New possible class of rapidly rotating neutron stars

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Talk overview:

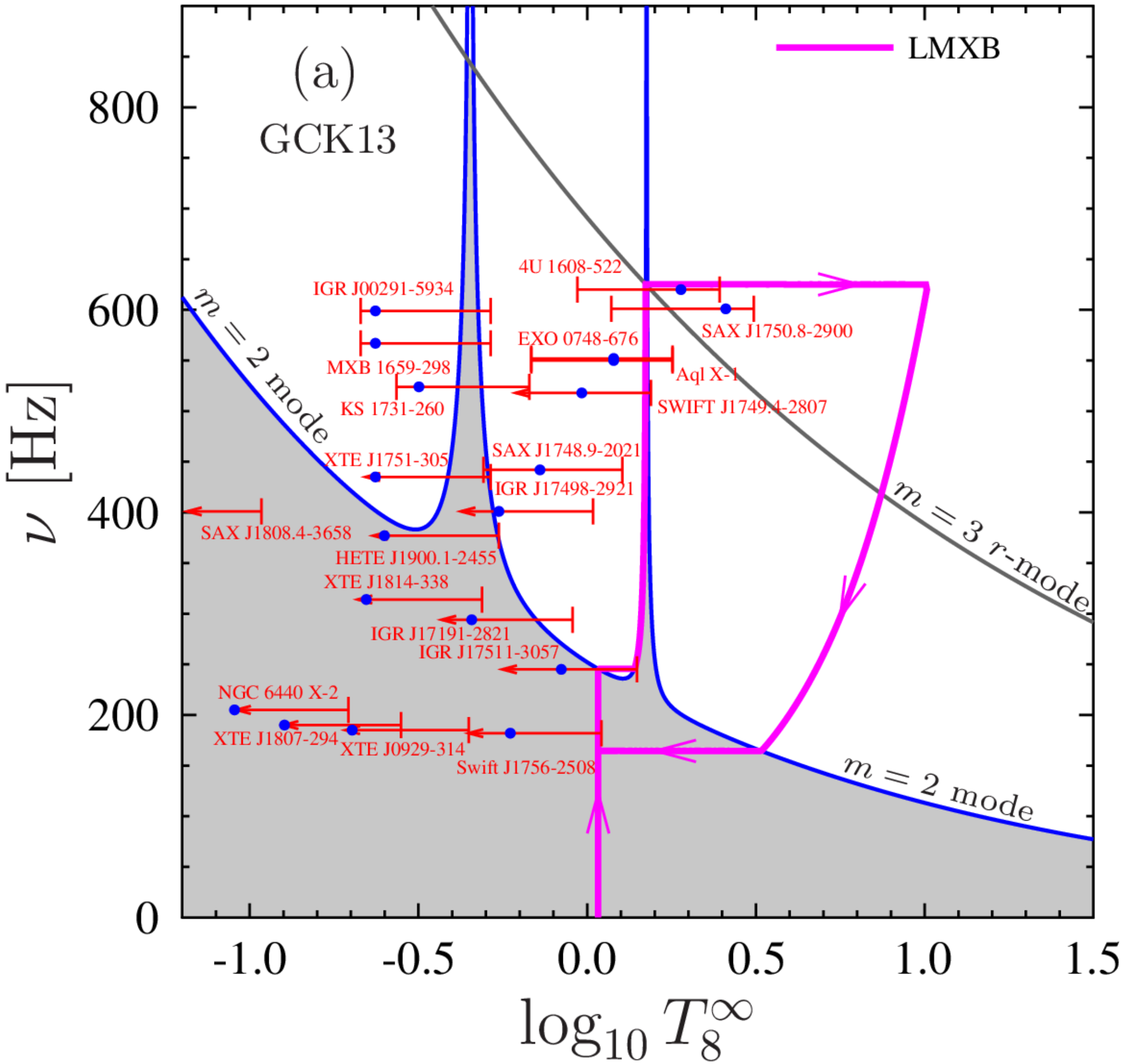
1) ***R-mode instability and NSs fate after LMXB phase: possibility of NS heating by unstable r-mode***
2) ***Evolution of r-mode heated nonaccreting NS. Hypothesis of "Hot widows"/HOFNARs***

   HOFNAR (HOt and Fast Non-Accreting Rotators)

   "Hot widow" (in analogy with "black widow" pulsars)
3) ***"Hot widows"/HOFNARs vs observations***

(see also google.com)

Evolution of NSs in LMXBs: climbing up the stability peak



- Absent in the standard scenario
- High temperature is supported by damping of the unstable mode

