13/11/12-14, The Ephemeral Universe, Curtin, Perth

Strongly anisotropic scintillation from the dusty ISM?

Artem Tuntsov
Manly Astrophysics

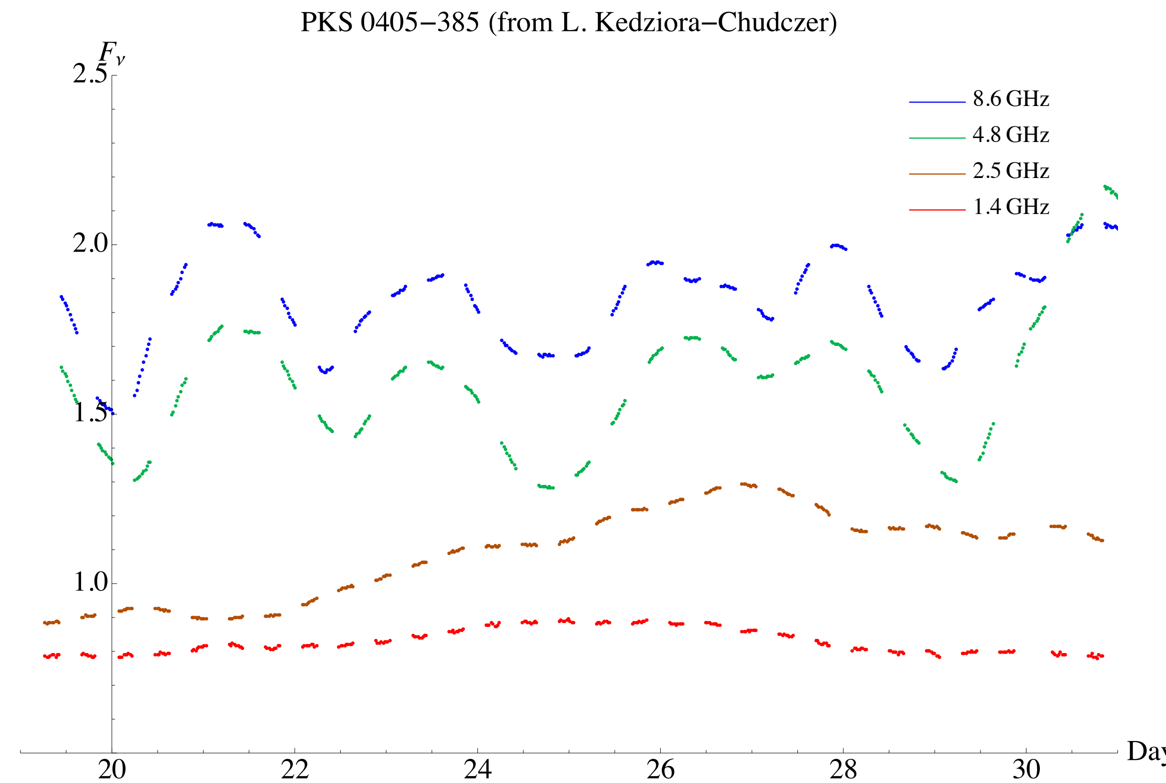
Most prominent scattering

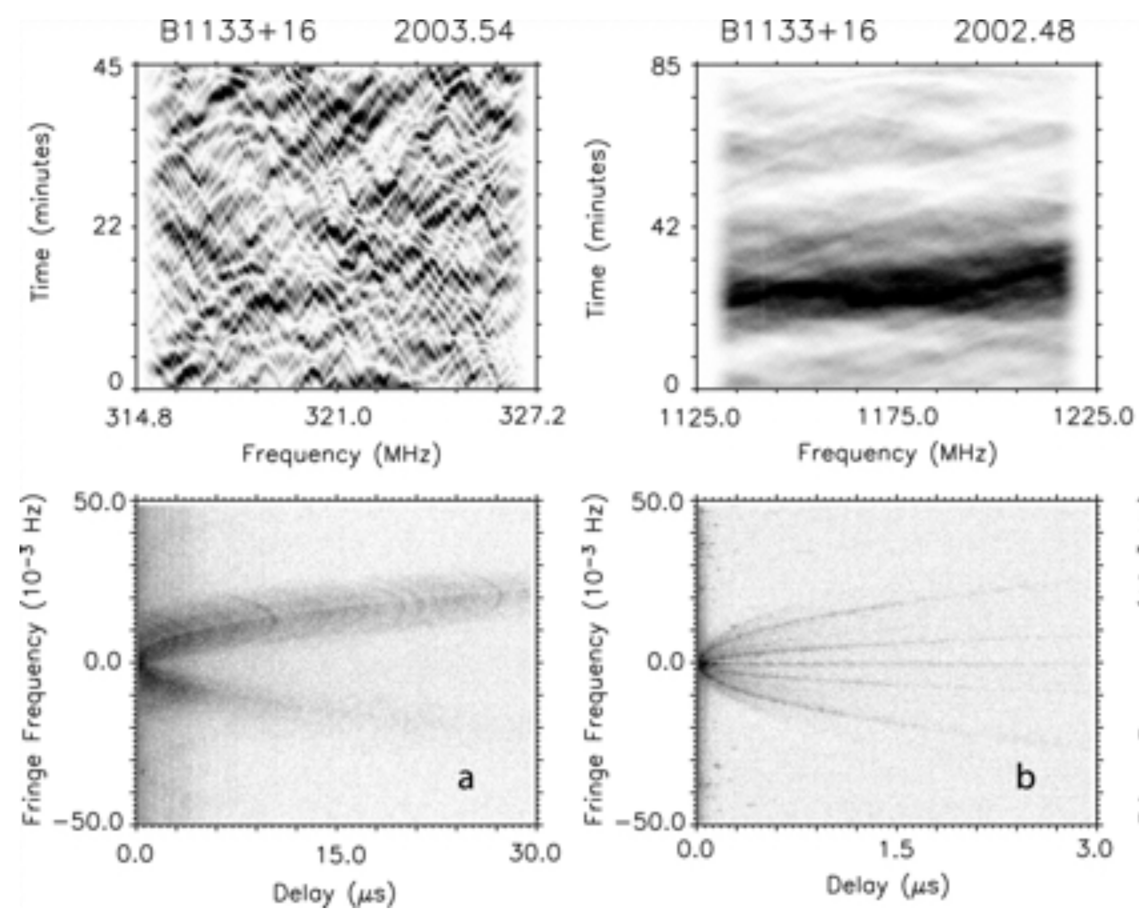
- Extreme intra-day variables (IDVs):
  (PKS1257-326, PKS0405-385, J1819+3845, …)

- Pulsar parabolic arcs:
  (just about any one when you look close enough)

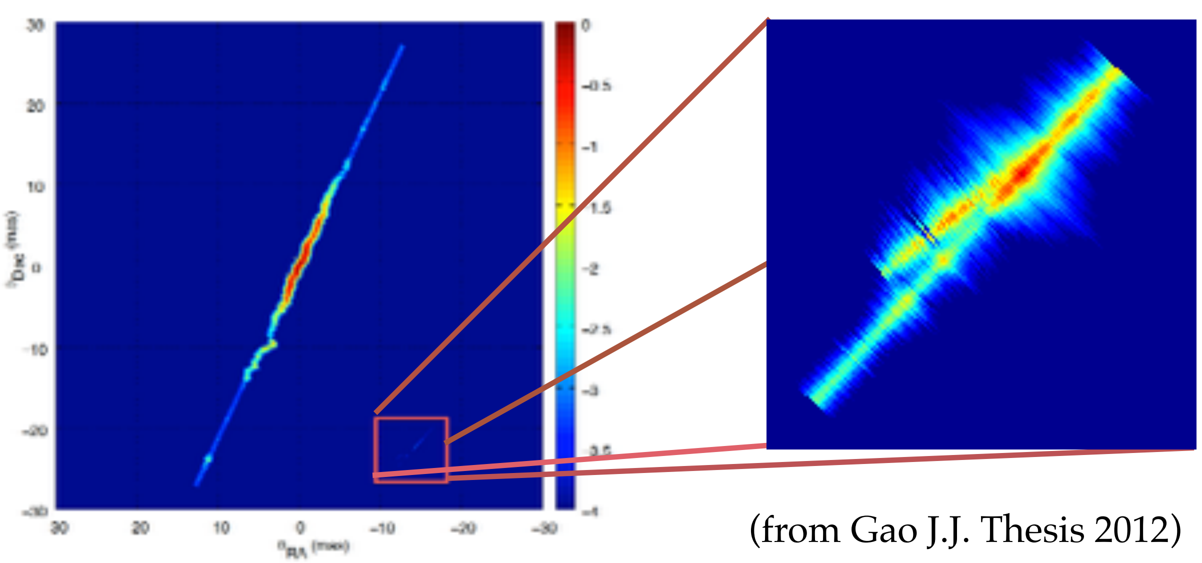
Often show evidence for much anisotropy:

