Astrophysical Sources of Stochastic Gravitational-Wave Background

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GWDAW 12, Boston, Dec. 2008

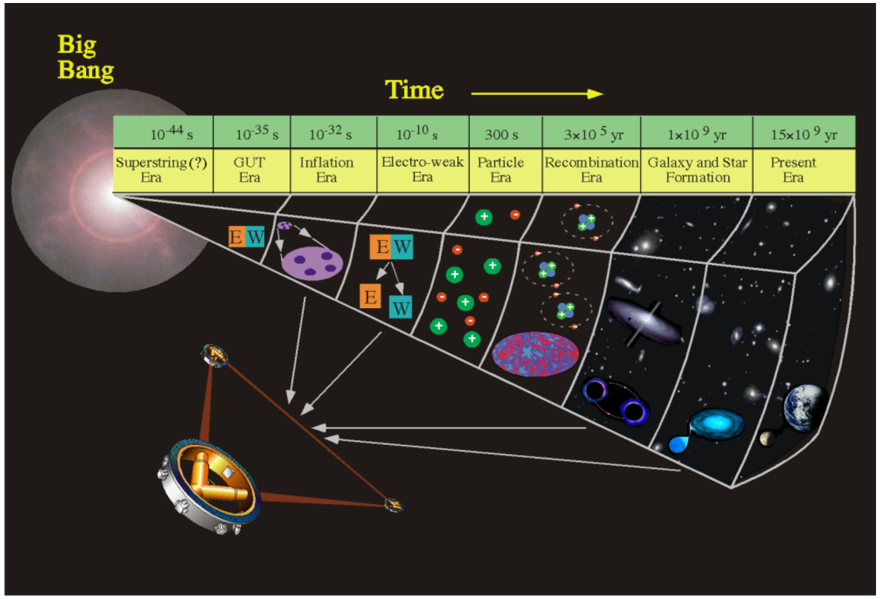
LIGO-G070843-00-0

Stochastic Background

A stochastic background of gravitational waves (SGWB) has resulted from the superposition of a large number of unresolved sources since the Big Bang.
We distinguish between two contributions:

- **Cosmological SGWB:**
  signature of the early Universe
  inflation, cosmic strings, phase transitions…

- **Astrophysical SGWB:**
  sources since the beginning of stellar activity
  compact binaries, supernovae, rotating NSs, core-collapse to NSs or BHs, supermassive BHs…



Plan of this talk

- Spectral properties of Astrophysical Backgrounds (AGBs)
- Detection regimes (resolved sources, popcorn, continuous)
- Some predictions
- Astrophysical constraints with advanced detectors

Spectral properties of AGBs

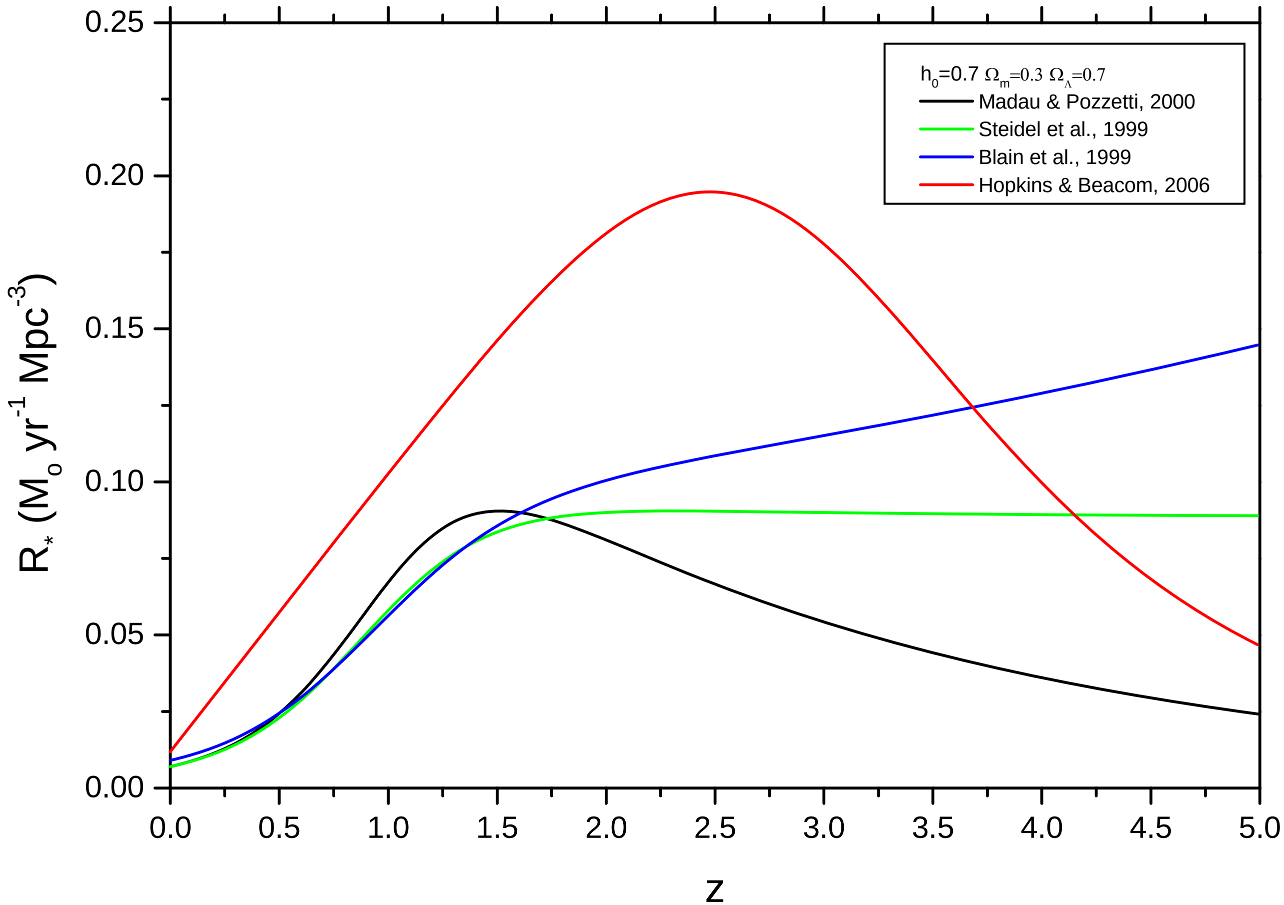
$$\Omega_{gw}(\nu_o)=\frac{8\pi G}{3c^3H_0^2}\nu_o\int_0^{z_{\sup}(\nu_o)}\overbrace{\frac{dR^o(z)}{dz}}^{\text{source cosmic rate}}\overbrace{\frac{1}{4\pi r^2(z)(1+z)}\frac{dE_{gw}}{d\nu}(\nu_o)}^{\text{fluence of single sources}}dz$$

$$\text{where } z_{\sup}(\nu_o)=\begin{cases}\dfrac{\nu_{\max}}{\nu_o}-1 \text{ for } \nu_o<\dfrac{\nu_{\max}}{1+z_{\max}}\\ z_{\max}\sim 6 \text{ otherwise}\end{cases}$$

AGB spectra are determined by:

- the cosmological model (H_0=70 km/s/Mpc, Ω_m =0.3, Ω_Λ=0.7)
- the star formation history
- the spectral properties of individual sources $dE_{gw}/d\nu$

Cosmic Star Formation Rate



Detection Regimes

The **nature** of AGBs is charaterized by the **duty cycle**, the ratio between the **average event duration** τ^o and the **time interval between successive events** Δt^o.

$$D(z) = \int_0^z \frac{\overline{\tau}^o(z')}{\Delta t^o(z')} dz' \quad \text{where} \begin{cases} \overline{\tau}^o = (1+z')\overline{\tau} \\ \Delta t^o(z') = \left[\frac{dR^o}{dz'}(z') \right]^{-1} \end{cases}$$

- **resolved sources (D <<1):**

burst data analysis, optimal filtering

- **popcorn noise (D~1)**

Maximum Likelihood statistic (Drasco et al. 2003), Probability Event Horizon (Coward et al. 2005)

