Terrestrial low-frequency bursts: Escape paths of radio waves through the bow shock

A fascinating investigation

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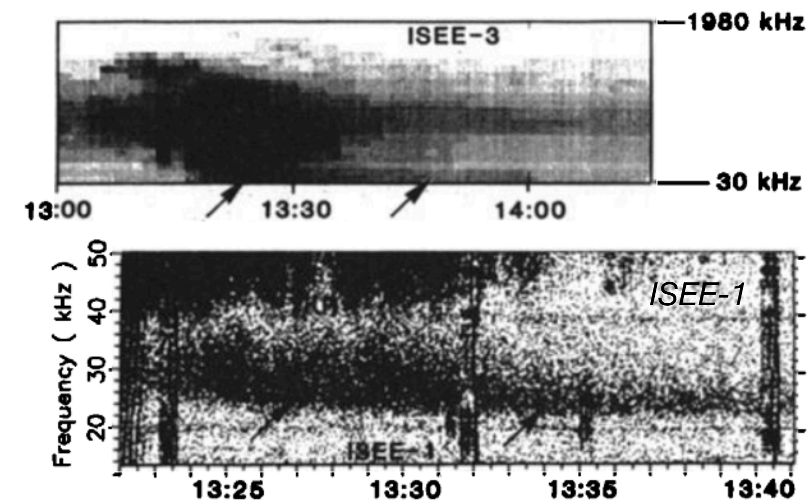
Planetary and Space Science, 52, 643–660, 2004

**and JLS's last paper*

Context

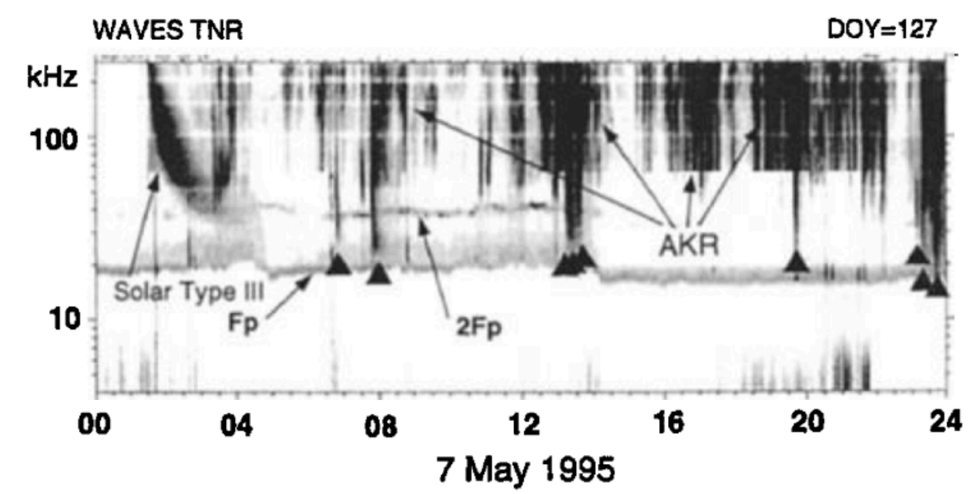
- ITKR : the isotropic terrestrial kilometric radiation

[Steinberg, Lacombe, Hoang, GRL 1988]



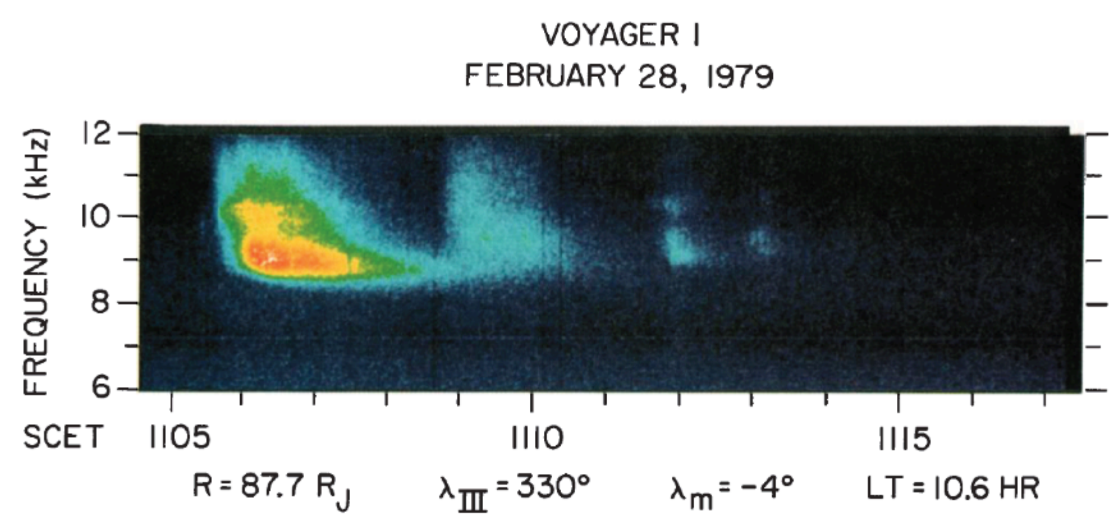
- LF bursts

[Kaiser et al., GRL 1996; Desch et al., GRL 1996]



- Jovian type III bursts / QP bursts

[Kurth et al., JGR 1989; MacDowall et al., PSS 1993]

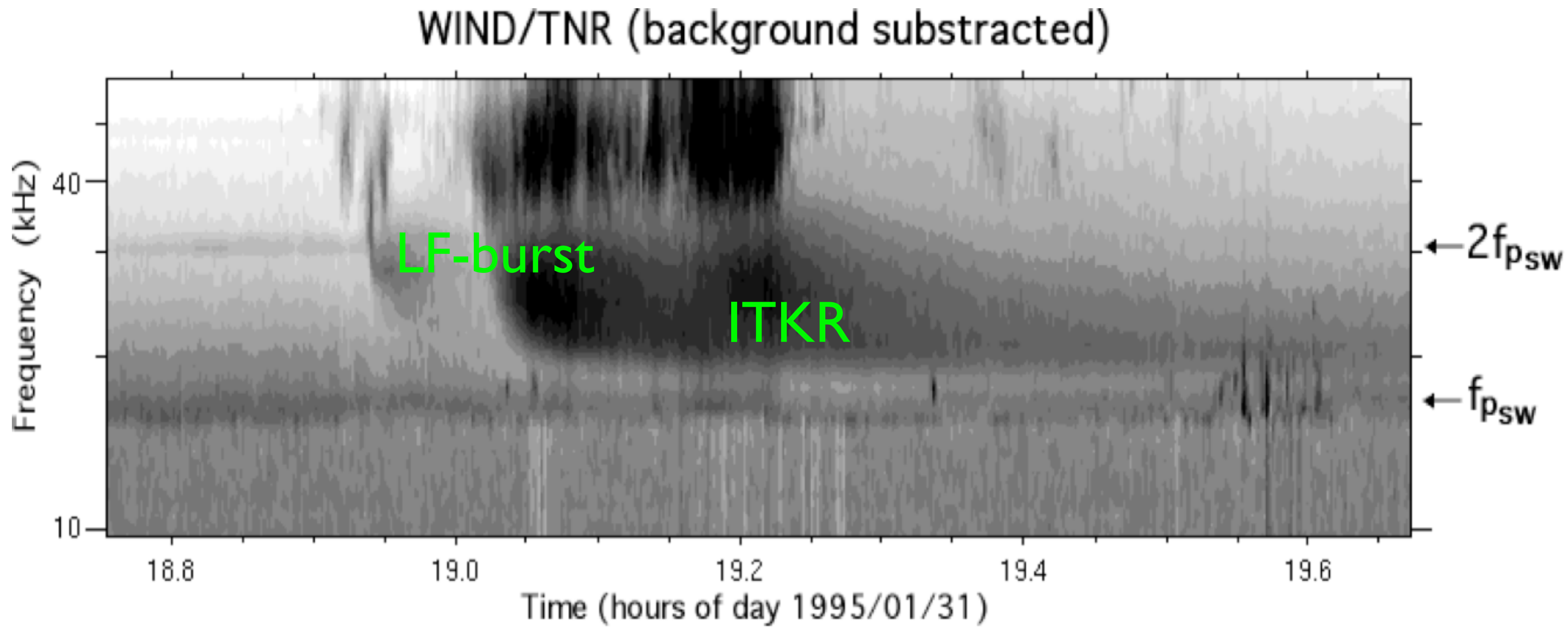


Context

- Correlated with AKR (substorms, SW speed & IMF, auroral source near Earth)
- AKR LF cutoff at 2 f_{psw} = BS nose ↔ LF burst / ITKR < 2 f_{psw}
- $P_{LF\ burst}$ ~ 500 kW = a few % of AKR power
- LF burst origin : Sporadic electron acceleration/injections ? (reconnection ? tail ?...)

- LF burst: small source (a few °) [Kaiser et al., GRL 1996]

  \+ long diffuse tail ~isotropic (ITKR)



⇒ tailward propagation to/from/through the Mtail ?

