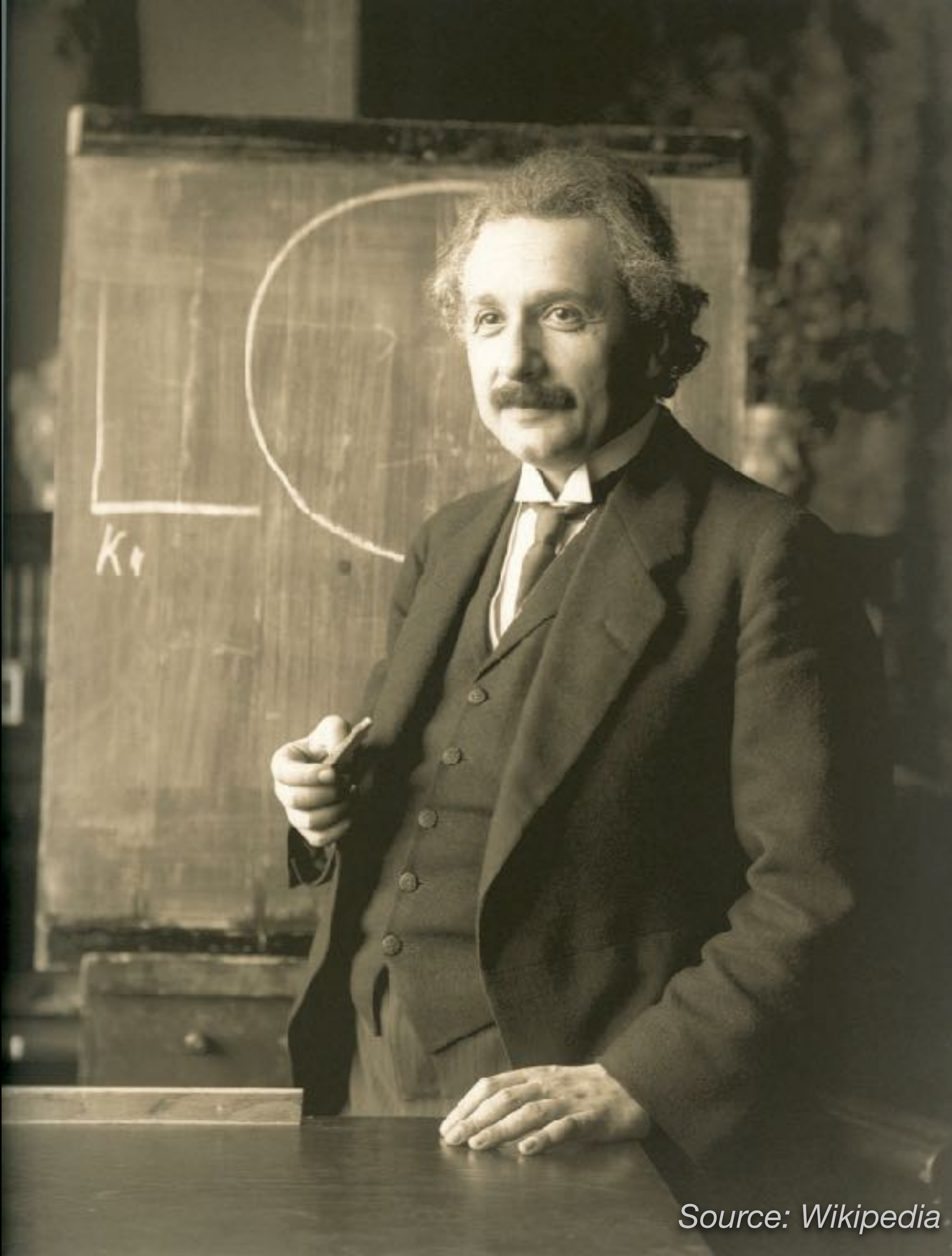
Composite optical/X-ray image of the Crab Nebula
(Optical: NASA/HST/ASU/J. Hester et al.
X-Ray: NASA/CXC/ASU/J. Hester et al.)

Search for Continuous Gravitational Waves from Spinning Neutron Stars

Speaker : Ling Sun
Supervisor : Andrew Melatos
OzGrav, University of Melbourne

Agenda

- *Background (GW, detections, sources)*
- *Hidden Markov models*
- *Low-mass X-ray binary (LMXB) — Scorpius X-1*
- *Young supernova remnant (SNR) — SN1987A*
- *Post-merger remnant — GW170817*
- *Other contribution & future work*



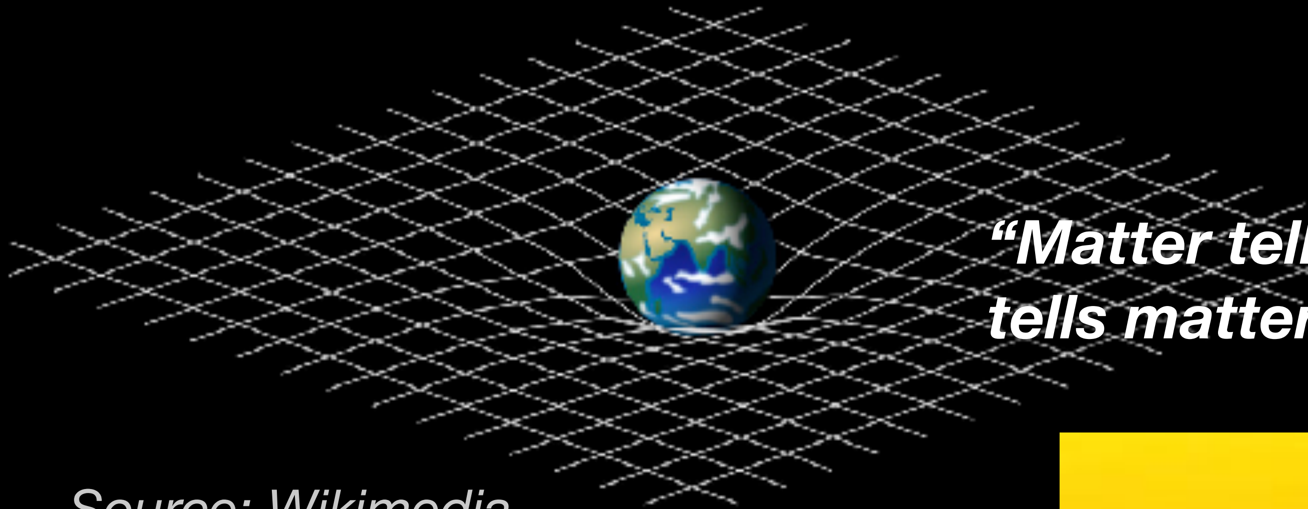
Source: Wikipedia

100 years ago…
1915 - 1916
Einstein predicted
gravitational waves…

100 years later…
2015.09.14
LIGO detected the first
gravitational-waves event!

More detections…
…
To be continued

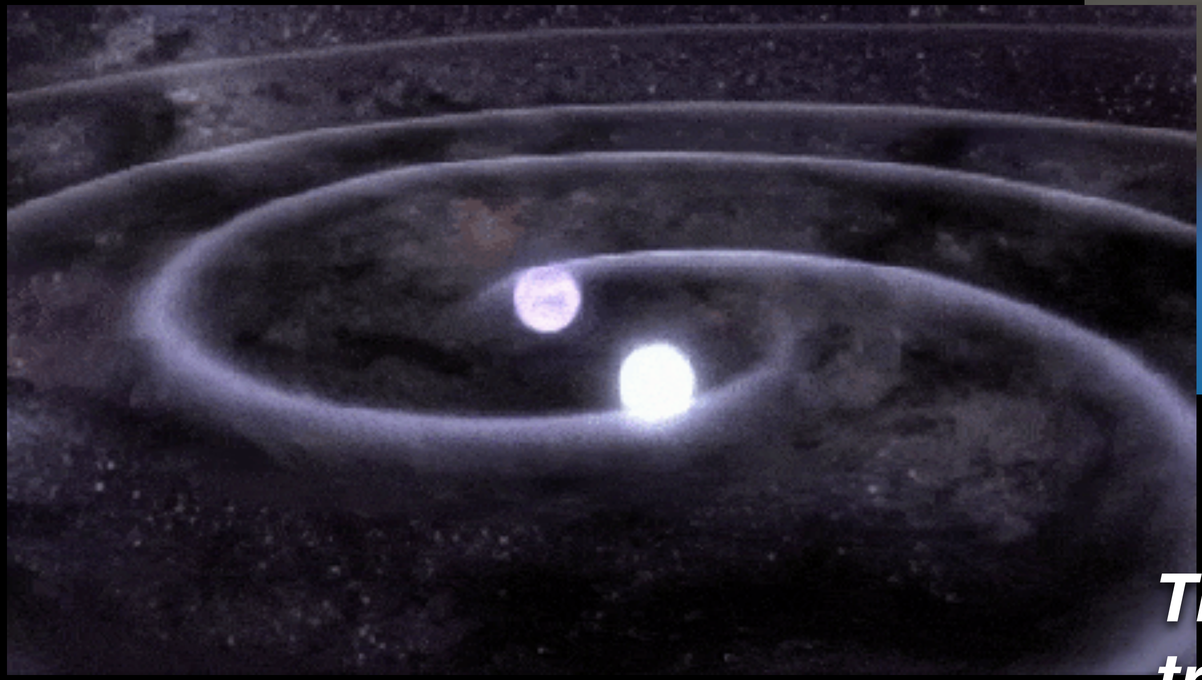
What are gravitational waves?



Source: Wikimedia

"Matter tells spacetime how to curve, and spacetime tells matter how to move." — John Archibald Wheeler

Credit: Qimono/Flickr

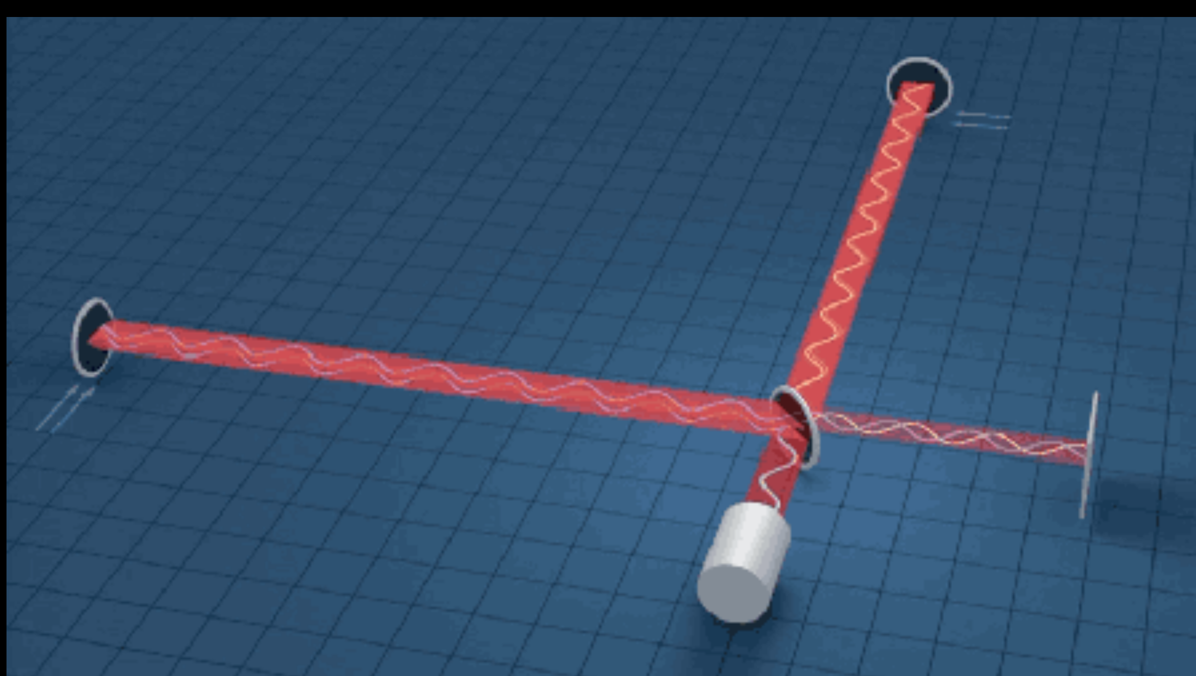


Credit: NASA/Dana Berry, Sky Works Digital

They are 'ripples' in the fabric of spacetime, traveling at the speed of light.

What is Laser Interferometer Gravitational-Wave Observatory?

Credit: LIGO/Virgo

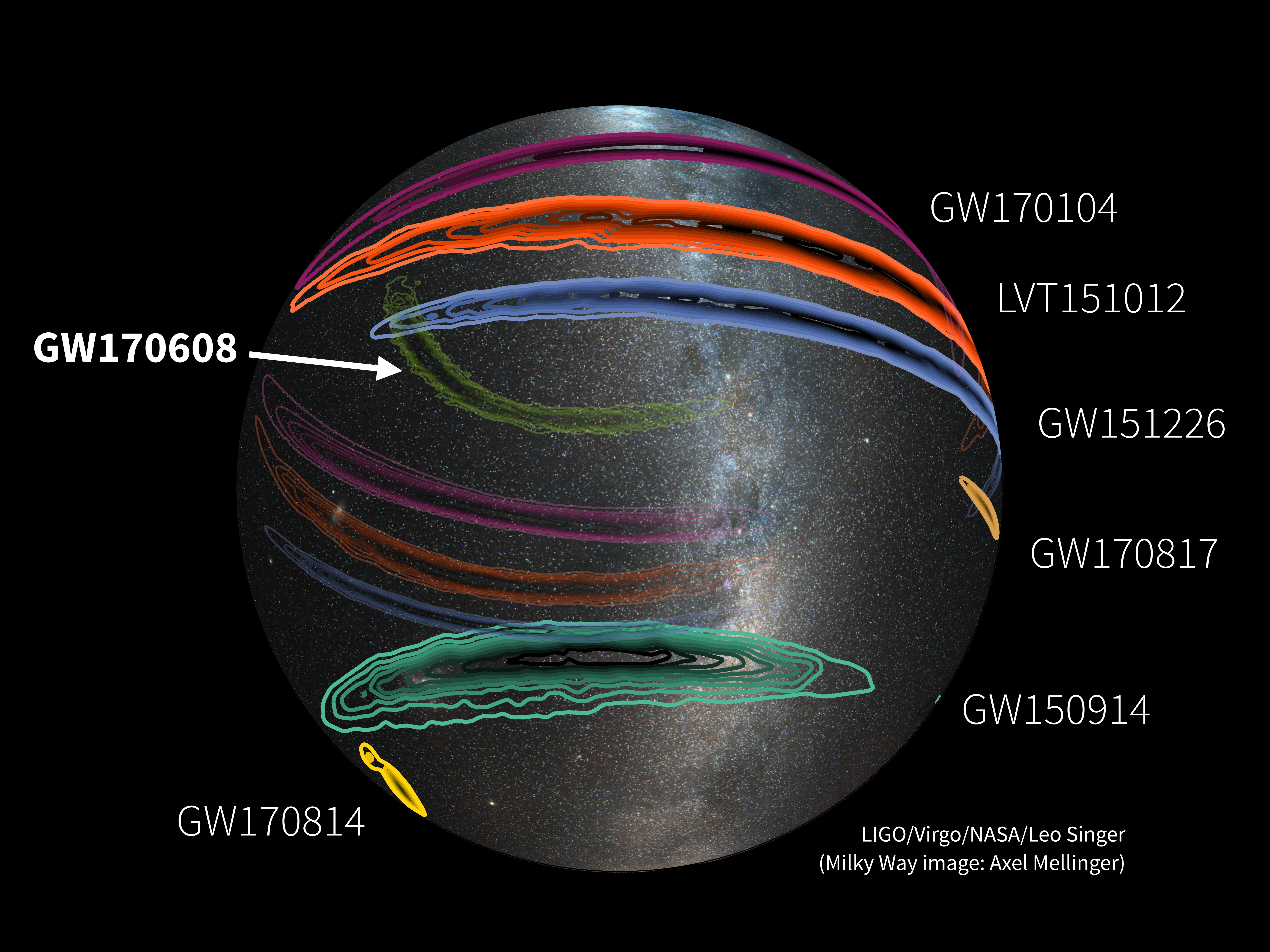


1/10,000 of a proton!

