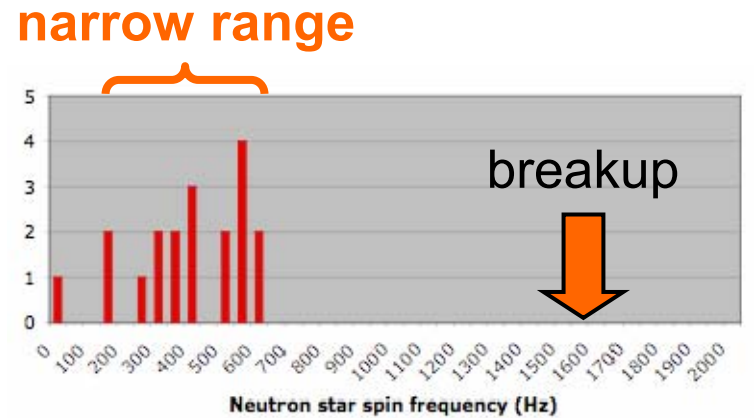
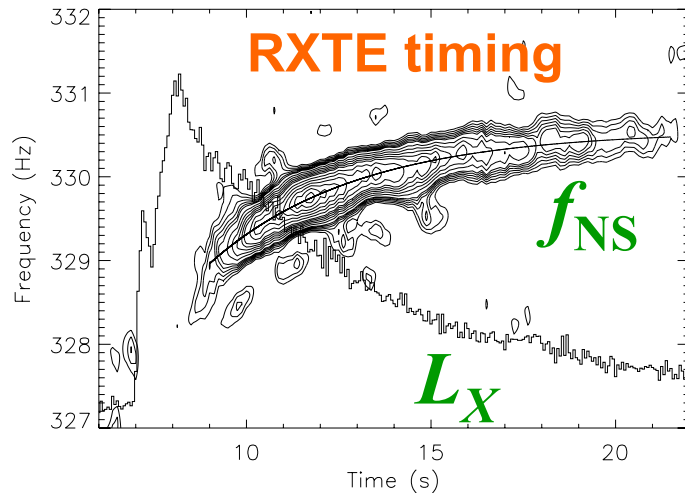


GRAVITATIONAL WAVES FROM ACCRETING NS

A. Melatos, D. Payne, C. Peralta, M. Vigelius
(U. Melbourne)

1. X-ray timing → LMXB spins → GW “stalling”
→ promising **kHz sources!**
2. Thermal mountains & r-modes
- 3. Magnetic mountains:** GW spectrum
4. Precession & superfluid circulation

NS SPINS IN LMXBs



- Low-mass $\sim M_{\text{Sun}}$ X-ray binaries: disk accretion
- **kHz oscillations** in thermonuclear X-ray bursts
- Simultaneous pulses \rightarrow **stellar spin**
- Much slower than breakup (Chakrabarty et al. 03)

GW “STALLING”

- **GW torque** $\propto \varepsilon^2 f^5$ balances **accretion torque** $\propto (dM/dt) R_{\text{disk}}^{1/2}$ (Wagoner 84; Bildsten 98)
- Minimum **quadrupole moment**

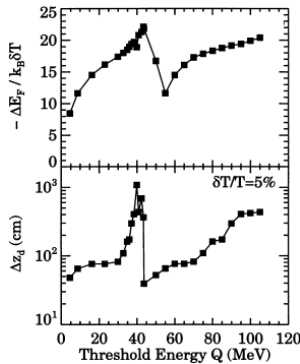
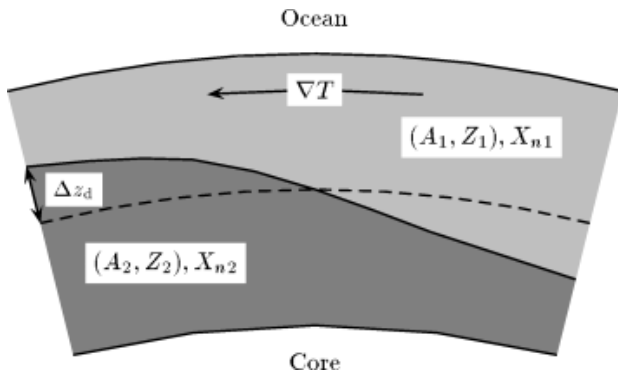
$$\varepsilon = 4 \times 10^{-8} \left(\frac{dM / dt}{10^{-9} M_{\text{Sun}} \text{yr}^{-1}} \right)^{1/2} \left(\frac{f}{300 \text{Hz}} \right)^{-5/2}$$

- Narrow range of f since $N_{\text{GW}} \propto f^5$ (steep!)
- **BUT** rad'n pressure $\rightarrow N_{\text{acc}} < 0$ (Andersson et al. 05)

Promising sources (e.g. Sco X-1):

known period, sinusoidal, persistent & strong!

