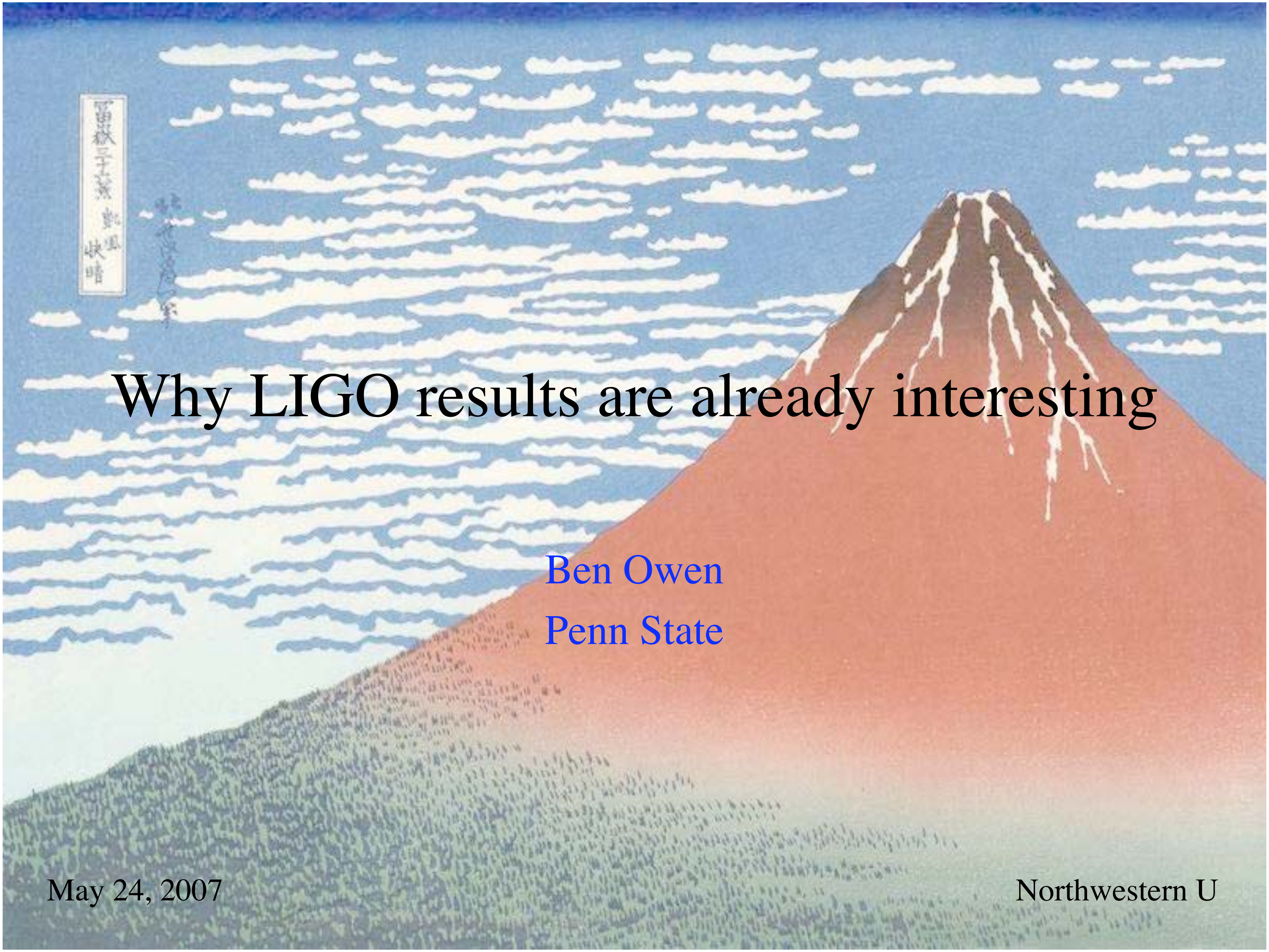

Why LIGO results are already interesting

Ben Owen
Penn State

May 24, 2007 Northwestern U

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Gravitational wave astronomy begins

- After decades of preparation, we've cracked open Einstein's window on the universe


