Gertsenshtein-Zel′dovich effect: A plausible explanation for fast radio bursts?

Ashu Kushwaha

Department of Physics, IIT Bombay

in collaboration with

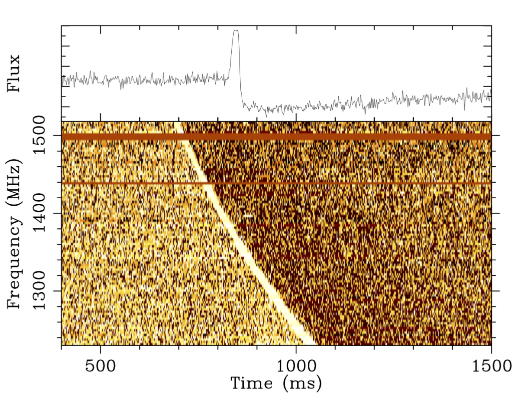
Sunil Malik and S. Shankaranarayanan,
arXiv: 2202.00032

International Conference on the Physics of the Two Infinities,
Kyoto University

29 March, 2023

Introduction to FRBs

- Burst of radio waves lasting for only few milli-seconds.
- Lorimer Burst—first FRB reported in 2007, Parkes telescope, Australia
- Estimated rate is 1000/entire sky/day.
- Astrophysical origin.



Lorimer et al (2007)

Observational progress

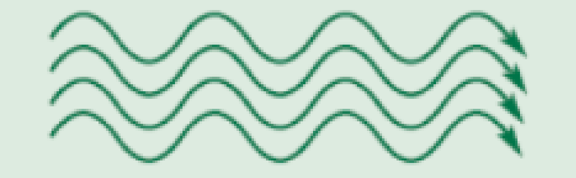
JVLA: Jansky Very Large Array, **LOFAR:** Low-Frequency Array,
CHIME: Canadian Hydrogen Intensity Mapping Experiment

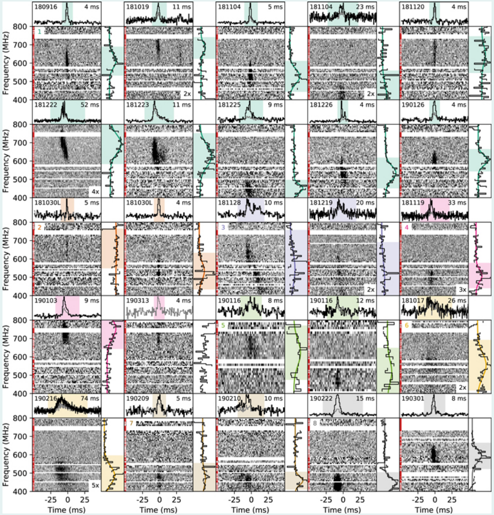
Petroff et al (2019)

Features of FRBs:

- Lasts for few milli-seconds to less than a second.
- > 600 FRBs reported, with peak flux in range 0.1Jy – 700Jy.
- Repeating and non-repeating FRBs.
- FRB radiation must be coherent. $\longrightarrow$ Key feature for FRB that any model should explain.

Kumar & Bosnjak, MNRAS (2020)





CHIME/FRB Collaboration (2019)

What is the astrophysical mechanism to explain FRBs?

Proposed models/hypothesis: What could FRBs be?

- Neutron stars collapsing to black holes, ejecting magnetic hair (Falcke & Rezzolla ’14)
- Merger of charged black holes (Zhang ’16; Liu et al.’16)
- Magnetospheric activity during neutron star merger (Totani ’13)
- White dwarf merger (Kashiyama et al.’13)
- Pulses from young neutron stars (Cordes & Wasserman ’15, Kashiyama & Murase ’17)
- Asteroids/comets falling onto neutron stars (Geng & Huang ’15)
- Sparks from cosmic strings (Vachaspati ’08; Yu et al. ’14)
- Evaporating primordial black holes (Rees ’77; Keane et al. ’12)
- Axion stars (Tkachev ’15; Iwazaki ’15)
- Quark novae (Chand et al. ’15)
- Dark matter-induces collapse of neutron stars (Fuller & Ott ’15)
- Black hole interacting with an AGN (Das Gupta & Saini ’17; Waxman ’17)
- Black hole superradiance (Conlon & Herdeiro)
- **And many more models/ hypothesis....**

