Astronomy 503
Observational Astronomy

Prof. Gautham Narayan

Fall 2024

Lecture 01: Introduction

ASTR 503: Observational Astronomy

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Lecture: Astro 134, Tue & Thur, 1400 – 1530
🌍: https://github.com/gnarayan/ast503_2024_Fall
Office Hours: Astro 129, Swing by if my door is open, or Teams

COURSE DESCRIPTION & LEARNING GOALS

This course will cover observational techniques in astrophysics with a decidedly practical applications perspective - i.e. you'll be coding, you'll be doing data analysis, and you probably won't be doing much deriving. ASTR 310 or strong familiarity with Python is required. We'll be covering gamma ray, x-ray, ultraviolet, visible, infrared, sub-mm, mm, and radio astronomy; photometry, imaging, spectroscopy, and polarimetry; gravitational waves; cosmic rays; neutrinos; positional astronomy; noise; statistics; data analysis; optics, and writing proposals to use the facilities we'll talk about.

The TA is **Joseph Weller** (Office hours TBD).

Everything goes here i.e. you are going to need to get comfortable with git

Course Description

- This course will cover modern astronomical techniques with an emphasis on the production and propagation of light, photon detection, instrumentation, data analysis, and statistics.
- We will cover all wavelengths: gamma-rays, x-ray, ultraviolet, visible, infrared, sub-mm, mm, and radio astronomy. We will touch upon cosmic rays, dark matter, and gravitational waves.
- We will cover the techniques of astrometry, photometry, imaging, spectroscopy, and interferometry.
- As with the modern field of astronomy, the course will be heavy with data analysis and programming.
- My goal is for this course to be a boot camp for real world of research and the astronomy profession.

My goals for this course:

- **Language:** I hope to introduce you to all the observational concepts, techniques, and technologies that will allow you to be conversant in the modern field of astronomy.
- **Practical Tools:** I want to provide you with the tools you need to get into active research, work with data, and <u>write proposals</u>.
- **Work Together:** All modern astrophysics is collaborative. The age of single-author papers from a lone genius is done. You have to <u>work together</u> to figure things out.

What you need to do to get an A:

- Instructions and assignments are going to be deliberately (as opposed to accidentally) vague, ill-defined, and open ended. (just like real research). If you don't know what to do, write how might approach a problem. We can't grade blank space, but we can give you partial credit for thinking.

- You need to do the homework assignments (they will build upon one another and culminate in the final project) - largest component of your grade.

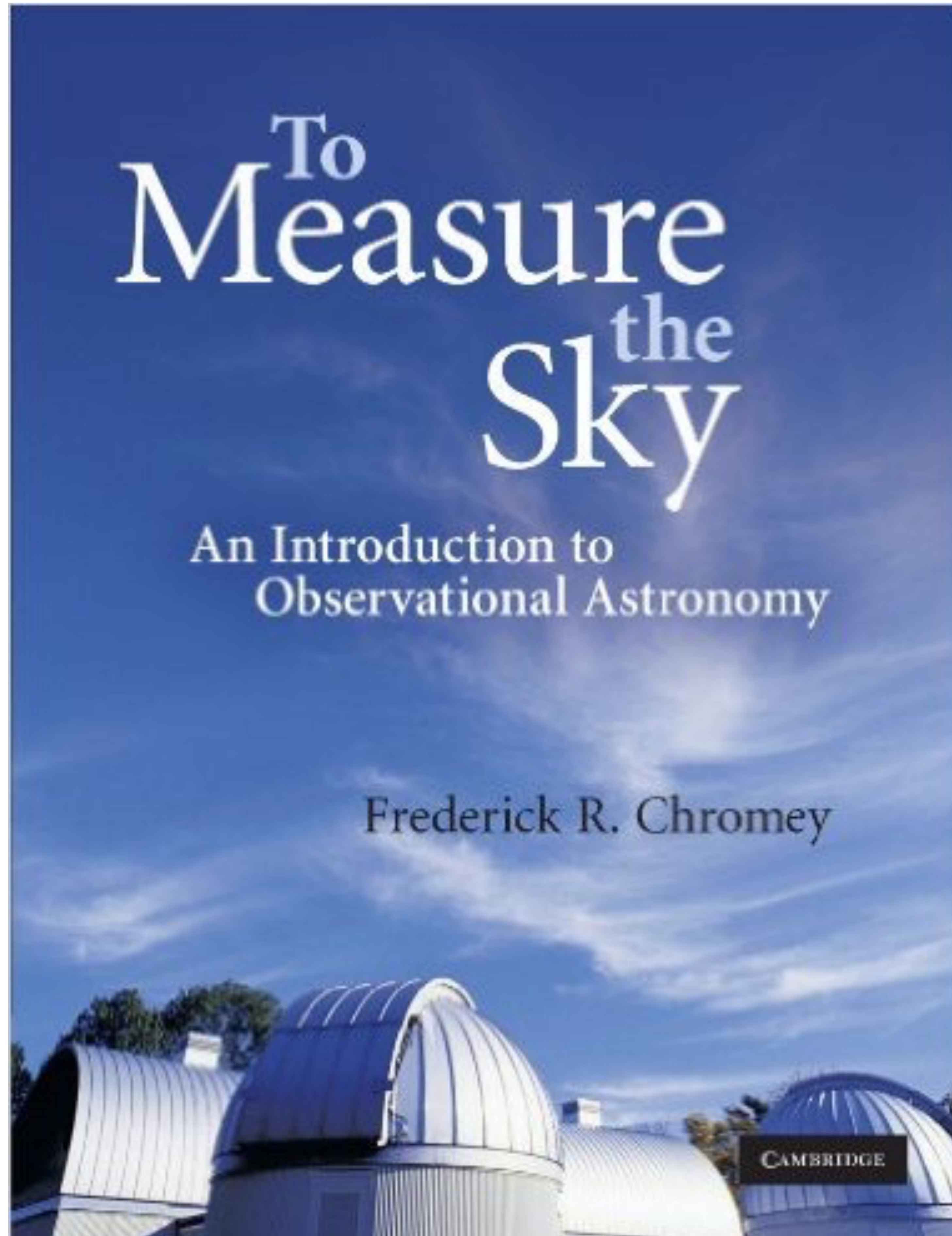
- Don't worry about your grade. It doesn't matter unless you are an undergrad, and then only if you are not a senior. Just do your best. (just like the real world). If you have the option of doing something that yields a research result, prioritize that.

Life Skills

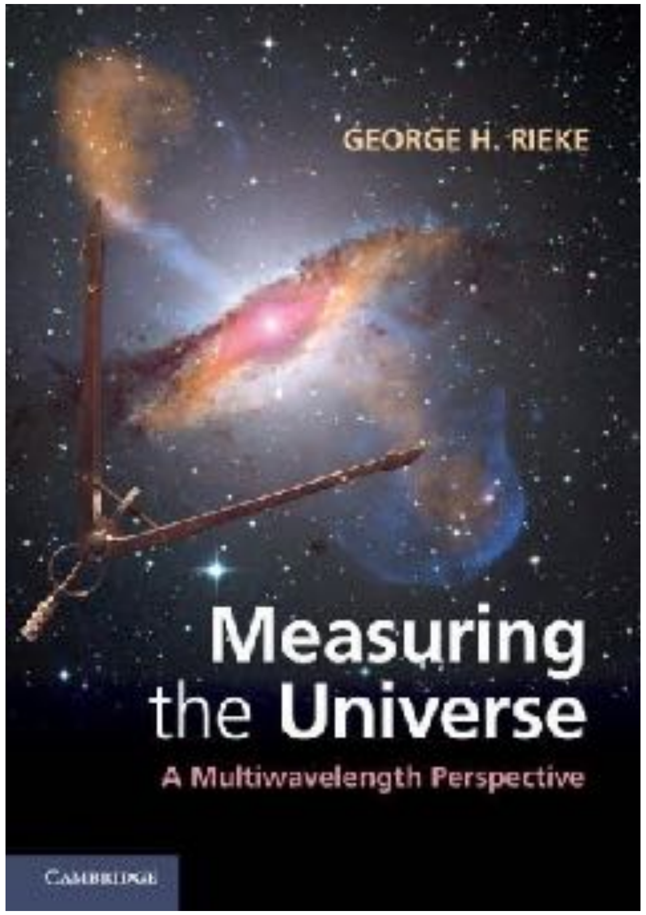
- **Technology:** New instrumentation is essential to observational astronomy. We will study the basic physics of radiation detection. We will gain a general understanding of modern astronomical facilities.
- **Wavelengths:** We will work across the electromagnetic spectrum, and beyond.
- **Data Analysis:** We will analyze real data from state-of-the-art facilities. We will work with large data sets. We will make simulations.
- **Statistics:** We will study error in astronomical measurements: origins, types, characterization, and mitigation.
- **Communication:** How to plot data, make a pretty image, and use LaTeX.
- **Time:** Students will write a (mock) proposal for time on a (real) telescope.

Books

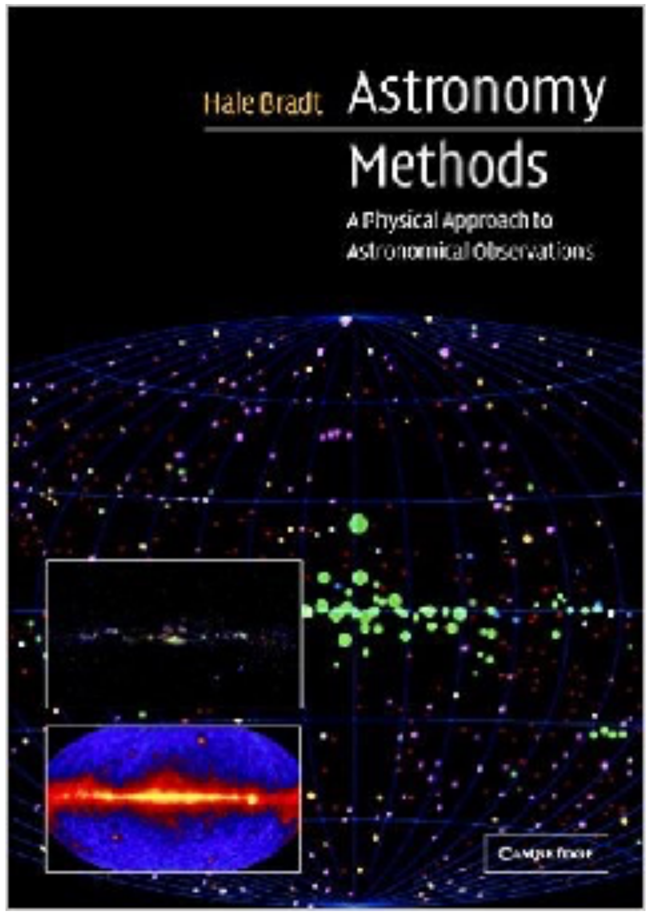
Main (general purpose undergraduate) textbook.



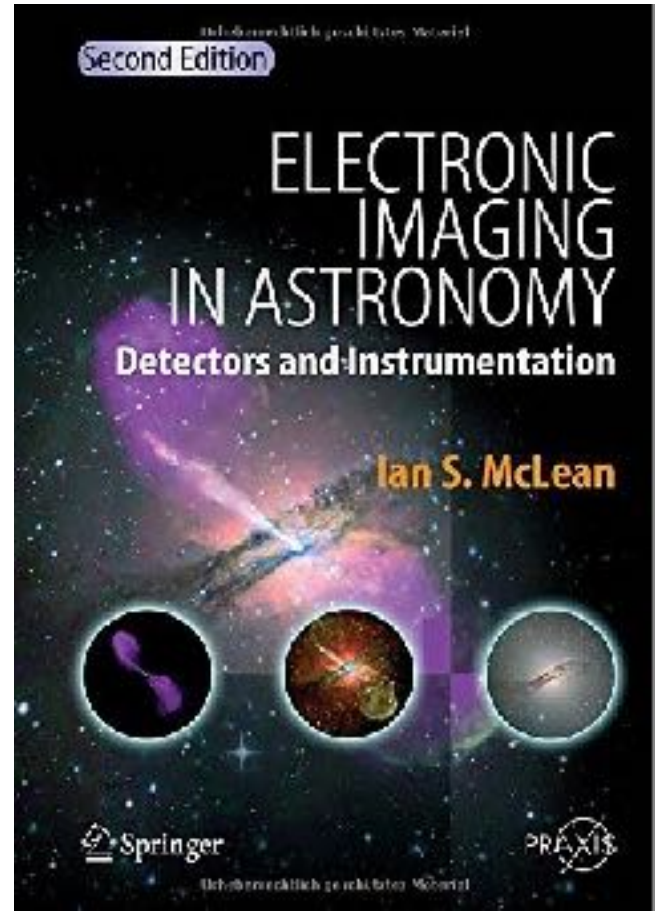
Supplemental Books



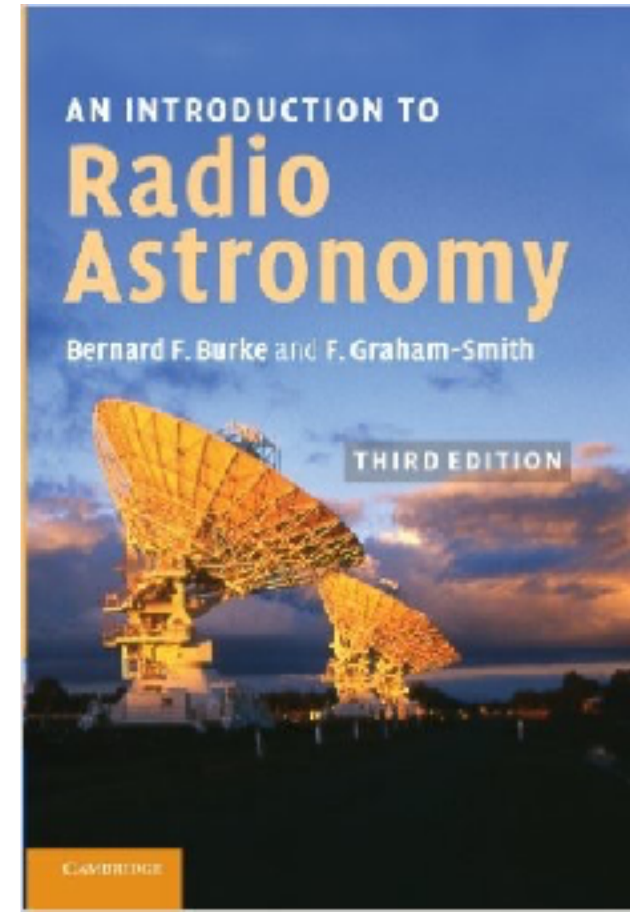
Rieke:
Good job covering the physics of photon detection at all wavelengths. Particularly infrared.
Used for grad-level course.



Bradt:
Best for high energy astrophysics.

