Future* Space-Based Gamma-ray Observatories

Judy Racusin
NASA/GSFC

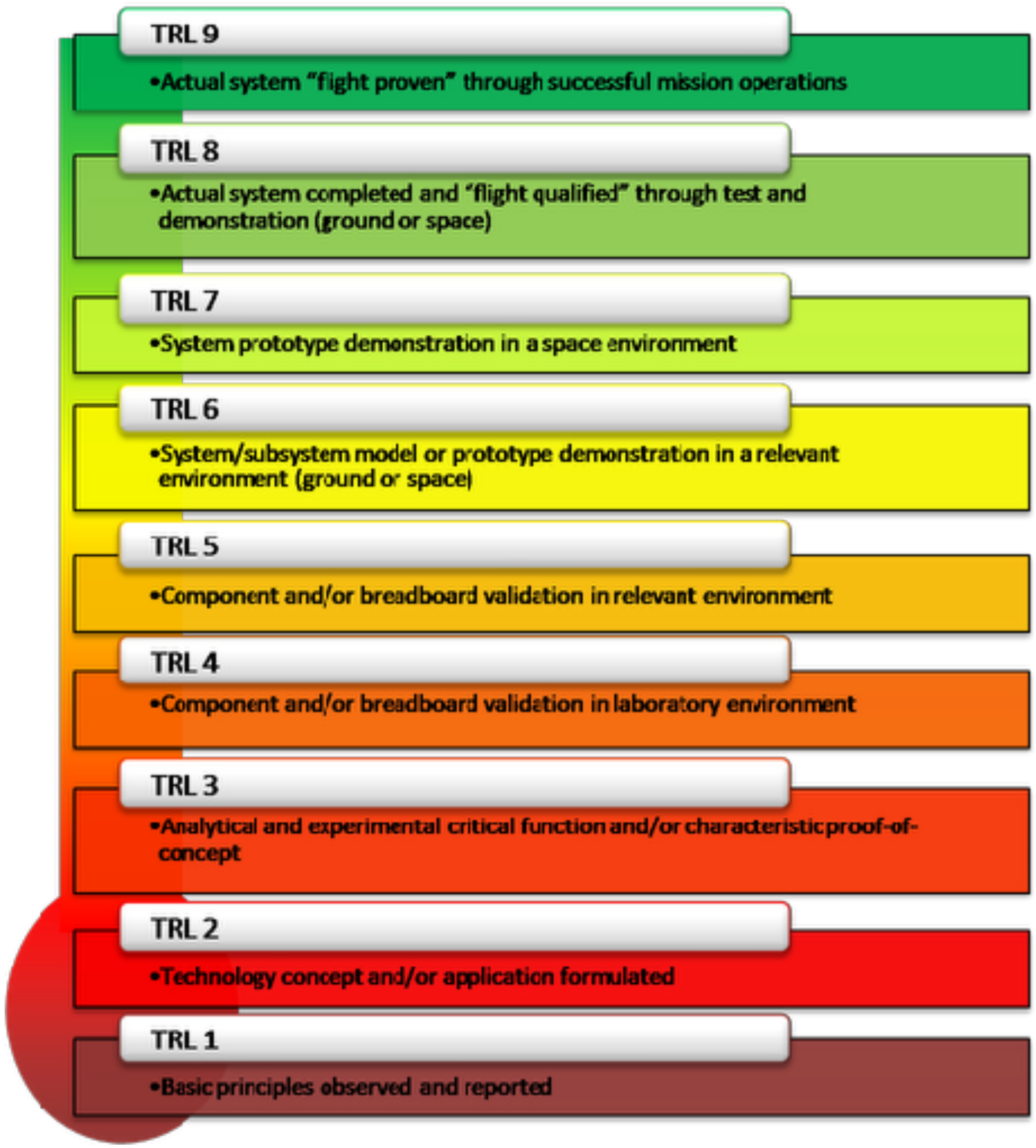
*** A hopeful future, but not a guaranteed one**

Fermi Summer School, 2018

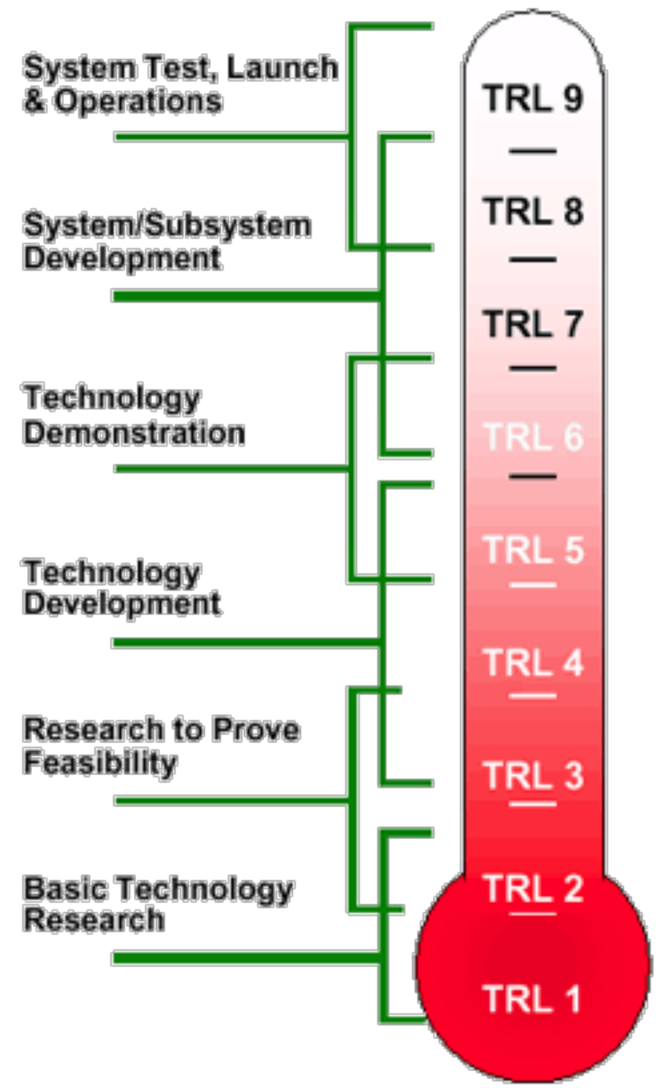
What's next?

- To get approved, a new mission/instrument must do one or more of the following:
    - improve sensitivity by $\gtrsim$1 order of magnitude
    - explore new phase space (energy range, spatial resolution, spectra resolution)
    - new capability (e.g. polarization, fast response, multiwavelength)
- To have these capabilities, new technologies or combinations of technologies are required
- However, to get approved, a new mission/instrument should not use any new technologies that are deemed risky - low technology readiness level (TRL)

TRL



https://www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html

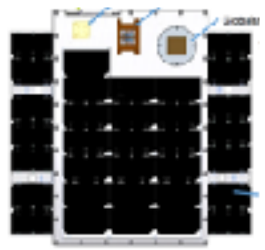
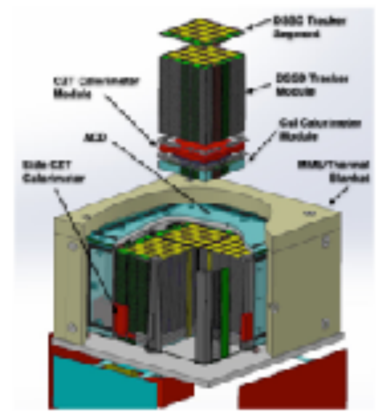


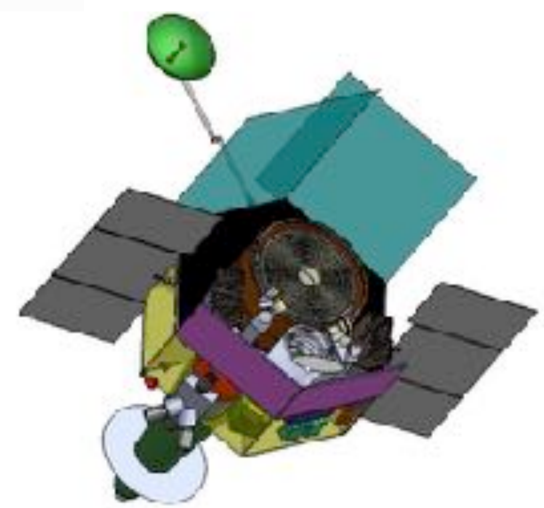
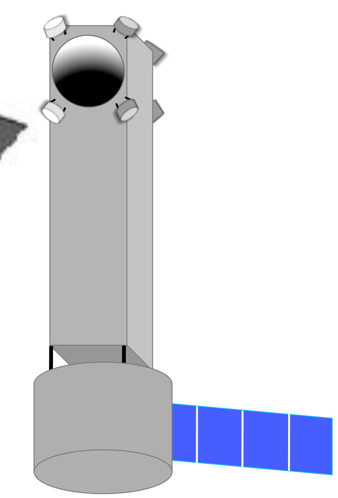
Broad Open Questions in Gamma-ray Astrophysics

- Origin of cosmic rays
- Origin of astrophysical neutrinos
- Where/what is dark matter?
- Emission mechanisms in astrophysical sources
- Emission sites
- Census/evolution of objects as a function of mass, luminosity, age, etc. of astrophysical source types
- Weird objects observed well in one band, but most of emission in poorly observed adjacent band

A Subset of Gamma-ray Missions/Concepts

- BurstCube
- AMEGO
- TAO
- TAP
- Nimble

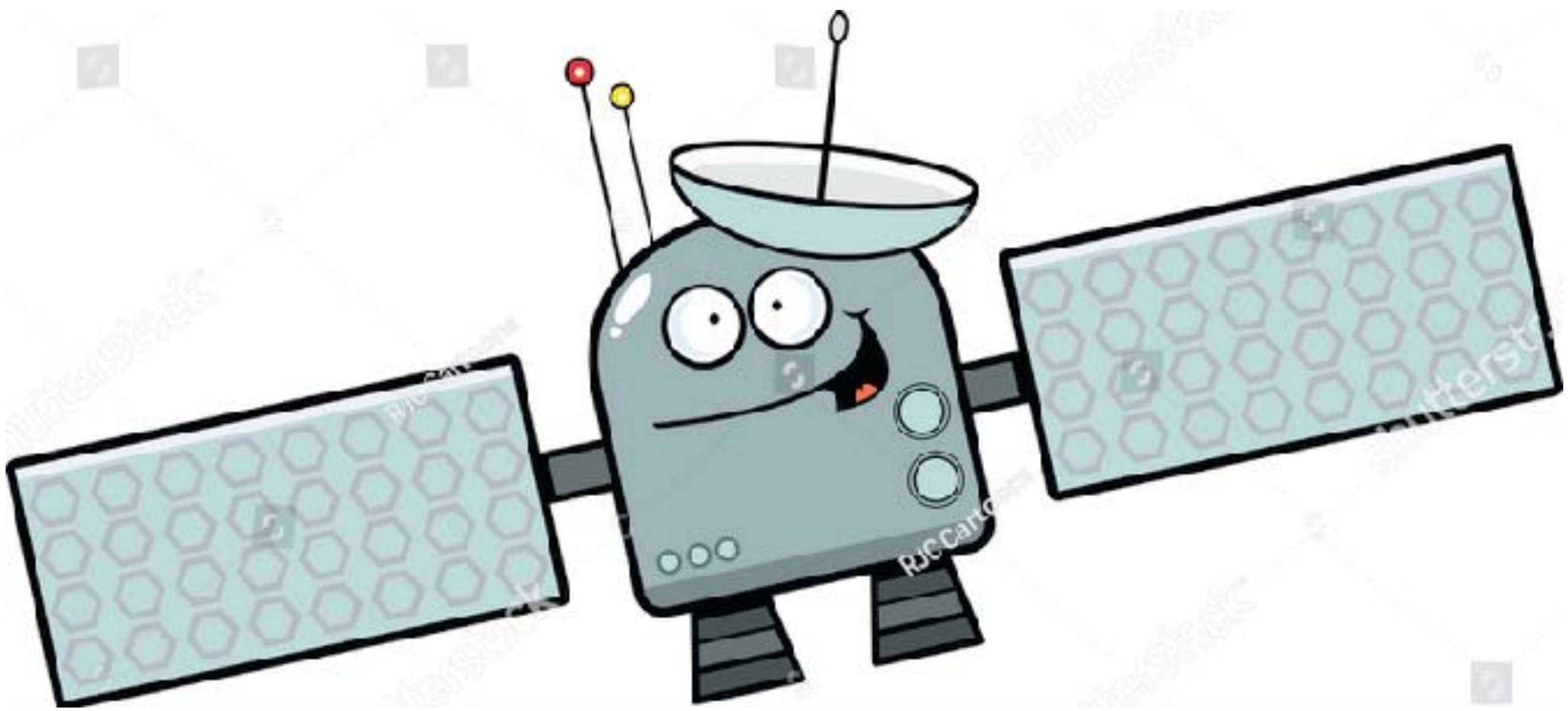



Not remotely to scale

How to make a space-based telescope

- Develop technologies (few years - decades)
  - simulations
  - in the lab
  - beam tests
  - balloon flights/sounding rockets/cubesats
- propose, propose, propose again (1+ years)
- phase A study (1 year)
- further down select
- get selected
- build instruments (few years)
- reviews, reviews, and more reviews (years)
- instrument integration into spacecraft (1+ years)
- reviews, reviews, and more reviews
- environmental testing (1+ years)
- don’t get cancelled for going over cost + reviews
- launch
- don’t blow up
- work on orbit
- science (2+ years)

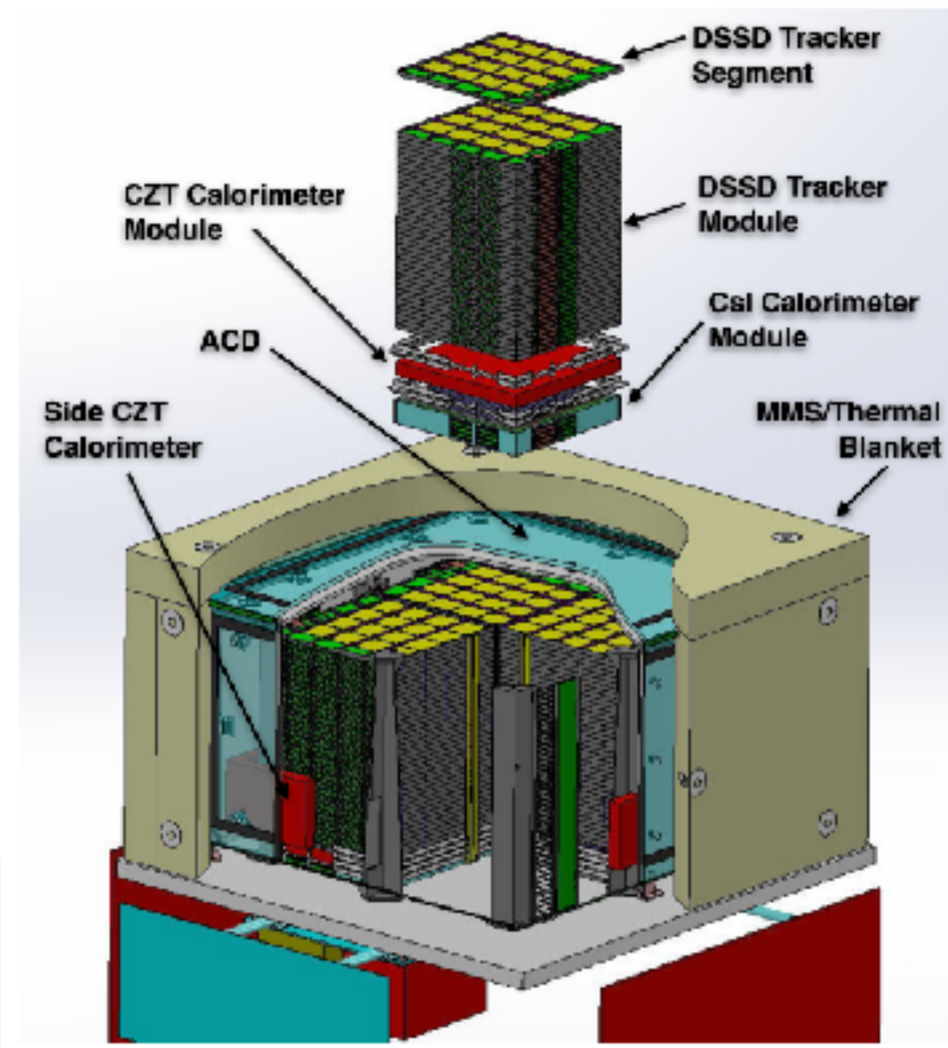
Quiz
Build a Gamma-ray Mission



kahoot.it

All-sky Medium Energy Gamma-ray Observatory (AMEGO)

- Use of well-tested, proven technologies (Si tracker, CsI calorimeter, Plastic ACD)
- Designed to fit within a probe class budget - Concept for the 2020 Decadal Survey
- Designed to be modular for ease of development, testing, and integration.
- 10 year mission goal



Energy Range	0.2 MeV - >10 GeV
Angular Resolution	3° (1 MeV), 10° (10 MeV)
Energy Resolution	<1% below 2 MeV; 1-5% at 2-100 MeV; 10% at 1 GeV
Field-of-View	2.5 Sr
Sensitivity ($erg\ cm^{-2}\ s^{-1}$)	$4x10^{-6}$ (1 MeV); $4.8x10^{-6}$ (10 MeV); $1x10^{-6}$ (100 MeV)

AMEGO Science

Understanding Extreme Environments

Astrophysical Jets

Understand the formation, evolution, and acceleration mechanisms in astrophysical jets

Compact Objects

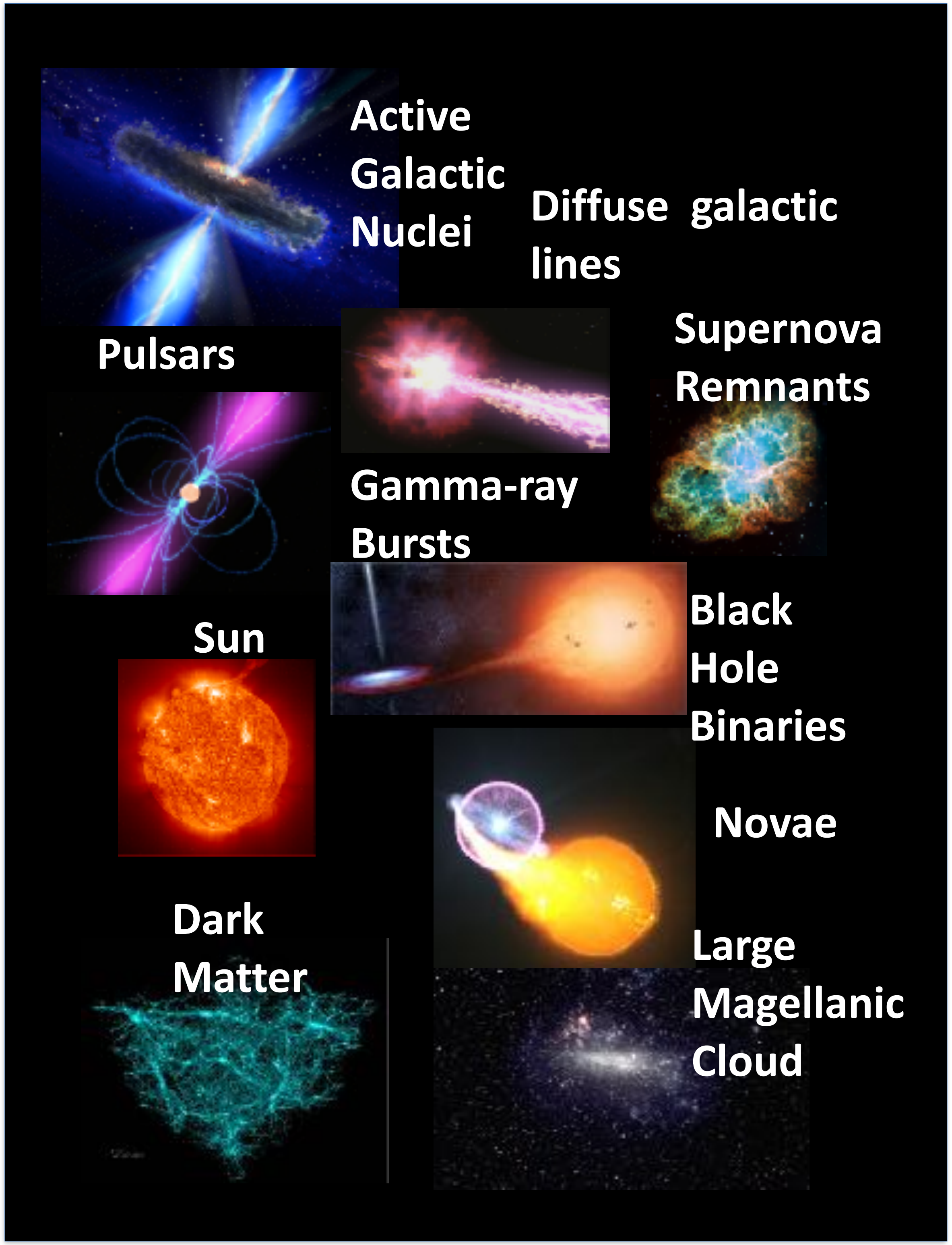
Identify the physical processes in the extreme conditions around compact objects

