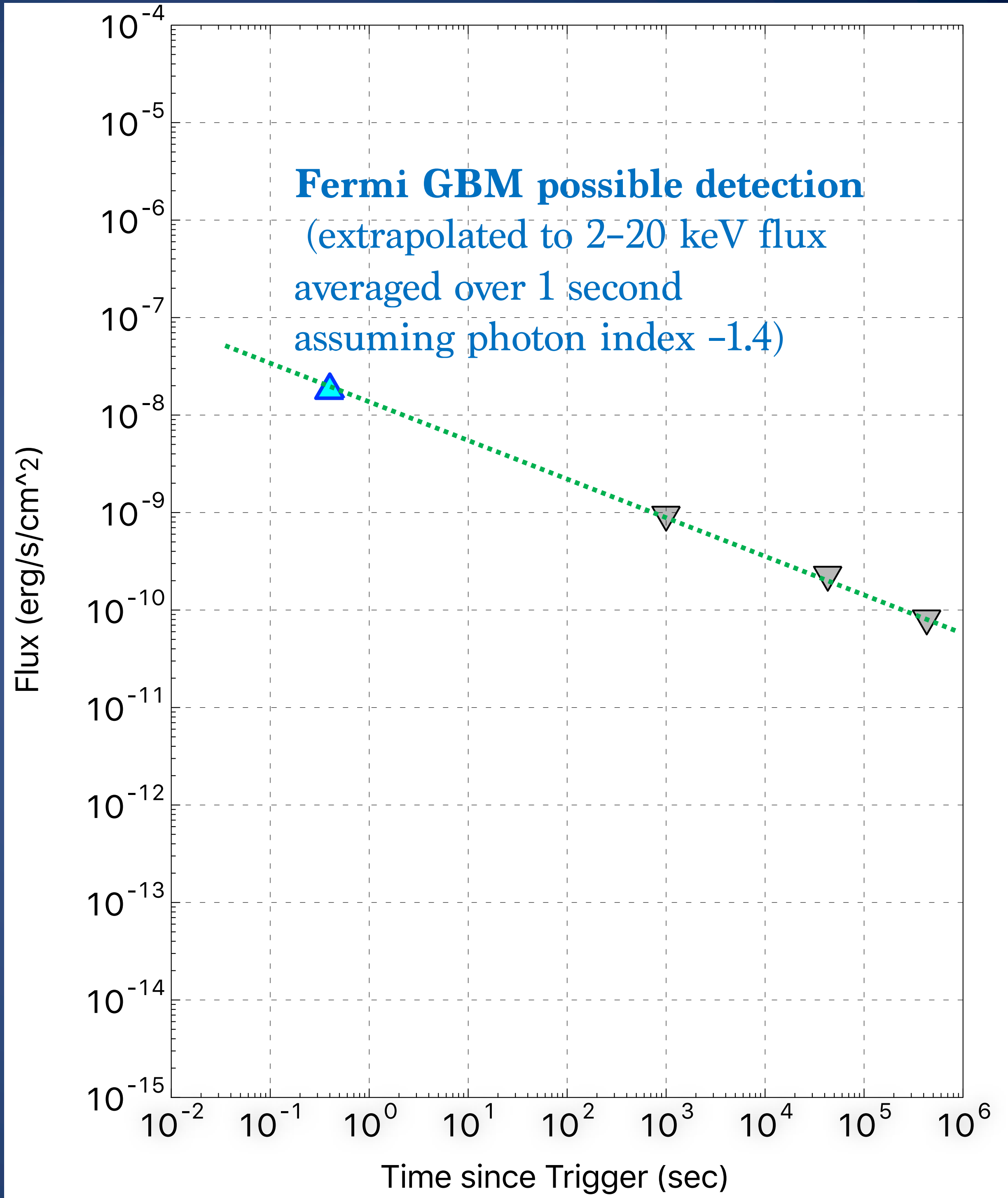


power-law index $-1.40^{+0.18}_{-0.24}$ and amplitude $0.002^{+0.002}_{-0.001}$ photons s^{-1} cm^{-2} keV^{-1}

Connaughton et al. 2016

MAXI on GW150914

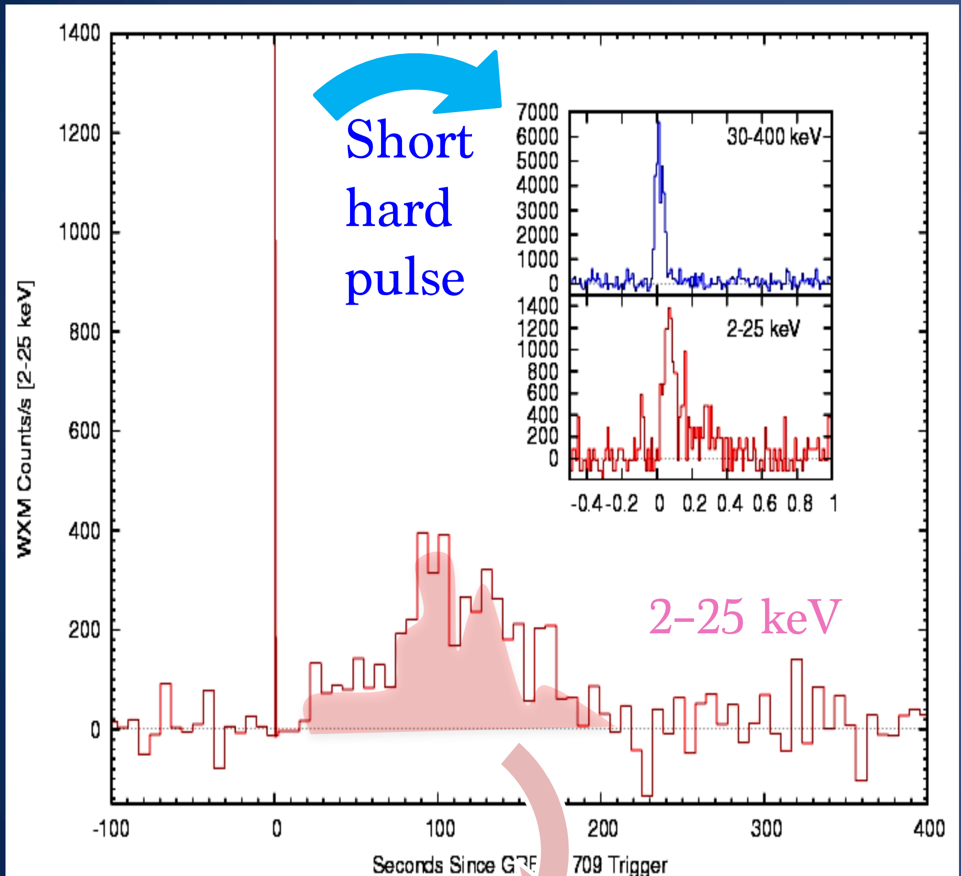
MAXI could have marginally detected GBM SGRB if it was in the field of view



Short GRB 050709

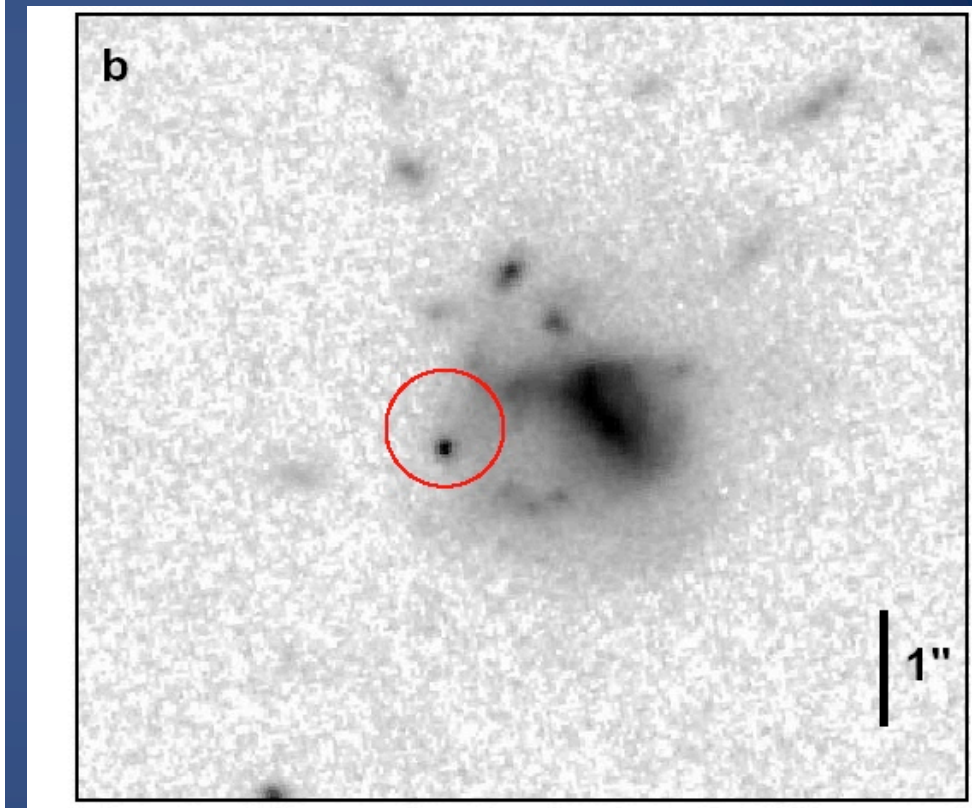
The only short GRB observed in soft X-ray

HETE-2 Villasenor et al. 2005



“Soft extended emission”

HST Fox et al. 2005



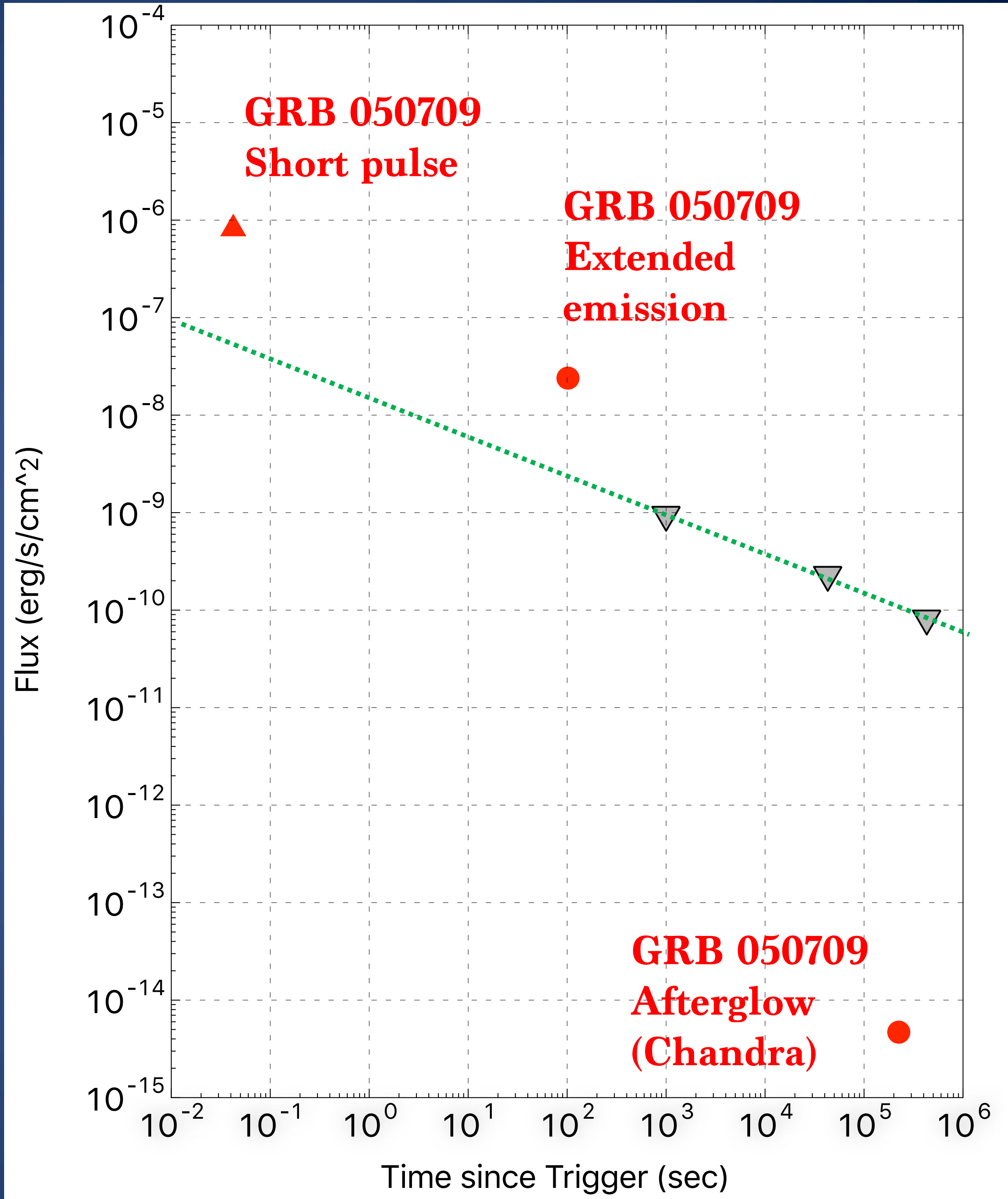
z=0.160

Dwarf irregular galaxy

SFR = 0.2 M_{sun}/yr

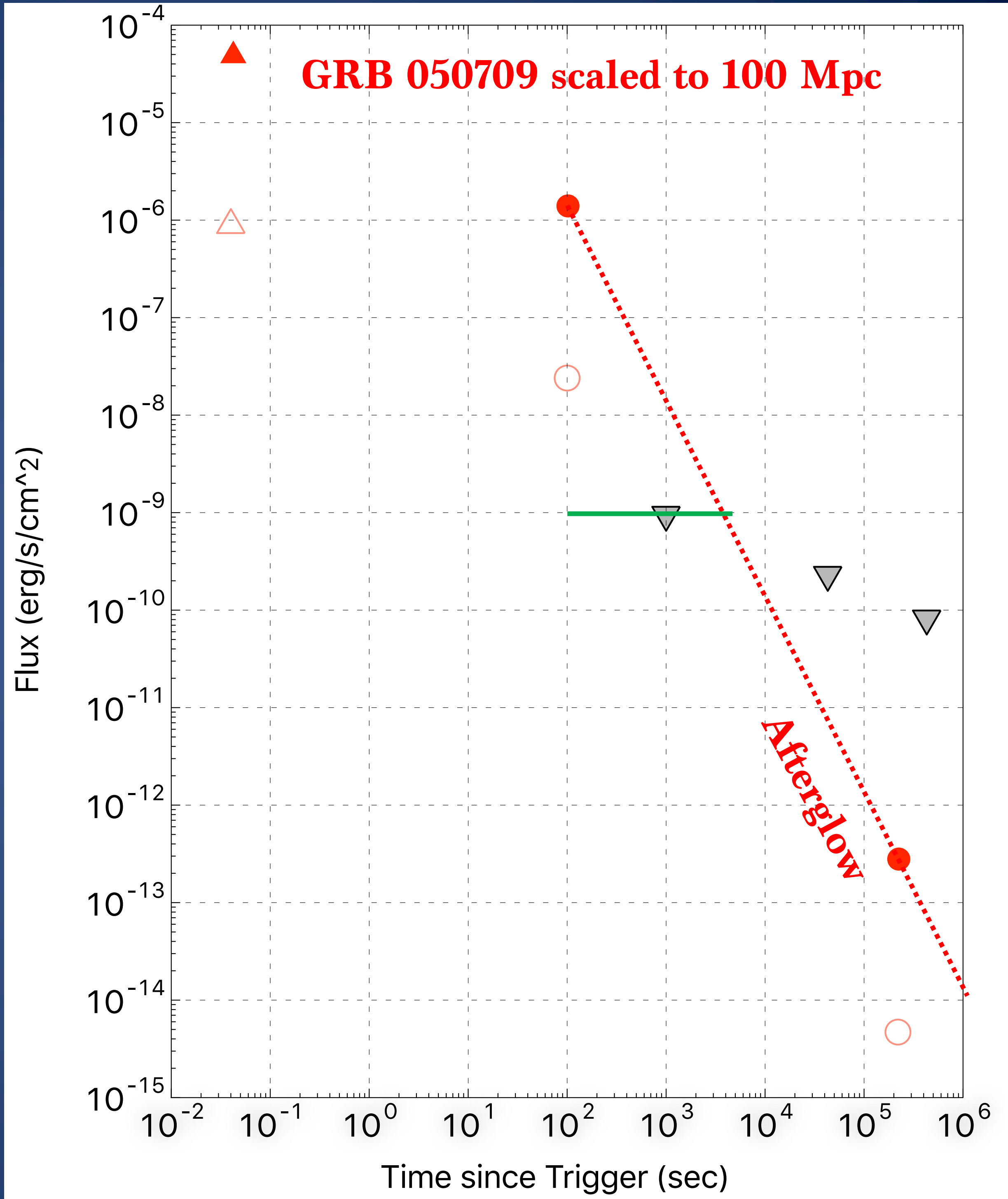
MAXI sensitivity for SGRB in GW range

MAXI could easily detect "short pulse" and "soft extended emission" of GRB 050709