- Morphological
  (little power within parabola - Cordes+ 2006, Walker+ 2004)
- Kinematical
  (two-station experiments - Walker, de Bruyn, Bignall 2009)
- Direct Imaging
  (if can be converted to images - Rickett, Coles, Gao 2012)





(from Cordes, Rickett, Stinebring, Coles 2006)



(from Gao J.J. Thesis 2012)

Performance of 1D Power-law models

Assume:

- Pure 1D Gaussian fluctuations
  (across filament**s**, not along **a** filament)
- Power-law, inner/outer scale **if needed**
- power law index β between 2 and 4
  (1D Kolmogorov is 1+5/3~2.67)

Simulate and compare:

- PKS 1257-326 (Bignall+ 2003):
  - individual light curves
  - inter-band (C/X) correlations and lags
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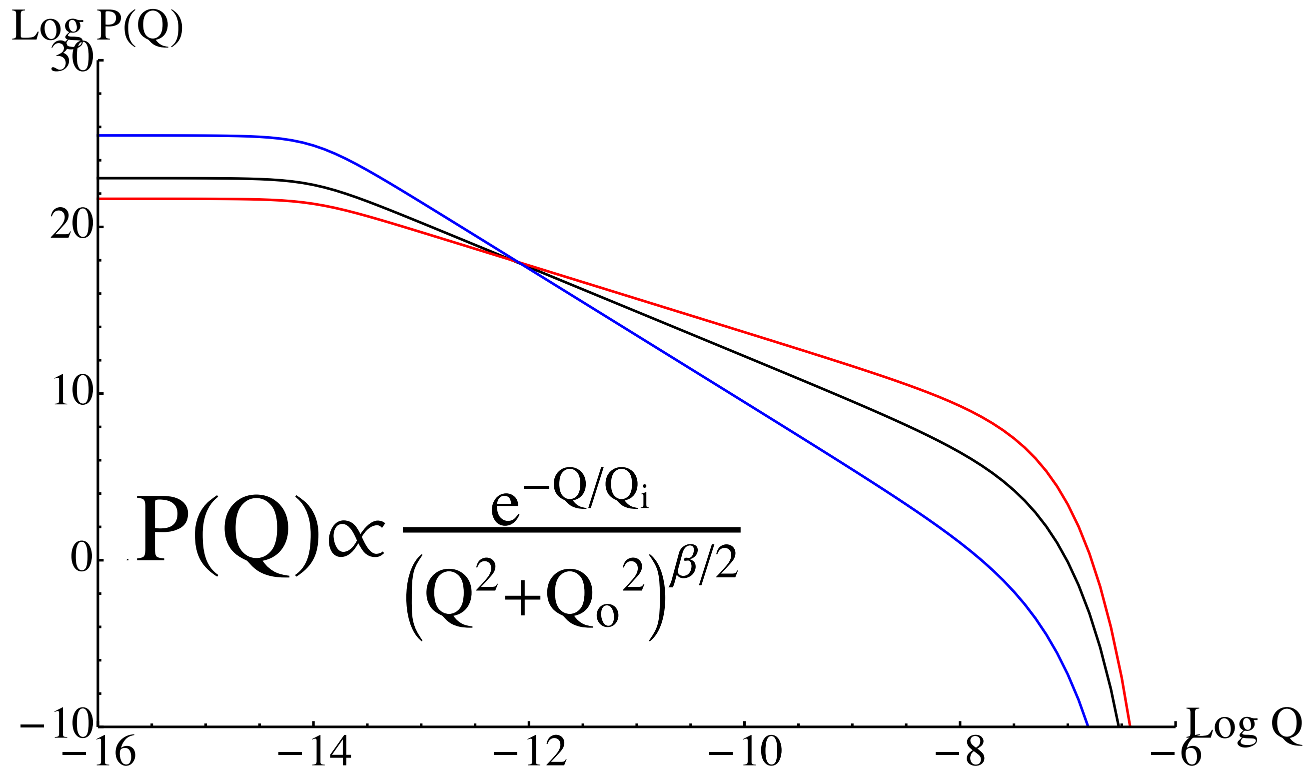
PSR and IDV analyses done independently

Infer:

- Models fit data, constraints are weak
- Two constraint sets are consistent
- Broadly Kolmogorov (2.5≲β≲3)

  (unless such inner/outer scales that not quite power law)
- when fixed (β≈3), outer scale ≲$10^{13\text{-}14}$ cm
- **Amazingly, both screens can physically be the same thing: $n_e \approx 10$ - $30\ cm^{-3}$**



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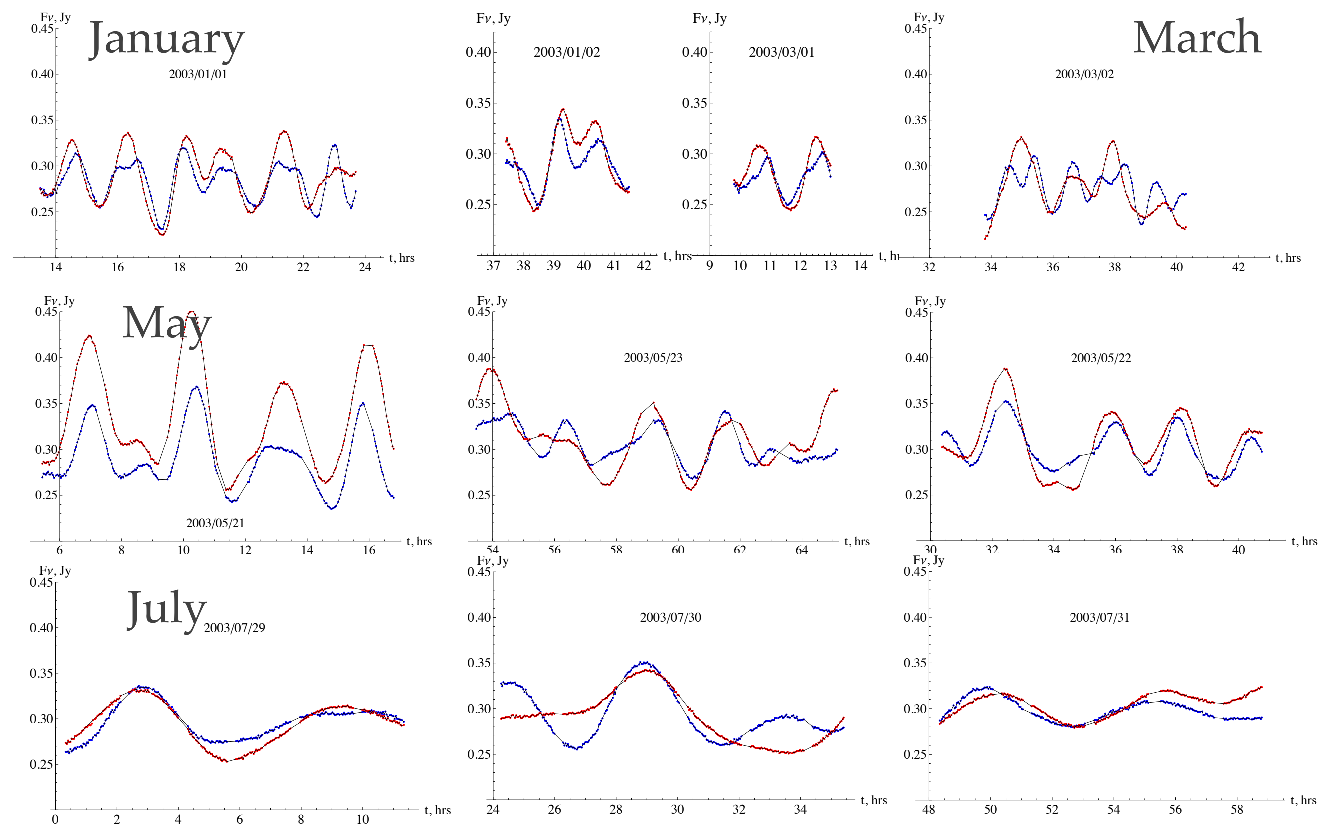

