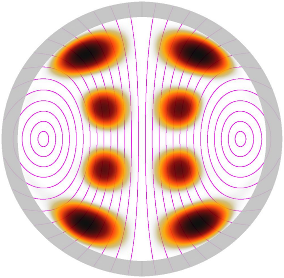
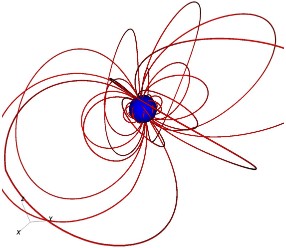
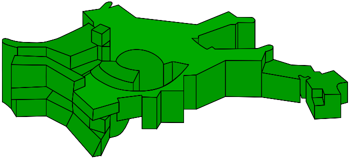
What can magnetar QPOs tell us about the NS EoS

Michael Gabler



E. Müller,
P. Cerdá-Durán, T. Font,
N. Stergioulas





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1. Introduction
    - Contraints on NS properies
    - Magnetar quasi-periodic oscillations (QPOs)
        - Observations
        - Elastic oscillations
        - Alfvén oscillations

2. Superfluid magneto-elastic QPOs inside the magnetar
    - Superfluid effects
    - Different regimes and damping of crust modes
    - Different constraints
        - Outbreak
        - High-frequency QPOs
        - Identifying observed frequencies

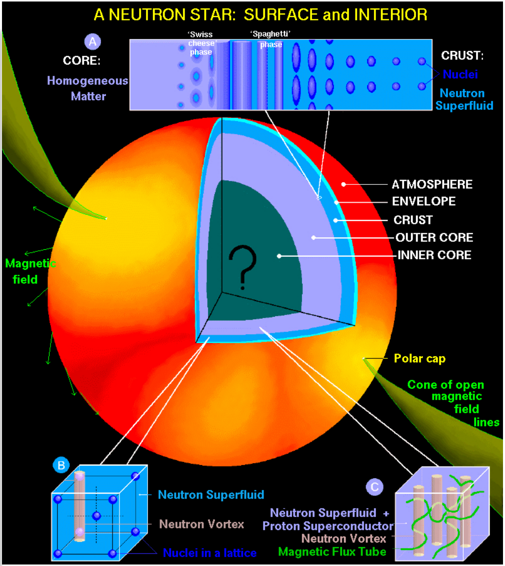
3. Constraining neutron star properties with QPOs

4. Conclusions

Neutron stars (NS) as unique laboratory

- Ultra-dense matter: interior of NS widely unknown
  - Nuclear matter ???
  - Hyperons ???
  - Quarks ???

  expected properties:
  - Superfluidity
  - Superconductivity
  - Color superconductivity
  - ...
- Exotic physics in strong magnetic fields ($B \gtrsim B_{\mathrm{QED}}$):
  - Appearance of chain molecules
  - One-photon pair creation
  - Photon splitting
  - ...



(D.Page)

Ways to constrain the NS equation of state

Radius and compactness constraints

- Gravitational redshift of spectral lines: $z = 1 - (1 - 2GM/Rc^2)^{-1/2}$
- X-ray burst (PRE)
- Burst oscillation pulses (distorted by GR effects depending on compactness)

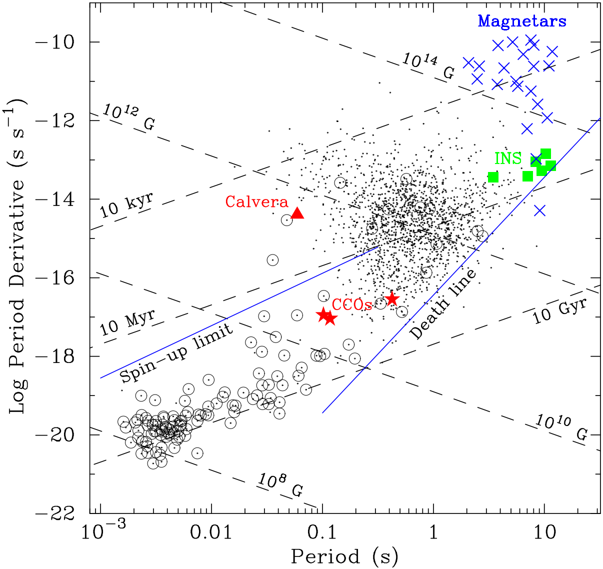
Gravitational Waves

- Tidal interaction during NS merger
- Oscillations of hyper-massive NS after merger
- Magnetar giant flares

Problems

GW wave detectors not sensitive enough,
uncertainties in distances and atmospheric models,
...

Different classes of NS



(Halparn et al. 2013)

Accreting Pulsars

(circled dots)

- accretion spins up NS
- maximum spin period observed 716Hz

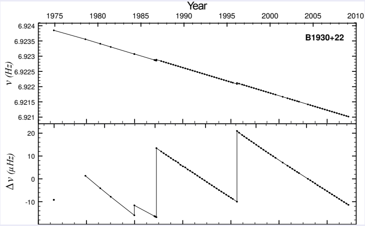
Isolated Neutron stars

(green squares)

- Thermal emission from surface
- model dependent:
  - distance?
  - absorption?
  - atmosphere?

Pulsar glitches

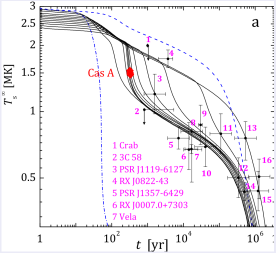
- Pulsars spin down continuously
- Occasionally sudden jumps: 'glitches'
- Neutron superfluid vortices couple to crust through pinning only
- Once $\Delta\Omega_{\mathrm{SF-crust}}$ too large, SF vortices unpin collectively $\Rightarrow$ glitch



Espinoza et al. 2011

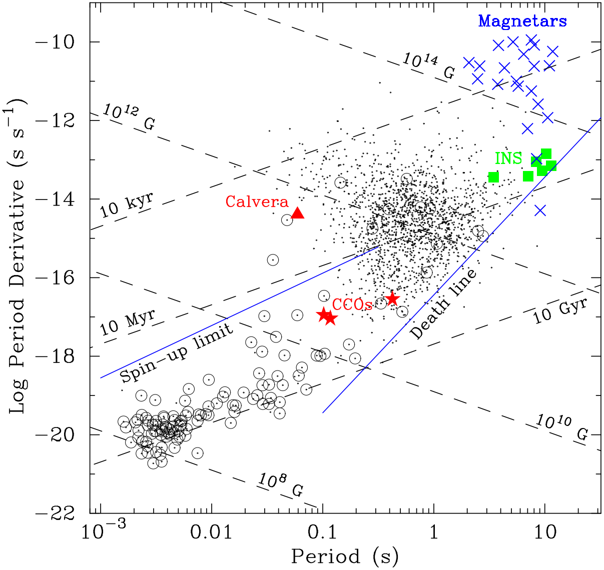
Cassiopeia A cooling

- Neutron stars cool by ν and photon emission
- Cooling curve of Cas A shows steep decrease in T_S^∞
- Good fit only for models that include superconducting protons and superfluid neutrons



