Understanding Combined Results From Multiple GW Searches Using Information Theory

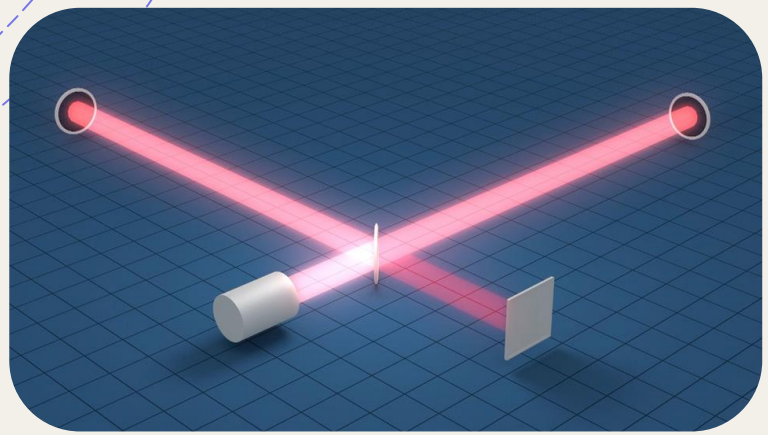
Oleksandra “Sasha” Lukina

Mentor: Derek Davis

LIGO SURF 2023

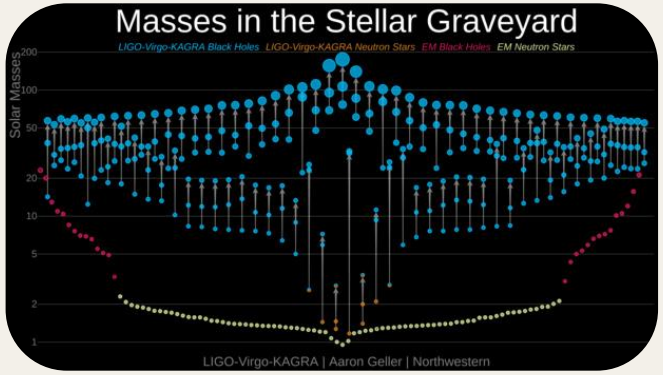
LIGO Caltech University of South Dakota

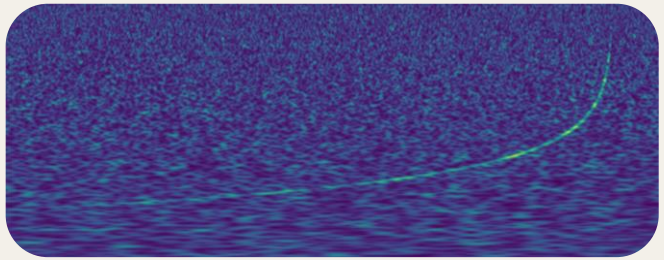
Motivation



Detector Data

Astrophysics





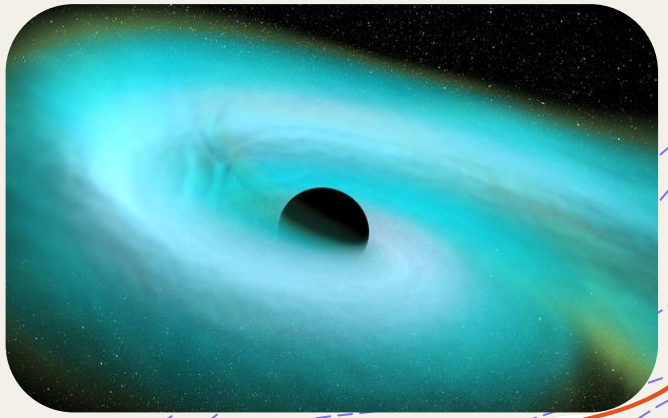
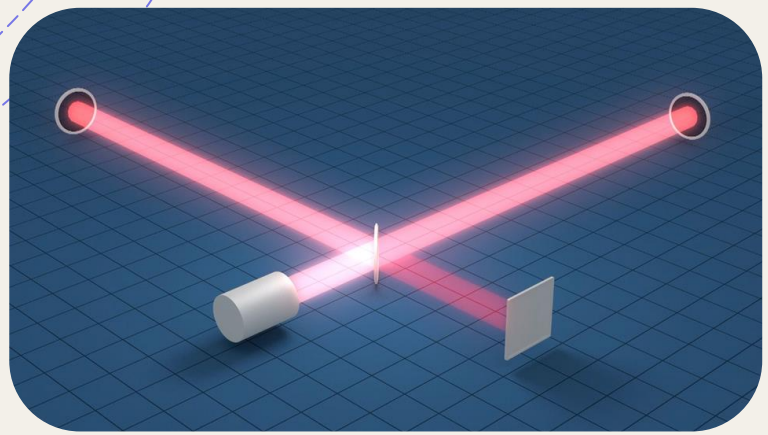