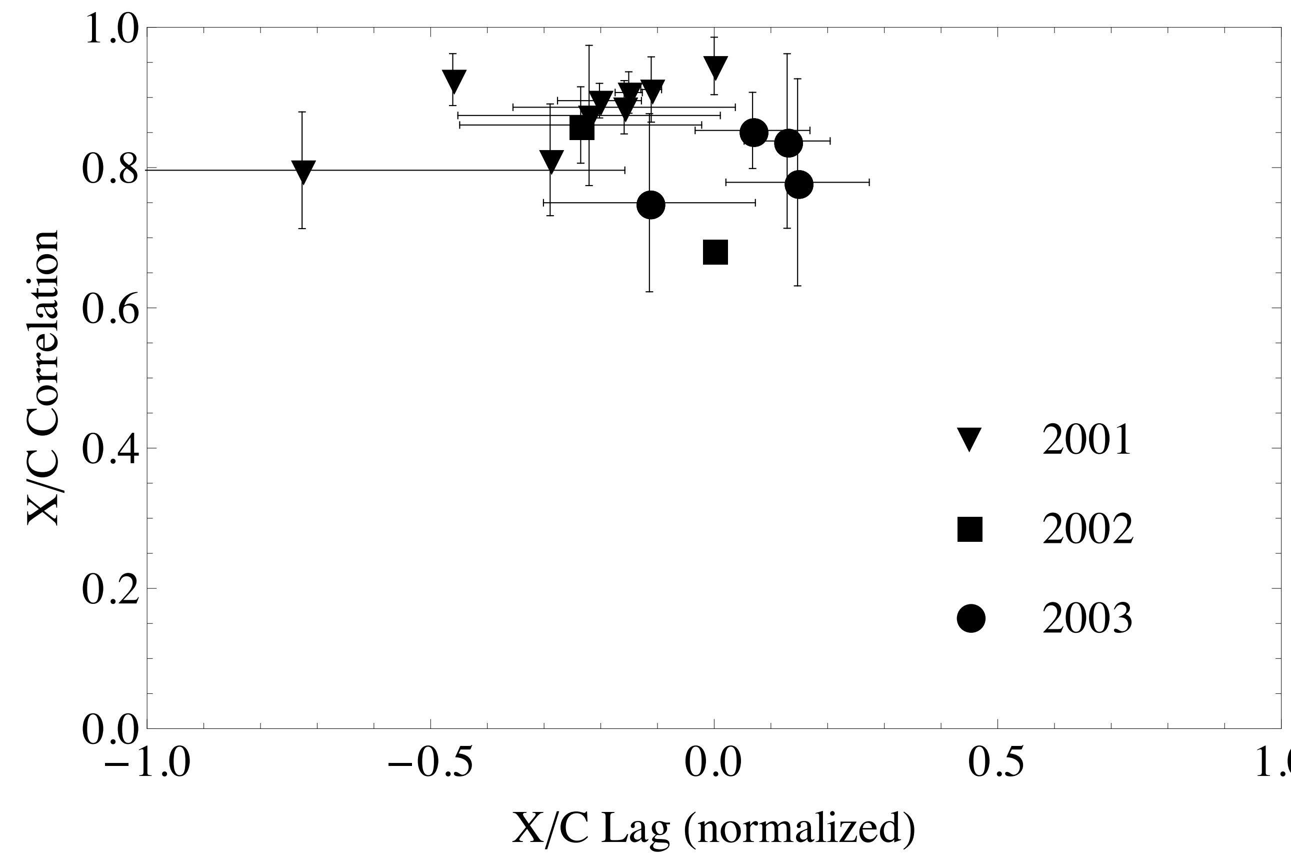

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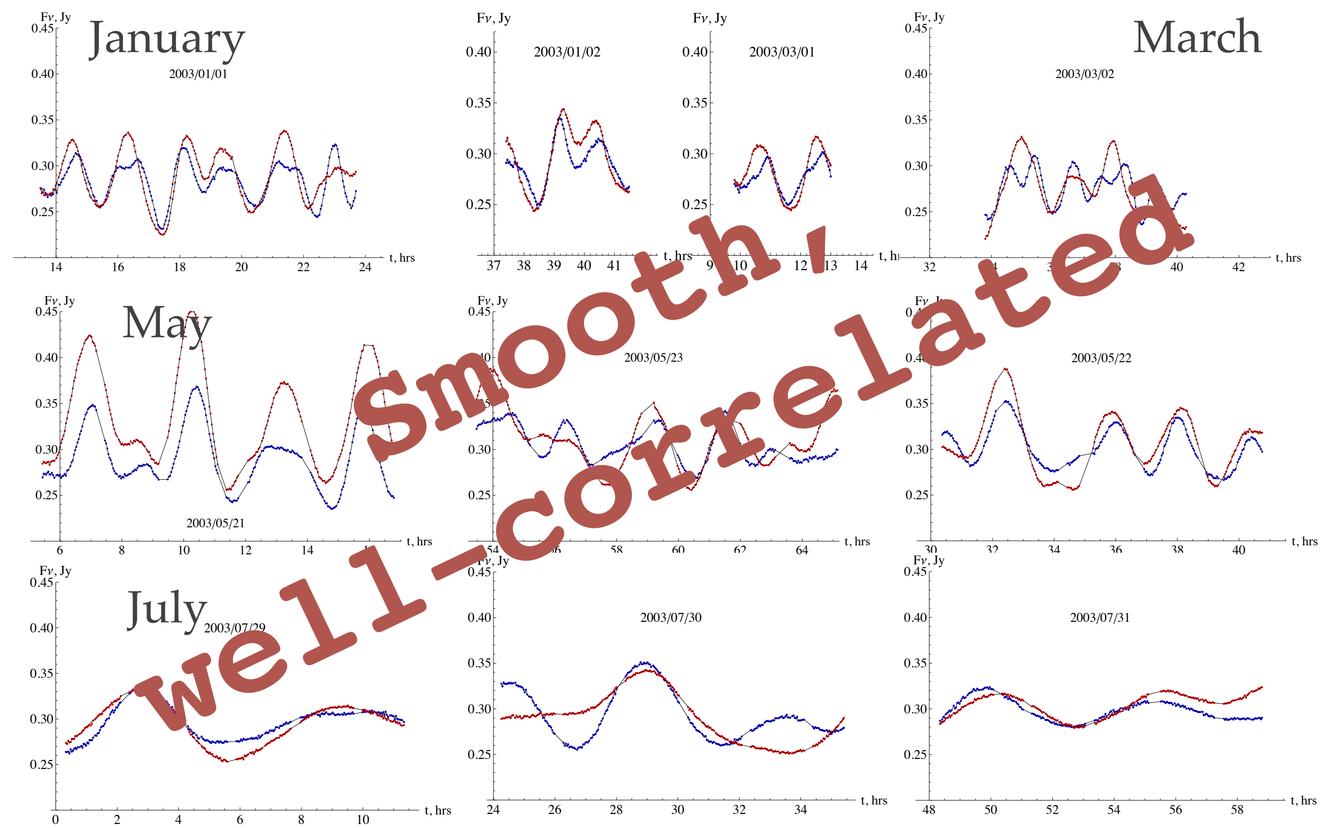

