Leveraging High-Throughput Computing to Search for Continuous Gravitational Waves

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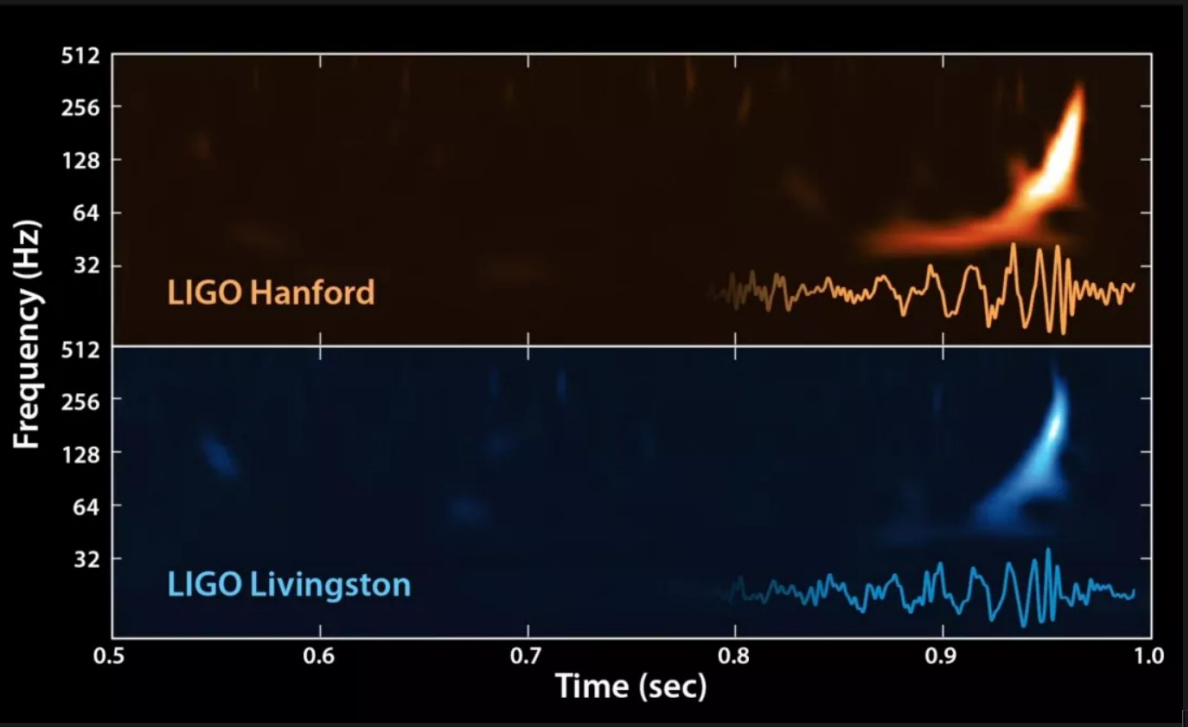
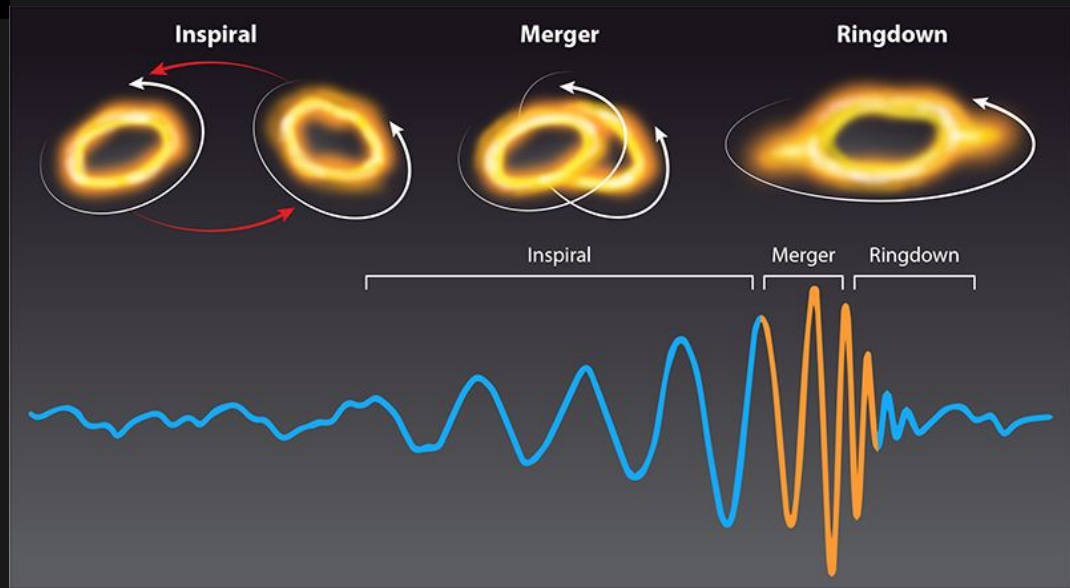
Gravitational Waves Detection



[Credit: https://www.space.com/31894-gravitational-waves-ligo-search-complete-coverage.html]



