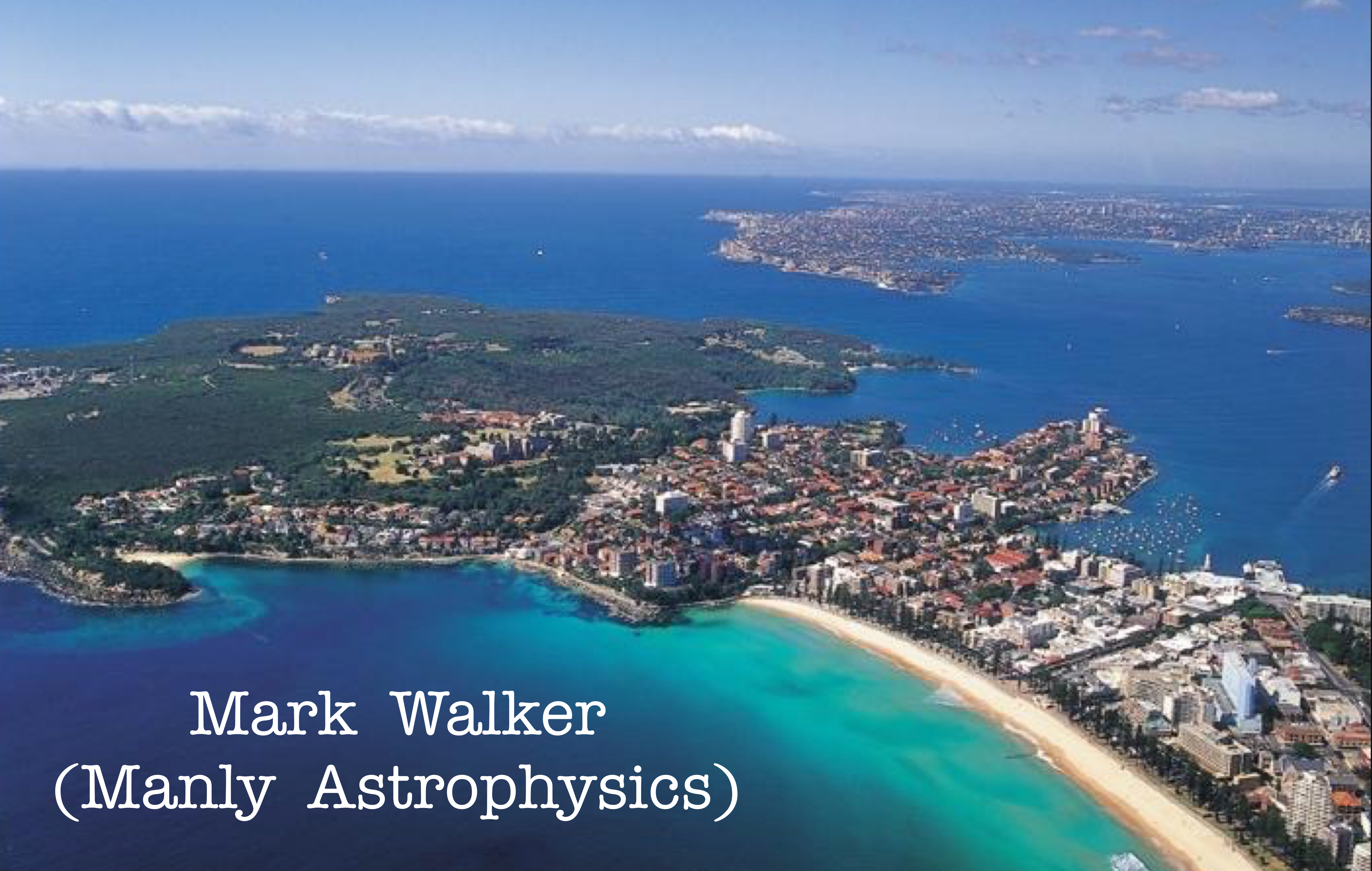
Introduction to Scintillations

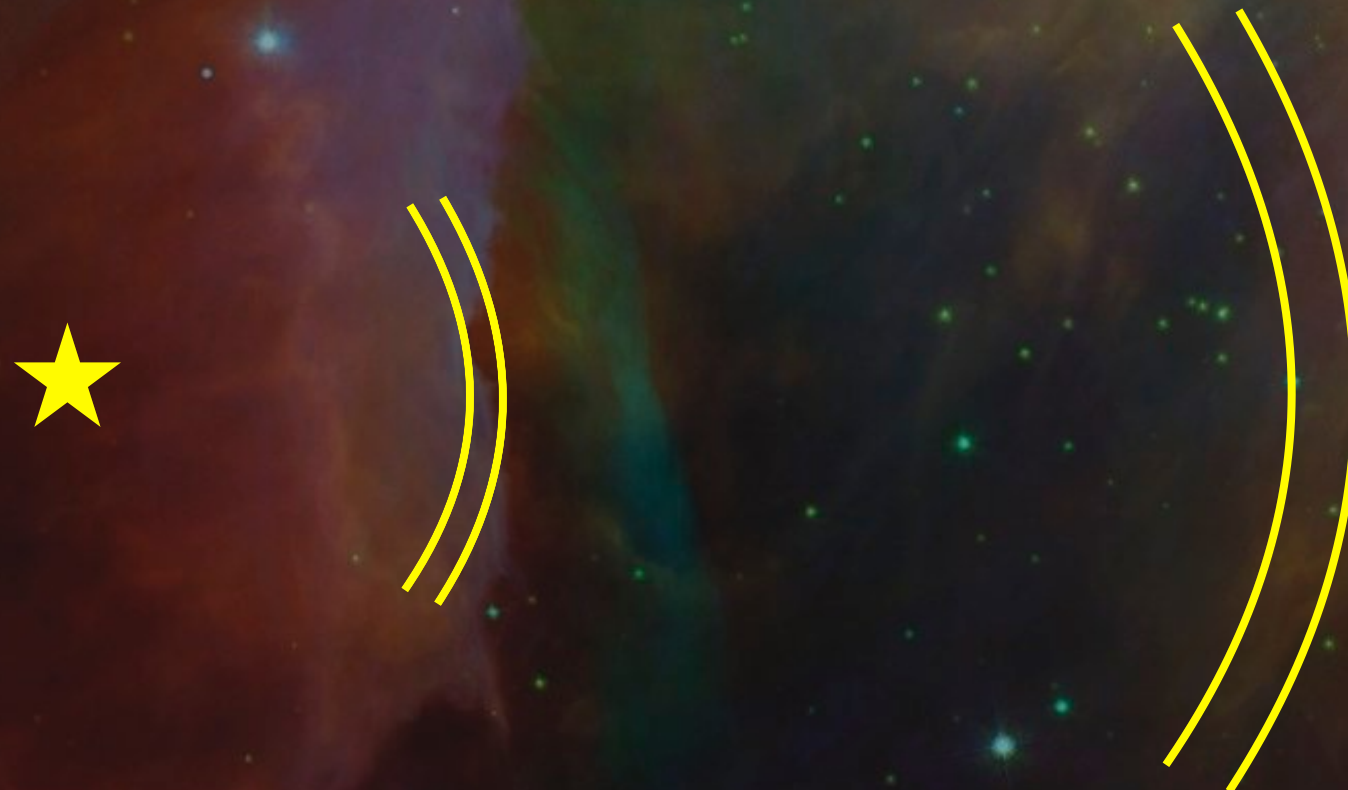


Mark Walker
(Manly Astrophysics)

Overview

- Basic physics of scintillation
- Context: Ionosphere vs. Solar Wind vs. Interstellar
- Current trends in interstellar scintillation

Physics of Scintillations



Waves in vacuum:
Spherical wavefronts,
no scintillation.

Physics of Scintillations

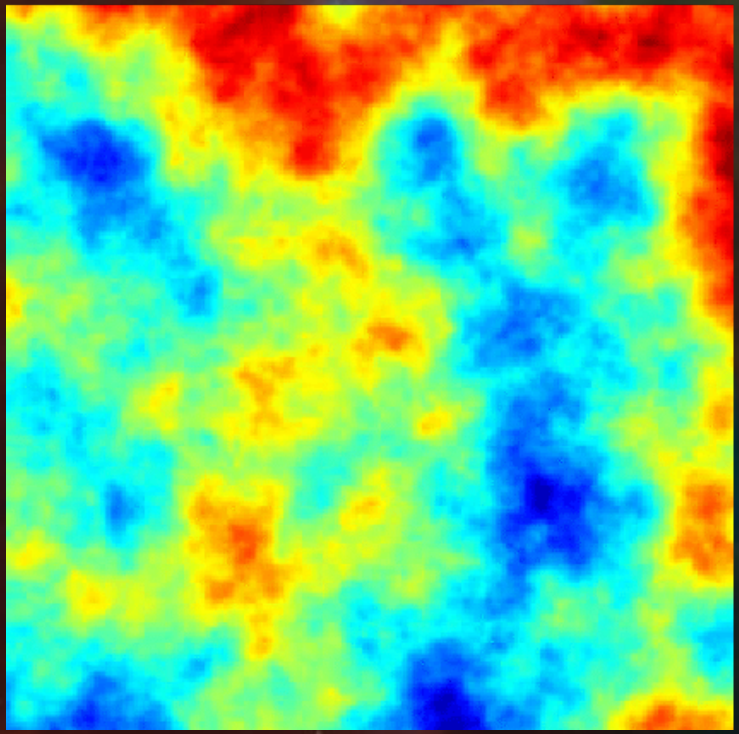
Waves in a medium:
Inhomogeneities introduce phase structure.
Amplitude structure develops gradually
as a result of phase structure.

Physics of Scintillations

"Thin screen" approximation:
phase changes introduced in a single plane.

"Frozen screen" approximation:
no change in screen structure during obs.