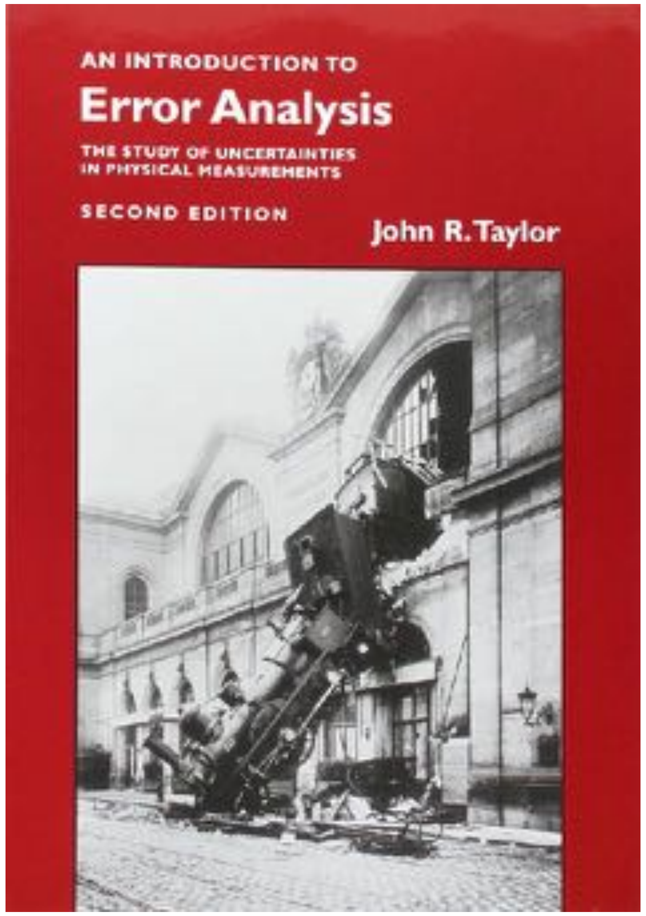


McLean:
Best for CCD astronomy and reduction.

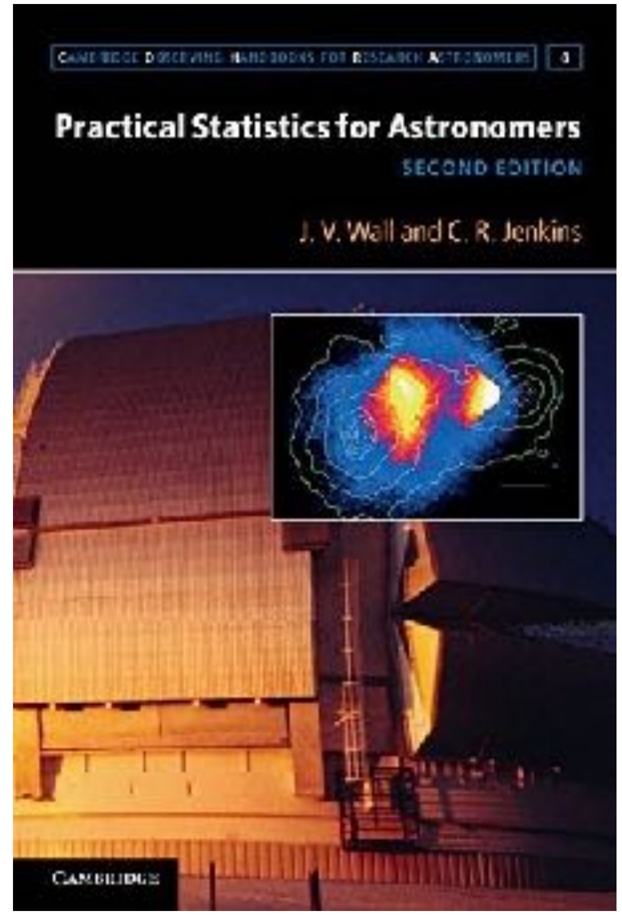


Burke:
Best for radio astronomy.

Statistics Books (You should have one)

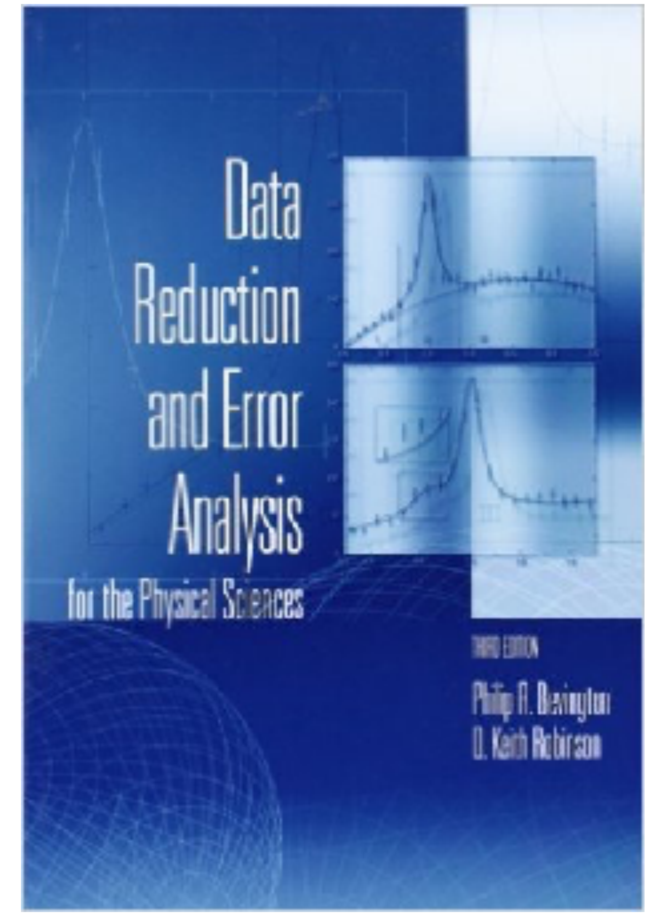


Taylor:
You should have it.
Standard. Cheap.
Level = easy.



Wall:
Practical if you are going to go to grad school.
Level = moderately difficult.

Recommended



Bevington:
Best level for this course.
Level = Just right.

While we cannot condone illegal activity, we also cannot in good faith recommend purchasing textbooks that are two decades old at the inflated prices charged by major publishers.

You do not need to purchase any of these books because there is no official book for this class.

If you choose to “acquire” these books by e.g. consulting your TA, all moral implications are on you.

Assignments

- ~8 HW assignments - 50%
  - Your lowest grade is dropped
  - The last one is an in-class presentation which you'll randomly pick the topic of
- 1 midterms (take home, open book, probably painful, no make ups) - 20%
- A final project will be in the form of a (mock) telescope proposal - 30%

Astronomy Boot Camp

- You'd better start learning to love Python now.
- You also need to learn LaTeX.

Final Project: Telescope Proposal

- think of science question
- figure out telescope
- write proposal
- due at end of semester
- start after midterm, get feedback
- I am the TAC
- 30% of grade

- **WEEK 0**
  First steps, light and radiation, wavelength, the atmospheree
- **WEEK 1**
  Luminosity, flux, distances, noise, statistics
- **WEEK 2**
  Fourier Transforms, optics, telescopes, astrometry
- **WEEK 3**
  Photons and matter, detectors in the UVOIR
- **WEEK 4**
  High-energy and coherent detectors and experiments
- **WEEK 5**
  Dark Matter and Gravitational Waves
- **WEEK 6**
  Working with image data
- **Oct. 10th**
  Midterm Assigned.
- **WEEK 7**
  Working with spectroscopy (no class Oct. 15, and not on Midterm)
- **Oct. 17th**
  Midterm due by Noon
- **WEEK 8**
  Interferometry and Map-making. Pick topics for in-class presentations.
- **WEEK 9**
  A survey of ground- and space-based facilities
- **WEEK 10**
  Instrumentation
- **WEEK 11**
  Surveys
- **WEEK 12**
  The landscape of astrophysics for the next decade
- **WEEK 13**
  Class presentations on special topics #1
- **WEEK 14**
  Class presentations on special topics #2. Pick facility/instrument for Final Exam Proposal Development
- **Dec. 17th**
  Final Proposal due by Noon.

preliminary and subject to change

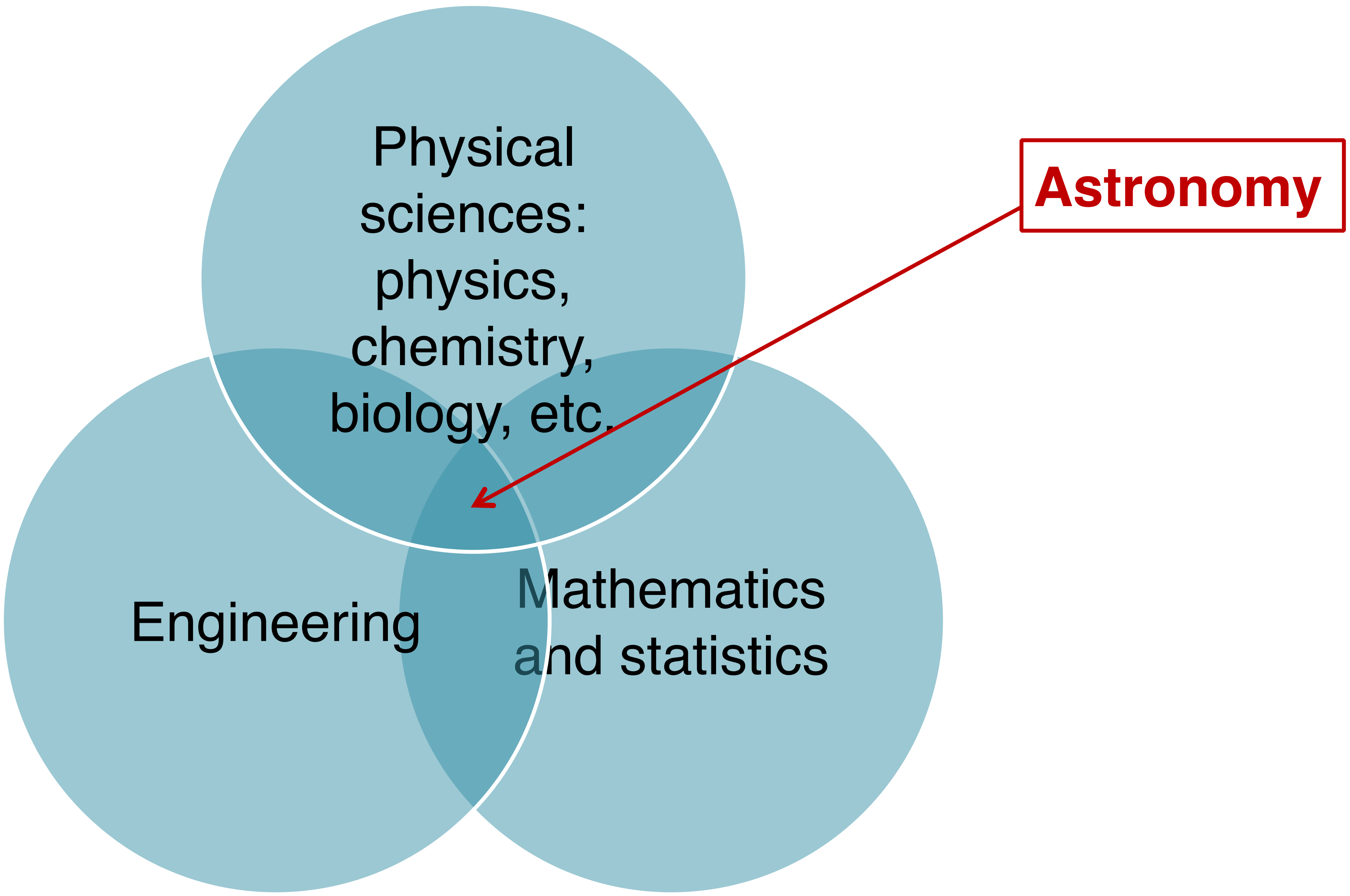
How it all (hopefully) fits together:

- midterm will be very qualitative and based off of lecture material
- lectures are how astronomy work - provide context for homework
- reading is to reinforce the lecture material, because there's more to every single topic than we can possibly cover
- homework is there to ramp up your observational astronomy skills
- everything is to lead up to the telescope proposal

my trajectory:

- undergrad (Illinois Wesleyan): asteroids and comets (optical) –> solar system formation –> elemental abundances
- grad (Harvard): supernovae (UV, Optical, IR, sometimes gamma rays) –> dark energy –> surveys + catalogs
- postdoc (NOIRLab): *HST (UVOIR)* + spectroscopy + calibrating large surveys –> astrostatistics
- Lasker Fellowship (STScI): AI and Astrostatistics on big surveys –> using ancillary information that we get for "free" –> Rubin
- faculty: So. Many. Surveys. *Swift*, *Hubble*, *JWST, TESS/Kepler*, anything we can get our hands on that is ground-based (PI for SCIMMA, co-PI for YSE, Rubin DESC Analysis Coordinator)

Astronomy is interdisciplinary



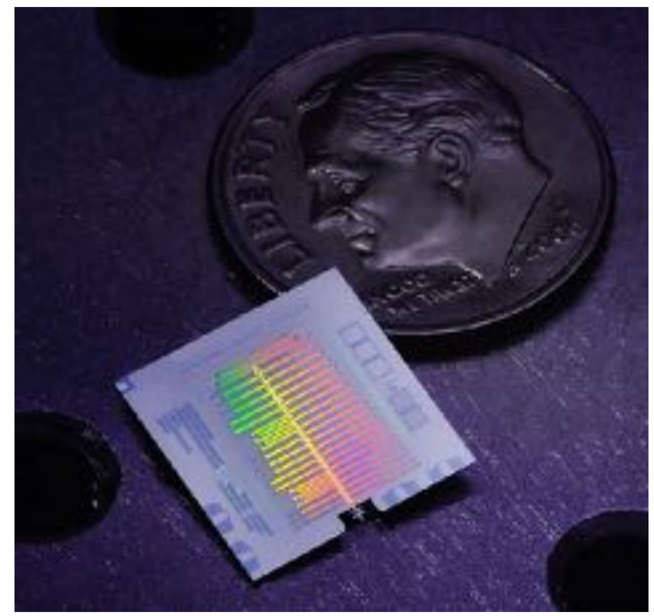
Preface

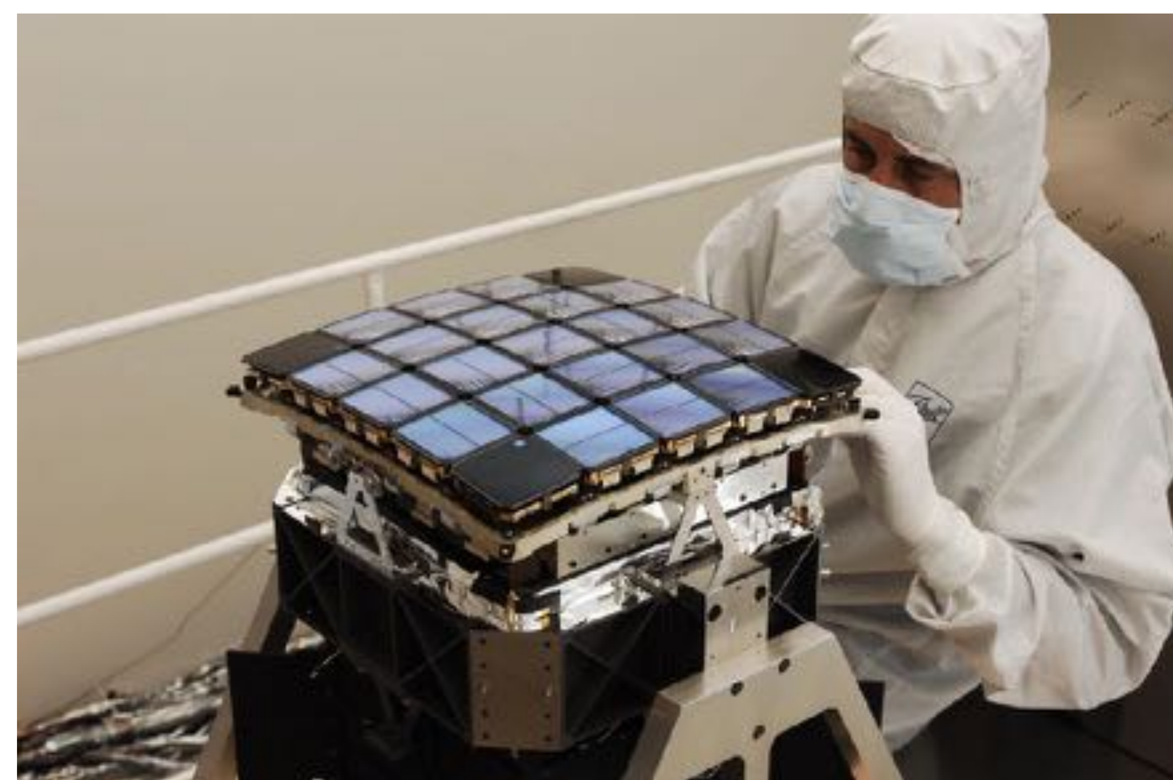
- Throughout history, astronomy has relied heavily on advances in technology.
- In some cases, astronomers have been the driving force in developing the technology.
- Today's telescopes and observatories, whether on the ground or in space, are "high-tech" places where state-of-the-art electronic equipment is used to collect and analyze all forms of light.
- Driven by new technology, discoveries and revelations about the universe have been coming at an incredible pace in recent years.
- Yet the demand for more sensitivity and better equipment is greater now than ever before.
- Would-be astronomers must reckon on acquiring a wide range of skills, or on working as a member of a multi-disciplinary team.