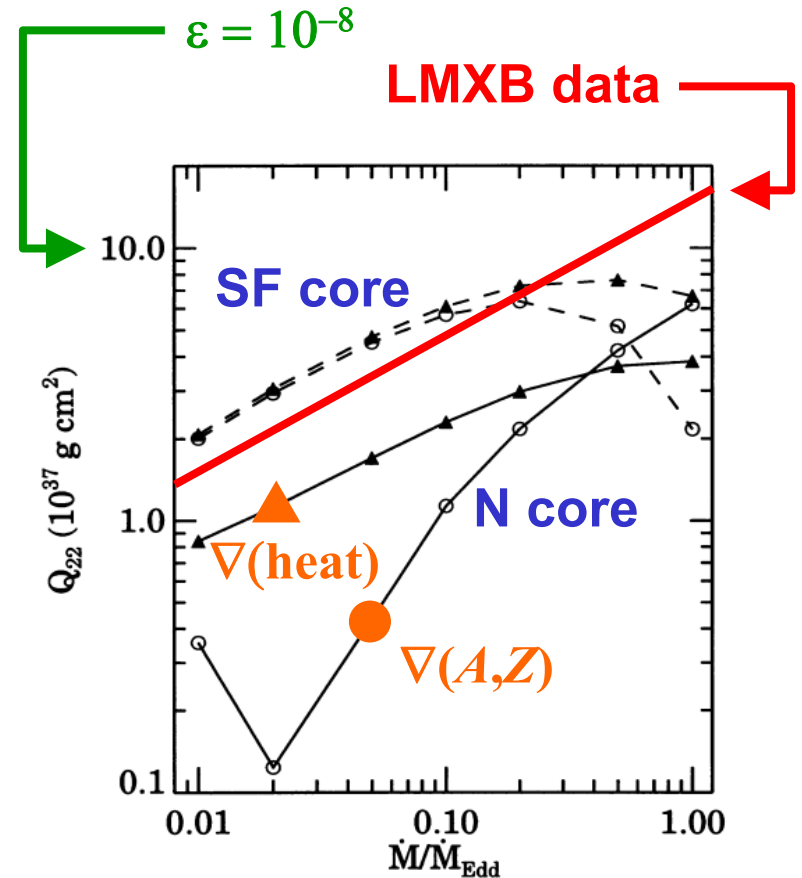
I. THERMAL MOUNTAIN



- Lateral ∇T
- **e^- capture** $(A, Z) \rightarrow (A, Z-1)$
- Occurs at lower ρ in hot spots (Bildsten 98)
- “Wavy” capture layers $\rightarrow \varepsilon$
- (A, Z) & heating gradient $\leftrightarrow \nabla T \leftrightarrow$ thermal conductivity & nuclear reaction rate

- Is ε large enough?
- **Elastic** crust adjusts
→ reduces ε
- Need $\Delta T/T \approx 5\%$ at base of outer crust
- Slow conduction & cracking ($\mu_{\text{shear}} < NkT$), so ε persists