Physics of Scintillations



Phase structure imposed on wavefront due to passage through a medium:

$$\phi(x, y) = \frac{2\pi}{\lambda} \int \left\{ n(x, y, z) - 1 \right\} \, \mathrm{d}z$$

In the radio, the dominant refractive index, n, is usually due to ionised gas, so

$$\phi(x, y) \rightarrow -N_e(x, y)\, \lambda\, r_e$$

Classical radius of electron

Calculations of Scintillations

Electric field, u, is calculated via the Fresnel-Kirchoff integral:

$$u = \frac{1}{2\pi i r_F^2} \int \mathrm{d}x \, \mathrm{d}y \; \exp\left(i\phi + i\frac{(x^2 + y^2)}{2r_F^2} \right)$$

Fresnel scale: $r_F = \sqrt{\frac{D\lambda}{2\pi}}$

Plays a key role when $\phi \ll 1$

Calculations of Scintillations

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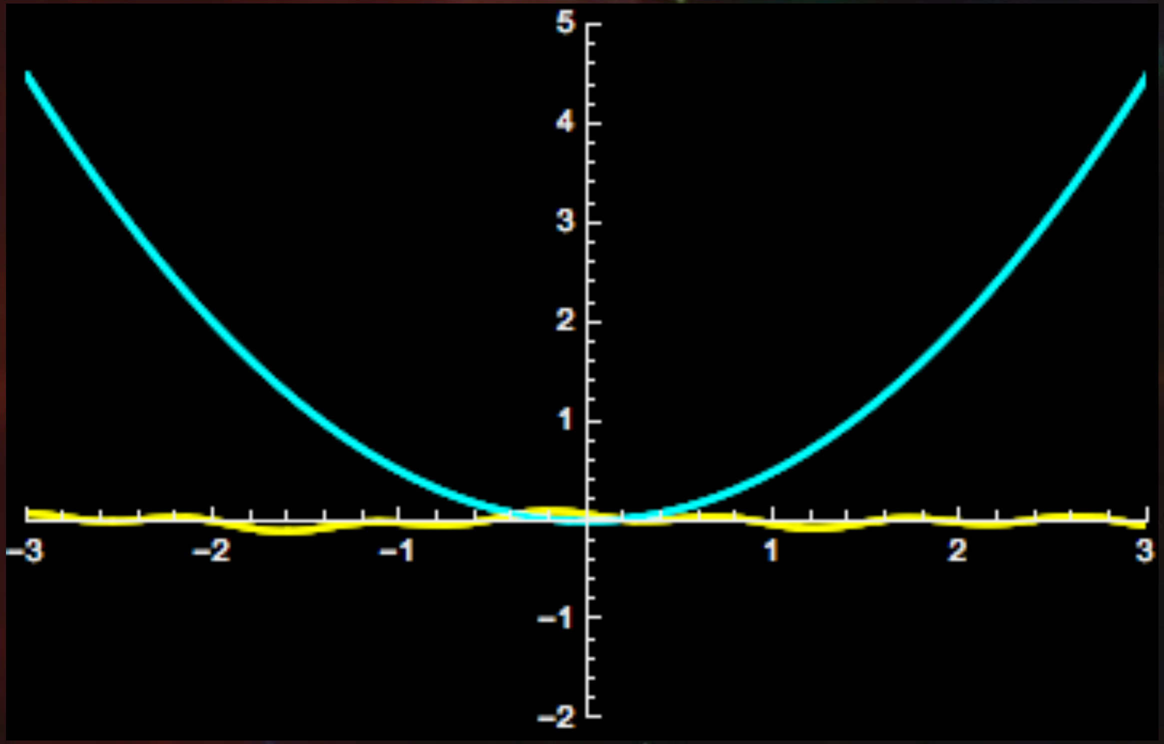
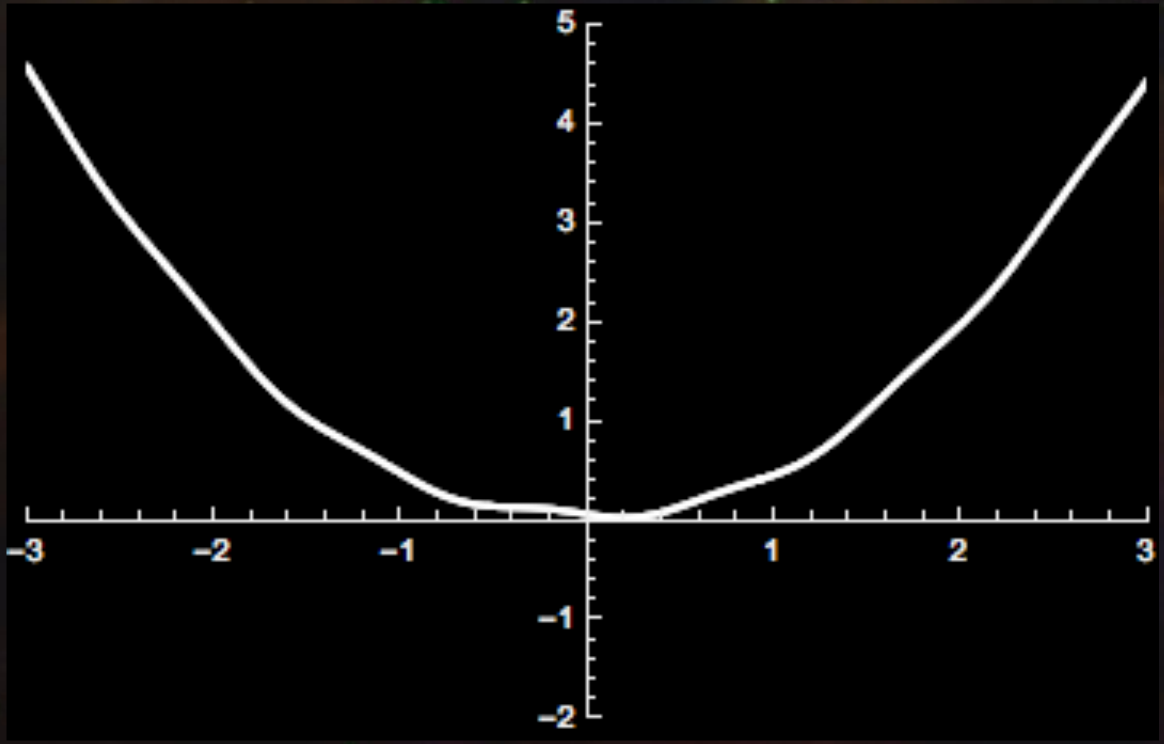
Geometric + Screen



Total Phase



"Weak Scattering"

Manly Astrophysics

Calculations of Scintillations

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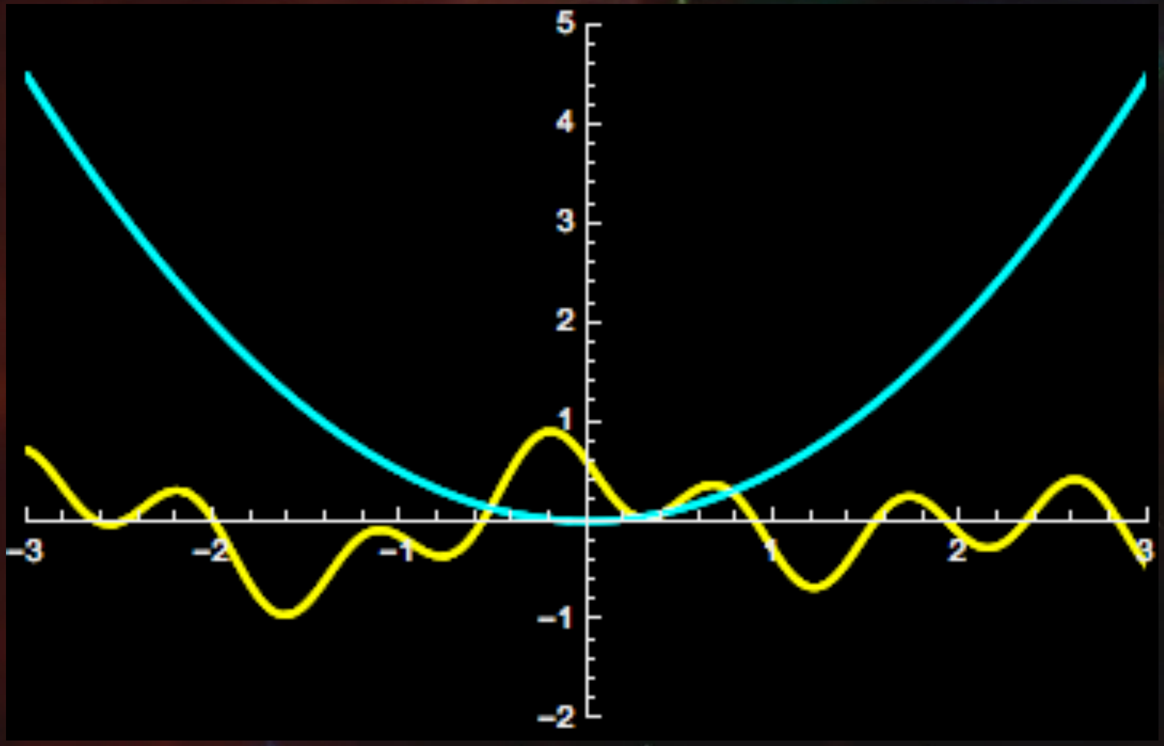
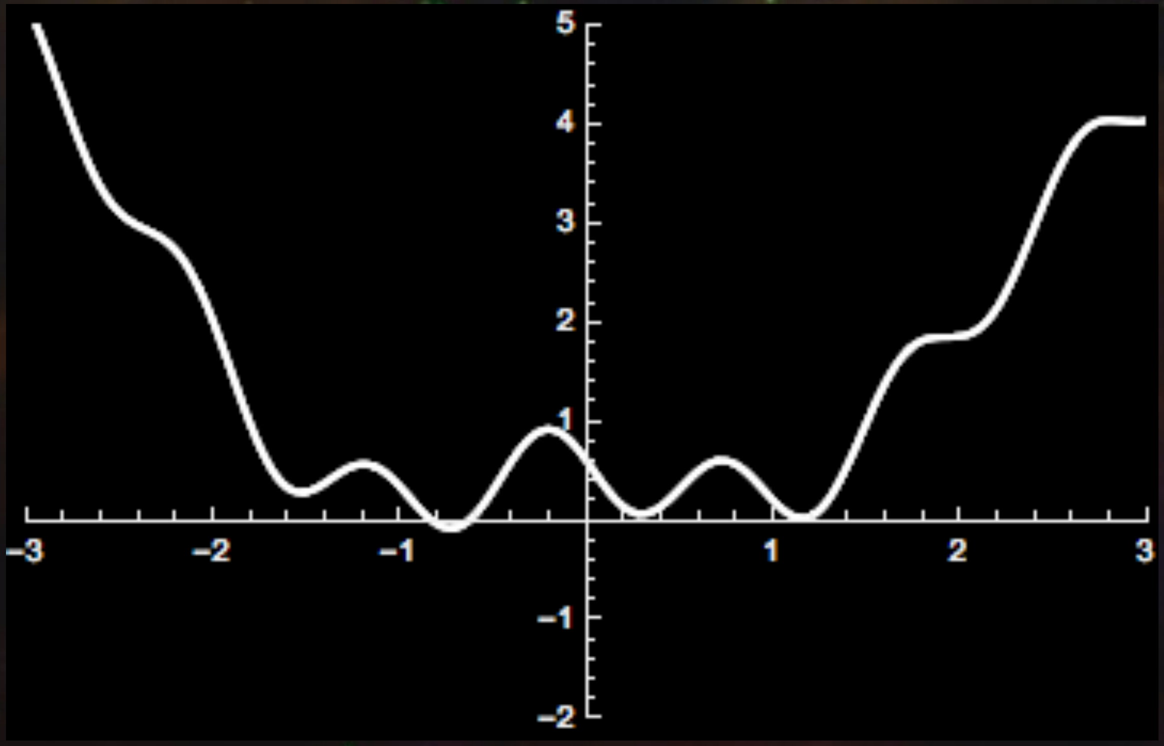