Shternin et al. 2011

Spin period - spin down $P\dot{P}$ diagram:



(Halparn et al. 2013)

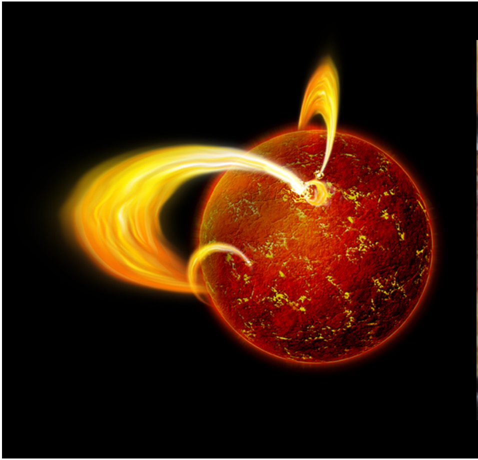
Observations

- High $P\dot{P}$
- High X-ray luminosity
- Repeated $\gamma-$bursts
- 3 giant flares

Magnetar

- Magnetic dipole spin down: $B \sim 10^{15}$ G
- Strong B powers X-ray luminosity
- Magnetic field evolution can account for bursts and power giant flares luminosity

Magnetar giant flare ...



... or just a Takoyaki

Observations - quasi-periodic oscillations (QPOs)

Confirmed QPO frequencies

SGR 1806-20: 18, 26, 30, 92
150, 625, 1840 Hz

SGR 1900+14: 28, 53, 84,
155 Hz

(Israel et al. 2005, Strohmayer & Watts 2006, ...)

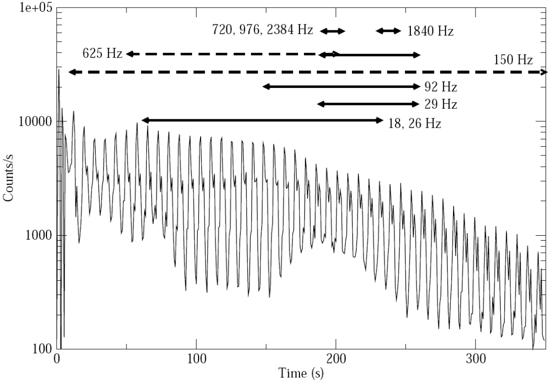
QPOs in normal bursts

93, 127 and 260Hz

(Huppenkothen et al. 2014)

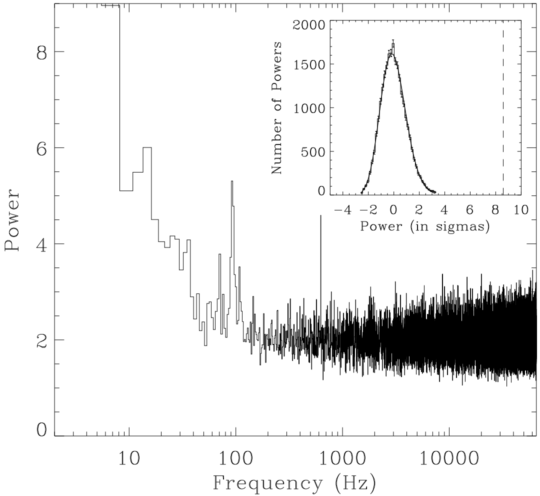
Unconfirmed QPOs

17, 21, 36, 59, and 116 Hz
(Hambaryan et al. 2011)



Strohmayer & Watts 2006

Challenges in the detection of QPOs



(Strohmayer & Watts 2006)

Need for more and better data! (Intermediate flares)

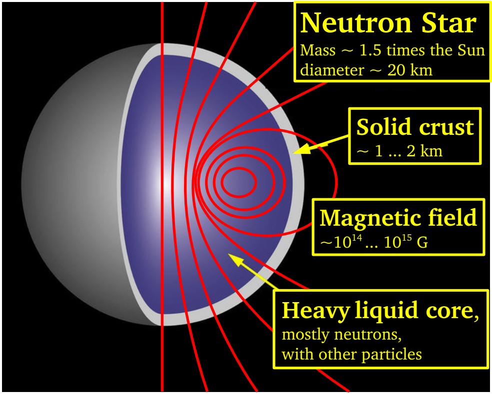
- Clear signals at $f \sim 625\,\text{Hz}$ and $92\,\text{Hz}$
- Ok for $f \gtrsim 30\,\text{Hz}$
- Unclear for $f < 30\,\text{Hz}$
- Only 3 giant flares

$\Rightarrow$ More sophisticated techniques

$\Rightarrow$ Analysis of normal bursts

- BUT time variability of the burst is of the order of $100\,\text{ms}$
- Hard to distinguish intrinsic variability from QPO (in short bursts)

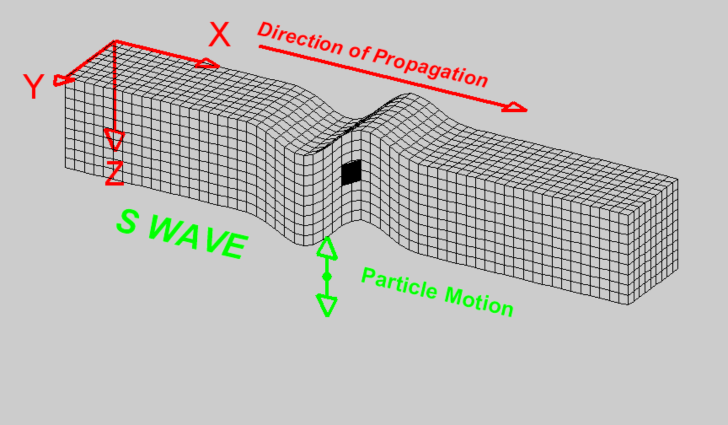
Where do the QPOs come from? Are they Starquakes?