$$W_{\rm Diss} \approx L_{\rm cool} - K_n \dot{M} c^2$$

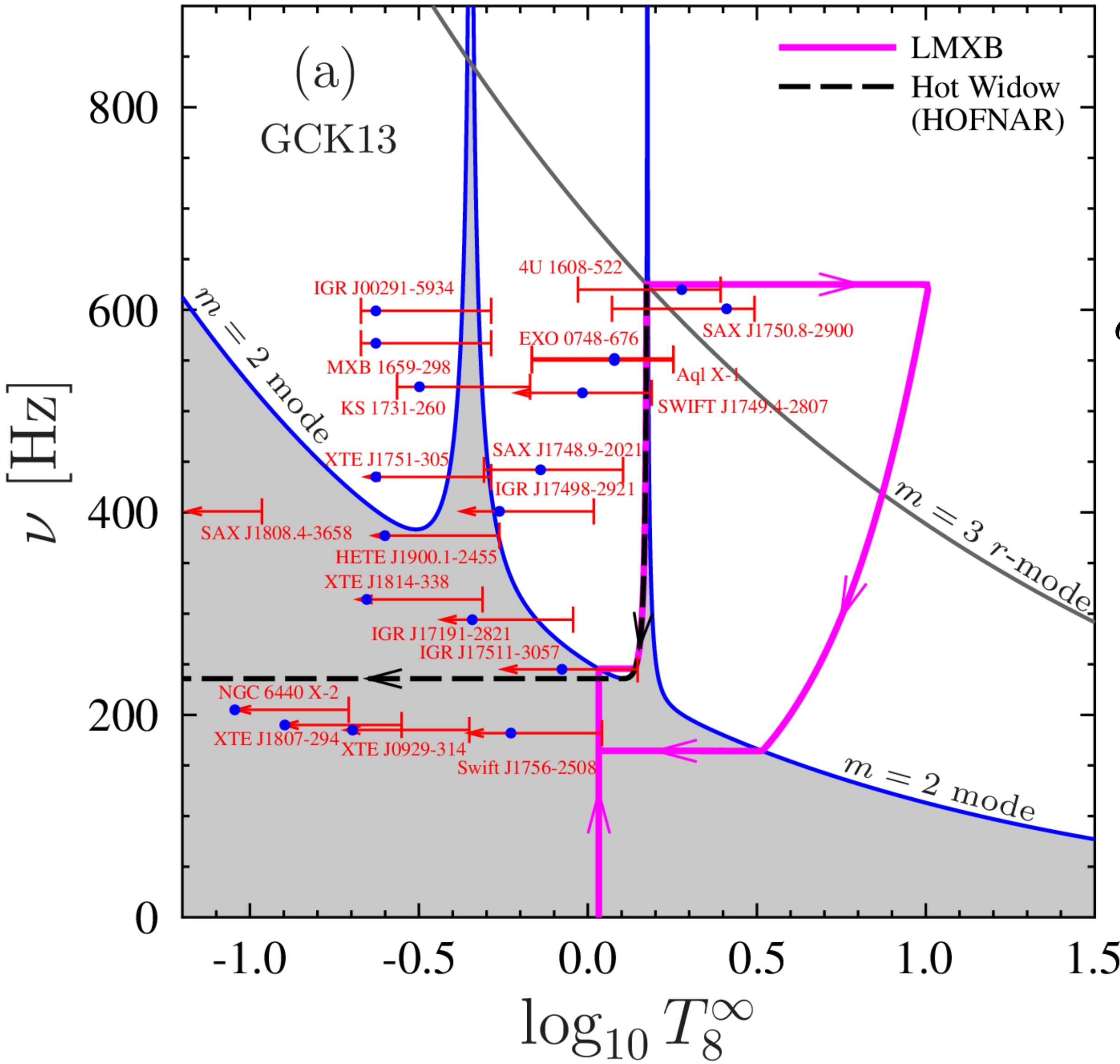
⇩

$$\alpha^{(\rm eq)} \sim 10^{-6} \ll \alpha_{\rm sat}$$

- NS is attached to the stability peak by the mode instability

Accretion spin up

Evolution of NSs in LMXBs: descending the stability peak



- Absent in “no r-mode” scenario
- High temperature is supported by damping of the unstable mode

$$W_{\text{Diss}} \approx L_{\text{cool}}$$

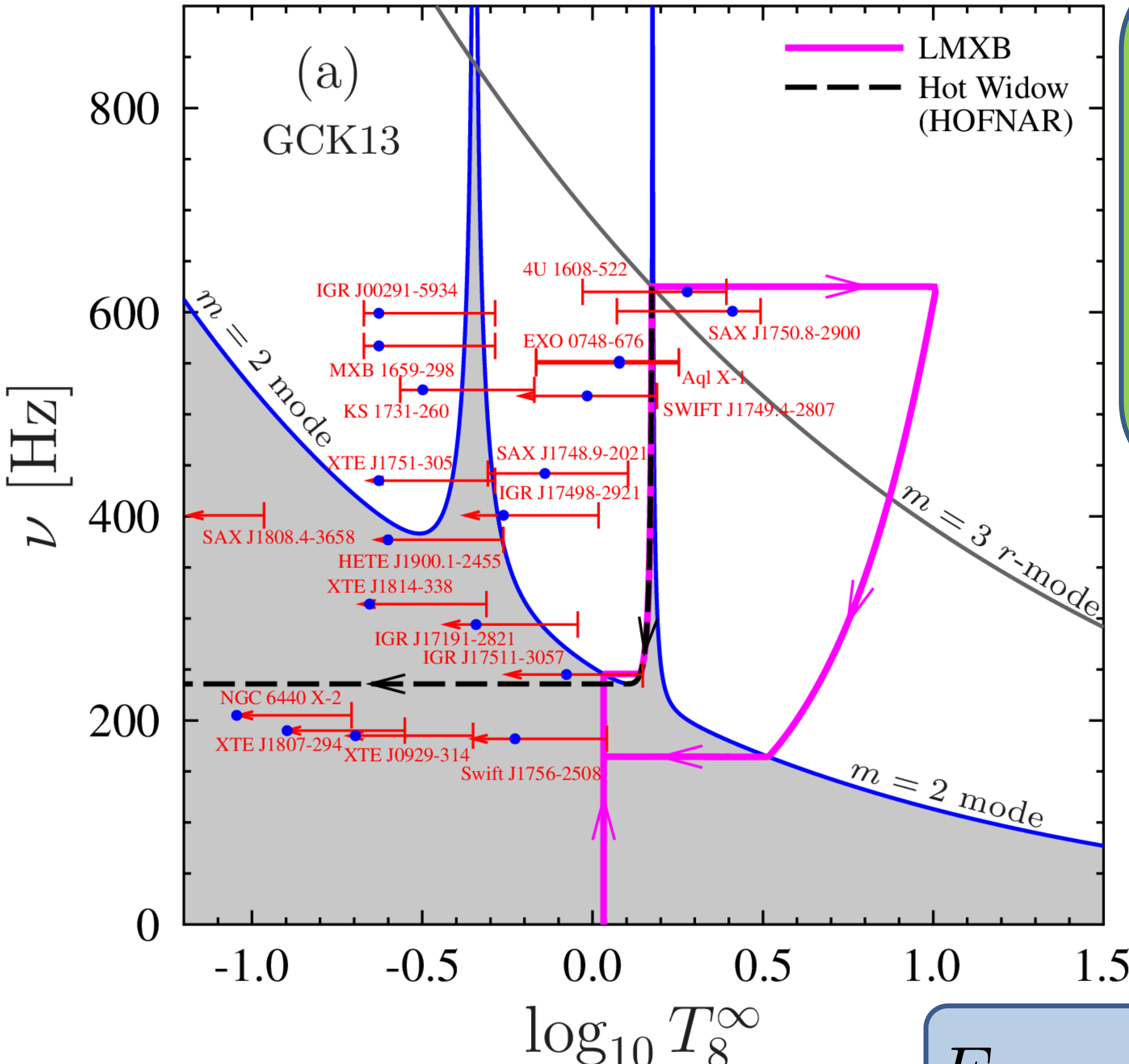
⇩

$$\alpha^{(\text{eq})} < \tilde{\alpha}^{(\text{eq})} \sim 10^{-6} \ll \alpha_{\text{sat}}$$

- NS is attached to the stability peak by the mode instability

The star is **heated by** dissipation of excited **oscillation mode** and **braked by gravitational waves** emitted by this mode (and magneto-dipole losses)