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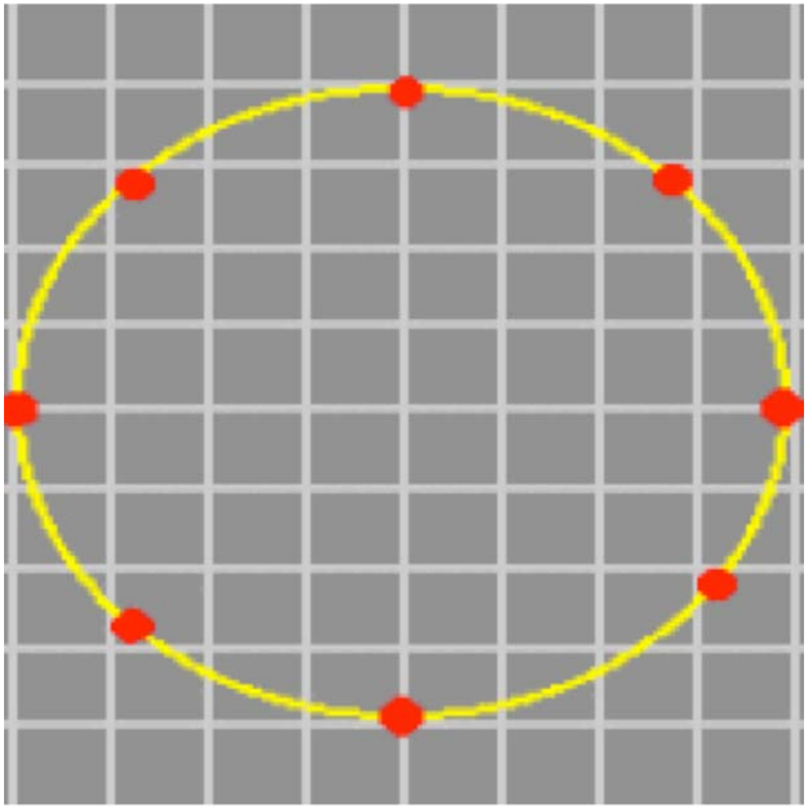
Gravitational wave astronomy begins

- After decades of preparation, we've cracked open Einstein's window on the universe (**gravitational waves**)
- Let's narrow it down to a single pane:
  - **LIGO** (other detectors: LISA, VIRGO, bars…)
  - **Neutron stars** (other sources: black holes, Big Bang…)
  - **Periodic signals** (others: inspirals, bursts, stochastic background)
- Types of **searches & how they work**
- What **upper limits** can say (now)
- What **detections** can say (sooner than we thought?)