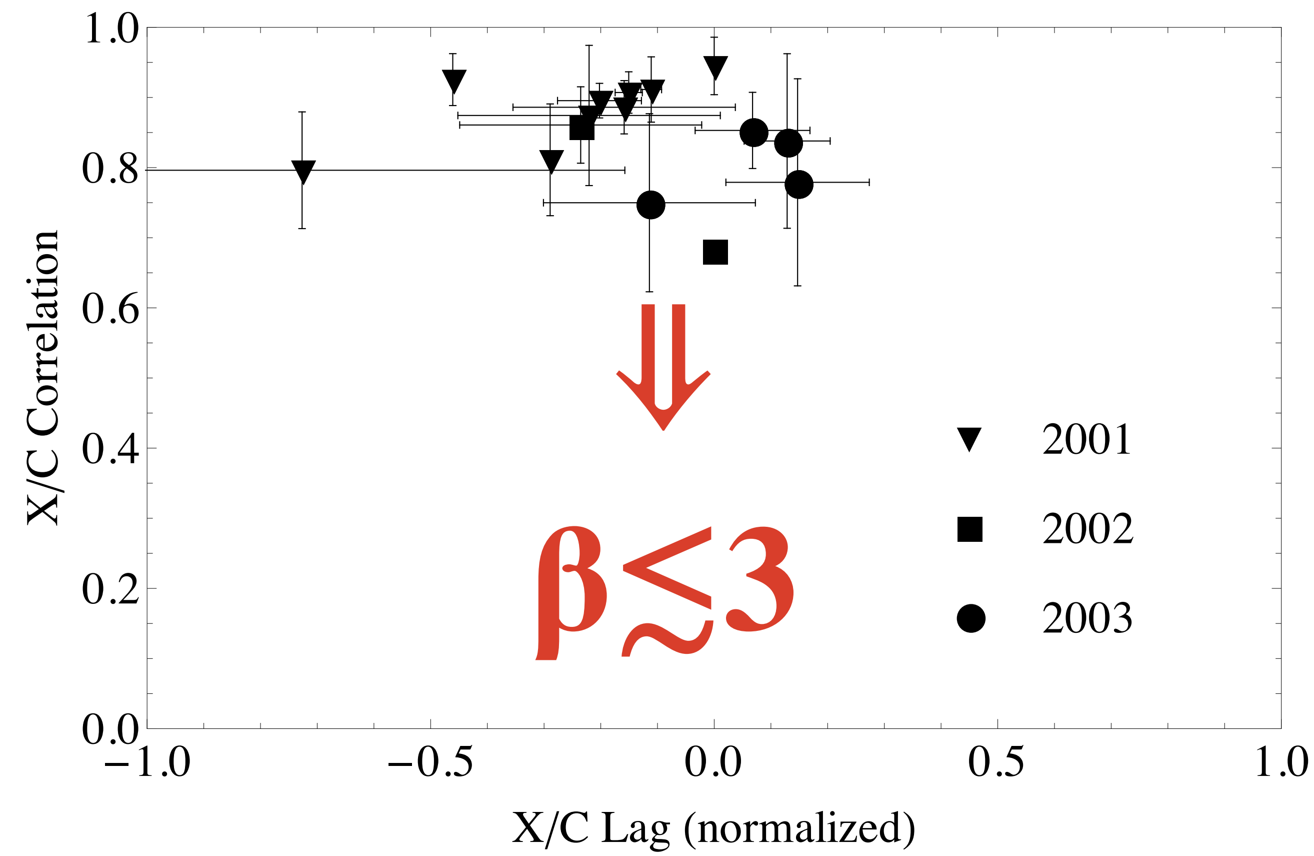

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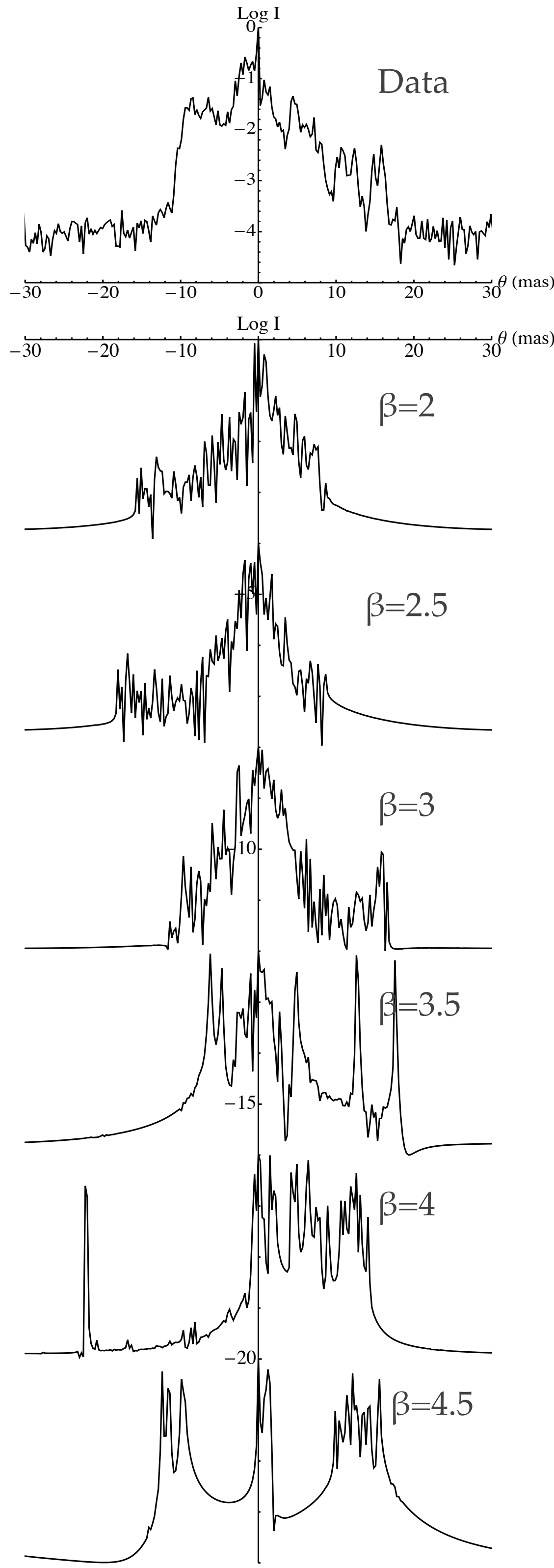

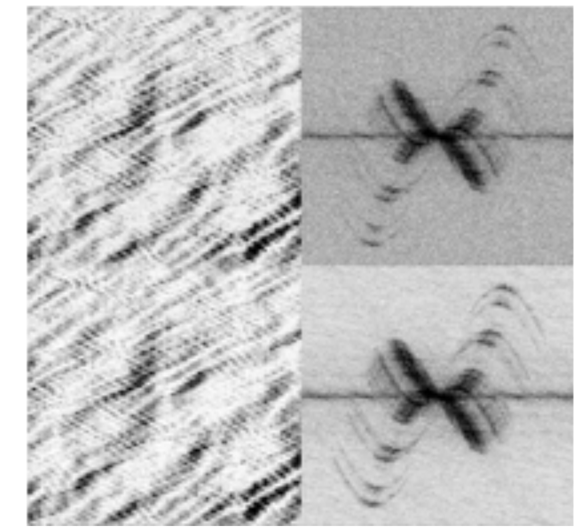

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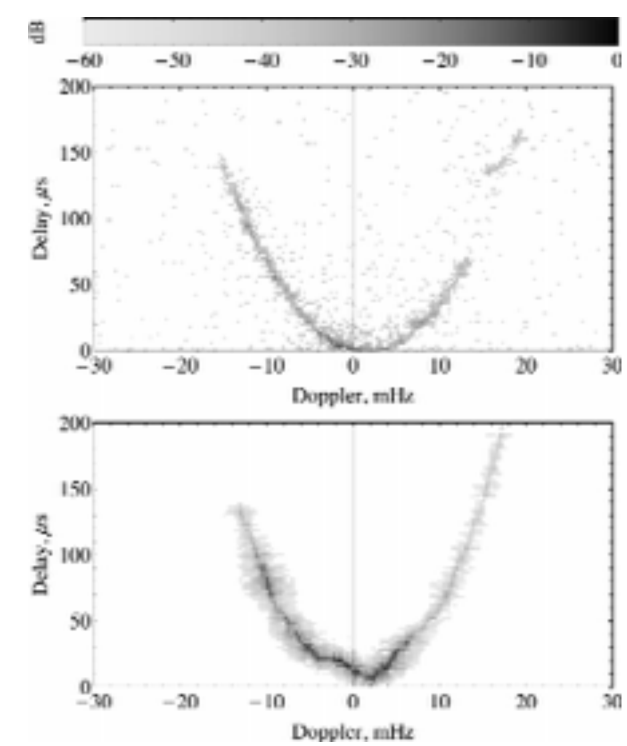

