ACTIVITY IN NEUTRON STARS

A. Melatos (Melbourne)

1. Rotational glitches

GPE SIMS

2. Superfluid turbulence

3. Magnetic crust-core decoupling

EXCLUDE MAGNETARS

I. “ACTIVE INGREDIENTS”

Slow, erratic phenomena in radio pulsars:
glitches, nulling, orthogonal mode switching

DRIVER

- Heat flux… but NS **stably stratified** thermally
- EM **spin down** → crust-core shear

field decay in magnetars

INTERMITTENCY ↔ STORAGE

- Pinned superfluid
- Closed magnetic flux tubes

Hall effect in magnetars

CASCADE TO SHORT SCALES

- Local random pinning → global **inhomogeneity**
- Shear viscosity → turbulent **eddies**
- Magnetorotational and Tayler instabilities

STELLAR COMPONENTS

- Rigid **crust** $\rightarrow$ EM braking
- Inviscid n condensate $\rightarrow$ **superfluid**
- Viscous p^+ + e^- + uncondensed n
  – **mutual friction** with n condensate
  – locks **(?)** magnetically to crust

- Array **(?)** of quantized **vortices** with $\kappa = h/2m_n$
  – "wave function" $\Psi_s \propto e^{i\theta(x)}$ implies $\mathbf{v}_s \propto \nabla\theta$
  – **pinned** to nuclear lattice ($E_{\mathrm{pin}} \sim \mathrm{MeV}$)

Where is angular momentum stored?

(A) Inner crust SF ($I_{res} \approx 10^{-2} I_0$) plus “crust” ($I_c \approx I_0$), i.e. lattice + p^+ + e^- + core n locked magnetically

1. Constant crust-SF lag over long term: $\langle \dot{\Omega}_{res} \rangle = \langle \dot{\Omega}_c \rangle$

2. SF glitches (no creep): $\langle \dot{\Omega}_{res} \rangle = \langle \Delta\Omega_{res,g} \rangle / \langle \Delta t_g \rangle$

3. AM conserved in glitch: $I_{res} \Delta\Omega_{res,g} = -I_c \Delta\Omega_{c,g}$

(Link et al. 99)

$$\frac{\langle \Delta\Omega_{c,g} \rangle}{\langle \Delta t_g \rangle} = -\frac{I_{res}}{I_c} \langle \dot{\Omega}_c \rangle$$

few % from radio timing

(B) Inner crust & core SF (e.g. $^3P_2$) ($I_{res} \approx I_0$) plus "crust" ($I_c \approx 10^{-2} I_0$) comprising lattice + p^+ + e^-

- **Bragg entrainment** reduces SF mobility relative to lattice (Chamel 12; Andersson et al. 12; Newton et al. 15)
- "Crust not enough", $I_{res} > 0.1 I_0$
- Consistent if creep dominates

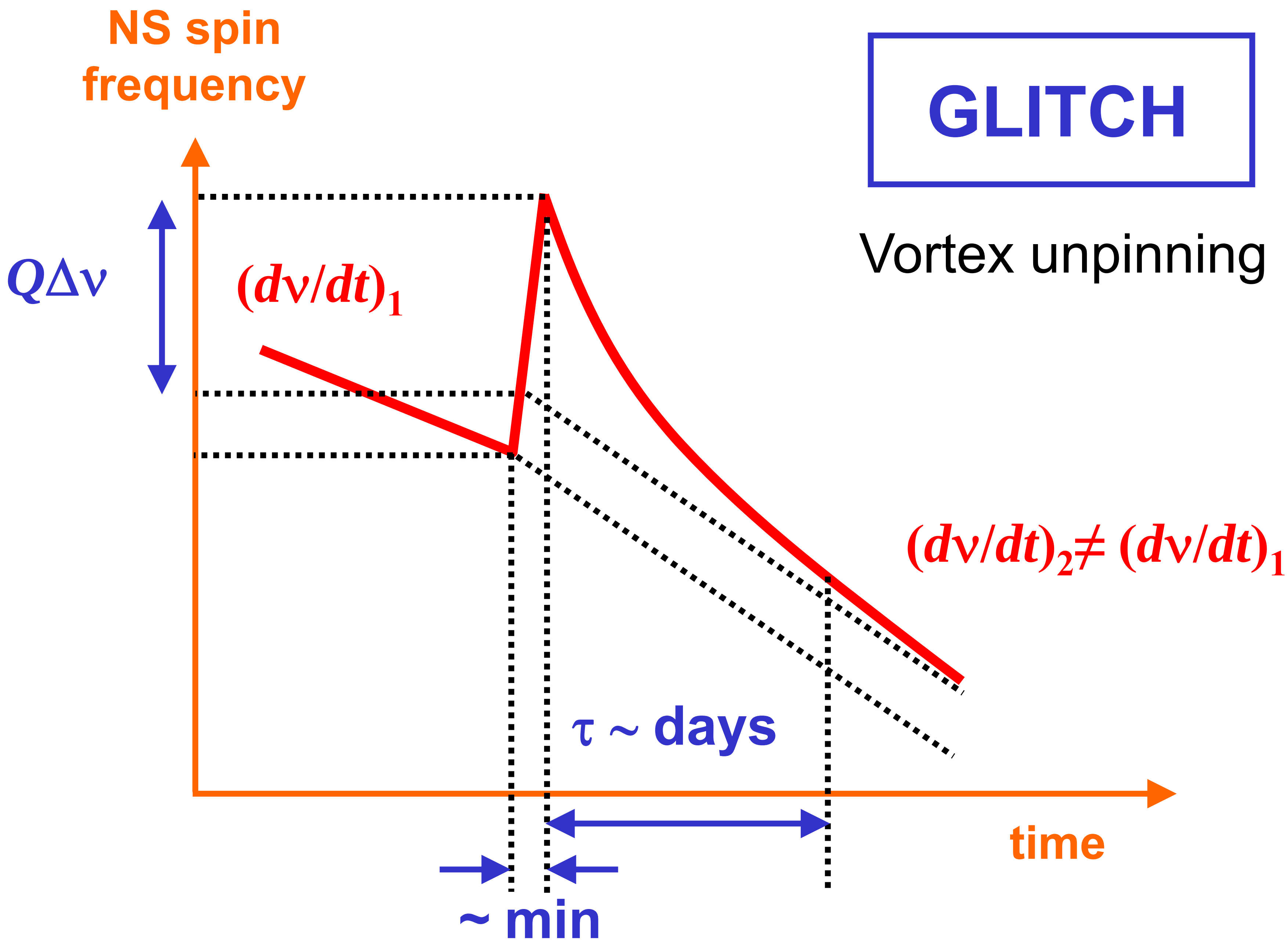
Superfluid **vortex**-superconductor **fluxoid** coupling

- **Strong…** if not tangled… (Ruderman et al. 98; Link 12)
- **Weak…** e.g. snow plow (Pizzochero 11; Haskell et al. 12), type I superconductor (Jones 06)

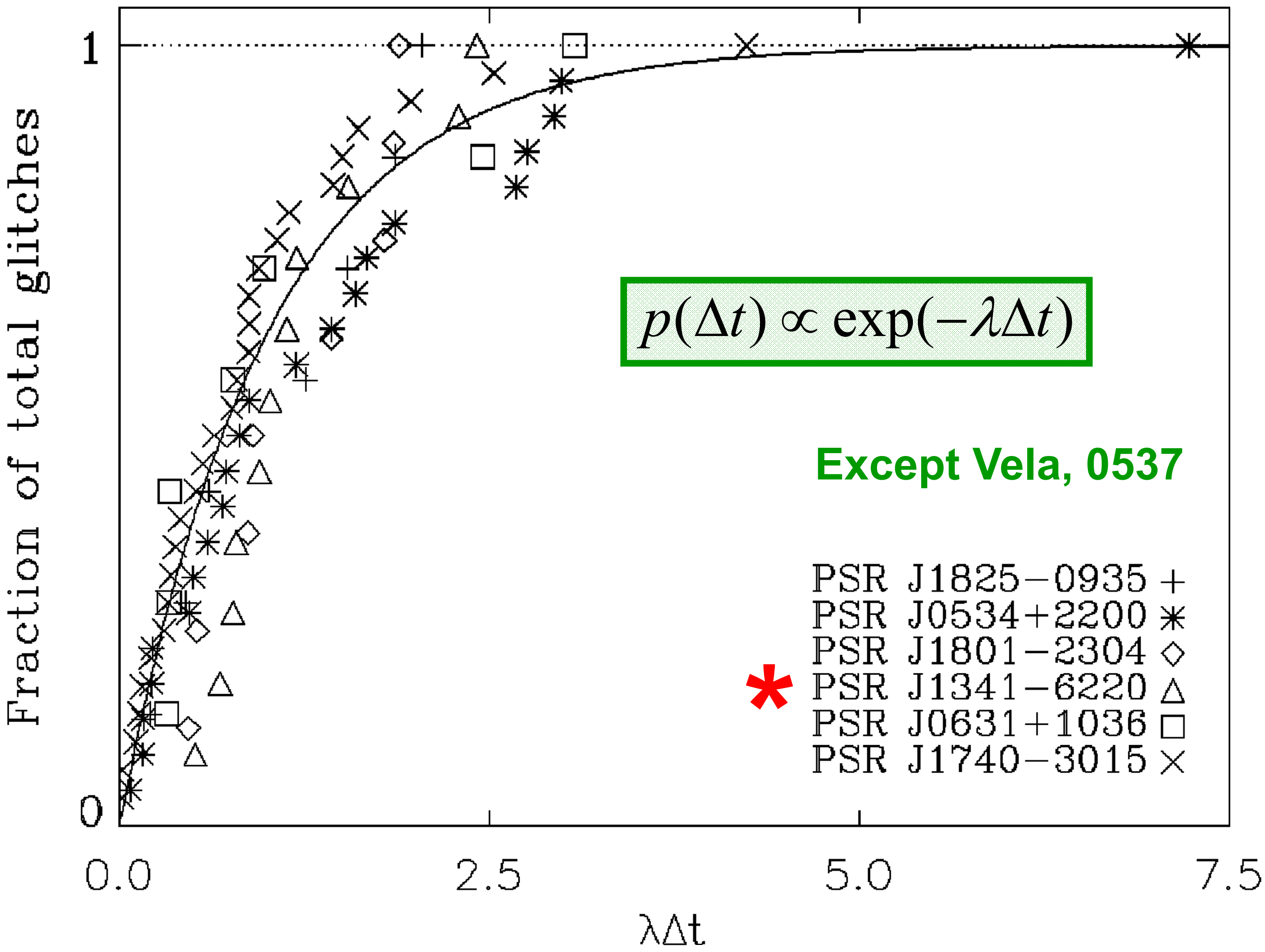
II. GLITCHES

Gross-Pitaevskii simulations:

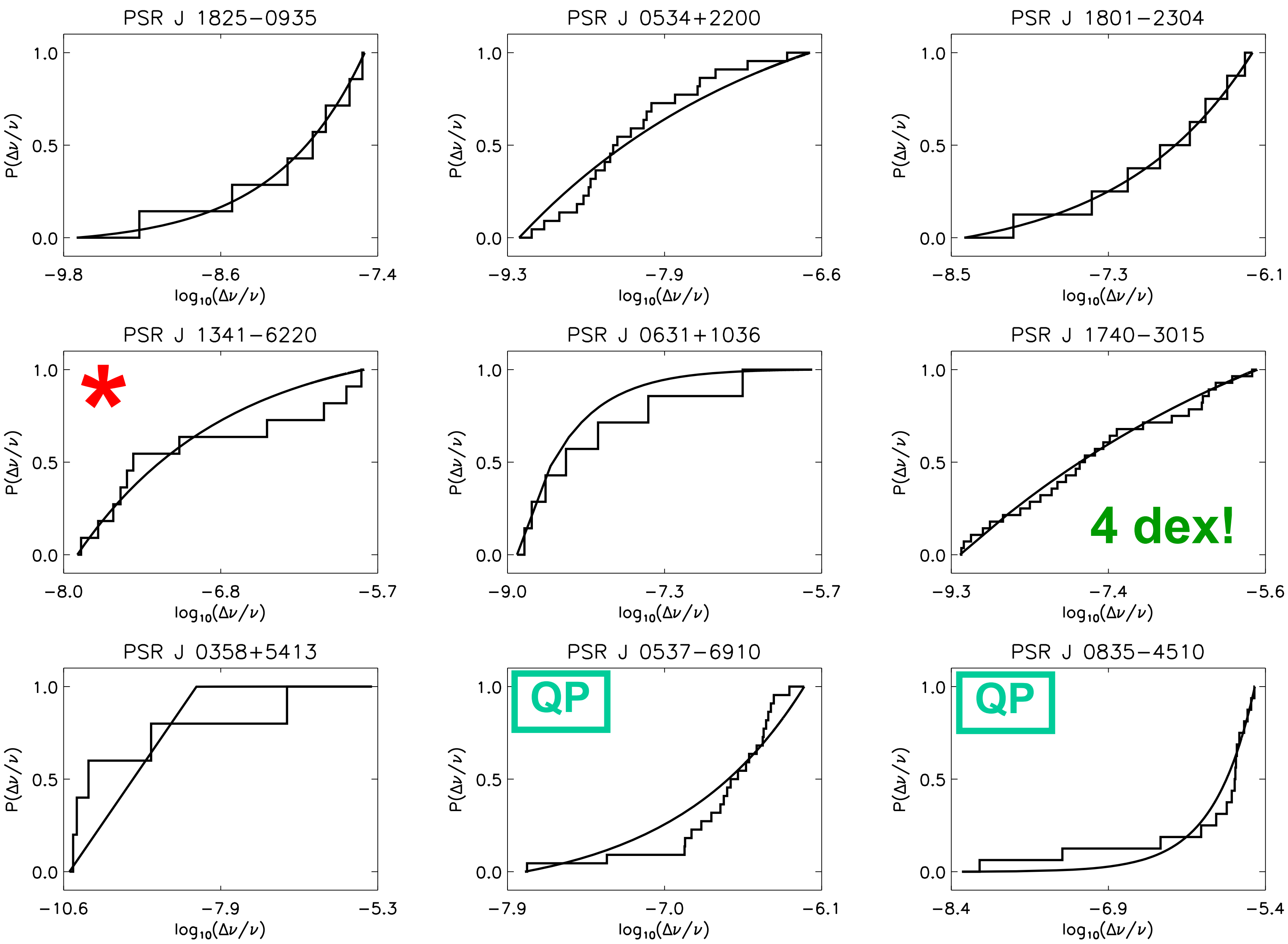
trigger mechanism and long-term statistics



GLITCH
Vortex unpinning
NS spin frequency
QΔν
(dν/dt)1
(dν/dt)2≠ (dν/dt)1
τ ~ days
time
~ min

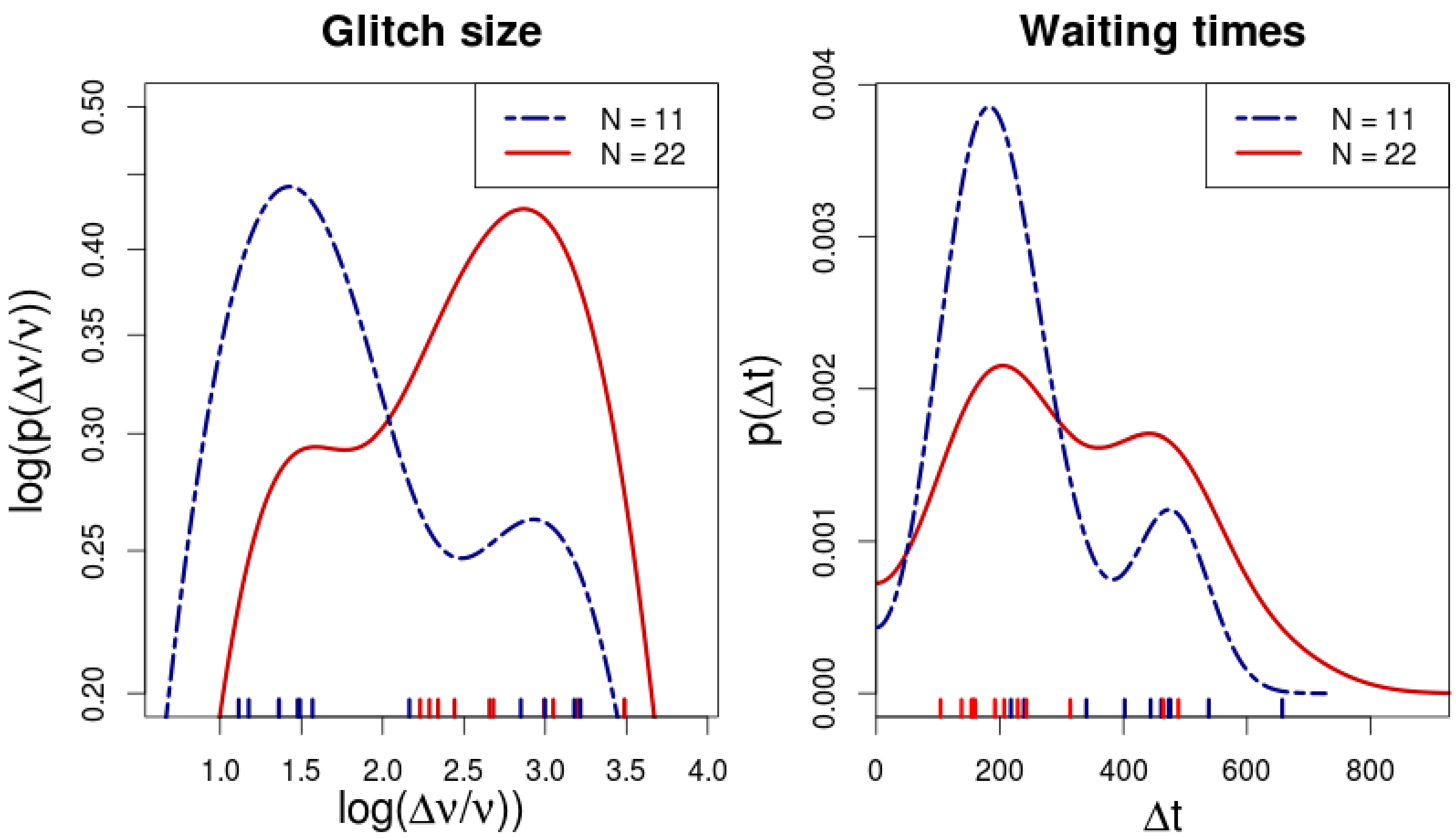


"Poisson" waiting times (Melatos et al. 08)



Power-law sizes (Melatos et al. 08)

$$p(\Delta\nu) \propto (\Delta\nu)^{-a}$$



PSR 1341-6220: a leopard can change its spots

(Melatos et al. 15)

- **Avalanche dynamics**

- Self-organized criticality
- Earthquakes, sand piles

- Slow, global driver
- Impulsive, local relaxation

- “Stick-slip” motion

San Francisco
1906

SF vortices **unpin** and **move** → glitch

10^{16} vortices per star

10^{6} to 10^{12} vortices per glitch

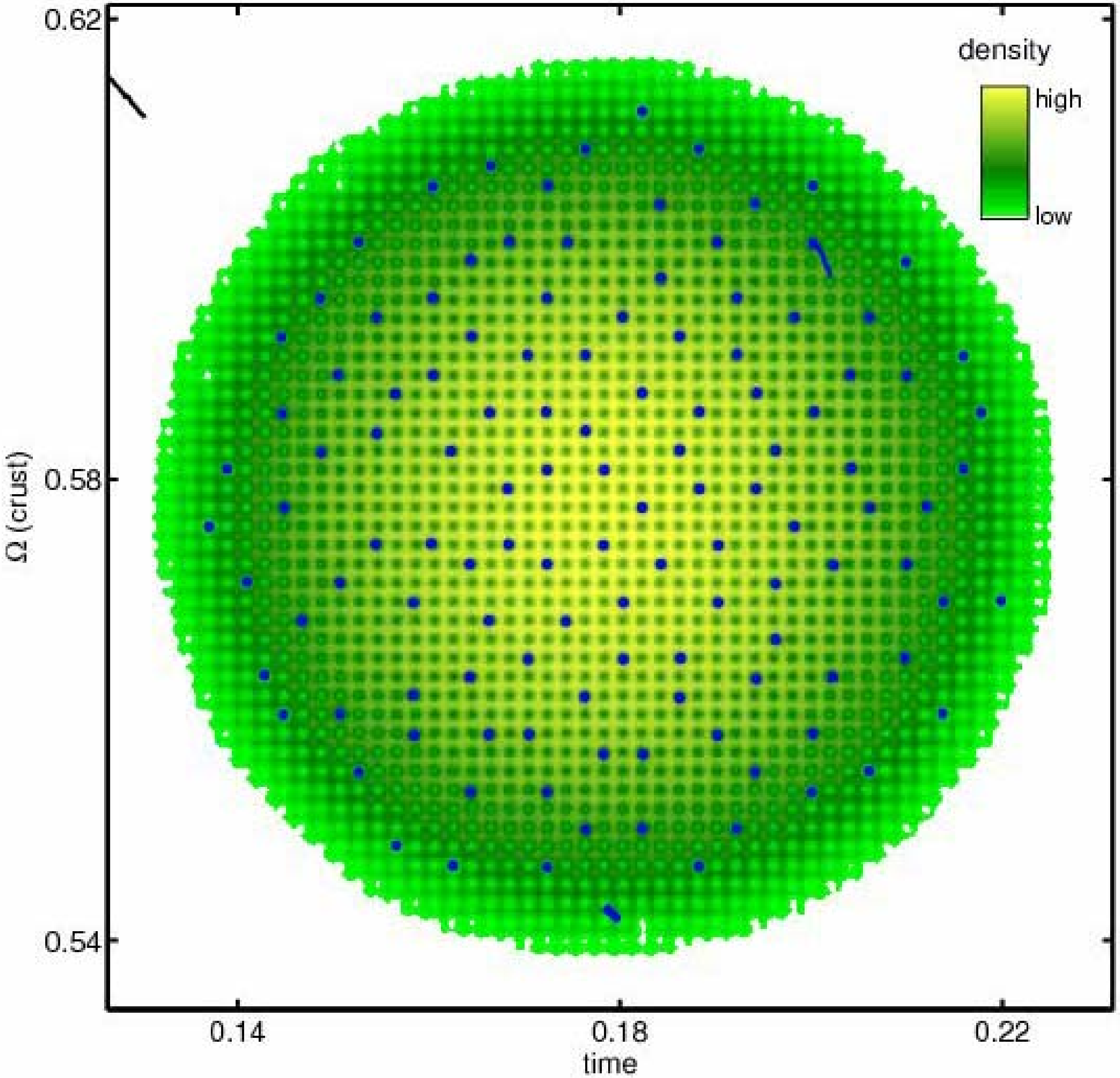
Central limit theorem →

narrow range of sizes and waiting times…

… not seen except in Vela and 0537

Vortex motion must be correlated – how?