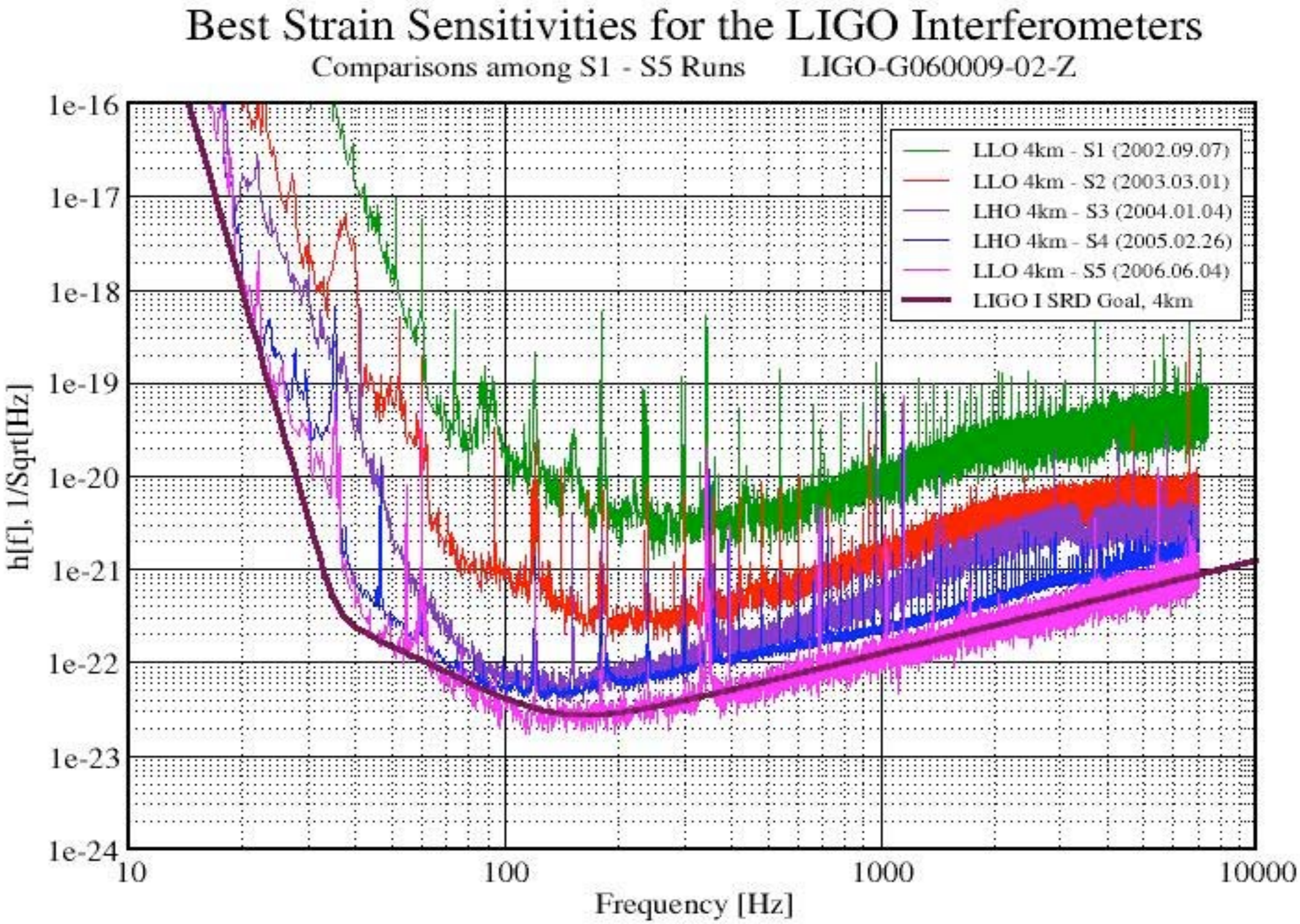
Gravitational waves



- Early prediction from **general relativity** (Einstein 1916)
- Travel at c; **shearing motion** perpendicular to propagation
- Borne out by Hulse-Taylor pulsar (1993 Nobel Prize)
- (LIGO funded 1994…)
- Sourced by changing **quadrupole moment**
- Very **weak coupling to matter** means strain $h < 10^{-22}$

LIGO: The Laser Interferometer Gravitational-wave Observatory

Image: LIGO/Caltech



Best Strain Sensitivities for the LIGO Interferometers
Comparisons among S1 - S5 Runs LIGO-G060009-02-Z
LLO 4km - S1 (2002.09.07)
LLO 4km - S2 (2003.03.01)
LHO 4km - S3 (2004.01.04)
LHO 4km - S4 (2005.02.26)
LLO 4km - S5 (2006.06.04)
LIGO I SRD Goal, 4km
h[f], 1/Sqrt[Hz]
1e-16
1e-17
1e-18
1e-19
1e-20
1e-21
1e-22
1e-23
1e-24
10
100
1000
10000
Frequency [Hz]

When does LIGO get interesting?

- Advanced LIGO: planned start **2014** (not full sensitivity?)
  - 10× better strain down to 4× lower frequencies
  - Multiple NS/NS binaries predicted per year (Kalogera's group) - if this doesn't see anything, it's even more interesting than if it does!
- Enhanced LIGO: small upgrade, restart **2009**
  - About 2× better strain with astrophysical payoffs despite down time (Nutzman et al ApJ 2004, Owen CQG 2006)
- Initial LIGO: S5 to **end fall 2007** (1yr 3× coincidence)
  - S1 to S4 data: 25 Abbott et al papers (2 PRLs) + several in prep.
  - S5 data: Several in prep. including ApJL & PRL
  - Even **now** could see something, so upper limits are interesting!

Indirect limits on gravitational waves

- Direct limits always interesting, more so if we beat these:
  - (some discussion in Abbott et al gr-qc/0605028)
- Spindown limit (*f* and *df/dt* observed):
  - Assume all *df/dt* due to GW emission: $h_{\rm IL} \propto D^{-1}\sqrt{I(df/dt)/f}$
- Age-based limit (no *f* or *df/dt*):
  - Same assumption means *t=f/(4df/dt)*: $h_{\rm IL} \propto D^{-1}\sqrt{I/t}$
- Accretion-torque limit (low mass x-ray binaries):
  - GWs balance accretion torque: $h_{\rm IL} \propto \sqrt{F_x/f}$
- Supernova limit (the 10^9 neutron stars we don't see):
  - Assume galaxy is a plane: $h_{\rm IL} \propto \sqrt{R_{\rm SN}}$