Possible origin of the observed frequencies

- Discrete Shear modes (crust)?
- Alfvén oscillations at the turning points of a continuum (core+crust)?
- Magnetospheric oscillations?

Shear waves



Larry Braile, Purdue University

Torsional shear modes

Samuelsson & Andersson 2007

Observed frequency in Hz		Shear mode	
SGR 1806-20	SGR 1900+14	n	l
18		???	???
26		???	???
30	28	0	2
	53	0	4
92	84	0	6
150		0	10
	155	0	11
625		1	
1840		3	

(Shoemaker & Thorne 1983, Duncan 1998, Strohmayer & Watts 2005, Piro 2005, Sotani et al. 2007, Samuelsson & Andersson 2007, Steiner & Watts 2009, Deibel et al. 2014, Sotani et al. 2016, ...)

- No magnetic field
- Free slip / zero traction at crust core interface
- Relativistic estimates for f:

$\Rightarrow$ $n = 0$:

$$f^2 \sim \frac{\mu_S}{\rho} \frac{(l-1)(l+2)}{RR_c}$$

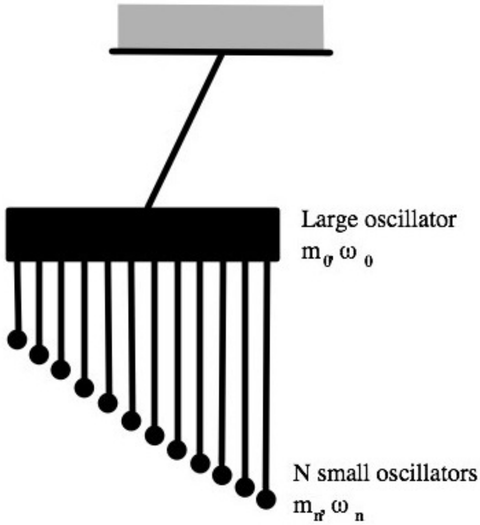
R_c - radius of crust

$\Rightarrow$ $n > 1$:

$$f \sim \sqrt{\frac{\mu_S}{\rho}} \frac{n}{\Delta}$$

Δ - crust thickness

A toy model for Alfvén continuum



van Hoven & Levin 2010

- Big pendulum with large mass
- Many small oscillators
- Each small pendulum has different f

⇒ Quasi-continuum

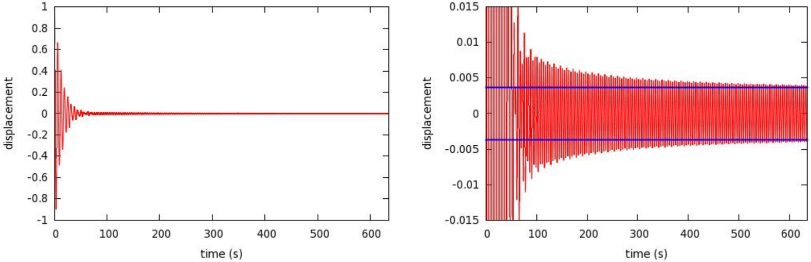
- Excite big pendulum

⇒ Strong damping of oscillation

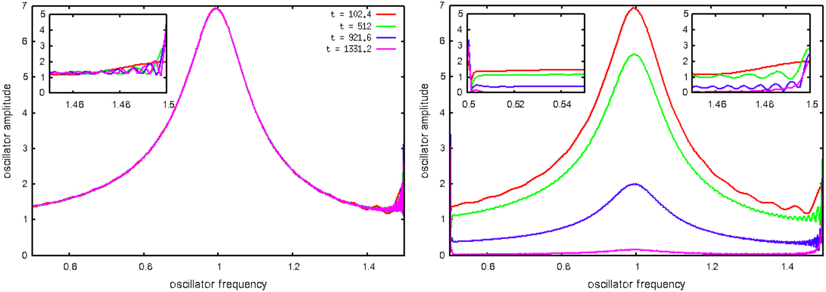
- Excitation of small oscillators
- Increasing oscillations at the edge of the continuum

A toy model for Alfvén continuum

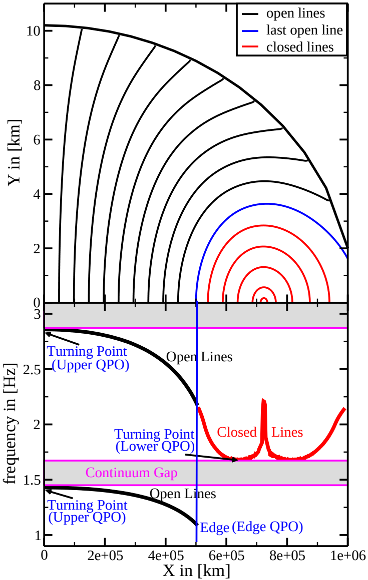
Time evolution of displacement



Oscillator amplitude



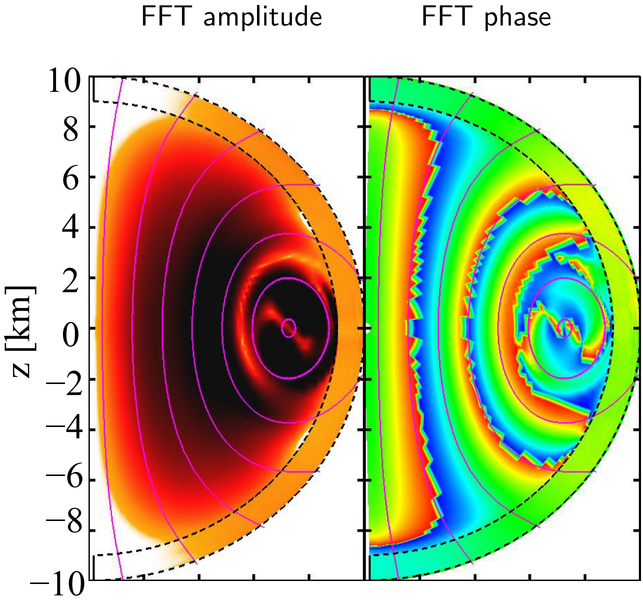
The Alfvén continuum



- Each field line has proper eigenfrequency
  (purely poloidal magnetic field + torsional oscillations)
- Field lines are coupled through:
  (i) surface boundary conditions
  (ii) the crust
- Long-lived QPOs exist at the turning-points or edges of the continuum
- Gaps between successive Alfvén overtones

(Levin 2006 & 2007, Sotani et al.2007 & 2008, Cerdá-Durán et al. 2009, Colaiuda et al. 2009)