Dark Matter

Test models that predict dark matter signals in the MeV band

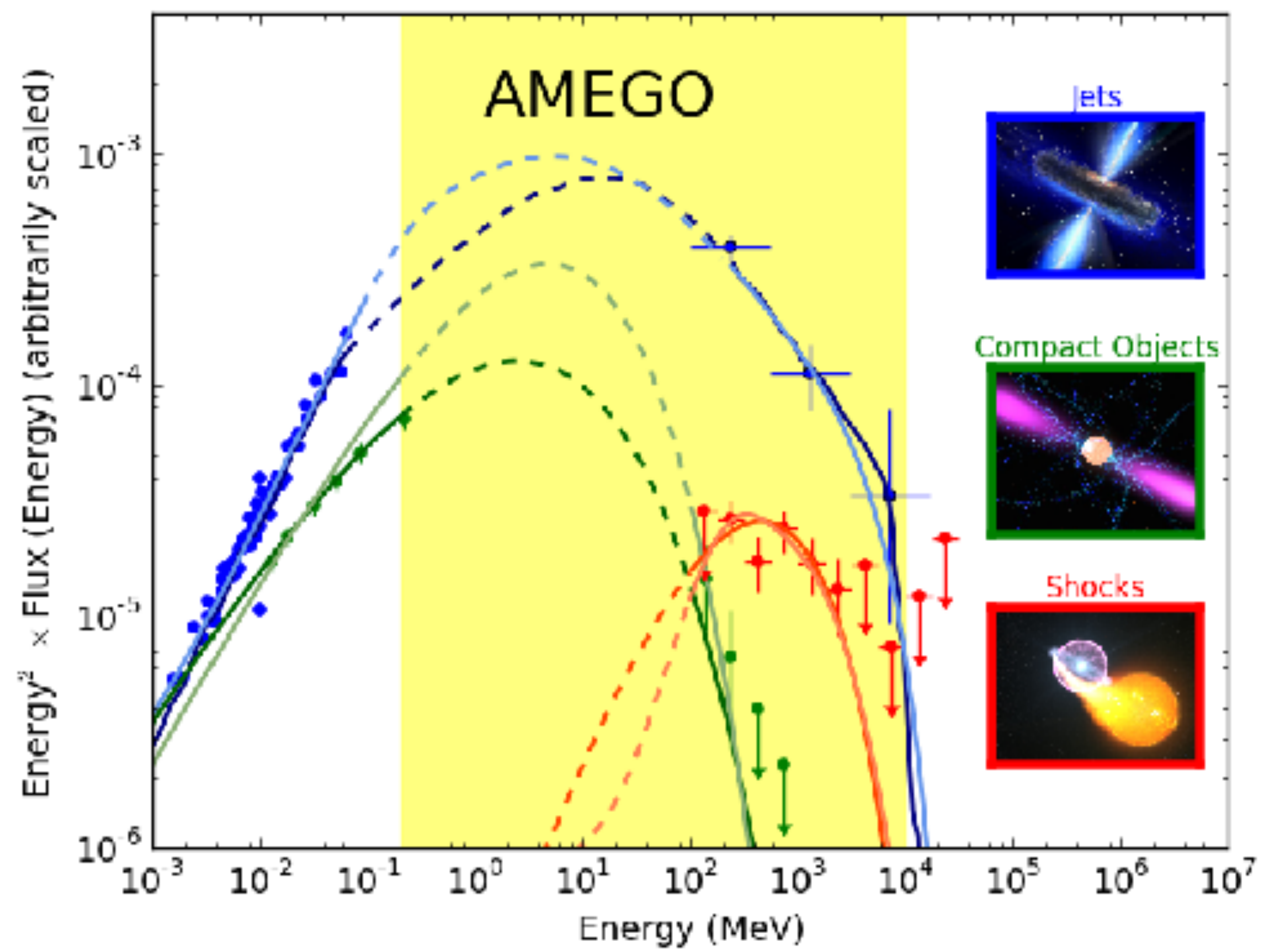
MeV Spectroscopy

Measure the properties of element formation in dynamic systems

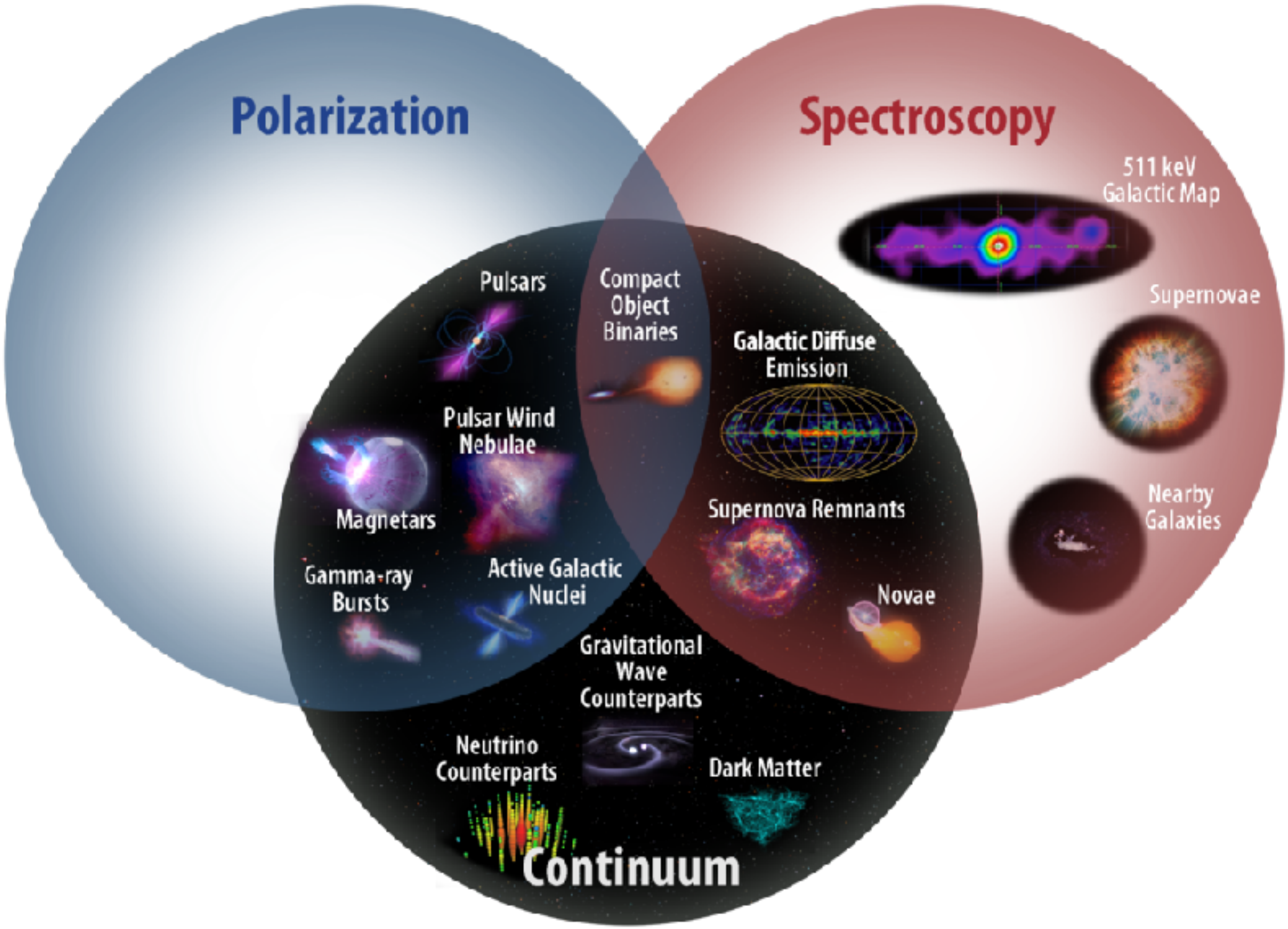


Extreme Astrophysics

- Understanding how the Universe works requires observing astrophysical sources at the wavelength of peak power output crucial for source energetics
- *Fermi*, NuSTAR, and *Swift* BAT have uncovered source classes with peak energy output in the poorly explored MeV band



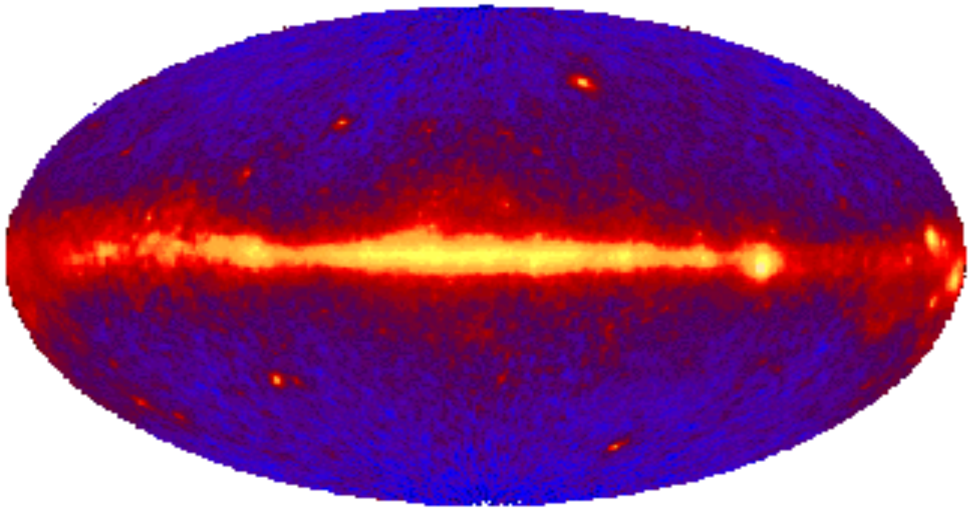
AMEGO Science Capabilities



AMEGO

Why Look in the MeV Range?

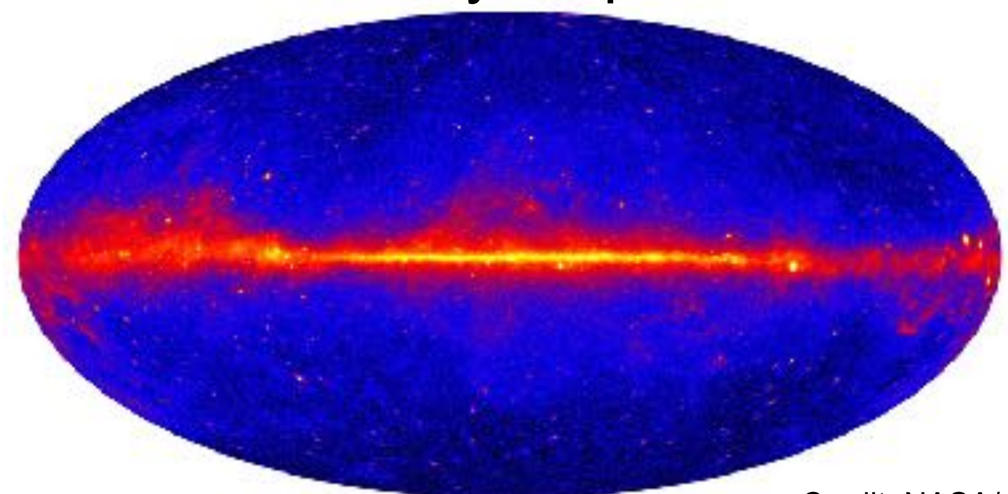
EGRET All-Sky Map Above 100 MeV



Credit: EGRET Team

~200 Sources Detected

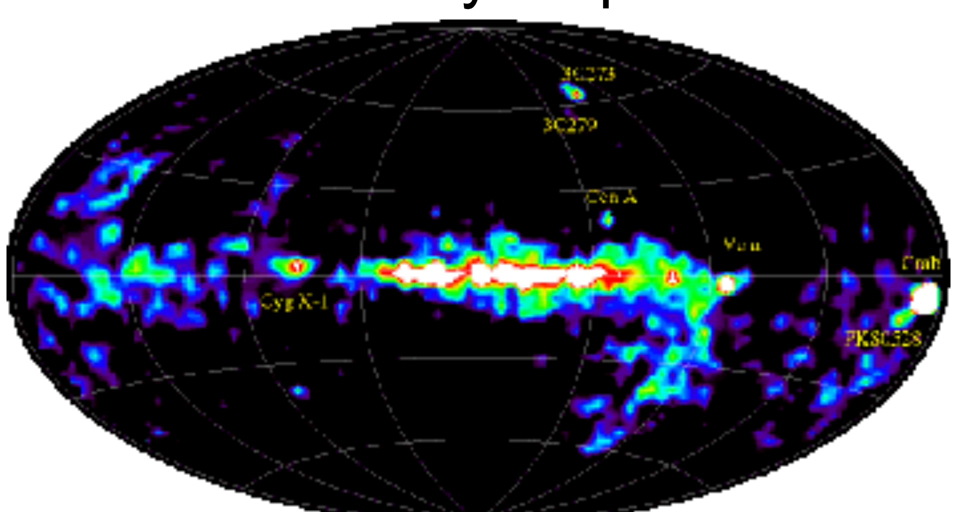
Fermi-LAT All-Sky Map Above 1 GeV



~3000 Sources Detected

Credit: NASA/ DOE/Fermi LAT Collaboration

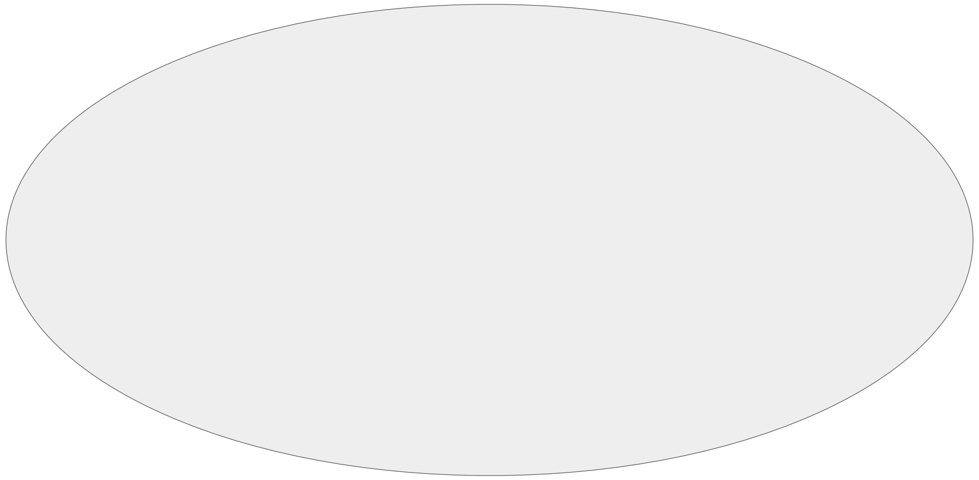
COMPTEL All-Sky Map 1 - 30 MeV



Credit: COMPTEL Collaboration

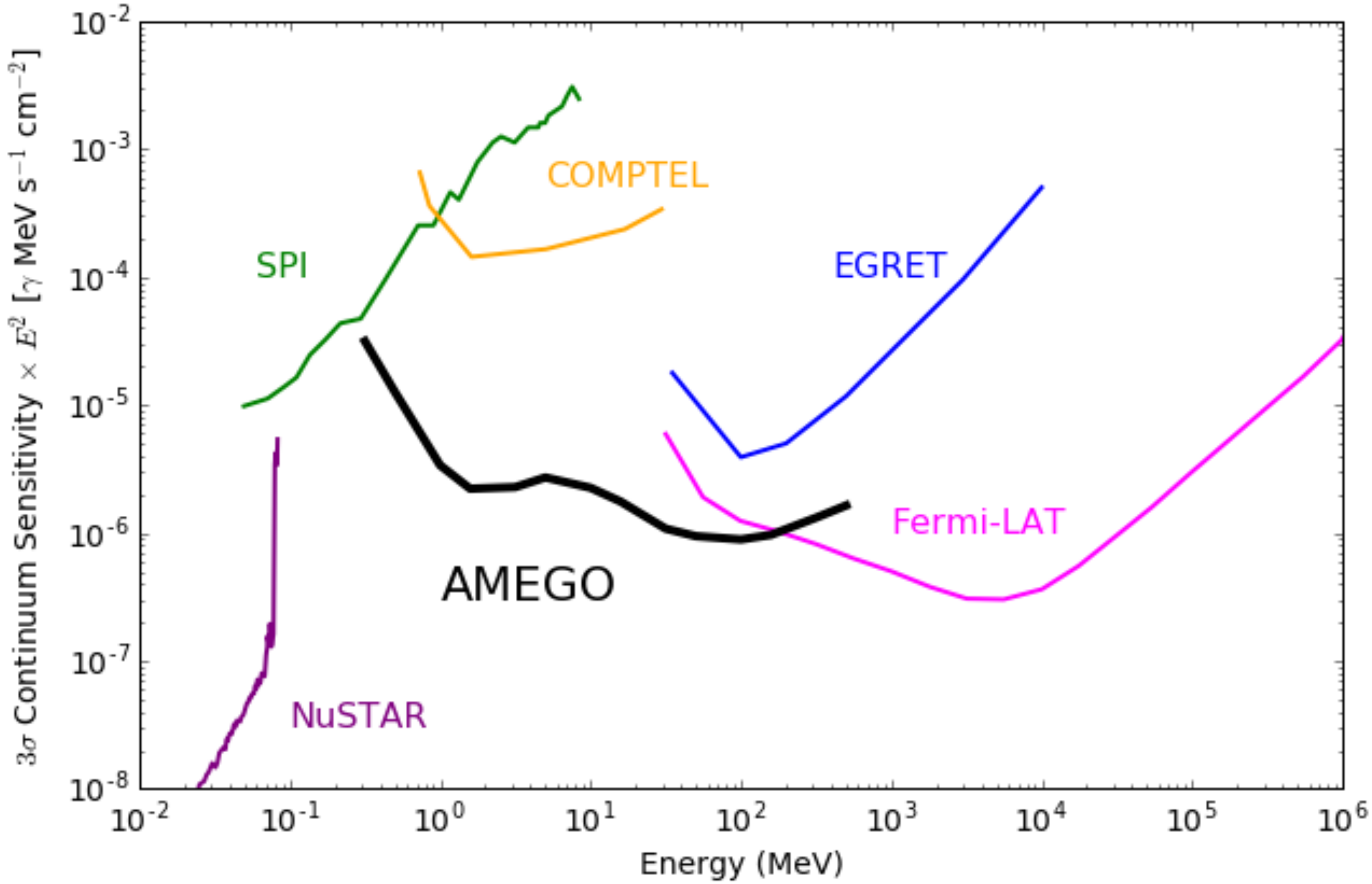
Tens of Sources Detected

AMEGO All-Sky Map? 100 keV - 10 GeV



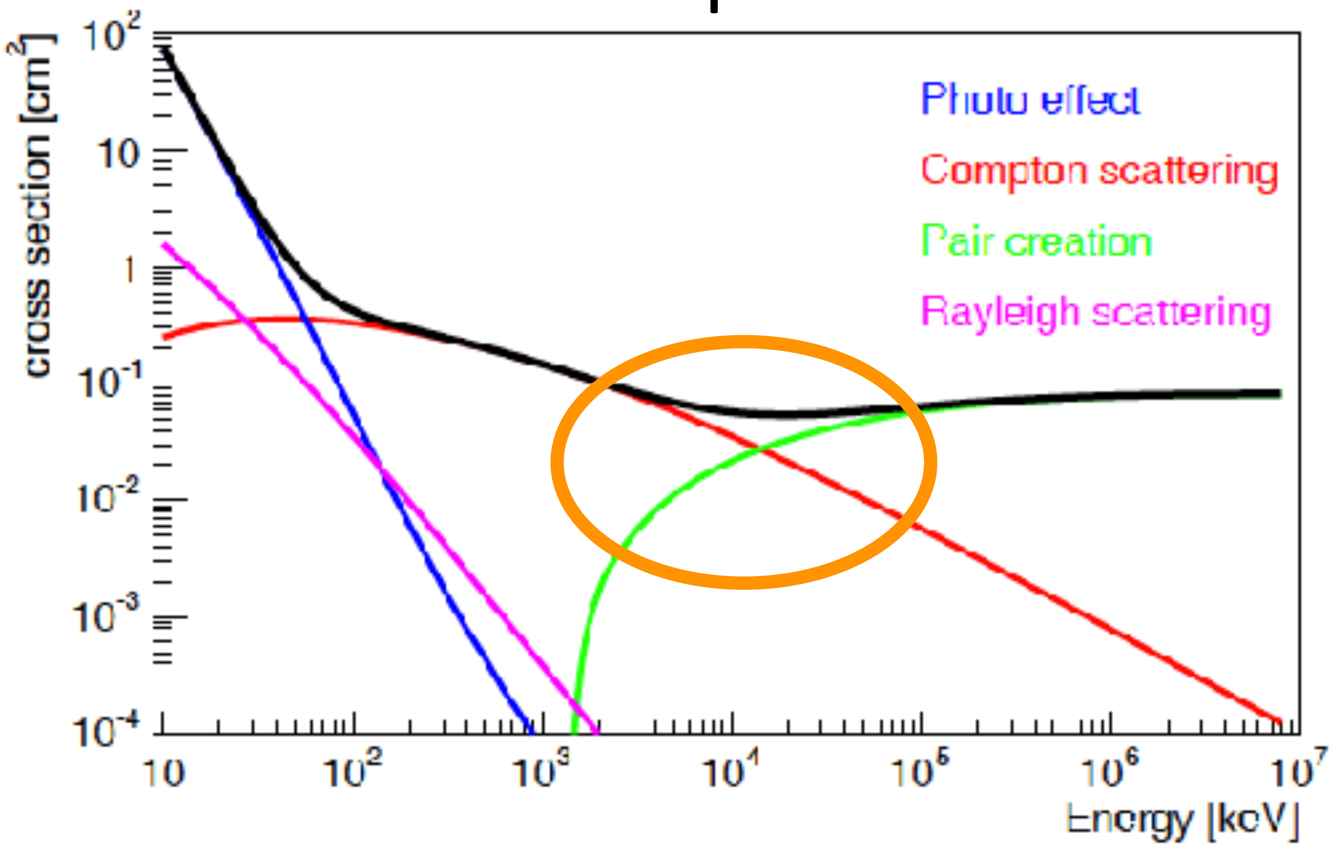
AMEGO Capabilities

Mission Averaged Sensitivities

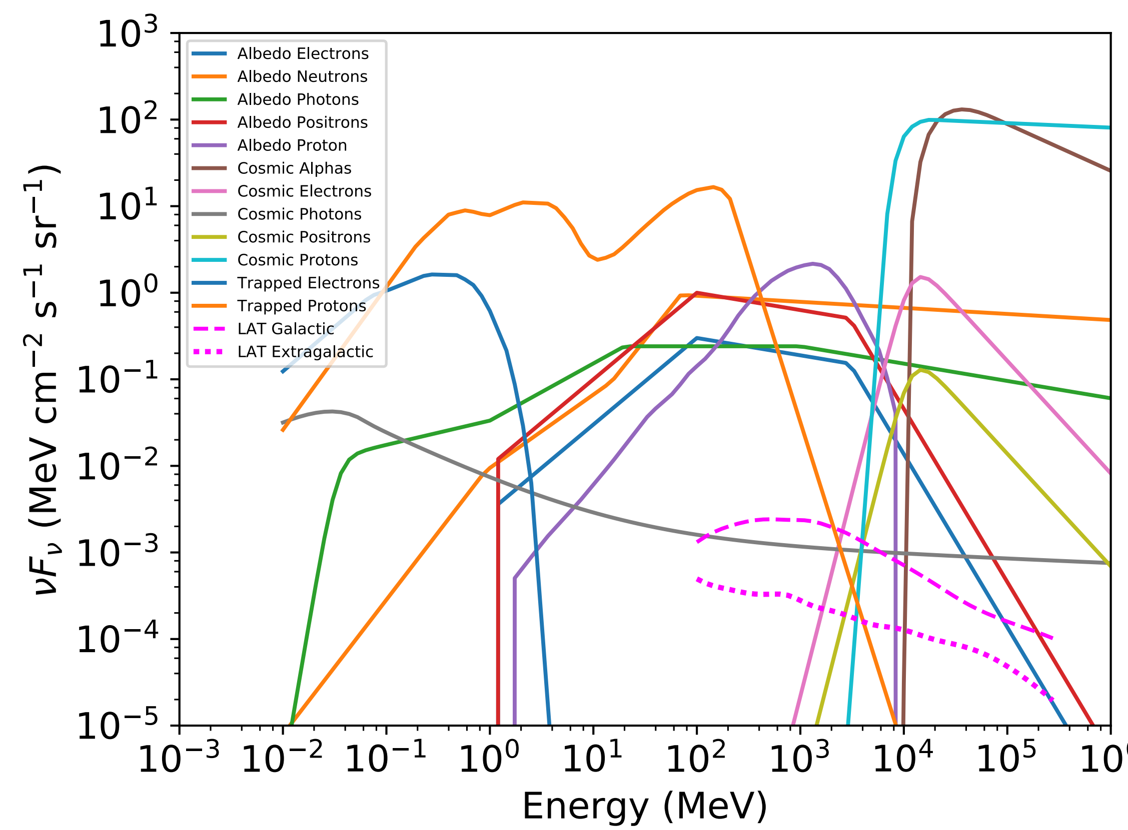


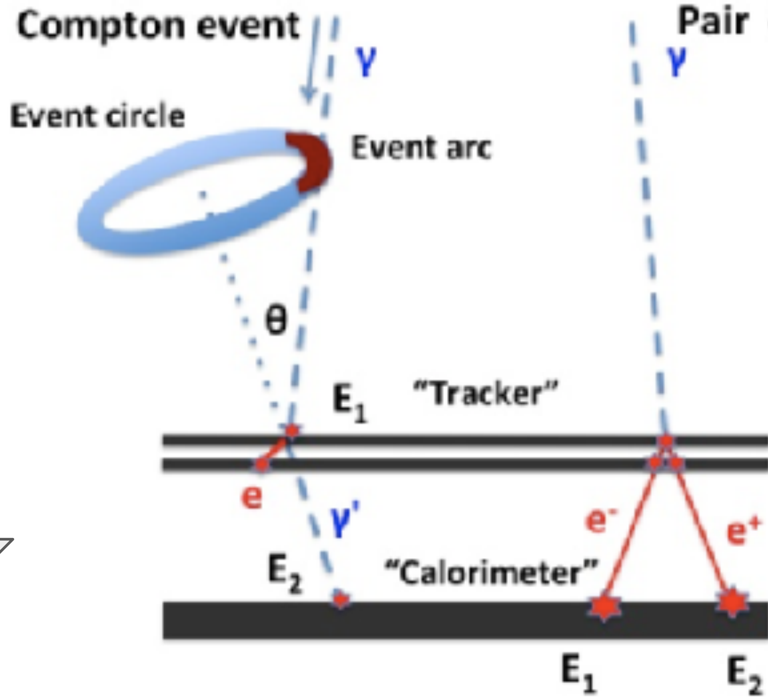
Challenges in the MeV Band

Compton Scattering / Pair Production Interaction Processes Compete



Large Backgrounds in the MeV Band



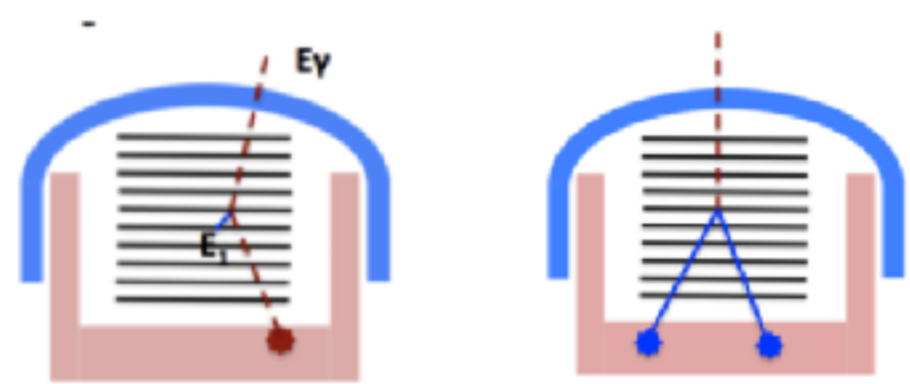


Above ~10MeV: ɣ converts to pair (e-/e+) in a multi-layer Si-strip tracker (no additional conversion material).