GW correlated with thermal **X-rays**

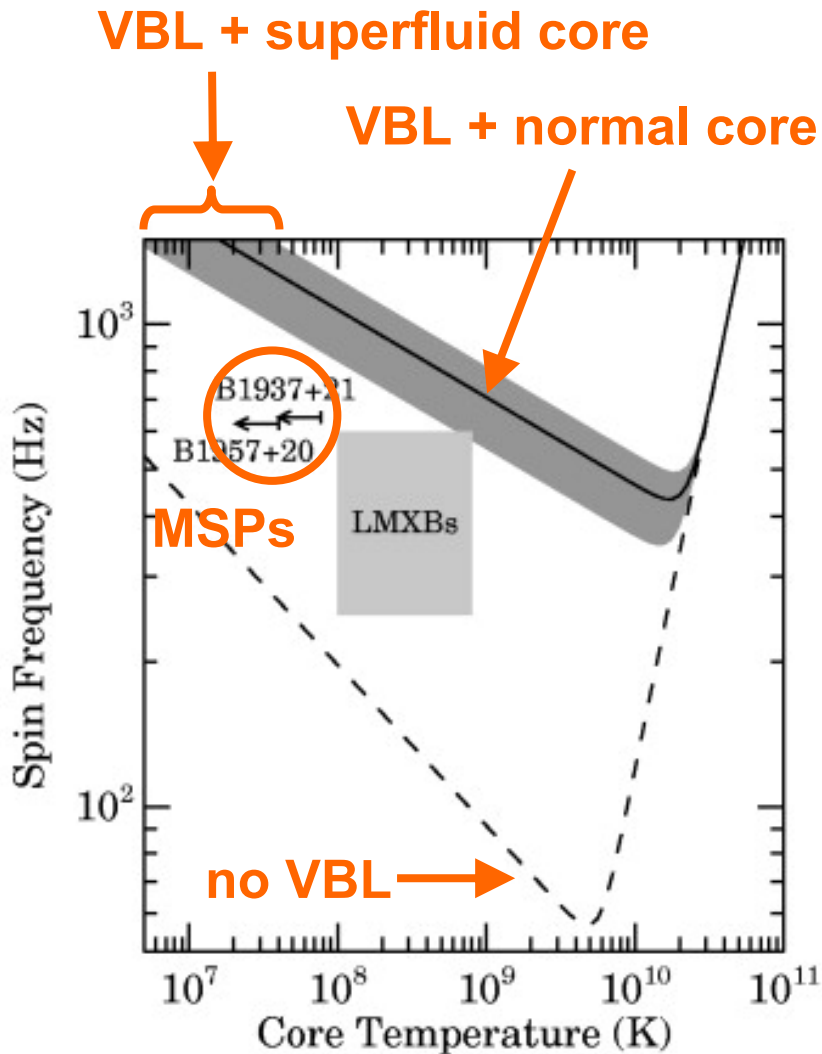


(Ushomirsky et al. 00)