Total Phase

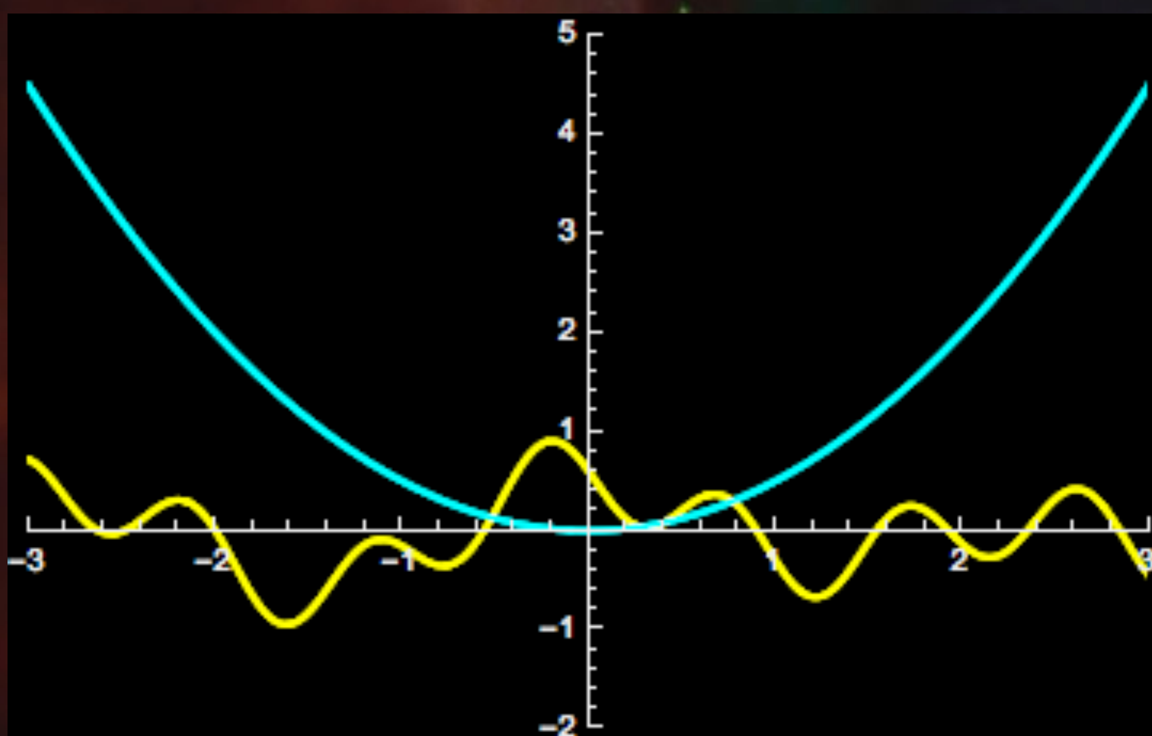


“Strong Scattering”

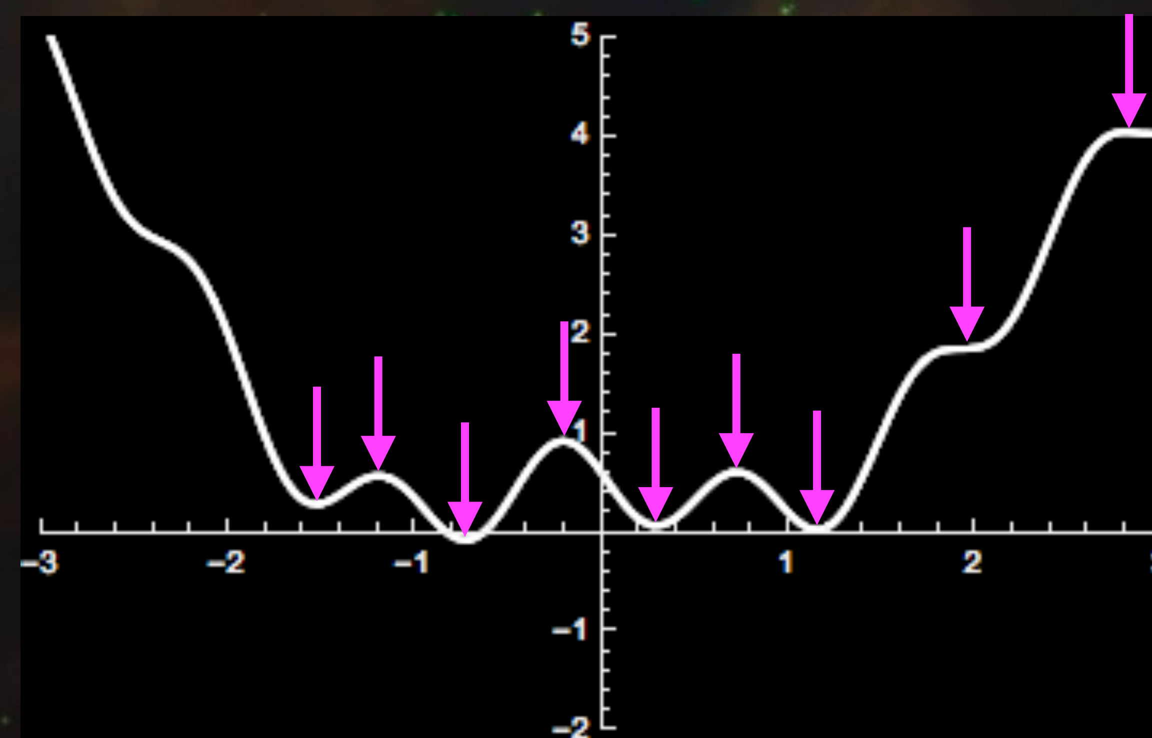
Stationary Phase Points

Real and imaginary parts of the integrand oscillate rapidly.
Except near points of stationary phase.
Those points dominate the total electric field.