IMAGE CREDIT: T. PYLE; AARON GELLER; DEBORAH FERGUSON, BHAVESH KHAMESRA, KARAN JANI

Motivation

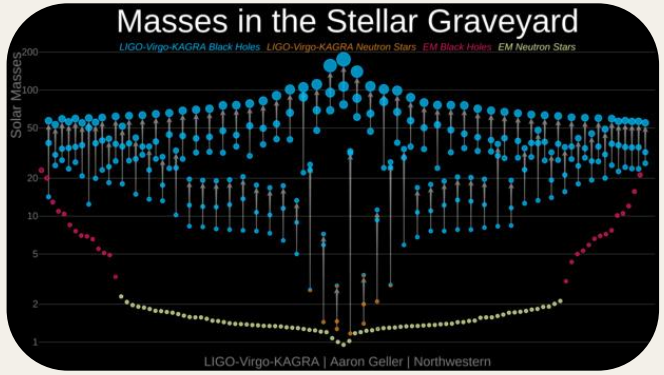


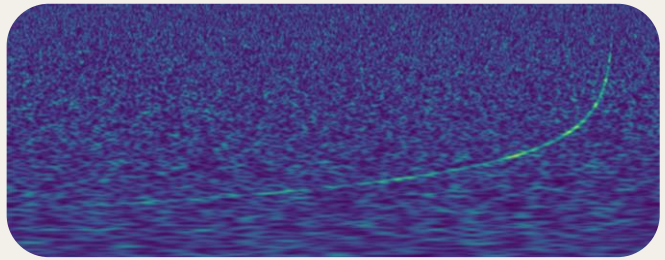
WB

Search Pipelines

PyCBC

gstLAL





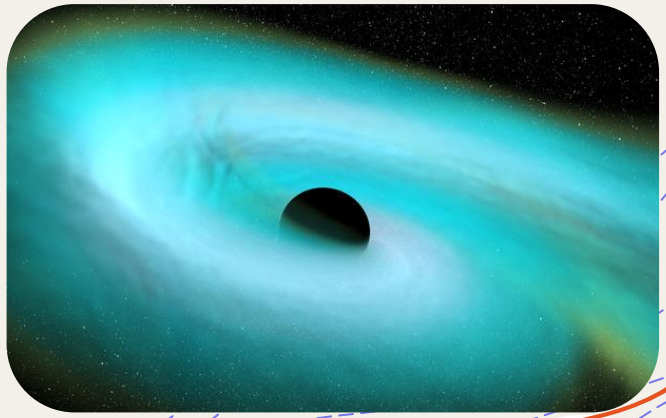
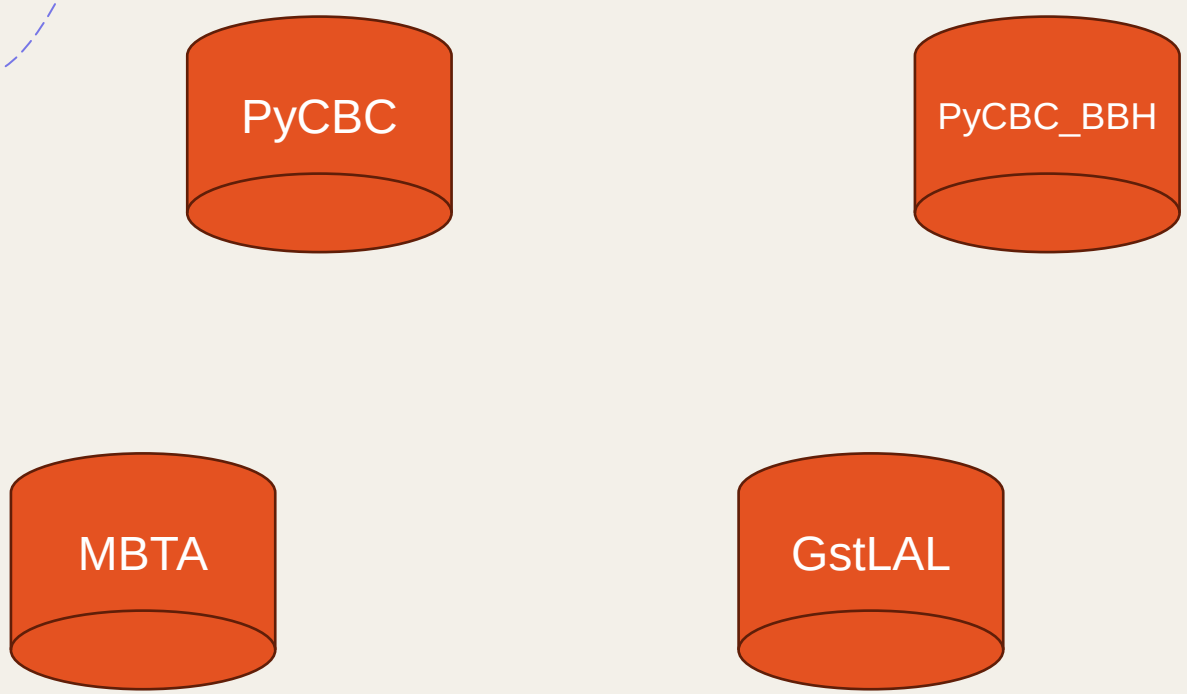


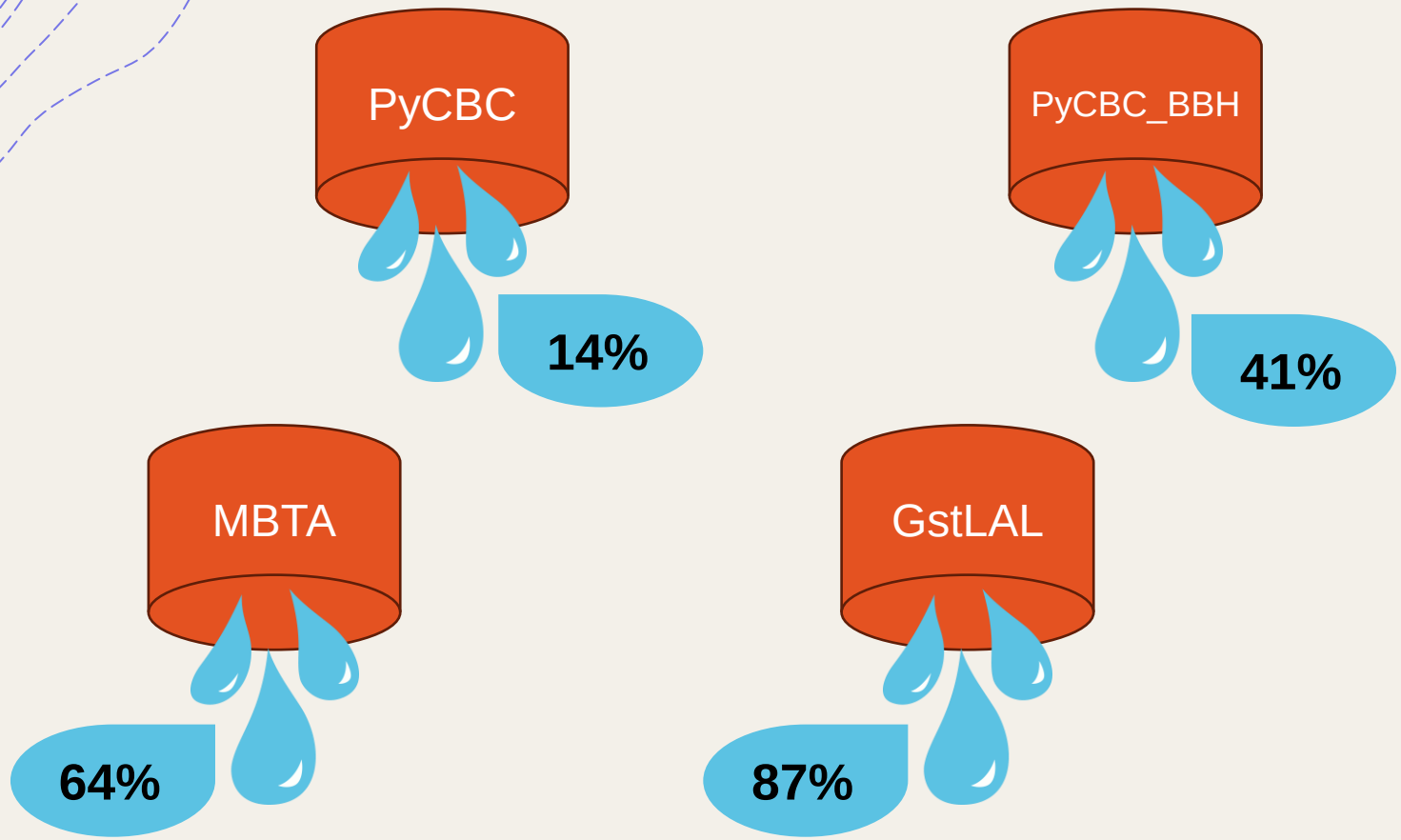
IMAGE CREDIT: T. PYLE; AARON GELLER; DEBORAH FERGUSON, BHAVESH KHAMESRA, KARAN JANI