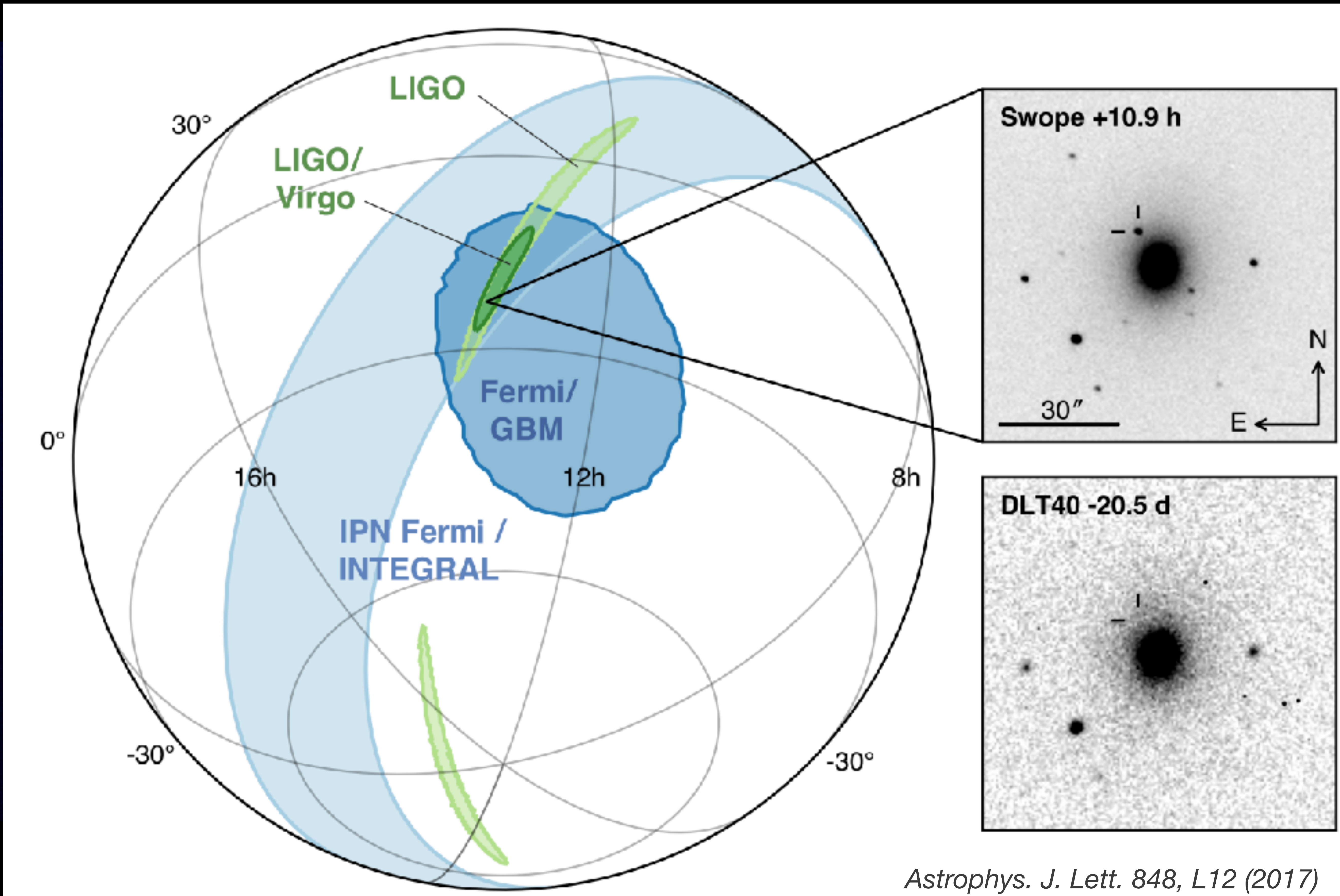
$$\Delta L \sim 10^{-19}\,\mathrm{m}$$

$$h_0 = \frac{\Delta L}{L}$$

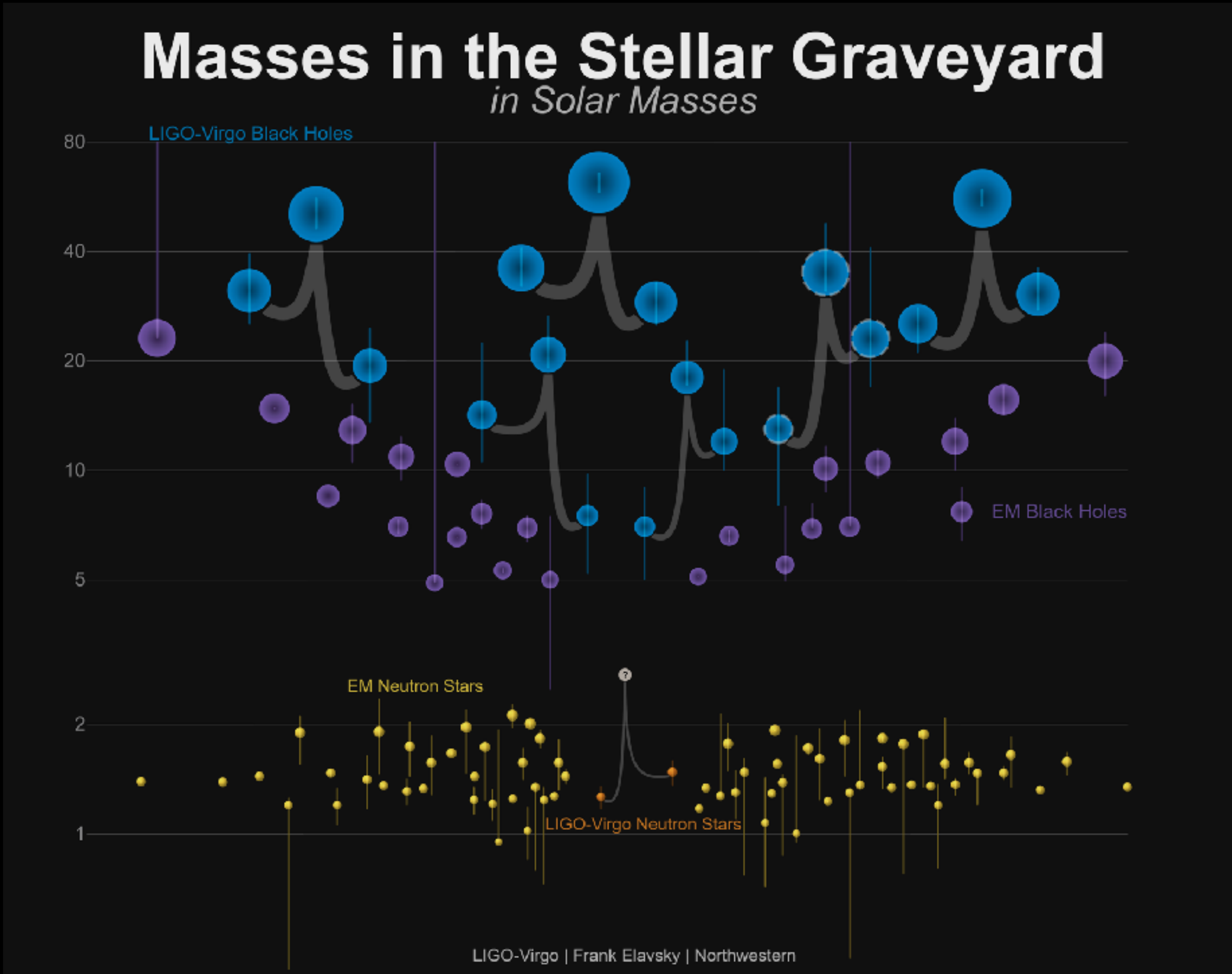
L = 4 km


GW170104
LVT151012
GW170608
GW151226
GW170817
GW150914
GW170814
LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)

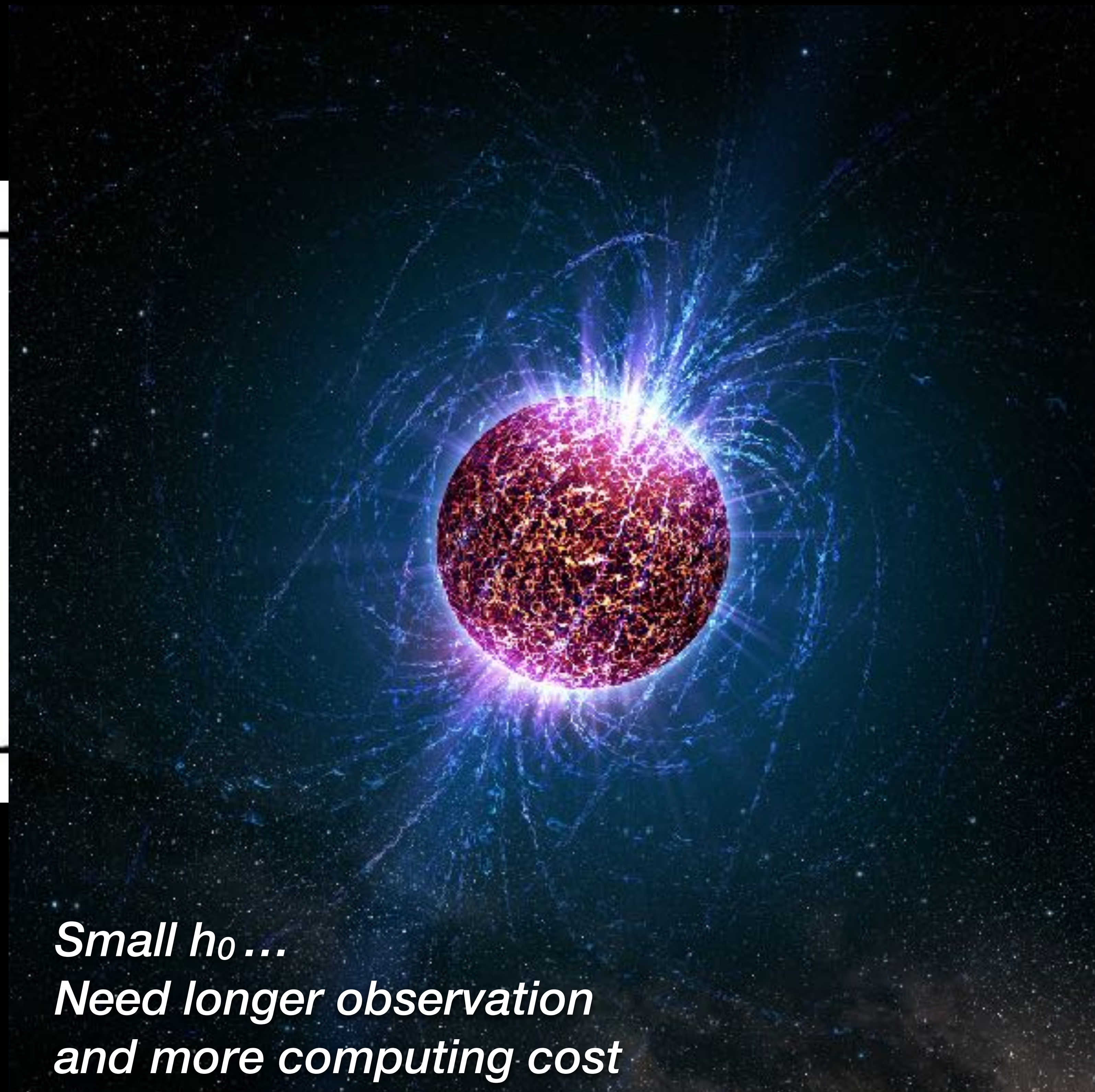
Binary neutron star coalescence - GW170817



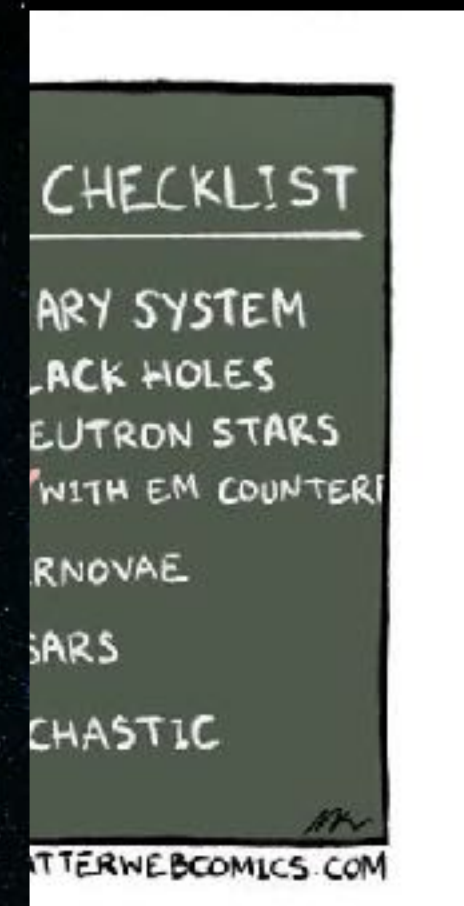
Astrophys. J. Lett. 848, L12 (2017)


Masses in the Stellar Graveyard
in Solar Masses
LIGO-Virgo Black Holes
80
40
20
10
5
2
1
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
LIGO-Virgo | Frank Elavsky | Northwestern

What else?



Small h_0 …
Need longer observation
and more computing cost



Continuous wave data analysis categories

- *Targeted searches for pulsars with known sky position and ephemerides*

- *Directed searches for neutron stars with known sky position but unknown rotation frequency*

- *All-sky searches over the entire sky for unknown neutron stars*

Challenges in directed searches

We do not know the spin frequency of the star

- *Need to search a broad range of frequencies — a lot computing cost*

The spin frequency is wandering

- *Internal - fluctuating magnetospheric or superfluid torques*
- *External - fluctuating accretion torque*
- *Can not do coherent search over a long duration*

Rapid spin down of young targets

- *Need to search higher time derivatives of frequency*

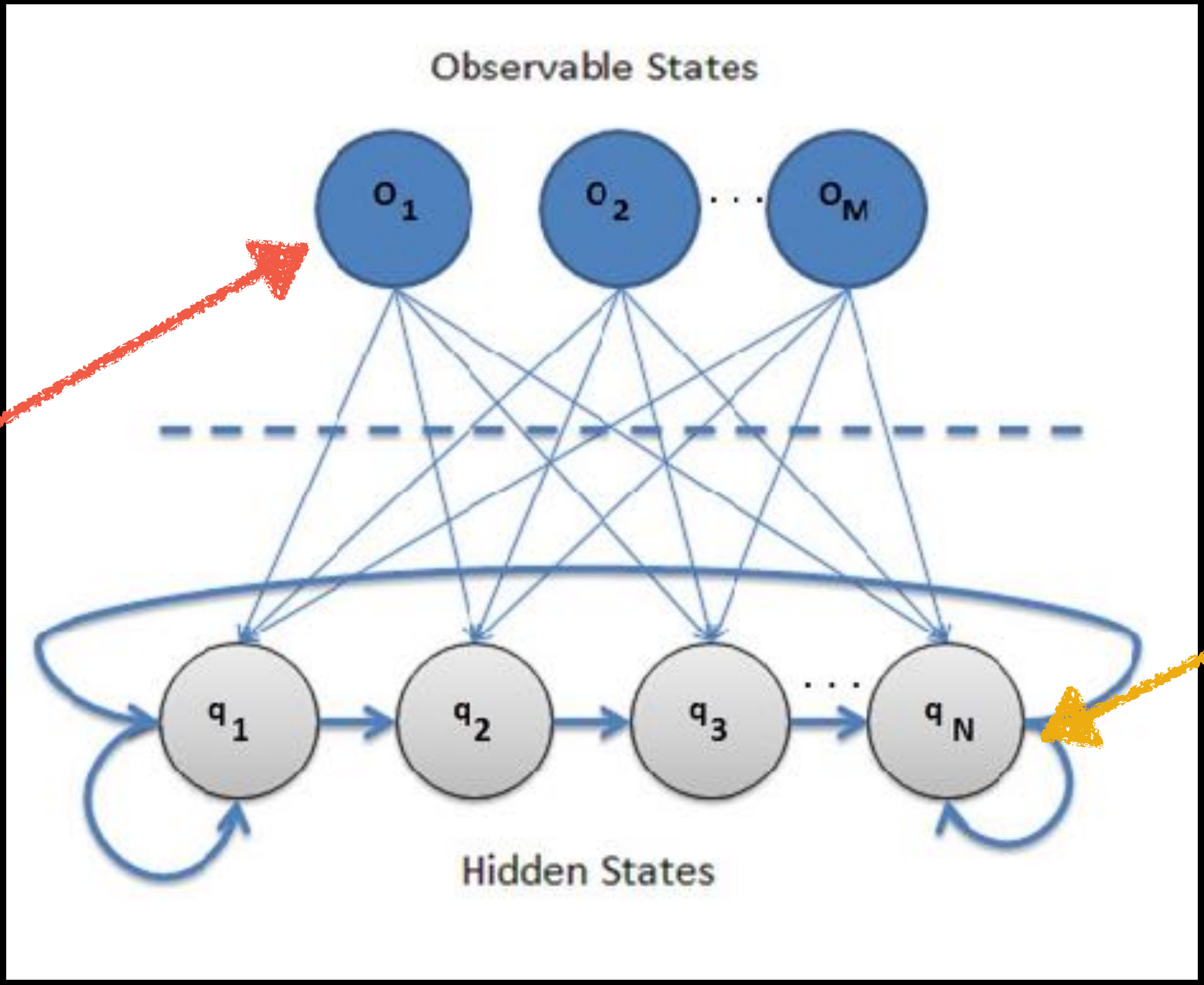
Hidden Markov models

[1] Suvorova, Sun, Melatos, Moran, Evans, Phys. Rev. D 93, 123009 (2016)

