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Future X-ray/gamma-ray follow-up observations for the multi-messenger transients

Masanori Ohno (Hiroshima University)

2017’ : a dawn of the MM follow-up observation era

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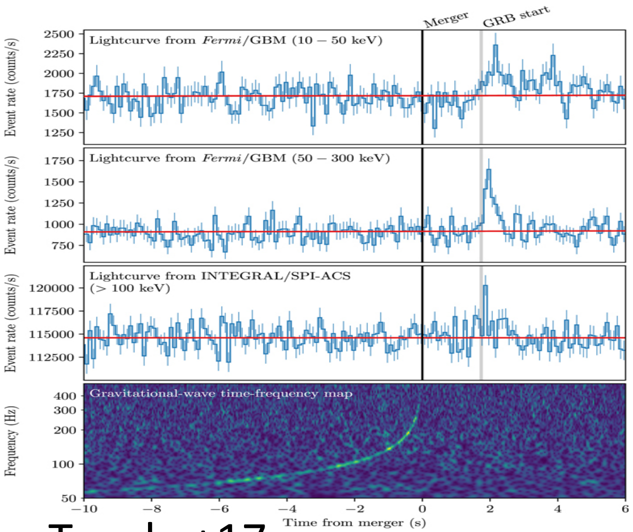
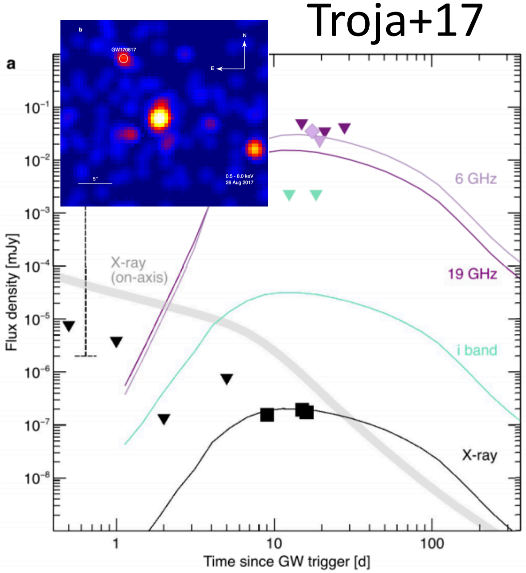
Abbott+17

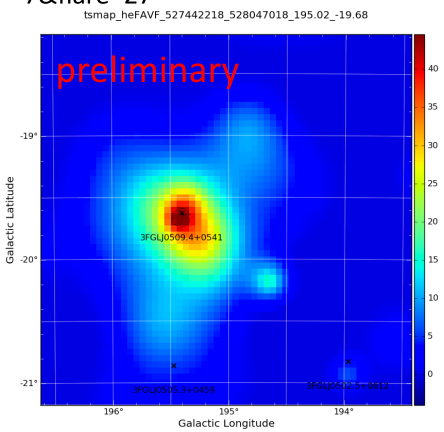


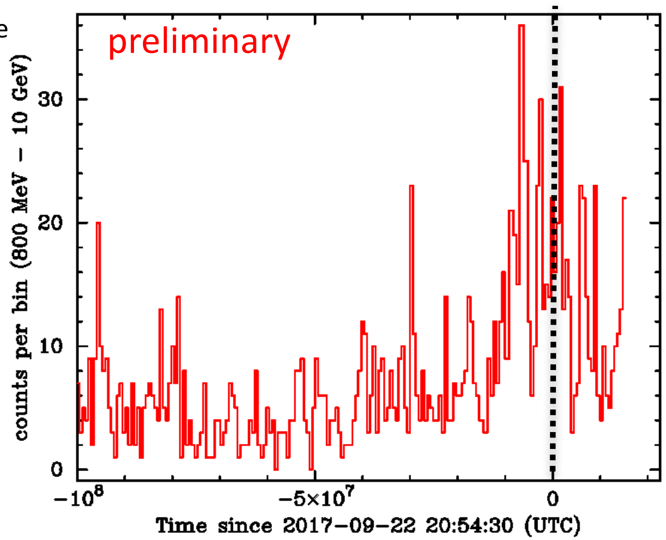
Troja+17



Tanaka+17 (Atel#10791)

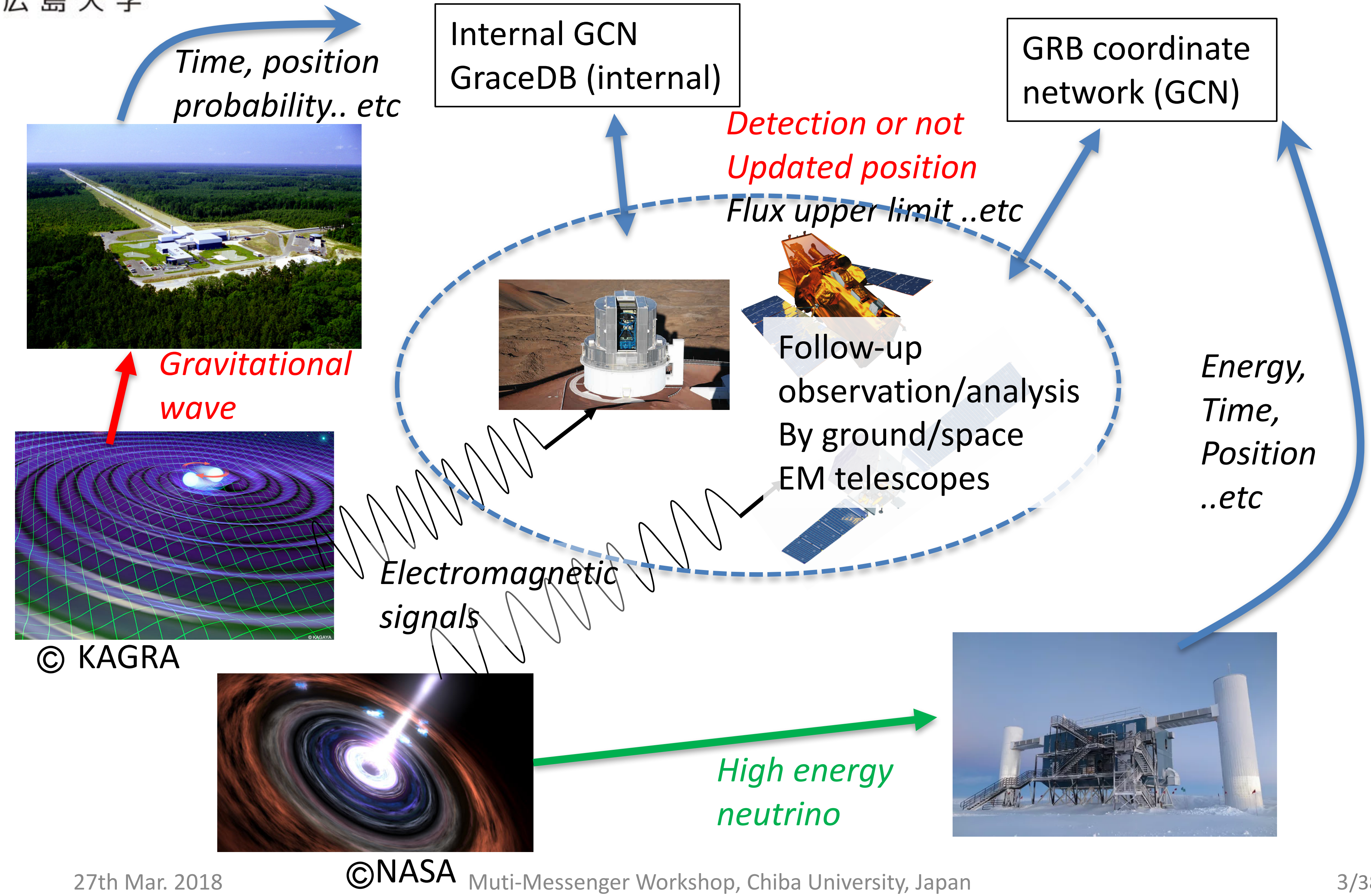
https://fermi.gsfc.nasa.gov/ssc/data/access/lat/FAVA/SourceReport.php?week=477&flare=27





- EM counterpart from NS-NS merger event GW170817/GRB170817A
- Gigantic campaign of follow-up observation in any EM wavelengths successfully carried out
- More detections/follow-up obs. are needed for modeling and short GRB association
- High-E IceCube ν and blazar activity was found for IceCube-170922A/TXS0506+056
- Future continuous monitoring for this candidate and further detection is expected

Current MM follow-up system



Why X-ray/gamma-ray ?

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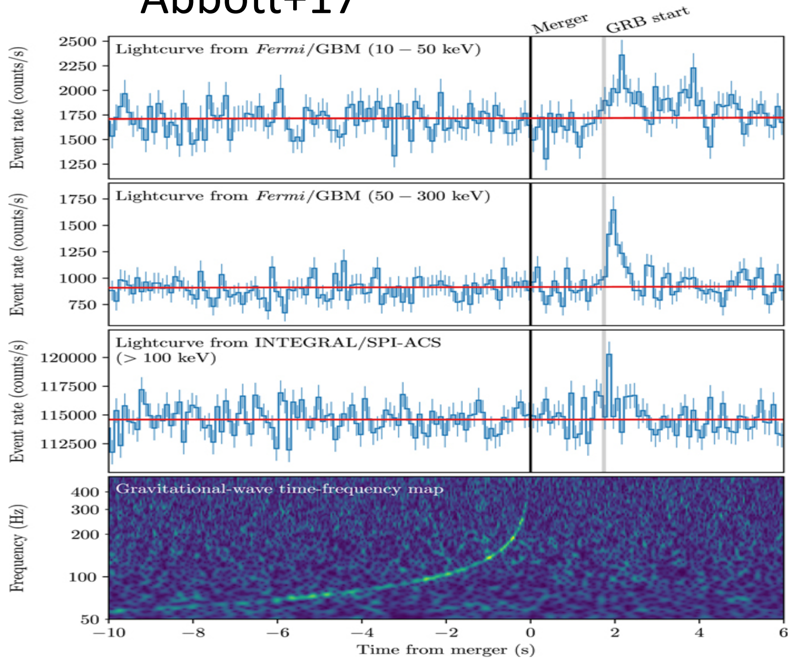
- **NS-NS(BH) merger and short GRB association !**
- **X-ray/gamma-ray spectral features from NS-NS merger environment (circumstellar medium, r-process elements)**
- **Monitoring observation w/ wide field of view instruments**

Abbott+17



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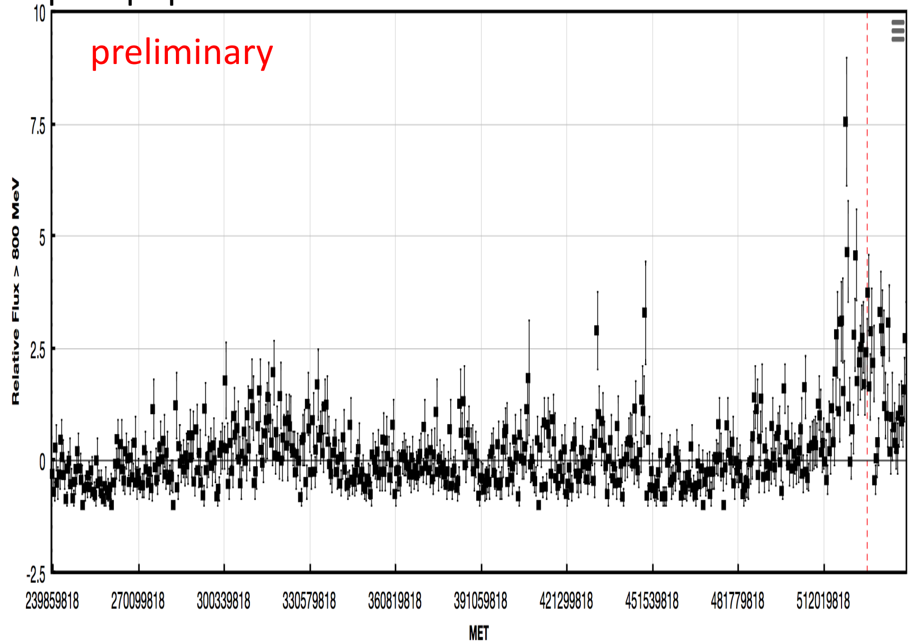
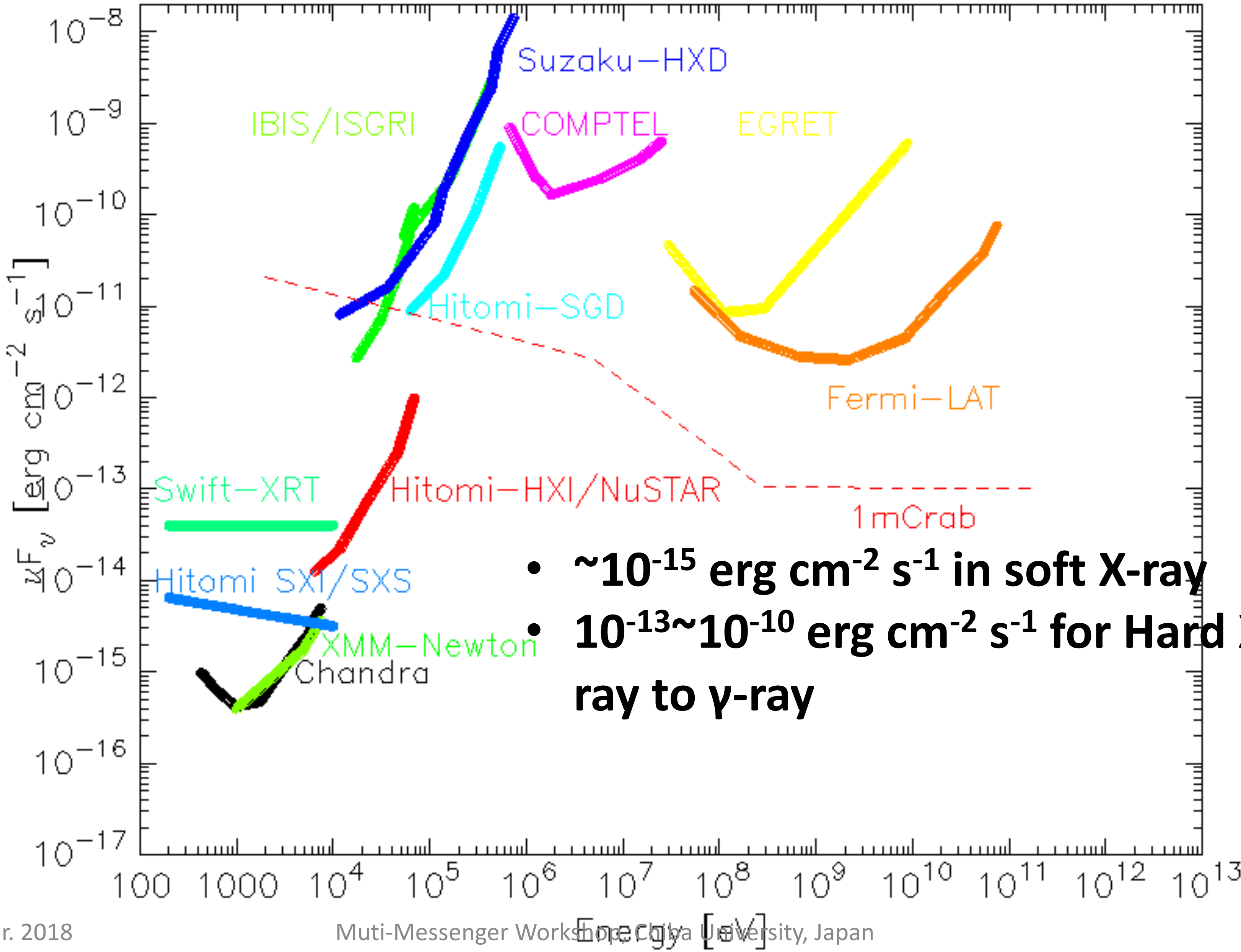
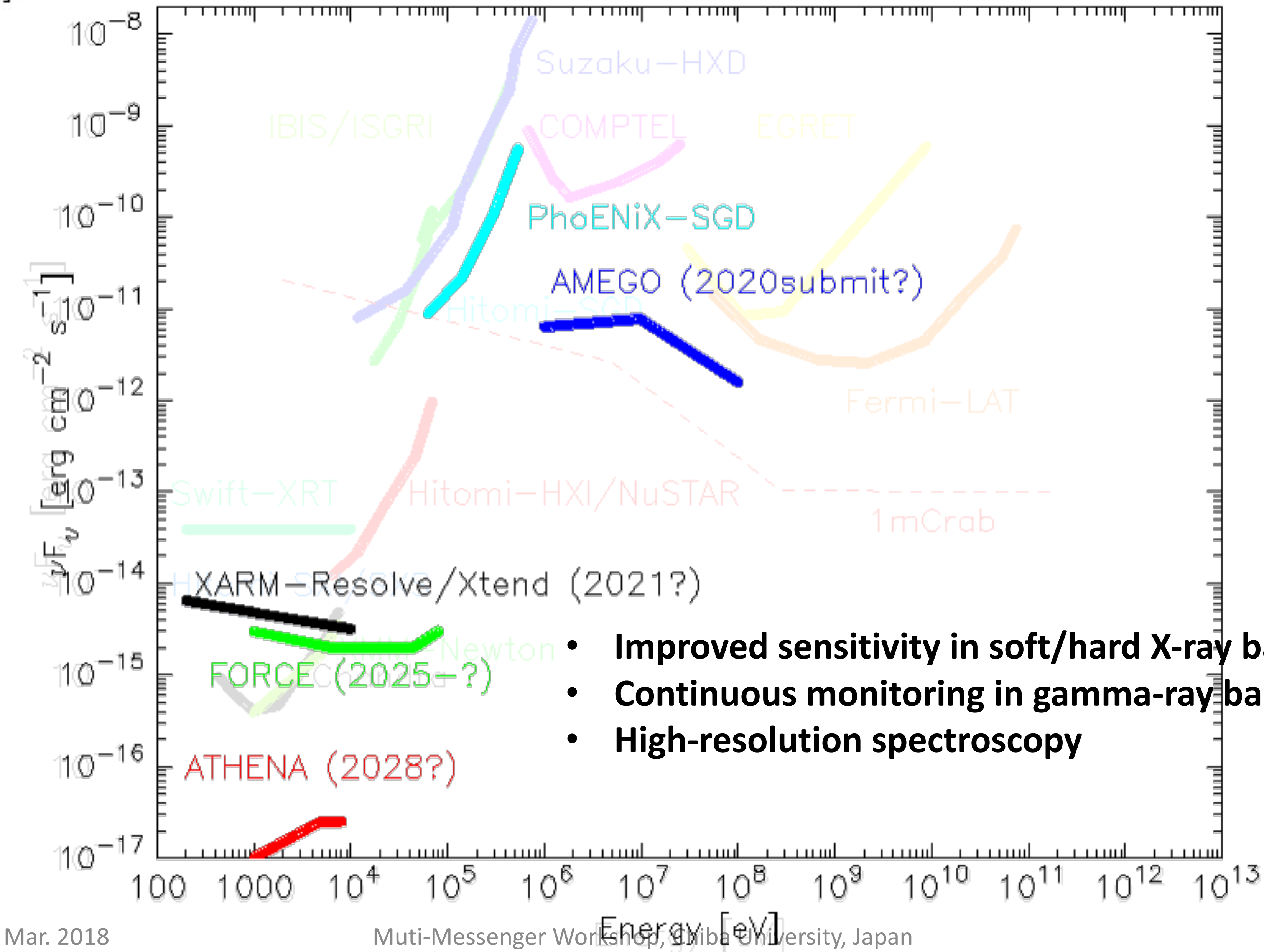