- **gaussian stochastic background (D>>1)**

cross correlation statistic (isotropic/anisotropic)

Models

➢ Core collapse supernovae

- **Neutron star formation:** *Blair & Ju 1996, Coward et al. 2001-02, Howell et al. 2004, Buonanno et al. 2005*
- **Stellar Black Hole formation:** *Ferrari et al. 1999, de Araujo et al. 2000-04*

➢ Neutron stars

- **tri-axial emission:** *Regimbau & de F. Pacheco 2001-06*
- **bar or r-modes:** *Owen et al. 1998, Ferrari et al. 1999, Regimbau 2001*
- **phase transitions:** *Sigl 2006*

➢ Stellar Compact Binaries

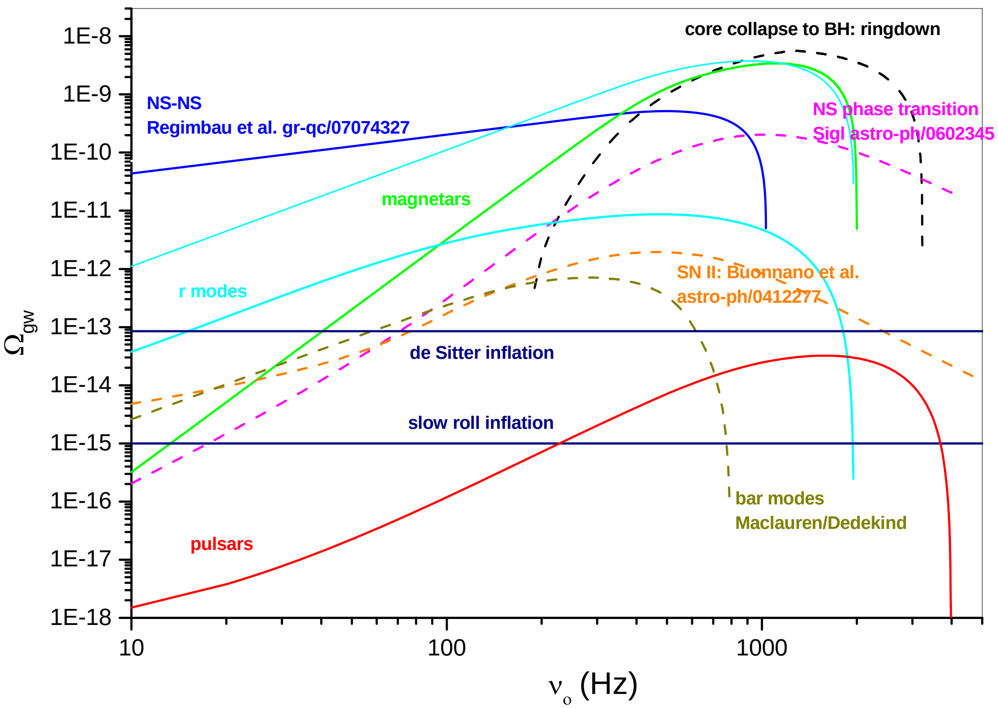
- **near coalescence (NS, BH):** *Regimbau et al. 2006-07 , Coward et al. 2005 (BNS), Howell et al. 2007 (BBH)*
- **low frequency inspiral phase:** *Ferrari et al. 2002, Farmer & Phinney 2002, Cooray 2004 (WD-NS)*

➢ Capture of compact objects by SMBHs *: Barack & Cutler 2004*

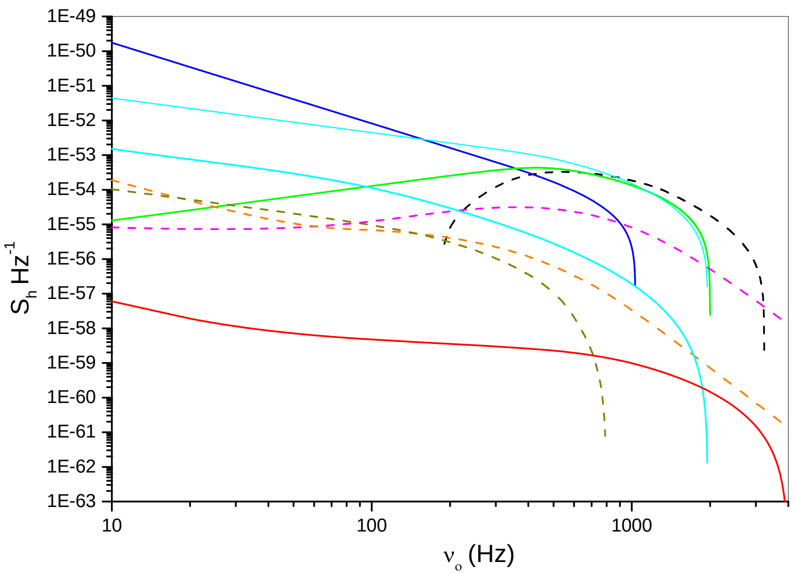
Spectra

The shape of AGBs is characterized by:

- **cutoff** at the maximal emission frequency ν_{max}
- **maximum** which depends on the shape of the SFR and ν_{max}
- often well approximated by **power laws at low frequency**



spectal energy density: $S_h(\nu_o) = \frac{3H_0^2}{4\pi^2}\nu_o^{-3}\Omega_{gw}(\nu_o)$



Tri-axial Neutron Stars

- **source rate:**

follows the star formation rate (fast evolution of massive stars)

$$\frac{dR^0}{dz}(z) = \lambda_p \frac{R^*(z)}{(1+z)} \frac{dV}{dz}(z)$$

$$\begin{cases} \lambda_p = \text{mass fraction of NS progenitors in the range 8-40 } M_\odot \\ R^*(z) = \text{cosmic star formation rate} \end{cases}$$

- **spectral energy density**:

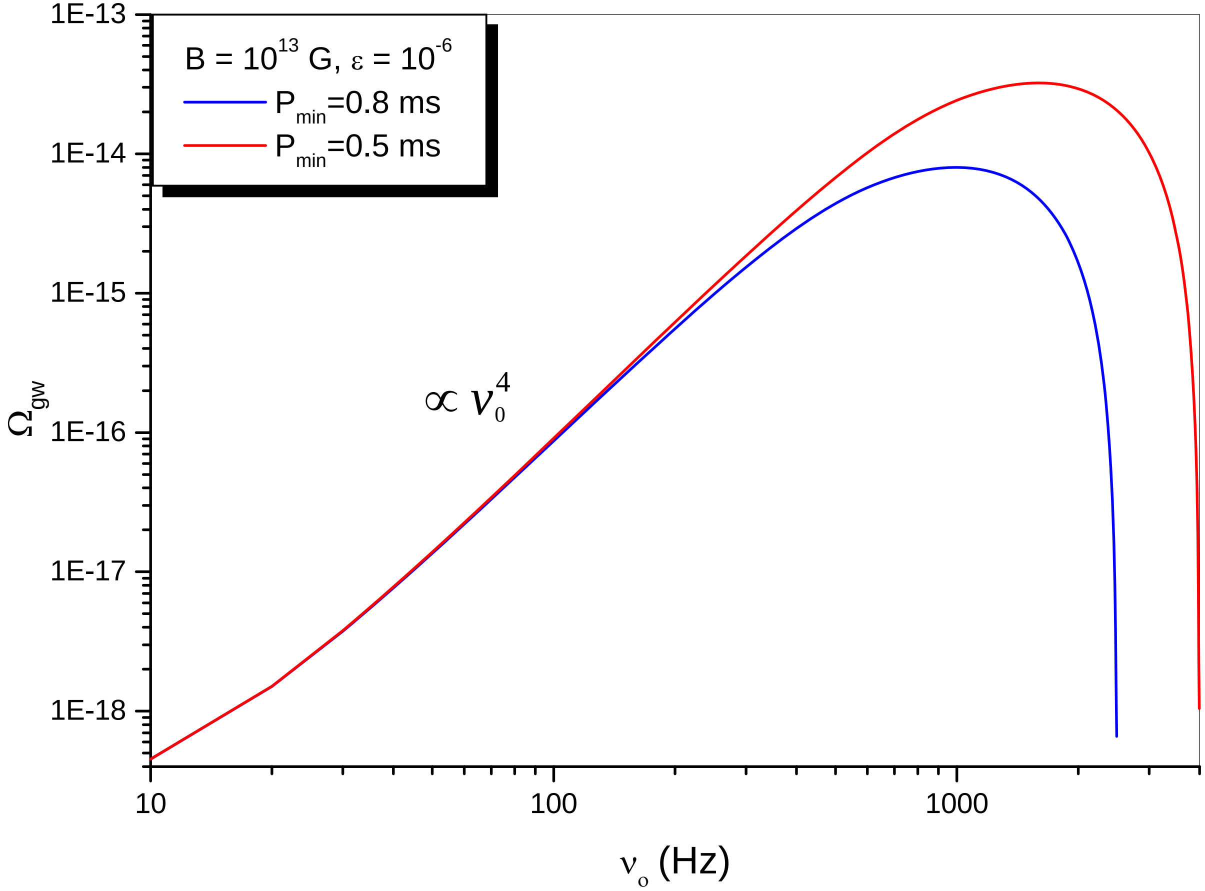
$$\frac{dE_{gw}}{d\nu} = \frac{192\pi^4 G I^3}{5c^2 R^6} \frac{\varepsilon^2}{B_{dip}^2 \sin^2\alpha} \nu^3 \text{ with } \nu \in [0; 2/P_0]$$

