Gamma-Ray Bursts in the Multi-Messenger Time-Domain Era

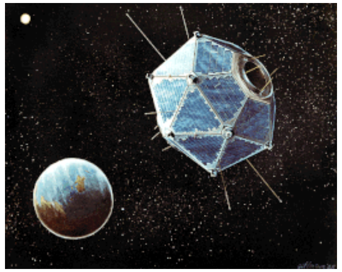
Amy Lien
University of Tampa

Time Domain and Multi-Messenger Astrophysics NASA Workshop. Aug. 22, 2022

OUTLINE

- From the past: what do we know and do not know?
- To the future: what will we have?
- What do we need?
  - New missions?
  - New theories?
  - Something else?

Timeline of GRB history



~ 1960s Vela Satellite

- First GRB detected in 1967.
- Paper published in 1973.

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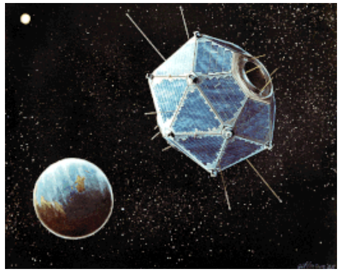

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THEORIES OF γ-RAY BURSTS* (1975)

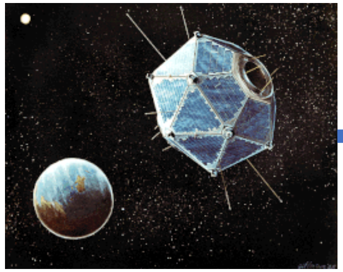
M. Ruderman

Department of Physics
Columbia University
New York, New York 10027

INTRODUCTION

Most theoretical astrophysicists function well in only one or two normal modes. Therefore, we often tend to twist rather strenuously to convince ourselves and others that observations of new phenomena fit into our chosen specialties. As expected, there has been no lack of response by the theoretic community in suggesting an enormous variety of models for γ-ray bursts, such as the following: expanding supernovae shocks,[1,2] neutron star formation,[3] glitches,[2,4,6] neutron stars in close binaries,[7] black holes in binaries,[7,11] novae,[8] white holes,[9] flares on "normal" stars,[10,36] flares on flare stars,[X] flares on white dwarfs,[12,25] flares on neutron stars,[6,13] flares in close binaries,[7] nuclear explosions on white dwarfs,[8] comets on neutron stars,[14] Jupiter,[15] antimatter on conventional stars,[16] magnetic bottles and instabilities in the solar wind,[X] relativistic dust,[17] vacuum polarization instabilities near rotating charged black holes,[18] instabilities in pulsar magnetospheres,[13] and "ghouls."[27] (For theorists who may wish to enter this broad and growing field, I should point out that there are a considerable number of combinations, for example, comets of antimatter falling onto white holes, not yet claimed.)

Timeline of GRB history



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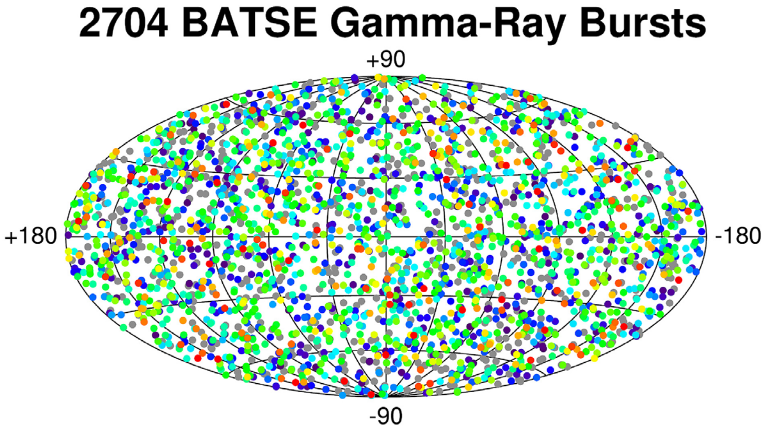
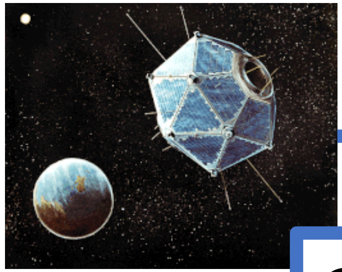


1991-2000 CGRO/BATSE

- All-sky survey: 20 keV to 2 MeV.
- Strongly suggesting cosmological origins.
- Constrain GRB energetics.
- Short-long GRB classifications.
- First four soft gamma-ray repeaters.

Timeline of GRB history



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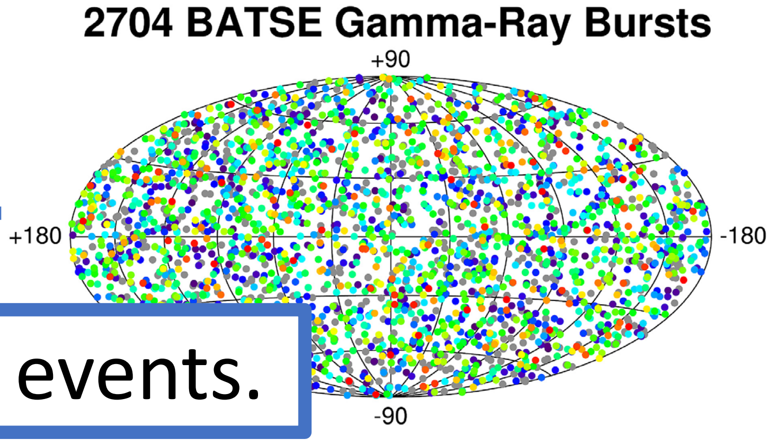
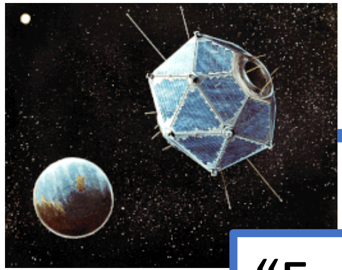


GRBs are by nature multi-messenger events.