Sensitivity in previous/current X/Gamma-ray observations



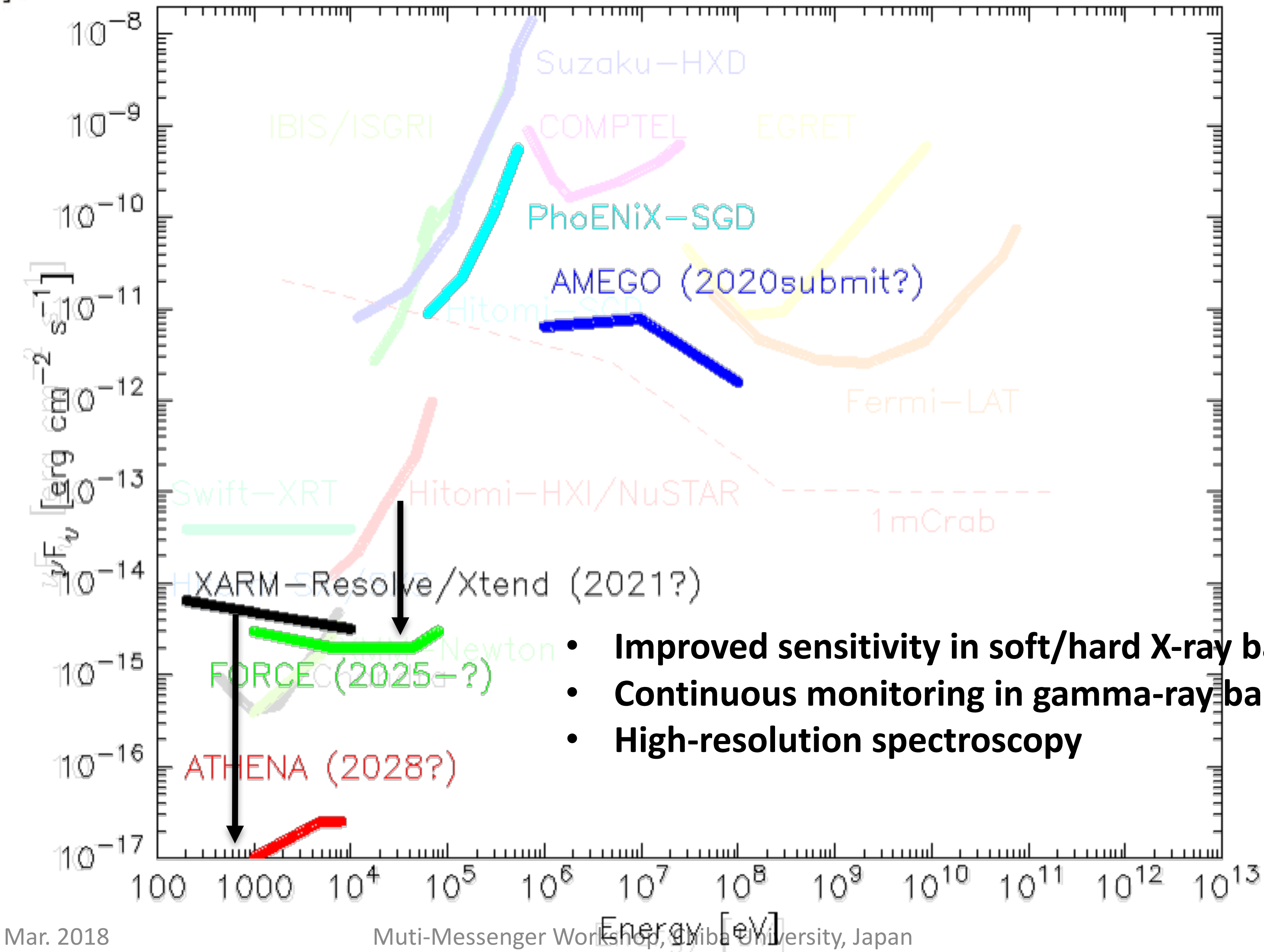
- **~10^{-15} erg cm^{-2} s^{-1} in soft X-ray**
- **10^{-13}~10^{-10} erg cm^{-2} s^{-1} for Hard X-ray to γ-ray**

Sensitivity in "future" X/Gamma-ray observations



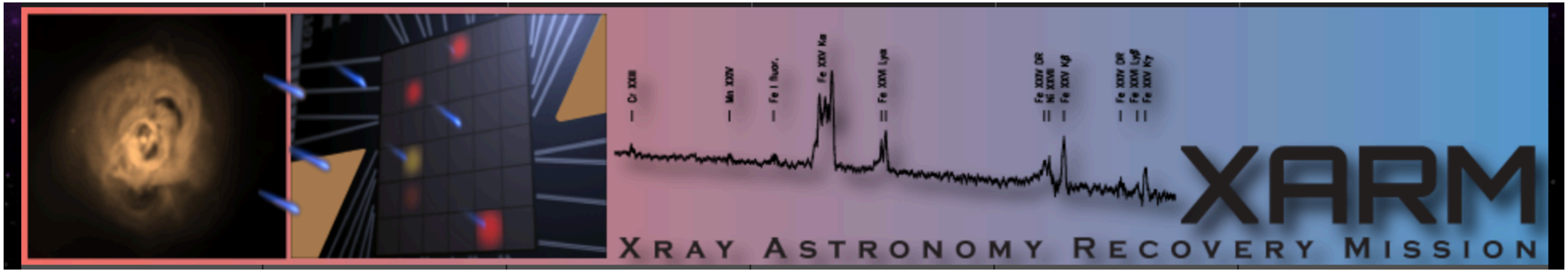
- **Improved sensitivity in soft/hard X-ray band**
- **Continuous monitoring in gamma-ray band**
- **High-resolution spectroscopy**

Sensitivity in “future” X/Gamma-ray observations

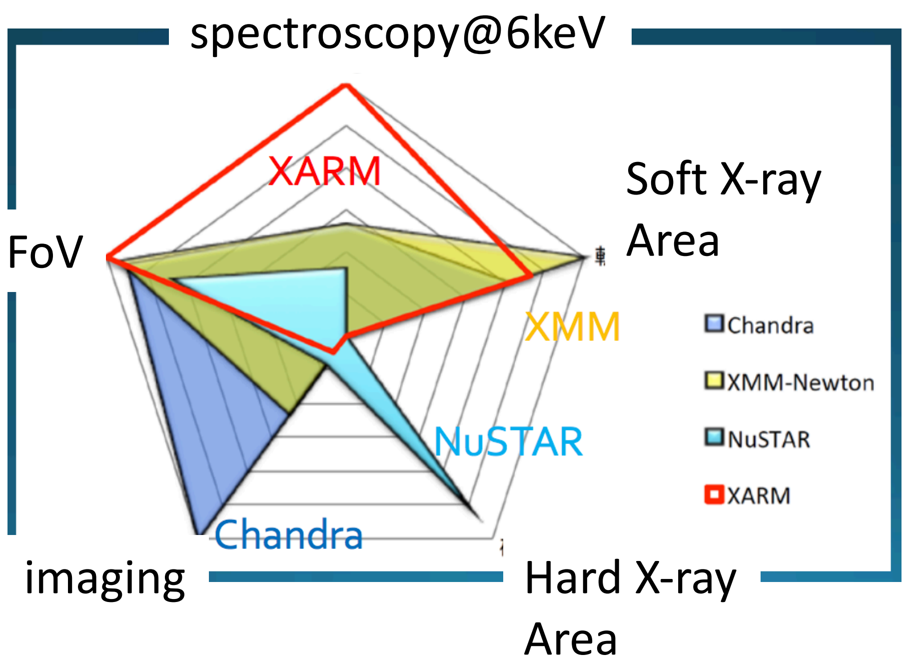


- **Improved sensitivity in soft/hard X-ray band**
- **Continuous monitoring in gamma-ray band**
- **High-resolution spectroscopy**

X-ray Astronomy Recovery Mission (XARM) : 2021~



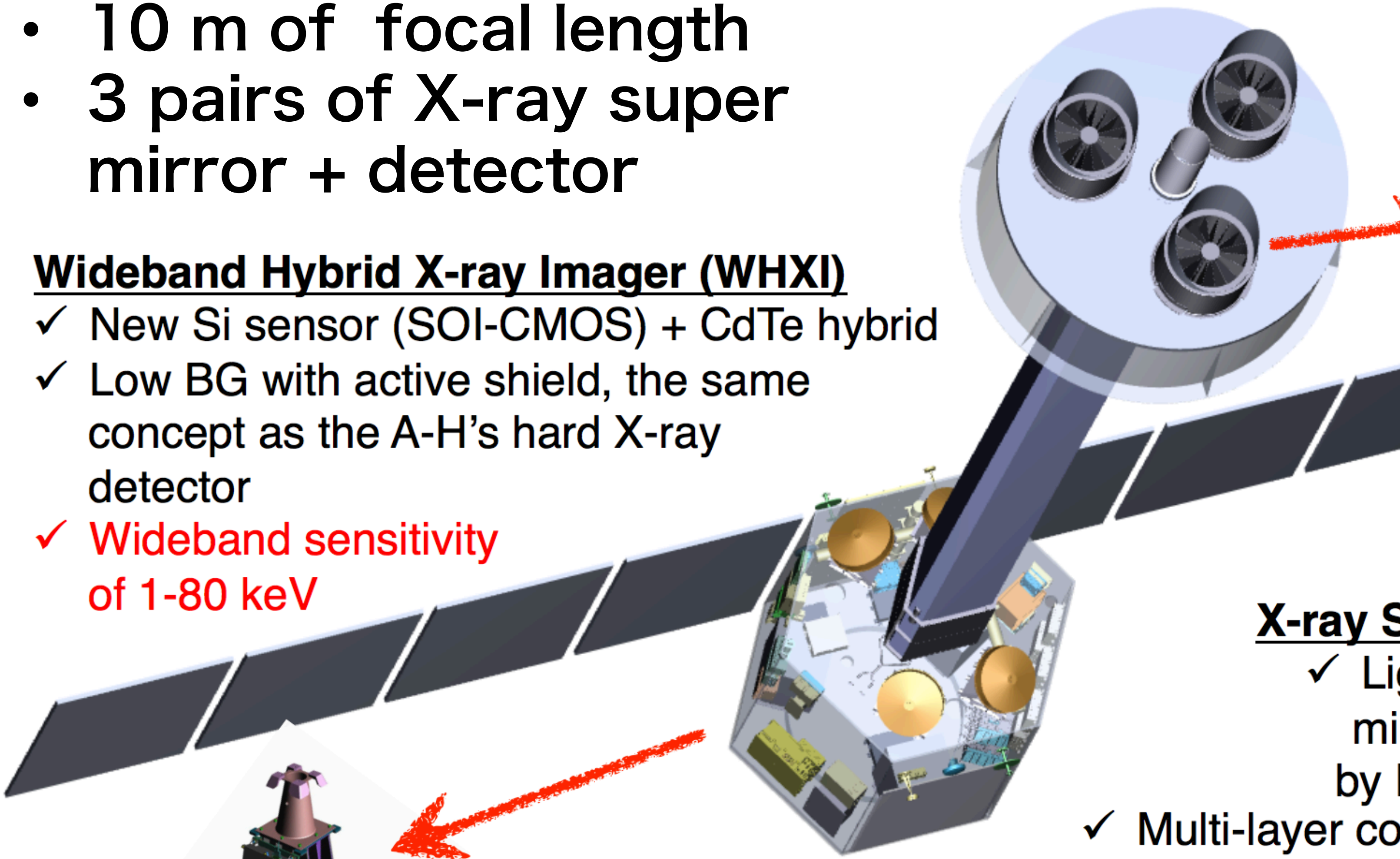
	FOV/pix	ΔE (FWHM @6keV)	Energy band
Resolve (XMA+ X-ray microcalorimeter)	2.9’□/6x6 pix	7 eV (goal 5 eV)	0.3—12 keV
Xtend (XMA + X-ray CCD)	38’□/1280 x1280 pix	<250 eV at EOL (<200 eV at BOL)	0.4—13 keV

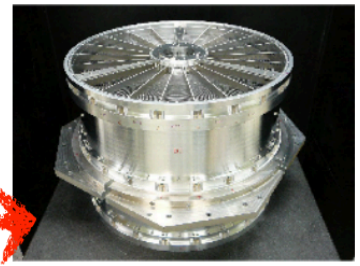


Tashiro 17th heapa workshop

Focusing On Relativistic universe and Cosmic Evolution (FORCE): 2025(?)~

- 10 m of focal length
- 3 pairs of X-ray super mirror + detector



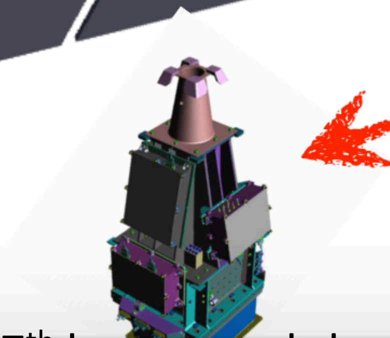


Wideband Hybrid X-ray Imager (WHXI)

✓ New Si sensor (SOI-CMOS) + CdTe hybrid

✓ Low BG with active shield, the same concept as the A-H's hard X-ray detector

✓ Wideband sensitivity of 1-80 keV



X-ray Super-mirror

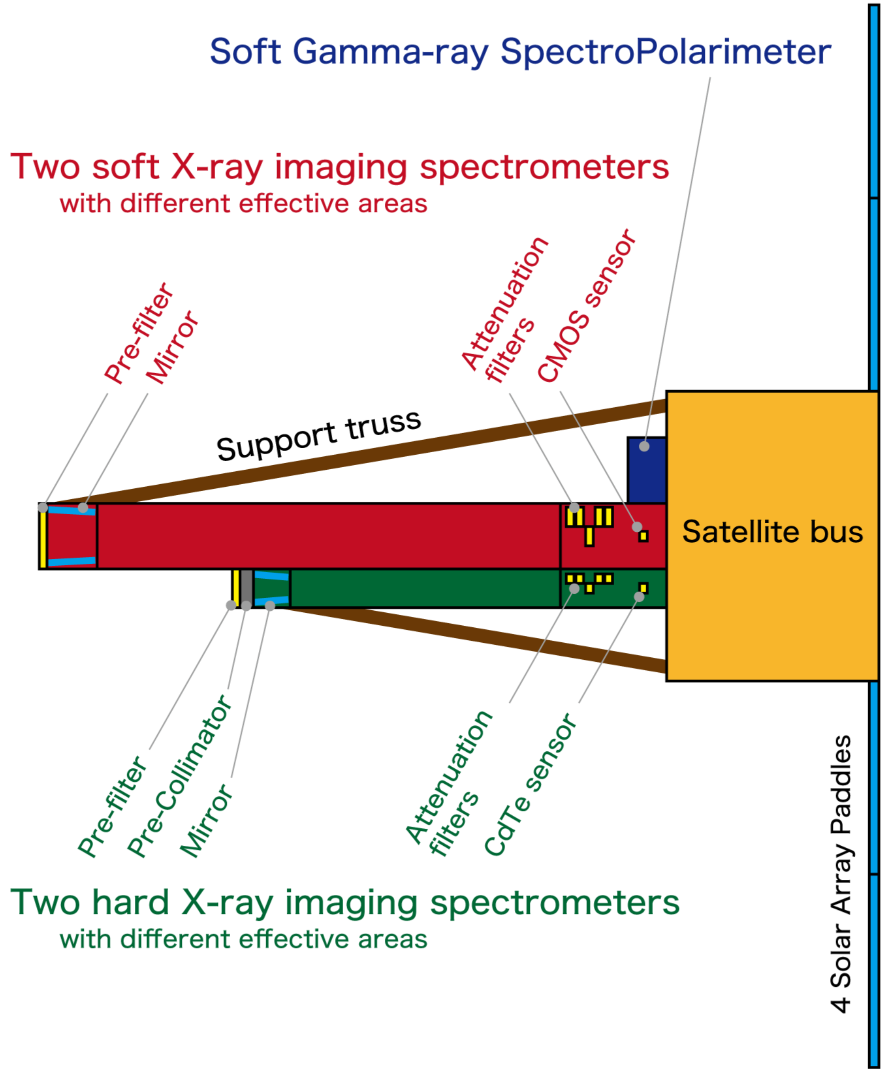
✓ Light-weight Si mirror provided by NASA/GSFC

✓ Multi-layer coating directly on the Si mirror surface

✓ Unprecedented angular resolution of <15” in hard X-ray

➔ 2~3 x 10^{-15} erg cm^{-2} s^{-1} sensitivity (10-40 keV)