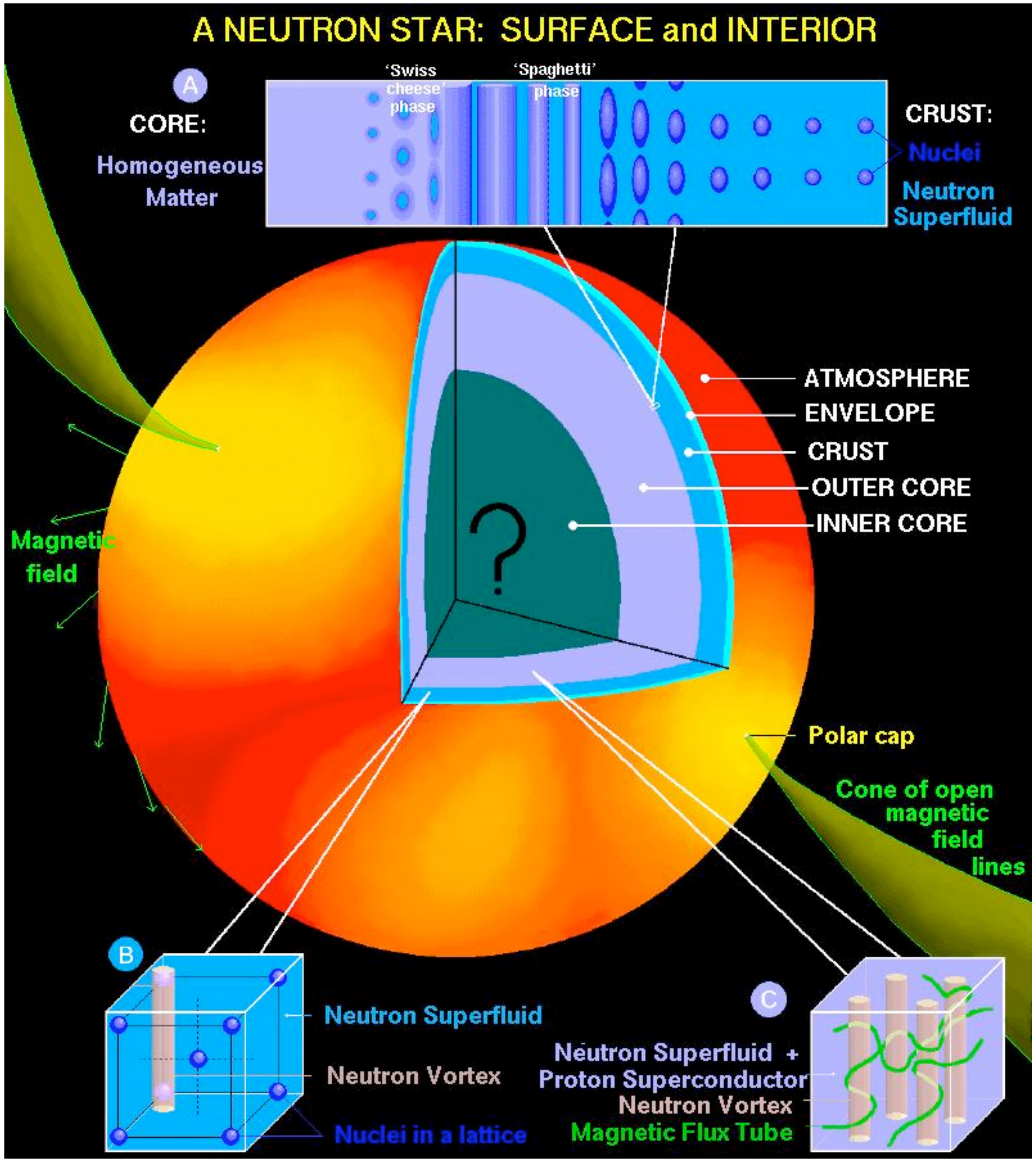


Image: Dany Page

Gravitational waves from mountains

- How big can they be? (Owen PRL 2005)
  - Depends on structure, **shear modulus** (increases with density)
  - Put in terms of **ellipticity** $\varepsilon = (I_{xx}-I_{yy})/I_{zz} \sim \Delta R/R$
- Standard neutron star
  - Ushomirsky et al MNRAS 2000
  - **Thin crust**, < 1/2× nuclear density: $\varepsilon <$ few$\times 10^{-7}$
- Mixed phase star (quark/baryon or meson/baryon hybrid)
  - Glendenning PRD 1992 … Phys Rept 2001
  - **Solid core** up to 1/2 star, several× nuclear density: $\varepsilon < 10^{-5}$
- Quark star (ad hoc model or color superconductor)
  - Xu ApJL 2003 …, Mannarelli et al hep-ph/0702021
  - **Whole star solid**, high density: $\varepsilon <$ few$\times 10^{-4}$

Gravitational waves from normal modes

- P-modes, t-modes, w-modes…
- Most fun are **r-modes**
- Subject to **CFS instability** (grav. wave emission)
- Could be kept alive in **accreting neutron stars**… (…and explain their spins…) (Stergioulas Living Review)
- Persistent gravitational wave emission is a robust prediction if **strange matter in core** (hyperons, kaons, quarks)