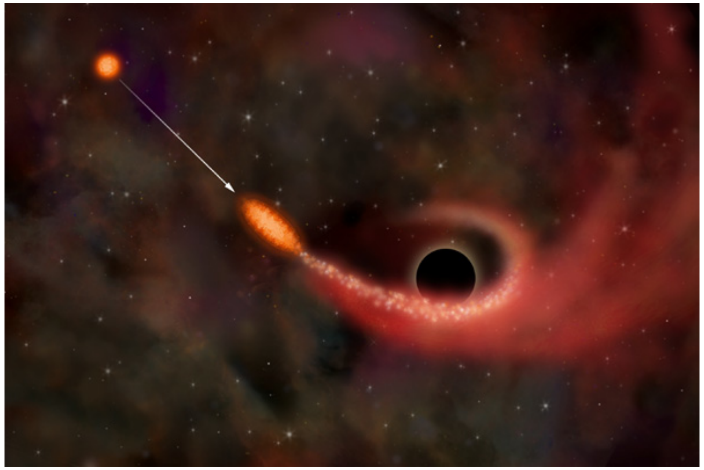
MAXI sensitivity for SGRB in GW range

"Soft extended emission" or X-ray afterglow of a short GRB at O2 BNS range may be detected by MAXI in the following scan

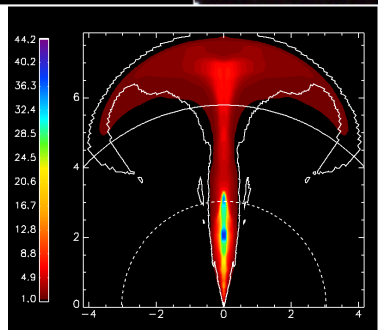


Short soft X-tray transients

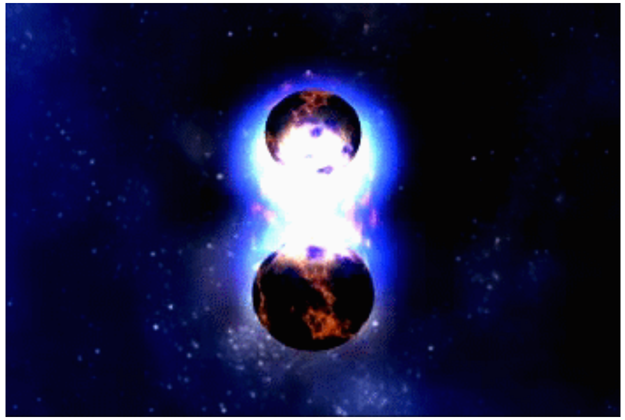
Tidal disruption



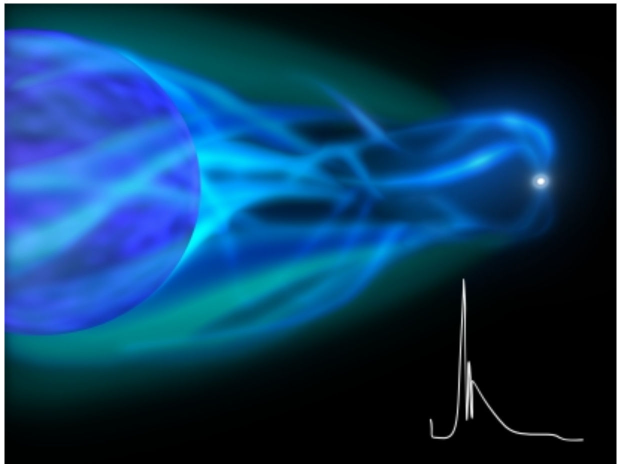
Supernova /GRB shock breakout



Merging neutron star binary



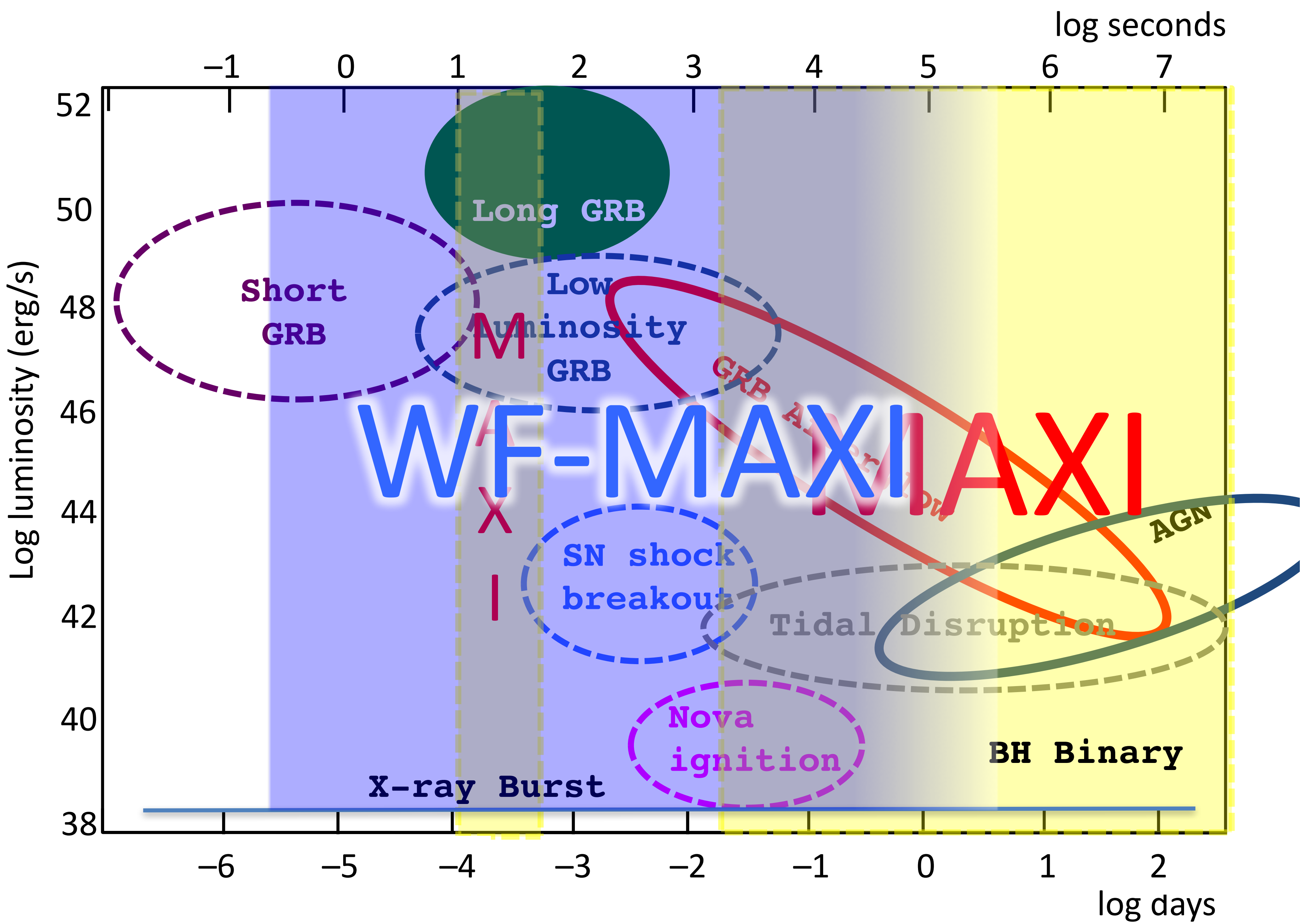
➔ short GRBs associated with GW events



Supergiant fast X-ray transient

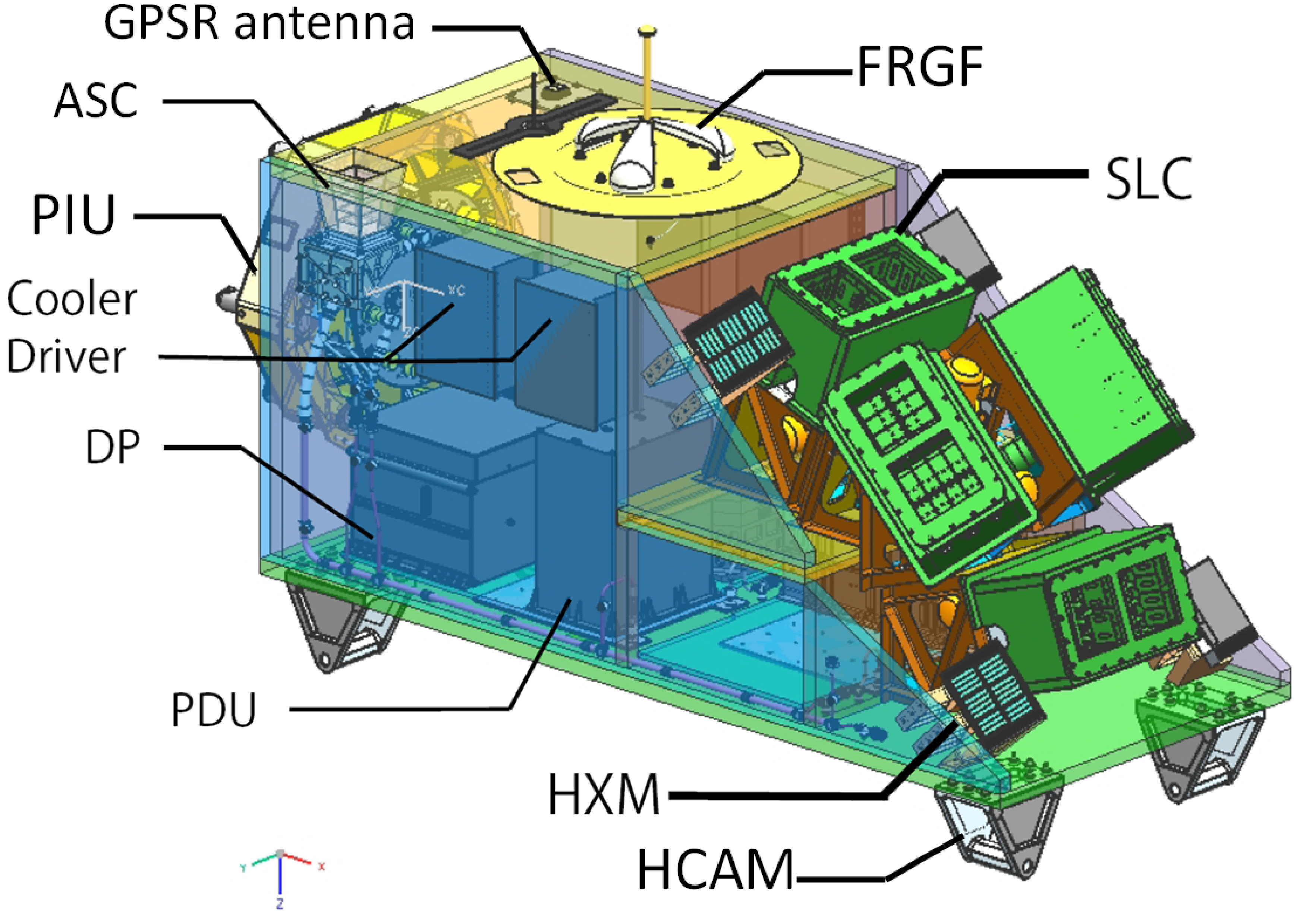
Or, priviously unknown soft X-ray transients

X-ray transients: L-Δt



“Wide-Field MAXI” on ISS

N. Kawai + WF-MAXI Team



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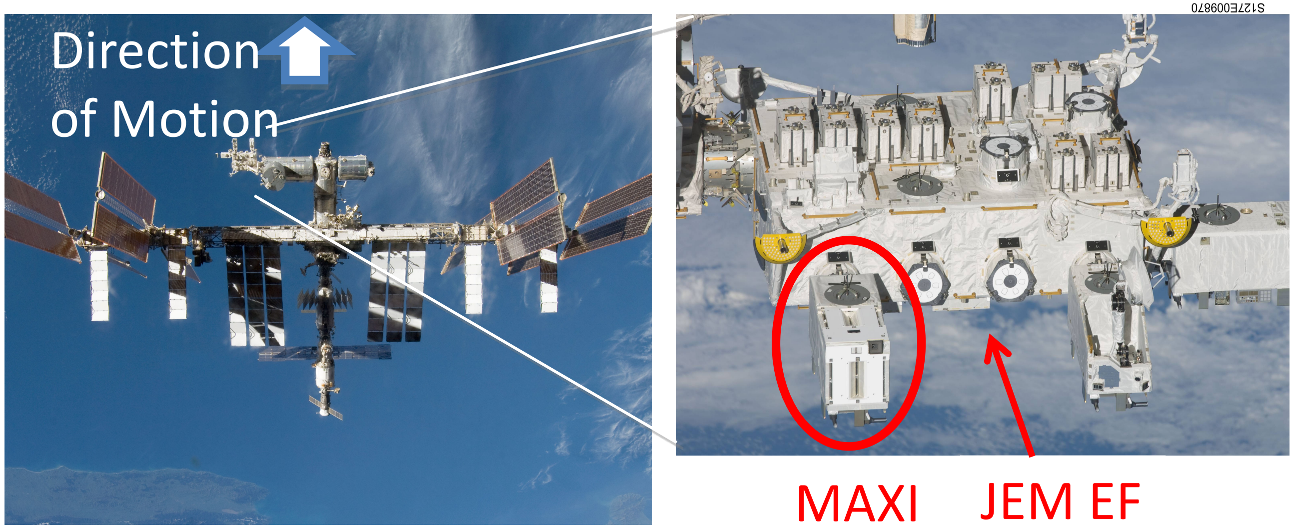
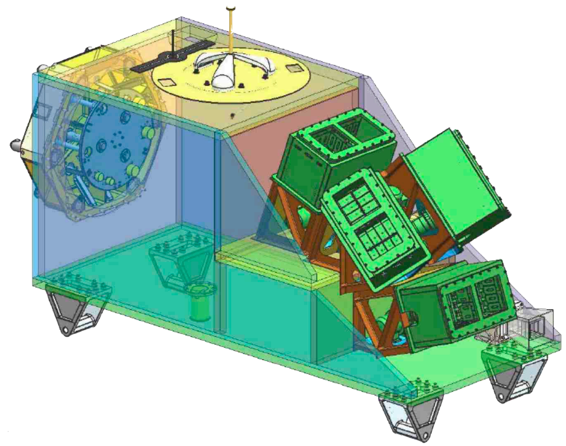




goals	• **Counterparts for GW sources (adv. LIGO/VIRGO, KAGRA)** • **First large-sky monitor for short soft X-ray transients**
field of view	≈ **20% of the sky** **(covers 80% sky in 92 min)**
Instruments	Soft X-ray Large Solid Angle Camera (SLC: **0.7–10** keV) Hard X-ray Monitor (HXM: 20 keV–1 MeV)
sensitivity	50 mCrab /30 s (SLC)
pos. accuracy	0.1°
platform	ISS/JEM (Selection in 2014, operation 2018–)