Search Pipelines



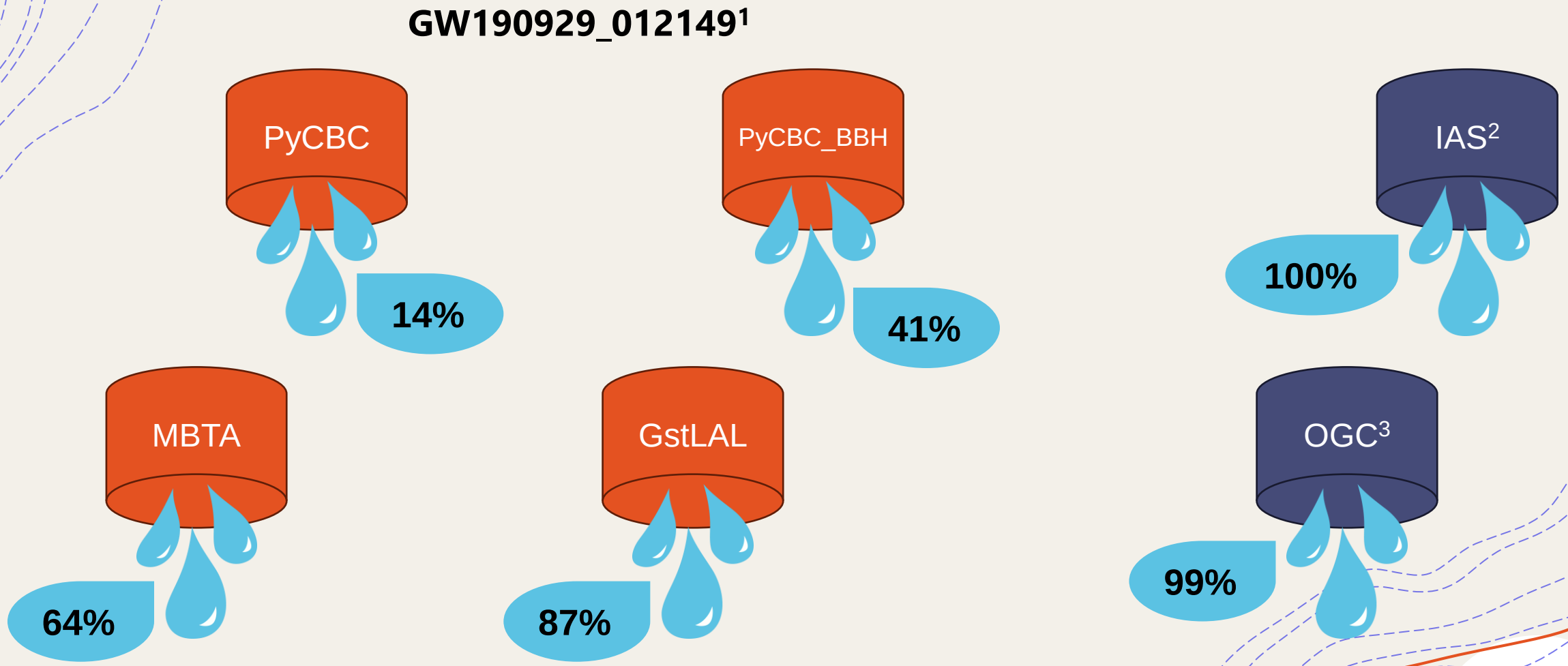
Search Pipelines

GW190929_012149[1]



1: GWTC-2.1, LIGO, VIRGO, 2021

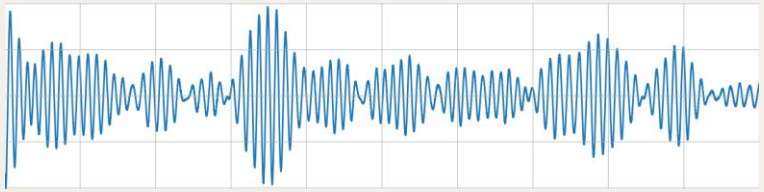
Search Pipelines



1: GWTC-2.1, LIGO, VIRGO, 2021; 2: OLSEN ET AL, 2021; 3: NITZ ET AL, 2021

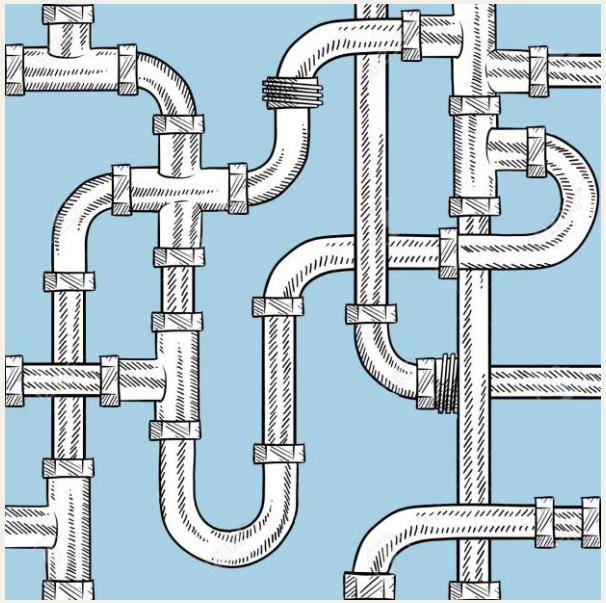
What is a good way to combine results from multiple pipelines and what can we learn from it?