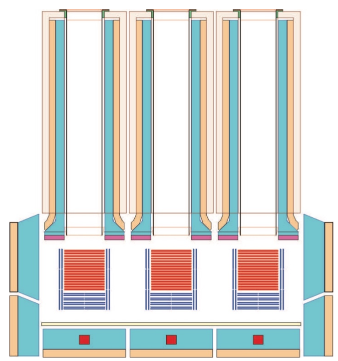
Physics of Energetic and Non-thermal plasmas in the X resion (PhoEniX)

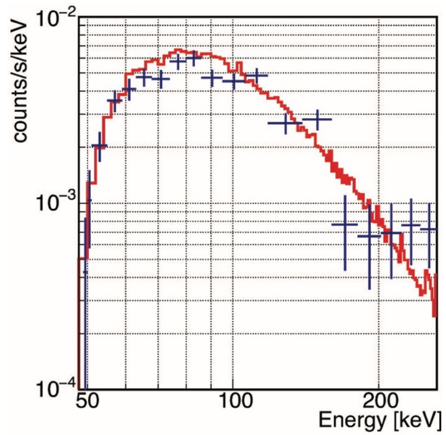


Soft X-ray & Hard X-ray imaging spectroscopy Of solar flare

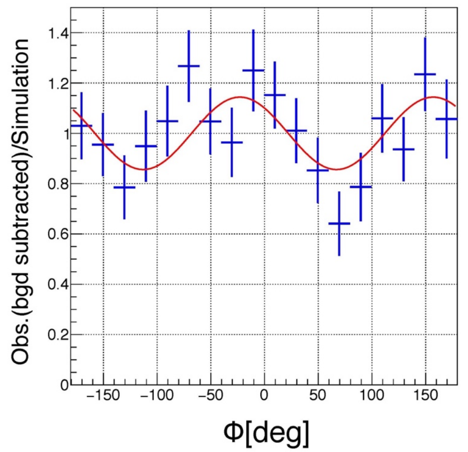
+

Soft gamma-ray spectroscopy and polarimetry With soft gamma-ray spectropolarimeter (Same as the Hitomi-SGD)



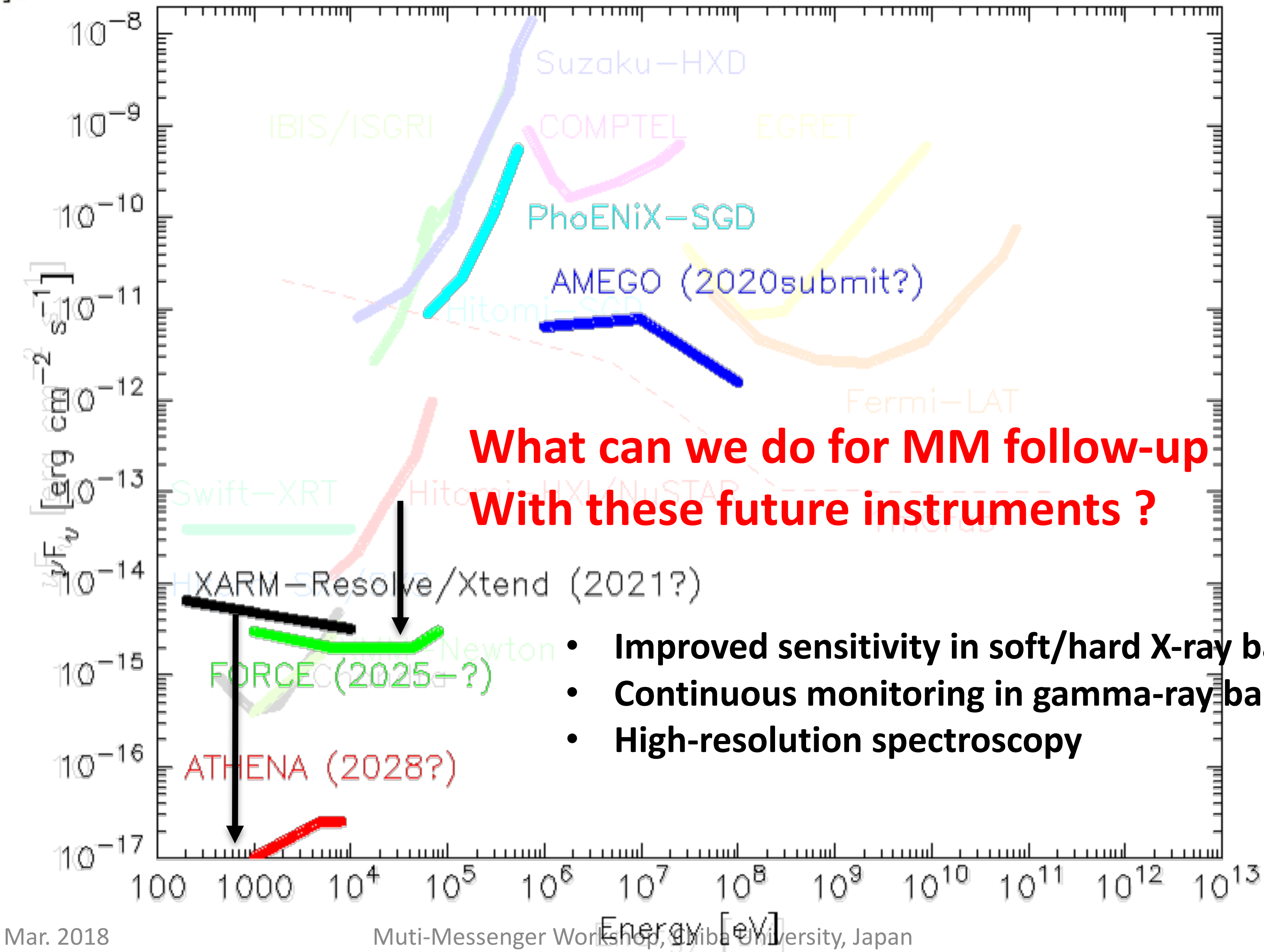


Spectroscopy and polarimetry have been performed for the Crab nebula with only 5 ks exposure !



Narukage 17th heapa workshop

Sensitivity in "future" X/Gamma-ray observations

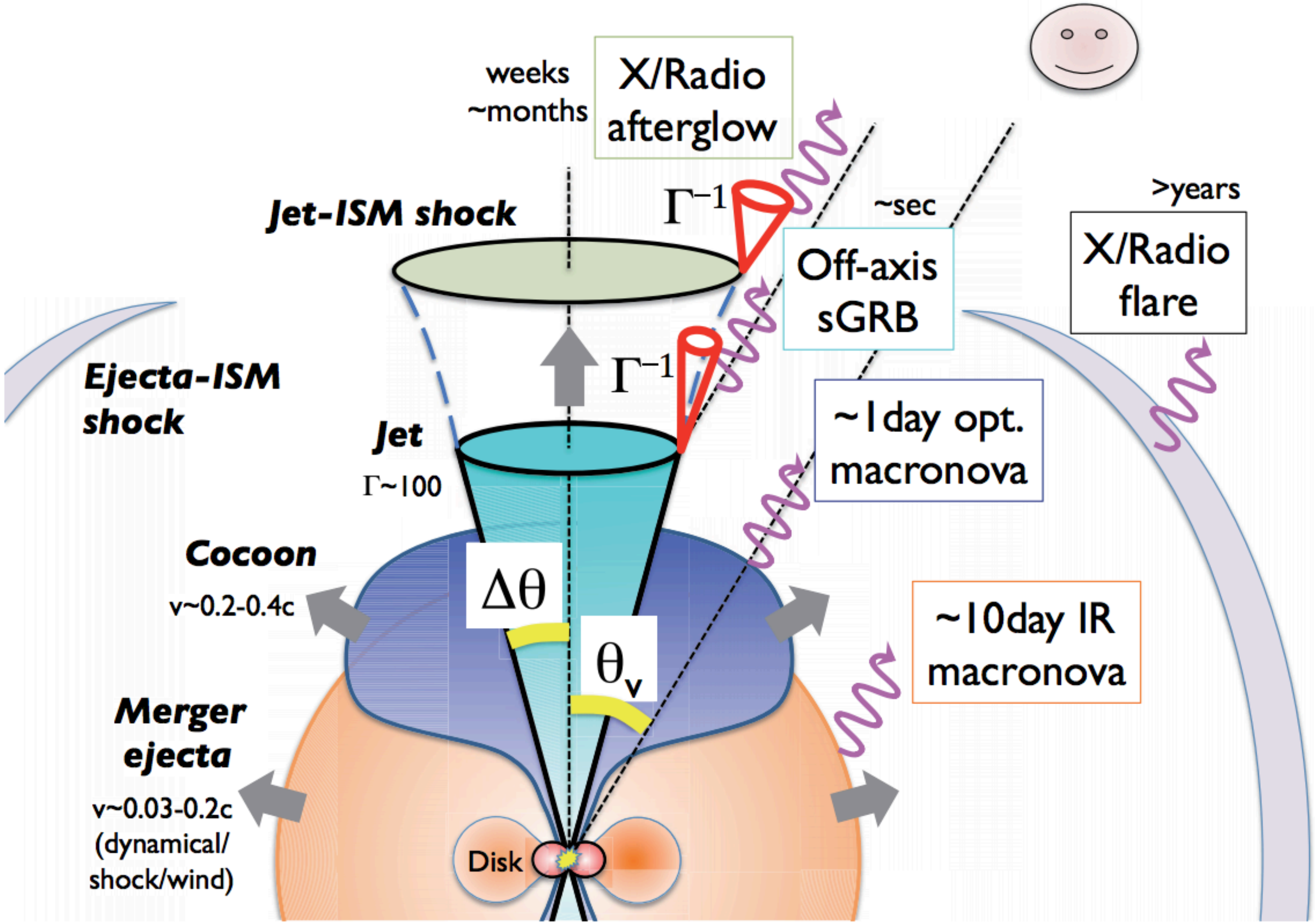


What can we do for MM follow-up
With these future instruments ?

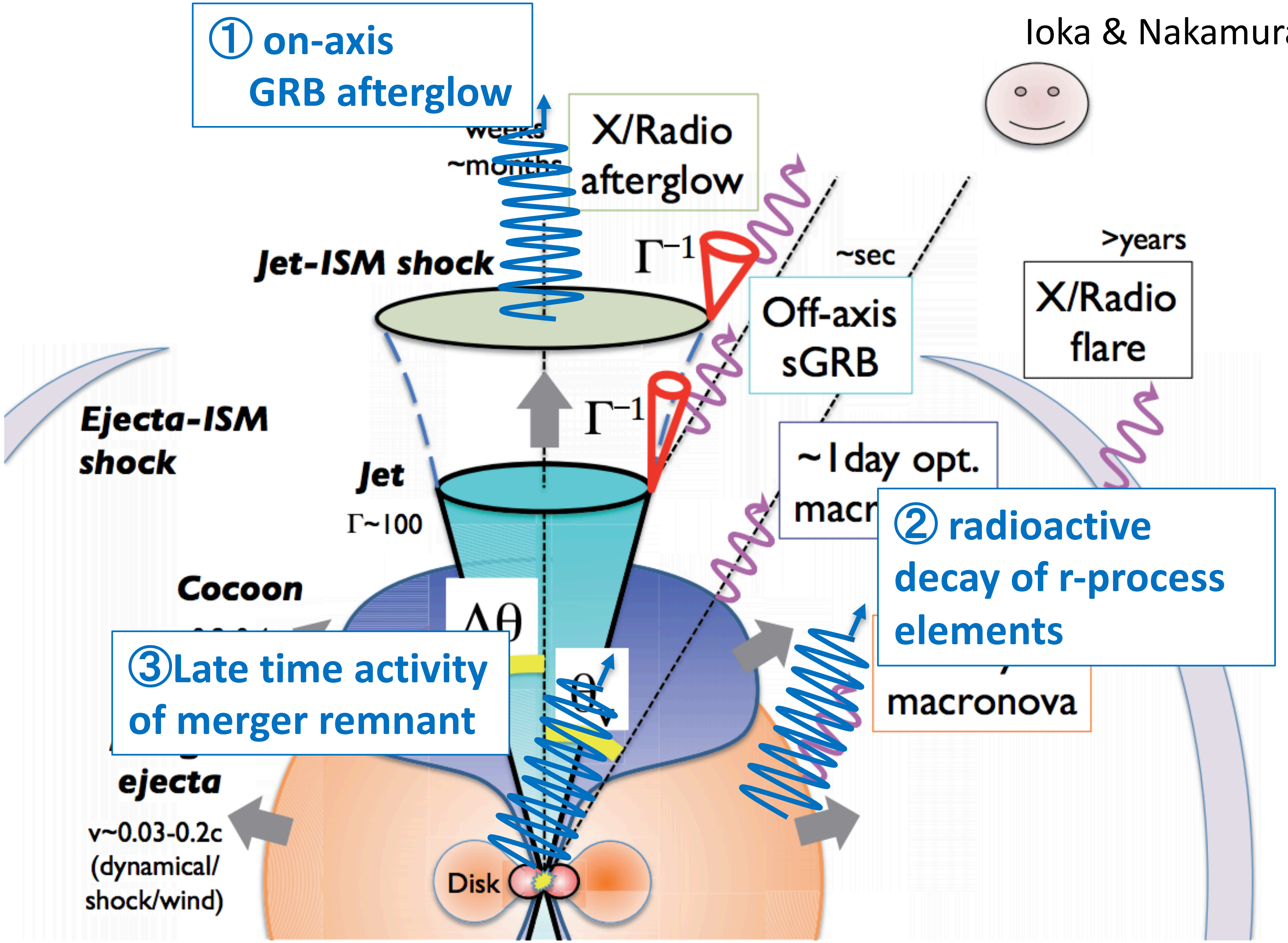
- Improved sensitivity in soft/hard X-ray band
- Continuous monitoring in gamma-ray band
- High-resolution spectroscopy

Science Case: NS-NS merger

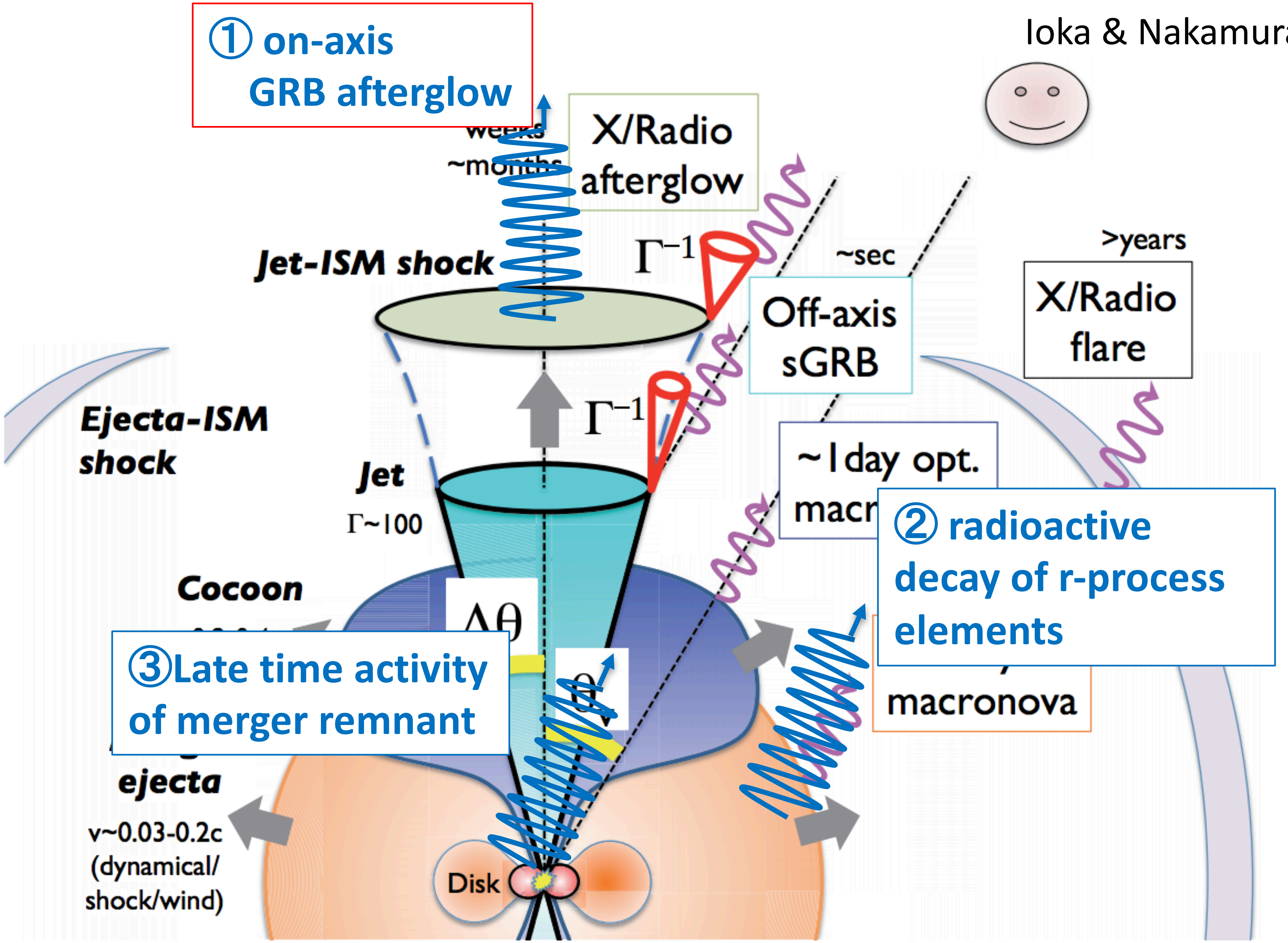
Ioka & Nakamura+17



Science Case: NS-NS merger



Science Case: NS-NS merger



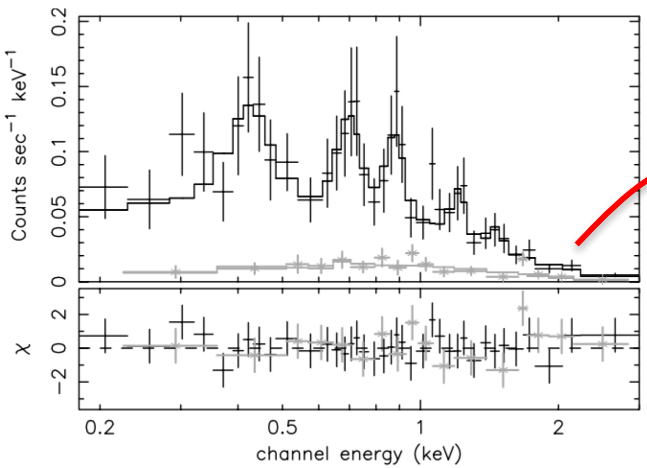
① On-axis GRB afterglow

- **Quick follow-up observation (<1-day) of GW event may detect a nominal X-ray afterglow**