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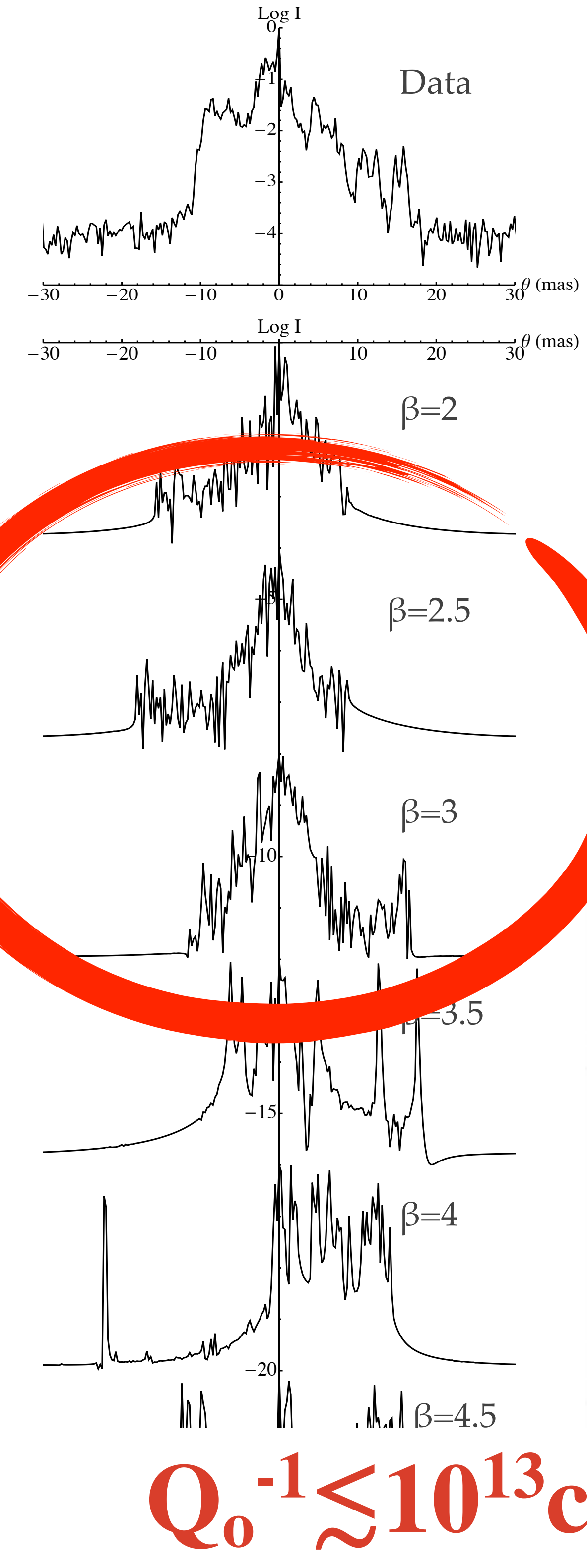
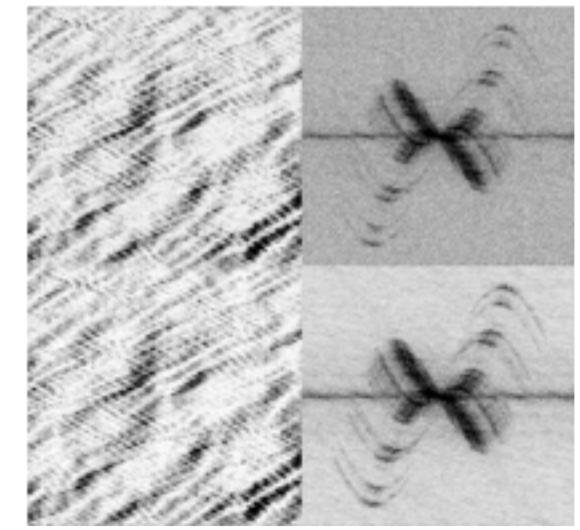


⇒2.5≲β≲3



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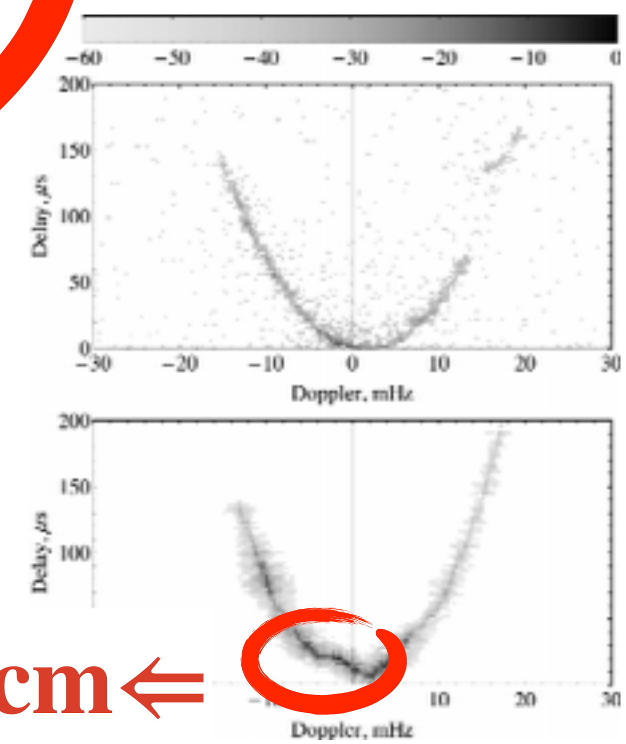

Q_o^{-1}≲10^{13}cm⇐

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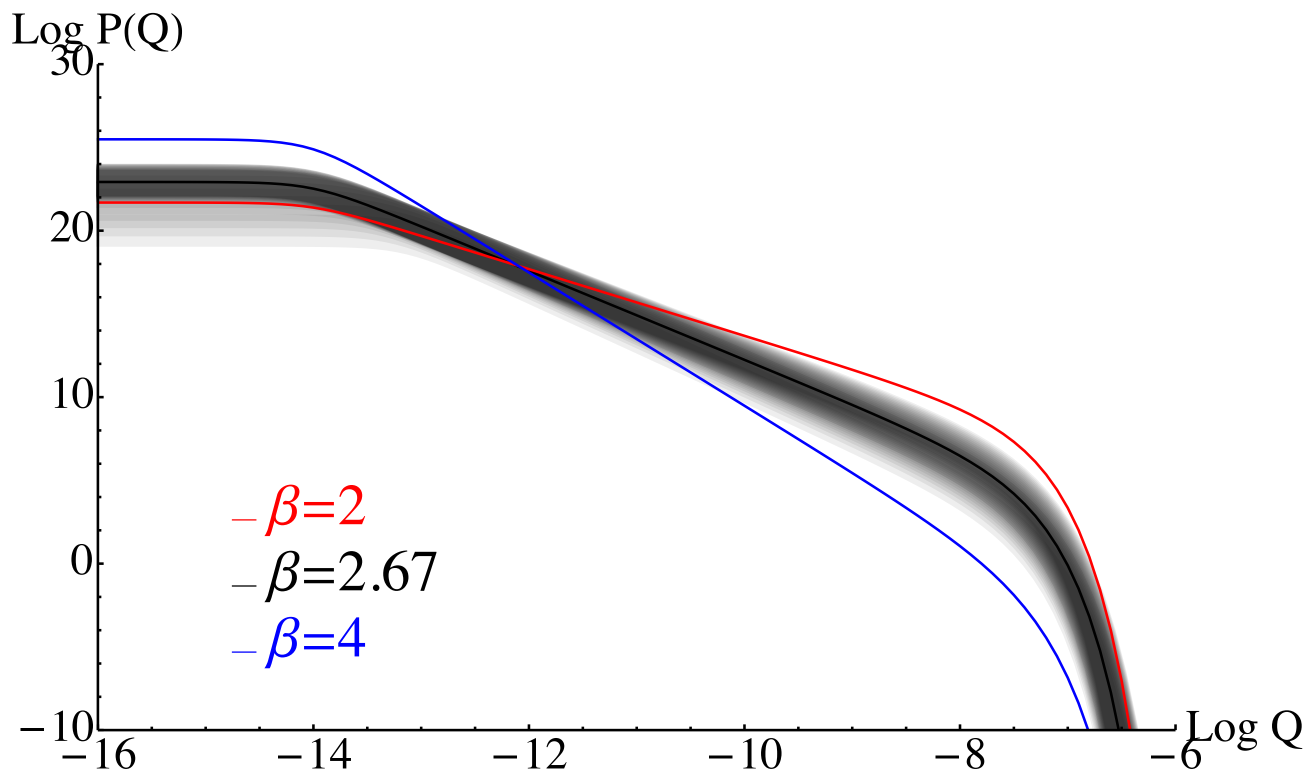

Such structures have no place in the ISM

- **T~10^4 K ⇒ P=n_eT~10^5 cm^{-3} K (think ESE)**
- **Even worse for 1D structures: whatever stretches them, should apply even greater stresses**

(Tuntsov, Bignall, Walker 2013)

Two ways out

Boring: refine the model

- Intermittency of turbulence
- Non power-law or non-Gaussianity of fluctuations
- Finite scattering anisotropy
- Source anisotropy or non-trivial structure
- Smooth plasma distribution along l.o.s.
- ???????

to reduce implied n_e - or get rid of anisotropy

Fun: question pressure/balance

- Favourable geometry
- New ISM phases with necessary pressure and anisotropy
- Short-lived structures
- Naturally anisotropic media
- Non-conventional $P(n_e)$ or T
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to squeeze them in.

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Dust!