WF-MAXI evaluation

- Application for ISAS Small Project (Feb 2014)
  → Not selected by Advisory committee for Space Science

(3)

- Extra-success (GW counterpart) has high science value
- Sky coverage 20% x Observing efficieny 50% → 10 % coverage
- Chance of finding GW counterpart is low; high risk
- should compare the chance/cost with that by ground observation alone

(4)

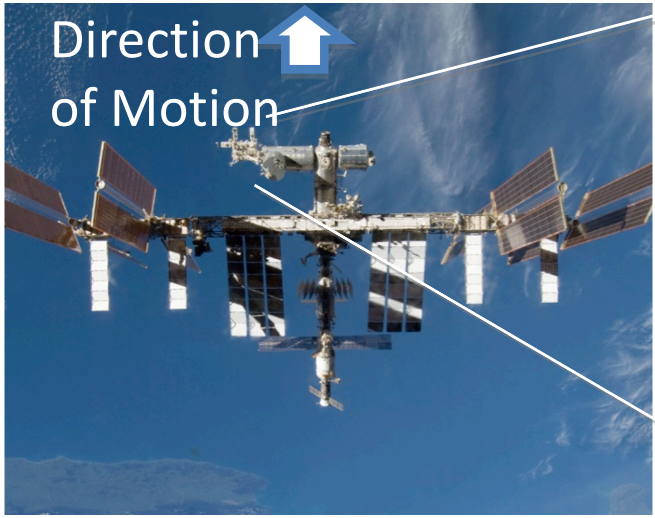
- Future plan of the High Energy Astrophysics community is yet to be decided, and the position of this project is unclear.
- However, GW has high priority in Cosmic Ray community.
- Therefore it may be better to re-define it as a Cosmic Ray mission

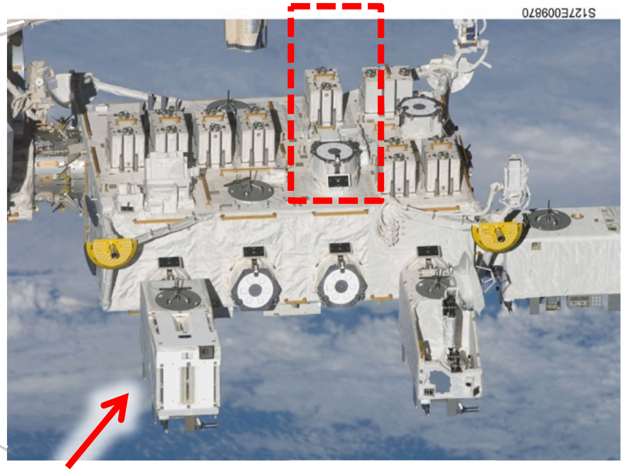
(5)

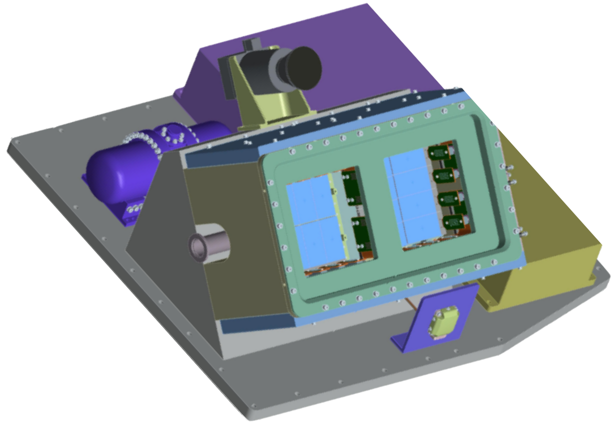
- Selection committee considers the science output is not sufficient to justify its total cost (5 bn JPY) , and asked the proposer to find a way to reduce the cost
- Cost reduction results in less probability to achieve the extra-success.

"iSEEP" Wide-Field MAXI

Proposed Feb 2015







goals	**Localization/notification of X-ray transients** GW counterparts, black hole binaries, GRBs ···
field of view	≈ **10% of the sky** **(covers 80% sky in 92 min)**
Instruments	Soft X-ray Large Solid Angle Camera (SLC: **0.7–10** keV)
sensitivity	50 mCrab /100 s (SLC)
pos. accuracy	0.1°
platform	ISS/JEM (Selection in 2015, operation 2019–)

Impact of the Scale Down

- Sky Coverage
  - Instantaneous coverage ×1/2
  - Daily Coverage ×2/3
- Sensitivity
  - Average effective area ×2/3
- Detection rate
  - short transients ×1/4
  - long transients ×1/2

iWF-MAXI proposal evaluation

- Application for ISAS Small Project (Feb 2015)
- Recommended by Advisory committee for Space Science (July 2015)
- Evaluation result by ISAS (December 2015)
  - Optimization of the size and cost reduction are evaluated.
  - Insufficient system design, e.g. thermal control
  - Success criteria for the primary goal (GW detection) is not defined due to uncertainty.
  - Mission life limited by Japanese participation to ISS (–2020).
  - Overall evaluation: NOT SELECTED "The science goals of iWF-MAXI will be mostly achieved by Indian ASTROSAT (launched in September 2015), which is expected to perform all-sky monitor sufficiently…"

iWF-MAXI evaluation

However,

- ASTROSAT Scanning Sky Monitor
  - Cannot obtain fine localization of transients shorter than 10 min
  - Has low energy threshold > 2 keV

  ➔ Difficult to achieve iWF-MAXI's science goals
- Japanese participation to ISS extended until 2024
- LIGO detection of GW

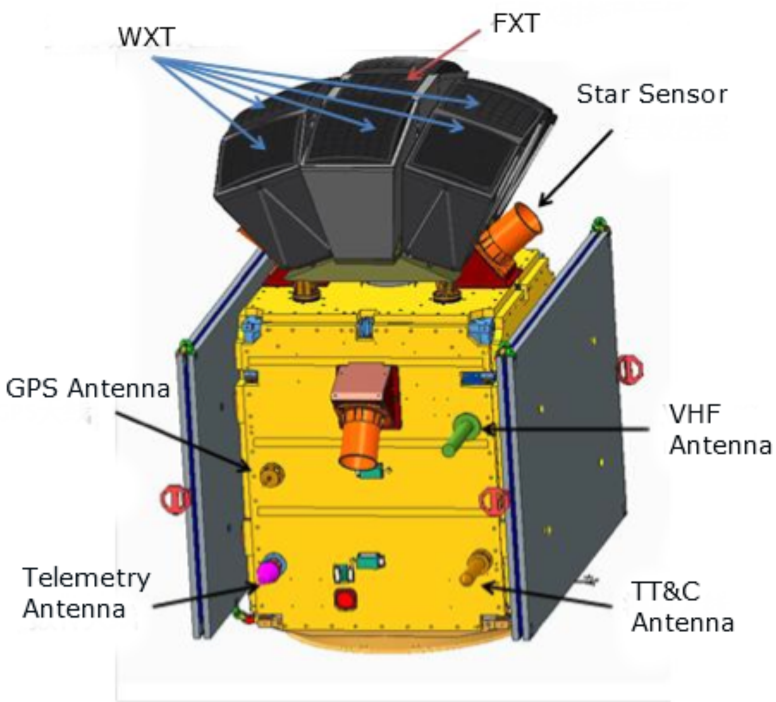
➔ **New proposal**

Einstein Probe

Yuan 2015, Swift 10 years

Mission profile

- Observing modes
  - Survey mode
  - X-ray follow-up observation
  - Target of opportunity
- Orbit:
  - 600km circular, 97min period
  - inclination <30°
- Fast Alert downlink (to trigger multi-wavelength follow-up world-wide)
  - The VHF network (in collab. French)
  - Chinese relay satellites
  - Mass: 380 kg (payload 150kg)
  - Power: < 450w (payload 200w)
- proposed launch: ~2020/2021
- Life time: 3(+2) years



credit: MicroSat

Einstein Probe

Yuan 2015, Swift 10 years

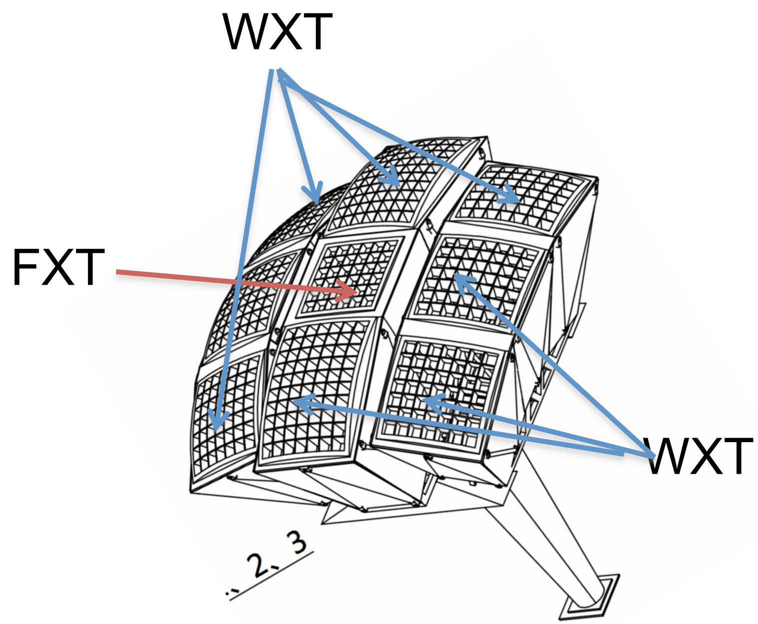
Payload

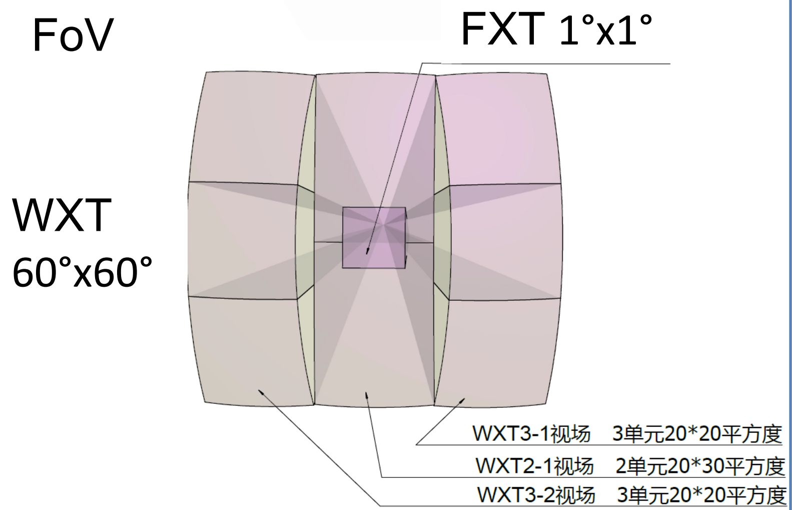
Wide-field X-ray telescope (WXT)

Micro-pore lobster-eye focusing optics
Gas detectors (based line)
Focal length: 375mm
FoV 60°*60° (~1.1 sr)
FWHM ~ 4'
Bandpass: 0.5-4keV
Effective area ~4cm^2 @1keV

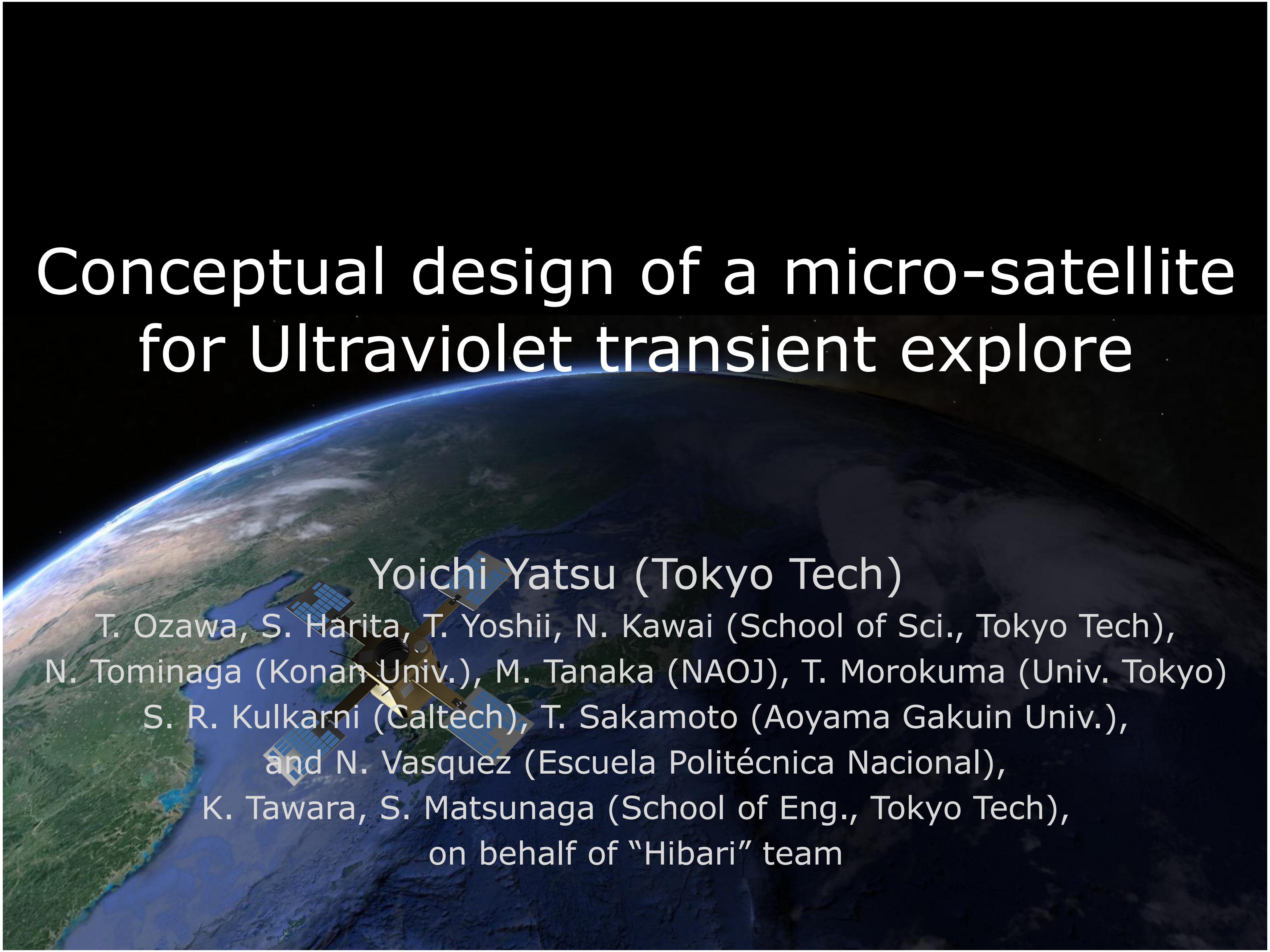
Follow-up X-ray telescope (FXT)