Population synthesis (Regimbau & de F. Pacheco 2000, Faucher-Giguere & Kaspi 2006) *:*

- ***initial period:*** *normal distribution with <Po>~250 -300 ms and σ~80 -150ms*
- ***magnetic field:*** *log-normal distribution with <log B>~13 G*

Energy density spectrum

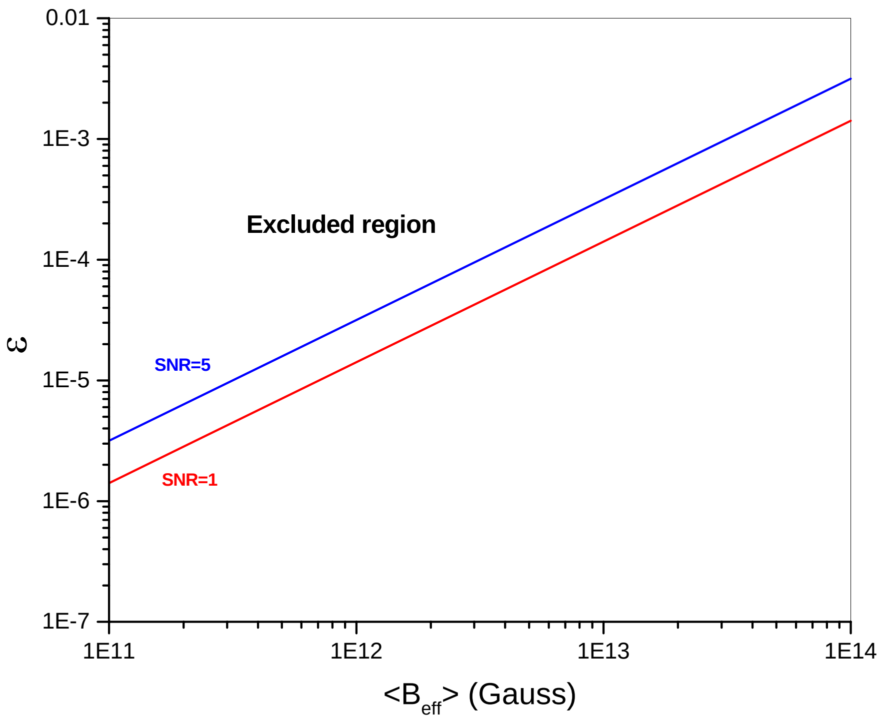
Spectrum from the cosmological population of rotating NSs, assuming initial period and magnetic field distributions derived from population synthesis.



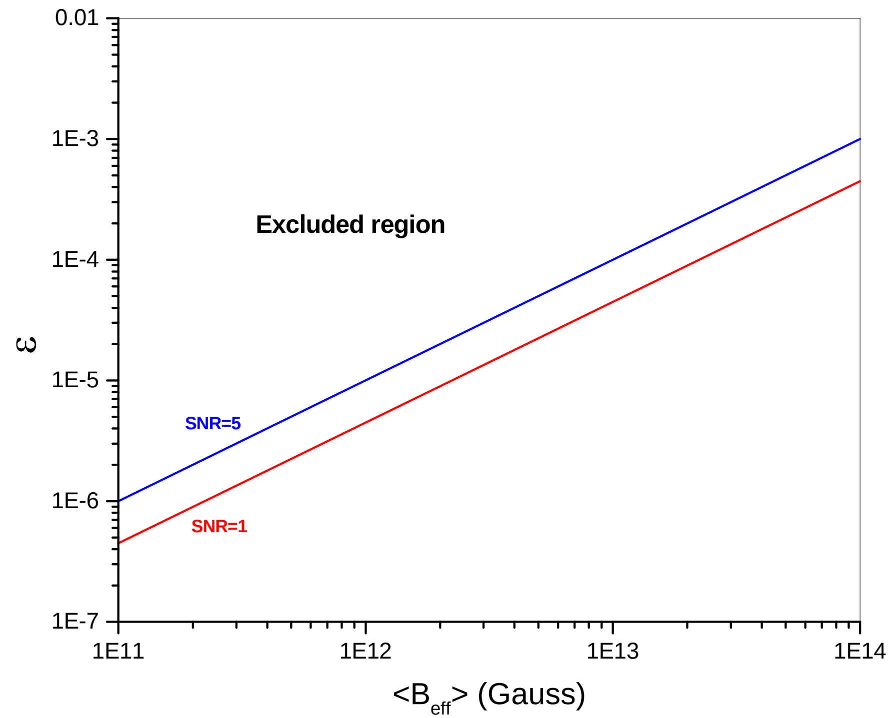
Constraints on ε–B*

Constraints given by **coaligned and coincident detectors** (ex: H1-H2), for T=3 yrs of observation, in the range 10-500 Hz.

Advanced detectors (Ad LIGO sensitivity)



3rd generation detectors (Einstein Telescope)



**2-D projection, assuming the distribution of initial period derived from population synthesis.*

Double Neutron Stars

Last thousands seconds before the last stable orbit in [10-1500 Hz]: 96% of the energy released.

- **source rate:**

$$\frac{dR^0}{dz}(z) = f_b \beta_{ns} \lambda_p \int \frac{R^*(t_c - t_d)}{1+z_f} P(t_d) dt_d \frac{dV}{dz}(z)$$