- ɣ direction is determined by measuring the position of the pair components as they pass through the Si-strip layers and a calorimeter.
- ɣ energy is determined by evaluating the energy deposited in the Si-strips and in the calorimeter.

Below ~10MeV: ɣ scatters a low-energy e- in Si-strip. Scattered ɣ can be absorbed in a calorimeter.

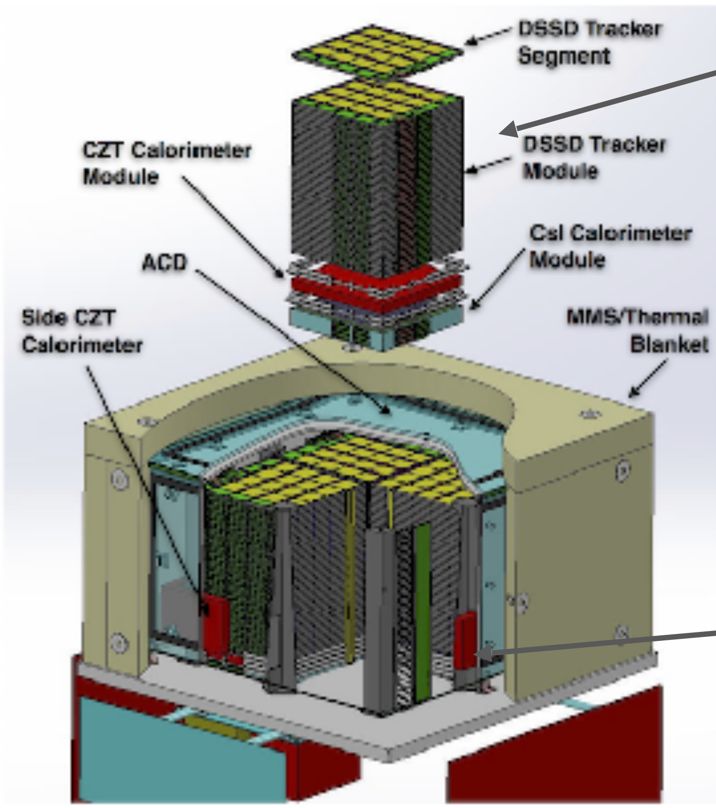
- ɣ direction is a circle or arc on the sky determined by position and energy measurements of the low-energy e- and absorbed ɣ.
- ɣ energy is determined by evaluating the energy deposited in the Si-strips and in a calorimeter.



b) Compton event, 1 hit in Tracker

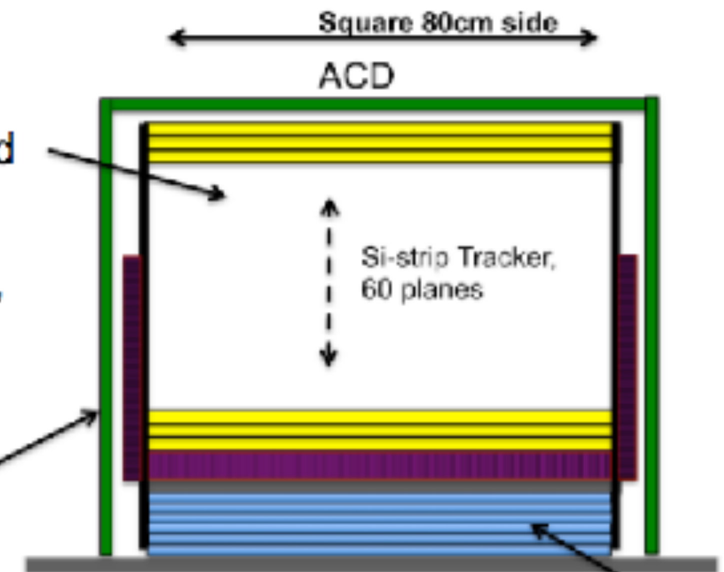
a) Pair production event

AMEGO Details



Tracker: Incoming photon undergoes pair production or Compton scattering. Measure energy and track of electrons and positrons

- 60 layer DSSD, spaced 1 cm, Strip pitch 0.5 mm



CZT Calorimeter: Measure location and energy of Compton scattered photons

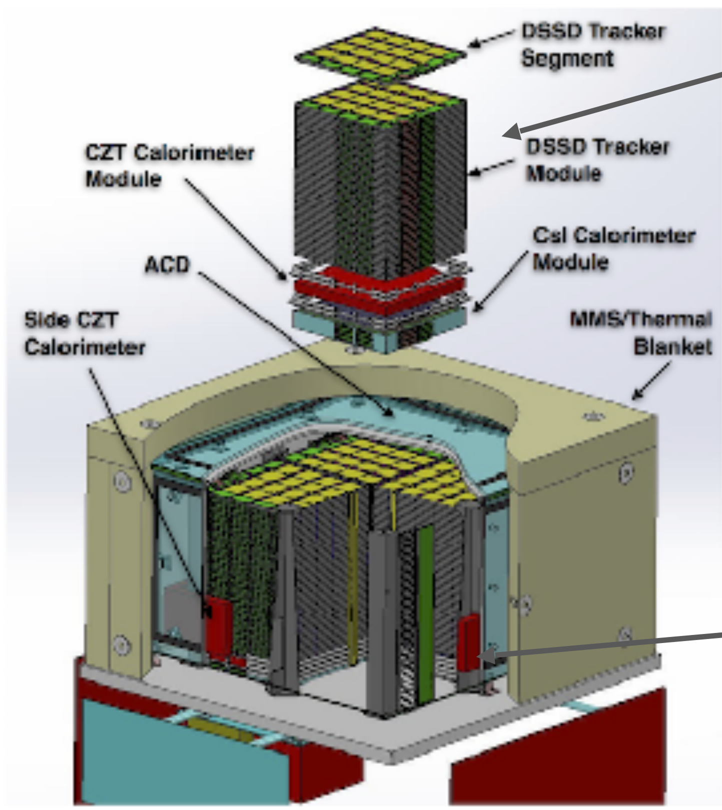
- Layer of 0.6 x 0.6 x 2 cm bar CZT

CsI Calorimeter: Extend upper energy range

- 6 planes of 1.5 cm x 1.5 cm bars

- Use of **well-tested, proven technologies** (Si tracker, CsI calorimeter, Plastic ACD, …)
- Designed to fit within a probe class budget:
  - Concept for the 2020 decadal review
- Designed to be **modular** for ease of development, testing, and integration.
- 10 year mission goal (similar to *Fermi*)

AMEGO Details



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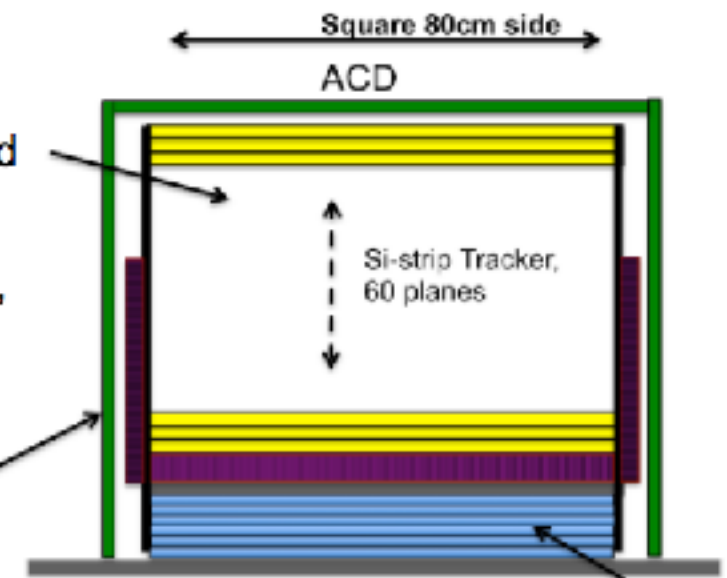

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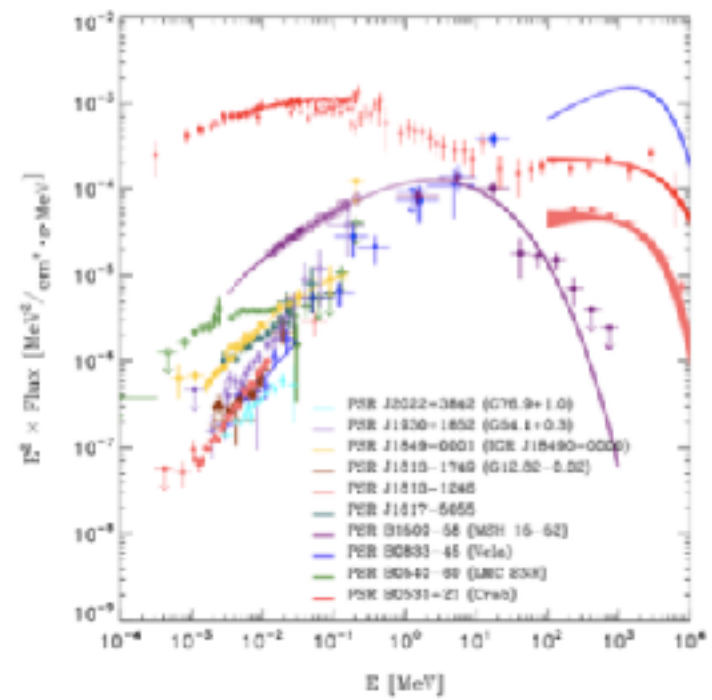
Extreme Conditions Around Compact Objects

Example 1: *Soft Gamma-ray Pulsars*

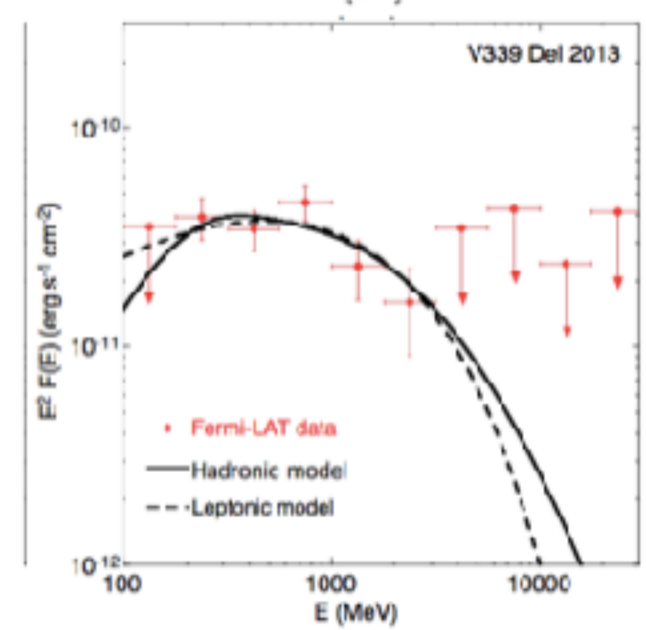
- Seen in hard X-ray but not *Fermi*-LAT, **peak lies in MeV band**
- 11 MeV pulsars known
  - Extremely energetic Edot > 10^{36} erg
- Possible "hidden" population of energetic soft gamma emitting pulsars



Example 2: *Novae*

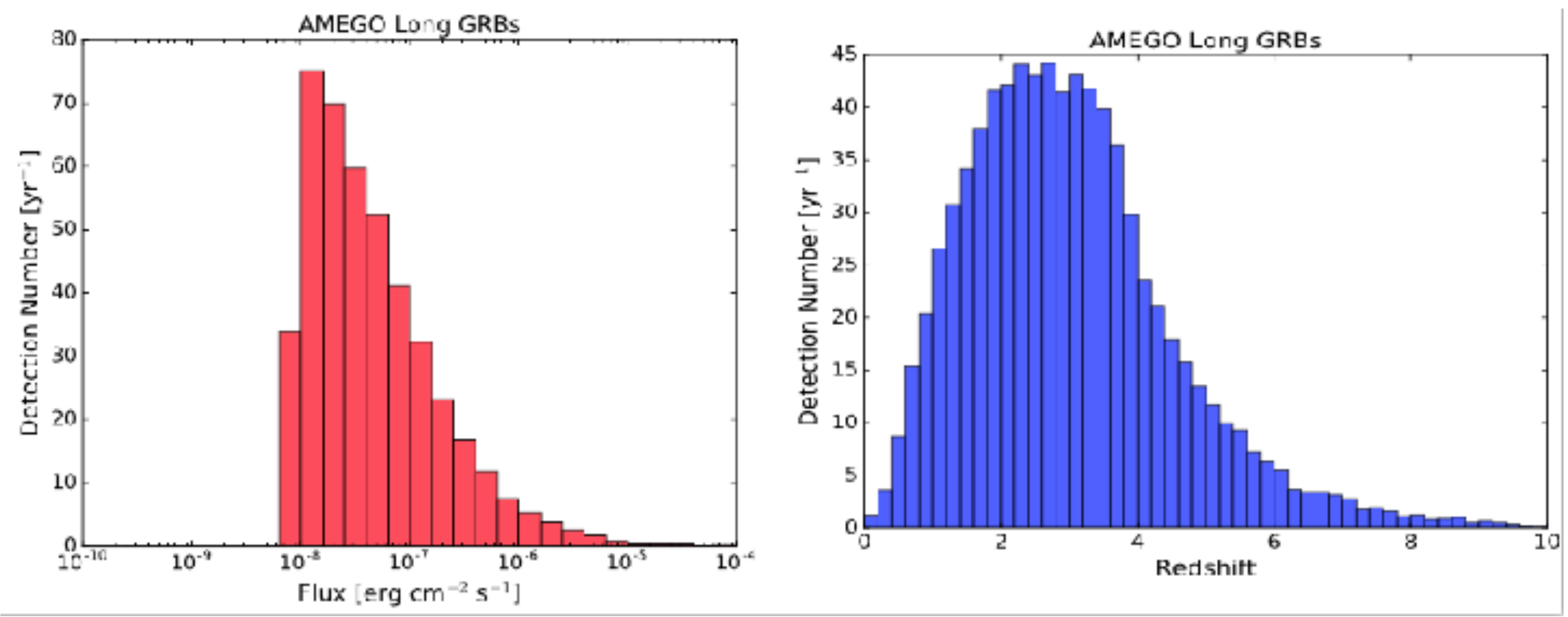
- How do close binary star systems like classical novae eject mass during outbursts?
- Shocks in the expanding nova envelope produce gamma rays.

AMEGO will measure the energy spectrum below 100 MeV to **determine the shock properties** and **identify novae** missed by optical observations.



Jets: Gamma-ray Bursts

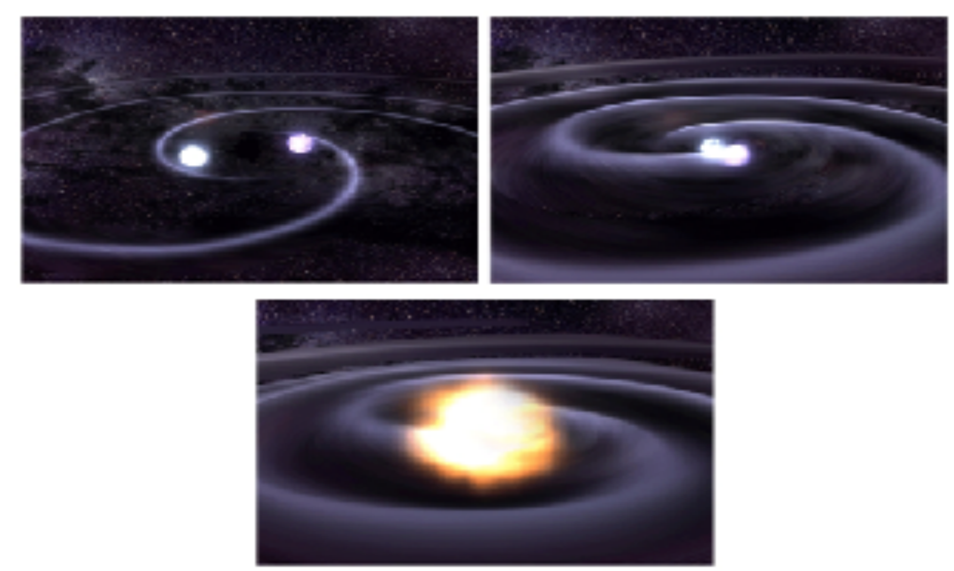
- Simulations using Lien et al. 2014 method
  - ~400 Long GRBs/yr (~19 @ z>6)
  - ~80 Short GRBs/yr
- Polarization - 20% MDP for brightest 1% of AMEGO GRB
  - AMEGO observations will probe the GRB emission mechanism and jet composition



GRBs and Gravitational Waves

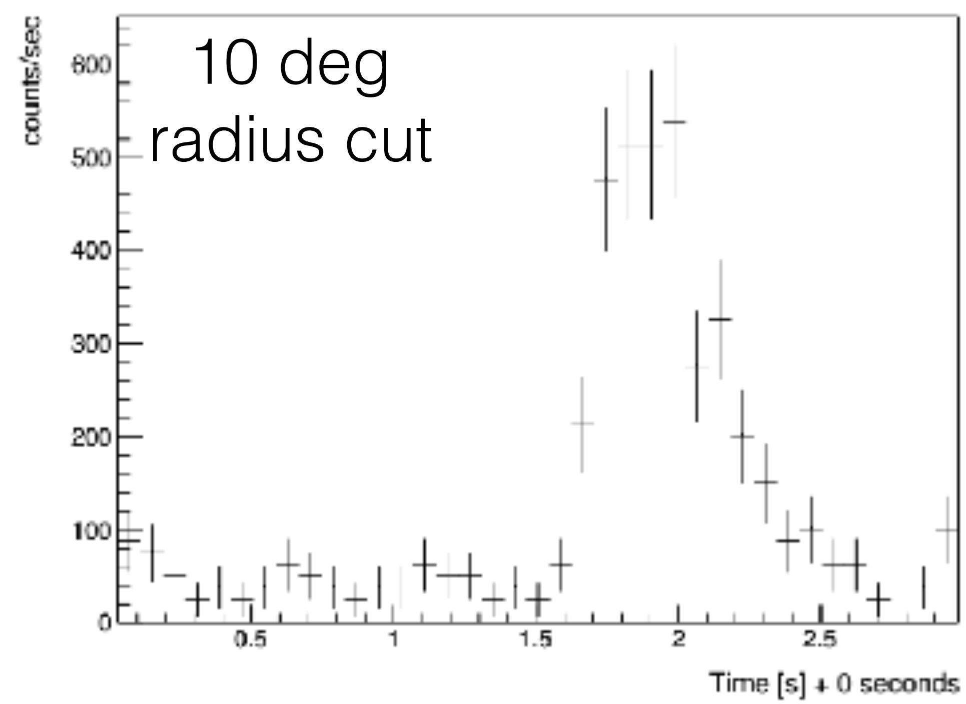
- LIGO sensitive to gravitational waves produced in merger of compact objects (NS-NS, NS-BH and BH-BH)
- Compact mergers involving NS are presumed progenitors for short GRBs
- Searches for counterparts to LIGO GW events at high energies have focused on EM radiation expected from short GRBs - Perfect for *AMEGO*!
- Both observatories bring complementary information: Gravitational radiation → inspiral characteristics; *AMEGO* → jet properties & environment

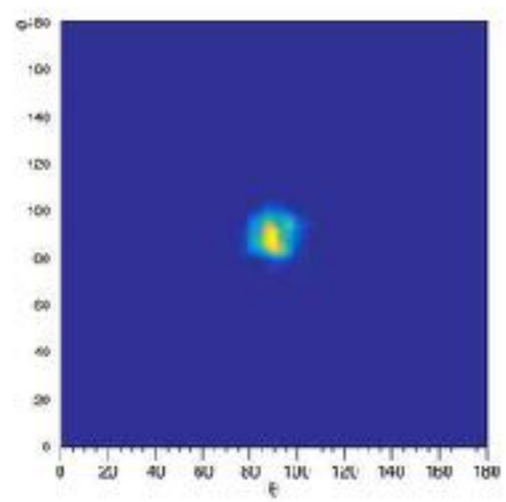
AMEGO will detect ~80 sGRB/year with sub-degree localization - significantly more than any currently operating GRB detector

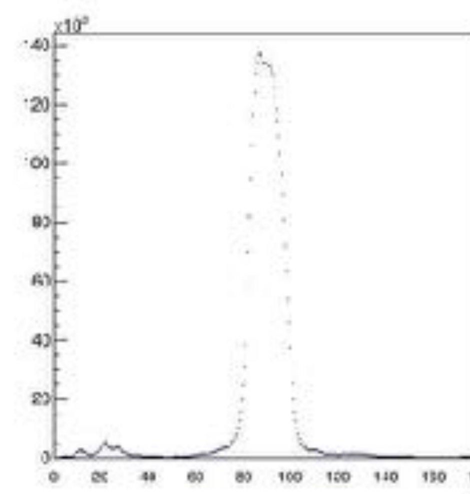


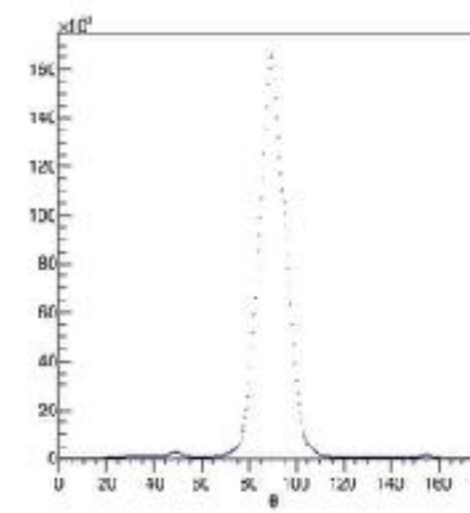
GRB 170817A (GW170817)

- At 43 Mpc, it was nearby, but sub-luminous (viewed slight off-axis? structured jet?), and would only have been detected by GBM onboard out to ~80 Mpc - gamma-ray horizon problem?
- AMEGO could have detected GRB 170817A out to > 130 Mpc, with a localization of <6 deg radius (1σ)
- Significant optimizations/ permutations yet to sir to range of GBM GRBs with different properties





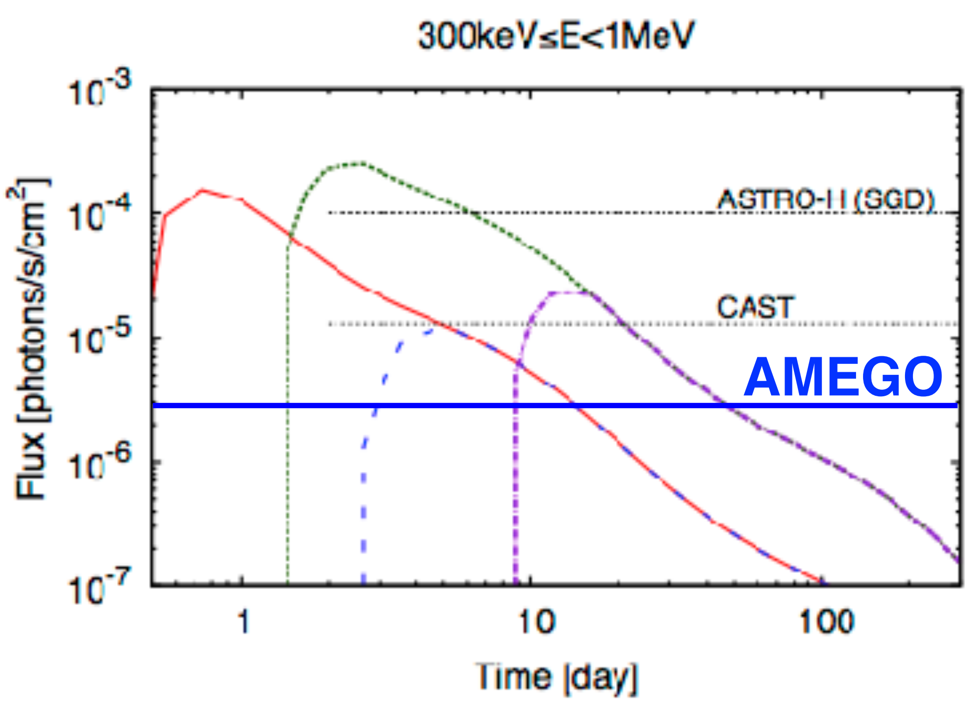




Other Gamma-ray Signatures in Neutron star mergers

- Radioactive decay of r-process nuclei ejected in compact binary merger power optical/infrared kilonovae
- Variety of decay products, including gamma-rays
  - ejecta is relatively transparent to gamma-rays, so they can escape
  - Significant fraction of the radioactive energy might be released in gamma-rays
- Can we see gamma-rays from compact mergers?
  - We'd detect a lot of SNIa first, but worth considering

