Searching for Intermediate-Duration Gravitational-Wave Transients

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Outline

- Definition and motivation
- Potential sources
- The intermediate pipeline
- Algorithms
- Detecting supernovae with GW+ν
- Conclusions

Typical GW Searches

- Most GW searches fall into one of the following categories:
  - **pulsars (CW)**: persistent, narrow-band, highly constrained
  - **bursts**: fleeting (typically <1 s), broadband, unconstrained (e.g., short GRBs chirps)
  - **inspirals (CBC)**: transient (typically <10 s), highly constrained (see Samaya Nissanke's talk)
  - **stochastic**: persistent, broad-band, unconstrained

Expanding the Playing Field

- Some sources do not fall neatly into these categories:
  - **microquasar flares**: <1000 s (optical), broadband, unconstrained [7]
  - **long GRBs**: ~10 s, narrowband, somewhat constrained [6]
  - **pulsar glitches**: last up to weeks, narrowband $d\Omega/\Omega \leq 10^{-4}$ (0.1 Hz speedup for a 1 kHz pulsar), constrained [8]
  - **nearby supernovae**: GW emission up to ~10 s, broadband, unconstrained [1]
  - **Other?**
- It is worthwhile to develop flexible search algorithms to look for less conventional transient (**seconds - weeks**) sources.

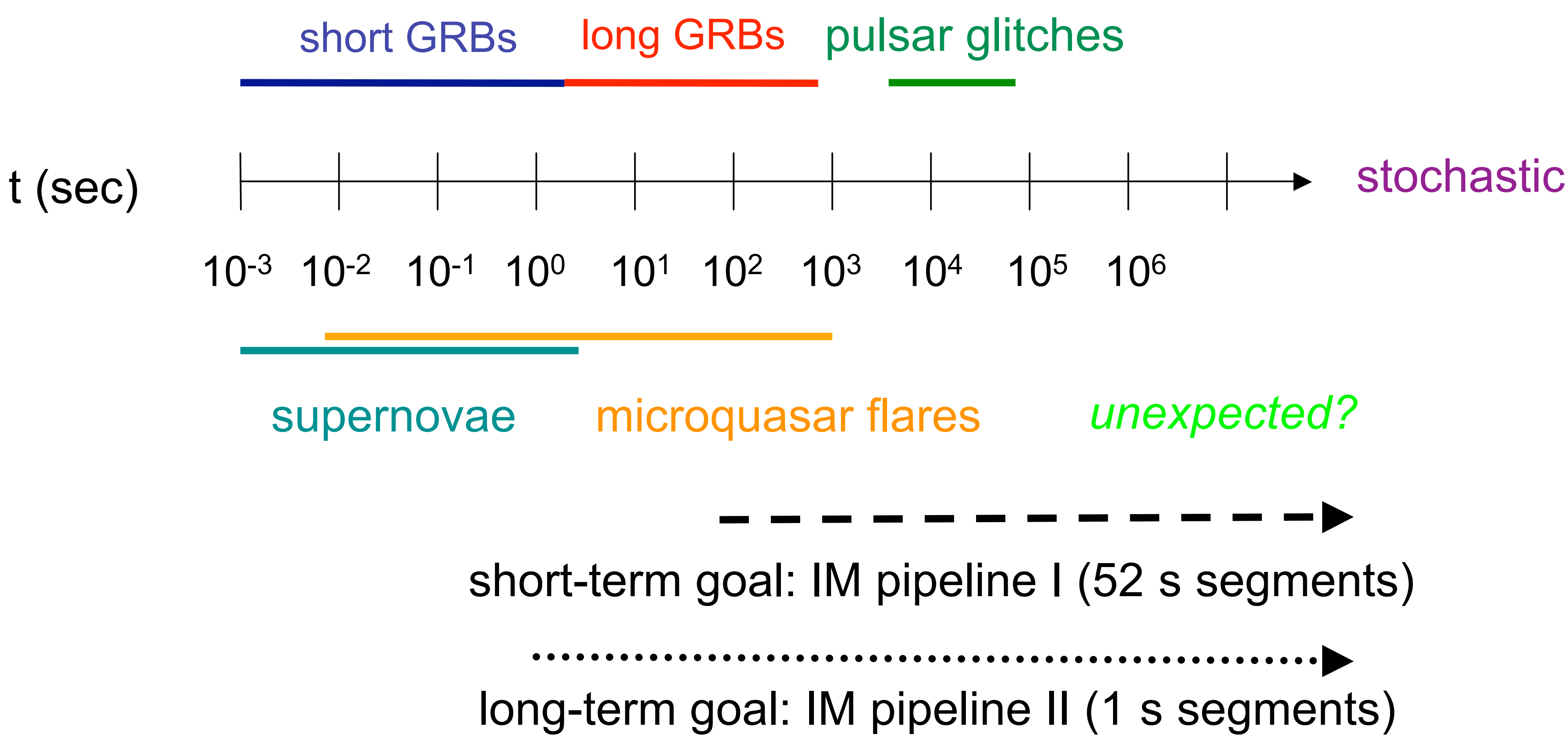
ν from GW Transients

- GW transients are also well-established candidates for neutrino emission.
  – **MQ flares**: e.g., SS433, GX339-4, Cygnus X-3, GRO J1655-40, XTE J1118+480 [5]
  – **long GRBs**: e.g., 080319B [2,3], 030329 [4]
  – **supernovae**: (albeit at lower energies) e.g.,. SN 1987A [9,10]
- In the future, LISA may probe low-f sources such as AGN [11]—also HEN emitters [16].
- GW+HEN collaboration can help detect these interesting sources.

