MNRAS, 2019,458
arXiv:1901.01029

Kinetic simulations of synchrotron maser emission from shocks in Fast Radio Bursts

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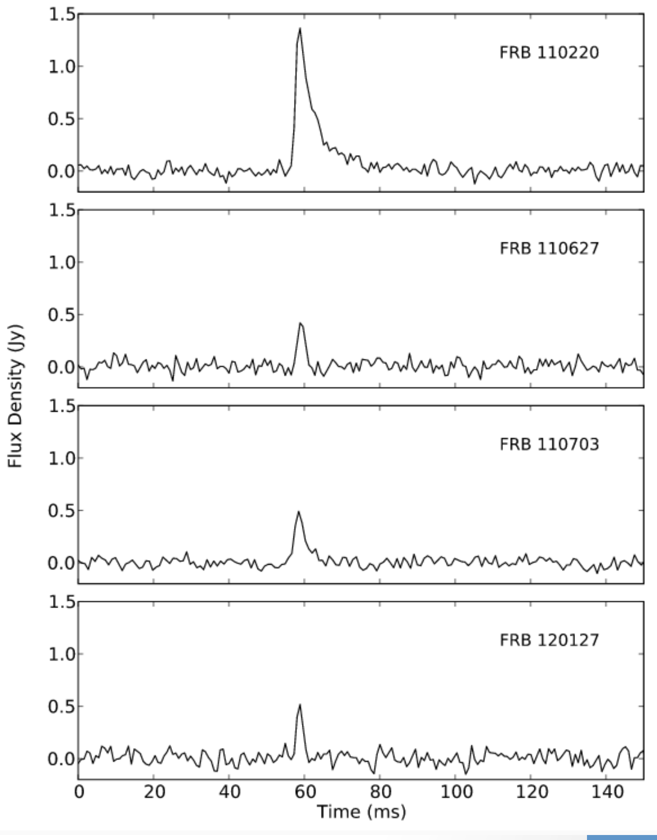
What are FRBs

- Short (ms) and intense (Jy) pulses in ~GHz frequency band
- Two repeaters among ~50 objects. Repeaters are extragalactic
- Unkwonwn sources (magnetars favoured for repeaters). Likely compact objects
- Unknown emission mechanism but must be coherent:

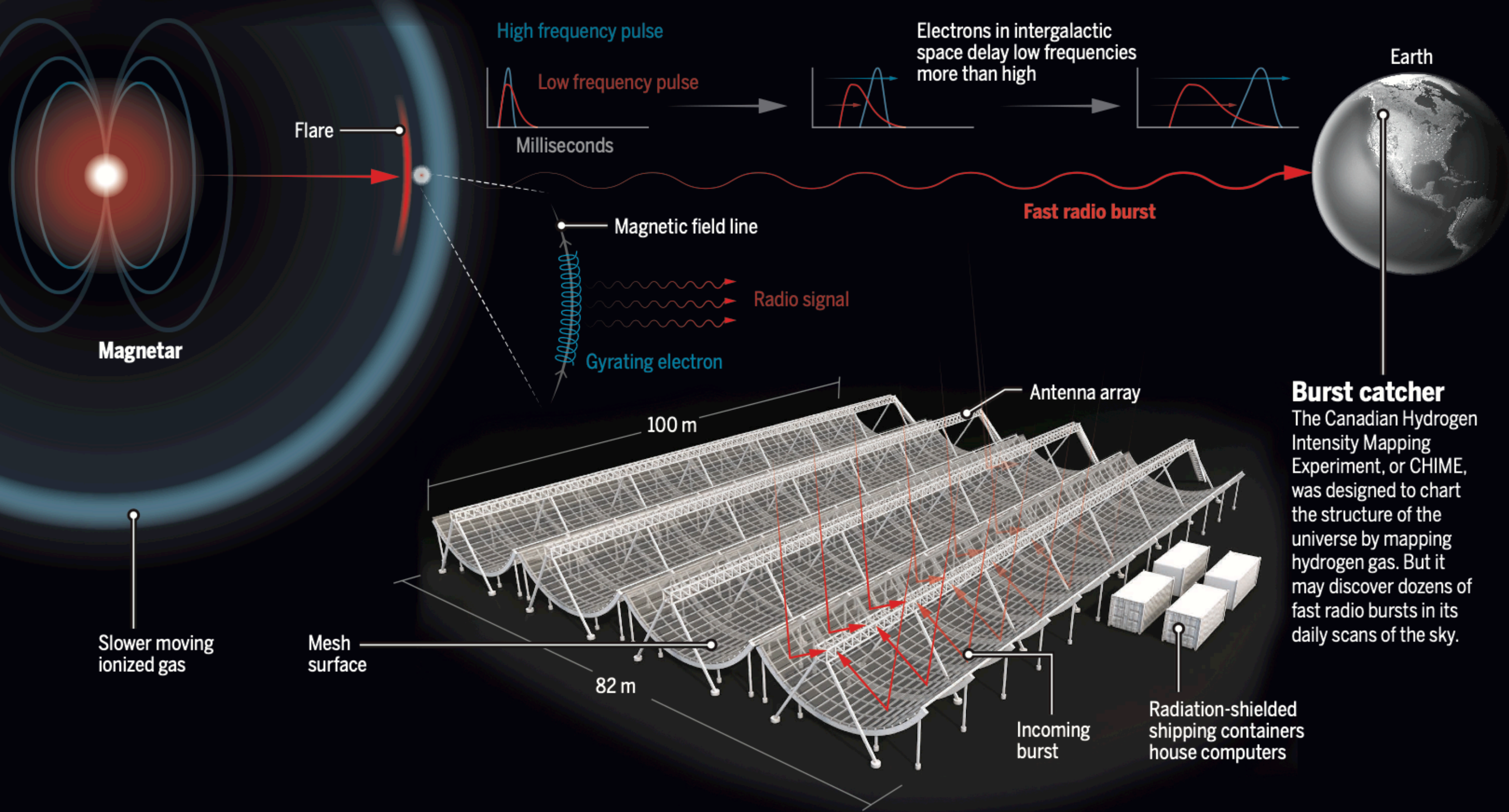
  brightness temp. $T_B \sim 10^{35}$ K
- More theories than discovered FRBs



Thornton et al 13

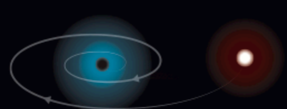
Shots in the dark

Fast radio bursts have puzzled theorists since their discovery in 2007. Their short duration and stretched frequencies imply compact, distant sources. One possibility is a magnetar, a highly magnetized neutron star, the city-sized cinder of an exploded star. Young magnetars blast out flares of electrons and ions. When a flare hits slower moving clouds of ions, it creates a shockwave. Electrons in the shockwave gyrate around magnetic field lines and emit a laser-like pulse of radio waves.

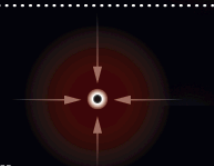


Engine room

So much is unknown about FRBs, including whether repeaters and single FRBs come from the same sources, that many possible explanations

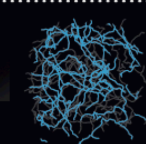


Merger
One massive object--a white dwarf, neutron star, or black hole--merging with anothercould produce a



Collapse
A neutron star collapsing into a black hole or a star made of quarks could emit a single radio

Galactic jets
Giant black holes at galactic centers emit jets. Bursts could occur when jets hit a nearby



Fault in our stars
Cosmic strings, defects in the fabric of space leftover from the big bang, could kink and

Why Synhrotron Maser for FRBs?