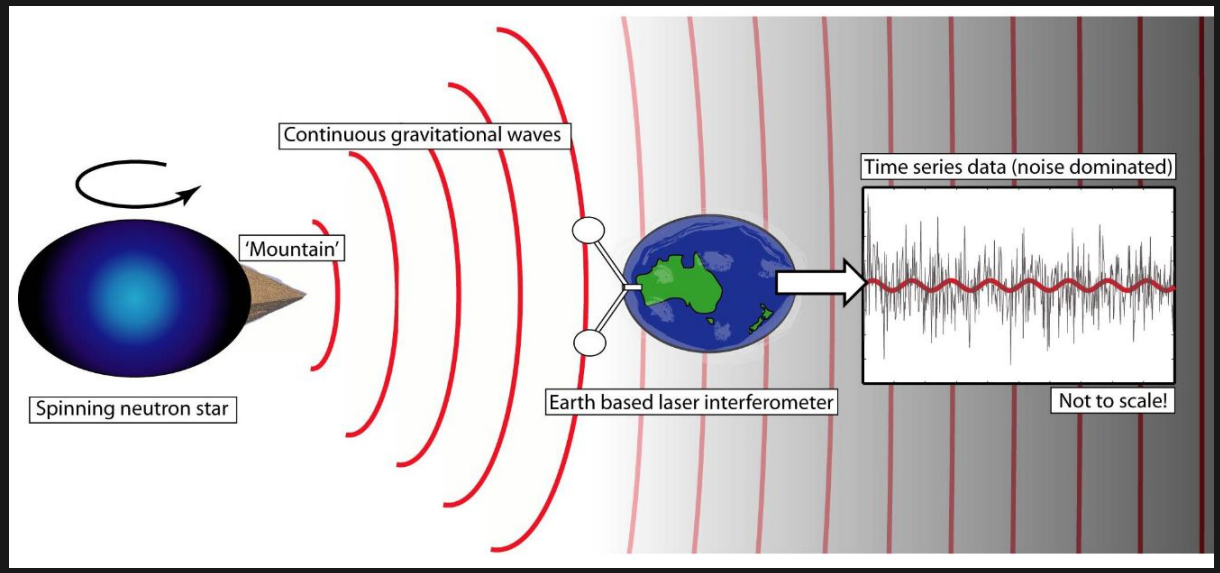
LIGO Detectors

[Hanford]

[Credit: https://ligo.org/]

[Livingston]

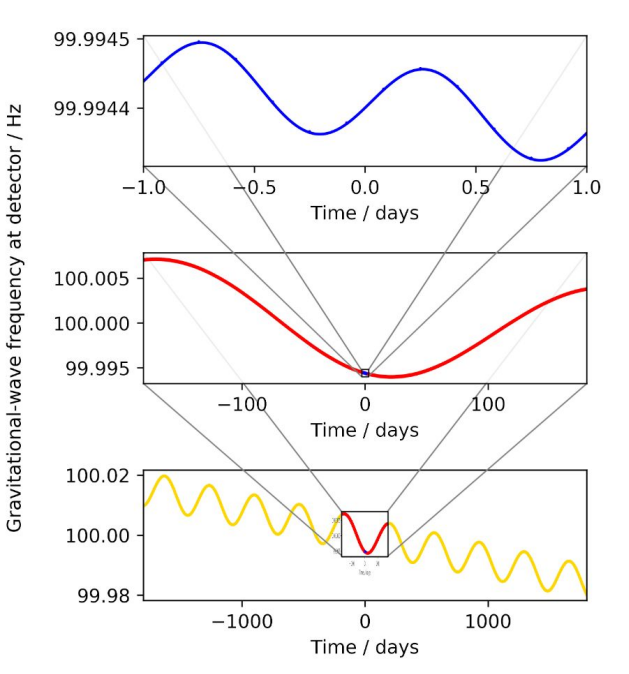
Continuous Gravitational Waves



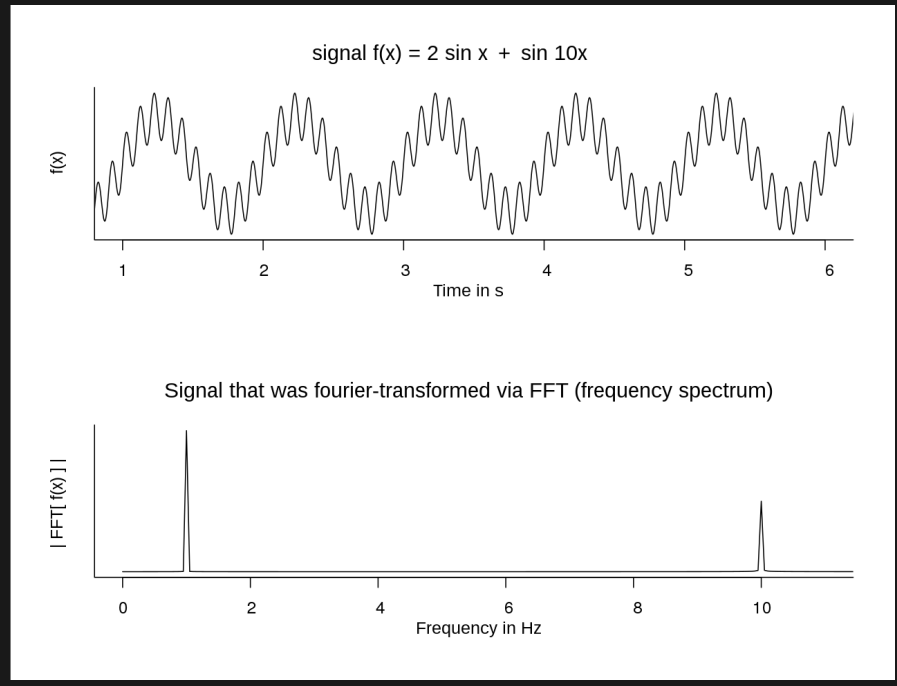
[Credit: Graham Woan, https://indico.cern.ch/event/469963/contributions/2267231/attachments/1335682/2008962/Woan_CWoverview.pdf]

- Produced by non-axisymmetric neutron stars (“neutron stars with a bump”)
- Persistent unlike from black hole / neutron stars mergers
- Looking for length change > a million times smaller than the nucleus of an atom
- Integrate data over months to years to average out the noise
- Simple sinusoid with slowly changing frequency

Continuous Gravitational Waves



[Credit: Karl Wette, arXiv:2305.07106 [gr-qc]]