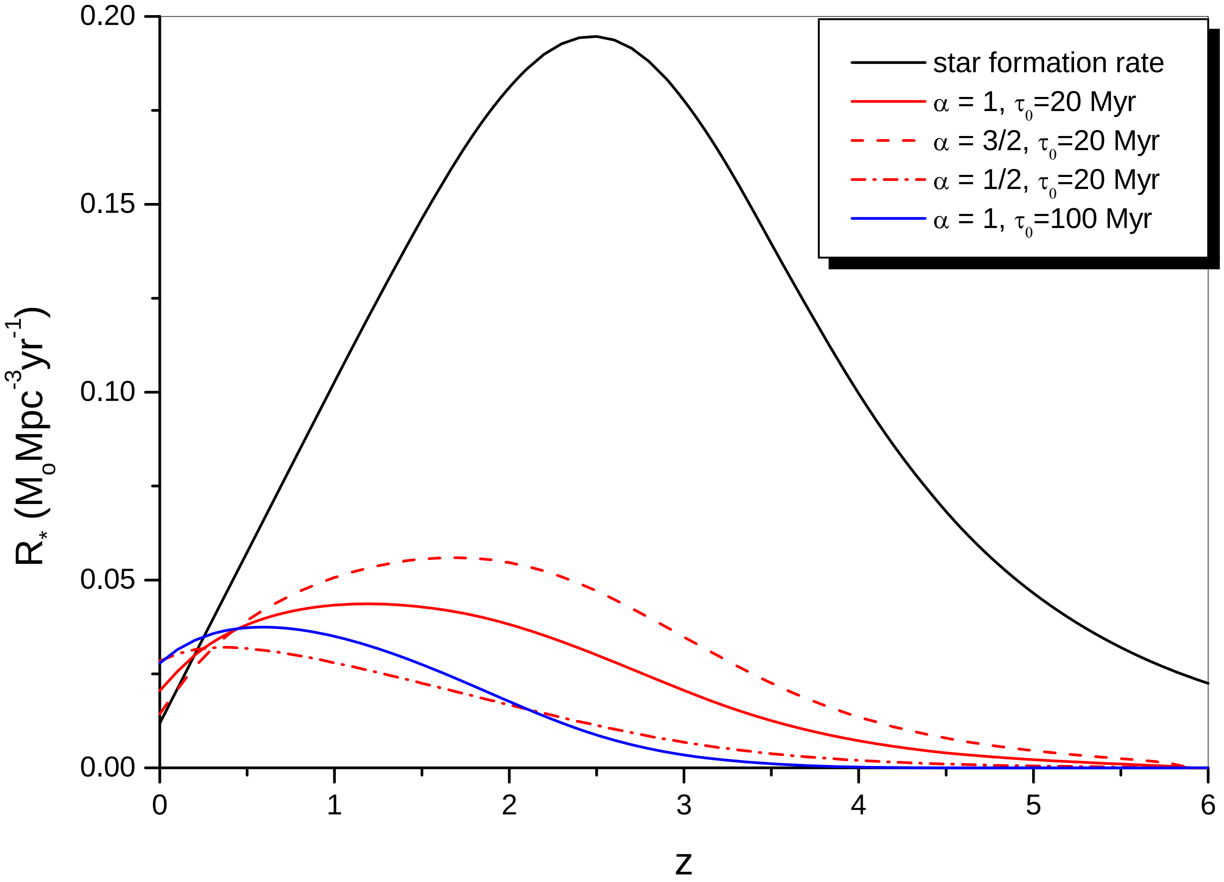
- λ_p = mass fraction of NS progenitors in the range 8-40 $M_\odot$
- f_b: fraction of massive binaries formed among all stars
- β_{NS}:fraction of massive binaries that remain bounded after the second supernova
- $R^*(z)$ = cosmic star formation rate
- $P(t_d)$: probability for a newly formed NS/NS to coalesce in a timescale t_d

- **spectral energy density**:

$$\frac{dE_{gw}}{d\nu} = \frac{(\pi G)^{2/3}}{3} \frac{m_1 m_2}{(m_1 + m_2)^{1/3}} \nu^{-1/3} \text{ with } \nu \in [10 \text{ Hz}; \nu_{lso}]$$

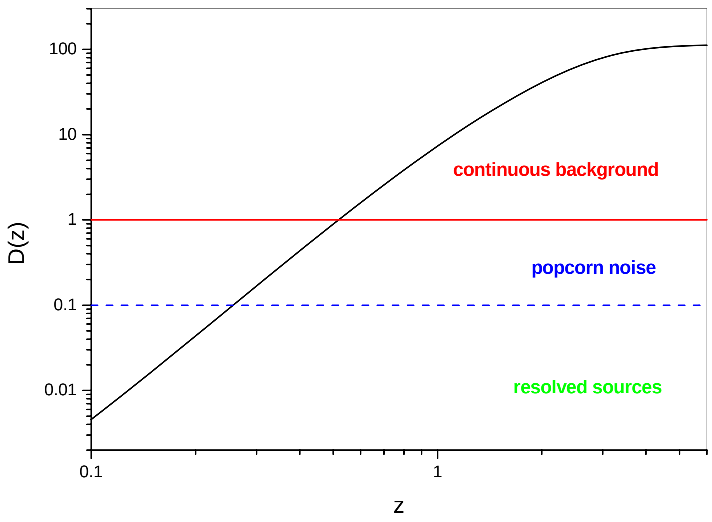
Cosmic coalescence rate

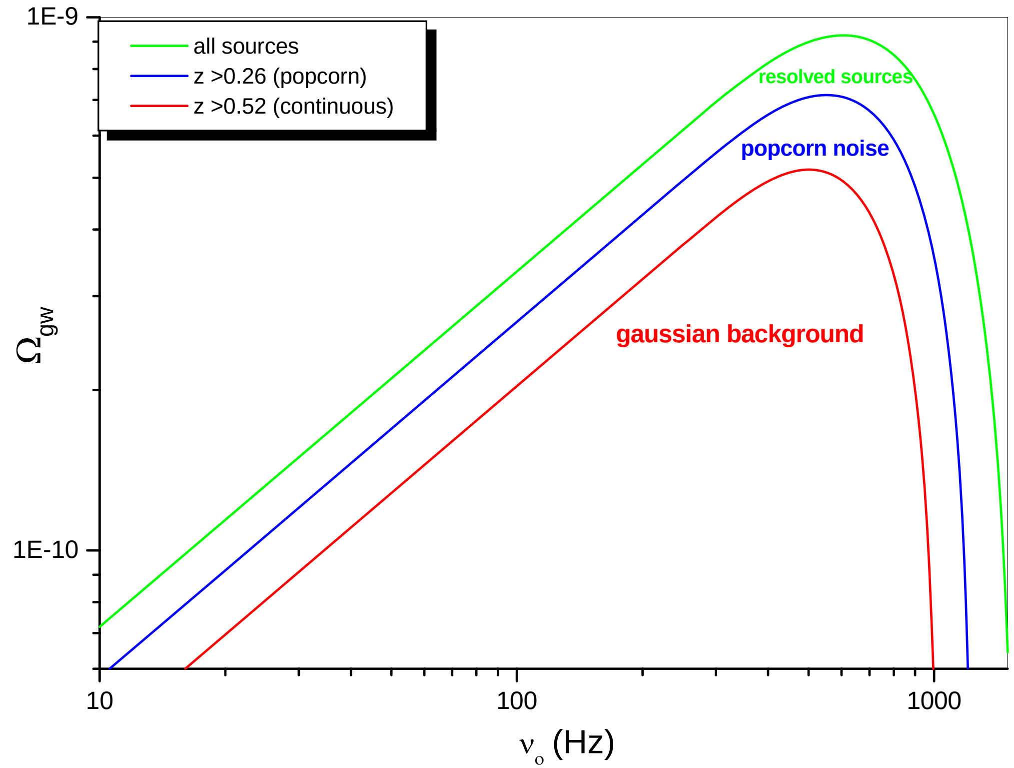
$P(t_d) \propto t_d^{-\alpha}$ with minimal delay τ_o



