Anticipating an Avalanche of Astrophysical Transients

Daryl Haggard
McGill University
Canada Research Chair
IPAG Visitor (through July 2023)

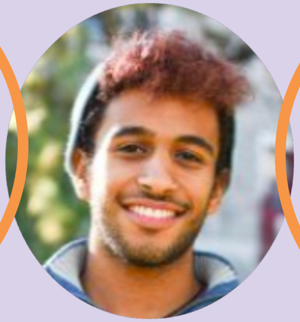
MEGA McGill Extreme Gravity & Accretion Group

Prof. Daryl Haggard

Dr. Kristen Dage

Dr. Bailey Tetarenko

Dr. Mervyn Chan*



Soud Al Kharusi*

Nicholas Vieira*

Anan Lu

Nicole Ford*

Nayyer Raza

Élodie Lescure*

Collaborators & Recent Grad Students

Prof. Jess McIver

Prof. John Ruan

Dr. Hope Boyce

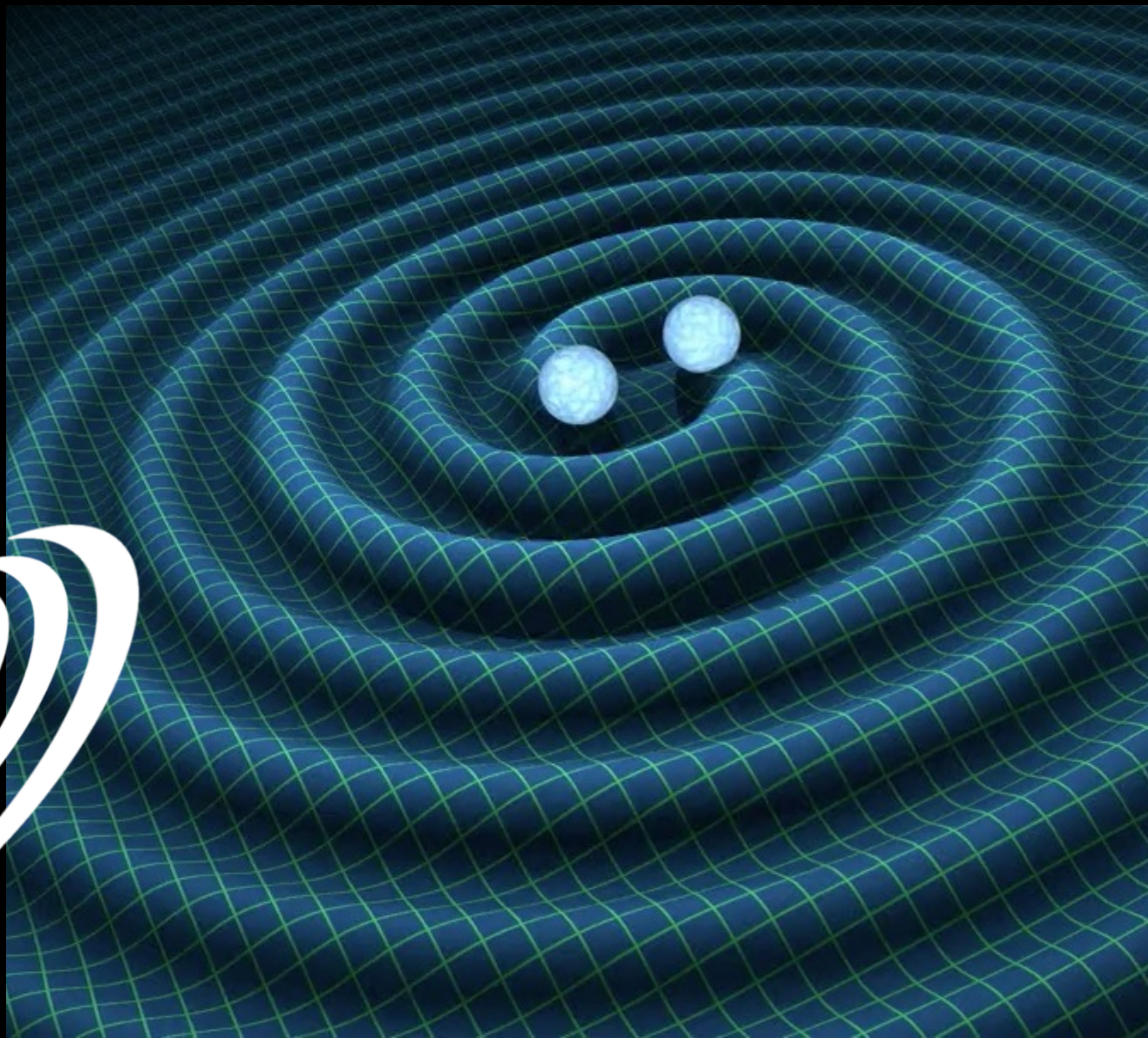
Samuel Gagnon-Hartman*

Plus many alumni, post-bac, and undergrad researchers at McGill!

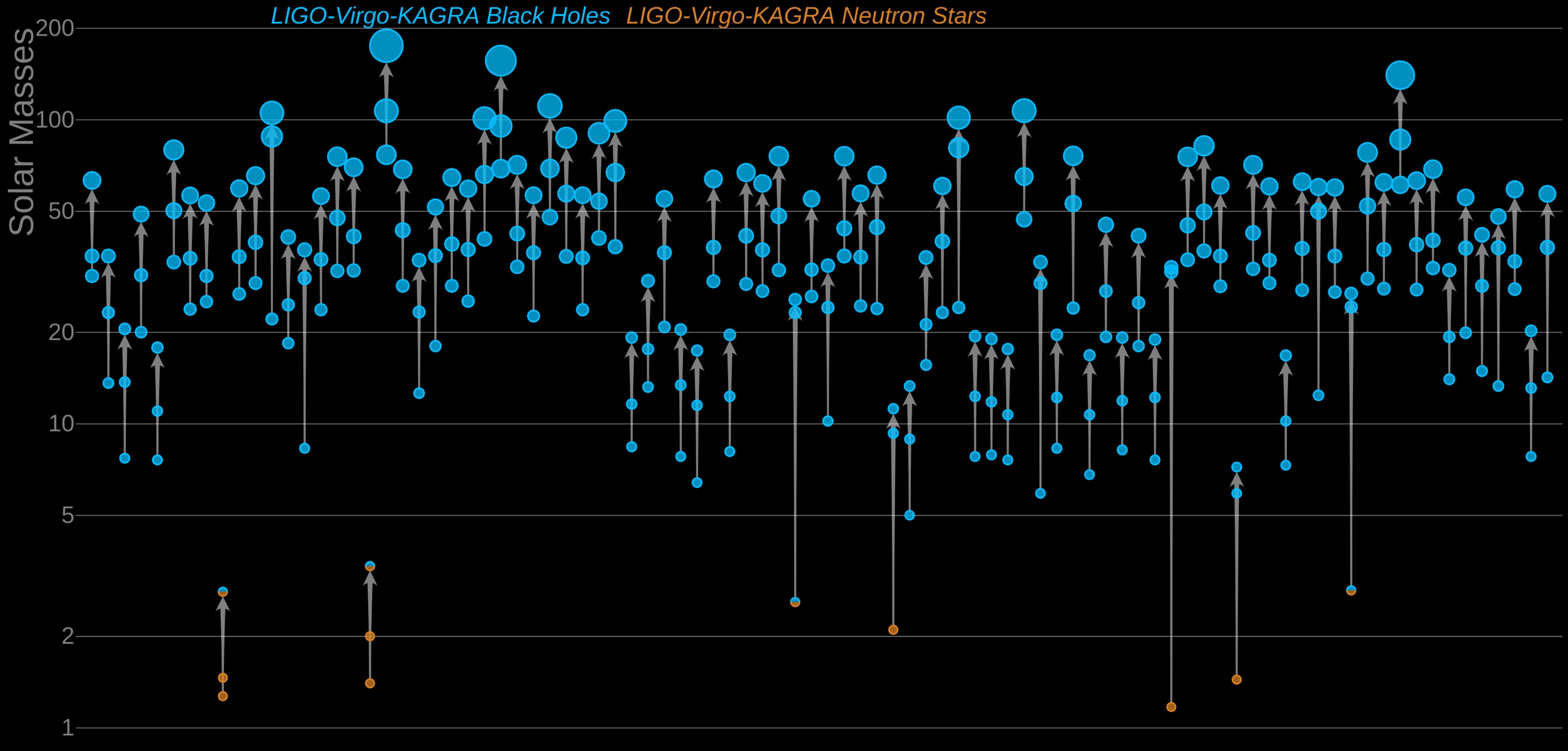
A New Era of Black Hole Discover

- Detecting gravitational waves is a triumph of ingenuity
- Discoveries offer new tests of GR
- Have also uncovered a spectacular unseen population of BHs and BH-BH mergers
- GW experiments have also seen NS-NS and BH-NS collisions

LIGO
VIRGO
KAGRA



Masses in the Stellar Graveyard



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

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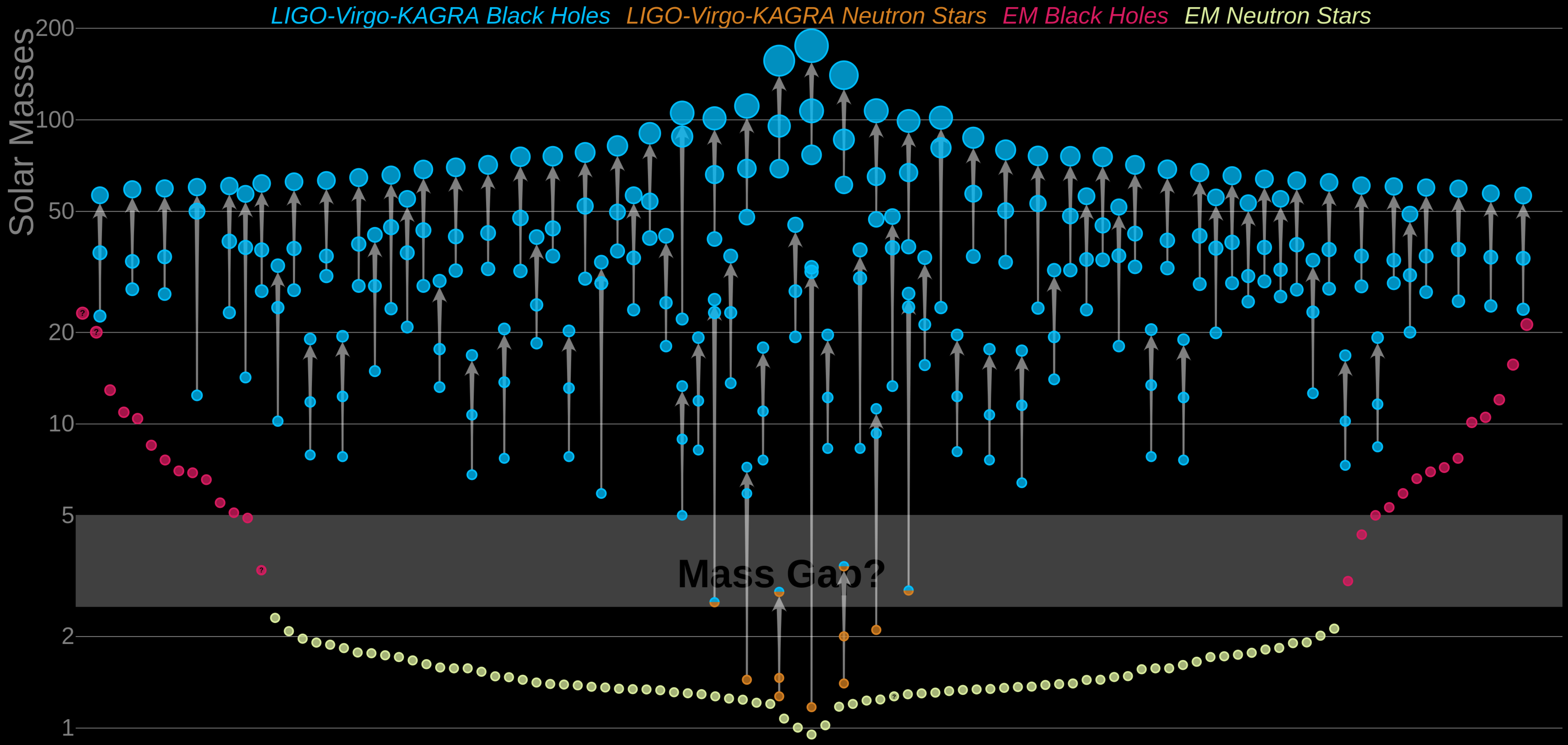

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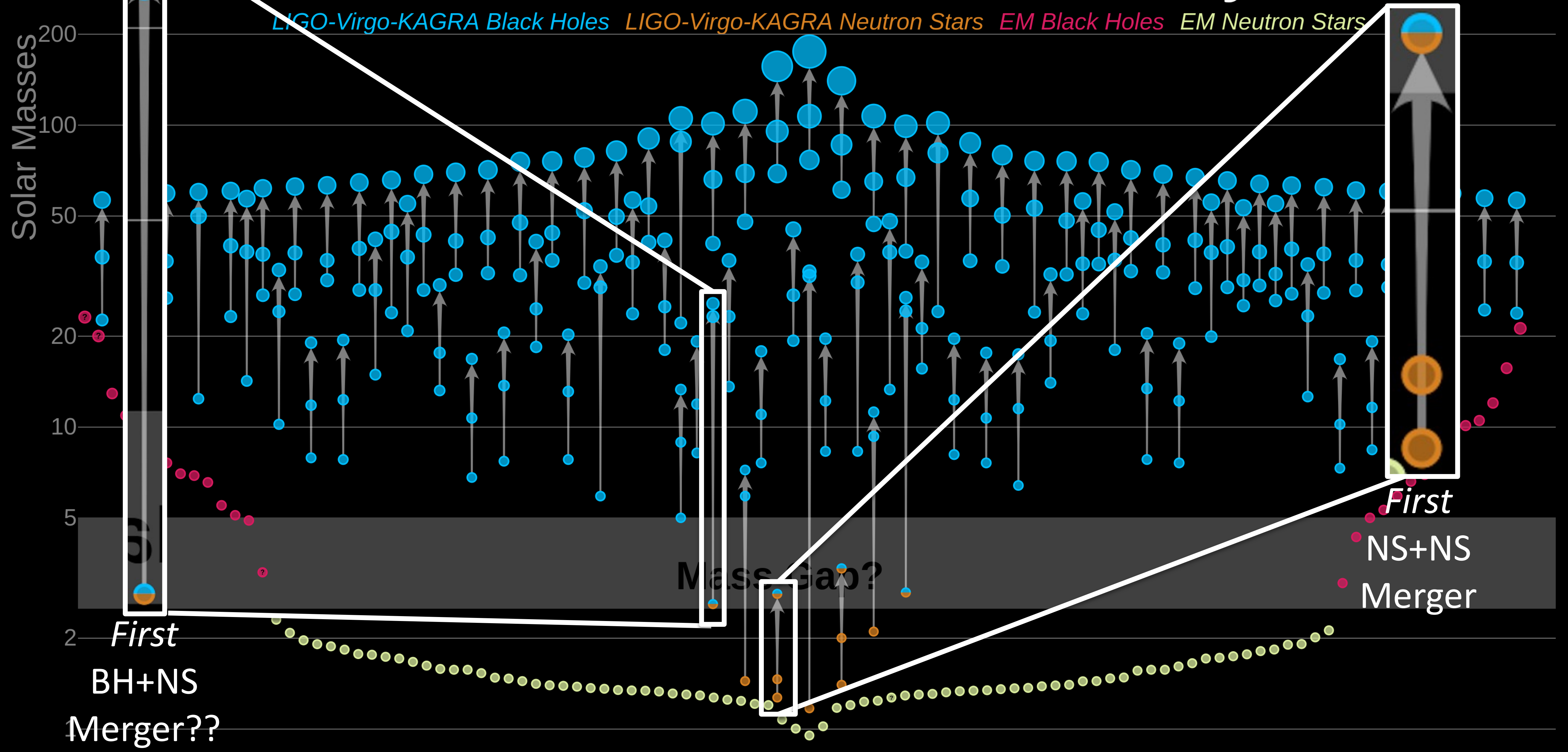
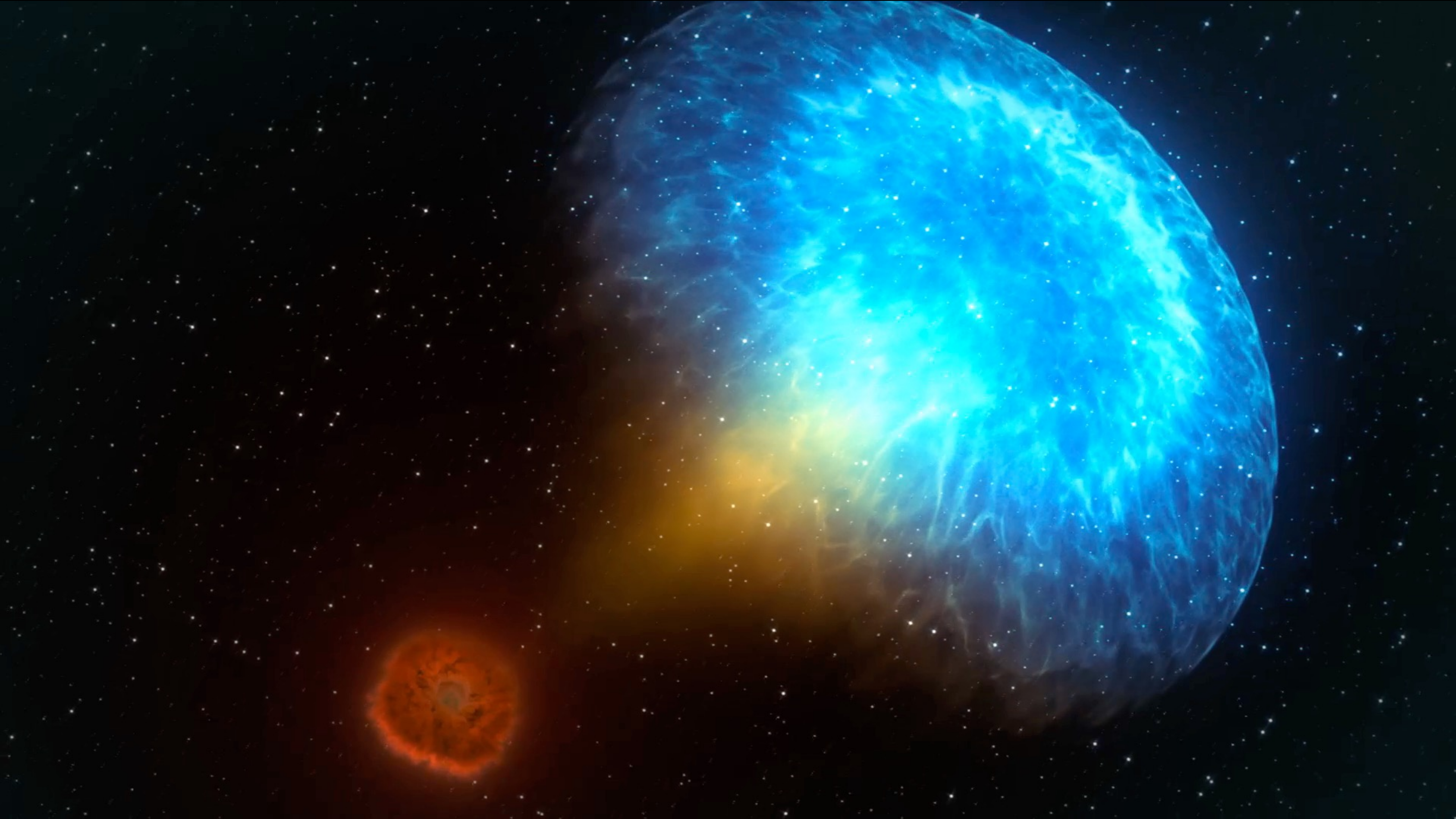
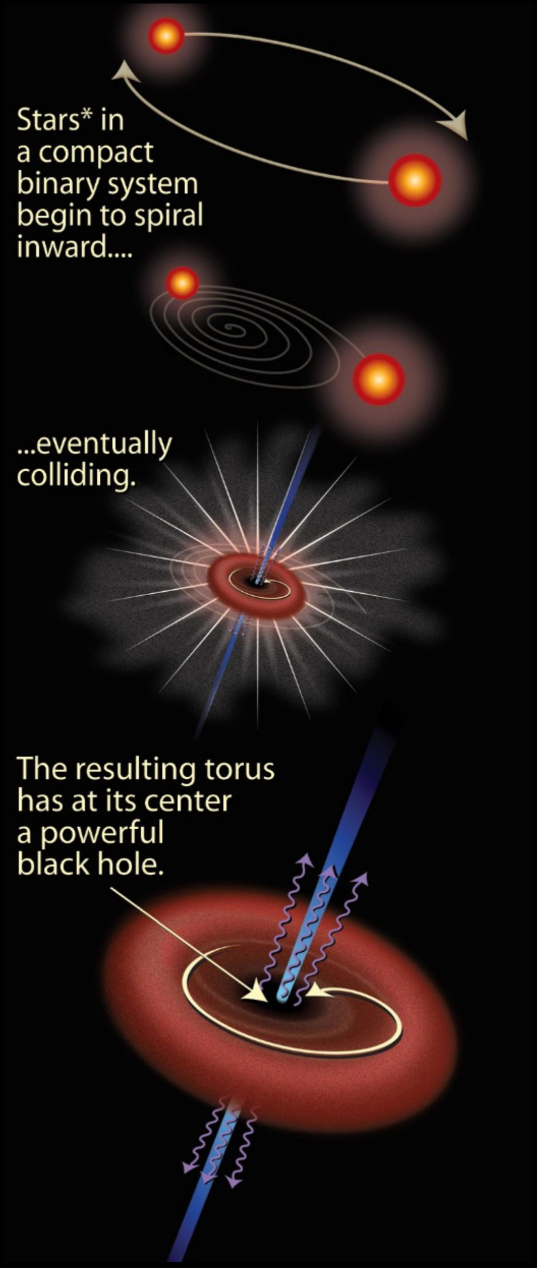
Masses in the Stellar Graveyard