- One of few coherent mechanisms in plasma astrophysics
- Magnetar flares are associated with powerful blast waves (Lyubarsky 2014, Beloborodov 2017)
- However, efficiency and spectrum of emission are typically postulated and very poorly constrained by non-linear physics

Mechanism

Synchrotron maser at magnetized relativistic shocks

- Naturally produced in magnetized relativistic shocks (Gallant et al 92)

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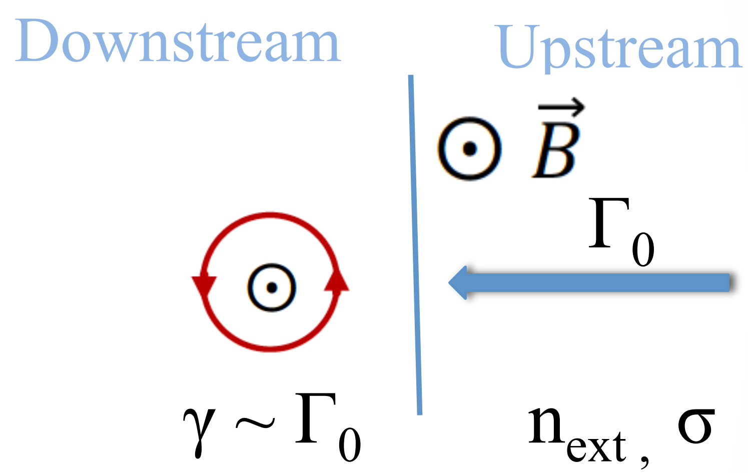

$$\sigma = \frac{B_{z,0}^2}{8\pi\gamma_0 N_0 m_e c^2}$$

Mechanism

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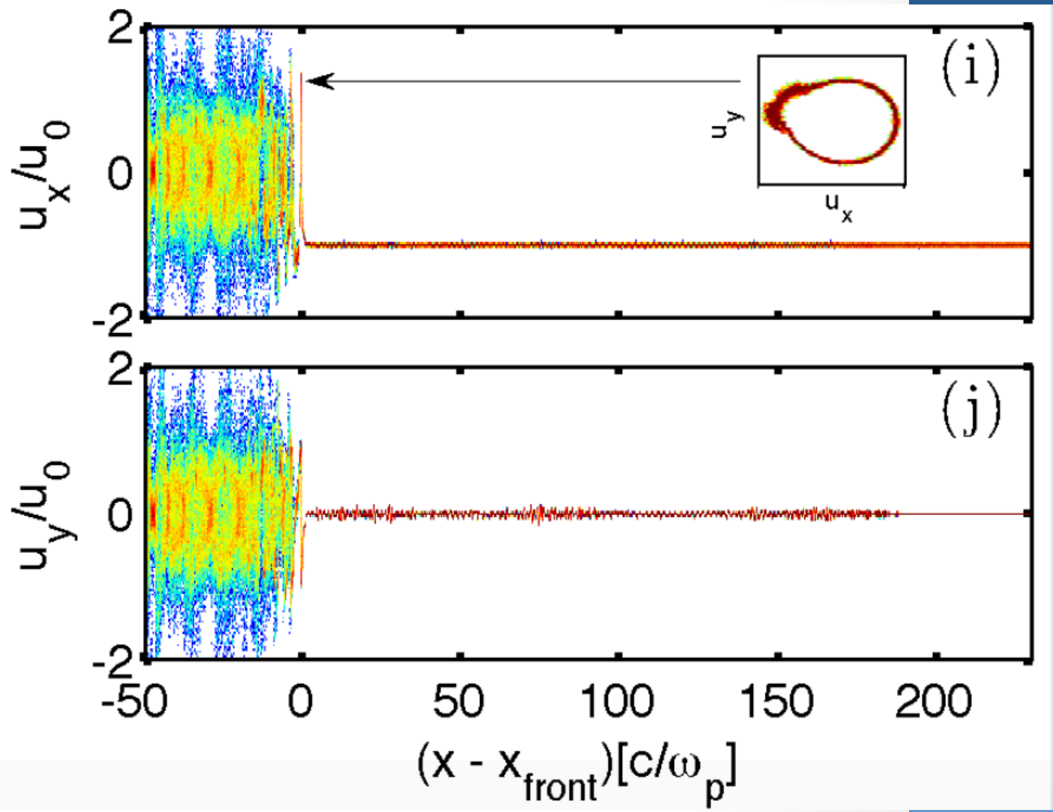
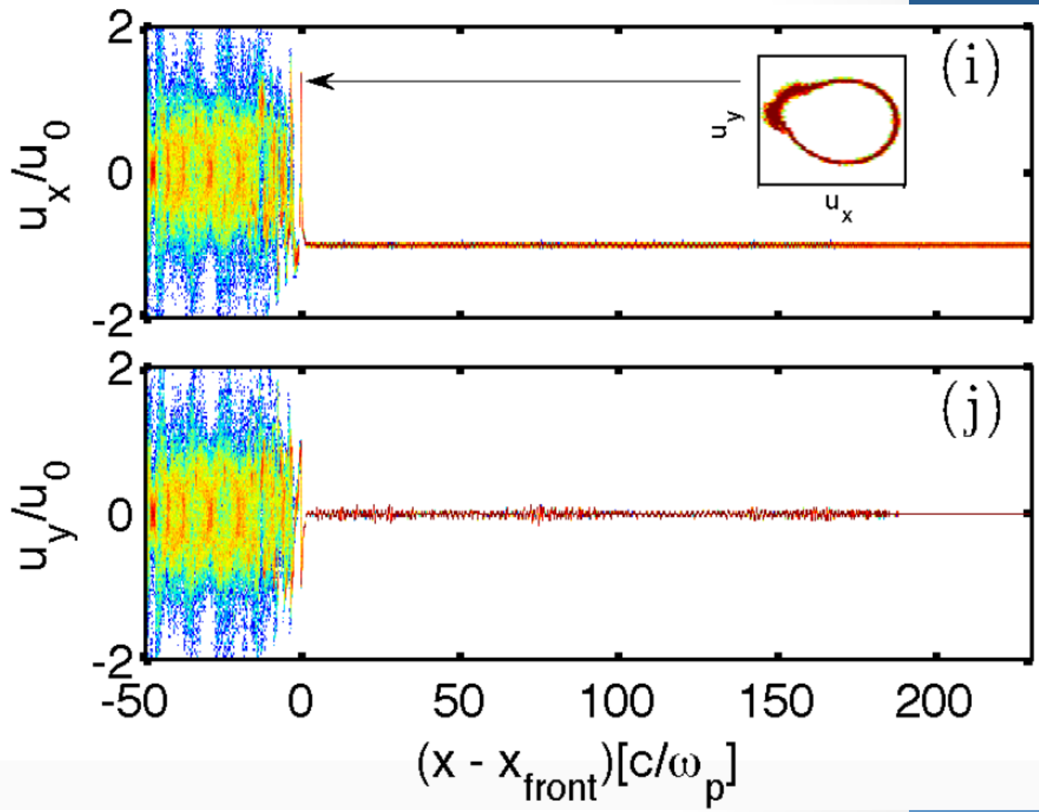