Geometric + Screen



Total Phase



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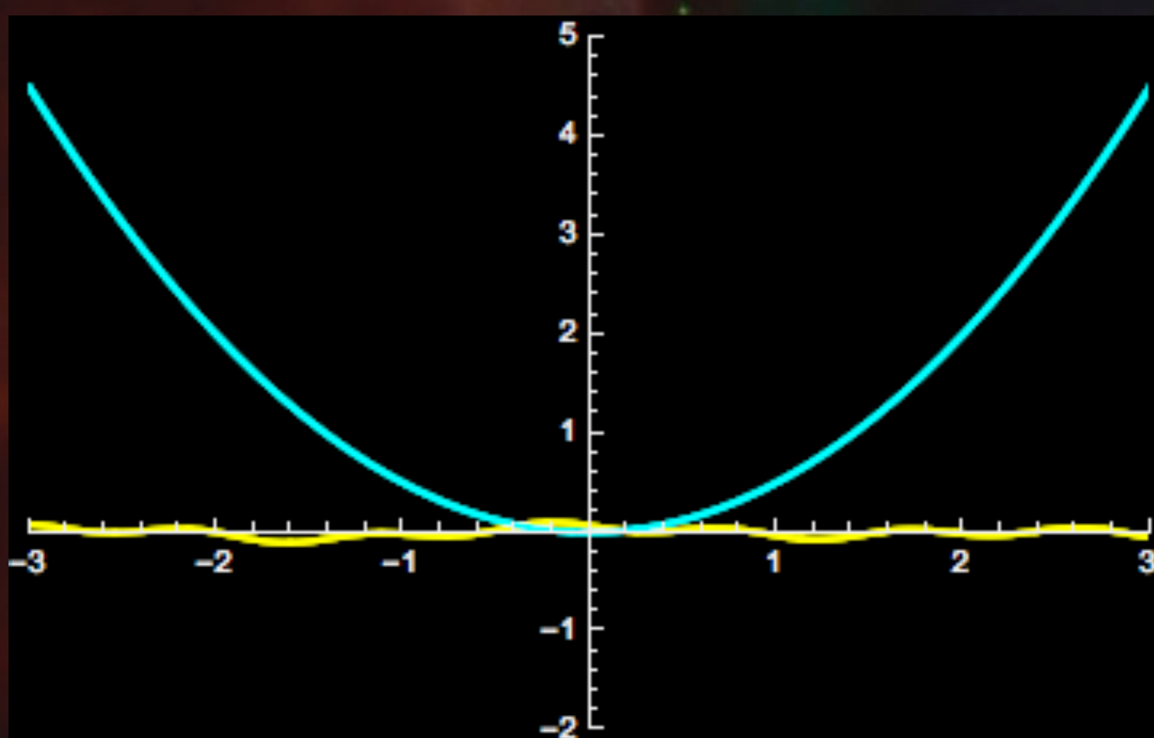
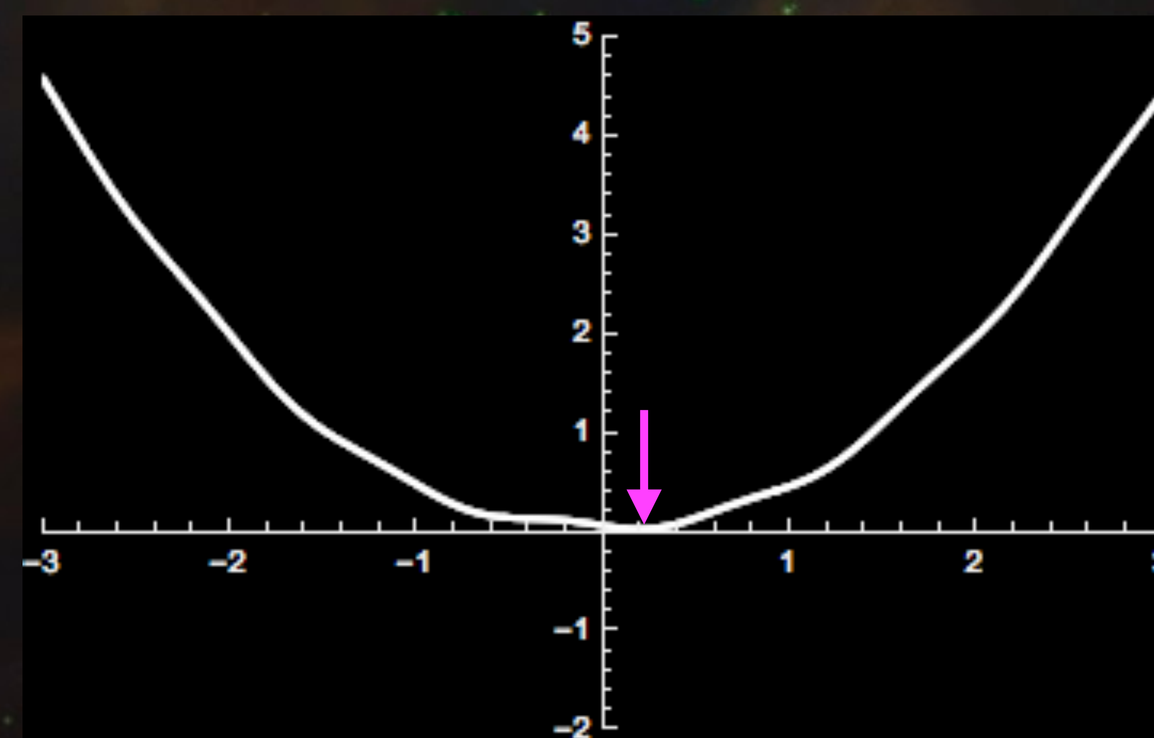


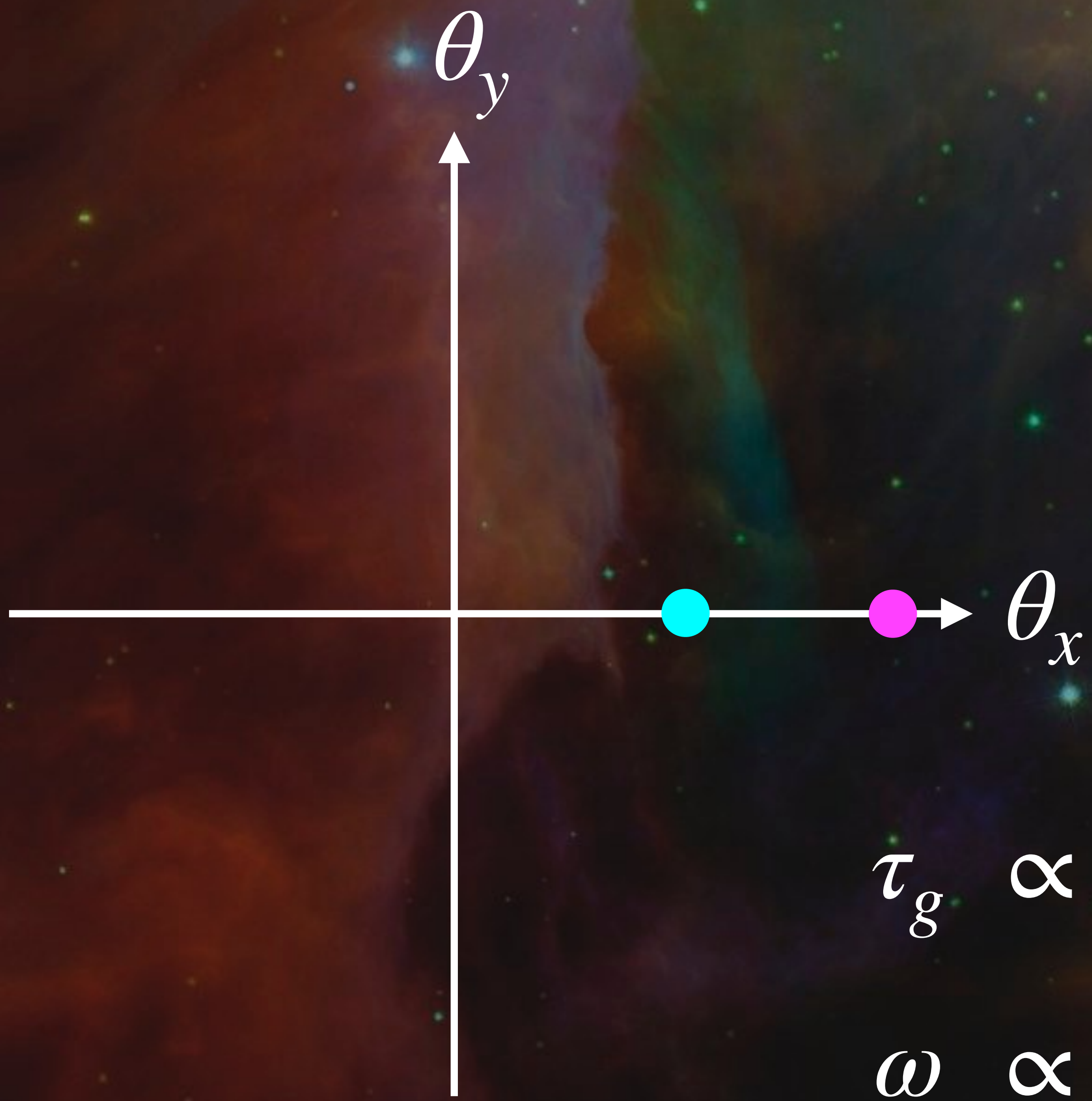
Total Phase

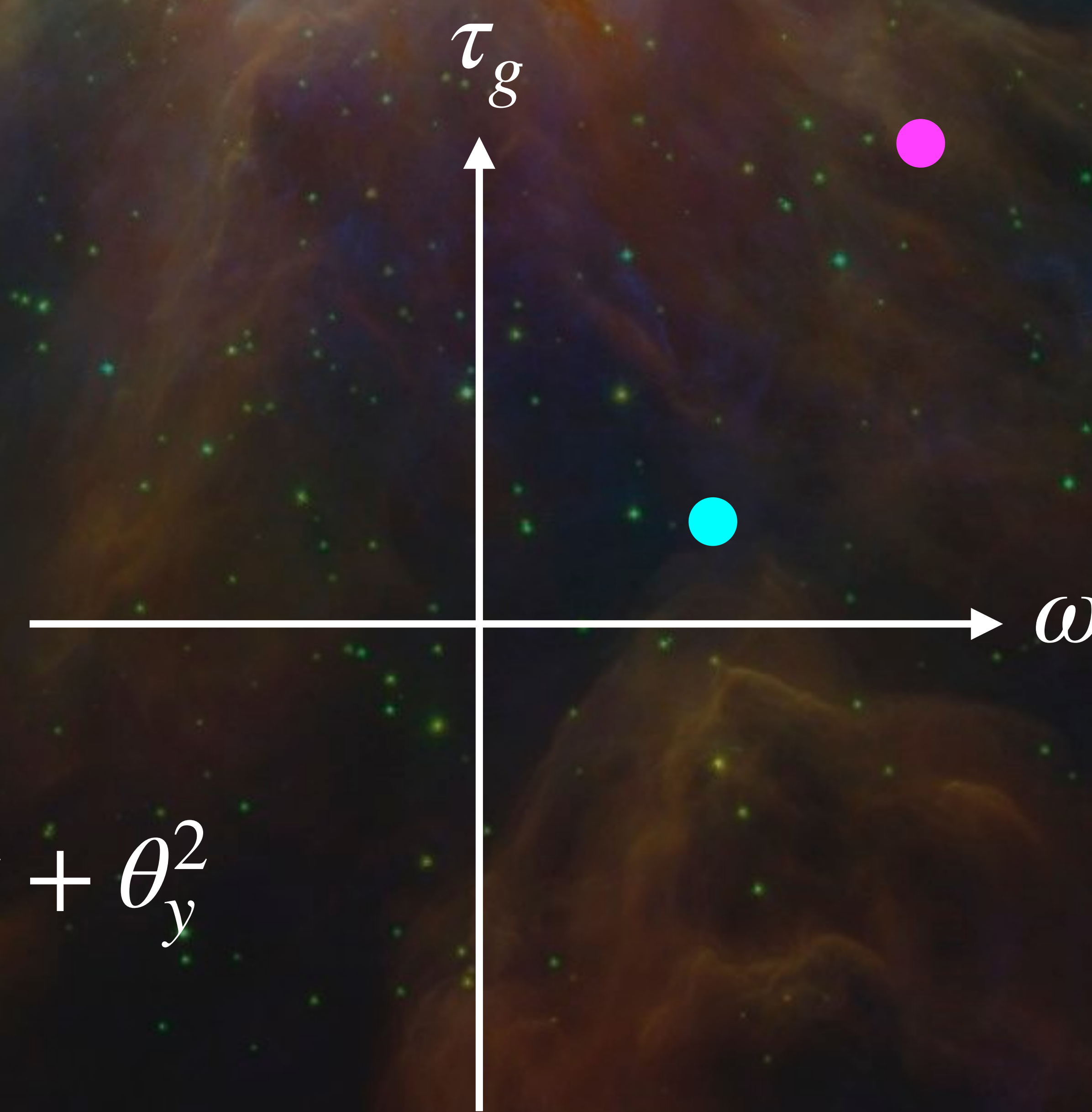


“Weak Scattering”