Energy density spectrum

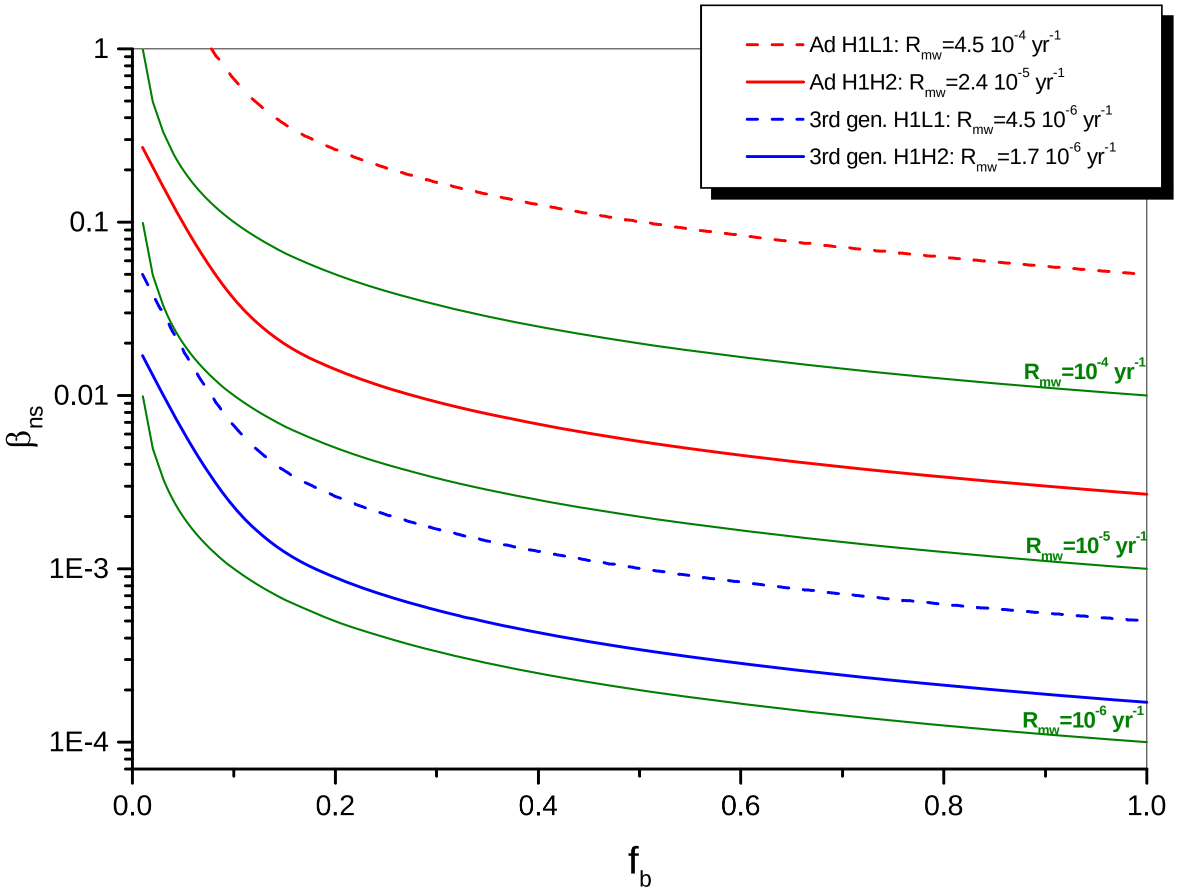
Spectrum for the three regimes (resolved sources, popcorn noise and gaussian background), assuming a galactic coalescence rate R_{mw}=3. 10^{-5} yr^{-1} and a coalescence time distribution with parameter α=1 and τ_0=20Myr.





Constraints on f_b-β_{ns}*

Constraints given on the fractions f_b and β_{ns} for **T= 3 years** and **SNR=1**.



**2D projection, assuming a coalescence time distribution with parameter α=1 and τ_0=20Myr.*

Summary and Conclusions

➢Why are AGBs important (and need to be modeled accurately)?

✓carry information about the star formation history, the statistical properties of source populations.
✓ may be a noise for the cosmological background

➢How do AGBs differ from the CGB (and need specific detection strategies)?

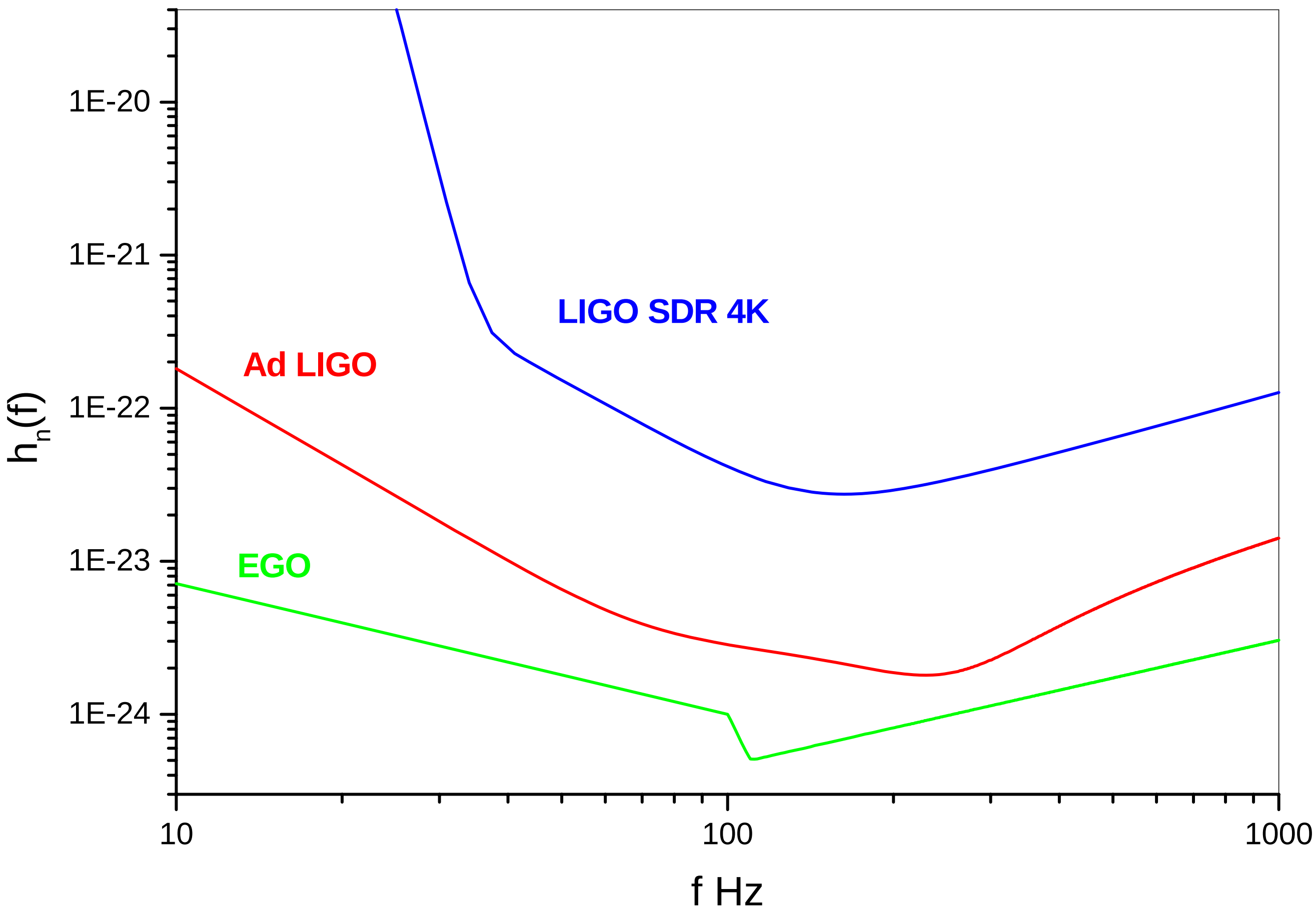
✓ anisotropic in the local universe (directed searches)
✓different regimes: shot noise, **popcorn noise** and gaussian
(maximum likelihood statistic, Drasco et al.; probability event horizon Coward et al.)
✓spectrum characterized by a **maximum** and a cutoff frequency

➢ Advanced detectors may be able to put interesting constraints

✓NS ellipticity, magnetic field, initial period
✓rate of compact binaries
....