Hidden Markov Model

- *Markov Chain - A random process with discrete states, changing from one state to another; The next state only depends on the current state; The transition is governed by a transition probability matrix.*

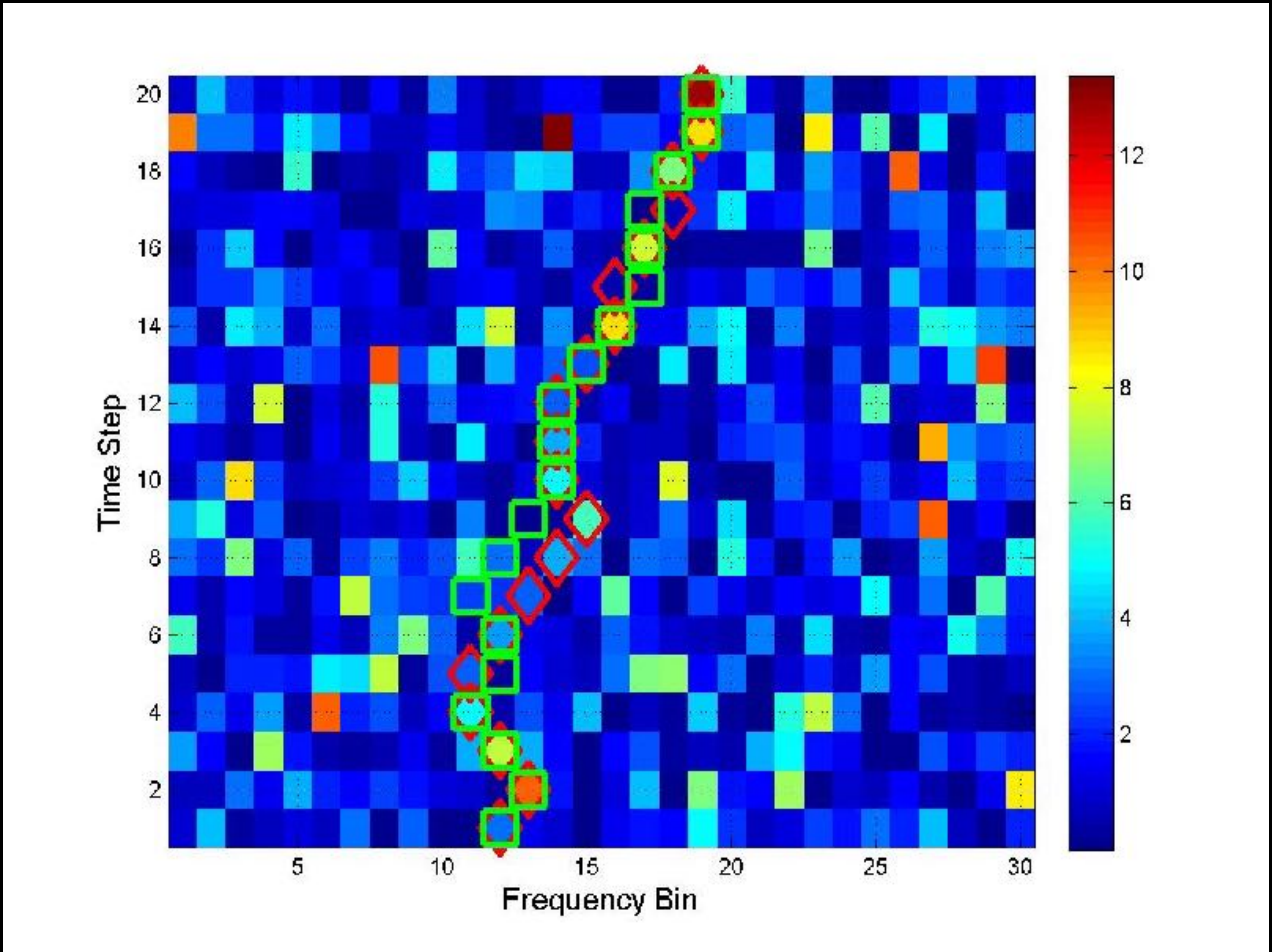
- *Hidden Markov Model - States are not directly observable.*



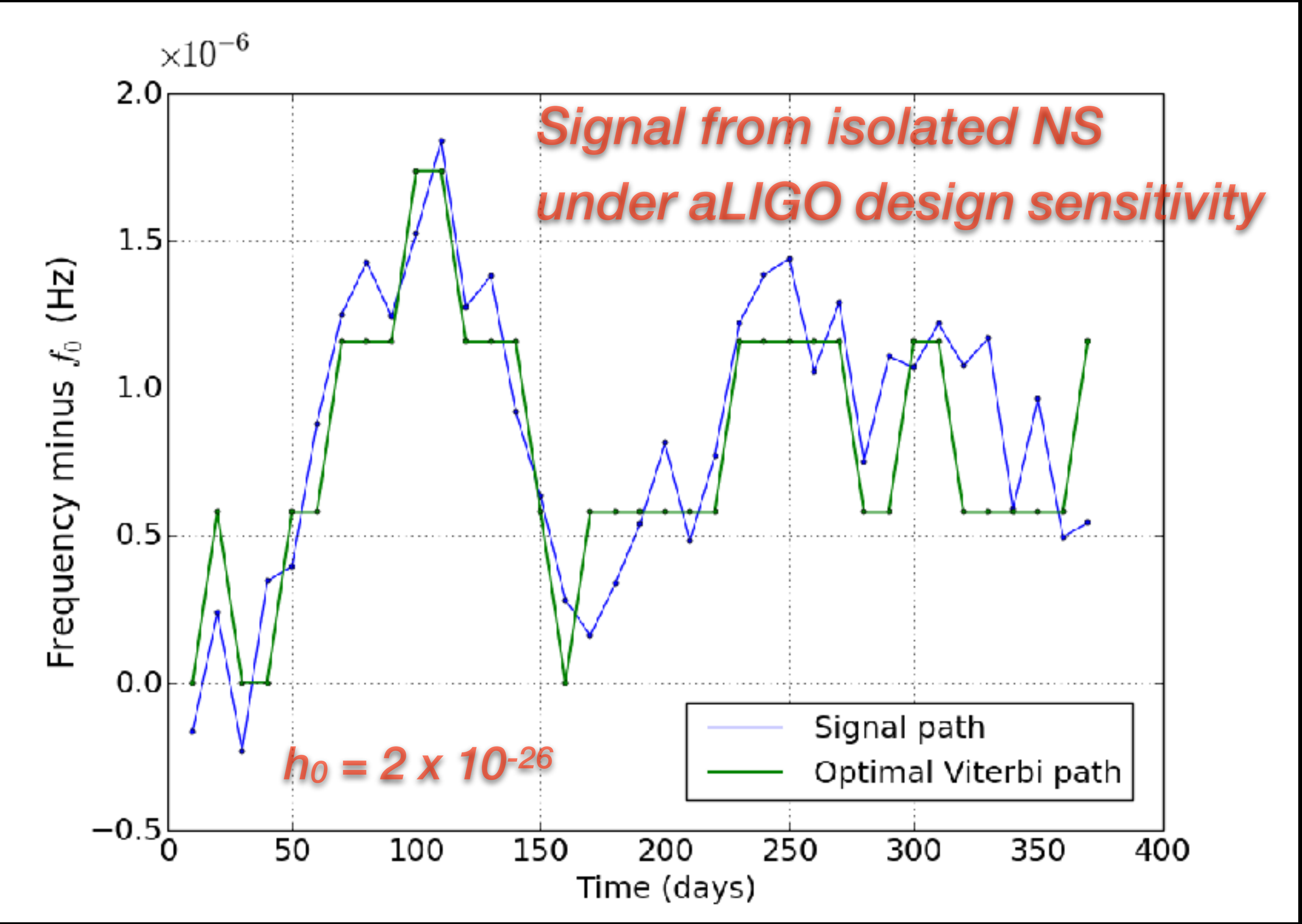
LIGO noisy raw data

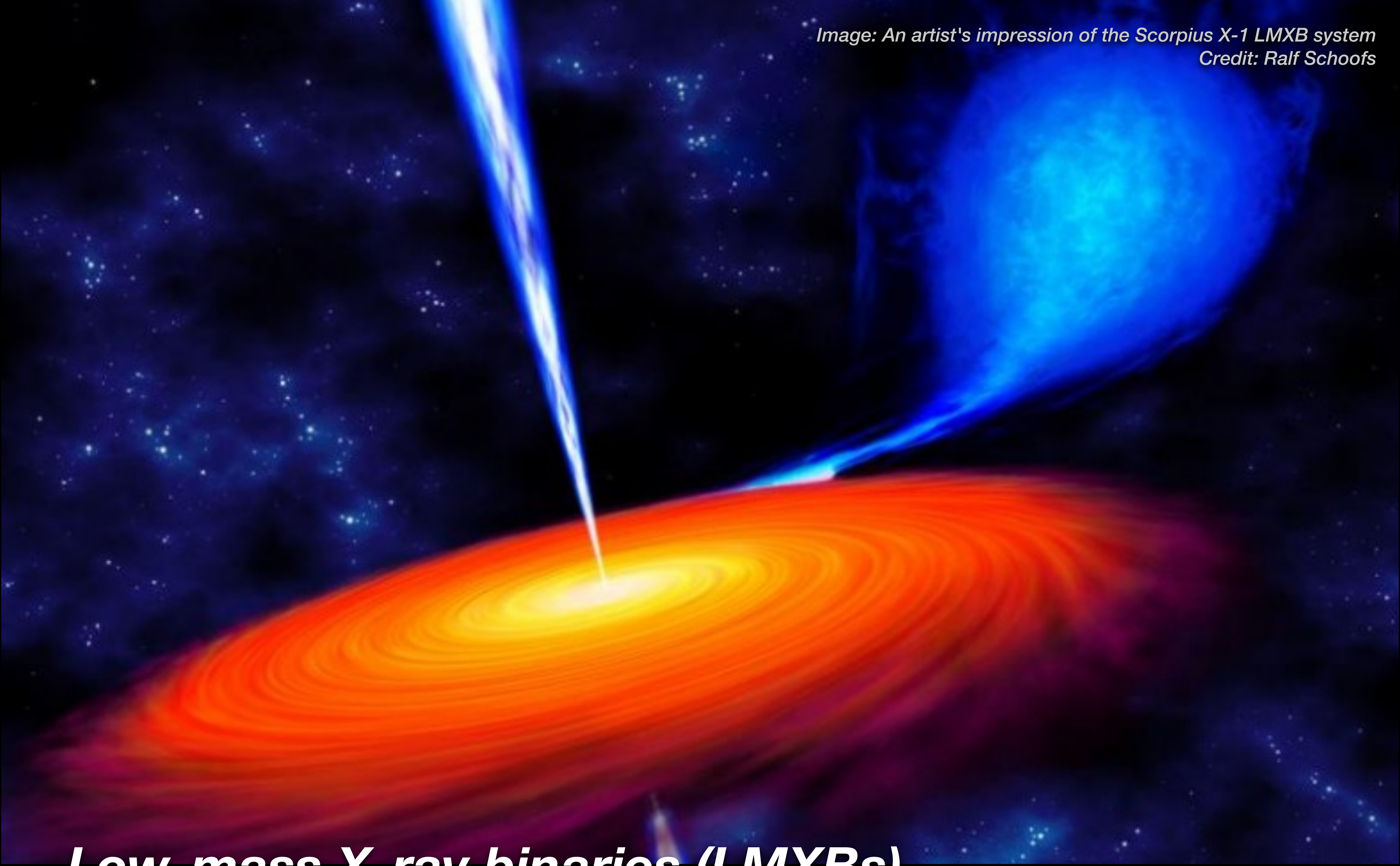
Spin-wandering GW signal

Viterbi Algorithm and Optimal Path



Tracking Spin-wandering Signals





Low-mass X-ray binaries (LMXBs)
— HMM tracking

[2] LIGO Scientific Collaboration and Virgo Collaboration, Phys. Rev. D 95, 122003 (2017)

Low-mass X-ray binary (LMXB)

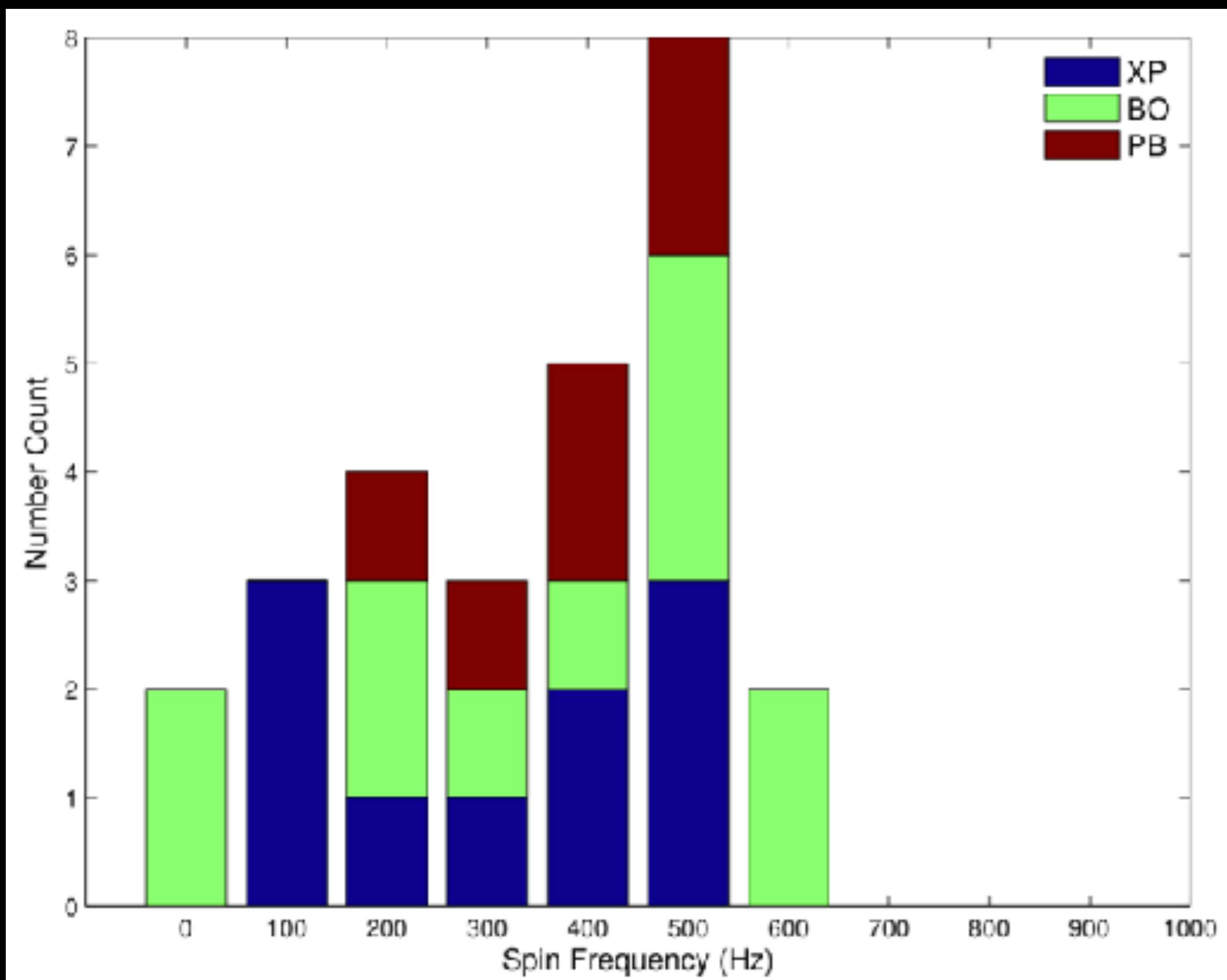


Image: Sammut PhD Thesis (2015)

- *Torque-balance theory — accretion spins the star up; GW emission slows it down*

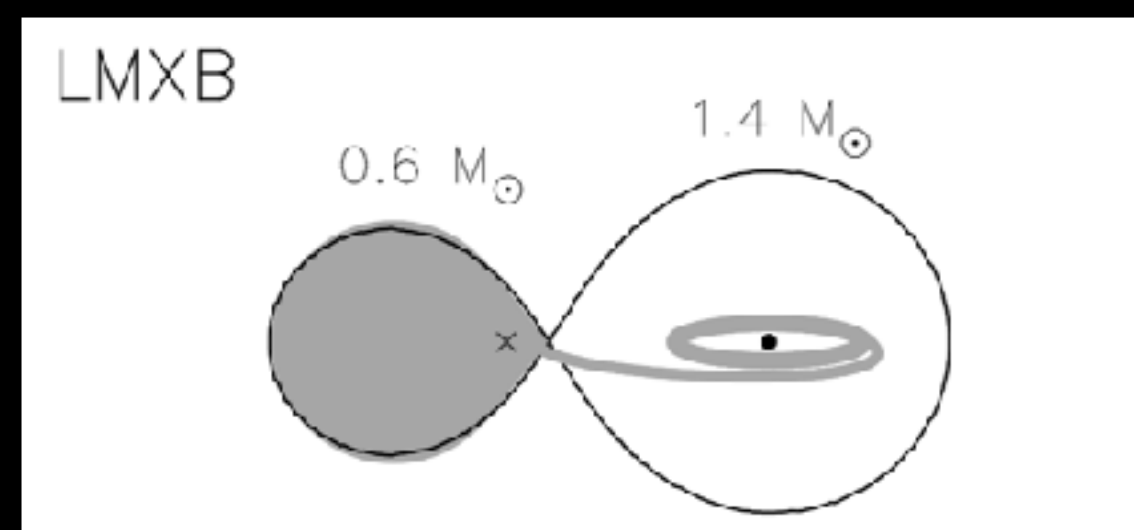


Image: Tauris et al., Formation and evolution of compact stellar X-ray sources

Why is Scorpius X-1 interesting?