Micro-pore K-B/Wolter-I optics
Si (CCD) or gas detector
Focal length: 1400mm
FoV 1°
Effective area ~60cm^2 @1keV
FWHM ~ 4'
Bandpass: 0.5-4keV





Ultraviolet mission



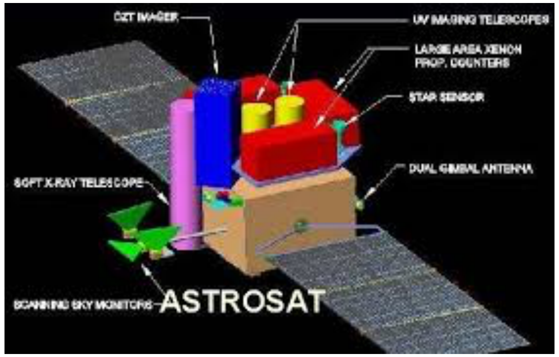
Conceptual design of a micro-satellite for Ultraviolet transient explore

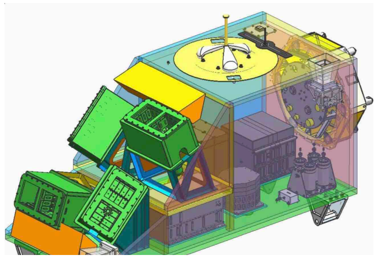
Yoichi Yatsu (Tokyo Tech)

T. Ozawa, S. Harita, T. Yoshii, N. Kawai (School of Sci., Tokyo Tech),
N. Tominaga (Konan Univ.), M. Tanaka (NAOJ), T. Morokuma (Univ. Tokyo)
S. R. Kulkarni (Caltech), T. Sakamoto (Aoyama Gakuin Univ.),
and N. Vasquez (Escuela Politécnica Nacional),
K. Tawara, S. Matsunaga (School of Eng., Tokyo Tech),
on behalf of "Hibari" team

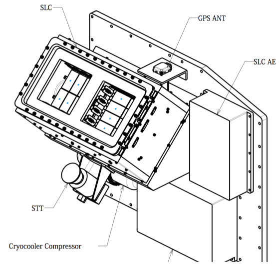
Background

- Rejection of WF-MAXI / iWF-MAXI
  - ASTROSAT: a complemental detector(?) is on orbit
  - Shrinking budget => < $2 million





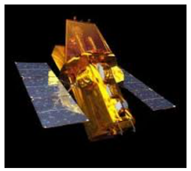
Original model of WF-MAXI with full-size BUS for JEM
Cost~ $50M



miniture version with iSEEP-BUS
Cost~ $10M

80% is for Tests and Documents

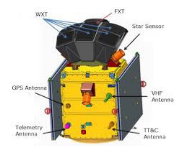
- What can we do with <$2M?



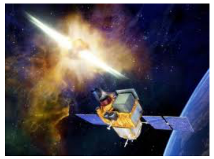
LOFT

eROSITA

HXMT



Einstein Probe



SVOM

Future missions have effective area larger than several thousands cm^2!!

=> micro-satellite is too small comparing with these X-ray missions.

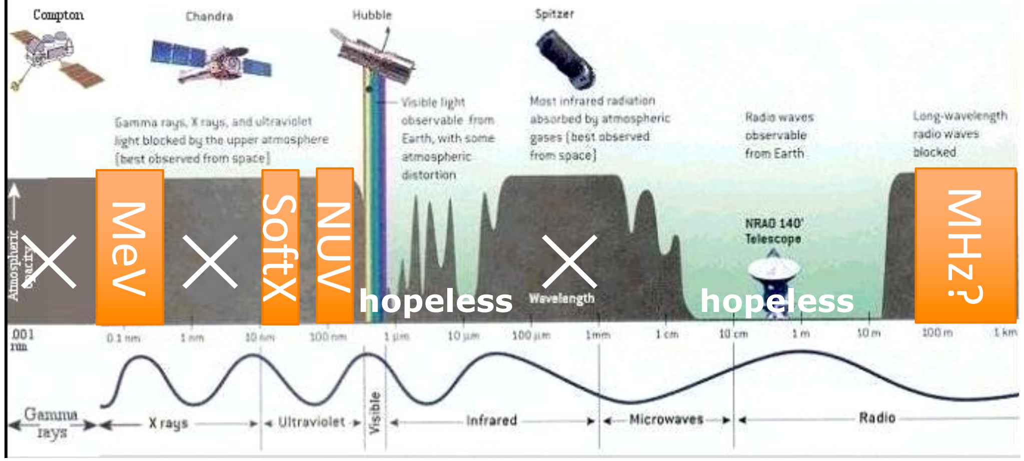
Survey of the other energy band

- Wide-field/High-cadence missions in other energy bands
  - **Radio**: LOFAR, MWA, SKA etc
  - **IR/Opt**: many robotic telescopes
  - **X/ γ**: Swift, Fermi, MAXI, CALET, AstroSAT, CTA



Existing energy bands are almost covered by big projects.

- Where is the frontier in EM astronomy?
  - MeV…△(cannot use optics)
  - Soft X…△(technically difficult)
  - Radio… ??
  - **UV…**◎



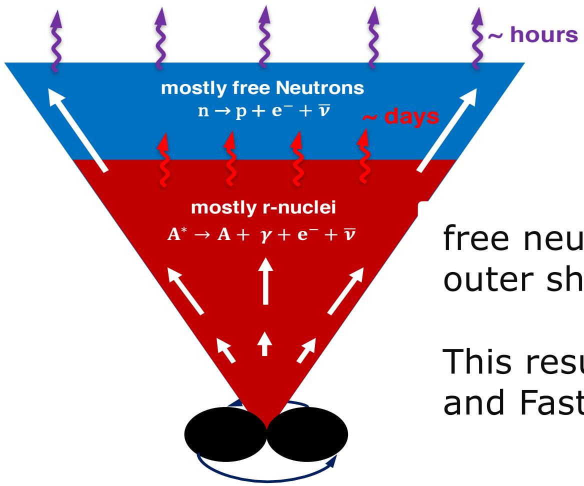
UV (NUV) is most hopeful because we can use:
- optics (but with special glass for UV)
- CCD (back-illuminated CCD is required)

GW follow-up in UV

- ◆ Expected source
  - ➢ NS-NS merger ⇒ r-nuclei
  - ➢ kilonova (macronova)

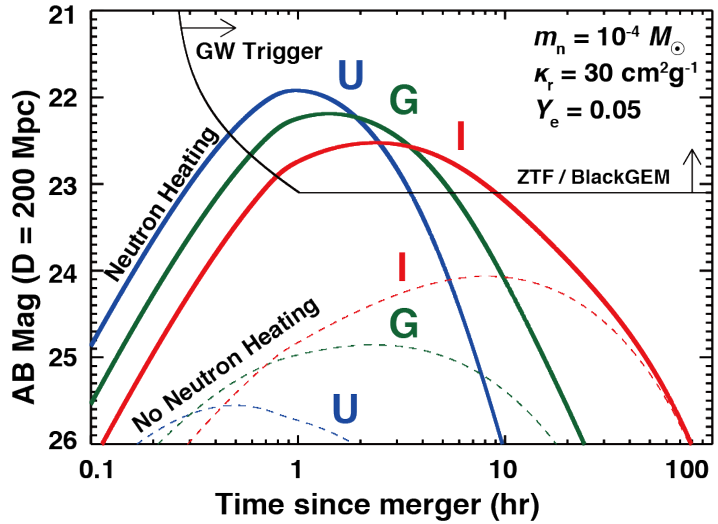
The color, luminosity & variability are still model dependent!

- ◆ Possible scenario which favors UV emission
  - ➢ free neutron beta-decay (Metzger et al. 2015)



free neutrons survive in outer shell of the Ejecta

This result in Blue, Bright and Fast EM emission



UV from free-N will be Brighter and Faster than IR.
Therefore the UV telescope can be suit for the GW follow-up.

Summary: UV emission from NS mergers

by M. Tanaka

	Timescale	Wavelengths	AB Mag @ 100 Mpc	AB Mag @ 200 Mpc	Note
Early thermal	~ 15 min	UV	~26	~27.5	Too rapid cooling
Early non-thermal	~ 1 sec	UV	~>24 @ 1hr	~>25.5 @ 1hr	Depends on ambient density
Radioactivity (main ejecta)	~10 days	Opt-NIR	~21	~22.5	Not UV
Radioactivity (free neutron)	~ 1 hr	UV	~20.5	~22	*Uncertain* assuming M ~ 10^{-4} Msun

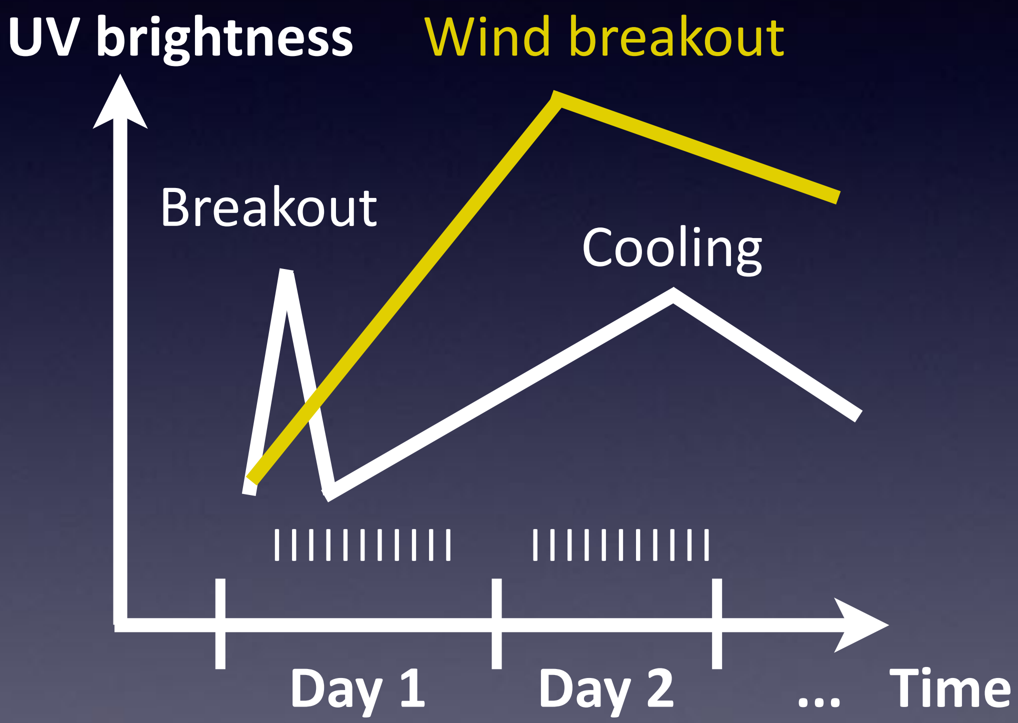
Survey with Hibari: 22.5 mag -100 deg^2 in 1 hr

Survey with Hibari

22.5 mag - 100 deg^2 every 1 hr

=> ~ 100 supernova detections / year

by M. Tanaka



Uniqueness

- UV wavelength
- Continuous coverage

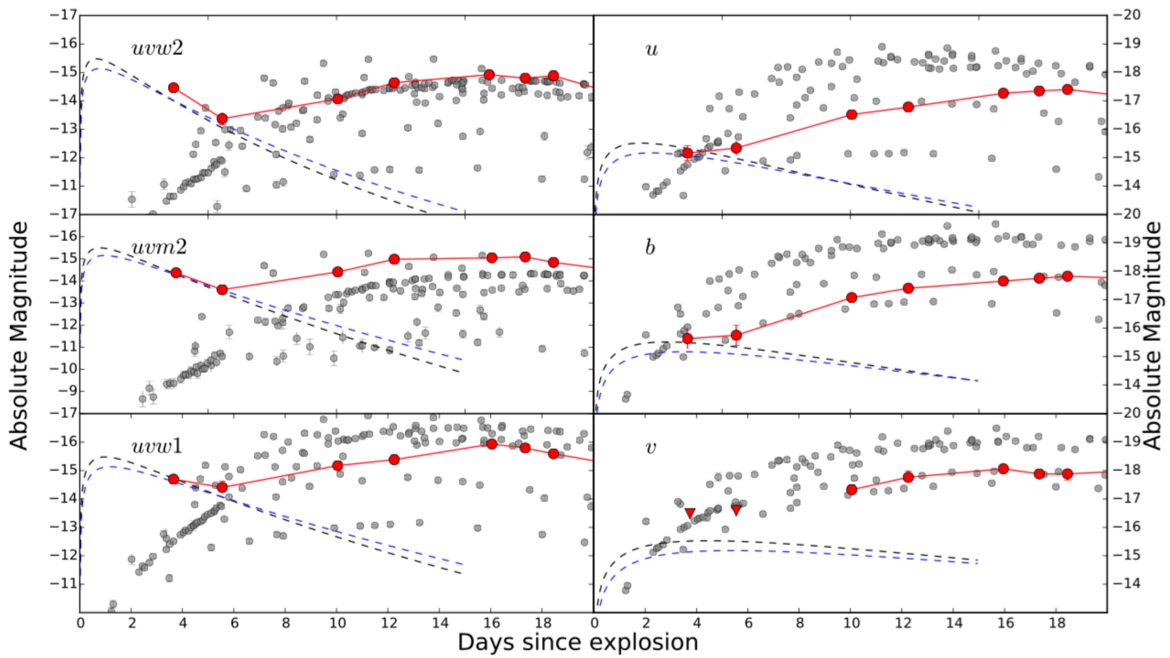
More interesting with

- coordinated (optical) surveys from the ground
- Rapid spectroscopy

=> Unique probe of the last stage of stellar evolution

more science goals

- Ultraviolet pulse of Type 1a SN
  - Interaction of ejecta on the companion star



Yi Cao et al. 2015

- Other science goals
  - Neutrino events
  - SN survey in UV can
  - with neutrino astronomer
  - Tidal disruption events
  - Active Galactic Nuclei, etc.
  - Atmospheric emission(BG?)