Extra Slides

Sensitivity



Magnetars

- about **10-20%** of the radio pulsar population
- super-strong crustal **magnetic fields (B_{dip}~10^{14} – 10^{16} G)** formed by dynamo action in proto neutron stars with **millisecond rotation period P_0 ~0.6 – 3 ms** (break up limit - convective overturn).
- strong magnetic fields can induce significant **equatorial deformation**
  - **pure poloidal field** (Bonazzola 1996)

$$\varepsilon_B = g \frac{R^8 B^2 \sin^2 \alpha}{4GI^2} \simeq 3.7 \times 10^{-4} g_{100} R_{10}^8 I_{45}^{-2} B_{15}^2$$

The distortion parameter g depends on both the EOS and the geometry of the magnetic field: g~1-10 (non-superconductor), ***g~100-1000 (type I superconductor)****, g>1000-10000 (type II superconductor, counter rotating electric current)*

  - **internal field dominated by the toroidal component** (Cutler 2002, dall'Osso et al. 2007):

$$\varepsilon_B \sim -1.6 \times 10^{-4} < B_{t,16}^2 >^2 \quad \text{when } B_t >> B_p$$

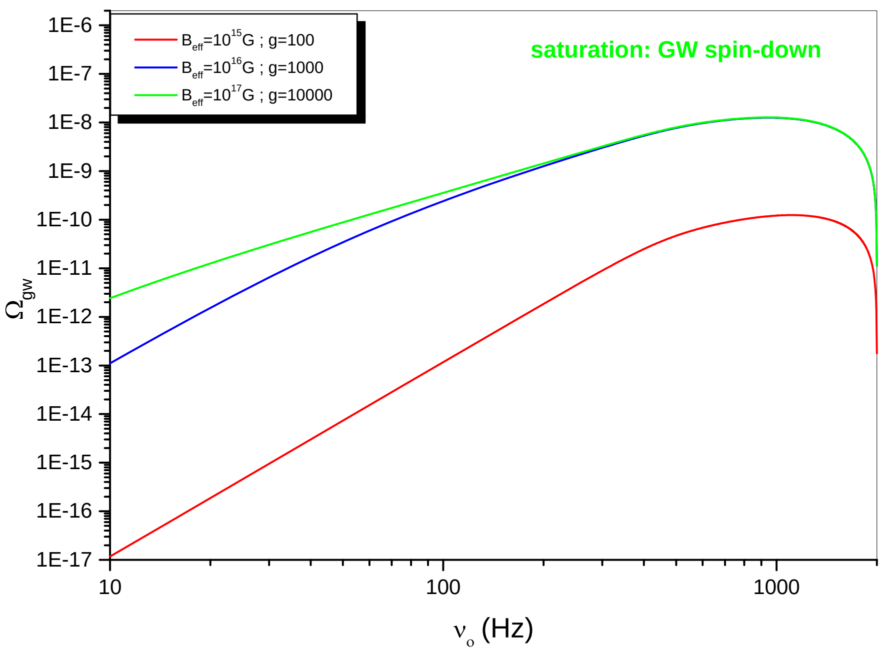
- **spectral energy density**

$$\frac{dE_{gw}}{d\nu} = K\nu^3 \left[1 + \frac{K}{\pi^2 I}\nu^2\right]^{-1} \quad \text{where } K \sim \begin{cases} 3.9 \times 10^{37} g_{100}^2 B_{15}^2 & \text{(pure poloidal field)} \\ 7.1 \times 10^{36} B_{t,16}^4 B_{15}^{-2} & \text{(toroidal internal field)} \end{cases}$$

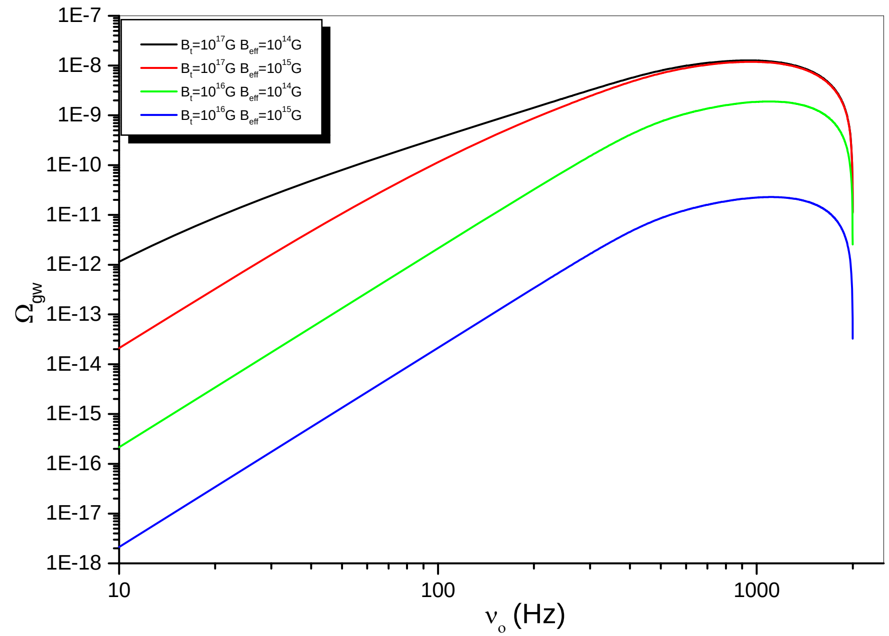
Energy density spectrum

Spectrum from the cosmological population of magnetars, assuming an initial period P_i =1 ms and a galactic rate R_{mw}=0.1 per century.

pure poloidal magnetic field



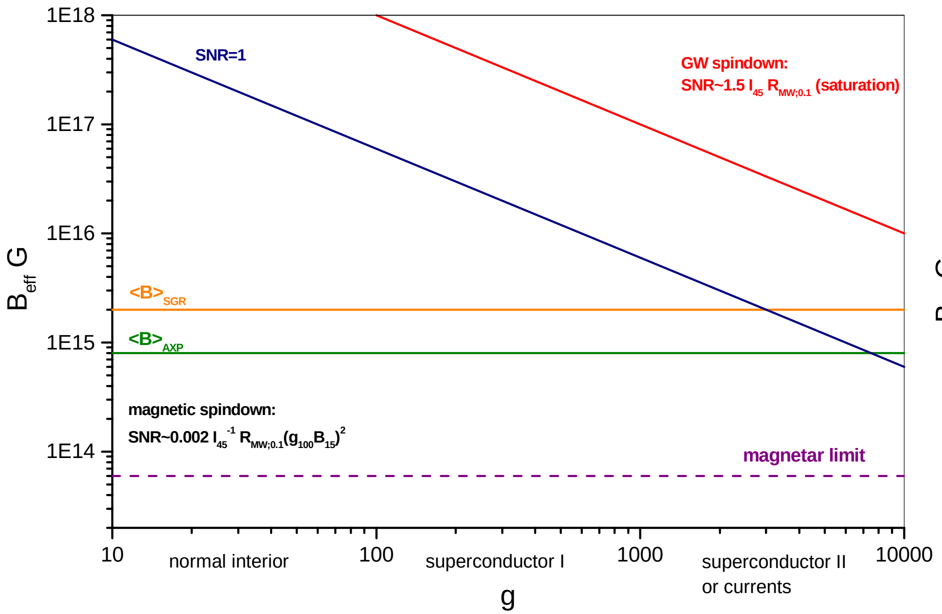
toroidal internal magnetic field



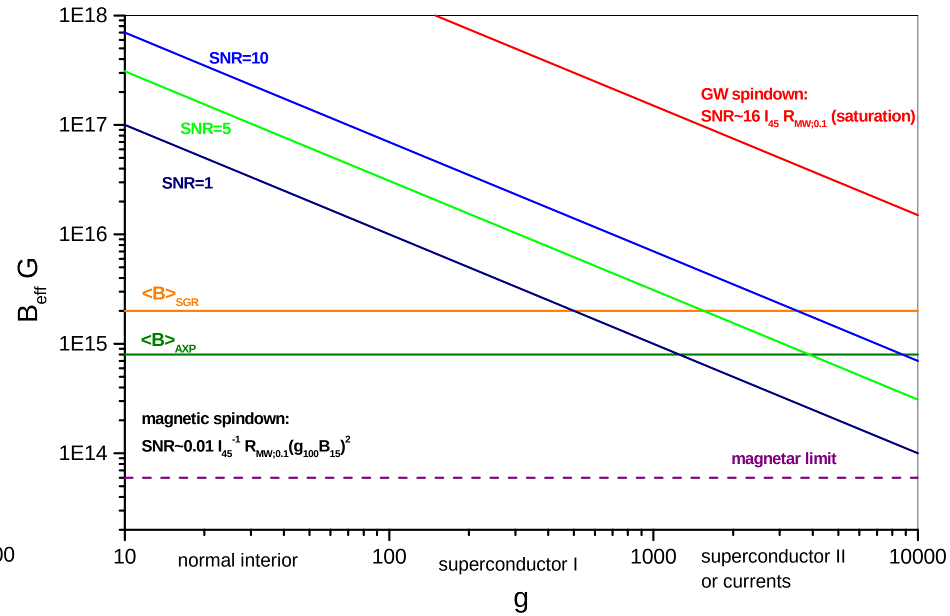
Constraints on g-B

Constraints given by **coaligned and coincident detectors** (H1-H2), for T=3 yrs of observation, , in the range 10-500 Hz.