- *Accretion in LMXB is a natural method of powering GW emission.*
- *Torque-balance theory — accretion spins the star up; GW emission slows it down — the more X-ray luminous, the stronger GW emission*
- *Scorpius X-1 — the brightest LMXB in our galaxy; sky position and orbital period well observed*

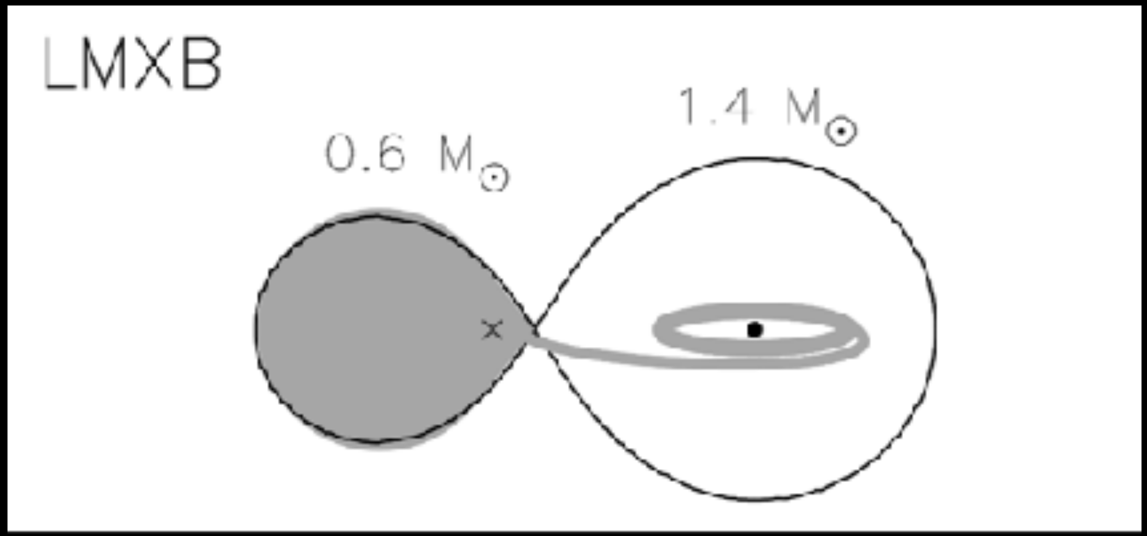
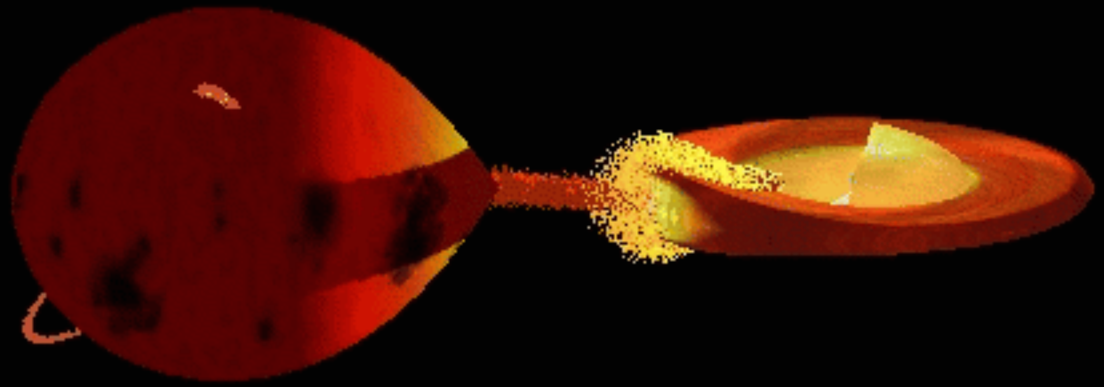


Image: Tauris et al., Formation and evolution of compact stellar X-ray sources

Before HMM tracking…

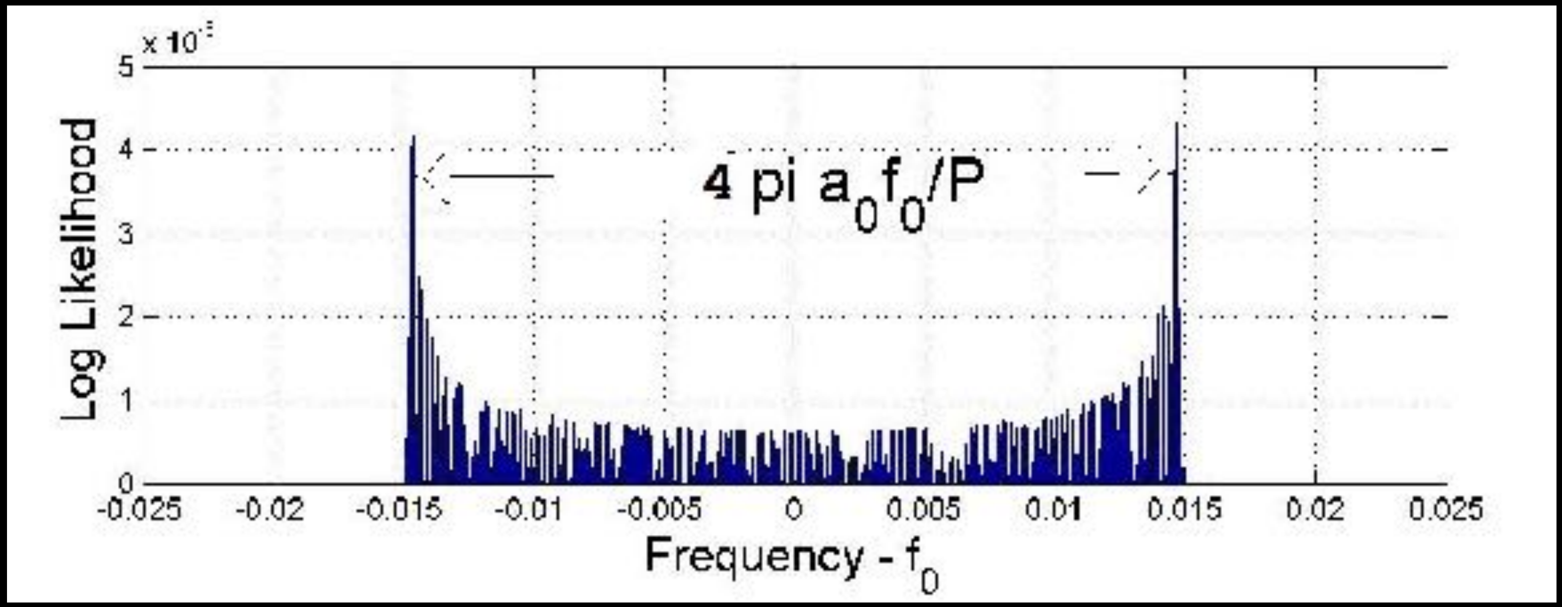
- *Signal is Doppler modulated*
  a_0 - projected semi-major axis
  P - orbital period



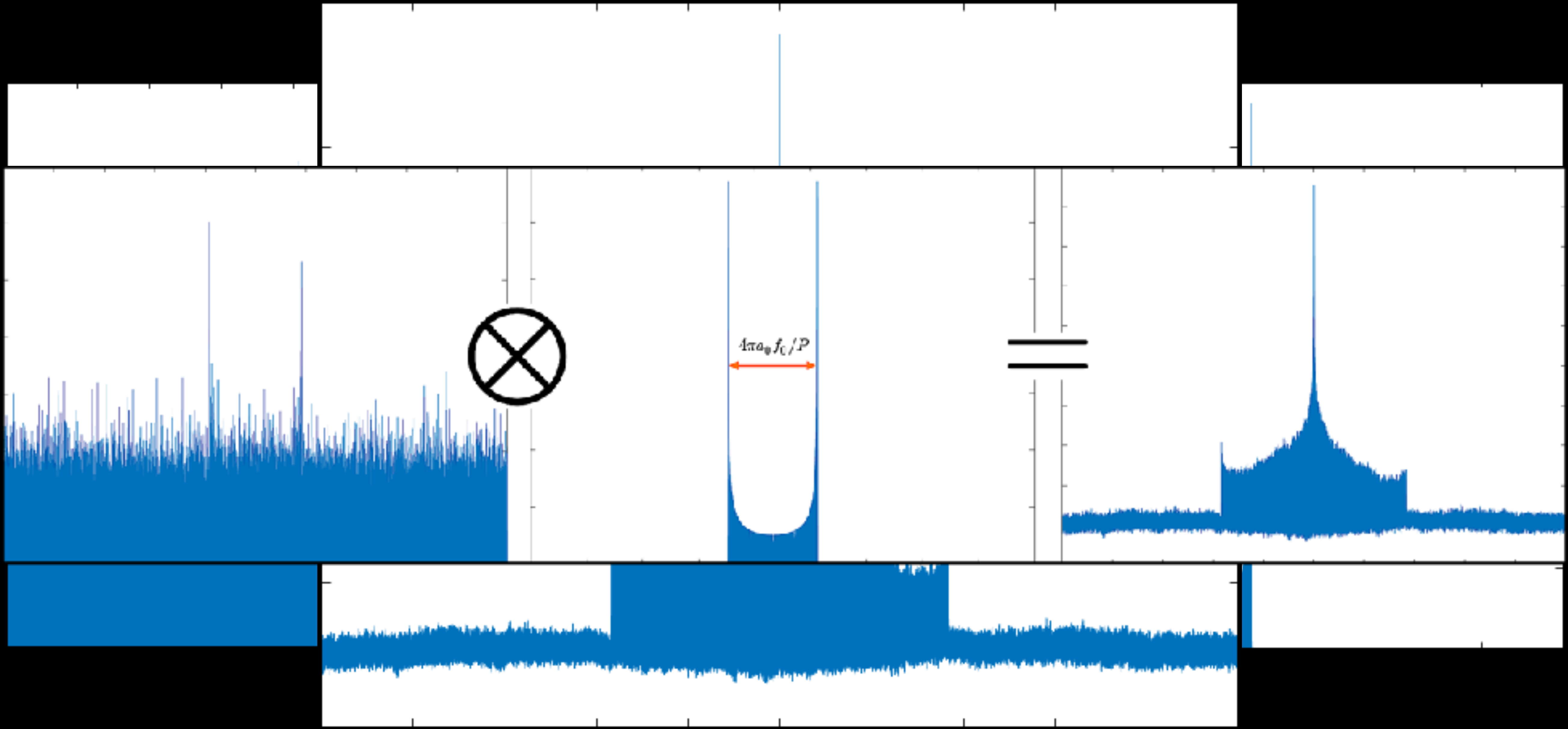
Intermediate polar animation by Dr Andy Beardmore, Keele University

$$h_{+,\times}(t) \propto \sum_{n=-\infty}^{\infty} J_n(2\pi f_0 a_0) \cos[2\pi(f_0 + n/P)t]$$

Use a Bessel-weighted matched filter

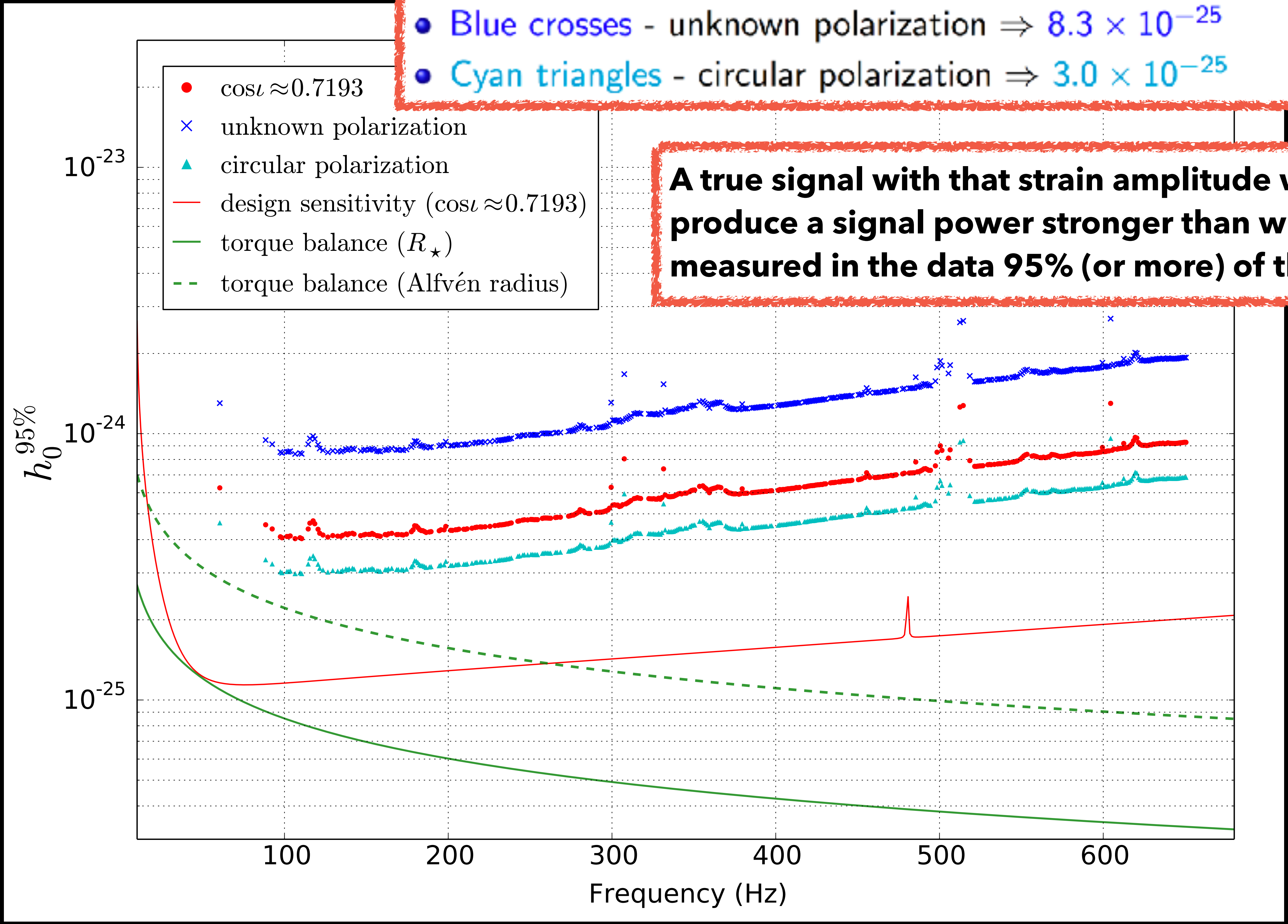


Remove the Doppler modulation



Search results in the first Advanced LIGO observing run

- Red dots - electromagnetically restricted $\iota = 44^\circ \Rightarrow 4.0 \times 10^{-25}$
- Blue crosses - unknown polarization $\Rightarrow 8.3 \times 10^{-25}$
- Cyan triangles - circular polarization $\Rightarrow 3.0 \times 10^{-25}$



A true signal with that strain amplitude would produce a signal power stronger than what was measured in the data 95% (or more) of the time.