Need detailed follow-up observations

Competitor/Collaboration

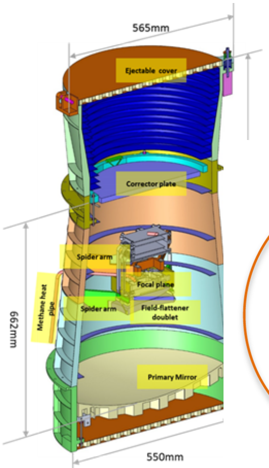
from Wikipedia

- A lot of Telescopes…
- Recent NUV Imaging mission:
  - GALEX (Φ1.2°)
  - UVOT/Swift (17′x17′)
  - ASTROSAT (28′)
  - **ULTRASAT (210 deg^2 21.5mag 900s)**

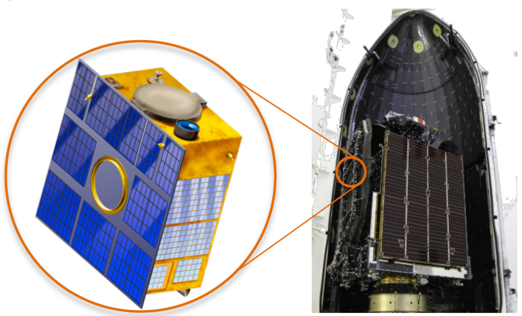
FoV is not enough for GW astronomy

Ultraviolet space telescopes [edit]

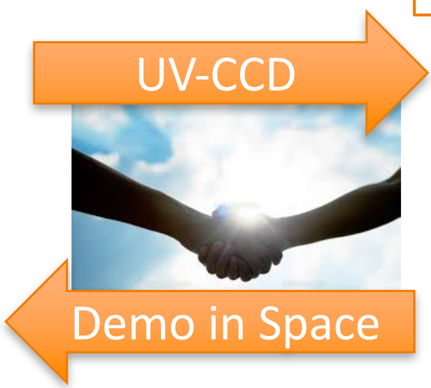
- - Far Ultraviolet Camera/Spectrograph on Apollo 16 (April 1972)
- + ESRO - TD-1A (135-286 nm; 1972–74)
- - Orbiting Astronomical Observatory (#2:1968-73. #3:1972-81)
- - Orion 1 and Orion 2 Space Observatories (#1:1971; 200-380 nm spectra; #2:1
- + - Astronomical Netherlands Satellite (150-330 nm, 1974–76)
- + ESA - International Ultraviolet Explorer (115-320 nm spectra, 1978–96)
- - Astron-1 (1983–89; 150-350 nm)
- - Glazar 1 & 2 on Mir (in Kvant-1, 1987-2001)
- - EUVE (7-76 nm, 1992-2001)
- - FUSE (90.5-119.5 nm, 1999-2007)
- + ESA - Extreme ultraviolet Imaging Telescope (on SOHO imaging sun at 17.1,
- - GALEX (135-280 nm, 2003-2013)
- + ESA - Hubble Space Telescope (Hubble STIS 1997–115–1030 nm) (Hubble W
- - Swift Gamma-Ray Burst Mission (170–650 nm spectra, 2004--)
- - Hopkins Ultraviolet Telescope (flew in 1990 and 1995)
- - ROSAT XUV[2] (17-210eV) (30-6 nm, 1990-1999)
- - Far Ultraviolet Spectroscopic Explorer, 1999-2007
- - Galaxy Evolution Explorer, 2003-2012
- - Public Telescope (PST)[3][4][5] (100-180 nm, Launch planned 2019)
- - Astrosat (130-530 nm, launched in September 2015)

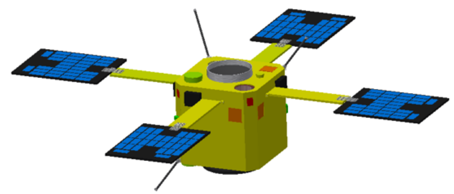


may be the most recent shape



Caltech/JPL/Israel



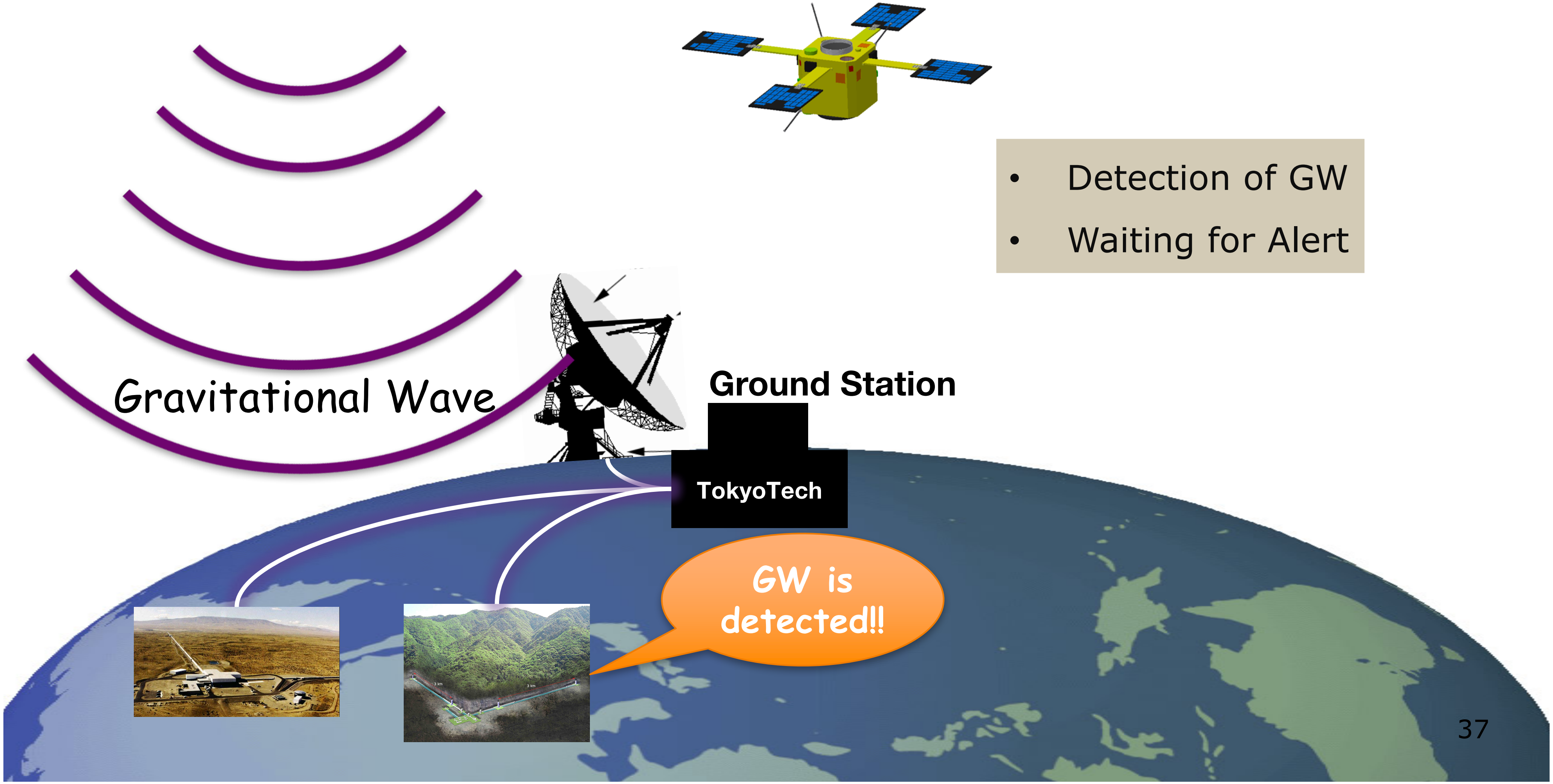


Tokyo Tech small satellite team

Only the ULTRASAT can be used for GW follow-up.

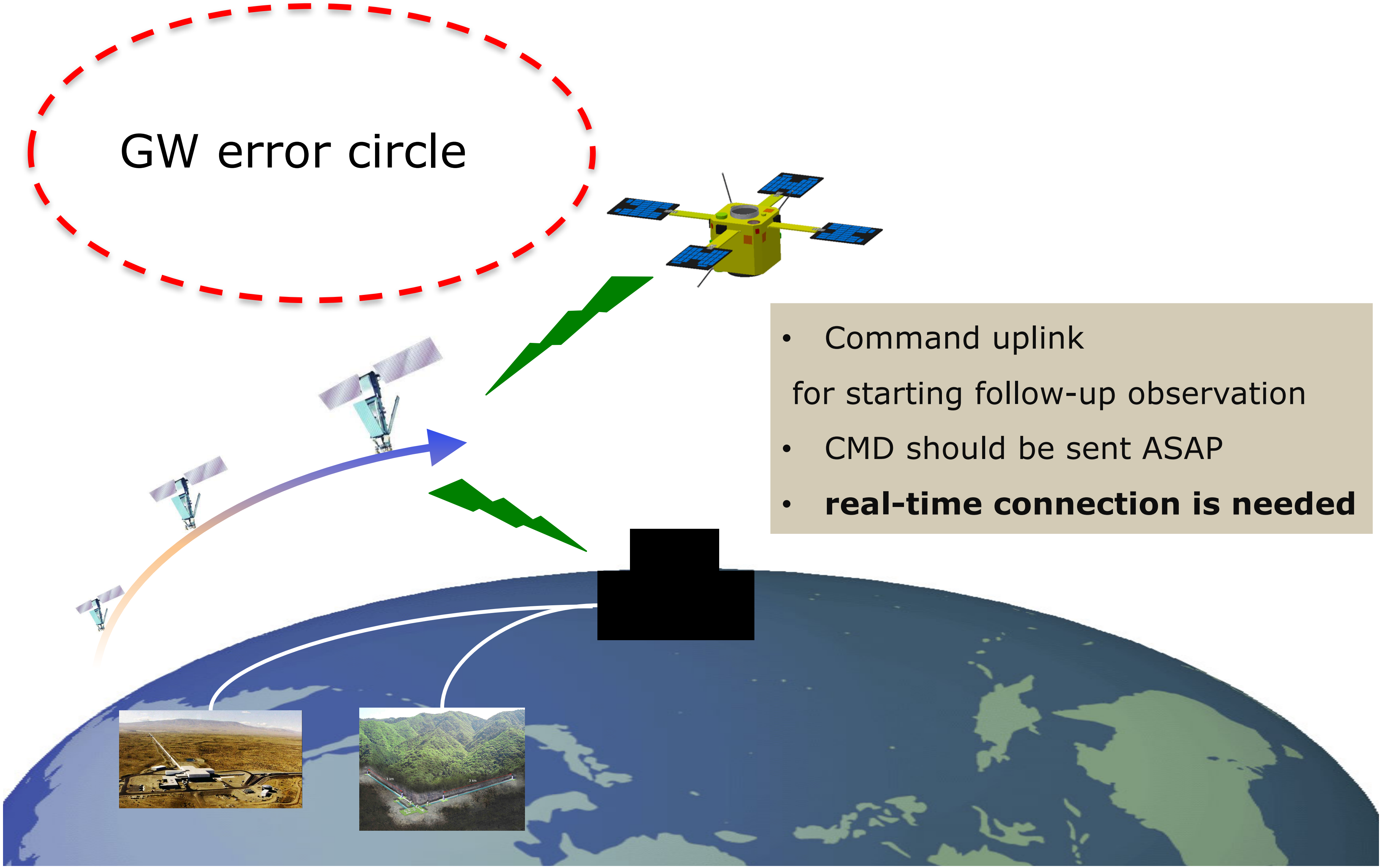
- Caltech was searching for a chance to demonstrate their detector on orbit.
- We were searching for the UV-detector.

Mission Sequence: Arrival of Gravitational Wave



- Detection of GW
- Waiting for Alert

Command uplink for follow-up Obs

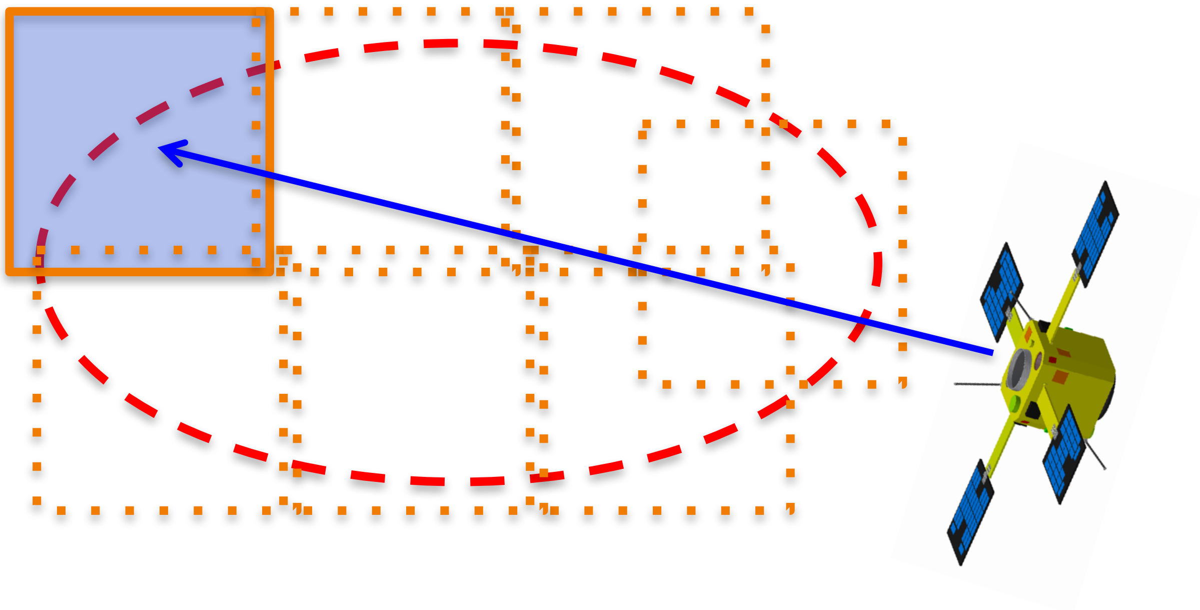


- Command uplink

for starting follow-up observation

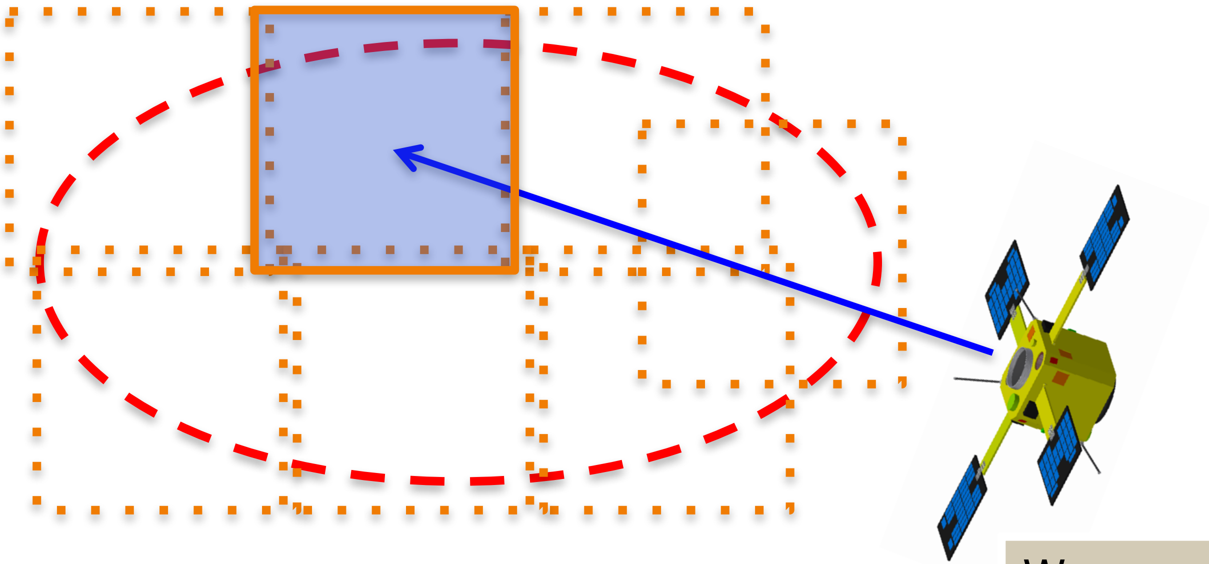
- CMD should be sent ASAP
- **real-time connection is needed**