LIGO-Virgo-KAGRA | Aaron Geller | Northwestern



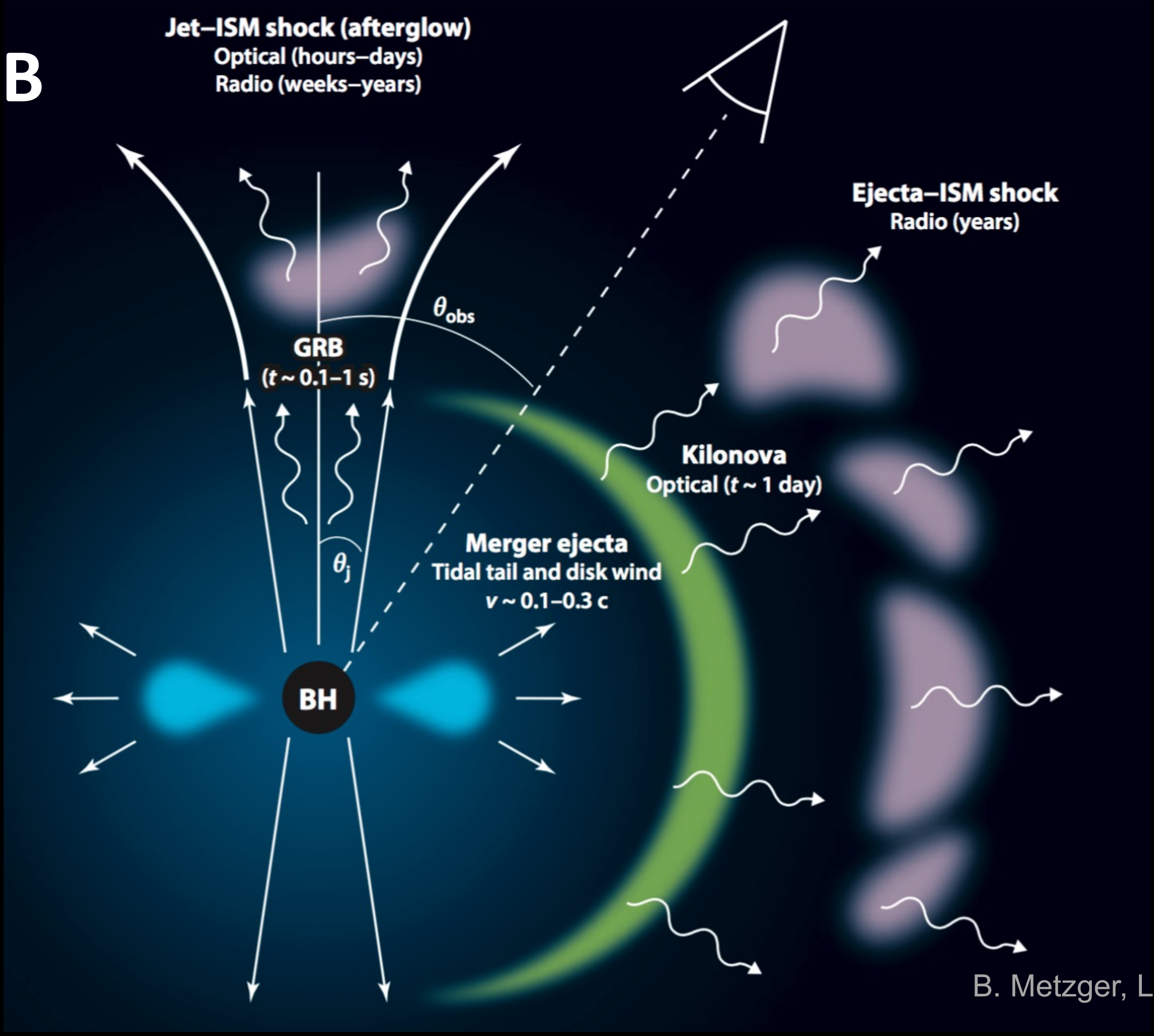
GW170817 confirmed NS merger origin for short GRBs



- Accretion onto central compact remnant launches relativistic jet
- Shocks within the jet emit short pulse of Gamma-rays (**GRB**)
- Relativistic jet shocks the ISM, producing synchrotron afterglow emission from X-ray through radio
- NS-NS merger also causes an explosion called a “kilonova” (**KNe**)

Slide Credit: J. Ruan

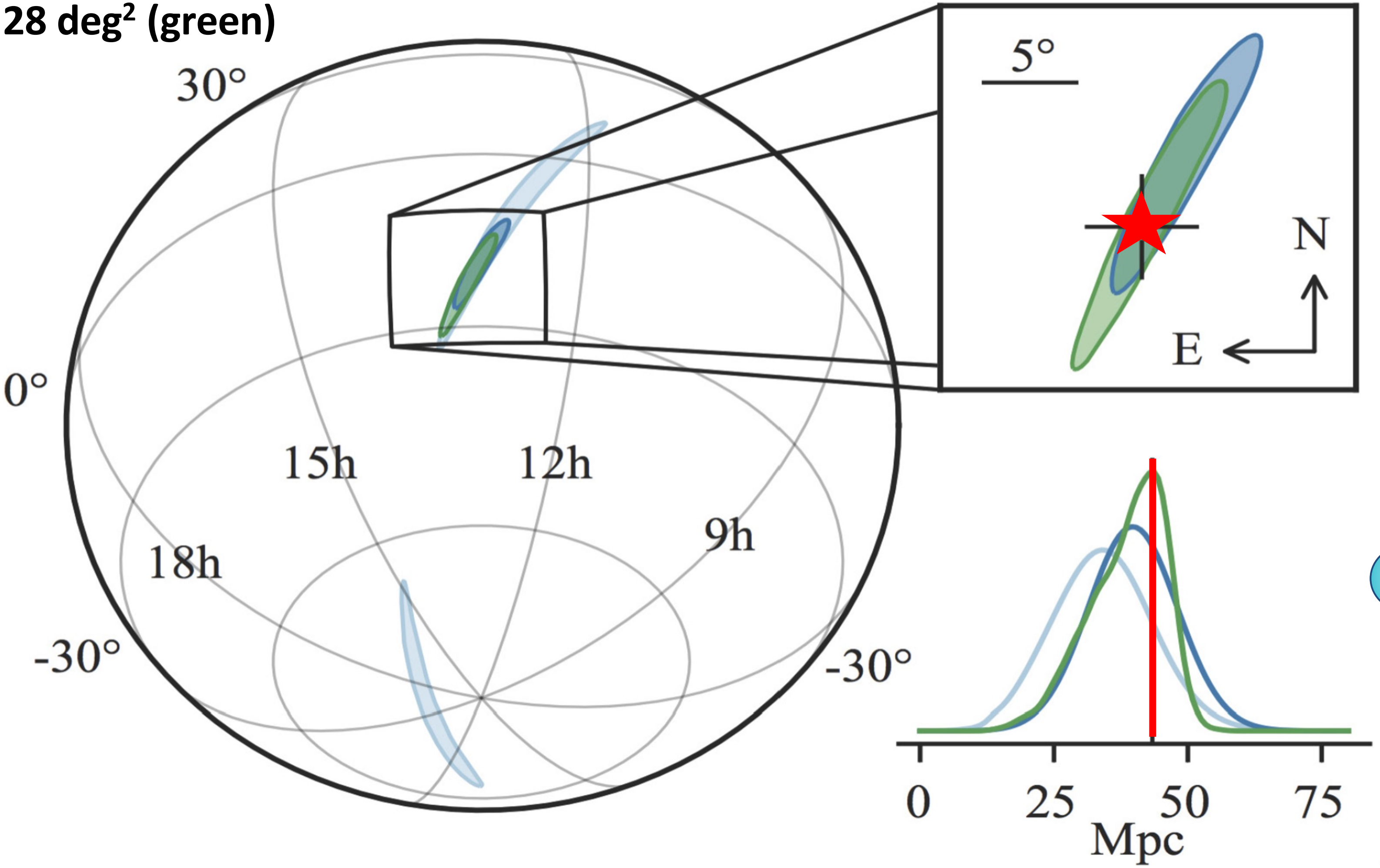
KNe & GRB



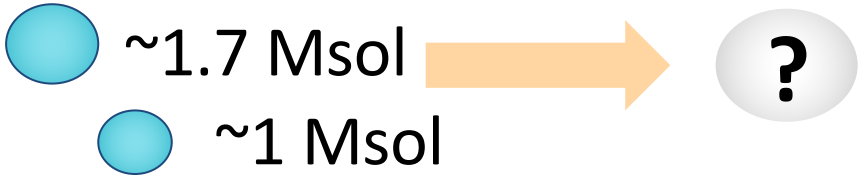
B. Metzger, Living Reviews

GW170817

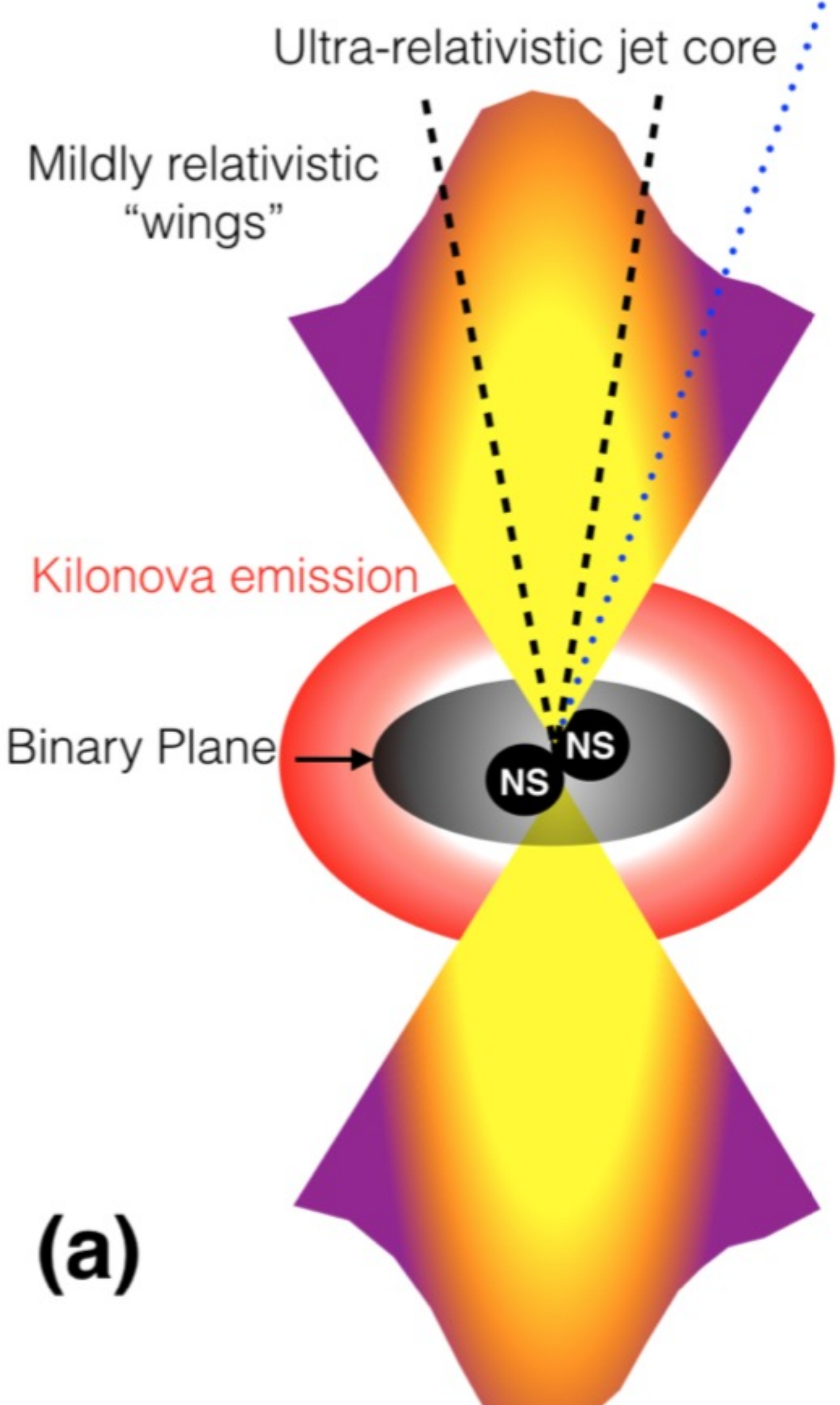
28 deg² (green)

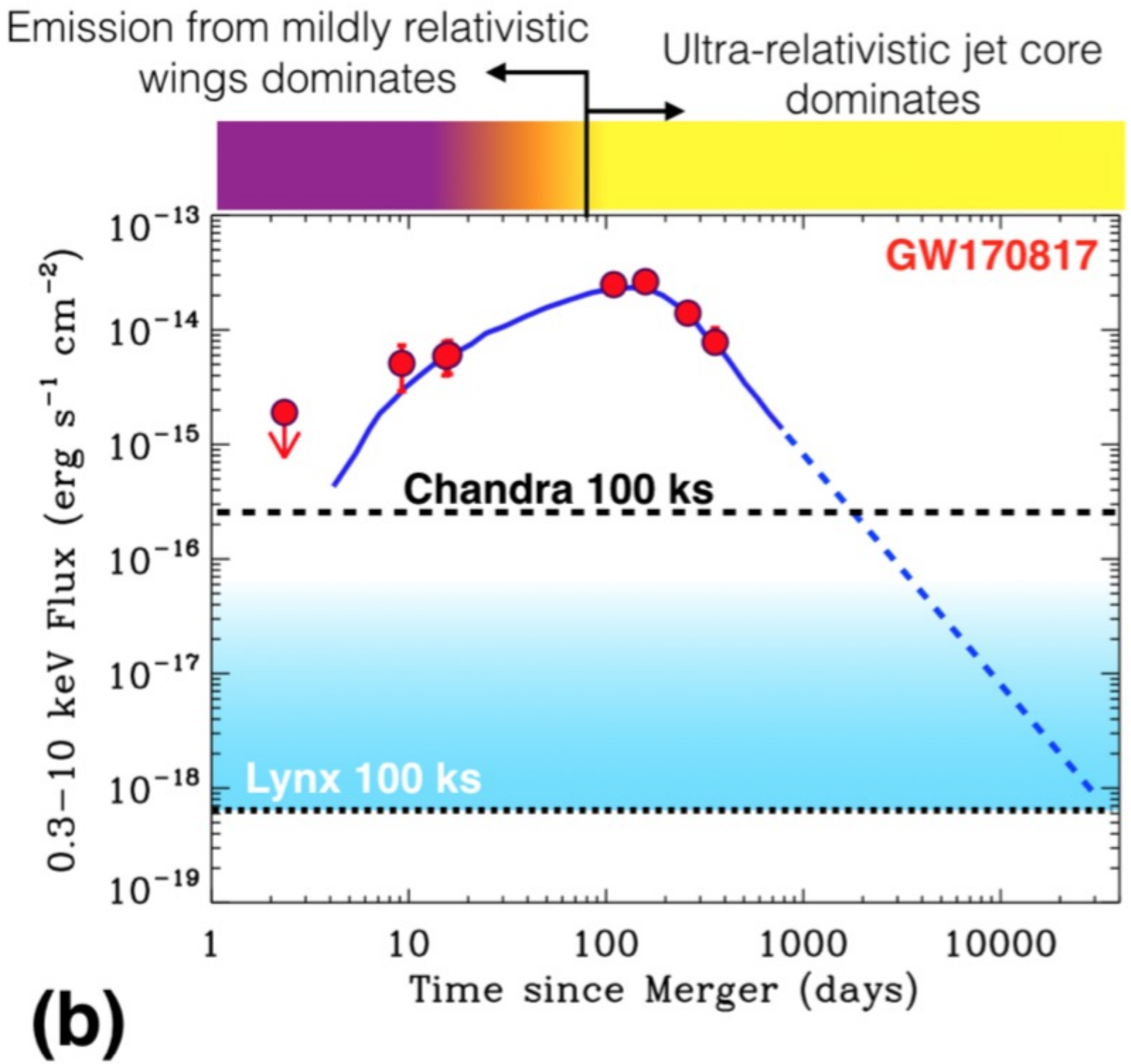


- **localized** within a sky **region** of 28 deg² (90% probability)
- luminosity distance of 40 (+8 −14) Mpc
- merger remenant was likely a BH but could be a massive NS



Slide credit: Nicole Ford

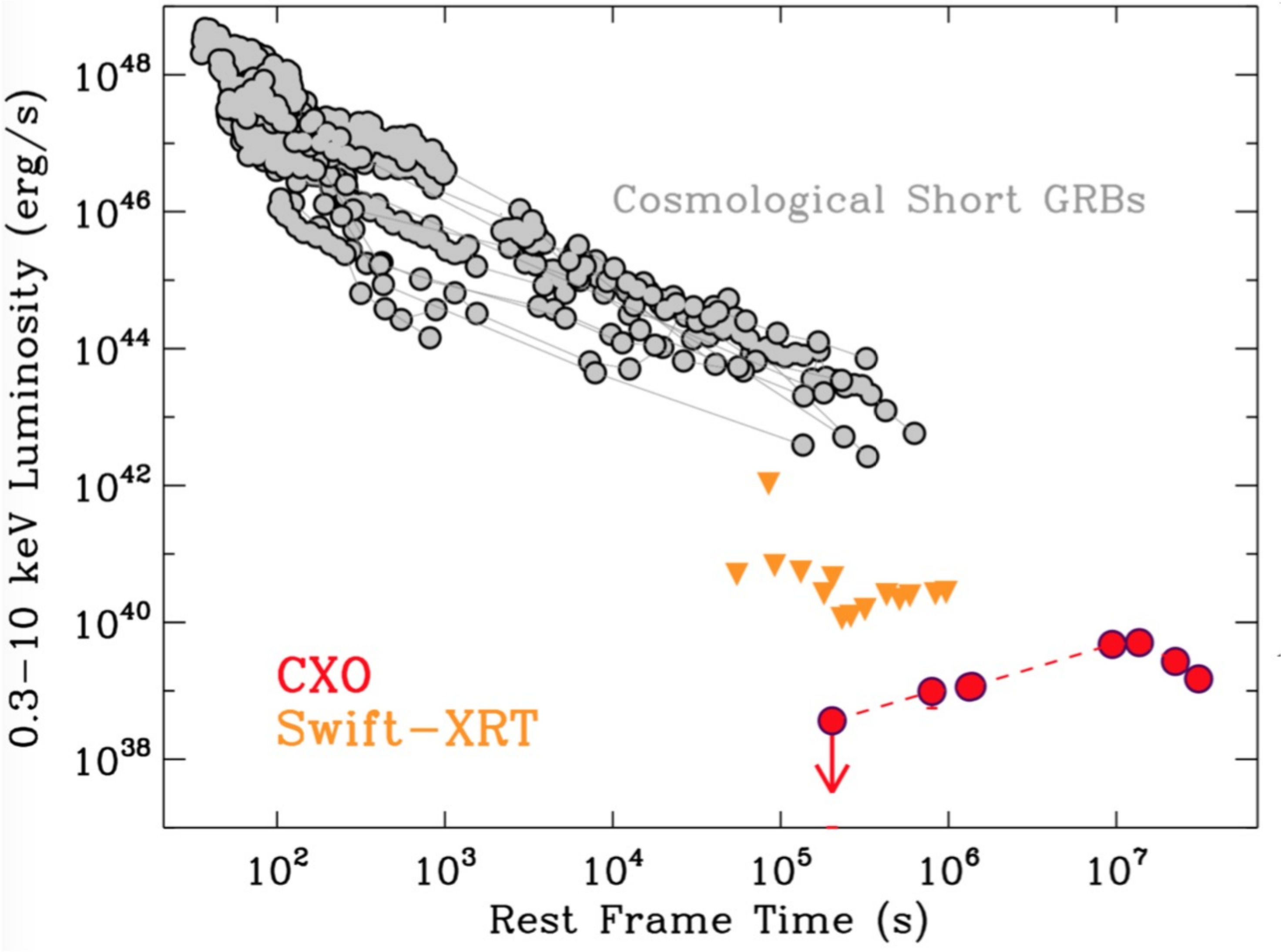




Margutti, Fong, & **DH** 2019

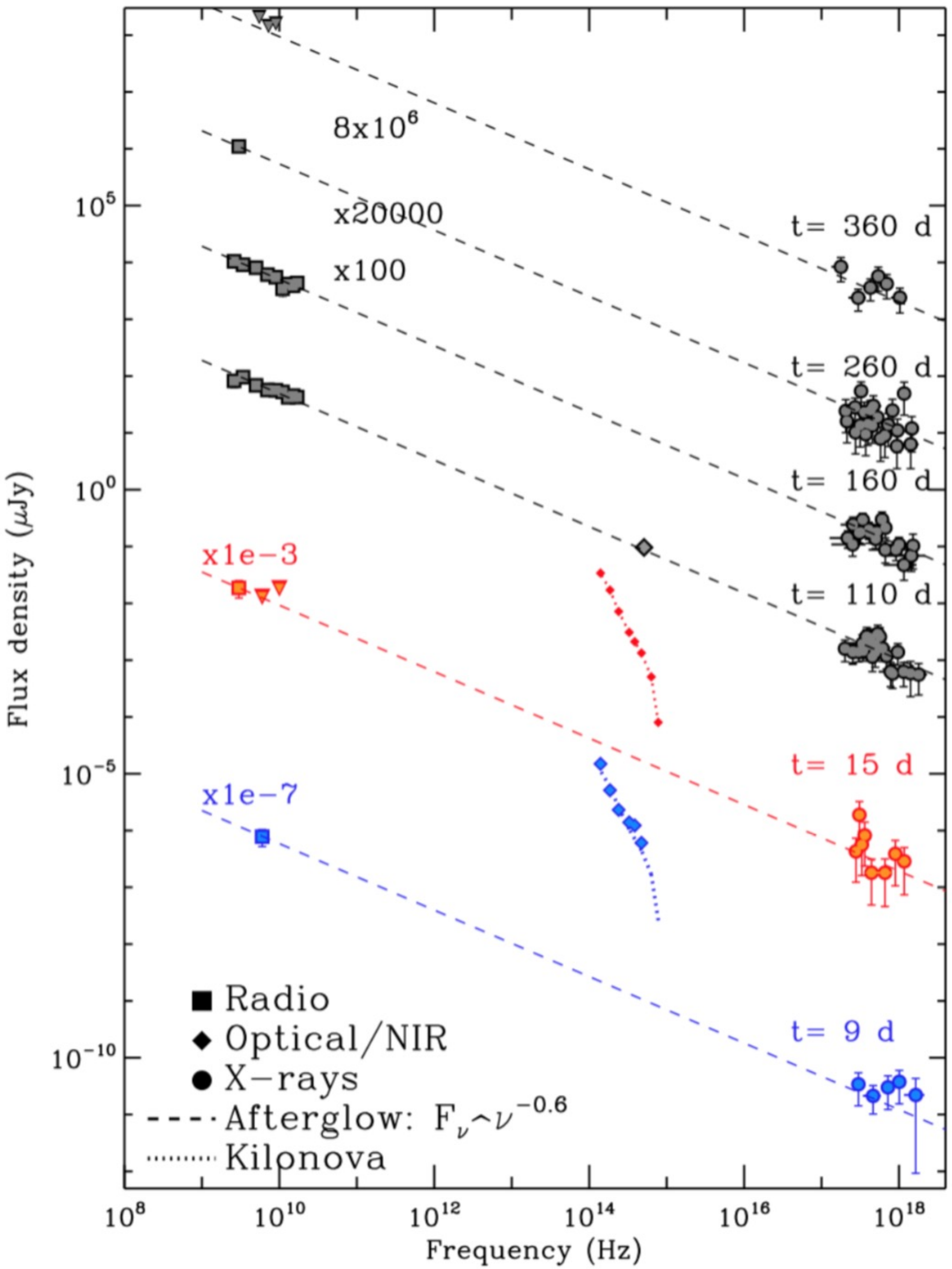
GW170817 vs. sGRBs

Margutti, Fong, & **DH** 2019



- GW170817's rising X-ray emission & low luminosity (despite being close!) set it apart from most sGRBs
- After peak, the decline is consistent with SGRB afterglows
- Expected from a jet pointed away from our line of sight