ALMA

Astronomy & Technology

- Almost all modern astronomical research is carried out by instrumentation that converts radiant energy to electronic signals which can be digitized for storage & manipulation by computers
- A large modern observatory requires an enormous breadth of engineering, scientific, and managerial skills to operate efficiently
- You are all aware of the remarkable advances in astronomical science in recent years, from planets around other Suns, to the acceleration of the universe and the presence of dark matter and dark energy, to imaging black holes
- These discoveries were, and continue to be, *enabled* by advances in the technologies used by astronomers. **It is that fundamental link that I want you to keep in mind.**





Observational Astronomy

- All astronomers talk about "going observing", but what does this mean?
- In most cases, to obtain an allocation of "observing time" an astronomer must submit a telescope proposal with a well-argued scientific case for specific observational experiment.
- Deadlines are set typically twice or three times per year.
- Selection is done by peer review, that is, by a committee formed from the body of scientists who actually use the facility.
- All major telescopes are heavily oversubscribed. So writing good proposals is very important.
- The meaning of “observing” is changing now with the era of space telescopes, queue observing, survey science, and big data.
- Astronomers need to know what archival data is available, how to access data, and how to analyze data.

History of astronomical discoveries

Malcolm Longair

2009

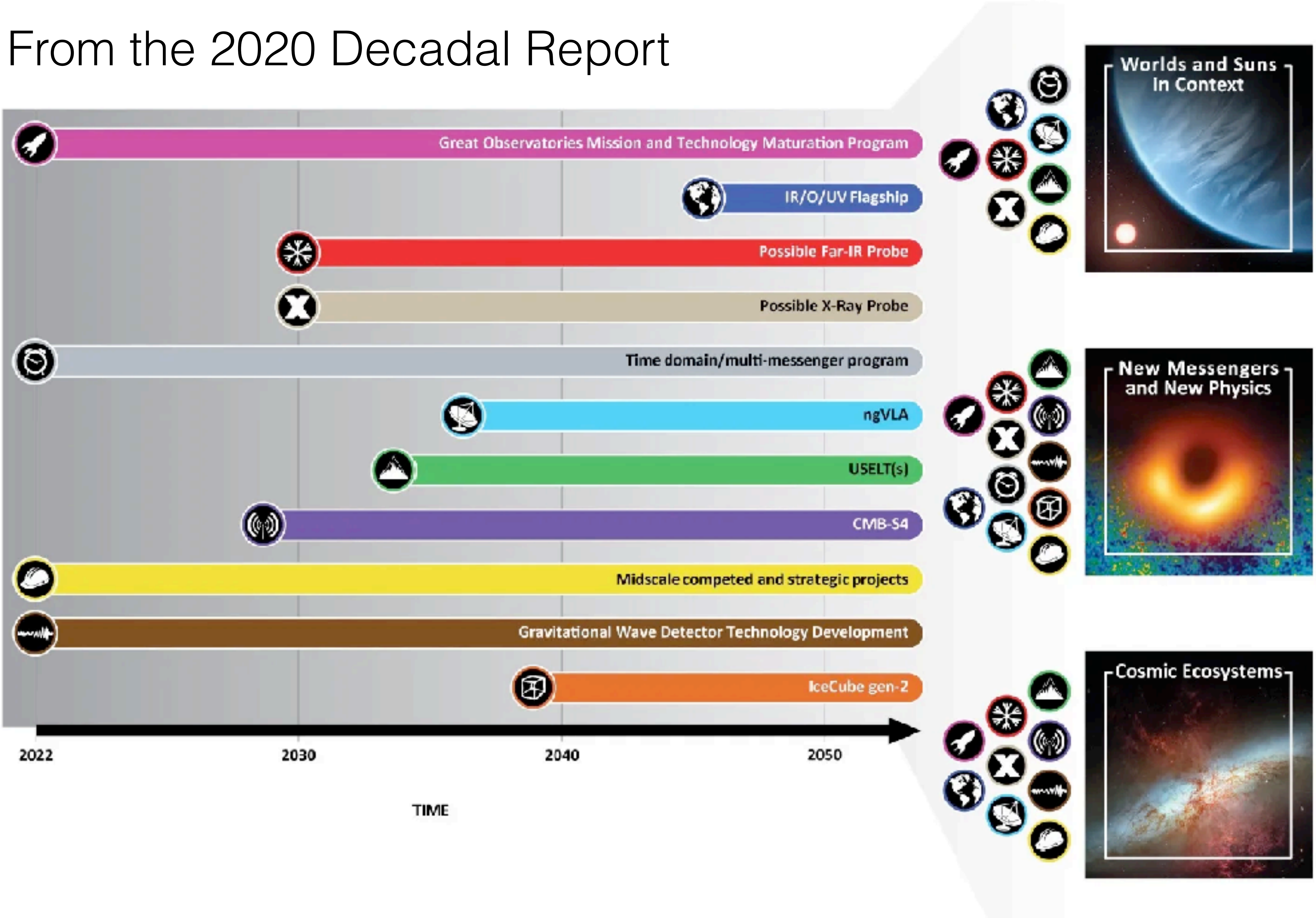
The route to astronomical, astrophysical and cosmological discovery is often tortuous, but the essential ingredients are well known.

- New technology, including instrumentation,
- New ways of doing astronomy,
- Precision observation,
- Extensive databases,
- Capitalising upon discoveries in other disciplines,
- Relevant theory,
- Imagination,
- Luck.

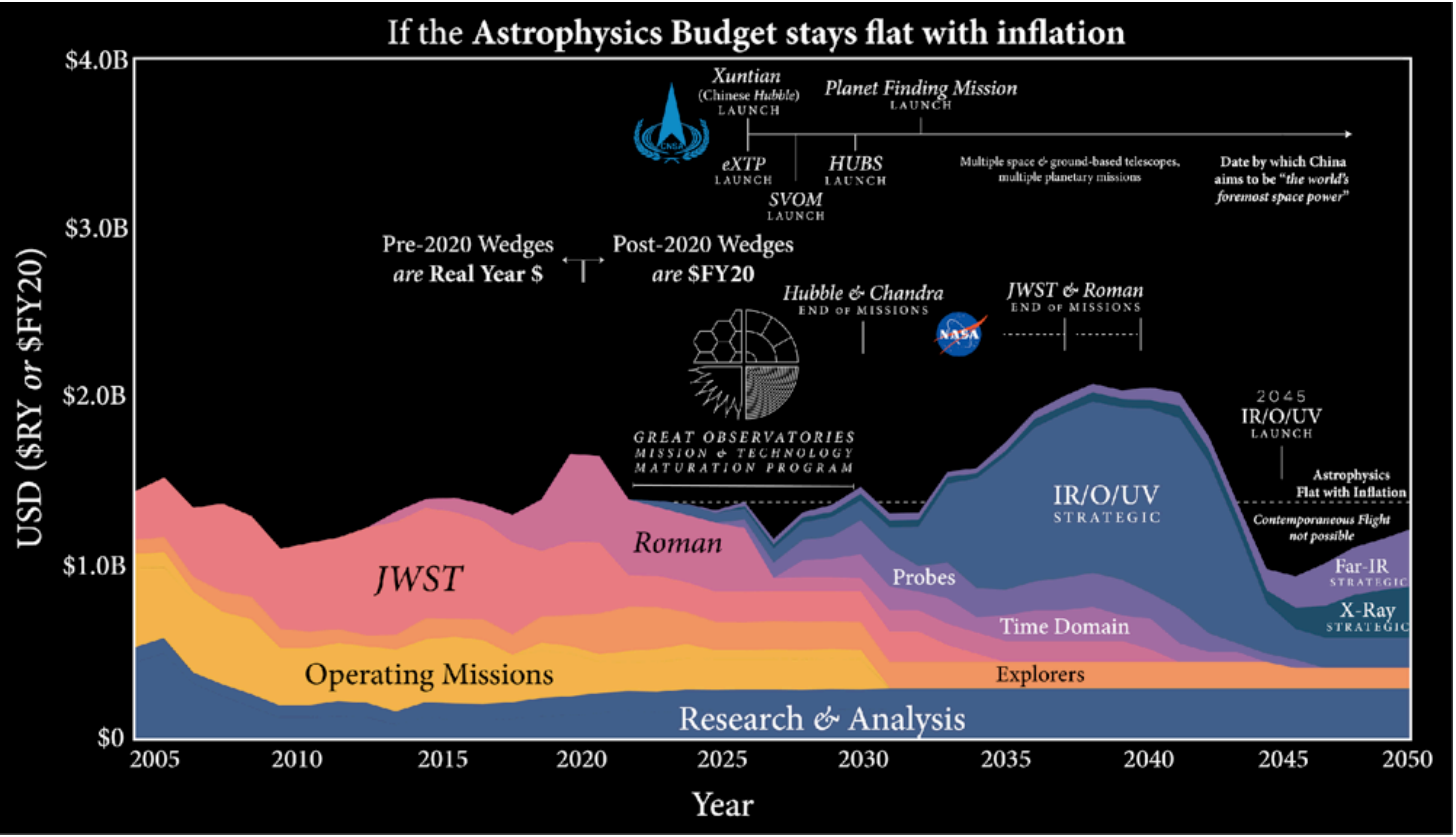
The Technology Spiral

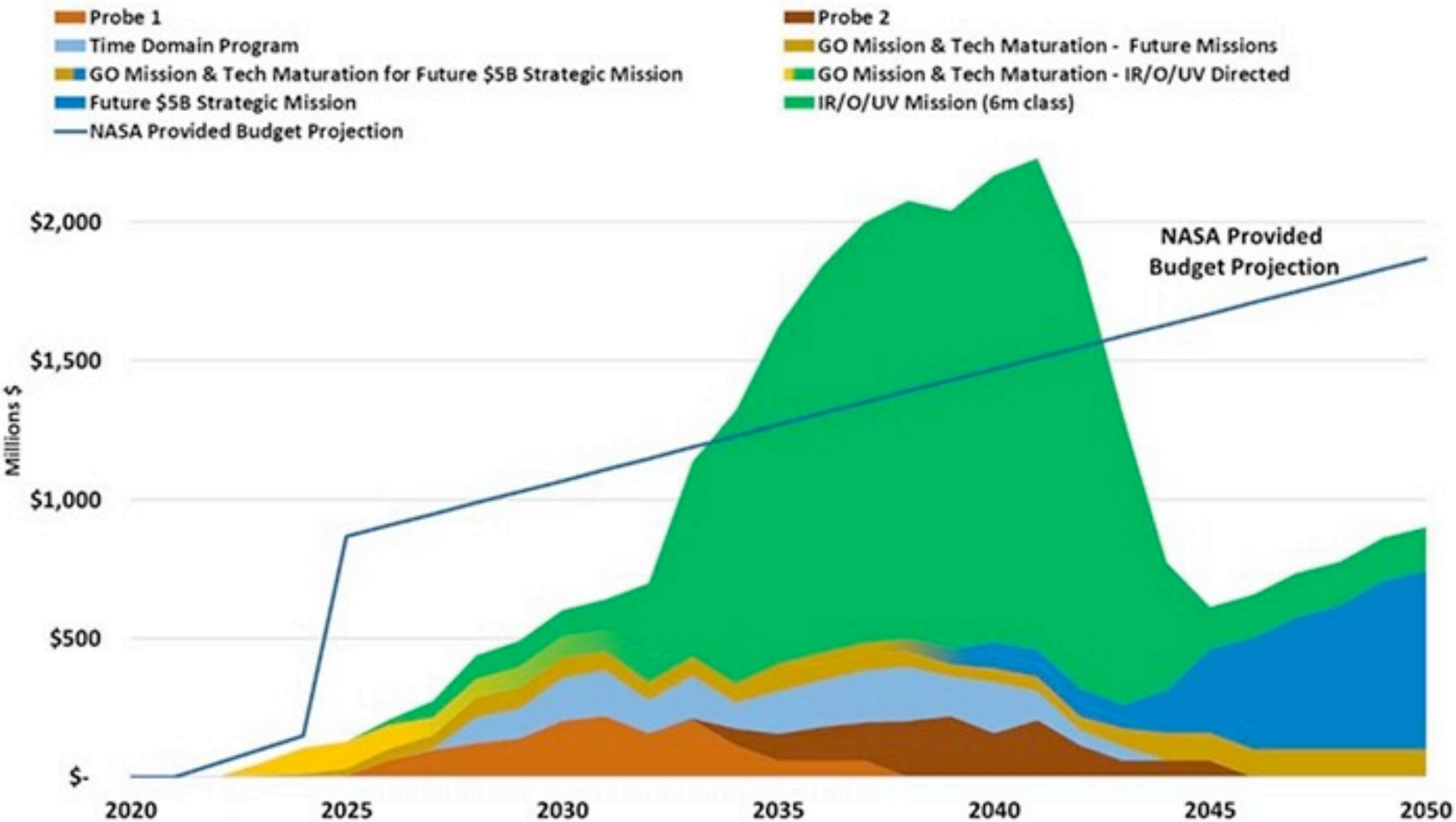
- Each new development in technology, and each new facility, helps to provide answers to old questions, and brings previously impossible observations within reach.
- Inevitably, the new observations uncover a host of new questions, which in turn, drive the quest for even better (bigger, more expensive) instruments.
- Progress in studying the universe has always been related to:
  - "deeper" surveys of the cosmos reaching to ever fainter objects,
  - or higher resolution yielding more and more fine detail,
  - or larger statistical samples from which generalizations can be made,
  - or broader spectral response to sample all the energy forms passively collected at Earth.
- That trend has continued since the Renaissance of the 16th century to the present day in an ever-increasing technology spiral.
- As more and more facilities are built, more money must be spent operating and maintaining them. And so, even though we have never had more instruments than now, it feels like it's harder than ever because there are more astronomers trying to use existing facilities and less money available to build new, super-expensive facilities.