Advanced detectors (Ad LIGO sensitivity)



3rd generation detectors (Einstein Telescope)

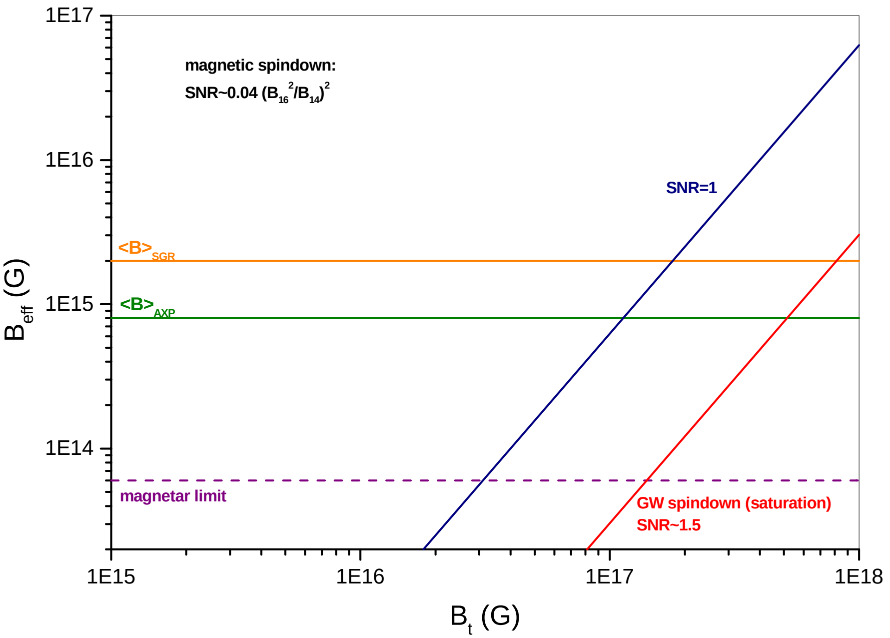


If no detection, we can rule out the model of spindown dominated by GW emission

Constraints on B_t–B

Constraints given by **coaligned and coincident detectors** (ex: H1-H2), for T=3 yrs of observation, in the range 10-500 Hz.

Advanced detectors (Ad LIGO sensitivity)



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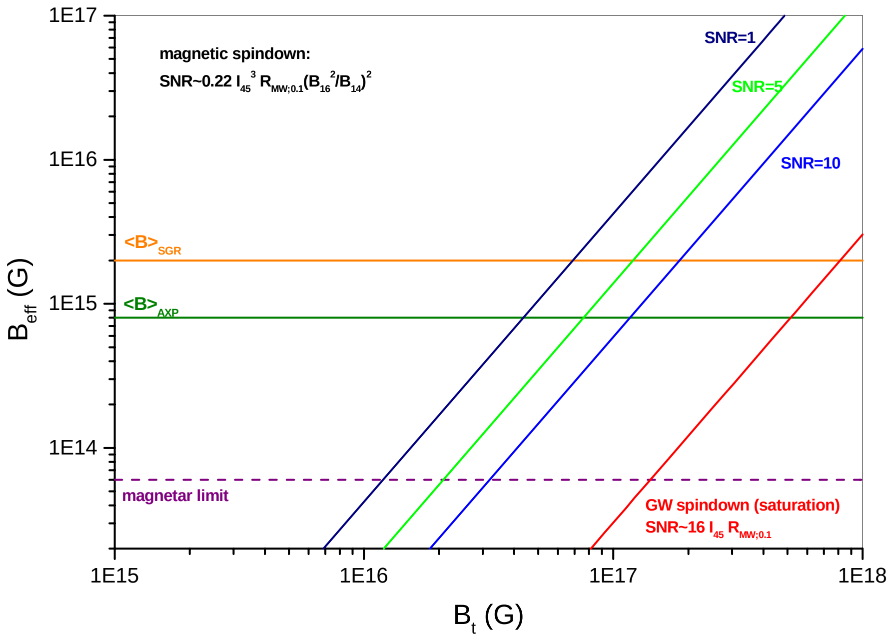


If no detection, we can rule out the model of spindown dominated by GW emission

NS Initial Instabilities

- **source rate:**

Only the small fraction of NS born fast enough to enter the instability window:

$$\frac{dR^0}{dz}(z) = \xi\lambda_p \frac{R^*(z)}{(1+z)} \frac{dV}{dz}(z)$$

$$\begin{cases} \lambda_p = \text{mass fraction of NS progenitors in the range 40-100 M}_{\odot} \\ \xi = \text{fraction of newborn NS that enter the instability } (\xi = \int_{P_{\min}}^{P_{\max}} g(P_0)dP_0) \\ R^*(z) = \text{cosmic star formation rate} \end{cases}$$

Population synthesis ((Regimbau & de F. Pacheco 2000, Faucher-Giguere & Kaspi 2006) *:*

- ***initial period:*** *normal distribution with <Po>~250 -300 ms and σ~80 -150ms*

- **spectral energy density**:

$$\frac{dE}{d\nu} = \frac{2E_0}{\nu_{\text{sup}}^2}\nu \qquad \begin{cases} \text{r-modes: } E_0 = \Delta E_K \\ \text{bar-modes: } E_0 = E_{MacLauren} - E_{Dedekind} \end{cases}$$

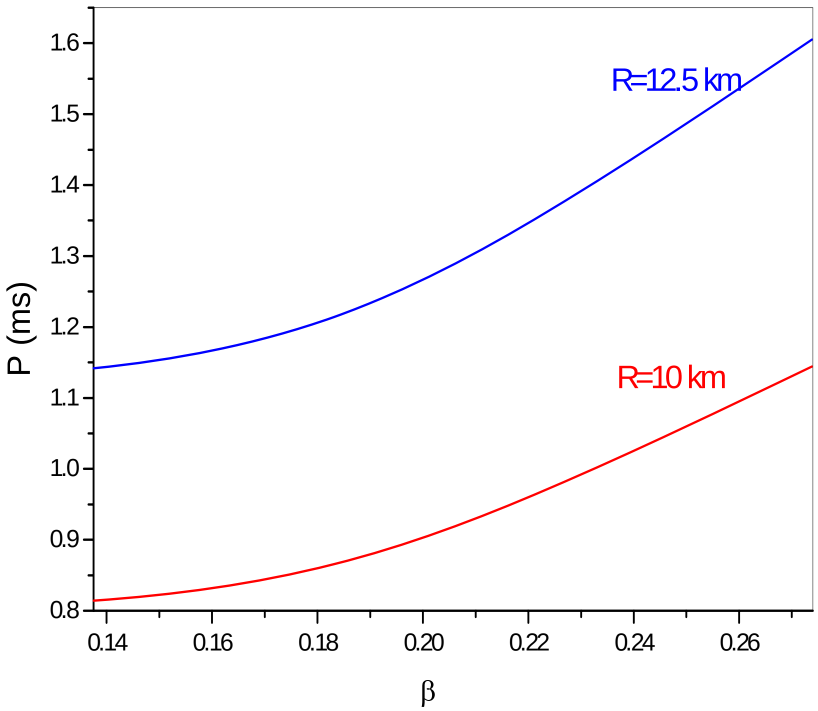
Instability windows

Bar modes:

secular instability: 0.14< β <0.27

-R=10 km: P_o ~0.8-1.1 ms (ξ~2e-5)