Margutti, Fong, & **DH** 2019



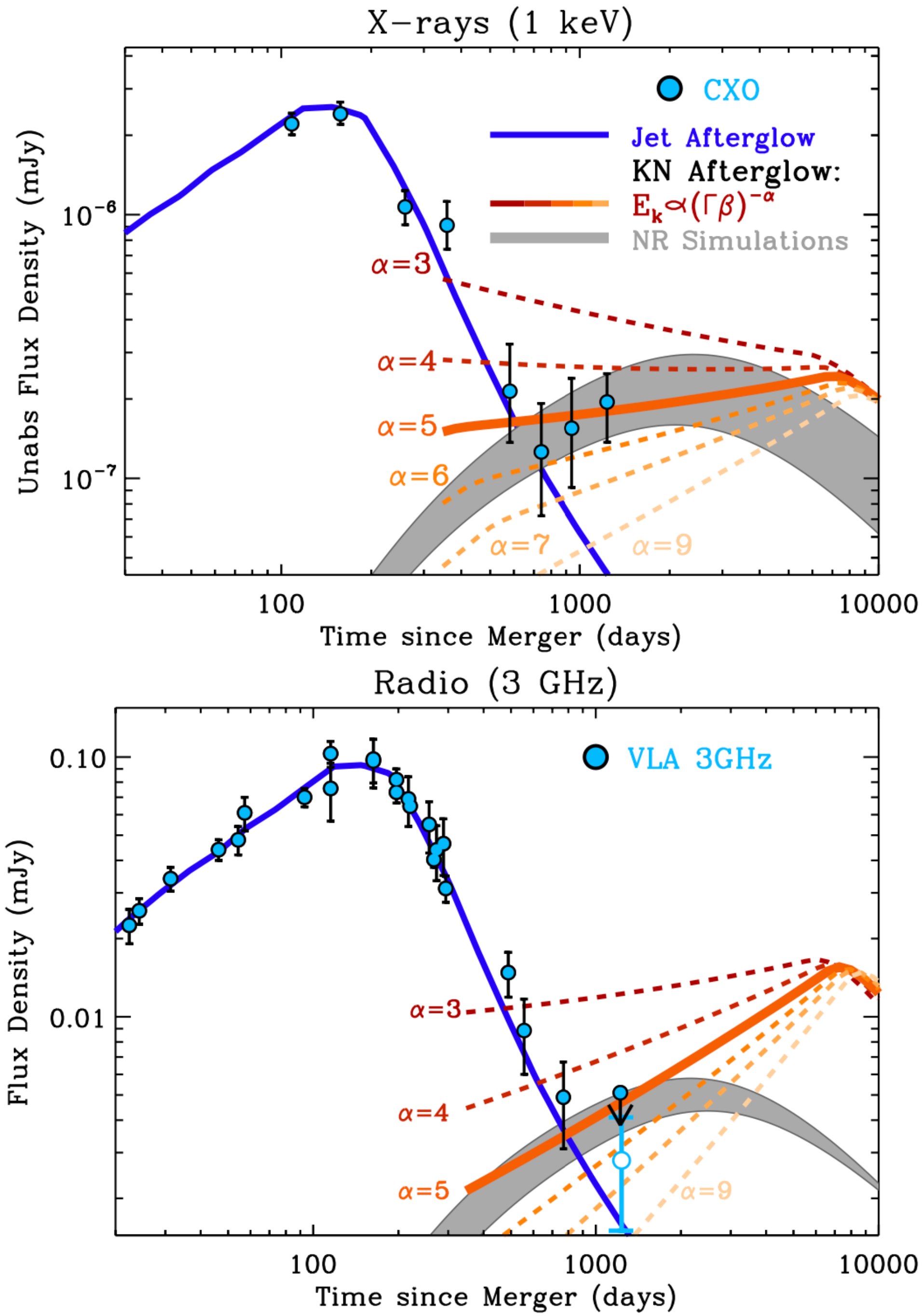
GW170817 SED

- Radio-to-X-ray SED shows *no evolution* in the first ~360 days after merger

$$F_\nu \propto \nu^{-\alpha},\ \alpha = 0.6$$

- Radio & X-ray from non-thermal synchrotron afterglow emission
- UV/optical/NIR from kilonova until ~100 days post-merger
- Relativistic outflow emission dominates UV/optical/NIR after 100 days

Hajela et al. 2022



GW170817 Afterglows

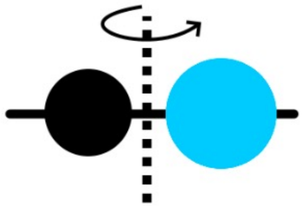
- X-ray and radio observations of GW170817 over the first ~3.3 years (1234 days) since the merger
- Emission modeled by off-axis (~30°) structured relativistic jet w/ E_{tot} ~ 10^{50} erg and low density medium (n ~ 10^{-2} cm^{-3}; **blue lines**)
- *New component*: synchrotron radiation from a mildly relativistic shock due to the dynamical ejecta, “kilonova afterglow” (**red lines**)

But also see Troja et al. 2022 …

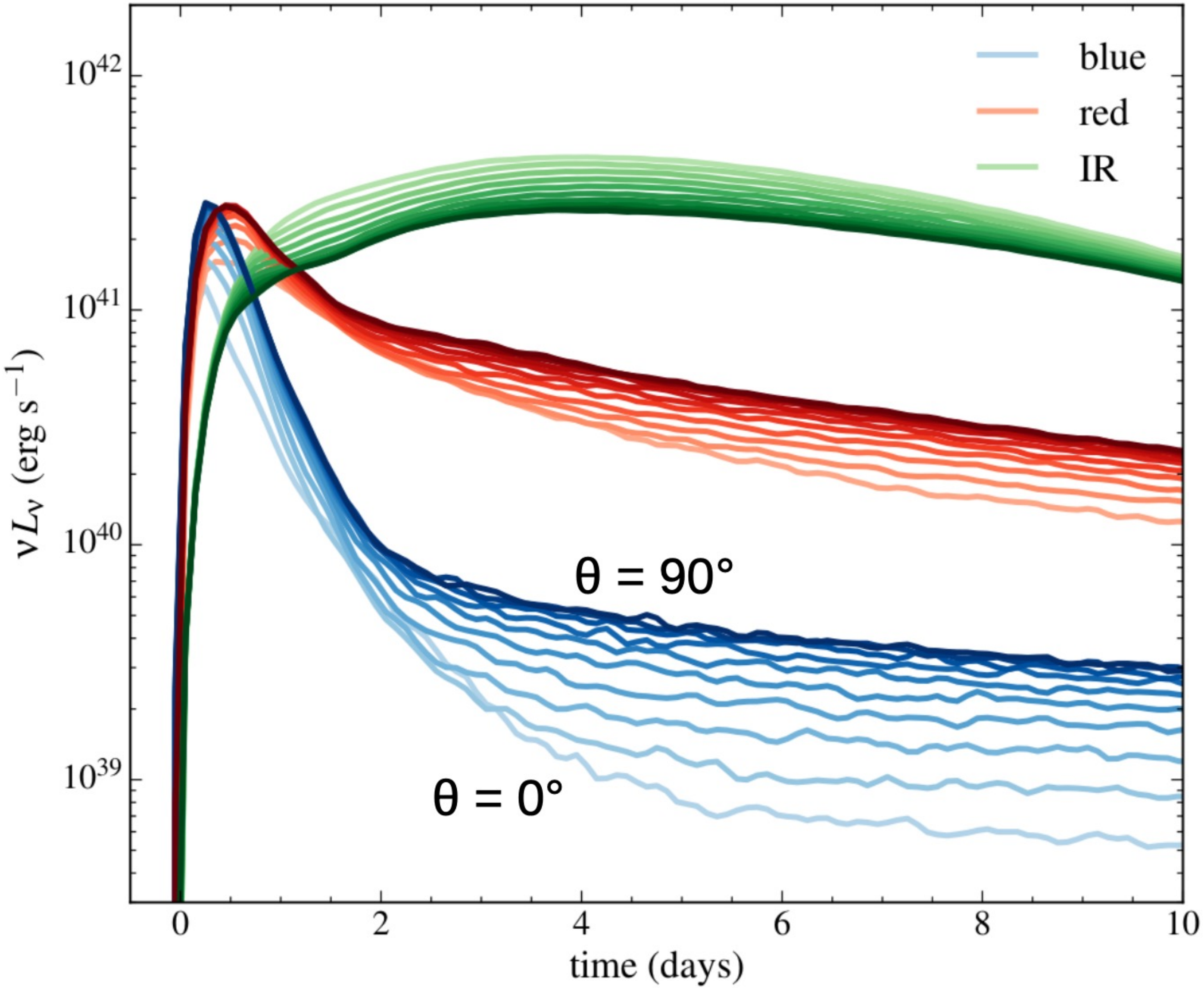
Kilonovae from BH/NS Mergers?

- Early peak, rapid fading in bluer wavelengths
- Slower fading in red/IR wavelengths
- Dependence on viewing angle

polar
θ = 0°

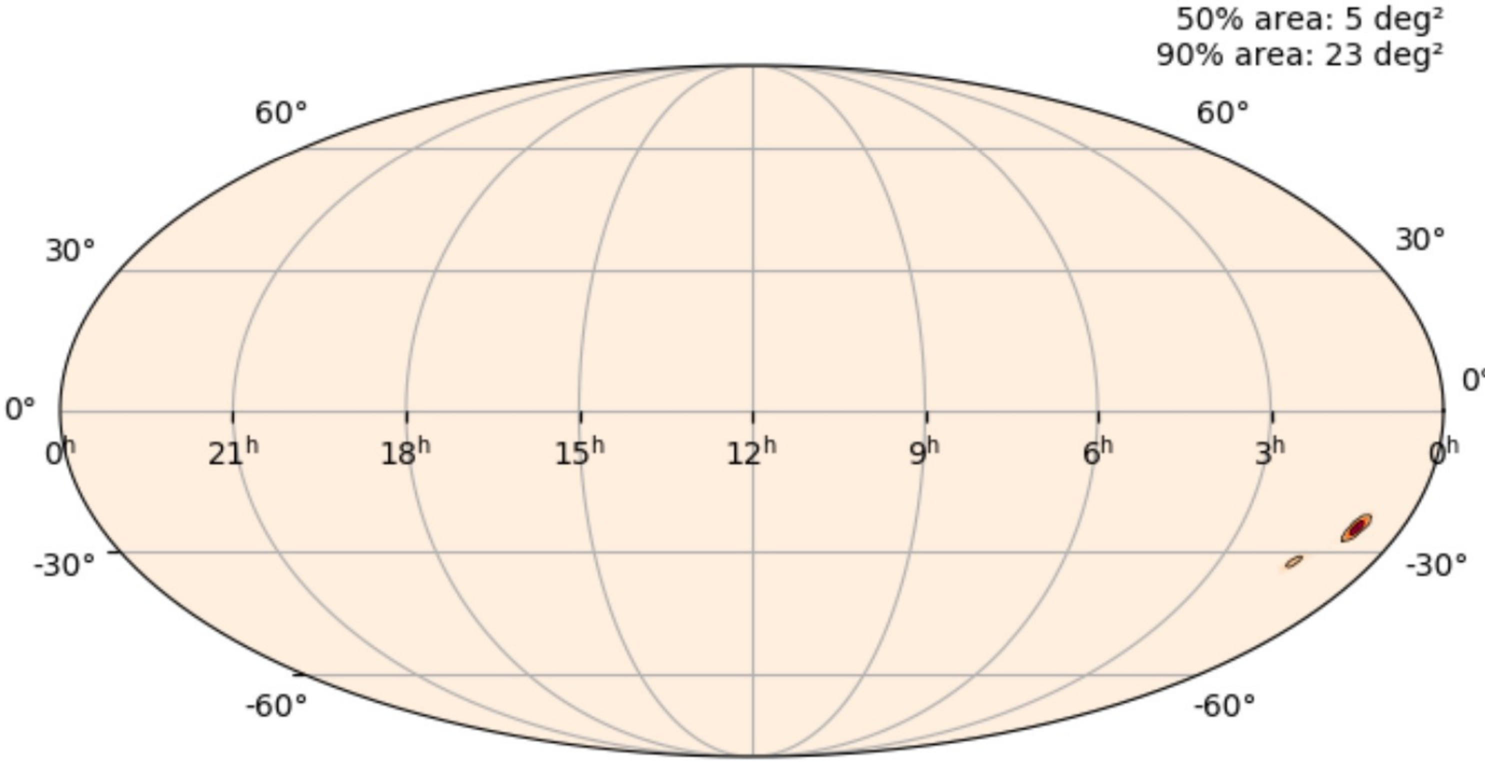


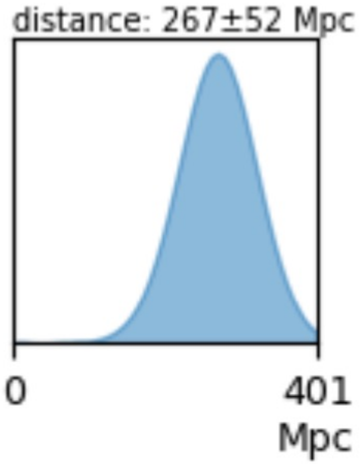
equatorial
θ = 90°

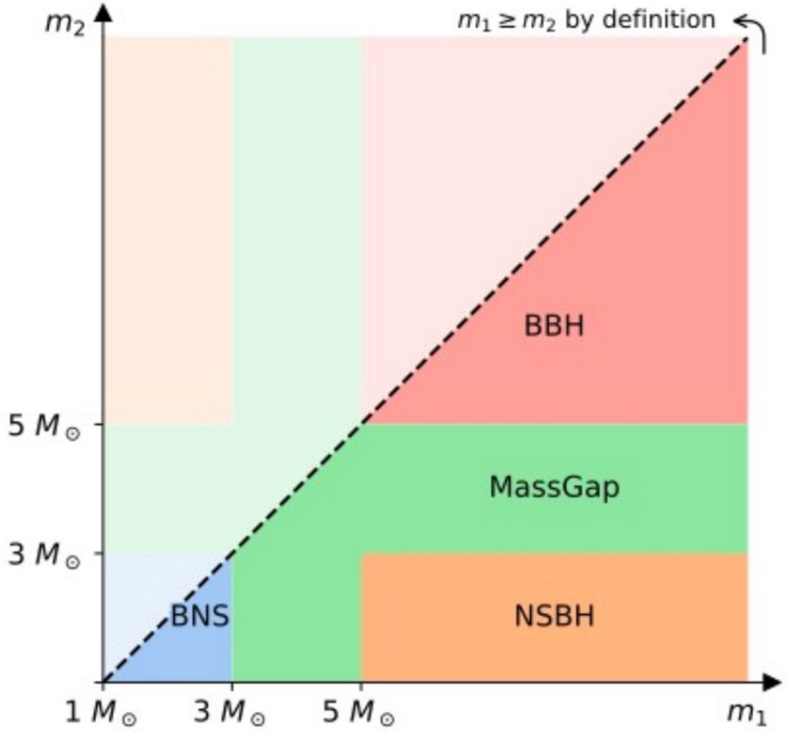


Fernández, et al, 2017

GW190814



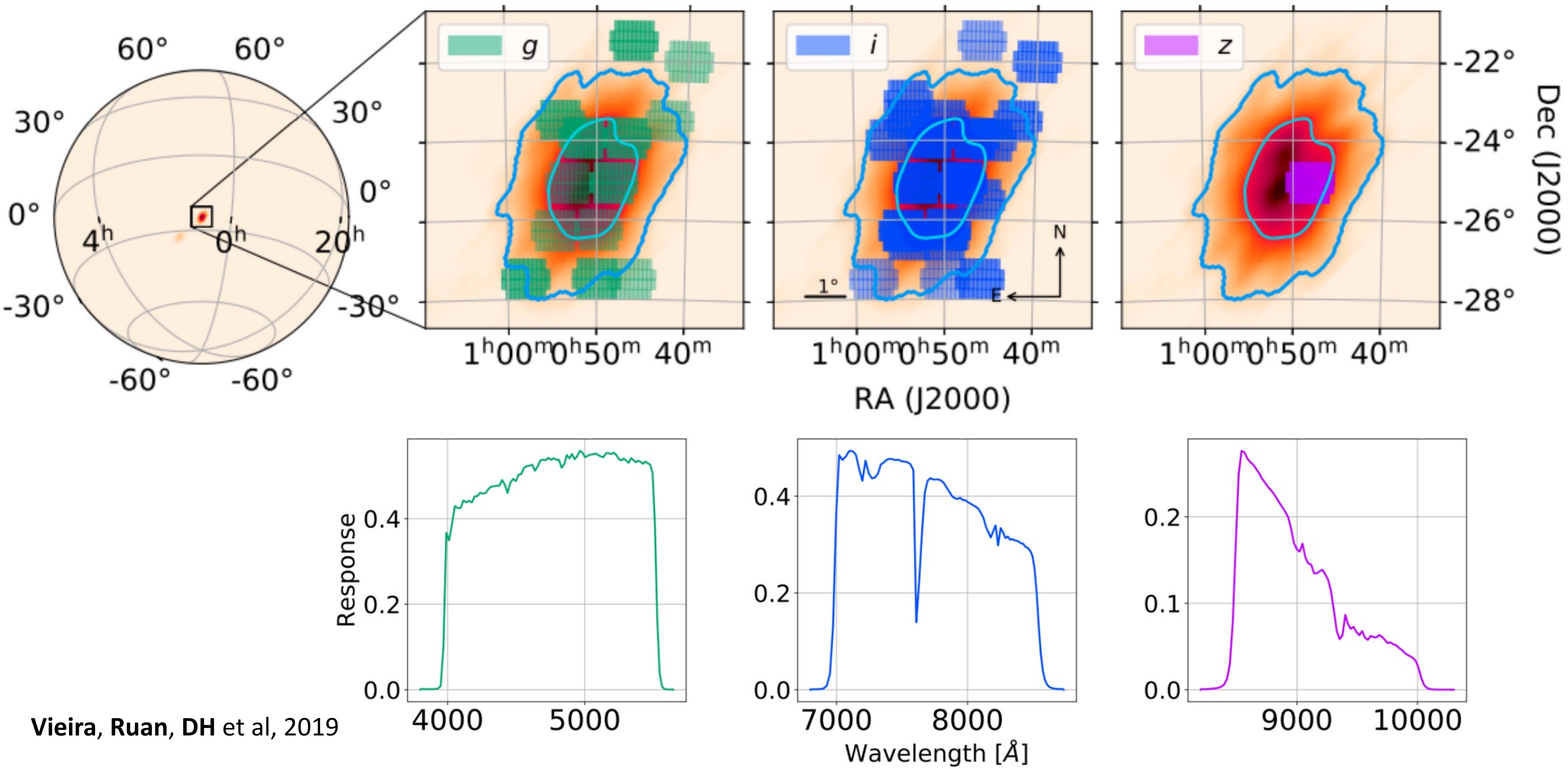




- ***First*** potential merger between a BH and NS
- Binary NS mergers cannot produce observed abundances of the heaviest r-process elements – can NS-BH mergers help?