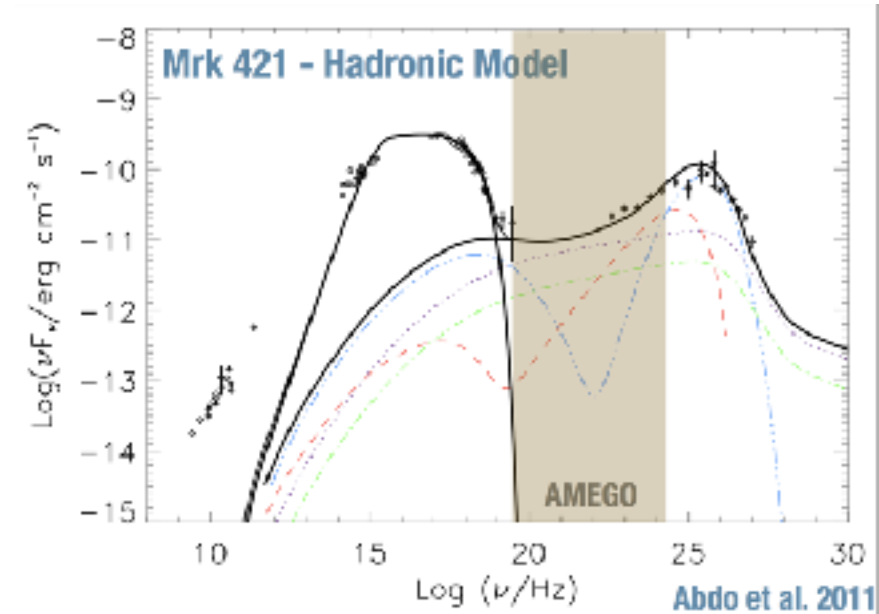
Detectable by AMEGO at 3 Mpc for all parameters considered (but likelihood of a merger that close is probably small)

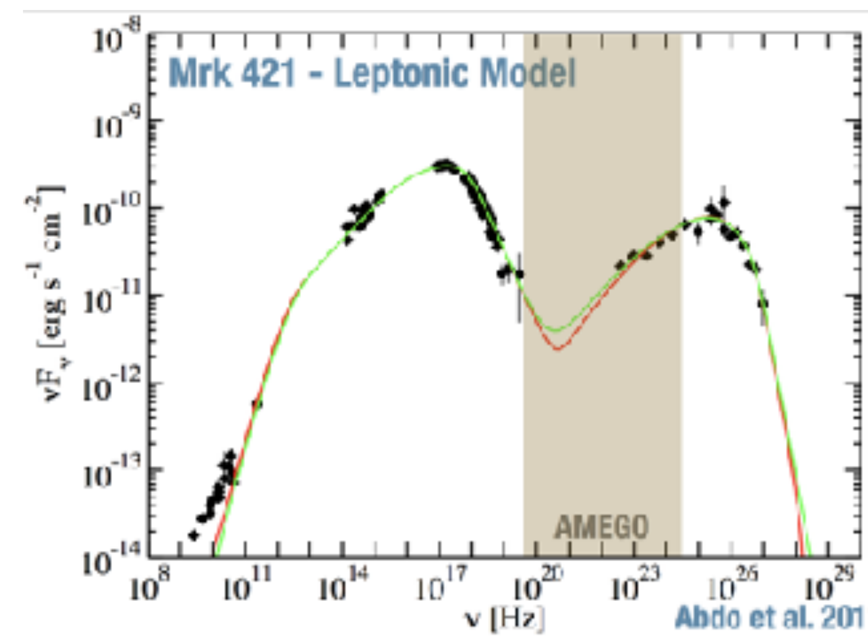


Hotokezanka et al

Jets: Blazars

- MeV blazars have their **peak power output** in the MeV Band and are **powerful probes of the growth** of supermassive black holes.
  - Large jet power and accretion luminosity
  - Often found at very large redshift
  - Harbor massive black holes ($10^9\ M_\odot$)
- AMEGO will measure AGN spectral energy distributions and variability:
  - Determine the **maximum particle energies**, study **magnetic field strength**, **jet content**, & the gamma-ray **emission location**.
  - Differentiate hadronic and leptonic models with **polarization**.





Searching for Dark Matter Signals

Example: *Axions*

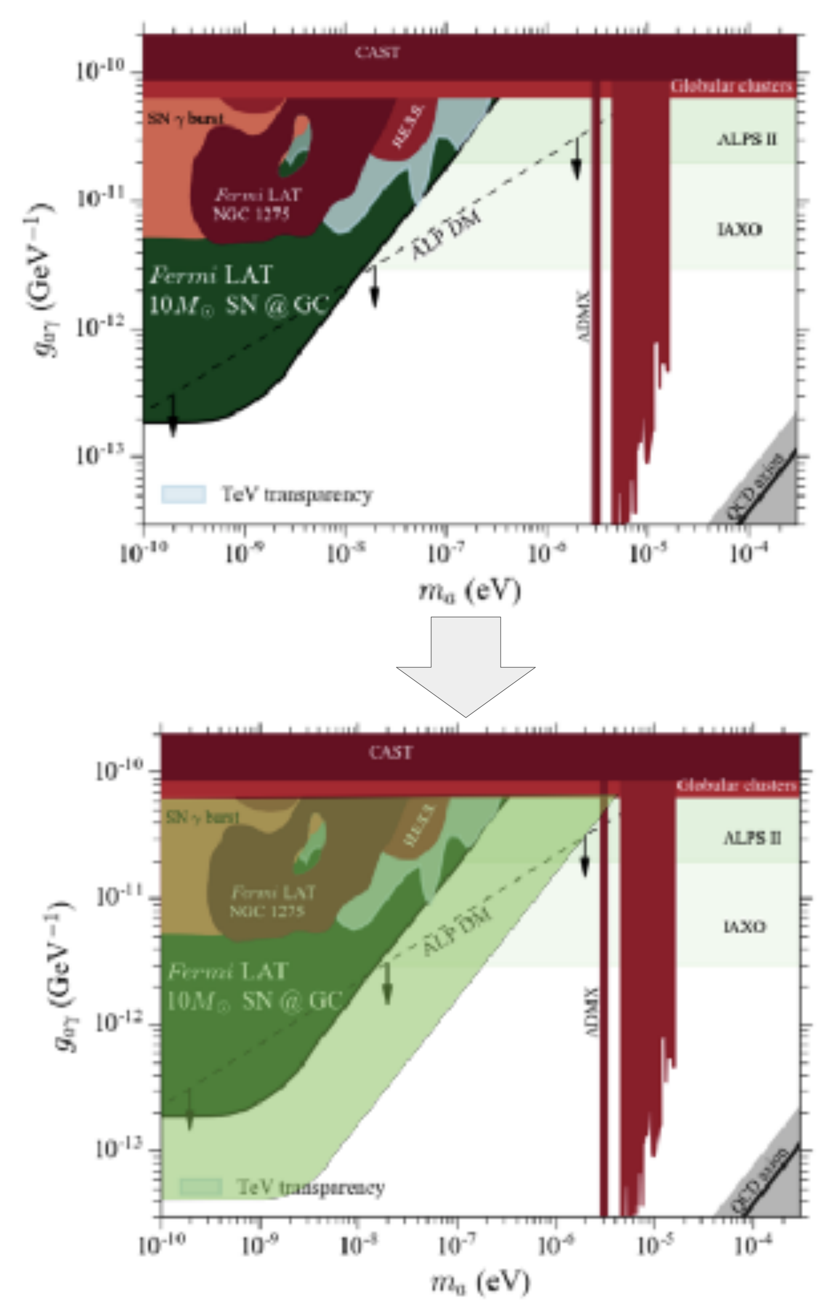
Axions in neutron stars (hep-ph/0505090)

- emission process for axions with mass up to a few MeV
- production in Gamma Ray Bursts

Axions produced in supernovae (arXiv:1410.3747)

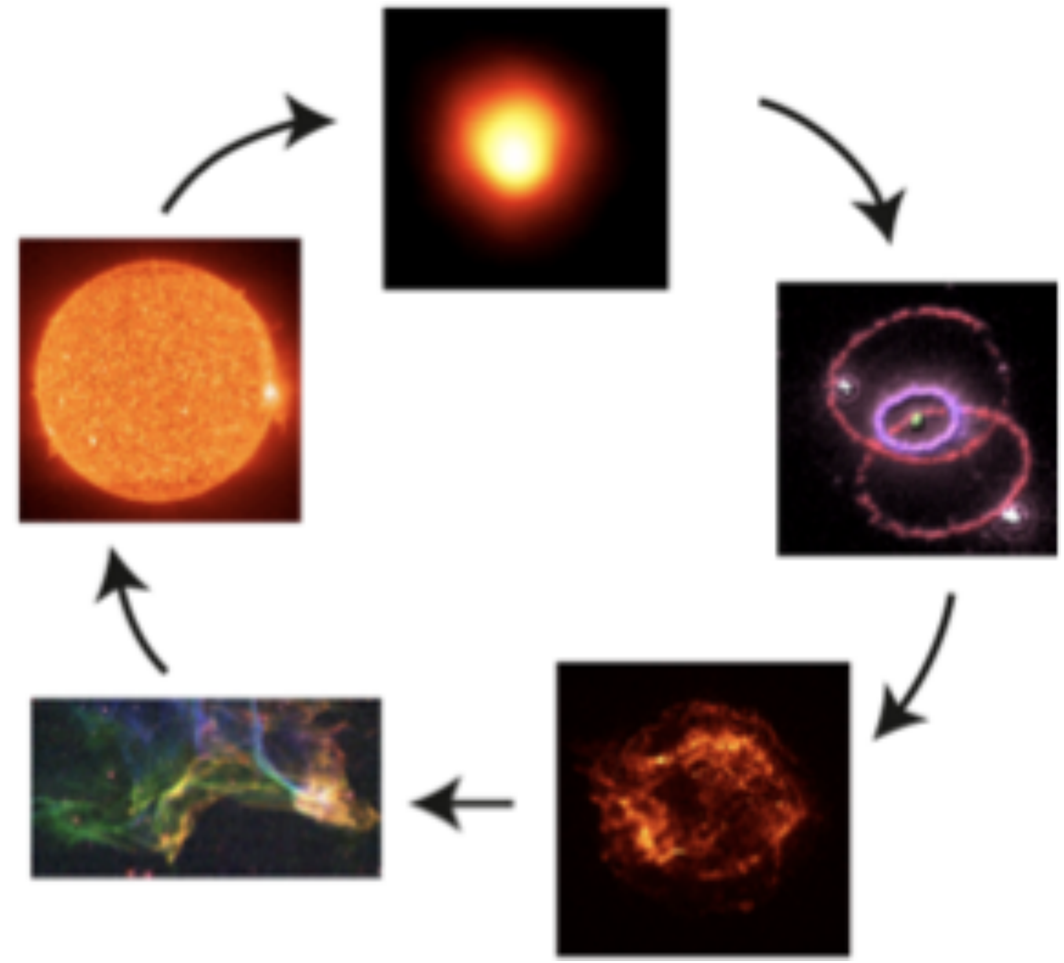
- core collapse supernova (SN1987A)

Current upper limits would be limited by the PSF below 100 MeV



Element Formation in Dynamic Systems

Nuclear lines explore Galactic chemical evolution and sites of explosive element synthesis (SNe)

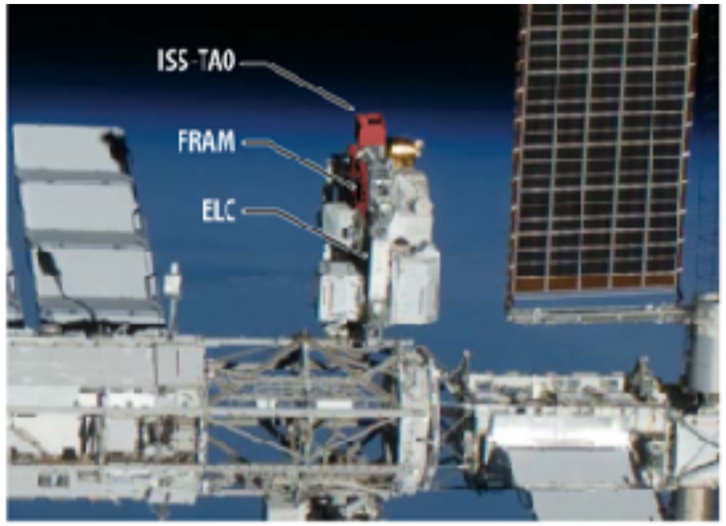


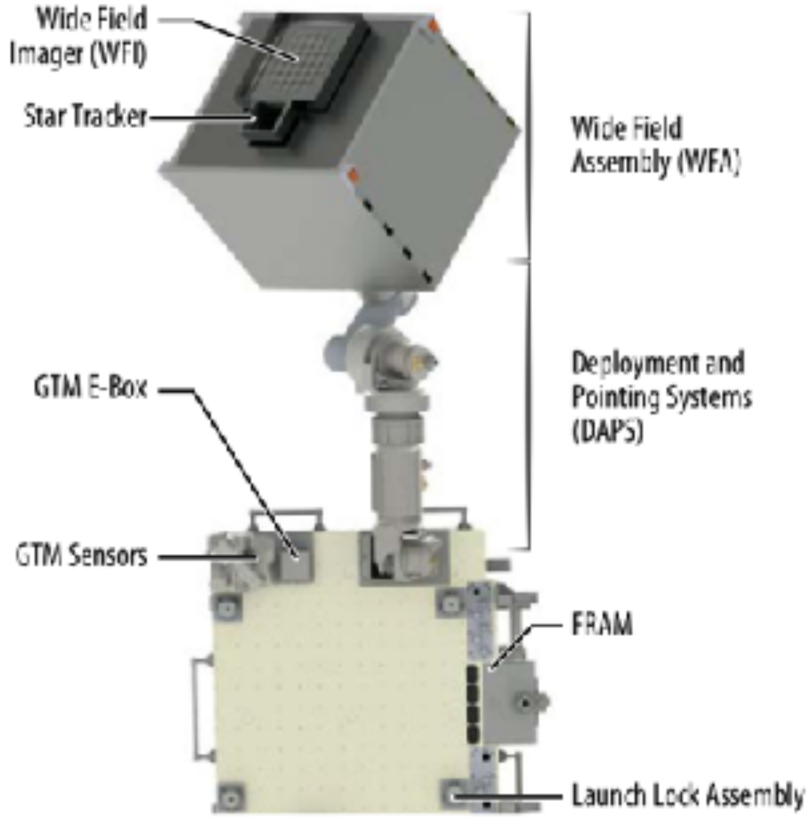
- Electron-positron annihilation radiation
  - $e^{+} + e^{-}$ -> 2g (0.511 MeV)
- Nucleosynthesis
  - Giants, CCSNe (^{26}Al)
  - Supernovae (^{56}Ni, ^{57}Ni, ^{44}Ti)
  - ISM (^{26}Al, ^{60}Fe)
- Cosmic-ray induced lines
  - Sun
  - ISM

56Ni: 158 keV 812 keV (6 d)
56Co: 847 keV, 1238 keV (77 d)
57Co: 122 keV (270 d)
44Ti: 1.157 MeV (78 yr)
26Al: 1.809 MeV (0.7 Myr)
60Fe: 1.173, 1.332 MeV (2.6 Myr)

TAO-ISS Mission

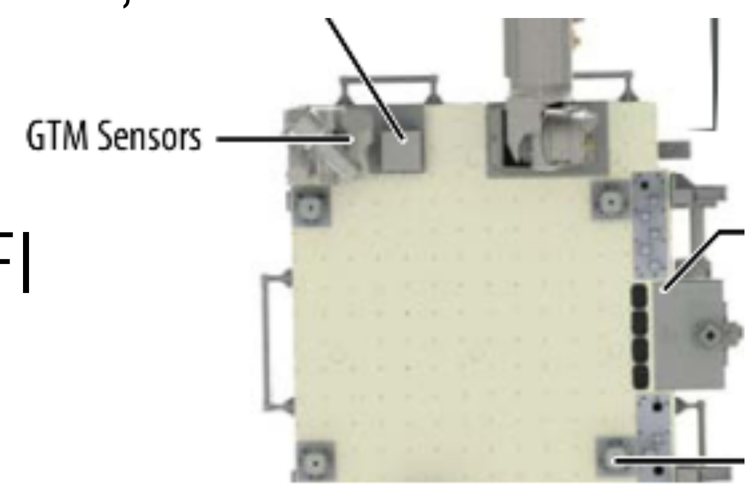
- Mission of Opportunity (MoO) proposed in 2016, currently in Phase A study
- ISS payload designed for ELC-3 inboard port
- ISS benefits and challenges
  - ample power, continuous uplink/downlink 80% of the time, sufficient data rates
  - complicated background, field of regard
- Instruments
  - Gamma-ray Transient Monitor (GTM)
  - Wide-field Imager (WFI)
- Operations:
  - Sky Survey & Target of Opportunity
  - Rapid (4 deg/s) autonomous repointing to new transients
- 2 year mission (5 year goal)
- launch in early-2022

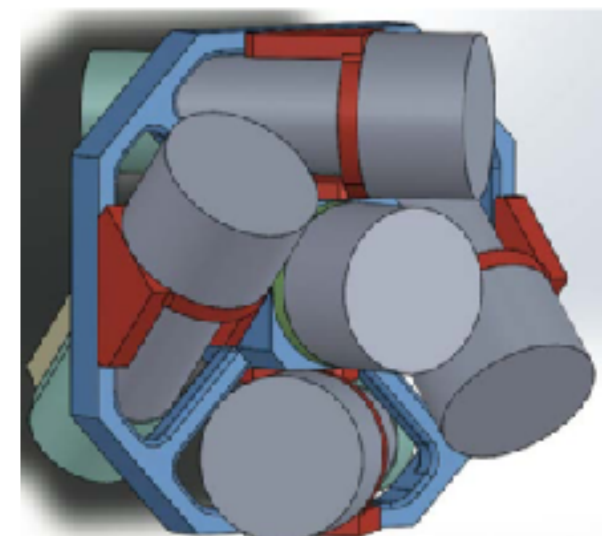




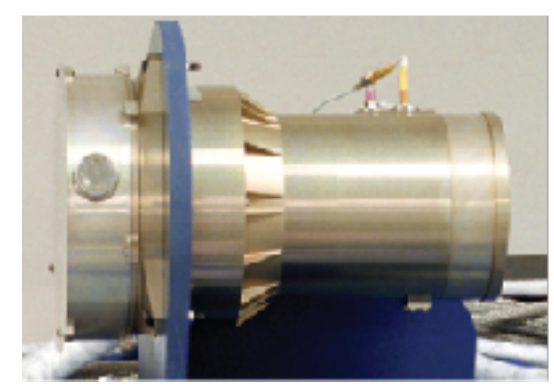
Gamma-ray Transient Monitor (GTM)

- Contributed by Israeli Space Agency, Technion
- 4 x NaI scintillators read out by PMTs
- Scintillators: 7.62 cm diameter, 2.54 cm thickness
- FoV ~1.6π ster
  - some obscuration by WFI
- Energy range 15 - 800 keV
- Onboard triggering in 3 timescales and 3 energy ranges
- Localization capability (~100's deg^2)
- Continuous data and triggered datasets (much like Fermi-GBM)





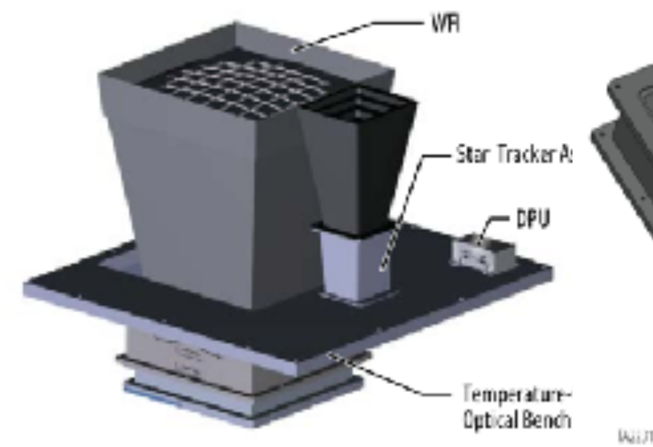
5 detectors shown, but current design is 4 detectors

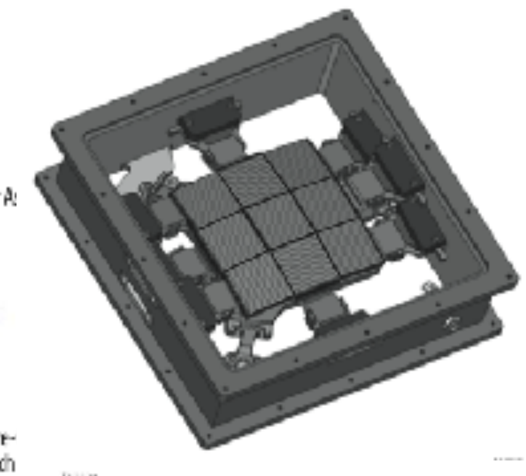


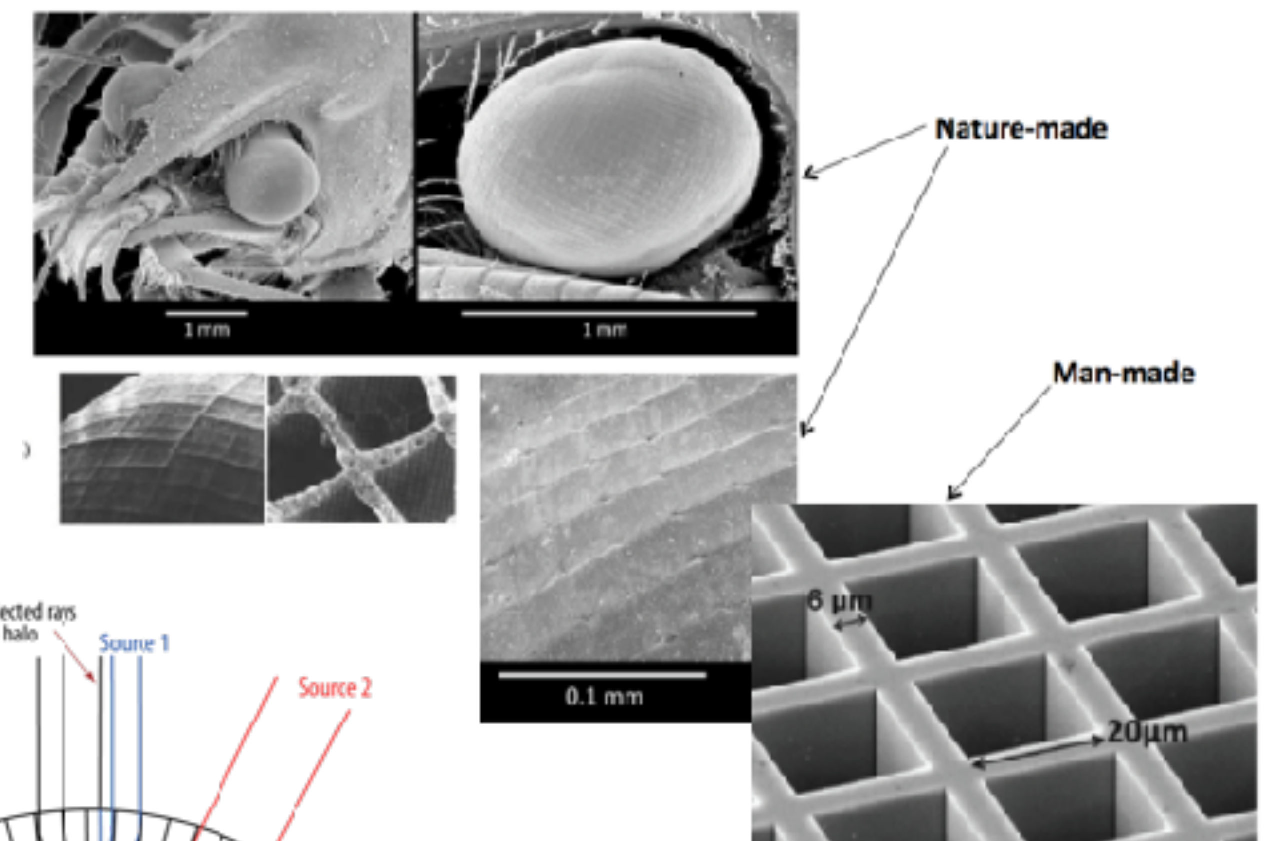
Fermi-GBM NaI

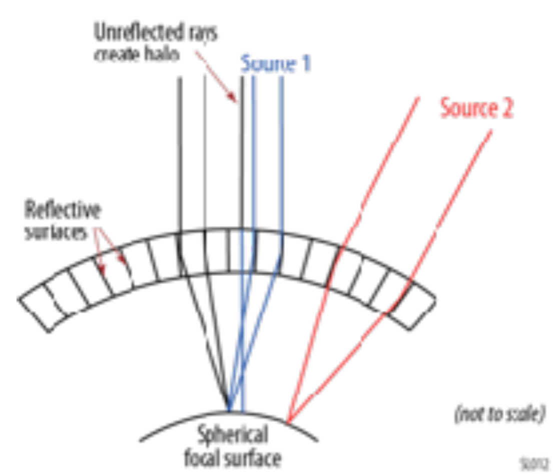
Wide Field Imager (WFI)