Continous phase



Superfluid neutron star core - (Newtonian) two-fluid model

Neutrons

$$\partial_t \rho_n + \nabla \cdot (\rho_n \mathbf{v}_n) = 0$$

$$(\partial_t + \mathbf{v}_n \nabla)(\mathbf{v}_n + \varepsilon_n \mathbf{w}_{pn}) + \nabla(\Phi + \mu_n) + \varepsilon_n w_k^{pn} \nabla v_n^k = 0$$

Charged particles (protons)

$$\partial_t \rho_p + \nabla \cdot (\rho_p \mathbf{v}_p) = 0$$

$$(\partial_t + \mathbf{v}_p \nabla)(\mathbf{v}_p + \varepsilon_p \mathbf{w}_{np}) + \nabla(\Phi + \mu_p) + \varepsilon_p w_k^{np} \nabla v_p^k = \frac{(\nabla \times \mathbf{B}) \times \mathbf{B}}{4\pi \rho_p}$$

$\mathbf{w}_{np} = -\mathbf{w}_{pn} = \mathbf{v}_n - \mathbf{v}_p$, ε entrainment parameter

Superfluid neutron star core - one-fluid approximation

Effective one fluid model (decoupling n from p): $\rho \to \rho_p \sim 0.05\rho$

$$v_A^2 = \frac{B^2}{\rho} \to \frac{B^2}{\varepsilon_\star X_c \rho} = \frac{B^2}{\rho_p}$$

Fundamental QPOs

Exist as before but with:

$$f_{\rm sf} \sim \frac{1}{t_A} \sim \frac{v_A}{R} \sim \frac{B}{R\sqrt{\rho_p}} \sim \frac{B}{R\sqrt{0.05\rho}} \sim 5 \times f_{\rm n}$$

To match observed QPOs non-superfluid:

$$2 \times 10^{15} \lesssim B \lesssim 10^{16}\,\mathrm{G}$$

superfluid

$$5 \times 10^{14} \lesssim B \lesssim \mathrm{few} \times 10^{15}\,\mathrm{G}$$

Magneto-elastic QPOs inside the magnetar

$\mathbf{B^2 << \mu_S}$ $\mathbf{B \sim 10^{13} G}$ $\mathbf{B \sim 10^{15} G}$ $\mathbf{B^2 >> \mu_S}$