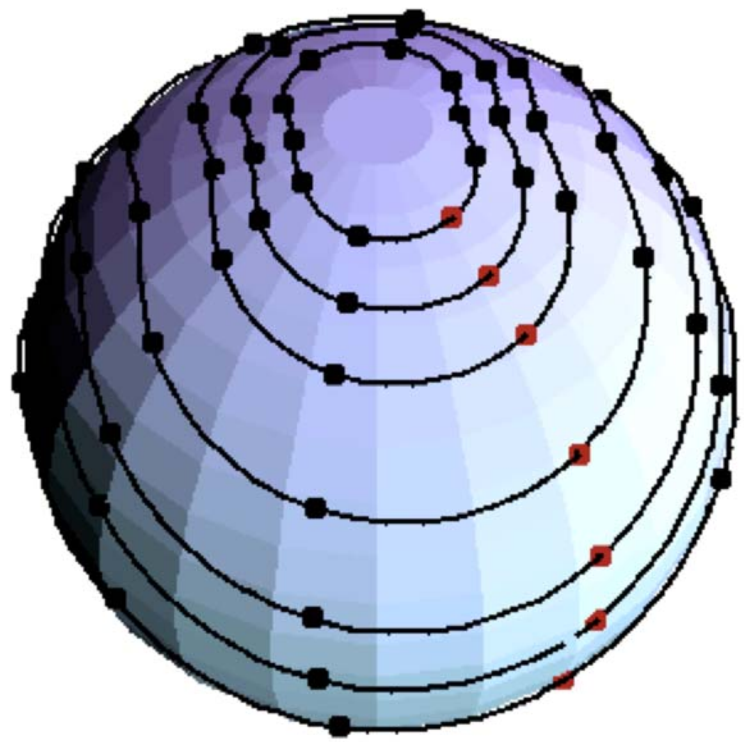
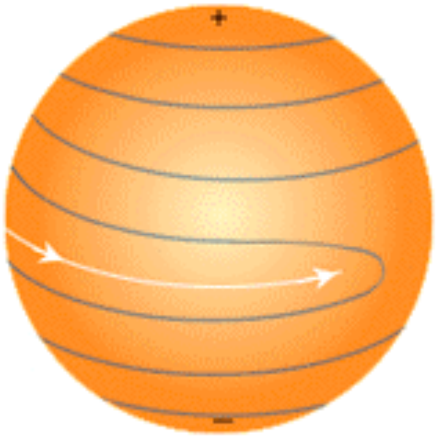
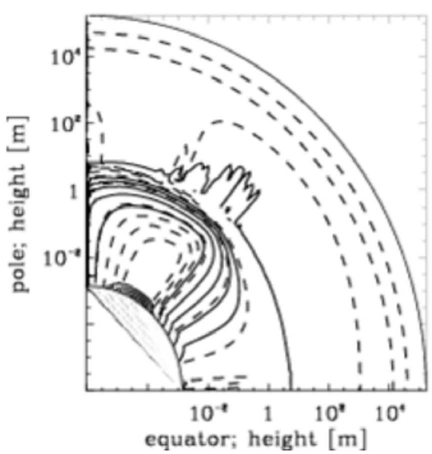


Image: Chad Hanna & Ben Owen

Gravitational waves from B fields



- Differential rotation (young NS) makes **toroidal B-field**
- Instability makes field axis leave rotation axis (Jones 1970s)
- Ellipticity 10^{-5} good for GWs (Cutler PRD 2002)



- Accreting NS: **B-field funnels** infalling matter to magnetic poles
- Could sustain ellipticity of 10^{-5} (Melatos & Payne 2000s)
- Smeared spectral lines as mountains quiver

Data analysis for periodic signals

- Intrinsic frequency drift is slow except for occasional glitches
- Can use **matched (optimal) filtering** or equivalent
- Time-varying **Doppler shifts** due to Earth's motion
- Integrate time T, coherently build signal-to-noise as $T^{1/2}$
- Computational cost scales (usually) as several powers of T
- **Searches defined by data analysis challenges** (most need sub-optimal techniques)