Gertsenshtein-Zel′dovich effect

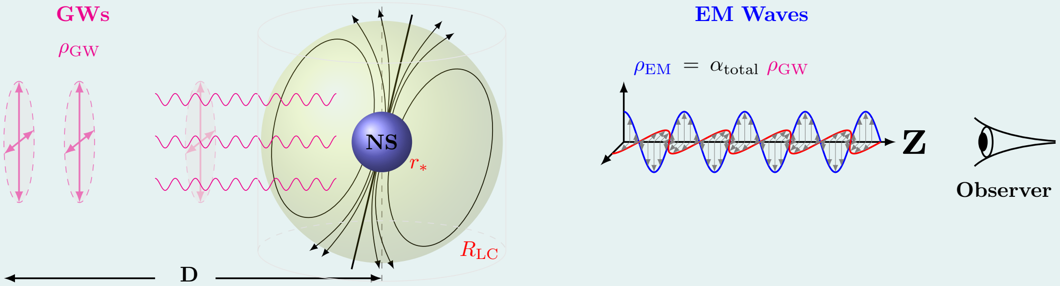
Gertsenshtein effect: In 1962, Gertsenshtein showed that electromagnetic wave passing through a **strong transverse magnetic field** will produce gravitational wave of the same frequency and wave vector.

Gertsenshtein-Zel'dovich effect (EM wave $\rightleftharpoons$ GW wave)

- When an EM wave (**E,B**) propagates in the presence of magnetic field B_0, there appears a stress tensor proportional to BB_0 which is variable in space and time. **This tensor is a source of GW**.
- When a GW propagates through the field B_0, there occurs a stretching and compression of the magnetic field $h(x,t)B_0$, where $h(x,t)$ is the variation of the metric in the GW. The field $h(x,t)B_0$ is the **source for the EM wave.**

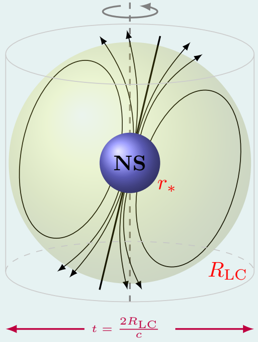
Zel'dovich (1973)

Connection between GZ effect and FRBs



Assumption and features

- Compact objects (NS/magnetar) have strong gravity environment, with $B^{(0)} \sim 10^8 - 10^{15}$G.
- Due to the rotation of the NS, small time-dependent magnetic field arises — $\delta B_y \sin(\omega_B t)$.
- Earlier studies have shown $\left|\frac{\delta \mathbf{B}}{\mathbf{B}^{(0)}}\right| < 0.1$, therefore we take $|\delta \mathbf{B}/\mathbf{B}^{(0)}| \sim 10^{-2}$.
- For $10^7 < \mathrm{R_{LC}(cm)} < 10^9 \implies 10^{-3} < t\,(\mathrm{s}) < 0.1$



$t < 1\mathrm{s} \implies$ **induced EMW will appear as a burst lasting for less than 1s.**

GZ effect

- Consider a monochromatic circularly polarized GW propagating along z-axis through magnetized region in space. The two polarizations of GW are

$$h_+ = A_+ \, e^{i(k_g z - \omega_g t)}, h_\times = i A_\times \, e^{i(k_g z - \omega_g t)}, \tag{1}$$

- Transverse magnetic field is : $\mathbf{B}(t) = \Big(0, B_y^{(0)} + \delta B_y \sin(\omega_B t), 0\Big)$.

- **Faraday's law** $\implies \mathbf{E}(z,t) = \Big(-\frac{z\,\omega_B \delta B_y}{c}\cos(\omega_B t), 0, 0\Big)$.