$\rightarrow \mathbf{B}$

predominantly shear modes

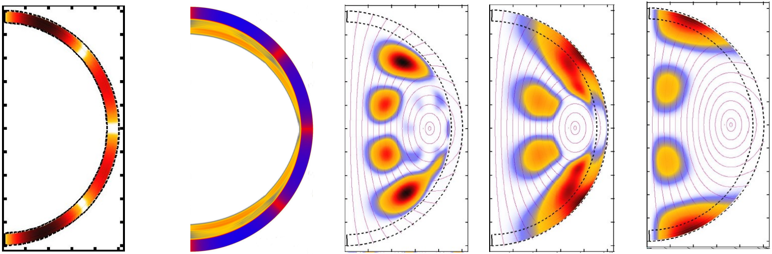
shear modes strongly damped

magneto-elastic QPOs

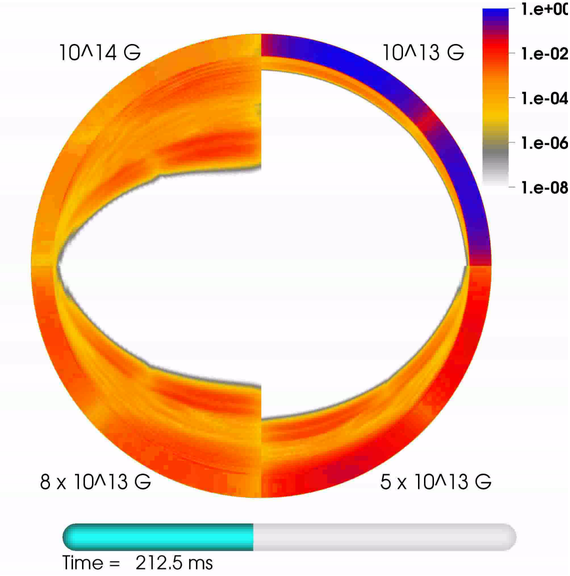
confined to core

reach surface

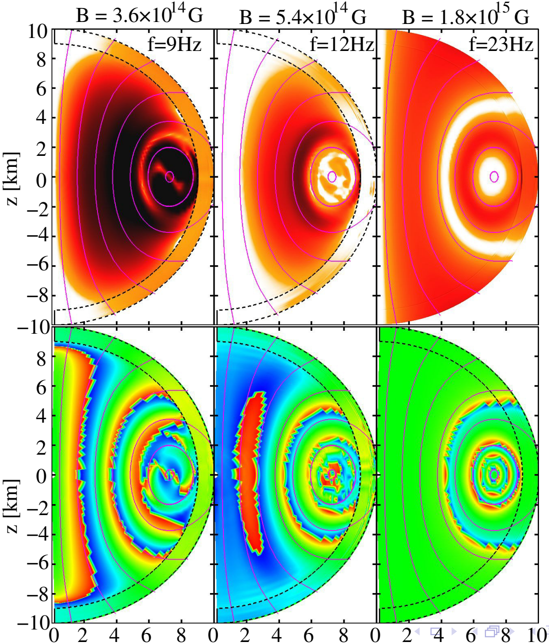
predominantly Alfvén QPOs



Damping of crust modes

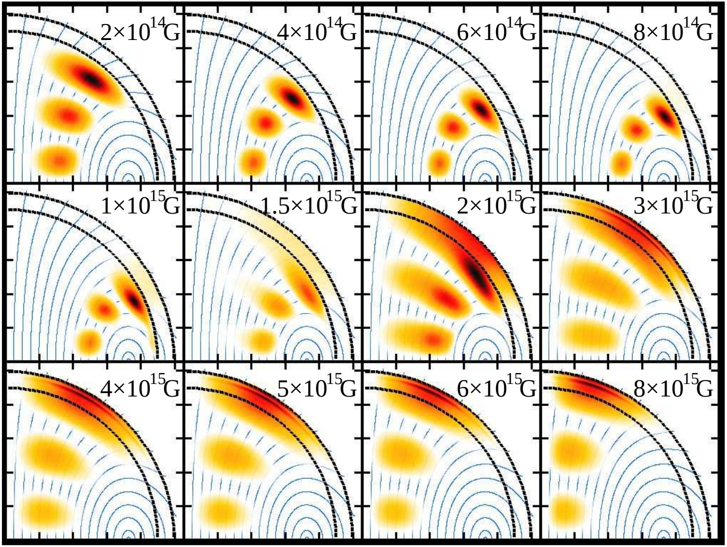


Continous vs constant phase



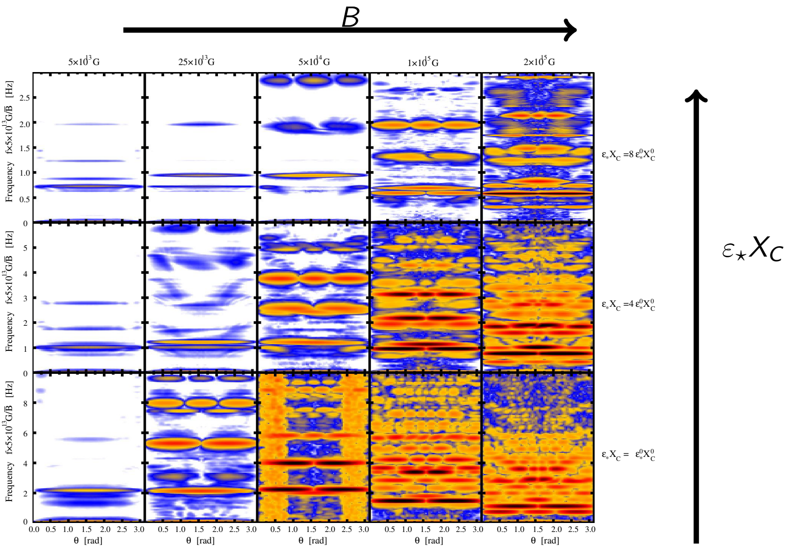
Magneto-elastic QPOs break out to surface

Magnitude of the FFT at different B



Magneto-elastic QPOs break out to surface

Magnitude of the FFT at the surface



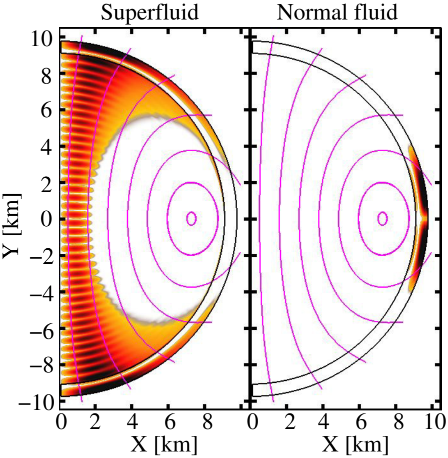
High frequency QPOs

Normal fluid

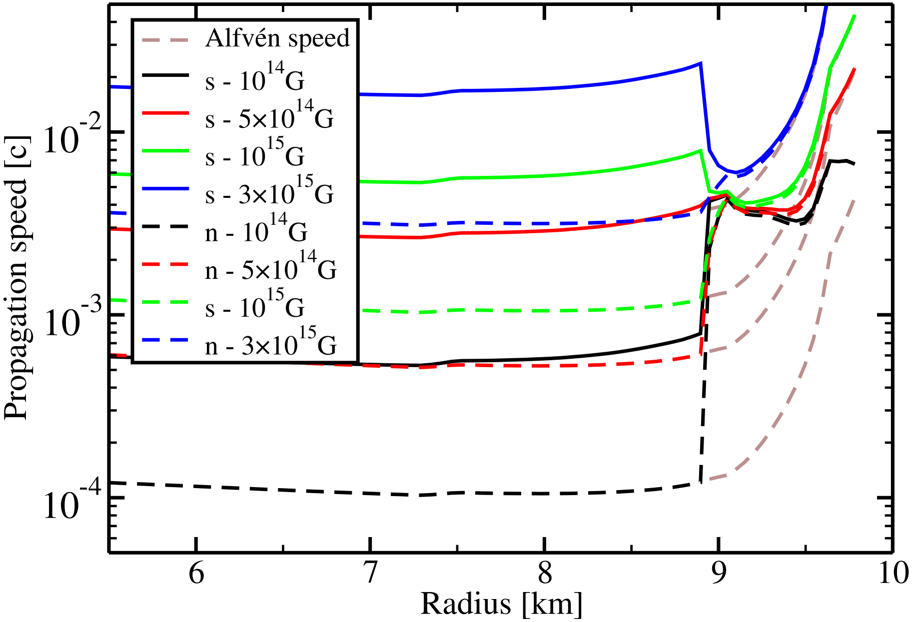
- $n = 1$ radial shear mode structure
- Localized close to equatorial plane
- $\hat{B} \perp \hat{r} \Rightarrow$predominantly shear mode only in crust

Superfluid

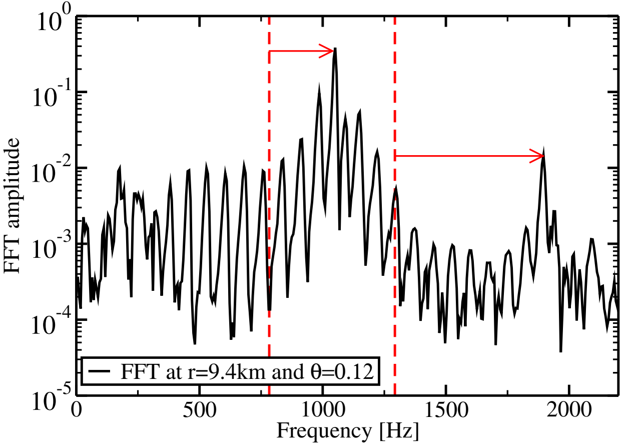
- $n = 1$ radial shear mode structure
- Close to pole
- Resonance with Alfvén overtone of core



Propagation speeds



High frequency QPOs



- Initial perturbation with crustal mode (red dashed lines)
- Resonantly excited magneto-elastic oscillation always at higher frequency
- $f_{2_{t_n}} = f^0_{2_{t_n}} (1 + a_{2_{t_n}} \bar{B}_{15})^{1/2}$