From the 2020 Decadal Report

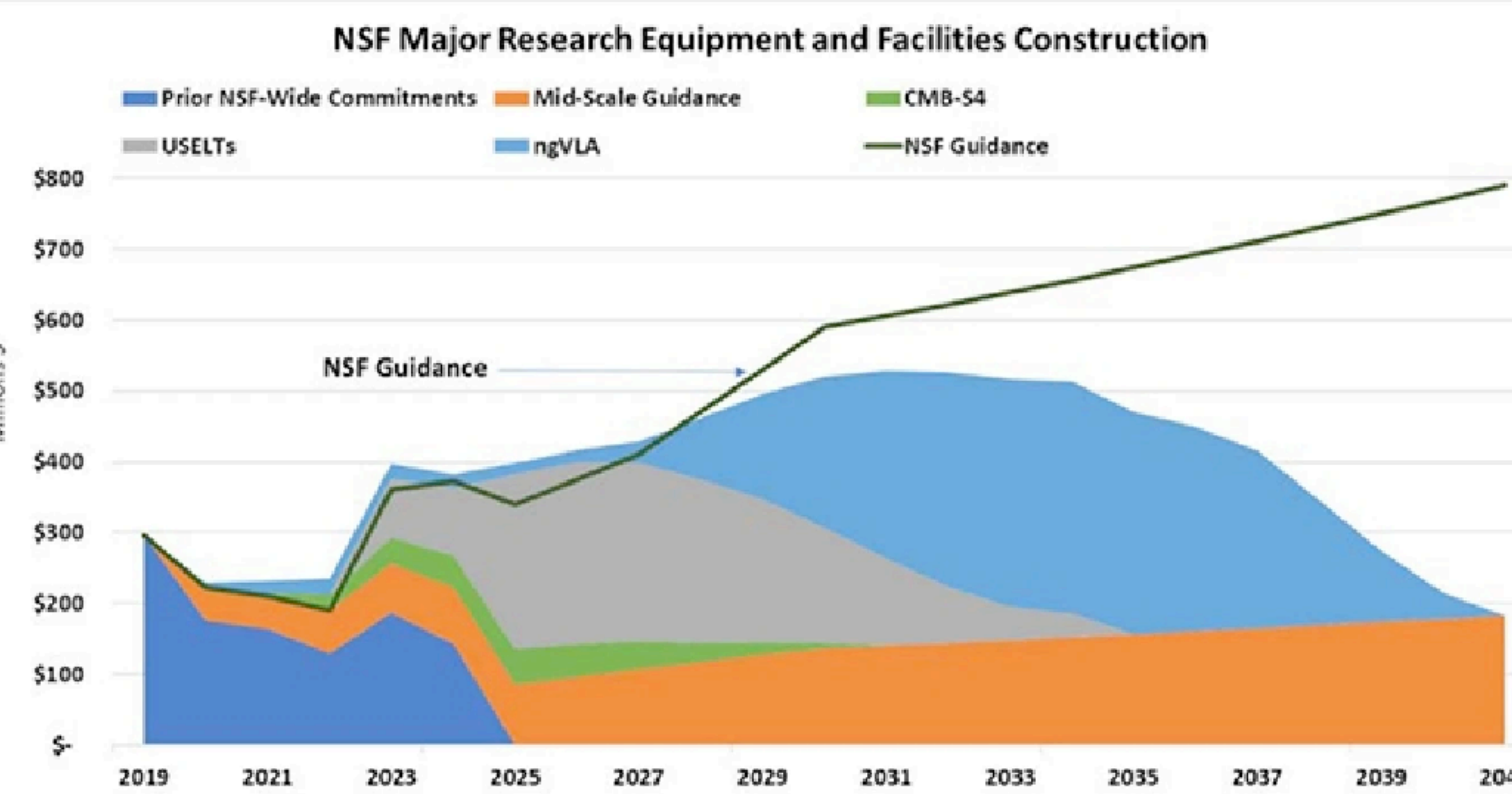


From the 2020 Decadal Report





Probe 1
Probe 2
Time Domain Program
GO Mission & Tech Maturation - Future Missions
GO Mission & Tech Maturation for Future $5B Strategic Mission
GO Mission & Tech Maturation - IR/O/UV Directed
Future $5B Strategic Mission
IR/O/UV Mission (6m class)
NASA Provided Budget Projection
NASA Provided Budget Projection
Millions $
$2,000
$1,500
$1,000
$500
$-
2020
2025
2030
2035
2040
2045
2050


NSF Major Research Equipment and Facilities Construction
Prior NSF-Wide Commitments
Mid-Scale Guidance
CMB-S4
USELTs
ngVLA
NSF Guidance
$800
$700
$600
$500
$400
$300
$200
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NSF Guidance
2019
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2035
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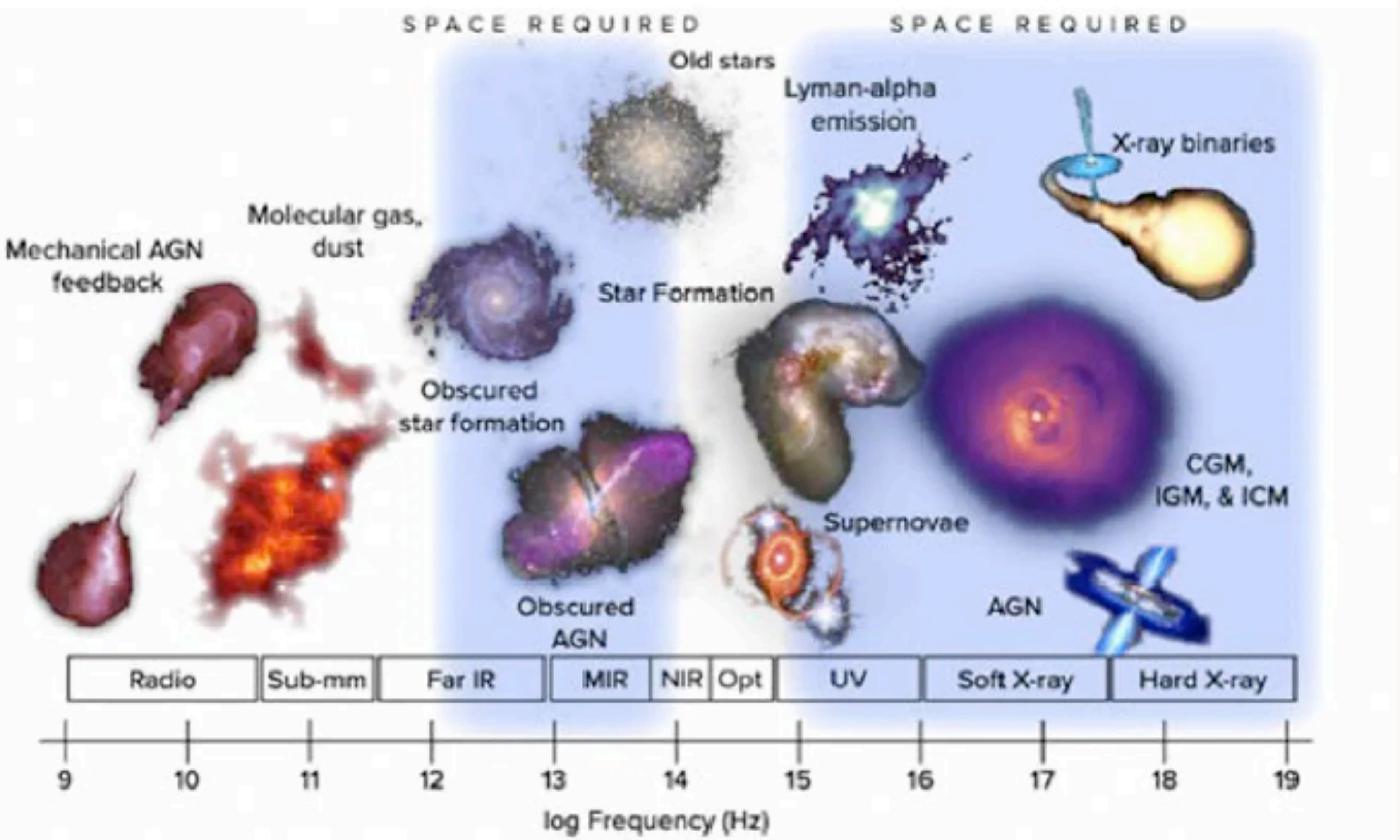
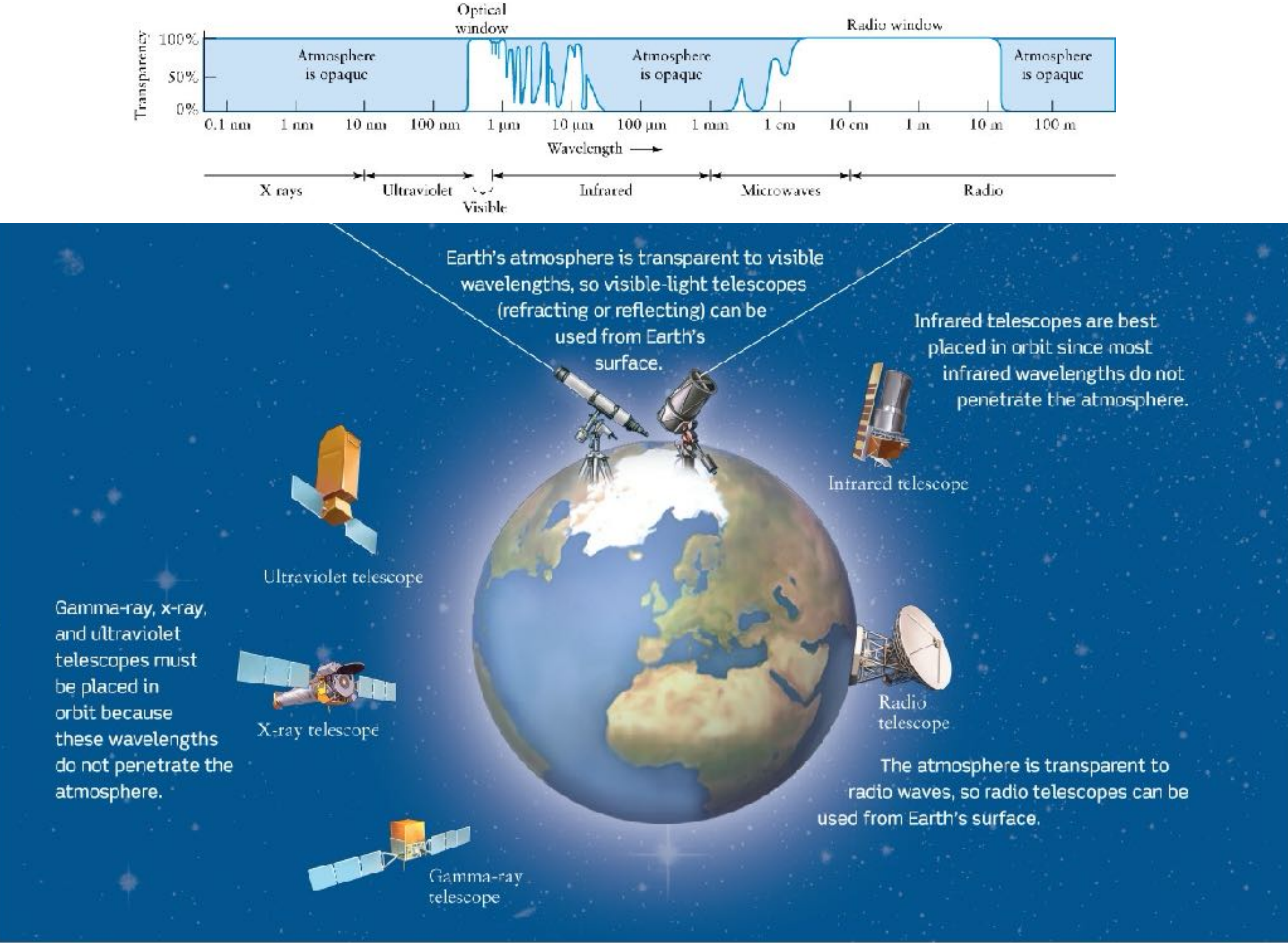
2039


SPACE REQUIRED
SPACE REQUIRED
Old stars
Lyman-alpha emission
X-ray binaries
Molecular gas, dust
Mechanical AGN feedback
Star Formation
Obscured star formation
CGM, IGM, & ICM
Supernovae
Obscured AGN
AGN
Radio
Sub-mm
Far IR
MIR
NIR
Opt
UV
Soft X-ray
Hard X-ray
9
10
11
12
13
14
15
16
17
18
19
log Frequency (Hz)

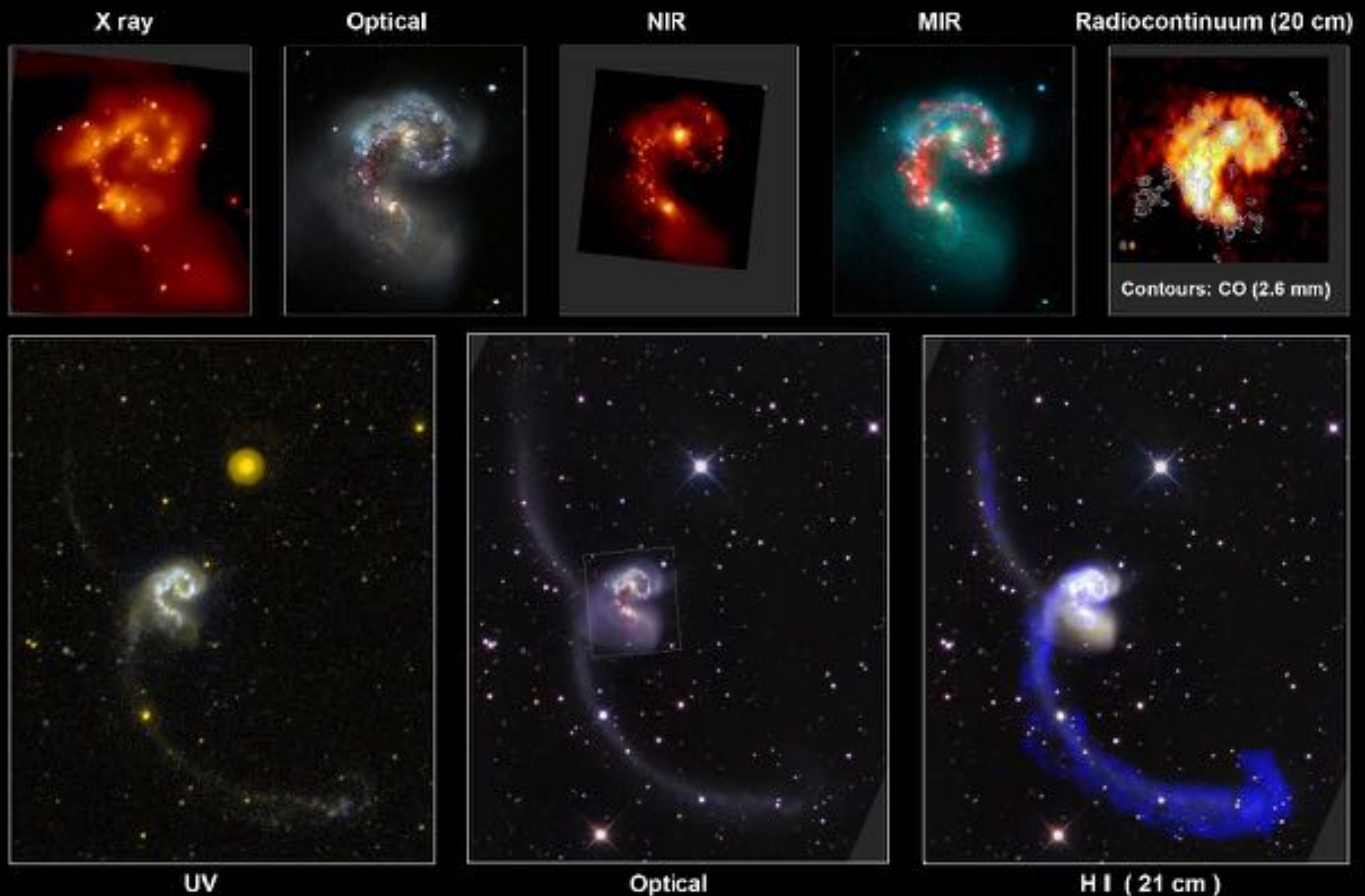

Arches cluster
X-ray binary 1E 1743.1-2843
Sagittarius A*
15 pc (6' 35")