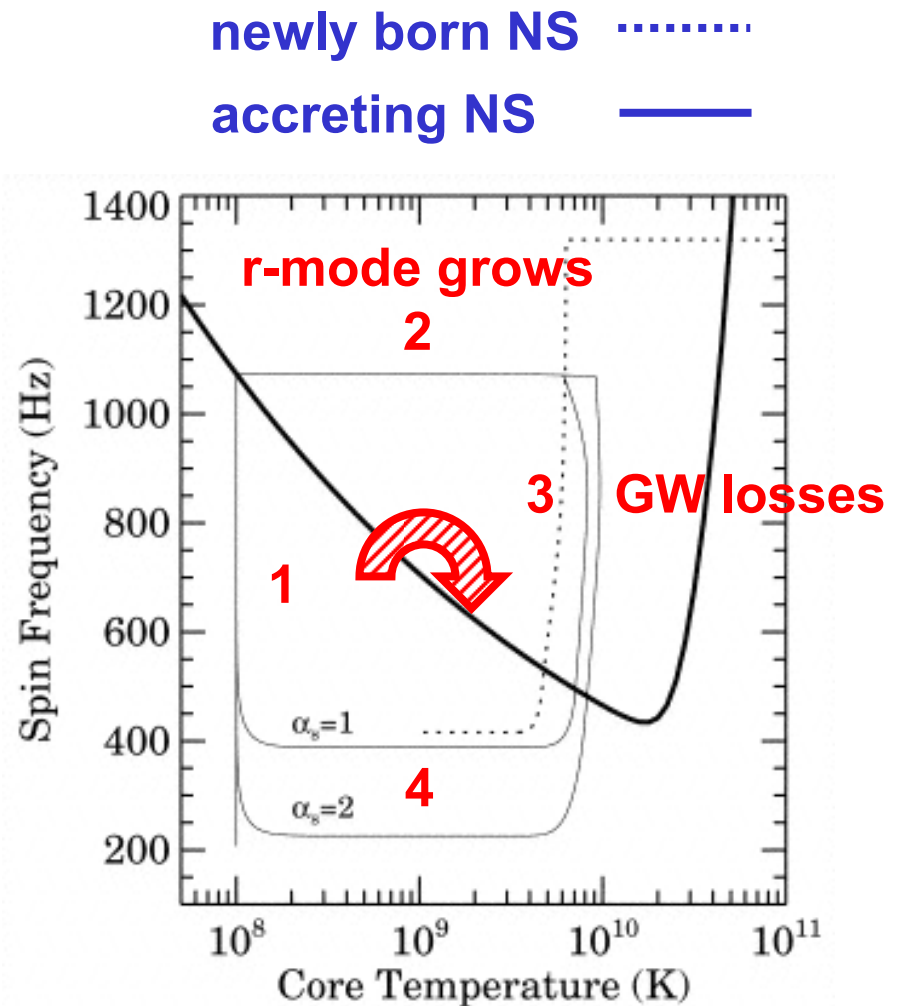
II. r-MODES

- Rossby waves continuously excited in core (Andersson et al. 99); cf. ocean r-modes (Heyl 04)
- Amplitude ($\rightarrow \varepsilon$) set by shear modulus, normal-superfluid **friction** (Lindblom & Mendell 99), **boundary layer** viscosity (Bildsten & Ushomirsky 00), radial crust-core coupling (Levin & Ushomirsky 01)
- **Thermal instability** (Levin 99)

Quiescent $L_X \sim 10^{34}$ erg s⁻¹ from NS transients, e.g. Aql X-1... **not seen!** (Brown & Ushomirsky 00)



Onset of instability
(Bildsten & Ushomirsky 00)



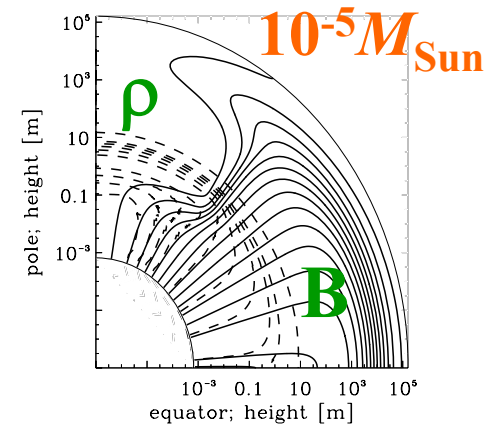
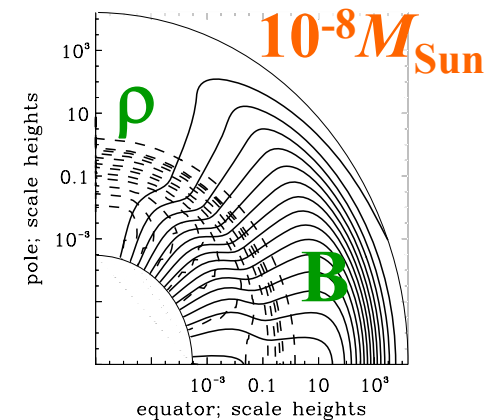
Thermal runaway cycle
(Levin 99)

III. MAGNETIC BURIAL

- Polar accretion
- **Equatorward spreading**
- Hydro pressure balanced by tension in compressed equatorial **B**:

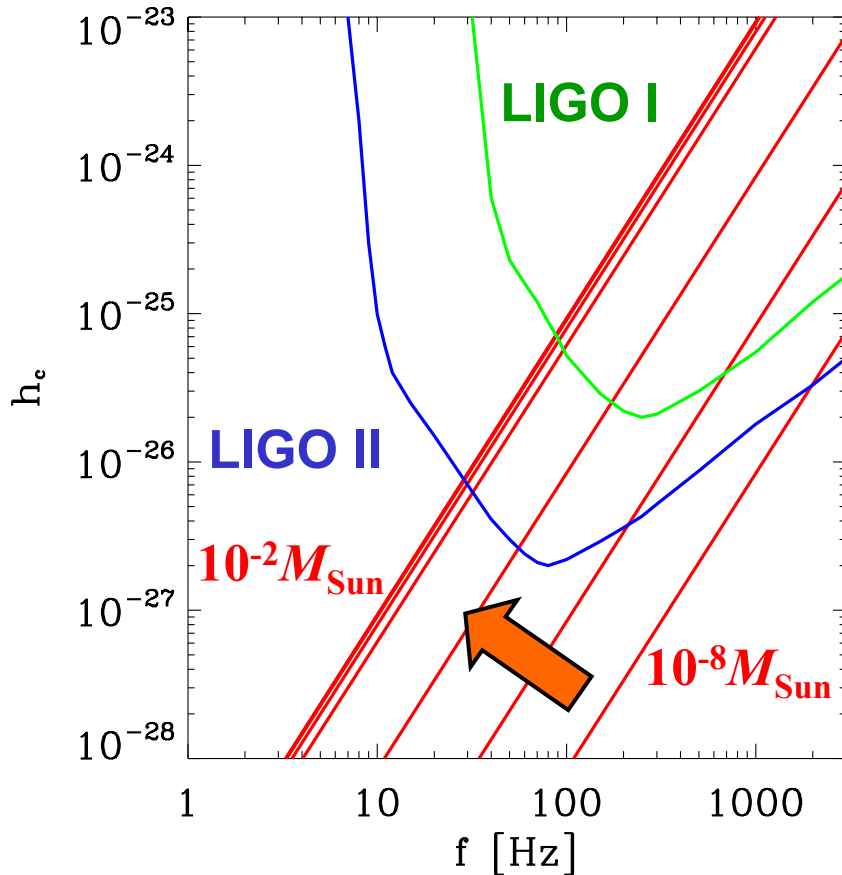
$$(\nabla \times \mathbf{B}) \times \mathbf{B} - \rho \nabla \Phi - \nabla P = 0$$

- Flux freezing $\rightarrow \int ds \rho/|\mathbf{B}|$
- Need $10^{-5} M_{\text{Sun}}$ (cf. Brown & Bildsten 98)



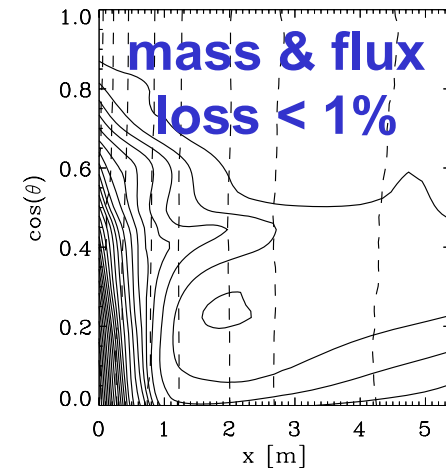
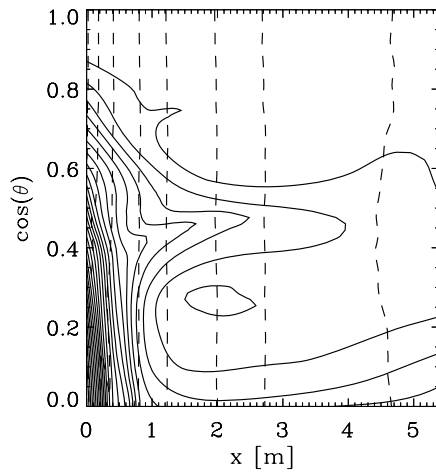
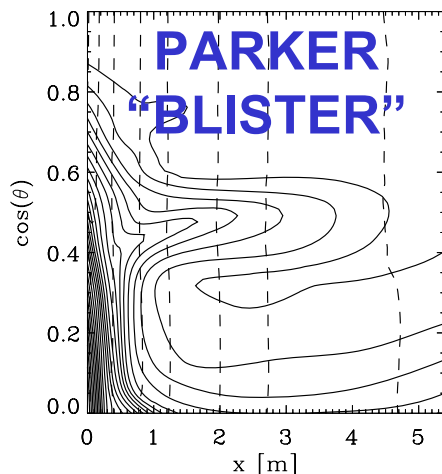
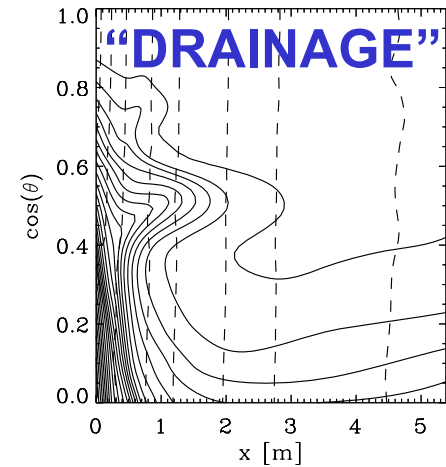
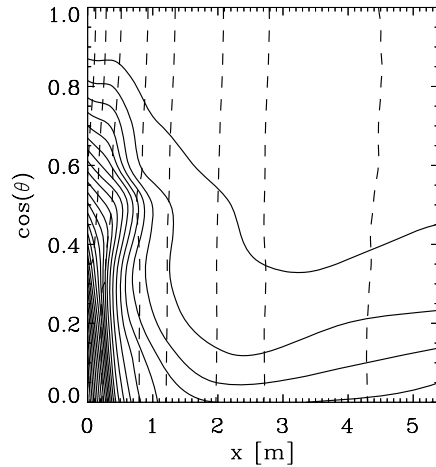
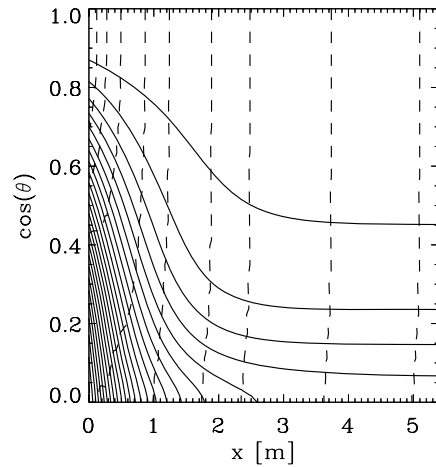
(Payne & Melatos 04)