Tiling observation #1



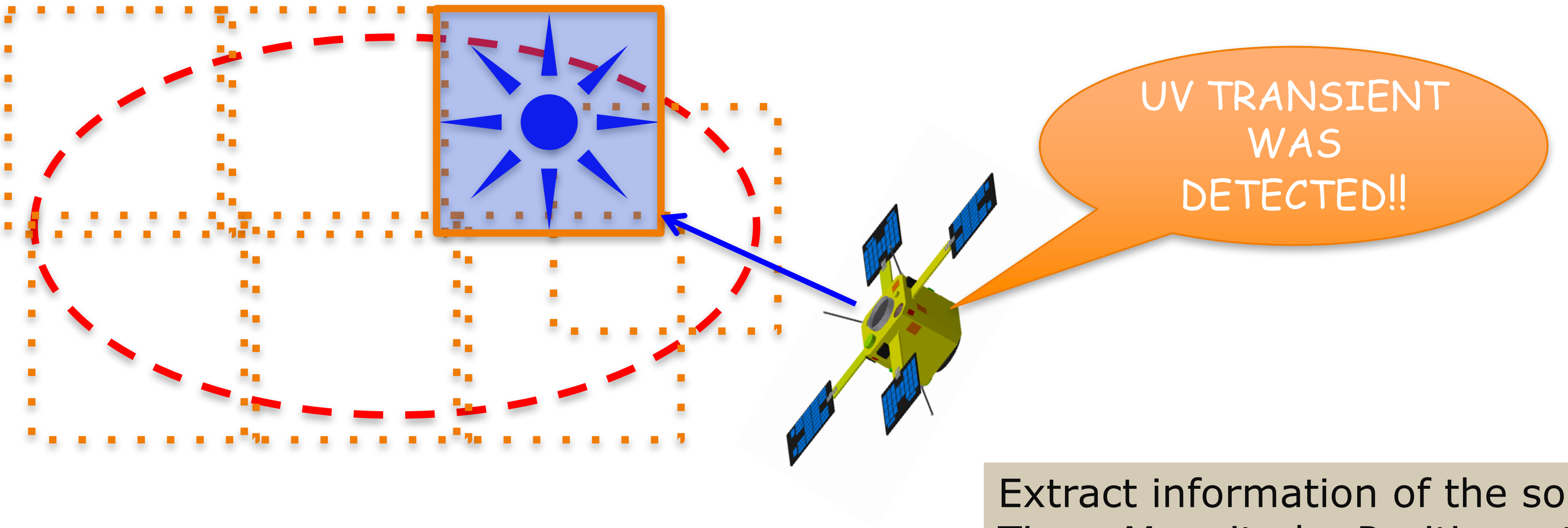
The satellite promptly starts observation
Tiling Obs needs quick and stable **Att control.**

Tiling observation #2



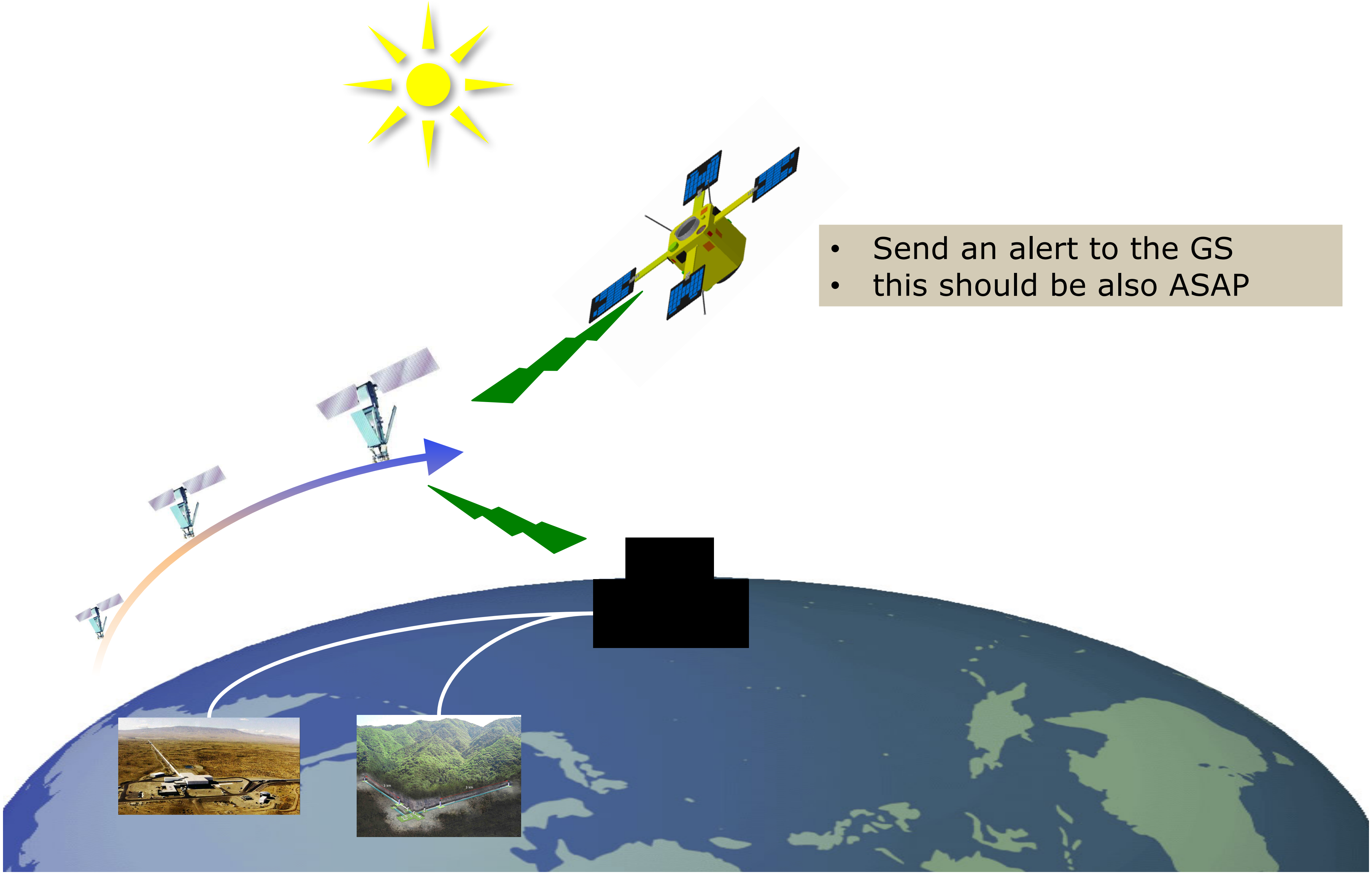
We cannot transfer all the data to the ground instantly.
⇒ **On-board analysis (reduction & detection) is required!!**

Tiling observation #3



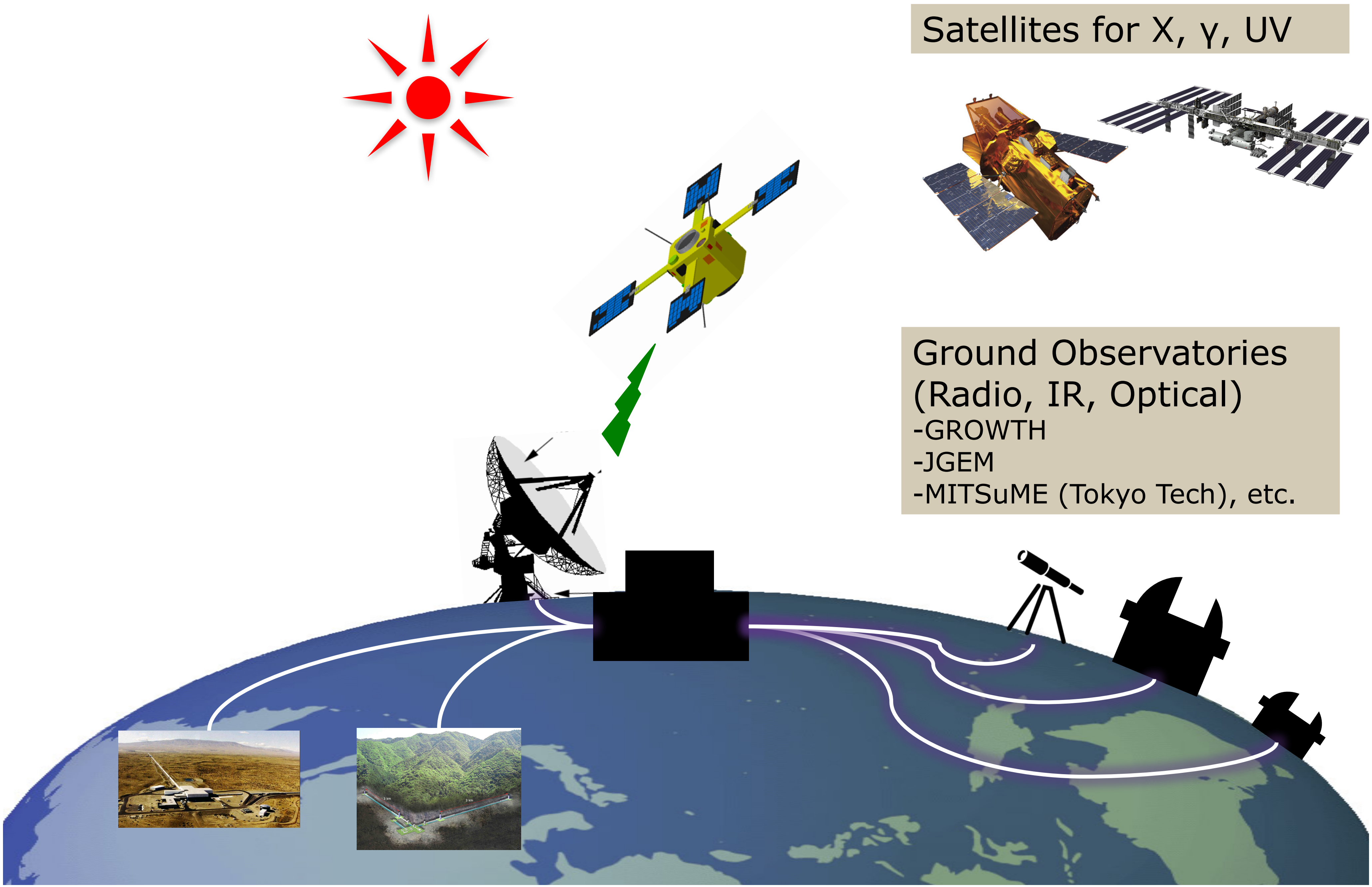
Extract information of the source:
Time, Magnitude, Position, etc.

Alert to the Ground station



- Send an alert to the GS
- this should be also ASAP

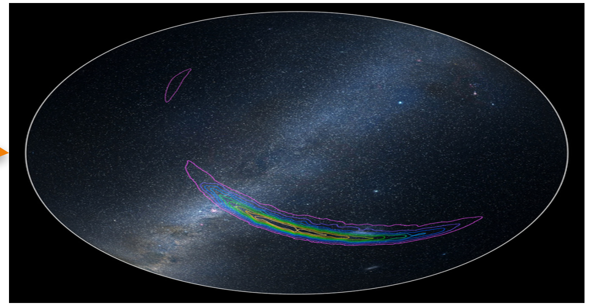
Multi-messenger astronomy

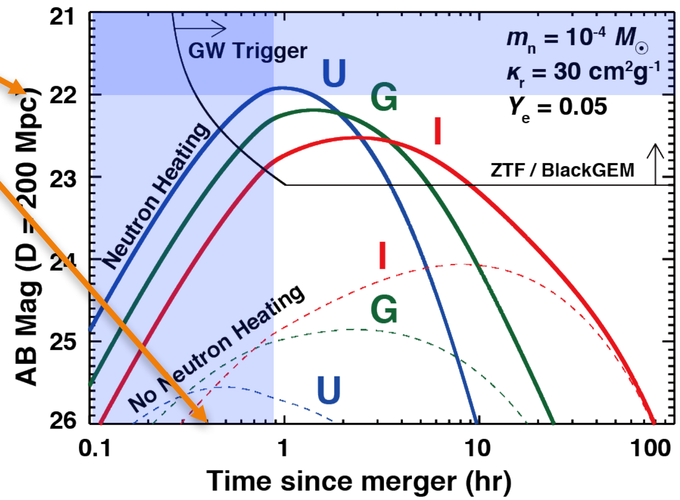


Mission Requirements

Goal > 1 NS-NS merger/yr (Assuming 10 NS merger yr^{-1})

- Target Profile in NUV (Neutron Heating):
  - Error-circle: **> 100 deg^2**
  - Rise time: **< 1 hr**
  - Flux: **> 22 mag**
  - Position Accuracy: **< 10"**