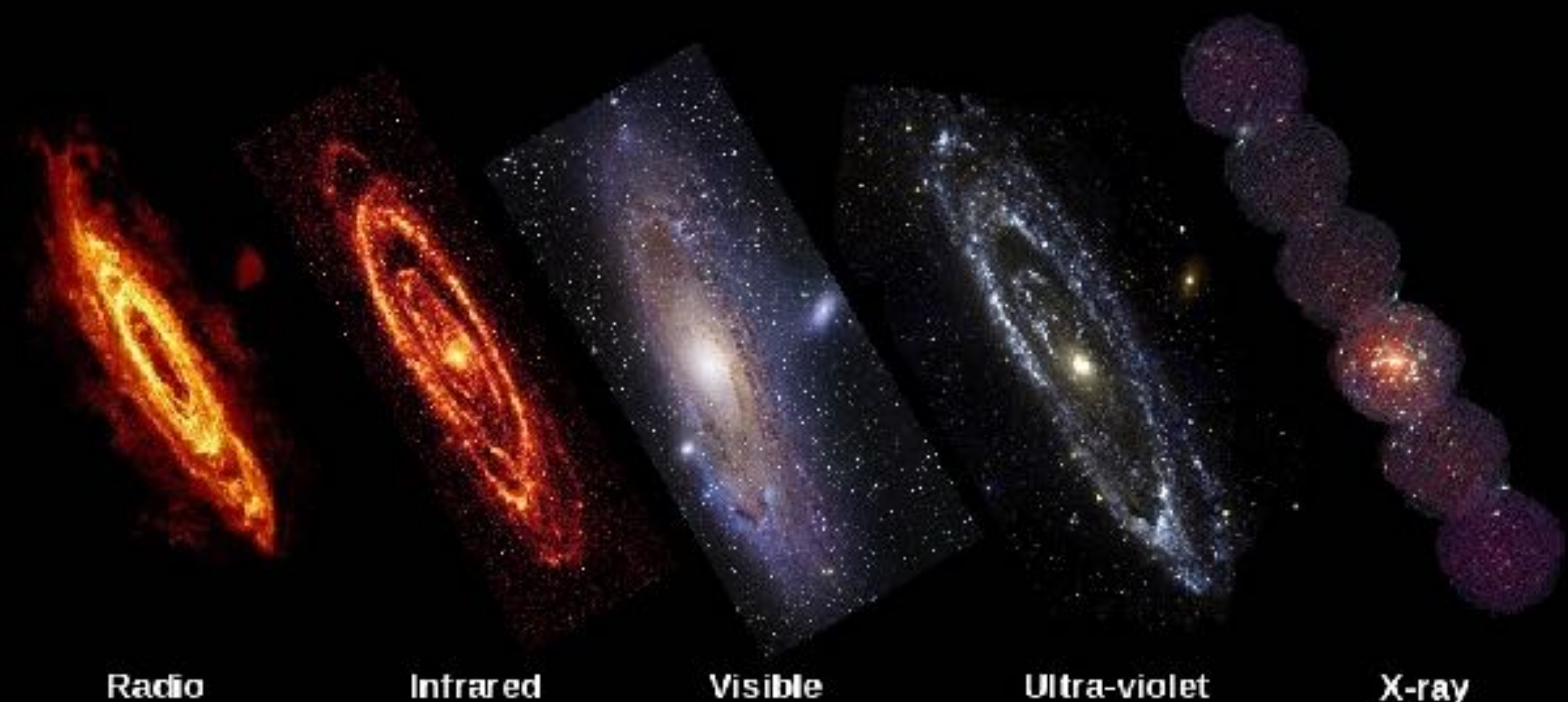


Optical window
Radio window
Transparency
100%
50%
0%
Atmosphere is opaque
Atmosphere is opaque
Atmosphere is opaque
0.1 nm
1 nm
10 nm
100 nm
1 µm
10 µm
100 µm
1 mm
1 cm
10 cm
1 m
10 m
100 m
Wavelength
X rays
Ultraviolet
Visible
Infrared
Microwaves
Radio
Earth's atmosphere is transparent to visible wavelengths, so visible-light telescopes (refracting or reflecting) can be used from Earth's surface.
Infrared telescopes are best placed in orbit since most infrared wavelengths do not penetrate the atmosphere.
Infrared telescope
Ultraviolet telescope
Gamma-ray, x-ray, and ultraviolet telescopes must be placed in orbit because these wavelengths do not penetrate the atmosphere.
X-ray telescope
Radio telescope
The atmosphere is transparent to radio waves, so radio telescopes can be used from Earth's surface.
Gamma-ray telescope

multiwavelength astronomy

- Progress in astronomy is fueled by new technical opportunities.
- For a long time, steady and overall spectacular advances were made in telescopes and, more recently, in detectors for the optical.
- In the last 60 years, continued progress has been fueled by two technical advancements. The first is opening new spectral windows: radio, *x*-ray, infrared, gamma ray.
- We haven't run out of possibilities: submillimeter, hard X-ray/gamma ray, cold IR telescopes, adaptive optics (AO), neutrinos, gravitational waves, and the time-domain are some of the remaining frontiers.





What makes a galaxy ?

(or any generic space cloud)

Stellar Mass

—> How many stars have formed

optical and near-infrared SED

Star Formation Rate

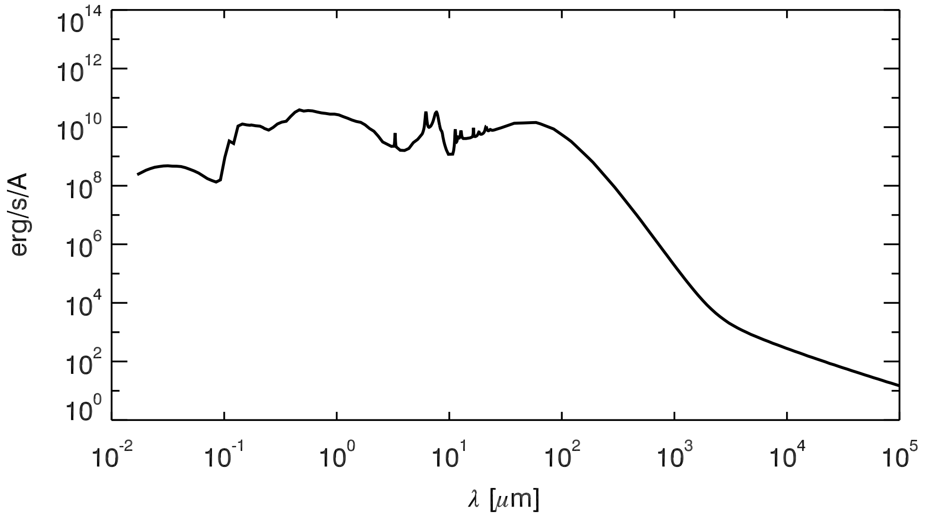
—> How many stars are being formed

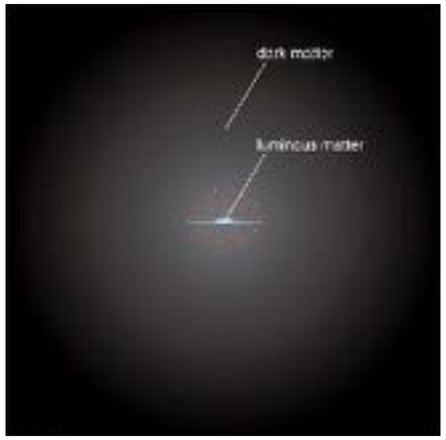
L_{FIR}, [CII]λ158μm, H_2O, H-α, Pa-α

Gas Mass

—> star formation potential

CO, [CI], M_d

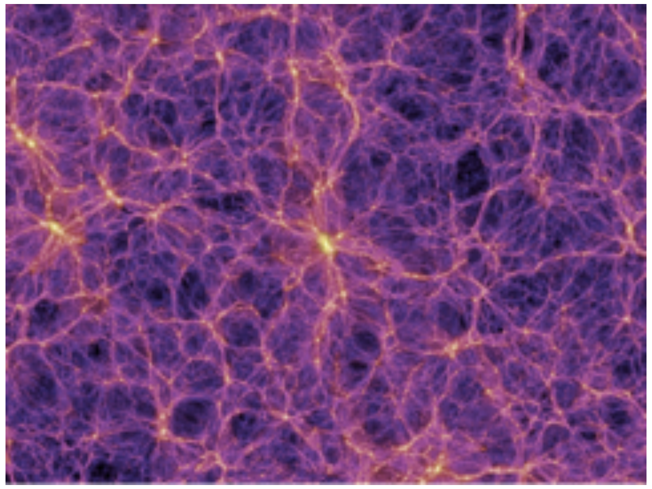




Central Black Hole

—> What is it's role?

SEDs, [OIII], PAH

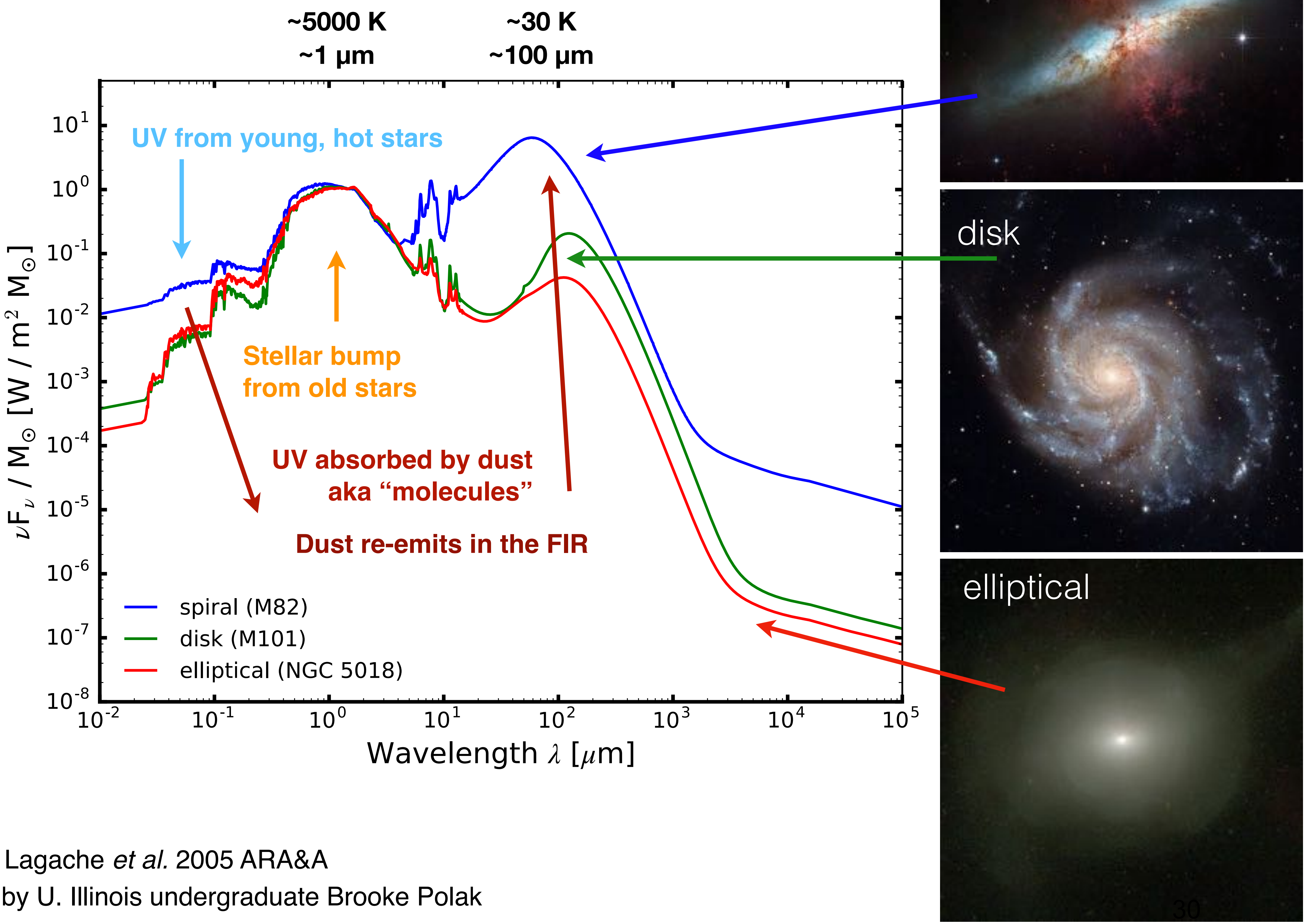


Environment and Dark Matter

—> What is it's role?