"Hot widows"/HOFNARs



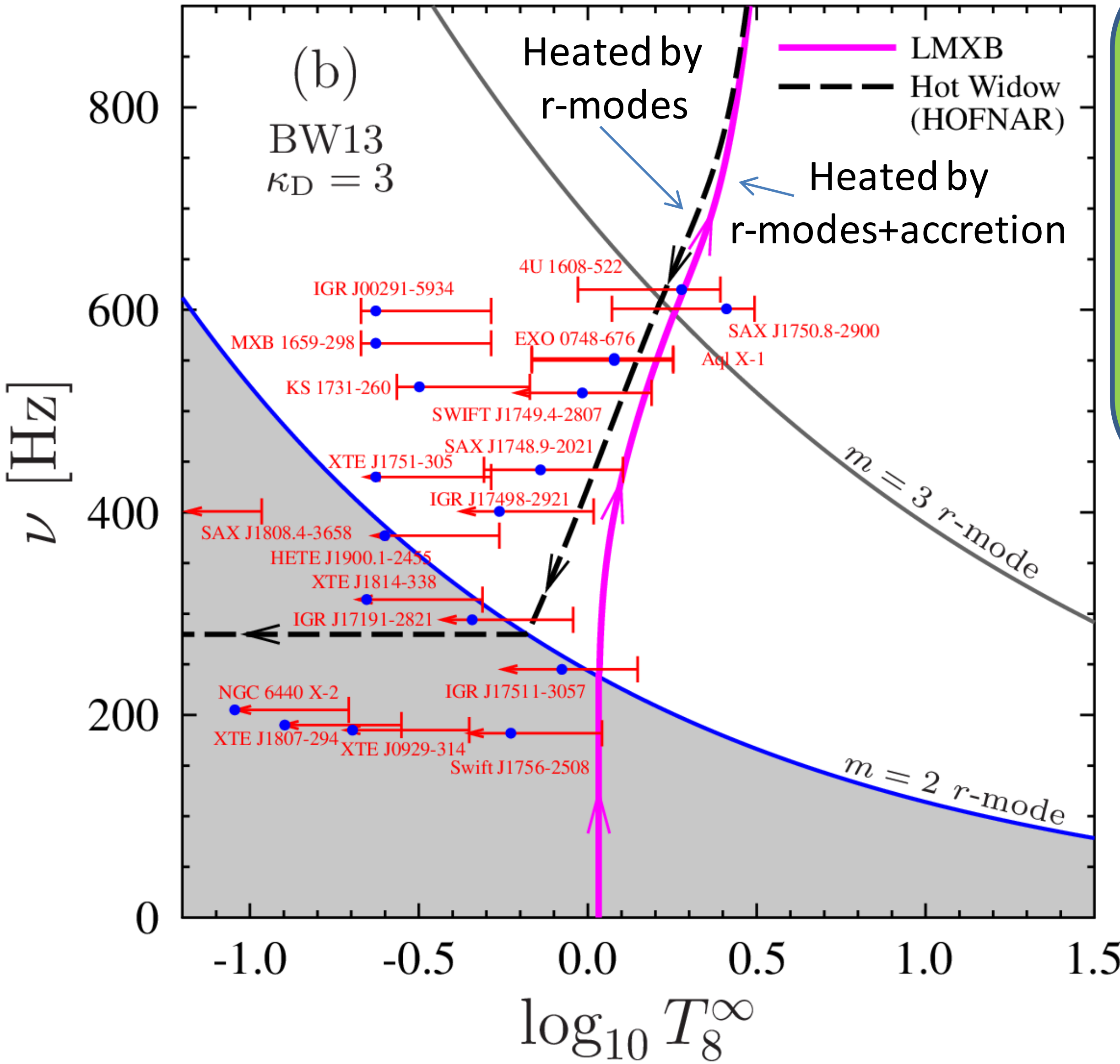
The star is **heated by** dissipation of excited **oscillation mode** and **braked by gravitational waves** emitted by this mode (and magneto-dipole losses)

$$\frac{dE_{\rm rot}}{dt} = -3\,L_{\rm cool}$$

$$\tau_{\rm live} \sim \frac{E_{\rm rot}}{3\,L_{\rm cool}} \sim 10^9{\rm yr}$$

$$E_\nu = L_{\rm cool}\tau_{\rm live} \sim 10^{51}\ {\rm erg}$$

“Hot widows”/HOFNARs without stability peak



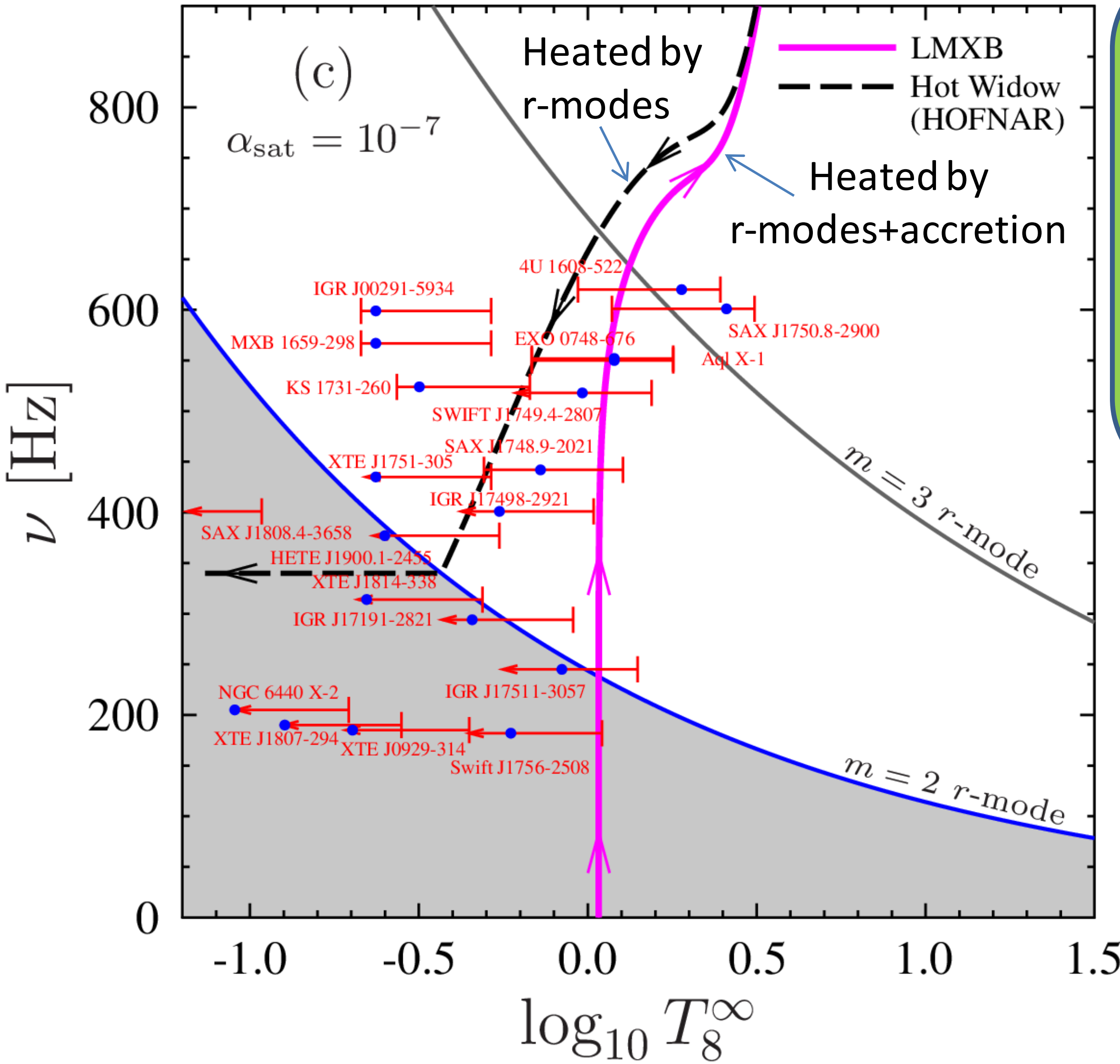
The star is **heated by** dissipation of excited **oscillation mode** and **braked by gravitational waves** emitted by this mode (and magneto-dipole losses)