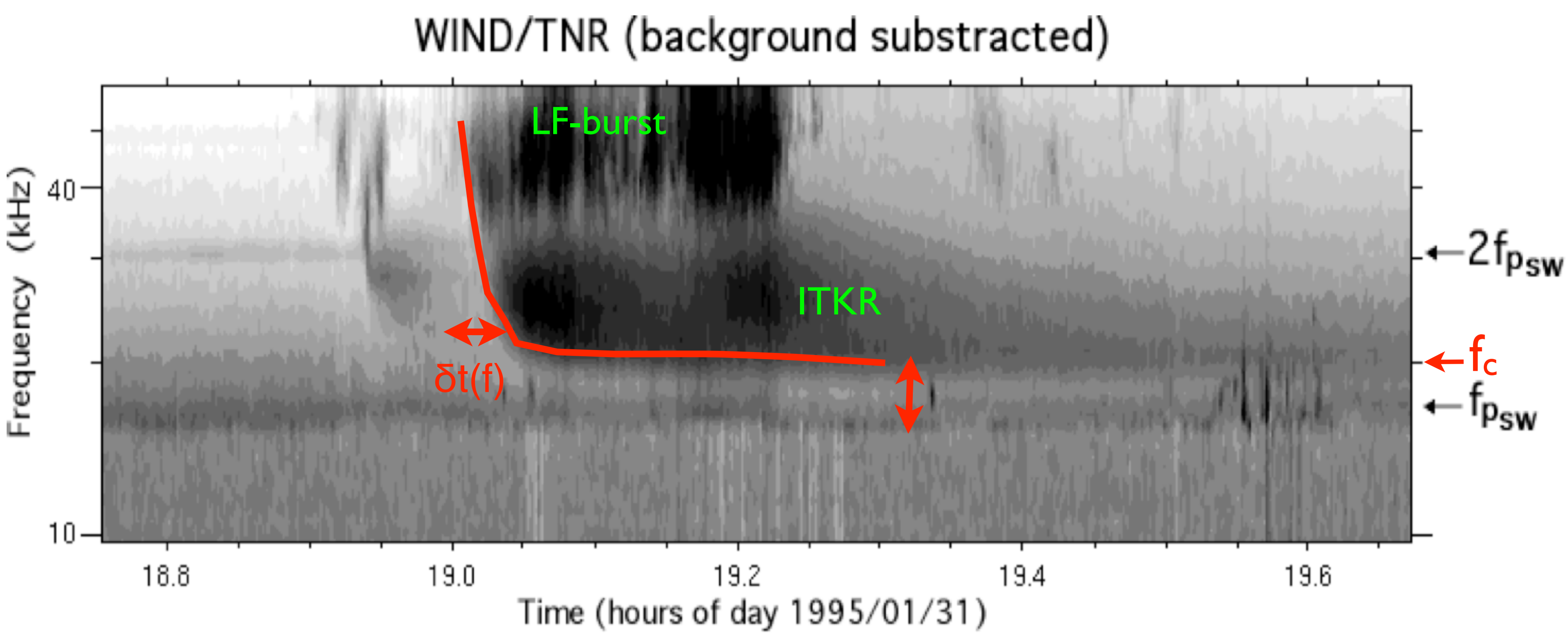
in Msheath [Desch & Farrell, 2000] ? but requires $V < V_g$

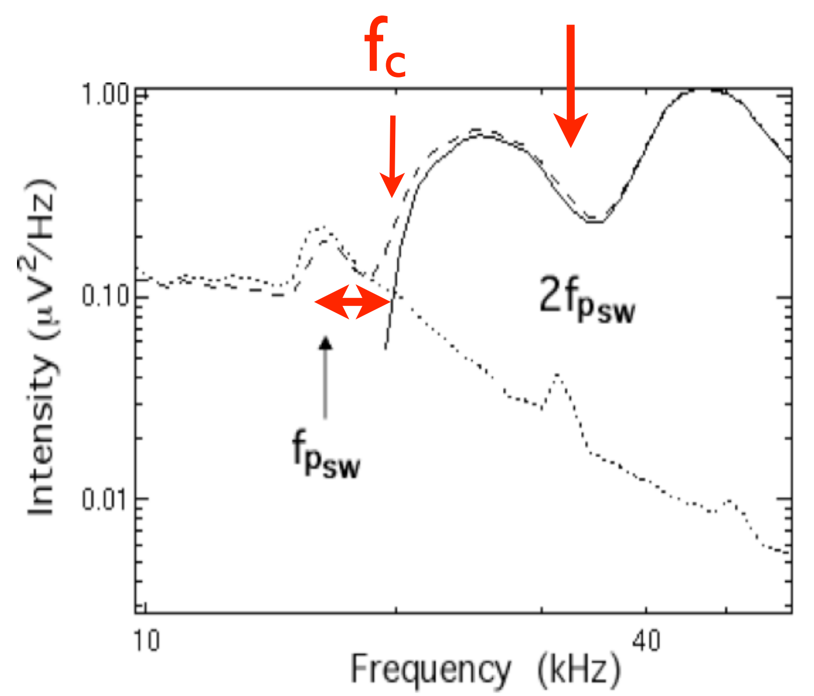
MS escape far downstream (100's R_E) ?

The Study

- 119 bursts analyzed in Wind/Waves observations near L1 (60-200 R_E upstream of Earth) 12/1994 - 5/1995

- Spectrum from 2 f_{psw} down to $f_c > f_{psw}$ (f_c strongly correlated to f_{psw} ⇒ propagation-related)





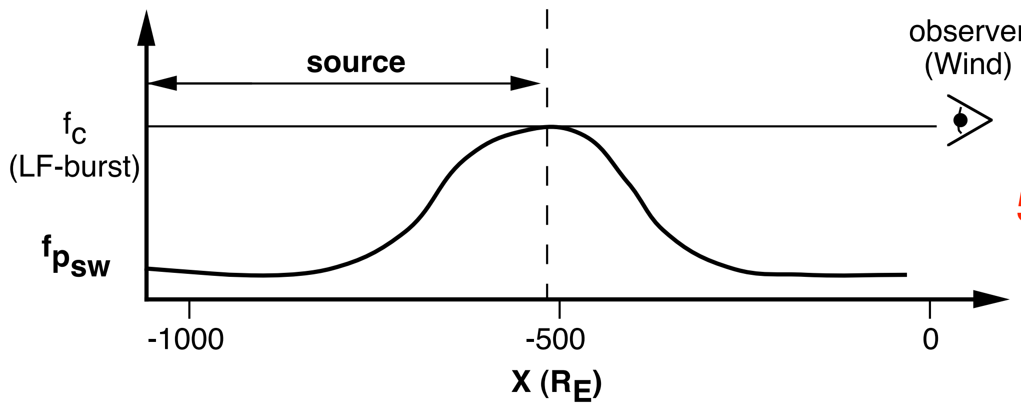
Questions

- Why $f_c > f_{psw}$? (average ~ 1.28 f_{psw})
- δt(f) ? (minutes)
- Spectral dip at ~2 f_{psw} ?

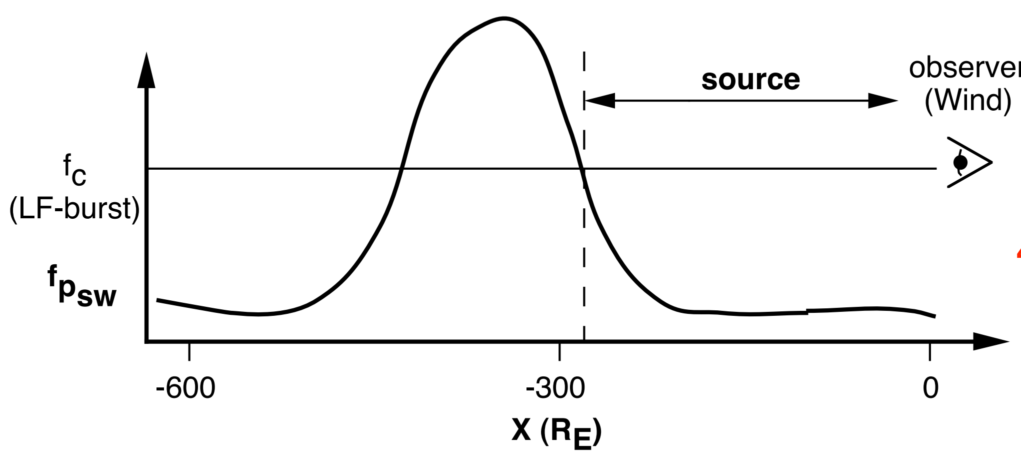
Results (1)

- SW parameters (t) measured every 6 minutes ⇒ projected at Earth

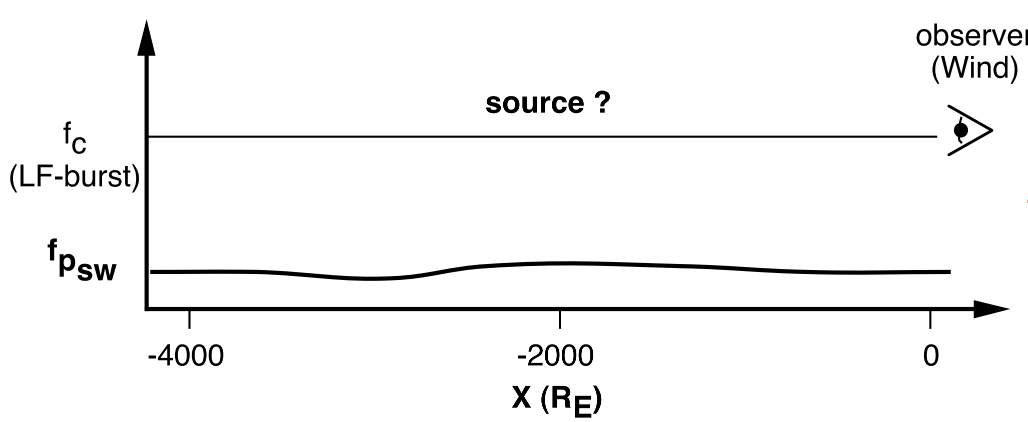
  ⇒ generally no SW overdensity ≥ f_c



5 cases



4 cases



110 cases

Model (1)