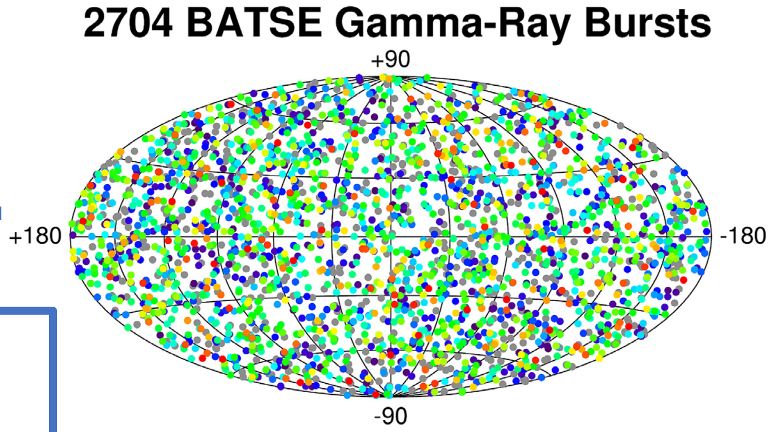
~ 1980s: Fireball models (e.g., Cavallo & Rees 1978; Paczynski 1986; Goodman 1986; Paczynski 1990; Shemi & Piran 1990; Feminor et al 1993; Meszaros et al. 1993 Harding & Baring 1994)

~ 1980s: Neutron star mergers as candidates for GRBs (e.g., Haensel & Schaeffer 1982; Paczynsky 1986; Eichler et al. 1989)

Timeline of GRB history

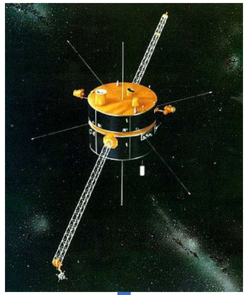


~ 1960s V



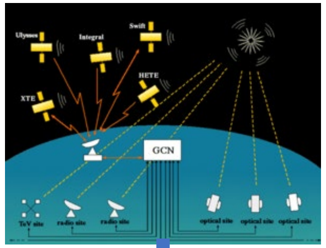
"From the discovery of GRBs through the 1980s, GRB 790305b was the only event to have been identified with a candidate source object: nebula N49 in the Large Magellanic Cloud. All other attempts failed due to poor resolution of the available detectors. The best hope seemed to lie in finding a fainter, fading, longer wavelength emission after the burst itself, the "afterglow" of a GRB."

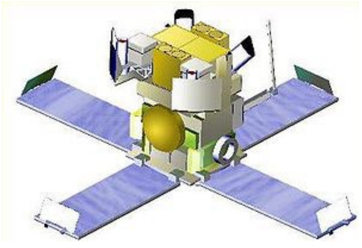
– History of gamma-ray burst research, wiki.



Konus-Wind (1994 - Present)
~20 keV – 20 MeV.
At L1, no Earth occultation.
3050 GRBs till Dec. 2018.

~1997 to Present: GCN



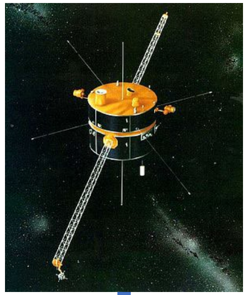


1996-2002 BeppoSAX

- Carry both a wide-field camera (20 x 20 deg; Coded aperture) and four Narrow field instrument (0.1 to 300 keV) that pointed at the same direction.
- First arc-minutes positions of GRBs.
- First radio counterpart detection in 1997.
- First redshift measurement.
- First direct observation that implies the GRB-supernova connection.
- 1082 GRBs.

HETE-2 (2000-2006)

- First instruments for precise localization and transmit coordinates in near real time (< 10 s)
- First optical counterpart for short-hard GRB.
- Discoveries of X-ray flashes.
- ~60 GRBs.



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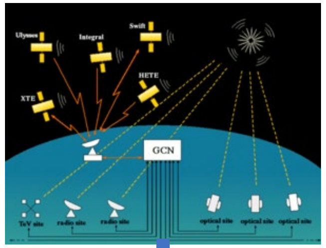

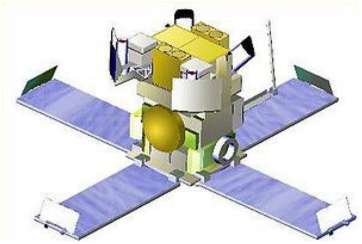

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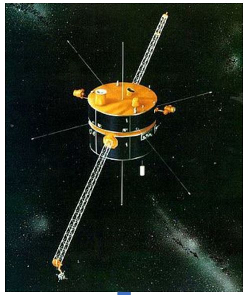
Mission Goal of HETE-1:
“to carry out the first multi-wavelength study of GRBs with ultraviolet (UV), X-ray, and gamma-ray instruments mounted on a single, compact spacecraft. A unique feature of the HETE-1 mission was its capability to localize GRBs with ~10 arcseconds accuracy in near real time aboard the spacecraft, and to transmit these positions directly to a network of receivers at existing ground-based observatories enabling rapid, sensitive follow-up studies in the radio, infrared (IR), and visible light bands.”
- HETE-1 wiki

and
s
10 s)
part

By 2001: > 40 GRB afterglows are detected
In X-ray and optical; > 12 in radio
(Meszaros 2002).



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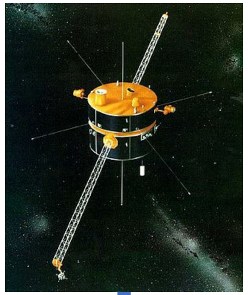
Swift (2004 to Present)
- BAT (15-150 keV), XRT (0.3-10 keV), UVOT (UV/optical).
- Prompt localization and data transmission enabling prompt multi-wavelength follow-up observations.
  → Large sample of GRB localizations, afterglow data, redshift measurements.
- High-redshift GRBs.
- Flares and plateau in the XRT light curves.
- 1553 GRBs.

Fermi (2008 - Present)
- GBM: 8 keV to 40 MeV; 2356 GRBs will 2018 (Von Kienlin et al. 2020)
- LAT: 20 MeV to 300 GeV; 186 GRBs till 2018 (Ajello et al. 2019).
- Wide-band spectral coverage.
- High-energy spectra for GRBs.

Optical telescopes

Radio telescopes



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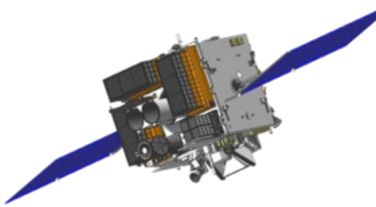
AGILE (2007 - Present)
GRID: 30 MeV – 50 GeV.
SuperAGILE: 18-60 keV.
MCAL: 350 keV – 100 MeV
394 GRBs till Nov. 2020.

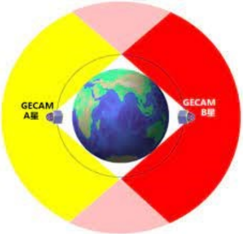
Astrosat (2015 - Presents)
~ 20 bright GRBs in five year



Swift (2004 to Present)

Fermi (2008 - Present)

2017: GW170817



GECAM (Dec. 2020 - Presents)
91 GCNs (some are SGRs).