The Intermediate Pipeline

- To this end, the LIGO stochastic group has developed 52 s intermediate (IM) data frames as part of a new “intermediate pipeline.”
- IM frames contain quantities used in stochastic analyses such as the cross spectral density between two detectors.
- We are also investigating using shorter segments (~1 s) and/or higher resolutions (currently 0.25 Hz).
- Work is just beginning on search algorithms.

IM Pipeline Transients



IM Pipeline: An Overview

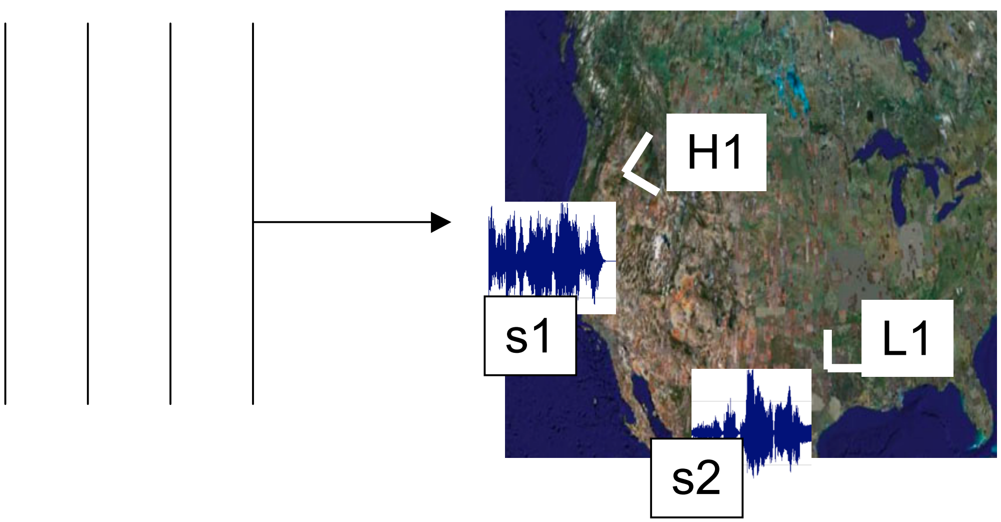
- There are numerous ways to combine data from multiple detectors to search for GWs.
  - E.g., matched filtering triggers at each detector, look for coincidences.
- The IM pipeline cross-correlates data from Hanford (H1) and Livingston (L1) + …
- Noise at H1 and L1 is uncorrelated, so cross correlation digs below the detector noise given enough time.
- Used in stochastic search.

Low-Latency and Flexible

- Unlike the stochastic search, however, we can see transient signals and even generate low-latency triggers (useful for GW+HEN studies).
- Aim for great flexibility in the IM search algorithms.
  - Waveforms are not highly constrained.

Gravitational-Wave Radiometry

- We define P(Ω) as the GW power emanating from $\Omega=\{\theta,\phi\}$.
- It can be estimated using the cross correlation C(f,t) of ≥2 spatially separated detectors.



$$C(f,t) = \frac{2}{\tau}\widehat{s}_1^*(f,t)\widehat{s}_2(f,t)$$

Detection Statistic

- At a given frequency f, the GW strain SNR is given by

$$SNR(f,t,\vec{\Omega}) = \frac{Y}{\sigma} = \mathrm{Re}\left[\frac{C(f,t)}{\sqrt{P_1(f,t)P_2(f,t)}}\,\mathrm{phase}\big(\gamma(f,t,\vec{\Omega})\big)\right]$$

- **C(f,t)** = cross correlation spectrum (signal)
- **P(f,t)** = power spectral density (noise)
- γ is the overlap reduction function (geometry)
  - See, e.g., [15].

Directionality

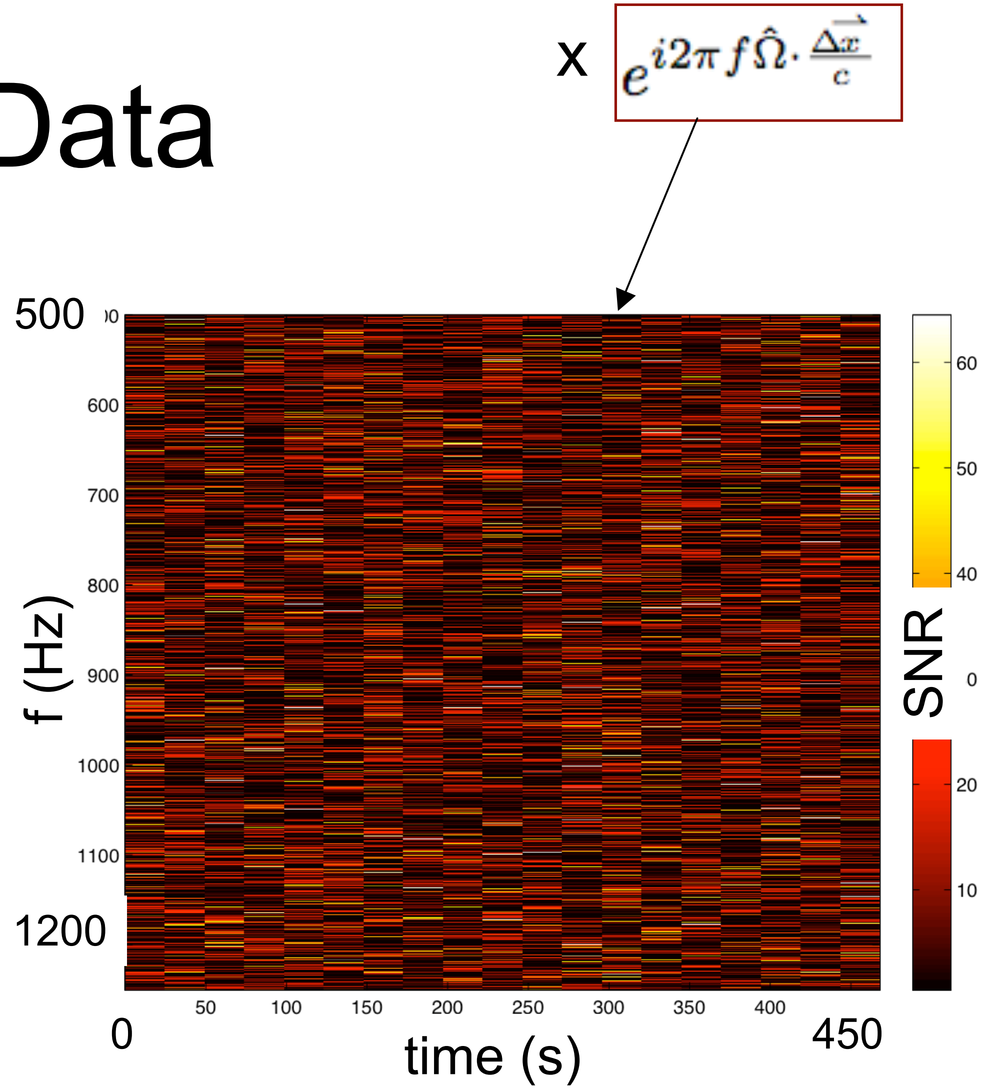
- The overlap reduction function (γ) encodes information about the time delay between two interferometers (**Ω•x**/c) as a complex phase.
  - Different time delays for different directions, **Ω**.
- Information about detector orientations, F, (encoded in the magnitude of γ) affects sensitivity but not SNR.