Manly Astrophysics

Position on sky vs. delay, Doppler

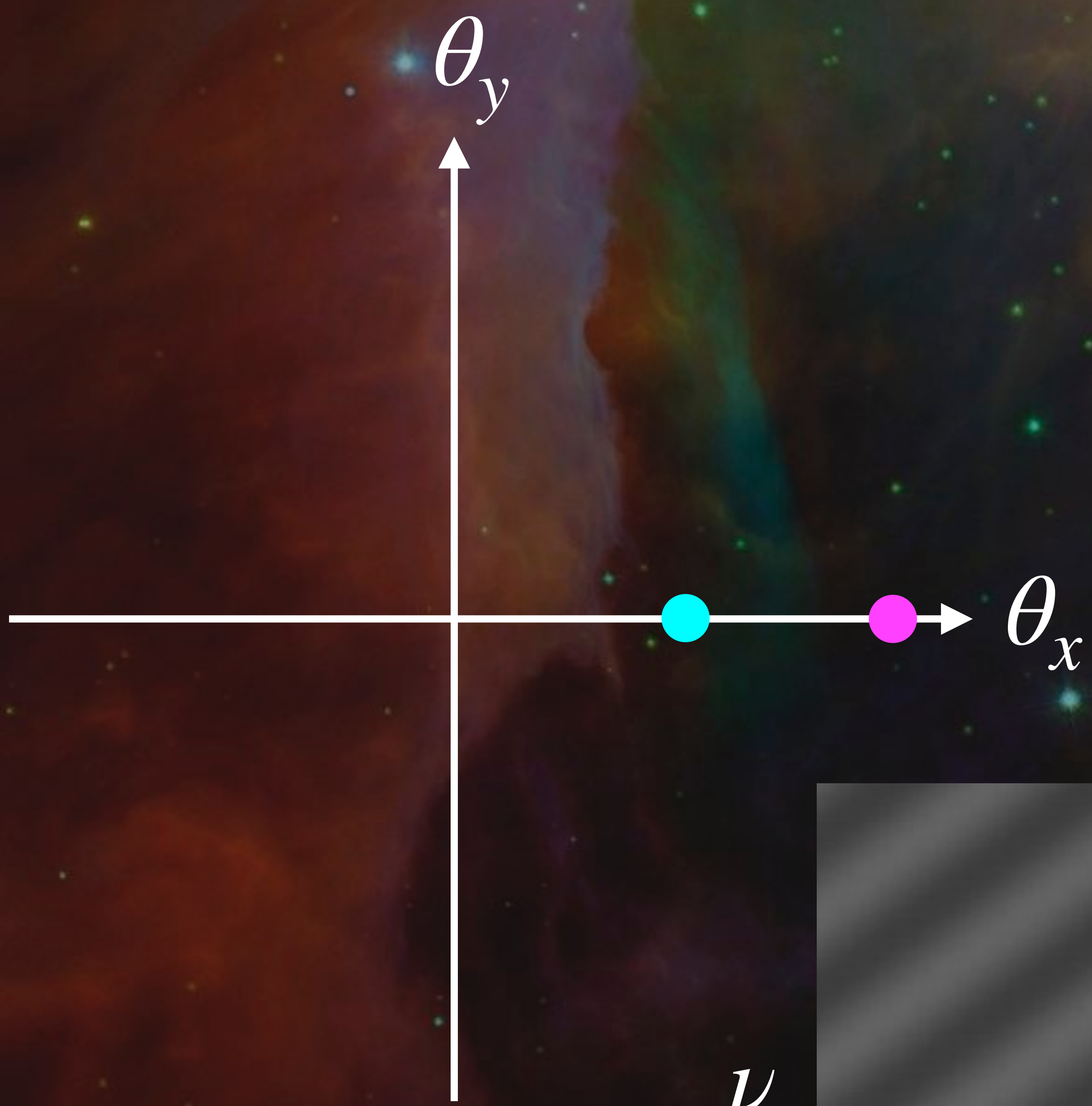


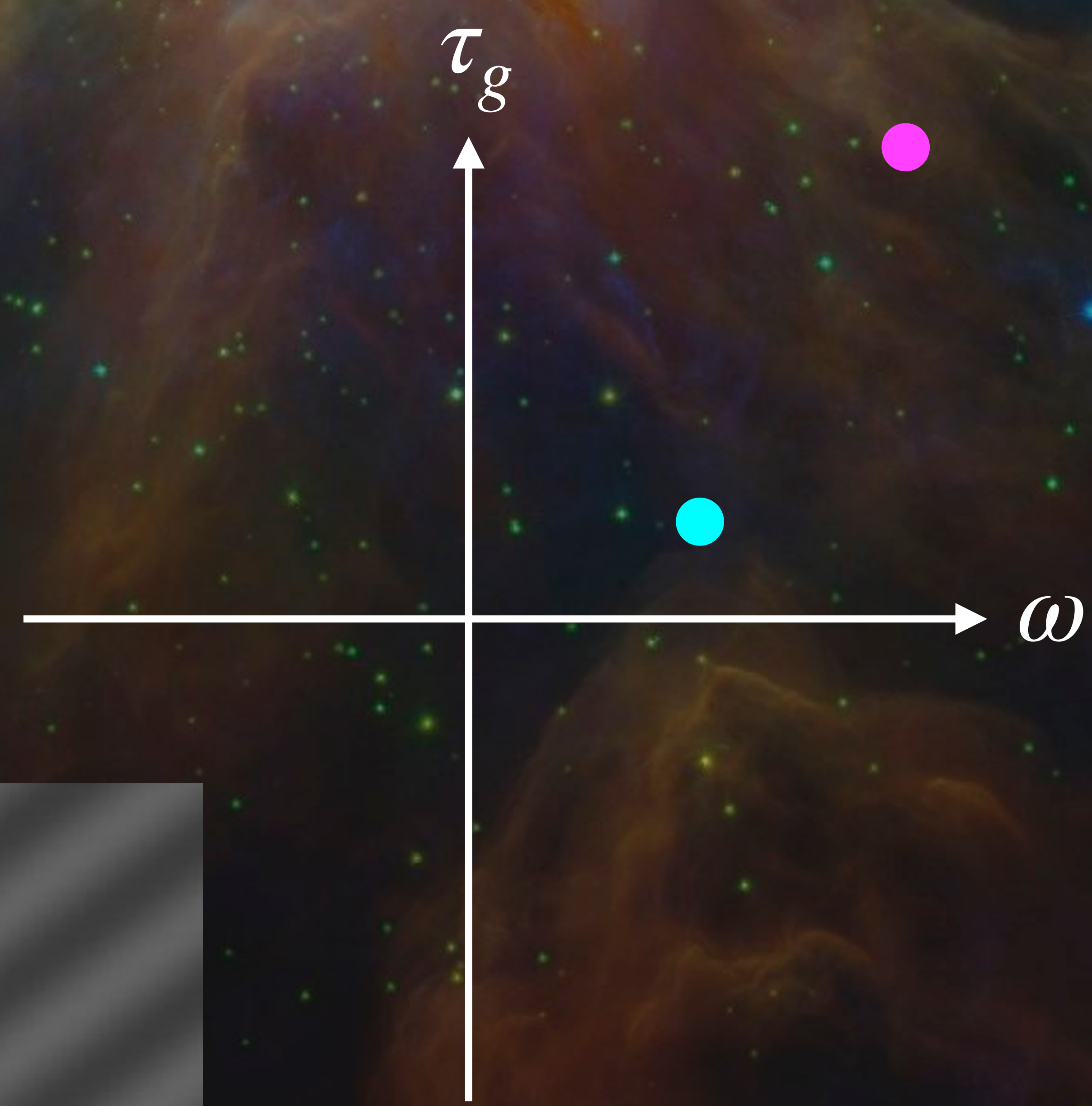


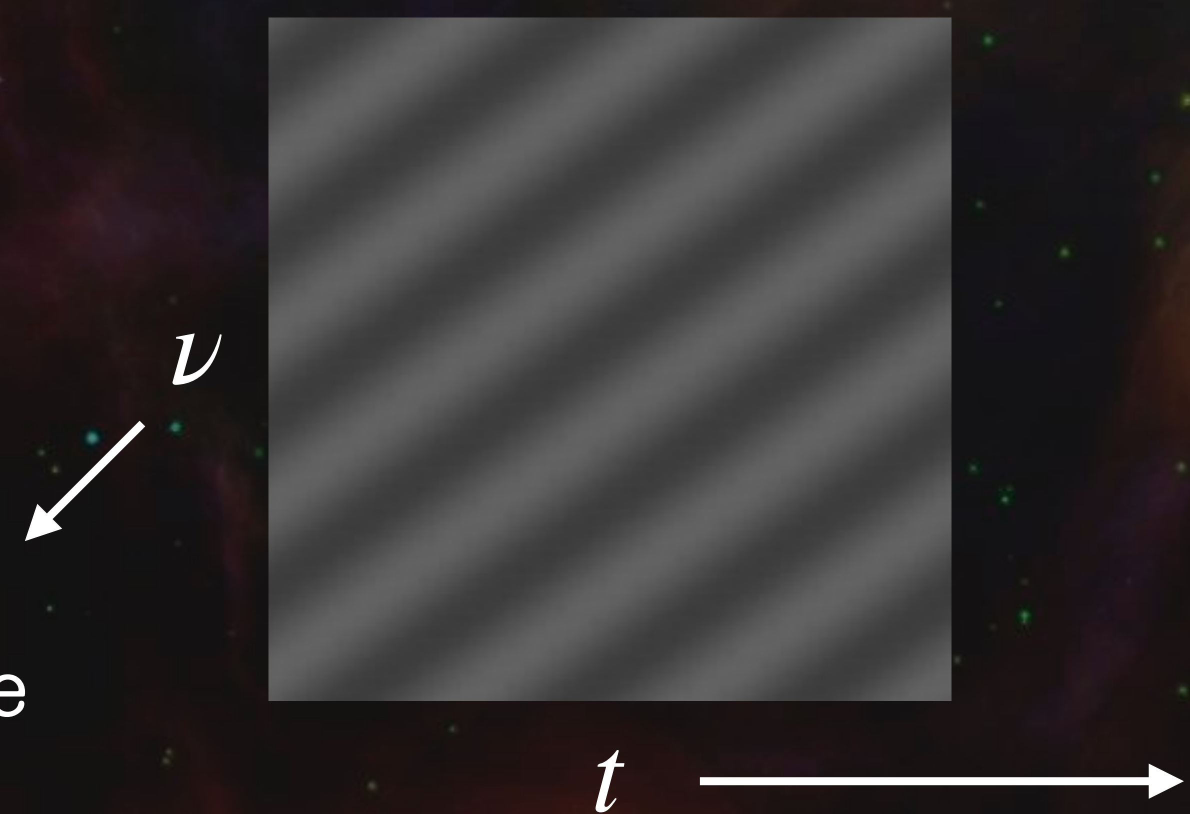
$$\tau_g \propto \theta_x^2 + \theta_y^2$$

$$\omega \propto \theta_x$$

Position on sky vs. delay, Doppler







Radio frequency:
Fourier conjugate
to total delay