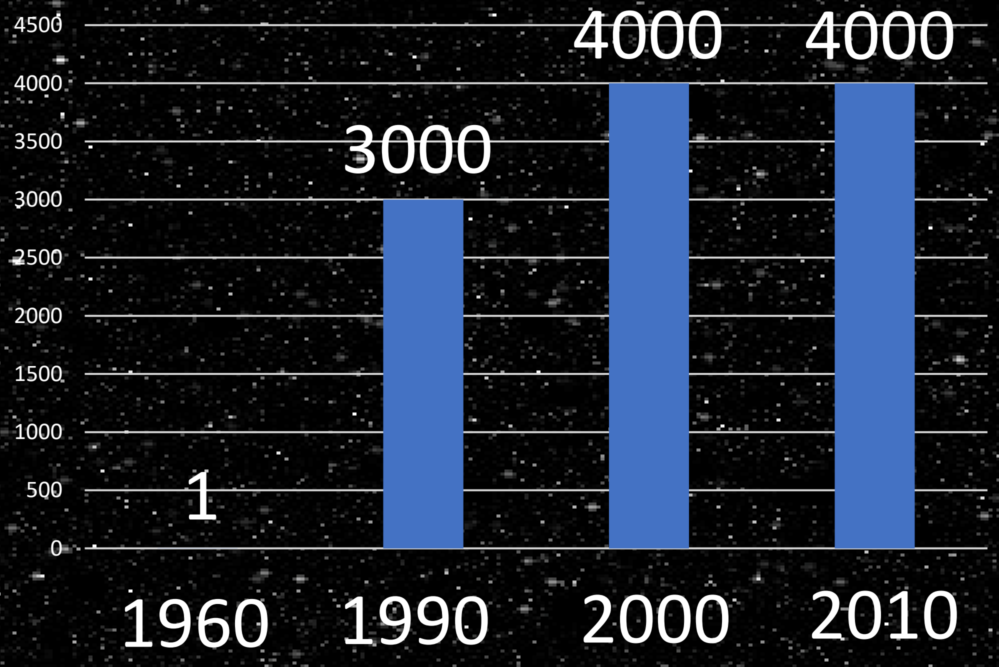
INTEGRAL (2002-Present)

- IBIS (15 keV - 10 MeV); SPI (18 keV – 8 MeV).
- GRBs weren’t one of the main science goals, but has published 59 GRBs from Dec. 2002 to Feb 2012 in the spectral catalog.

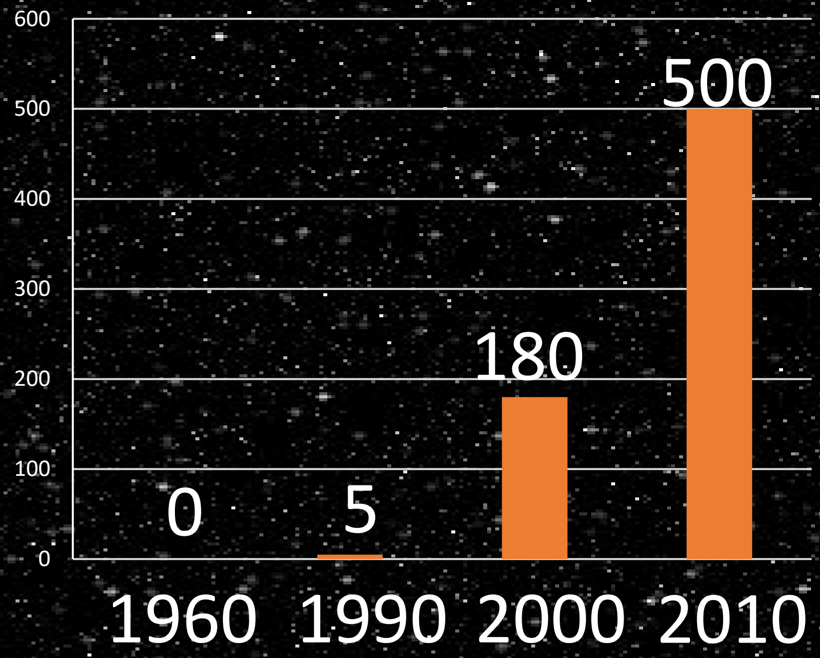
2019: First two TeV GRB detections (MAGIC and HESS)

Summary of GRB data so far

Gamma-ray bursts (GRBs)



GRBs with redshifts
and multiwavelength afterglows



Summary of what we have learned from the last few decades

- GRBs are much more complicated/diverse than we thought….
  - No one theoretical model an easily explain all the bursts.

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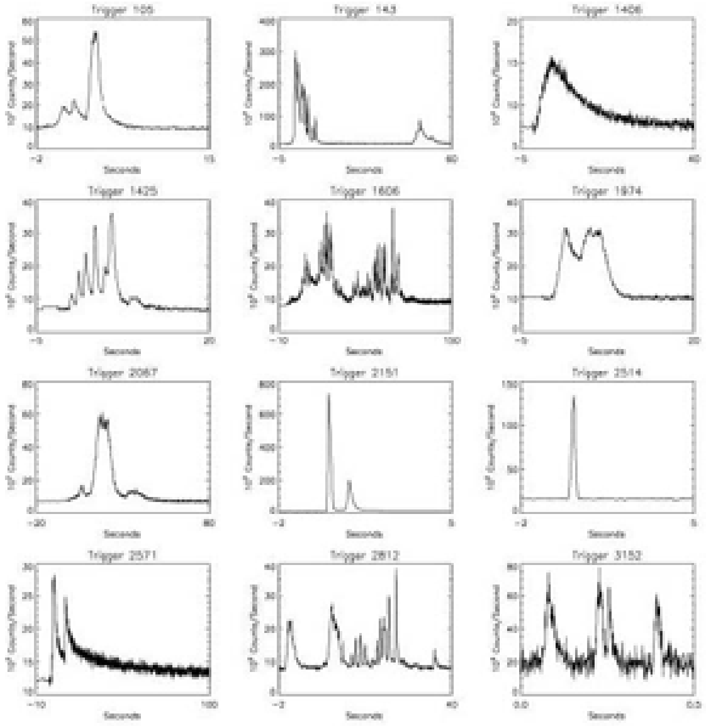
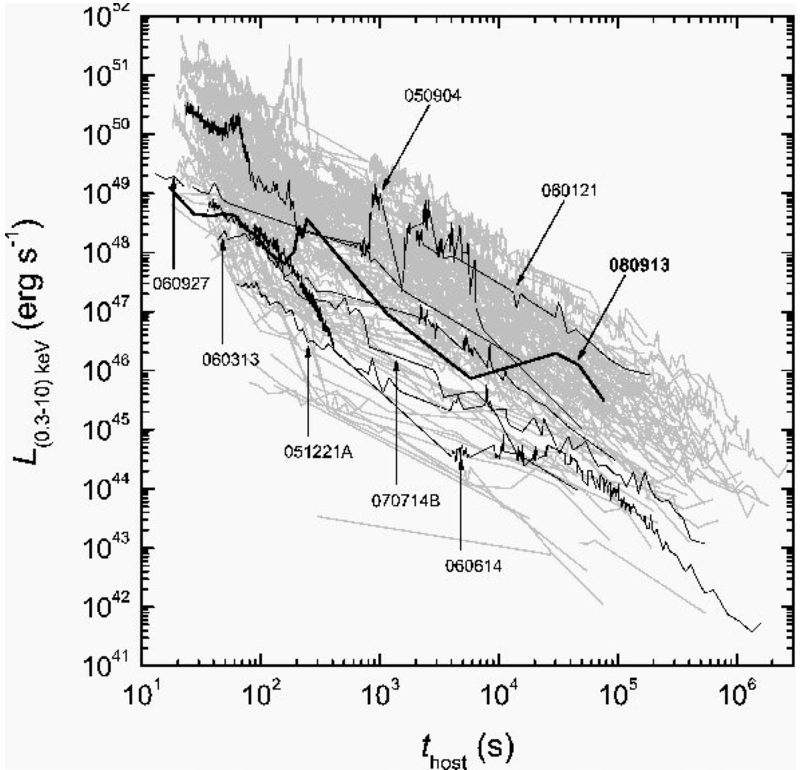
Gamma-ray light curves of GRB prompt emissions