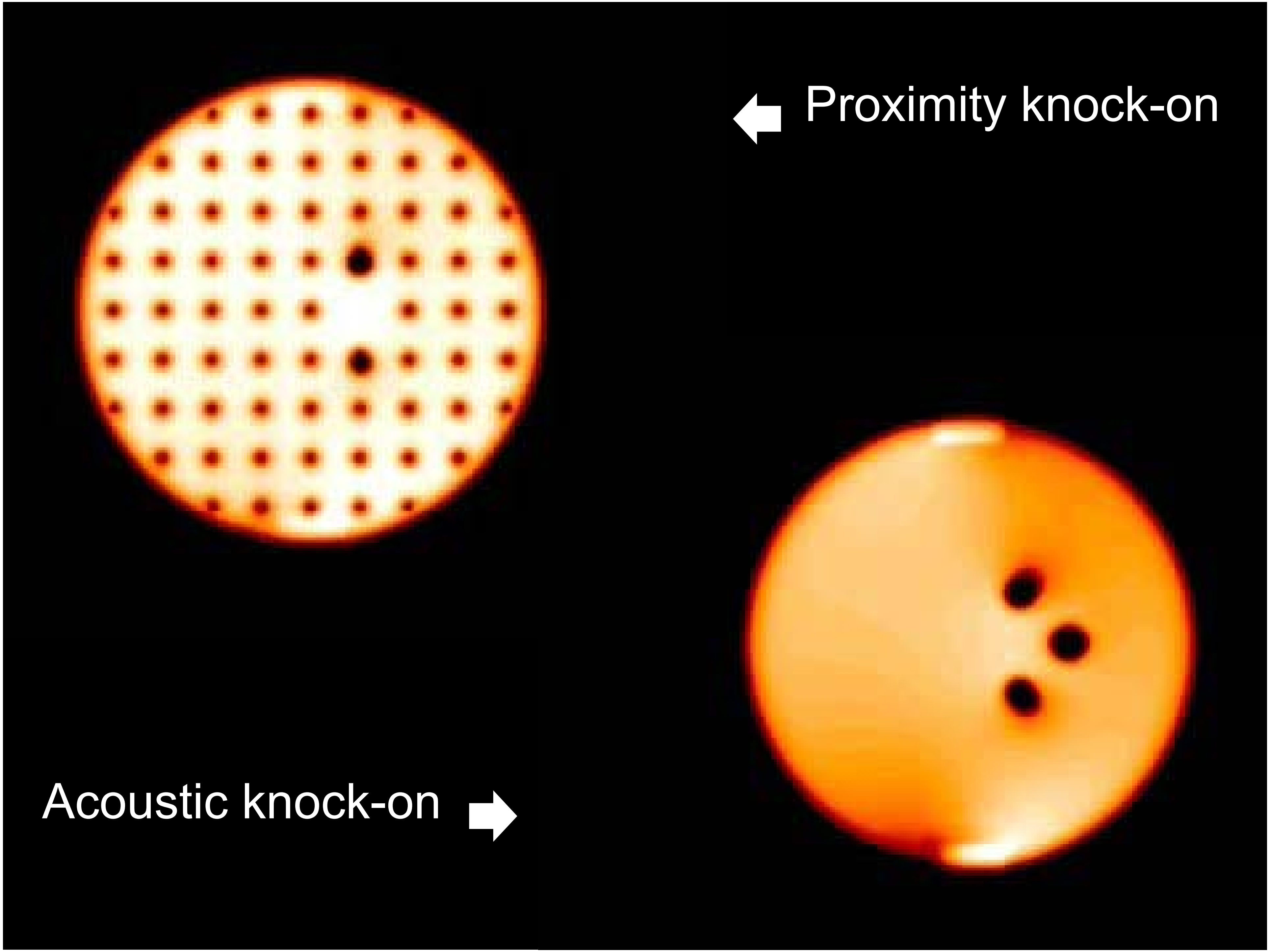
stochastic GPE

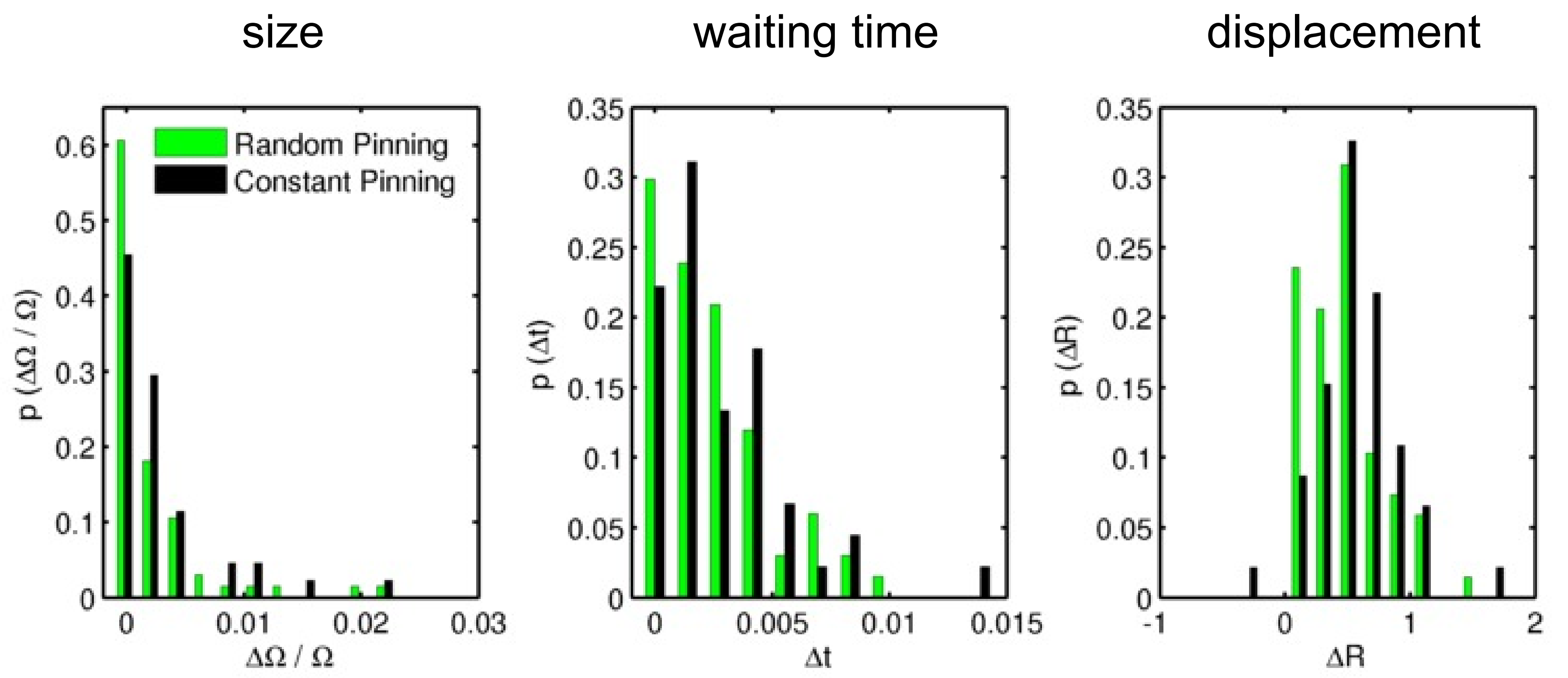


- Glitches occur at random times
- Range of sizes

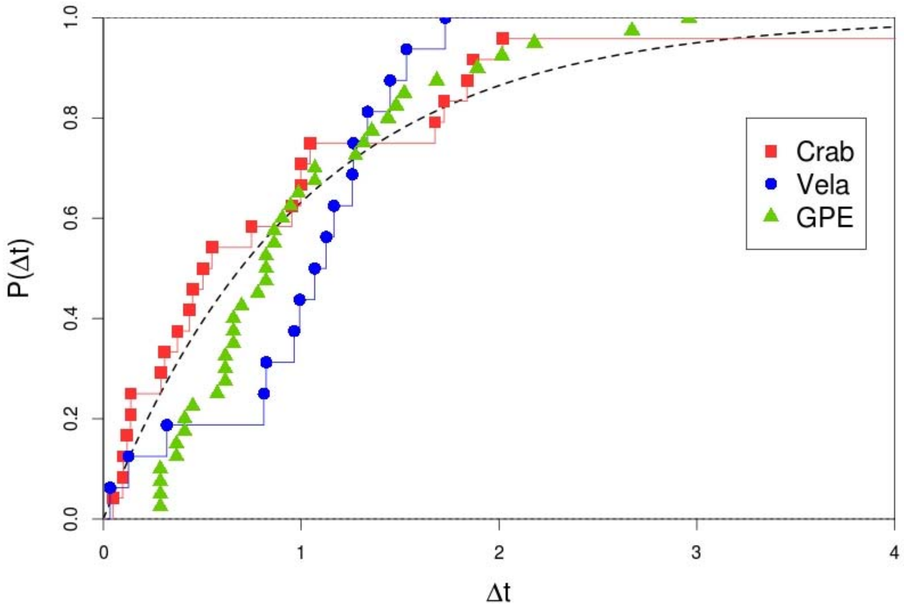
- Vortices unpin **collectively**
- Move in **"herds"** covering a wide area

- **Dodge** sites and **exit** system ("slalom skier")
- **Skip** sites and **repin** ("fill in gaps")

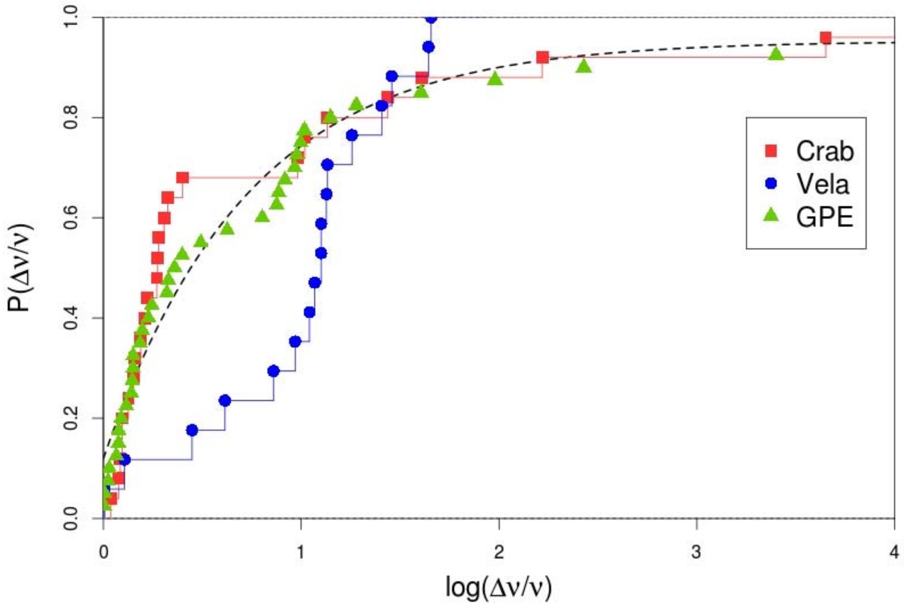

Proximity knock-on
Acoustic knock-on



- Power-law $\Delta\Omega$, Poisson Δt (small N still…)
- Similar for uniform & random pinning