Identifying observed frequencies

- Frequency ratio of low frequency magneto-elastic QPOs (odd, even) is roughly

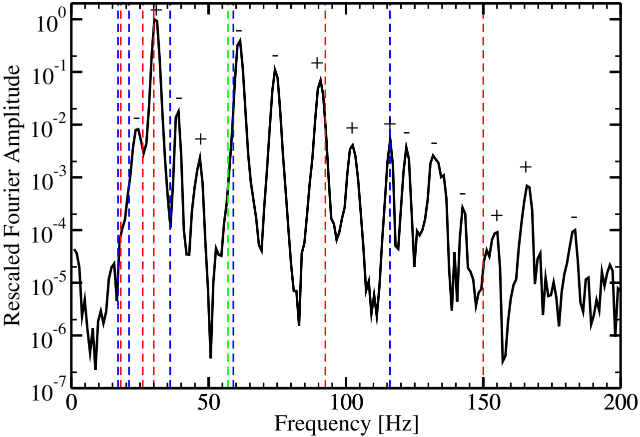
$$1 : 2 : 3 : 4 : 5 : \ldots$$

- Different magnetic field configurations gives more than one fundamental
- High frequency QPO as resonance of higher Alfvén overtone in core with $n > 0$ crustal mode if core is superfluid

SGR 1806-20: (18), 26, 30, 92, 150, 625, 1840 Hz

SGR 1900+14: 28, 53, 84, 155 Hz
or 28, 53, 84, 155 Hz

One particular example



- Match fundamental with 30Hz QPO
- Other observed QPOs $f > 30$Hz match nicely
- Problems for $f < 30$Hz

- APR+DH EoS
- $\bar{B} = 1.1 \times 10^{15}$ G
- $\varepsilon_{\star} X_C = 0.046$
- $M = 1.4 M_{\odot}$
- $R = 12.26\,\mathrm{km}$

Empirical relations

Outbreak of oscillations

- Outbreak for $\varepsilon_\star X_c = 4 \times \varepsilon_\star^0 X_c^0$ and $\bar{B} = 10^{15}$ G
- All terms in equations contain either $\sqrt{\mu}$ or $(\varepsilon_\star X_c)^{-1/2}\,\bar{B}_{14}$
- $\mu_{cc} \lesssim \mu_{cc}^{ref}\,(17.23\varepsilon_\star X_c)^{-1}\ \ \bar{B}_{14}^2$

High frequency QPO

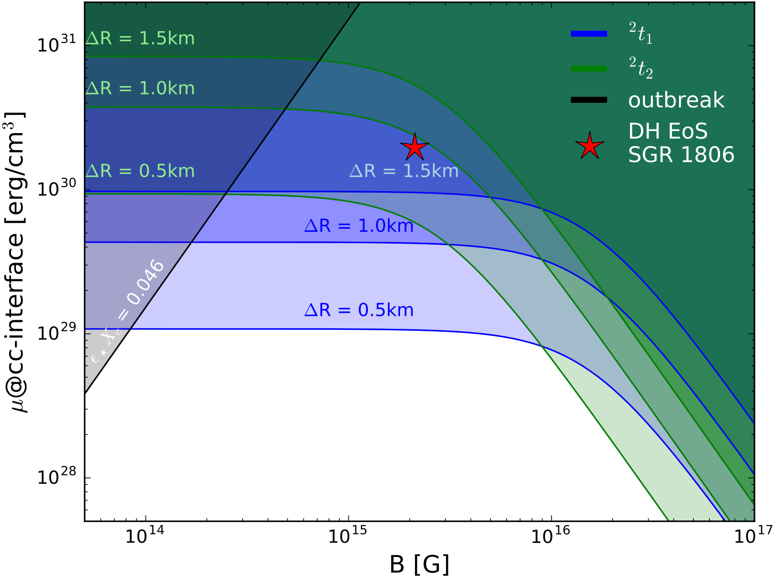
- $f_{{}_2t_n} = f^0_{{}_2t_n}(1 + a_{{}_2t_n}\bar{B}_{15})^{1/2}$
- assuming $v_s = const. \Rightarrow f_0 = \frac{v_s}{\Delta R} = \sqrt{\frac{\mu_{cc}}{\rho cc}}\frac{1}{\Delta R} \quad \Rightarrow \quad \mu_{cc} \lesssim \frac{f^2_{\rm obs}\Delta R^2 \rho_{cc}}{1+a_{{}_2t_n}B^2_{15}}$

Matching the frequency of ${}^2U_2$

$$f_{{}_2U_2}[\mathrm{Hz}] \quad = \quad \left(2.8 \times (\varepsilon_\star X_c)^{-0.55}\sqrt{\frac{\mu_{cc}}{\mu_{cc}^{\rm ref}}} + 0.66\,(\varepsilon_\star X_c)^{-0.33}\,\bar{B}[10^{14}\mathrm{G}]\right) \times \left(\frac{1-4.58M/R+6.06(M/R)^2}{1-4.58(M/R)_{\rm ref}+6.06(M/R)^2_{\rm ref}}\right)$$

(Sotani et al. 2008)

Constraint on shear modulus at base of the crust



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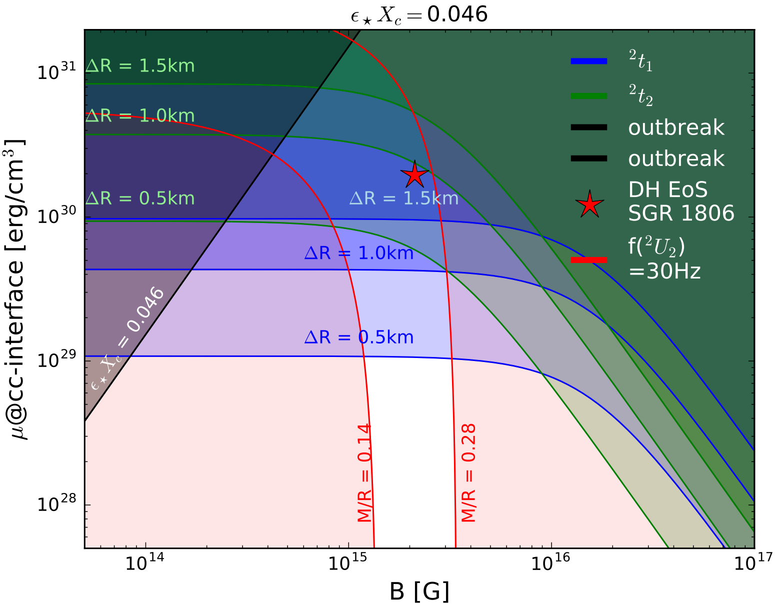