Abbott et al., Phys. Rev. D. 95, 122003 (2017)

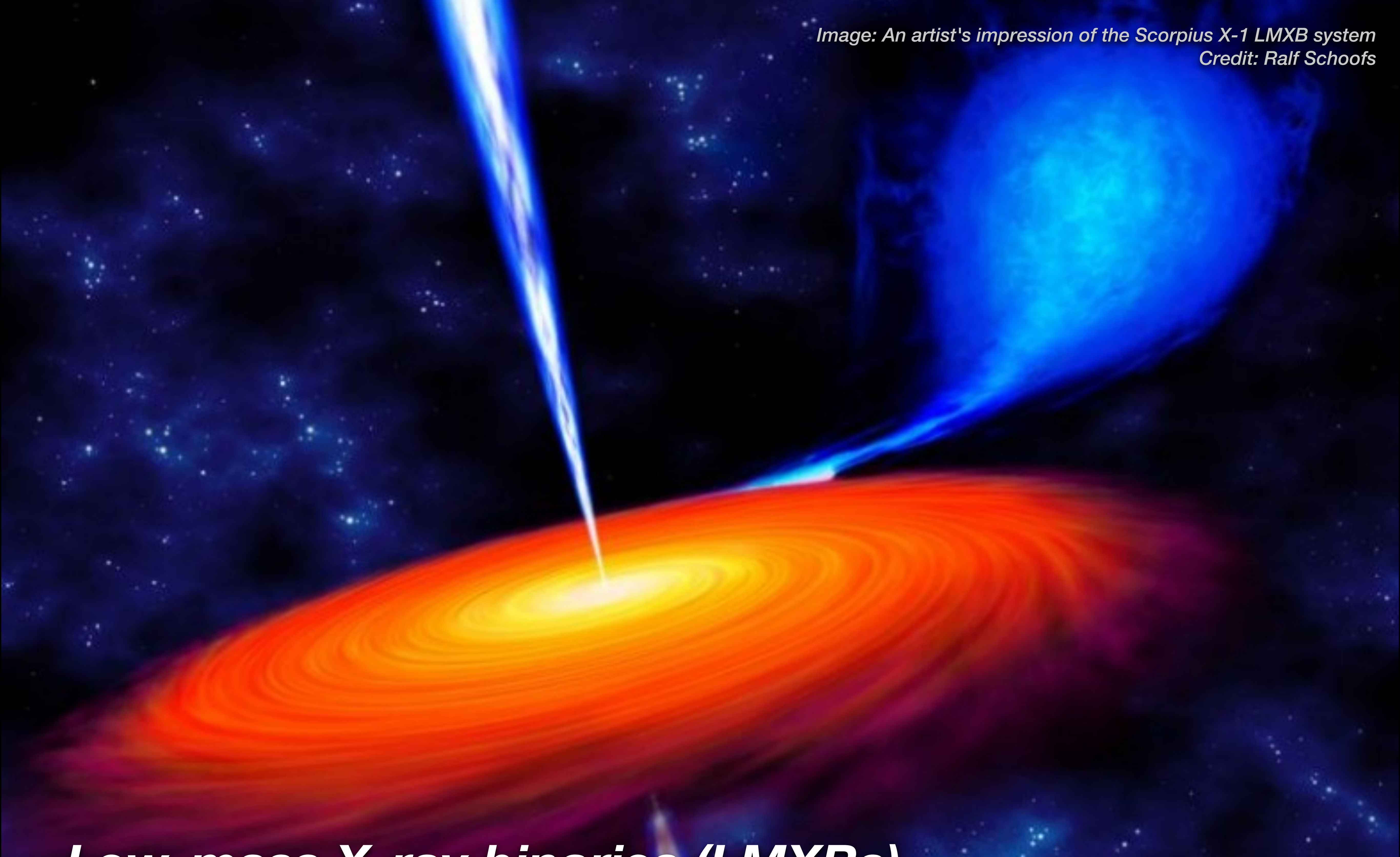
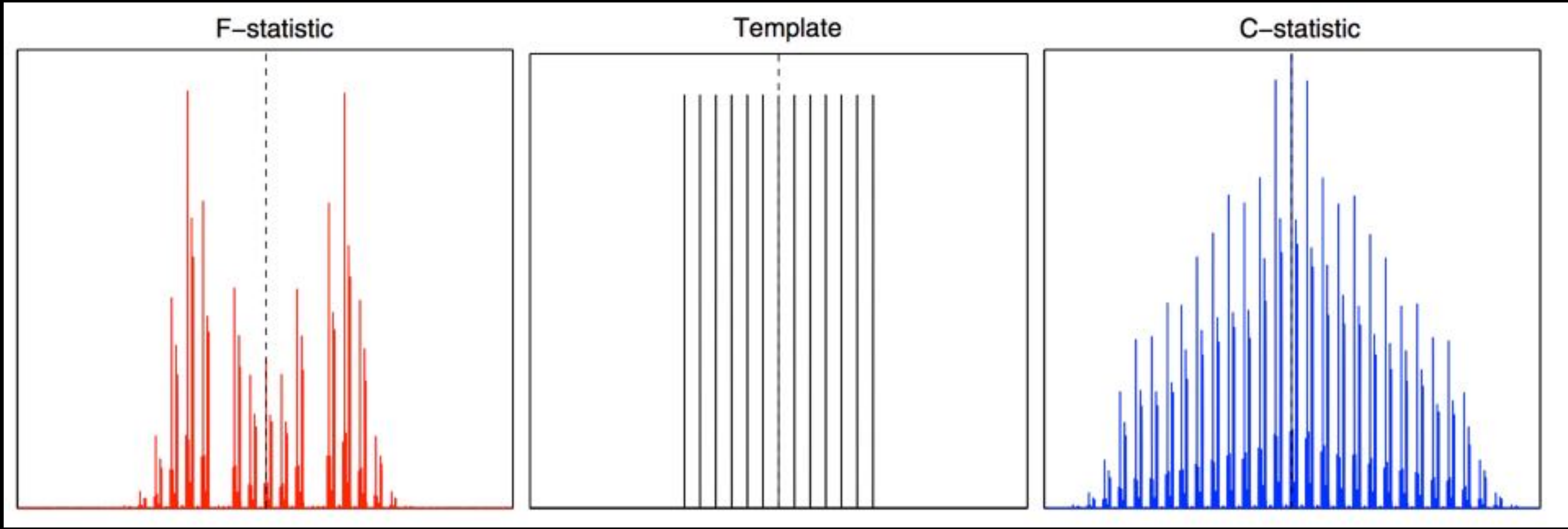


Image: An artist's impression of the Scorpius X-1 LMXB system
Credit: Ralf Schoofs

Low-mass X-ray binaries (LMXBs)
— Sideband search

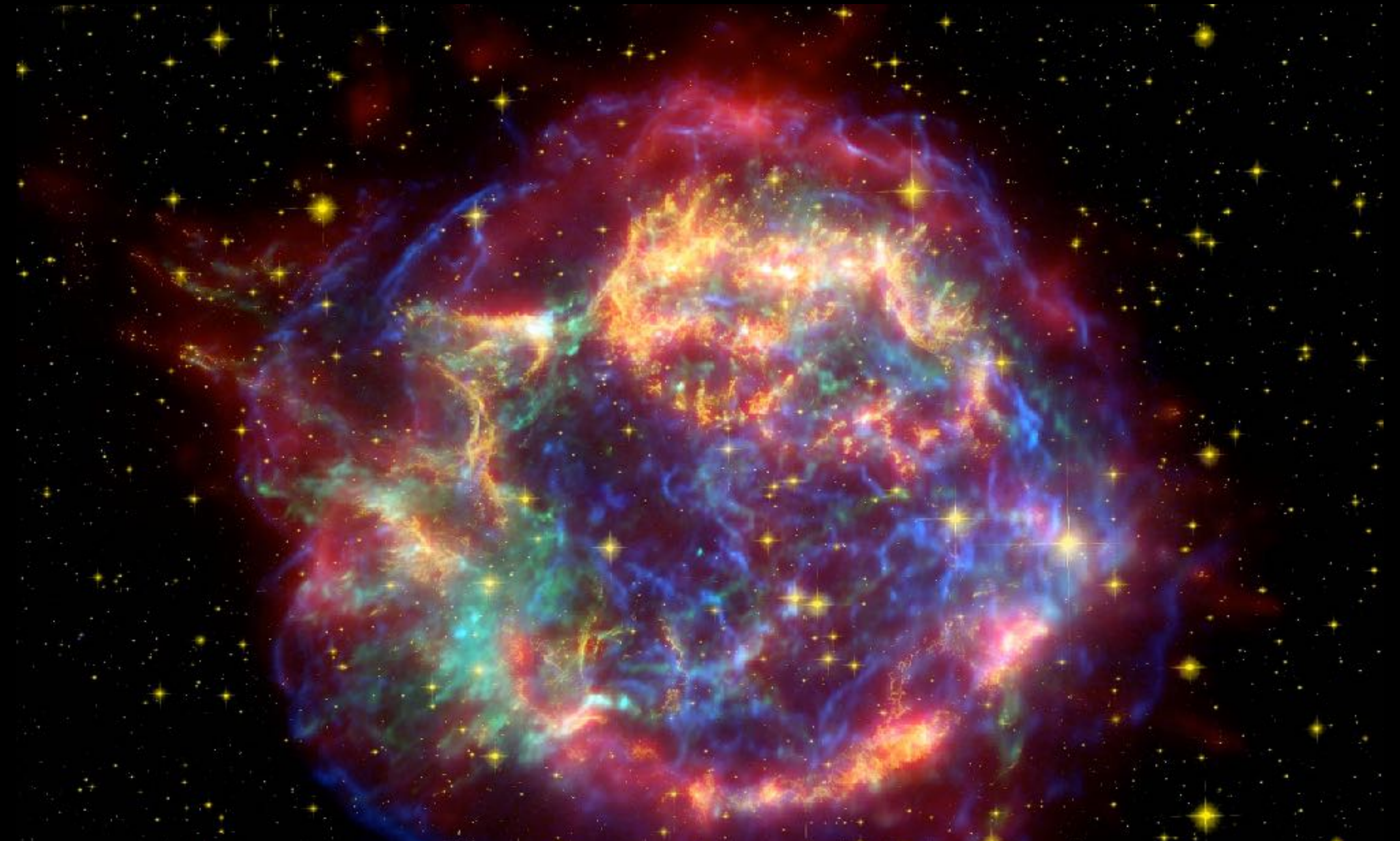
[3] Sun, Melatos, Sammut, LIGO-T1600457 (2016)

Sideband Search (Advanced LIGO O1)



Sammut et al., PRD 89, 043001 (2014)

- *Only search a 10-day data stretch (avoid the impact of spin wandering)*
- *The search was conducted using the Initial LIGO S5 data*
- *Less sensitive than HMM tracking*
- *O1 results improve on previously published S5 results by a factor of ~4*



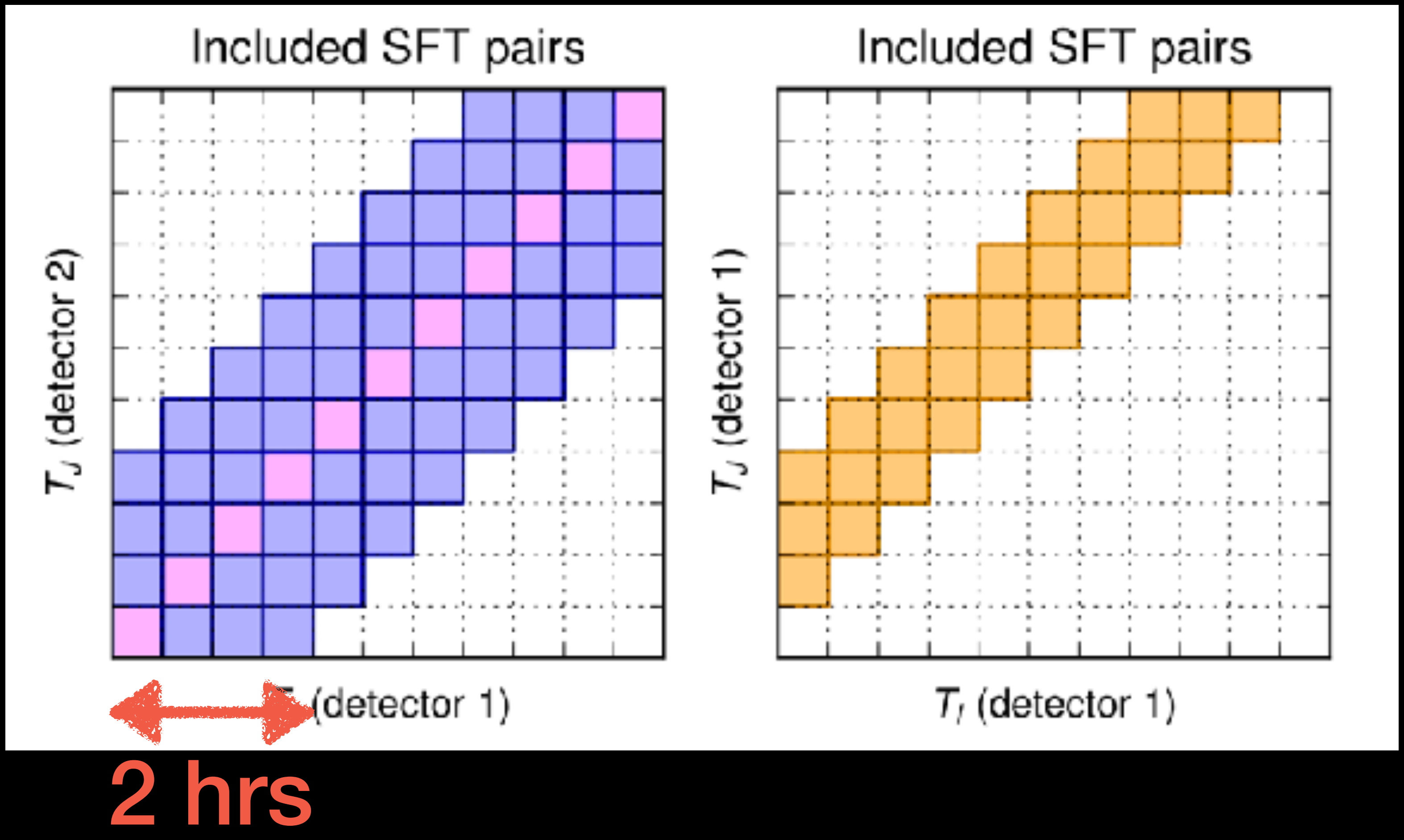
Young supernova remnants (SNRs)
— Cross-correlation search

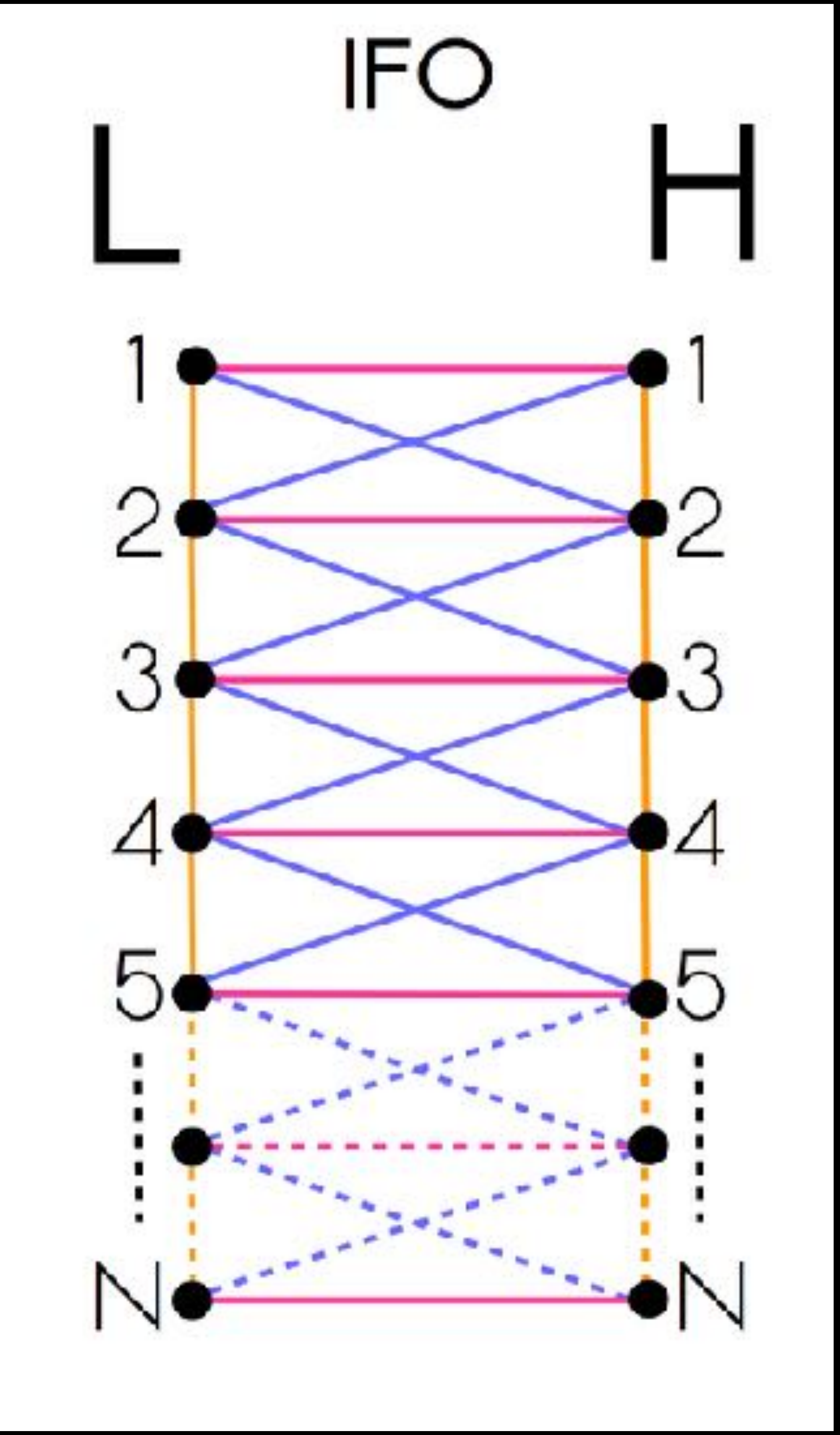
[4] Sun, Melatos, Lasky, Chung, Darman, Phys. Rev. D 94, 082004 (2016)

Cross-Correlation Method

- *A semi-coherent search strategy*
  (Dhurandhar et al. 2008; Chung et al. 2011)
- *Short Fourier Transform (SFT) segments (30 min) for long T_{obs} (1 year, 4 months, etc.)*

Credit: J. T. Whelan





Detection Statistic

- *SFTs are paired and multiplied*

$$\mathcal{Y}_{IJ} = \frac{\tilde{x}^*_{k_I,I}\tilde{x}_{k_J,J}}{(\Delta T)^2}$$

- *Detection statistic is a weighted sum of $\mathcal{Y}_{IJ}$ over all SFT pairs.*

$$\rho = \sum_{IJ}(\underbrace{u_{IJ}}\mathcal{Y}_{IJ} + u^*_{IJ}\mathcal{Y}^*_{IJ})$$

Weights - parameters of the source, including

1) Fast phase evolution terms (i.e. f, f’, etc.)
2) Slow functions of orientation (i.e. ψ, ι, etc.)