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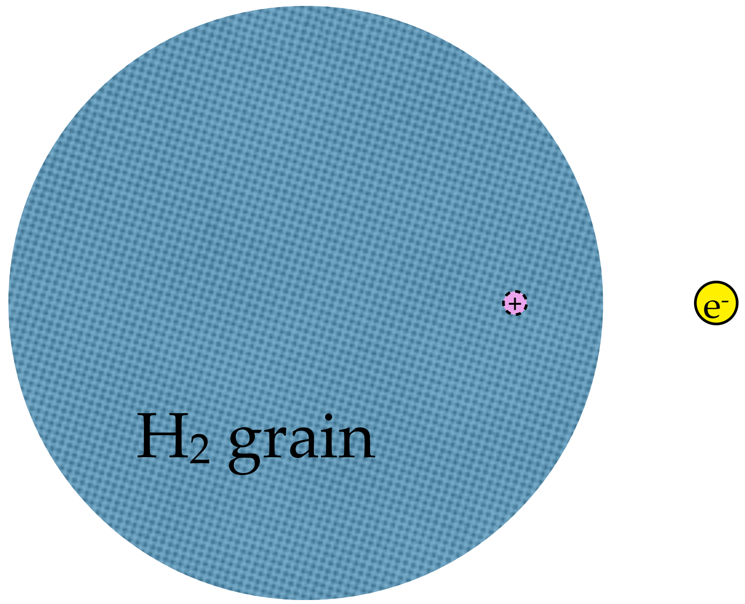
(Tuntsov, Bignall, Walker 2013)

Dust(y) plasma

Dust:

- Present in ISM
- May be naturally anisotropic (comets)
- If made of solid H_2, can provide abundance of (nearly) free electrons:
  - negative electron affinity
  - slow charge build-up ⇒ stabilisation
  - ions lodge into lattice
  - electrons can move along surface



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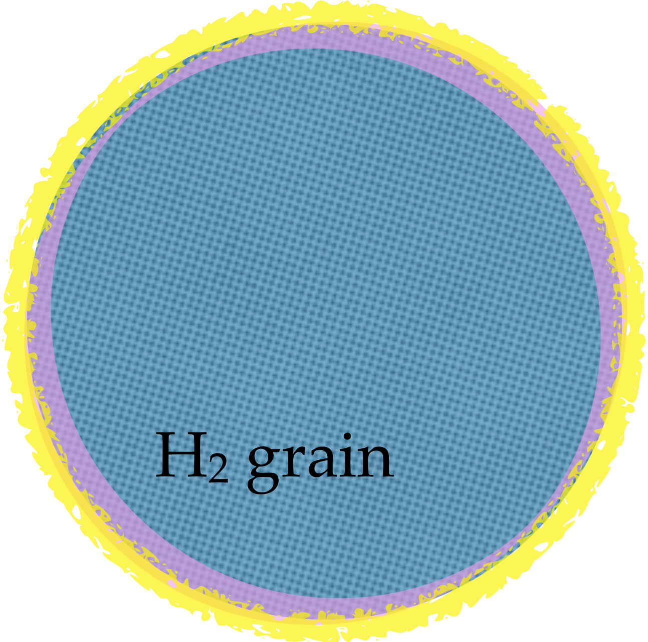

$\Sigma_e \sim 10^{14}\ \mathrm{cm}^{-2}$

$T_{\mathrm{triple\ point}} \approx 14\ \mathrm{K}$

$P_{\mathrm{sat}} << P_{\mathrm{ISM}}$

(Walker 2013)

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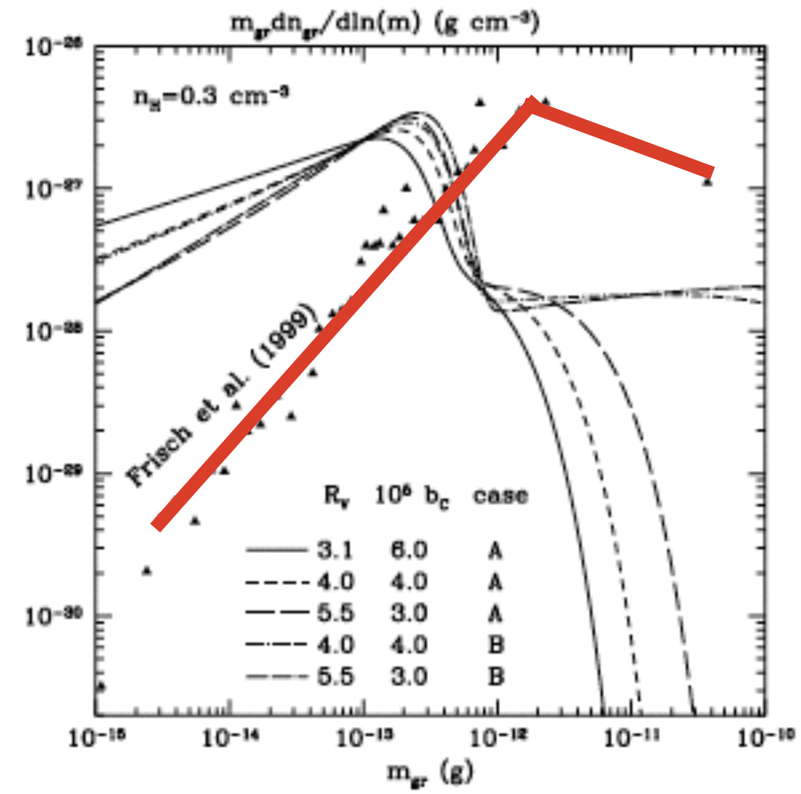
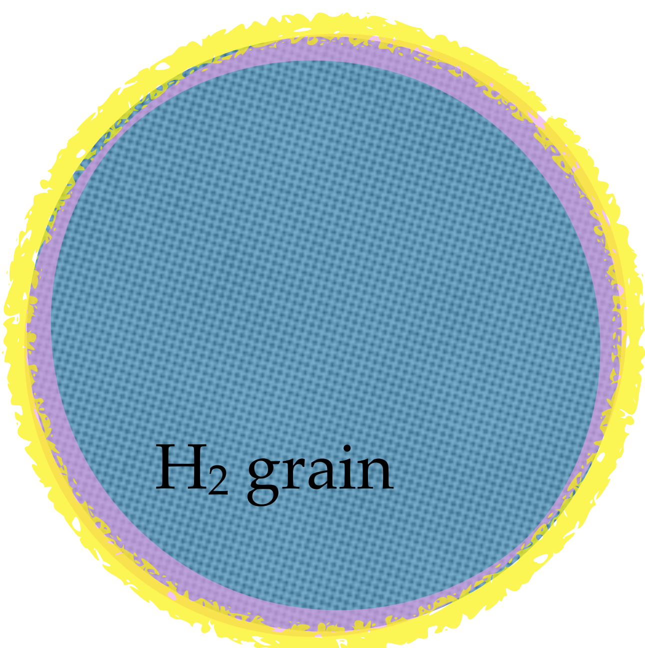


(Weingartner & Draine 2001, Frisch+ 1999)



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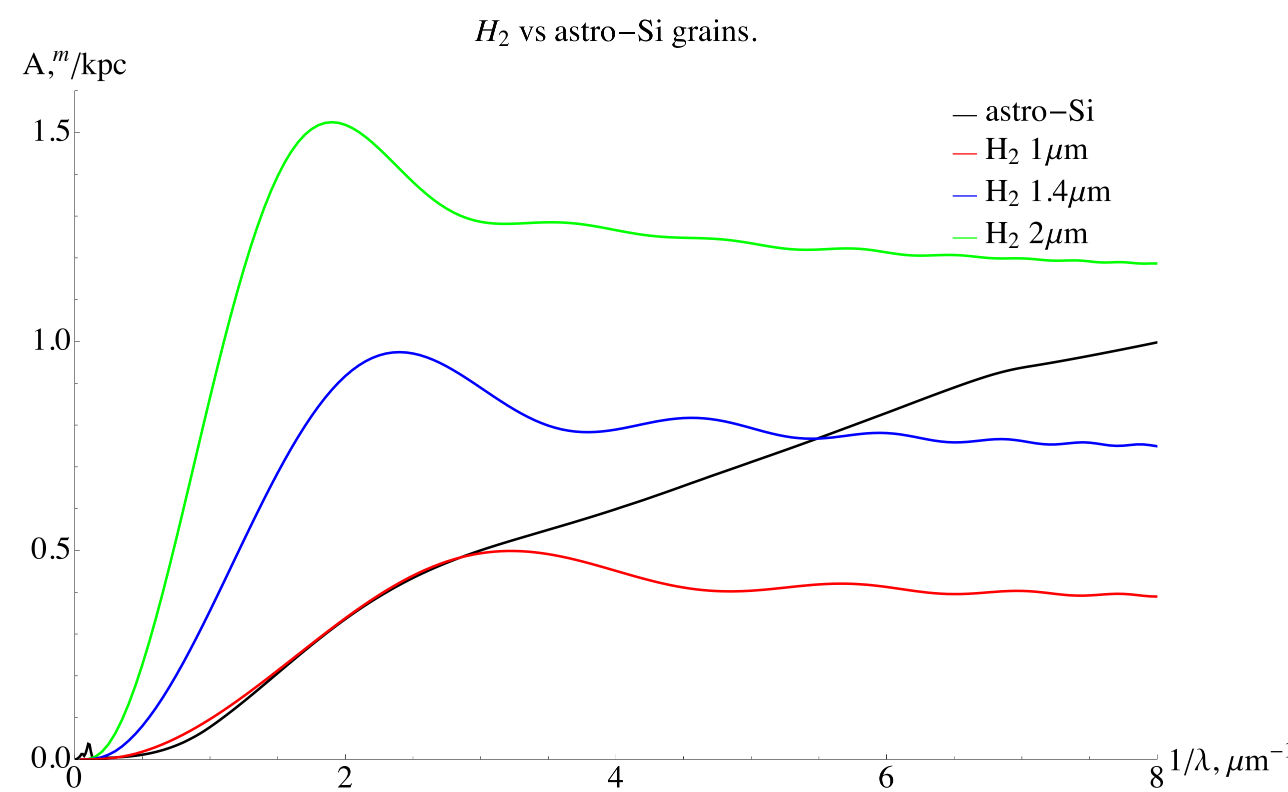