$$\gamma_{\hat{\Omega},t}(f) = \frac{1}{2}\sum_A \underline{e^{i2\pi f\hat{\Omega}\cdot\frac{\overrightarrow{\Delta x}}{c}}}\; \underline{F_1^A(\hat{\Omega})F_2^A(\hat{\Omega})}$$

$$F_i^A(\hat{\Omega}) = e_{ab}^A(\hat{\Omega})\frac{1}{2}(\hat{X}_i^a\hat{X}_i^b - \hat{Y}_i^a\hat{Y}_i^b)$$

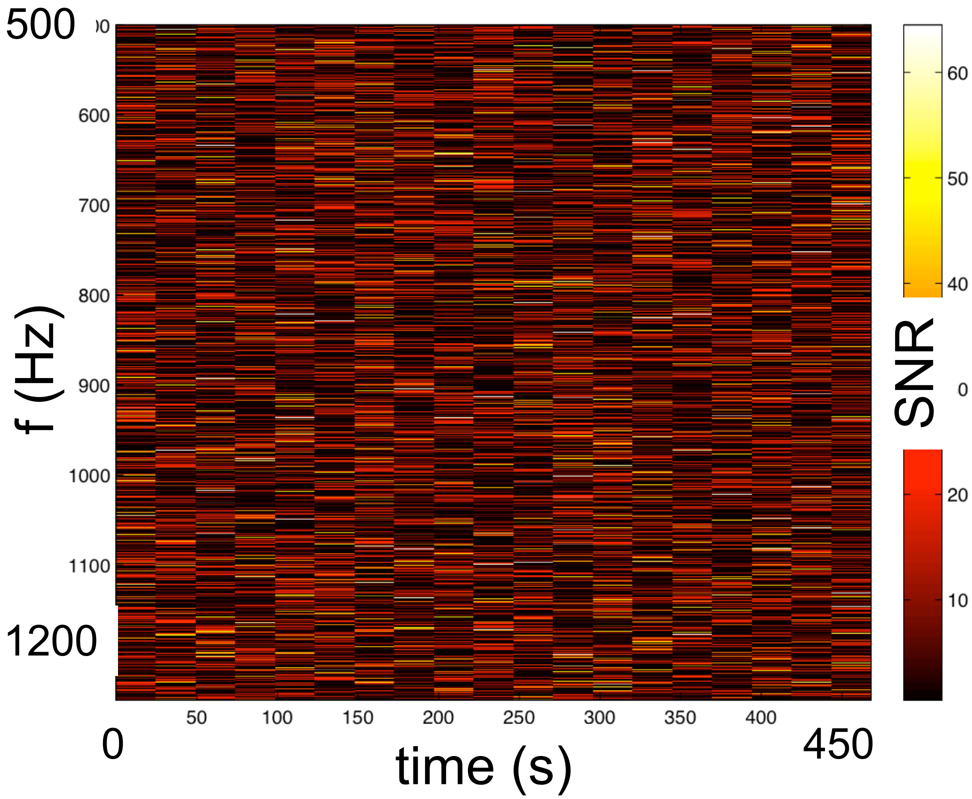
Intermediate Data

- We can visualize cross-correlation data as an ft-map of Re[SNR] (right).
- We search in different directions by multiplying by an array of phases, and then taking the real part of the product.
- We record a separate ft-map of σ in order to estimate sensitivity (and strain).



Intermediate Data

- In this example we consider 468 s segments of data divided into 26 s segments
- We consider frequencies between 500-1200 Hz with a resolution of 0.25 Hz.