density, gravitational lensing

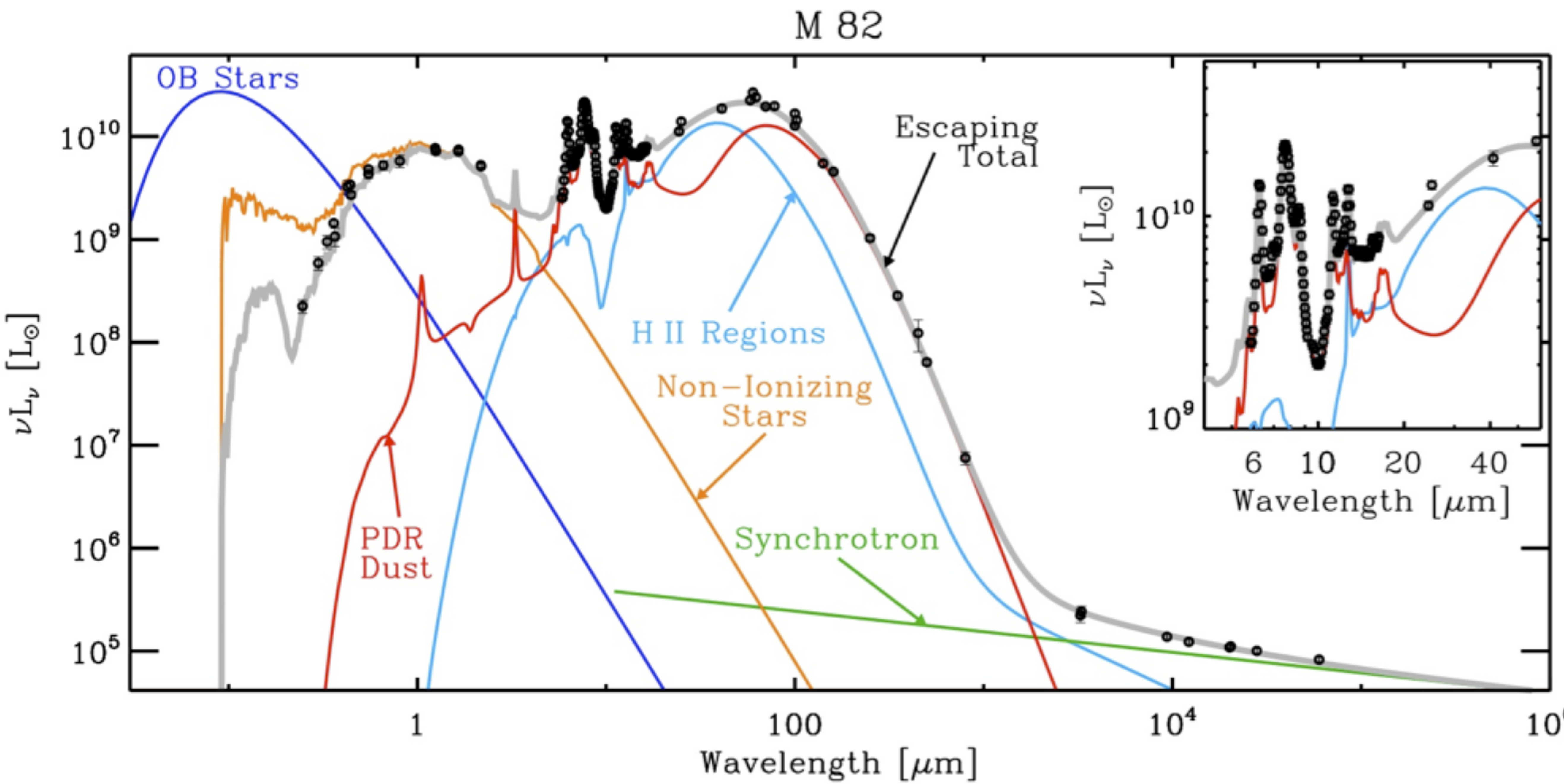
Spectral Energy Densities of Galaxies



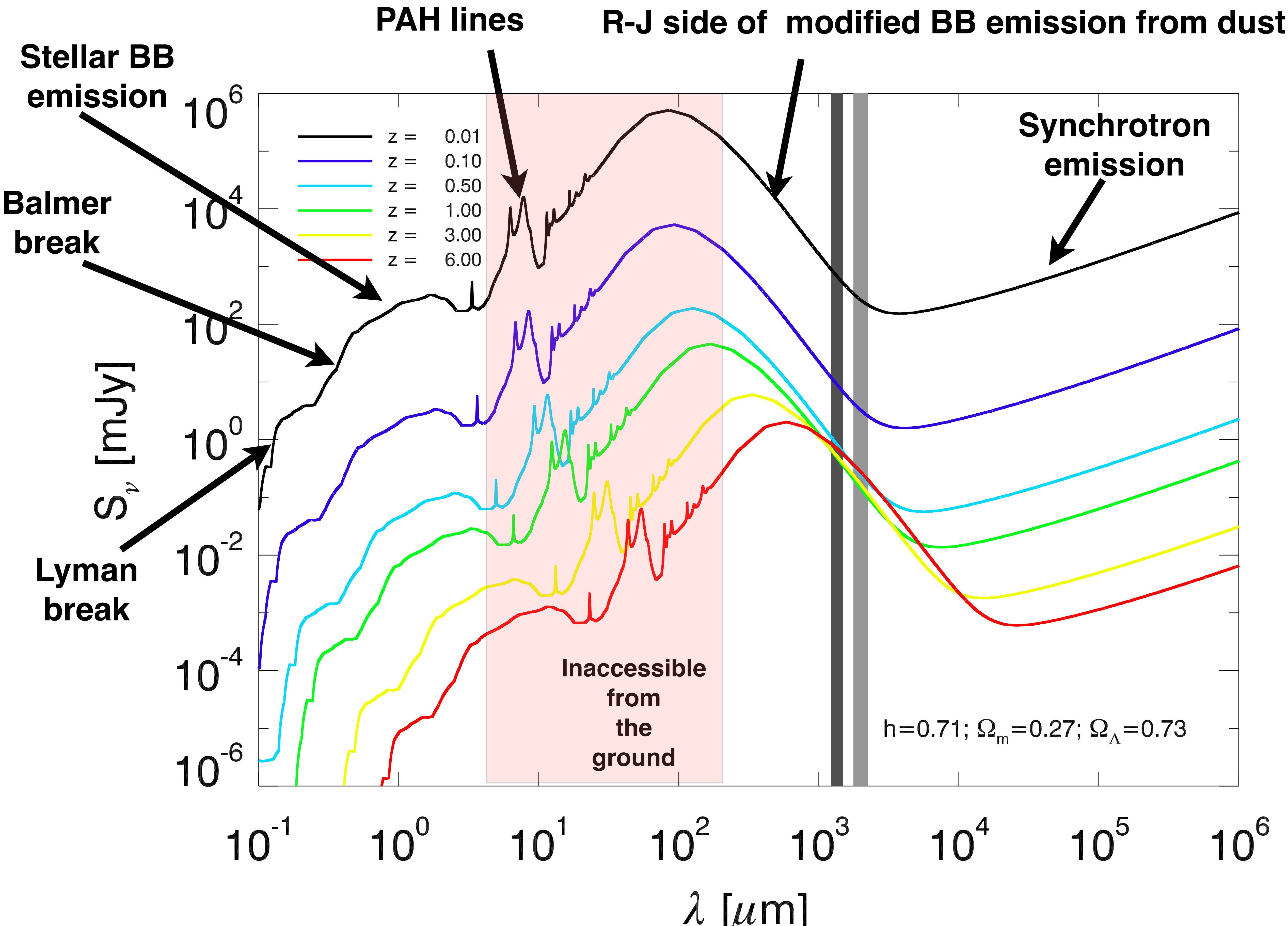
see Lagache *et al.* 2005 ARA&A

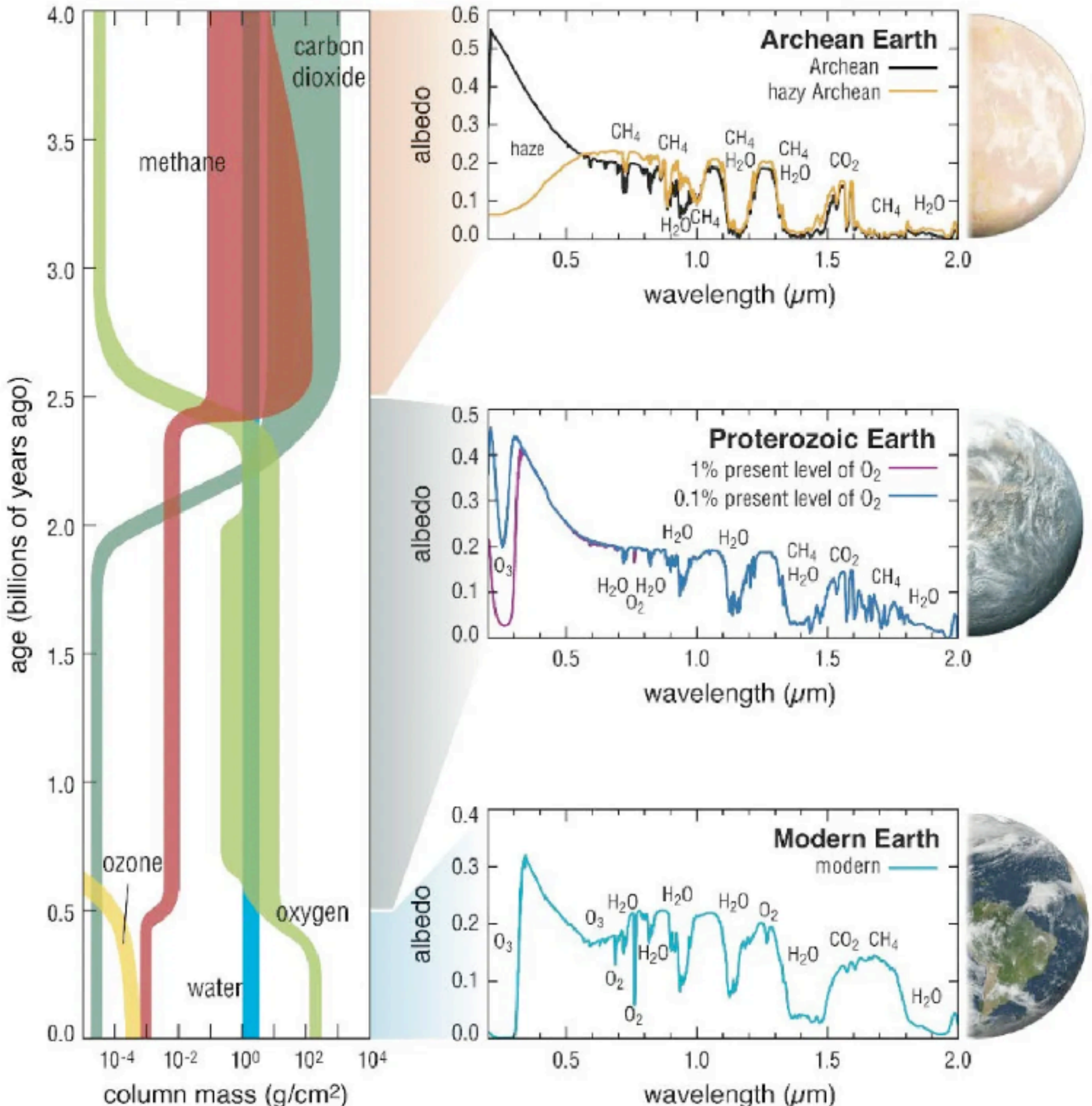
plot by U. Illinois undergraduate Brooke Polak

The galaxy spectral energy distribution



Galliano, Dwek & Chanial 2008

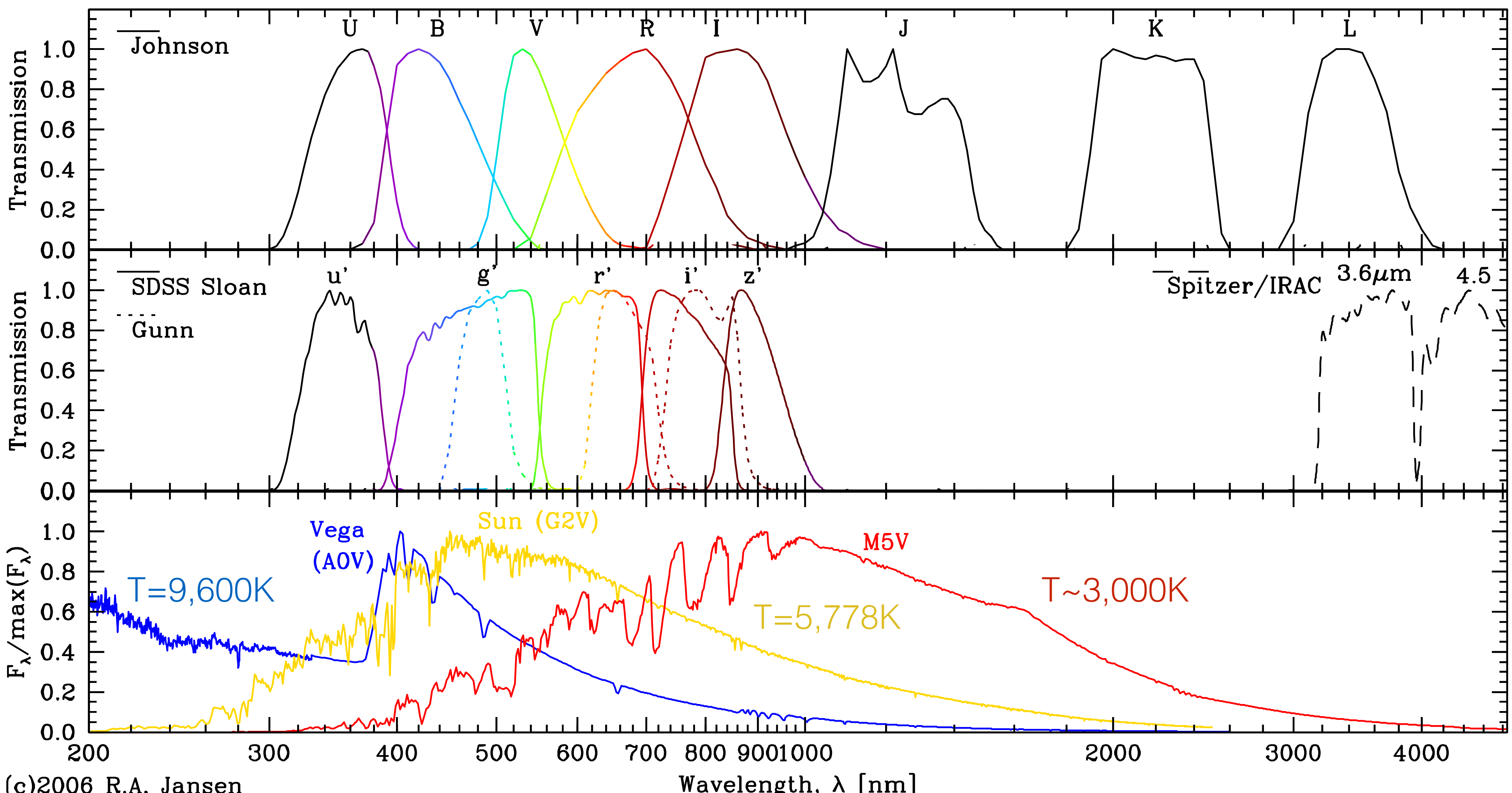

PAH lines
R-J side of modified BB emission from dust
Stellar BB emission
Balmer break
Lyman break
Synchrotron emission
z = 0.01
z = 0.10
z = 0.50
z = 1.00
z = 3.00
z = 6.00
Inaccessible from the ground
h=0.71; Ω_m=0.27; Ω_Λ=0.73
S_ν [mJy]
λ [μm]
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}



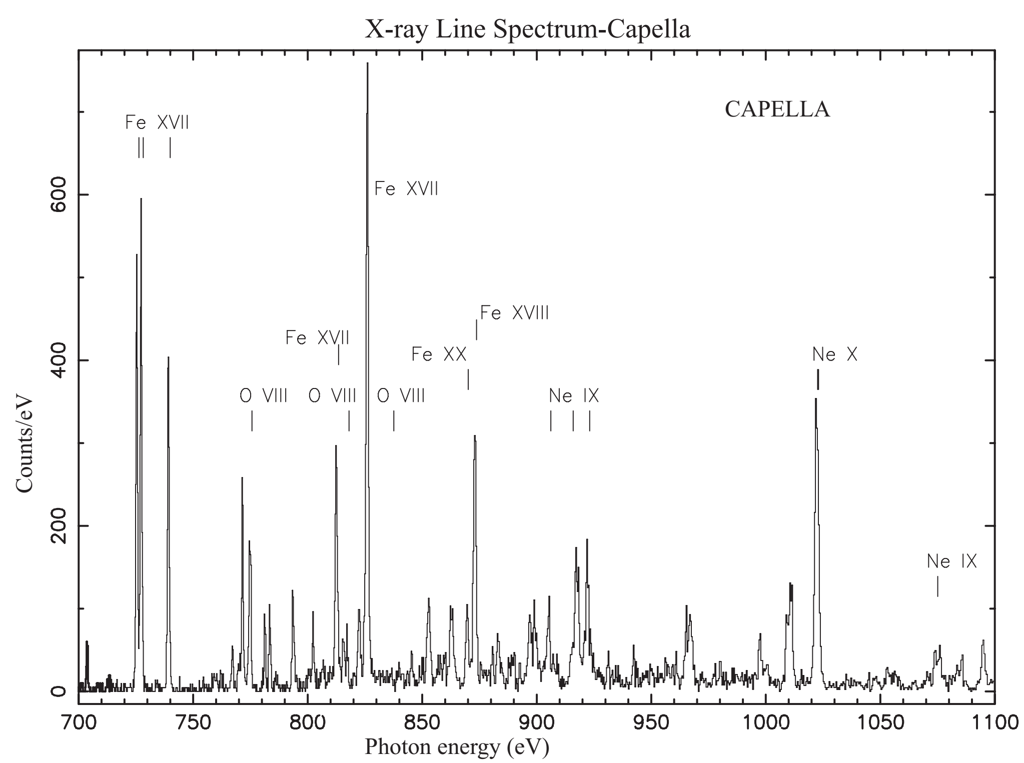
carbon dioxide
methane
ozone
oxygen
water
age (billions of years ago)
column mass (g/cm2)
Archean Earth
Archean
hazy Archean
haze
Proterozoic Earth
1% present level of O2
0.1% present level of O2
Modern Earth
modern
albedo
wavelength (μm)