Credit: BATSE

X-ray light curves of GRB afterglows



Greiner et al. (2008)

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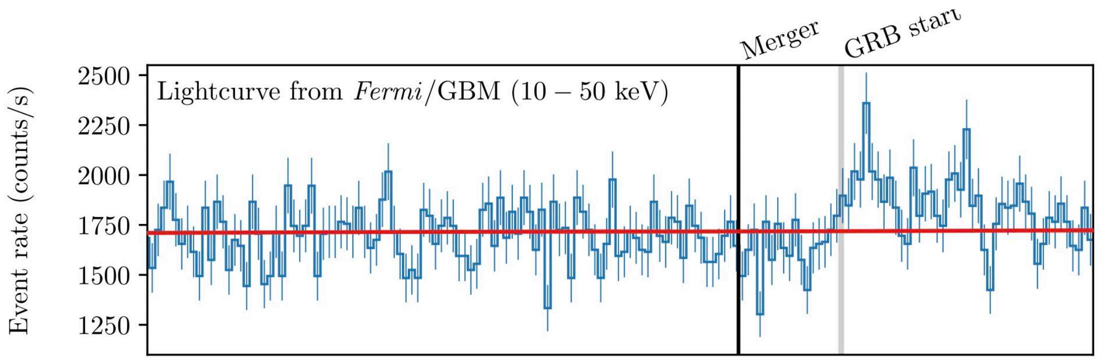

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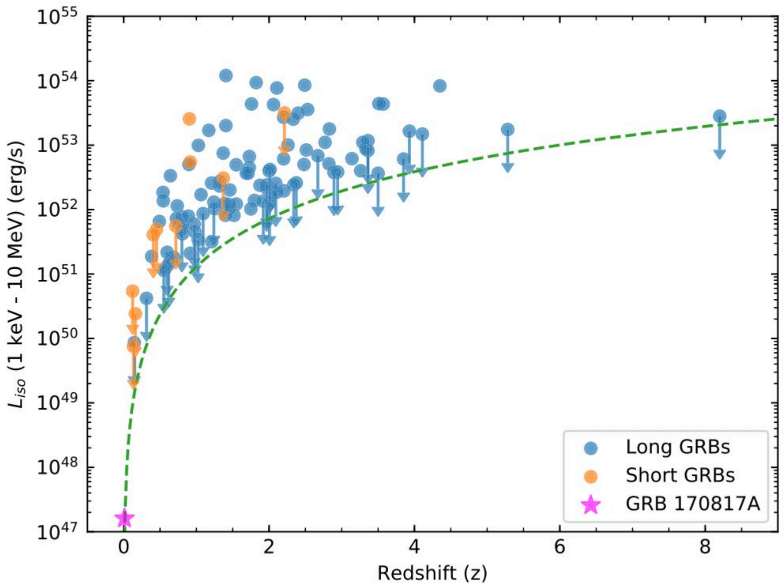
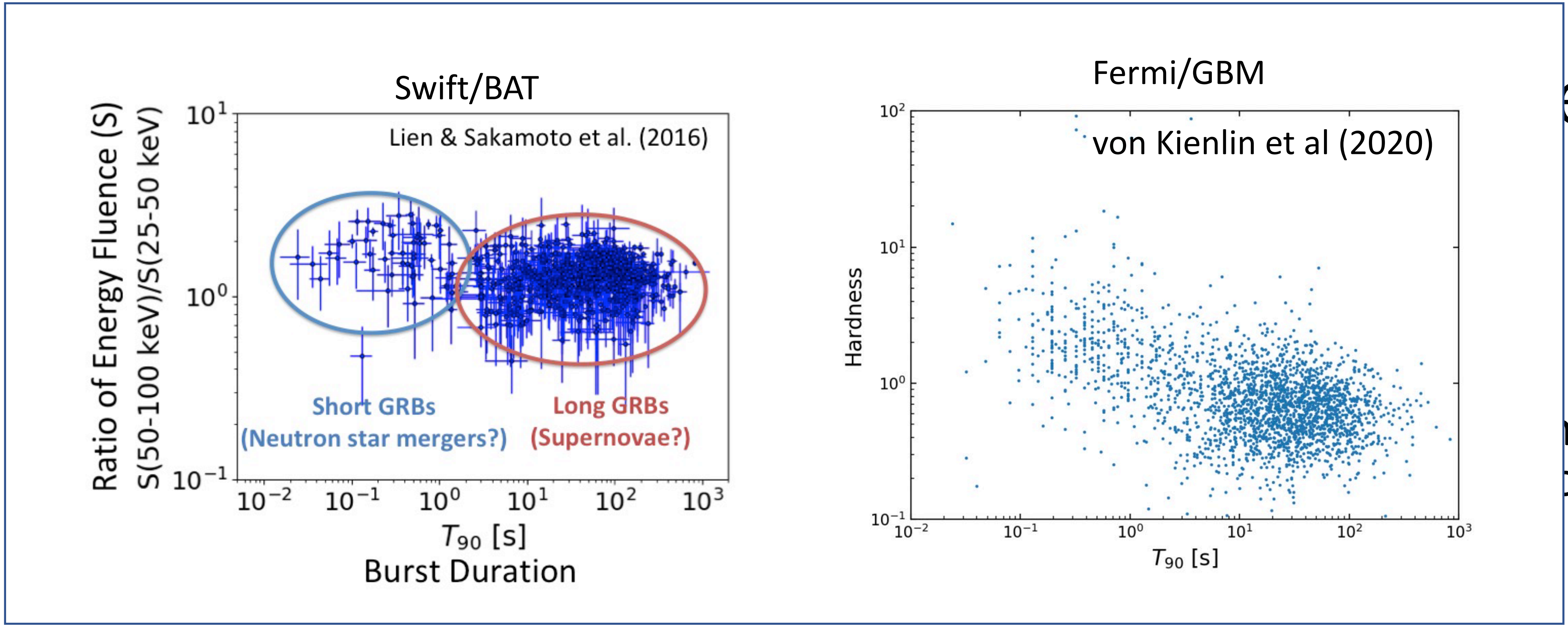
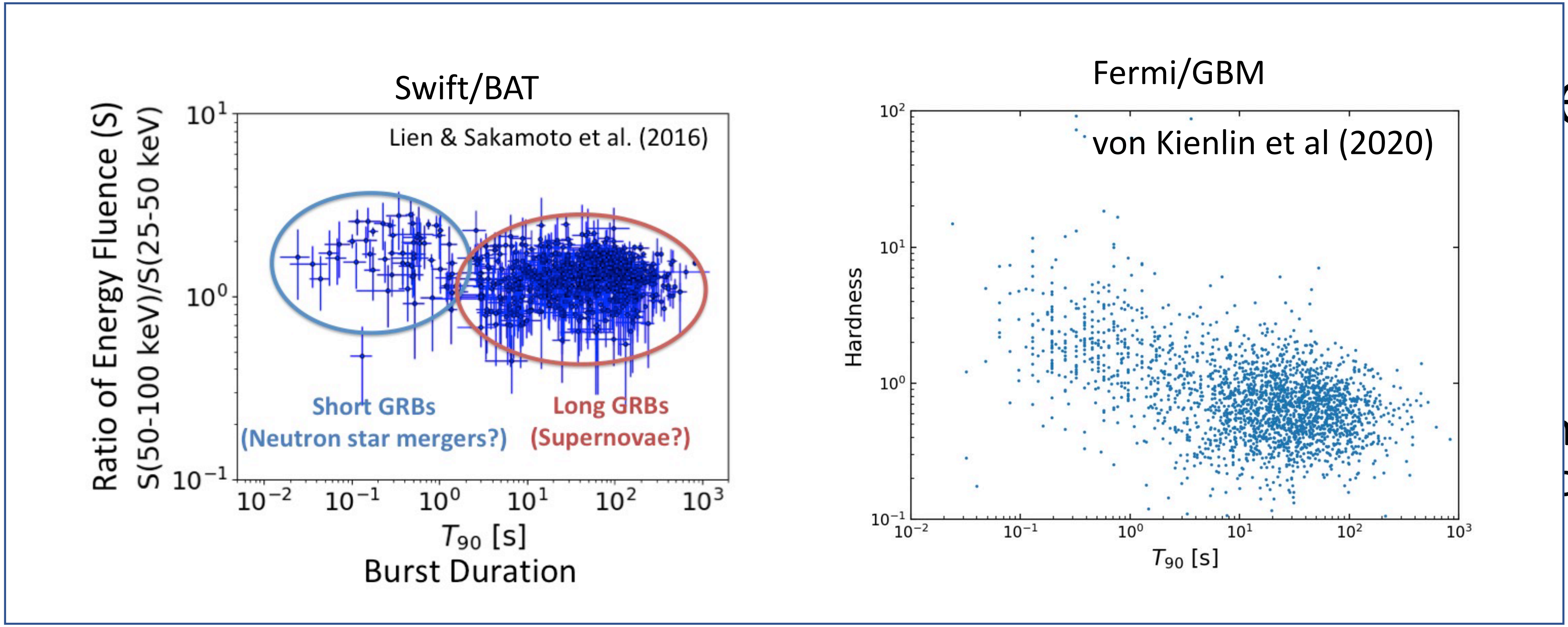