$$\frac{dE_{\rm rot}}{dt} = -3\,L_{\rm cool}$$

$$\tau_{\rm live} \sim 4\times10^9{\rm yr}$$

$$E_\nu = \frac{1}{3}\Delta E_{\rm rot} \sim 10^{51}\ {\rm erg}$$

“Hot widows”/HOFNARs without stability peak



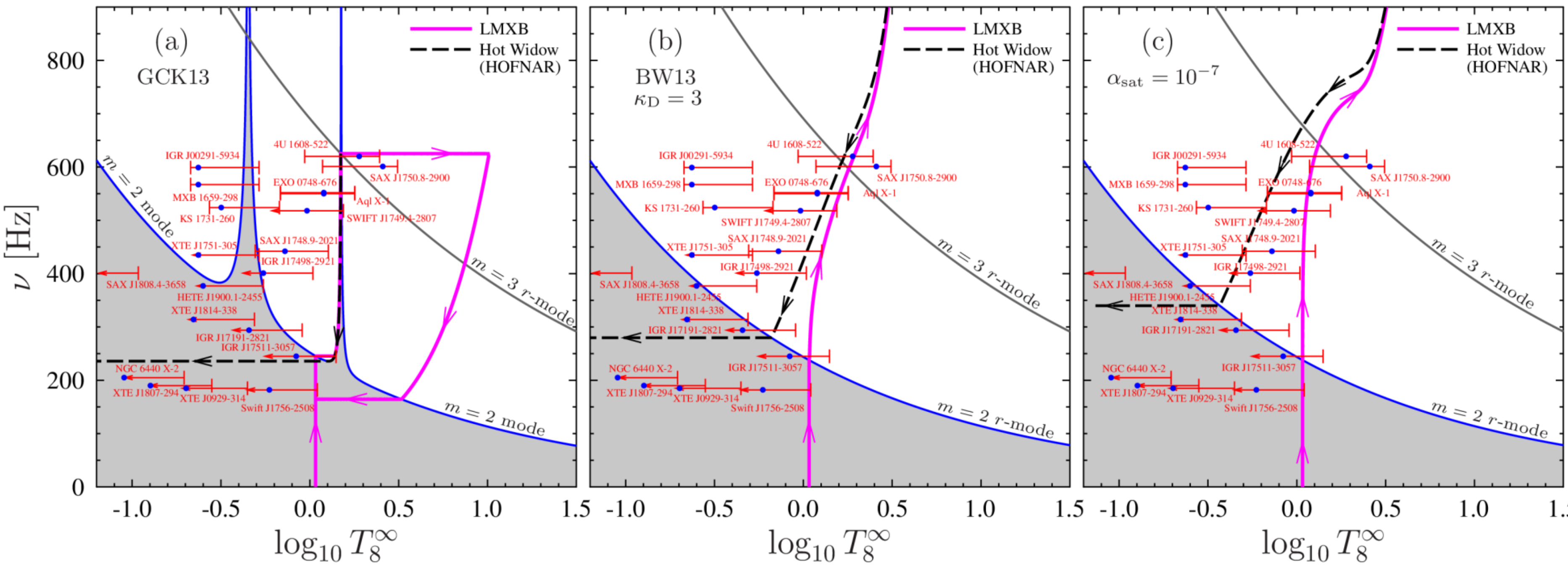
The star is **heated by** dissipation of excited **oscillation mode** and **braked by gravitational waves** emitted by this mode (and magneto-dipole losses)

$$\frac{dE_{\rm rot}}{dt} = -3\, L_{\rm cool}$$

$$\tau_{\rm live} \sim 8 \times 10^{10} {\rm yr}$$

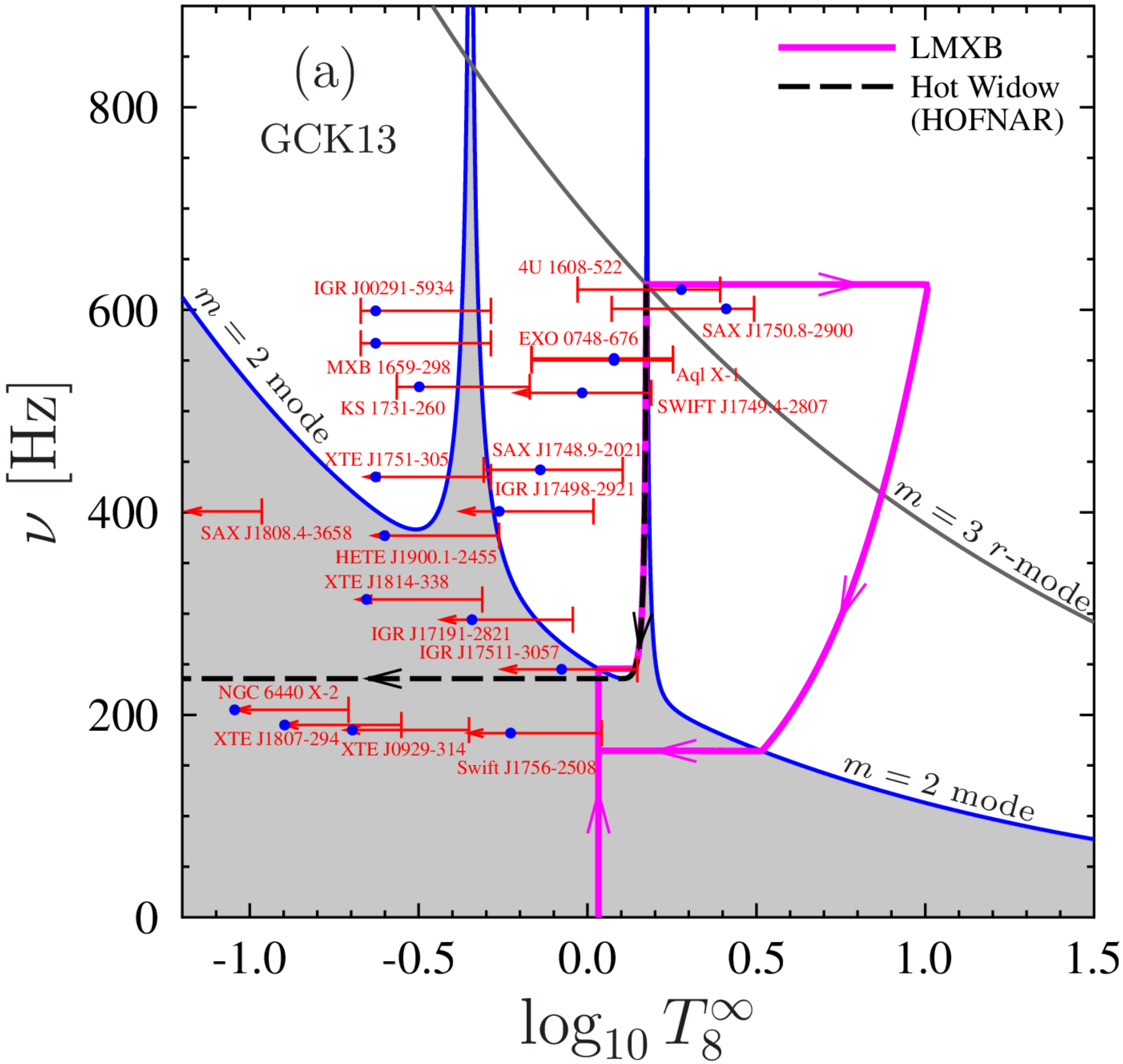
$$E_\nu = \frac{1}{3} \Delta E_{\rm rot} \sim 10^{51} \ {\rm erg}$$