Narrowband vs. Broadband Sources

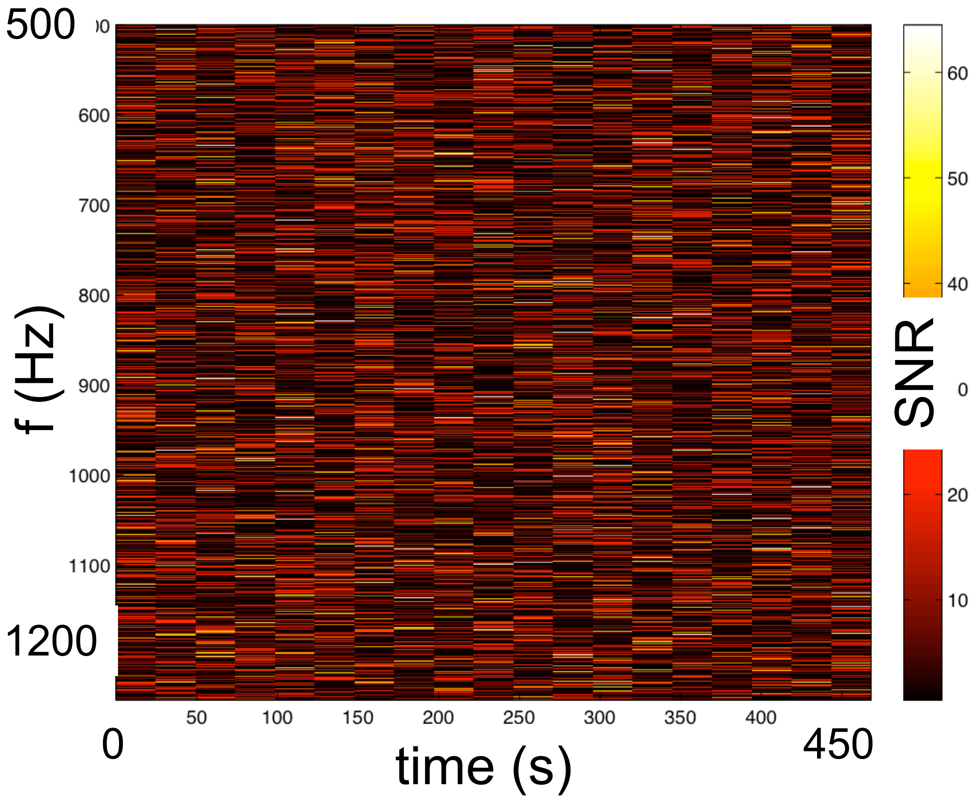
- Broadly speaking, transient signals come in two varieties: narrowband and broadband.
- We are thus investigating two detection strategies.
- Consider two illustrative cases…

Microquasars

- Binary systems; accretion of neighboring star mimics properties of AGN.
- Optical flares observed to last O(1000 s) [12].
- Segalis and Ori [7] investigated GWs from the accretion/ejection of blobs by MQs.
- Spectrum depends on mass and momentum of ejected blob(s) [7]: **broadband.**
- Many unknowns: Γ, δm, t_{acc}, N_{blobs}
- $\Delta h = 4G\Gamma m/c^2R$

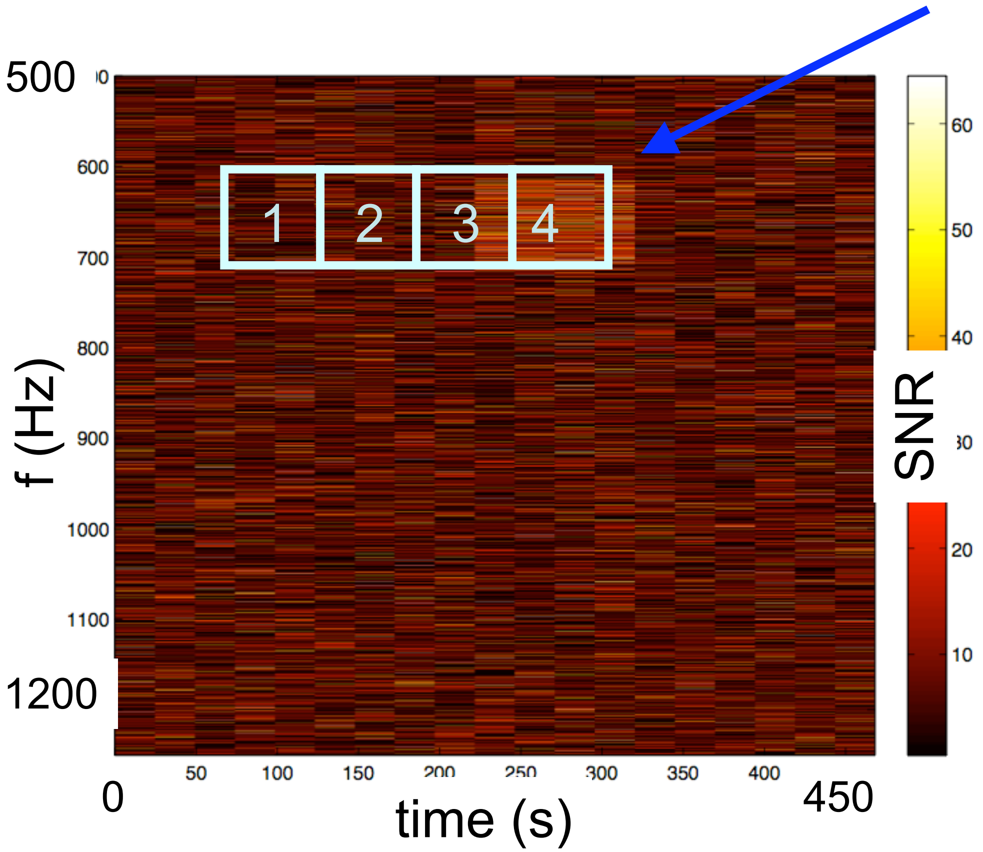
Test Data

- ft-map no injection, (pure detector noise)
- 468 s data
- 500-1200 Hz
- Inject 80 s white noise from 600-700 Hz.