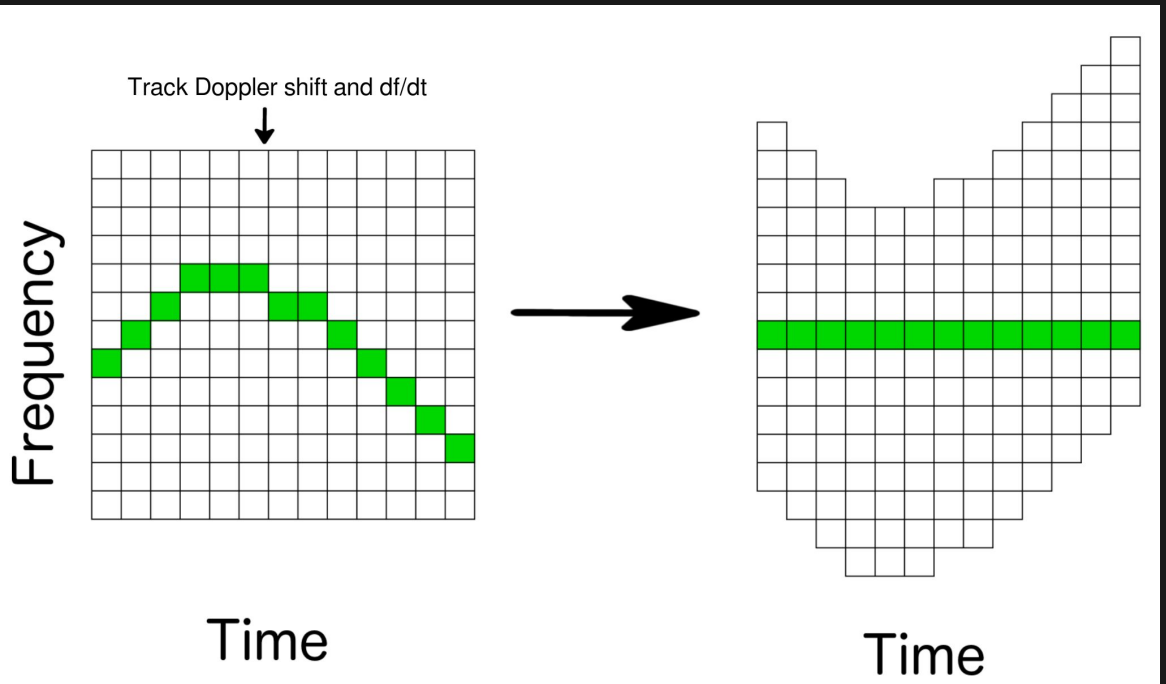


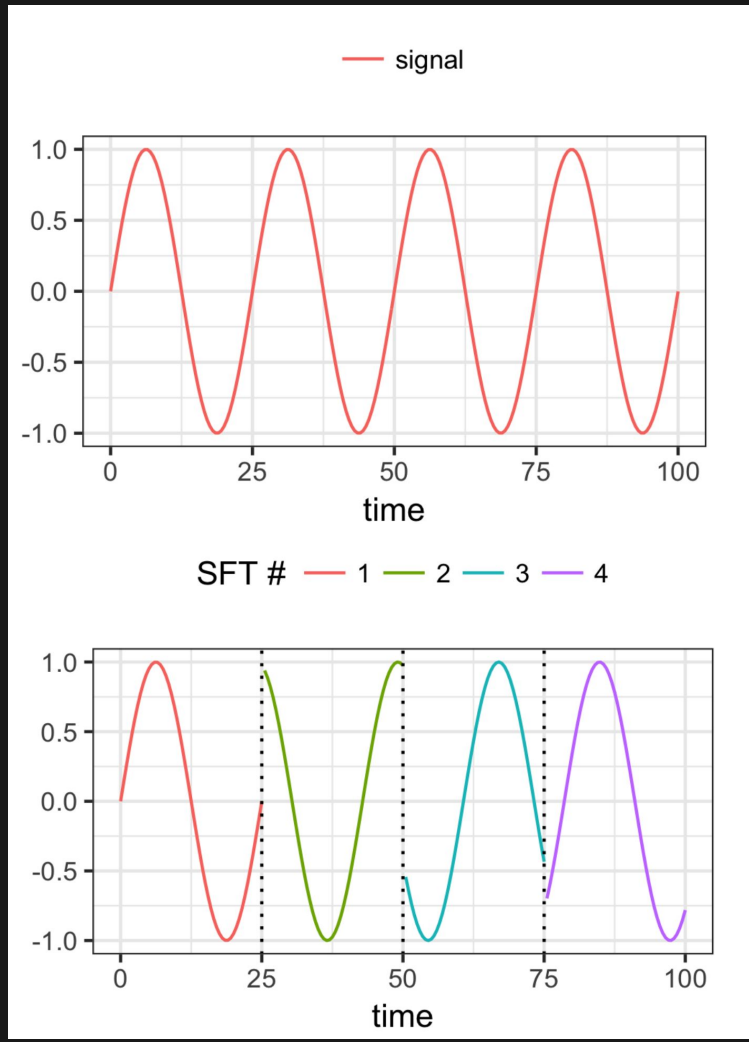
[Credit: https://commons.wikimedia.org/wiki/File:Simple_time_domain_vs_frequency_domain.svg]

- Calculate power for each search template (frequency, sky location, etc)
- Enforce signal coincidence between the two detectors at Hanford and Livingston
- Follow up large power outliers with further stages that enforce tighter data constraints

Detection Algorithm

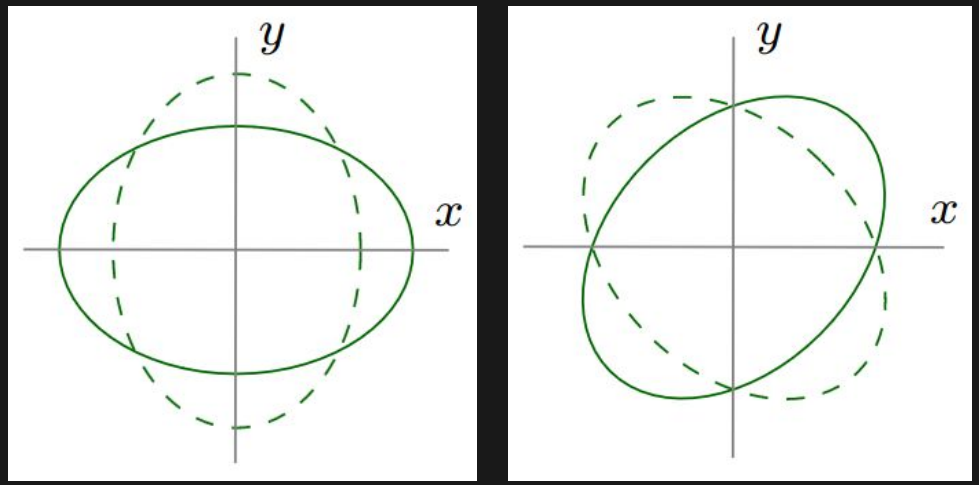
- Divide year long data into 2 hour segments called Short Fourier Transforms (SFTs)
- Slide power bins and add power together





Why Care?