➔ Strong evidence for association of short GRB and compact merger

- **…+ spectral feature by high resolution spectroscopy reveal circumstellar environment (XARM-resolve, ATHENA)**
- **Only expected from SN but NS-NS merger (3rd GW telescopes) ??**

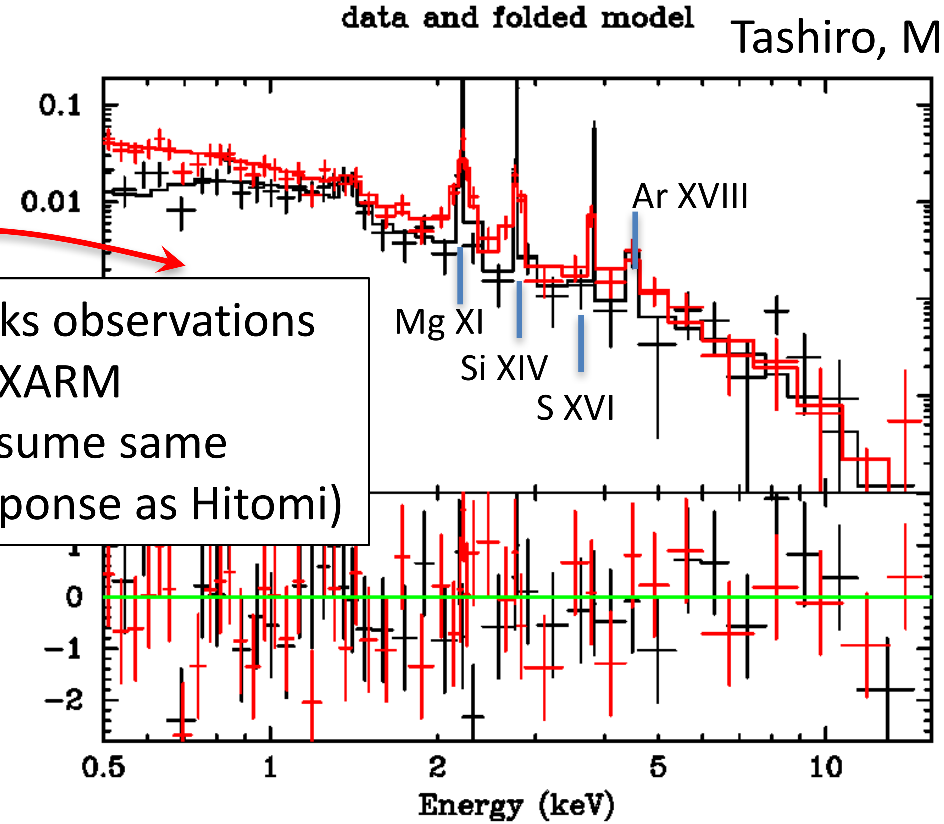
Modified from Tashiro, MO+14



Reeves+04 reported soft X-ray lines From GRB011211 in XMM-Newton Spectrum

F(2-10 keV)~10^{-12} erg s^{-1} cm^{-2}

20 ks observations by XARM (assume same response as Hitomi)



Expected event rate

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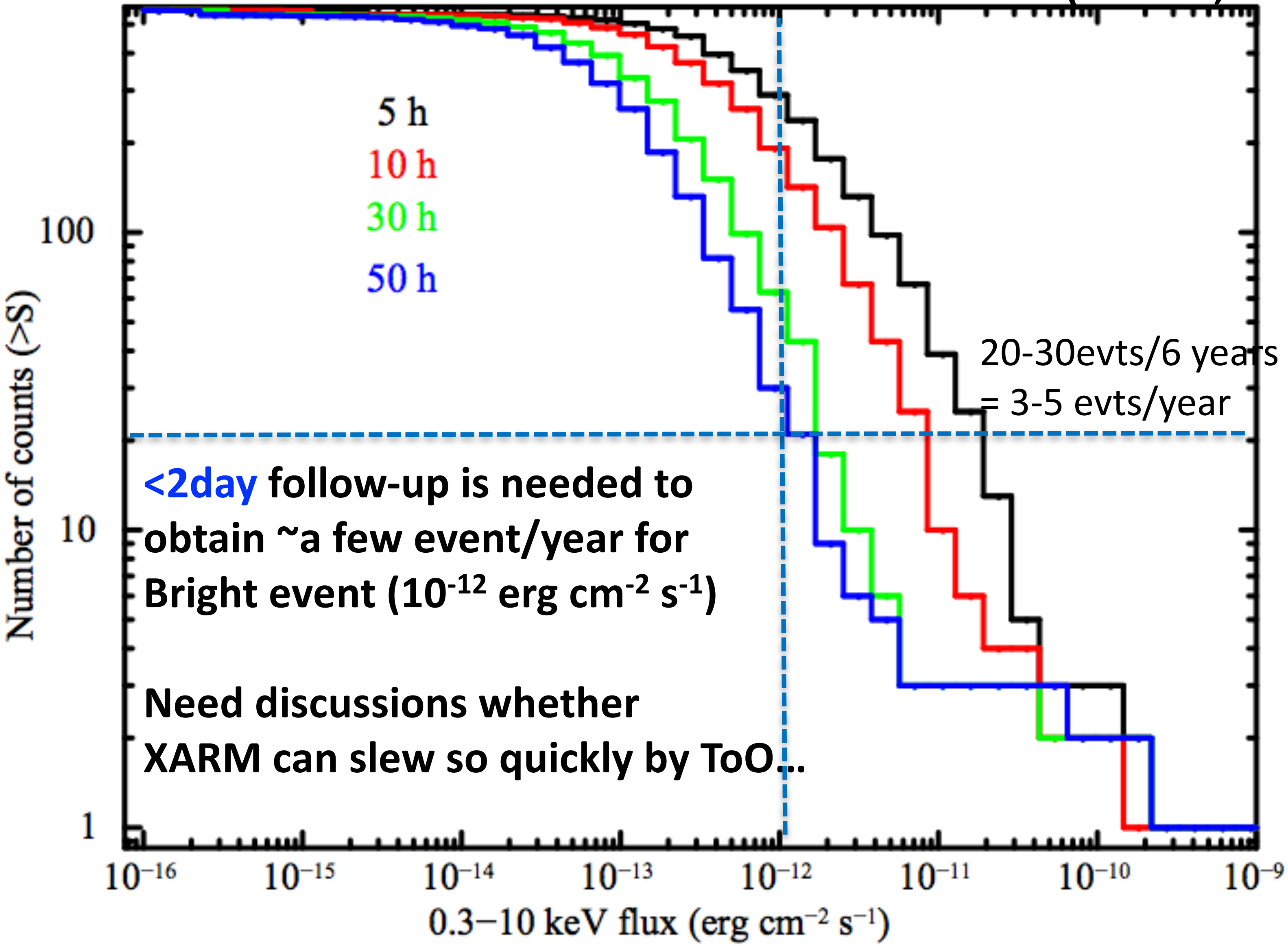
Using 6-years Swift-XRT data, expected event rate for each Flux level and observation start time is calculated (Tashiro, MO+14)



Science Case: NS-NS merger

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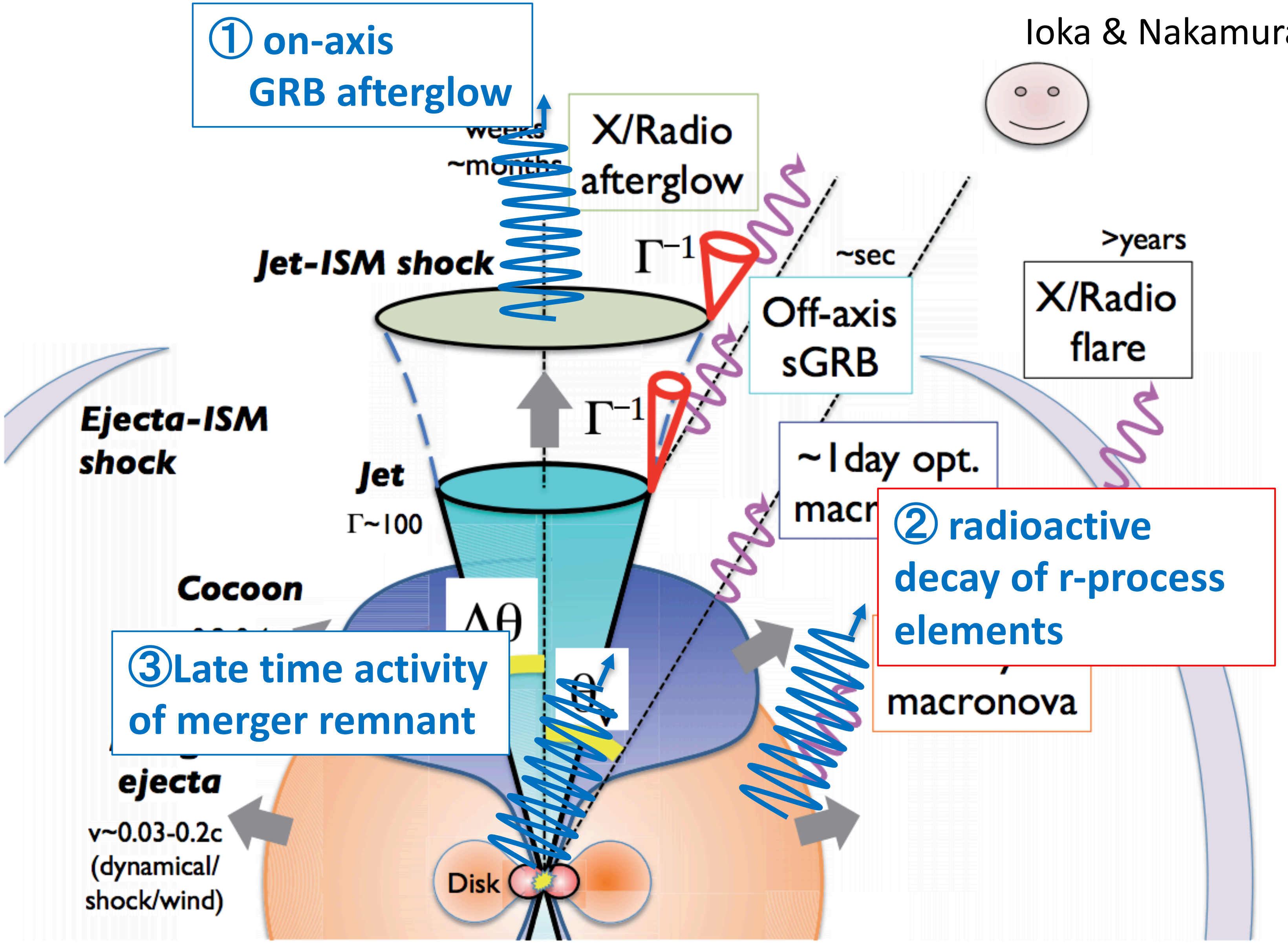
Ioka & Nakamura+17



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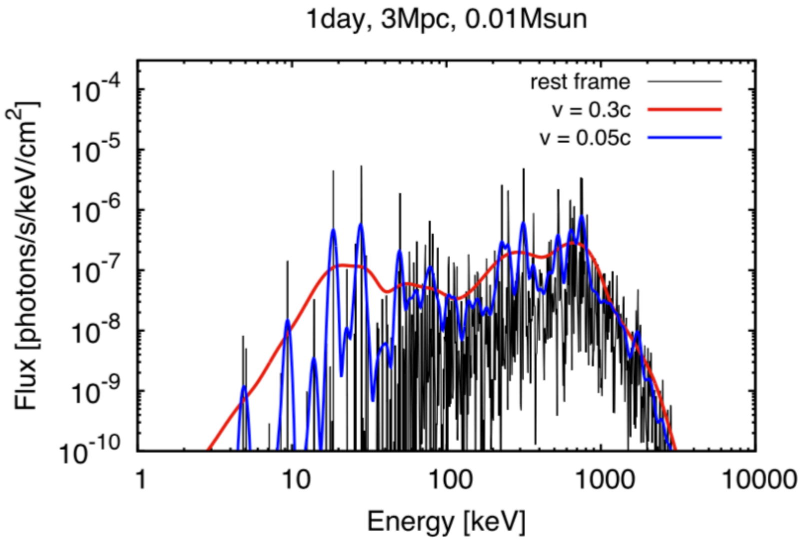
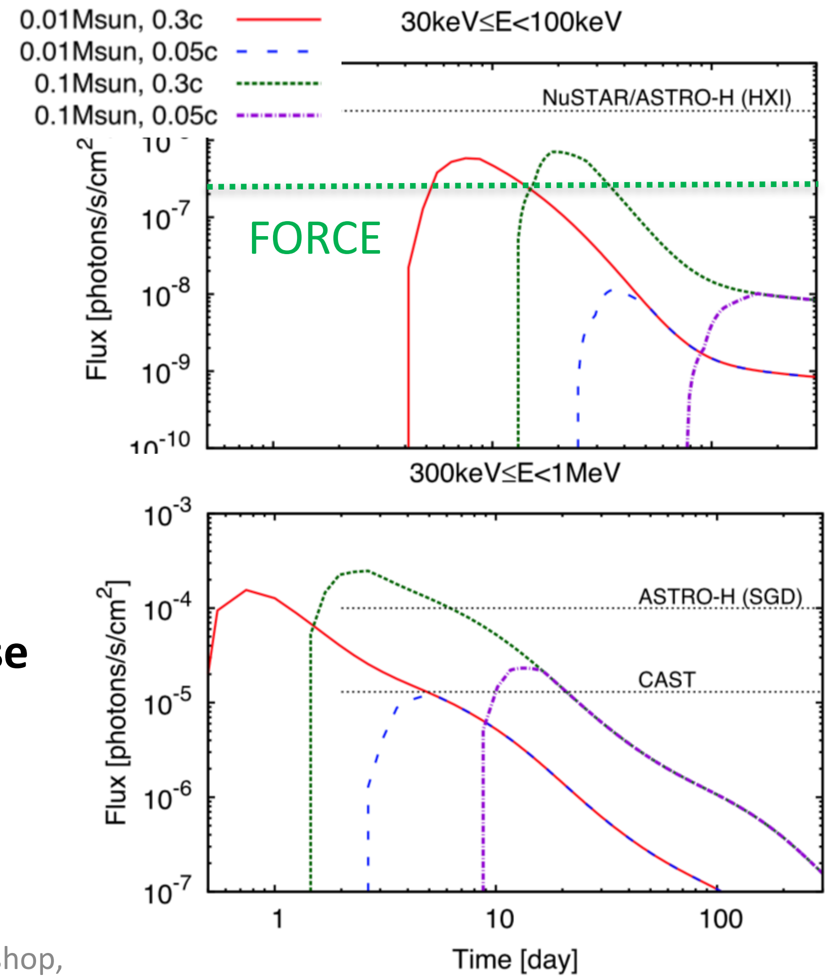
② gamma-rays from r-process elements

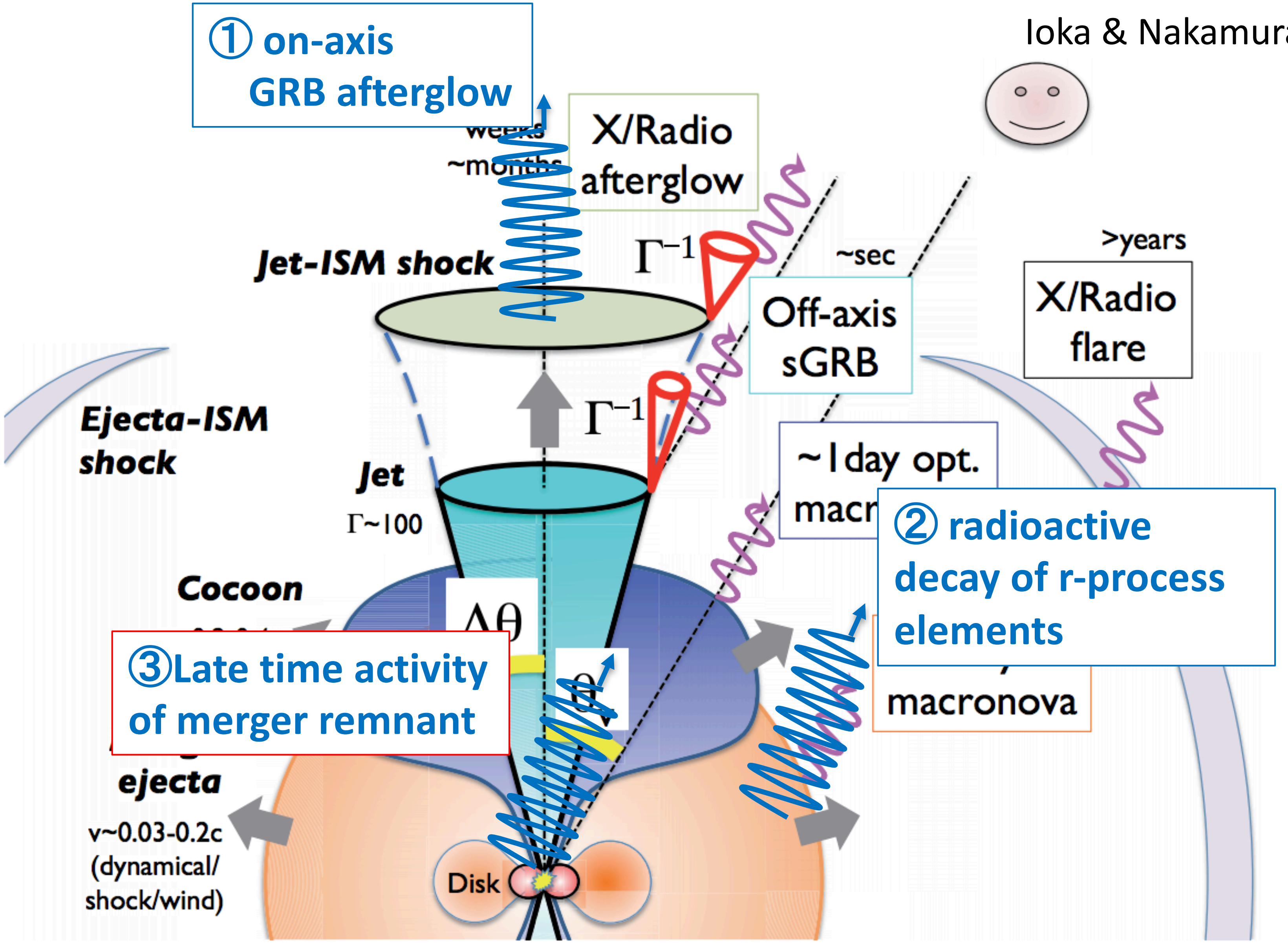
- Detection of gamma-ray due to specific lines can provide a evidence for the r-process (same case for the ^{56}Ni and ^{56}Co from Ia SN (Churazov+14., Terada+17 ..etc)) in hard X-ray and gamma-ray band ➔ NuSTAR, FORCE, PhoeNIX-SGD !
- Expected light curve and spectra are provided by Hotokezaka et al. 2016





- Any hope ? for >1day, 3Mpc, 0.01Msun case
- Dimmer by ~2 order of magnitude for GW170817 (40Mpc)
- Too challenging..