Broadband Injection

- ft-map with toy-model broadband injection
- Example box search:
  - tile ft-map
  - sum the SNR in each box.
  - Compare with expected value from time-shifted data.
- See, e.g., W. Anderson et al. [13].



Long GRBs (with lumpy tori)

- M. van Putten's proposes that high-amplitude GWs may be emitted from the torus of a collapsing star [6] (see also Kobayashi & Mészáros) [18].
- Rate of ~1/year within 100 Mpc with $h \sim 10^{-21}$ [6].
- Frequency range of (1-2 kHz)/(1+z)—(LIGO noise is $<3 \times 10^{-22}/\mathrm{Hz}^{1/2}$ in this band)
- Duration of 10-15 s [6].
- Signal described as df/dt ~ constant [6] **(narrowband)** corresponds to line on an ft-map**.**

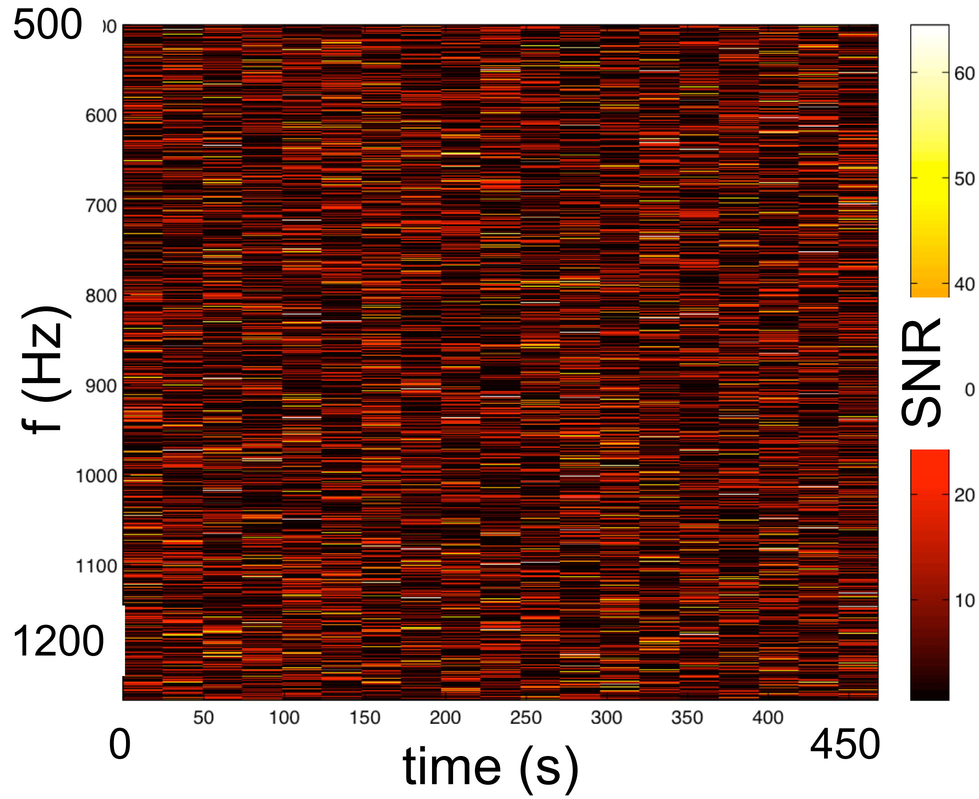
Radon Transform

- One way to look for narrow lines in 2D images is with a Radon transform.
  - Like a Fourier transform.
  - Lines are transformed into points in Radon space.
  - Converts (x,y) coordinates to (θ,b).
- Used in medical imaging.
- Prepackaged Matlab routines.
- Invertible.
- See related work by P. Raffai et al. [14].

Test Data

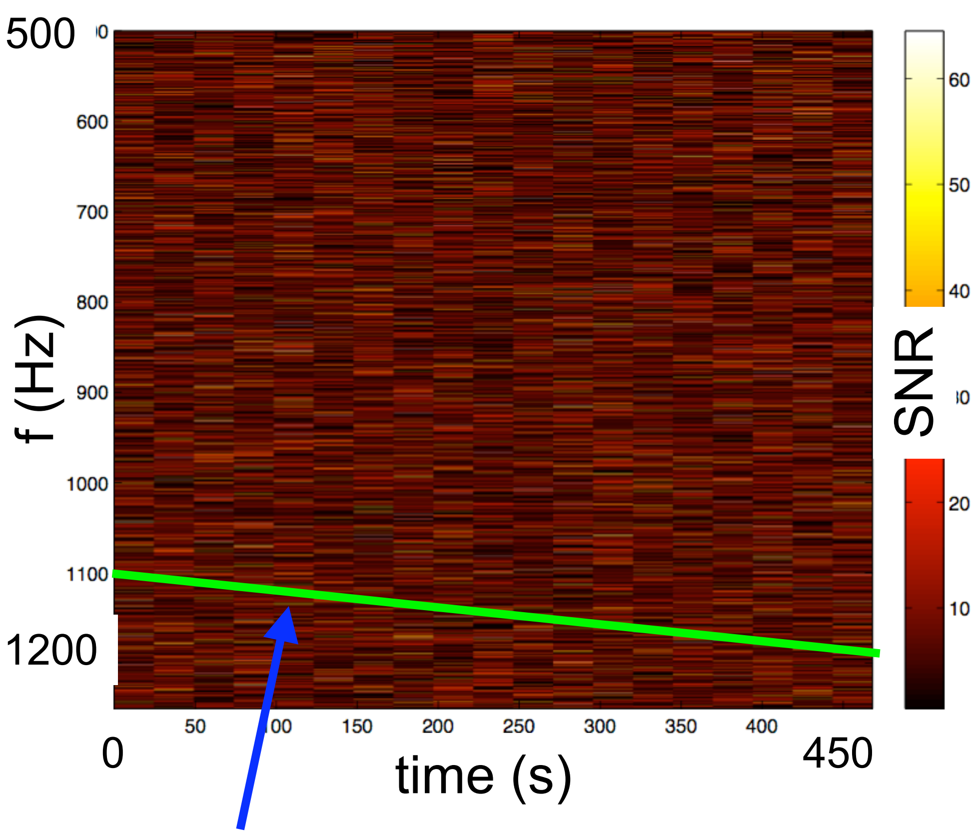
- ft-map no injection, (pure detector noise)
- 468 s data
- 500-1200 Hz
- Inject:

  f=1100 Hz + 0.2 Hz t(s)



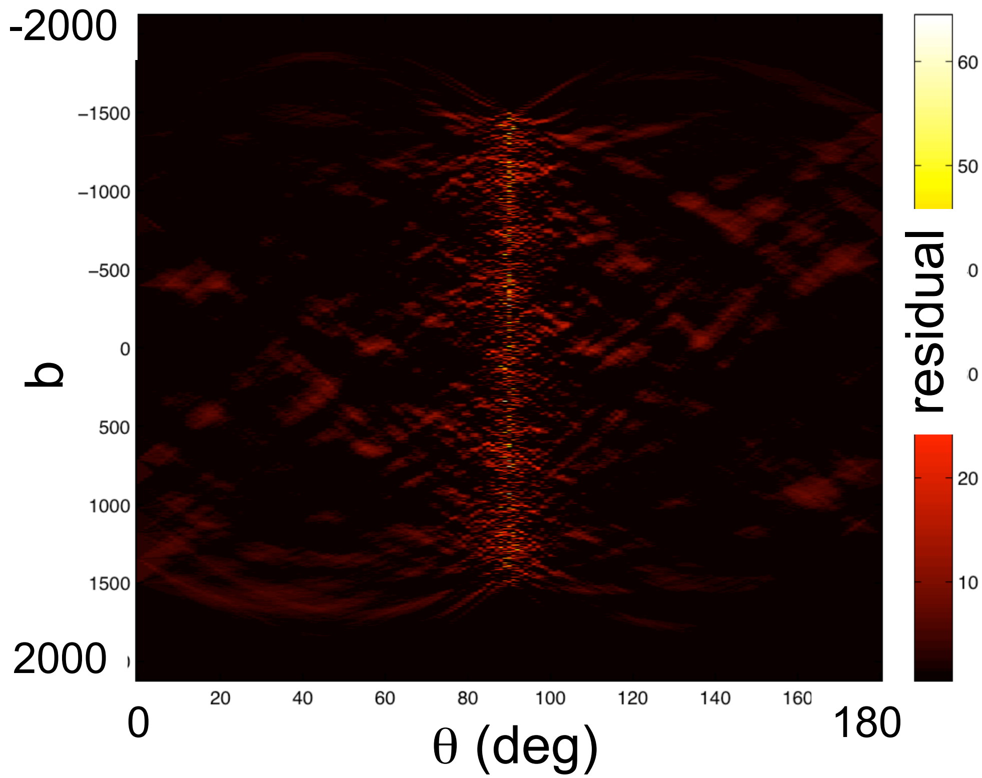
Narrowband Injection

- ft-map with toy-model narrowband injection with detector noise.
- The frequency wanders ~100 Hz over the 468 s map.



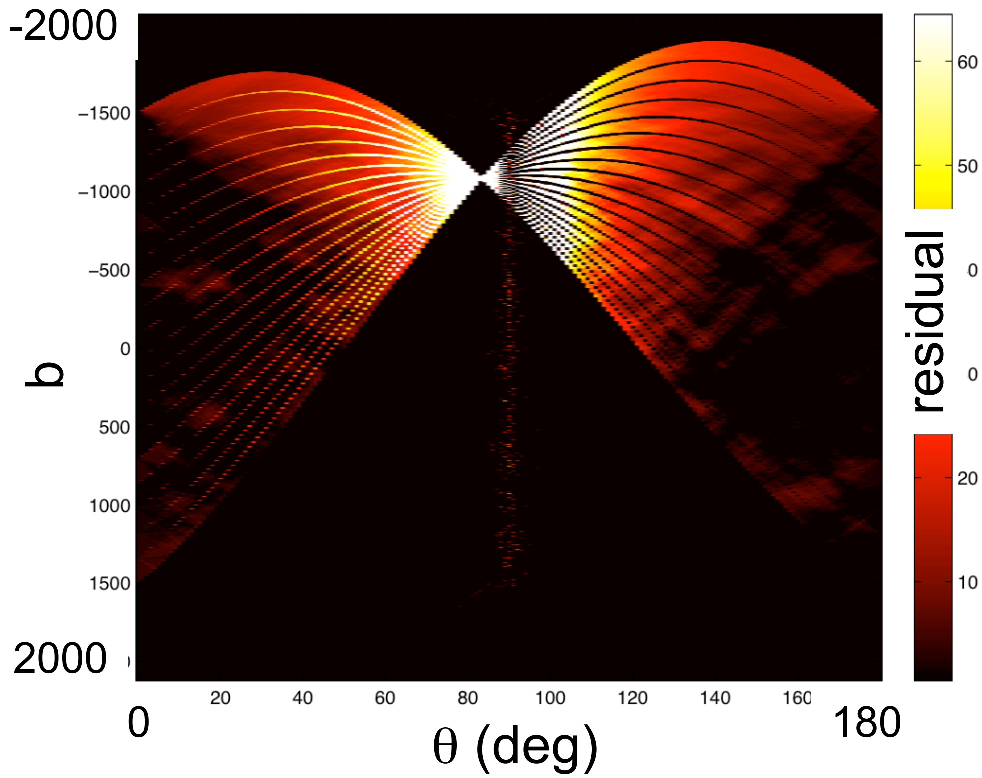
Radon Transform of Noise

- Radon transform of ft-map with pure detector noise.
- Bright spots at 90° may correspond to glitchy frequencies, overlapping segments, or maybe binning… investigating.