Mechanism

Synchrotron maser at magnetized relativistic shocks

- Naturally produced in magnetized relativistic shocks (Gallant et al 92)
- Inversion of population (ring-distribution) at the shock front
- Linearly polarized (X-mode wave)



1D PIC Simulations

Precursor wave train emission in high-sigma shock

Density

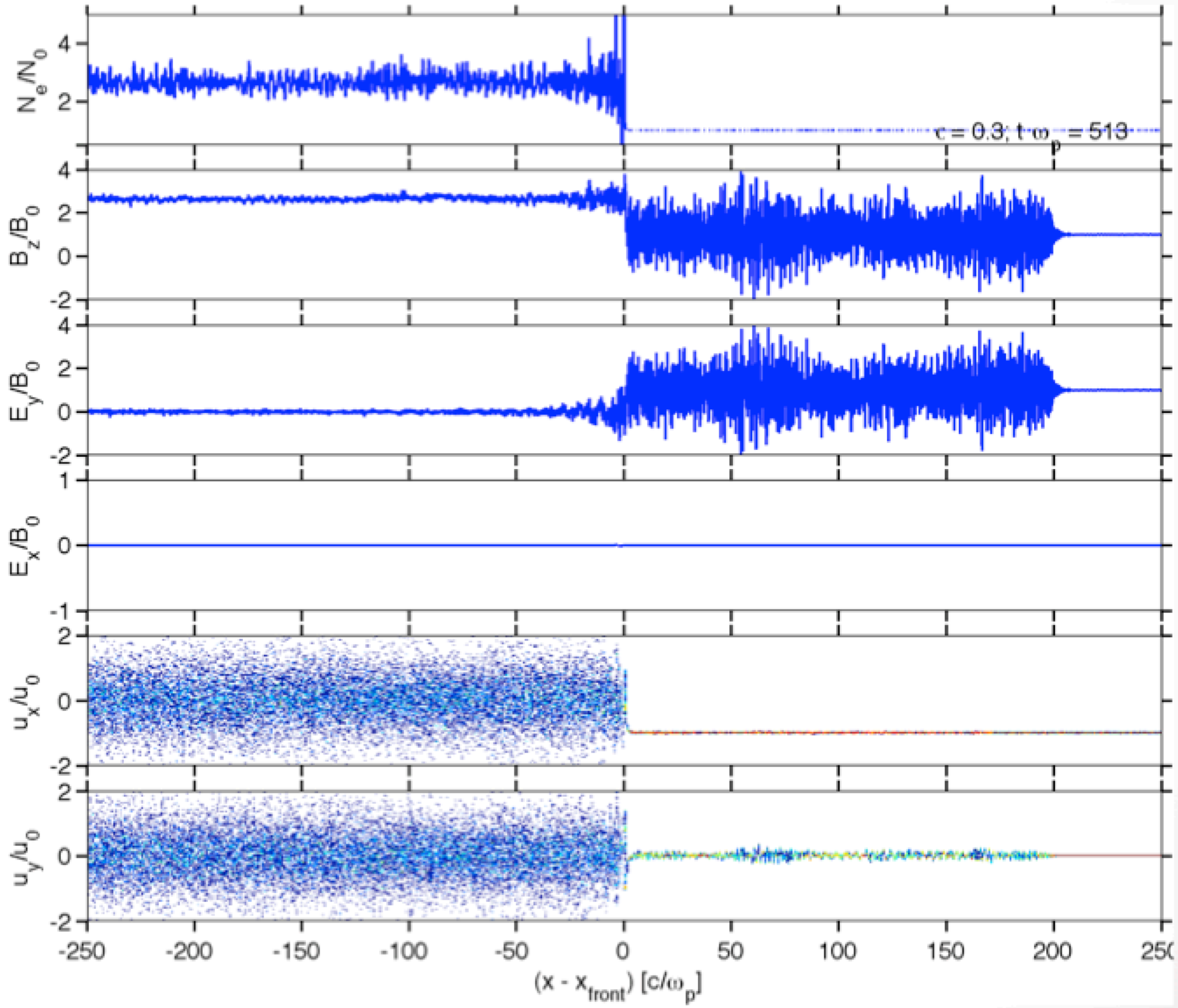
Bz

Ey

Ex

x-px

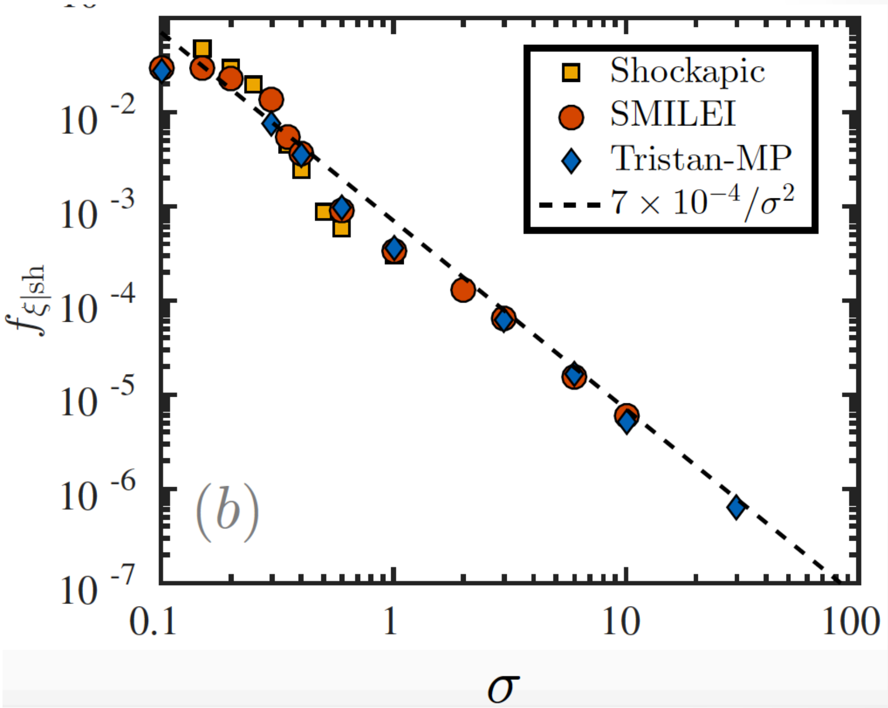
x-py



1D PIC Simulations

Wave energy vs usptream magnetization

- Low-σ : up to 3% efficiency (emitted wave energy/ incoming) Maximal at σ~0.1
- σ>>1: efficiency ~ $7\text{x}10^{-3}/\sigma^2$