- Would give us direct information about the equation of state of nuclear matter
- Only direct probe to the inside of neutron stars
- Would reveal information about the population of neutron stars
- Continuous gravitational waves' polarization would allow tests of departure from Einstein's general theory of relativity and alternate theories of gravity



[Credit: Isi et al., arXiv:1710.03794 [gr-qc]]

Parameter Space

Frequency	30 - 150 Hz
Rate of frequency change	$[-1 \times 10^{-8}, 1 \times 10^{-9}]$ Hz / s
Sky position (right ascension x declination)	All Sky
Polarization	24 x 8

- ~8×10^{16} (80 quadrillion) templates!
- ~ Number of stars in 800K galaxies

Solution:

High-Throughput Computing

- 150 K Stage 0 jobs
- 500 billion templates / job

Additional Solution:

Caching of similar calculations

OSG School

- Joined OSG User School 2020
- Learning about checkpointing and stash particularly helpful
- OSG Mentorship proved to be invaluable!
- OSG School + computational resources made the project possible- publication coming soon!

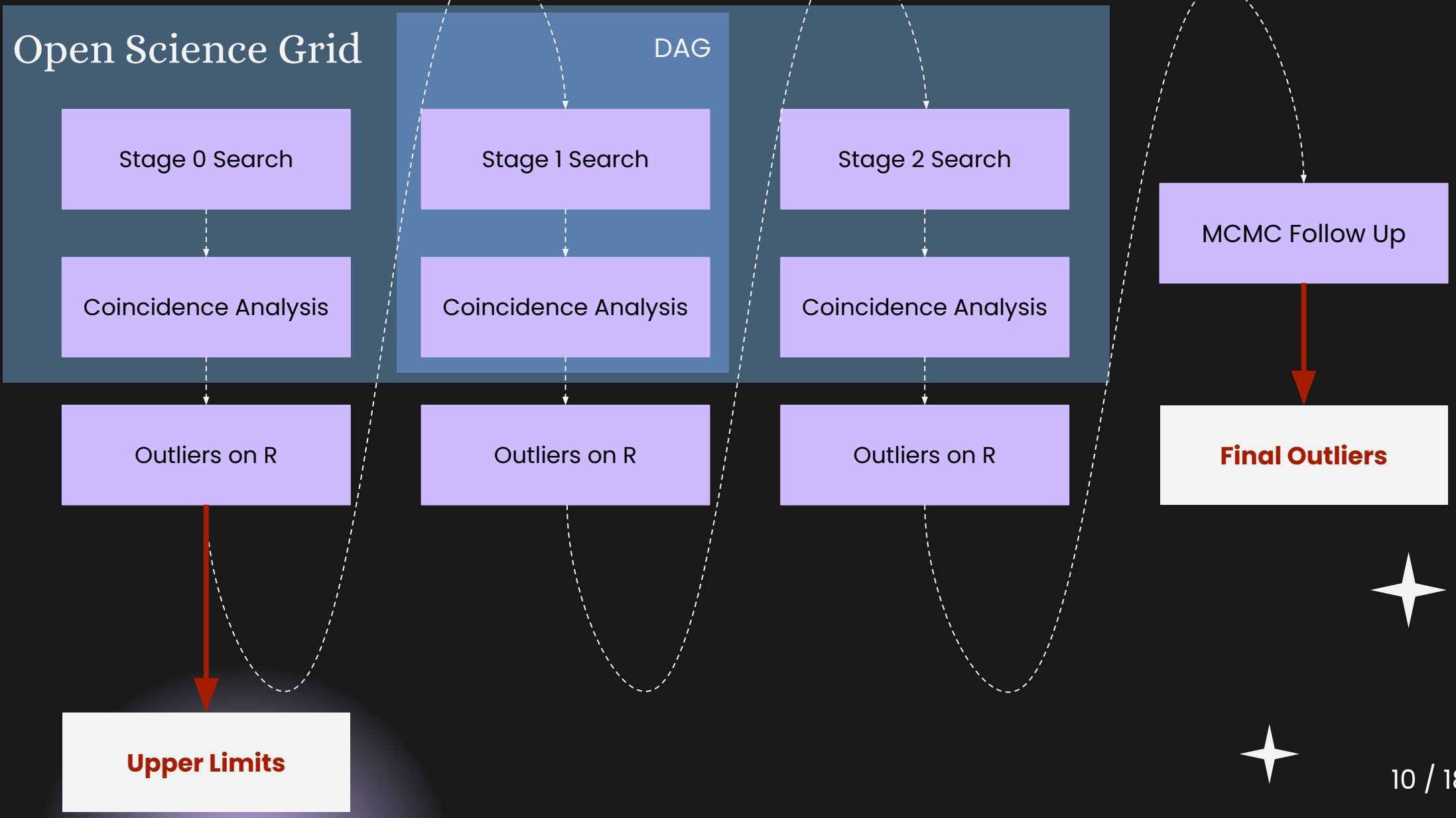
Input Size of 7+ GB:

- Attempt 1: Reading through /cvmfs ❌
- Attempt 2: Reading from /public through stash ✅

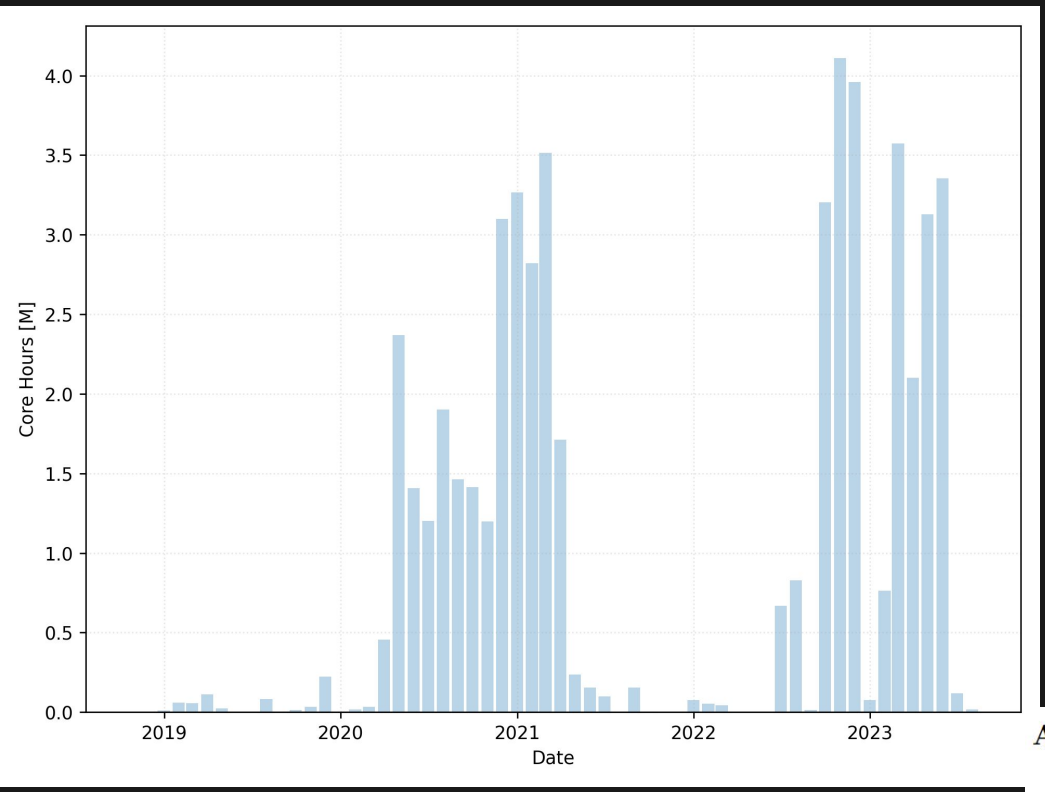
Runtime of 10+ hours:

- Fix: Checkpointing

Workflow


Open Science Grid
DAG
Stage 0 Search
Stage 1 Search
Stage 2 Search
Coincidence Analysis
Coincidence Analysis
Coincidence Analysis
Outliers on R
Outliers on R
Outliers on R
MCMC Follow Up
Final Outliers
Upper Limits

LIGO Computing



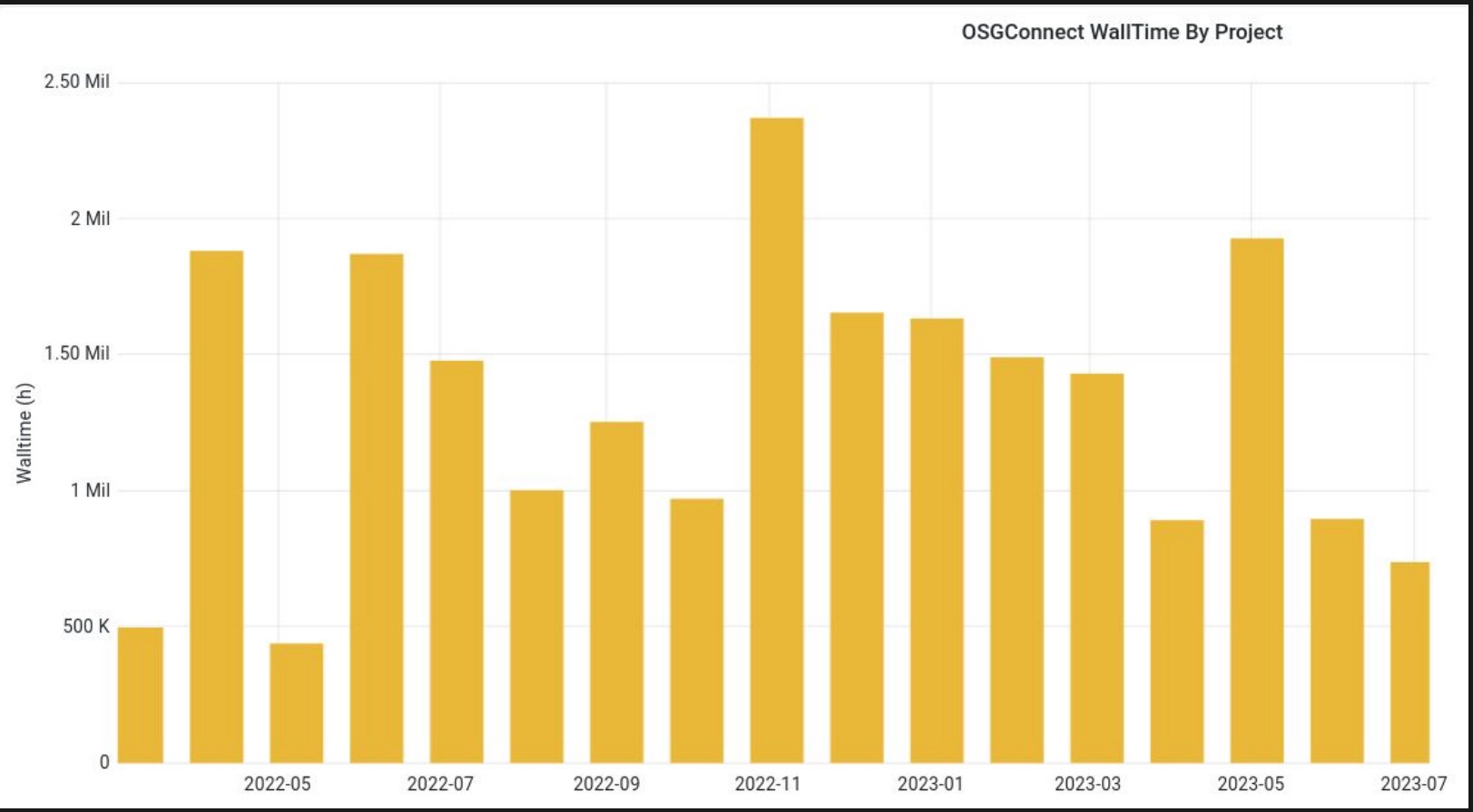
- 53 M core hours
- 0.95 M hours / month
- 32 K hours / day

All-sky Search for Continuous Gravitational Waves from Isolated Neutron Stars in the Early O3 LIGO Data

LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration
(compiled October 12, 2021)

We report on an all-sky search for continuous gravitational waves in the frequency band 20-2000 Hz and with a frequency time derivative in the range of $[-1.0, +0.1] \times 10^{-8}$ Hz/s. Such a signal could be produced by a nearby, spinning and slightly non-axisymmetric isolated neutron star in our galaxy. This search uses the LIGO data from the first six months of Advanced LIGO's and Advanced Virgo's third observational run, O3. No periodic gravitational wave signals are observed, and 95% confidence-level (CL) frequentist upper limits are placed on their strengths. The lowest upper limits on worst-case (linearly polarized) strain amplitude h_0 are $\sim 1.7 \times 10^{-25}$ near 200 Hz. For a circularly polarized source (most favorable orientation), the lowest upper limits are $\sim 6.3 \times 10^{-26}$. These strict frequentist upper limits refer to all sky locations and the entire range of frequency derivative values. For a population-averaged ensemble of sky locations and stellar orientations, the lowest 95% CL upper limits on the strain amplitude are $\sim 1.4 \times 10^{-25}$. These upper limits improve upon our previously published all-sky results, with the greatest improvement (factor of $\sim$2) seen at higher frequencies, in part because quantum squeezing has dramatically improved the detector noise level relative to the second observational run, O2. These limits are the most constraining to date over most of the parameter space searched.