- **Geometrical model for the Earth's bow shock:**

  hyperboloid of revolution

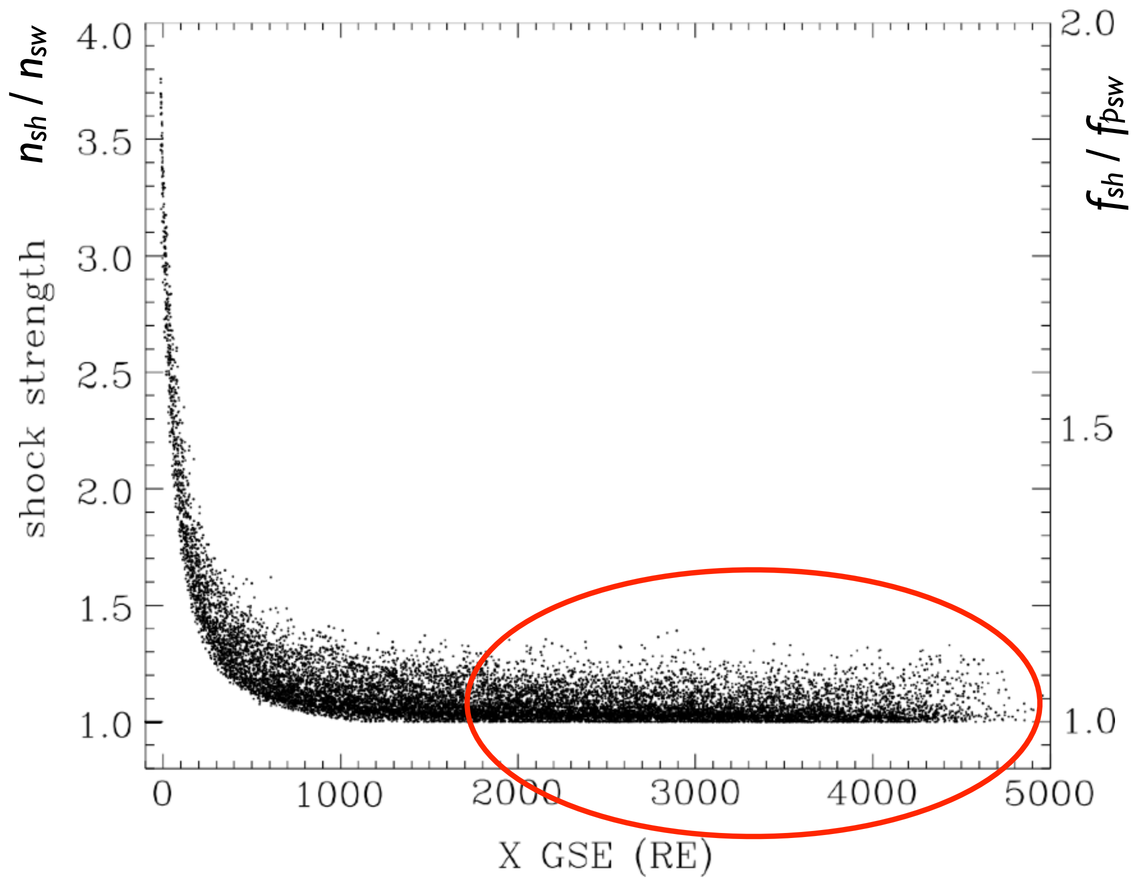
  asymptote = fast mode Mach cone of aperture **α** ($\sin \alpha = 1/M_f$)

  + orbital aberration

⇒ α and orientation depend on SW parameters (N_e, β)

⇒ θ_{BN} vary around & along shock, N_e jump from Rankine-Hugoniot relations

= **GM3** (Greenstadt, Mach, 3D) model



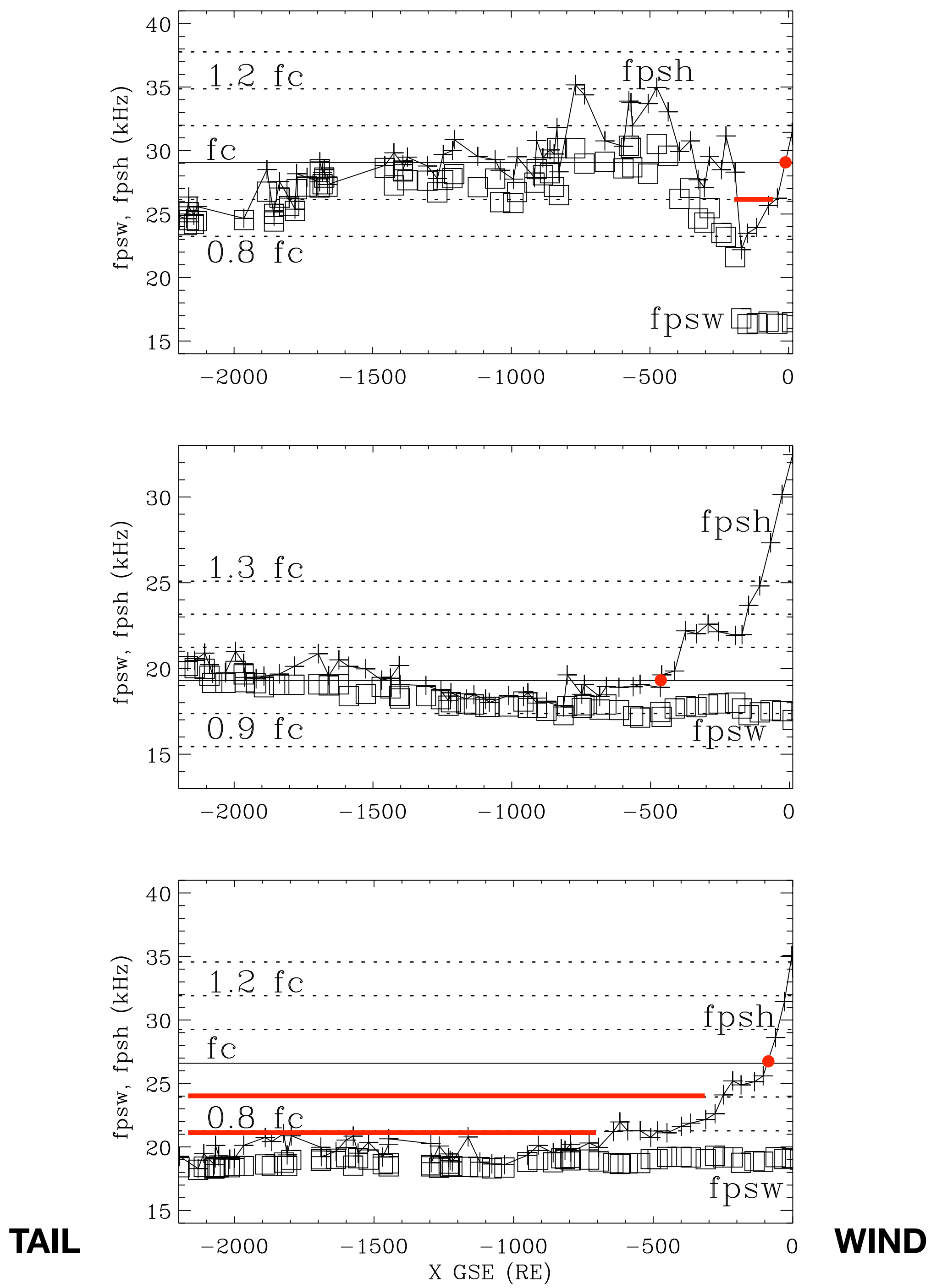
Results (2)

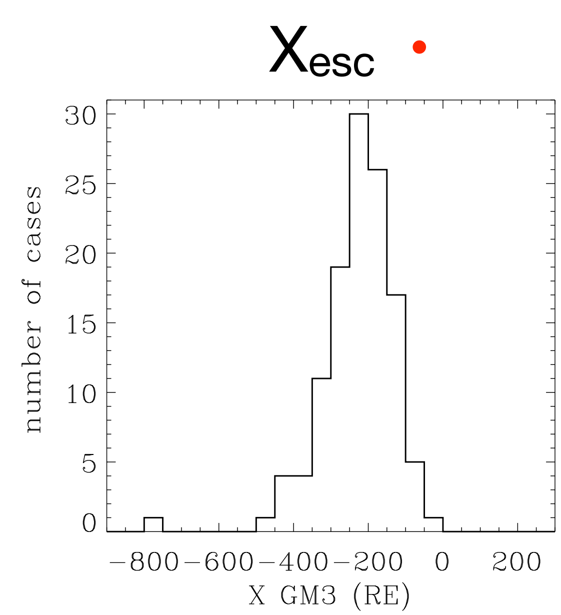
- GM3 BS : shape, orientation, N_e jump for each observed LF burst