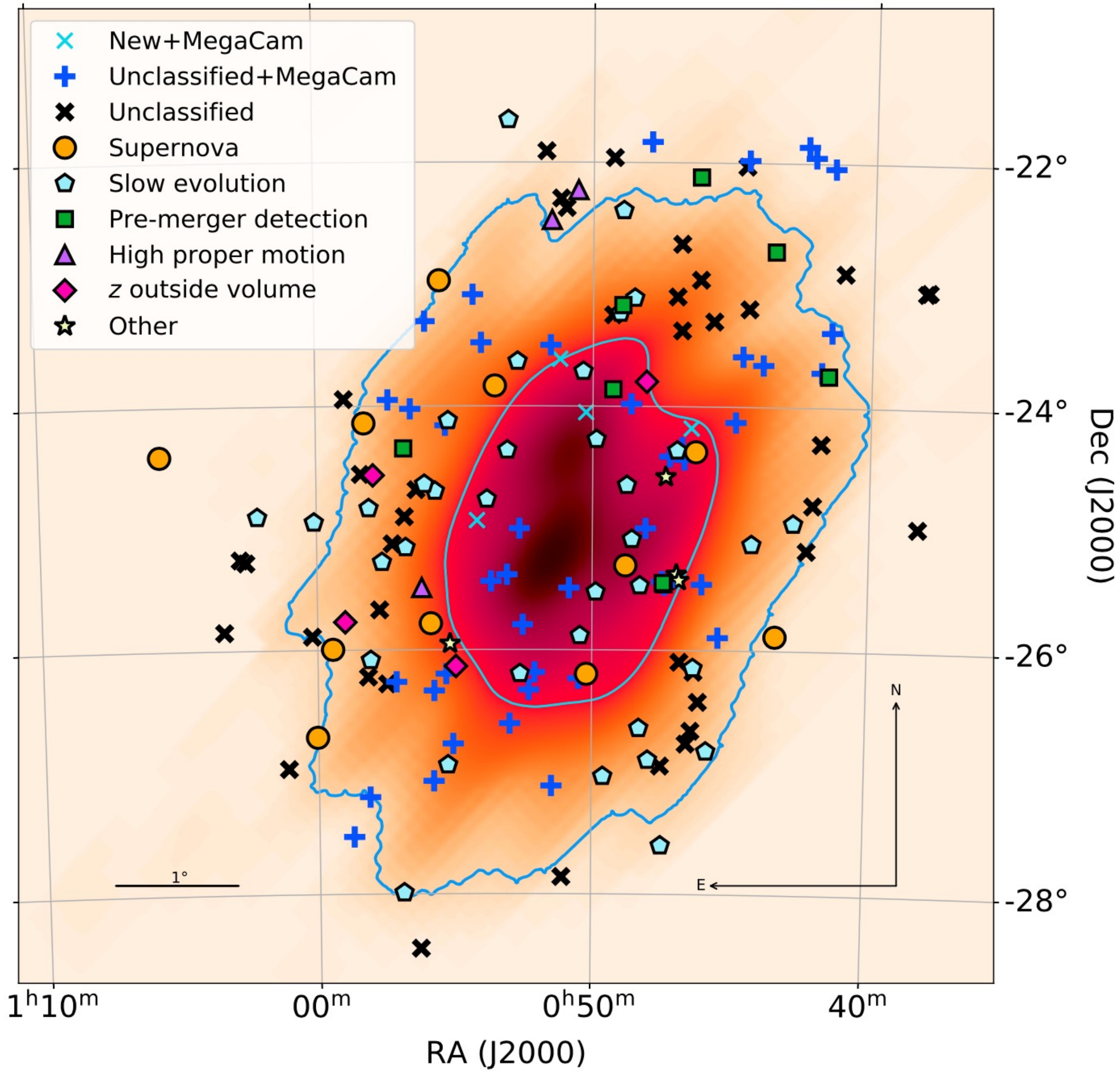
Slide credit: Nick Vieira

Canada-France-Hawaii Telescope Follow-up: GW190814



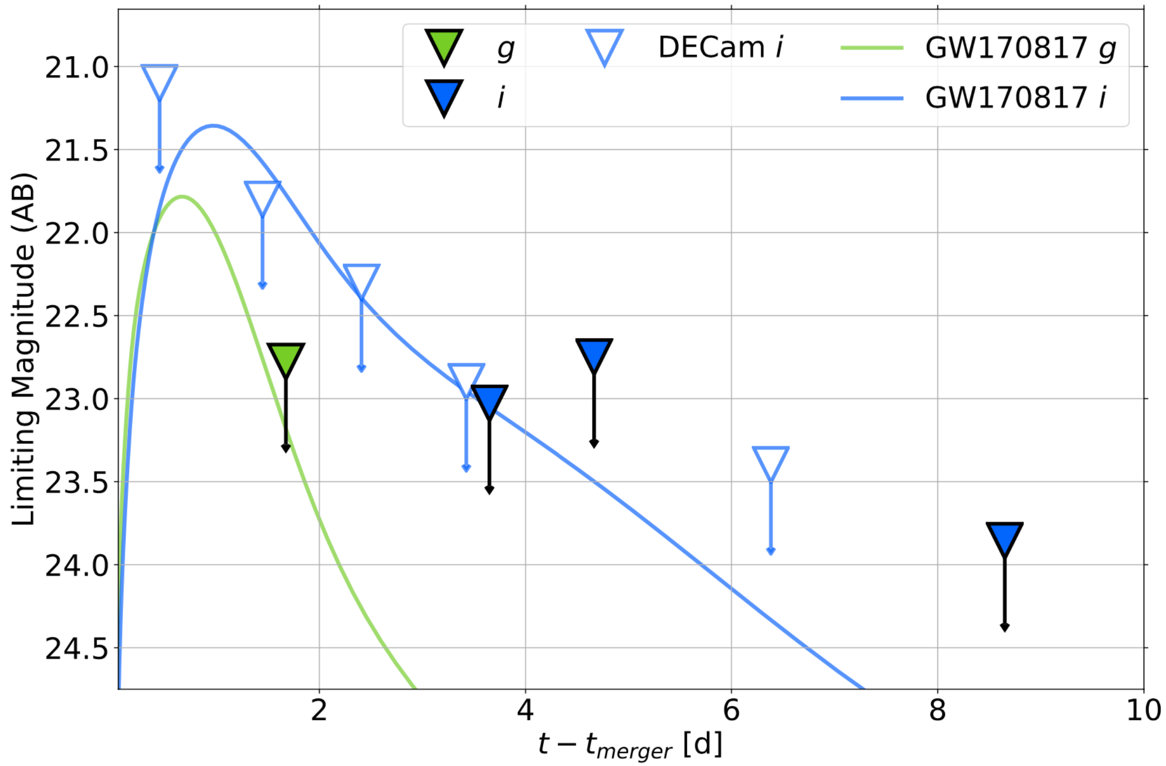
Vieira, **Ruan**, **DH** et al, 2019

Sadly no EM counterpart…



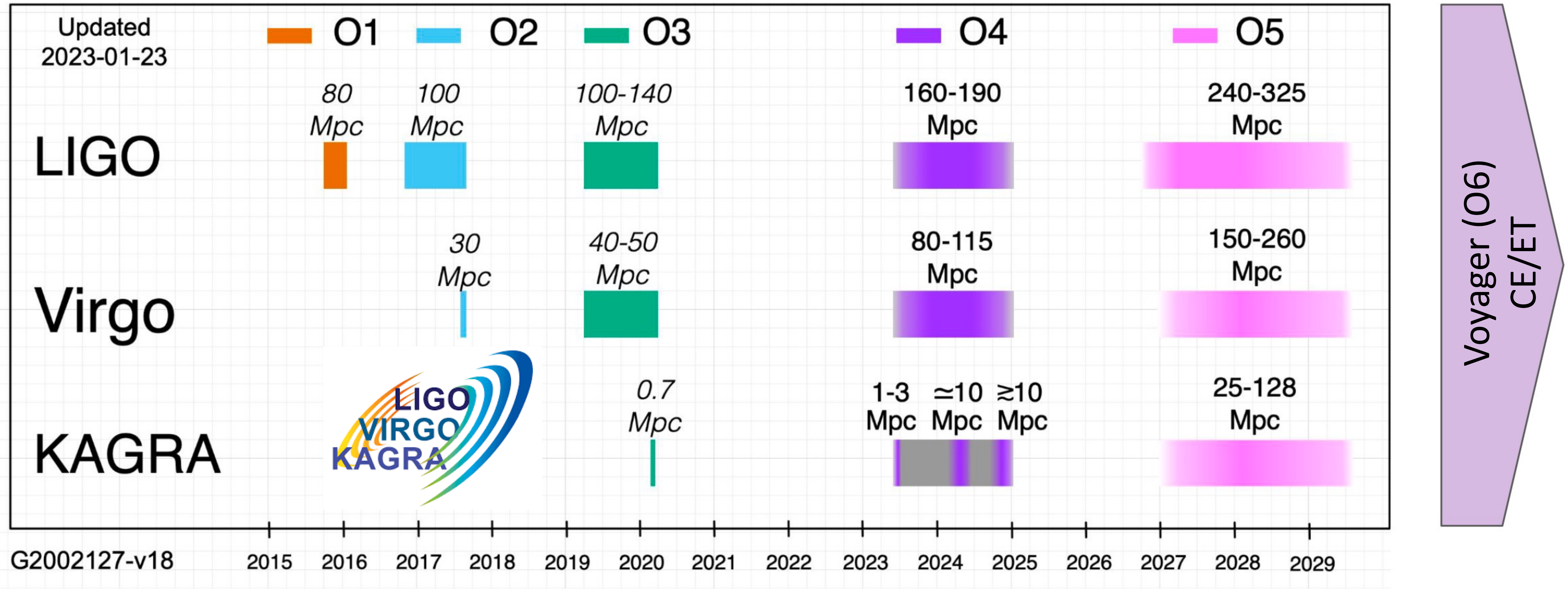
- **>100 candidates** reported in 2 weeks
- Many w/ spectral/photo classification
- Early hunt: visual inspection
- Most sources came from **image differencing** pipelines

Vieira, **Ruan**, **DH** et al, 2019



Slide credit: Nick Vieira

LIGO-Virgo-KAGRA will soon make a come-back…



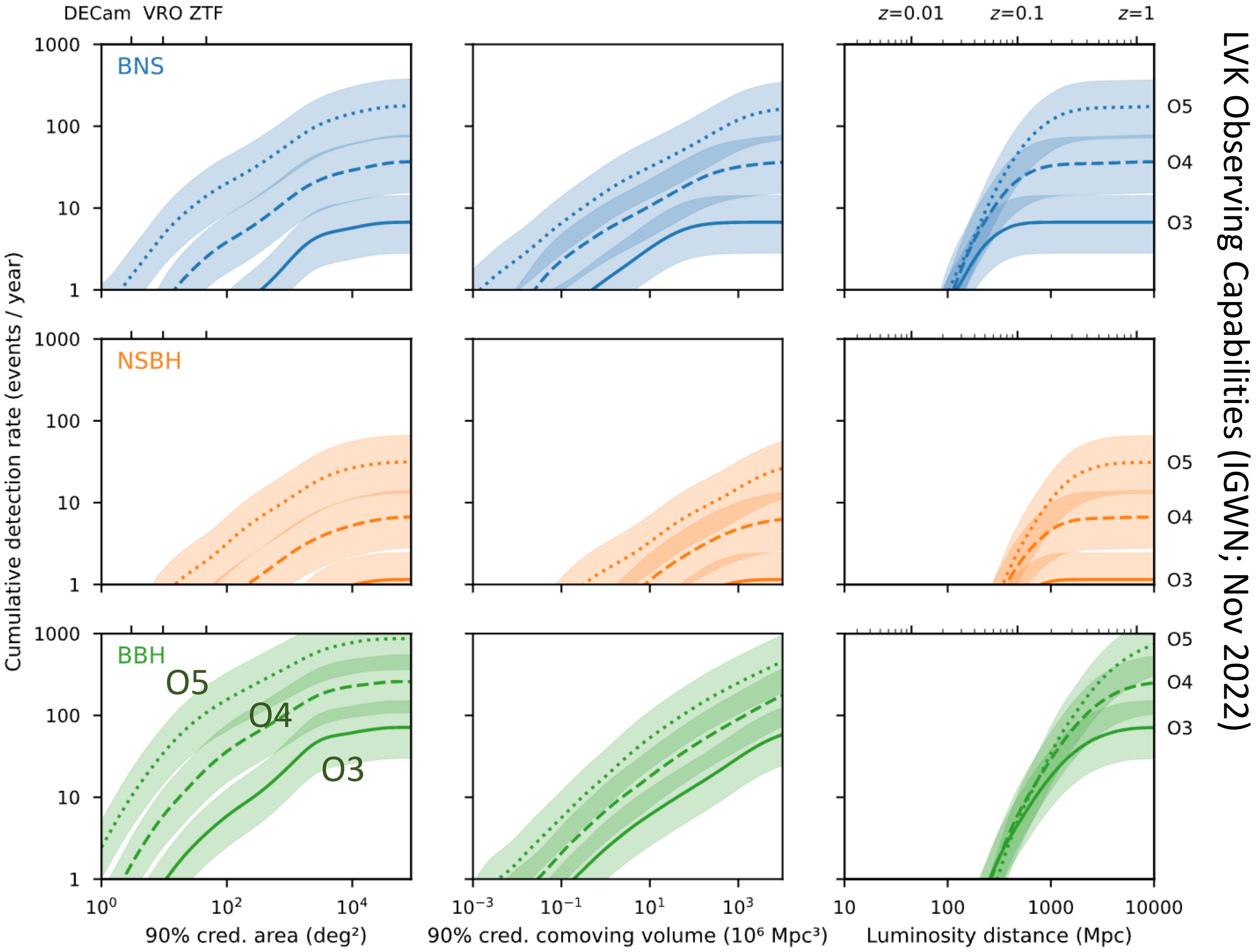
LIGO-Virgo-KAGRA anticipate observing to dovetail with next generation facilities

Observing Run 4 (O4):

- Science run will begin **24 May 2023,** w/ ***18 calendar months*** of observing
- Additional observing time will increase the scientific output of O4; coating development for O5 will be finalized; O5 test masses will subsequently be coated for expected start of run in early 2027

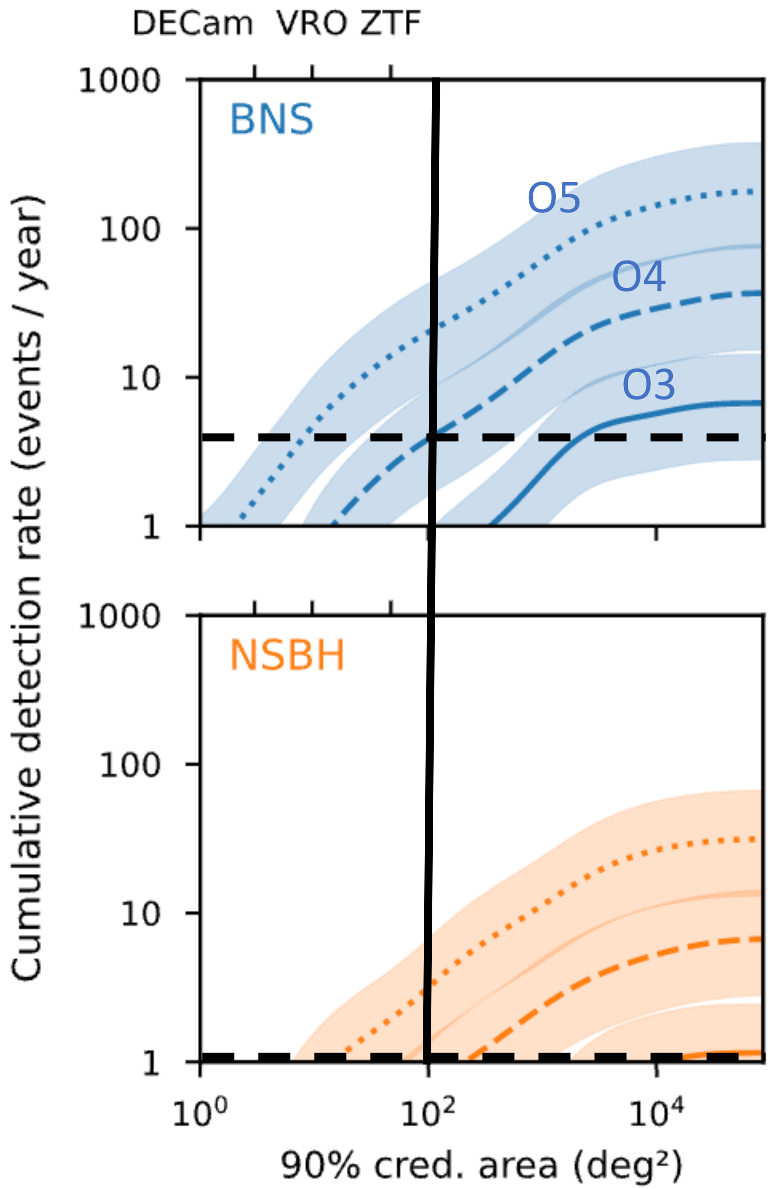
LVK Observing Plan (updated Nov. 2022)

- Localizations in O4/O5 (KAGRA only online part of O4, no LIGO India)
- Improved sensitivity & longer 18-month run for O4 improves rates
- Expect further improvements for O5 (w/ fulltime KAGRA!)



LVK Rates for O4 & O5

- Predictions based on O1, O2, O3 and outcomes of recent upgrades
- EM follow-up must accommodate large localizations (~100 deg^2)
- Expect 2-10 NS-NS and NS-BH mergers in O4
- Expect 10+ NS-NS and NS-BH mergers in O5



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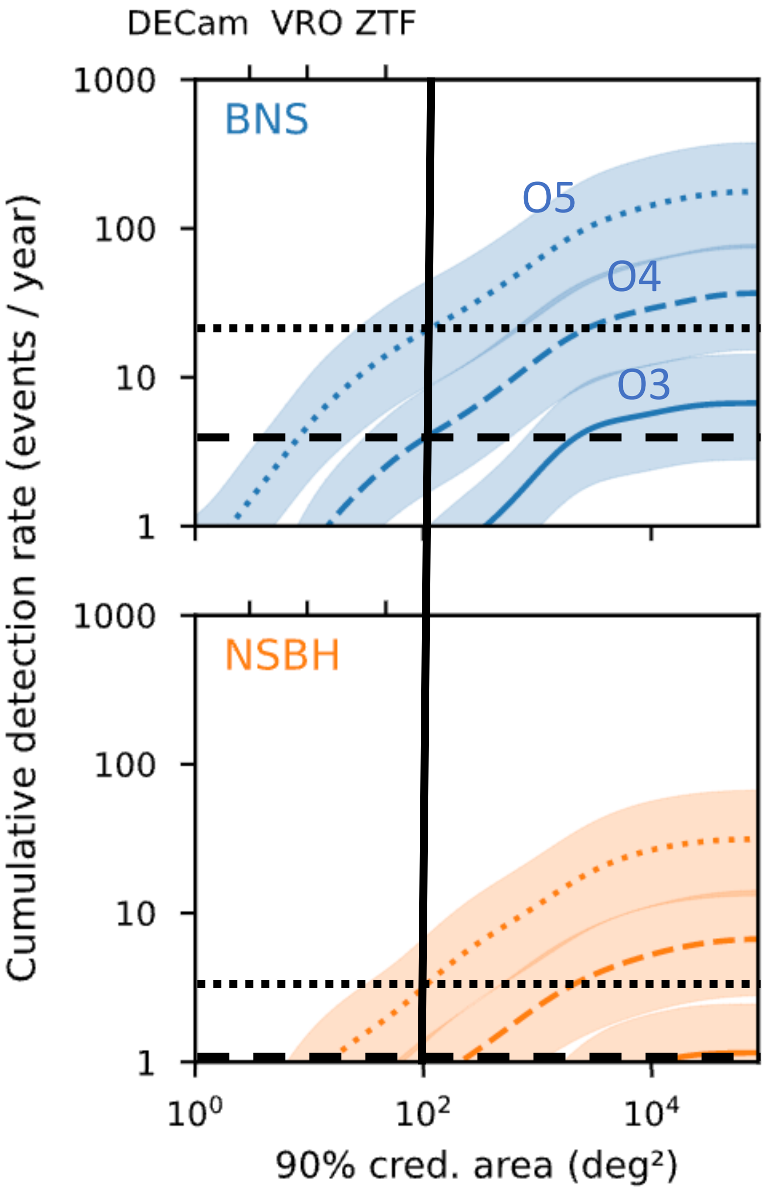


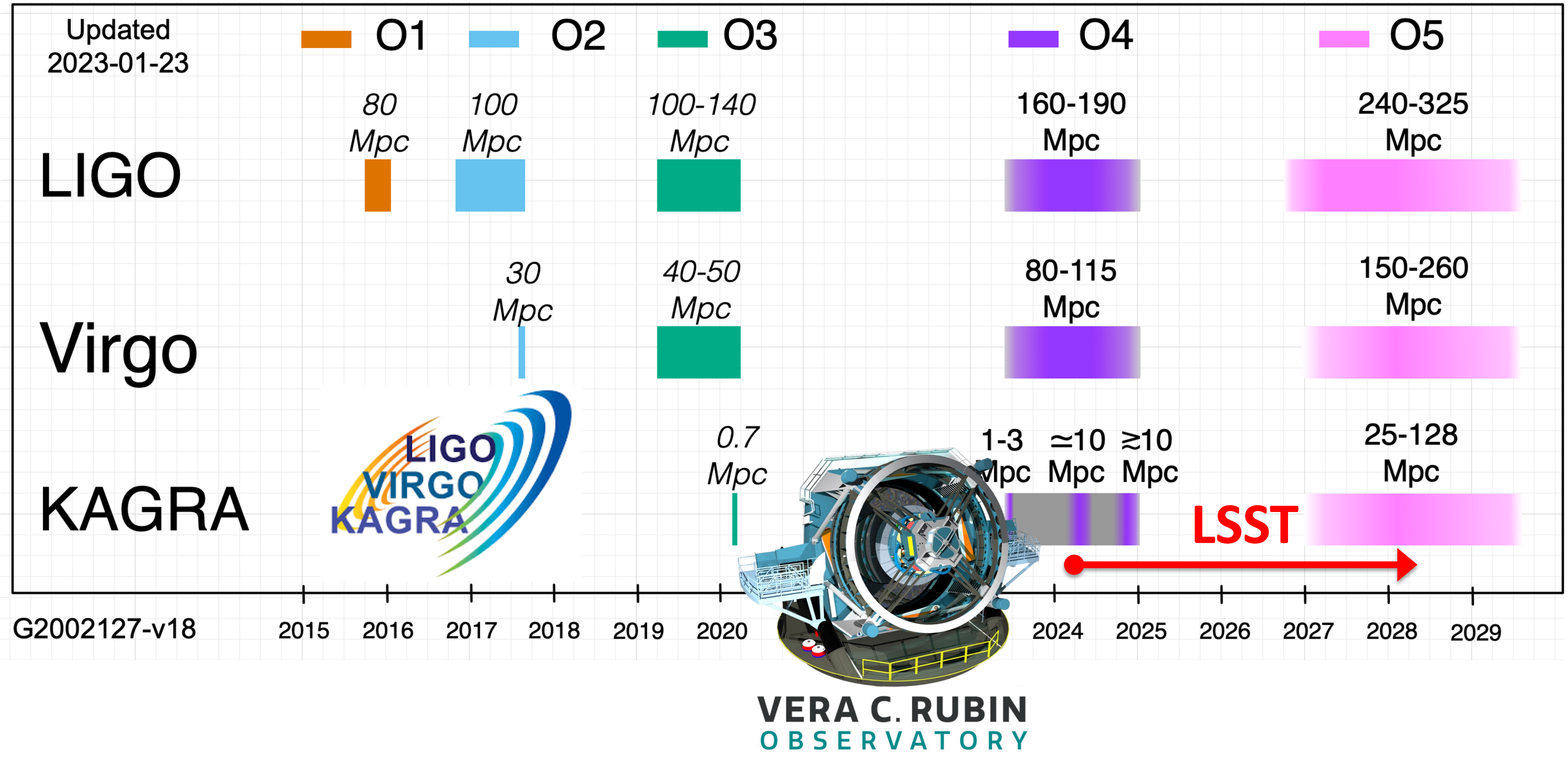
O5 Merger rates
(5-95% confidence)

Within 10 sq degrees:
- BNS: 5 (+7, -3) yr^{-1}
- NSBH: <1 yr^{-1}

Within 20 sq degrees:
- BNS: 11 (+12, -6) yr^{-1}
- NSBH: 1 (+3, -1) yr^{-1}

Within 100 sq degrees:
- BNS: 26 (+33, -14) yr^{-1}
- NSBH: 3 (+4 , -2) yr^{-1}

Expect 2-10 NS-NS / BH-NS GW mergers in O4 (100 deg^2) – ***the search for EM counterparts is back on***!!

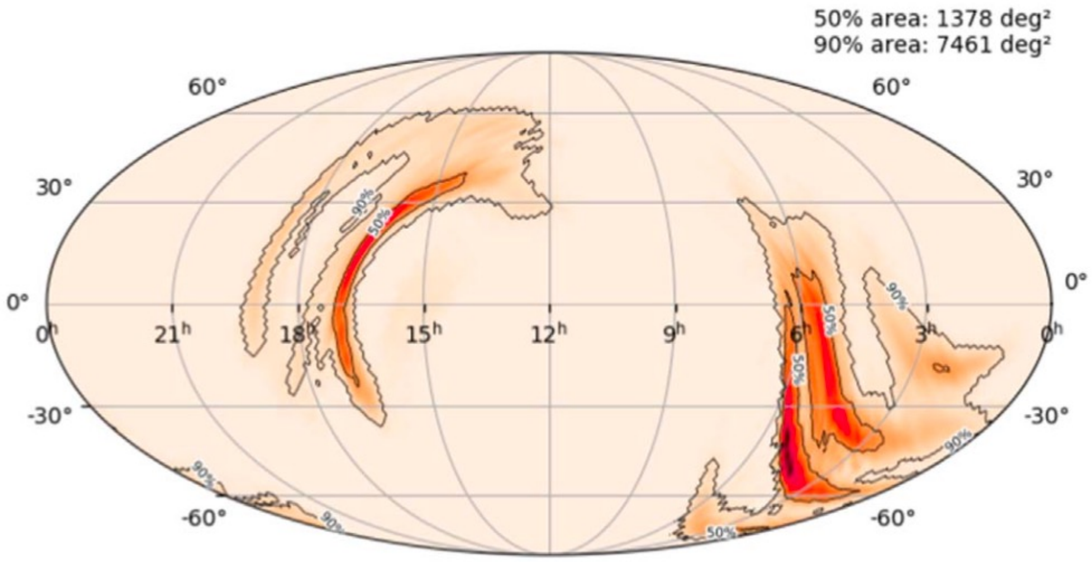


Should You Trigger?: GWSkyNet

GWSkyNet is a machine learning classifier

– developed by UBC LIGO team (Cabero et al 2020)

– facilitates potential EM follow-up obs



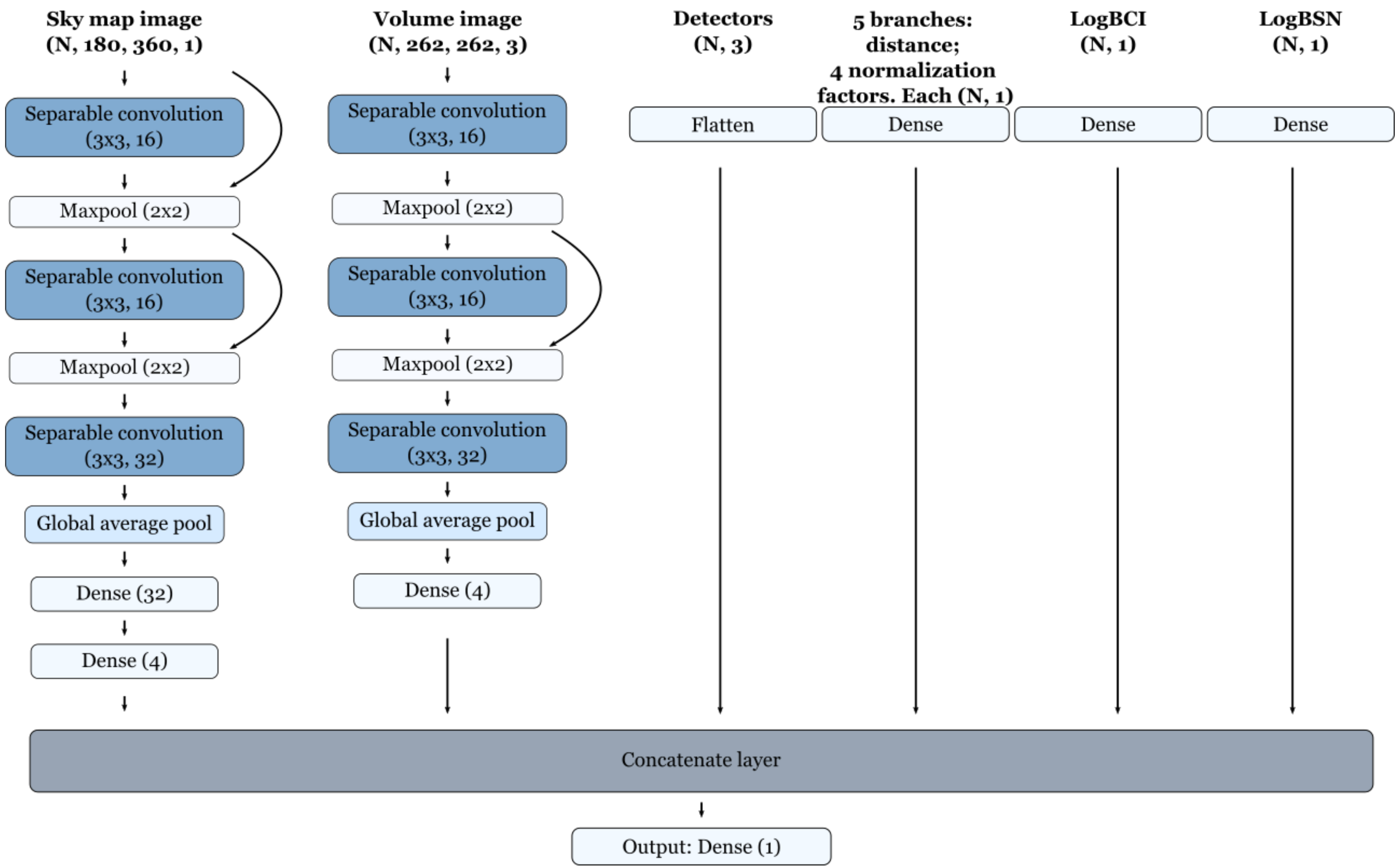
– distinguishes between astrophysical events and instrumental artifacts in low-latency using public alert data as inputs