Phase Tracking for Young Target

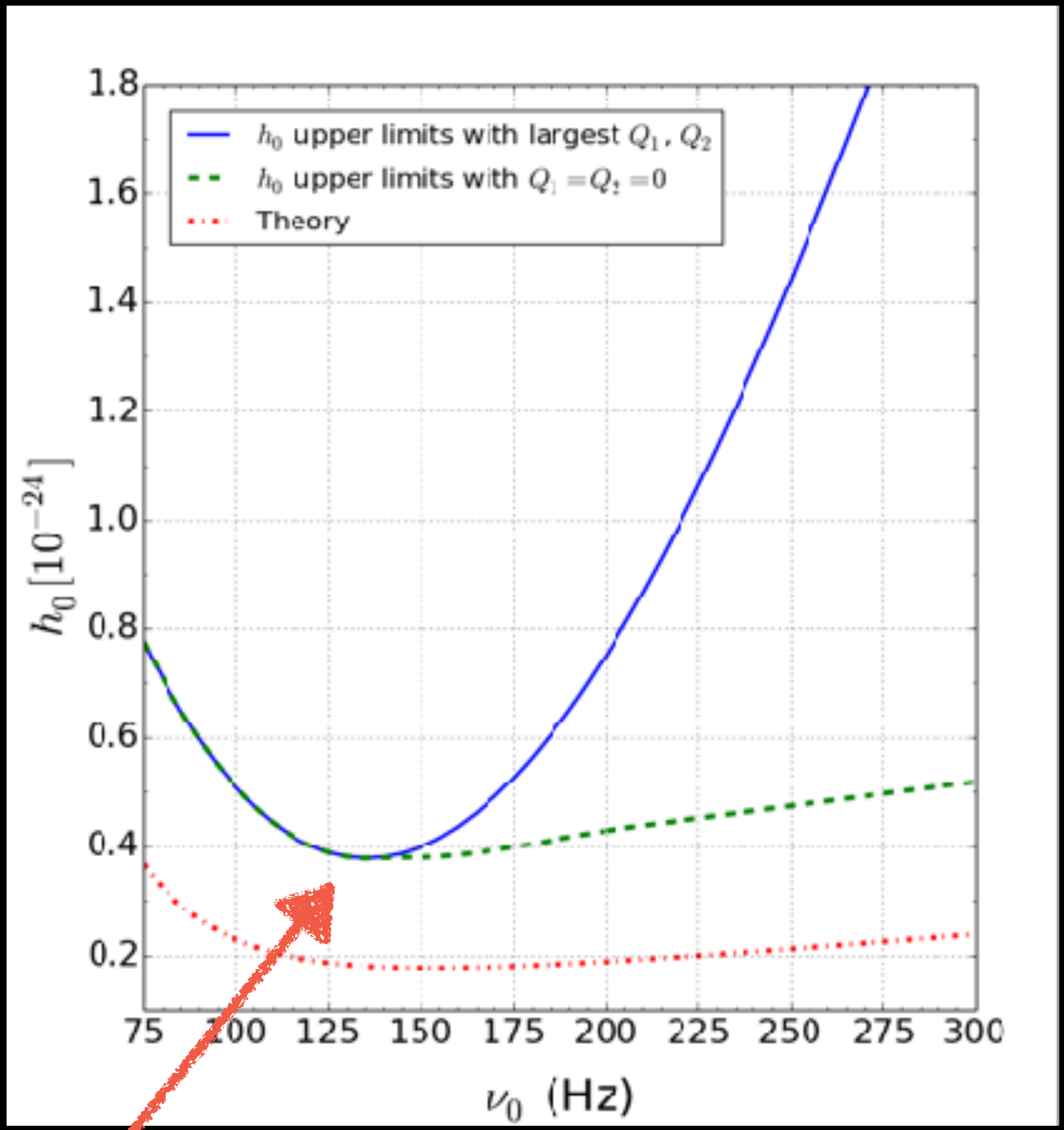
Search over $\{\nu_0, Q_1, Q_2, n\}$ ***instead of*** $\{\nu, \dot{\nu}, \ddot{\nu}, \dddot{\nu}, \cdots\}$

$$\boxed{\dot{\nu} = -Q_1 \nu^5 - Q_2 \nu^n}$$

$Q_1 \propto \epsilon^2$ ← ***Gravitational spin down***

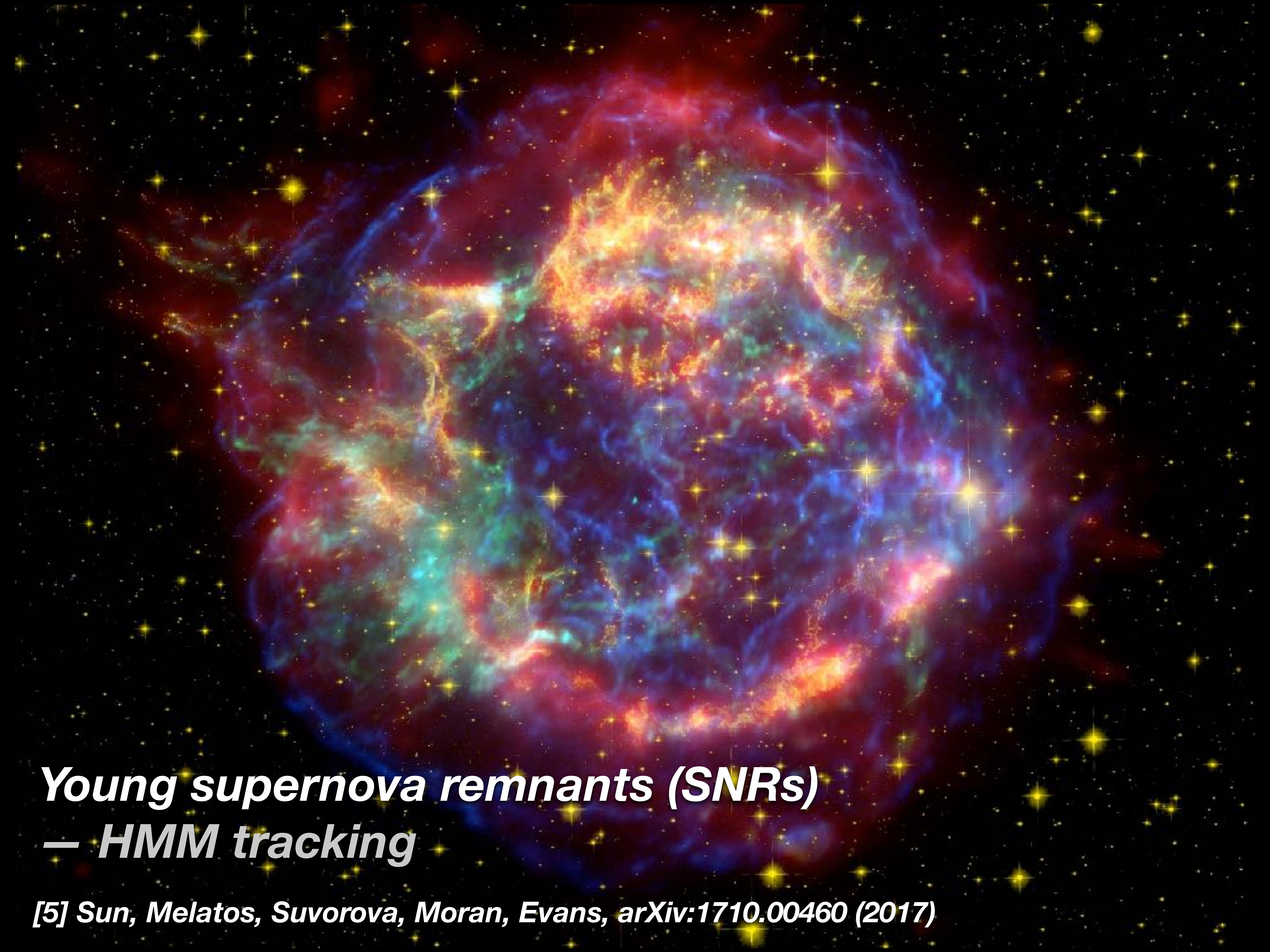
$Q_2 \propto B^2$ ← ***Electromagnetic spin down***

Cross-Correlation Search for SN 1987A (Initial LIGO S5)



Sun et al., 2016

- *Type II core-collapse supernova (February 1987)*
- *Large Magellanic Cloud (α = 5h 35m 28.03s, δ = –69∘16′11.79′′, d = 51.4 kpc.)*
- *Initial LIGO upper limit $h_0 \sim 3.8 \times 10^{-25}$*



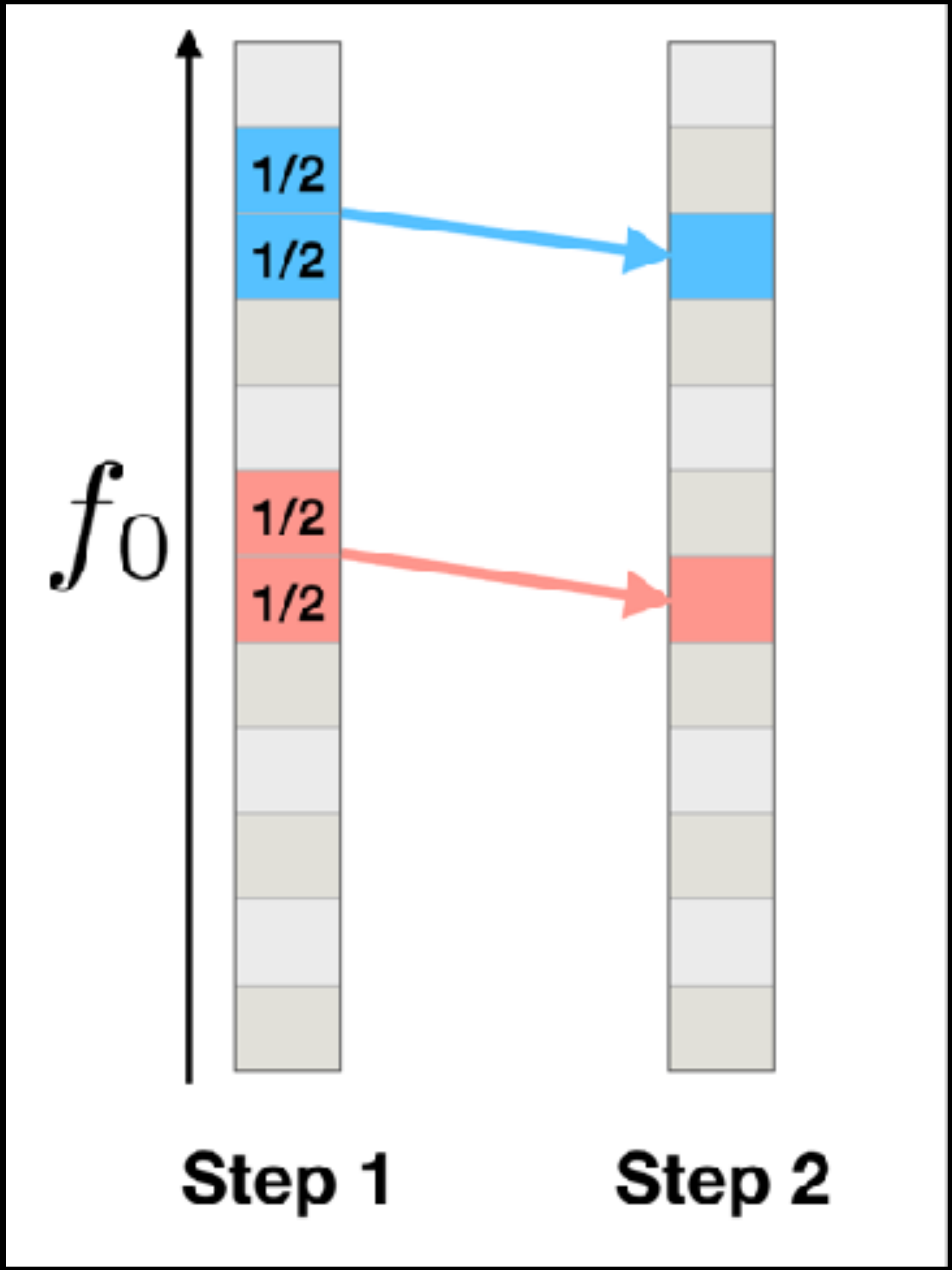
Young supernova remnants (SNRs)
— HMM tracking

[5] Sun, Melatos, Suvorova, Moran, Evans, arXiv:1710.00460 (2017)

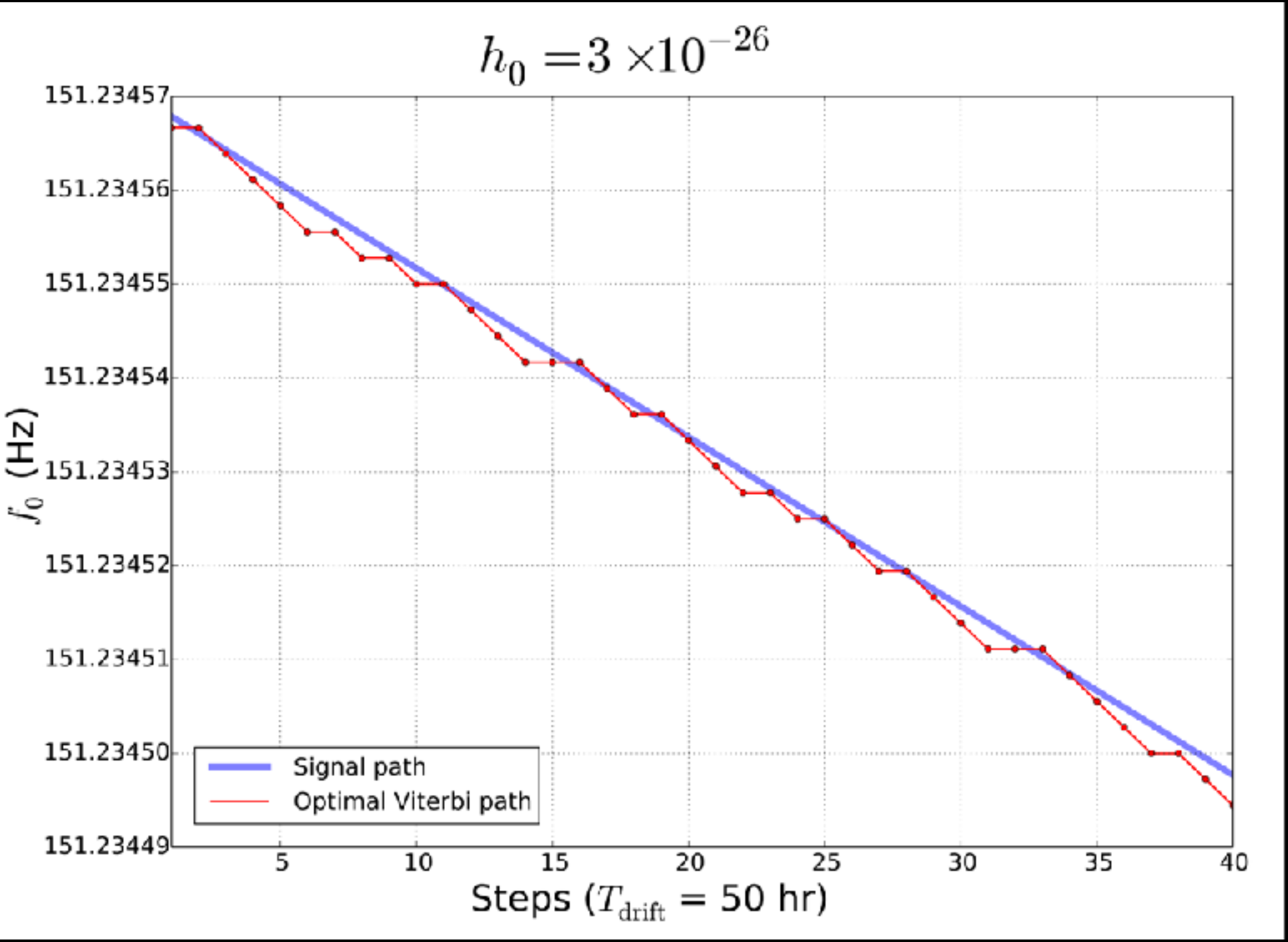
Frequency tracking

Weak spin wandering (timing noise)