- Multi-channel (lobster) optics with CCD focal plane (Angel 1979)
  - MCO commercially available from Photonis
  - CCDs from MIT/Lincoln Labs
- 45 cm focal length
- FoV: 18.6° x 18.6°
- Sensitivity: 10^{-10} erg cm^{-2} s^{-1} (60 s), 4×10^{-12} erg cm^{-2} s^{-1} (10 ks)
- Energy Range: 0.3-5 keV
- Centroid: ≲ 1 arcmin
- Temporal resolution: 2 s



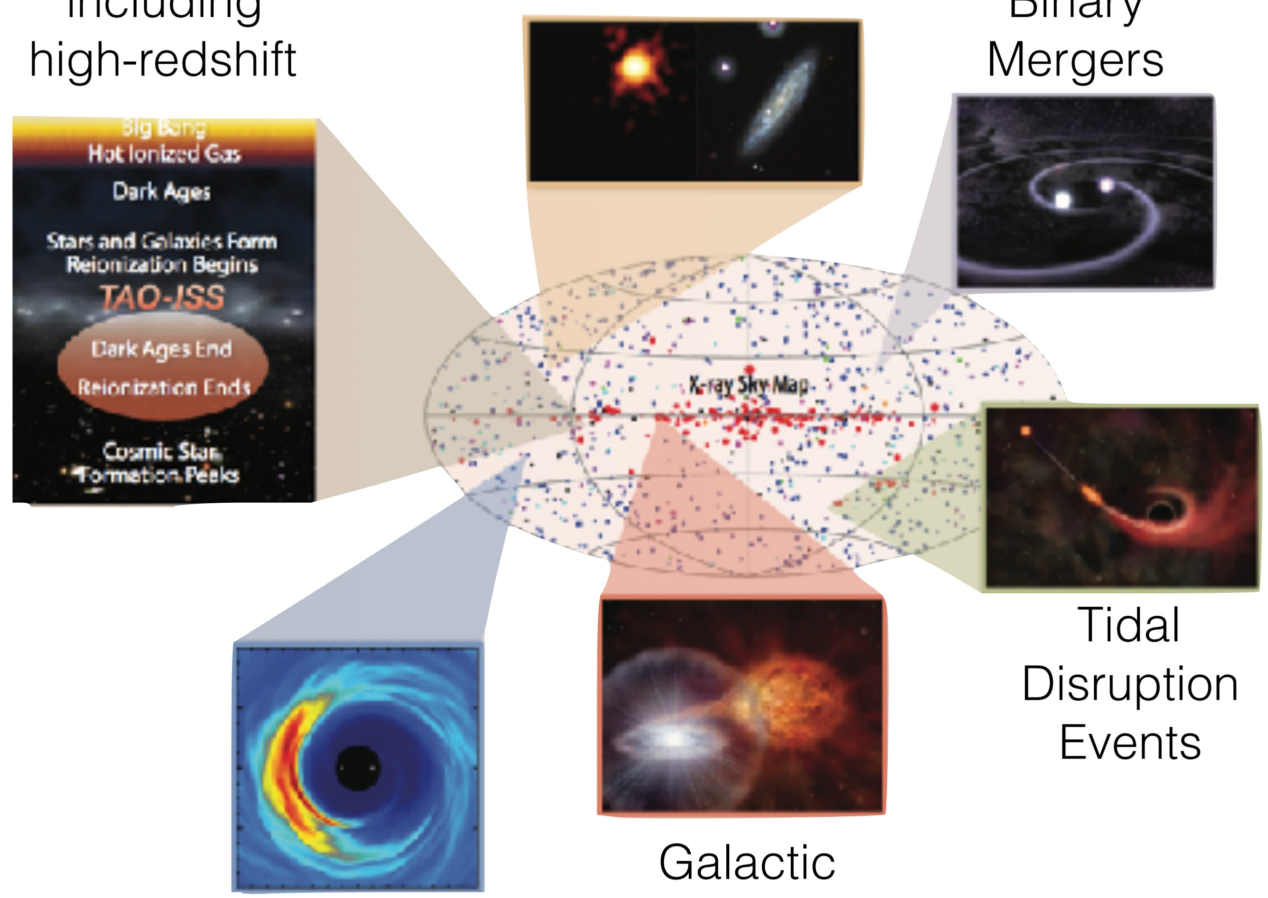






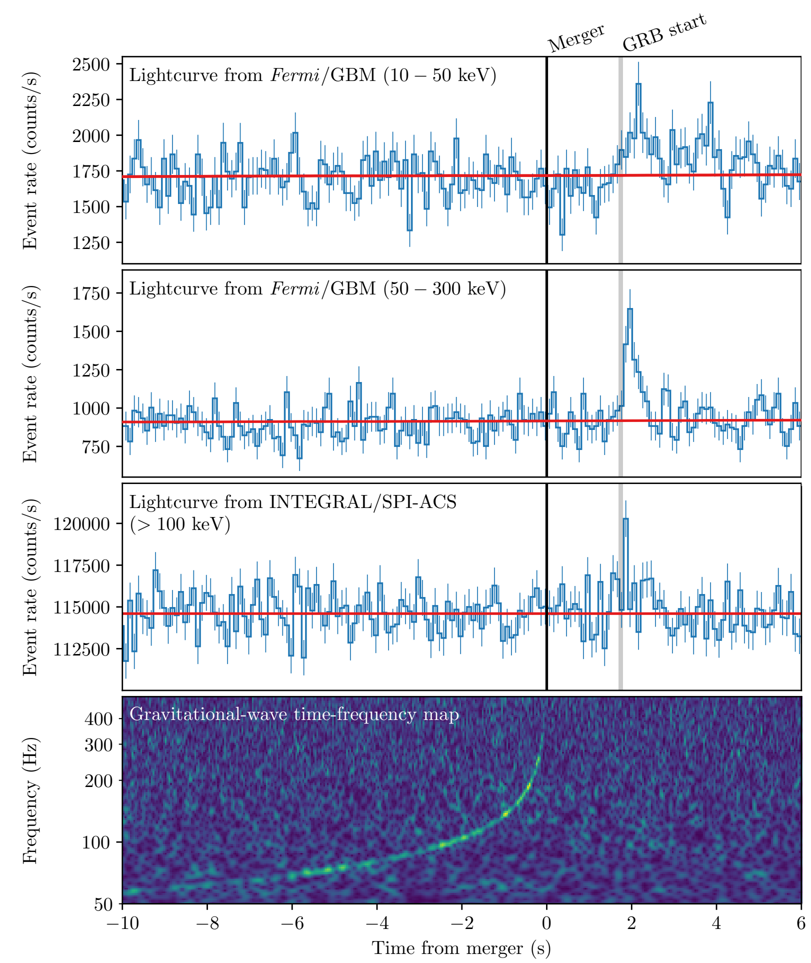
TAO-ISS Science

- X-ray Counterparts to Gravitational Wave Sources
- Highest Sensitivity Survey of the Transient X-ray Sky Ever Performed

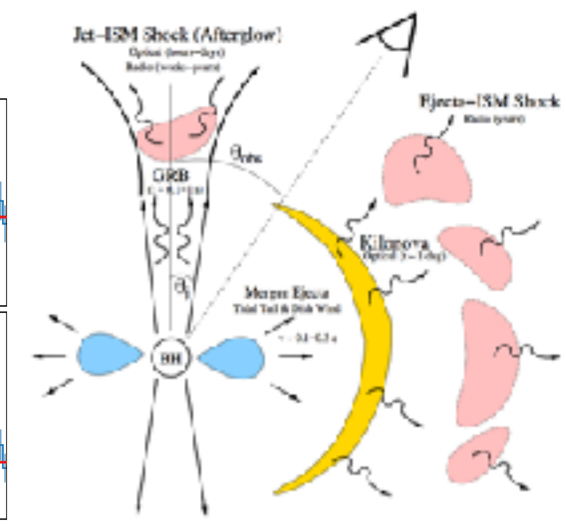


Astrophysical Context of Gravitational Wave Sources

- TAO will detect GW counterparts via
  - GTM short GRBs
  - X-ray transients in LIGO-Virgo localizations
  - X-ray transients in WFI
- Autonomous follow-up observations within seconds - minutes after merger
- TAO will provide high-energy observations of a population of NS-NS mergers, and possibly NS-BH
- Localizations lead to redshift measurements, host galaxies, environments, accretion disk interactions, merger ejecta



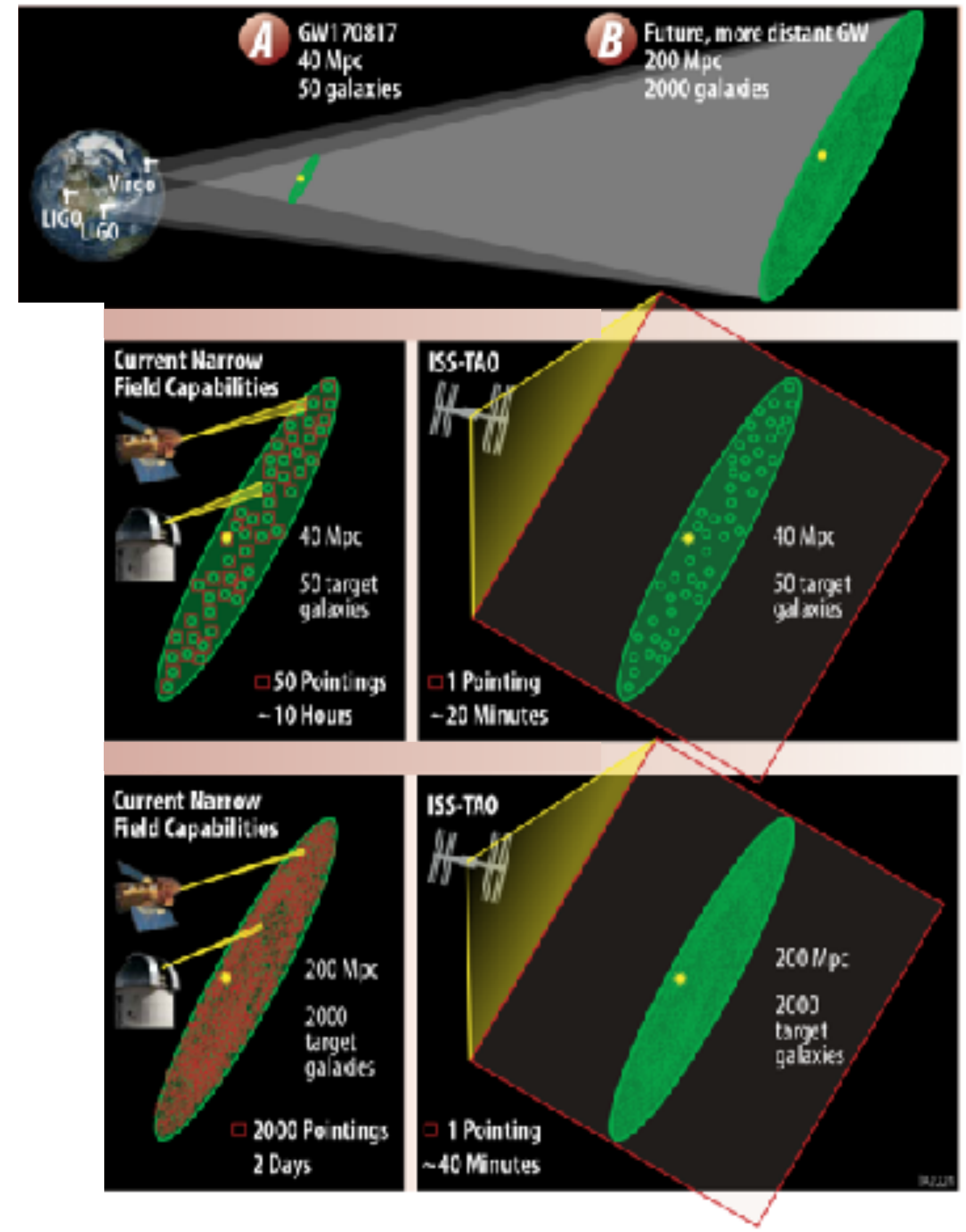
Abbott et al. 2017, ApJL



Metzger & Berger (2012)

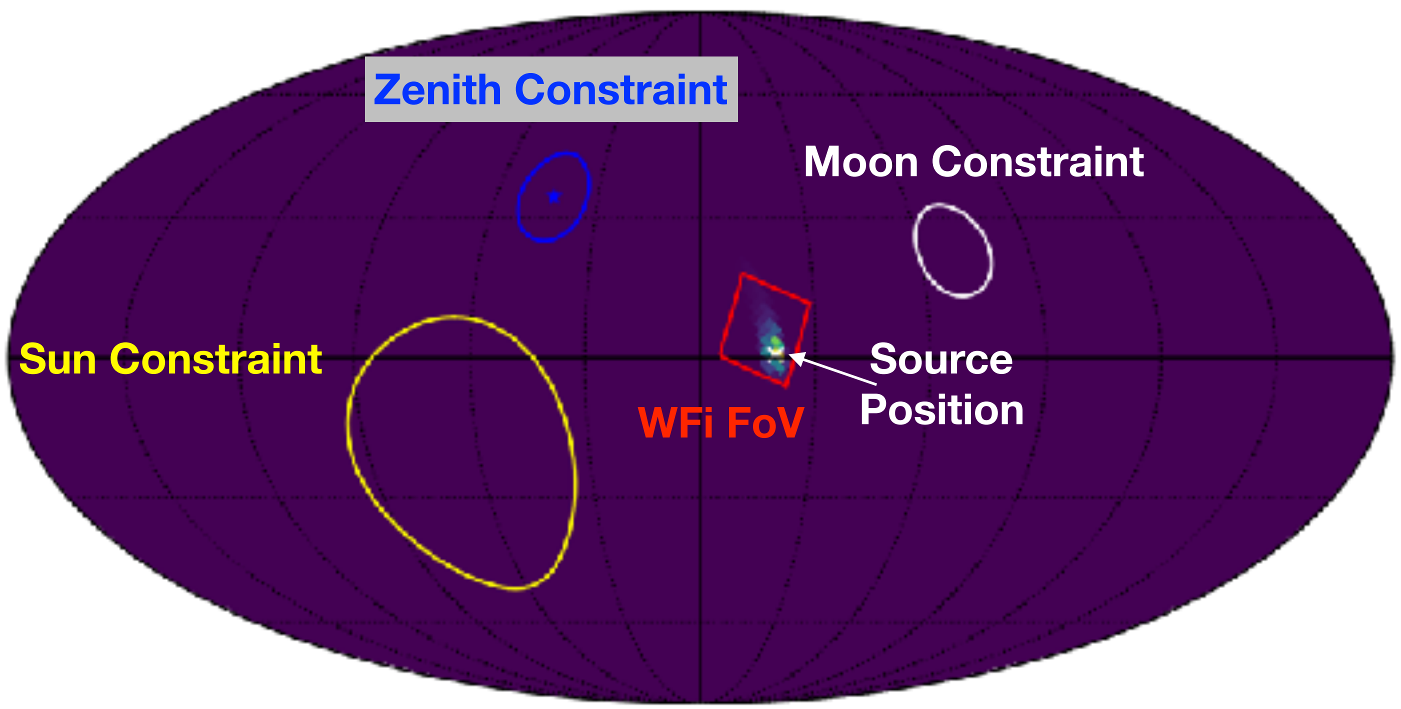
ISS-TAO as an Ideal Instrument for GW Counterparts

- Wide FoV X-ray telescope is an important asset in the era of a high rate of GW triggers
- Source distances will increase as GW detectors become more sensitive
- Galaxy catalogs are less complete as distance increases
- TAO will provide rapid localizations of on-axis sGRBs with it's large FoV without galaxy targeting

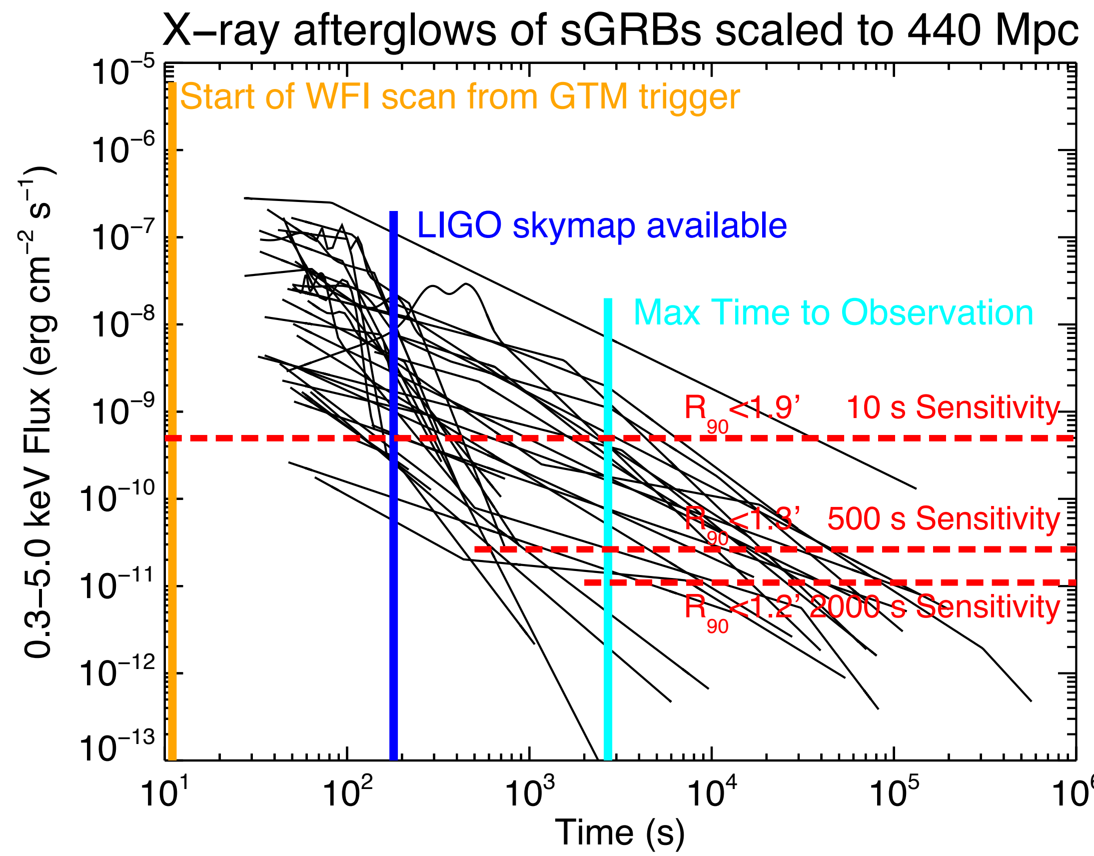


GW Counterparts

Simulated 3-detector LIGO/Virgo Skymap at 2020 Sensitivity



Ongoing simulations to get better fidelity on the TAO mission and instrument requirements and their impact on source rates

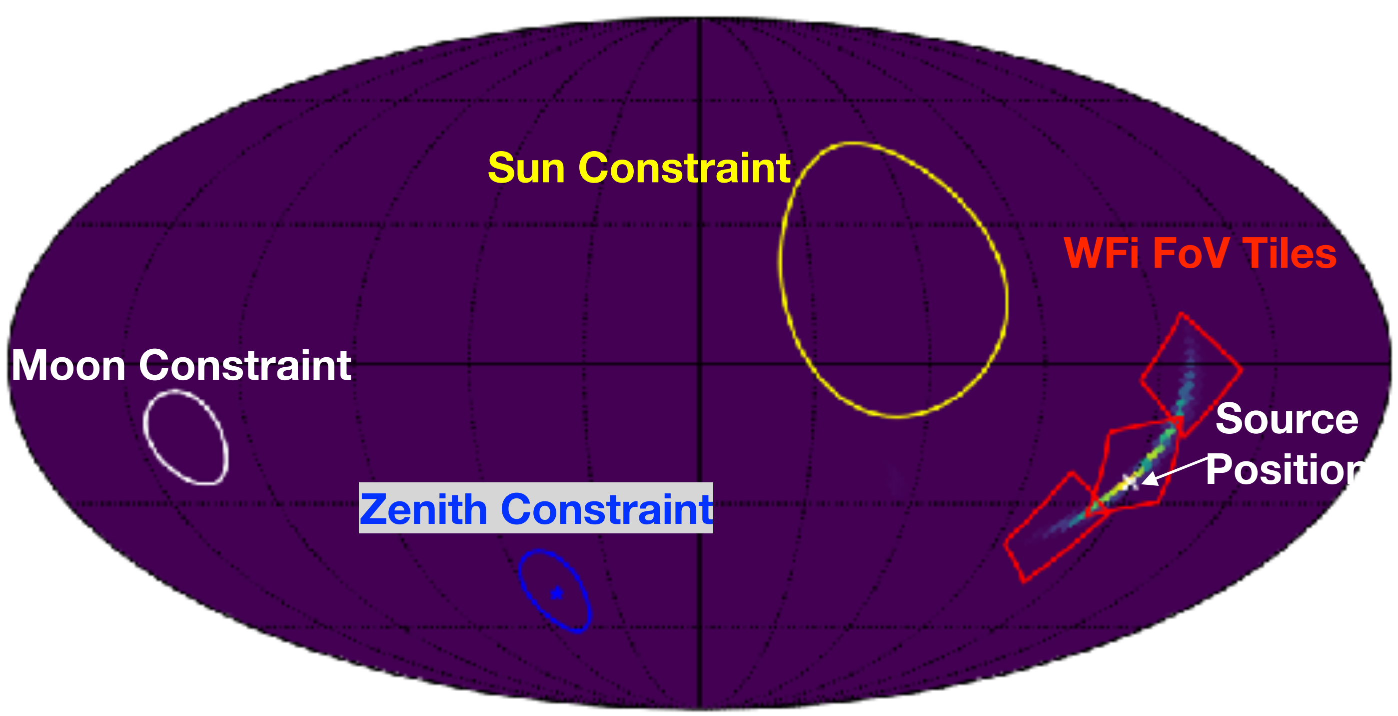


TAO-ISS GW Counterpart Rates:

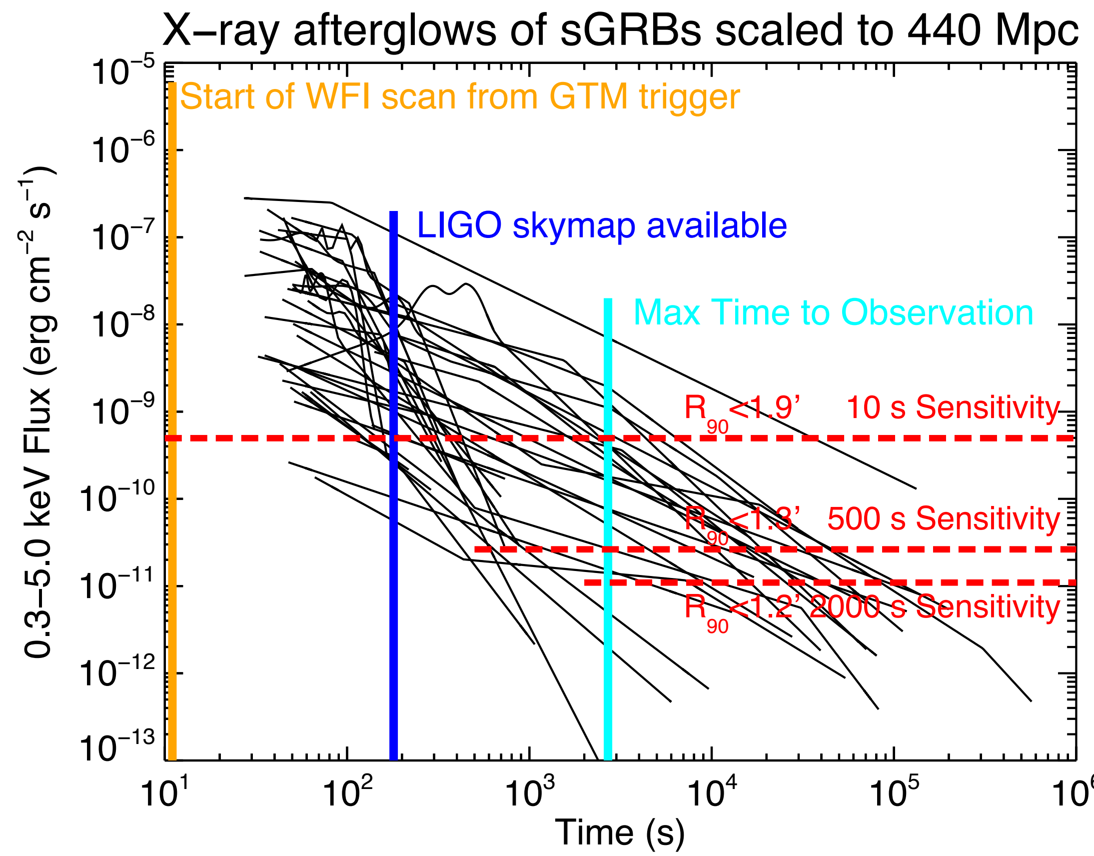
NS-NS: 1-10 yr^{-1}
NS-BH: 8-24 yr^{-1}

GW Counterparts

Simulated 2-detector LIGO/Virgo Skymap at 2020 Sensitivity



Ongoing simulations to get better fidelity on the TAO mission and instrument requirements and their impact on source rates

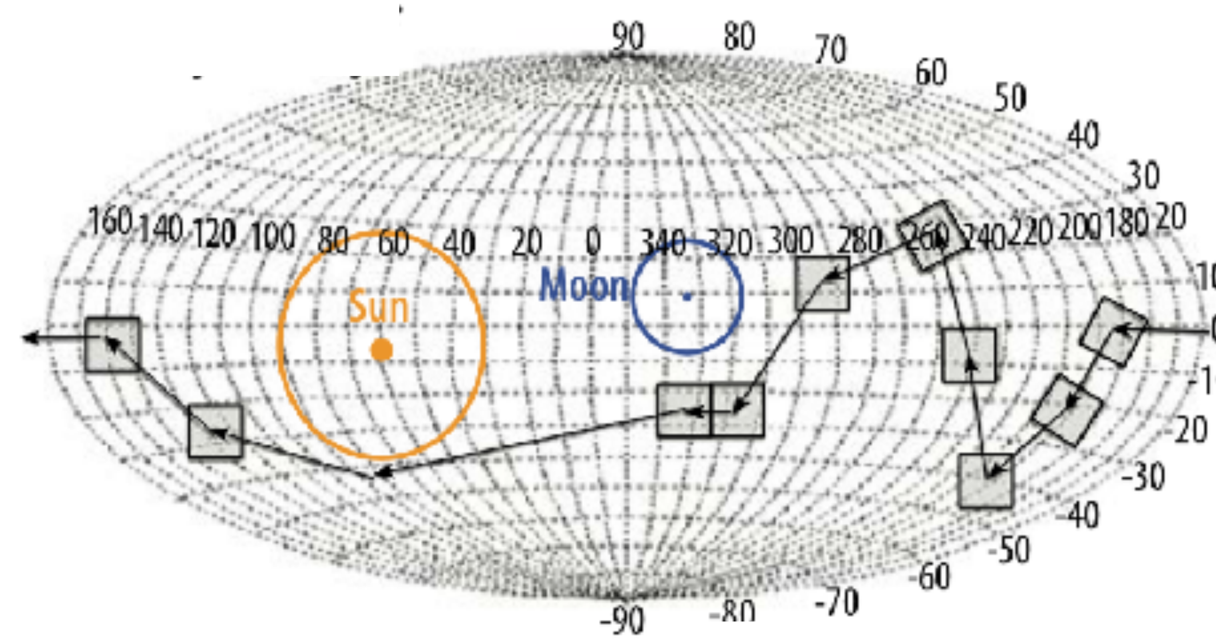


TAO-ISS GW Counterpart Rates:

NS-NS: 1-10 yr^{-1}
NS-BH: 8-24 yr^{-1}

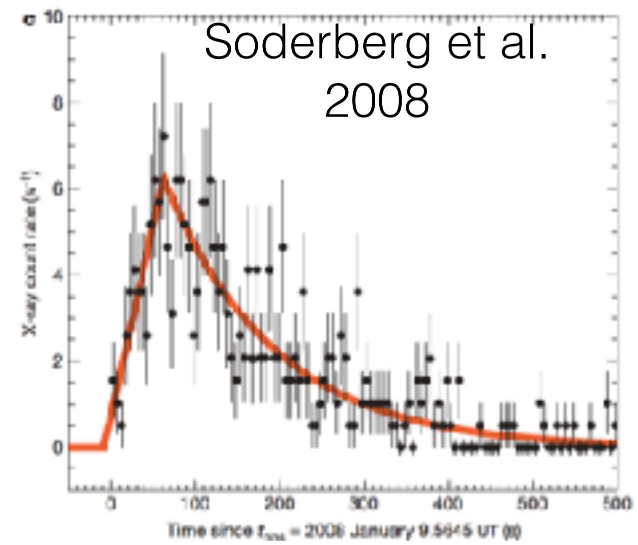
WFI Sky Survey

- When not chasing GW counterparts or other ToOs, TAO will conduct a soft-X-ray survey of the sky
- WFI will observe >50% of sky every 12 hours, 95% of the sky every 6 months
- Monitor variable sources (AGN, binaries, galactic flaring sources) on regular cadence
- Discover new transients and automatically follow up some of them

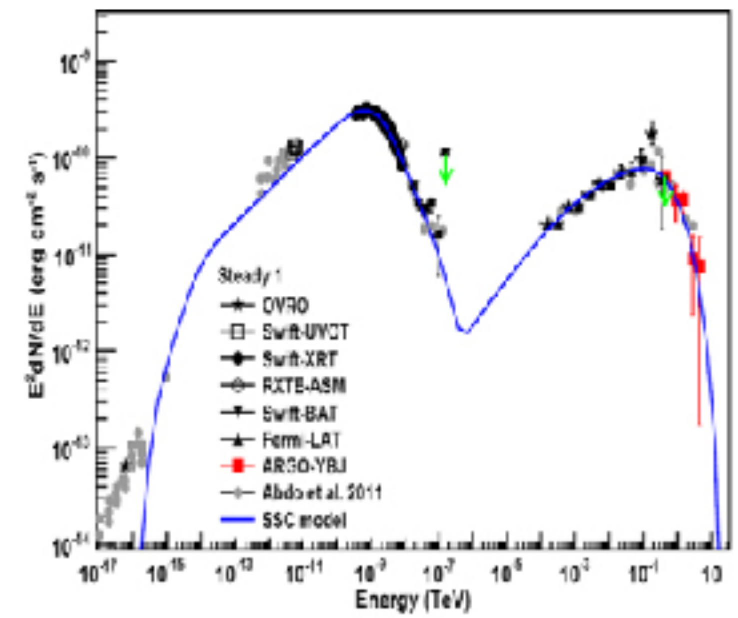


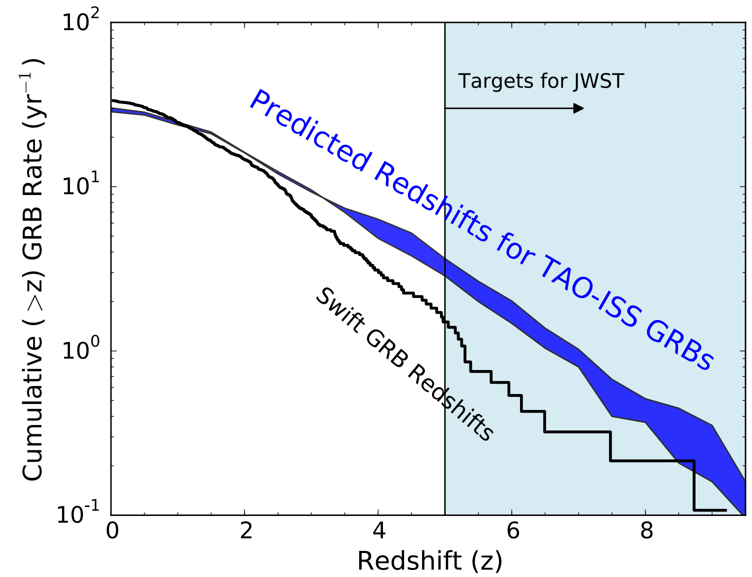
ISS-TAO Transient Sources

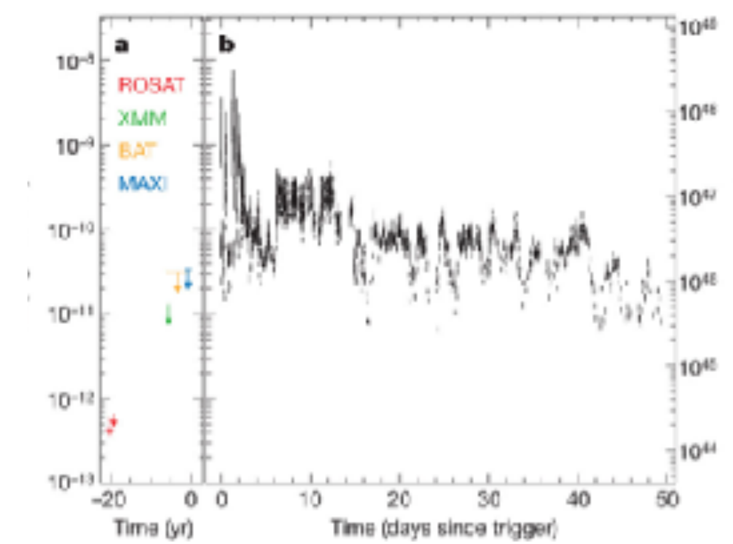
- Gamma-ray Bursts
- Core Collapse SNe shock breakouts
- Tidal Disruption Events
- AGN/Blazar Monitoring
- Stellar Super Flares
- Novae
- Thermonuclear Bursts
- Binaries
- Counterparts to FRBs?
- Counterparts to neutrinos?



Soderberg et al. 2008



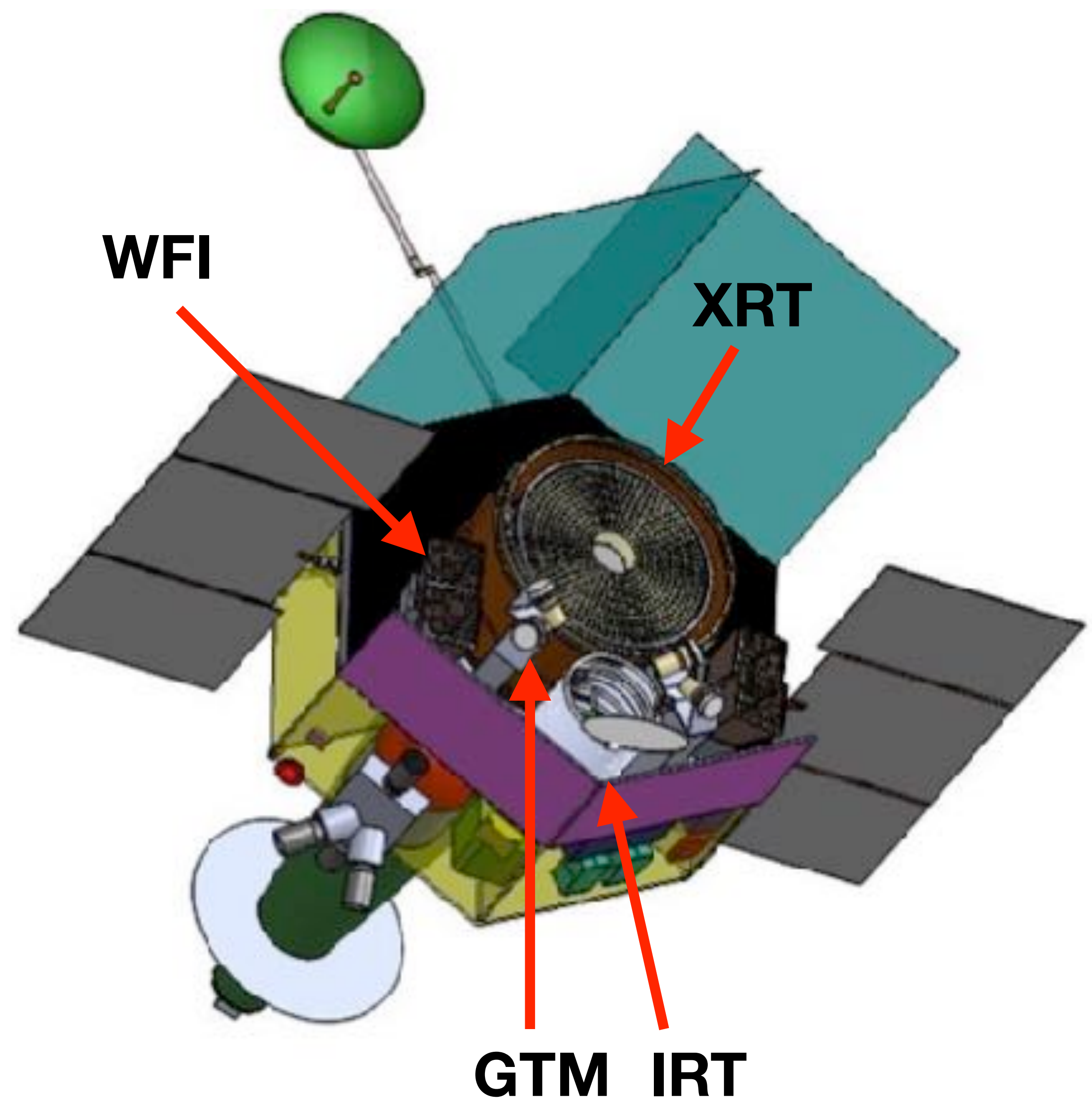




Burrows et al. 2011

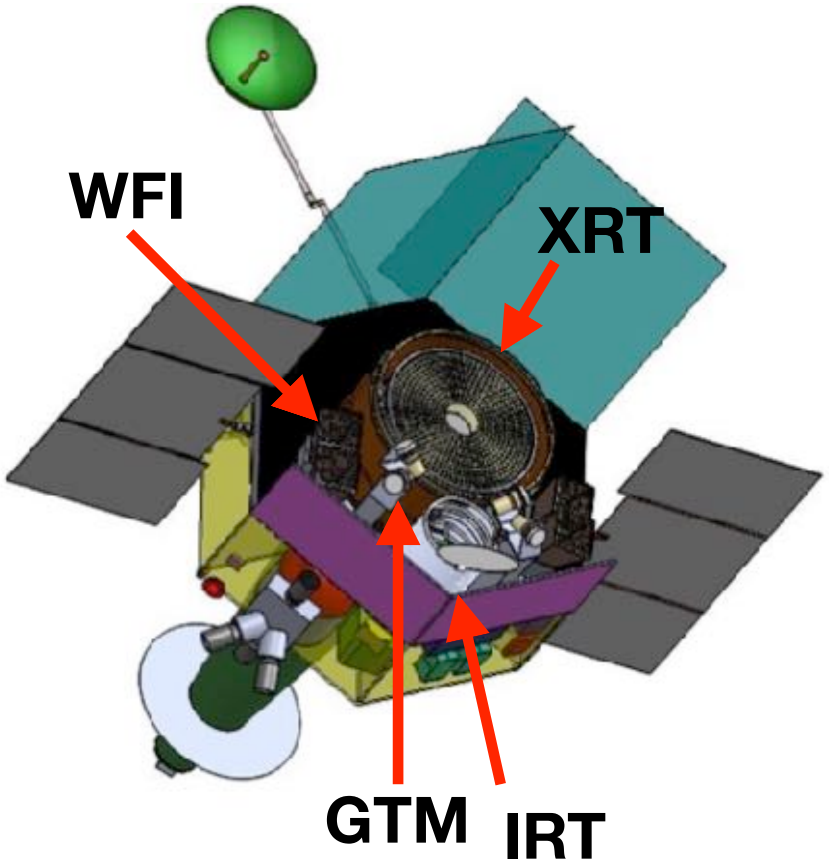
TAP Mission

- Probe (<$1B including launch)
- Launch ~2028, 5 yr mission (goal 10 yrs)
- Probably Low Earth orbit (600 km, <10 inclination)
  - Exploring MEO & L2
  - Field of Regard, SAA, backgrounds, communication tradeoffs
- Autonomous rapid-response (~50° in 70 sec) observatory (like *Swift*) with multi-wavelength detection and follow-up. Also able to respond quickly to uplinked targets.
- When not chasing transients, TAP will monitor sources of interest, conduct IR and/or X-ray sky surveys



TAP Instruments

- Wide Field Imager (WFI)
- X-ray Telescope (XRT)
- Infrared Telescope (IRT)
- Gamma-ray Transient Monitor (GTM)

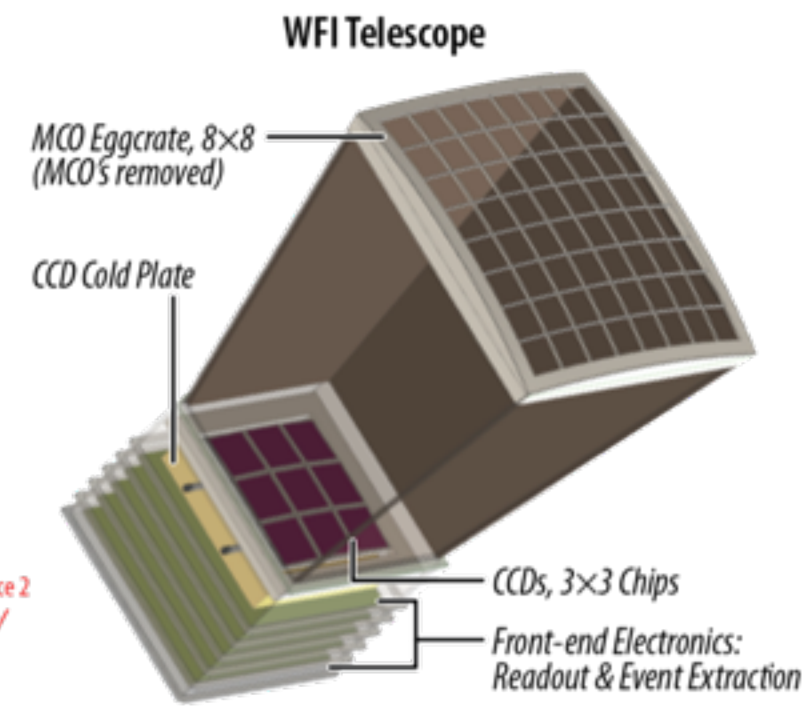


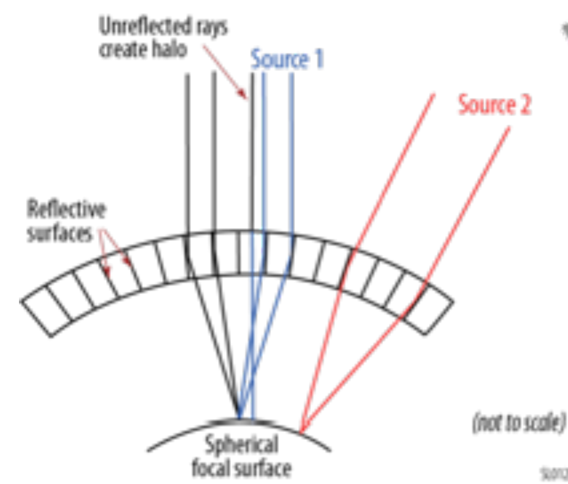
Parameter	WFI	XRT	IRT	GTM
FoV	4 x 19x19° (0.5 sr)	1° square	1x1°	4 π sr
Aperture Diameter	n/a	130 cm; fl=500 cm	70 cm	n/a
PSF/FWHM	8 arcmin	3 arcsec	1 arcsec	n/a
Energy Range	0.3 - 5 keV	0.5 - 6 keV	0.6 - 2.5 μm	10 keV - 1 MeV
Sensitivity	10^{-11} erg/sec cm^2 (2k sec)	2x10^{-15} erg/sec cm^2 (2k sec)	23 mag (300 sec)	1 ph/cm^2/s
Mass (MEV)	140 kg	256 kg	86 kg	29 kg
Power (MEV)	276 W	370 W	119 W	25 W
Telemetry (MEV)	5 GB/day	0.3 GB/day	0.8 GB/day	0.09 GB/day
TRL	6	5	6	6

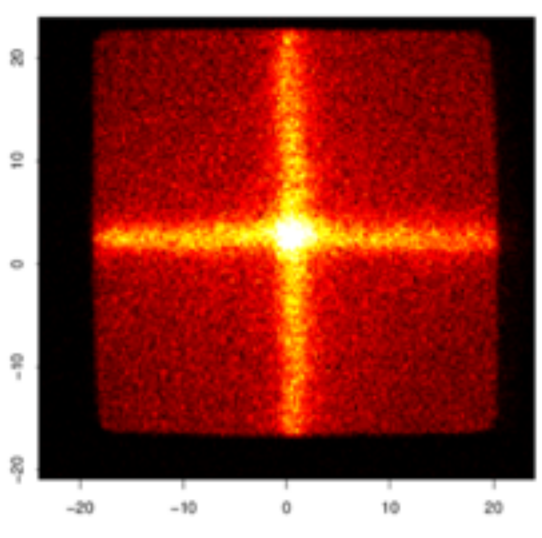
Wide Field Imager (WFI)

Multi-channel (lobster) optics (MCO) with curved focal plane covered by CCDs

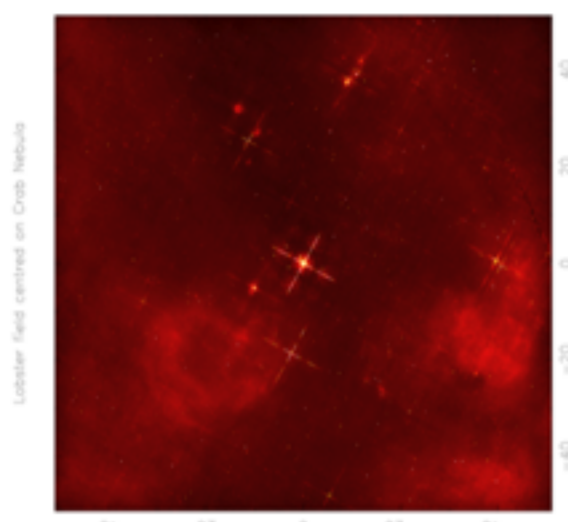
Parameter	WFI
FoV	4 x 19x19° (0.5 sr)
Aperture Diameter	n/a
PSF/FWHM	8 arcmin
Energy Range	0.3 - 5 keV
Sensitivity	10^{-11} erg/sec cm^2 (2k sec)
Mass (MEV)	140 kg
Power (MEV)	276 W
Telemetry (MEV)	5 GB/day
TRL	6