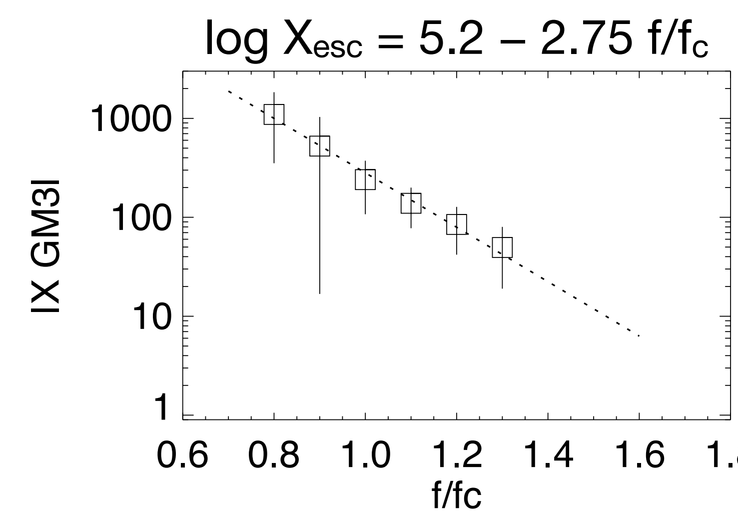
  ⇒ f_{psh} down to 2000-5000 R_E downstream, for each event

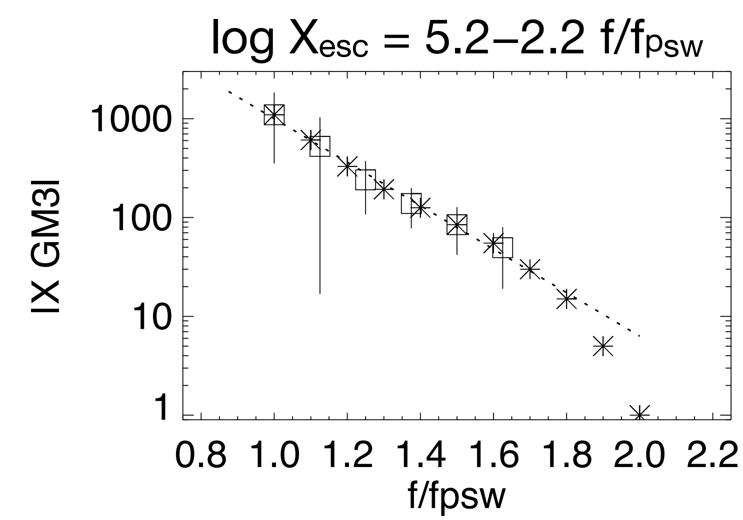
  ⇒ X_{esc} where $f_c \geq f_{psh}$, ~100-500 R_E , increases exponentially vs. f/f_{psw} and f/f_c

  ⇒ but this cannot explain the cutoff at f_c rather than e.g. 0.9 f_c or 0.8 f_c









Model (2)

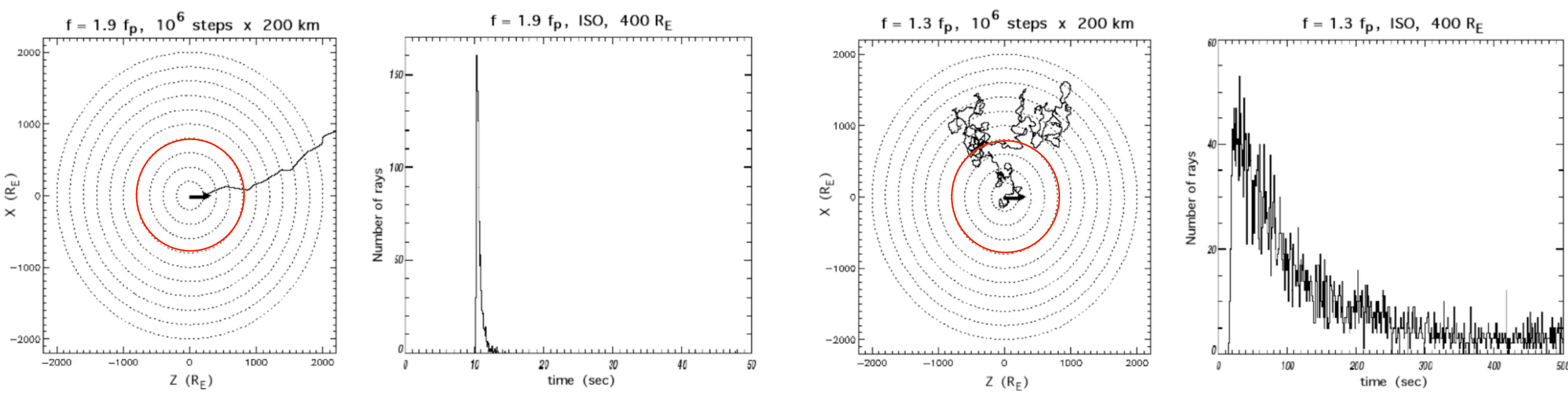
- **Ray-tracing in a scattering homogeneous plasma**

  Weak SW N_e gradient ⇒ locally homogeneous (N_e, δN_e)

  Scattering by $\Delta\theta^2 = b(f)\,\Delta S$ (scattering coeff. b(f) [Lacombe et al., AnG 1997], ΔS=200 km

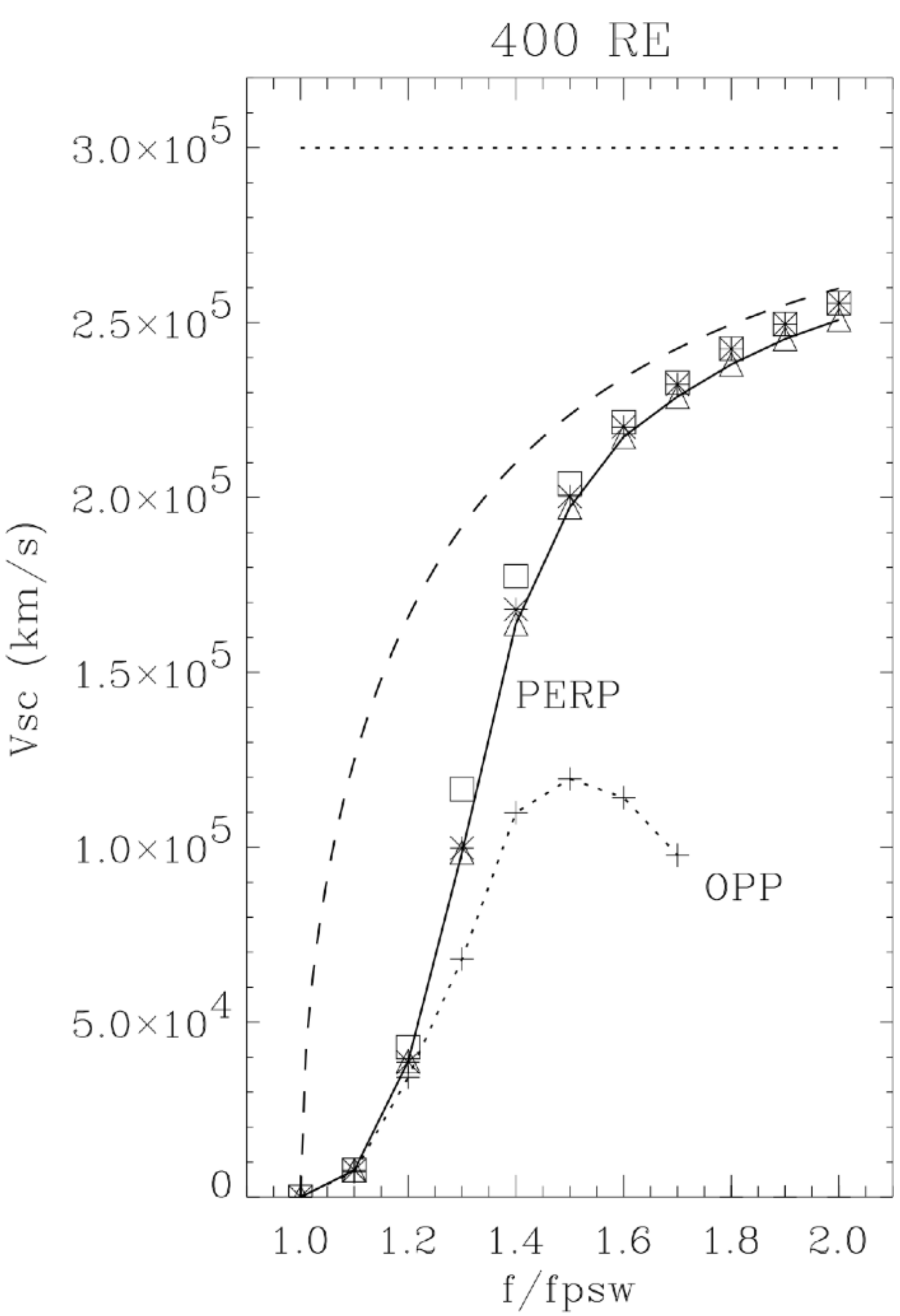
  1000 rays launched at 1.1–2 × f_{psw}, 1–2.5 10^6 steps each = 3–8 10^4 R_E
  ($\Delta\theta,\phi$) at each step ⇒ frame translated + rotated ($\Delta S,\Delta\theta,\phi$)