“Hot widows”/HOFNARs: origin and essential features



- **Hot rapidly rotating nonaccreting neutron stars**
- **Can be formed in LMXBs**, if r-mode instability is significant for NS evolution (some of observed NSs are unstable, the instability produces significant contribution to their heating)
- **Maintain high temperature** due to dissipation of unstable mode
- **Long life time** (~10^9 yr). **Huge energy budget** (~10^{51} erg)

Millisecond pulsars and “hot widows”/HOFNARs



<u>Observations:</u>

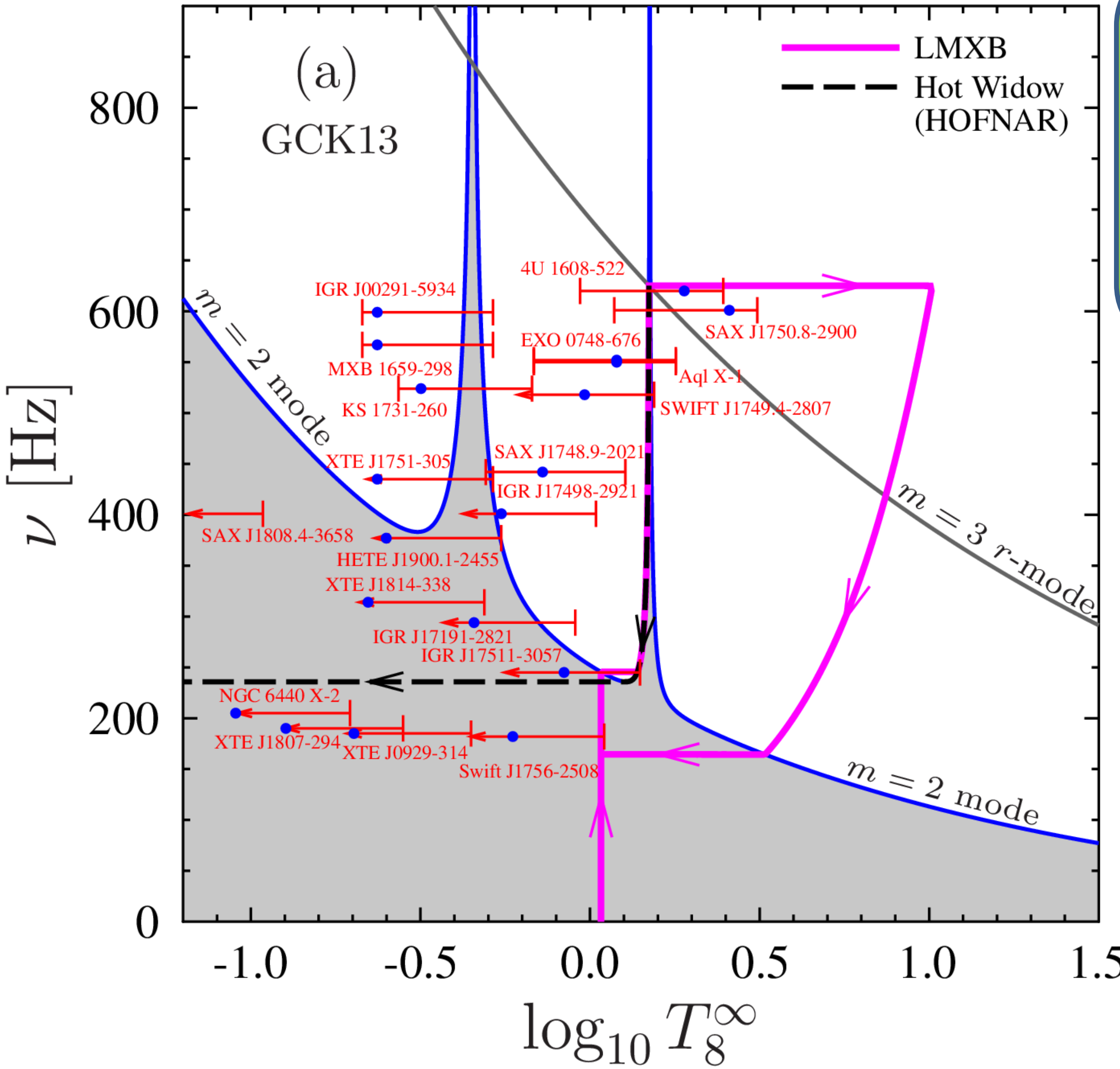
The surface of millisecond pulsars is cool (except for hot spots)

⇩

Typically, millisecond pulsars are not “hot widows”/HOFNARs.

If “hot widows”/HOFNARs exist, they can be attributed to **a new class** of neutron stars formed in LMXBs

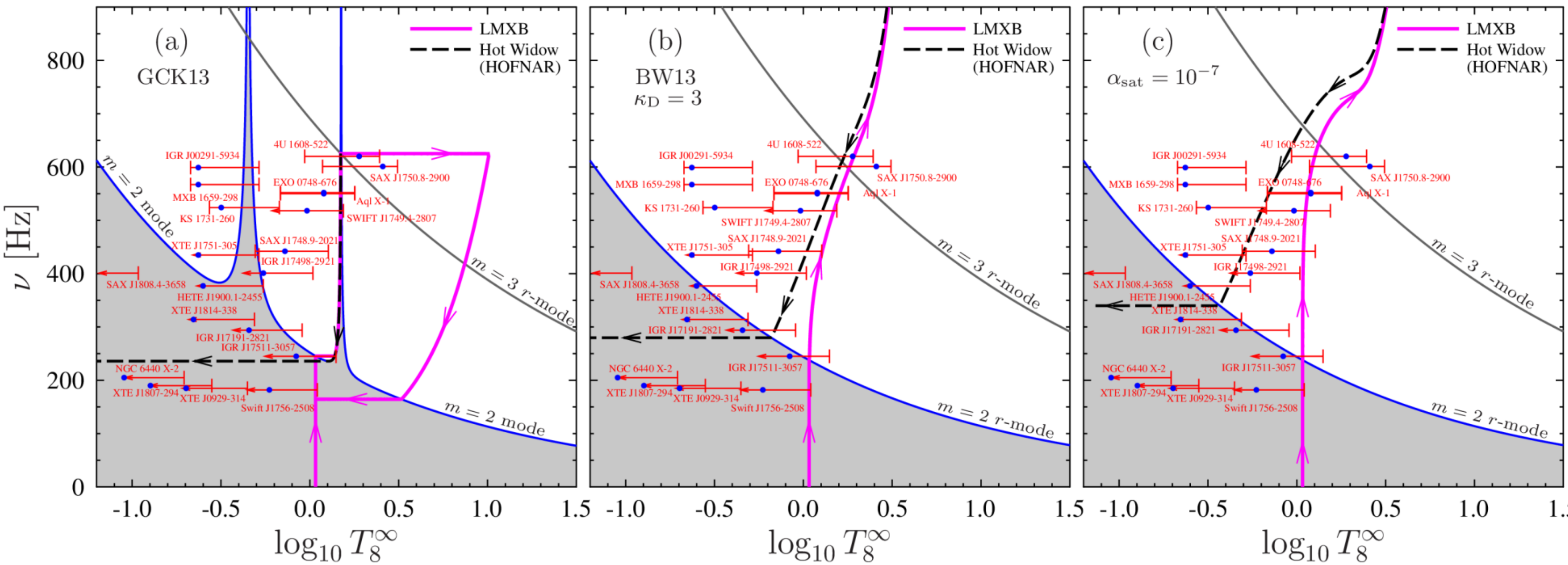
Millisecond pulsars and "hot widows"/HOFNARs