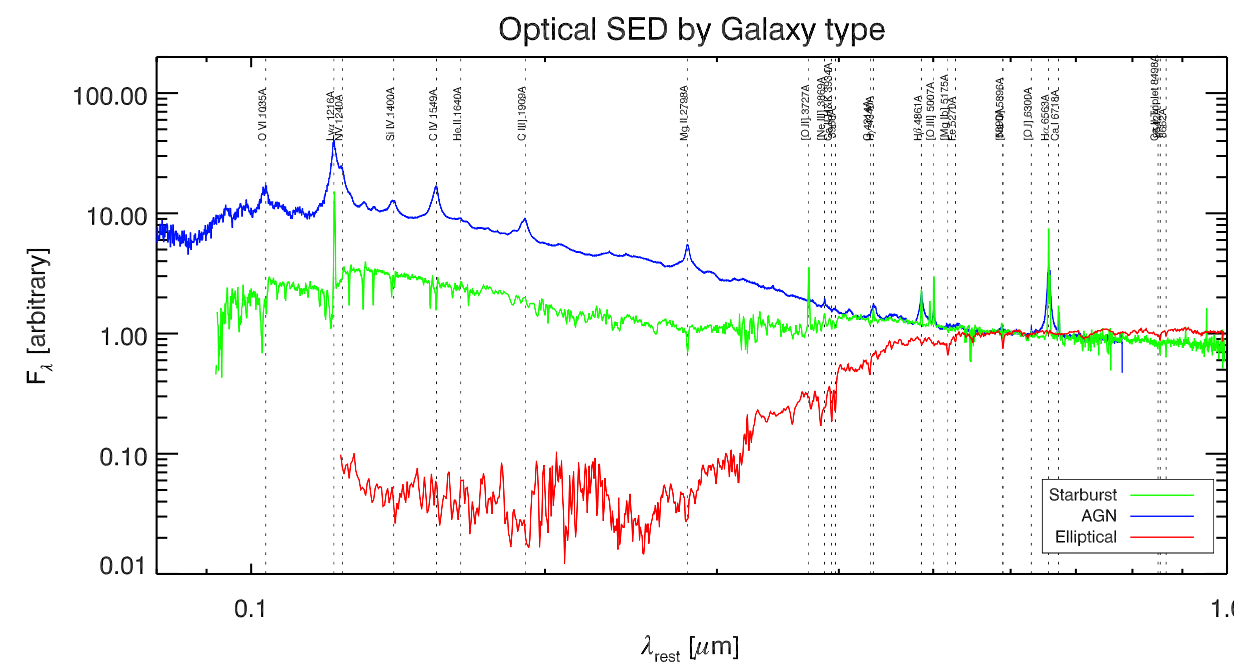
imaging filters

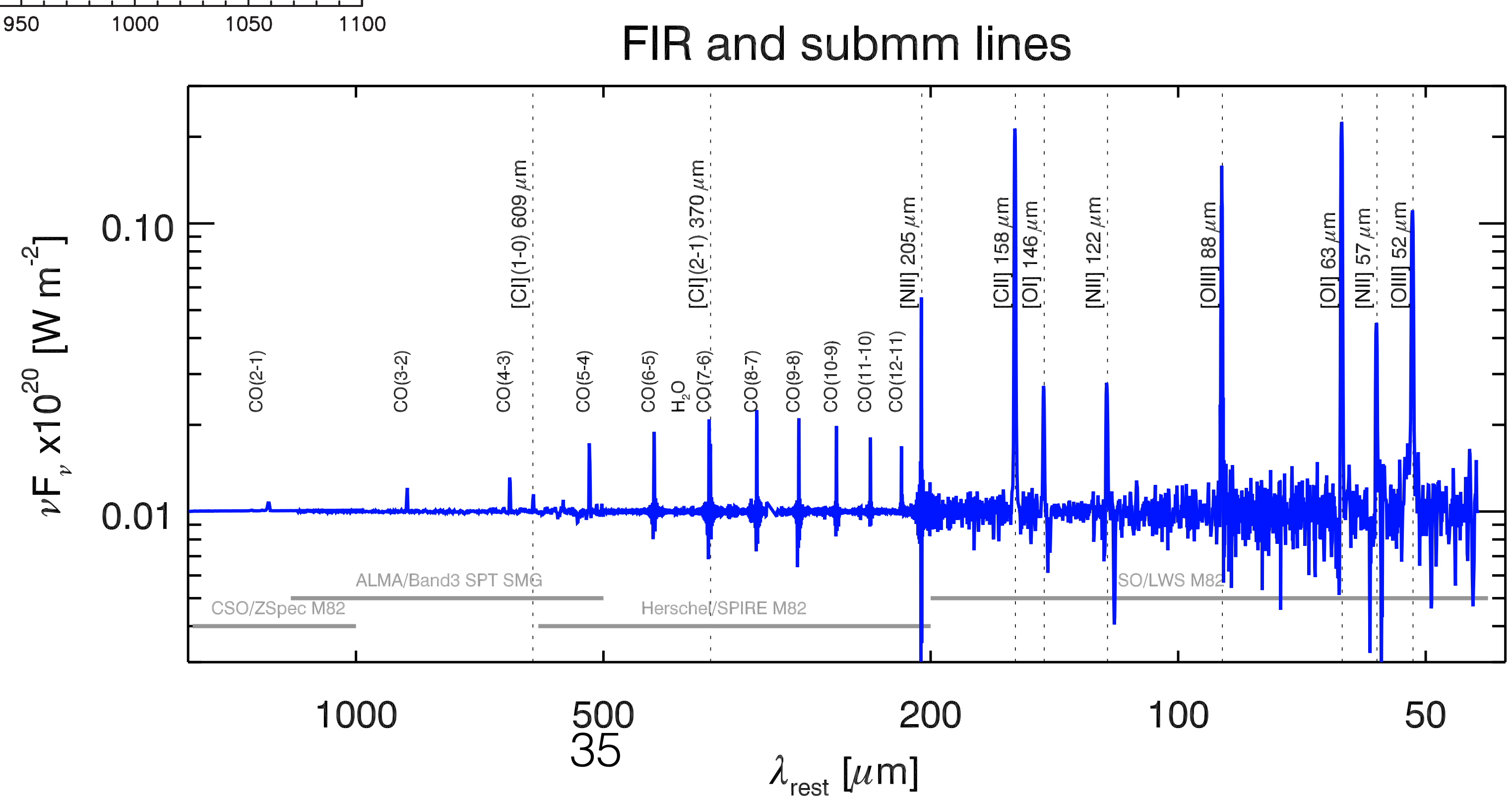
	u′	g′	r′	i′	z′
λ_{cen}, nm	354	477	623	762	915
FWHM	57	139	137	153	95



Spectroscopy is one link between astronomy and physics —> astrophysics

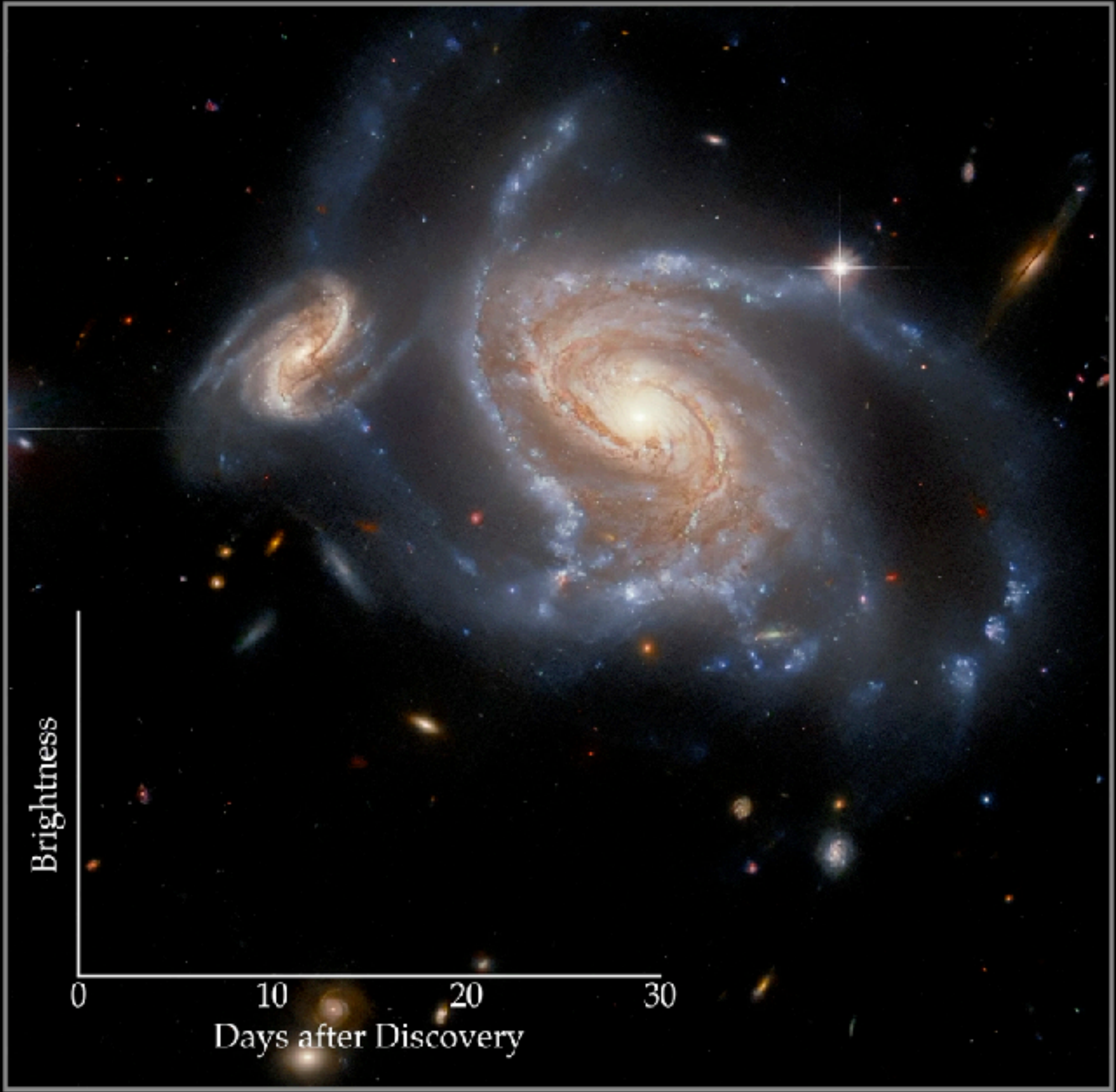






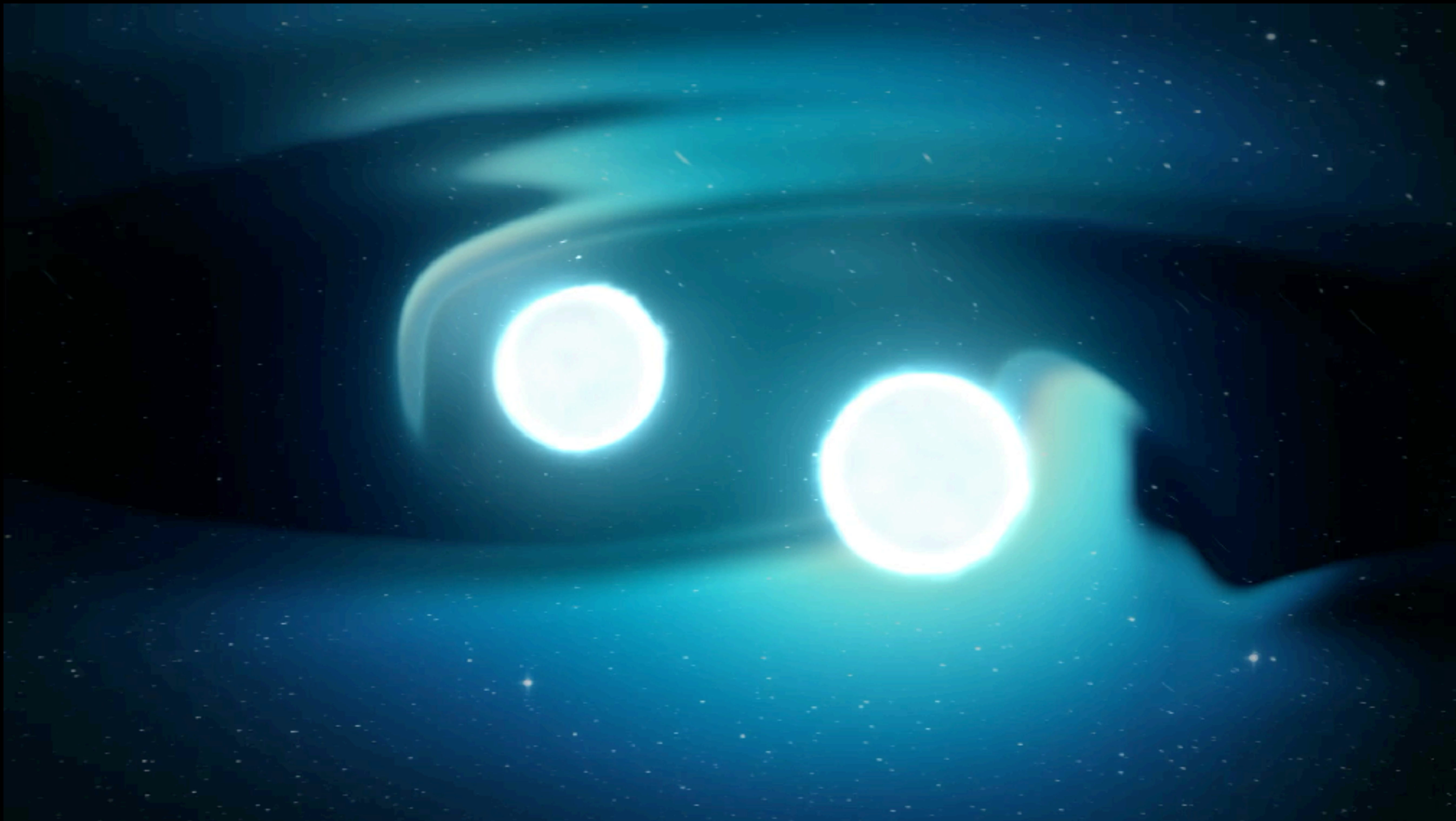
multi-time scale astronomy

- .In the last 60 years, continued progress has been fueled by two technical advancements. The second is moving away from single snapshots of sources to time-series.
- More than just longer time-baselines of observations - higher cadence enables you to find new sources e.g. GRBs were found by satellites looking for illegal nuclear weapons testing, or more recently FRBs in the radio, and of course…