Science Case: NS-NS merger

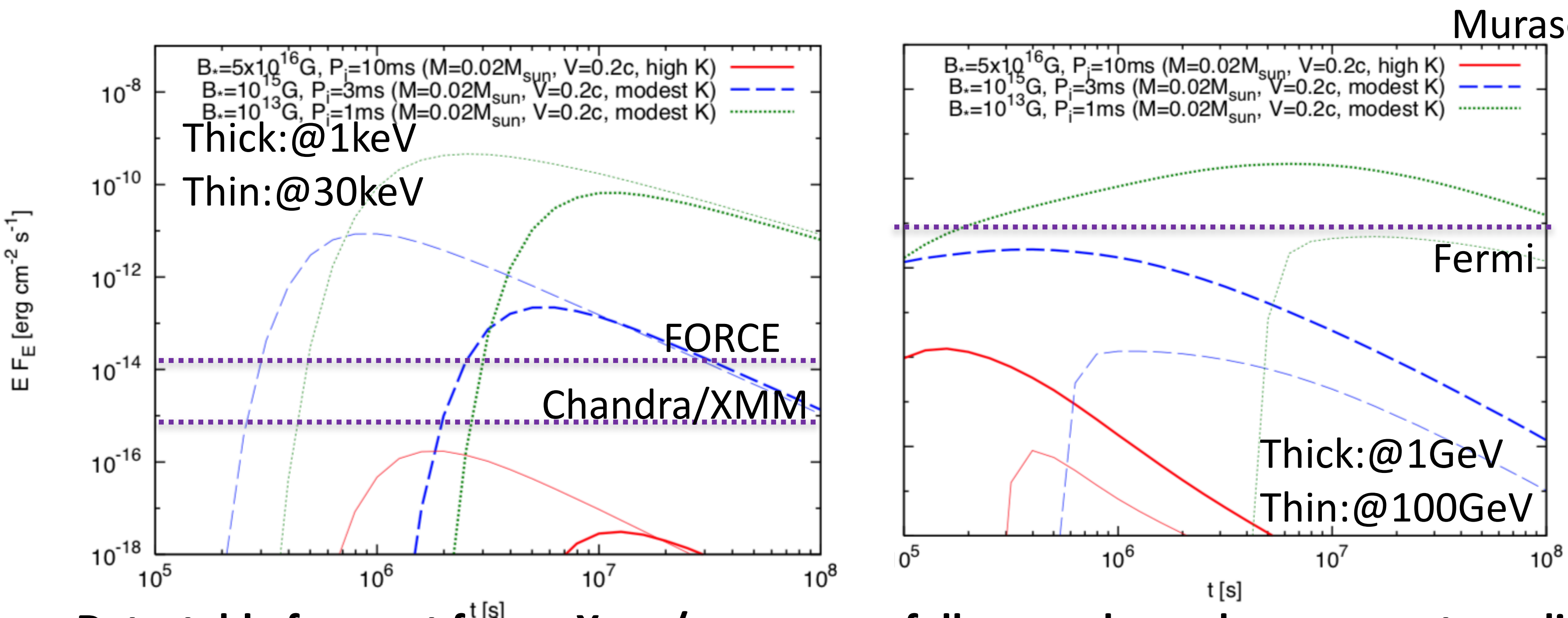


③ late time activity of merger remnant

- **The fate of the remnant depends on the EOS and total mass of NS-NS (massive NS ➔ BH (w/ disk), low-mass NS-NS ➔ long lived massive NS ?)**
- **Both cases, late time activity (BH disk emission, pulsar wind) could be expected**
- **Origin of extended emission of short GRB ?**

Expected Long-lived X-ray (left) and gamma-ray (right) light curve for pulsar case

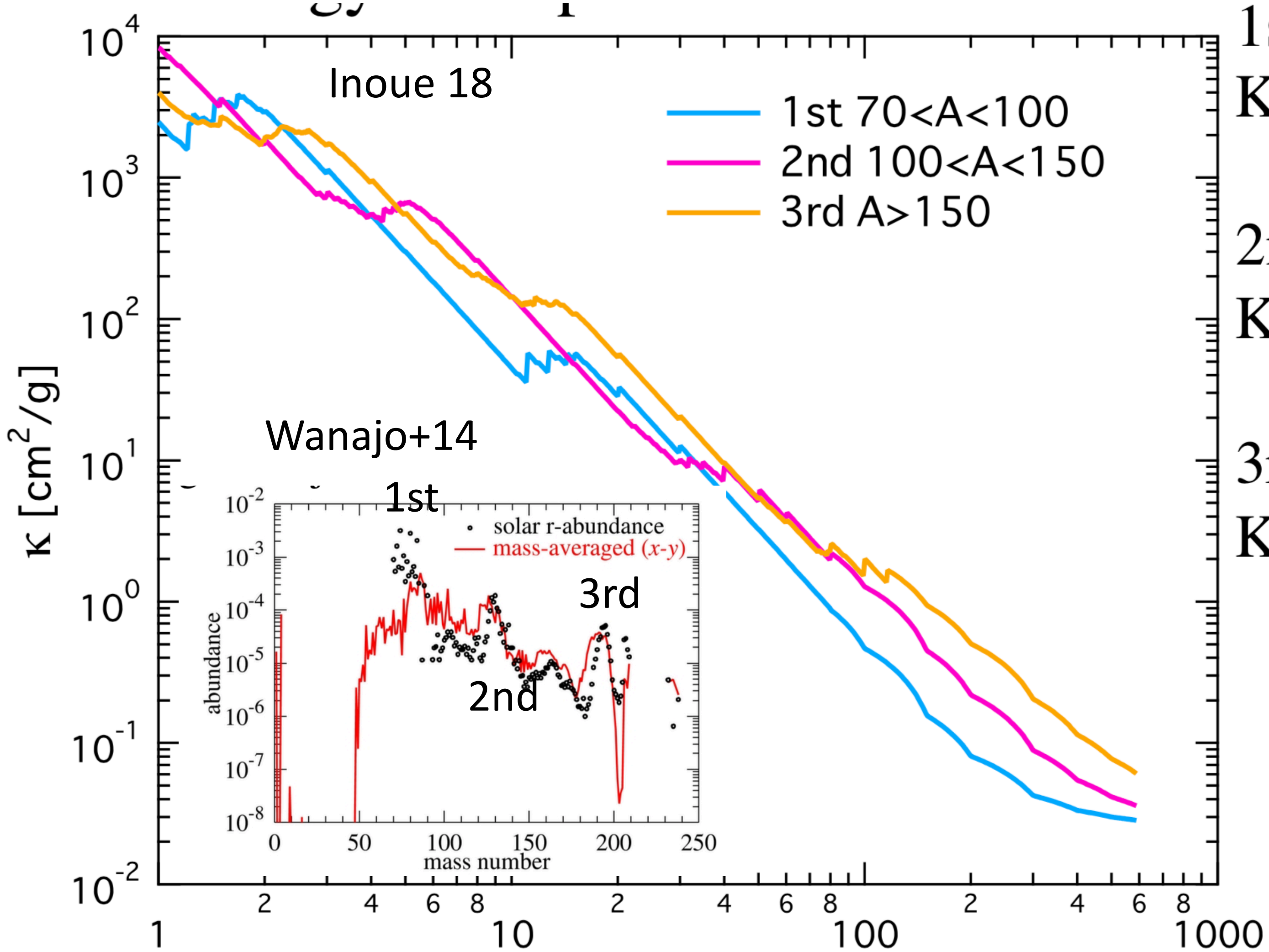
Murase+17



- **Detectable for most future X-ray/gamma-ray follow-up depend on remnant condition?**
- **But no detection is reported.**
- **Future monitoring is still valuable for detection/constraint on the remnant models**

③ late time activity of merger remnant

- **Late time X-ray emission may be illuminate the dynamical ejecta and absorbed by the r-process element ➔ spectral feature ?**



1st peak e.g. $^{80}Se^{34}$
K: 12.7keV, L: 1.66keV

2nd peak e.g. $^{127}I^{53}$
K: 33.2keV, L: 5.19keV

3rd peak e.g. $^{197}Au^{79}$
K: 80.7keV, L: 14.3keV

hard X-ray range
-> NuSTAR
FORCE
(XARM?)

③ late time activity of merger remnant

- **Late time X-ray emission may be illuminate the dynamical ejecta and absorbed by the r-process element ➔ spectral feature ?**

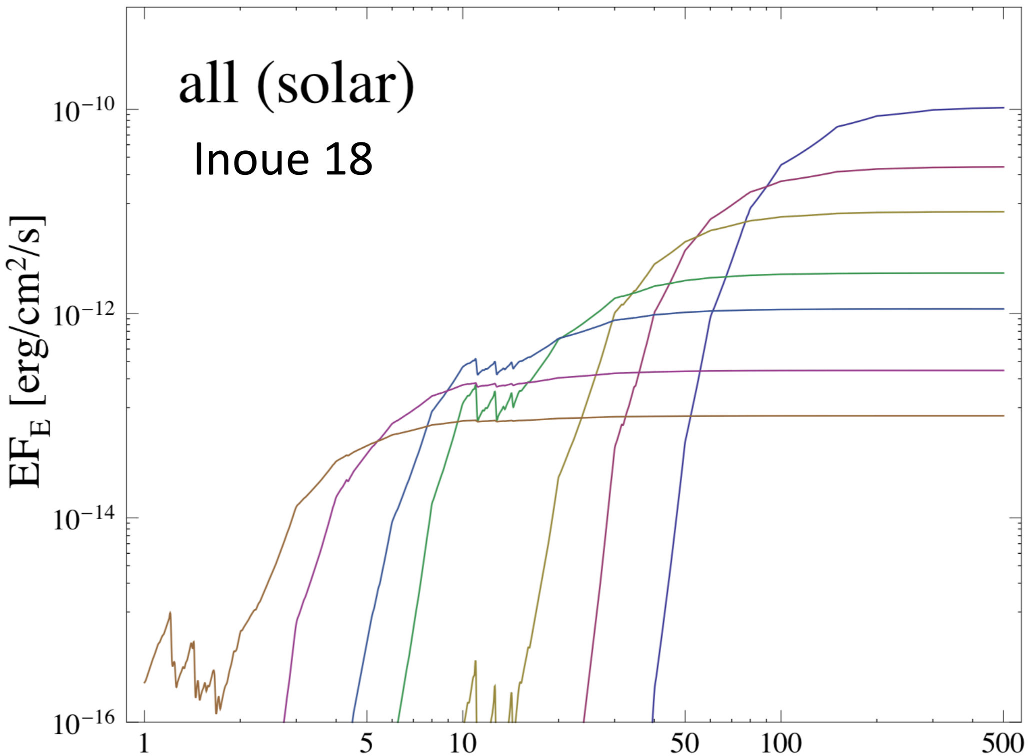
Shibata

unabsorbed spectra

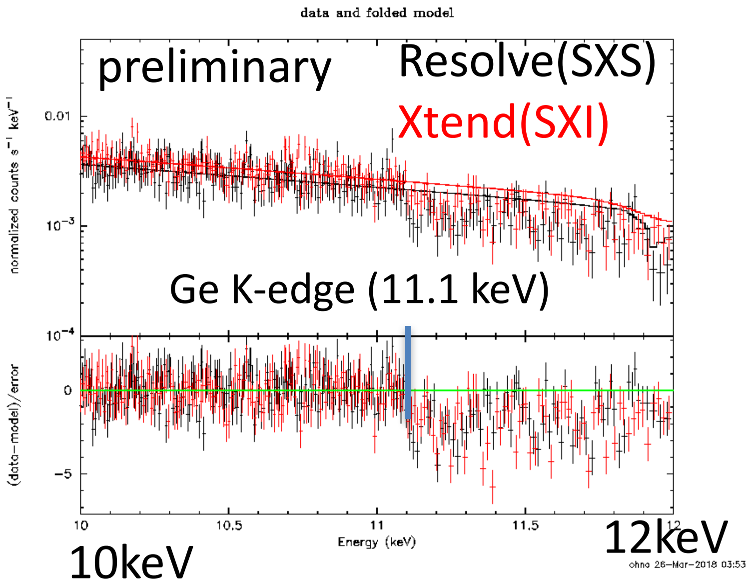
$EF_E = 10^{-9}$ erg/cm^2/s (E/10 keV)$^{-0}$ (t/10^{5}s)$^{-2}$

(similar to $B=10^{15}$G, P_0=3ms, D=40Mpc case of Murase+)

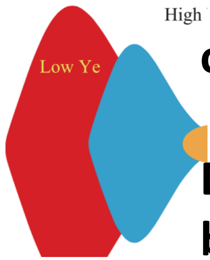
spherically symmetric, homologous expansion M=0.02 $M_\odot$, v=0.2c



XARM spectrum 1Ms@3x10^6 s



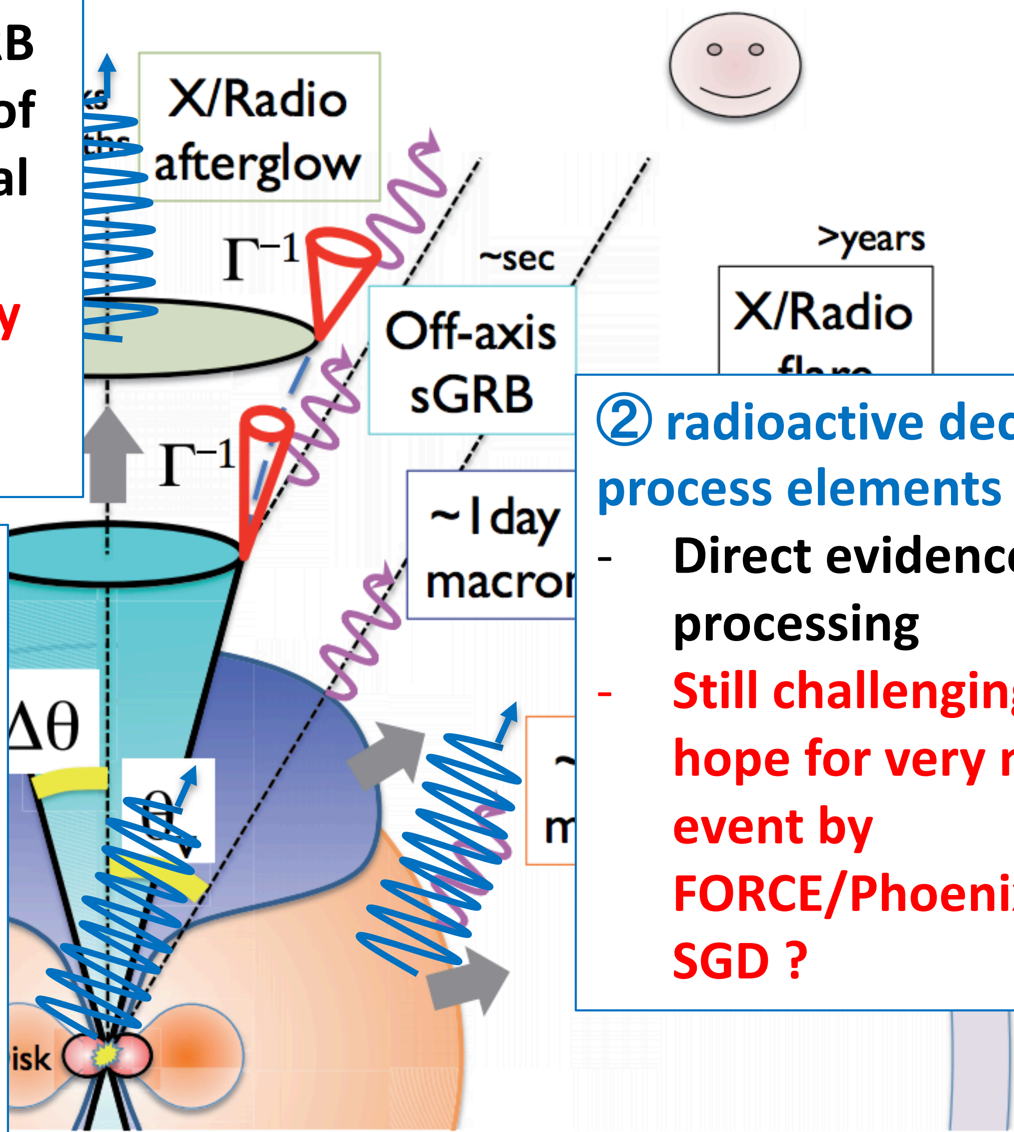
(PL index=1.0,
~3x10^{-13} erg s^{-1} cm^{-2}@10keV
optical depth of edge: 0.5)



Detectable ?, but XARM is not the best instrument ?
Fluorescence line ?