Radon Transform of Narrowband Injection

- Radon transform of ft-map for toy-model narrowband injection.
- Injection is obvious.
- SNR is concentrated.



Supernova GW+ν Proposal

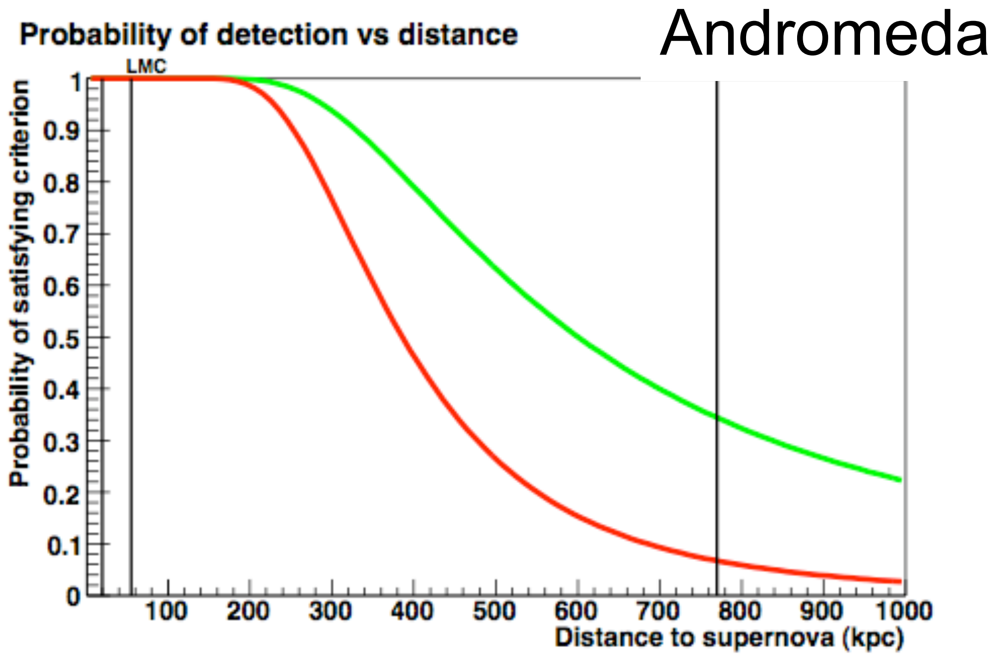
- Collaborators from LIGO, Virgo, Super-K, LVD, and Borexino collaborations:
  - W. Fulgione (U Torino, LVD), K Scholberg (Duke U, Super-K), F. Vissani (LNGS-Theory), L. Cadonati (U Mass, Amherst), E. Coccia (LNGS and U Rome II), S. D'Antonio (U Rome II), A. Di Credico (LNGS), V. Fafone (U Rome II), R. Frey (U Oregon), E. Katsavounidis (MIT), I. Leonor (U Oregon), C. Ott (Caltech), G. Pagliaroli (LNGS), E. Thrane (U Minessota)
- Proposal is awaiting approval.
- Additional collaboration w/ km^3 ν telescopes?

Scientific Rationale

- Core-collapse SN emit a huge flux of low-E ν $O(10^{53}$ erg) in a short duration O(10 s).
- Super-K can reliably detect Milky Way SN, but the probability of detecting a SN in Andromeda (770 kpc away) is small, <10%.
- The Milky Way SN rate is ~1/50 yr.
- SN may also emit GWs with strains detectable by current/planned experiments.
  – Predictions are model-dependent: 2×10^{-23} - 5×10^{-20} at 10 kpc [1]

GW+ν Coincidences Improve Detection Probability

- Requiring GW coincidence quadruples SK's Andromeda detection probability.
- Predicted O(10^{-23}) strain feasible with Adv. LIGO.



From GW+ν proposal

Figure 1: Estimated probability to satisfy Super-K burst search criterion as a function of distance. Red: standard search parameters[9]. Green: probability if only a single neutrino event is required, in coincidence with a GW signal.

SN Detection with HEN Telescopes

- Though designed for ν with E>TeV, large HEN telescopes can detect low-E ν by looking for an increase in the single counting rates of all optical modules [10].
- E.g., IceCube/AMANDA part of SNEWS (Supernova Early Warning System).
- Next GWNU planning session at TAUP, July 1-5, 2009!

Transient GWs from SN

- GW waveforms from supernovae are model-dependent, with a wide range of possibilities.