Scattering. Radio refractive index

Grains

- H_2 bulk: Essentially DC response at radio

  $\epsilon - 1 \approx 0.27 - 5\times10^{-15} i\, \nu_{GHz}$

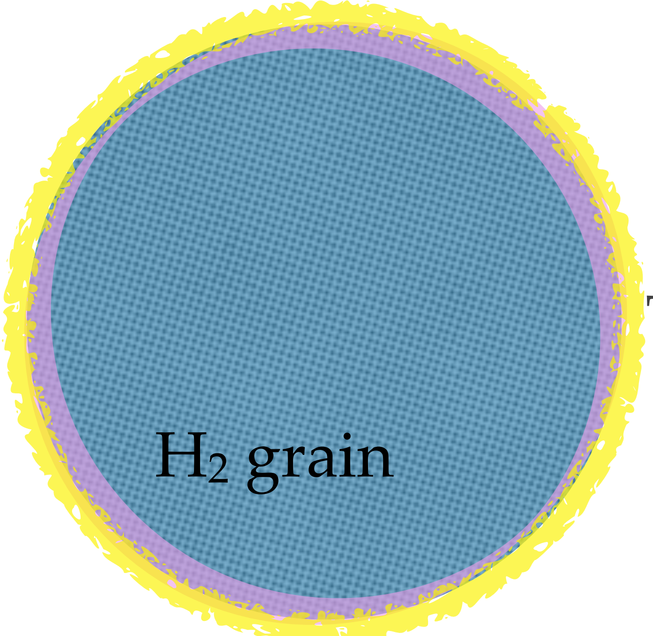
- Electron shell (dipole approximation):

  not a plasma - curvature

  $\epsilon - 1 = \frac{g\, \omega_{eff}^2}{\omega_{eff}^2 - \omega^2}, \quad g \sim \mathcal{O}(1)$

  $\omega_{eff}^2 = \frac{4\pi e^2 \Sigma_e}{m_e a}, \quad \omega_{eff} \approx 2\times10^{14}\, a_{\mu m}^{-1/2}\, s^{-1}$

  — *i.e.* $\epsilon \approx 1 + g = const$ at radio frequencies



$\boldsymbol{\Sigma_e \sim 10^{14}\ cm^{-2}}$

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(Walker 2013)

Medium

- Maxwell-Garnett law:

  $\epsilon_{medium} - 1 \approx f_V (\epsilon_{grain} - 1)$

  $n \approx 1 + \tfrac{1}{2} \langle f_V (\epsilon_{grain} - 1) \rangle$

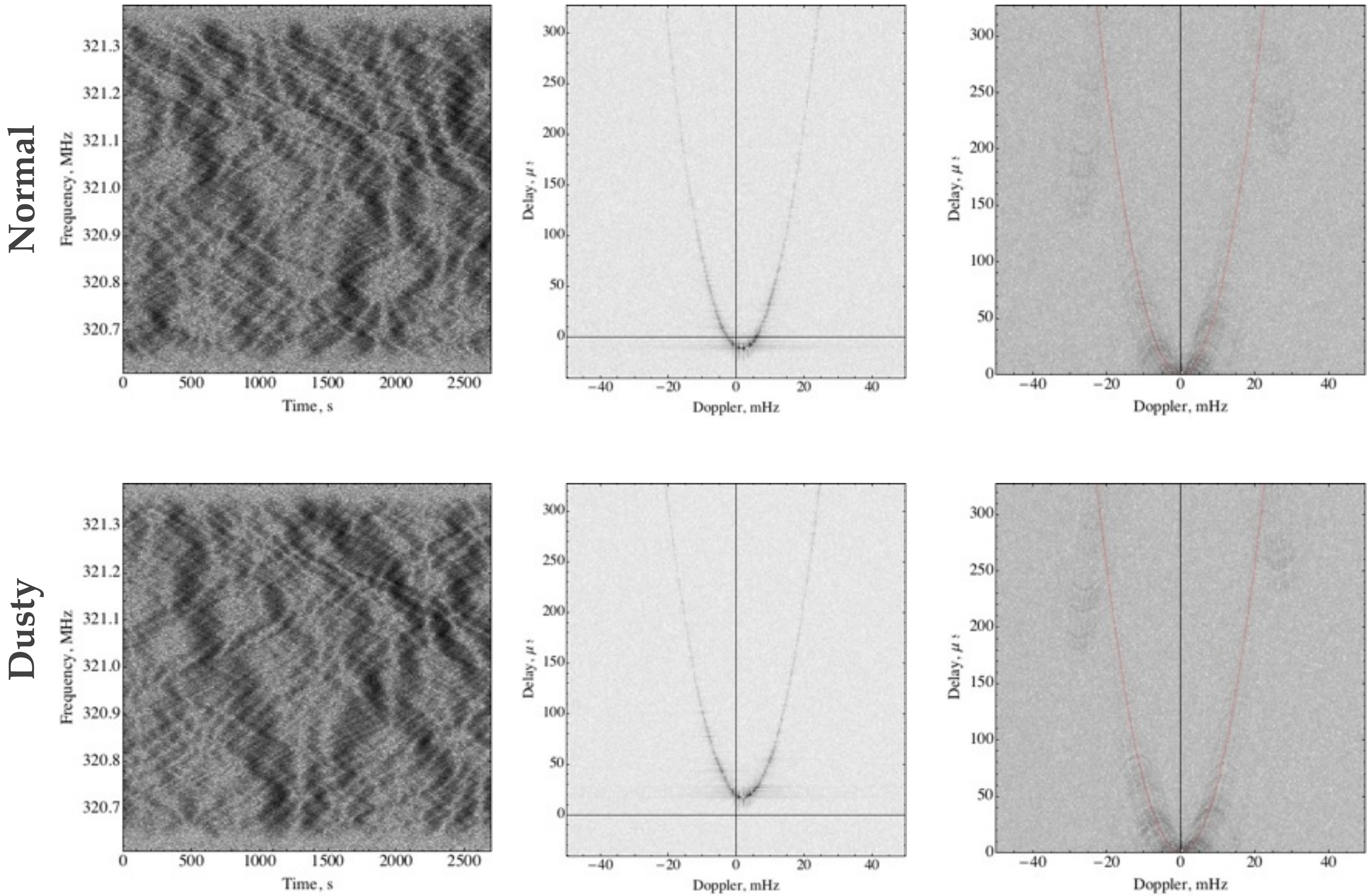
⇒ Phase delay:

$$\phi = \pi\, ƛ^{-1} \int dD\, f_V(\epsilon_{grain} - 1)$$

— **i.e.**, wrong twice:

- positive
- $\propto 1/ƛ$

Scattering. Impact on parabolic arcs



— i.e., not much impact at all (as shown in Cordes+ 2006)

Scattering. Band-to-Band scalings

Normal

- **$\langle \phi(r)\, \phi(r+s) \rangle \propto ƛ^2\, s^{\alpha}$**

  (Kolmogorov: $s^{5/3}$)

  - Scattering disc:

    $s_0 \propto ƛ^{-2/\alpha}$ $(ƛ^{-6/5})$

  - Scattering angle:

    $\theta_0 \propto ƛ^{1+2/\alpha}$ $(ƛ^{2.2})$

  - Bandwidth:

    $\Delta\nu \propto ƛ^{2+4/\alpha}$ $(ƛ^{4.4})$

- **Dispersive (wave-speed) delays:**

  $\phi \propto ƛ$, $\tau \propto ƛ^2$

Dusty

- **$\langle \phi(r)\, \phi(r+s) \rangle \propto ƛ^{-2}\, s^{\alpha}$**

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  - Scattering disc:

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  - Bandwidth:

    $\Delta\nu \propto ƛ^{2-4/\alpha}$ $(ƛ^{-0.4})$

- **Dispersive (wave-speed) delays:**

  $\phi \propto ƛ^{-1}$, $\tau \propto ƛ^0$

Scattering. Band-to-Band scalings

Normal

- **$\langle \phi(r)\, \phi(r+s) \rangle \propto \bar{\lambda}^2 s^{\alpha}$**

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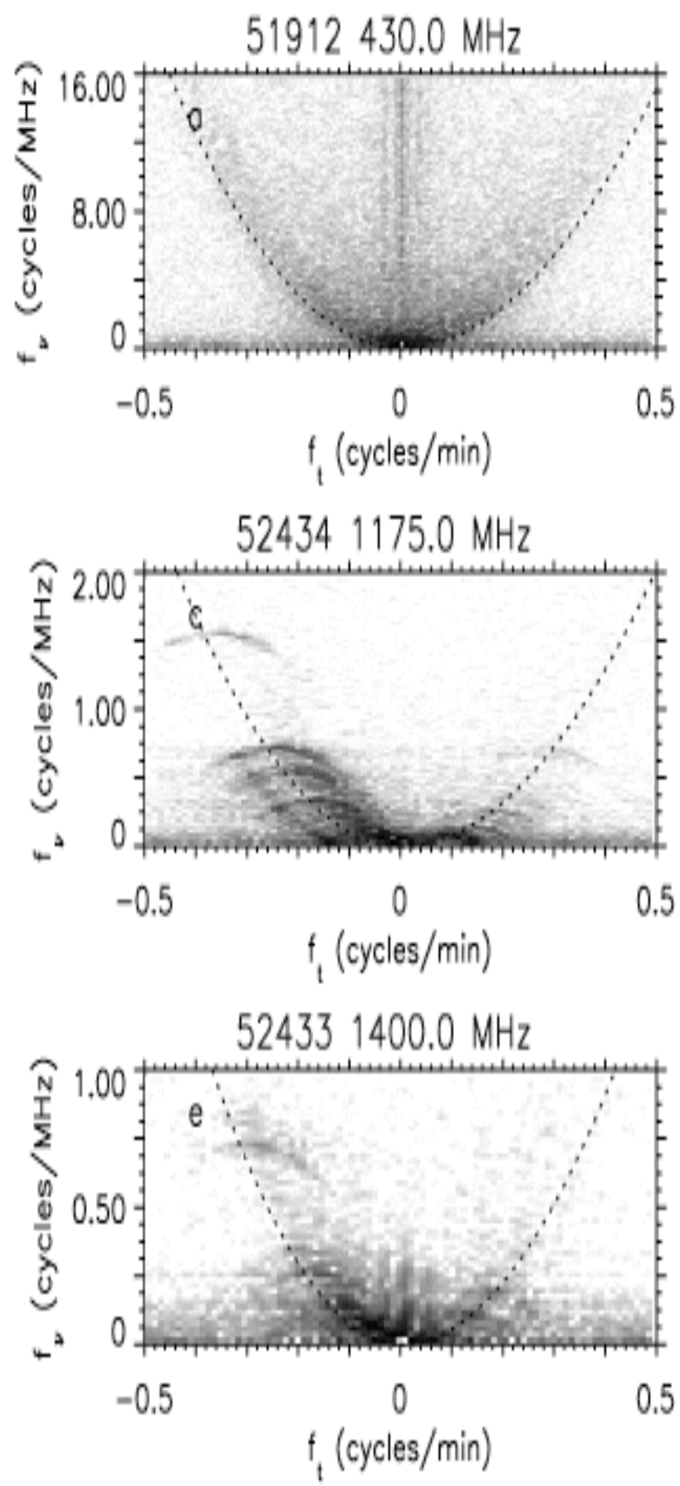

(Hill+ 2003)

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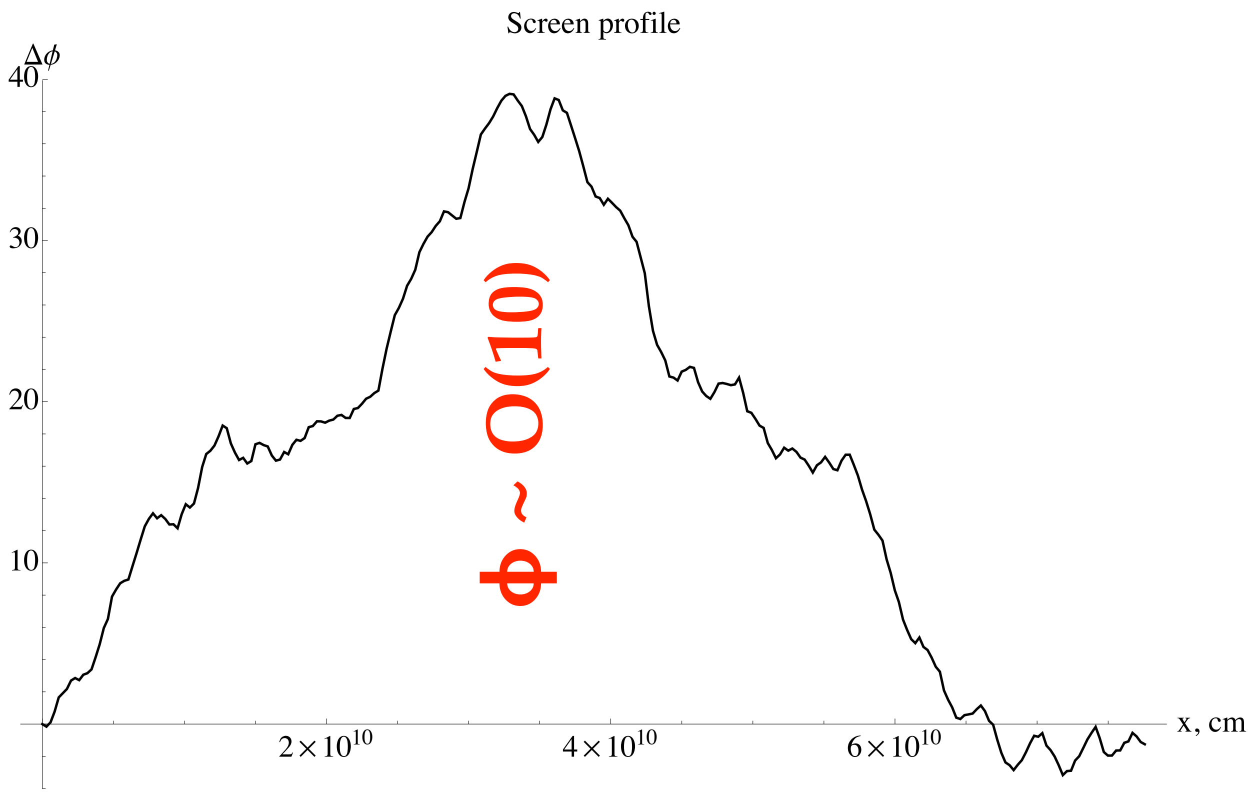
  $\phi \propto \bar{\lambda}^{-1}$, $\tau \propto \bar{\lambda}^0$

Final nail. Extinction.

Phase delay:

$$\phi = \pi\, \bar{\lambda}^{-1} \int dD\, f_V(\epsilon_{grain} - 1)$$

$$\sim \bar{\lambda}^{-1} \int dD\, N_{grain}\, \boldsymbol{a}^3$$



Extinction depth:

- $\boldsymbol{\tau} \sim Q_{ext}(\boldsymbol{\lambda})\, G$

$$\sim Q_{ext}(\boldsymbol{\lambda}) \int dD\, N_{grain}\, \boldsymbol{a}^2$$

$$\sim Q_{ext}(\boldsymbol{\lambda})\, \phi \bar{\lambda} / \boldsymbol{a} \sim 10^7\, Q_{ext}(\boldsymbol{\lambda})\, \bar{\lambda}_m / \boldsymbol{a}_{\mu m}$$

- $Q_{ext}(\boldsymbol{\lambda}) \approx (\boldsymbol{a}/\boldsymbol{\lambda})^2$ when $\boldsymbol{a} \ll \boldsymbol{\lambda}$

  ≈ 1 when $\boldsymbol{a} \gtrsim \boldsymbol{\lambda}$

— i.e., need $\boldsymbol{a}$~1 nm for PSR/IDVs

to be seen in the optical

Conclusions

- 1D scattering works well for (some) PSRs and IDVs
- H_2 dust is naturally filamentary and could produce scattering required
- However, it is unlikely to be responsible because:
  - band-to-band variations are contrary to observed
  - extinction is too high for realistic dust sizes

13/11/12-14, The Ephemeral Universe, Curtin, Perth

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Strongly anisotropic scintillation from the dusty ISM? - **Unlikely**

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Thank you!