- *Allow f_0 to move at most one bin over each step*
- *Short step size is required*
- *Emission probabilities: 1-D maximum likelihood estimator $\mathcal{F}(f_0)$*

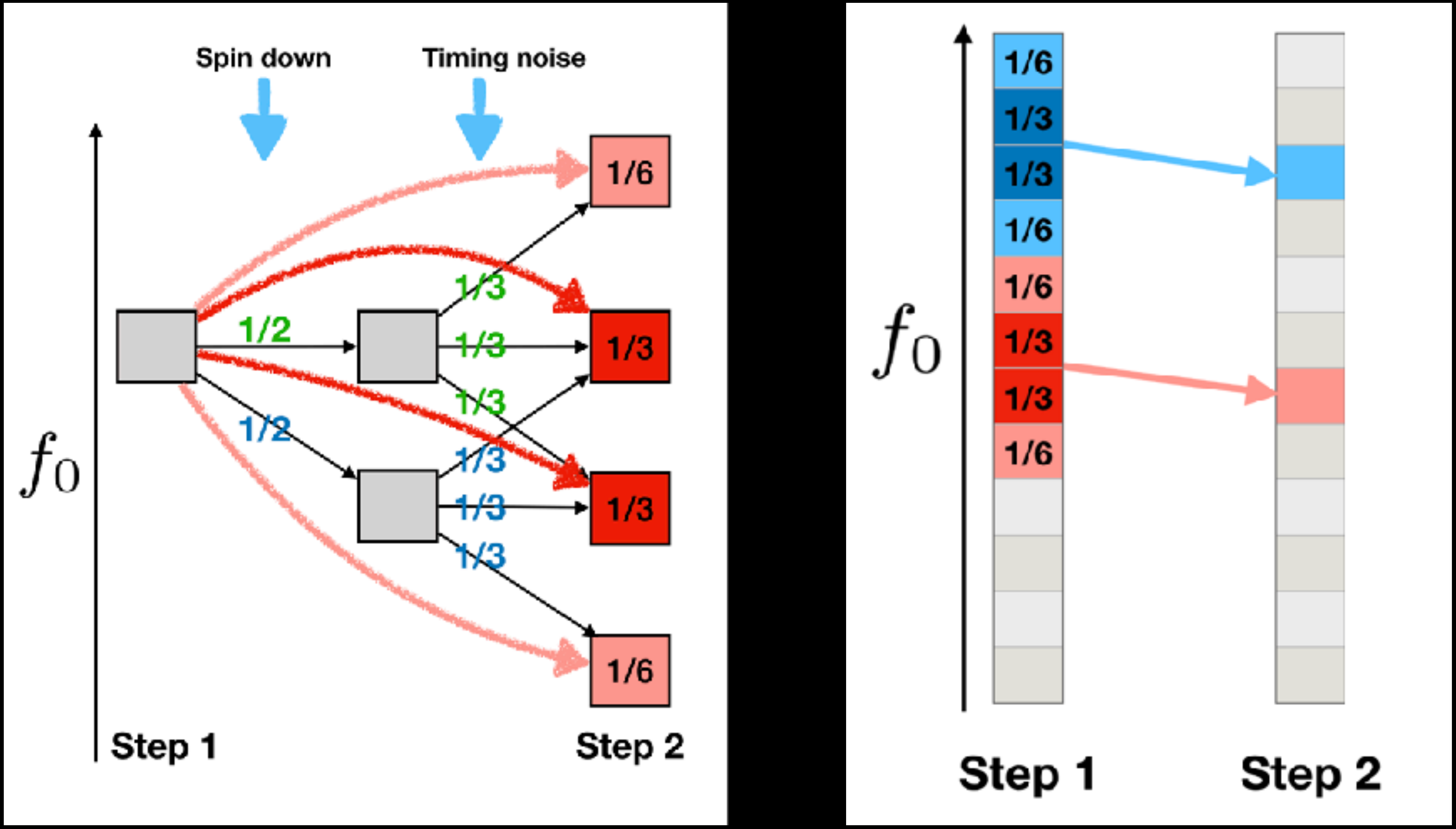


Tracking Example $|\dot{f}_0| \sim 10^{-11}\,\mathrm{Hz s}^{-1}$

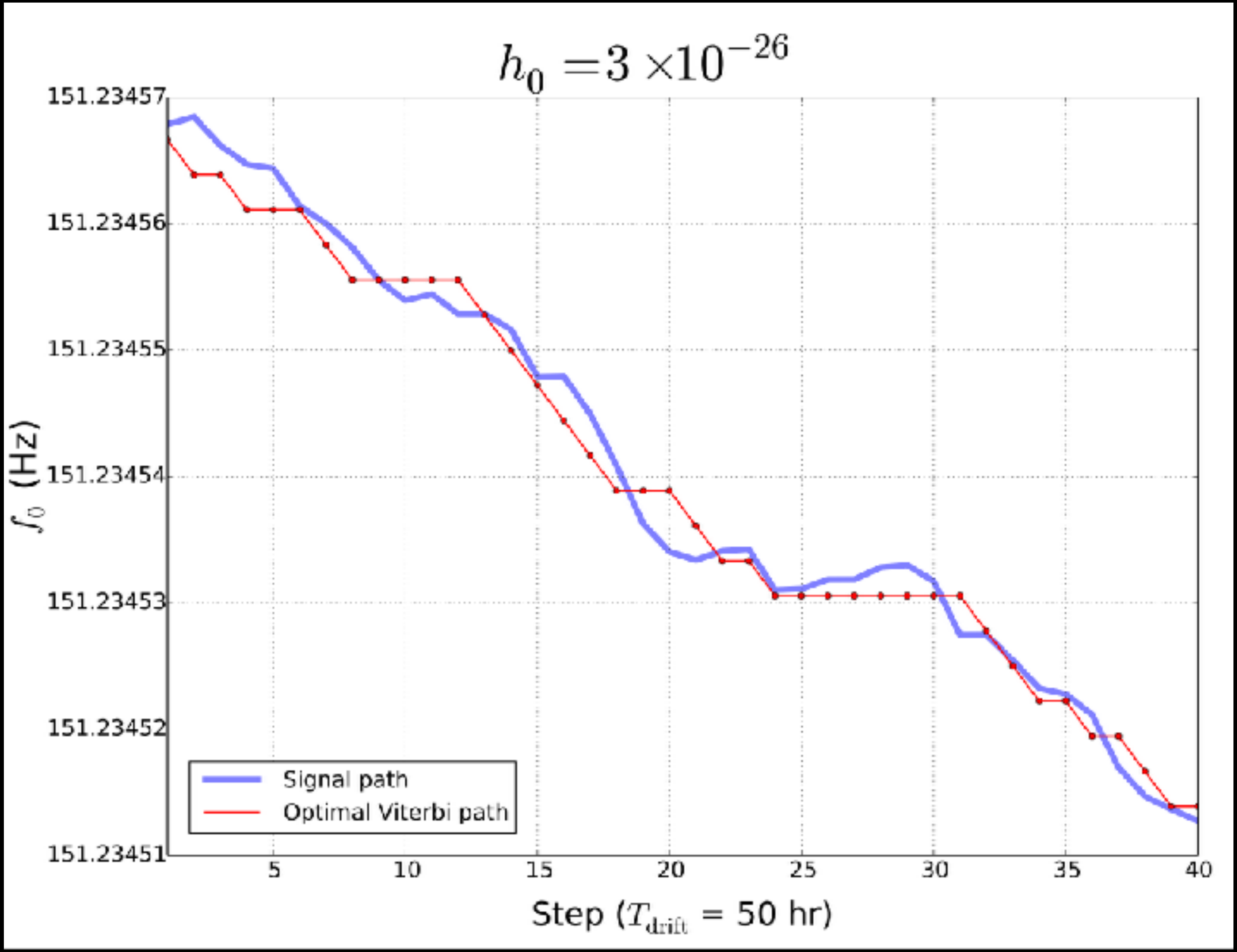


Frequency tracking

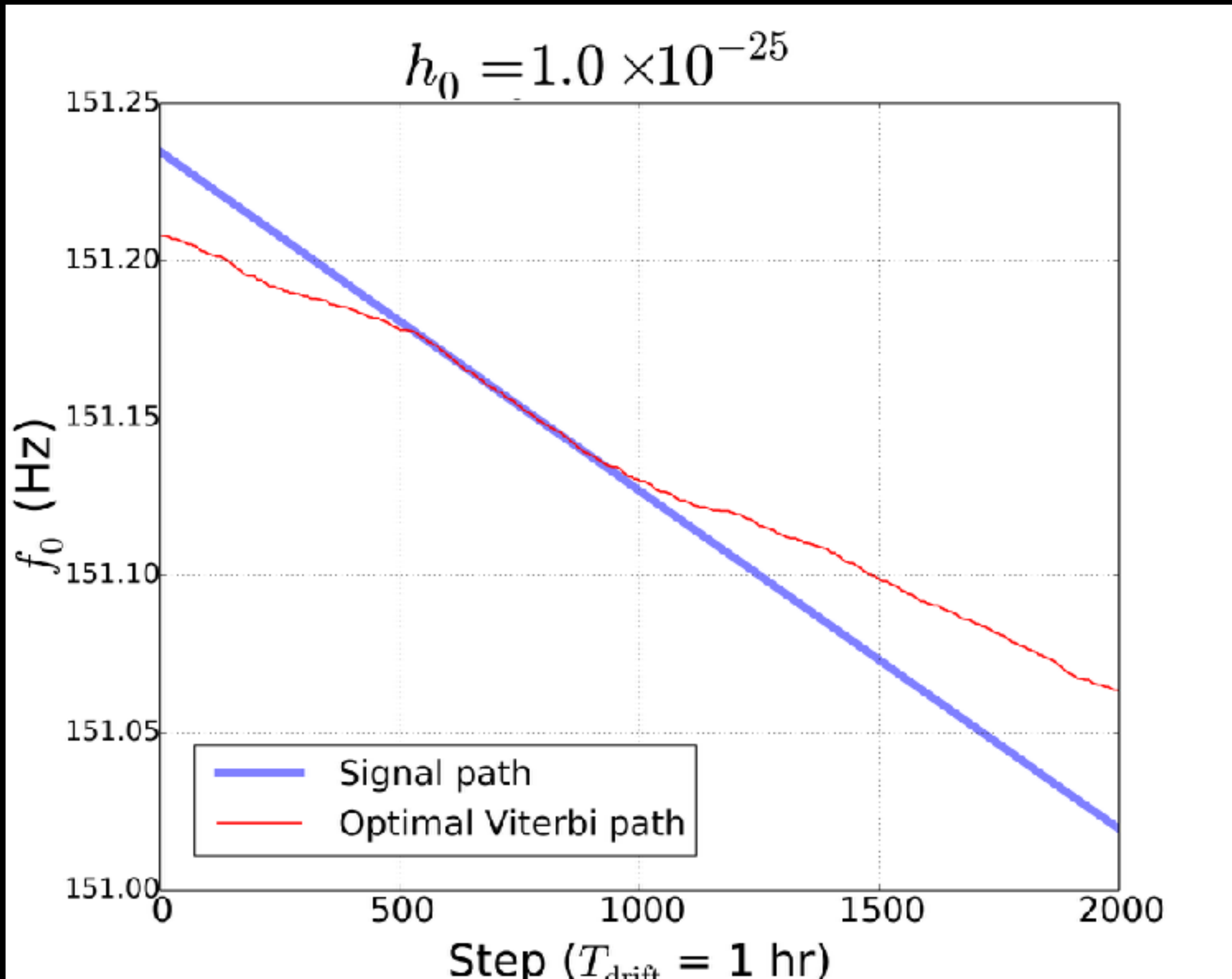
Strong spin wandering (timing noise)



Tracking Example $|\dot{f}_0| \sim 10^{-11}\,\mathrm{Hz s^{-1}}$

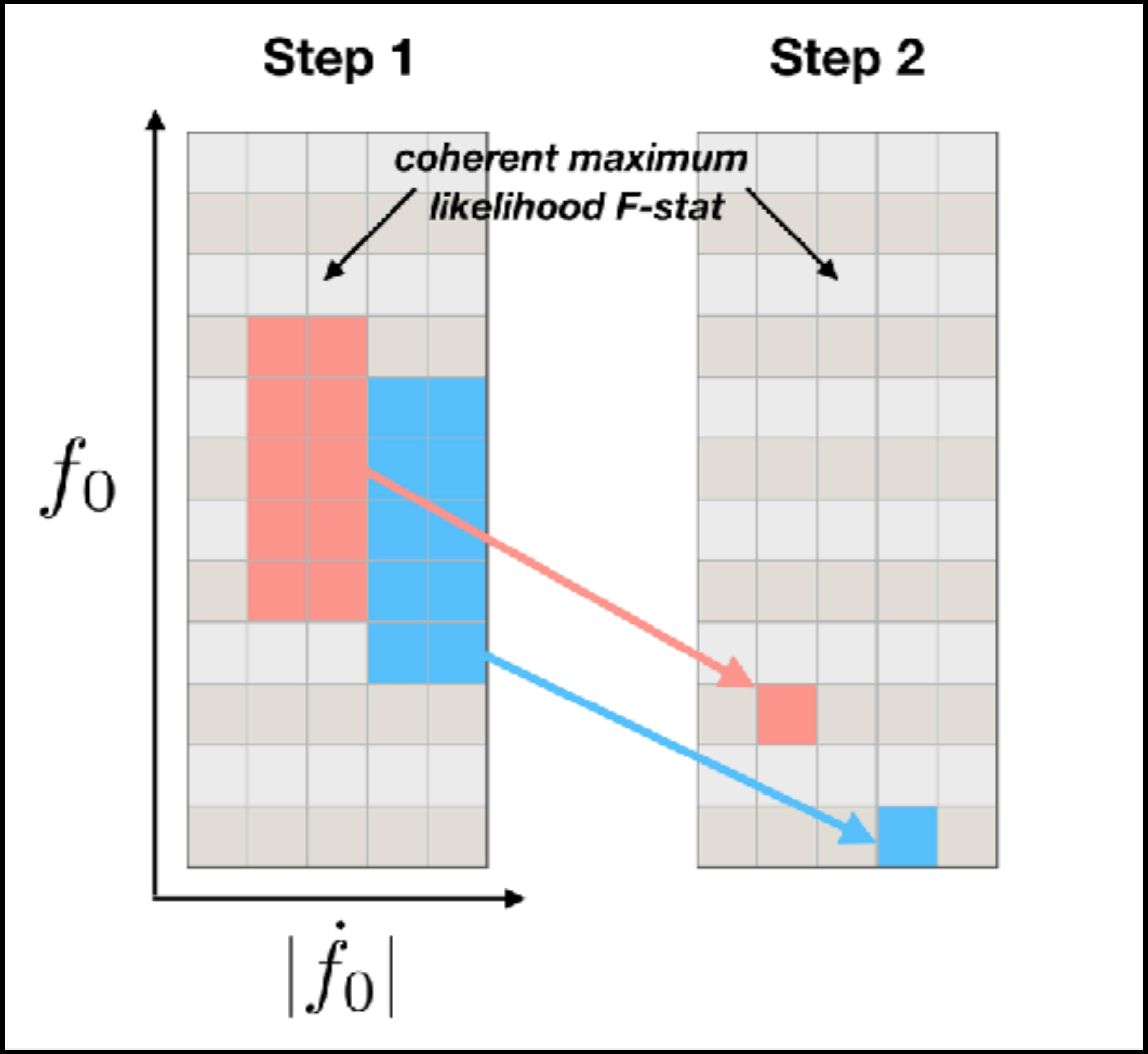


$|\dot{f}_0| \sim 10^{-8}\,\mathrm{Hz s}^{-1}$ ***Rapid spin down, negligible spin wandering***