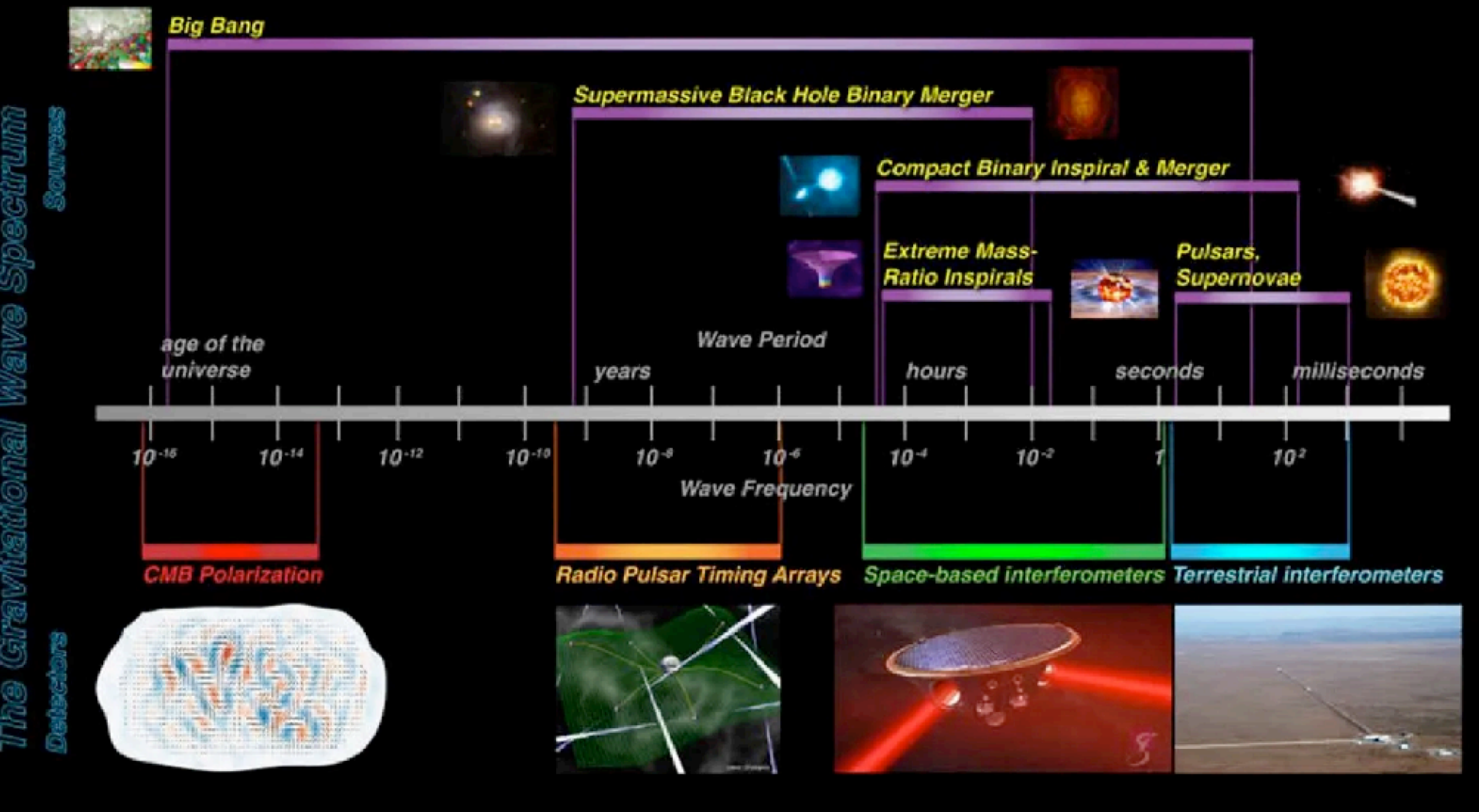
NGC 1356; ESA / Hubble & NASA

Alex Gagliano, 2024

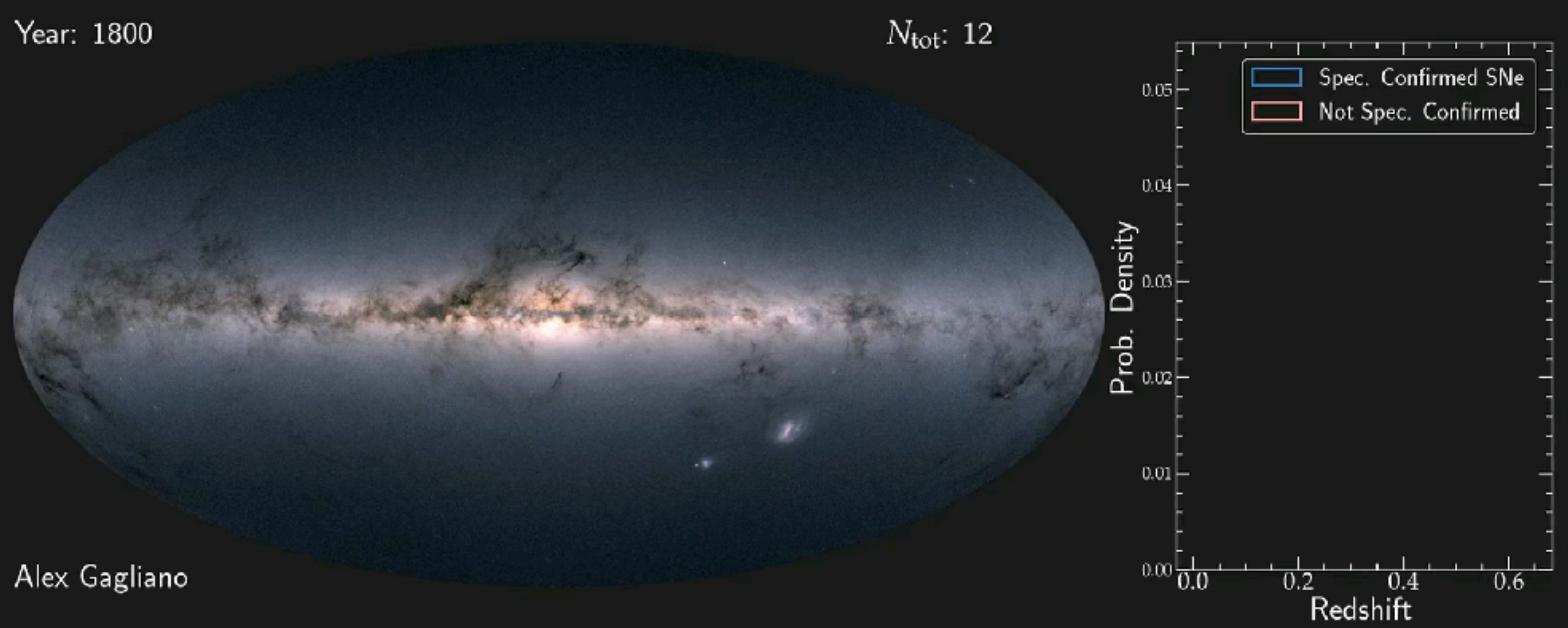


Gravitational Waves & LIGO —> LISA

Gravitational Wave Sources: Followup and Characterization

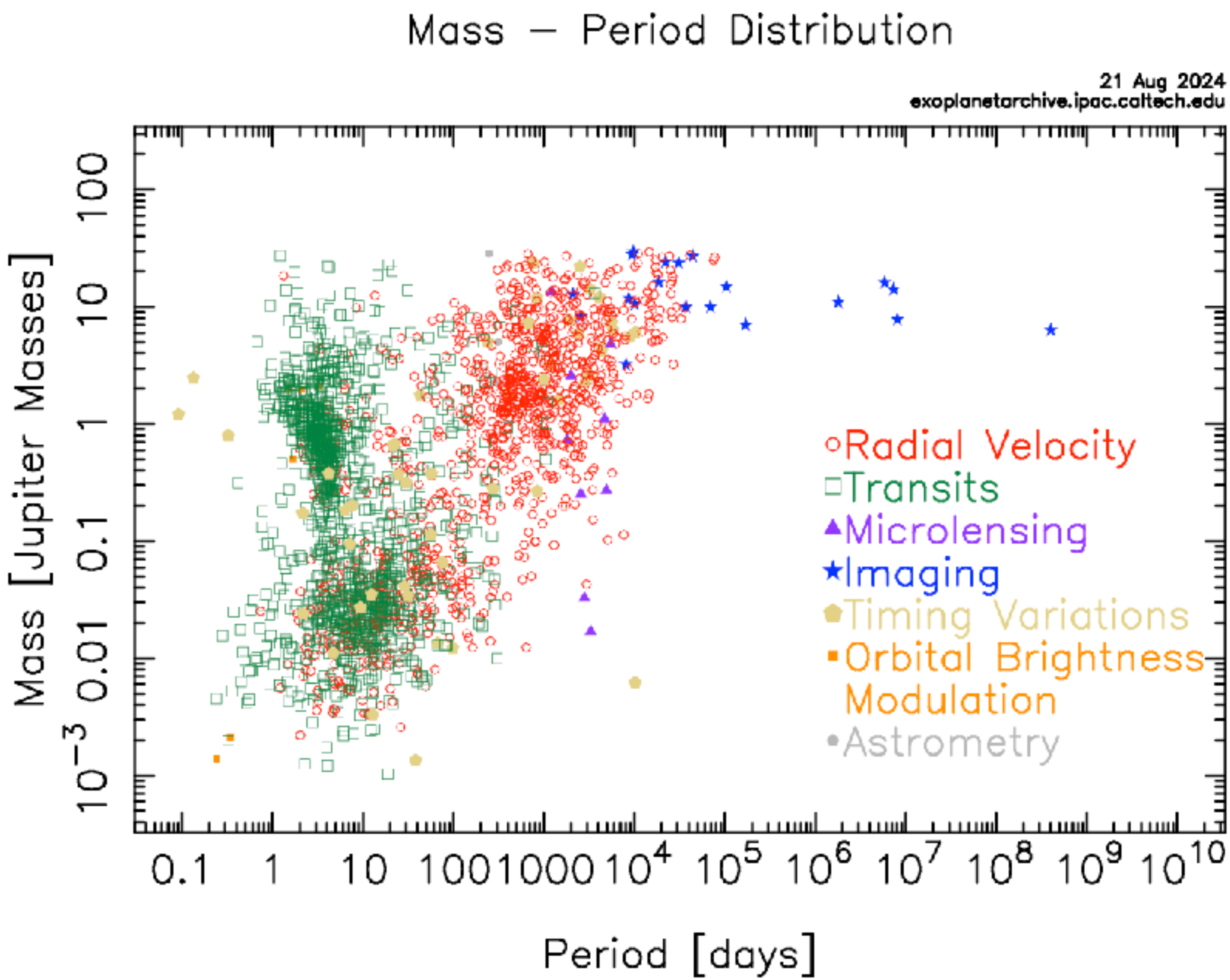


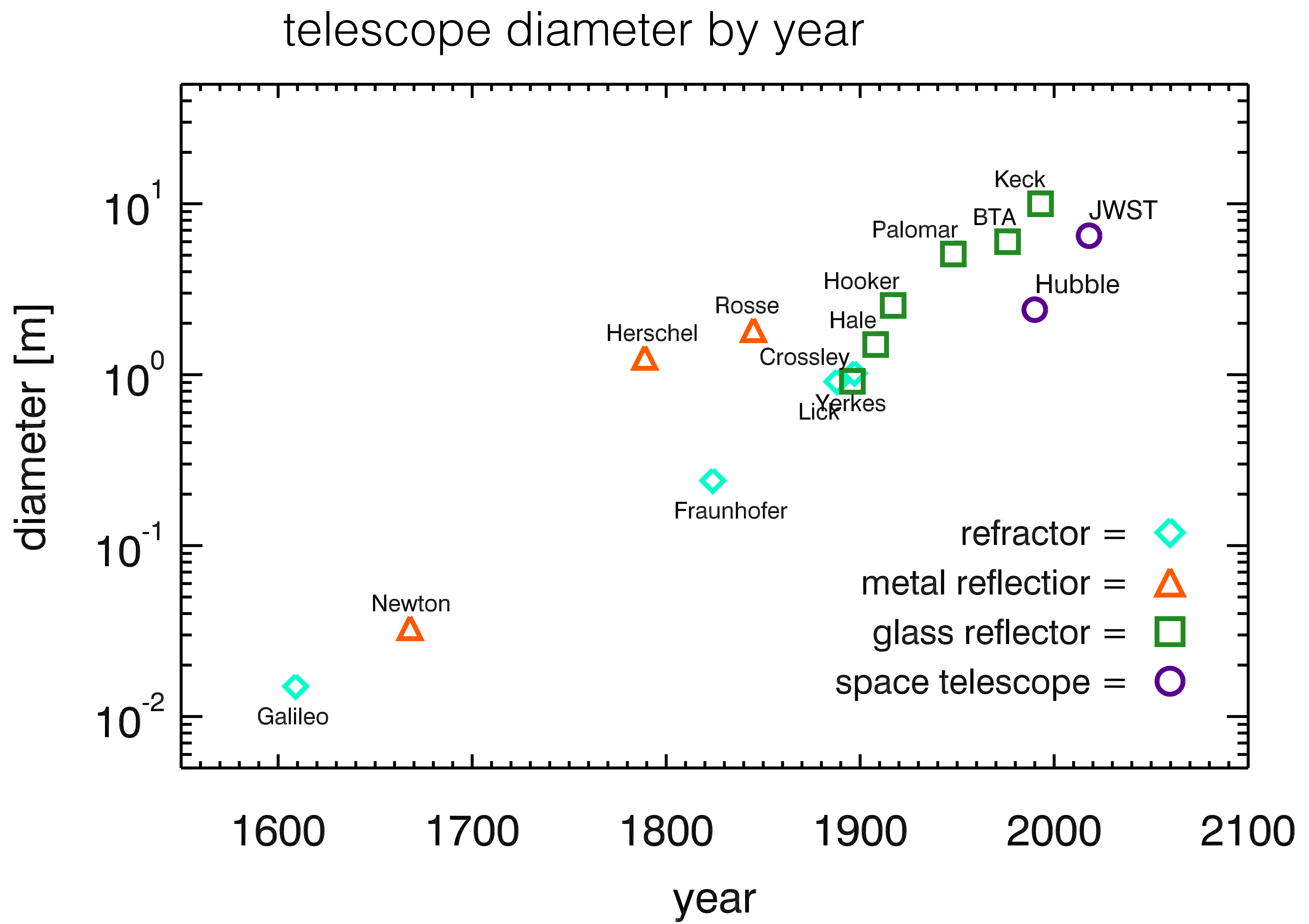
The Gravitational Wave Spectrum
Sources
Detectors
Big Bang
Supermassive Black Hole Binary Merger
Compact Binary Inspiral & Merger
Extreme Mass-Ratio Inspirals
Pulsars, Supernovae
age of the universe
Wave Period
years
hours
seconds
milliseconds
10^{-16}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
Wave Frequency
CMB Polarization
Radio Pulsar Timing Arrays
Space-based interferometers
Terrestrial interferometers


Year: 1800
N_{tot}: 12
Alex Gagliano
Spec. Confirmed SNe
Not Spec. Confirmed
Prob. Density
0.00
0.01
0.02
0.03
0.04
0.05
0.0
0.2
0.4
0.6
Redshift

Exoplanets:

Discovery and Characterization





telescope diameter by year
diameter [m]
year
10^{1}
10^{0}
10^{-1}
10^{-2}
1600
1700
1800
1900
2000
2100
Galileo
Newton
Fraunhofer
Herschel
Rosse
Crossley
Lick
Yerkes
Hale
Hooker
Palomar
BTA
Keck
JWST
Hubble
refractor =
metal reflectior =
glass reflector =
space telescope =

Building ever larger telescopes is infeasible, but the thirst for resolution is insatiable - so technology keeps pushing