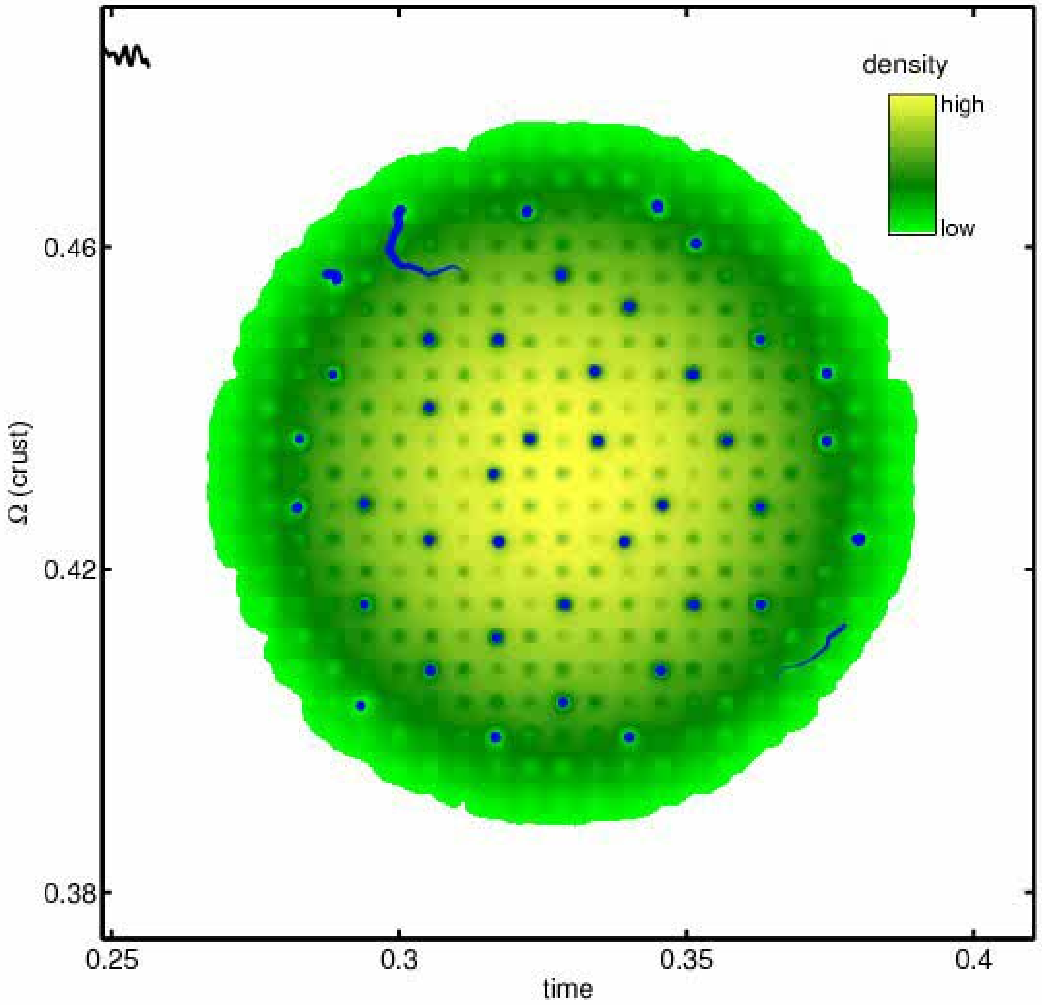


Waiting times:
theory & data



Sizes

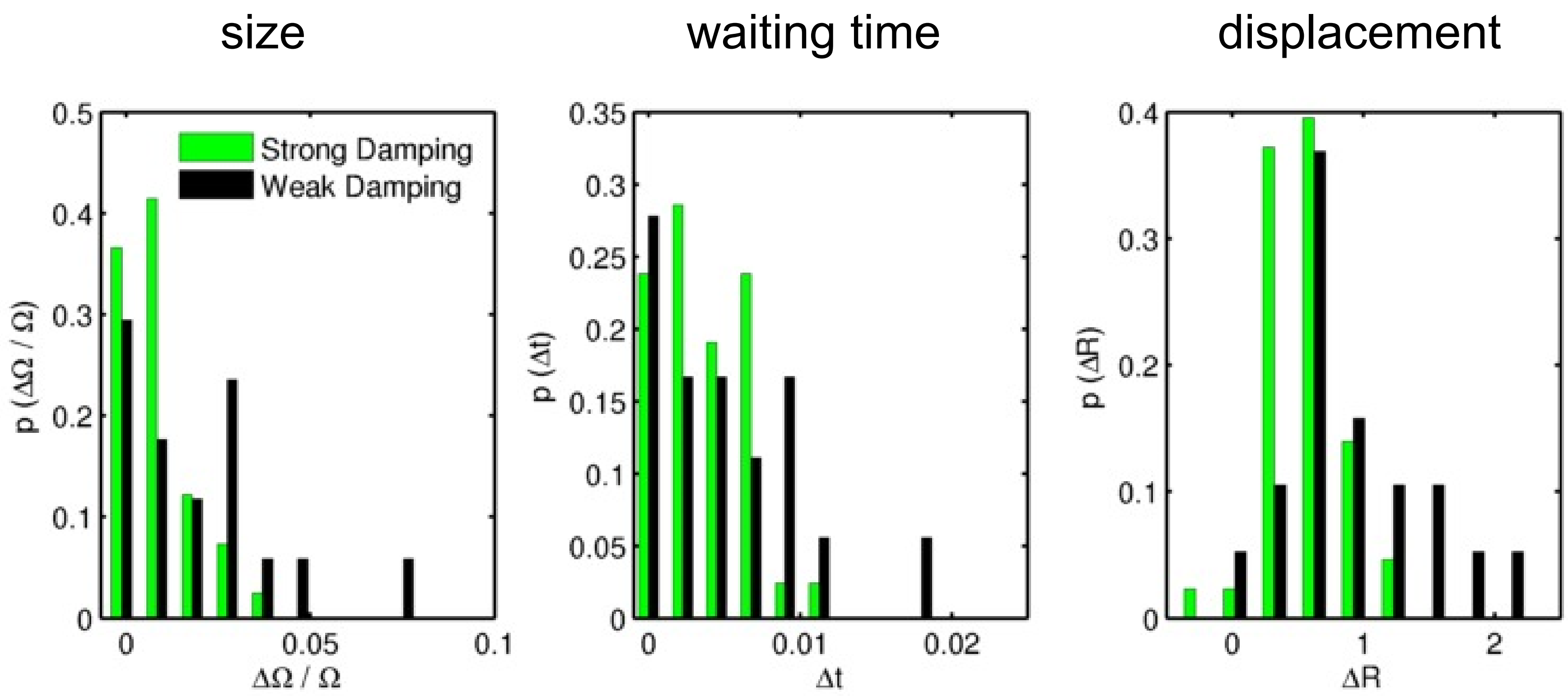
Minimum glitch size resolved in Crab?
(Espinoza et al. 14)



Weak damping

Acoustic unpinning

- Avalanches cover **more area**
- Post-glitch **recovery** more **complete**



Unpin acoustically even if Magnus weak

INTERESTING NUMBERS

Damping coefficient (dimensionless) in GPE

- Rate: condensate → excited states

$$\gamma = \frac{32\pi m_n g a^2 k_B T}{h^2} \approx 0.2\left(\frac{g}{3}\right)\left(\frac{a}{10\ \mathrm{fm}}\right)^2\left(\frac{T}{10^8\ \mathrm{K}}\right)$$

borderline!

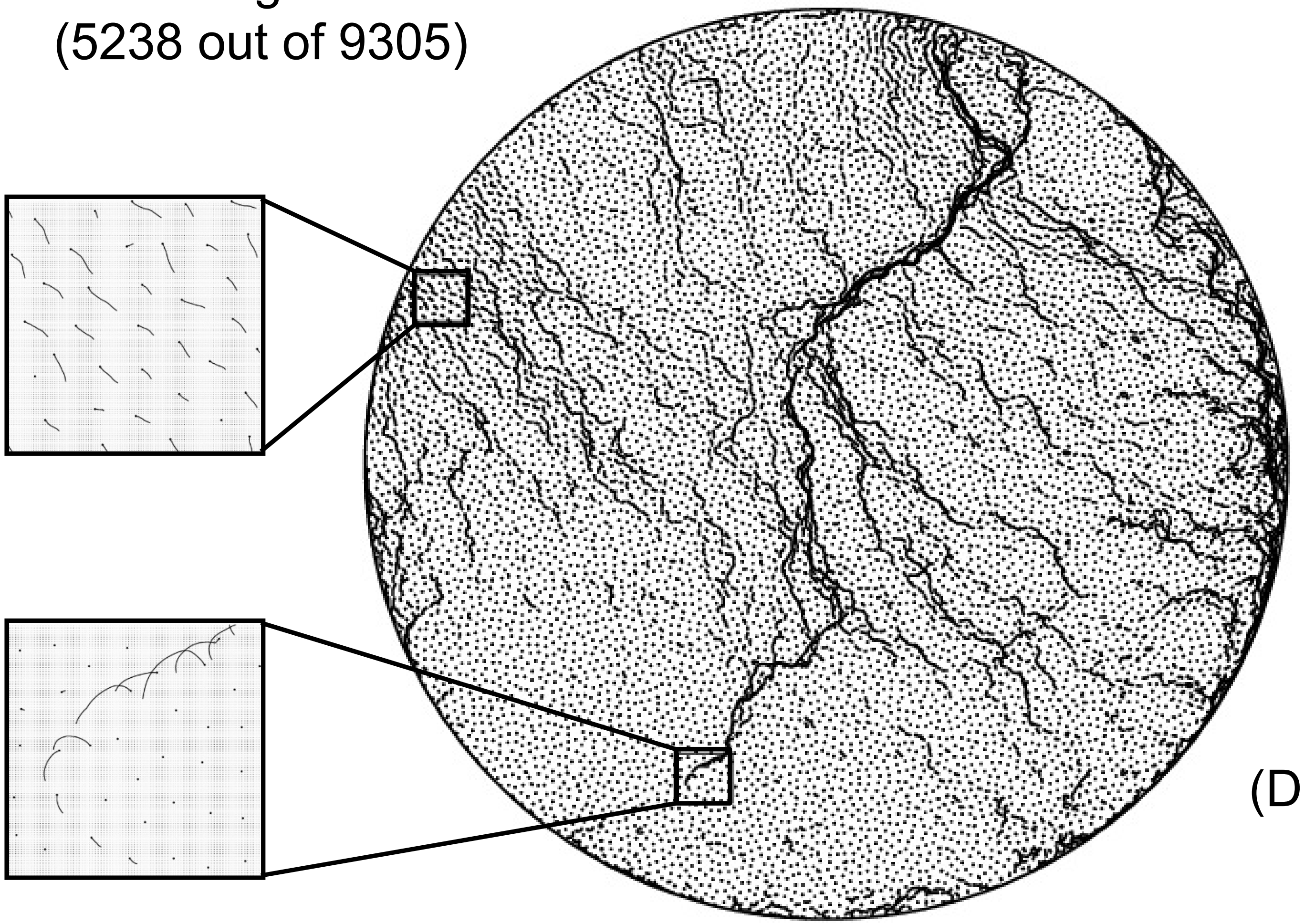
s-wave scatt'ng length (-ve!)

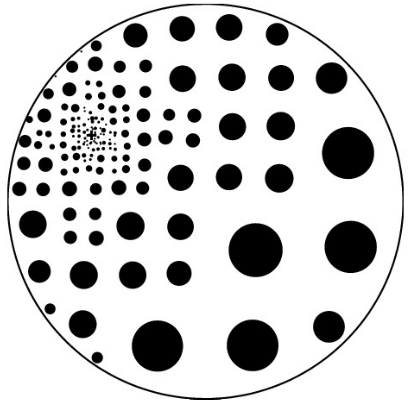
Fractional **glitch size**

- Need $N_{unpin} \sim N_{total}$ and/or $\Delta R >> \lambda_F \approx 10^{-7} R_*$ to explain largest glitches

$$\frac{\Delta\Omega_c}{\Omega_c} \approx \left(\frac{I_s}{I_c}\right)\left(\frac{N_{unpin}}{N_{total}}\right)\left(\frac{\Delta R}{R_*}\right)$$

Tracks of big avalanche
(5238 out of 9305)





Barnes-Hut
nesting

(Douglass et al. 15)

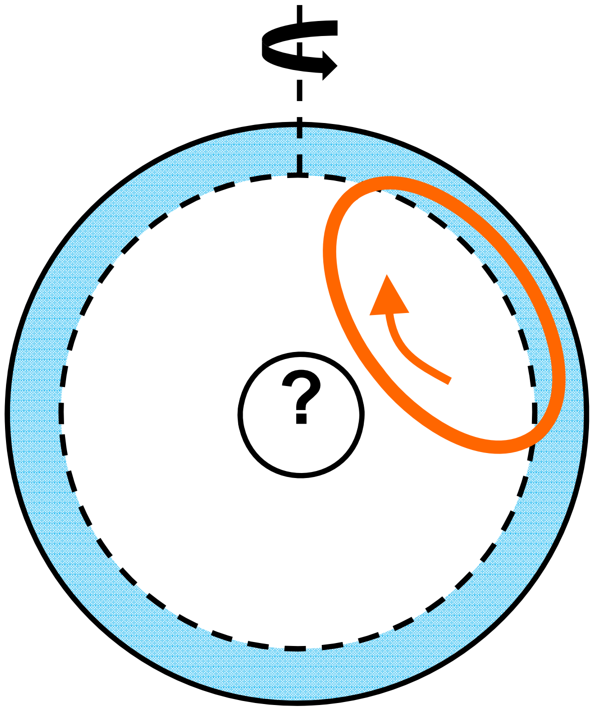
- Larger systems → **hierarchical** N-body code
- In progress (NB. can't do acoustic waves)

III. SF TURBULENCE

Macro… high-Re Kolmogorov eddies

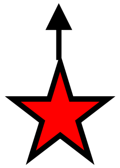
Micro… tangled unstable vortices

Interior fluid sucked into boundary layer, spun down, then recycled

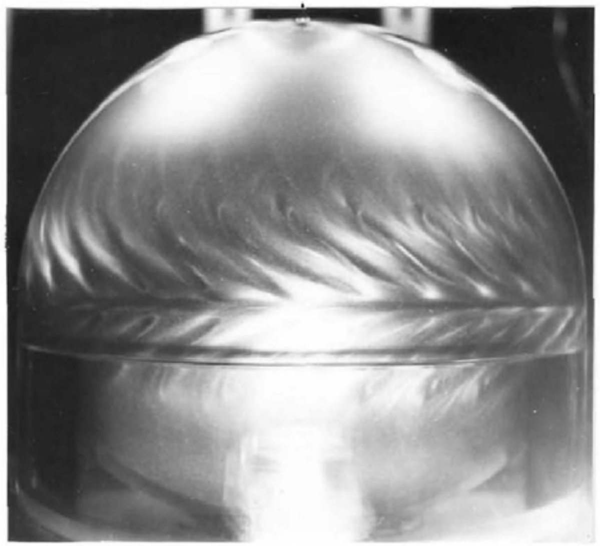


Ekman pumping ("cup of tea")