- In the absence of GWs, components of background EM field tensor $F^{(0)}_{\alpha\beta}$ are:

$$F^{(0)}_{01} = E_x = -F^{(0)}_{10} = -\frac{z\,\delta B_y \omega_B}{c}\cos(\omega_B t); \quad F^{(0)}_{13} = B_z = -F^{(0)}_{31} = B^{(0)}_y + \delta B_y \sin(\omega_B t)\,.$$

- Propagating GW induces EM field tensor $F^{(1)}_{\alpha\beta}$.
- Covariant Maxwell's equations (in the source-free region) are:

$$\partial_\mu \left[\left(\eta^{\mu\alpha} h^{\nu\beta} + h^{\mu\alpha} \eta^{\nu\beta} \right) F^{(0)}_{\alpha\beta} - \eta^{\mu\alpha}\eta^{\nu\beta} F^{(1)}_{\alpha\beta} \right] = 0 \, ; \qquad \partial_\mu \left(\eta^{\mu\nu\alpha\beta} F^{(1)}_{\alpha\beta} \right) = 0 \tag{2}$$

- Electric and magnetic fields induced due to GWs:

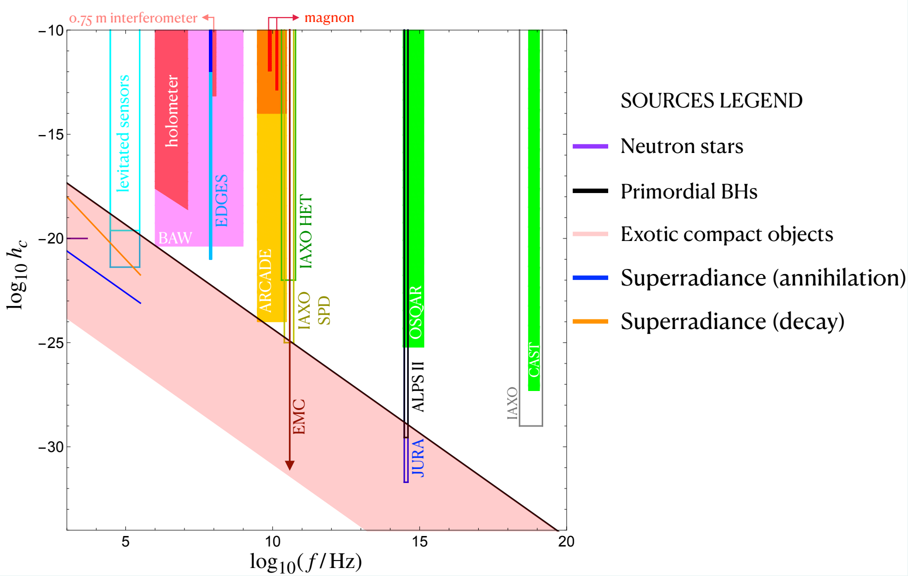
$$\tilde{E}_x \simeq -\frac{A_+}{2} B_y^{(0)} \left(1 - \xi\, \omega_B t\right) \; e^{i(k_g z - \omega_g t)} \tag{3}$$

$$\tilde{B}_y \simeq -\frac{A_+}{4} B_y^{(0)} \left(1 + 2\xi\, \omega_g t\right) e^{i(k_g z - \omega_g t)} \tag{4}$$

where $\xi \equiv \delta B_y / B_y^{(0)}$ and $\omega_B \ll \omega_g$ is used.

Details

Can high frequency GWs exist in the universe?

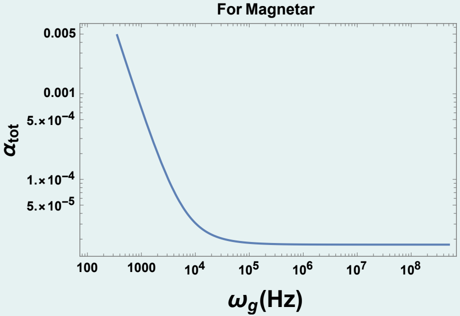


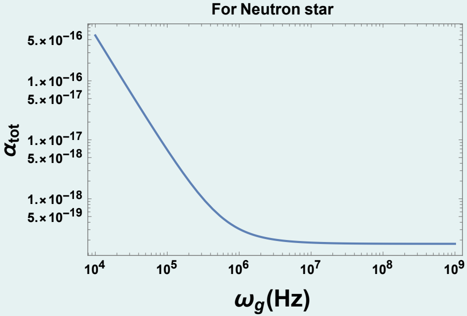
Aggarwal, etal (2020)

Step 1: Conversion factor

- The **conversion factor** (α) — ratio of the energy density of EM wave and GWs, integrating over the entire magnetosphere from the surface of the compact object to the light cylinder $R_{\rm LC}$.