Time:
Fourier conjugate
to Doppler-shift

Manly Astrophysics

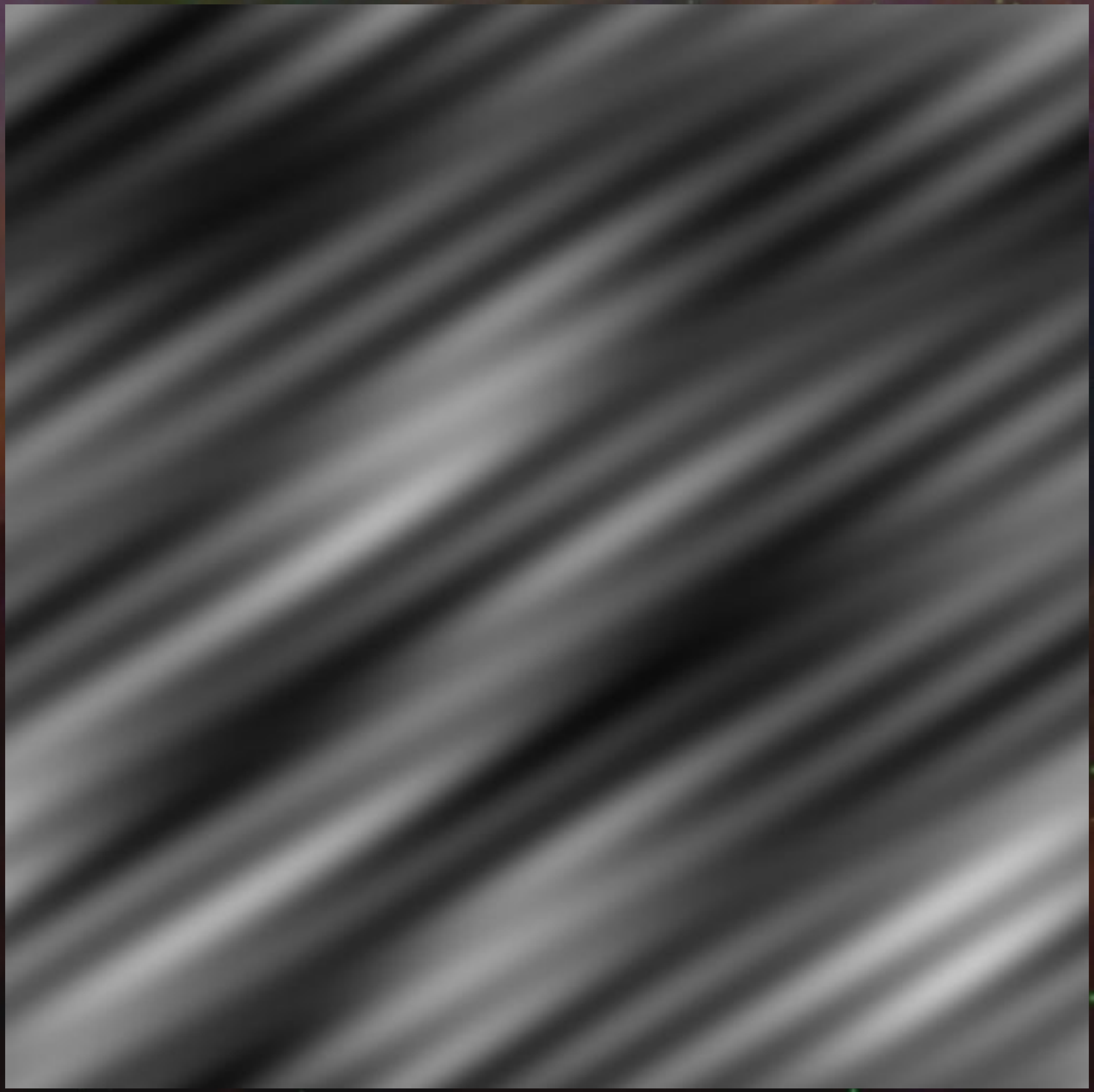
Dynamic Spectrum: built of interference fringes

2 stationary phase points, 1 interference fringe

Dynamic Spectrum: built of interference fringes

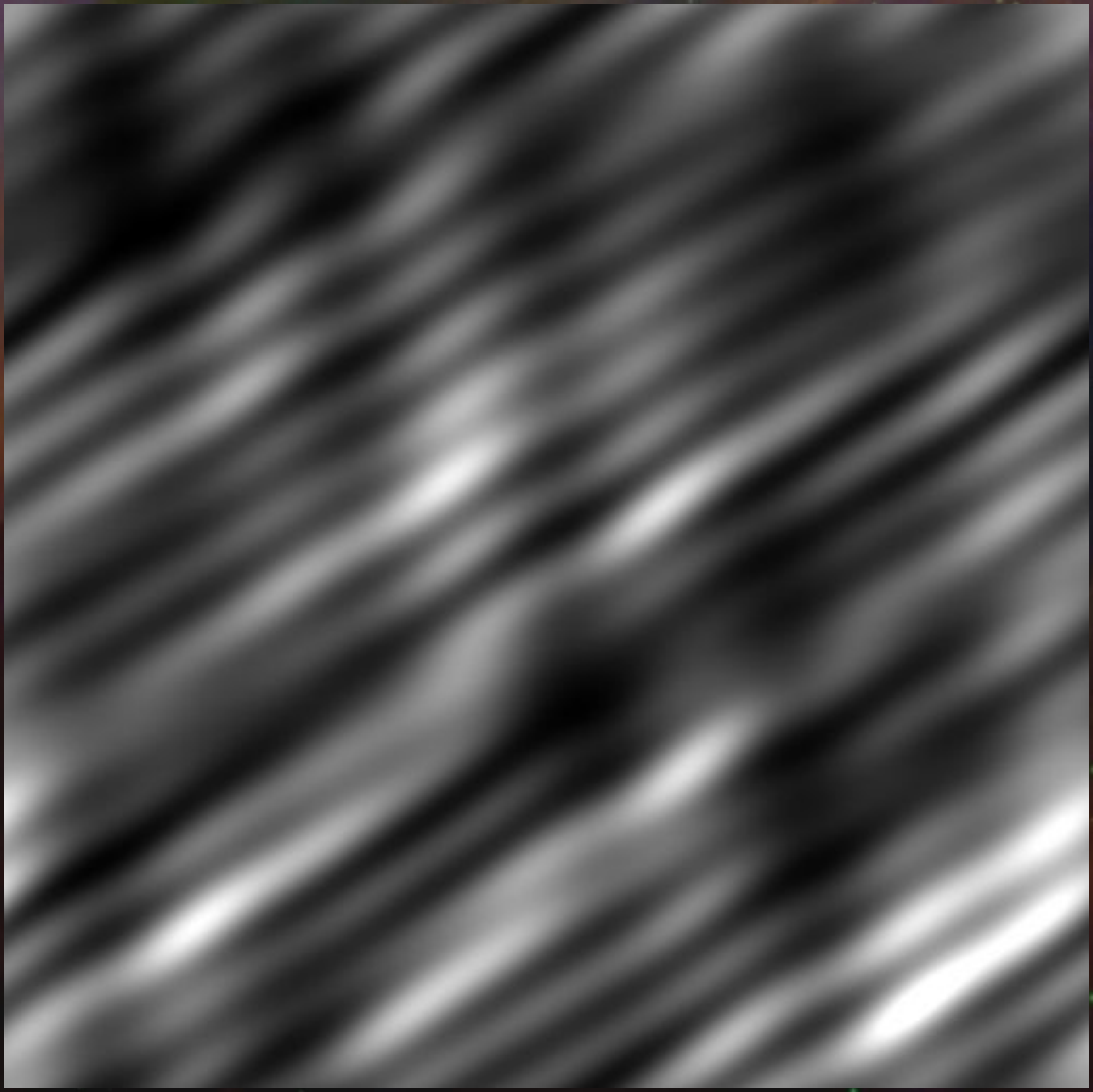
5 stationary phase points, 10 interference fringes