Science Case: NS-NS merger

Ioka & Nakamura+17



① on-axis GRB afterglow

- Evidence of short GRB association & study of environment material of NS-NS merger
- <1day observation by XARM may detect spectral features

② radioactive decay of r-process elements

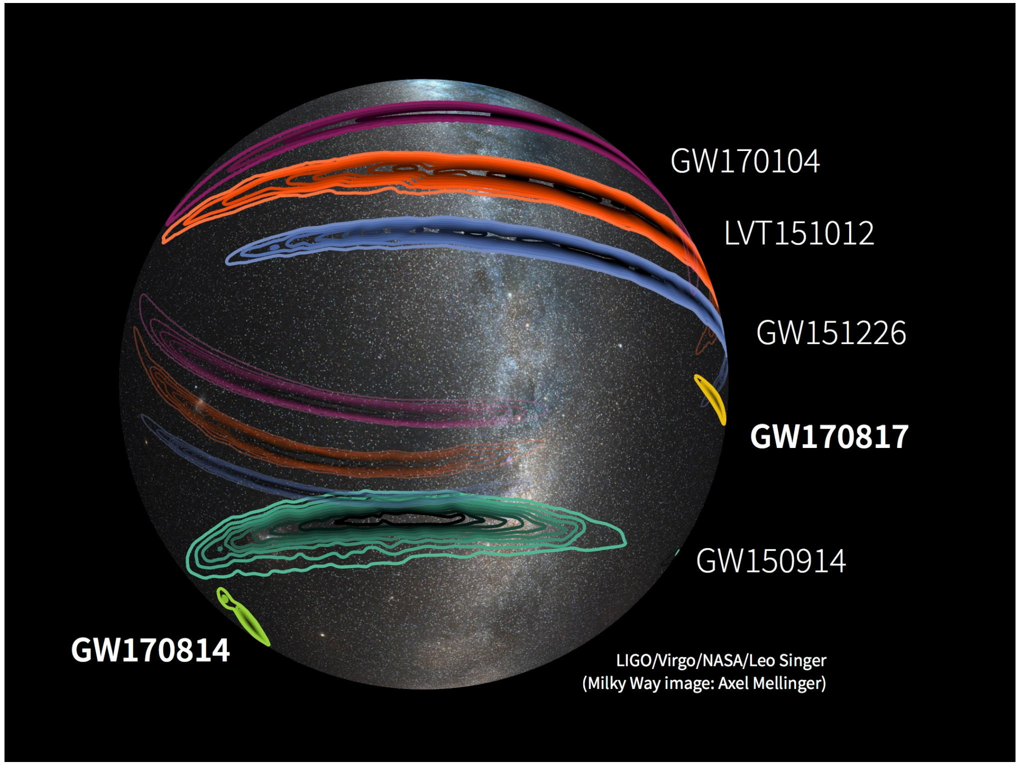
- Direct evidence of r-processing
- Still challenging.. Any hope for very nearby event by FORCE/Phoenix-SGD ?

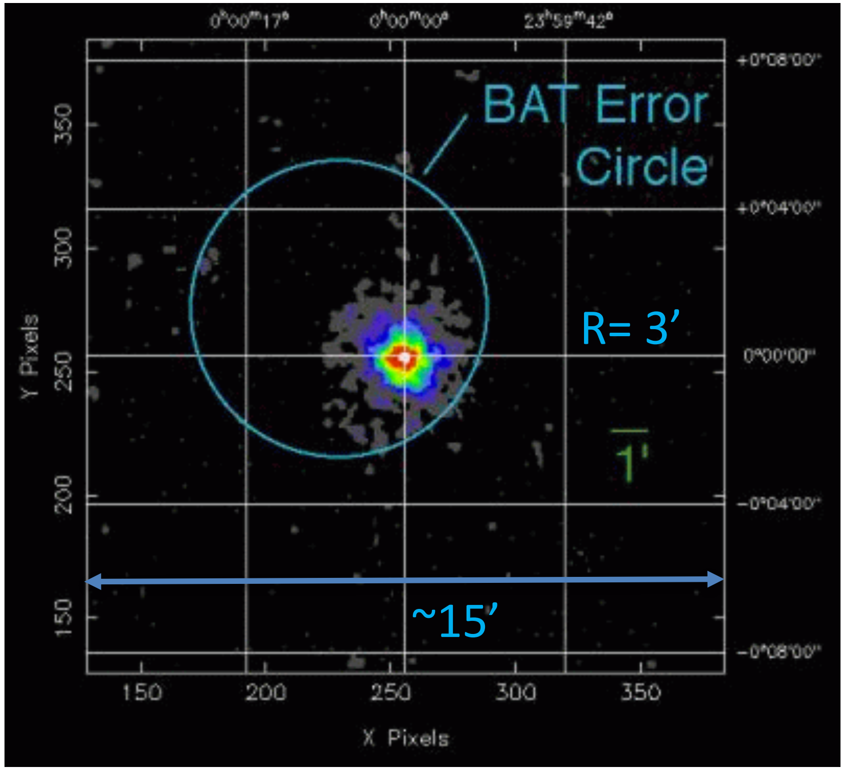
③Late time activity of merger remnant

- Evolution of the merger for its EOS/mass relation
- Bright X-ray/gamma-ray (+absorption feature) is expected depending on the remnant model

Localization is important..

- Localization error of GW telescopes is several tens of degree^2 and IceCube is also several degree^2
- Much larger than typical field of view of X-ray telescopes : ~30'x30' (and of course optical telescopes)
- Localization by all-sky gamma-ray instruments is important at least within ~10' and hopefully ~1' !





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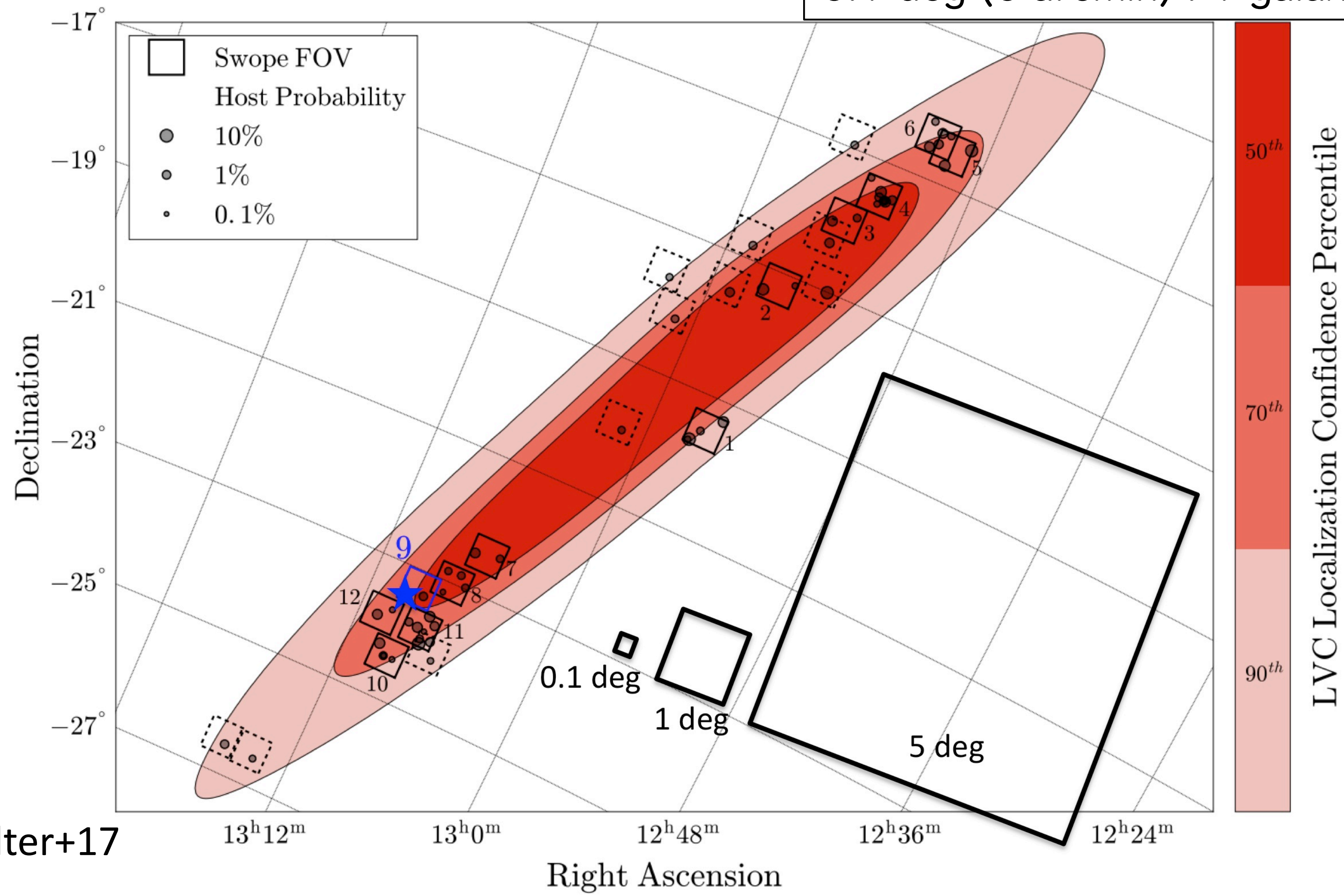
Localization is important..

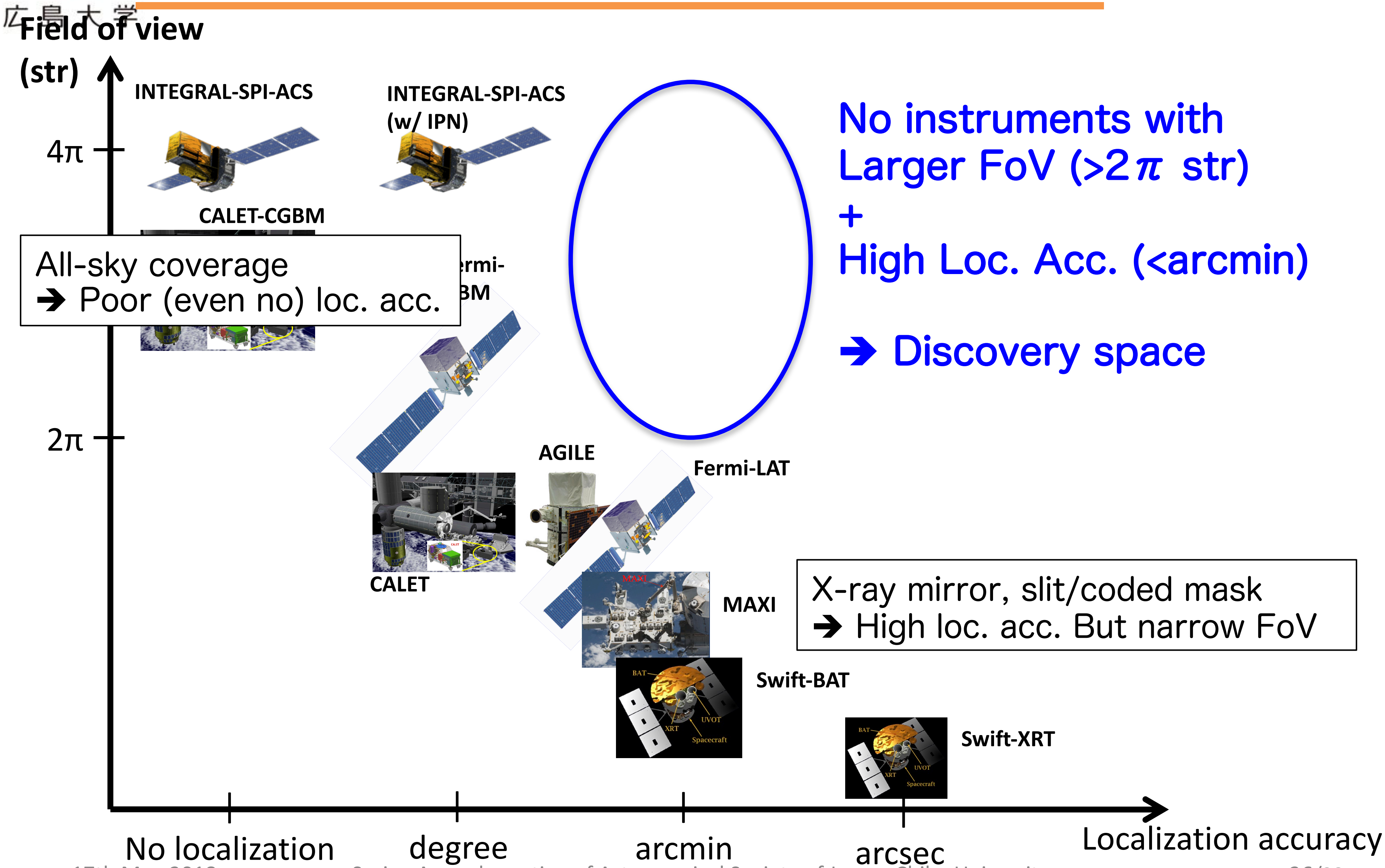
Case for GW170817

5 deg : ~30 galaxies 😿
0.1 deg (6 arcmin) : 1 galaxy ! 😺



Caulter+17

What do we need ?



Solution1: position sensitive detector w/ moderate FoV

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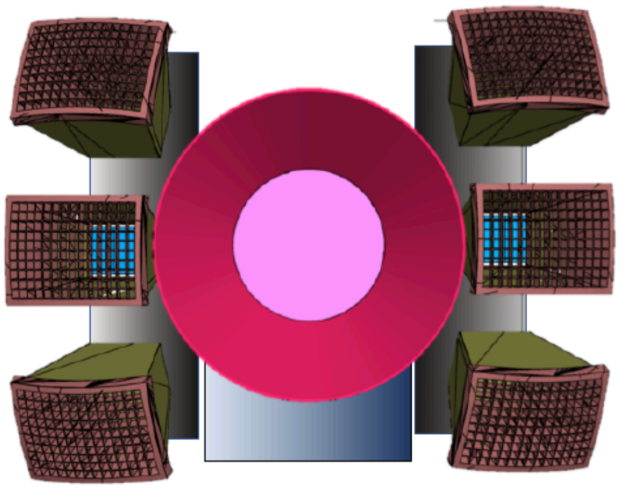
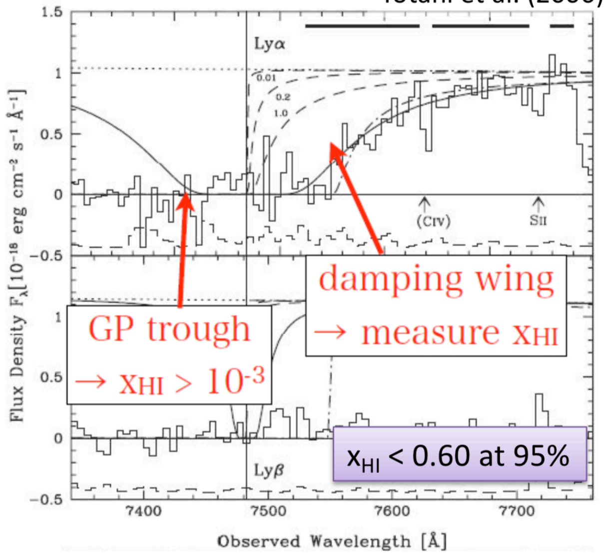
High-z Gamma-ray bursts for Unraveling the Dark Ages Mission (Hiz-GUNDAM)



GRB 050904 @ z = 6.295

Kawai et al. (2006)
Totani et al. (2006)



- **High sensitive prompt emission observation and localization of high-z GRB in X-ray band**
- **Self follow-up observations of afterglow in NIR band to detect Lyman-α dumping wing**

+ Promotion of MM (GW) astronomy !

Configuration of the wide field X-ray monitor

Energy band (keV)	0.5 – 4 keV
Telescope type:	Lobster Eye Optics
Optics aperture	240 x 320 mm^2
Optics configuration	6 x 8
Size of Lobster Eye optics	40 x 40 mm^2
Focal length	300 mm
Focal plane shape	spherical
Focal plane detectors	CMOS array
Size of Focal detector	120 x 160 mm^2
Number of CMOS	24 (4 CMOS x 6 units)
Pixel size	20 – 50 μm
Pixel Number	6000 x 8000 for 20 μm 2400 x 3200 for 50 μm
Field of View	~ 0.2 str
Angular accuracy	~ 60 arcsec

Solution1: position sensitive detector w/ moderate FoV

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Kanazawa-SAT^3 : Micro-satellite for alert the position and timing of X-ray transient

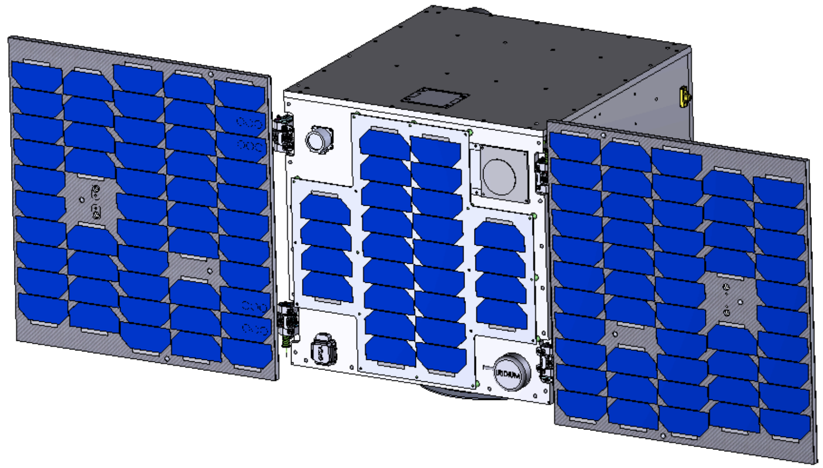
Launch target FY2019

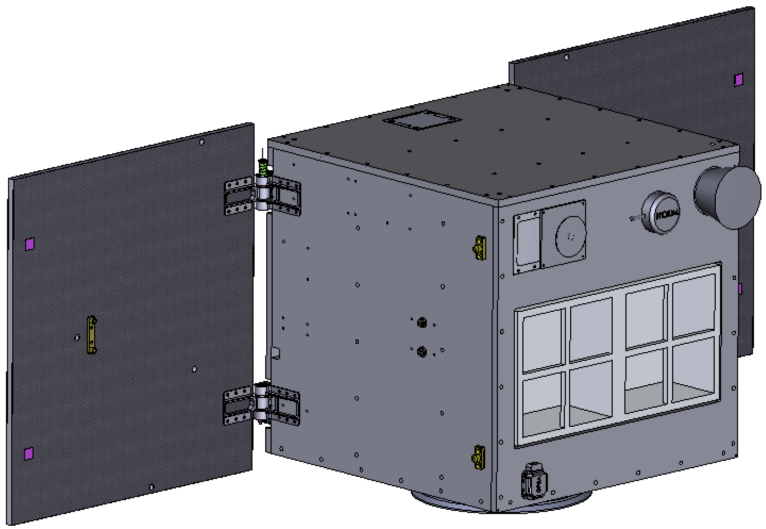
Satellite size 50 kg, 50 cm^3

Science instrument

X-ray imaging detector（T-LEX）
Coded mask + Silicon-strip detector
2 – 20 keV, 15arcmin, 1 sr, 100 cm^2