The conversion is efficient for a broad range of σ

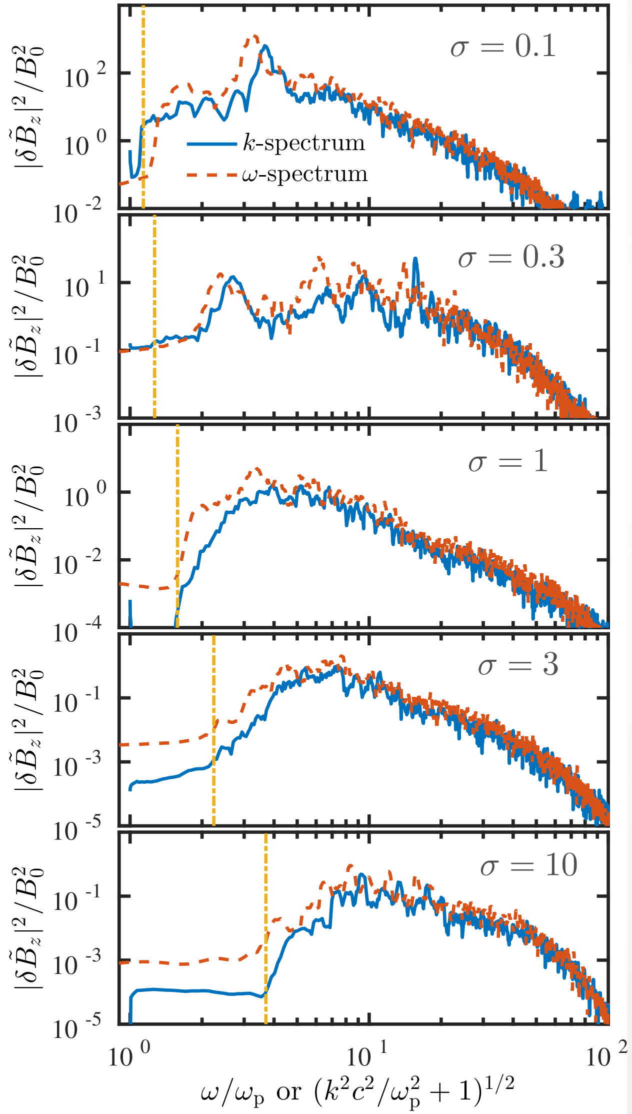
1D PIC Simulations

Emitted wave spectrum

- Large number of resonances -> non-monochromatic
- Low frequency cutoff (vertical orange lines)
- Intrinsic peak frequency in the observer frame: $\sim 3\Gamma(t)\nu_{\mathrm{p}}(t) \propto \Gamma n_{\mathrm{ext}}^{1/2}$