Millisecond pulsars and hot widows/HOFNARs are **different classes** of neutron stars formed in LMXBs

Simplified description:
If at the end of LMXB phase:
- NS is stable => millisecond pulsar
- NS is unstable => "Hot widow"/HOFNAR

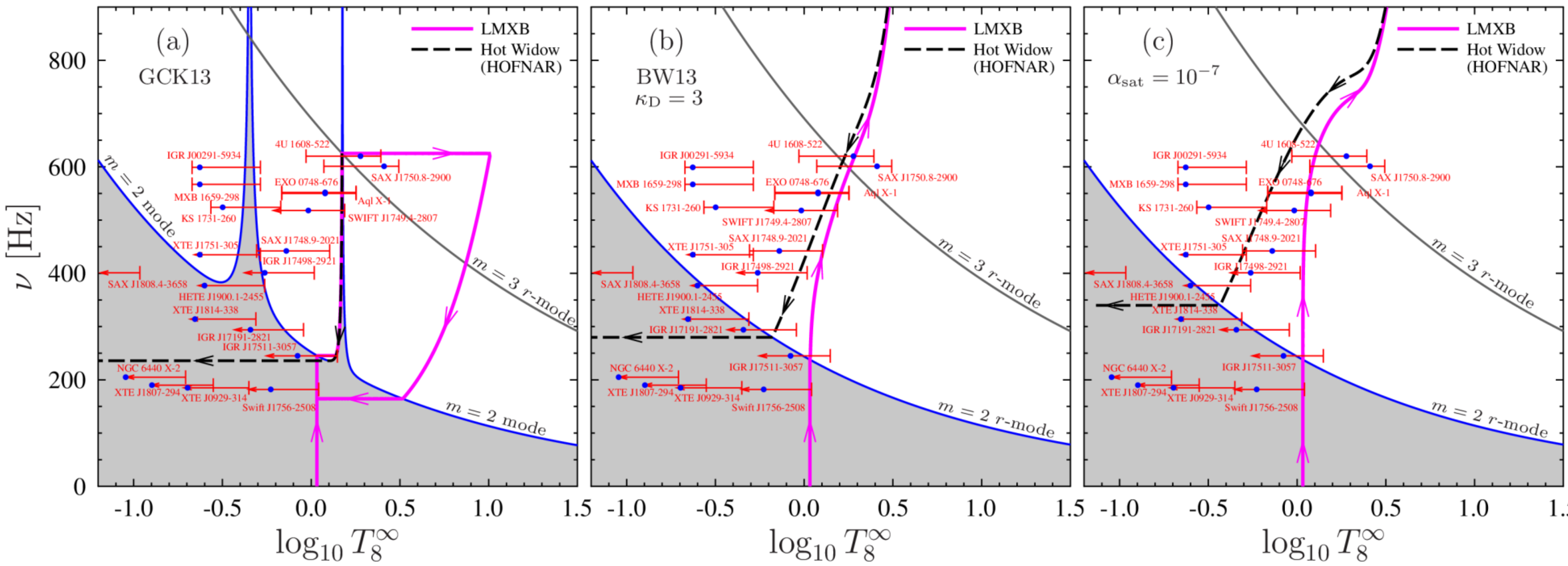
“Hot widows”/HOFNARs: magnetic field and other features



Hot rapidly rotating nonaccreting neutron stars

- **Can lose magnetic field** (by Ohmic dissipation), because they maintain high temperature ($T\sim10^8$ K) for a long time ($\sim10^9$ yr)
- **Uniform surface temperature** (no reasons for inhomogeneity)
- **No outbursts**

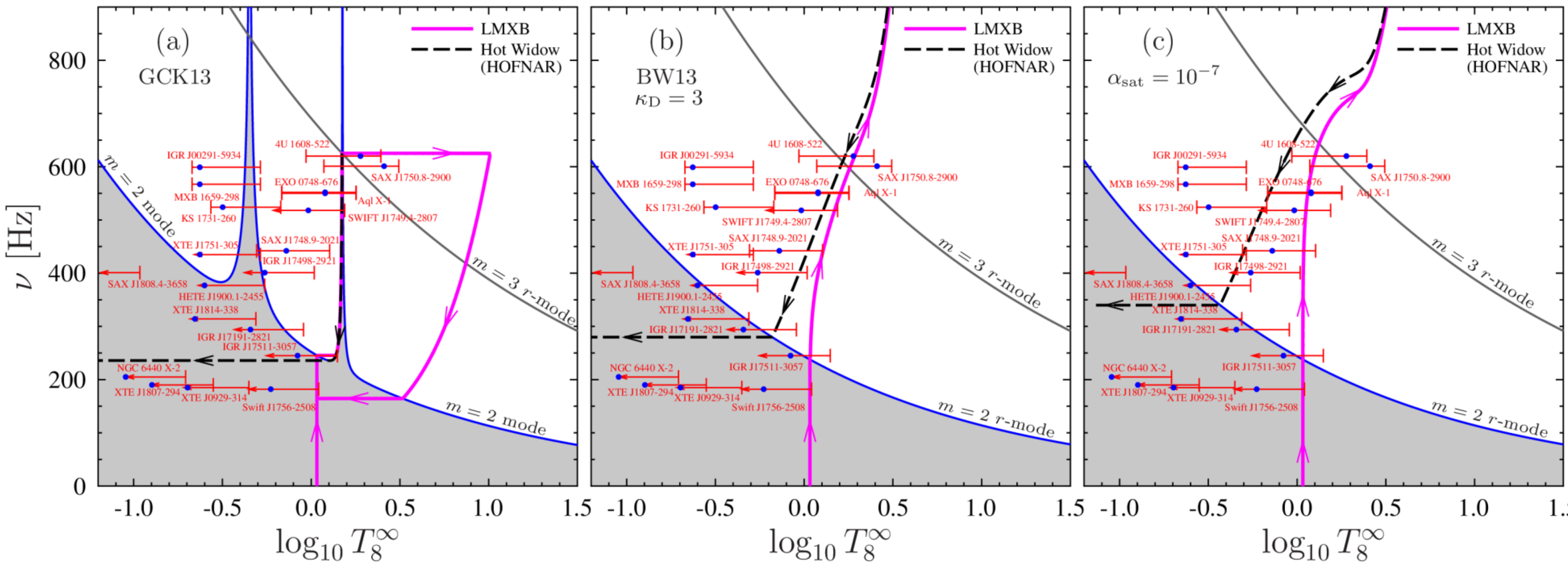
“Hot widows”/HOFNARs: observational features