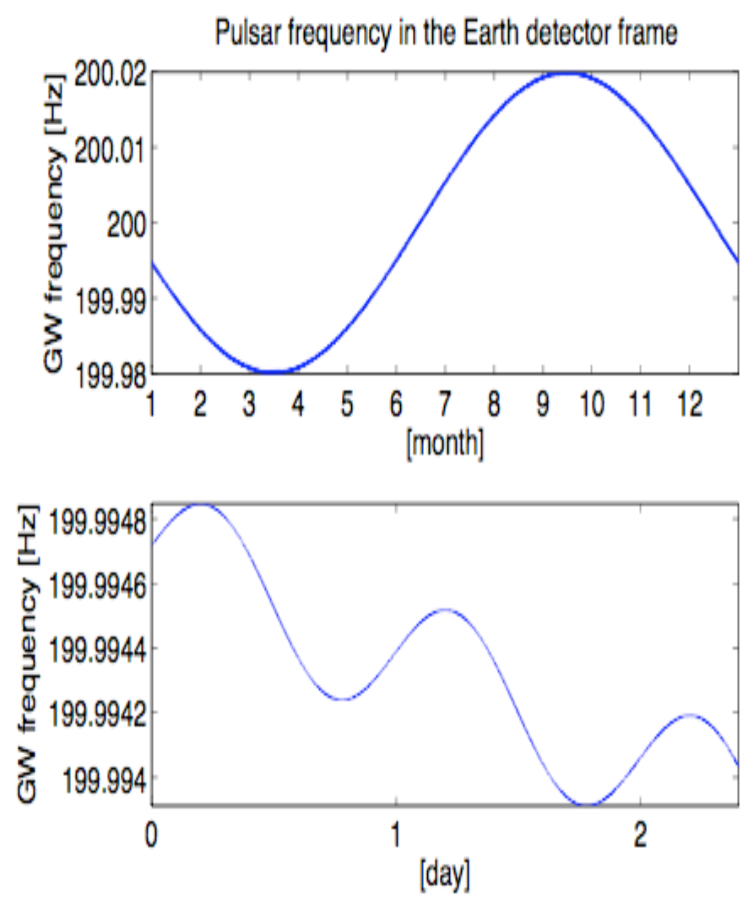


Image: Einstein@Home

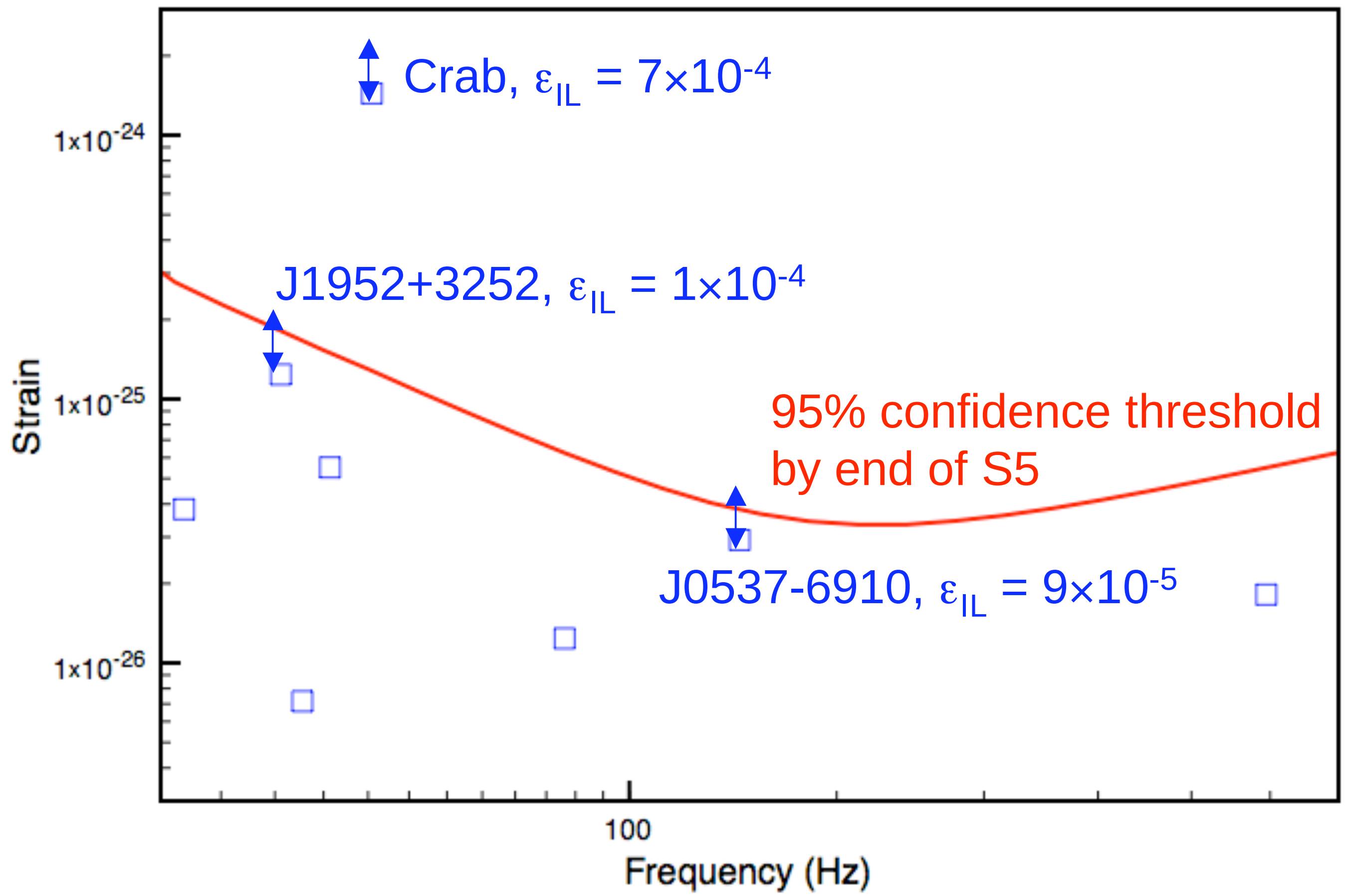
Periodic signals: Four types of searches