OSG Computing



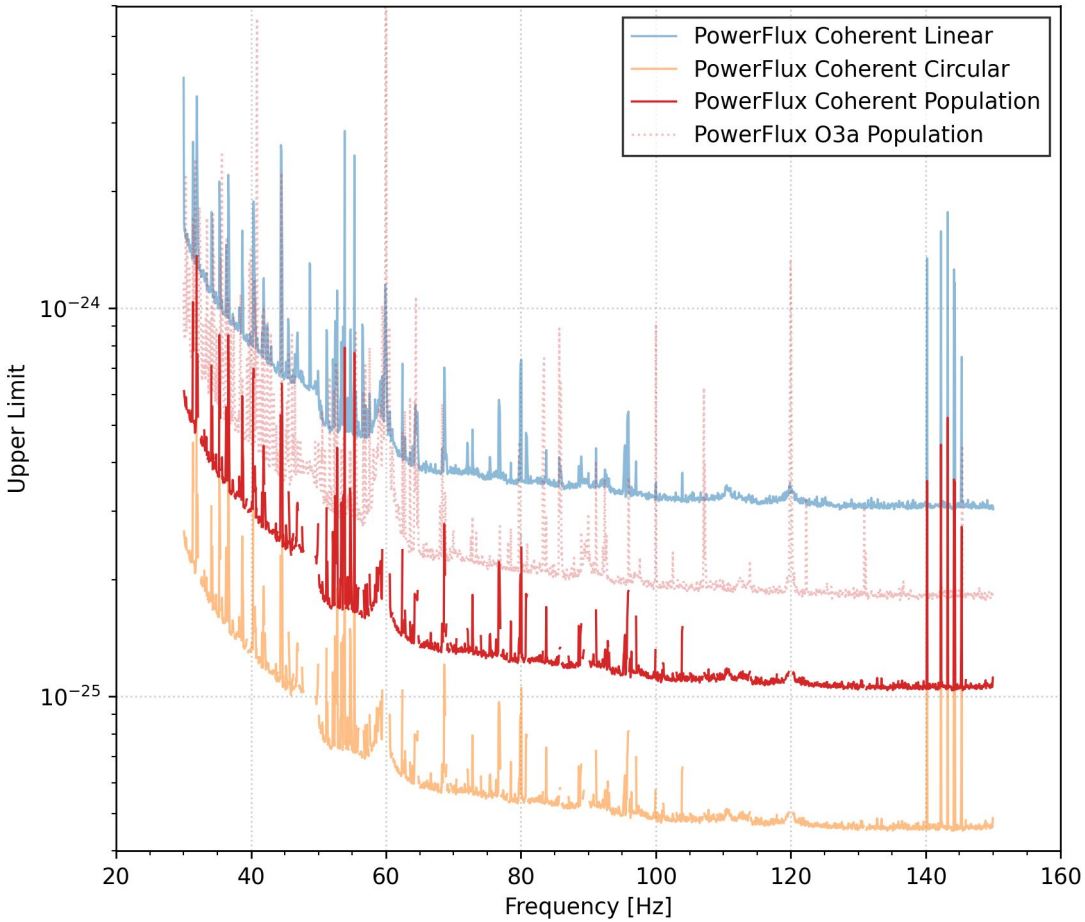
- 22.4 M core hours
- 1.4 M hours / month
- 47 K hours / day