Dynamic Spectrum: built of interference fringes



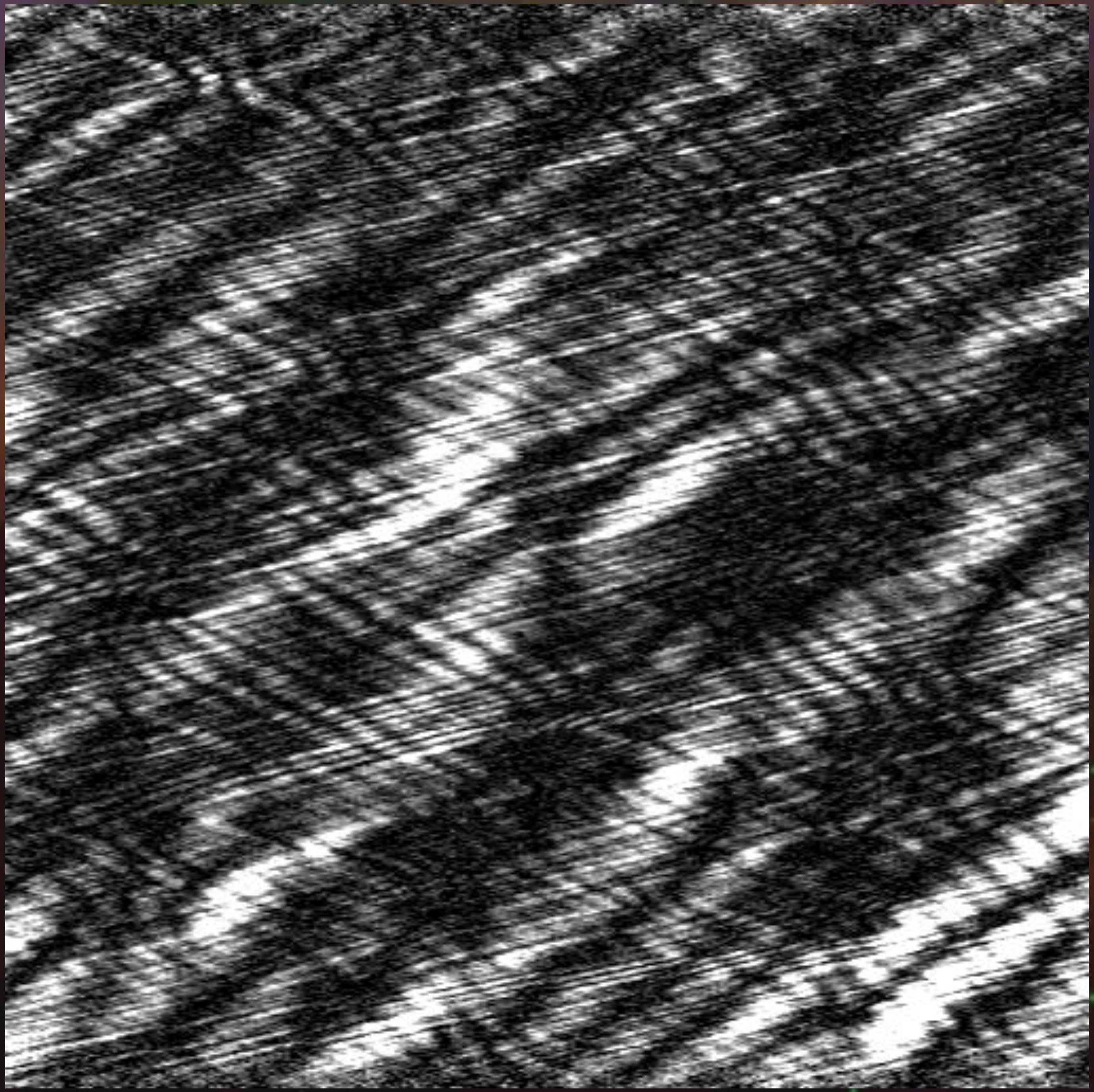
10 stationary phase points, 45 interference fringes

Dynamic Spectrum: built of interference fringes



20 stationary phase points, 190 interference fringes

Dynamic Spectrum: built of interference fringes



8×10^3 stationary phase points, 3×10^7 interference fringes

Strong scattering: separation of scales

"Diffractive Scintillation"
Wave interference yields intensity variations on small spatial (temporal) and frequency scales.

s_0 ↕

$\theta \sim \lambda / s_0$

$s_0 =$ Field coherence scale
$=$ Diffractive scale

Strong scattering: separation of scales

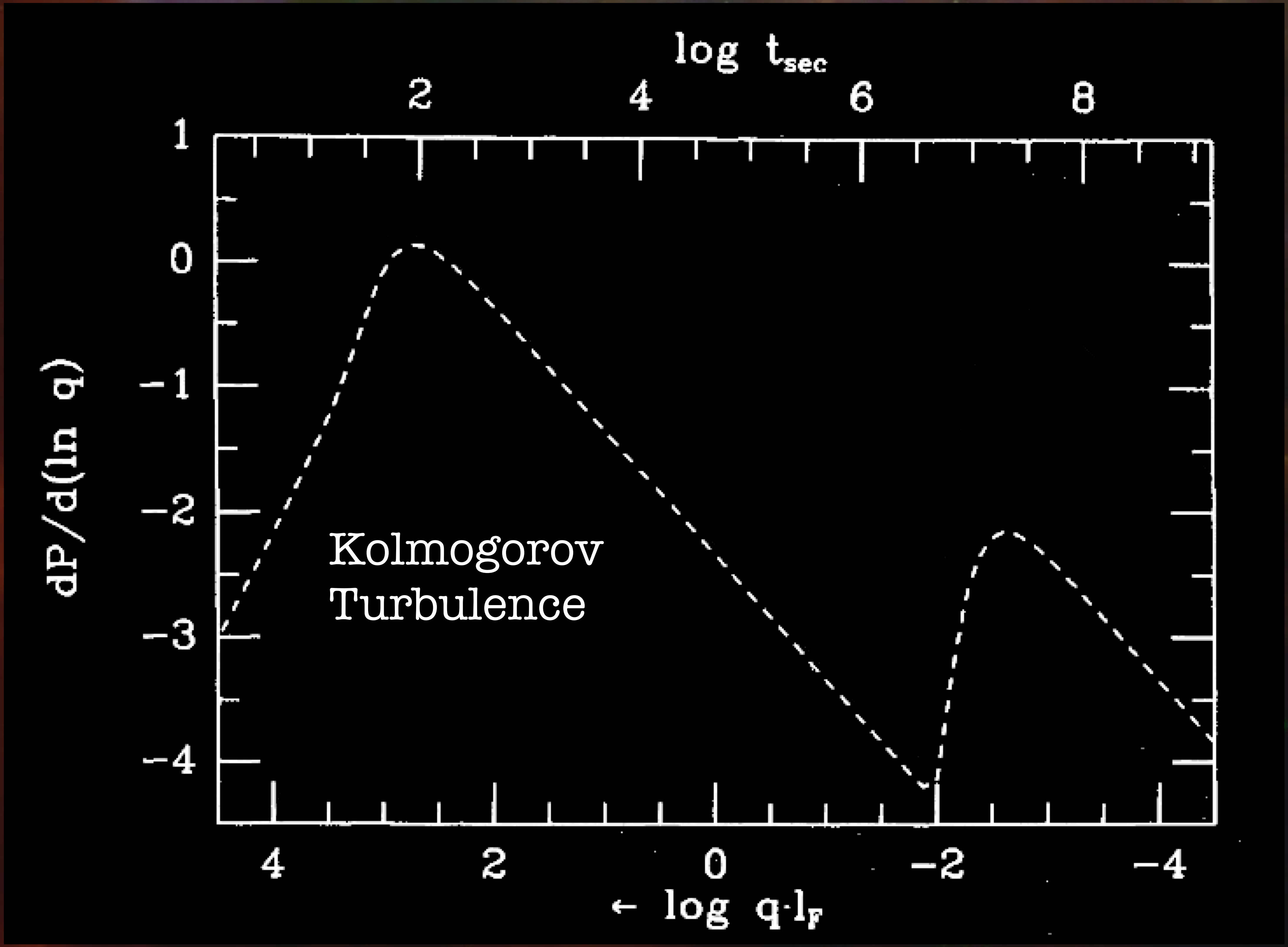
"Diffractive Scintillation"
Wave interference yields intensity variations on small spatial (temporal) and frequency scales.

"Refractive Scintillation"
(De)Focusing yields intensity variations on large spatial (temporal) and frequency scales.