Macroscopic Description of a Pipeline



Strain Data

Signal and Noise Models



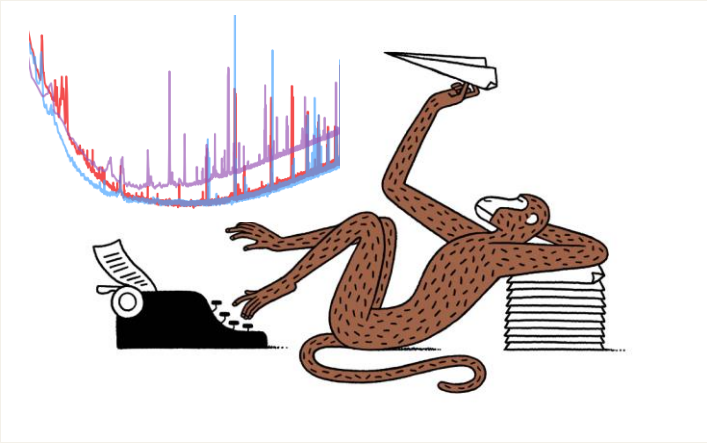
Search Algorithm

- Triggers
- False alarm rate
- p_{astro}

Measures of Candidate Significance

False Alarm Rate (FAR)

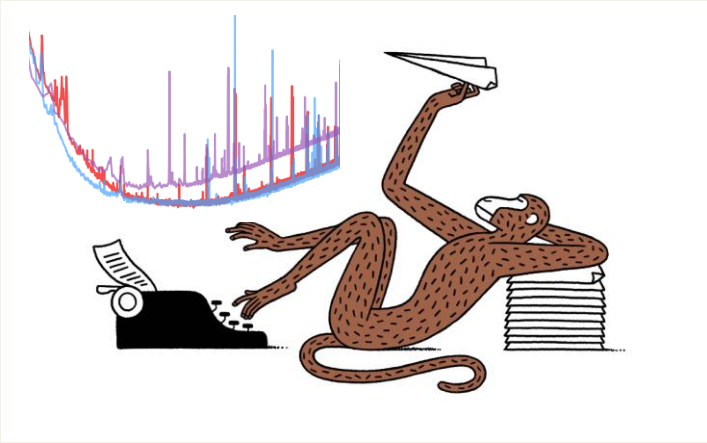
How regularly we would expect to see a noise event with the same, or higher, ranking statistic as the candidate.



Measures of Candidate Significance

False Alarm Rate (FAR)

How regularly we would expect to see a noise event with the same, or higher, ranking statistic as the candidate.



p_{astro}

Probability that a GW candidate has astrophysical origin and is not caused by terrestrial noise.

$$p_{astro} = \frac{\mathcal{L}_{astro}}{\mathcal{L}_{astro} + \mathcal{L}_{noise}}$$

Calculating Combined Significance

Pipeline 1

FAR 1

p_{astr} 1

Pipeline 2

FAR 2

p_{astr} 2

Pipeline 3

FAR 3

p_{astr} 3

Calculating Combined Significance

Pipeline 1

FAR 1

p_{astr} 1

Pipeline 2

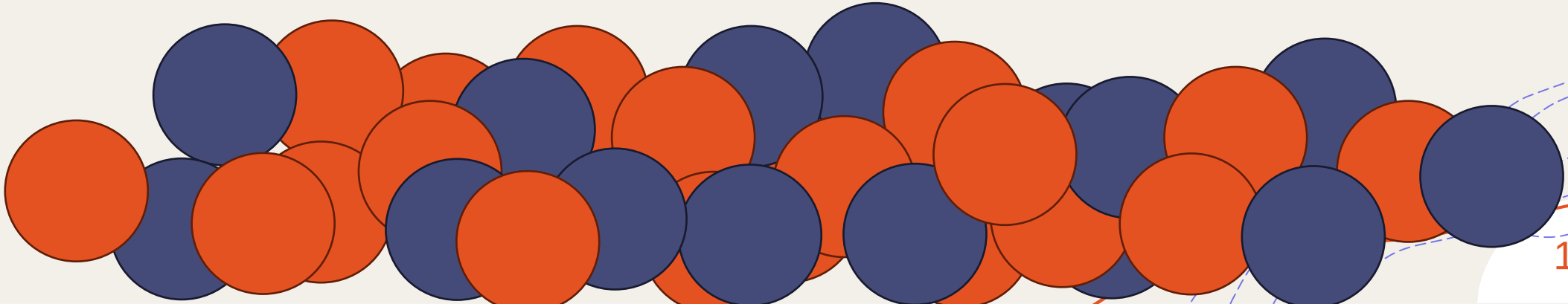
FAR 2

p_{astr} 2

Pipeline 3

FAR 3

p_{astr} 3



Calculating Combined Significance

Method 1. Combine FARs by applying the trials factor

- Calculate combined FAR for each candidate as

$$FAR_{trials} = \min(FAR_1, FAR_2, \ldots, FAR_N) \times N$$

- Calculate combined p_{astro} using the combined FAR distribution

Calculating Combined Significance

Method 2. Combine FARs by calculating a harmonic mean

- Calculate combined FAR for each candidate as

$$\frac{1}{FAR_{har}} = \frac{1}{N}\left(\frac{1}{FAR_1} + \frac{1}{FAR_2} + \ldots + \frac{1}{FAR_N}\right)$$

- Calculate combined p_{astro} using the combined FAR distribution

Calculating Combined Significance

Method 2. Combine FARs by calculating a harmonic mean

- Calculate combined FAR for each candidate as

$$\frac{1}{FAR_{har}} = \frac{1}{N}\left(\frac{1}{FAR_1} + \frac{1}{FAR_2} + \ldots + \frac{1}{FAR_N}\right)$$

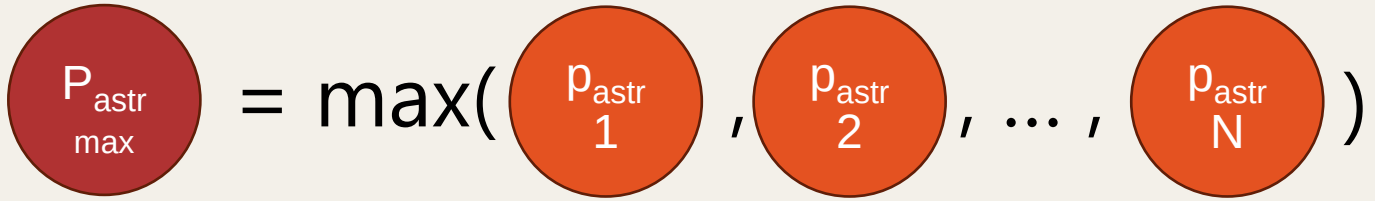
Best Choice for Dependent Tests[4]