– offers info complementary to that available in other low latency pipelines

– good performance: e.g., low false negative rate, especially for EM-bright src

GWSkyNet Architecture

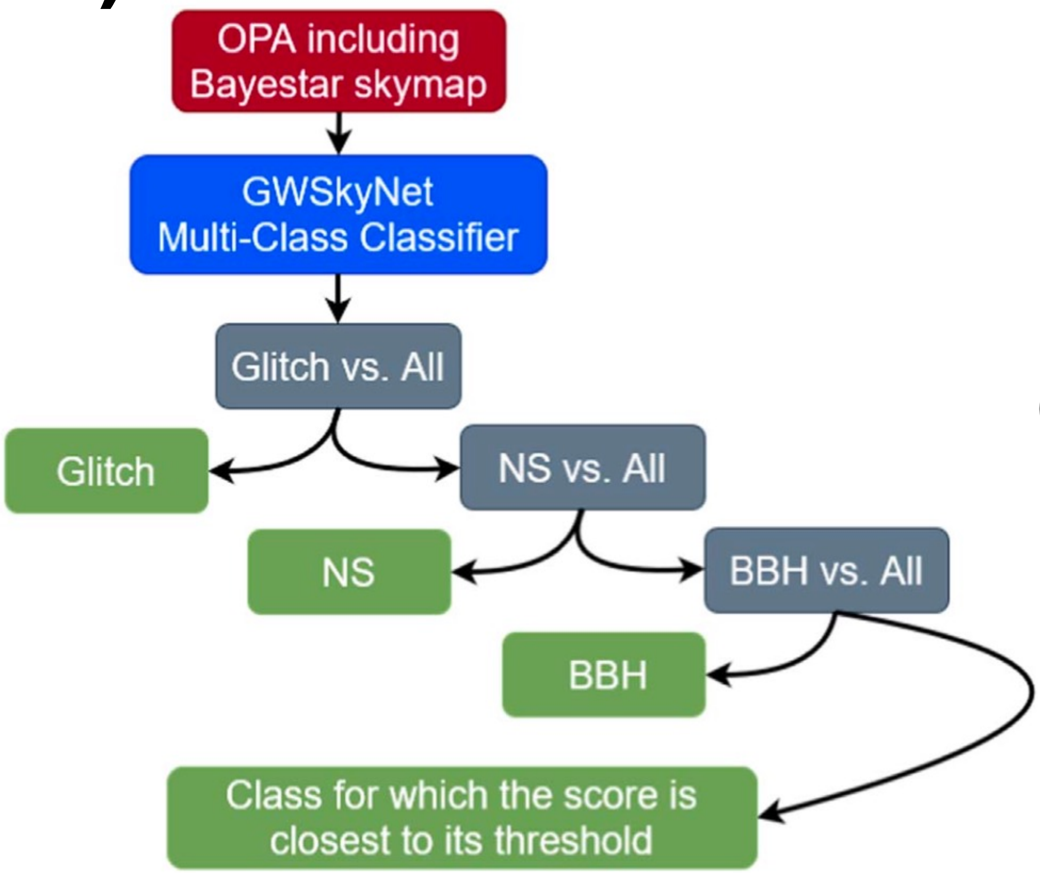
- Different branches in GWSkyNet's architecture analyze different features of inputs:
- Details in Cabero et al. 2020

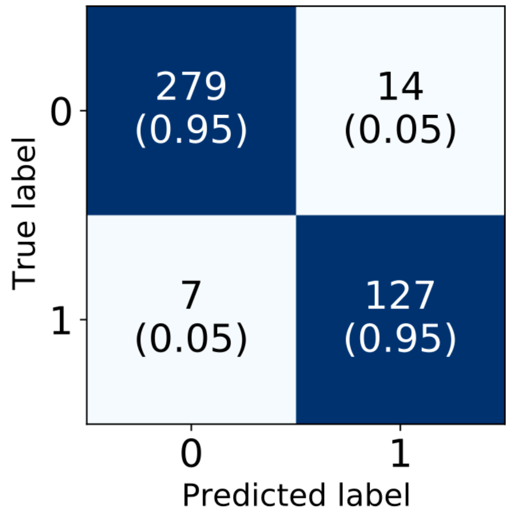


Slide credit: Mervyn Chan

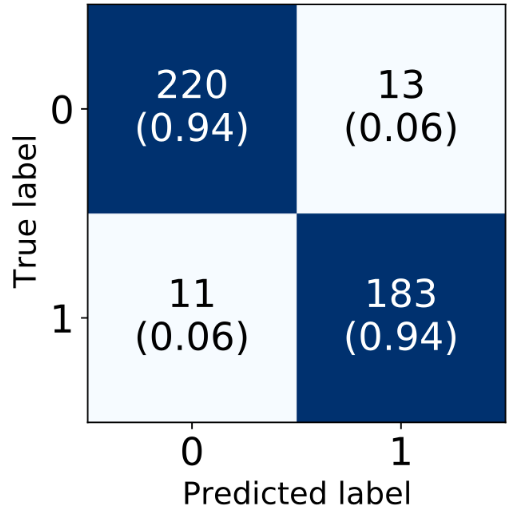
GWSkyNet(Multi)

- Multi-class classifier to distinguish between glitches and real sources PLUS offer rough classification
- Details in **Abbott**, **Buffaz**, et al. 2022
- More on interpretability/ explainability coming soon!



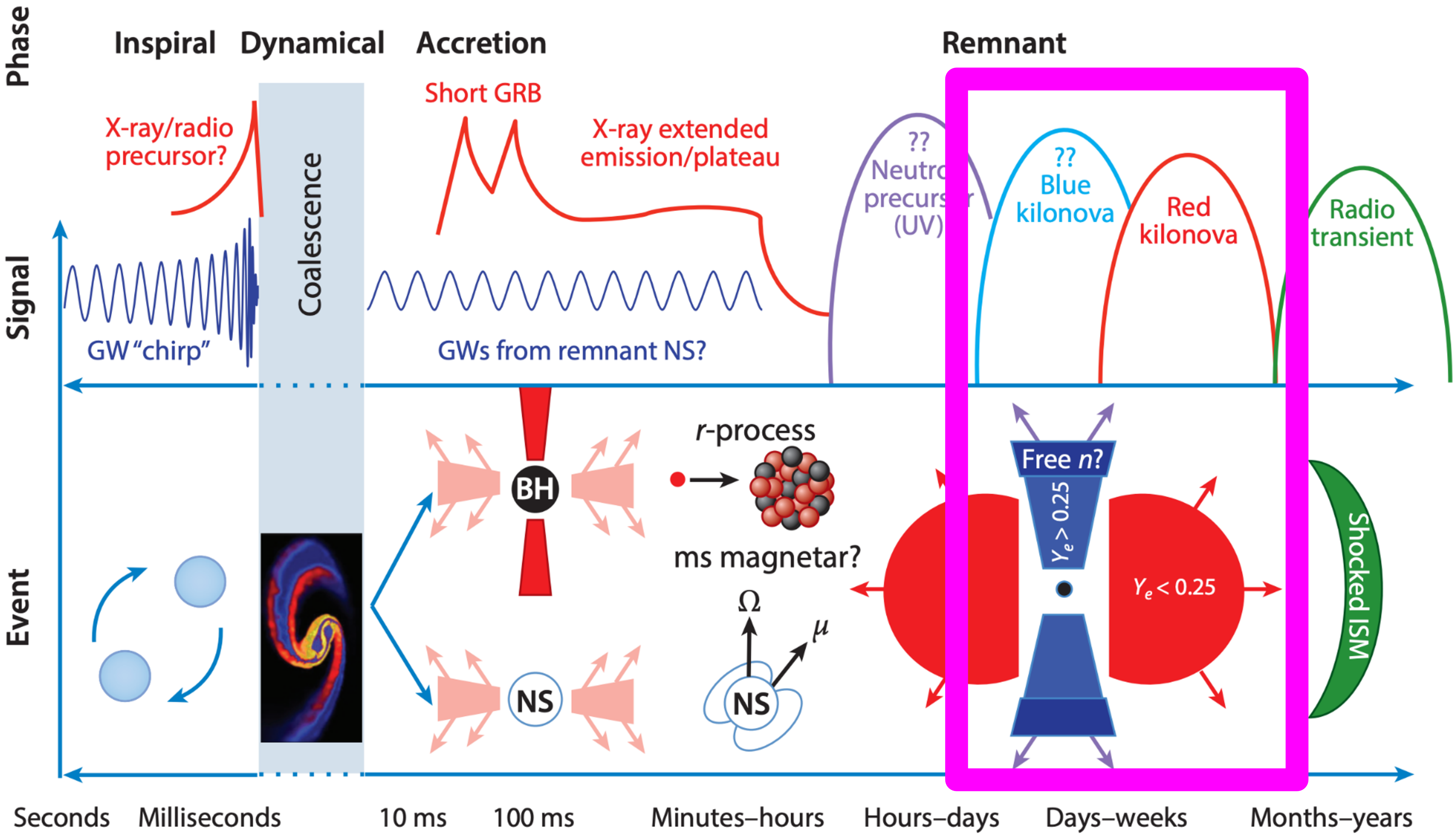


(a) Glitch-versus-all confusion matrix.



(b) NS-versus-all confusion matrix.

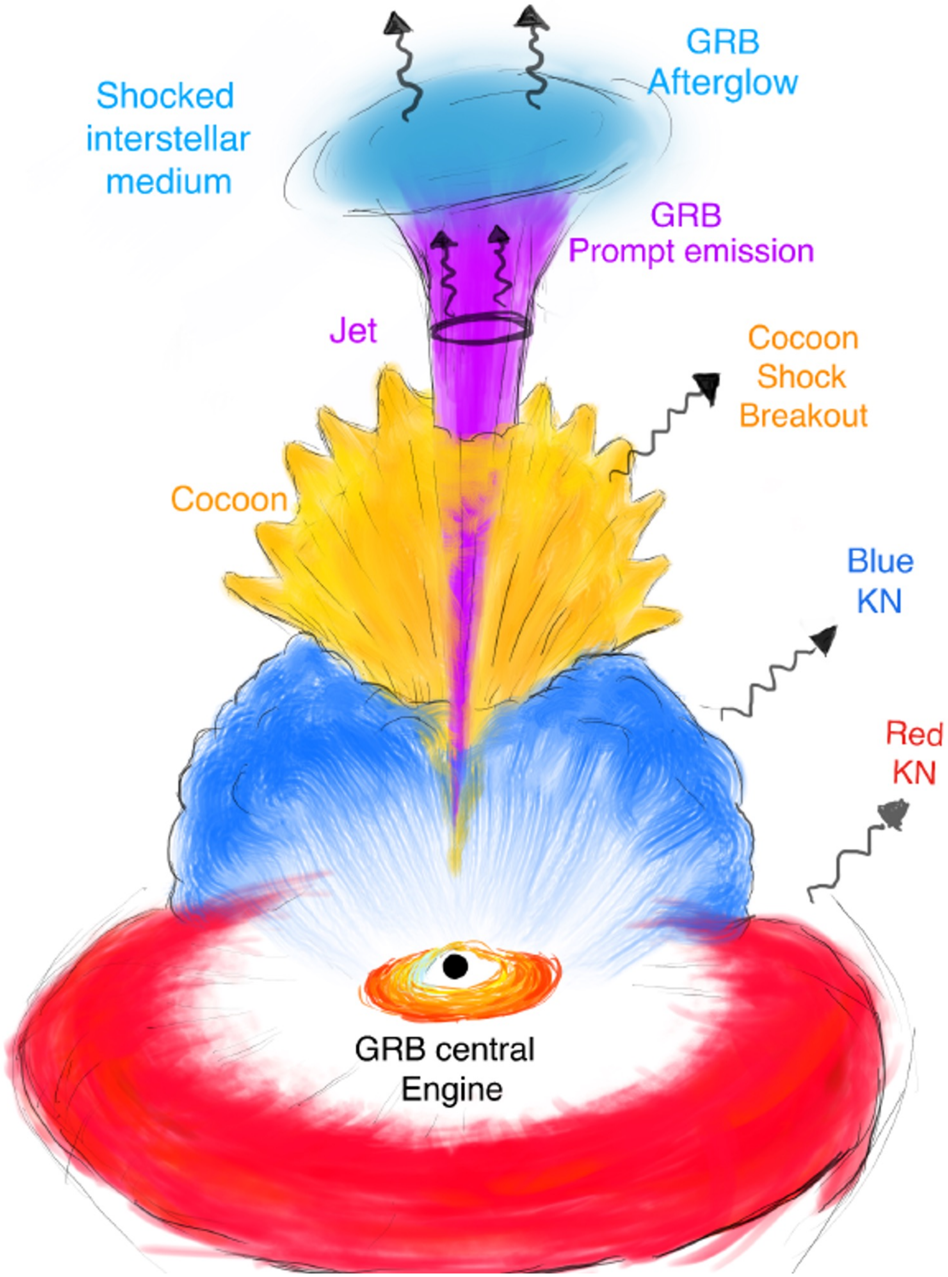
What about that Kilonova?



Fernández & Metzger 2016

Characterizing a Kilonova

- Short gamma ray burst: *seconds*
- X-ray/radio from structured relativistic jet: *months - years*
- ultraviolet/optical/infrared: *hours - days* up to a *week* = **Kilonova**
    - KNe tidal ejecta confined to the plane of the merger
    - Post-merger ejecta, *e.g.,* disk outflows: roughly isotropic



Slide Credit: N.Vieira

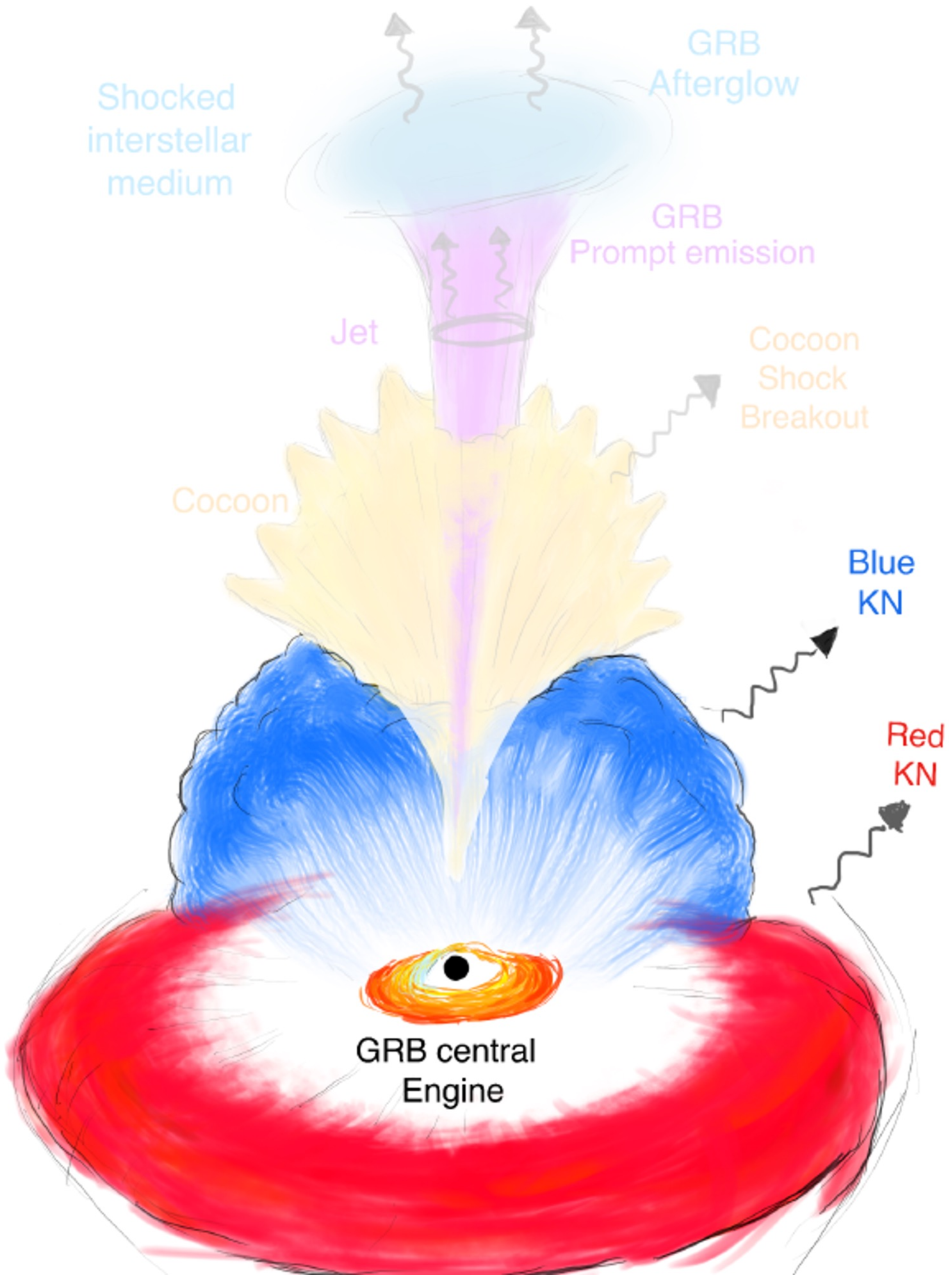
Ascenzi et al. 2021

Characterizing a Kilonova

- Short gamma ray burst: *seconds*
- X-ray/radio from structured relativistic jet: *months - years*
- ultraviolet/optical/infrared: *hours - days* up to a *week* = **Kilonova**
  - Multiple components:

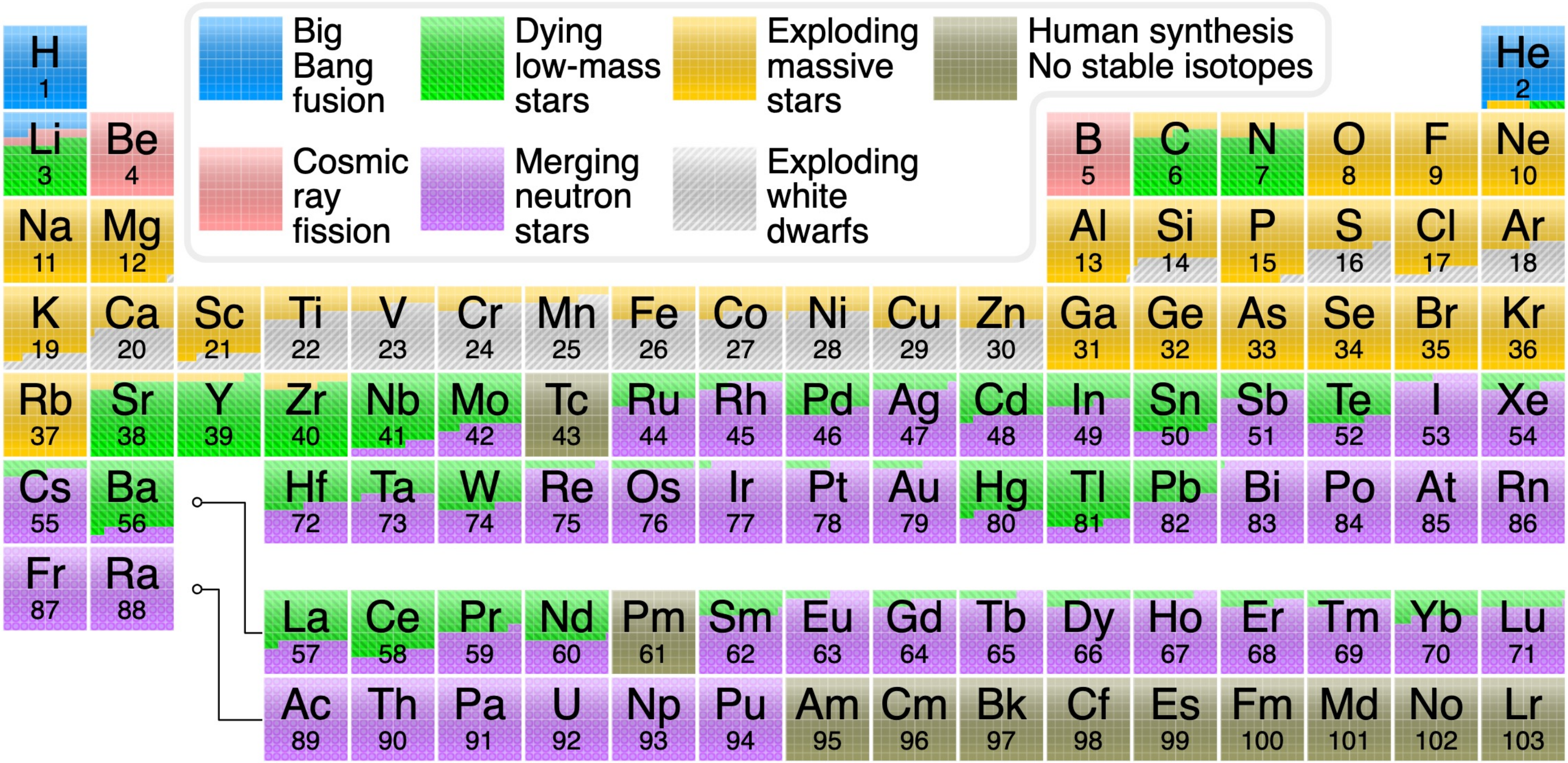
    Red: heavier *r*-process elements → large opacity in UV, optical