$$\alpha_{\rm tot} \simeq \frac{5\pi G|B_y^{(0)}|^2}{2c^2}\left[\frac{4}{15}\xi^2\left[\frac{R_{\rm LC}}{c}\right]^2 + \frac{2\xi R_{\rm LC}}{5\,\omega_g c} + \frac{1}{\omega_g^2}\right] \quad (5)$$





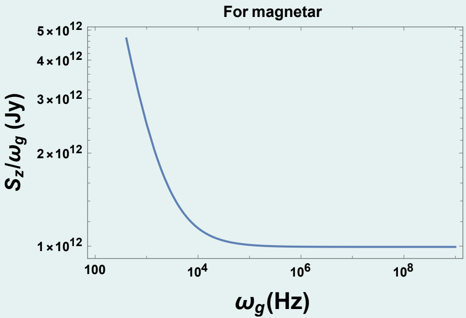
For magnetar, $B_y^{(0)} = 10^{15}$ G, $R_{\rm LC} = 10^9$ cm, $\omega_B = 1$ Hz and for NS, we set $B_y^{(0)} = 10^{10}$G, $R_{\rm LC} = 10^7$cm, $\omega_B = 1$kHz.

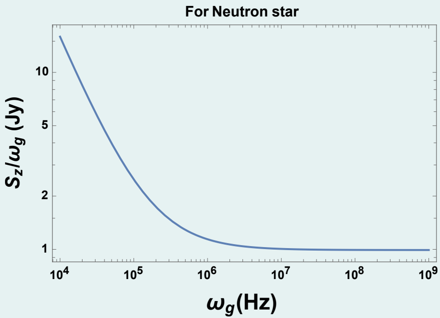
crossover-details

- The flux energy density is given by the **Poynting vector:** $S_z = \frac{c}{8\pi}\tilde{E}_x \times \tilde{B}_y$.

- Flux density carried by induced electromagnetic fields

$$S_z \simeq \frac{A_+^2 |B_y^{(0)}|^2 c}{128\pi}\left[\sqrt{\frac{24c^2\omega_g^2\alpha_{\rm tot}}{\pi G|B_y^{(0)}|^2} - 51} - \frac{6c^2\omega_g\omega_B\alpha_{\rm tot}}{\pi G|B_y^{(0)}|^2} - 1\right] \tag{6}$$





For both plots we have set $A_+ = 10^{-23}$ corresponding to a typical GW source. more plots

Peak spectral flux density

$R_{\rm LC}$ (cm)	$B_y^{(0)}$ (Gauss)	ω_g (MHz)	$\alpha_{\rm tot}$	$\rho_{\rm GW}$ (Jy cm^{-1} s Hz)	$\rho_{\rm EM}$ (Jy cm^{-1} s Hz)	$\frac{S_z}{\omega_g}$ (Jy)
10^9	10^{15}	1	1.74×10^{-5}	2.68×10^{15}	4.65×10^{10}	9.95×10^{11}
10^9	10^{12}	500	1.72×10^{-11}	6.71×10^{20}	1.15×10^{10}	9.94×10^5
10^8	10^{11}	1400	1.72×10^{-15}	5.26×10^{21}	9.07×10^6	961.57
10^7	10^{10}	1400	1.72×10^{-19}	5.26×10^{21}	9.07×10^2	0.99
10^8	10^9	1400	1.72×10^{-19}	5.26×10^{21}	9.07×10^2	0.09

The first two rows are for a typical **Magnetar** and the last three rows are for a typical **NS**. We have set $G = 6.67 \times 10^{-8}$ dyne cm^{2}gm^{-2}, c $= 3 \times 10^{10}$cm s^{-1}, $A_+ = 10^{-23}$ corresponding to a typical GW source.

Conclusion: *How does GZ effect explain origin of FRBs?*

- ☞ **Pulse-width:** $t = \frac{2R_{\rm LC}}{c} < 1{\rm s}$ provides natural explaination of burst lasting for less than 1s.

- ☞ **Peak-flux:** Model predicts the flux density < 1000Jy for **typical NS**, explaining the peak flux of the reported FRBs.

- ☞ Magnetars are less common than NSs with formation rate $\sim 1 - 10\%$ of all pulsars. Hence, probability that the GW passes through the magnetar in a typical galaxy is much lower.

- ✩ More than 600 FRBs have been reported and our model can explain 99% of them.