- Calculate combined p_{astro} using the combined FAR distribution

4: WILSON, 2018

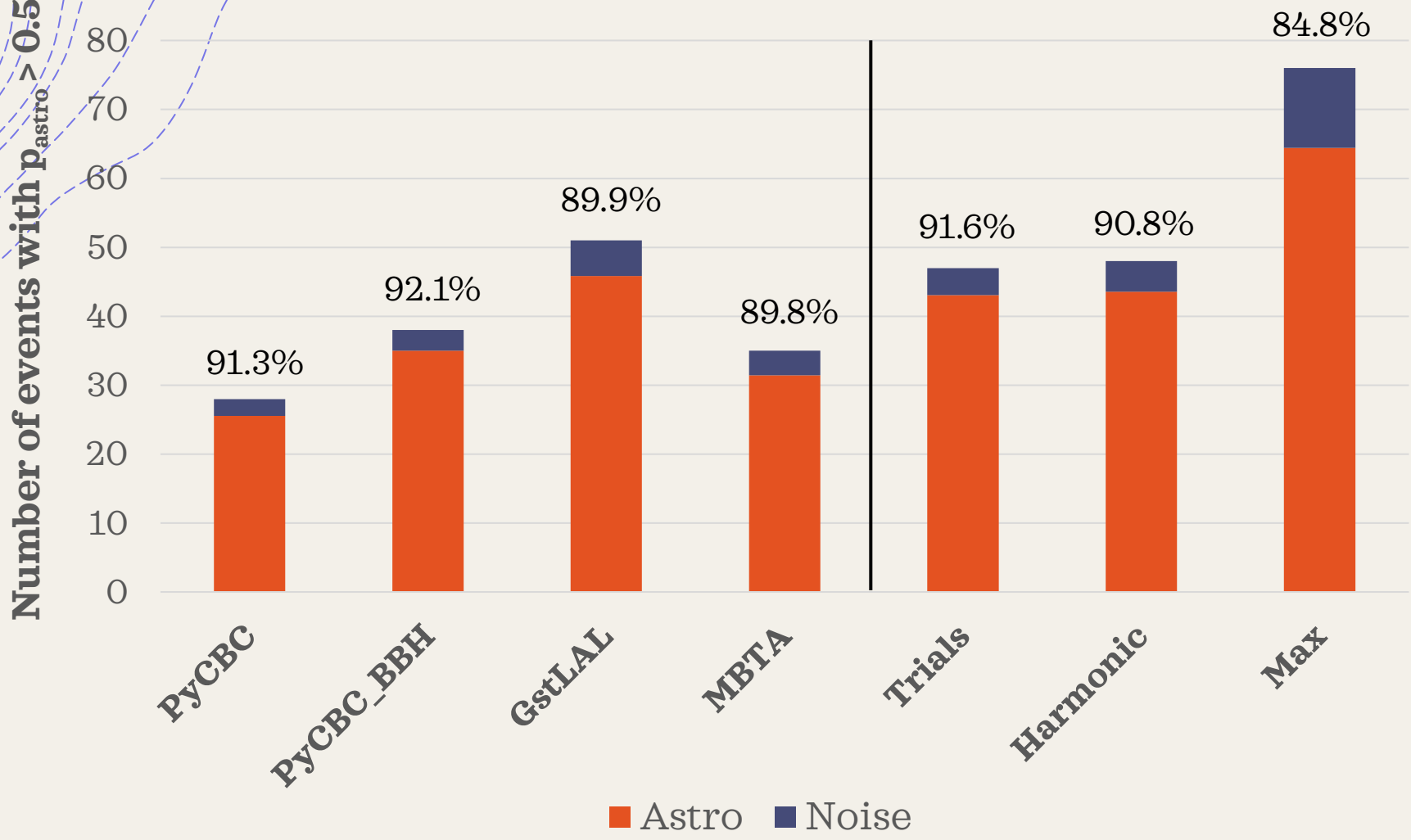
Calculating Combined Significance

Method 3. Find maximum p_{astro}



Results

P_{astro} Results with O3a Data

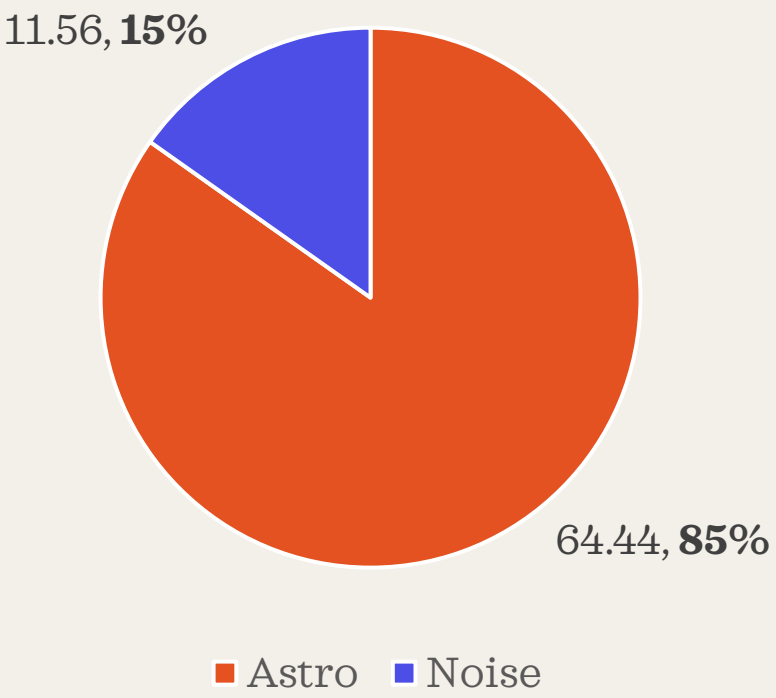


- **Number** = Astro + Noise
- **Astro** = the sum of all p_{astro} values
- **Noise** = Total – Astro
- Purity = Astro/Total (%)