Set by dynamic + ext. medium

- The spectrum is narrow $\Delta\nu / \nu_{\mathrm{pk}} \sim 3$



2D and 3D simulations

2D effect -> upstream plasma heating & filamentation

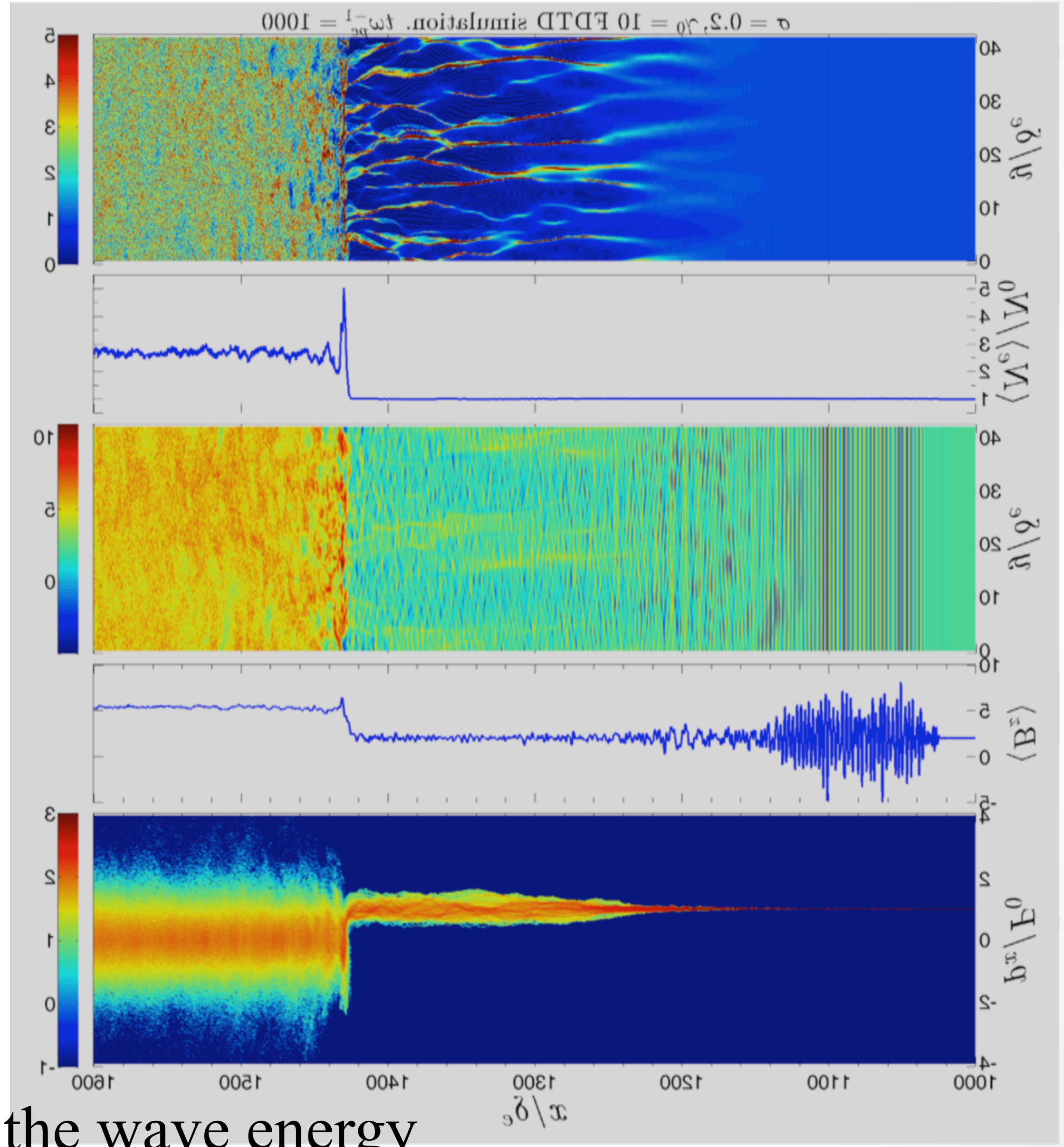
Density

<Density>

Bz

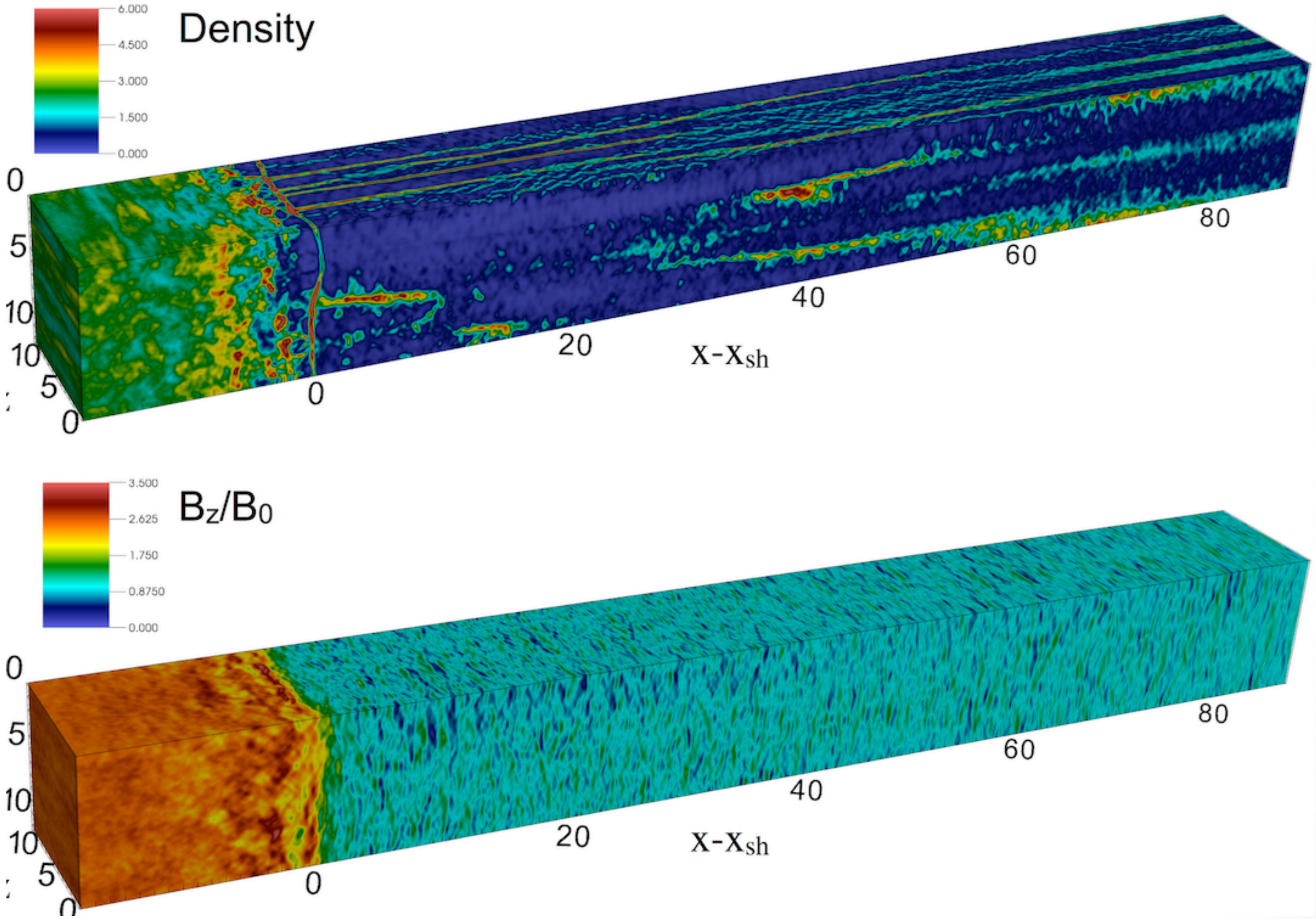
<Bz>

Phase space: x-px

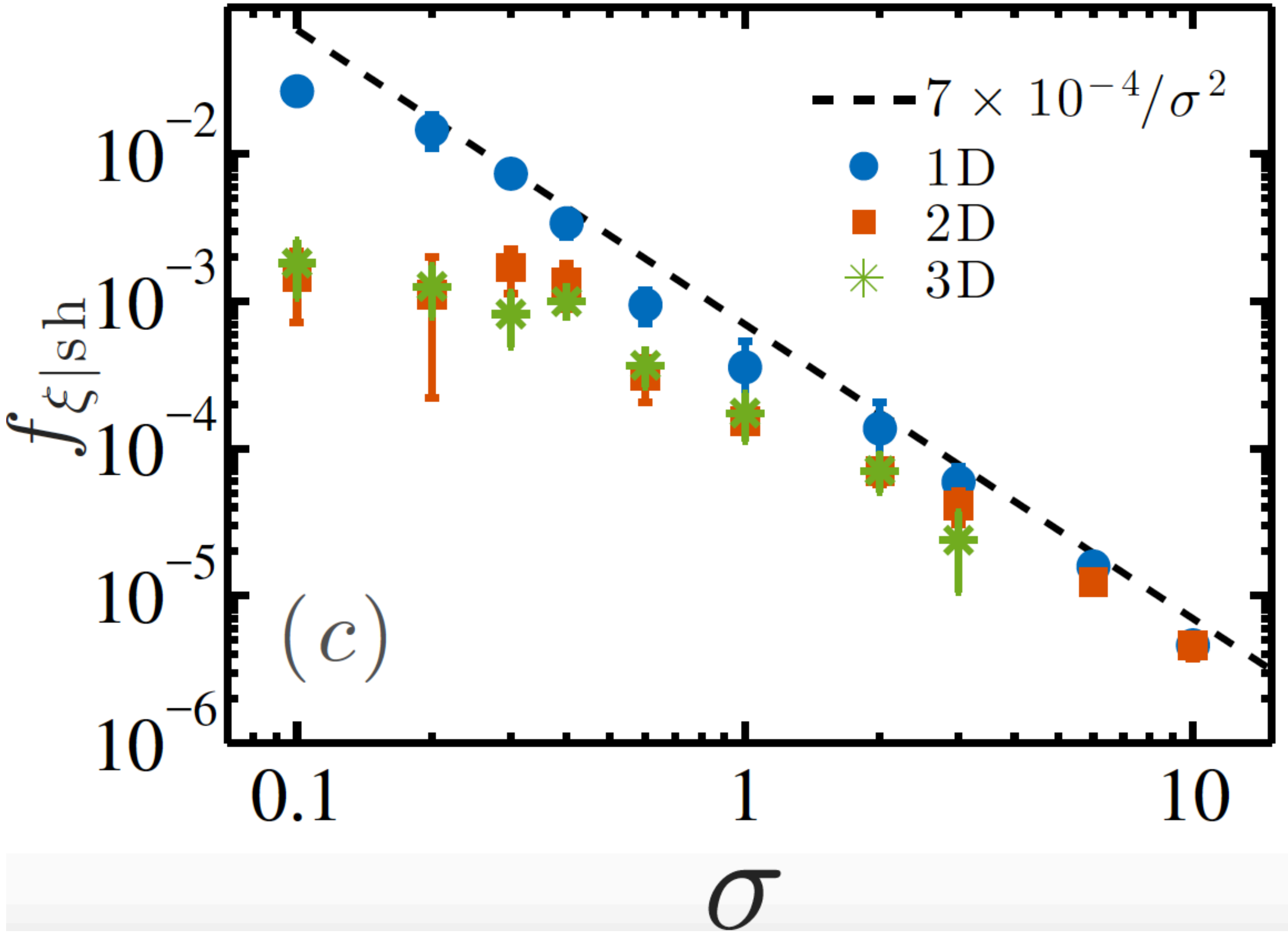


Result: reduction of the wave energy

3D very simular to 2D



2D & 3D vs 1D: wave energetics



Reduced but still reasonably high efficiency: up to 0.1%