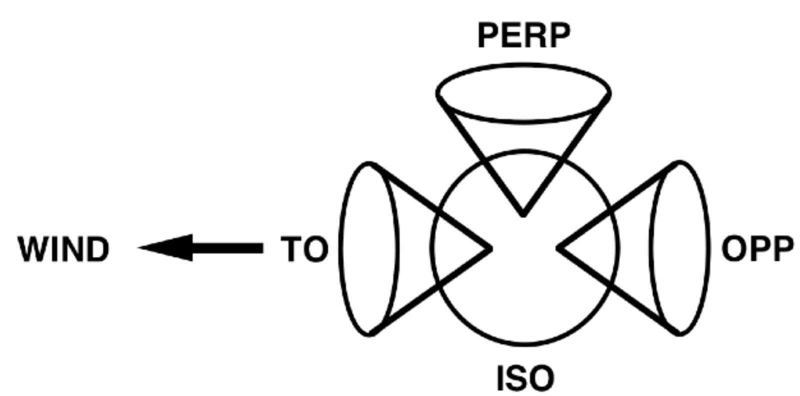
  At each step: R, direction(θ,ϕ), time $t=s/V_g$ ($s=k.\Delta S$, $V_g=c\mu$)
  N_{rays} counted at 200-2000 R_E vs. frequency (lost at R≥3000 R_E)

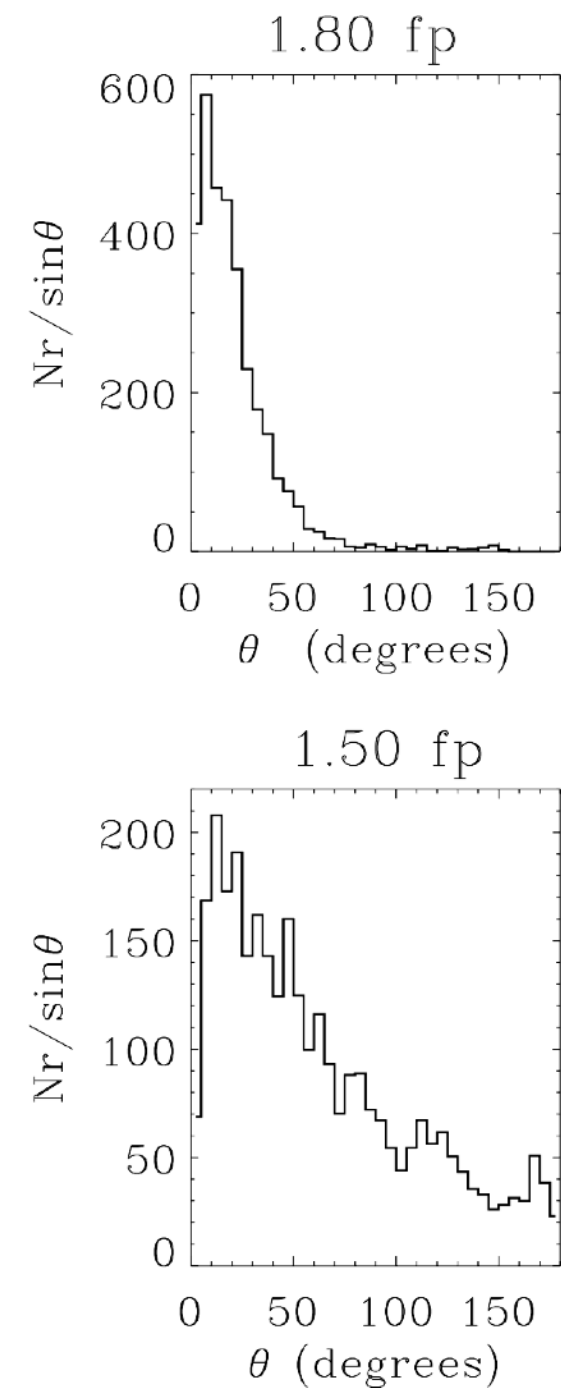


Model (2)

- V_{sc}(scattered rays) = t(5% rays reach R)
  ⇒ decreases with f/f_{psw} & when R,t increases
- Angular distribution ⇒ isotropisation with decreasing f/f_{psw} & increasing R,t





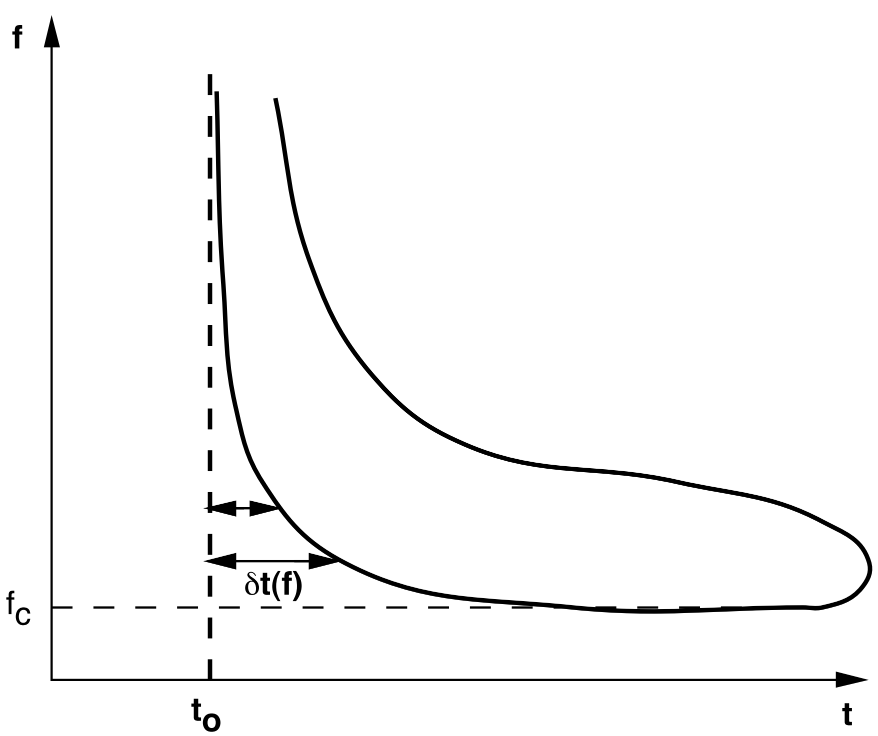


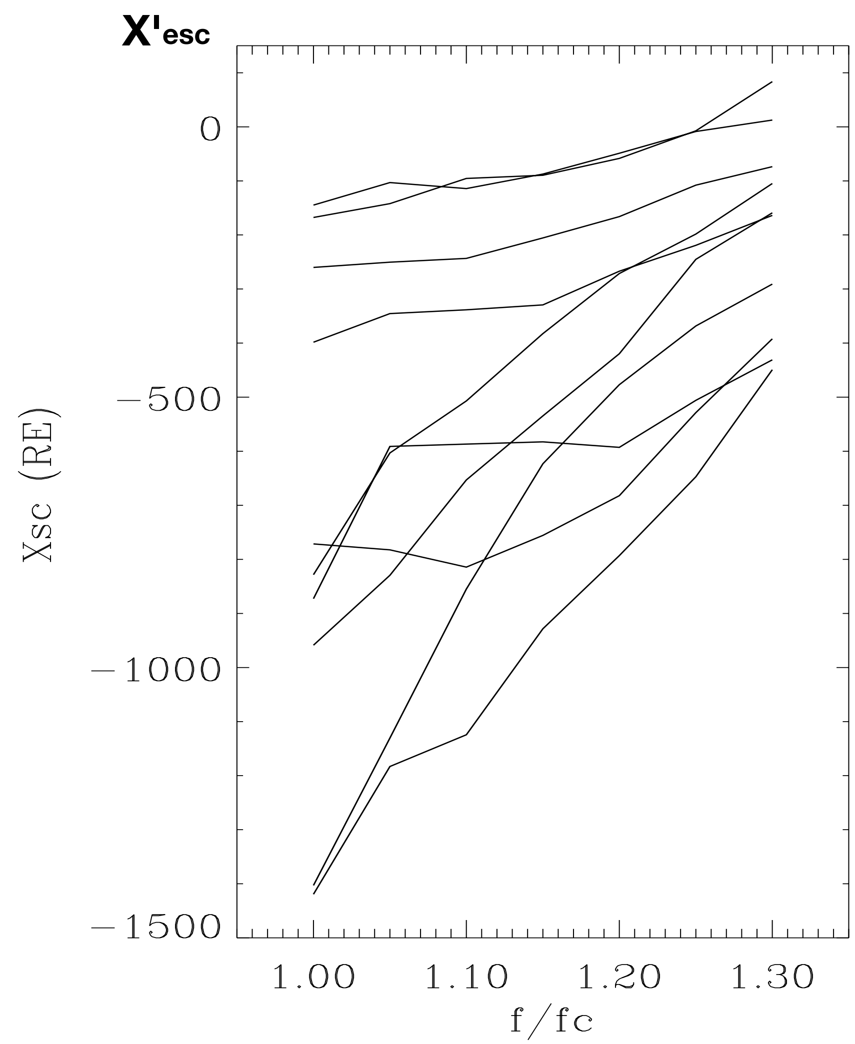
Results (3)