Hot rapidly rotating nonaccreting neutron stars

- Should be **observed in X-rays**
- **Absence of pulsar activity is possible** (low magnetic field, uniform surface temperature, no accretion)
- X-ray spectrum: **surface of hot (Teff~10⁶ K) neutron star**
- Can have companion star, but **it does not fill Roche lobe**

qLMXB candidates: observational features

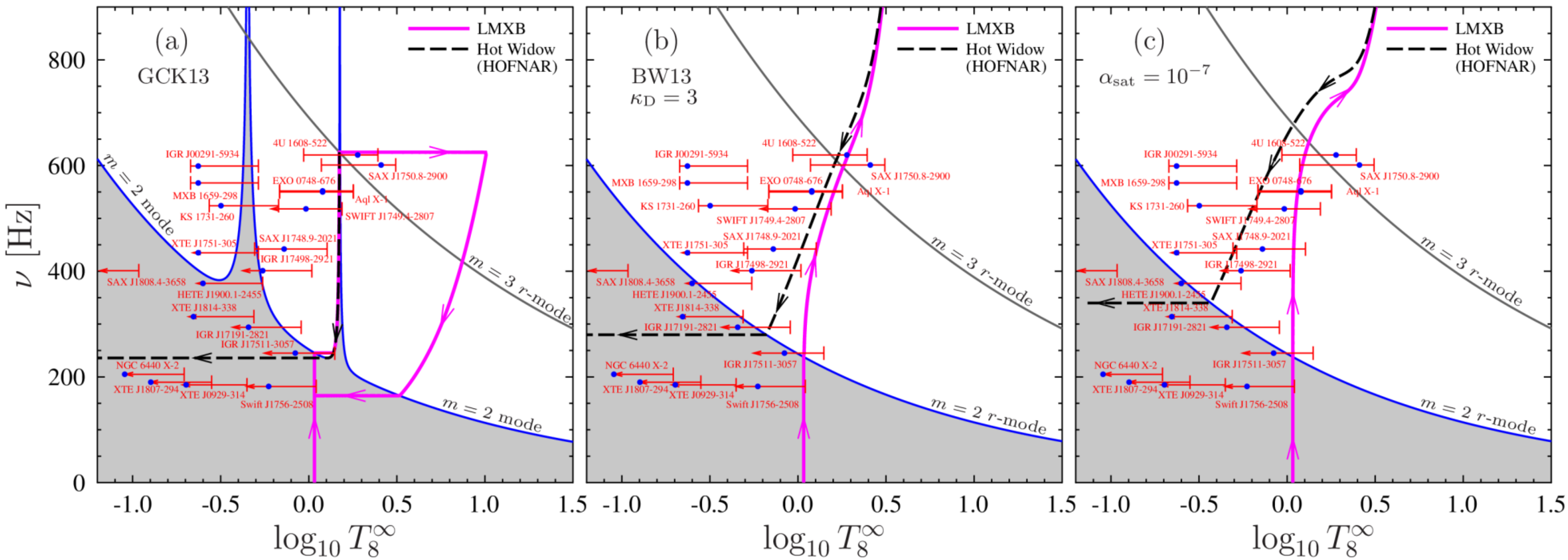


qLMXB candidates in globular clusters

- Are **observed in X-rays**
- **Absence of pulsar activity** (for most of them)
- X-ray spectrum: **surface of hot (Teff~10^6 K) neutron star**, nonthermal (power-law) contribution is low (less then 10% for most of them)

Rutledge et al., ApJ **529** (2000), 985; Heinke et al., ApJ **598** (2003), 501; Guillot et al., ApJ **738** (2011), 129

"Hot widows"/HOFNARs: candidate sources



Some of the sources, known as *qLMXB-candidates* (~30 in Galaxy globular clusters)**, can *in fact be "hot widows"/HOFNARs.***
***This means*:**

- **Companion-star (if exists) does not fill Roche lobe**
- **Accretion is not significant**
- Maintain their temperature for a long time (~10^9 yrs), due to **heating by excited *r*-mode**.

“Hot widow”/HOFNAR: identification criteria

Some of the sources, known as *qLMXB-candidates*,
can *in fact be “hot widows”/HOFNARs.*
***This means*:**

- **Companion-star (if exists) does not fill Roche lobe**
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Identification criteria for “hot widows”/HOFNARs:

- X-ray spectrum agree with a NS atmosphere thermal emission from whole NS surface at T_{eff} ~10^6 K
- Absence of significant accretion
- A companion star is absent or does not fill Roche lobe
- Very low variability

“Hot widow”/HOFNAR: 47 Tuc X5?

Identification criteria for “hot widows”/HOFNARs:

- X-ray spectrum agree with a NS atmosphere thermal emission from whole NS surface at $T_{eff} \sim 10^6$ K
- Absence of significant accretion
- A companion star is absent or does not fill Roche lobe
- Very low variability

Heinke et al. (2003): $T_{\rm eff} = 119^{+21}_{-18}$ eV

Heinke et al. (2003):
Eclipsing binary system. Orbital period 8.666±0.008 часов

Edmonds et al. (2002), Hubble Space Telescope

- Companion – red main-sequence star
- Presence of accretion disk is likely, but “detached disk”
- Evidence that the companion is not Roche lobe filling

«Using the Roche lobe formula…, the stellar radius for a 4100 K model, and NS the binary separation, we find that X5opt has *F~0.6,* **underfilling its Roche lobe**. Fainter cooler secondaries will underfill their Roche lobes by slightly larger amounts»

Summary

- “Hot widows”/HOFNARs (along with MSP) **should be formed** as a result of LMXB evolution, if r-mode instability is significant.
- “Hot widows”/HOFNARs **can be observed in X-rays**. Some of qLXMB-candidates can in fact be “hot widows”/HOFNARs.
- “Hot widows”/HOFNARs **can be identified**. For example, 47 Tuc X5, 47 Tuc X7, NGC 6397 U24 seem to be very good candidates.
- We found hints of “Hot widows”/HOFNARs existence in available observational data and theoretical estimates.