GW SIGNAL



(Melatos & Payne 05)

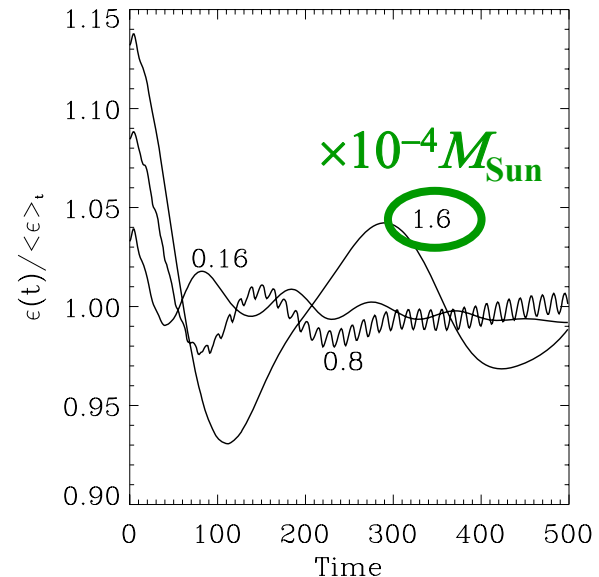
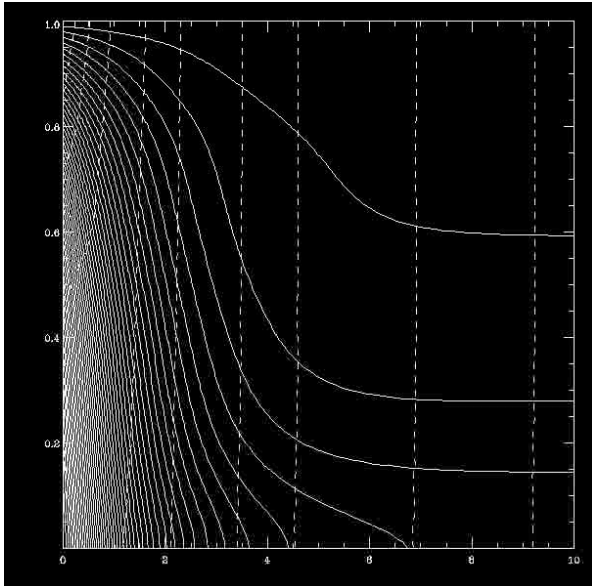
- Magnetic mountain
→ ε → wave strain h_c
- Integrate for one yr
- Resistivity, sinking...
- Magnetic moment ↓
(see NS binaries)
- Predict $h \propto \mu^{-1}$