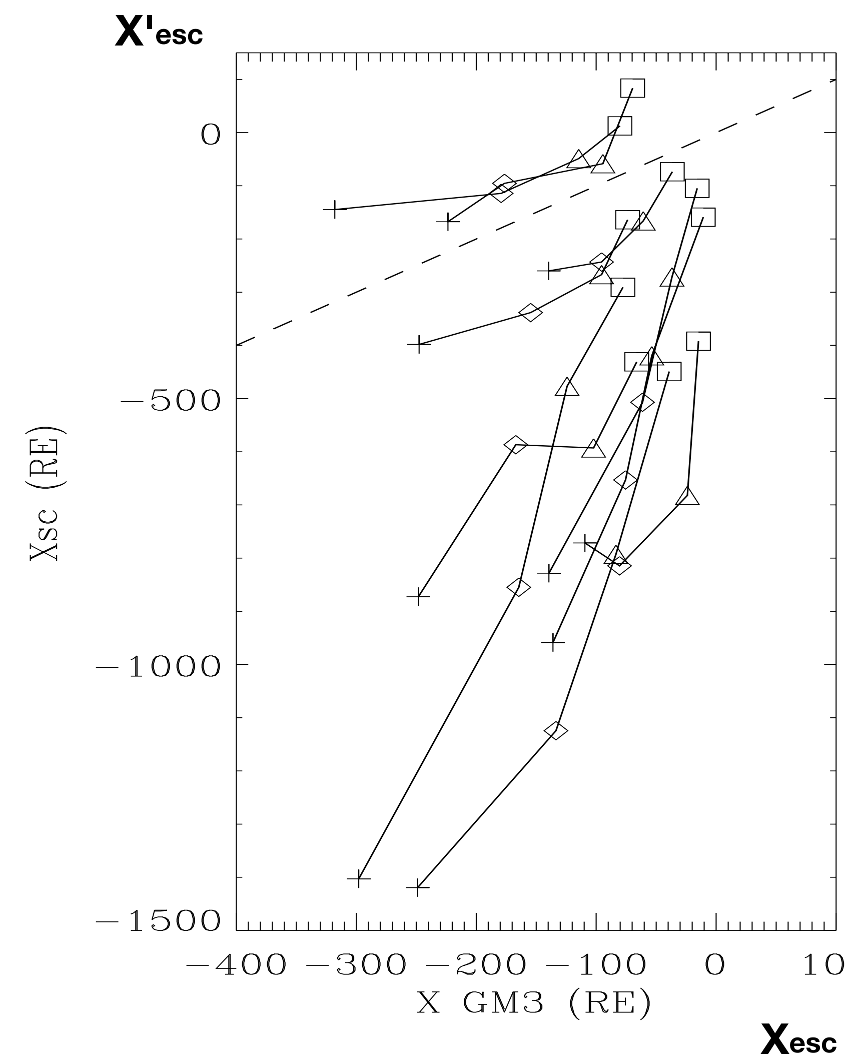
- Scattering in SW or Msheath (locally homogeneous) ⇒ V_{sc} decreases with f/f_{psw}
- Propagation through MS(wave guide) + MSheath & SW (scattering, ~)

  ⇒ observed $\delta t(f/f_{psw})$ → X'_{esc} (independent of shock model) > X_{esc}

(same trend ⇒ possible to reconcile them via b(f)↑, V_{sc}↓, GM3 profile (X_{esc}↑, N_e jump↑), Msheath guides waves downtail)



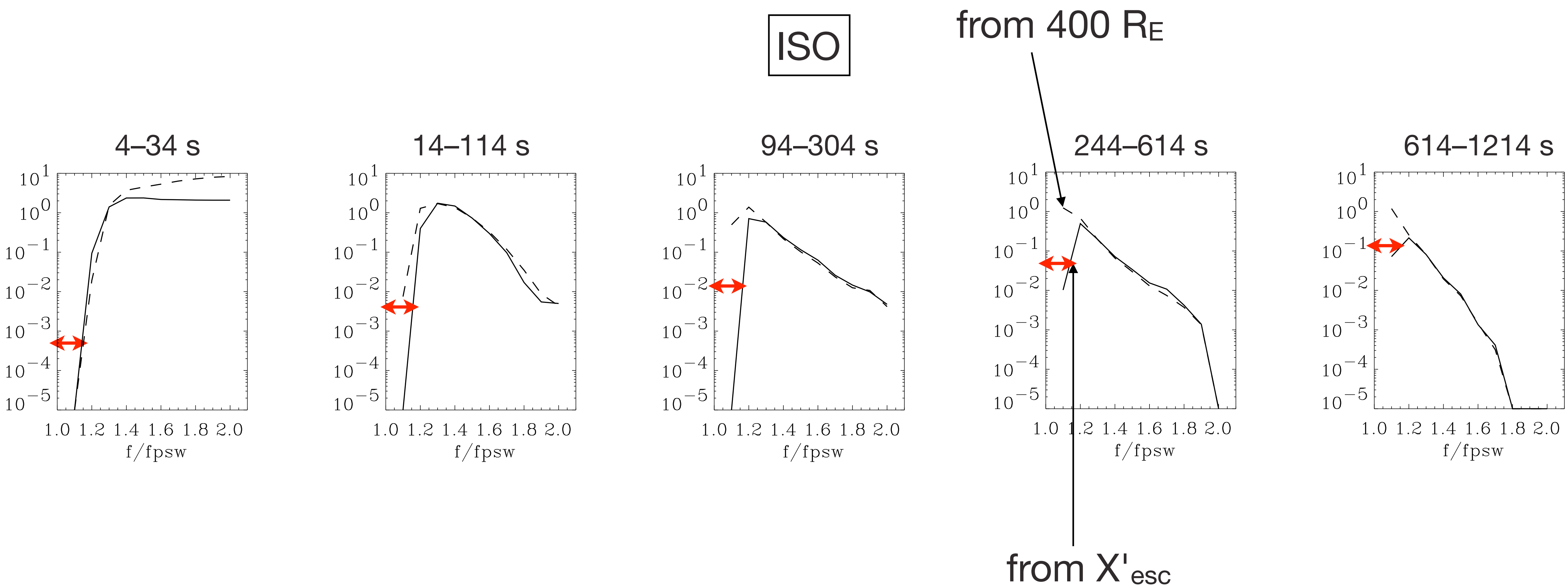




Results (3)

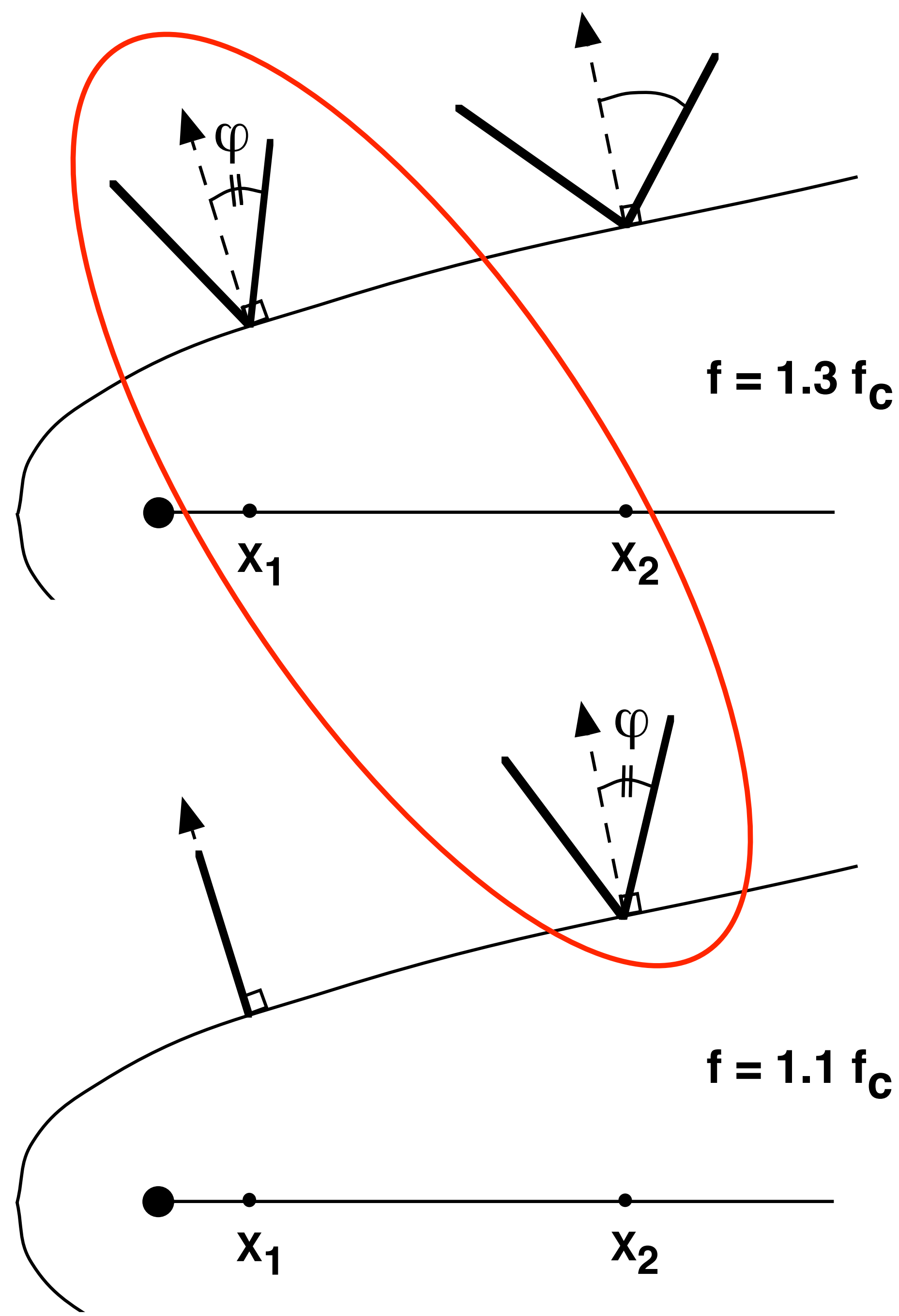
- Exponential increase of X'_{esc} + scattering ⇒ explains cutoff at $f_c > f_{psw}$ (rather than $< f_c$)

at e.g. 0.9 f_c ⇒ X'_{esc}↑, V_{sc}↓, δt↑ ⇒ time dilution + $1/R^2$ intensity decrease ⇒ signal undetectable