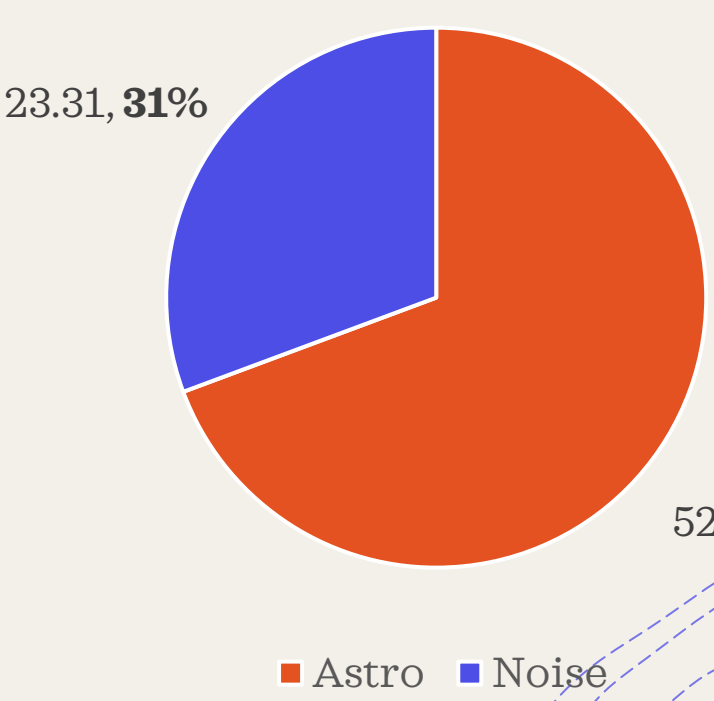
Purity Is Likely Overestimated

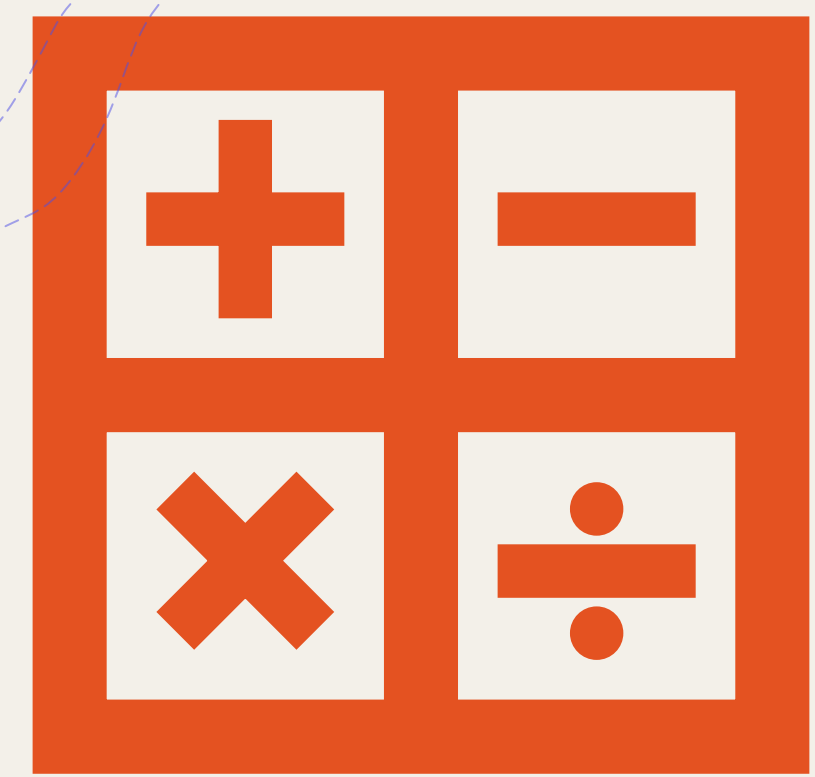
76 events for which max $p_{astro} > 0.5$

Sum of Max p-values



Sum of Harmonic p-values





How did we calculate p_{astro}?

P_{astro} Calculation

$p(\Lambda_s, \Lambda_n | \{x\})$

P_{astro} Calculation

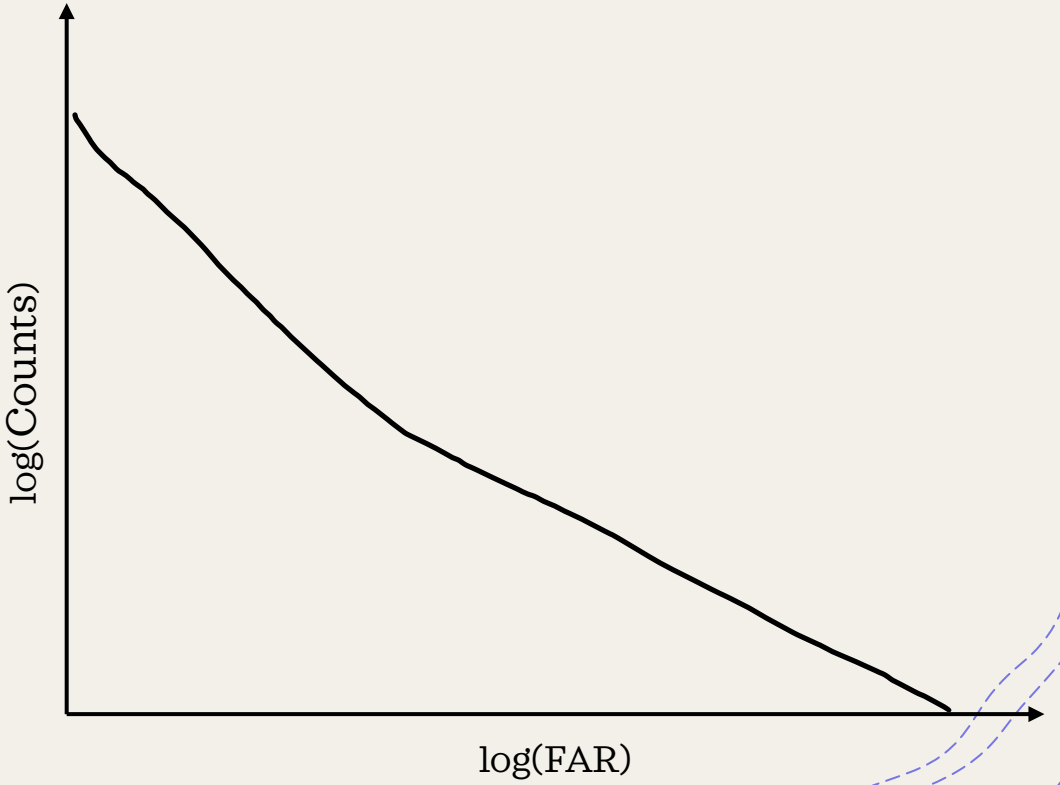
signal counts

noise counts

$$p(\Lambda_s, \Lambda_n|\{x\}) = \prod_{i=1}^{N} [\Lambda_s f(x_i) + \Lambda_n b(x_i)] e^{-(\Lambda_s+\Lambda_n)} \quad [5]$$