Summary

- “Hot widows”/HOFNARs (along with MSP) **should be formed** as a result of LMXB evolution, if r-mode instability is significant.
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- “Hot widows”/HOFNARs **can be identified**. For example, 47 Tuc X5, 47 Tuc X7, NGC 6397 U24 seem to be very good candidates.
- We found hints of “Hot widows”/HOFNARs existence in available observational data and theoretical estimates.
- Existence of “hot widows”/HOFNARs **proves *r*-mode instability**, and thus **gravitational wave emission by mass current quadrupole**
- “Hot widows”/HOFNARs have stable, pure thermal spectra => **X-ray spectra measurement of mass and radius** (as for qLMXBs).
- “Hot widows”/HOFNARs allow to study **NSs properties by r-modes.**

“Hot widows”/HOFNARs: hint 1

Some of the sources, known as *qLMXB-candidates*,
can *in fact be “hot widows”/HOFNARs*

Heinke (2011): “…Extrapolating to the full globular cluster system, **roughly 200 quiescent LMXBs are predicted** [Heinke et al. (2005)]. This indicates an average duty cycle of <3% for transient LMXBs in globular clusters, and suggests an **average recurrence time of ∼1000 years** (if 7 of ∼200 transients have entered outburst over the ∼40 years of X-ray satellites). However, if smaller outbursts (such as those from NGC 6440 X-2 or M15 X-3) are common, many neutron stars in quiescent LMXBs can be heated without ever producing major outbursts’’

J.-P. Lasota (2001): “Models with truncated and irradiated discs produce recurrence times **from 1 to 180 years**... It is probably impossible to reach such longevity in real systems… If we allow fluctuations of a factor of two, the ‘real’ quiescence time would rather be **∼ 40 years**”

CGK (2014): If some of qLMXB-candidates **are Hot widows/HOFNARs**, the number of LMXBs in globular clusters **is less than 200**. In this case observational estimates of the recurrence time should be reduced.

“Hot widows”/HOFNARs: hint 2

Some of the sources, known as *qLMXB-candidates*,
can *in fact be “hot widows”/HOFNARs*

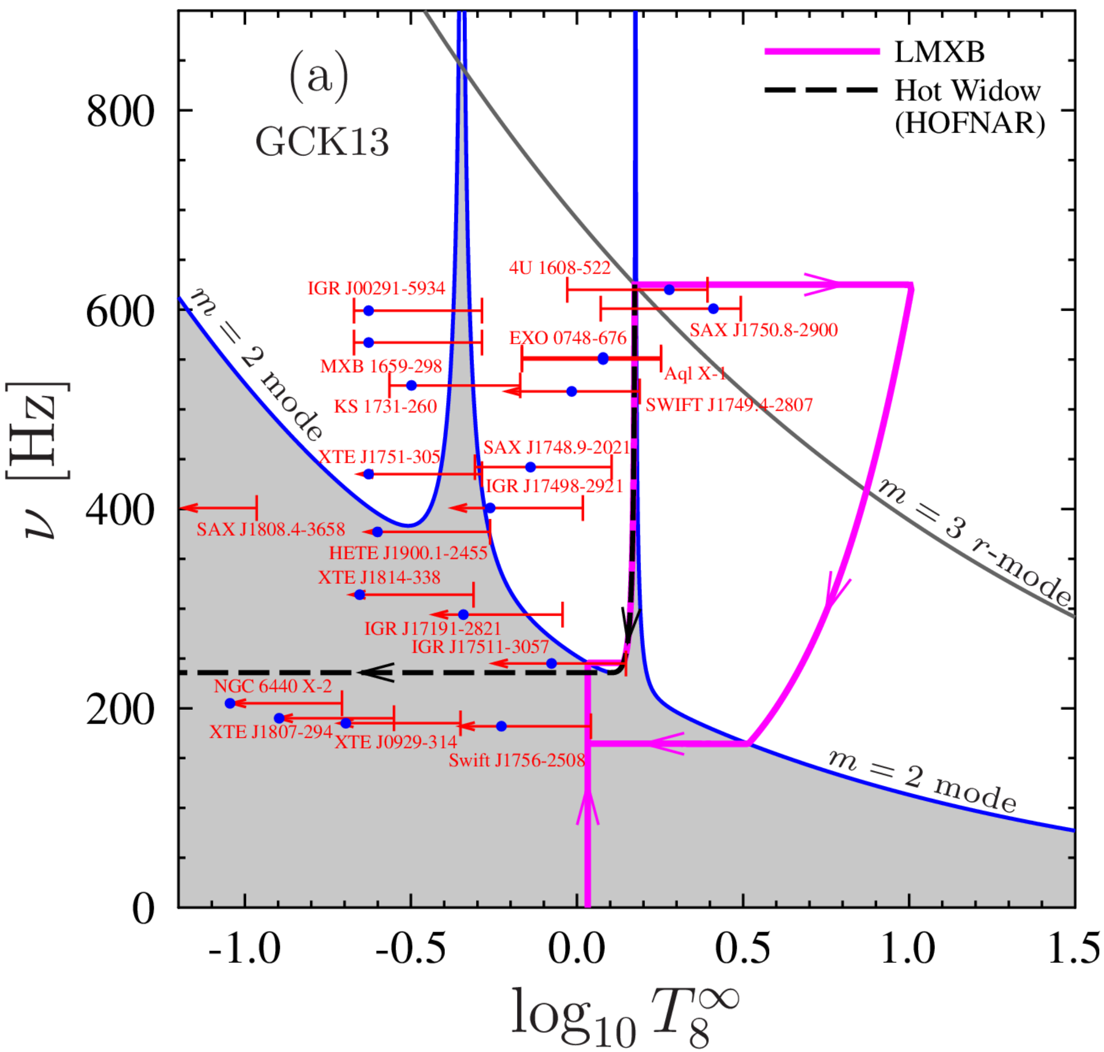
Ivanova et al. (2008): “We find from our simulations that **if all possible channels of NS formation and all possible mechanisms for their spin-up lead to MSP** formation, then **we overproduce MSPs**. However, we still **need these channels to produce observed LMXBs**. We propose that high *B-field* MSPs (which are short-living) can be formed not only during CC supernovae, but also due to physical collisions or accretion in a post-AIC system”

CGK (2014):

- If some of qLMXB-candidates **are “hot widows”/HOFNARs**, the number of LMXBs in globular clusters **is less then it was supposed before.**
- If not only MSP, but also “hot widows”/HOFNARs are formed as a result of NS spin up, the production of MSP is lower.

(Formation of “hot widows”/HOFNARS is a **channel of NS spin up, which does not lead to the MSP formation**)

“Hot widows”/HOFNARs: hint 3



Simplified description:
If at the end of LMXB phase:
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The average period of AXMSP – 3.3 ms, but for MSP – 5.5 ms. The braking on MSP stage can not explain the apparent difference in spin distributions. The additional braking at the Roche lobe decoupling phase is required [Tauris (2012)]

CGK (2014): If the most rapidly rotating hot AXMSP are unstable and became “hot widows”/HOFNAR, then periods of MSP should be lower than for AXMSP.