- The short/long classification doesn't always trace the physical origin.



- The short/long classification doesn't always trace the physical origin.
  - A short GRB with a supernova (GRB200826A; Ahumada et al. 2020; Rossi et al. 2020).
  - GRB 201015A: A short-soft pulse with a tail emission and later found to have a supernova counterpart (Markwardt et al. 2020; Rossi et al. 2021)
  - One long GRB with a kilonova (GRB 211211A; e.g. Rastinejad et al. 2022; Gompertz et al. 2022; Xiao et al. 2022).

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GRB theoretical models

Two-Component Jet Models
(Peng et al. 2005)

Millisecond magnetar model
(Day and Lu 1998; Zhang
and Meszaros, 2001)

Synchrotron internal shock models
(e.g., Yassine et al. 2020)

Synchrotron external shock models
(e.g., Piran & Nakar 2010)

Cannonball model

a-ray bursts and
ball model
999)

A turbulent model of
gamma-ray burst vari
(Narayan 2009)

A complete reference of
the analytical synchrotron external shock models
of gamma-ray bursts
(Gao et al. 2013)

Tests and Predictions for
the Structured Jet Model (2

Magnetar-Driven Magnetic Tower
as a Model for Gamma-Ray Bursts
and Asymmetric Supernovae
(Uzdensky & MacFadyen 2007)

Photosphere-internal shock model
(e.g., Toma et al. 2011)

A peculiar, long-duration gamma-ray burst from
a neutron star-white dwarf merger (2022)

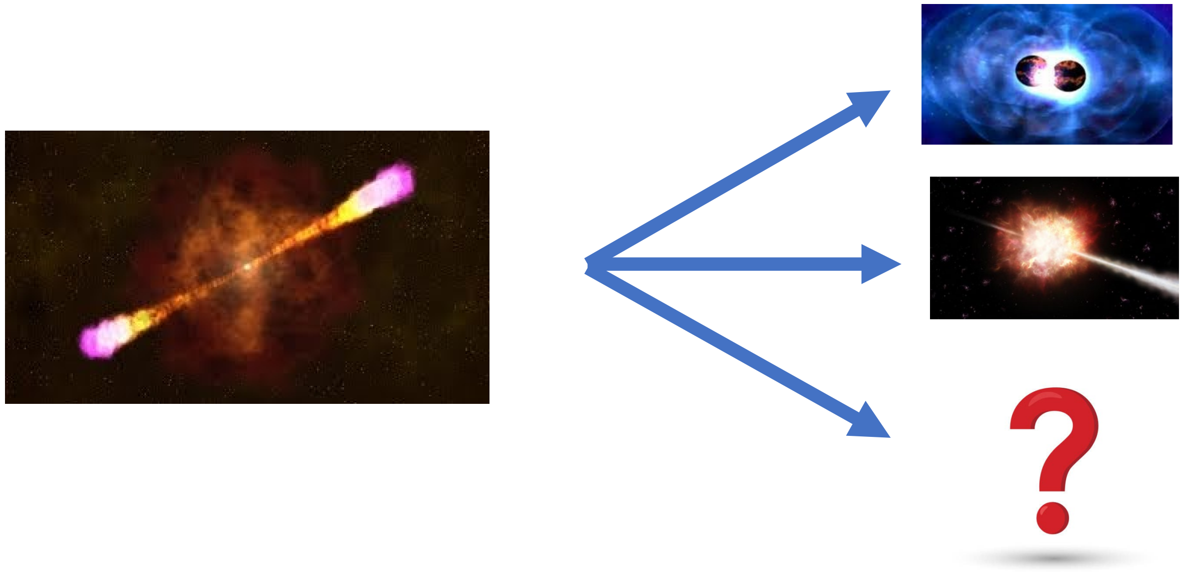
~~What do we need?~~

What do we want to achieve with GRBs?