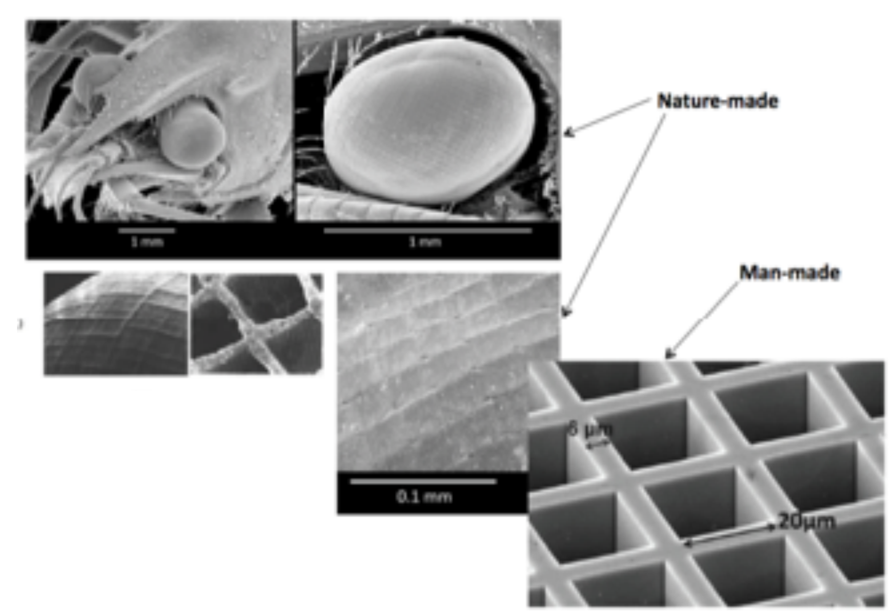






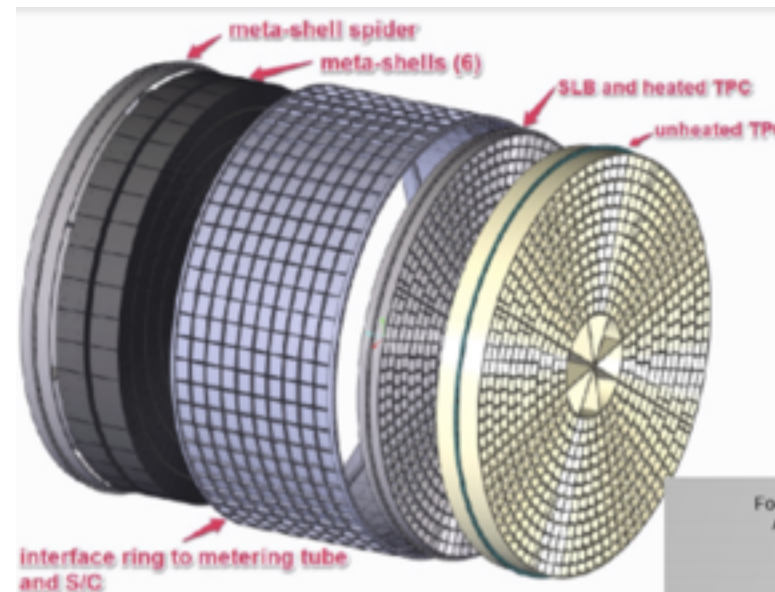
PSF of MCO measured on X-ray beam line (R. Willingale, U. Leicester) FWHM=7 arcmin

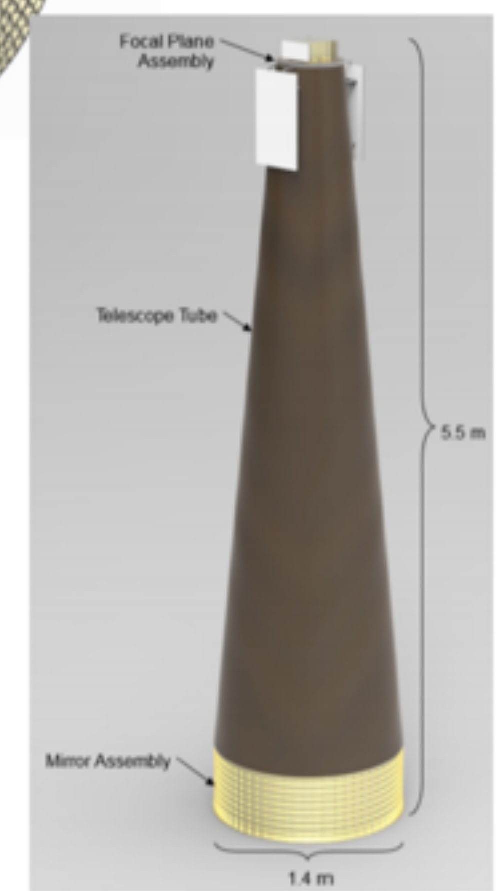




X-ray Telescope (XRT)

Parameter	XRT
FoV	1° square
Aperture Diameter	130 cm; fl=500 cm
PSF/FWHM	3 arcsec
Energy Range	0.5 - 6 keV
Sensitivity	2×10^{-15} erg/sec cm^2 (2k sec)
Mass (MEV)	256 kg
Power (MEV)	370 W
Telemetry (MEV)	0.3 GB/day
TRL	5

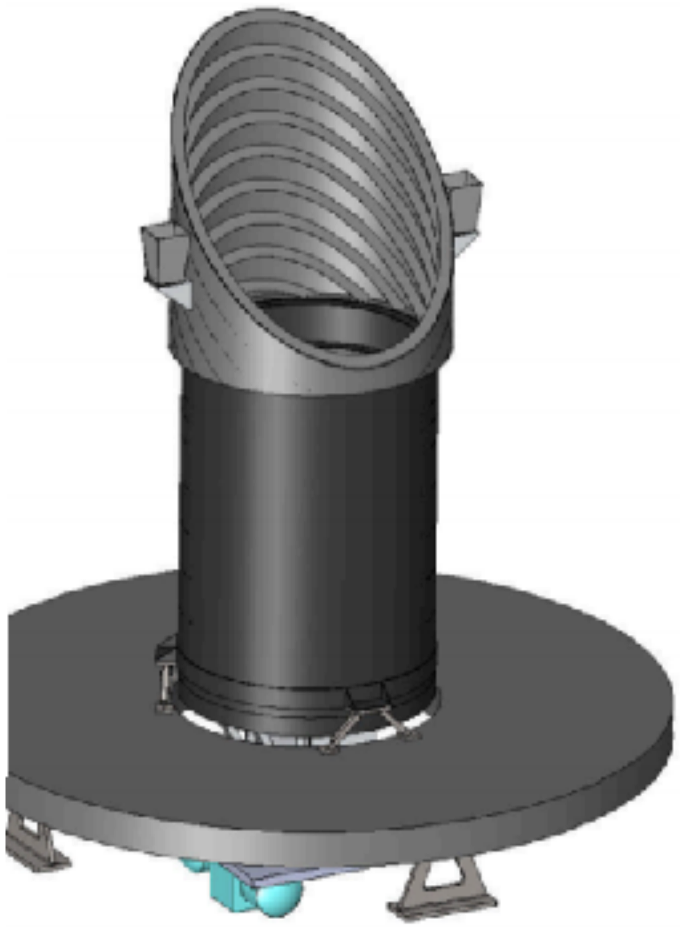




- Very sensitive grazing incidence X-ray telescope with single crystal silicon mirrors
- Current design is the same as *Star-X* concept (PI: Will Zhang, GSFC)
- XRT will enable arcsec localization, detailed follow-up of transients, and deep pointed observations

Infrared Telescope (IRT)

Parameter	IRT
FoV	1x1°
Aperture Diameter	70 cm
PSF/FWHM	1 arcsec
Energy Range	0.6 - 2.5 μm
Sensitivity	23 mag (300 sec)
Mass (MEV)	86 kg
Power (MEV)	119 W
Telemetry (MEV)	0.8 GB/day
TRL	6



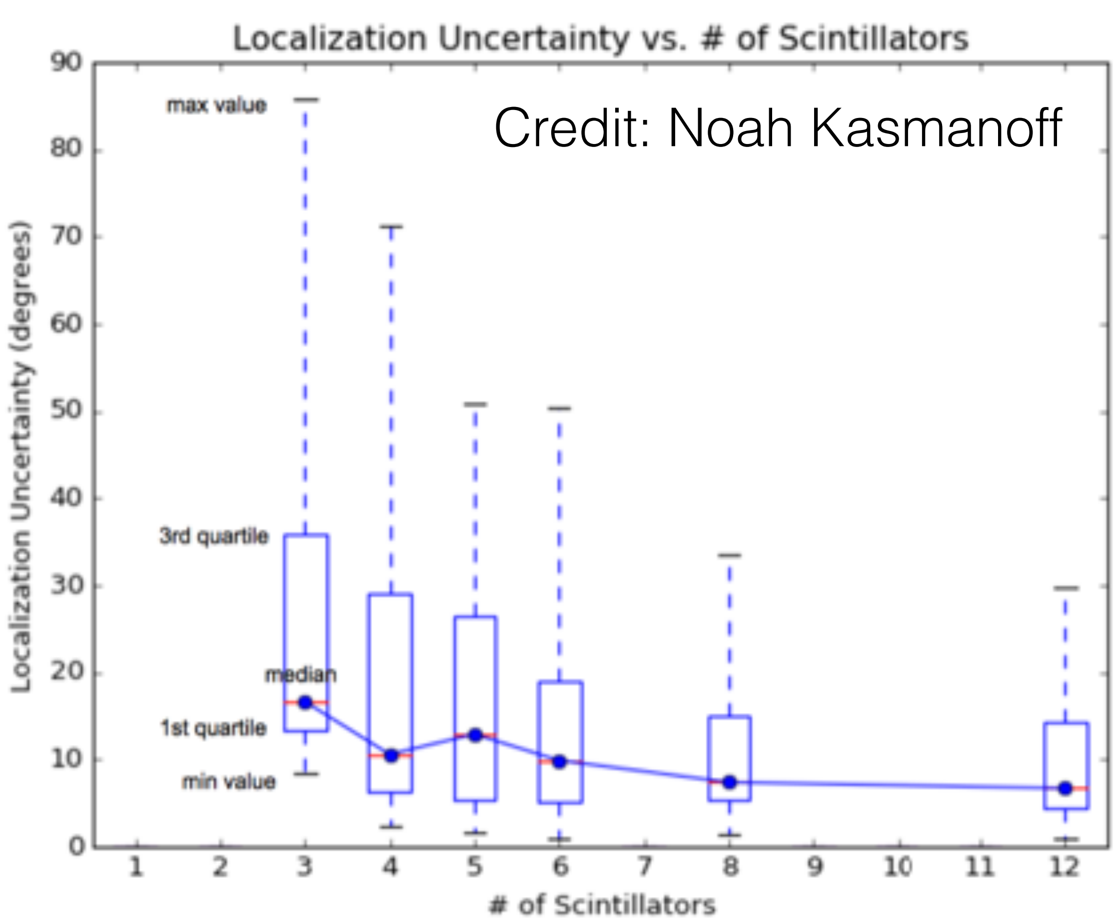
Current design includes door, rather than sun shade

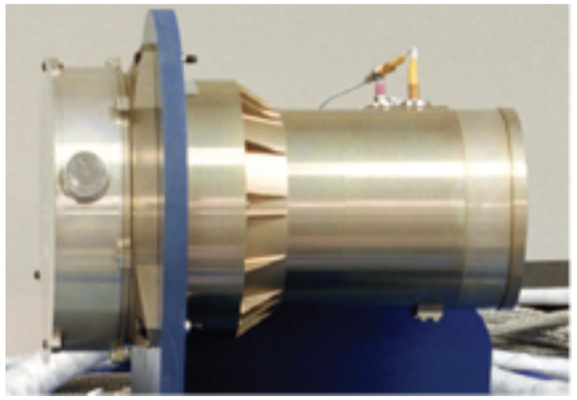
- Sensitive NIR telescope with 3 broad bandpasses, and R~30 spectrograph
- Enables sub-arcsec localization of transients, and rough redshifts

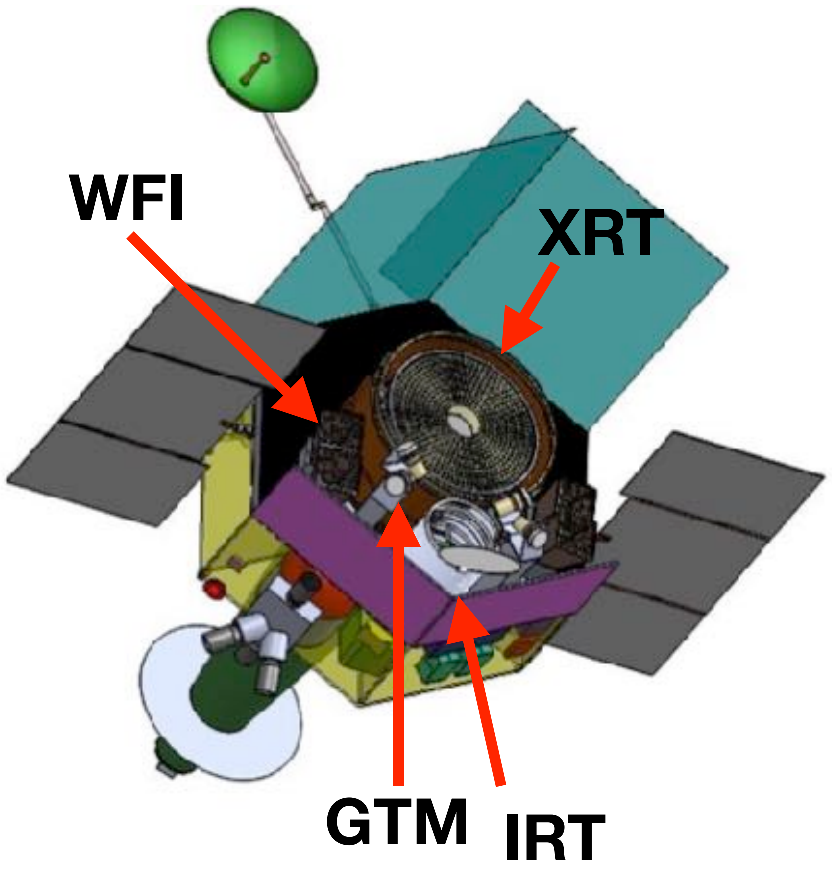
Gamma-ray Transient Monitor (GTM)

Parameter	GTM
FoV	4 π sr
Aperture Diameter	n/a
PSF/FWHM	n/a
Energy Range	10 keV - 1 MeV
Sensitivity	1 ph/cm^2/s
Mass (MEV)	29 kg
Power (MEV)	25 W
Telemetry (MEV)	0.09 GB/day
TRL	6

- Based upon *Fermi*-GBM NaI detectors
- Configuration will probably include 8 detectors
- Onboard triggering in 3 timescales and 3 energy ranges
- Continuous data and triggered datasets (much like GBM)

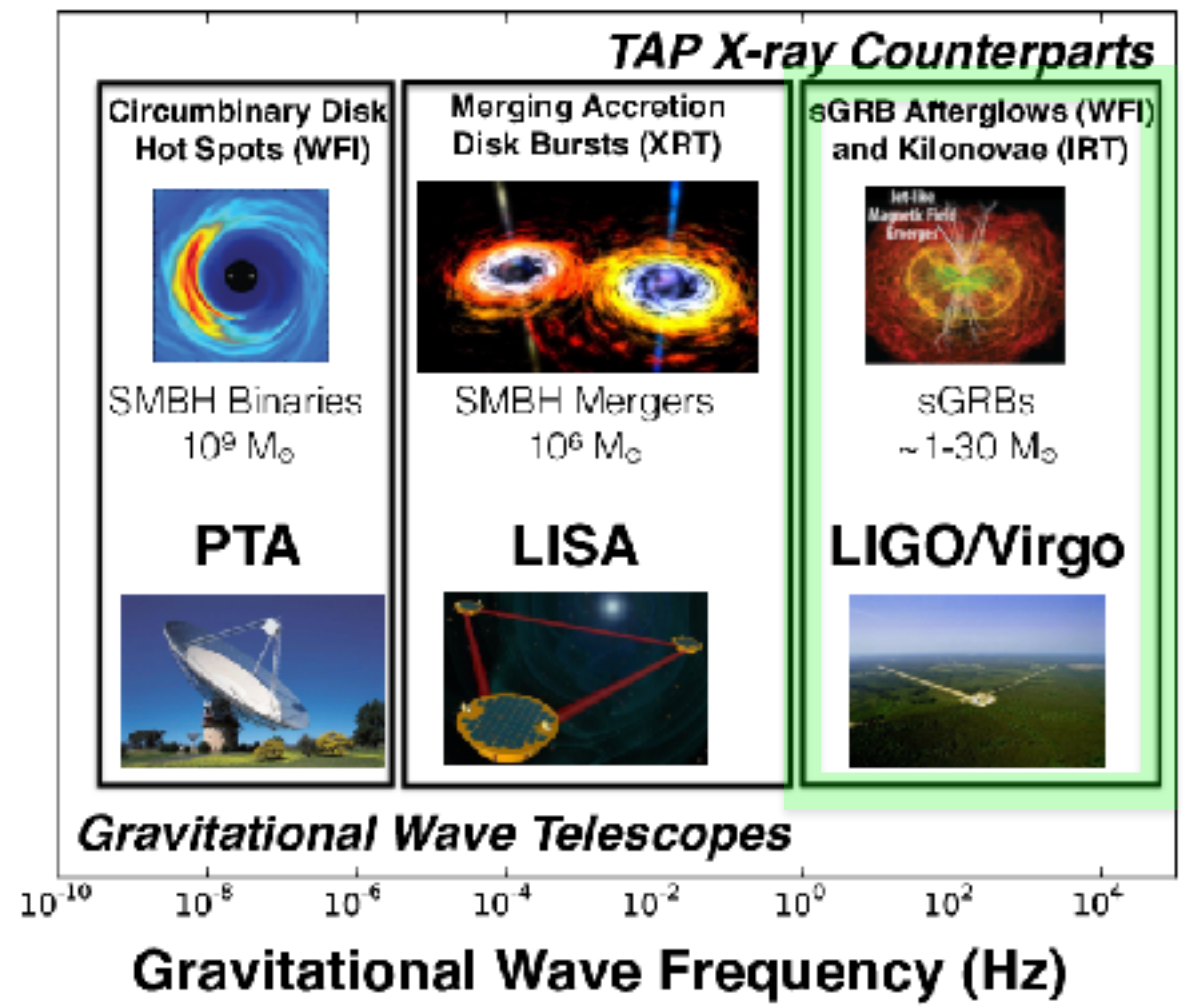






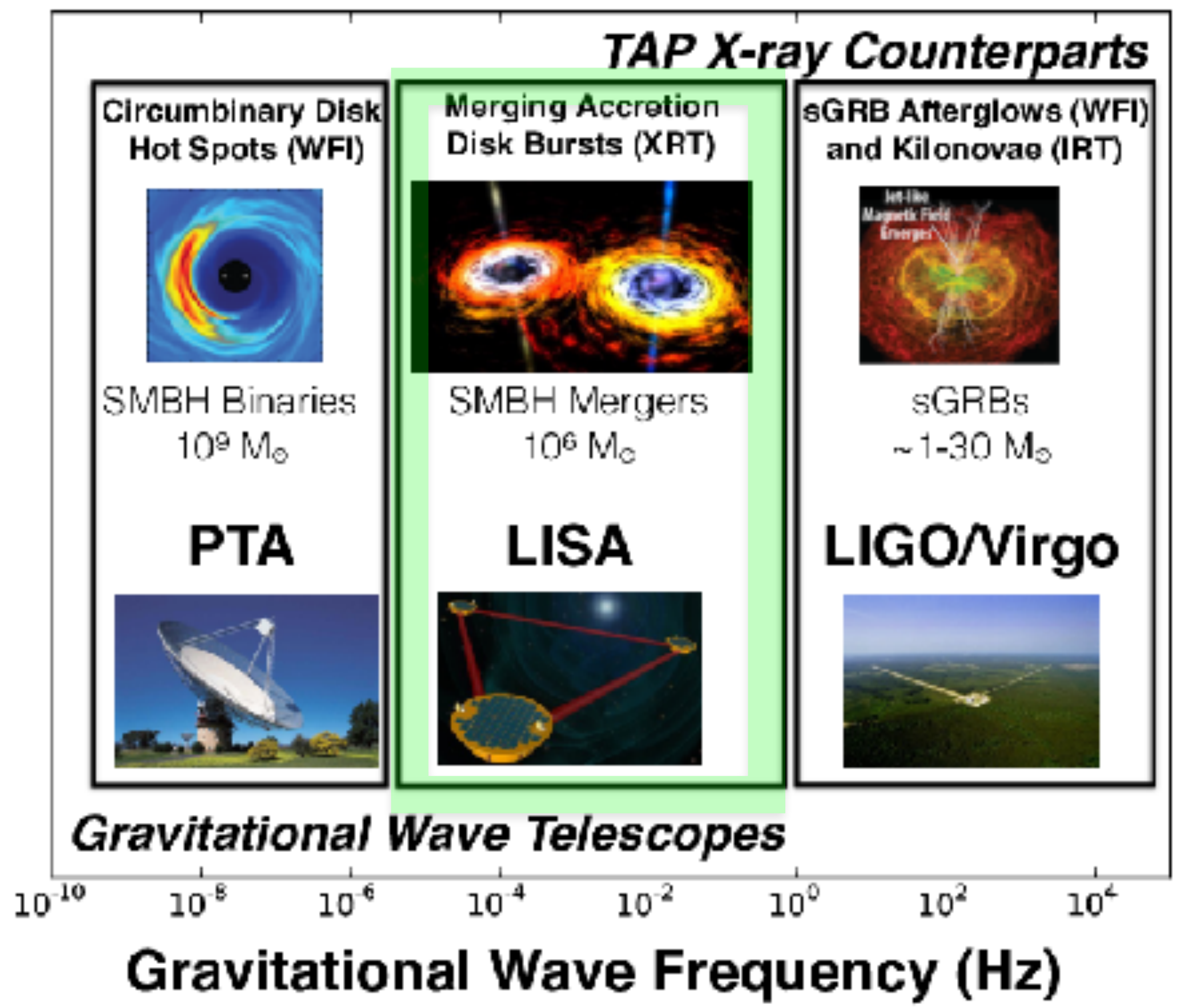
TAP Science: Gravitational Wave Counterparts

- LIGO/Virgo
  - GTM - short duration GRB p
  - WFI - X-ray afterglow follow- from GTM or GW localizatior arcmin positions
  - XRT - better localize GRB ar
  - IRT - even better localize, 3- low-resolution spectrum anc counterpart
  - 6-9 per year, x10 (IRT)



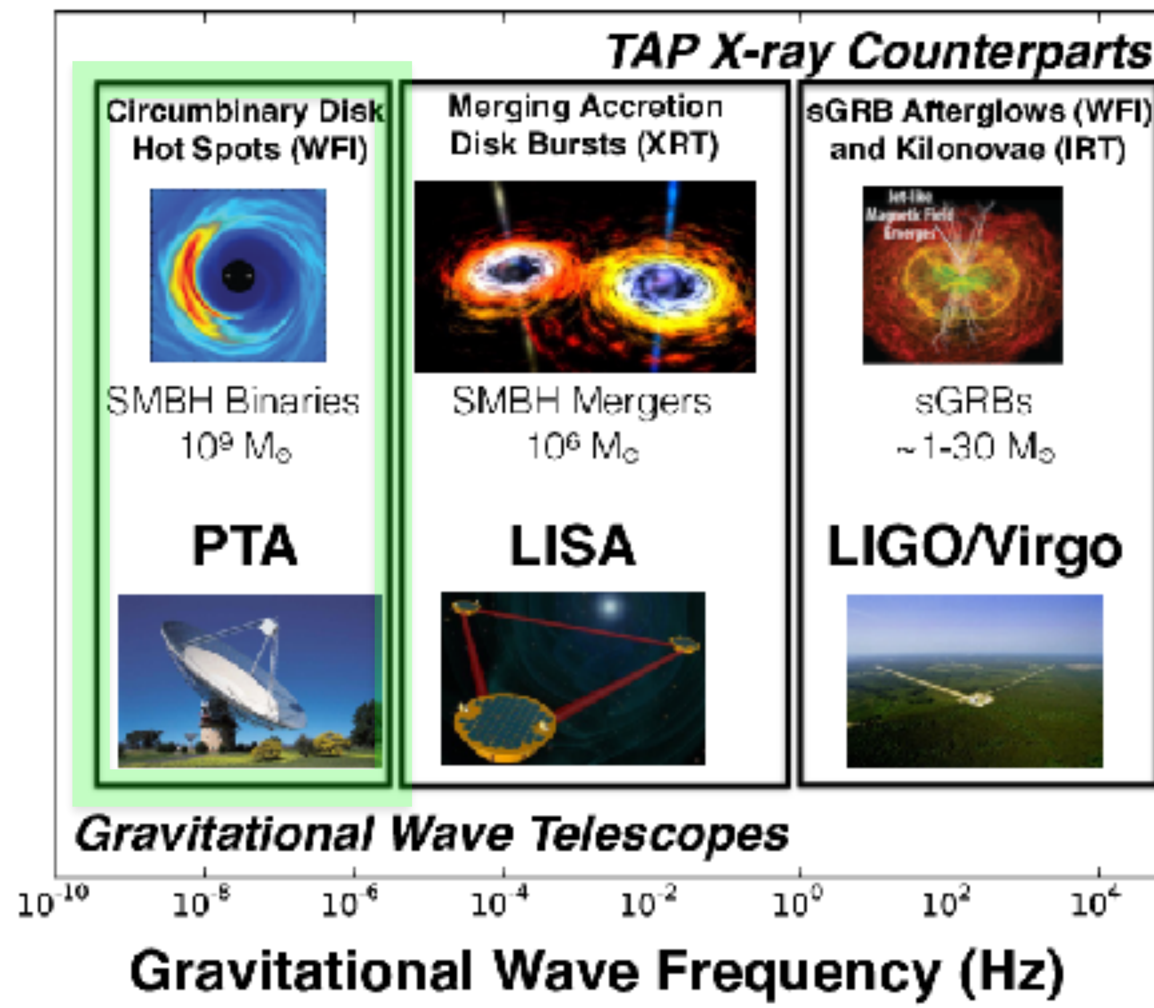
TAP Science: Gravitational Wave Counterparts