Astrophysical application to flares in magnetars

Metzger et al, 2019, MNRAS, 458

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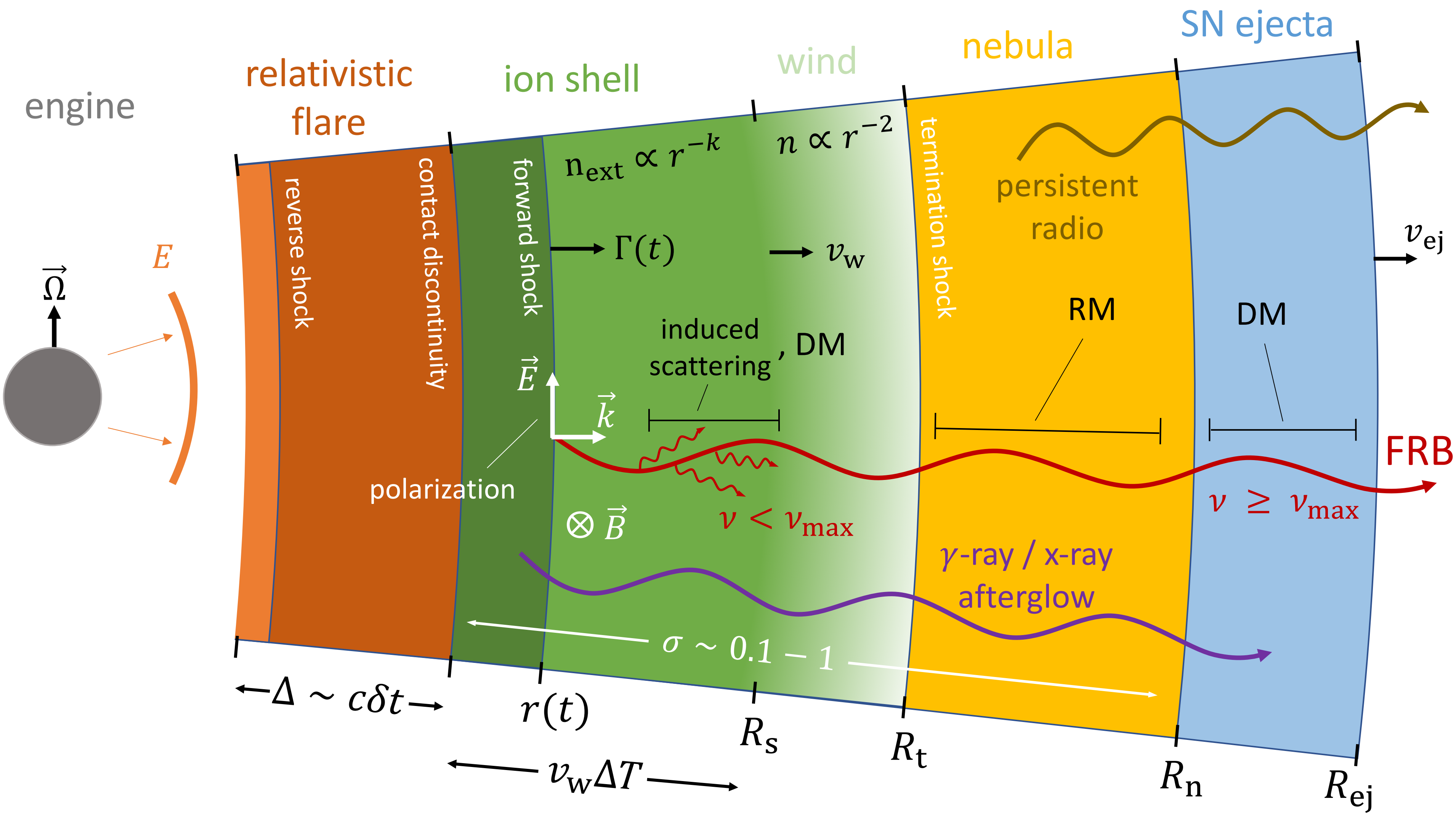
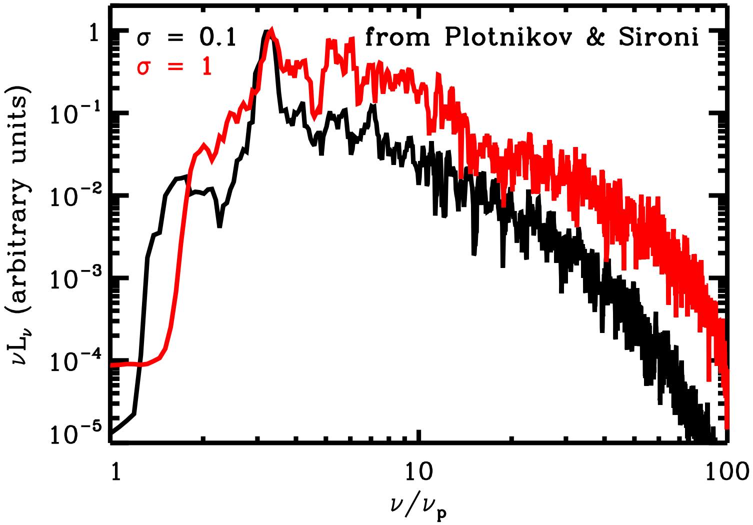


Application to flares in magnetars II

Observed spectrum may be different of the instrinsic:

Intrinsic

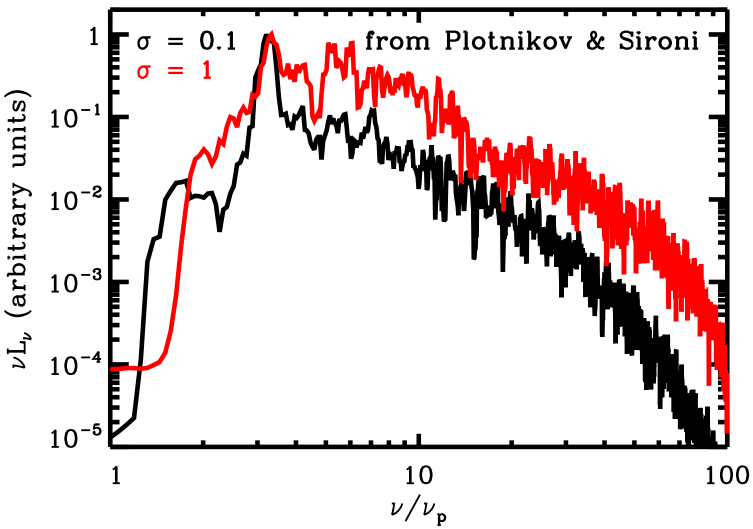


Application to flares in magnetars II

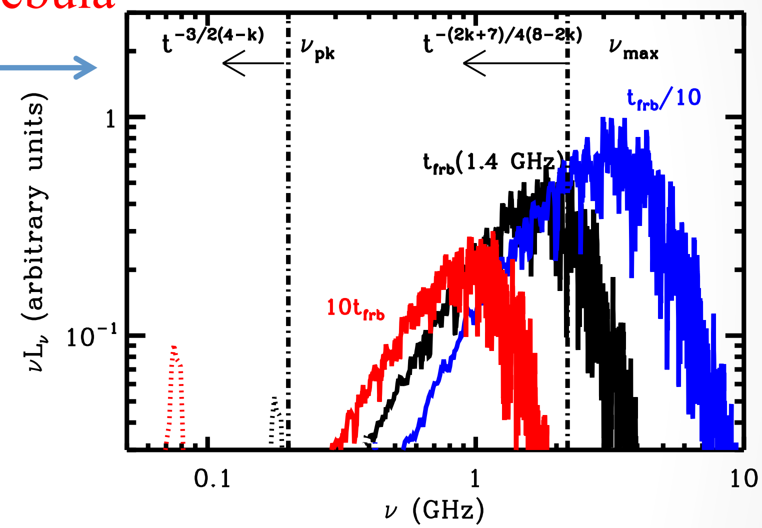
Observed spectrum may be different of the instrinsic:

Blast decel. +
Damped
in the nebula

Intrinsic



Escaping



- Observed frequency set by intrinsic + external medium

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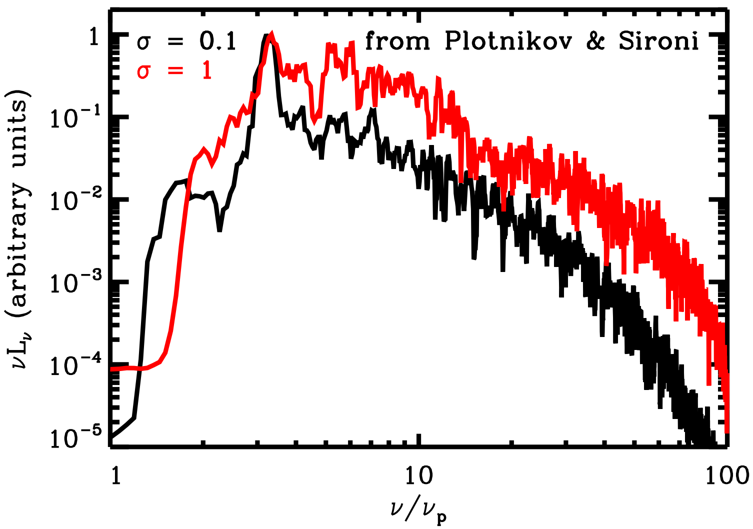

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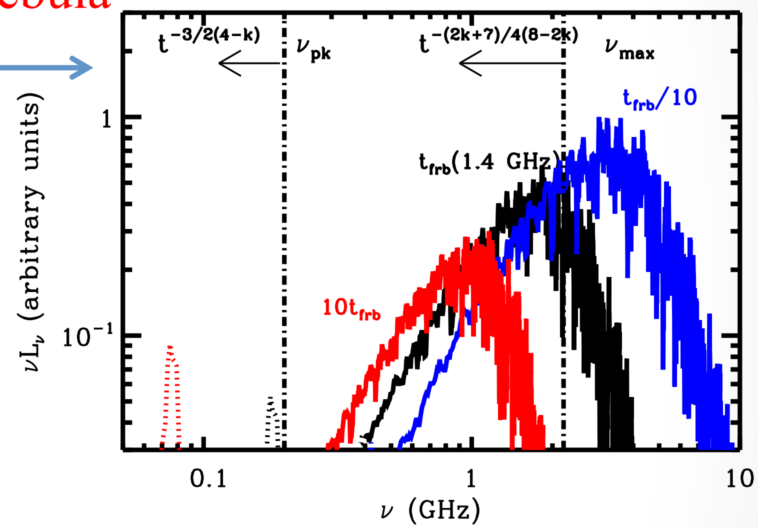

- Observed frequency set by intrinsic + external medium
- Explains downward ‘drift’ of peak frequency in time.

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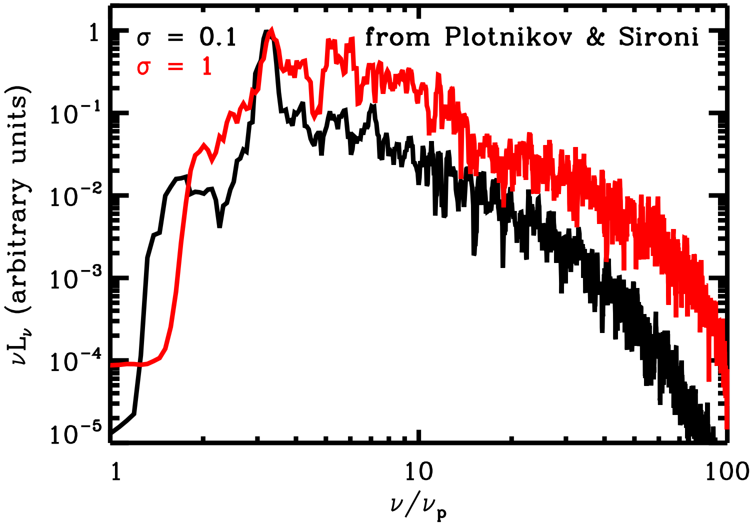

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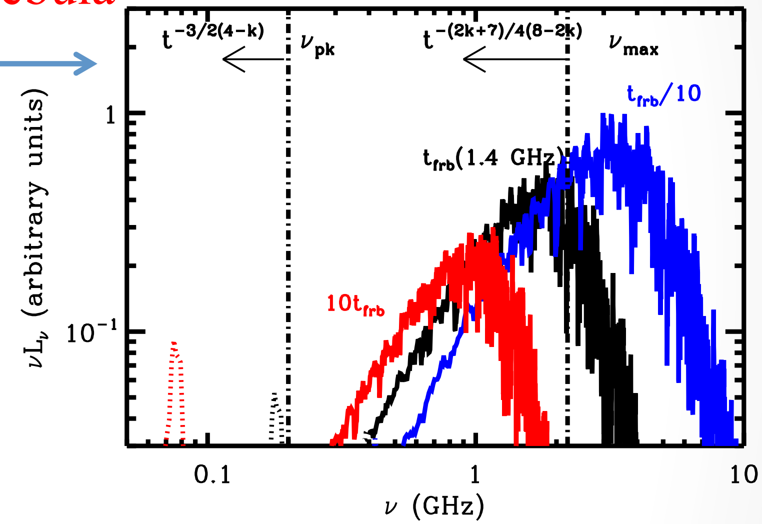


- Observed frequency set by intrinsic + external medium
- Explains downward 'drift' of peak frequency in time.
- Provides 'naturally' ~GHz frequency

$$\nu_{\max} \approx 1.7\ \mathrm{GHz}\ f_{\xi,-2}^{1/4} E_{43}^{5/32} \dot{M}_{21}^{15/32} \left(\frac{\beta_w}{0.5}\right)^{-45/32} \Delta T_5^{-27/32} t_{-3}^{-7/32}$$