    Blue: lighter *r*-process elements → smaller opacities



Ascenzi et al. 2021

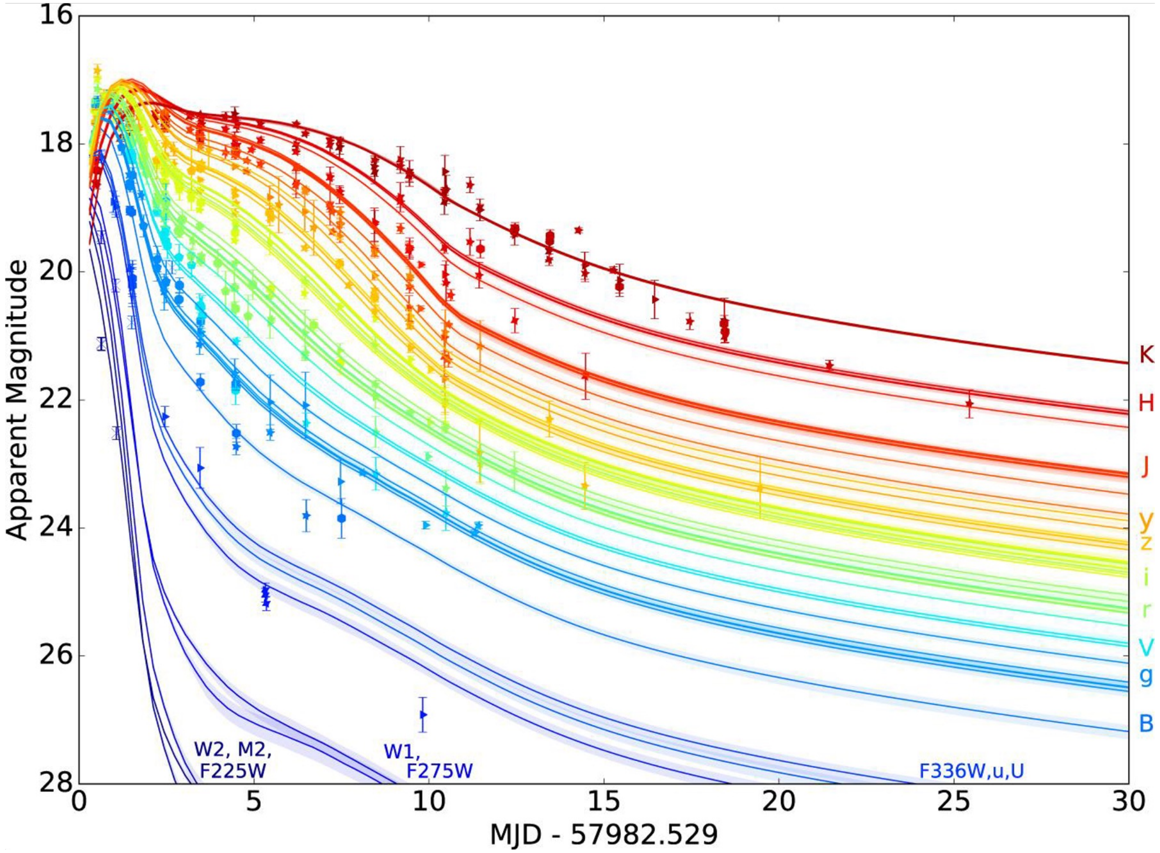
Slide Credit: N.Vieira



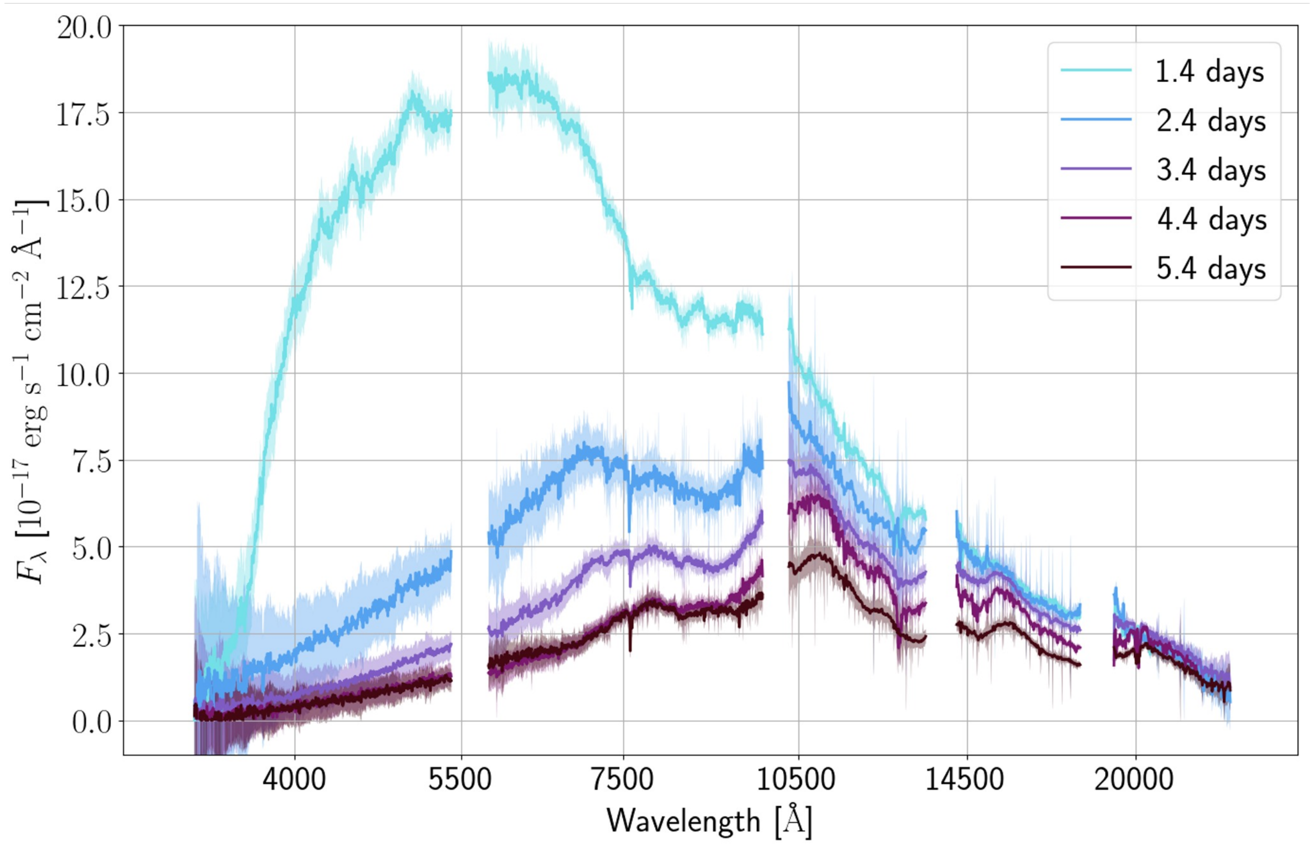
Big Bang fusion
Dying low-mass stars
Exploding massive stars
Human synthesis No stable isotopes
Cosmic ray fission
Merging neutron stars
Exploding white dwarfs
H 1
He 2
Li 3
Be 4
B 5
C 6
N 7
O 8
F 9
Ne 10
Na 11
Mg 12
Al 13
Si 14
P 15
S 16
Cl 17
Ar 18
K 19
Ca 20
Sc 21
Ti 22
V 23
Cr 24
Mn 25
Fe 26
Co 27
Ni 28
Cu 29
Zn 30
Ga 31
Ge 32
As 33
Se 34
Br 35
Kr 36
Rb 37
Sr 38
Y 39
Zr 40
Nb 41
Mo 42
Tc 43
Ru 44
Rh 45
Pd 46
Ag 47
Cd 48
In 49
Sn 50
Sb 51
Te 52
I 53
Xe 54
Cs 55
Ba 56
Hf 72
Ta 73
W 74
Re 75
Os 76
Ir 77
Pt 78
Au 79
Hg 80
Tl 81
Pb 82
Bi 83
Po 84
At 85
Rn 86
Fr 87
Ra 88
La 57
Ce 58
Pr 59
Nd 60
Pm 61
Sm 62
Eu 63
Gd 64
Tb 65
Dy 66
Ho 67
Er 68
Tm 69
Yb 70
Lu 71
Ac 89
Th 90
Pa 91
U 92
Np 93
Pu 94
Am 95
Cm 96
Bk 97
Cf 98
Es 99
Fm 100
Md 101
No 102
Lr 103

Exquisite Photometry and Spectroscopy

Can we infer abundances of individual elements from the spectra of GW170817's KNe?



Villar et al. 2017



Vieira et al. 2023

Data: Pian et al. 2017, Smartt et al. 2017

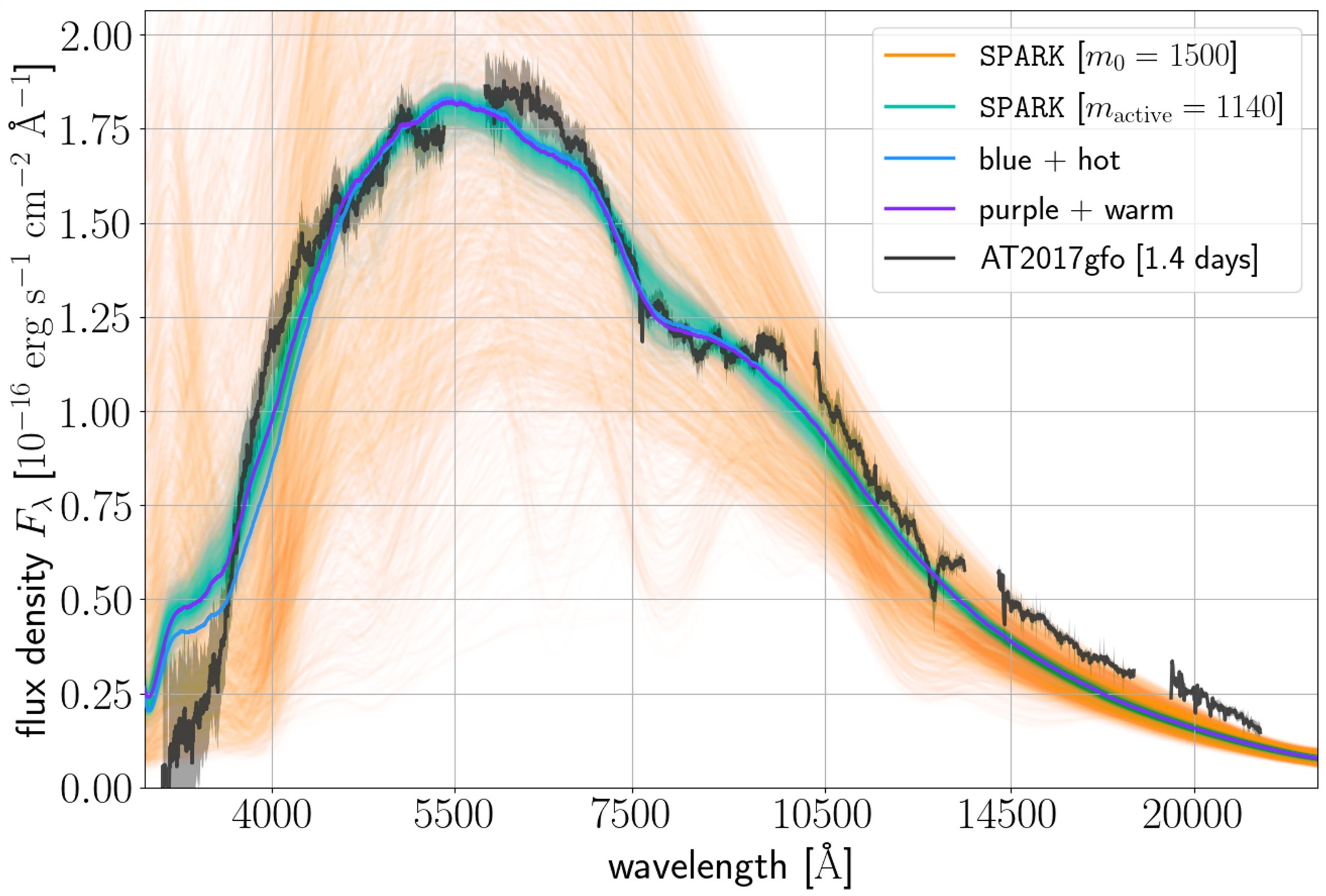
Spectral r-Process Abundance Retrieval for KNe (SPARK)

Spectral Retrieval: Generate many synthetic spectra & compare to obs

→ Fit for *r*-process abundance pattern of GW170817

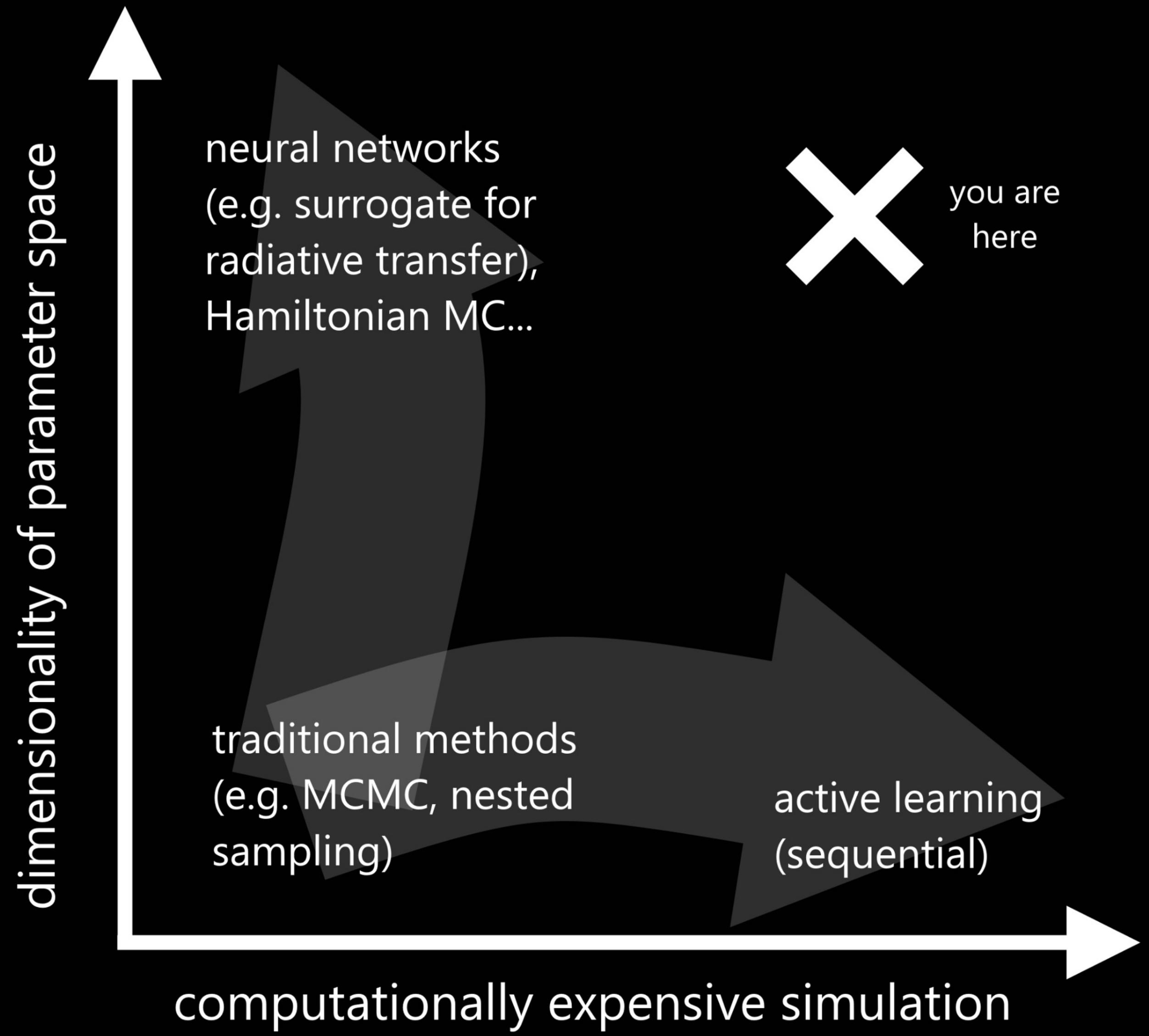
BUT this process is…

1. computationally expensive
2. many elements → high dimensionality if we naively fit for each abundance individually



Vieira et al. 2023

Inference regimes



Slide Credit: N.Vieira

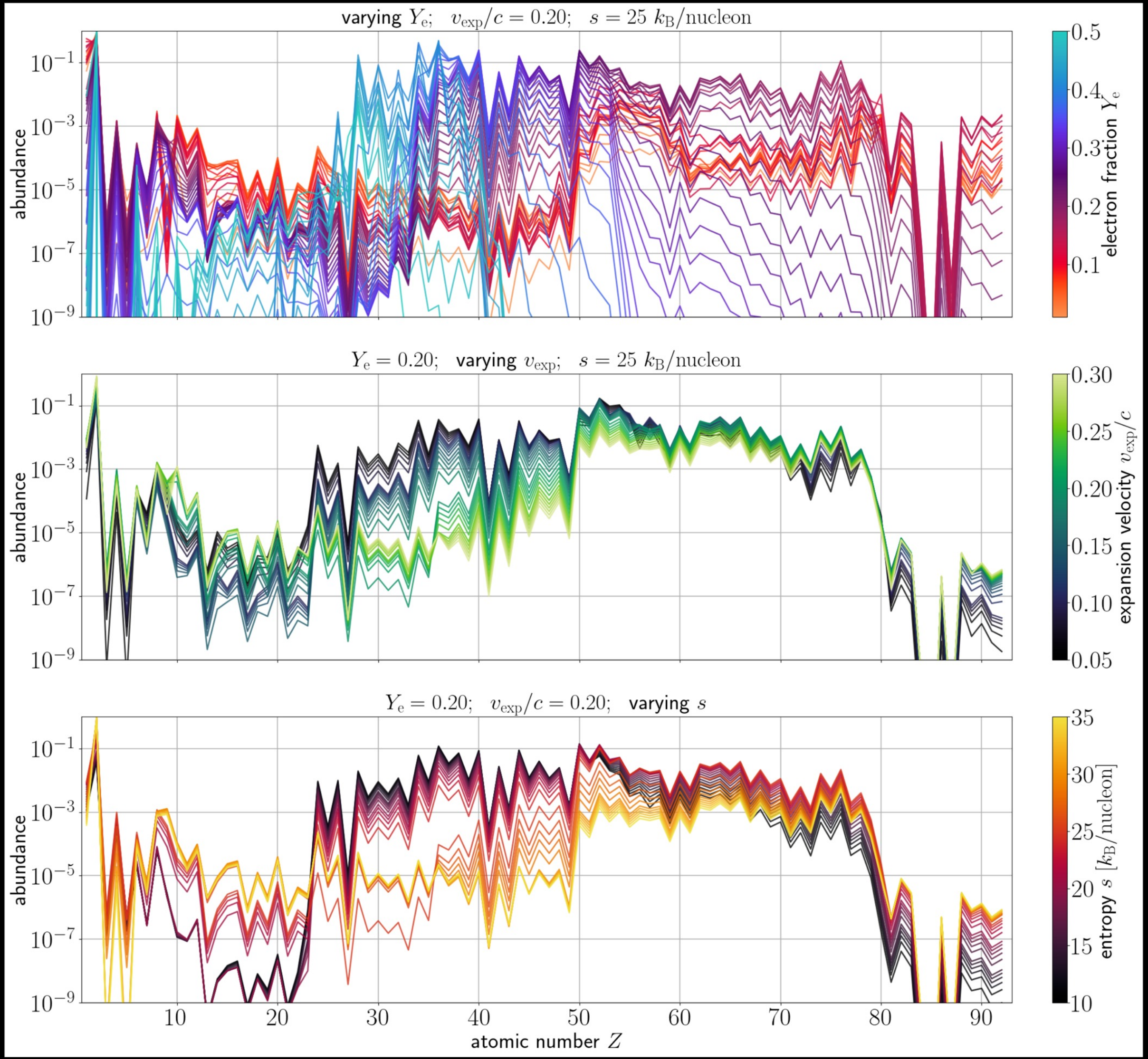
Parametrizing the abundances

- Parametrize using **electron fraction, expansion velocity,** and **entropy**

  $$Y_{\mathrm{e}},\, v_{\mathrm{exp}},\ \ s$$

- Constrain fundamental conditions of the *r*-process

Vieira et al. 2023;
Mapping from Wanajo et al. 2018



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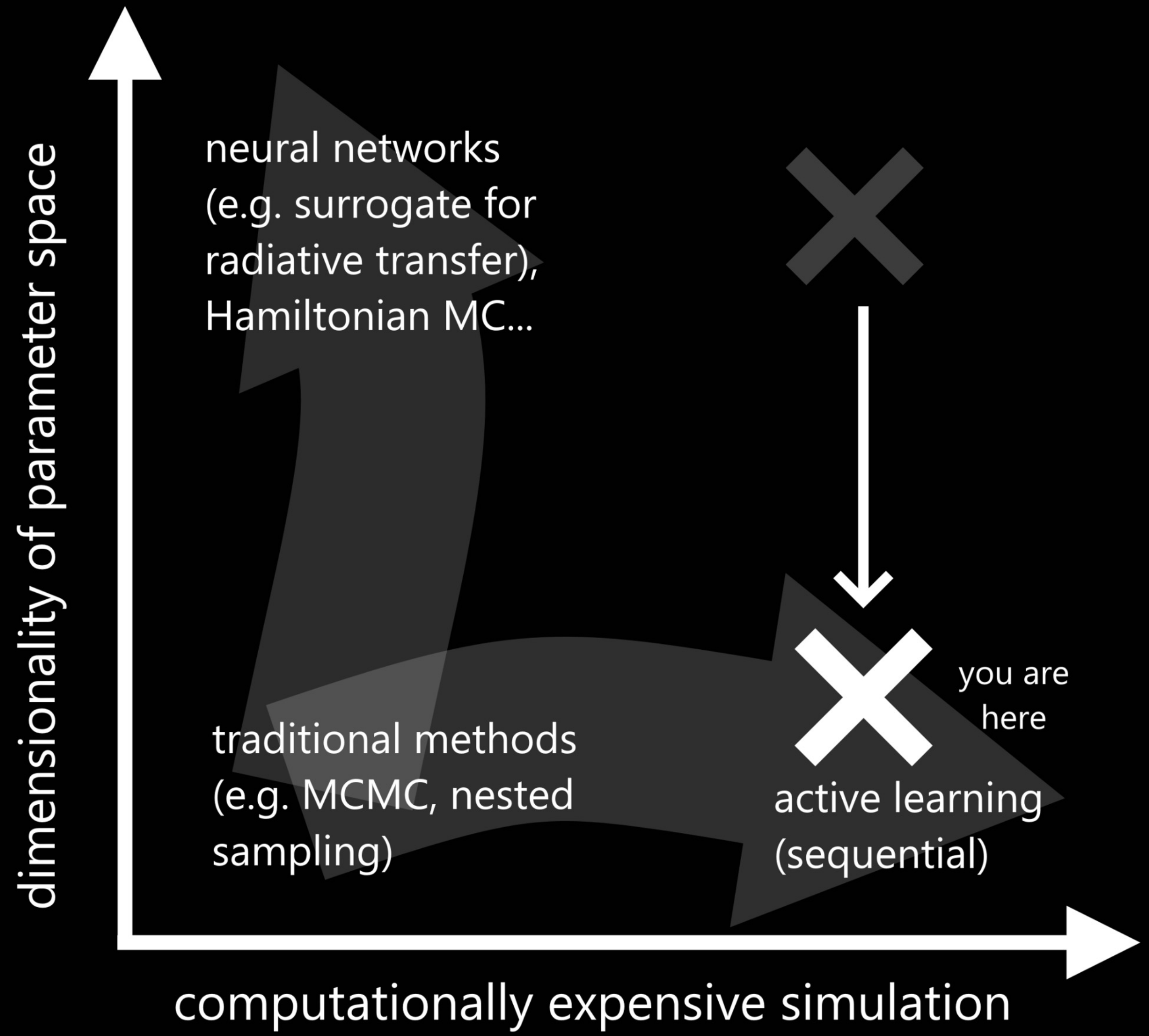
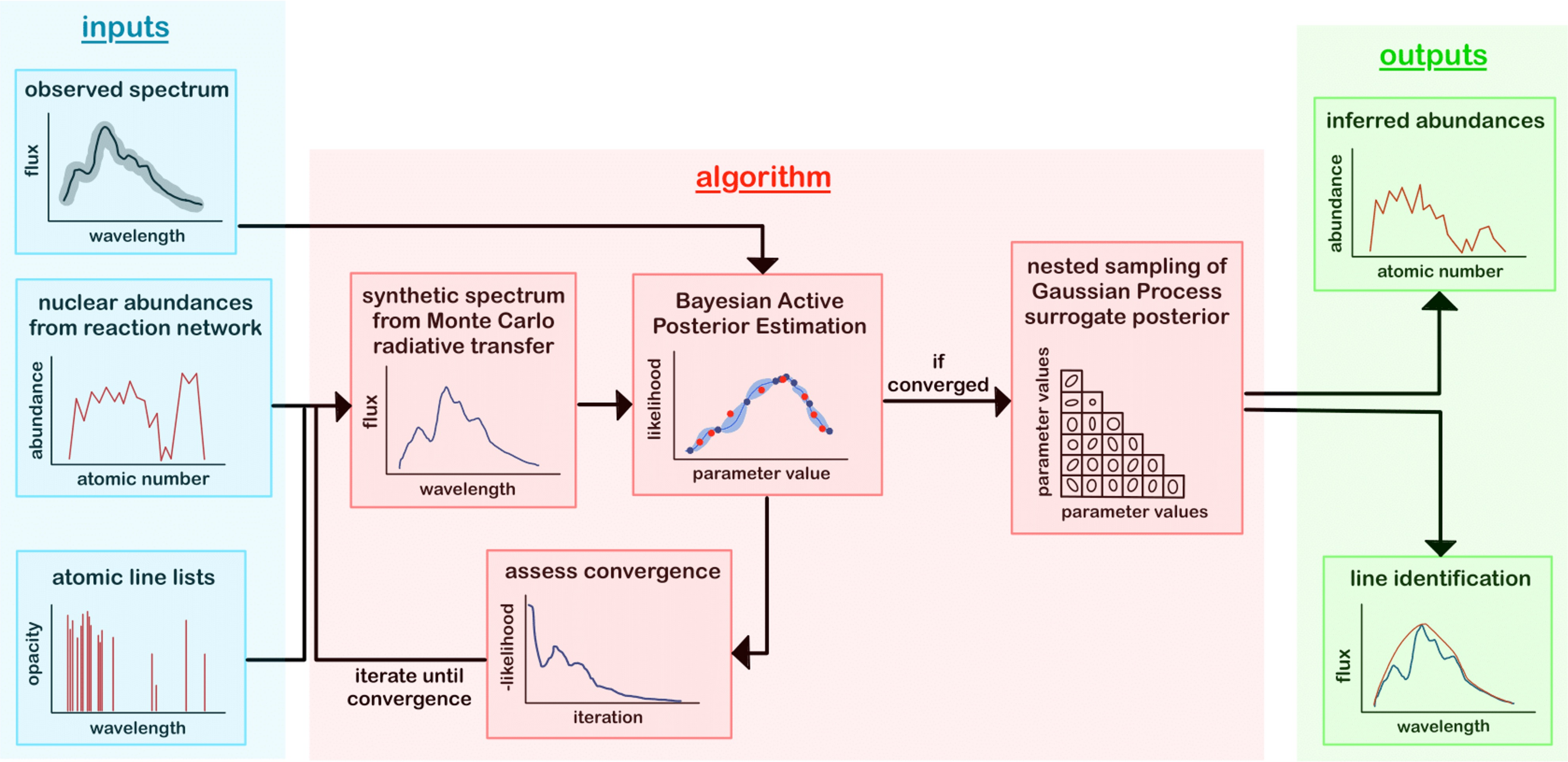