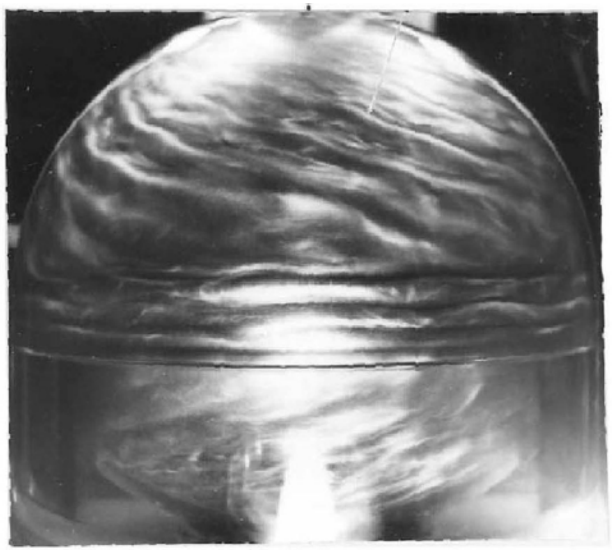
NS



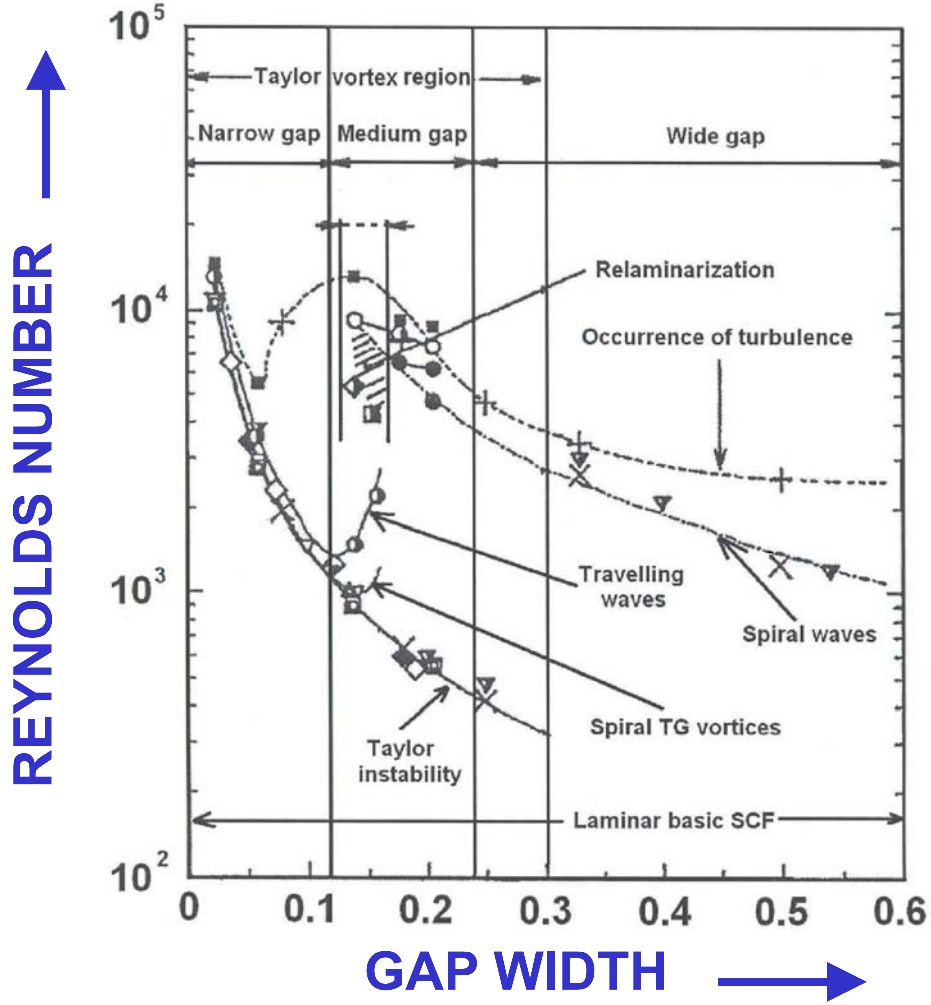
Herringbone: $Re_i=6\times10^3$

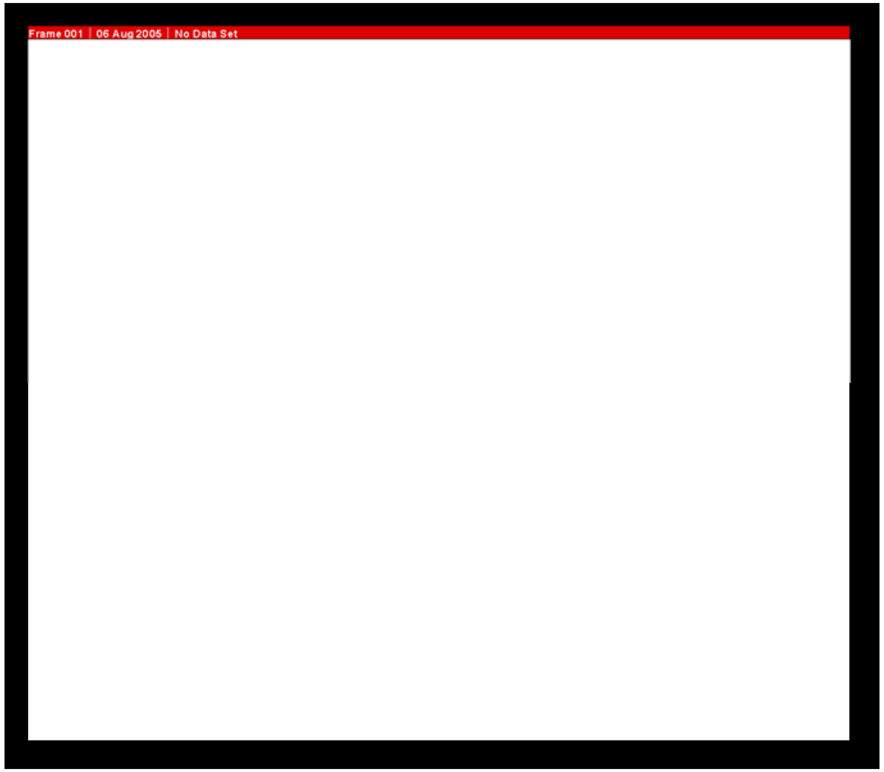


(Nakabayashi 83)



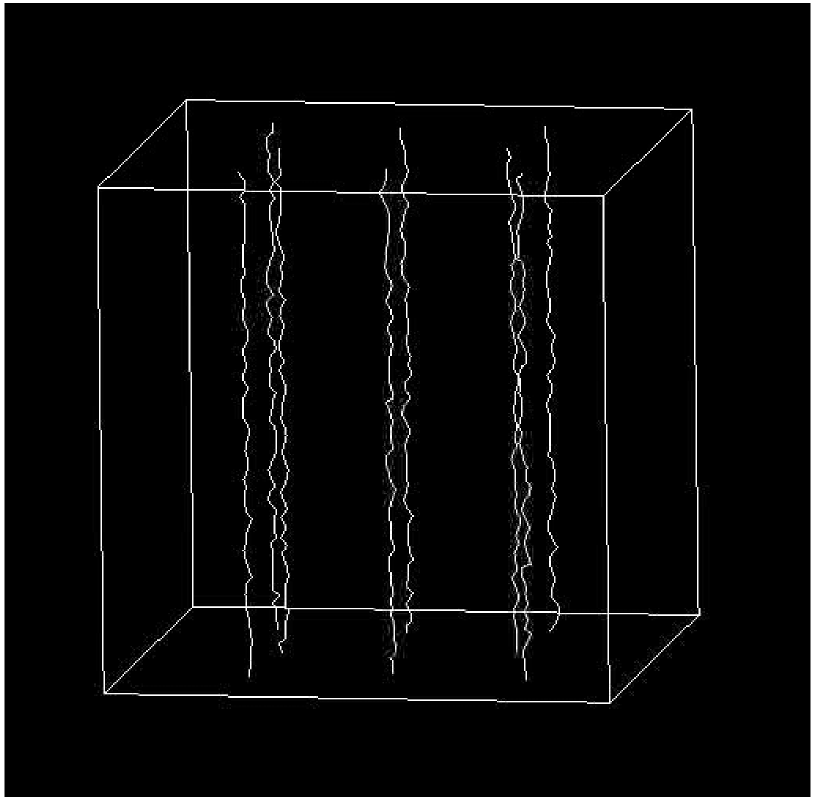
Taylor-Gortler: $Re_i=1\times10^4$





Two-component HVBK simulation

(Peralta et al. 05, 08)



Kinematic Schwarz equation

(Tsubota group)

VORTEX TANGLE

DONNELLY-GLABERSON INSTABILITY

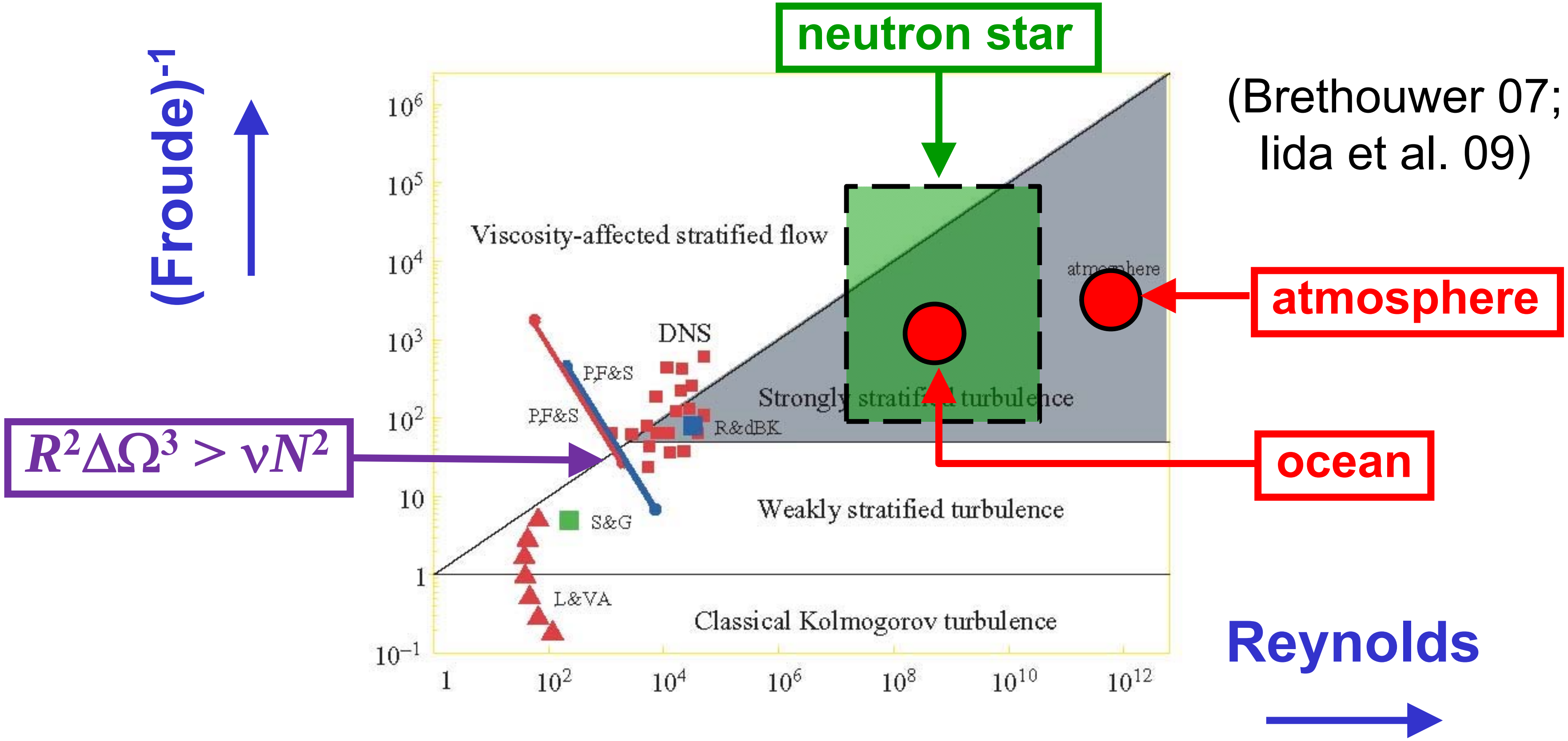
- Lab experiments (He, BEC) (Glaberson et al. 74)
- Ekman **counterflow** $V_{np} \approx R\Delta\Omega$ along vortices
- Mutual friction amplifies **Kelvin waves**
- Low threshold $V_{np} \sim \mathrm{mm\ s^{-1}}$, fast growth $> \Omega$

PINNING INSTABILITY (Glampedakis et al. 09; Link 12)