Summary

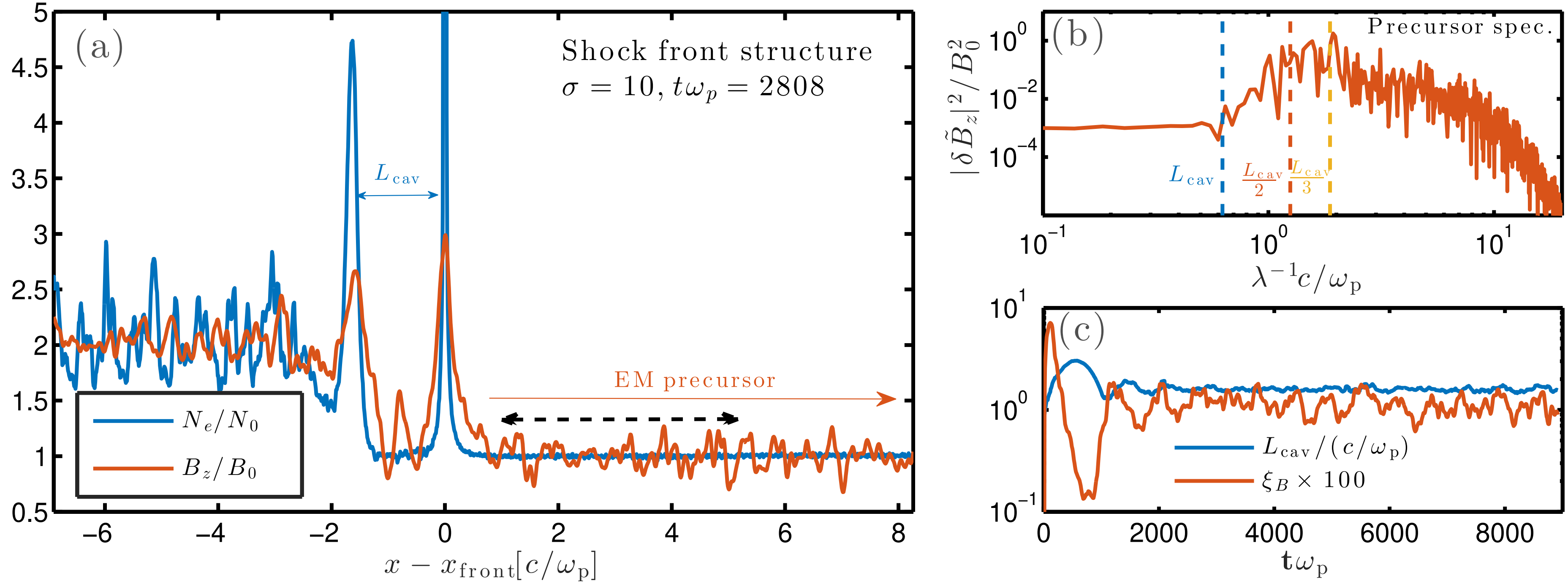
FRBs as maser emission from shocks in magnetar flares

Lyubarsky, 2014, Beloborodov, 2017
Plotnikoov & Sironi, 2019, MNRAS, 458
Metzger et al, 2019, MNRAS, 458

- Synchrotron maser emission is a viable FRB emission mechanism (*but not the only*)
- Naturally produces coherent, high brightness temperature, linearly polarized wave. Falls into GHz band under reasonable assumptions.
- Accounts for most features of two known repeater FRBs

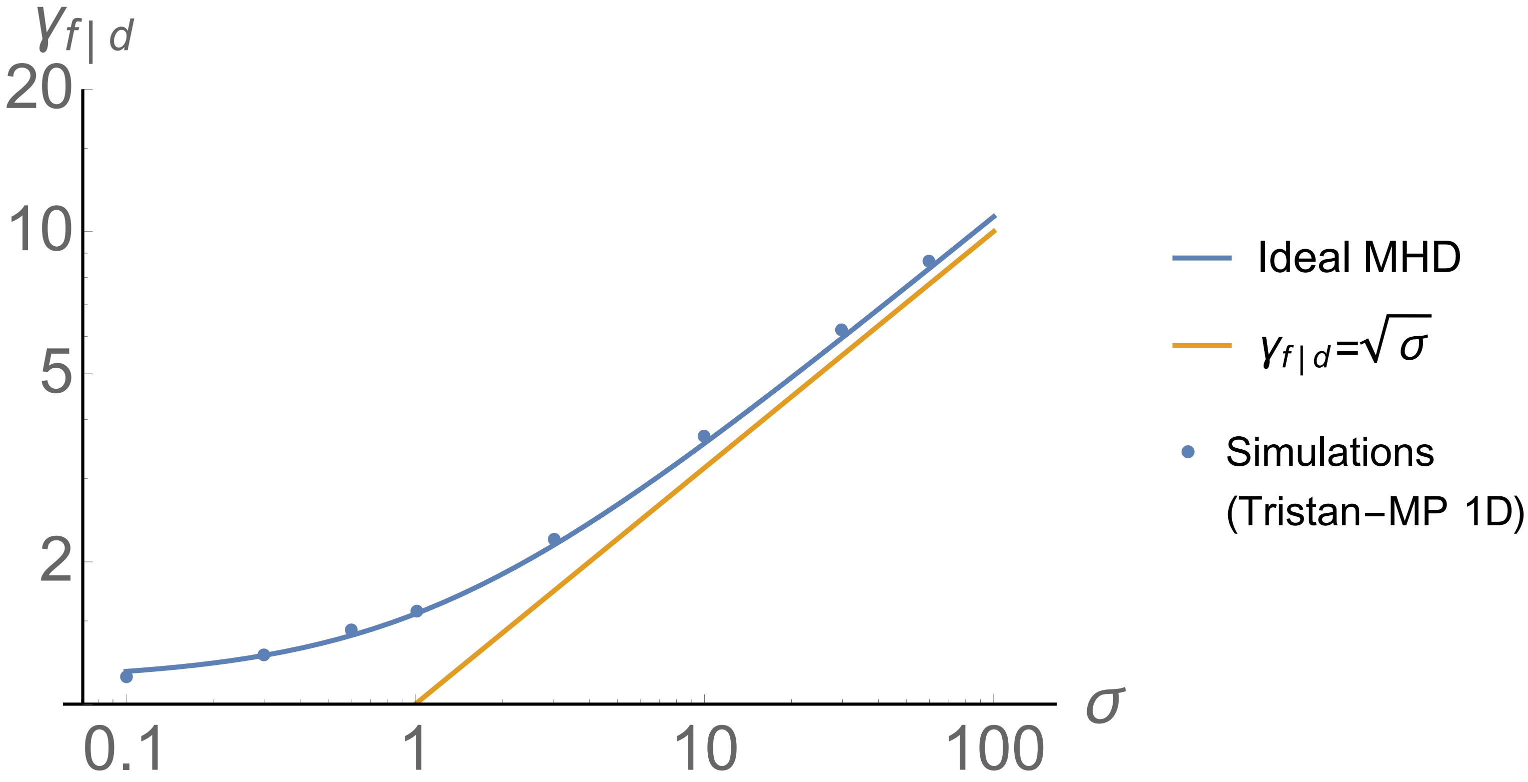
Supplements

Cavity in the shock structure



Rankine-Hugoniot reproduced?

Lorentz factor of the shock front = f(sigma):



Yes, to a good precision…
but small differences due to the wave turbulence
(especially around sigma=0.1)