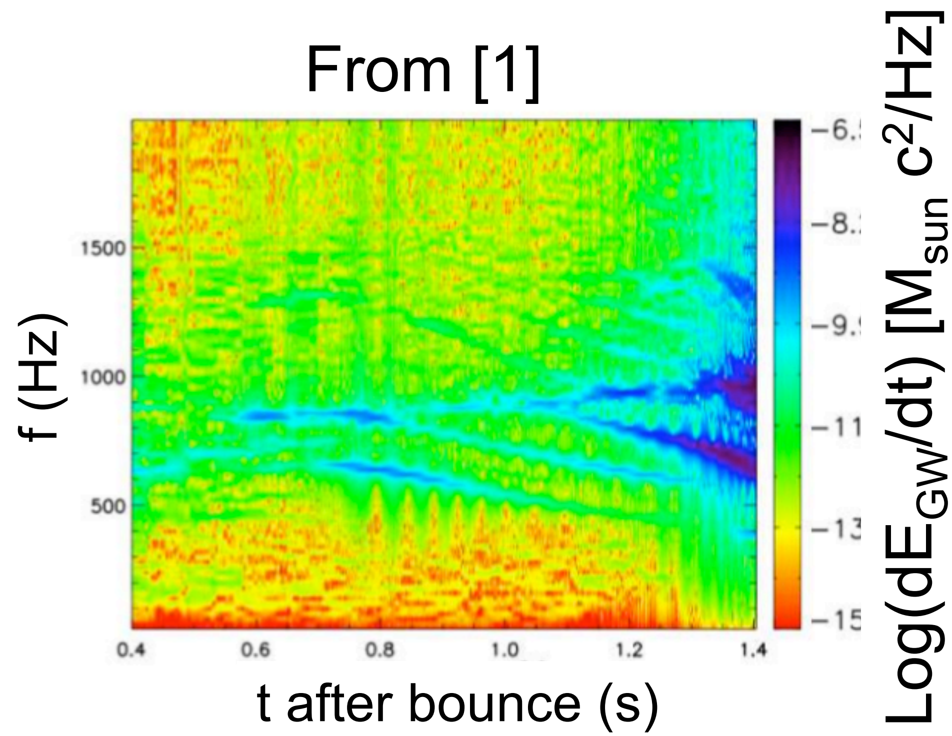
process	**typical h @ 10 kpc**	**typical f (Hz)**	**Δt (ms)**
prompt convection	10^{-23}-10^{-21}	50-1000	0-30
PNS convection	2-5x10^{-23}	300-1500	**500-4000**
ν-driven convection + SASI	10^{-23}-10^{-22} **w/ peaks at 10^{-21}**	100-1000	**100-1000**

From [1]

Transient GWs from SN

- Predicting spectra requires complicated computer simulations.
- Simulations allow for the possibility of GW signals with durations ≥ several seconds.
- Intermediate searches will complement burst searches.

From [1]



Future Work

- Develop search algorithms
  - Box, Radon, …
- Low-latency triggers for transients
  - Collaboration with HEN
- Technical details, e.g,
  - Nonstationary noise
  - Overlapping segments
- Targeted searches
- All-sky searches

Conclusions

- There are interesting GW+HEN sources with potentially long GW durations.
- We are developing an intermediate pipeline to search for these transient sources.
- Joint GW+HEN analyses will be useful to probe these transient signals.

References

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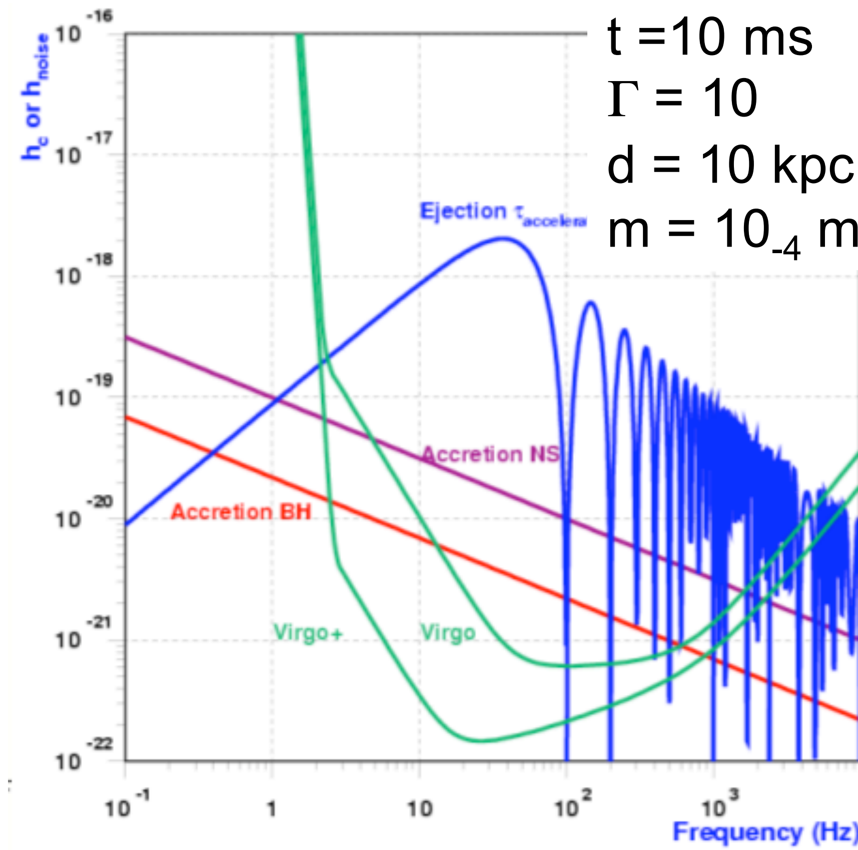
Extra Slides

GWs from Microquasar

- Cannonball model of Microquasar GWs.
- Characteristic frequency is angle-dependent with

  $f_{c\_max} = \gamma^2 / \Delta t.$
- $\Delta h = 4G\Gamma m / c^2 R$
- Multiple blobs?
- Γ = 2-5 [19]



t =10 ms
Γ = 10
d = 10 kpc
$m = 10_{-4}\ m_{sun}$

From [17]