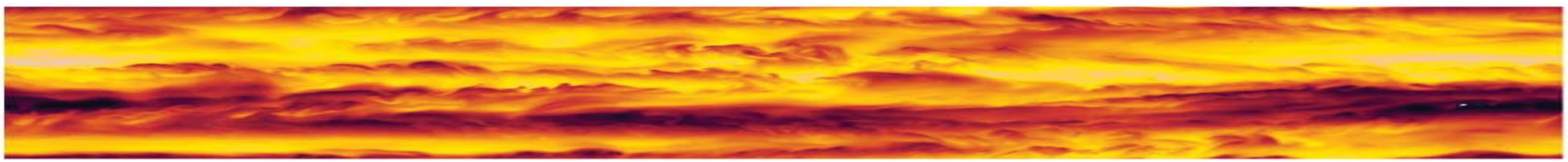
- Imperfect pinning $\rightarrow$ vortex creep $\rightarrow$ V_{np}
- Grows over days

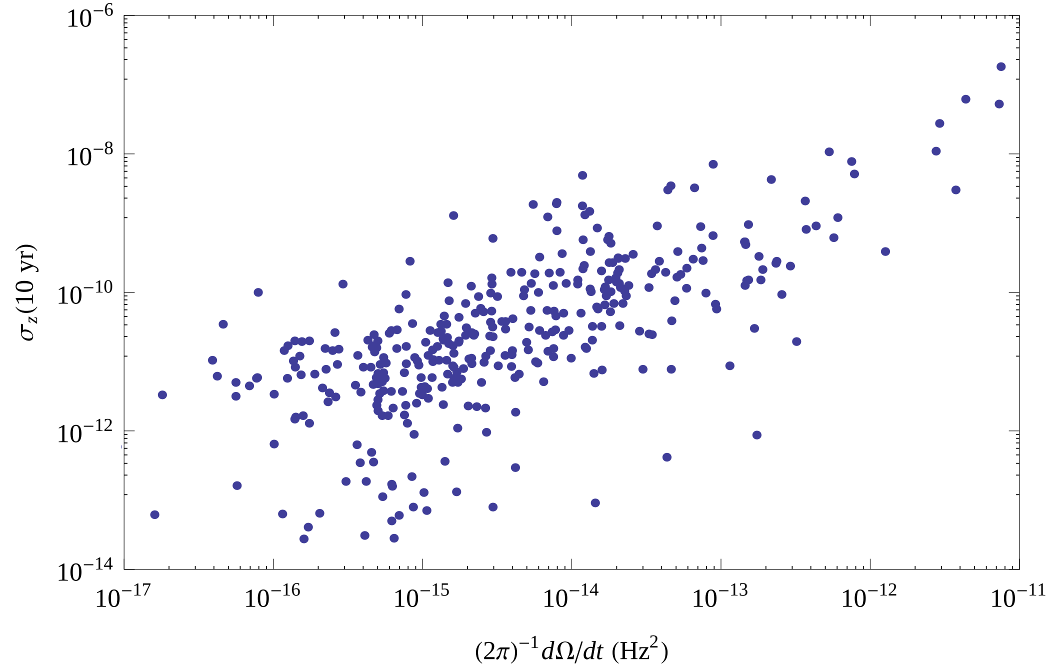
Quenched by stratification (ρ_p/ρ_n)?

(Reisenegger & Goldreich 92; Gusakov & Kantor 13)



Density field (e.g. cloud)

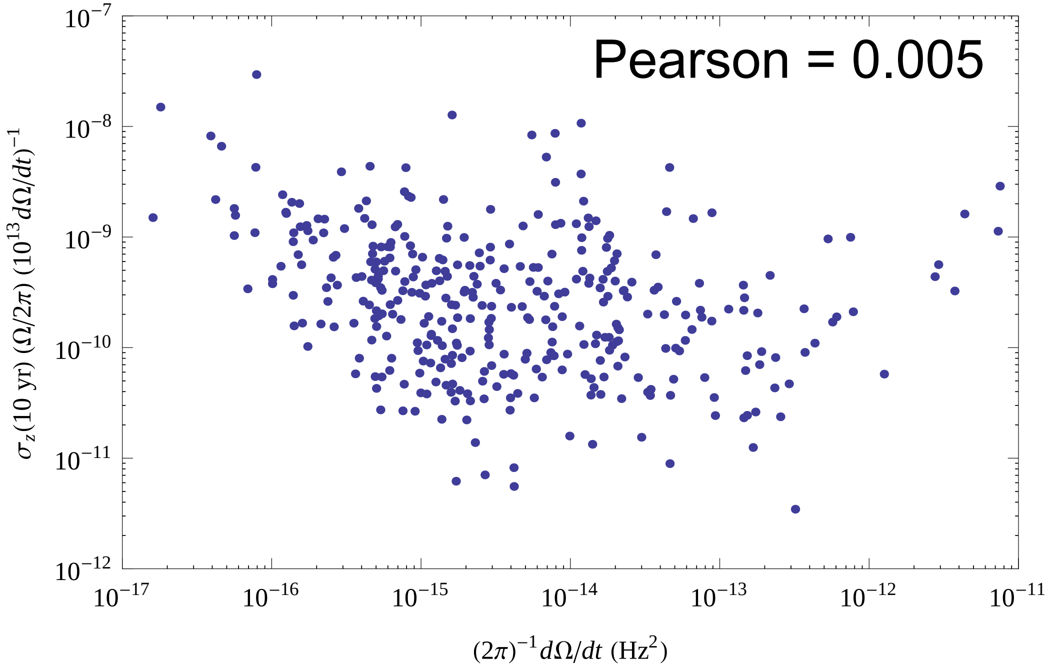




Timing noise measurements

(Hobbs et al. 10)

$$\sigma_z = (720)^{-1/2}\Omega^{-1}\left\langle \ddot{\Omega}^2 \right\rangle^{1/2} T_{obs}^2$$



Stochastic torque theory

(Melatos & Link 14)

$$\left\langle \ddot{\Omega}^2 \right\rangle \propto \left. \frac{d^4 \left\langle J_z(t) J_z(t+\tau) \right\rangle}{d\tau^4} \right|_{\tau=0}$$

IV. MAGNETIC ACTIVITY

Type I or II superconductor;

realistic magnetic geometry

Dendritic flux avalanche in MgB_2 (Johansen et al. 02)

“Many magnetic topologies (e.g. closed loops) **cannot enforce corotation”** (Easson 79)

Are there realistic topologies which can? Unknown!

Fossil super-rotation of core (Melatos 12)

- Tayler or MRI **dynamo** (Braithwaite 06)
- “Geomagnetic jerks”, precession, GWs…

Shear in closed flux tubes (Glampedakis & Lasky 15)

- Kelvin-Helmholtz turbulence? Field $\rightarrow$ crust?

– Proof: slight departure from corotation; $\mathbf{B}=\mathbf{B}_0+\mathbf{B}_1$

$$(4\pi)^{-1}(\mathbf{B}_0\cdot\nabla)(RB_{1\varphi}) = [K(\Omega_{line}-\Omega_{crust}) - k\dot{\Omega}_{crust} + c\dot{\Omega}_n]R^2 + F_{B\varphi}R$$

– **Non-conservative** Fermi liquid forces etc on **RHS** can't be balanced by pressure gradient

– Integrate along **closed $\mathbf{B}$ loop** → multivalued $B_{1\phi}$

– Plasma can't adjust; RHS depends on ***unperturbed*** state, except Ω_{line} (eq'n of motion independent of $\mathbf{B}$)

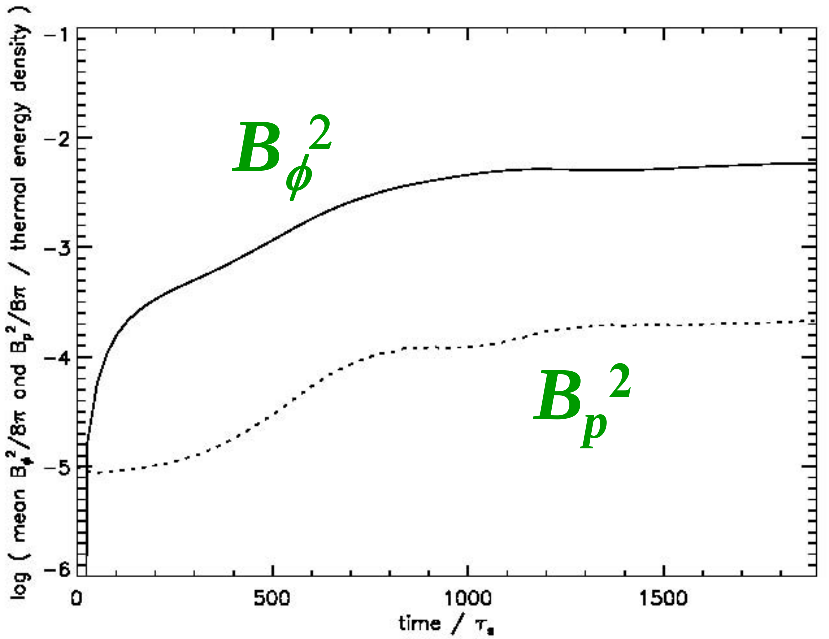
– Generalized to "twisted torus" (Glampedakis & Lasky 15)

– Role of stratification unsolved

A dynamo can exist in a stably stratified star…

…in fact it works better! (Braithwaite 06)

- Driven by shear not thermal convection
- Tayler or MRI instabilities



~1% KE

Wound-up B_ϕ
too weak
to shut off shear

V. GRAVITATIONAL WAVES

New observational constraints

$$h_{lm} = \frac{G}{c^5 d} \frac{\partial^2}{\partial t^2} \int d^3x Y_{lm}^* r^l \mathbf{x} \cdot \mathrm{curl}(\rho \mathbf{v})$$

$$\frac{GM}{Rc^2} \left(\frac{Rf}{c} \right)^2 \left(\frac{d}{R} \right)^{-1} \frac{\varepsilon_{\rho\mathbf{v}} V}{c}$$

Current quadrupole $\propto$ momentum flux $\propto$ T^{0i}

- Vortices reorganize during **glitch rise** $\rightarrow$ GW burst (Warszawski & Melatos 12)

$$\Delta t_{rise} > 10 \text{ ms}$$

- Ekman pumping during **glitch recovery** $\rightarrow$ monochromatic "long transient" (Bennett et al. 10)

$$N > 0.5 \text{ and } K > 3$$

- SF turbulence → **stochastic GW** (Melatos & Peralta 10; Lasky et al. 13)

$$\Delta\Omega/\Omega < 0.04 \quad \text{(individual)}$$

$$\Delta\Omega/\Omega < 0.01 \quad \text{(all MSPs in Universe)}$$

- Coherent LIGO searches for **known MSPs** near EM spin-down limits (Mastrano & Melatos 12)