~~What do we need?~~

What do we want to achieve with GRBs?

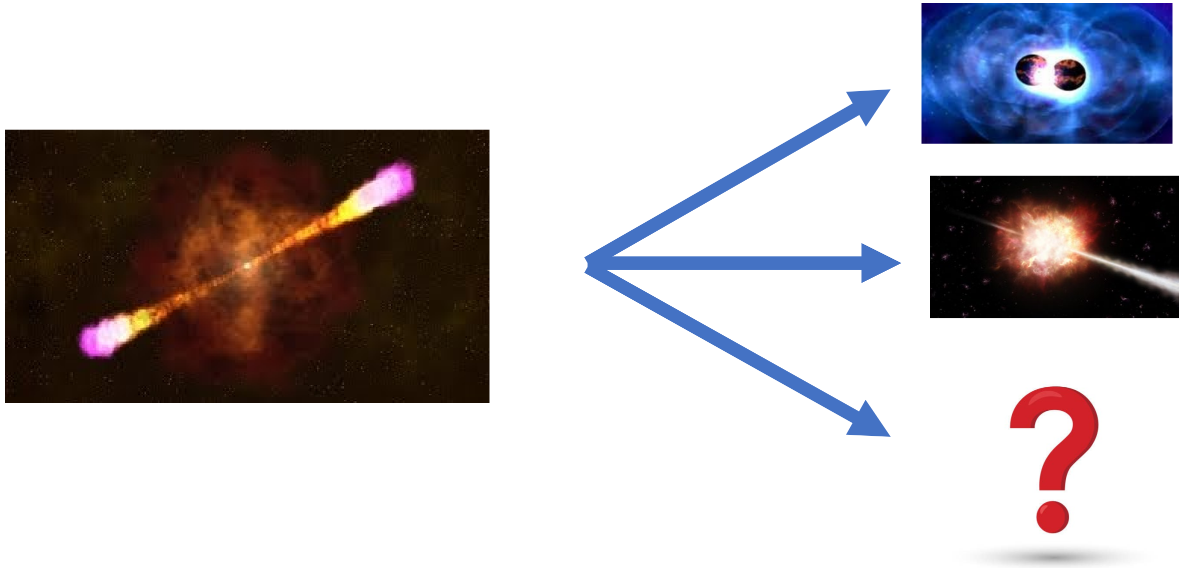
- Better connecting GRB observables with theoretical models.
- Using GRBs as a probe to the universe (especially the early universe).



What do we need to achieve these?

- Bett
- Usin … rse).

"If we find it hard to make a diagnosis,
it usually means that we do not have all the information."
- Dr. Ke, a Taiwanese medical doctor.



A quick overview of what information we have and don’t have

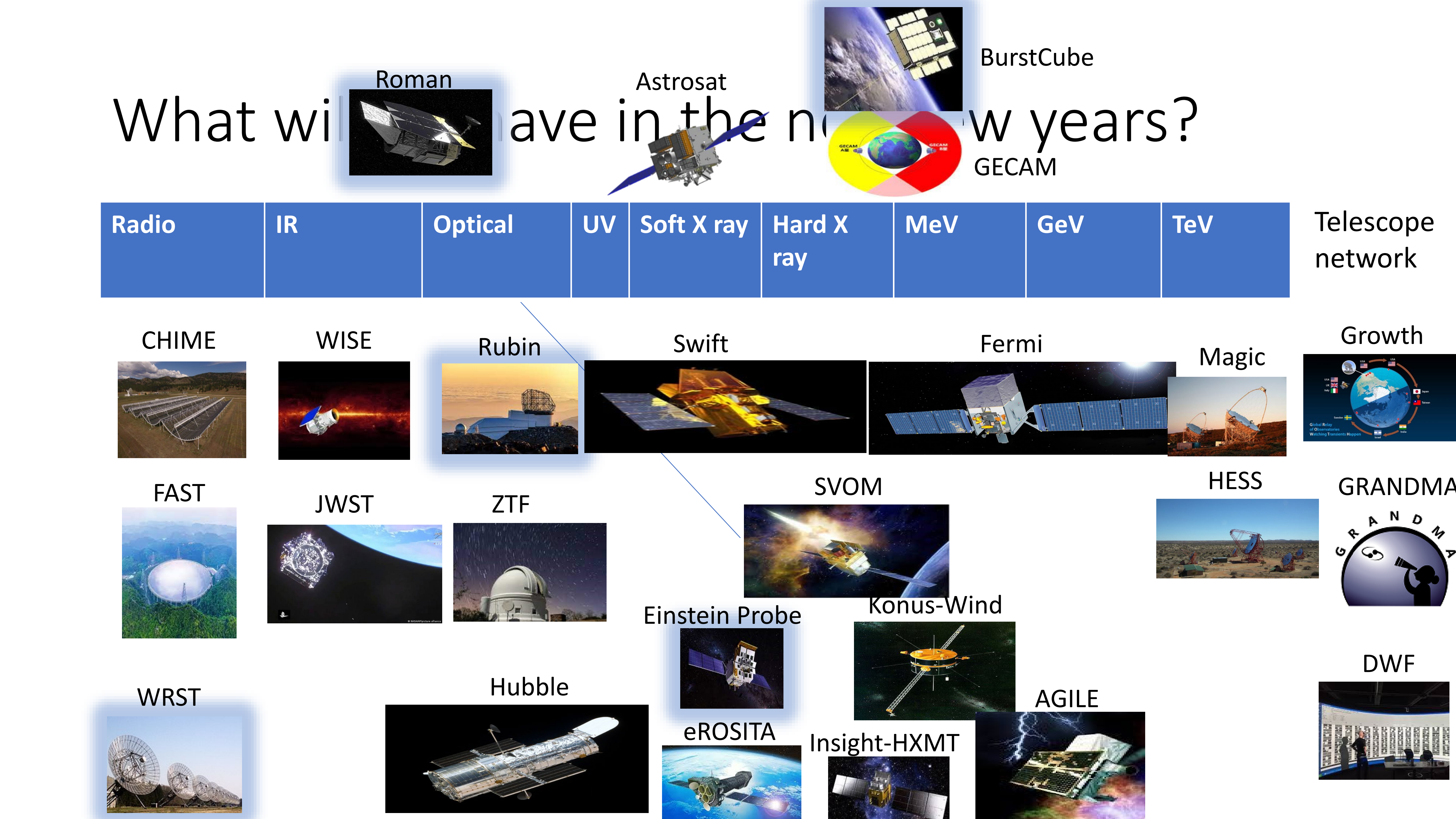
	Radio	IR	Optical	UV	Soft X ray	Hard X ray	MeV	GeV	TeV
Ho much data do we have?	Lots	Not much	Lots	Plenty(?) (for GRBs, not for kilonovae)	Lots	> Few thousands	> Few thousands	> thousands	2
What is lacking?					Prompt X-ray observation ?		Sensitivity for line detections?		