- ✩ The model offers a perspective on indirect detection of high-frequency GWs.

Thank you

Backup slides

Induced Electric and magnetic field: Details

$$\partial_\mu \left[\left(\eta^{\mu\alpha} h^{\nu\beta} + h^{\mu\alpha}\eta^{\nu\beta}\right) F^{(0)}_{\alpha\beta} - \eta^{\mu\alpha}\eta^{\nu\beta} F^{(1)}_{\alpha\beta}\right] = 0\,; \qquad \partial_\mu \left(\eta^{\mu\nu\alpha\beta} F^{(1)}_{\alpha\beta}\right) = 0\,. \tag{7}$$

where $\eta^{\mu\nu\alpha\beta}$ is an antisymmetric tensor and defined as $\eta^{0123} = 1 = -\eta_{0123}$. For the metric corresponding to the two-modes of polarization of GWs the two Maxwell's equations in terms of electric and magnetic fields are given by:

$$\frac{1}{c}\partial_t \tilde{E}_x - \partial_y \tilde{B}_z + \partial_z \tilde{B}_y + \left(B^{(0)} + \delta B_y \sin(\omega_B t)\right) \partial_z h_+ - \frac{z\,\delta B_y \omega_B}{c^2}\frac{\partial}{\partial t}\left(h_+ \cos(\omega_B t)\right) = 0 \tag{8a}$$

$$\frac{1}{c}\partial_t \tilde{B}_y - \partial_x \tilde{E}_z + \partial_z \tilde{E}_x = 0. \tag{8b}$$

The above two equations lead to the following wave equations:

$$\frac{1}{c^2}\frac{\partial^2 \tilde{E}_x}{\partial t^2} - \partial_z^2 \tilde{E}_x = -\frac{\delta B_y \omega_B}{c}\cos(\omega_B t)\,\partial_z h_+ - \frac{1}{c}\left(B^{(0)} + \delta B_y \sin(\omega_B t)\right)\partial_t \partial_z h_+ + \frac{z\,\delta B_y \omega_B}{c^3}\frac{\partial^2}{\partial t^2}\left(h_+ \cos(\omega_B t)\right) \tag{9a}$$

$$\frac{1}{c^2}\frac{\partial^2 \tilde{B}_y}{\partial t^2} - \partial_z^2 \tilde{B}_y = \left(B^{(0)} + \delta B_y \sin(\omega_B t)\right)\partial_z^2 h_+ - \frac{\delta B_y \omega_B}{c^2}\partial_t\left(h_+ \cos(\omega_B t)\right) - \frac{z\,\delta B_y \omega_B}{c^2}\partial_t \partial_z\left(h_+ \cos(\omega_B t)\right) \tag{9b}$$

Since GWs (and EM waves) propagate along the z-direction, we have $\tilde{E}_z = \tilde{B}_z = 0$, after a bit of algebra the wave equations for $\tilde{E}_x, \tilde{B}_y$:

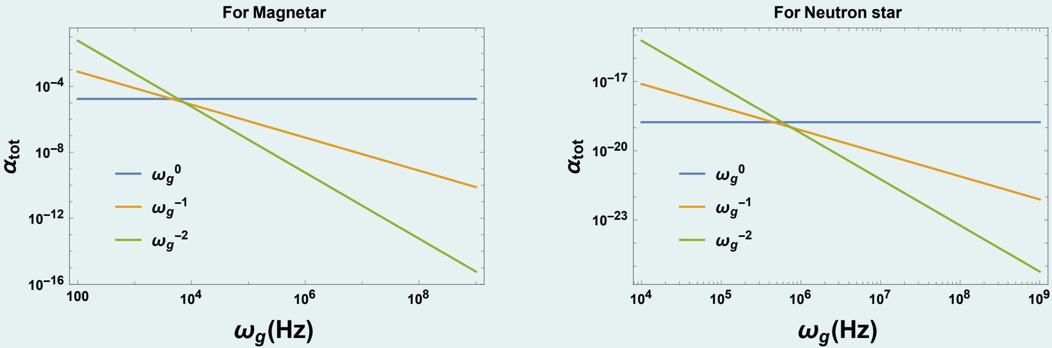
$$\frac{1}{c^2}\frac{\partial^2 \tilde{E}_x}{\partial t^2} - \partial_z^2 \tilde{E}_x = f_E(z', t') \tag{10a}$$