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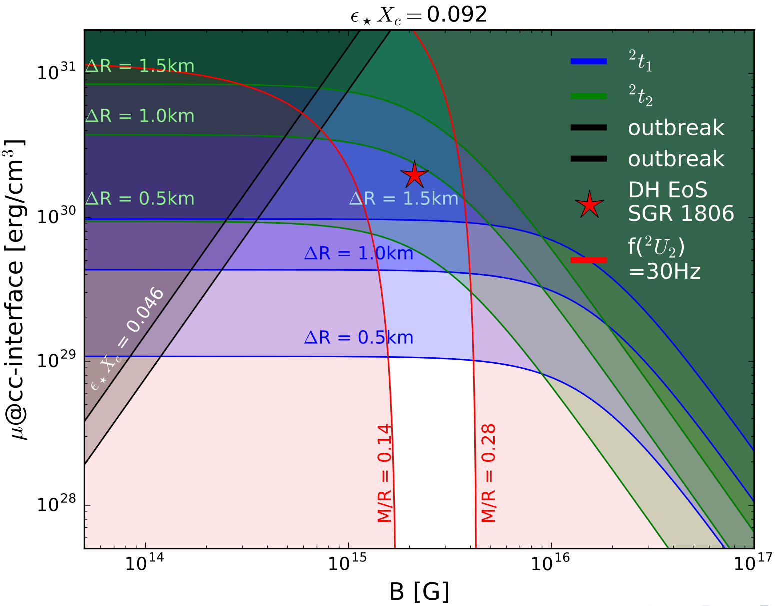
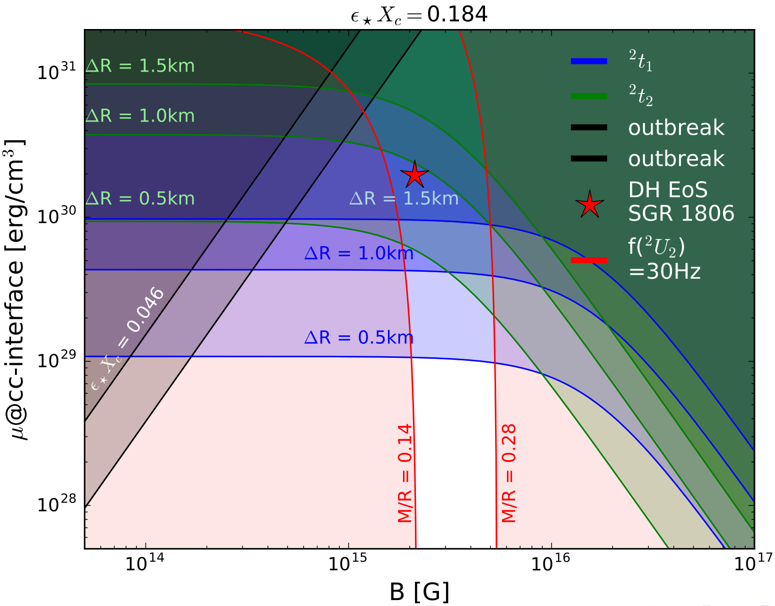
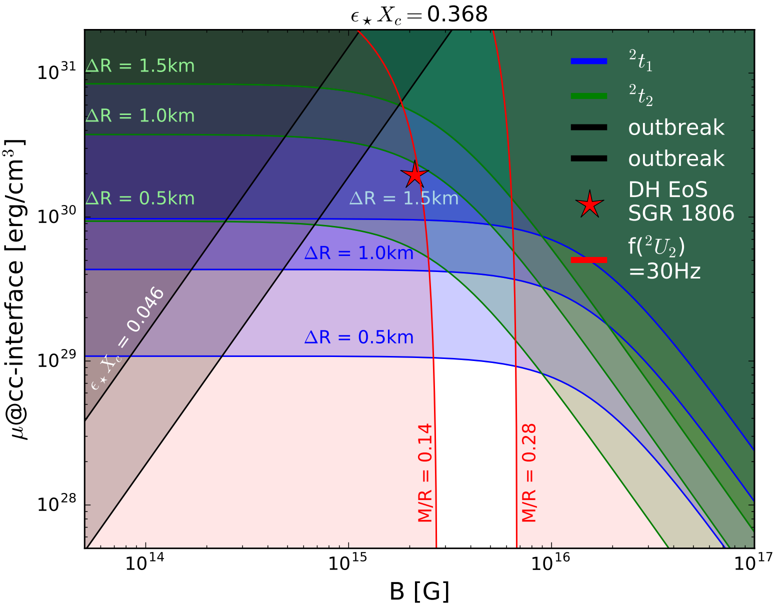