Slide Credit: N.Vieira

SPARK: Spectroscopic *r*-Process Abundance Retrieval for Kilonovae



Vieira et al. 2023

Radiative transfer with TARDIS

TARDIS!
Exploring supernovae made easy

- 1D Monte Carlo radiative transfer code for spectral synthesis
- Radiation-matter interactions in a stratified medium under homologous expansion (*e.g.*, supernovae, kilonovae)
- Produce a synthetic spectrum at a single point in time
- Computationally expensive

https://tardis-sn.github.io/tardis/

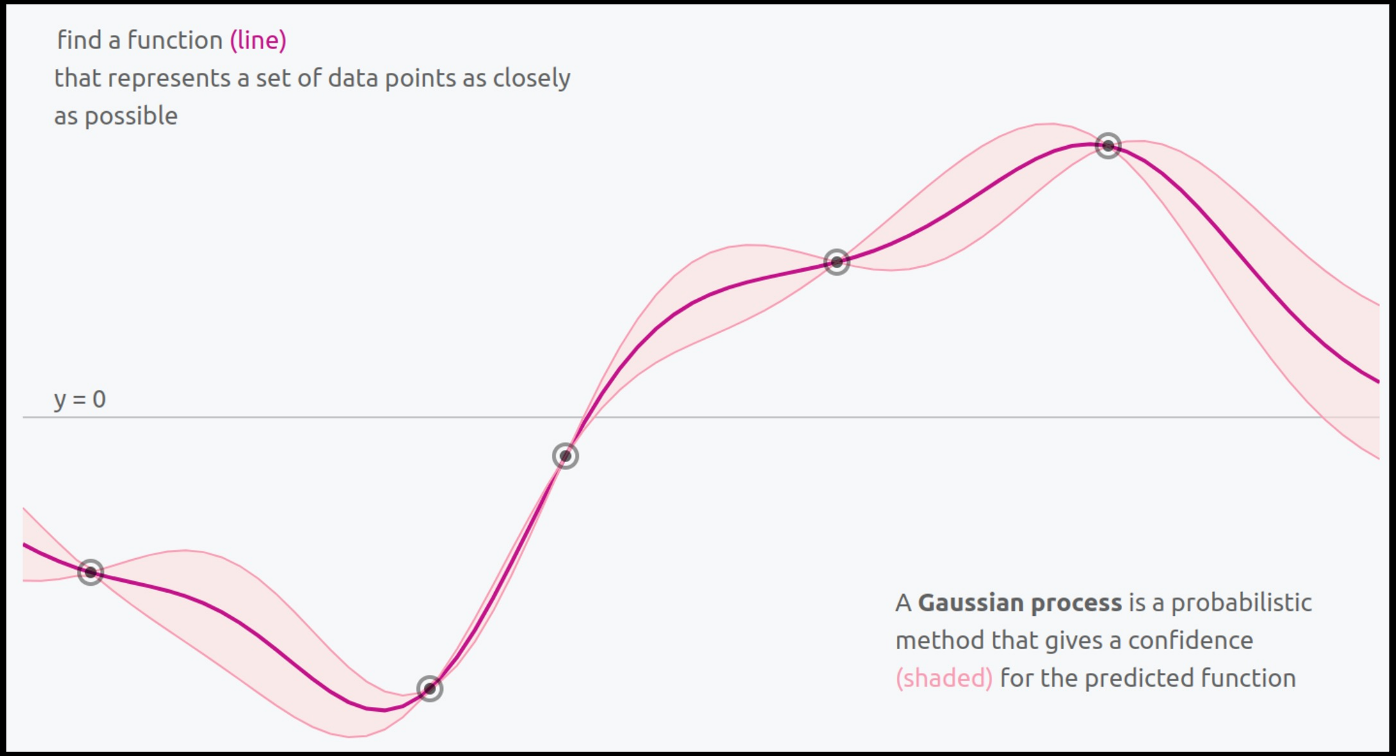
Gaussian Processes

- GPs can approximate a function by conditioning on data *and* can provide uncertainties
- In our case, we have some point θ_i and the function we care about is the **posterior**

$$p(\theta|X)$$

- Train our GP on pairs

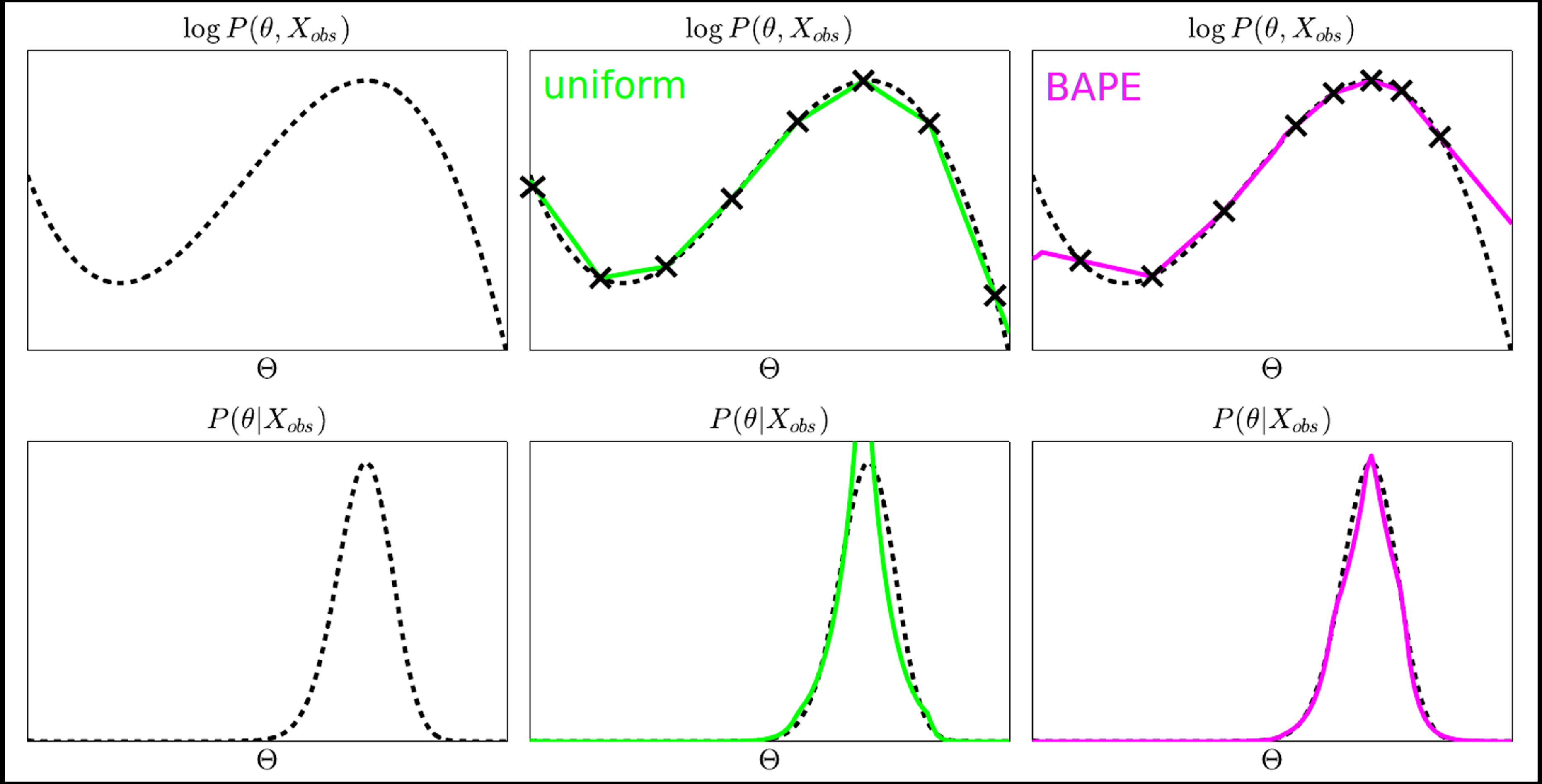
$$\theta_i,\ p(\theta_i|X)$$



Görtler et al. 2019
https://distill.pub/2019/visual-exploration-gaussian-processes/

Bayesian Active Posterior Estimation (BAPE)

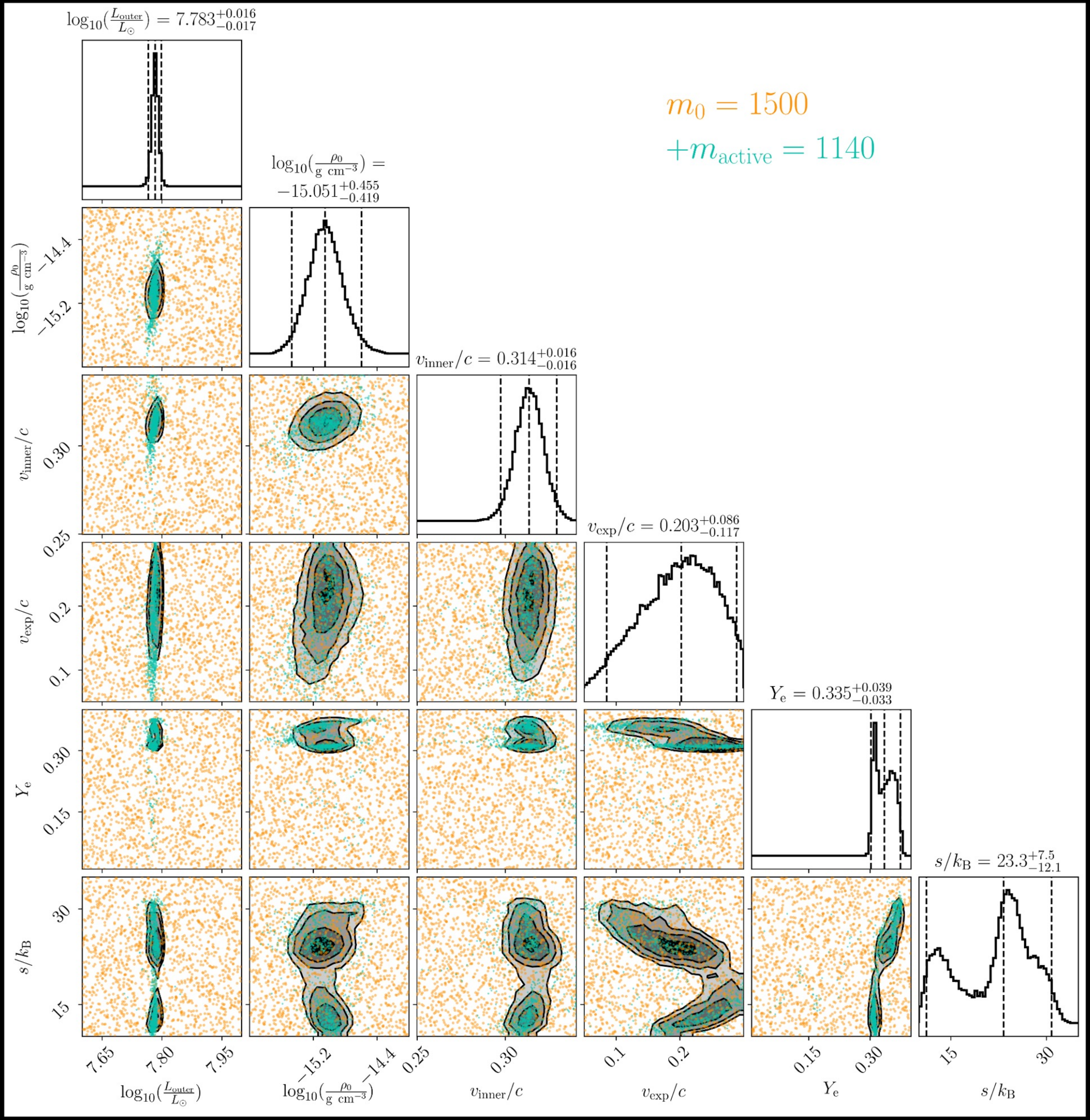
$$u^{\mathrm{EV}}(\theta) = \exp(2\mu(\theta) + \sigma^2(\theta))(\exp(\sigma^2(\theta)) - 1)$$



Kandasamy et al. 2017

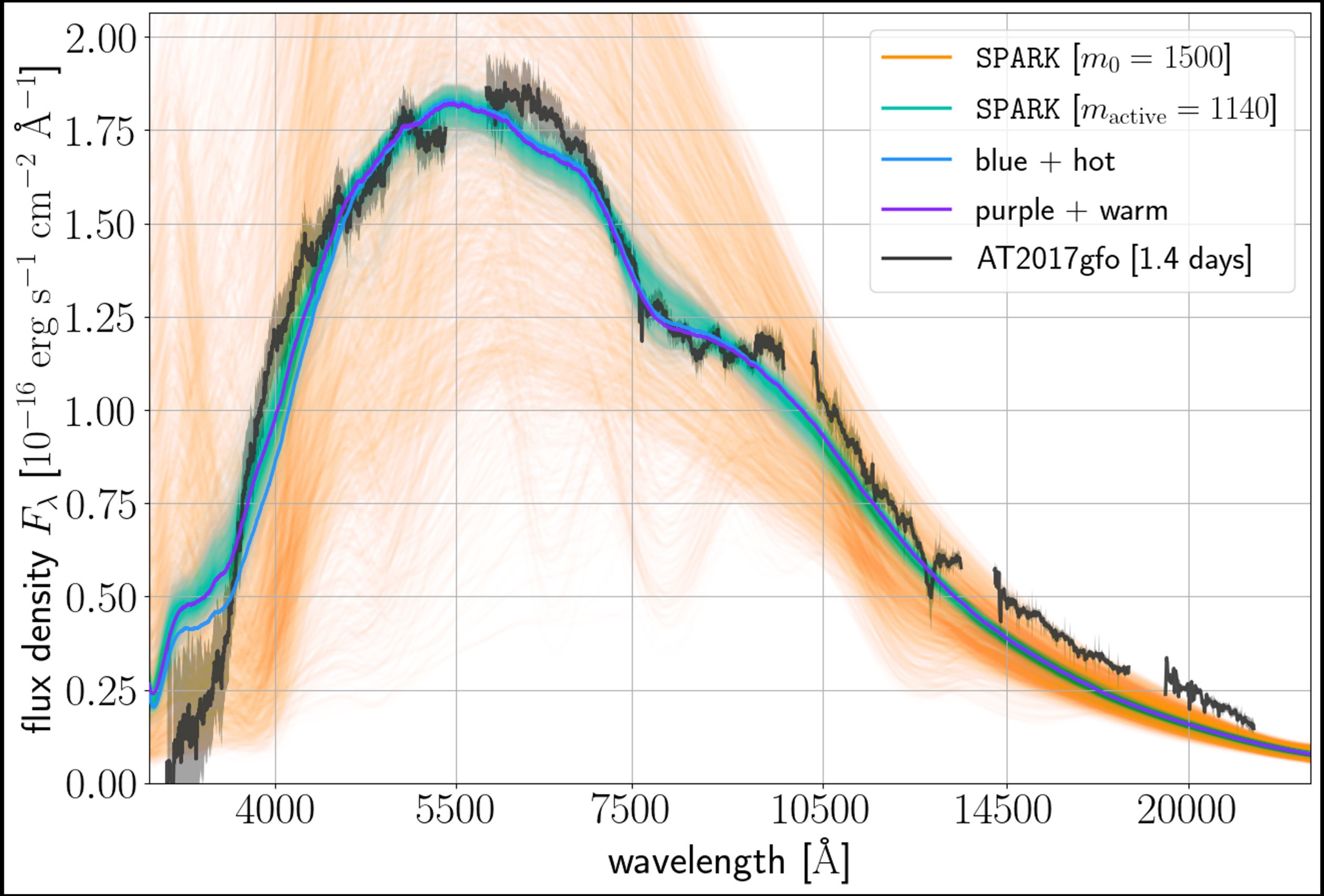
Posterior at 1.4 days

- BAPE sampled where expected
- only 1140 samples to adequately constrain the posterior
- **Bimodal!**
  - **blue** electron fraction, **hot** (high) entropy
  - **purple** electron fraction, **warm** (moderate) entropy



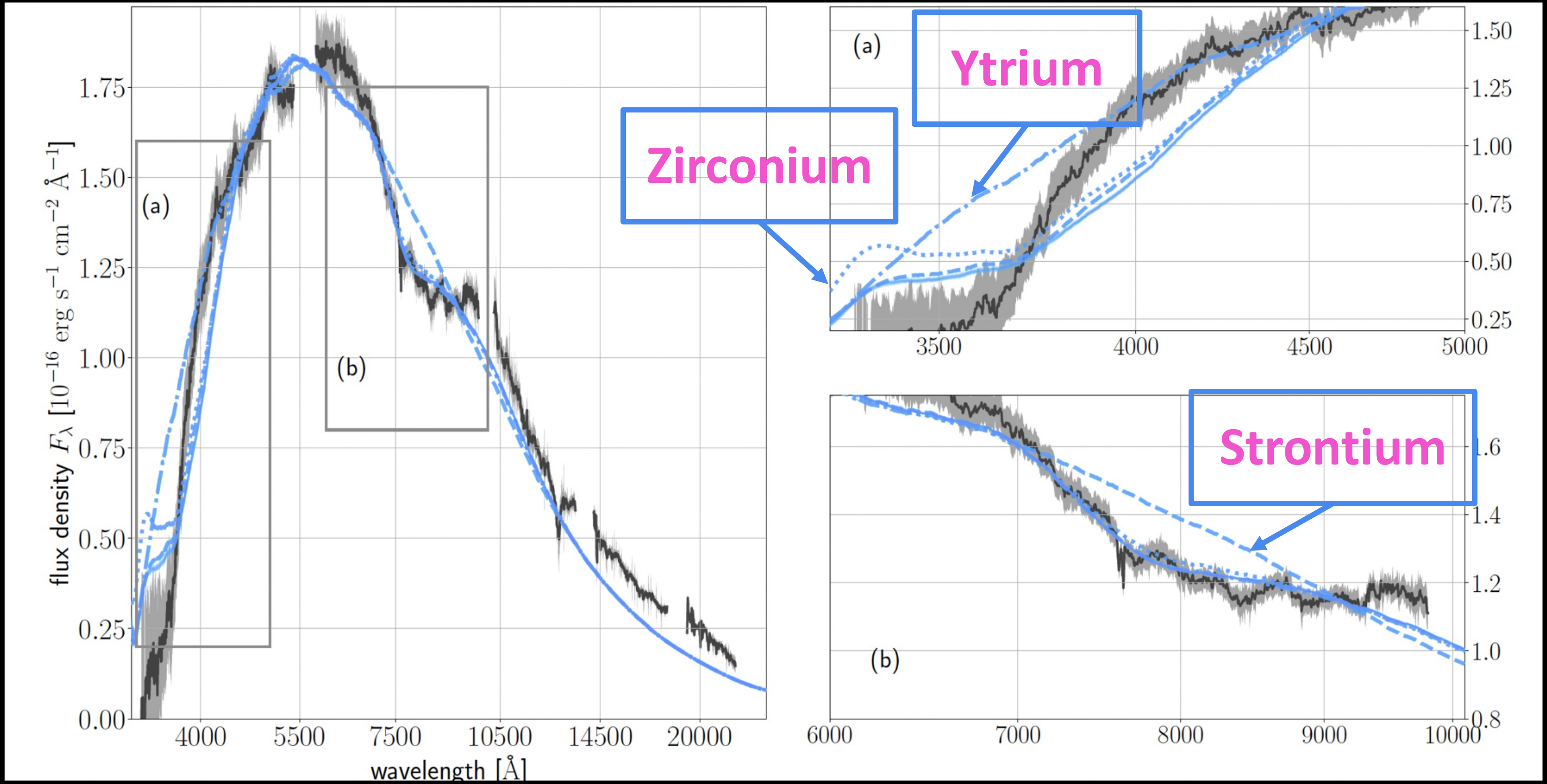
Vieira et al. 2023

All forward model evaluations & best fits



Vieira et al. 2023

What Do SPARK Fits Tell Us?