- LISA
  - will provide an early warning prior to SMBH mergers, allo observations with XRT, IRT
  - gas around system should p
  - peak luminosities comparab many times Eddington), with over a few dynamical times typical 10^7 $M_\odot$)
  - 10 - 100 yr^{-1} depending on f et al. 2016) (speculative)

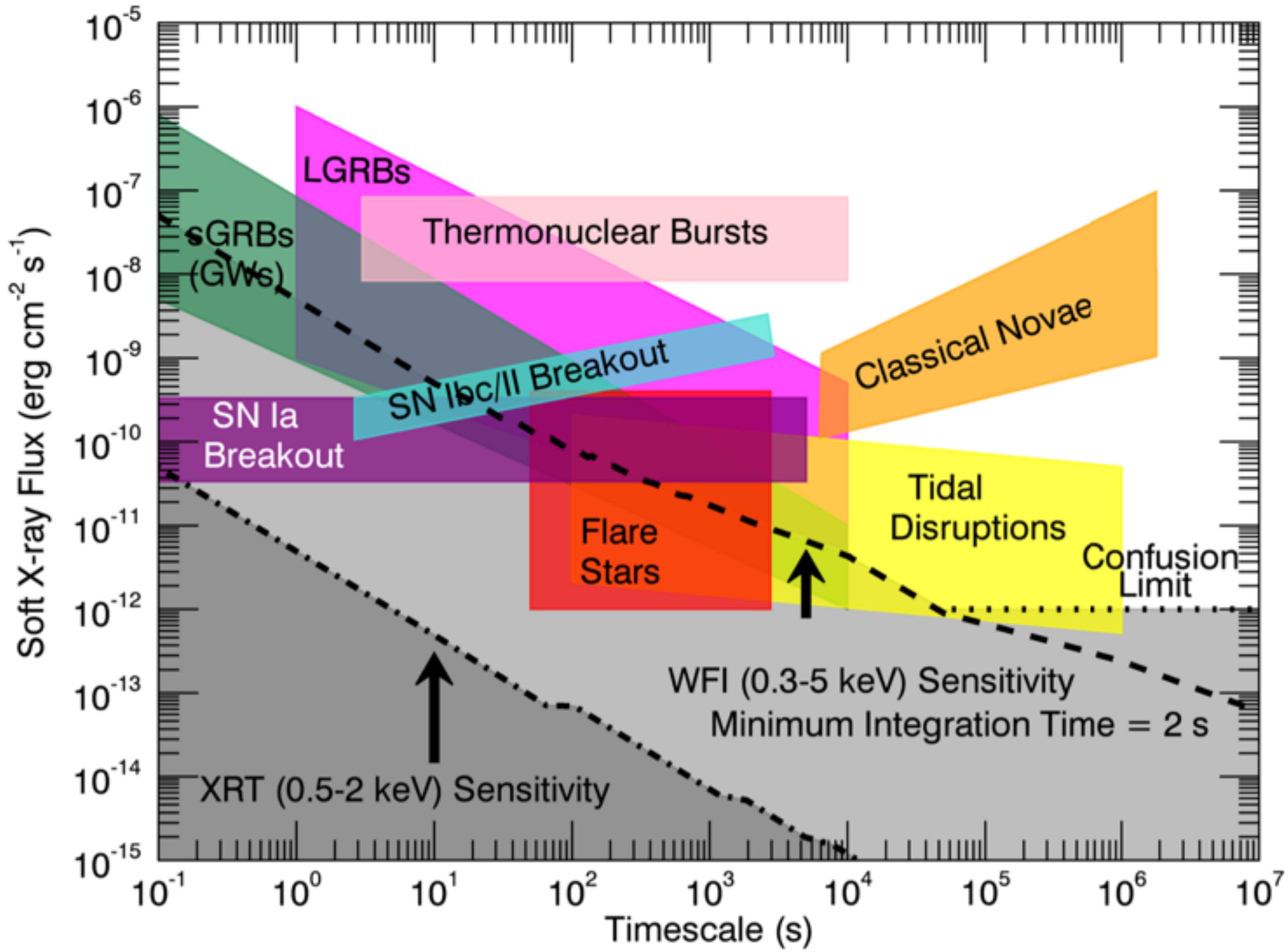


TAP Science: Gravitational Wave Counterparts

- Pulsar Timing Arrays (PTAs)
  - AGN binaries with orbital pe
periodicity in X-ray
  - WFI sky survey will provide f
enable searches
  - Distinguishing periodicity fro
challenge, but large sample
characterize normal behavio
  - ~10 per year (speculative)

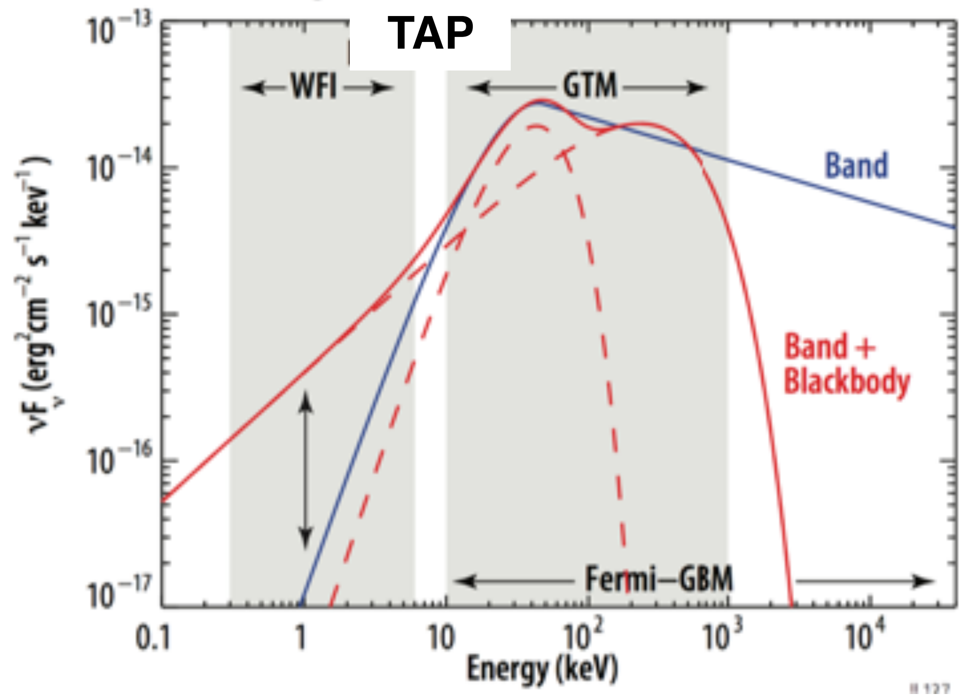


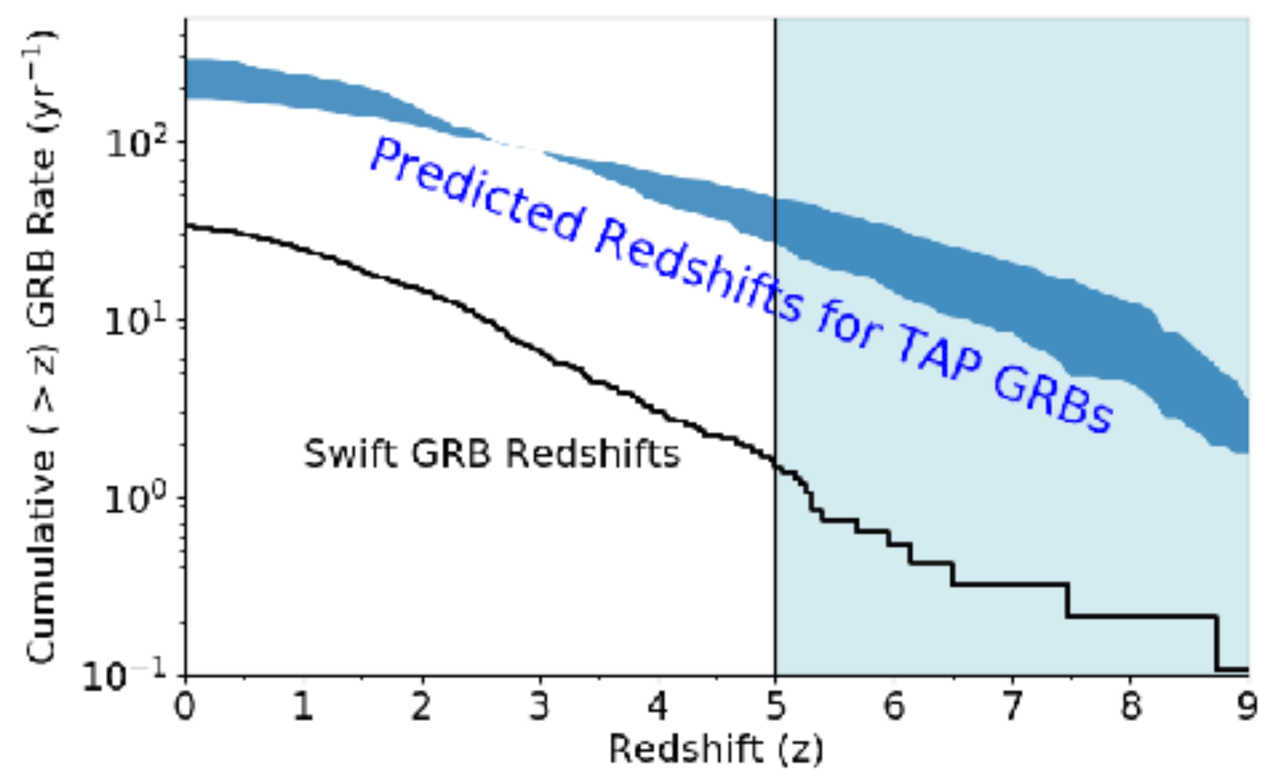
TAP Science:Transients



TAP Science:Transients High-Redshift GRBs

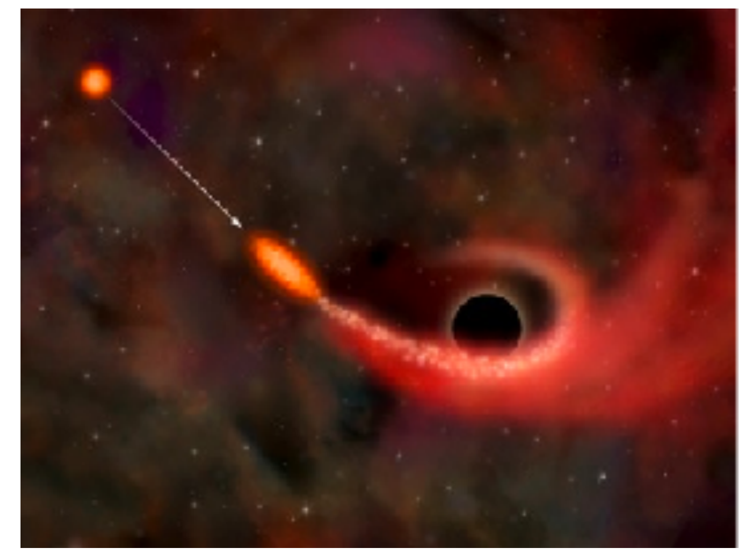
- TAP WFI detects prompt emission and afterglows
- Immediate follow-up with WFI/XRT/IRT allows accurate localization
- IRT will measure spectrum, and determine redshift within minutes, informing ground-based observers to take high-res spectra
- TAP will increase the number of high-z GRBs by an order of magnitude providing sources to probe cosmic chemical evolution
- ~350 GRBs per year, ~30 (z>5)

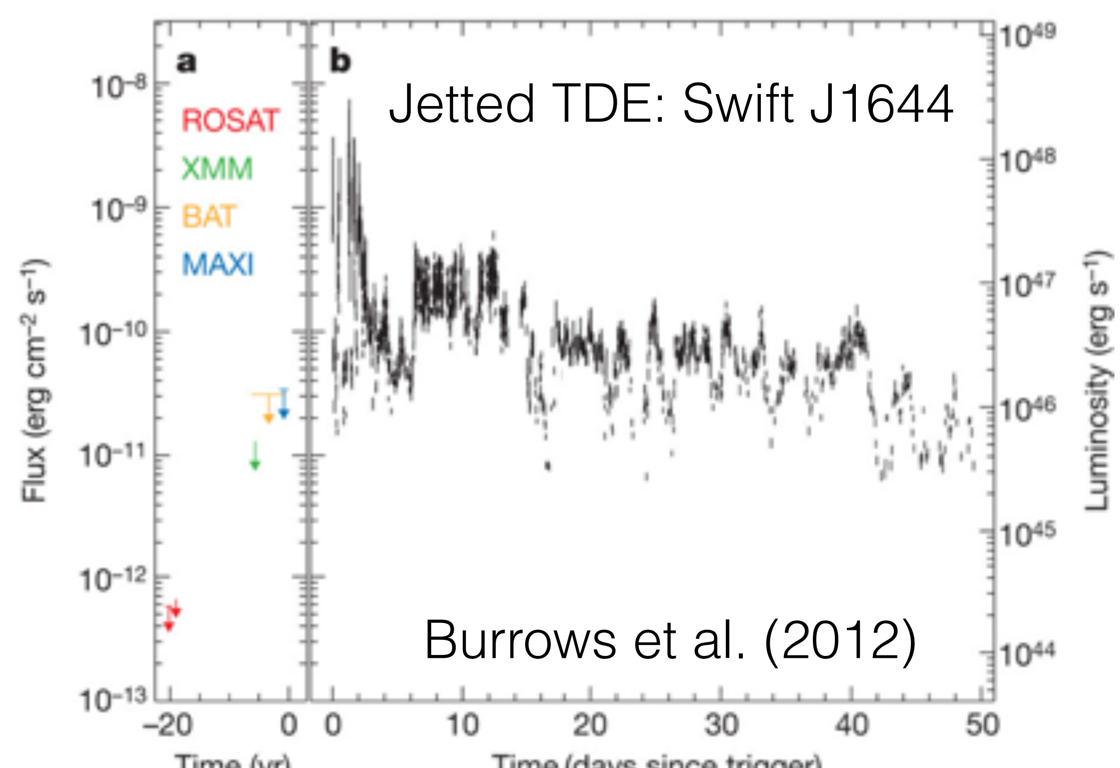




TAP Science: Transients Tidal Disruption Events

- WFI sky monitoring will be sensitive to new TDEs (both jetted and non-jetted) and monitor them as they fade
  - ~20 per year (jetted)
  - ~60 per year (non-jetted)
- XRT will be sensitive to non-jetted TDEs to larger volumes at rate of ~200 per year



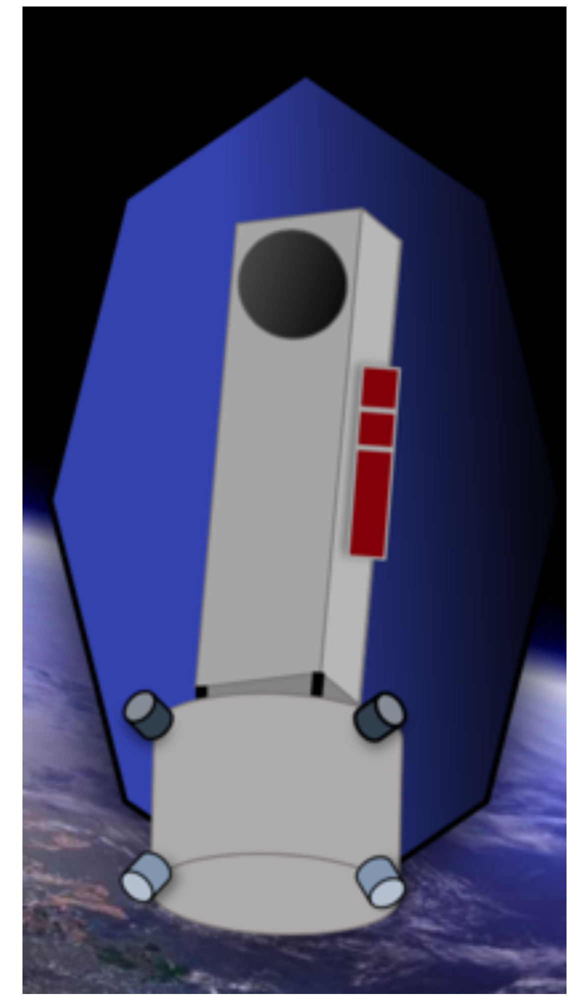


TAP Science: Transients

- Other topics include:
  - Supernova shock breaks
    - duration and temperature of the outburst are a diagnostic of the radius of the progenitor star
    - ~4 (WFI), ~20 (XRT) per year
  - multi-wavelength AGN monitoring
    - hundreds detected daily and thousands weekly in WFI/XRT/IRT
  - Supernovae monitoring (XRT, IRT)
  - Galactic transients (novae, thermonuclear bursts, stellar flares, CVs, binaries, magnetars)

Nimble

- SMEX concept for 2019 opportunity
- Science
  - Primary science
    - BNS merger GW counterparts
      - GRBs
      - Kilonovae
  - Secondary science
    - high redshift GRBs
    - transients
    - characterizing transiting exoplanet
- Rapid slewing, rapid communication spacecraft in sun-synchronous orbit

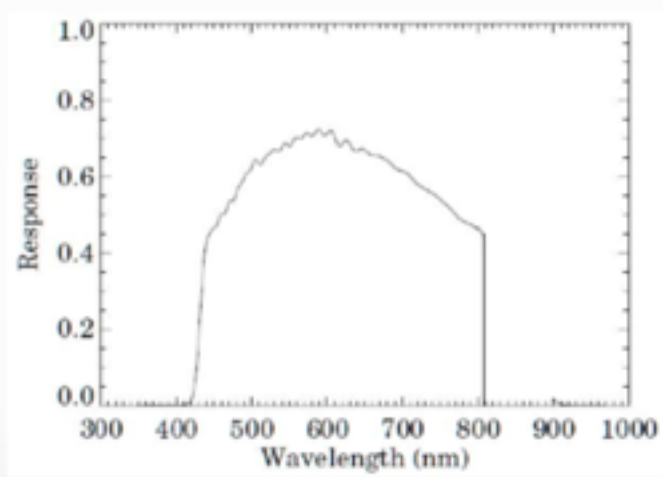


PI: J. Schlieder

Nimble Instruments

- High-energy All-sky Monitor (HAM) - BurstCube-like detectors
- Small UV Optical IR Telescope (SUVOIR)
  - simultaneous multi-band + prism narrow-field telescope
  - wide-field of view telescope

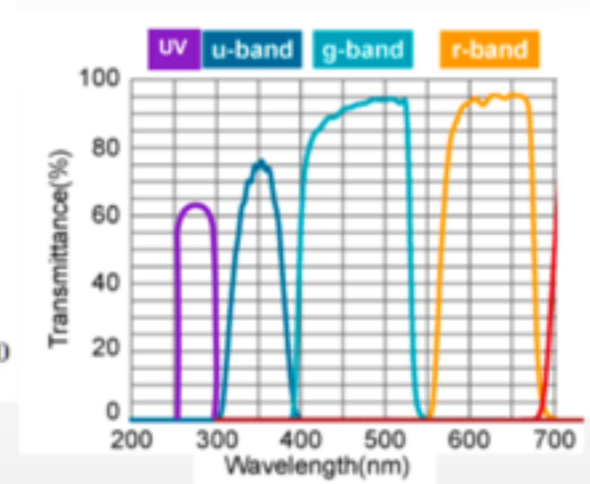
Wide Field Mode



Single wide-band filter
- Similar to *Kepler*
- 400 - 800 nm

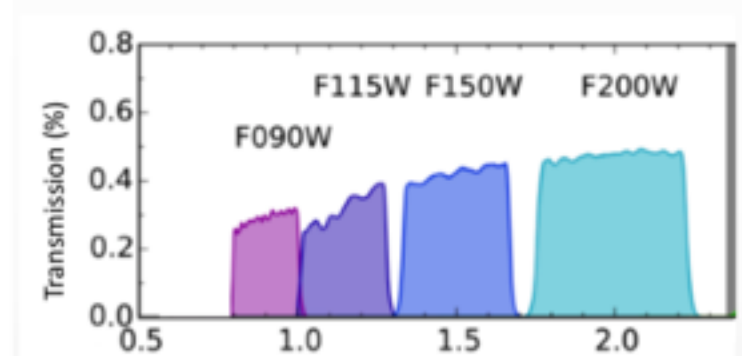
Narrow Field Mode

UV/Opt



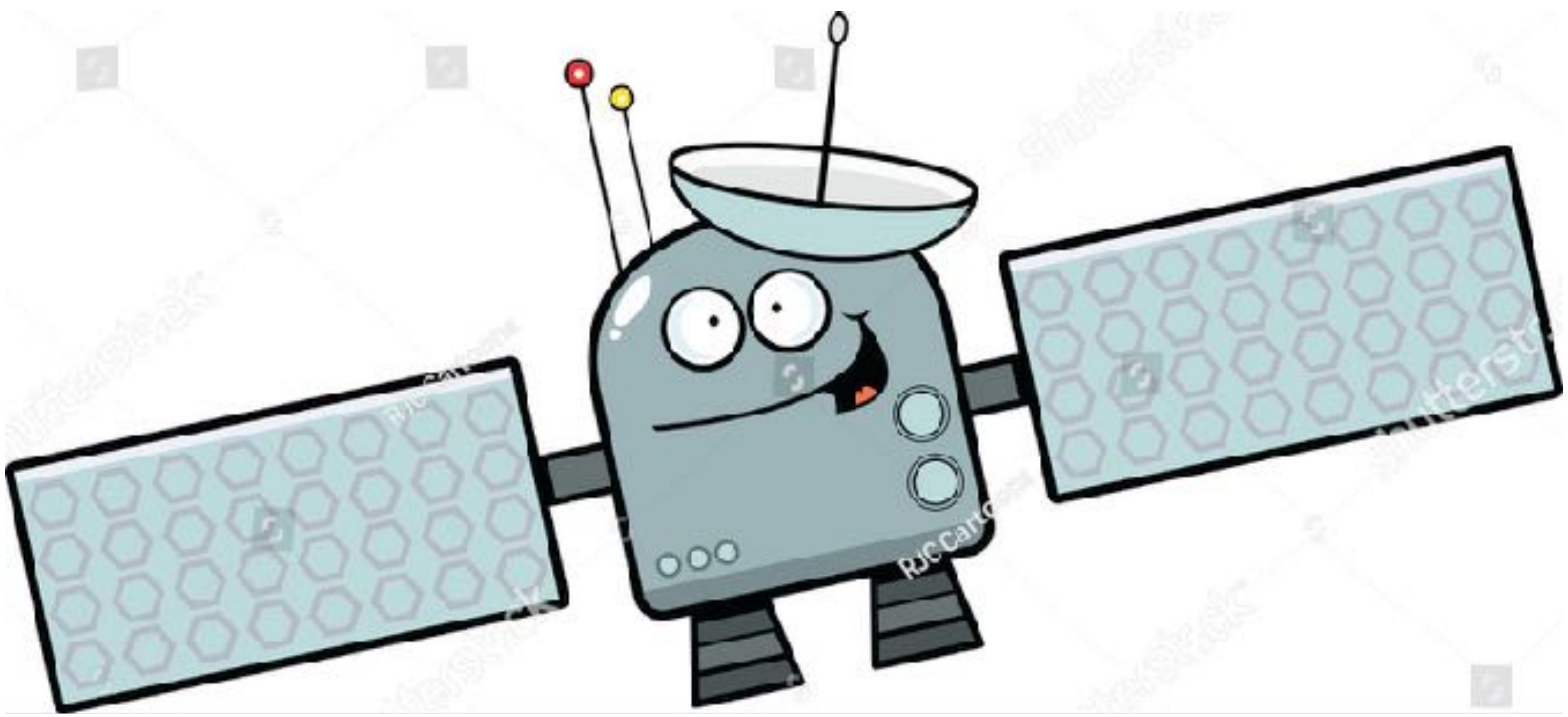
4 medium-band filters and a prism
- UV, u, g, r
- 250 - 700 nm
- R<100 fused silica prism

IR



4 medium-band filters and a prism
- JWST NIRCam filters
- 800 - 2300 nm
- R<100 fused silica prism

Quiz
Which gamma-ray mission is best suited?



kahoot.it