$$h_0 < 2\times10^{-26}$$

$$\varepsilon < 7\times10^{-8}$$

$$B_{int} < 10^{10}\ \mathrm{G} \quad \text{(superconductor)}$$

NB. Burial or decay starts with $B_{int} > 10^{12}$ G

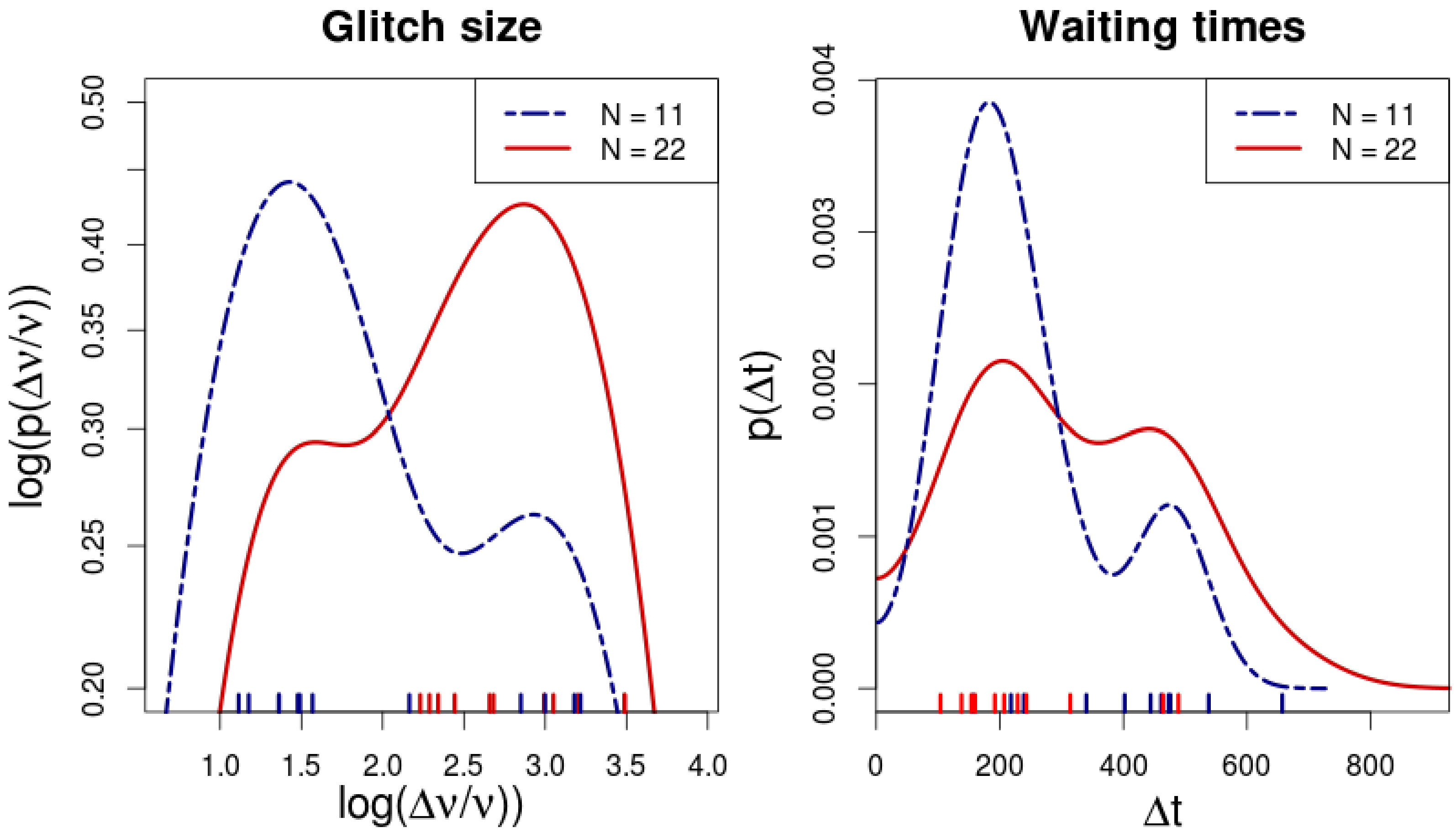
SUMMARY

- Intermittency $\leftrightarrow$ storage $\leftrightarrow$ self-organization
- **GPE** sim's of **vortex avalanches**
- Long-term statistics consistent with data

- **SF turbulence** (macro, micro) & buoyancy
- Timing noise

- Realistic magnetic geometry

- Gravitational wave constraints



PSR 1341-6220: a leopard can change its spots

(Melatos et al. 15)

RECENT SF HIGHLIGHTS

- Energy gap (Gusakov & Kantor 13)
- Neutrino emissivity (Leinson 13)

- **Transport coefficients** & mode damping with hyperons (Kantor & Gusakov 09; Shternin & Yakovlev 08)
- Thermal conductivity (Chamel 12)
- Color-flavor-locked **viscosity** & **mutual friction** (Mannarelli et al. 10, 08; Alford et al. 10, 08)

- **Entrainment** couples SF to crust (Chamel 13) ⟶ **extra** angular momentum **reservoir** for glitches

- Magnetic axis **alignment** (Barskuov et al. 13)

- Ab initio **pinning** (Avogadro et al. 08; Pizzochero 11)
- **“Snowplow”** glitch model (Haskell et al. 12)
- Modes, instabilities, **gravitational waves** (Passamonti & Andersson 12; Jones 10; Sidery et al. 10)

- **r-modes** (Ho et al. 11; Andersson et al. 10; Bondarescu et al. 09)
- **X-ray burst** cooling in LMXBs (Ho et al. 13)
- Rotochemical heating in MSPs (Reisenegger et al. 10)

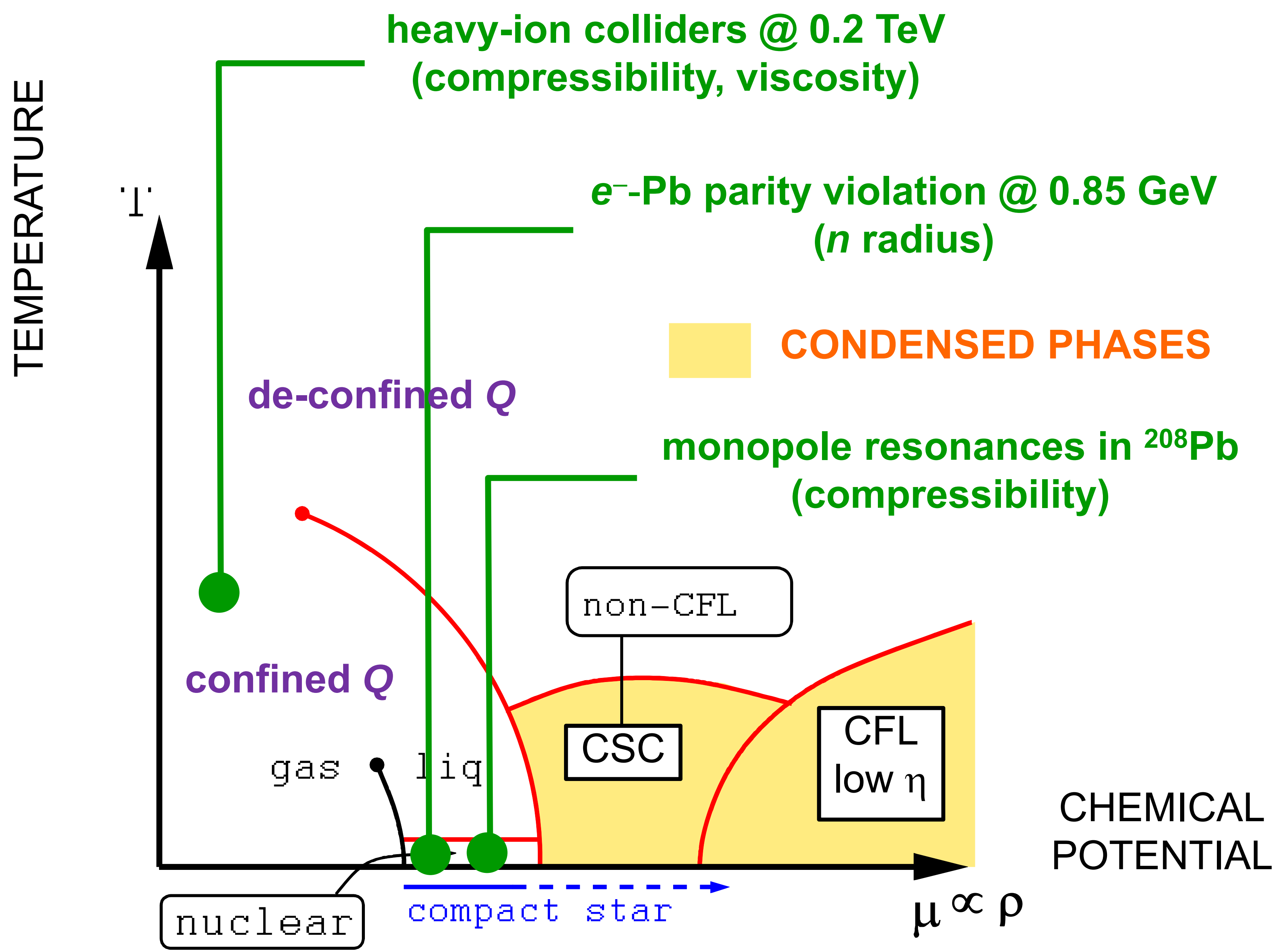
- **Dark matter** condensate (Kouvaris 12)

Radio

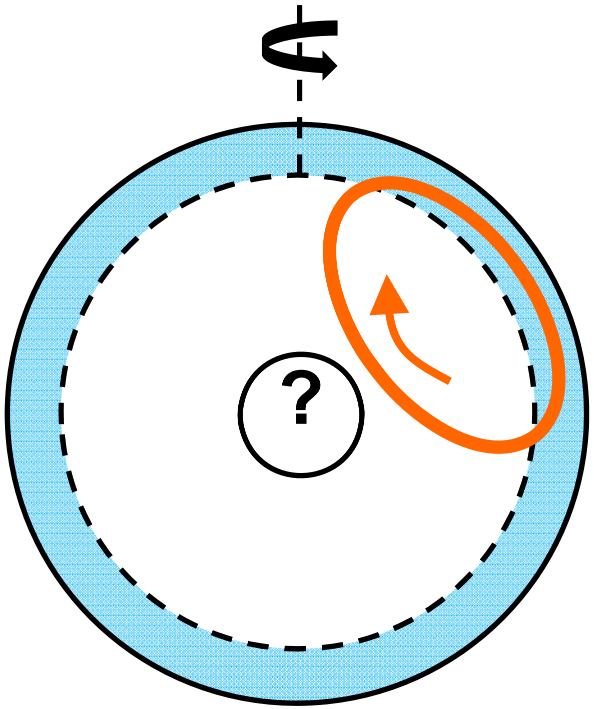
GW

NUCLEAR EXPERIMENTS

Multi-messenger lessons
from post-glitch recoveries


heavy-ion colliders @ 0.2 TeV
(compressibility, viscosity)
e⁻-Pb parity violation @ 0.85 GeV
(n radius)
CONDENSED PHASES
de-confined Q
monopole resonances in 208Pb
(compressibility)
TEMPERATURE
T
non-CFL
confined Q
CSC
CFL
low η
gas
liq
CHEMICAL
POTENTIAL
nuclear
compact star
μ ∝ ρ

Interior fluid sucked into boundary layer, spun down, then recycled



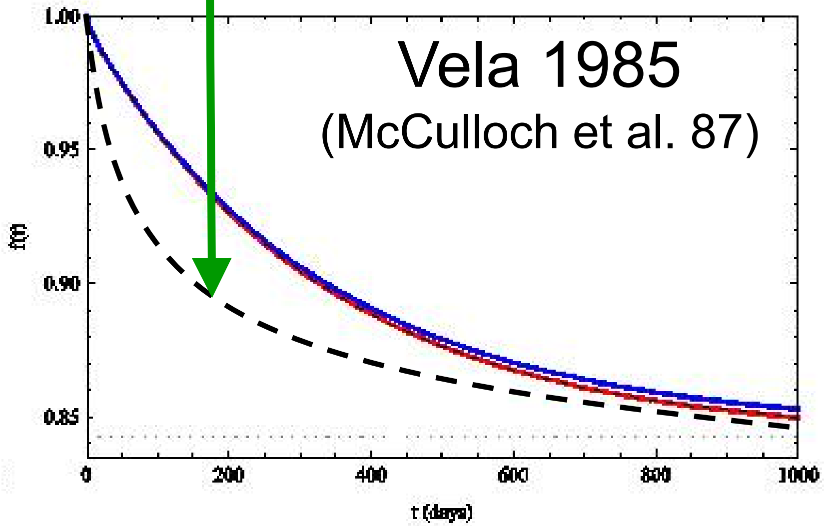
Ekman pumping (“cup of tea”)

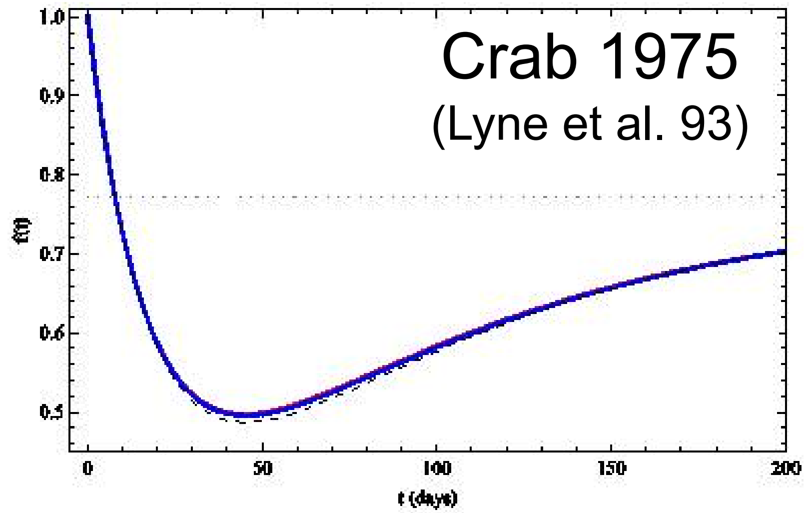
- Radio data → **two** time-scales
  - – viscous p^+-e^- component = Ekman circul'n
  - – n condensate = mutual friction
- Data inconsistent with magnetic locking

- Theory matches ^{4}He laboratory data to 1% with no free parameters (van Eysden & Melatos 11)

RADIO

single exponential ≠ fit!