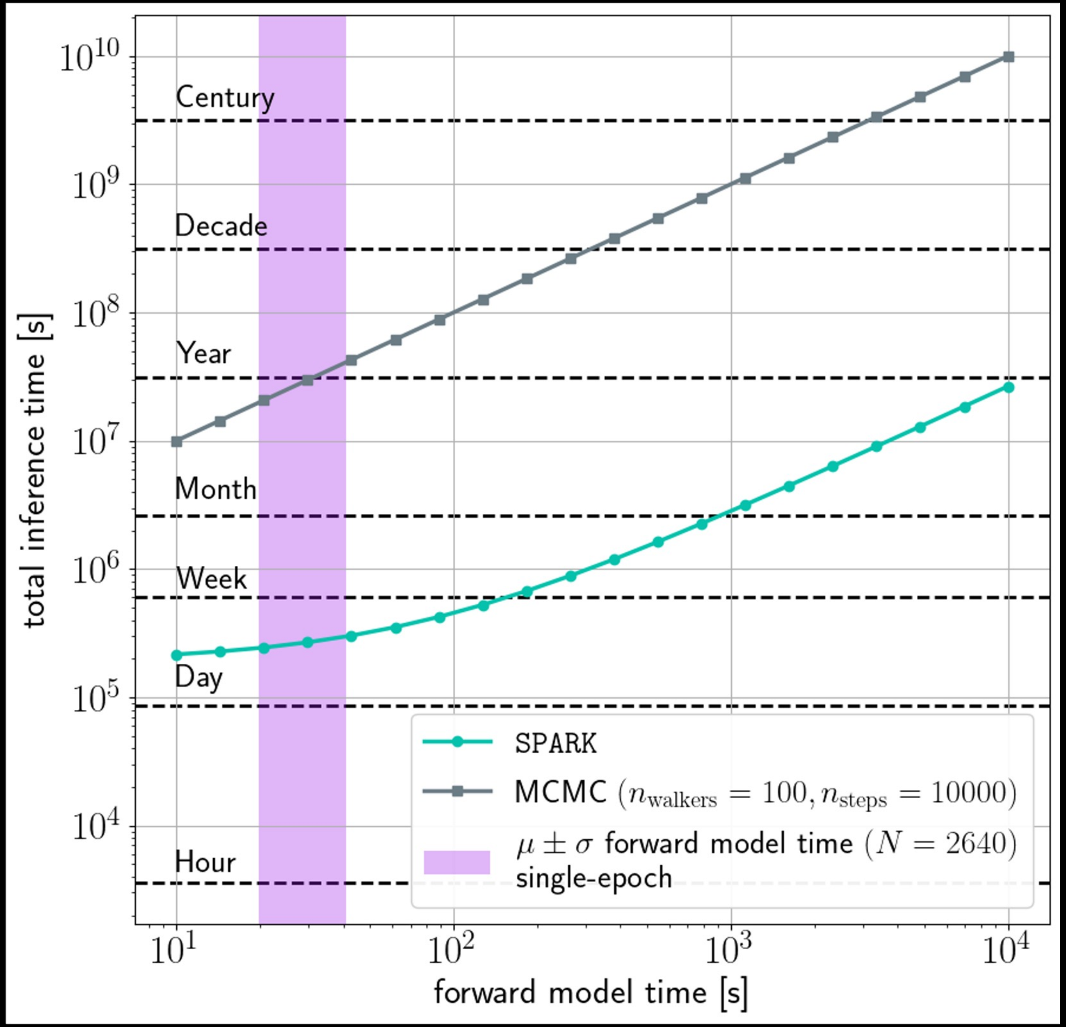
Vieira et al. 2023

Physical Parameters

parameter	SPARK blue+hot
$\log_{10}(L_{\rm outer}/L_\odot)$	$7.784^{+0.016}_{-0.018}$
$\log_{10}(\rho_0/{\rm g\ cm^{-3}})$	$-15.069^{+0.511}_{-0.409}$
$v_{\rm inner}/c$	$0.313^{+0.015}_{-0.016}$
$v_{\rm exp}/c$	$0.176^{+0.091}_{-0.099}$
Y_e	$0.351^{+0.025}_{-0.025}$
s [$k_{\rm B}$/nucleon]	$25.3^{+6.0}_{-4.5}$
$T_{\rm inner}$ [K]	3962^{+102}_{-109}
$M_{\rm ej}$ [$M_\odot$]	$> 3.5^{+4.2}_{-3.3} \times 10^{-5}$
[$M_\oplus$]	$> 11.8^{+13.8}_{-11.1}$
$X_{\rm lan}$	$\leqslant 5.6 \times 10^{-9}$

Slide Credit: Nicole Ford

Inference is now computationally tractable



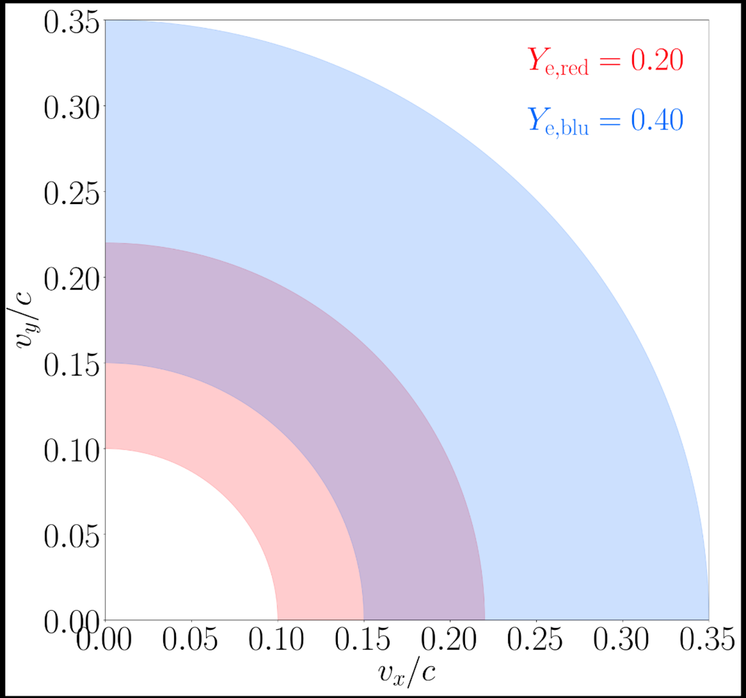
Vieira et al. 2023

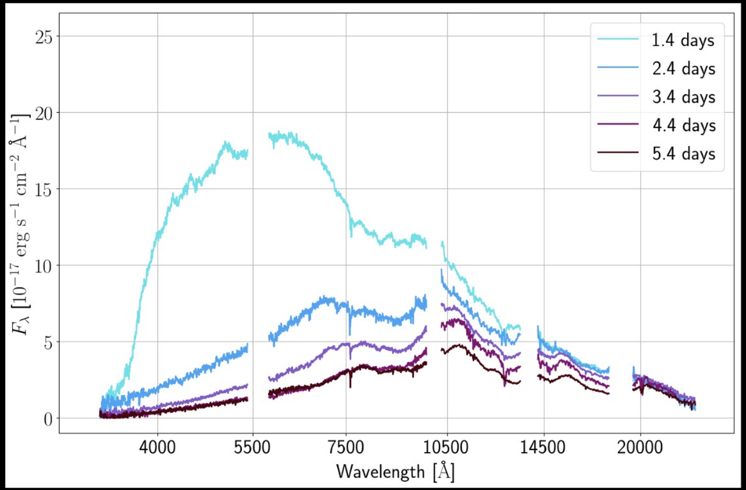
- Purple band: forward model evaluation time
- Typical MCMC would take a year
- **SPARK**: less than a week!

As our model develops in complexity, the purple band will move to the right.

SPARK Future Work

- Obtained the full abundance pattern of GW170817 at 1.4 days
- Established **SPARK** as a successful tool
- In the future:
  - **Multi-component** models
  - **Multi-epoch** fitting
  - Fit **new kilonovae** in O4 (starting in May 2023)!

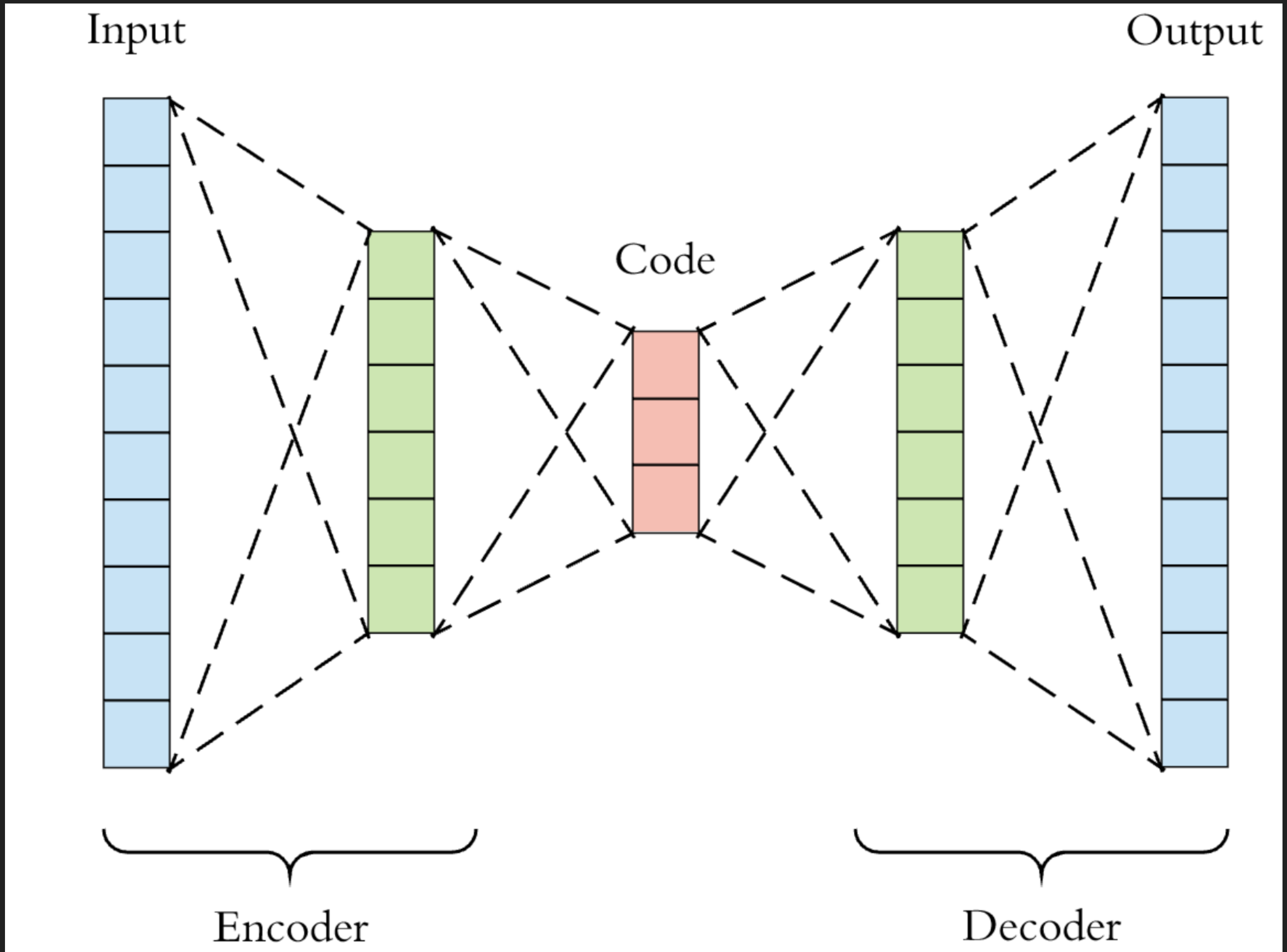




Vieira et al. in prep

Dimensionality Reduction

Auto Encoder = unsupervised, generative



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Training ~10 hrs/latent dimension configuration

Run AE w/ *n* different layer configurations, store models

Find **optimal #** of encoder/decoder dimensions

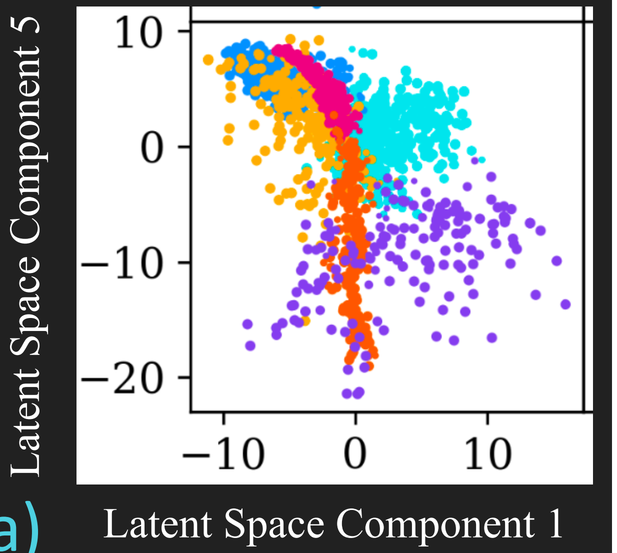
Find **optimal #** of latent space dimensions

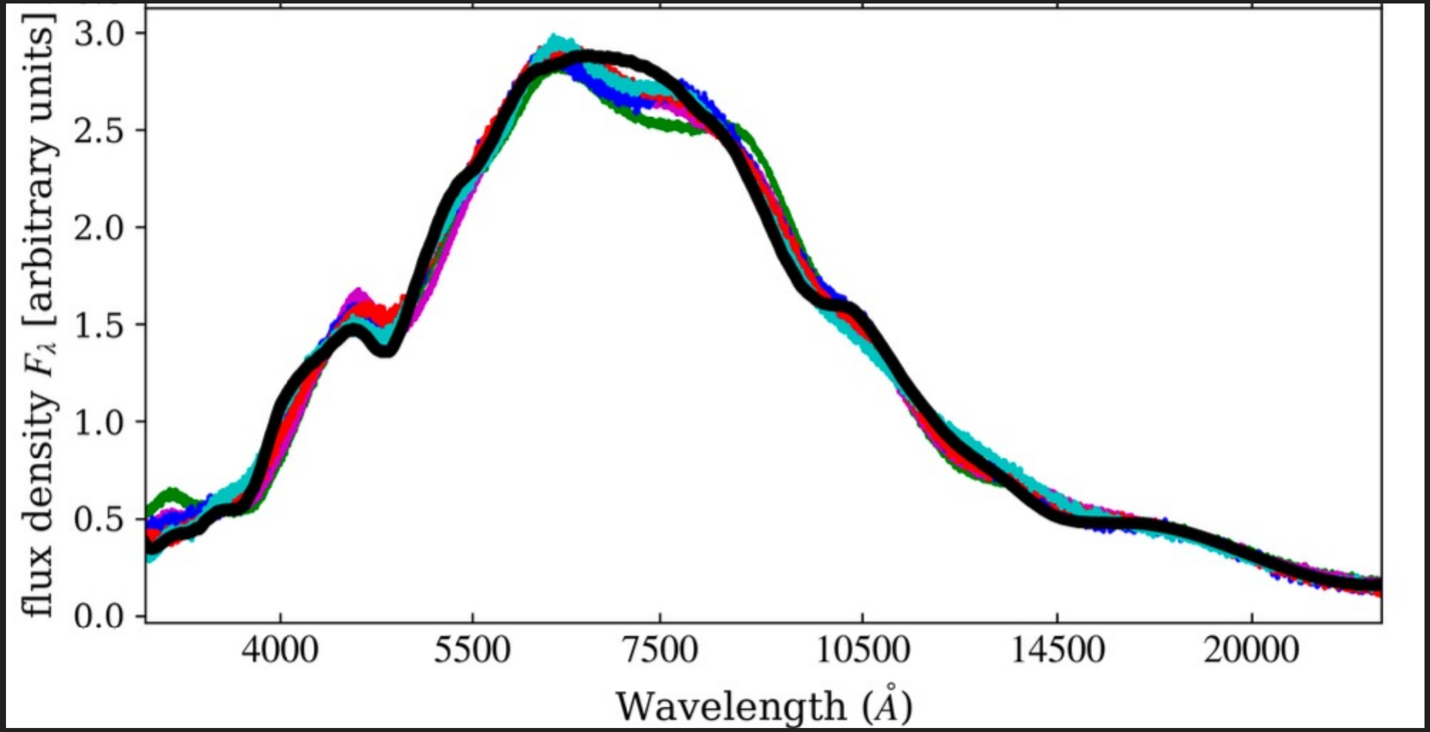
For our data, **5 dimensions!**

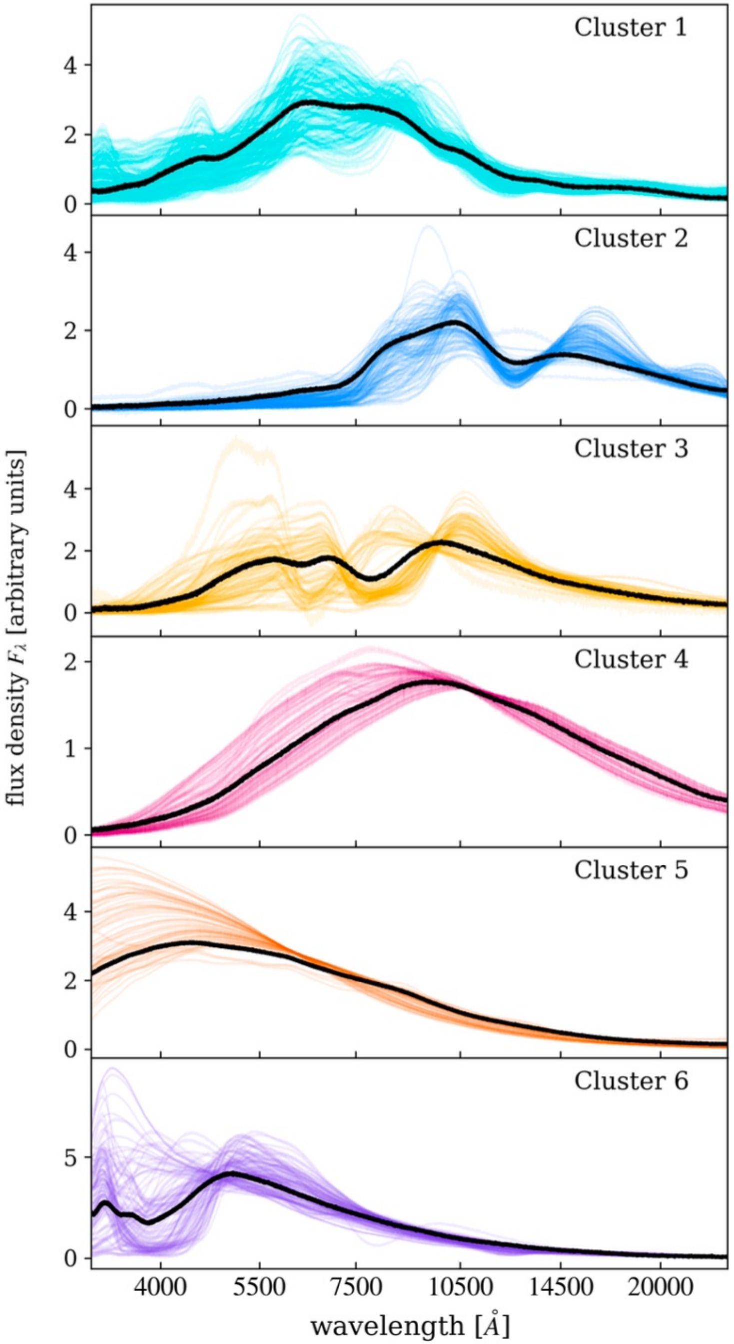
Clustering Analysis

Bayesian Gaussian Mixture Model ~ 5 min training

(observed spectrum at 1.5 days; modelled w/ 1500 SPARK spectra)







Ford et al. in prep

This is bound to get even more interesting…

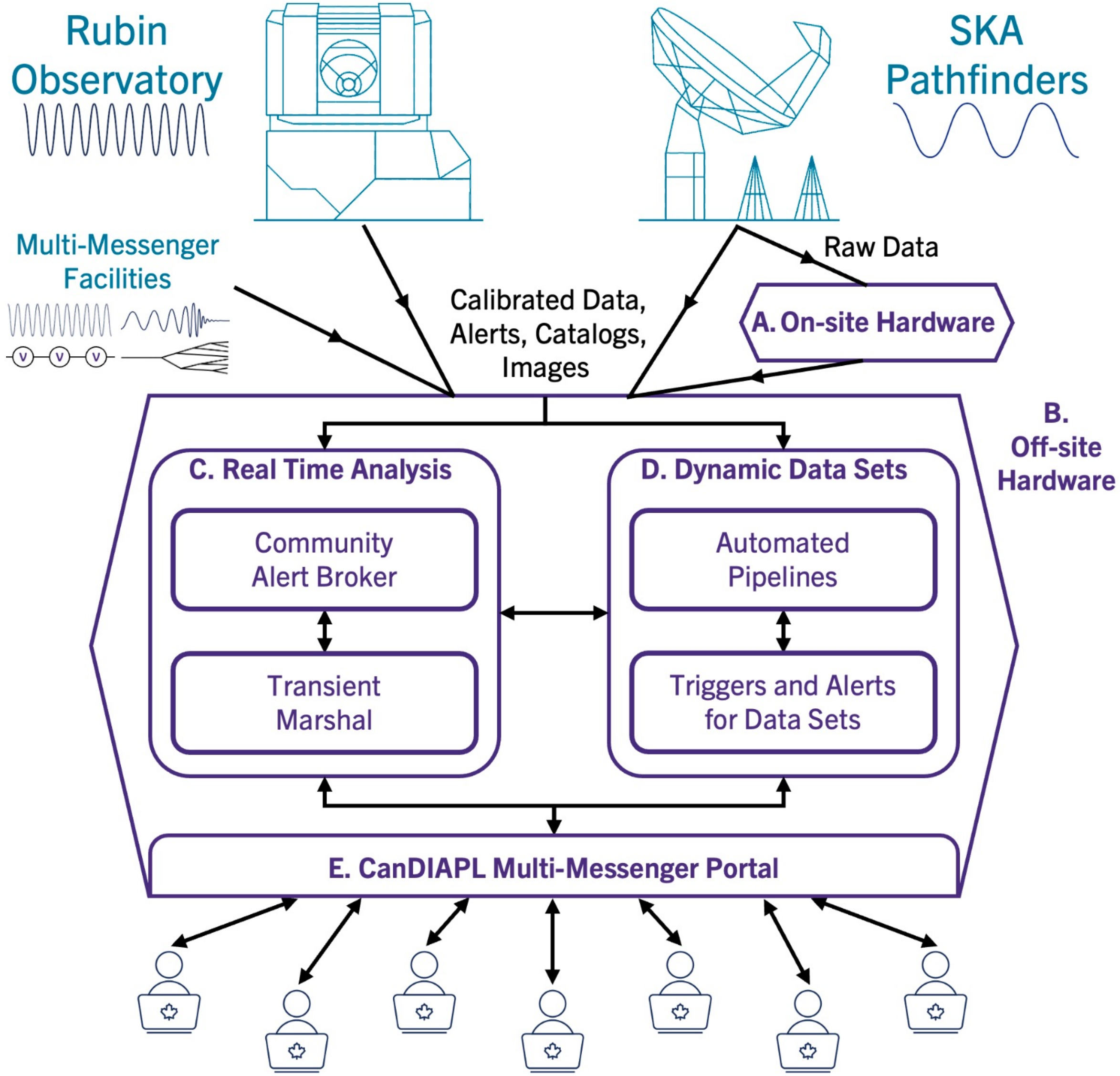
- *Next generation ground-based GW observatories*: **Cosmic Explorer** and/or Einstein Telescope
- *In space*: **Laser Interferometer Space Antenna** (LISA)
- ***Many*** future ground and space missions targeting transients and multi-messenger astrophysics: **CASTOR**, ULTRSAT, SVOM, **STAR-X**, UVEX, **Rubin/LSST**, SKA, ngVLA, **EHT/ngEHT**, **Strobe-X**, **AXIS**, **Arcus**, **Theseus**, Athena, Lynx, and more!

Advance planning some really BIG data!!

CanDIAPL = Canadian Data-Intensive Astrophysics PLatform (PI: Renée Hložek, UofT/Dunlap)

Motivated by

- Vera C. Rubin Observatory
- Square Kilometre Array
- SKA pathfinders:
  - Meer Karoo Array Telescope (MeerKAT)
  - Murchison Widefield Array (MWA)
  - Australian SKA Pathfinder (ASKAP)
- Multi-messenger Facilities




Black hole Folks!