Gamma-ray Detector（KGD）
CsI(Tl)scintillator
20 – 200 keV, 3 sr, 50 cm^2





Solution2: fleet of nano-satellite w/ triangulation

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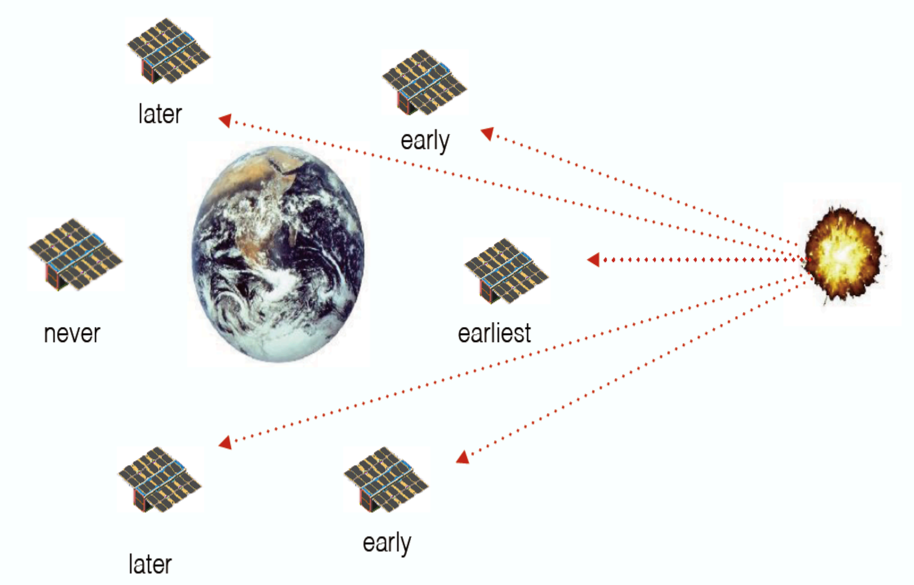
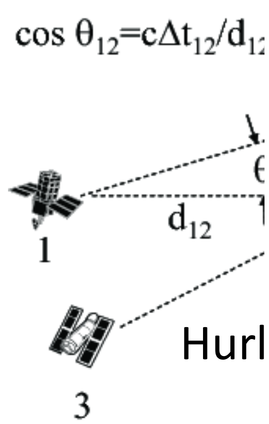
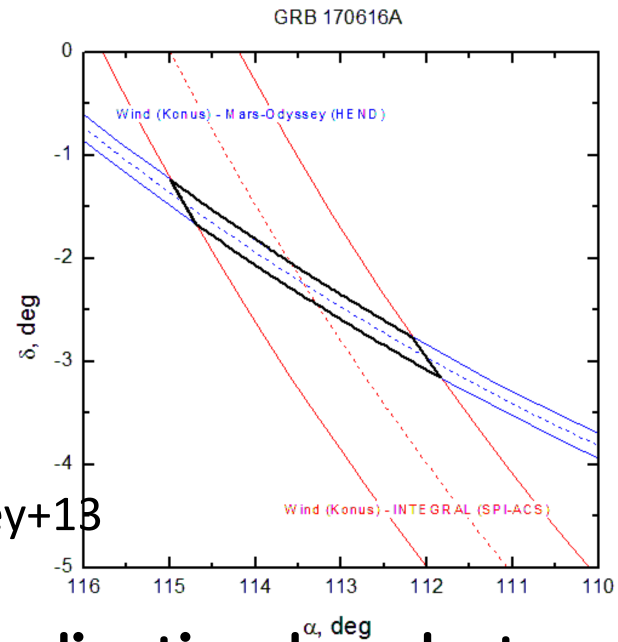




Hurley+13



us

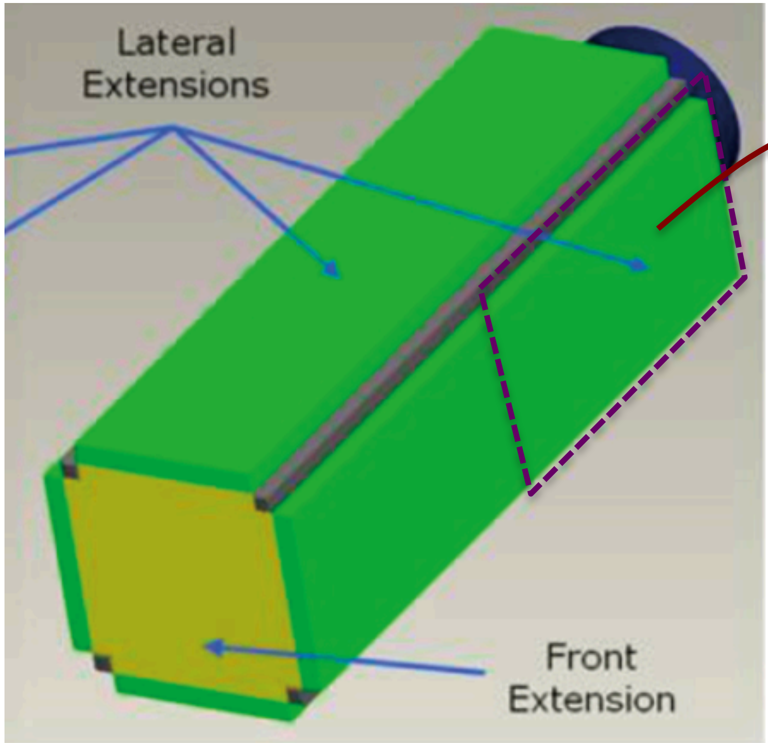
- **dozen satellite constellation**
  ➔ all-sky coverage
  (no earth shadow)
  huge effective area

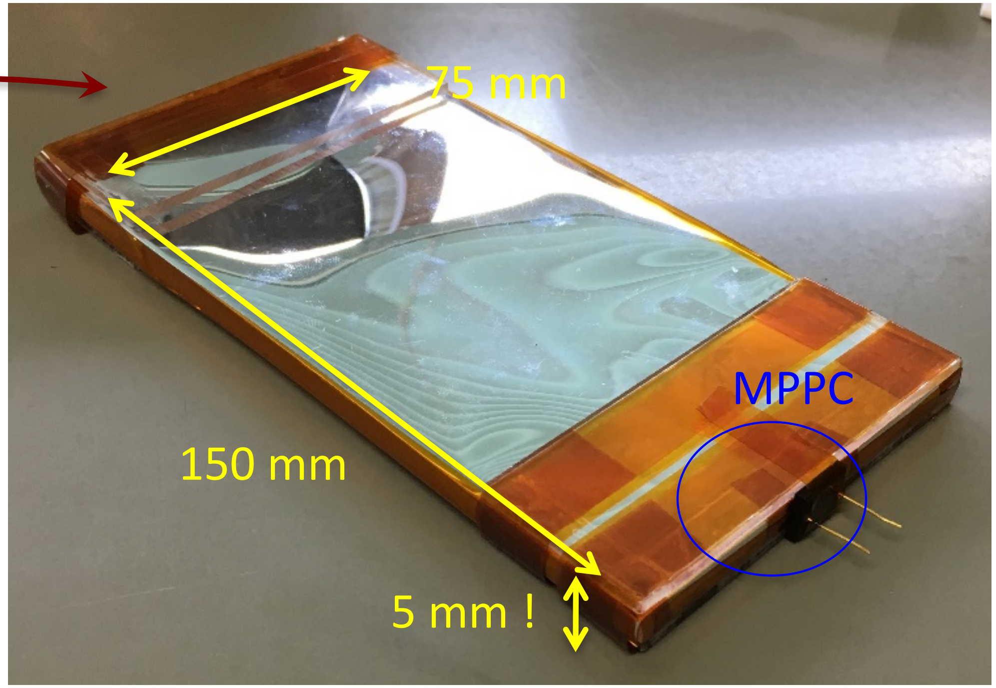
- **localization by photon arrival time**

High timing synchronization by
➔ μ-sec timing accuracy
results several arcmin localization accuracy ?

GRBCube : Japanese/Hungarian collaboration project

Detector Design

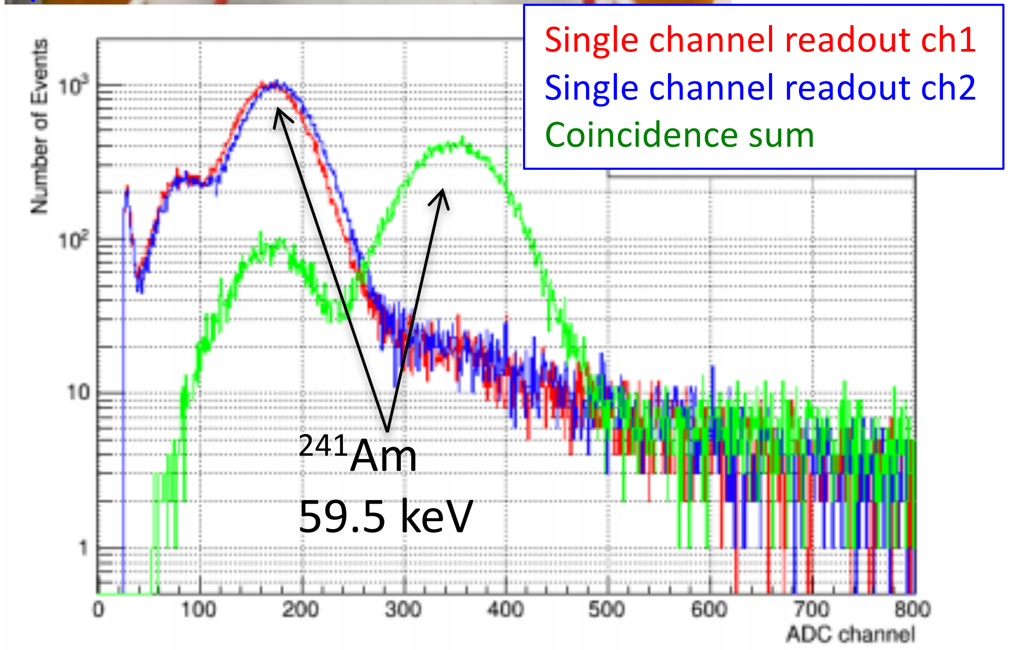


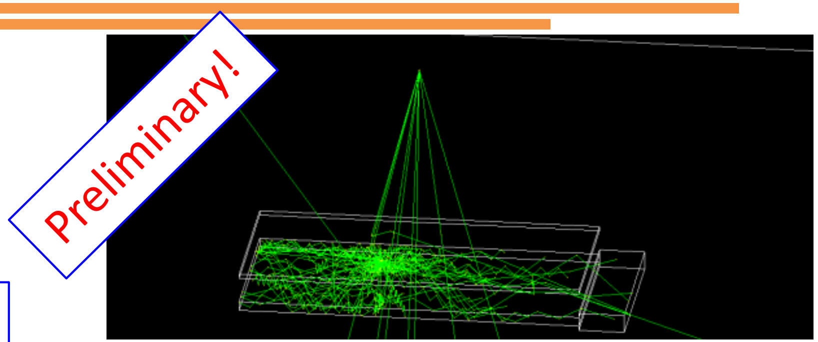


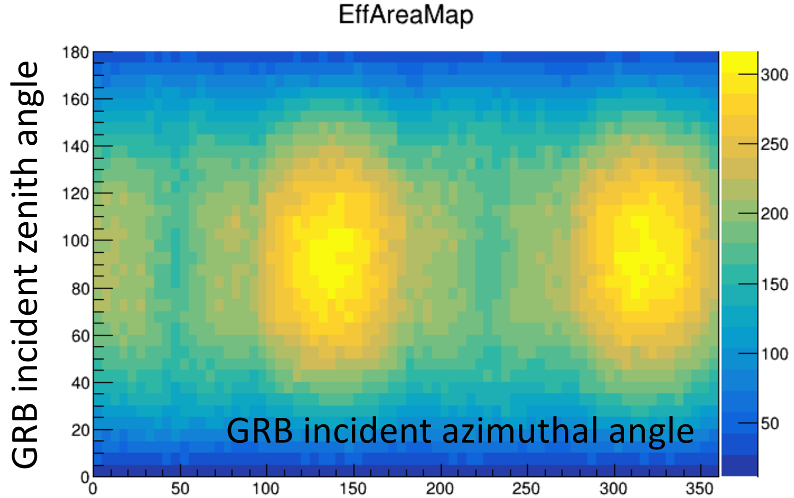
- one side of lateral extension (+inside) :
 ~268 cm^2 x 9mmt (+~80 cm^2)
 basic idea to maximize geometrical area
- challenging for such "large and thin" detector with small readout area

CsI scintillator readout by multi pixel photon counter (MPPC) is now being evaluated as the first feasibility study for their large light yield, compact readout area and low operational high voltage.

Spectral feasibility



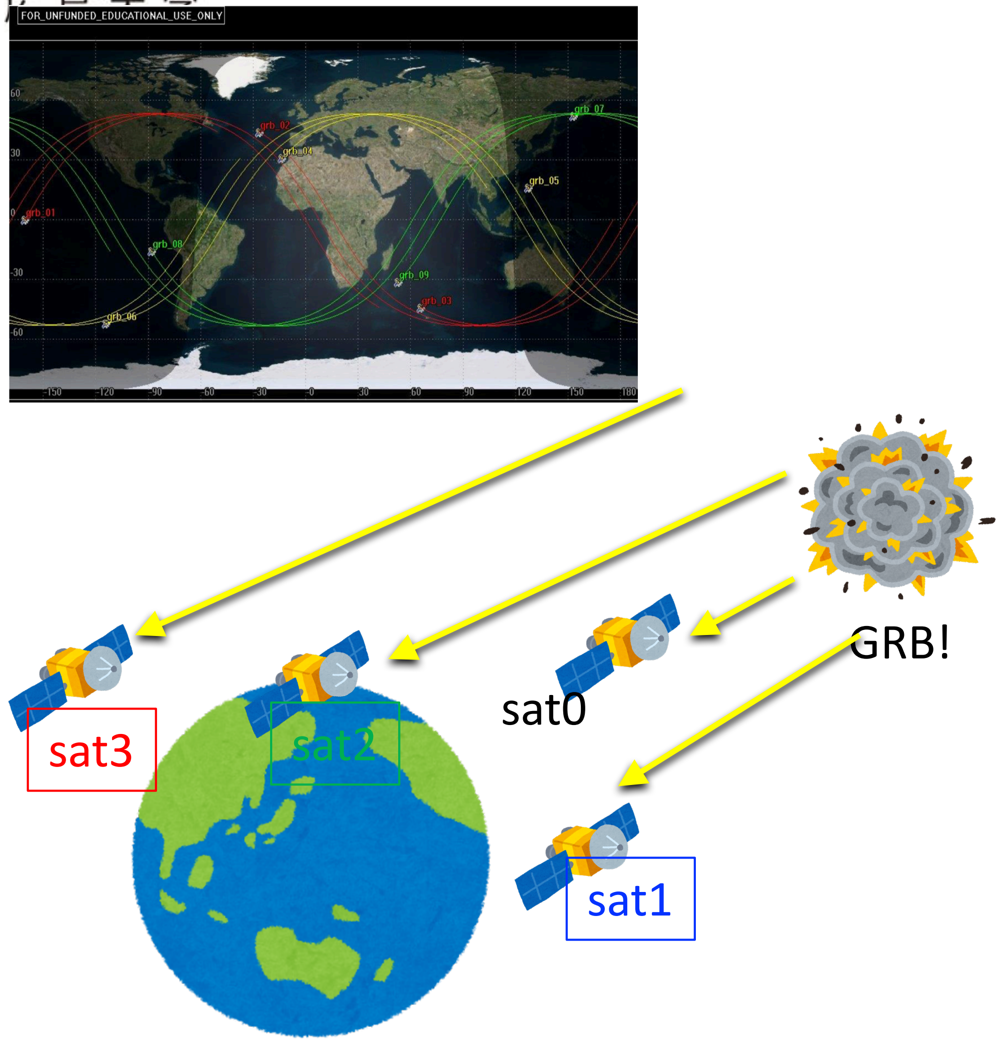


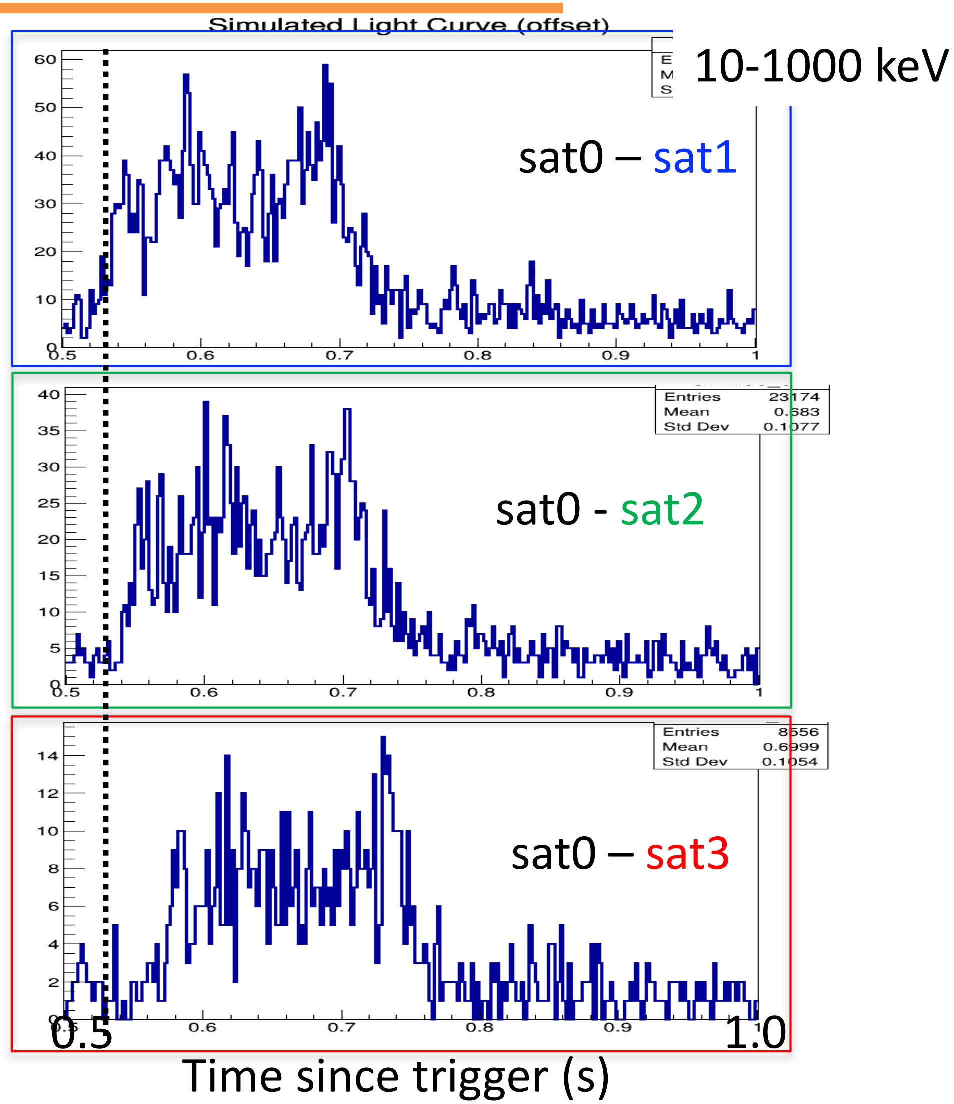


Energy threshold of ~10 keV is achieved for both single/multi channel readout (comparable to Fermi/GBM)
Energy range: 10-1000 keV (TBD)