A quick overview of what information we have and don’t have

	Polarization	GW	Neutrino	Cosmic Rays
Ho much data do we have?	Few	~ few hundreds; 1 GW-GRB	Lots (but no detection)	Lots (but no detection)
What is lacking?	Sensitivity?	Sensitivity; Position accuracy; FoV for the low-energy E&M wavelength.	Sensitivity?	Sensitivity?

What will we have in the next few years?

Radio	IR	Optical	UV	Soft X ray	Hard X ray	MeV	GeV	TeV



What wi ave in the n w years?
Roman
Astrosat
BurstCube
GECAM
Radio
IR
Optical
UV
Soft X ray
Hard X ray
MeV
GeV
TeV
Telescope network
CHIME
WISE
Rubin
Swift
Fermi
Magic
Growth
FAST
JWST
ZTF
SVOM
HESS
GRANDMA
Einstein Probe
Konus-Wind
DWF
WRST
Hubble
AGILE
eROSITA
Insight-HXMT

What will we have in the next few years

Polarization	GW	Neutrino	Cosmic Rays

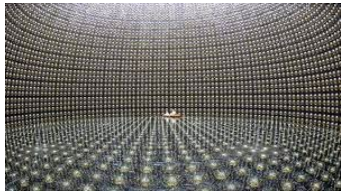
LIGO

VIRGO

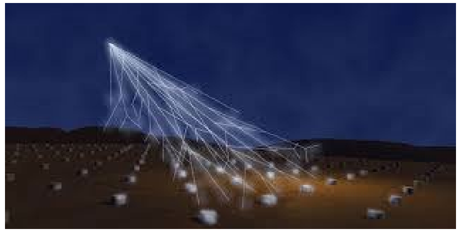
KAGRA

IceCube

Super-K

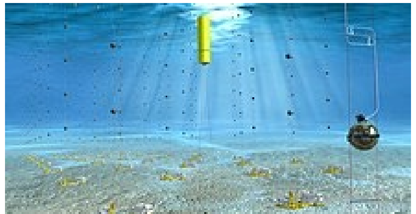


Pierre Auger



LHAASO

KM3Net



What will we have in the next few years

Polarization	GW	Neutrino	Cosmic Rays

LEAP

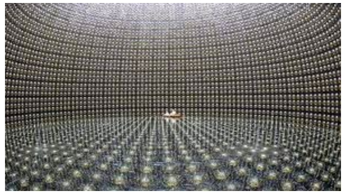
LIGO

VIRGO

KAGRA

IceCube

Super-K



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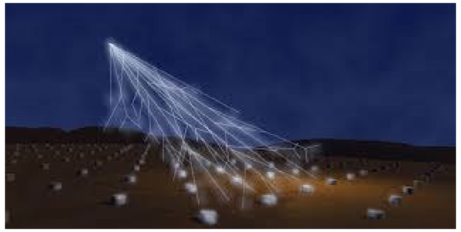

LHAASO

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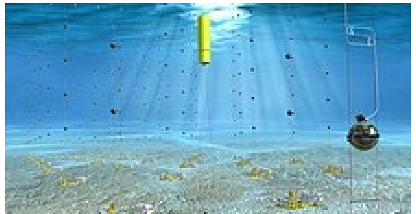


What will we have in the next few years?
Astrosat
BurstCube
GECAM
Radio
IR
Optical
UV
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MeV
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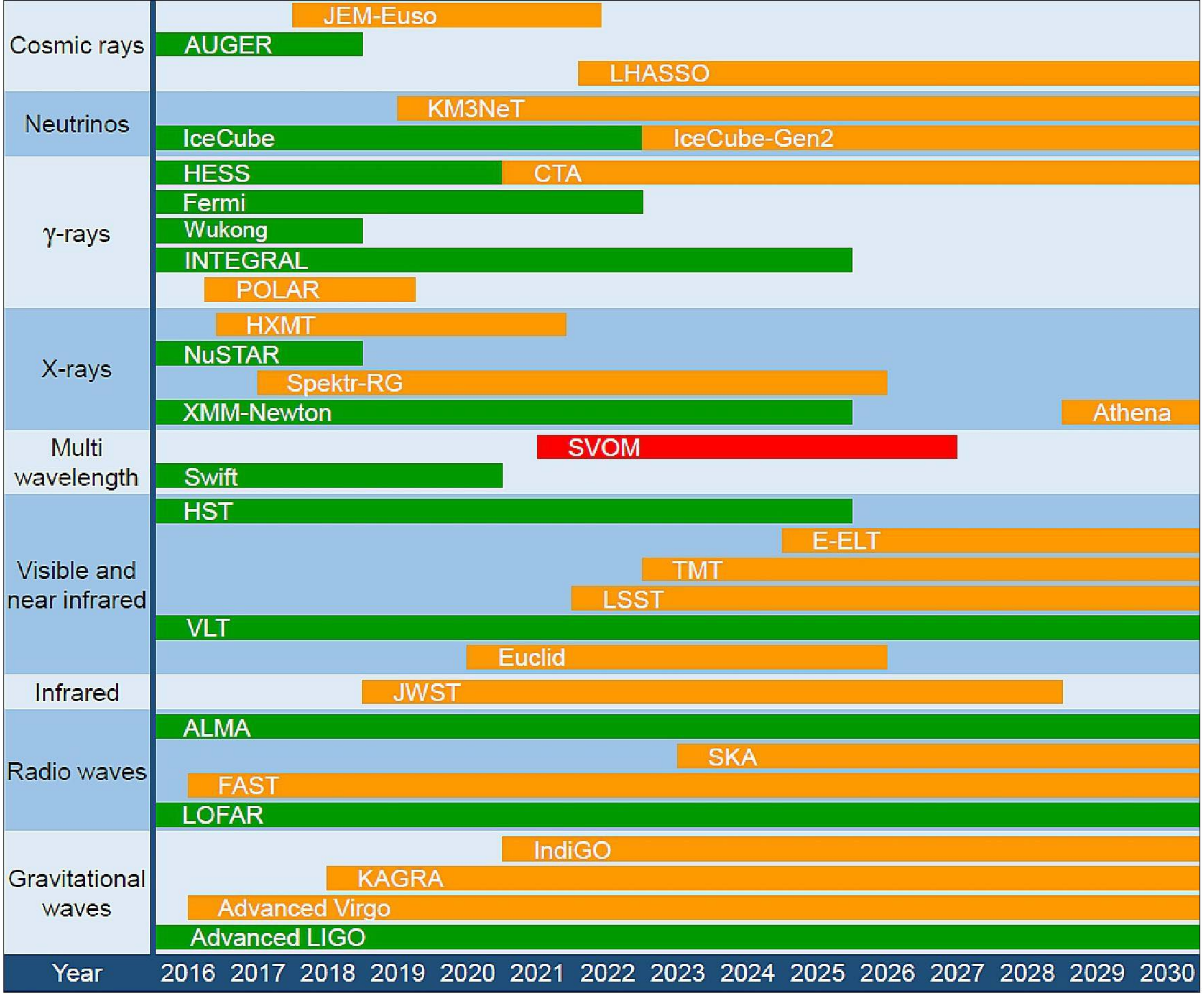
Rubin
UVEX
Swift
MoonBEAM
Magic
Growth
FAST
JWST
ZTF
STAR-X
SVOM
HESS
GRANDMA
Konus-Wind
Einstein Probe
DWF
WRST
Hubble
AGILE
Insight-HXMT