Results (4)

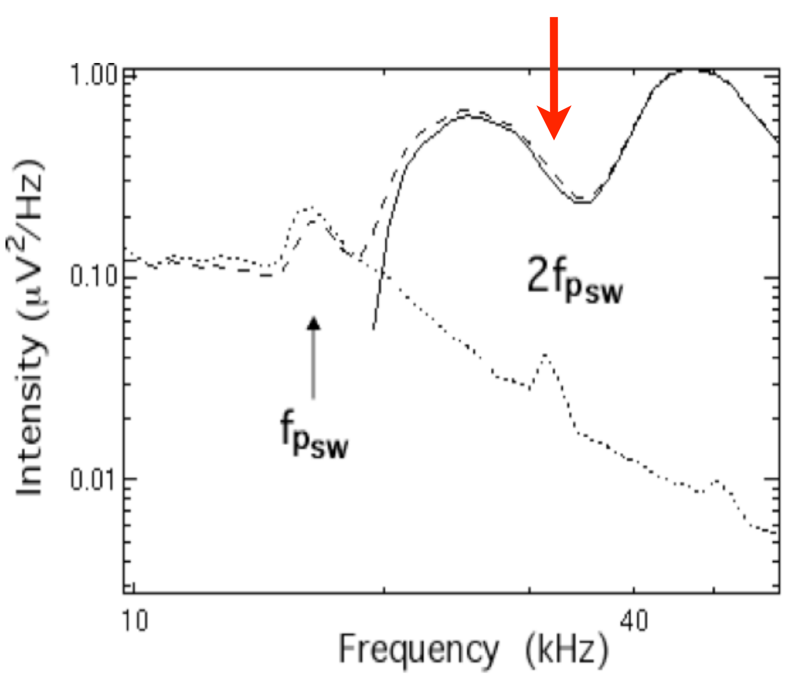
- Density jump at BS : Snell-Descartes law
  ⇒ exit cone ~20° at all f/f_c values because X_{esc} & jump variations compensate

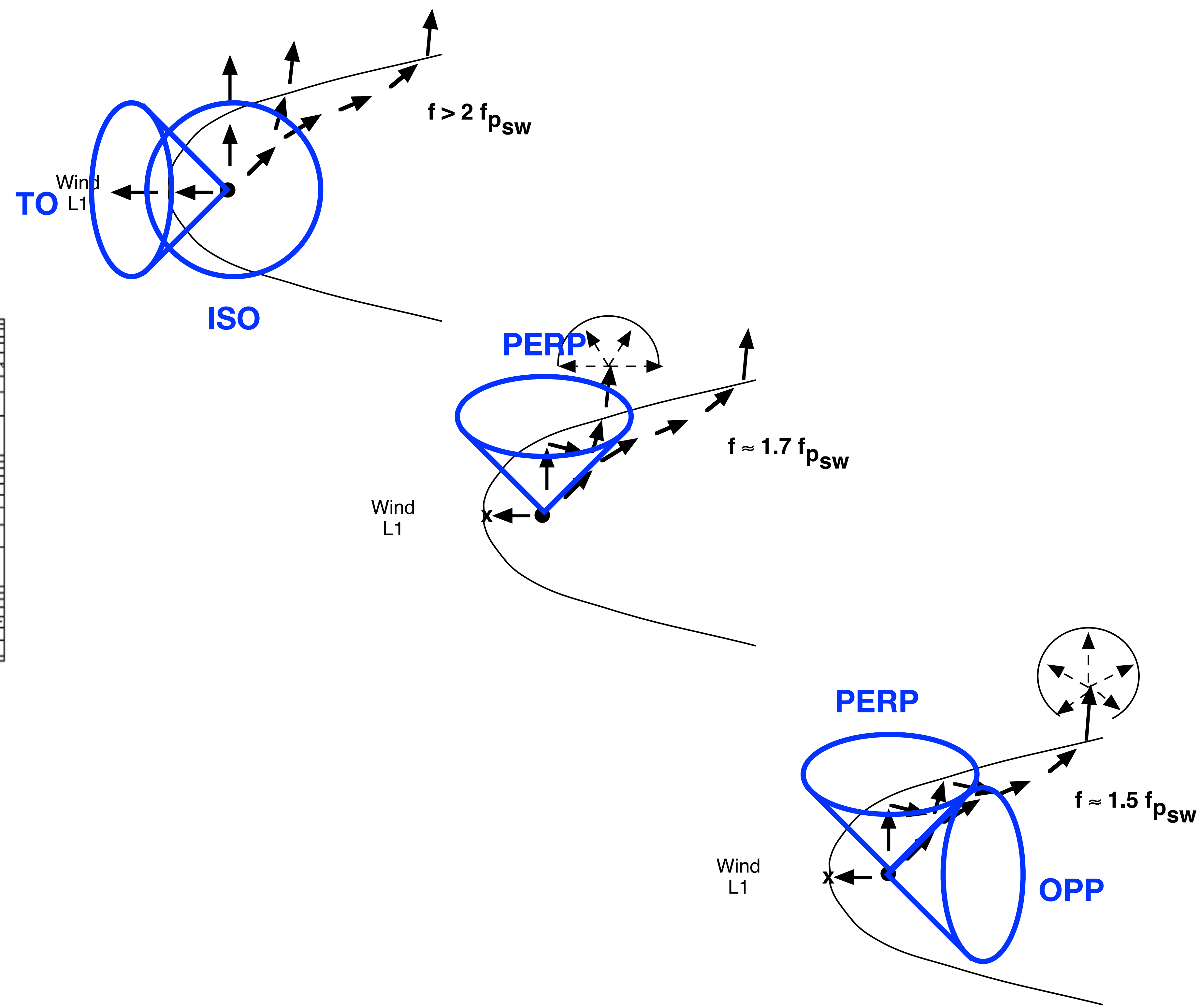


Results (5)

- Two-bump spectrum explained by angular distribution of rays exiting the BS

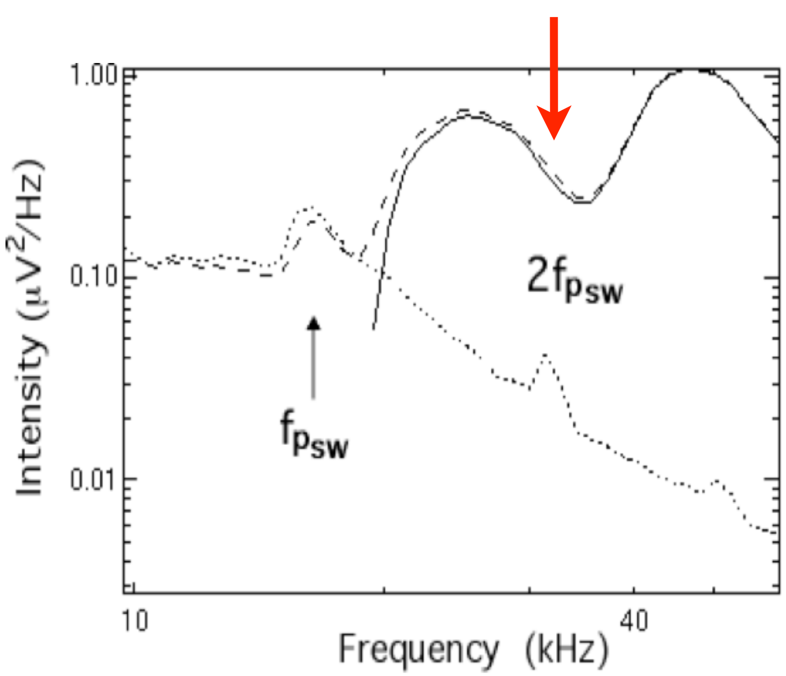
  ⇒ Angular distribution broadens with decreasing f and with time