$$\frac{1}{c^2}\frac{\partial^2 \tilde{B}_y}{\partial t^2} - \partial_z^2 \tilde{B}_y = f_B(z', t') \tag{10b}$$

where $f_{E/B}(z', t')$ are the forcing functions and are given by:

$$\begin{aligned} f_E(z', t') = &-\frac{A_+ B^{(0)} k_g \omega_g}{c} e^{i\left(k_g z' - \omega_g t'\right)} - \frac{iA_+ \delta B_y k_g}{2c}\left(\omega_+ e^{i\left(k_g z' - \omega_+ t'\right)} - \omega_- e^{i\left(k_g z' - \omega_- t'\right)}\right) \\ &- \frac{z' A_+ \delta B_y \omega_B}{2c^3}\left(\omega_+^2 e^{i\left(k_g z' - \omega_+ t'\right)} + \omega_-^2 e^{i\left(k_g z' - \omega_- t'\right)}\right) \end{aligned} \tag{11a}$$

$$\begin{aligned} f_B(z', t') = &-A_+ B^{(0)} k_g^2 e^{i\left(k_g z' - \omega_g t'\right)} - \frac{iA_+ \delta B_y k_g^2}{2}\left(e^{i\left(k_g z' - \omega_+ t'\right)} - e^{i\left(k_g z' - \omega_- t'\right)}\right) \\ &- \frac{iA_+ \delta B_y \omega_B}{2c^2}\left(\omega_+ e^{i\left(k_g z' - \omega_+ t'\right)} - \omega_- e^{i\left(k_g z' - \omega_- t'\right)}\right) + \frac{z' A_+ \delta B_y \omega_B k_g}{2c^2}\left(\omega_+ e^{i\left(k_g z' - \omega_+ t'\right)} - \omega_- e^{i\left(k_g z' - \omega_- t'\right)}\right) \end{aligned} \tag{11b}$$

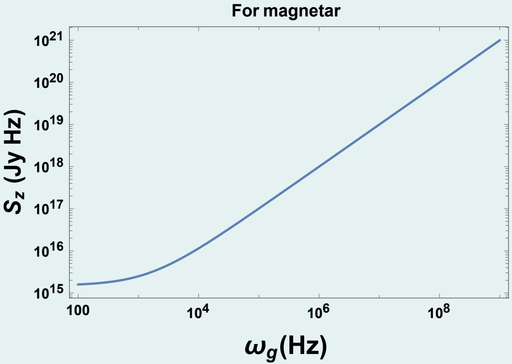


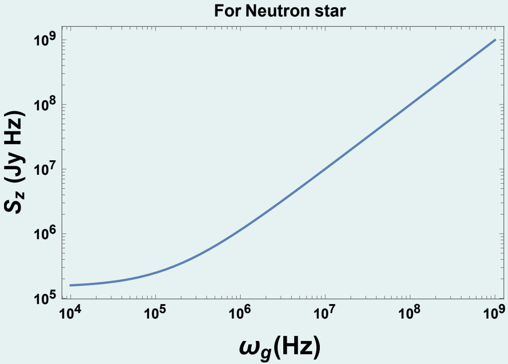
Log-Log plot of the three terms in the RHS of α_{tot} versus ω_g. For magnetar, we have set $B_y^{(0)} = 10^{15}\text{G}, R_{\text{LC}} = 10^9$ cm, $\omega_B = 1\text{Hz}$. For NS/milli-second pulsar, we have set $B_y^{(0)} = 10^{10}\text{G}, R_{\text{LC}} = 10^7\text{cm}, \omega_B = 1\text{kHz}$.

$\Longrightarrow$ Total conversion factor is independent of the incoming GW frequency.

Back

Poynting vector of the resultant EM waves





For Magnetar, we have assumed $B_y^{(0)} = 10^{15}\,\mathrm{G}$, $\mathrm{R_{Lc}} = 10^9$ cm , $\omega_\mathrm{B} = 1\,\mathrm{Hz}$. For milli-second pulsar, we have set $B_y^{(0)} = 10^{10}\,\mathrm{G}$, $\mathrm{R_{Lc}} = 10^7\mathrm{cm}$, $\omega_\mathrm{B} = 1\,\mathrm{kHz}$.

Back