Constraint on shear modulus at base of the crust

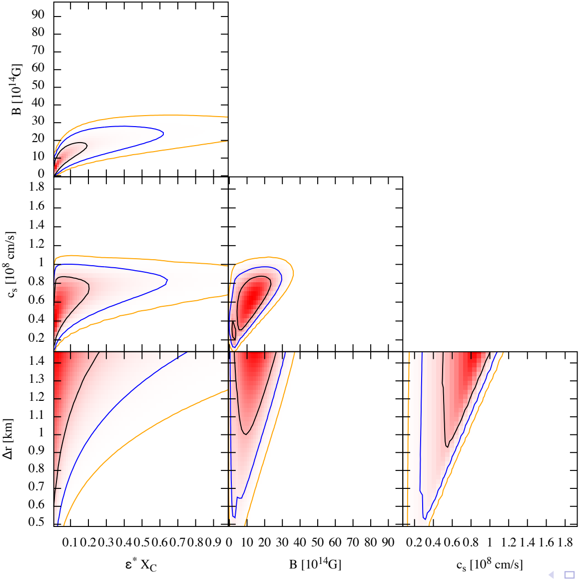


Constraint on shear modulus at base of the crust

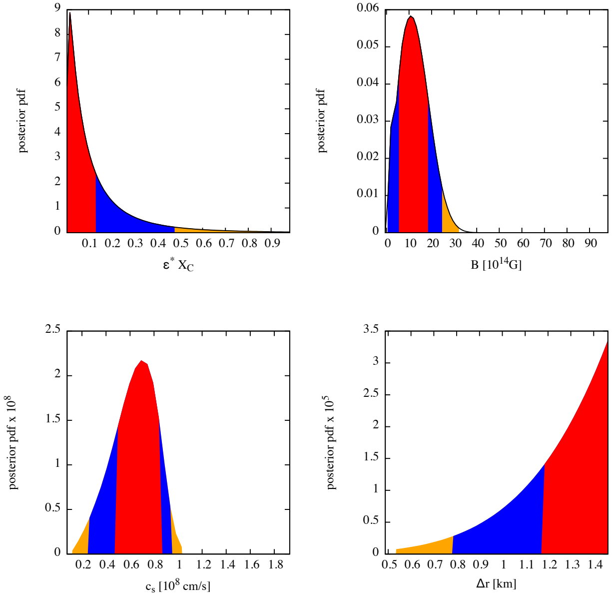


Preliminary - Inferring constraints on the EOS

4 parameters: B c_s Δr $\varepsilon_\star X_c$



Preliminary - Inferring constraints on the EOS



Conclusions

- Crustal modes are damped too efficiently
- Magneto-elastic oscillations can explain magnetar QPOs
- Constraints on EoS from
  - Outbreak of oscillations
  - High frequency QPO
  - Matching of fundamental ${}^{2}U_{2}$
- E.g. DH and $\bar{B} = 2.1 \times 10^{15}$G requires $\varepsilon_{\star} X_{c} = 0.184$ and $\Delta R \sim 2.0\,\mathrm{km}$ (in conflict with theoretical models)
- Inference gives
  - B-field estimates in agreement with spin-down magnetic field strengths
  - Preference for superfluid core
  - low shear speeds ($c_s \lesssim 10^8\,\mathrm{cm/s}$)

Conclusions II - meeting reality

- Problem: degeneracy between EoS, superfluid properties, magnetic field strength and configuration

⇒ Solution: see JEROME's talk
many simulations with different EoS and magnetic fields

- Problem:
  - Very limited observations
  - Robustness of observed pattern 1:3:5 ?
  - Dependence on B-strength ?

⇒ Solution: new satellites or new giant flares

- Further generalizations of model:
  - Coupled toroidal-poloidal oscillations
  - Superconductivity
  - Modulation mechanism for emission

Complicated problem and many papers published

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Magneto-elastic oscillations of ne
fields

Michael Gabler[1,2,3], Pablo Cerdá-D
and Ewald Müller[1]
[1] *Max-Planck-Institut für Astrophysik, Karl-Schwarzs*
[2] *Department of Physics, Aristotle University of Th*
[3] *Departamento de Astronomía y Astrofísica, Un*

10 May 2012

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abler[1,2], Pablo Cerdá-Durán[1], José A. Font[1], Nikolaos Stergioulas

nto de Astronomía y Astrofísica, Universitat de València, 46100 Burjassot (V
Institut für Astrophysik, Karl-Schwarzschild-Str. 1, 85741 Garching, Germ
f Physics, Aristotle University of Thessaloniki, Thessaloniki 54124, Greec

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Magneto-elastic oscillations and t
in magnetars

Michael Gabler[1,2,3], Pabl
and Nikolaos S
[1] *Max-Planck-Institut für A*
[2] *Departamento de Ast*
[3] *Department of P*

of crustal shear modes

Müller[1]

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Magneto-elastic oscillations o
magnetic field configuration

Michael Gabler[1,2], Pablo Cerdá
and Nikolaos Sterg
[1] *Departamento de Astronomía y*
[2] *Max-Planck-Institut für Astrop*
[3] *Department of Physics, Arist*

ber 2012

Magneto-elastic torsional oscillations of magnetars

Michael Gabler[1,2,3], Pablo Cerdá-Durán[1], José A. Font[2], Ewald Müller[1] and Nikolaos Stergioulas[3]
[1] Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, 85741 Garching, Germ
[2] Departamento de Astronomía y Astrofísica, Universidad de Valencia, 4610
(Valencia), Spain
[3] Department of Physics, Aristotle University of
E-mail: `miga@mpa-garching`

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Modulating the ma
magneto-elastic os

Michael Gabler[1,2], Pabl
nd Ewald Müller[1]
Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, D-85741 Garching, Germany
Departamento de Astronomía y Astrofísica, Universitat de València, 46100 Burjassot (Valencia), Spain
Department of Physics, Aristotle University of Thessaloniki, Thessaloniki 54124, Greece

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Coherent magneto-elastic oscillations in superfluid magnetars

Michael Gabler[1], Pablo Cerdá-Durán[2], Nikolaos Stergioulas[3], José A. Font[2,4],
and Ewald Müller[1]
[1] *Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, 85741 Garching, Germany*
[2] *Departamento de Astronomía y Astrofísica, Universidad de Valencia, 46100 Burjassot (Valencia), Spain*
[3] *Department of Physics, Aristotle University of Thessaloniki, Thessaloniki 54124, Greece*
[4] *Observatori Astronòmic, Universitat de València, C/ Catedrático José Beltrán 2, 46980, Paterna (València), Spain*

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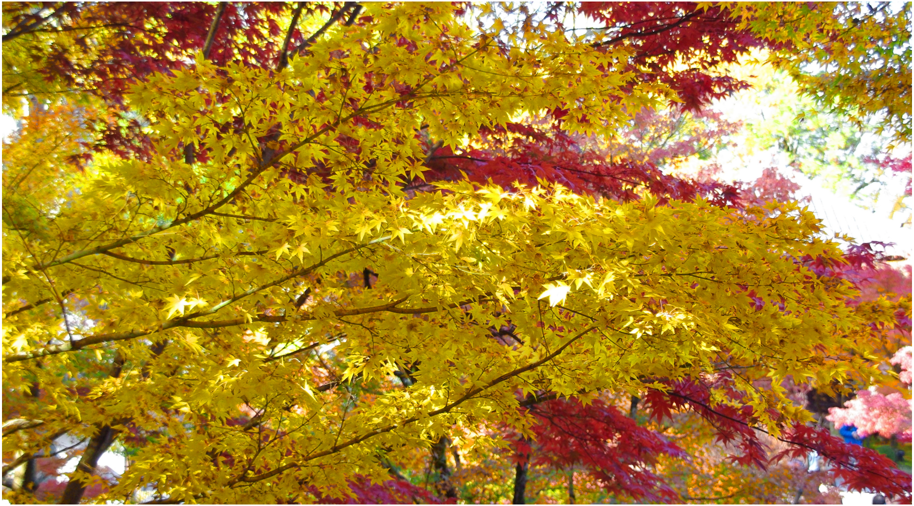
ABSTRACT

Some of you may become green with envy

It's only yellow press



You first become angry ... you are seeing red!

Be careful for not seeing the forest for the trees

But don't be afraid, there is light at the end of the tunnel

Doors will open

Sooner or later you will find epiphany

You will be able to walk on water

THANK YOU