Effective area for any incident angle is estimated by the Monte-Carlo simulation. 200~300 cm² is comparable/better than Fermi-GBM. This result is input to localization simulation

Localization simulation



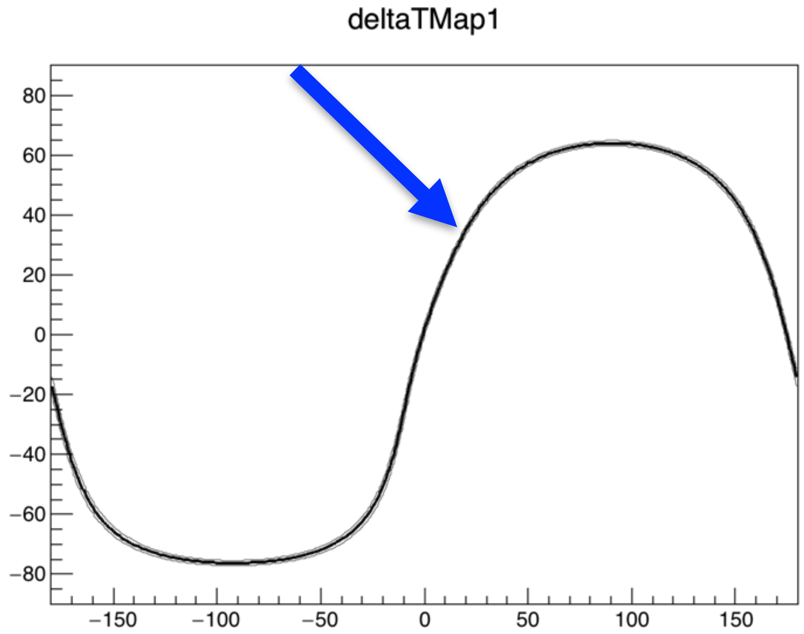


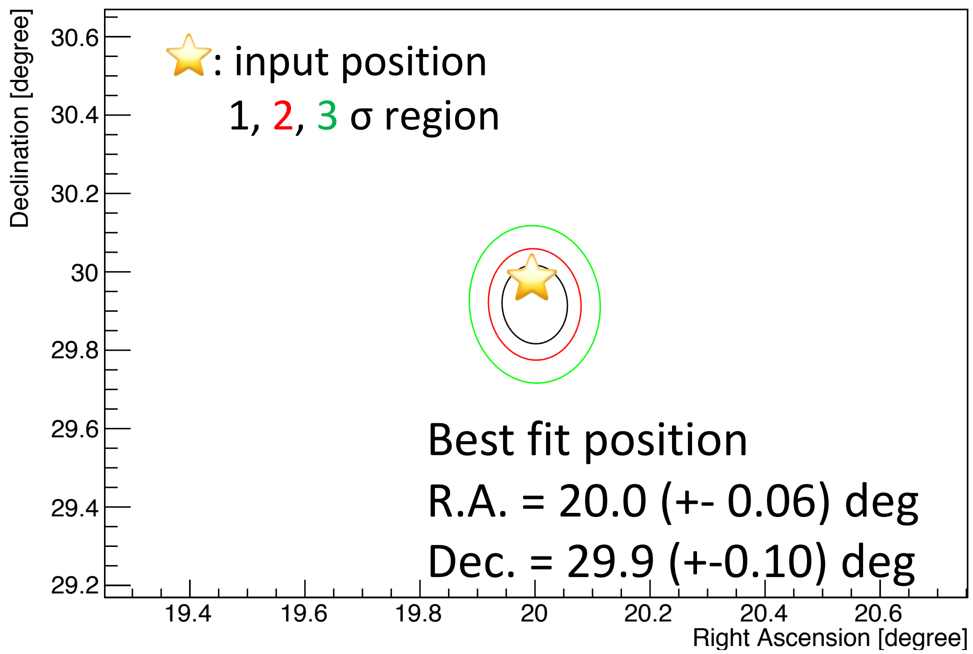
Satellite attitude, GRB position, predicted photon arrival time is estimated.

Simulated photon arrival time is estimated by the cross correlation analysis

Localization !

Intersection of annuli
➔ GRB position !





$$\chi^2 \equiv \sum_{i=0}^{N} \frac{\left\{\delta t_{\mathrm{sim,i}} - \mathrm{Norm} \times \cos\theta_{\mathrm{model,i}}(\mathrm{R.A.}, \mathrm{Dec.}) \times \mathrm{D/c}\right\}^2}{\sigma^2_{\mathrm{sim,i}}},$$

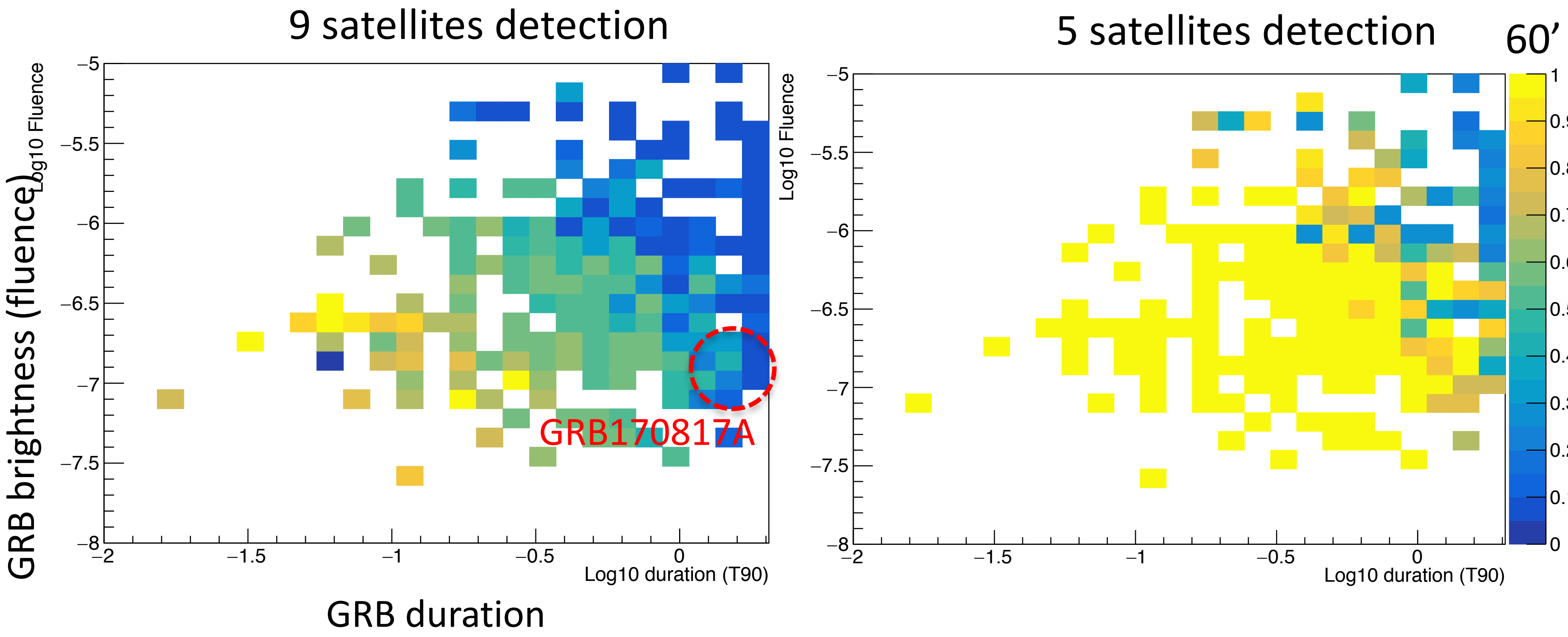
Mathematical approach is needed

GRB position and error is estimated by simple χ^2 minimization (Tanaka et al. 2017)

~0.1 $\mathrm{deg}_{1\sigma}$ (~10 arcmin) accuracy is achievable for bright/high-visibility case

Systematic analysis for Fermi-GBM short GRB

Localization accuracy of our concept is examined for all short GRBs listed in Fermi 3rd GRB Catalog (Bhar+16 T_{90}<2s: 326 samples)



- High localization accuracy for good photon statistics (brighter/longer)
- 5-10 arcmin accuracy for a good condition

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Event rate and localization

Sat. num.	Visibility prob.	Number ratio of Fermi sGRB for each localization accuracy		
		<10’	<15’	<20’
9	1.8%	27%	30%	37%
8	7.6%	26%	29%	33%
7	16%	5%	14%	19%
6	26%	2%	8%	13%
5	25%	1%	3%	8%
4	15%	1%	1%	1%

~12 % of Fermi-GBM sGRB: <20’ localization accuracy
Fermi GBM sGRB rate: 336 sGRBs/6 years ~ 60 sGRBs/year
➔ ~10 sGRBs/year for <20’ localization accuracy with our GRBCube concept ! (0.5-1° for GRB170817A..)

Towards a Network of GRB Detecting SmallSats' !

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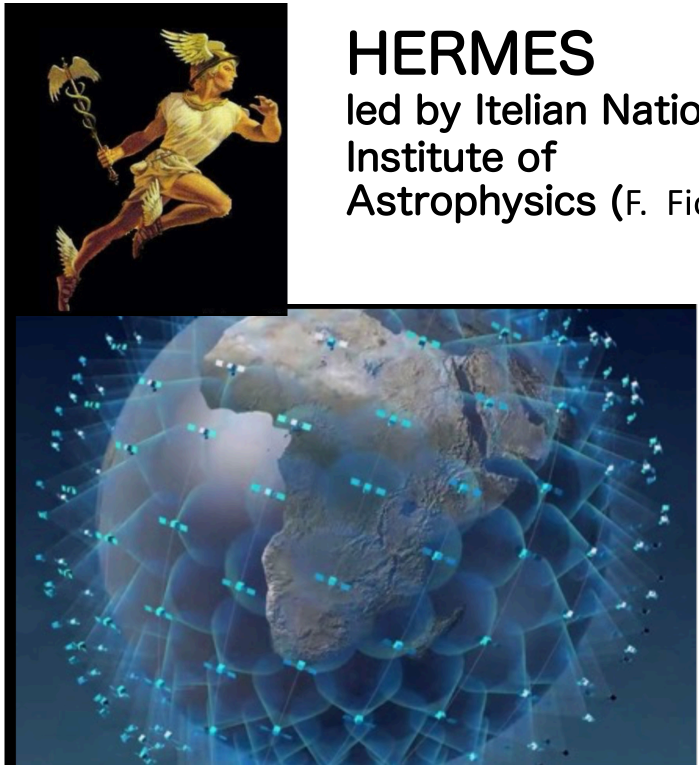
All-sky coverage with ~arcmin localization accuracy by the fleet of nano-satellite : similar ideas are rapidly growing in the world



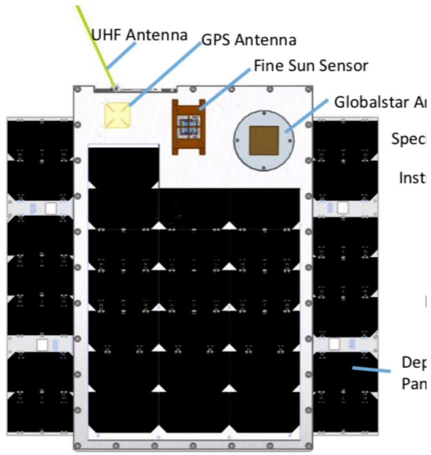
HERMES
led by Itelian National Institute of Astrophysics (F. Fiore)

- >100 of larger (6U) satellite ➔ arcsec accuracy !??
- Demonstration mission is approved

Tsinghua University to study Gamma-ray bursts by microsatellites

Xinhua | Updated: 2017-09-22 17:24

BEIJING -- China's Tsinghua University has unveiled a plan to launch 24 microsatellites between 2018 and 2023 to detect short Gamma-ray bursts and help the study of gravitational waves.

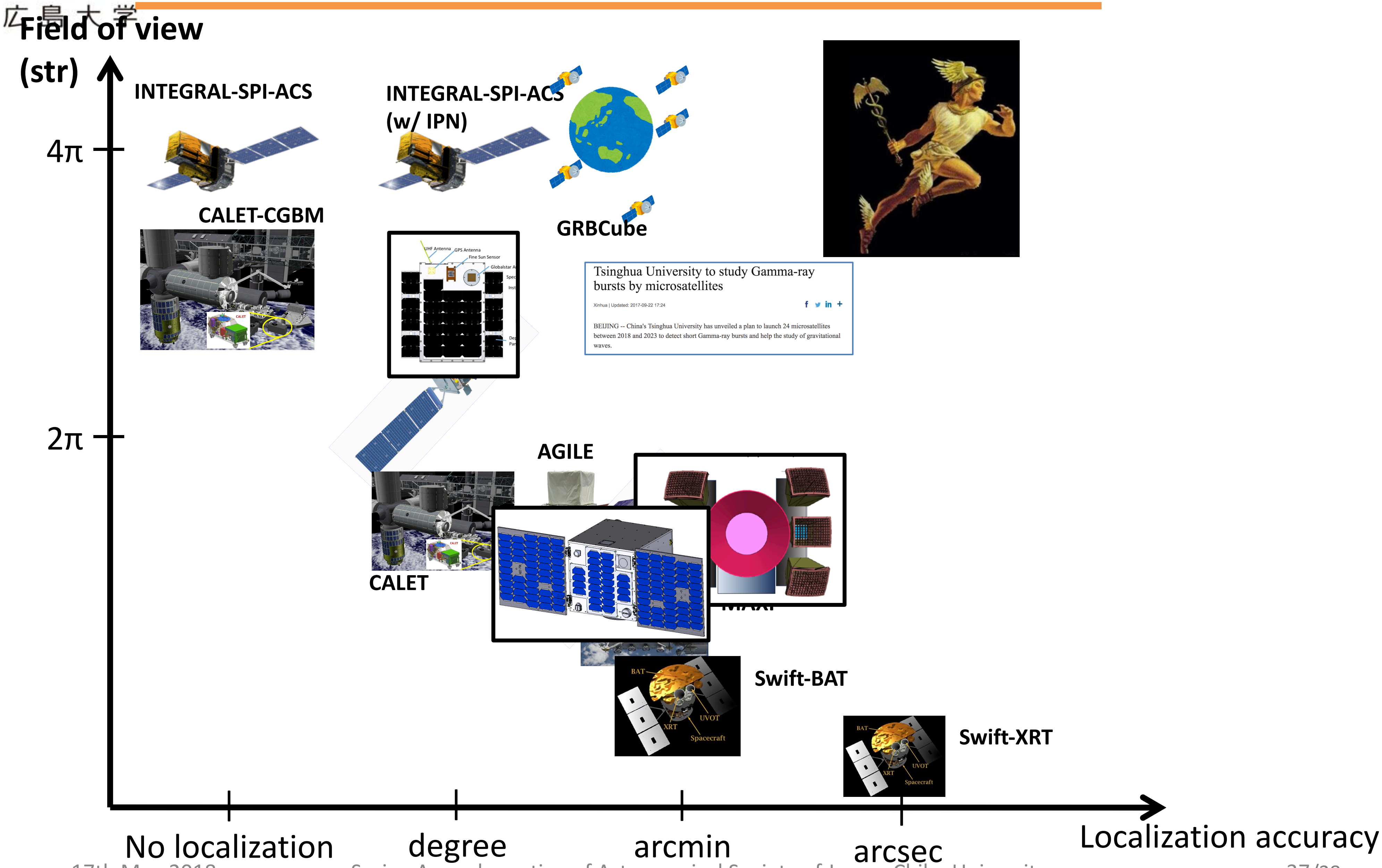


burstCube
led by NASA/GSFC (J. S. Perkins)

Single 6U cubesat with multiple CsI detectors
<7° localization accuracy (Racusin+17)

blackCat (U.S./Penn State), GECAM (China/CAS) .. Etc.

Future GRB follow-up



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Summary

- X-ray/Gamma-ray follow-up of MM transients is important for revealing the nature of their sources
- Future X-ray/Gamma-ray instruments such as XARM, FORCE.. etc. are expected to increase the sensitivity for searching spectral features and hard-Xray /gamma-ray emission from MM transients
- Some theoretical models can be tested or serendipitous discovery is always anticipated

Localization by gamma-ray observation is another key for future MM astronomy

- Many missions for GRB localization is proposing
- All-sky+arcmin localization is possible with fleet of nano-satellite
- Such world-wide network of GRB detection by small satellite probably becomes future main stream of GRB localization