- Known pulsars
  - **Position & frequency evolution known** (including derivatives, timing noise, glitches, orbit) ➔ Computationally inexpensive
- Unseen neutron stars
  - **Nothing known**, search over position, frequency & its derivatives ➔ Could use infinite computing power, must do sub-optimally
- Accreting neutron stars
  - **Position known**, search over orbit & frequency (+ random walk)
  - Emission mechanisms ➔ different indirect limit
- Non-pulsing neutron stars ("directed searches")
  - **Position known**, search over frequency & derivatives

LIGO searches for known pulsars

- What we've published: (with Kramer & Lyne)
  - Limits on 1 pulsar in S1: Abbott et al PRD 2004
  - Limits on 28 pulsars in S2: Abbott et al PRL 2005
  - Limits on 78 pulsars in S3 & S4: Abbott et al gr-qc/0702039
- What we're doing (S5):
  - Same + **more pulsars** (and more pulsar astronomers!)
  - **Crab** search allowing **timing difference** between EM & GW
- When it's interesting:
  - **Last year!** Beat the **spindown limit** $h_{IL} \sim 1.4\times10^{-24}$ on the Crab (assuming EM & GW timing are the same)
  - Even allowing 2.5 for **braking index** (Palomba A&A 2000)
  - If there's a high mountain (**solid quark matter**)…

LIGO searches for known pulsars



LIGO searches for unseen neutron stars

- What we've published:
  - S2 10 hours coherent search (Abbott et al gr-qc/0605028)
  - S2 few weeks "Hough transform" search (Abbott et al PRD 2005)
- What we're doing:
  - S4 & S5 with incoherent methods: PowerFlux, Hough, stack-slide
  - **Einstein@Home** (http://einstein.phys.uwm.edu) now on S5 - analyze LIGO data with your screensaver!
- When it's interesting:
  - **Supernova limit** roughly $h_{IL} \sim \text{few}\times 10^{-24} \sim \text{few}\times\text{Crab}$
  - Ellipticity cancels out of that limit, but matters w/realistic distribution of NS clustered towards galactic center
  - Nearing it in narrow band (CPU cost - **download Einstein@Home!**)