Is this (distorted) magnetic field unstable? **No!**

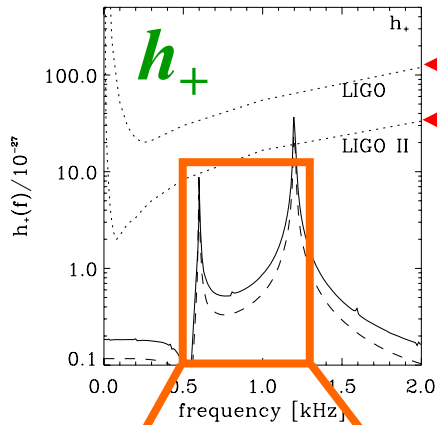
Parker instability “already” happened (and line tying)

MHD OSCILLATIONS

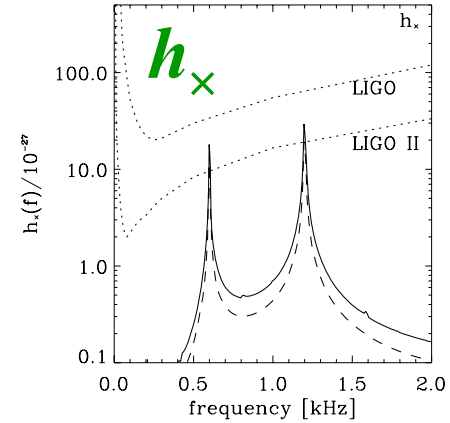


- Perturb in Zeus 3D: “sloshes” stably for $2500 T_{\text{Alfvén}}$
- **Alfvén** mode (slow) frequency depends on M_a
- **Sound** mode (fast) frequency independent of M_a

GW SPECTRUM

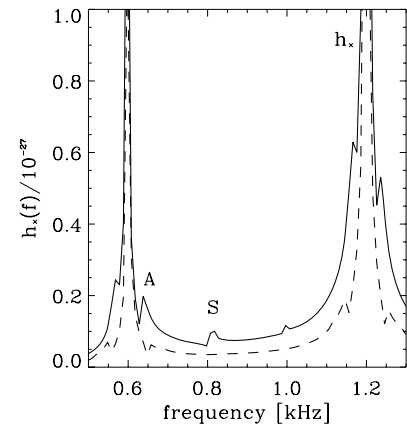
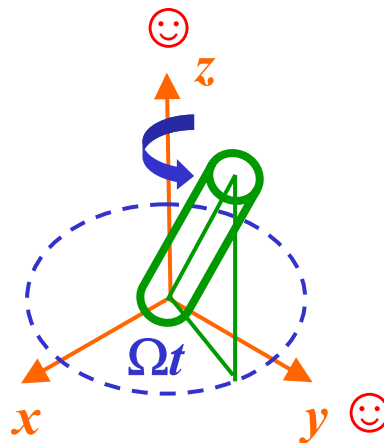
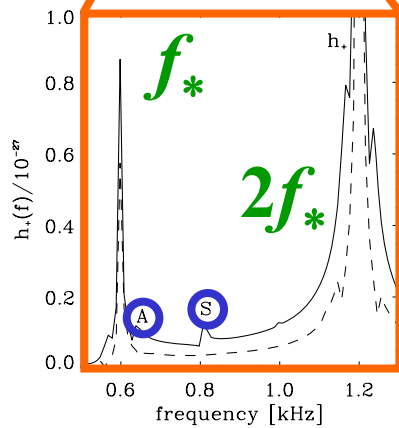


LIGO I
LIGO II



$$f_* \propto d^3 I_{xz} / dt^3$$

$$2f_* \propto d^3 I_{xy} / dt^3$$



PRECESSION

Magnetic mountain **inclined to Ω_***

- Precession **undamped**: GW near f_* and $2f_*$
- Precession **damped**: $e_3 \rightarrow \Omega_*$, no X-ray pulses, GW at $2f_*$ only (if triaxial)

Excitation

- Disk-magnetosphere torque (Jones & Andersson 02)
- Near-zone magnetic dipole torque (Melatos 00)