-R=12.5 km: P_o ~ 1.1-1.6 ms (ξ~3e-5)

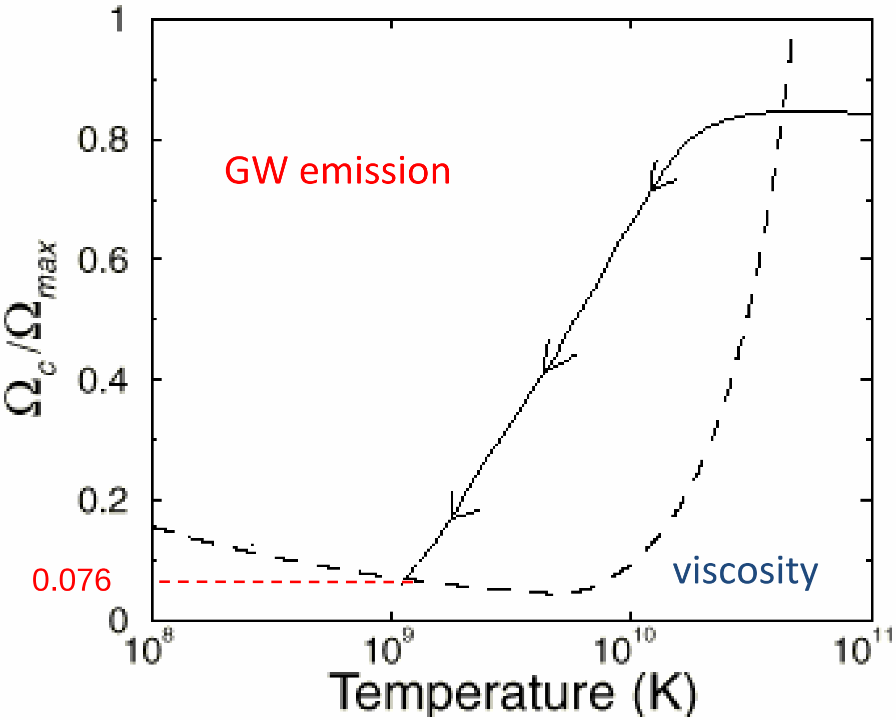


R modes:

$|\tau_{gw}(\Omega)| < \tau_v(\Omega, T)$

-R=10 km: P_o ~0.7-9 ms (ξ~5e-4)

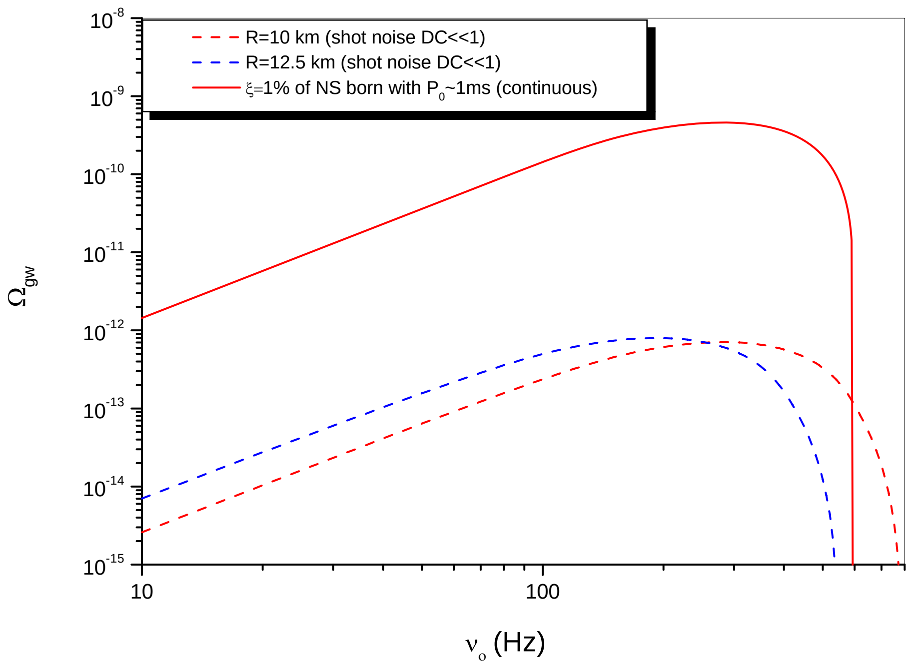
-R=12.5 km: P_o ~1-12 ms (ξ~8e-4)



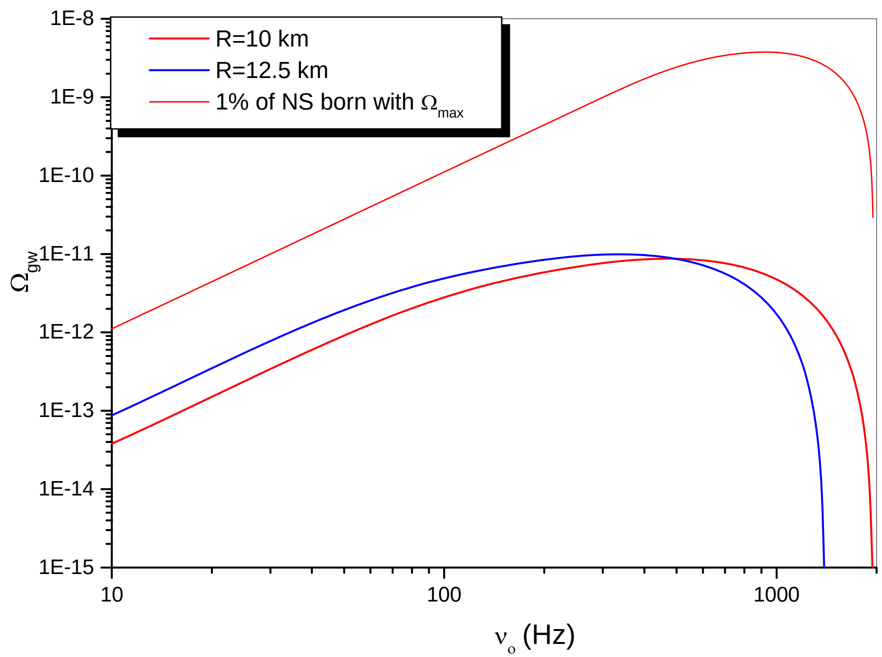
Energy density spectrum

Spectrum from the cosmological population of newborn NSs that enter the bar and r-modes instability windows.

Bar modes:



R modes:



Constraints on ξ

Constraints on the fraction of NS that enter the instability window of **bar modes** and **R modes** near the Keplerian velocity for **T= 3 years** and **SNR=1-5**.

Bar modes:

sensitivity	H1L1	H1H2
Advanced	-	2-4%
3rd gen.	4-9%	0.2-0.4%

R modes:

sensitivity	H1L1	H1H2
Advanced	-	2-5%
3rd gen.	4-10%	0.2-0.5%

Core collapse to BH (ringdown)

- **source rate:**

follows the star formation rate (fast evolution of massive stars)

$$\frac{dR^0}{dz}(z) = \lambda_p \frac{R^*(z)}{(1+z)} \frac{dV}{dz}(z)$$

$$\begin{cases} \lambda_p = \text{mass fraction of NS progenitors in the range 40-100 } M_\odot \\ R^*(z) = \text{cosmic star formation rate} \end{cases}$$

- **spectral energy density**:

All the energy is emitted at the same frequency (Thorne, 1987)

$$\frac{dE_{gw}}{d\nu} = \varepsilon M_c c^2 \delta(\nu - \nu_*(M_c)) \text{ with } \nu_*(\text{kHz}) \sim 13 / M_c (M_\odot)$$

mass of the BH: $M_c = \alpha M_p$ with $\alpha \sim 10 - 20\%$

efficiency: $\varepsilon < 7 \times 10^{-4}$

Energy density spectrum

Spectrum from the cosmological population of newborn distorted BHs. The resulted background is not gaussian but rather **a shot noise** with a duty cycle DC~0.01.