foreground model

background model



5: FARR, GAIR, MANDEL, AND CUTLER, 2015

P_{astro} Calculation

signal counts

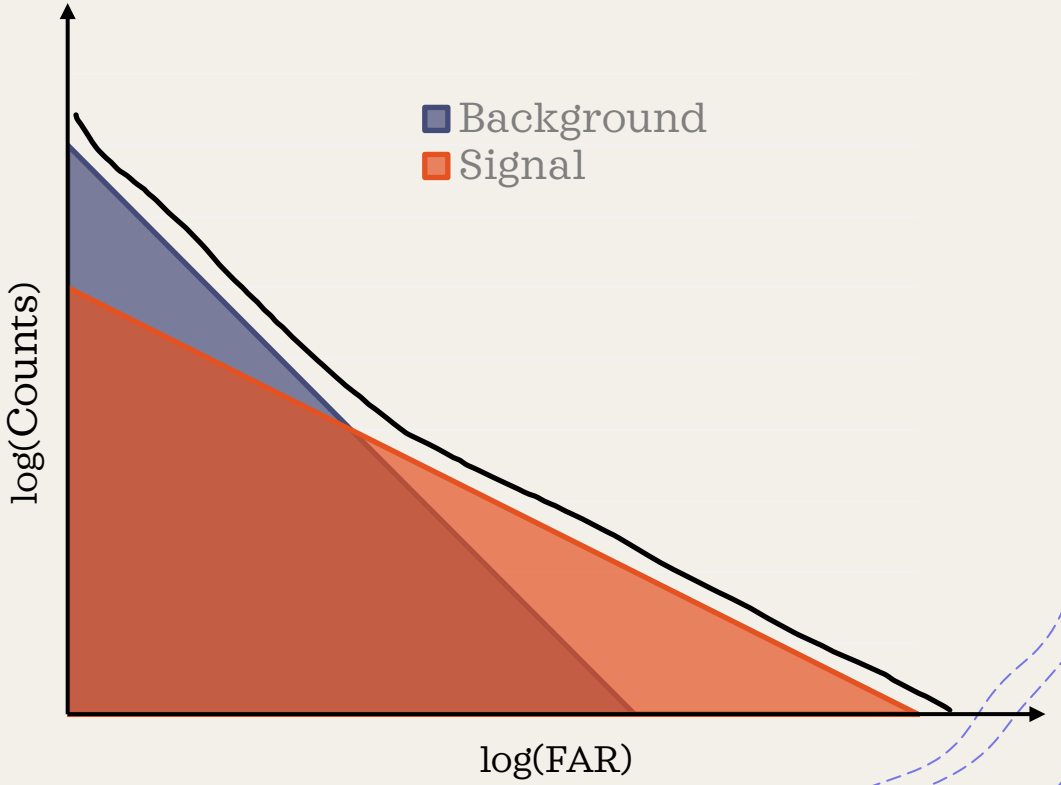
noise counts

$$p(\Lambda_s, \Lambda_n|\{x\}) = \prod_{i=1}^{N} [\Lambda_s f(x_i) + \Lambda_n b(x_i)] e^{-(\Lambda_s+\Lambda_n)} \quad [5]$$