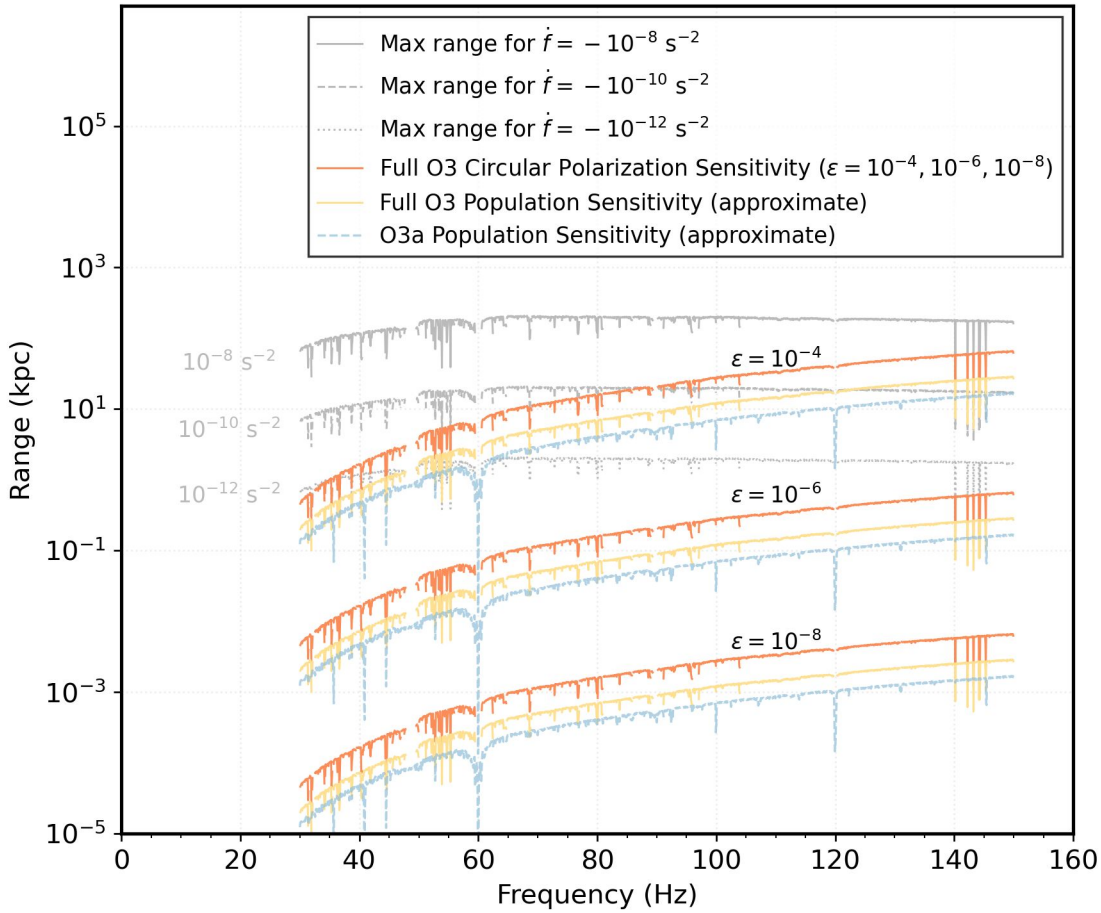
Current Challenge

- Slow transfer speed for large file transfers through stash

```
-- Schedd: login04.osgconnect.net : <192.170.231.217:9618?... @ 07/09/23 20:20:08
 ID          OWNER          HELD_SINCE  HOLD_REASON
36346541.0   aashish_tripat  7/5  11:49 Transfer input files failure at execution point slot1_1@glidein_1341992_70015588@node081.lawrence using protocol stash. Details: Error from slot1_1@glidein_1341992_
70015588@node081.lawrence: FILETRANSFER:1:non-zero exit (1) from /scratch/job_50664/glide_lCglFw/client/stash_plugin. |Error: Failed to download from http://osg-kansas-city-stashcache.nrp.internet2.edu:80
00/osgconnect/public/aashish_tripathee/full-o3/cleaned_30Hz_150Hz/H1/H1_split_aa_568800.splitsft + proxy=true: cancelled transfer, too slow.  Detected speed: 46.3 kB/s, total transferred: 6.6 MB, total tr
ansfer time: 2m30.000987547s;Failed to download from http://osg-kansas-city-stashcache.nrp.internet2.edu:8000/osgconnect/public/aashish_tripathee/full-o3/cleaned_30Hz_150Hz/H1/H1_split_aa_568800.splitsft
```

Results (Preliminary)





Other Tidbits

Projects / HTCondor / HTCONDOR-923

Parent directories not properly created in some cases.

Description

The following submit file's job goes on hold when it's scheduled the second time because the parent directory of a file in the checkpoint hasn't been created, assuming that `subdir` doesn't exist in the input sandbox.

```
1  universe                = vanilla
2  executable              = aashish.sh
3
4  input                   = /dev/null
5  output                  = aashish/out
6  error                   = aashish/error
```

Jobs led to the discovery of HTCondor bugs!

Projects / HTCondor / HTCONDOR-809

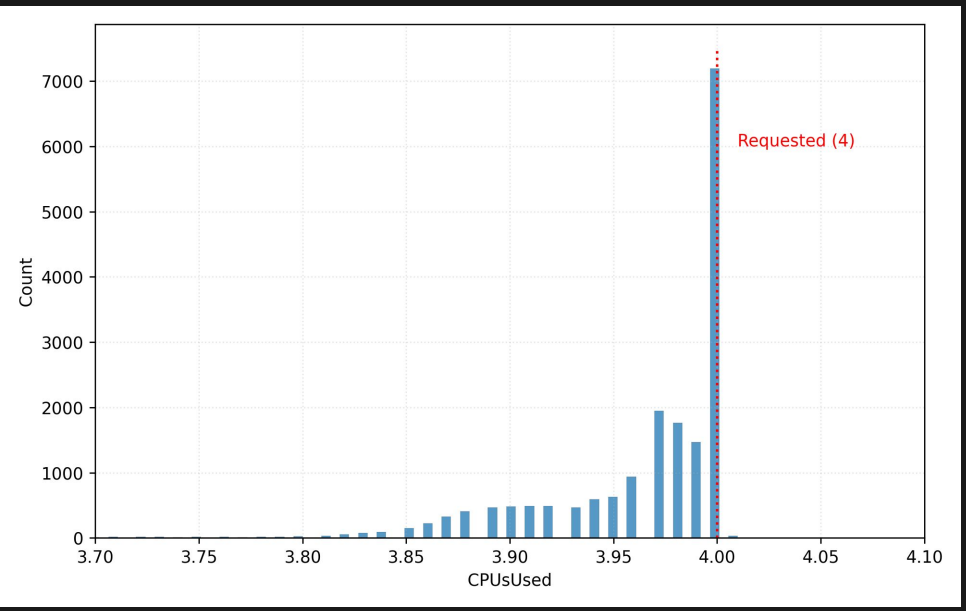
Self-checkpointing goes on hold after being rescheduled.

Description

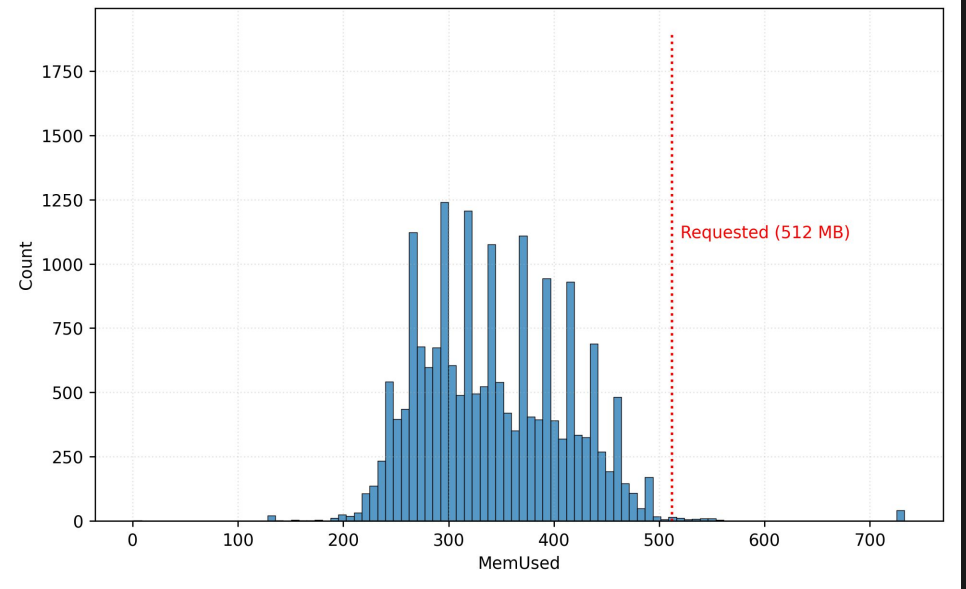
The following submit file will run normally in one go, but if evicted after a checkpoint, will fail to resume.