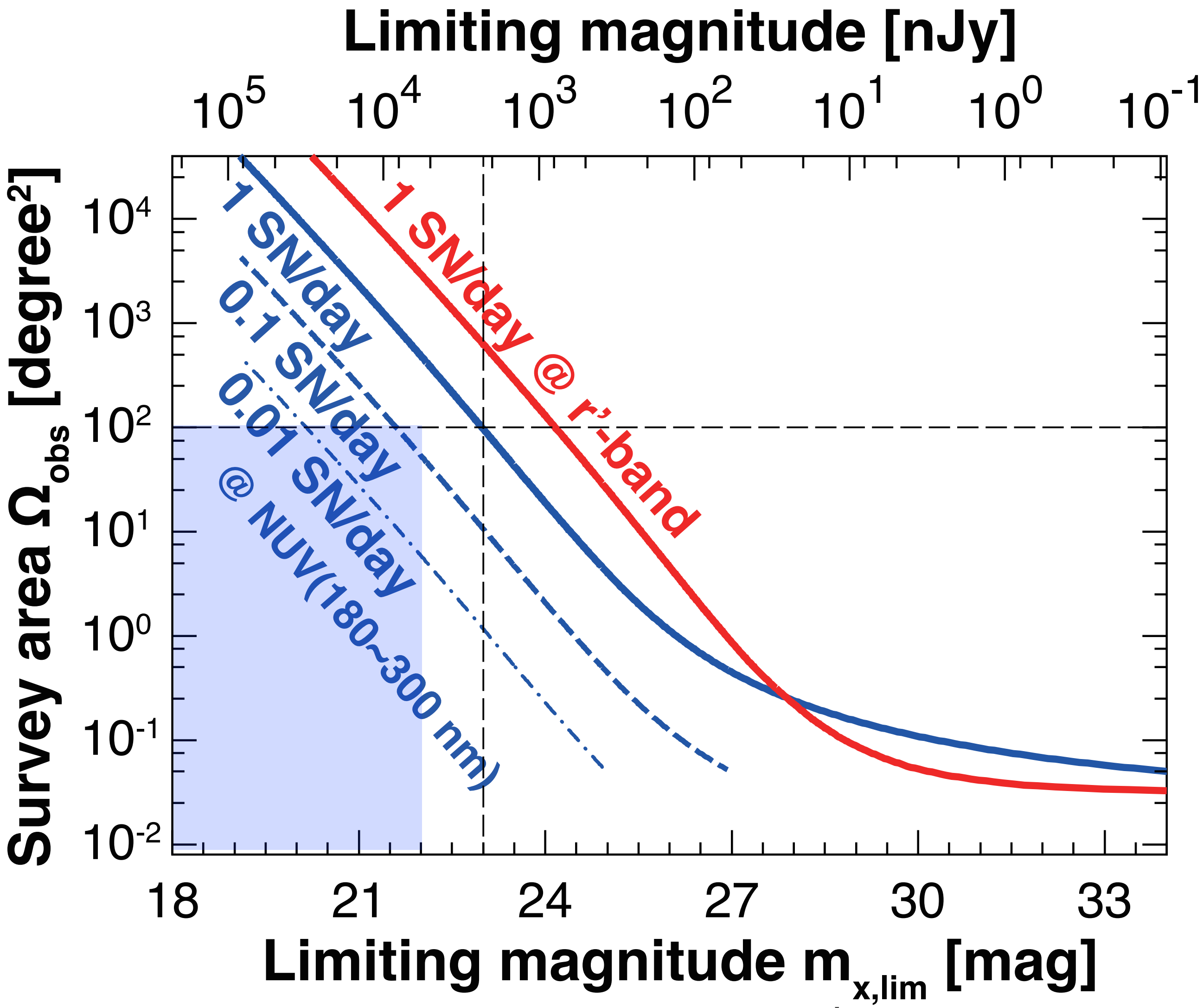




- Mission Requirements:
  - Detection Limit: **> 22mag**
  - Cadence: **> 2 cycle/hr**
  - Exposure: **< 0.5 hr / (100deg^2/FoV)**
  - Obs Duration: **> 1 hour** (with batt.)
  - Delay of Alert: **< 30 min**

We need:
-Wide field telescope which can detect 22 mag
-Attitude stability ~10"
-Quick MNV ~ a few deg/s

Such UV telescope will be useful for…



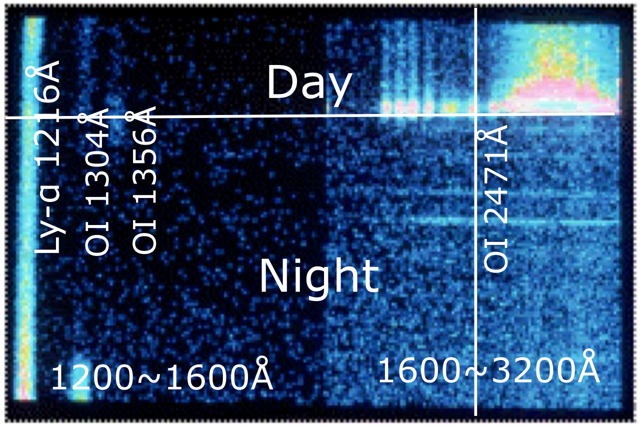
Based on Tominaga et al. 2011

0.1 SN Shockbreakouts /day !?

Estimation of Detection Limit

- Based on the UVOT/Swift DATA
  - Diameter: 300mm
  - Trans Rate x Q.E.: ~2.9 % (UVW1+UVM2)

  22 mag(Vega) ⇒ 152 photon / 1000s at NUV(UVW1+UVM2)



- Estimation for the UV-telescope on Hibari
  - Diameter: 200mm
  - OPT Trans Rate: 70% (Requirement)
  - Q.E.: 80% (Caltech's UV-CCD)
  - Electric Noise:
    - Readout Noise(RMS): **15.5 e- (5s x 60 frames)**
    - Dark@-30°C: **790 e-/pixel/300s**
  - Foreground (based on GALEX DATA):
    - Airglow(Local Time depend): **~78.6** [ph/s/cm2/str/Å] (-6<LS<+6h avg.)
    - Airglow(Sun Angle depend): **~675** [ph/s/cm2/str/Å] (120<S.A.180)
    - Zodiacal light: **~800** [ph/s/cm2/str/Å] (avoid ecliptic latitude)

    => **97 e-/pix/300s(night) / ~ 1000 e-/pix/300s (day)**

At 200-300 nm with 300s exposure we can detect

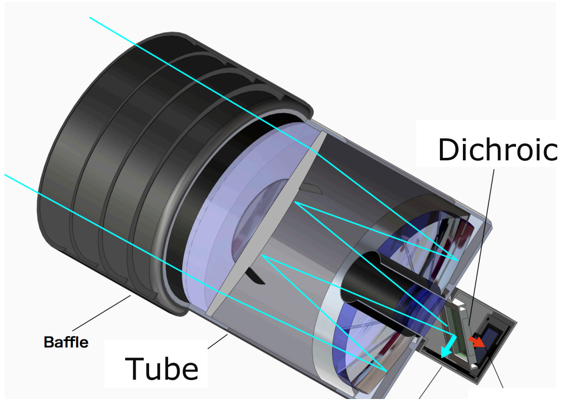
⇒ **22.5 mag in night-side**

⇒ **< 21.6 mag in day-side** (airglow is x200 higher than night)

Design of Telescope

Allowed payload size: < Φ250 mm, height < 400 mm

- Requirements to the optics:
  - **D:** **< Φ200 mm => Exposure time > 300 s for 22mag**
  - **FoV:** **> 17 deg^2 <= 100 deg^2 ÷ (30min/300s)**
  - **focal L:** **< 430 mm (from the CCD format and FoV)**
  - **PSF:** **15um (~2 pixel)**
- Base design:
  - Requirement: Short tube
  - ⇒ **Riccardi-Honders OPTICS**
  - D200mm (F3.0)/$8k



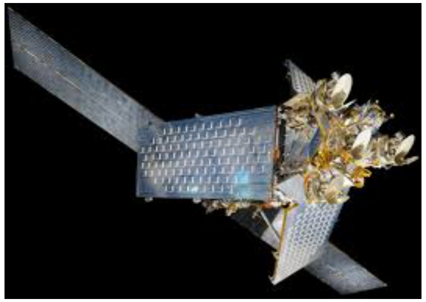
- Modification
  - BK7 ⇒ Fused Quartz or Synthetic Silica for UV
  - Shrink the focal length 600mm ⇒ 430 mm

The manufacturer (Italy) confirmed the NUV-transmission rate with fused Quartz.
We must shrink the focal length. (The base design still provide ~9 deg^2)

Estimation of data rate

- Alert(uplink) / Detection Notice(downlink)
  - Time : 24 bit
  - Coordinate: 12 bit x 2 (x 5 points)
  - Magnitude: 8 bit

  Total: ~146 bit (~18 Byte)



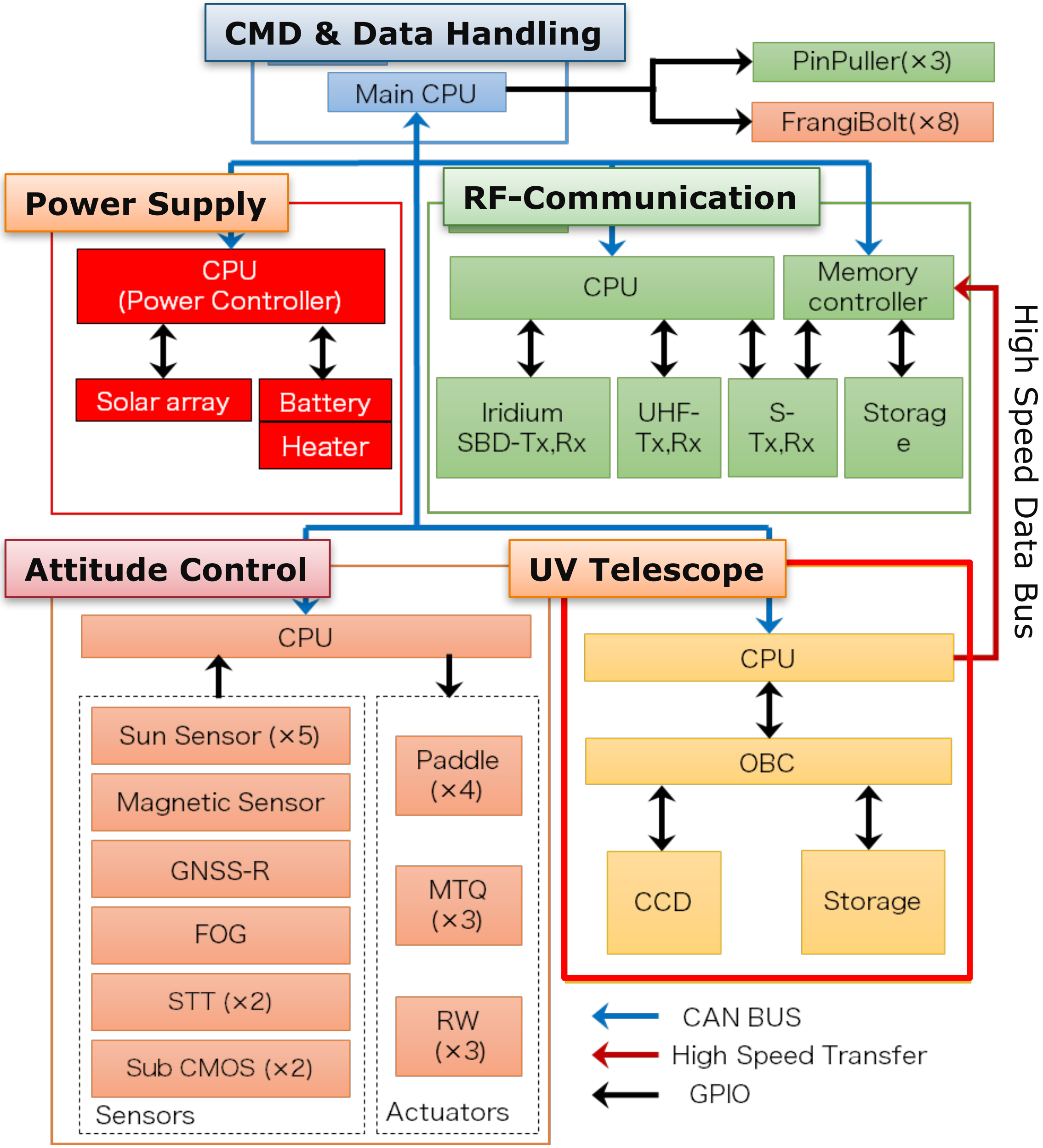
- Image Data
  - Raw Data: 2064×2046 pixel × 16bit = 8 MB/frame + Header

    on board data reduction/compression
  - Image combine: 10 sec × 6 frame (& Cosmic-ray subtraction)
  - Extract sub-regions
    - Object number: 5~10 (Target + Reference stars)
    - sub-region: 50x50 pixel (5 kByte/sub-region)
    - Header: ~1 kB (Coordinate+ Time + Temp,,,)

DATA RATE ~ 50 kByte /min

Assuming 10 hour continuous observation,
the total amounts of telemetry will be **~30 Mbyte/day**

System Block Diagram



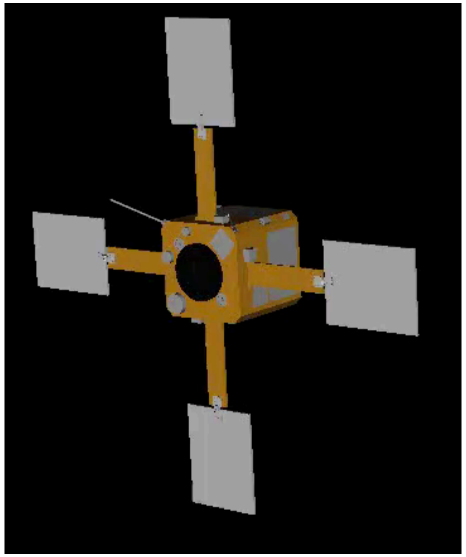
- System design is based on the experiences in TSUBAME project

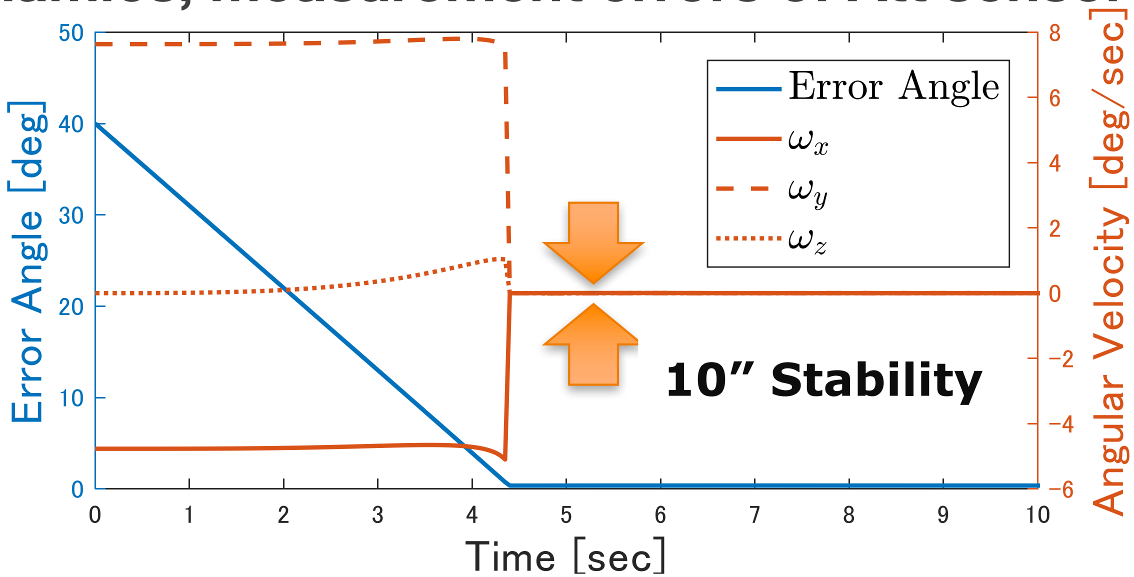
- Controlled by CDH
- 2 kind of Data BUS
- Redundant design