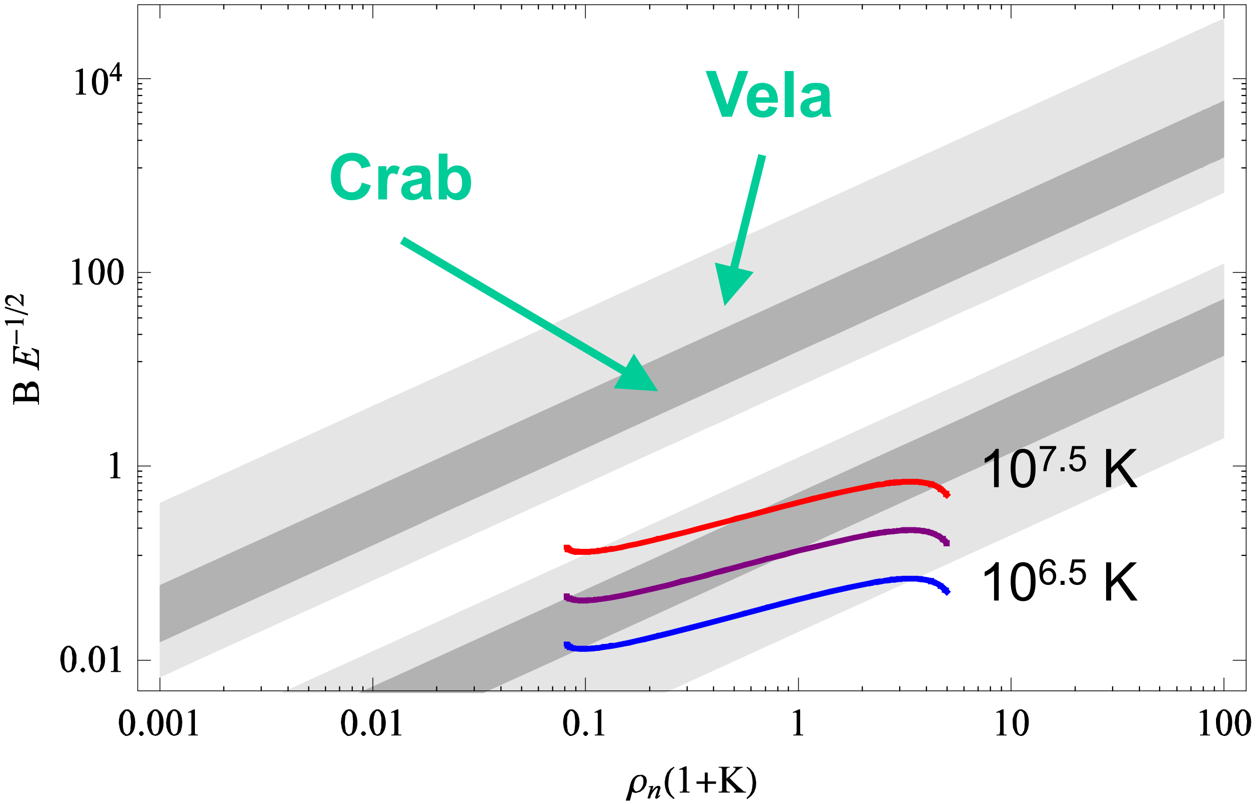
data theory

- Dual exponentials: Ekman, mutual friction
- Predict **overshoot** if internal lag obeys

$$\Omega_0 - \Omega_{n0} < \frac{7BE^{-1/2}}{20\rho_n K} - 1$$

RADIO

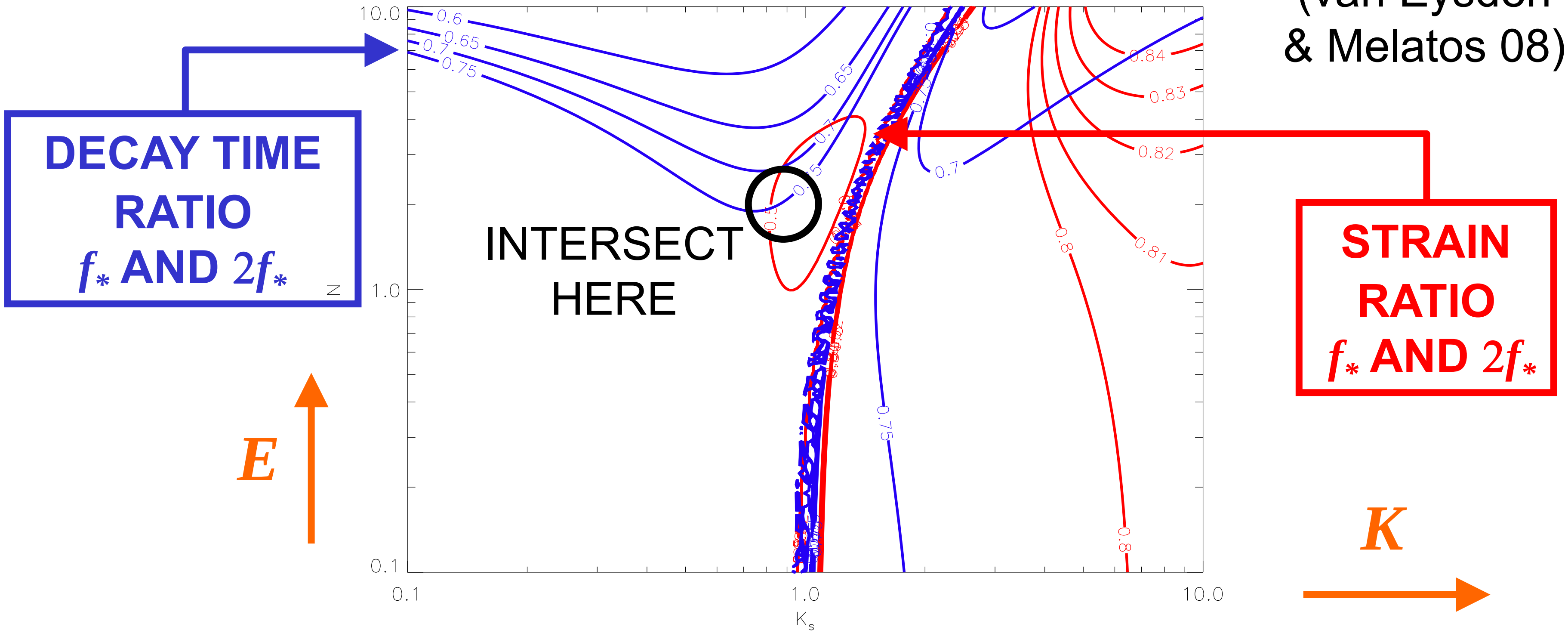
(van Eysden & Melatos 10)



- Good fit for "ordinary" ***n-p-e-μ*** matter
- $BE^{-1/2}$ too low for CFL (cf. 2SC)

GW

(van Eysden & Melatos 08)



- Periodic GW decaying over days to weeks
- Compressibility K, viscosity E → boundary layer thickness → GW amplitude, decay time

Init LIGO

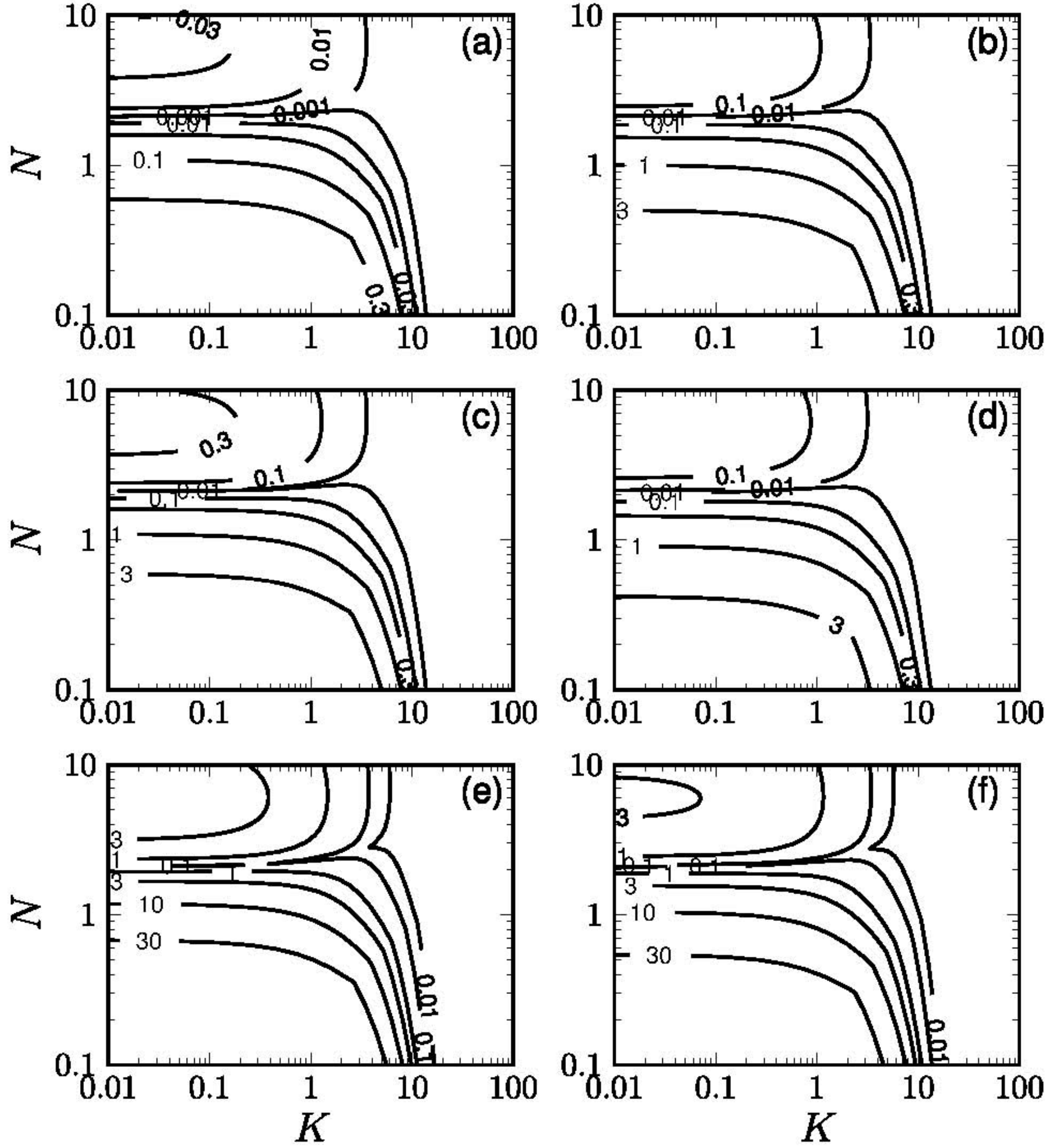
Adv LIGO
Zero detuning

Adv LIGO
NS optimum

Adv LIGO
BH optimum

ET

ET
Xylophone



Signal-to-noise contours (Bennett et al. 10)

SUPERCONDUCTOR

Differential rotation drives magnetic activity

- **Cas A** cooling → $^1S_0$ protons in core

- Incomplete **type II** Meissner expulsion
  - Fluxoids with quantized magnetic flux $\mathbf{\Phi = \mathit{h}/2\mathit{e}}$
  - More fluxoids (~10^{31}) than n vortices (~10^{16})

- **Entrainment** (current-current interaction) magnetizes n vortices
  - Opposite-current-carrying wires repel
  - **0.1 GeV** per junction, locked together (maybe…)

- **Maxwell stress** $\sim BH_{c1}$ $\mathbf{\sim 10^3 \mathit{B}^2}$

RECENT SC HIGHLIGHTS

- **Multifluid** "MHD" theory (Glampedakis et al. 11)

- Poloidal-toroidal **equilibria** & **stability** (Lander 13)
- Matching normal crust ↔ type II core (Henriksson & Wasserman 13; Sidery & Alpar 09)

- **Type I** in **macro** domains (Charbonneau & Zhitnitsky 07)
  - Chiral anomaly (e.g. QCD) → current **along** fluxoids
  - Attractive force → type I for $J > J_{crit}$
  - Cf. fluxoid instability → **tangle** when $J < J_{crit}$

- **Magnetar oscillations** (incl. fluxoid cutting & damping) (Gabler et al. 13; Glampedakis & Jones 14)

- Post-glitch, quasiperiodic, **magneto-inertial oscillations** (van Eysden 14; Glampedakis et al. 14)

- Crystalline **color superconducting** core: shear modulus, gravitational waves, cooling (Alford et al. 08; Glampedakis et al. 12; Negreiros et al. 12)

- Indirect spin-down limit on **GWs** from **buried type II** field in MSPs (Mastrano & Melatos 12)