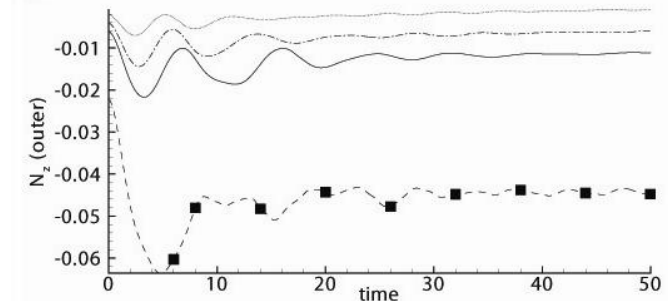
IV. SUPERFLUID CIRCULATION

EKMAN
PUMPING

$Re=10^4$

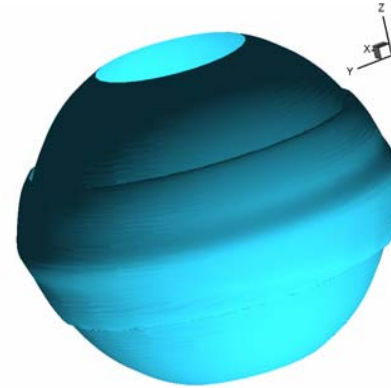
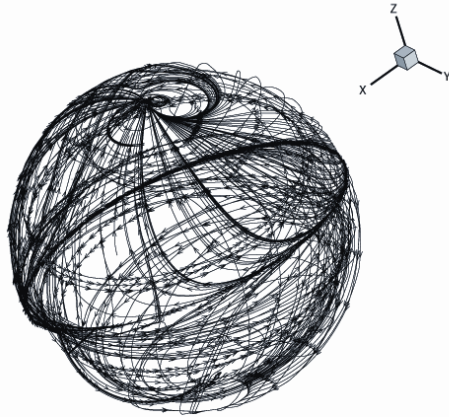


torque



- Rotation in sphere drives **meridional** circulation
- Time-dependent & asymmetric at **high $Re \sim 10^{11}$**
- Precession: **asymmetric KE** of fluid \rightarrow **GW**

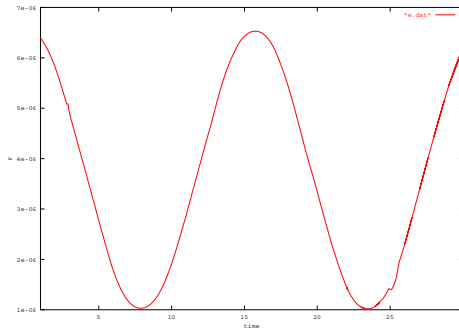
STREAM
LINES



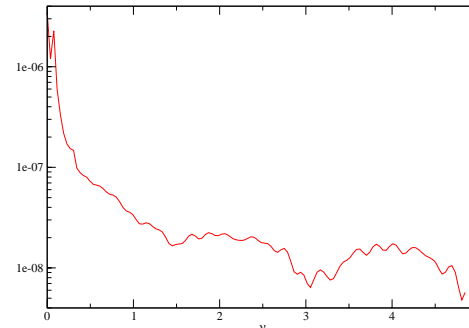
KE SURFACE
 $\rho u^\alpha u^\beta = \text{const}$

QUADRUPOLE

$\varepsilon(t)$



FFT \rightarrow $\varepsilon(f)$



- 3-dim superfluid **hydro code** (HVBK theory)
- GW near $2f_*$ broadened by Ekman & precession

SUMMARY

- LMXB spins \rightarrow GW “stalling” if $\epsilon \approx 10^{-8}$
- Thermal & magnetic mountains & r-modes
- Detectable by LIGO II
- Spectrum broadened by (MHD) oscillations
- **Precession**

- Accretion by SN fallback? (Watts & Andersson 03)
- Surface asymmetry after r-p burning? (Jones 05)



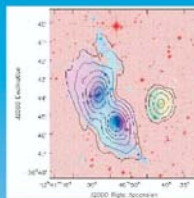
TEXAS IN AUSTRALIA

2006

*23rd Texas Symposium
on Relativistic Astrophysics*

*University of Melbourne
11-15 December 2006*

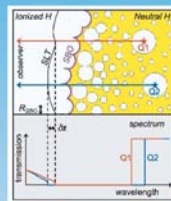
Clusters & AGN



Neutron stars & SNR



Gravitational waves



Epoch of reionization



Astroparticle physics

Gone!