foreground model

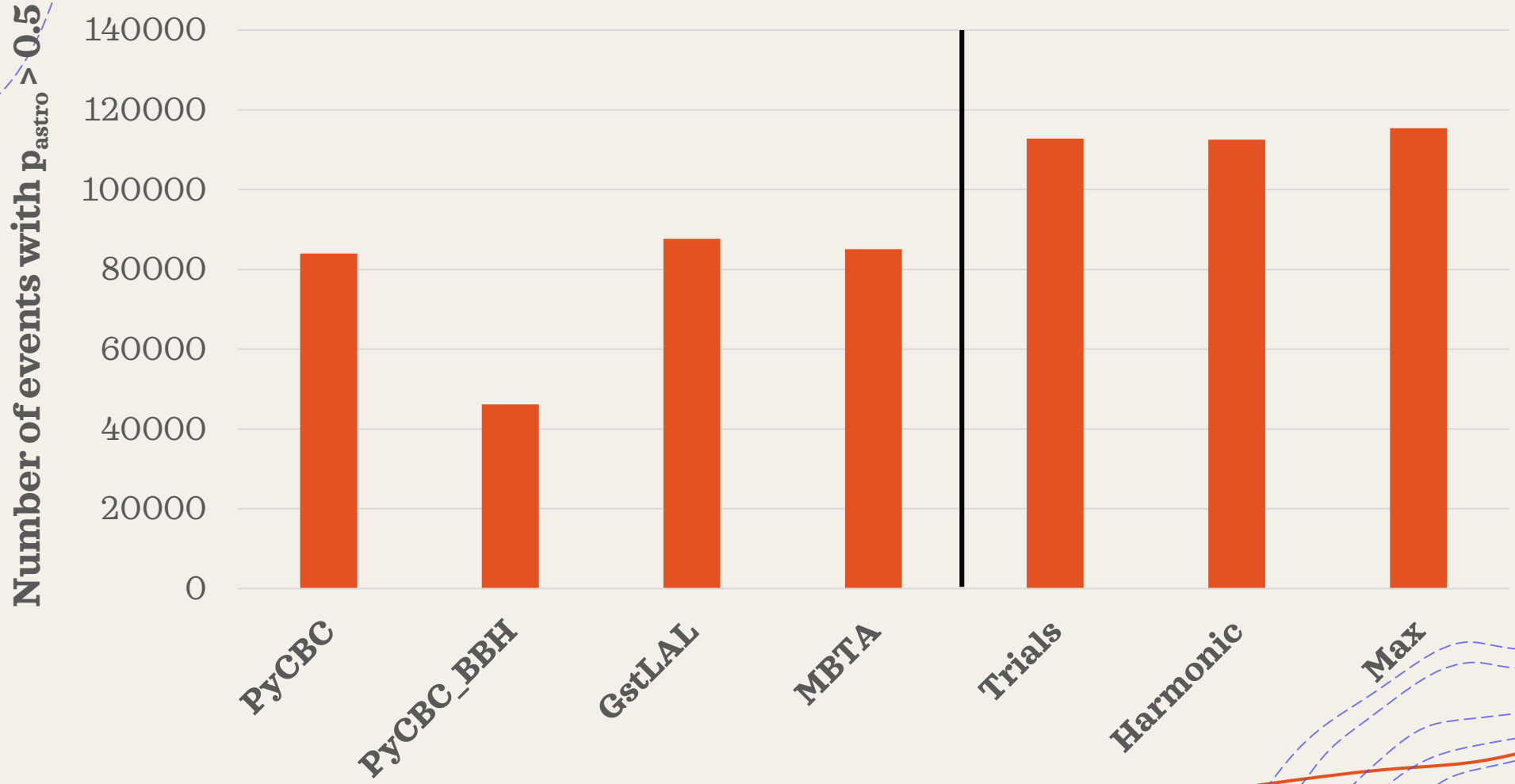
background model

$$p_{astro}(FAR) = \frac{\Lambda_s f(FAR)}{\Lambda_s f(FAR) + \Lambda_s f(FAR)}$$



5: FARR, GAIR, MANDEL, AND CUTLER, 2015

p_{astro} Results With Injections



Which pipelines contribute to the combination the most?

Optimal FAR Combinations for Different Number of Pipelines: Injections

Number of events with FAR < 1 yr^{-1}

1 pipeline

Pipeline	Events Detected
PyCBC	74619
PyCBC_BBH	38673
GstLAL	77289
MBTA	71454
CWB	18260

2 pipelines

PyCBC_BBH	85661			
GstLAL	86787	85920		
MBTA	79768	83633	86004	
CWB	76715	86004	78127	71763
	PyCBC	**PyCBC_BBH**	**GstLAL**	**MBTA**

$$\frac{1}{FAR_{gp}} = \frac{1}{2}\left(\frac{1}{FAR_g} + \frac{1}{FAR_p}\right)$$

Optimal FAR Combinations: Injections

Number of events with FAR < 1 yr^{-1}

g = GstLAL

p = PyCBC

b = PyCBC_BBH

m = MBTA

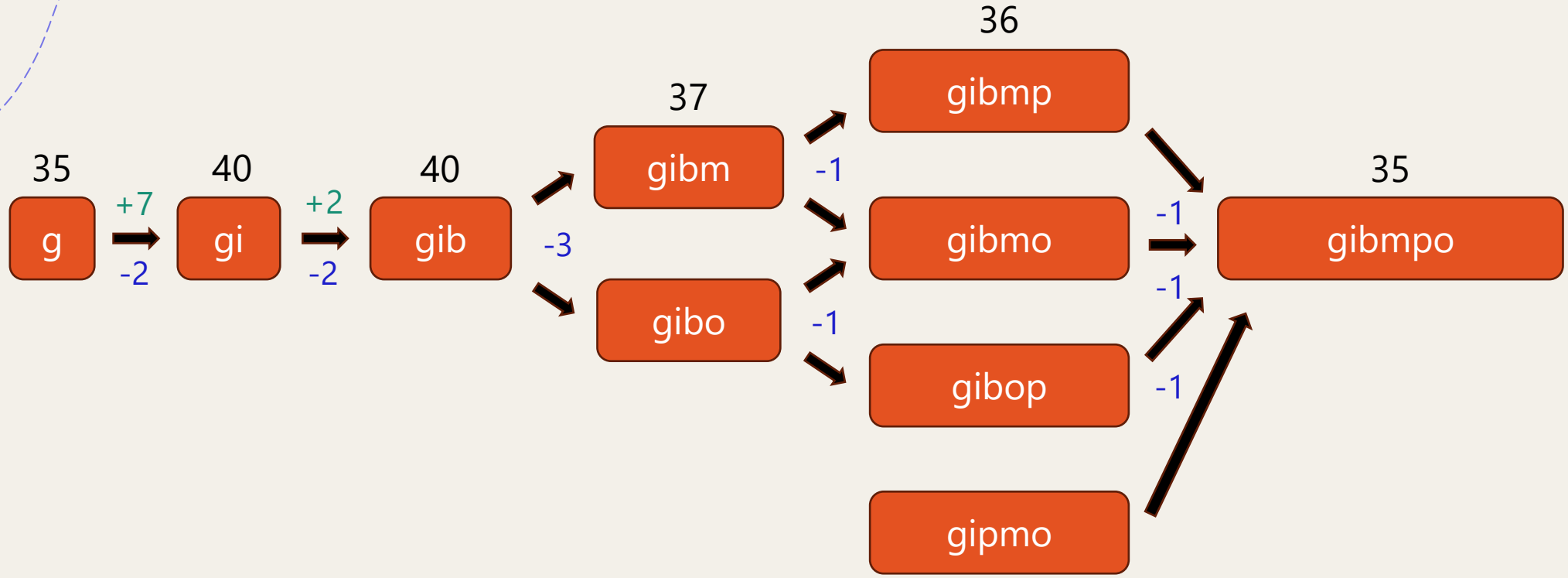
c = cWB

$$\frac{1}{FAR_{gpb}} = \frac{1}{3}\left(\frac{1}{FAR_g} + \frac{1}{FAR_p} + \frac{1}{FAR_b}\right)$$

…

$$\frac{1}{FAR_{gpbmc}} = \frac{1}{3}\left(\frac{1}{FAR_g} + \frac{1}{FAR_p} + \frac{1}{FAR_b} + \frac{1}{FAR_m} + \frac{1}{FAR_c}\right)$$

Optimal Pipeline Combinations: O3a



g = GstLAL, **p** = PyCBC, **b** = PyCBC_BBH, **m** = MBTA, **i** = IAS, **o** = OGC

Conclusions

- Combining results from multiple search pipelines increases the number of detected events in the injection sets.
- Applying the trials factor or calculating the harmonic mean FAR leads to higher purity of p_{astro} results as compared to using the maximum p_{astro} for real data.
- Purity of GWTC catalogs is likely overestimated.

Acknowledgements

+ My mentor Derek Davis
+ LIGO Lab
+ Caltech Student-Faculty Programs
+ National Science Foundation
+ SURF 2023 Students

Caltech

Thank you!