Attitude Control System

- Large Angle MNV… Attitude control by Variable Structure
- Small Angle MNV… Reaction wheels
- Suppression of disturbance & vibration… RW

Simulation(Software in the Loop Simulation) concerned disturbance, RW dynamics, measurement errors of Att sensors



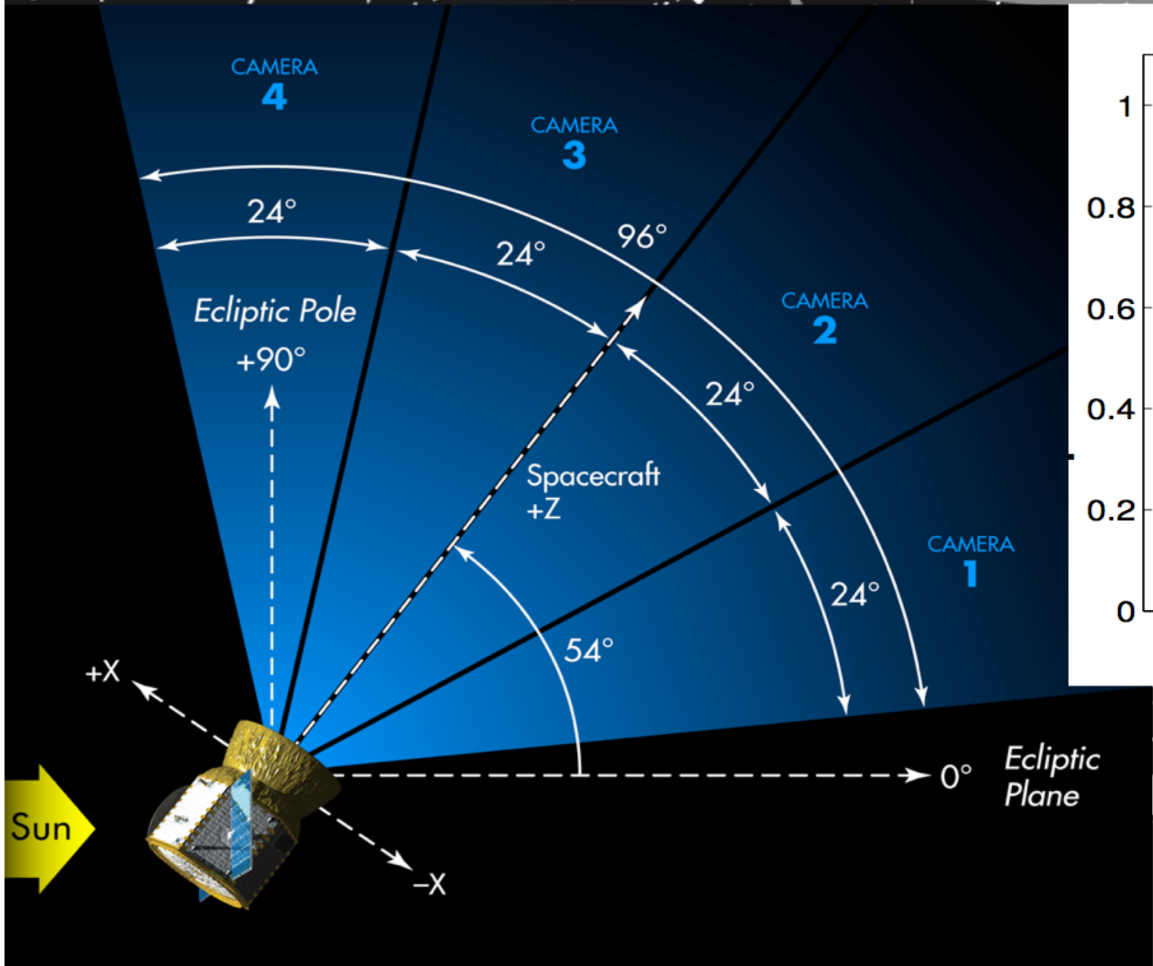


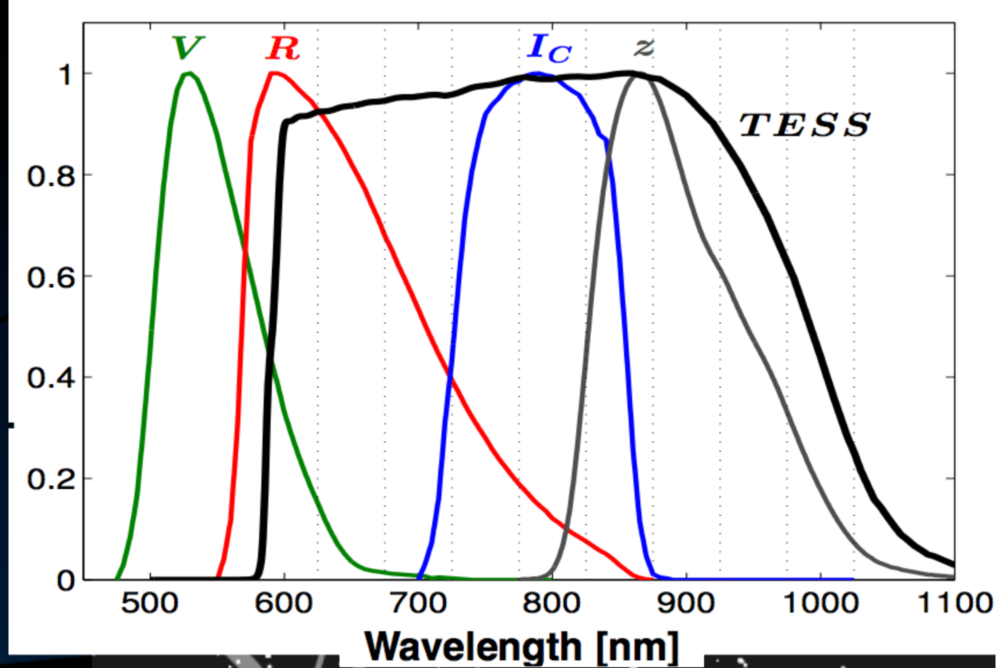
10″ stability is achieved
※ Consistency of the Software Simulator was confirmed by TSUBAME

Optical mission

Transiting Exoplanet Survey Satellite

Ricker et al. 2014





OBSERVATION PLAN

Ricker et al.: Transiting Exoplanet Survey Satellite

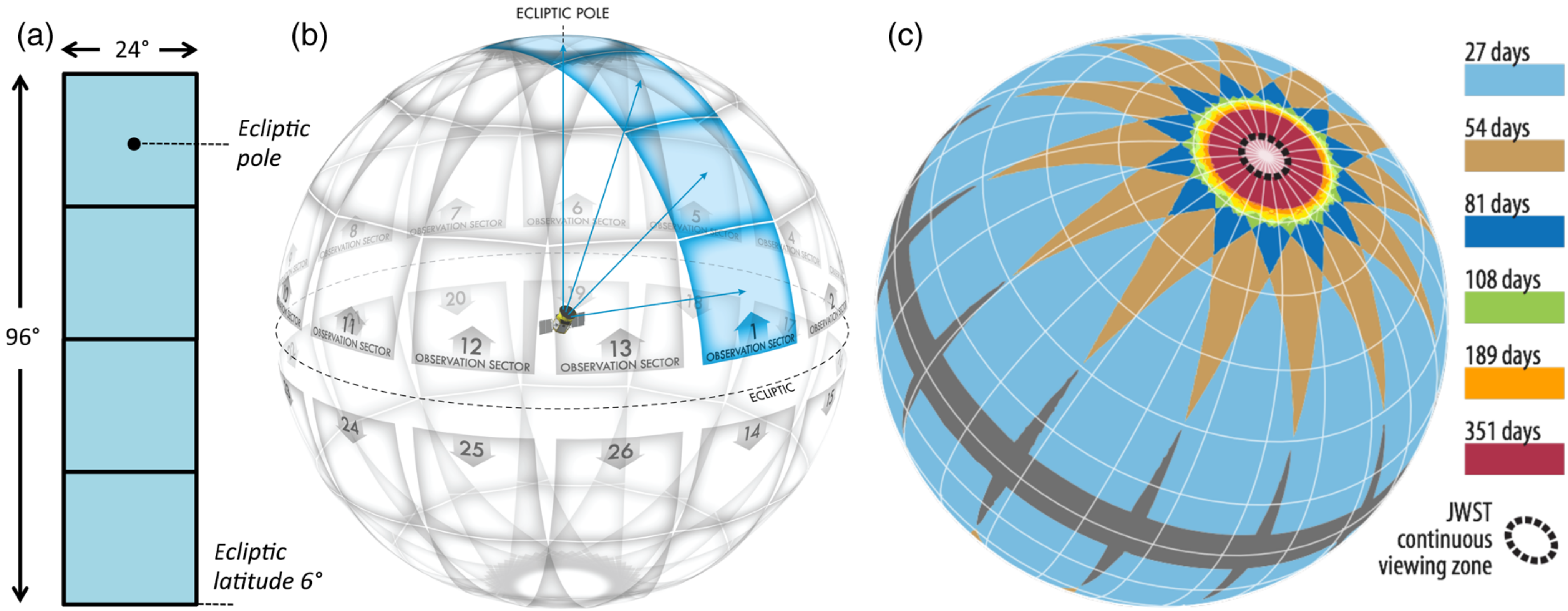
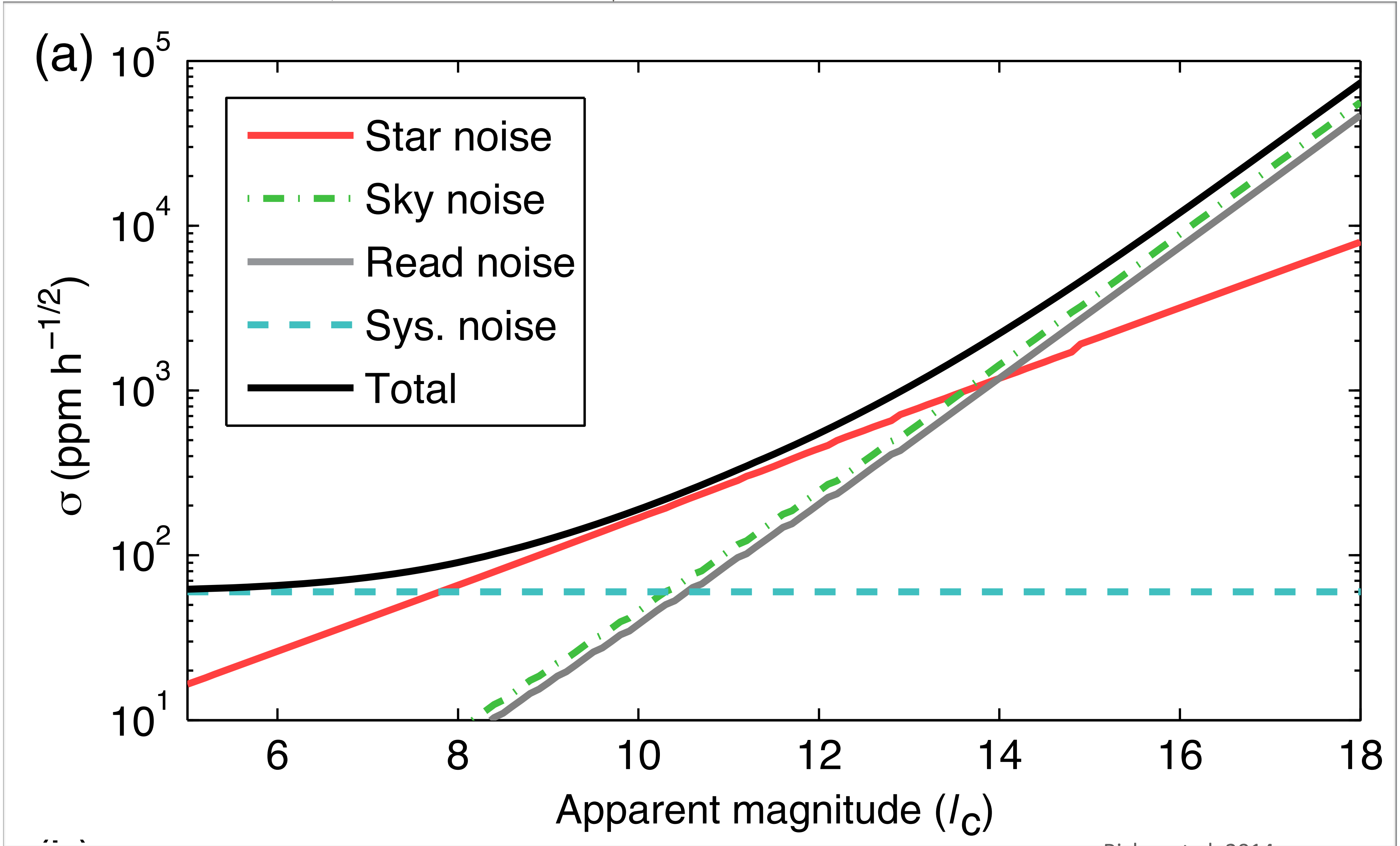


Fig. 7 (a) The instantaneous combined field of view of the four TESS cameras. (b) Division of the celestial sphere into 26 observation sectors (13 per hemisphere). (c) Duration of observations on the celestial sphere taking into account the overlap between sectors. The dashed black circle enclosing the ecliptic pole shows the region which James Webb Space Telescope will be able to observe at any time.

1 orbit: 13-d observation + 0.6-d downlink

Ricker et al. 2014
(astro-ph 1406.0151)

SENSITIVITY



Ricker et al. 2014
(astro-ph 1406.0151)

TARGETS AND DATA

- ~200,000 Preselected Stars
  - 2 min cadence
  - Almost all for Exoplanet+Asteroseismology
    - ~1000 targets/yr by guest observer proposal
      - 1st GO proposal due: fall 2016
    - Data release every 4 month

- ~20,000,000 Stars in FFI (Full Frame Images)
  - 30 min cadence
  - $\Delta M \approx 5$ mmag for 10^6 stars and galaxies ($Ic<14$-15)
  - Delivery delay TBD (1 week ~ 6 months)

POSSIBLE SUBJECTS

- GRBs: (orphan) afterglows
- AGN: continuous light curve
- Tidal disruption events at centers of galaxies
- Gravitational Wave: optical counterparts/kilonovae
- Supernovae and novae: pre-maximum light curve
- X/gamma-ray binaries: multi-wavelength monitoring
  - Outbursts of BH/NS binaries
  - Black widow pulsars
- Stars: super flares, super-orbital periodicities
- Asteroids, comets, TNO, …

PLANS?

- Launch ~early 2018
- Guest Observer Proposal ~Summer 2017
  - 2 min cadence targets
- FFI
  - new transient pipeline?: (e.g. ASAS-SN)
  - coordinated observations for specific targets
    - Follow-up (delay?)
    - Sampling/monitoring spectroscopy, multicolor,…