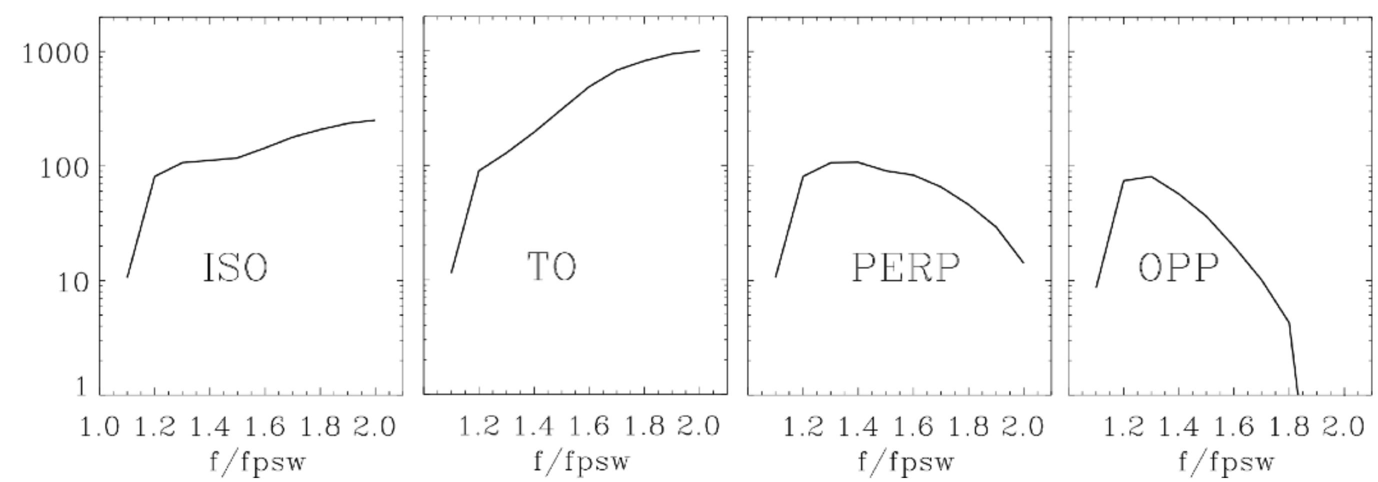


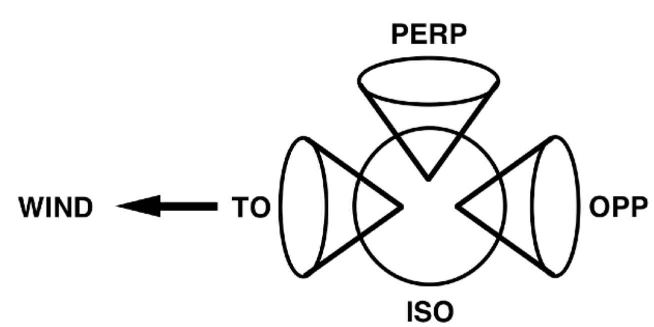


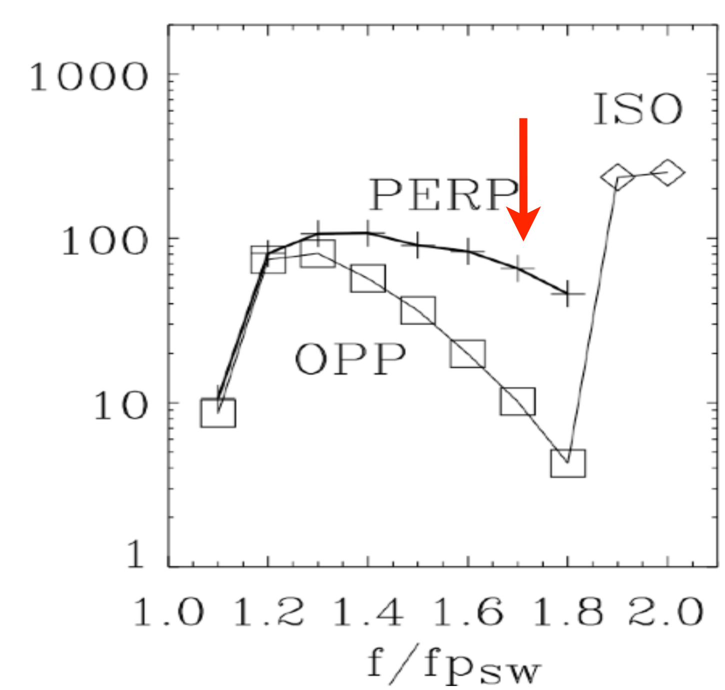
Results (5)

- Two-bump spectrum explained by angular distribution of rays exiting the BS
  - ⇒ Observed spectrum depends on angular distribution at shock exit
  - ⇒ Composite directivity of LF-burst + ITKR explains observed spectrum
  - ⇒ PERP or OPP < 2 f_{psw}, ISO < 2 f_{psw} (no spectral continuity, ≠ scattering)









- Spike seen directive at lower f from BS flanks / dayside ⇒ Ok with model
- At the same frequency, emission can be spiky then diffuse, depending on X'_{esc}

Conclusions

- f_c & $\delta t(f)$ explained by escape distance $X'_{esc} \propto X_{esc} = 10^{5.2-2.2\, f/f_{psw}}$ + scattering in SW
- Spectrum explained by angular distribution of rays leaving the shock + scattering

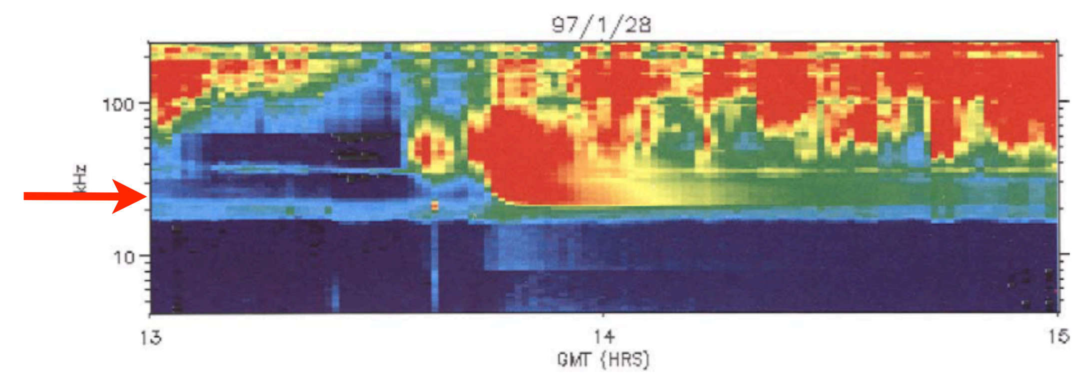
Consequences

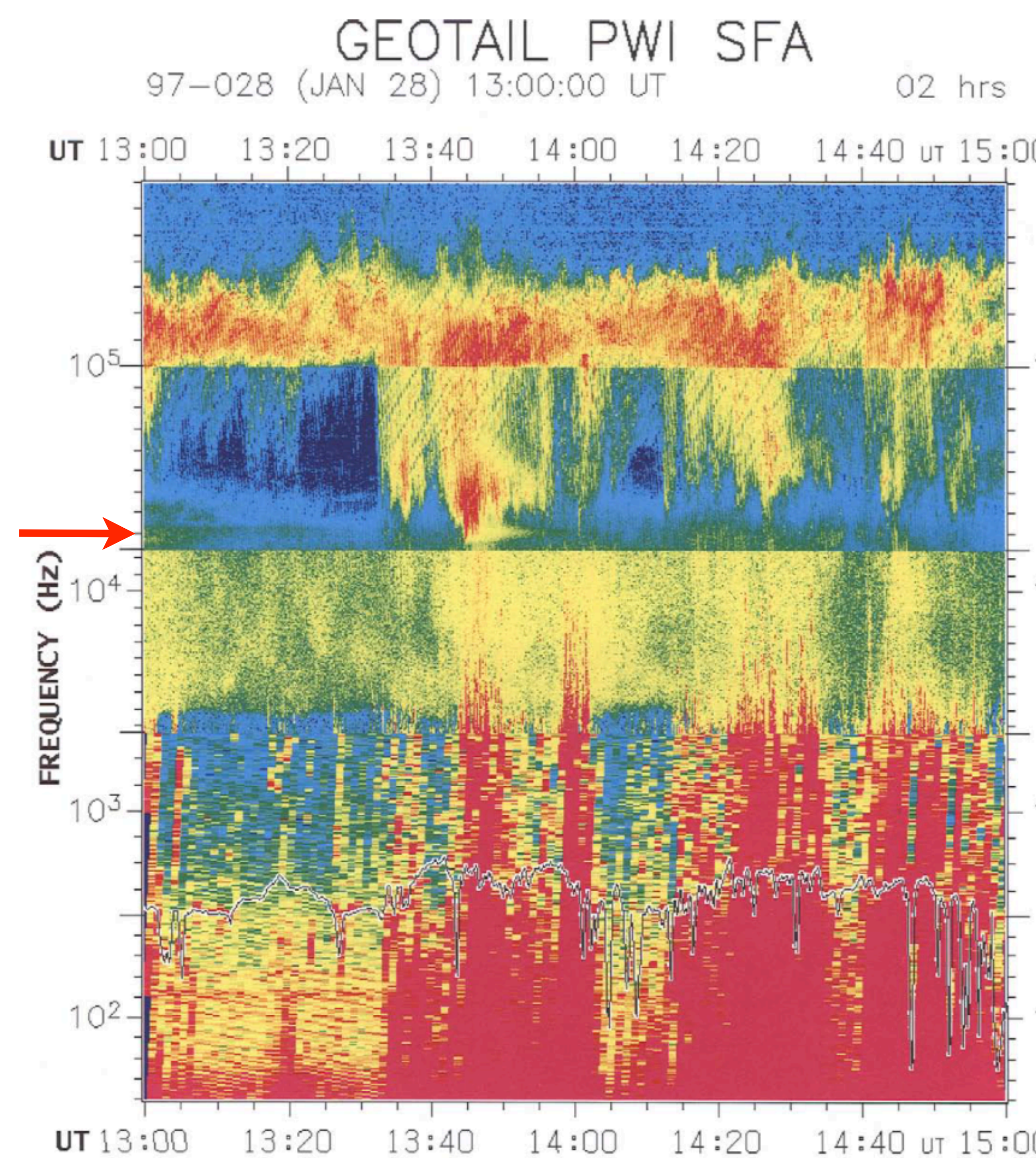
- GM3 shock model Ok, locally isotropic scattering Ok
- shock exists > 1000 R_E

Open Questions

- Source of LF burst / ITKR ?
- Relation to AKR, to substorms ?
- Why no AKR diffuse tail ?
  - ⇒ HF ⇒ LF burst = LF tail of AKR
  - ⇒ ~? LFE events at Saturn

[Reed et al. JGR 2018; Pazamickas et al. AGU 2004]





Further studies

- LF burst tail ~ f_{psw} when observed in the MS ⇒ ?

[Anderson et al., AGU 2002, COSPAR 2005]