WHAT GRB DATA WE STILL MISS?

- Polarization measurements.
- Infrared coverage.
- Gravitational wave domain.
- Prompt observations in wavelengths other than gamma rays and hard x rays.
- Data with good sensitivity in the MeV regime.
  - Time-resolved spectra and potential spectral lines.
- Low luminosity and soft GRBs.
- Increase GRB redshift measurements.



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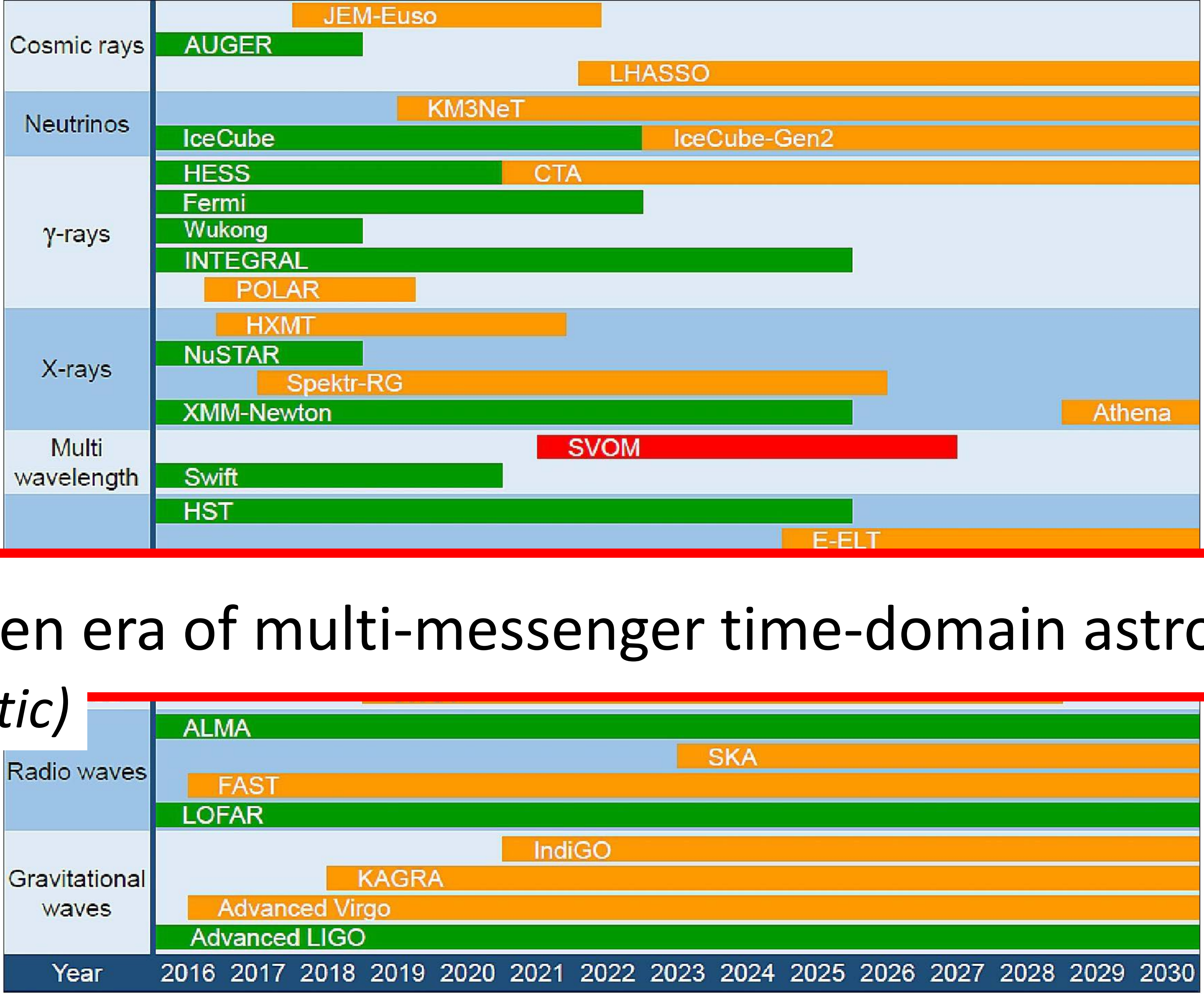

The golden era of multi-messenger time-domain astronomy

(Chaotic)

Ref: SVOM page

HOW DO WE PREPARE FOR THE INFLUX OF INFORMATION?

- Better methods to utilize the large amount of data.
  - Instruments for diverse and flexible science goals.
  - Open sources (data access and codes).
  - Human-friendly interface to search and use data.
    - For example, Simbad, XRT GRB interface, HEASARC, new GCN.
- Increasing interdisciplinary interactions.
  - Collaboration across different fields.
  - Prevent people from falling into individual information bubble.
  - Practical methods: workshops that encourages discussions and people from different fields to talk to each other.

SUMMARY

- What do we want to achieve with GRBs?
  - Better connections between GRB theoretical models and observations.
  - Understand the diversity in GRB data and models → Having a holistic picture of GRBs.
- What do we need?
  - Figuring out what information we lack the most.
  - Resources for theoretical works.
  - Preparing for the big-data era.
    - Building infrastructure to enable easy data usage and collaborations.
    - Increasing discussions between different fields.

Preparing for next galactic supernovae, kilonovae, and GRBs!
(e.g., MeV lines from neutron star mergers; Wang et al. 2022)