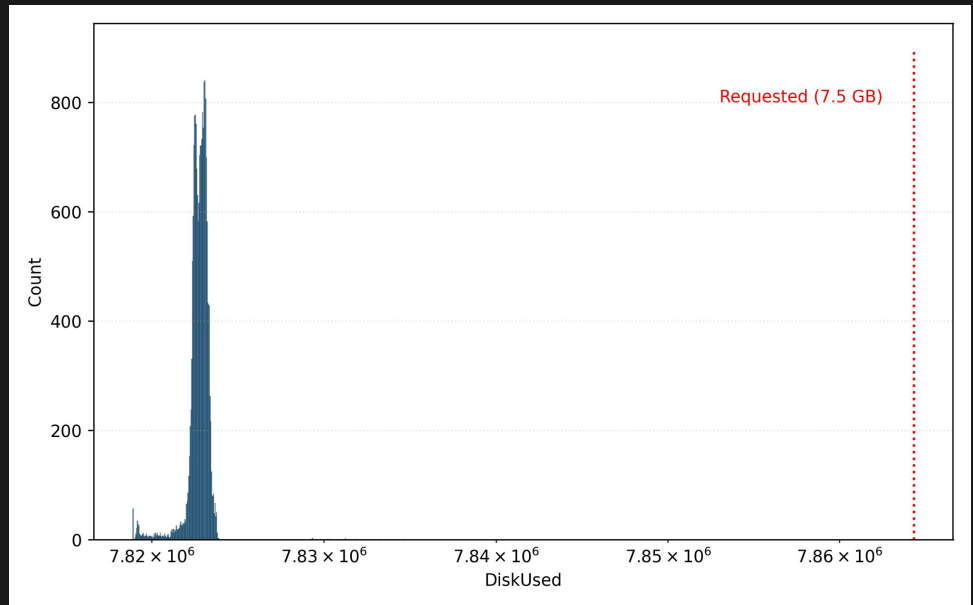
```
1  universe                = vanilla
2  executable              = aashish.sh
3
4  input                   = /dev/null
5  output                  = aashish/out
6  error                   = aashish/error
7
```

logs2csv

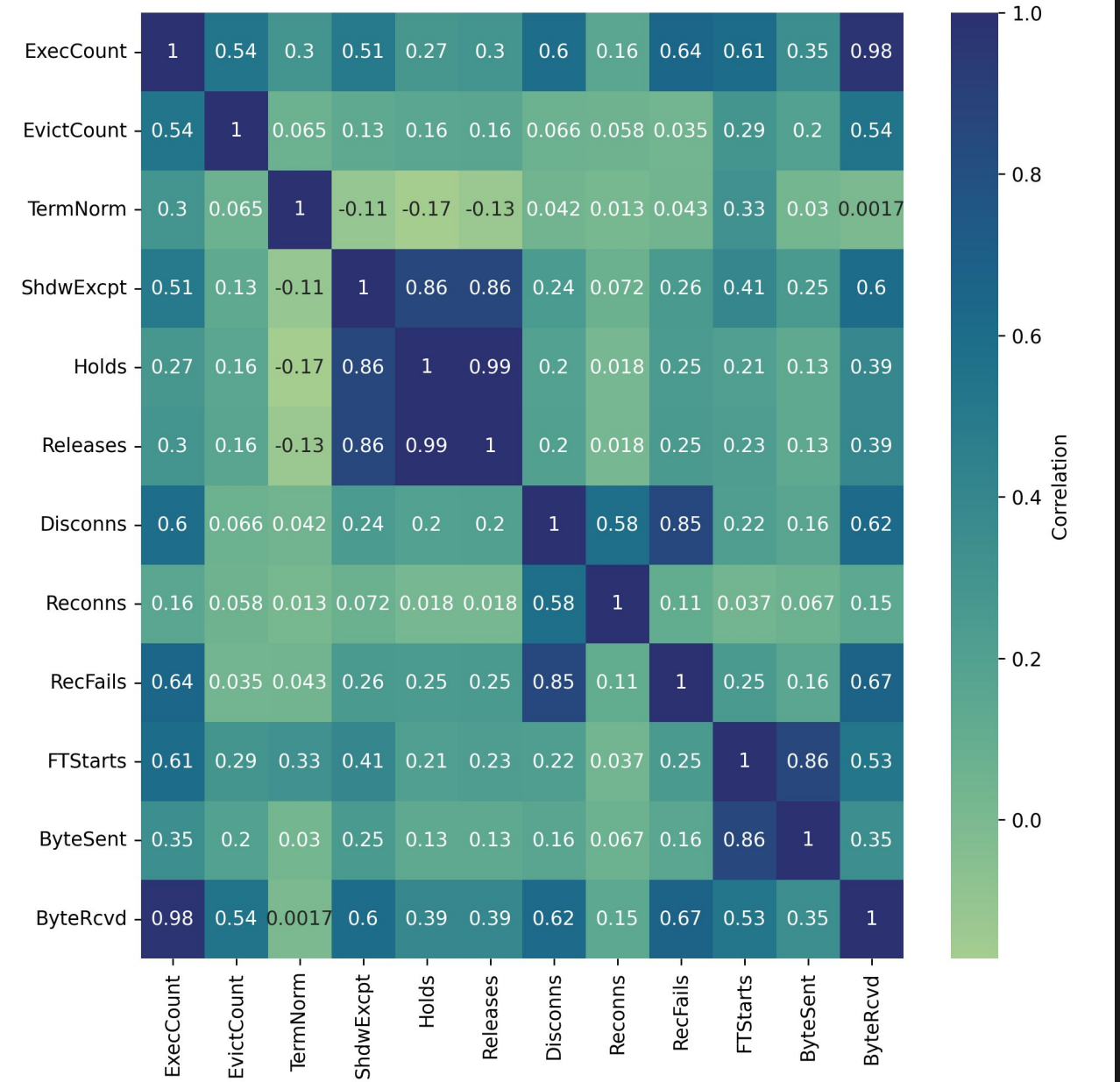


Helped pilot Tim Cartwright's logs2csv





logs2csv



Some interesting (but expected) correlations:

- ExecCount - (EvictCount, RecFails, ByteRcvd, Disconns)
- EvictCount - (ByteSent, ByteRcvd)
- ShdwExcpt - (Holds, Releases, TermNorm)
- Holds - (Releases, TermNorm)
- Disconns - (Reconns, RecFails, ByteRcvd)
- RecFails - ByteRcvd
- FTStarts- (ByteSent, ByteRcvd)

Acknowledgement

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- Christina Koch
- Todd Miller

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