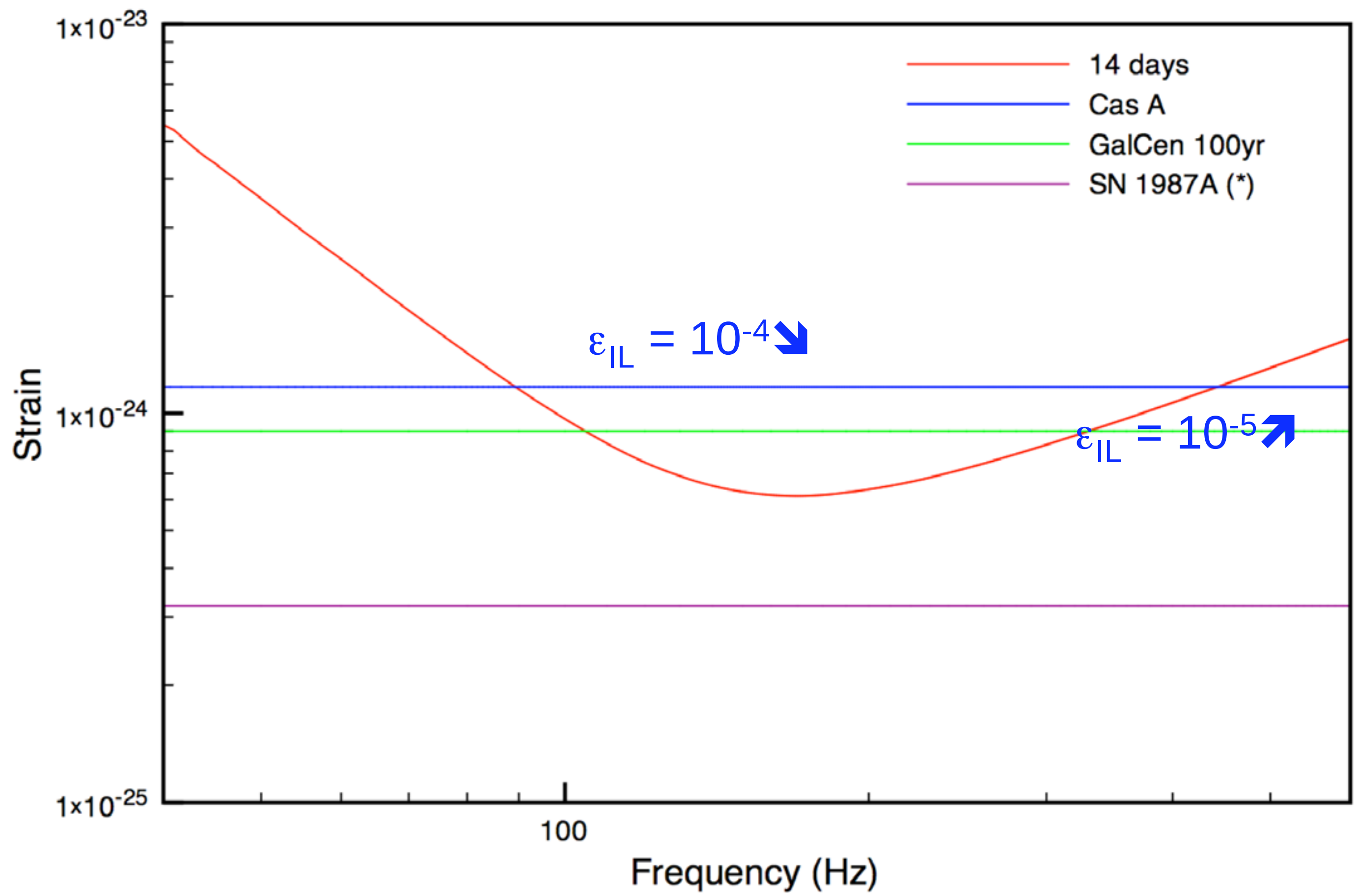
LIGO searches for accreting neutron stars

- What we've published:
  - S2 6 hours coherent **Sco X-1** (Abbott et al gr-qc/0605028)
  - S4 **Sco X-1** with "radiometer" (Abbott et al astro-ph/0703234)
- What we're doing:
  - Considering other sources (accreting millisecond pulsars)
  - Talking to **RXTE** people about timing
  - Cheering India for launching a satellite! (**AstroSat**)
- When it gets interesting:
  - **Sco X-1** is brightest x-ray source, $h_{IL} = \text{few}\times 10^{-26}$: advLIGO only
  - But it's much more likely to be radiating at the indirect limit!

LIGO searches for non-pulsing neutron stars

- What we're doing:
  - **Cas A** (youngest known object)
  - **Galactic center** (innermost parsec, good place for unknowns)
- When it gets interesting:
  - **Cas A** has $h_{IL} \sim 1.2\times10^{-24} \sim 1$ Crab
  - Preliminary results by GR18/Amaldi (July)
- How photon astronomers can help:
  - Narrow positions on suspected neutron stars (ROSAT➔Chandra)
  - Think of regions we're more likely to find something young
  - Where do we look?

LIGO searches for non-pulsing neutron stars



What can we learn from detections?

- Any detection is a big deal for physics - but astronomy?
- Signal now ➔ **high ellipticity** ➔ **exotic form of matter**
  - Which one? Could constrain with more theory work
- **EM vs. GW timing** tells us about emission mechanisms, **core-magnetosphere coupling**
- Accreting stars: **ratio of GW/spin frequency** tells us
  - Whether **emission mechanism** is mountain (2) or r-mode (~ 4/3)
  - If r-mode, precise ratio gives info on **equation of state**
  - If r-mode, star must have some kind of **strange matter** (hyperons, quarks, kaon condensate, mixed phase) to stay in equilibrium

What can we learn from upper limits?

- The obvious: “This star has **no mountains** higher than X”
  - Can’t say: “This star is not a strange star” - many stars could be flatter than the maximum (see millisecond pulsars)
- But with **accumulation of observations** - and work on mountain-building theory - we could **argue against a model**
- **Population constraints** with all-sky search
- Accreting stars: limits on **Alfven radius** of magnetosphere (assuming GW responsible for spin regulation)

Conclusions

- GW astronomy has started (in a small way) ***now***
- We can do more with initial LIGO with more help from photon astronomers
- More work on theory & its interface with observation is needed to take full advantage of present data, let alone prepare for advanced LIGO

- **Don't wait for advanced LIGO!**