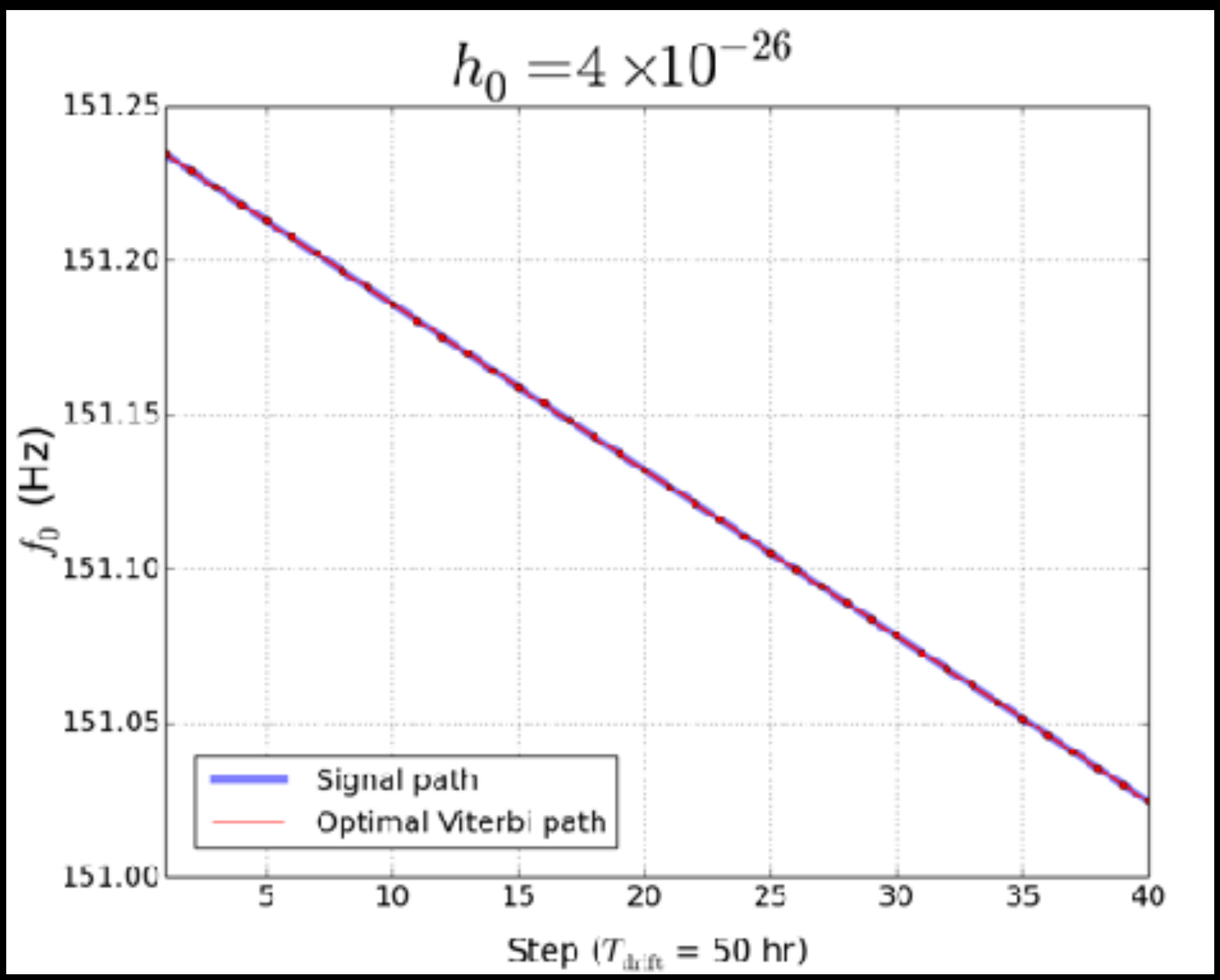
An alternative: 2-D $f_0, \dot{f}_0$ tracking

- Allow $\dot{f}_0$ to move at most one bin over each step
- Track limited frequency range according to $\dot{f}_0$
- Emission probabilities: 2-D maximum likelihood estimator $\mathcal{F}(f_0, \dot{f}_0)$



2-D Tracking Example

$$|\dot{f}_0| \sim 10^{-8}\,\mathrm{Hz s}^{-1}$$



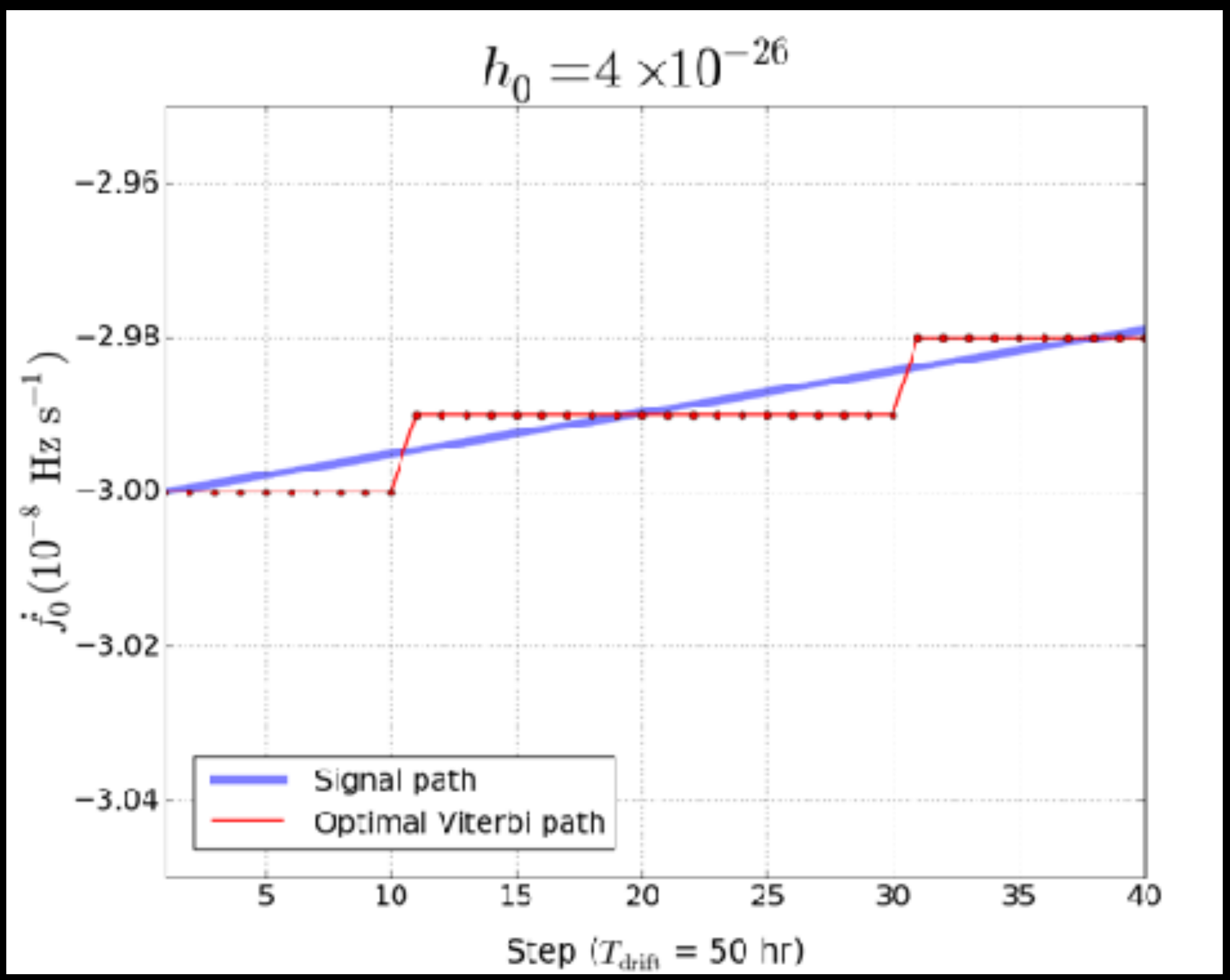


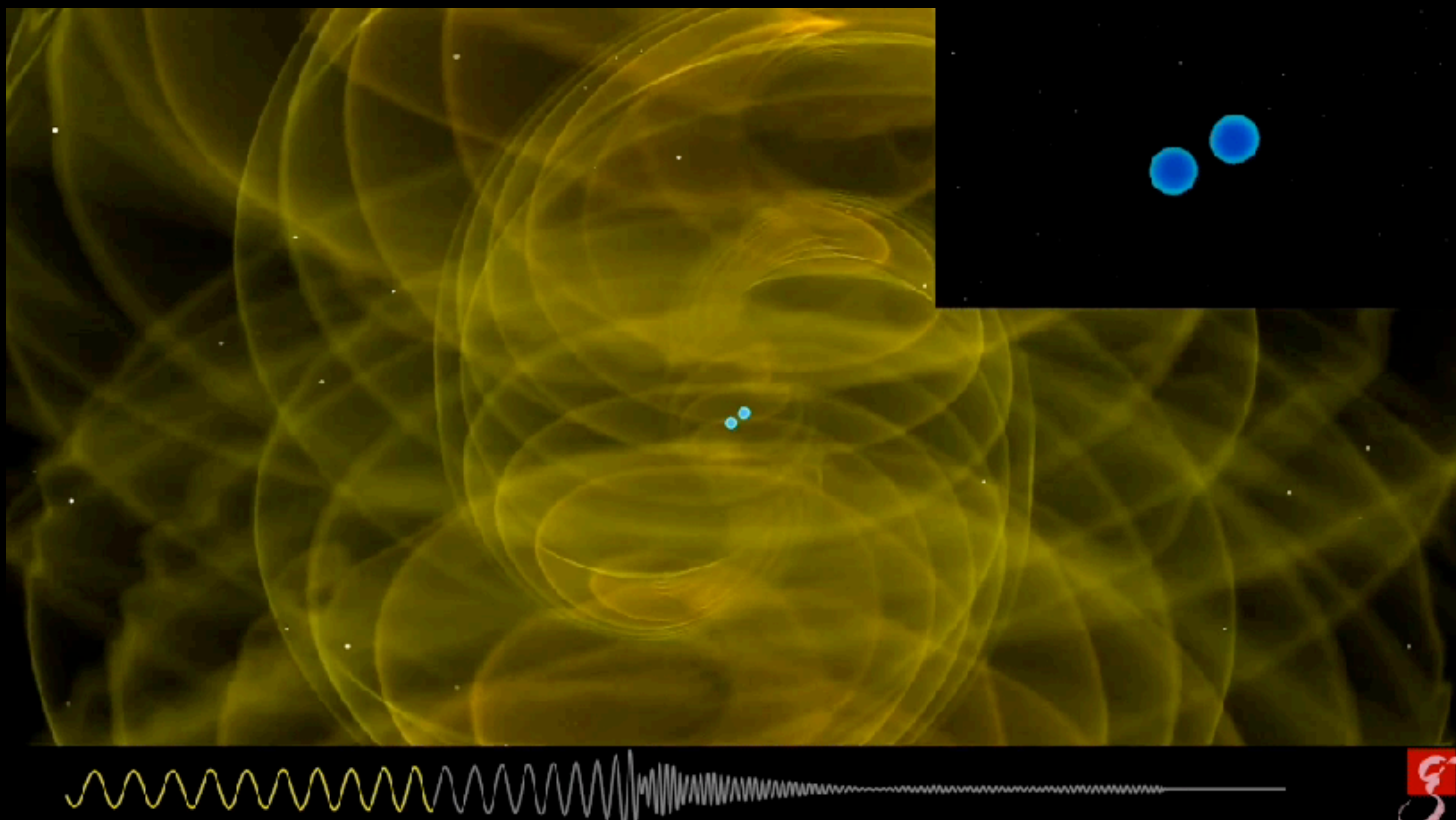
Image: Artist's illustration of two merging neutron stars. (Credit: NSF/LIGO/Sonoma State University/Aurore Simonnet)

GW170817 post-merger remnant — HMM tracking

[5] Sun, Melatos, Suvorova, Moran, Evans, arXiv:1710.00460 (2017)

What is left over after GW170817?

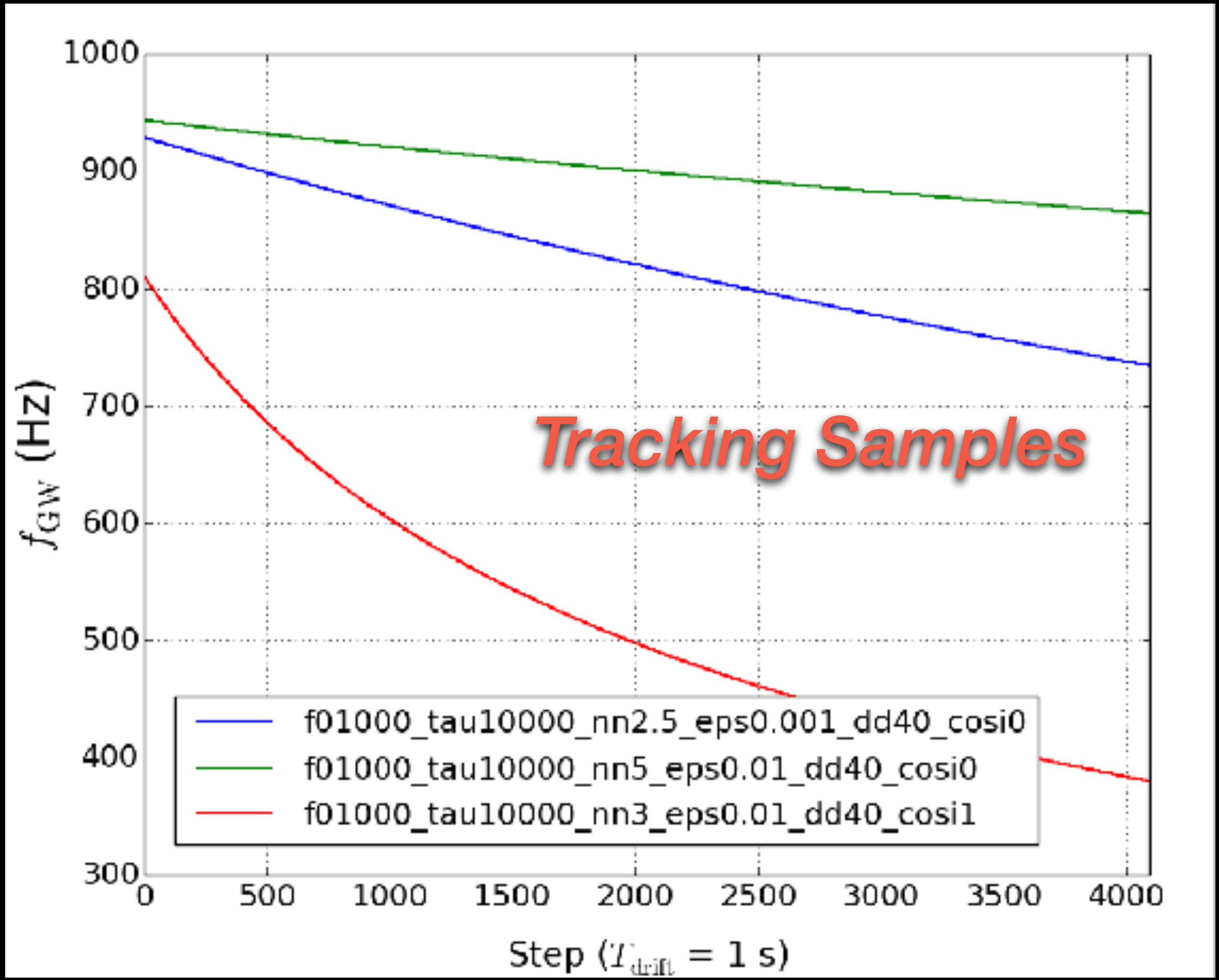
- Prompt formation of a BH
- Hypermassive NS that collapses to a BH in ~ < 1s
- Supramassive NS that collapses to a BH on timescales of ~10 – 10^4 s
- Formation of a stable NS



Credit: T. Dietrich, S. Ossokine, H. Pfeiffer, A. Buonanno/Max Planck Institute for Gravitational Physics/BAM collaboration

What is left over after GW170817?

- *HMM tracking can be readily applied to the post-merger search for long-duration quasi-CW signals (spin-down timescale ~10^2 — 10^4 s)*
- *Unmodelled search; allow the spinning-down signal to wander*
- *Use 1-sec SFTs to cope with the extremely rapid spin down*



Other contribution

- *Advanced LIGO O1 Hardware injection verification*
- *Test the front-end calibration*
- *HMM tracking for Sco X-1 v2.0 (led by Clearwater & Suvorova)*

[6] Biwer et al, Phys. Rev. D 95, 062002 (2017)

[7] Suvorova, Clearwater, Melatos, Sun, Moran, Evans, Hidden, arXiv:1710.07092, accepted for publication in PRD (2017)

Ongoing & Future work

- *Complete the GW170817 post-merger remnant search*
- *Further improve the methods, and search upcoming interferometer data*
- *Search other CW sources, e.g., ultralight boson cloud around a BH*
- *Extend my research to gravitational-wave physics more broadly*

Thanks!

Questions?

Credit: Joe McNally/Getty Images