$$L = \text{Refractive scale}$$
$$= D\lambda / s_0$$

Refractive and Diffractive Scintillations

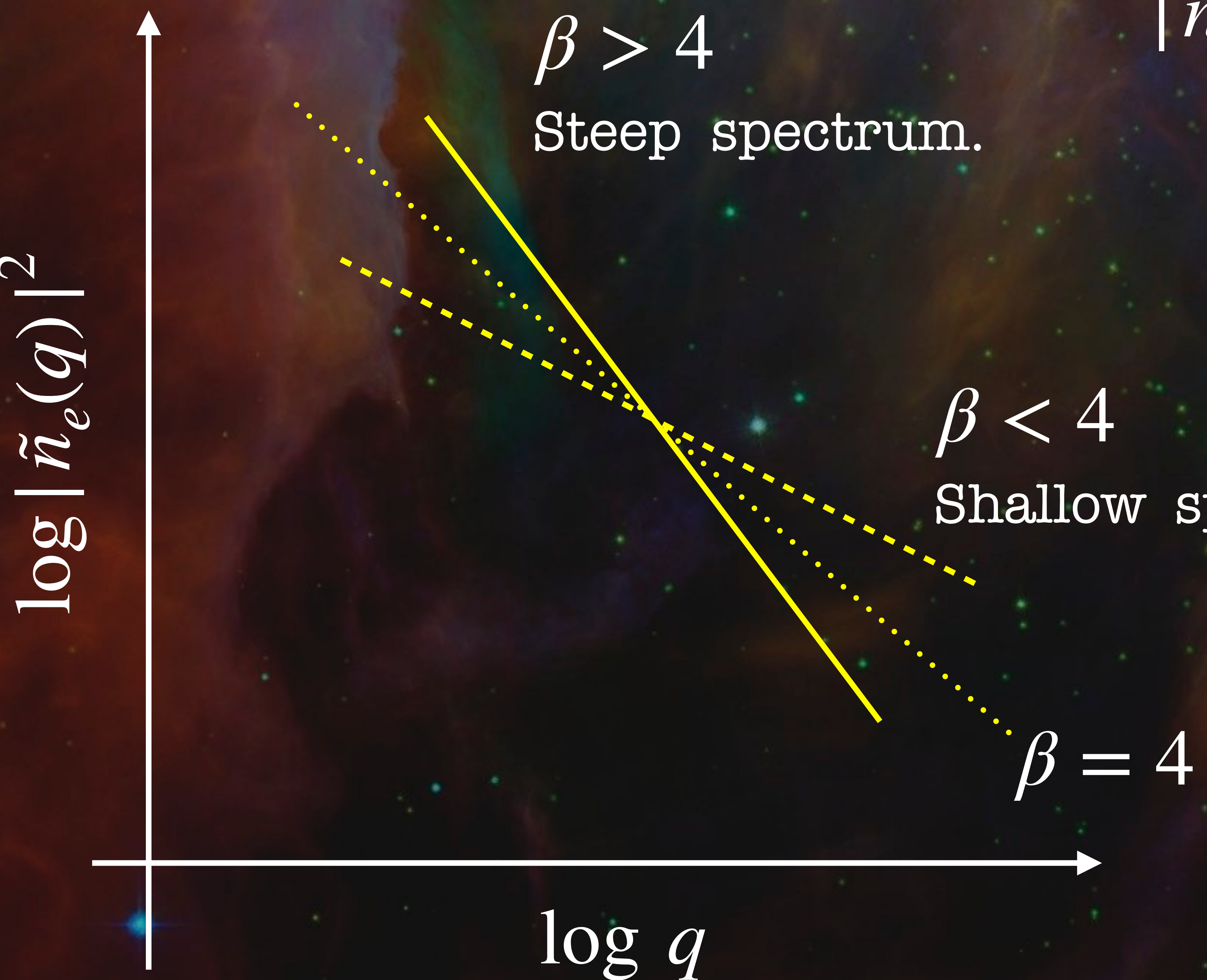
Goodman & Narayan 1985 MNRAS



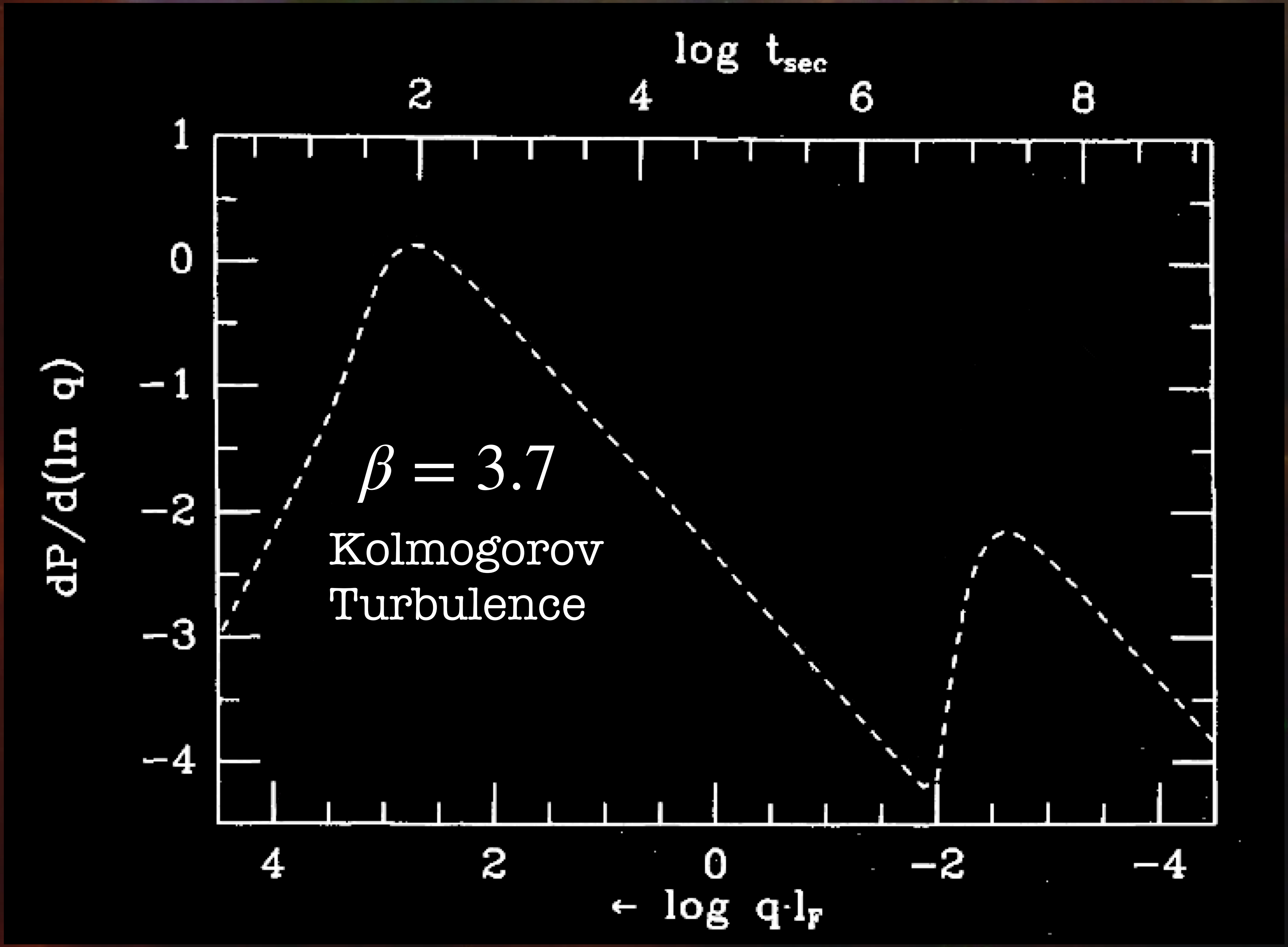
Manly Astrophysics

Steep vs. shallow density fluctuation spectra

$$|\tilde{n}_e(q)|^2 \propto q^{-\beta}$$



Steep vs. shallow fluctuation spectra



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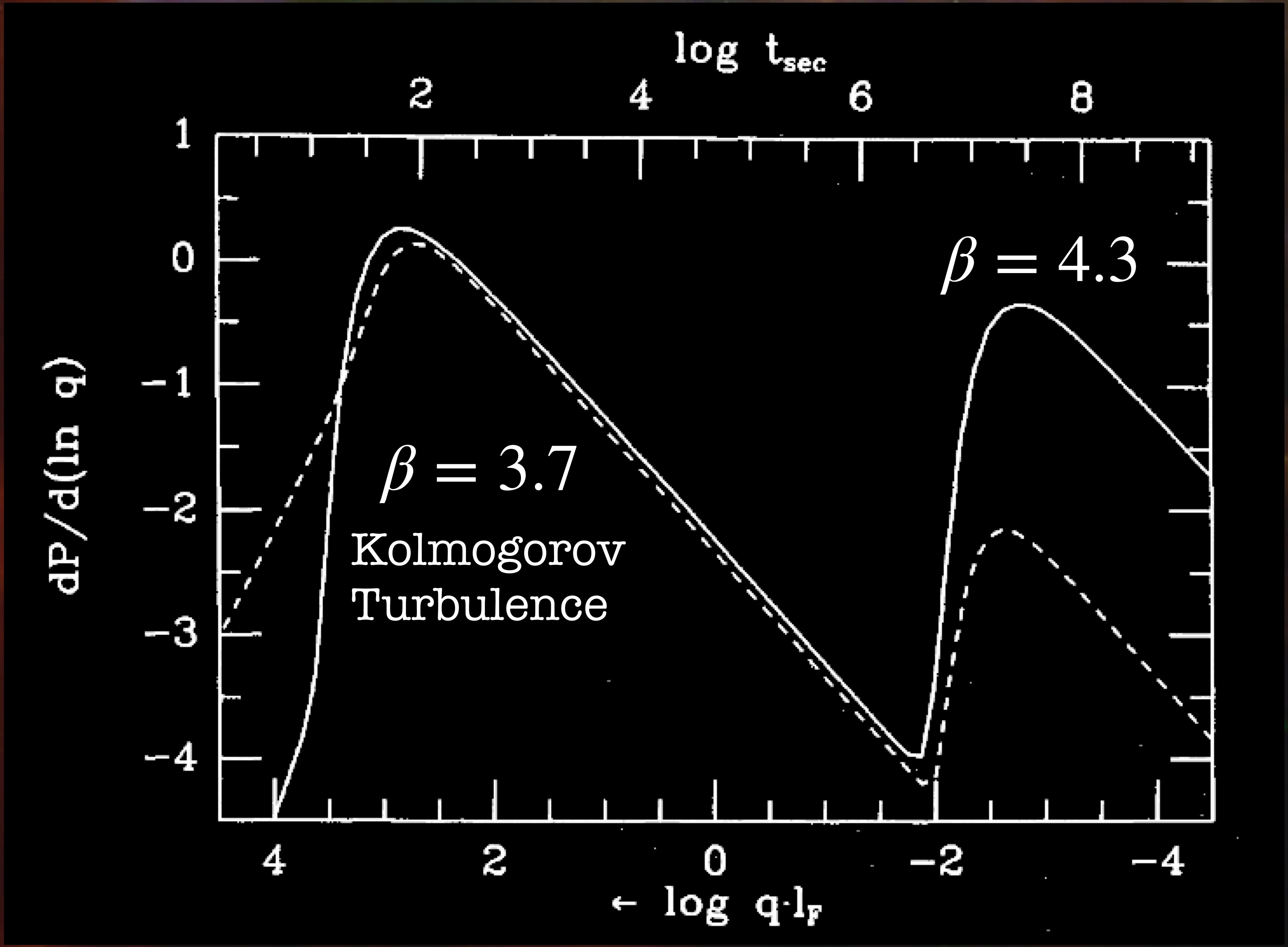
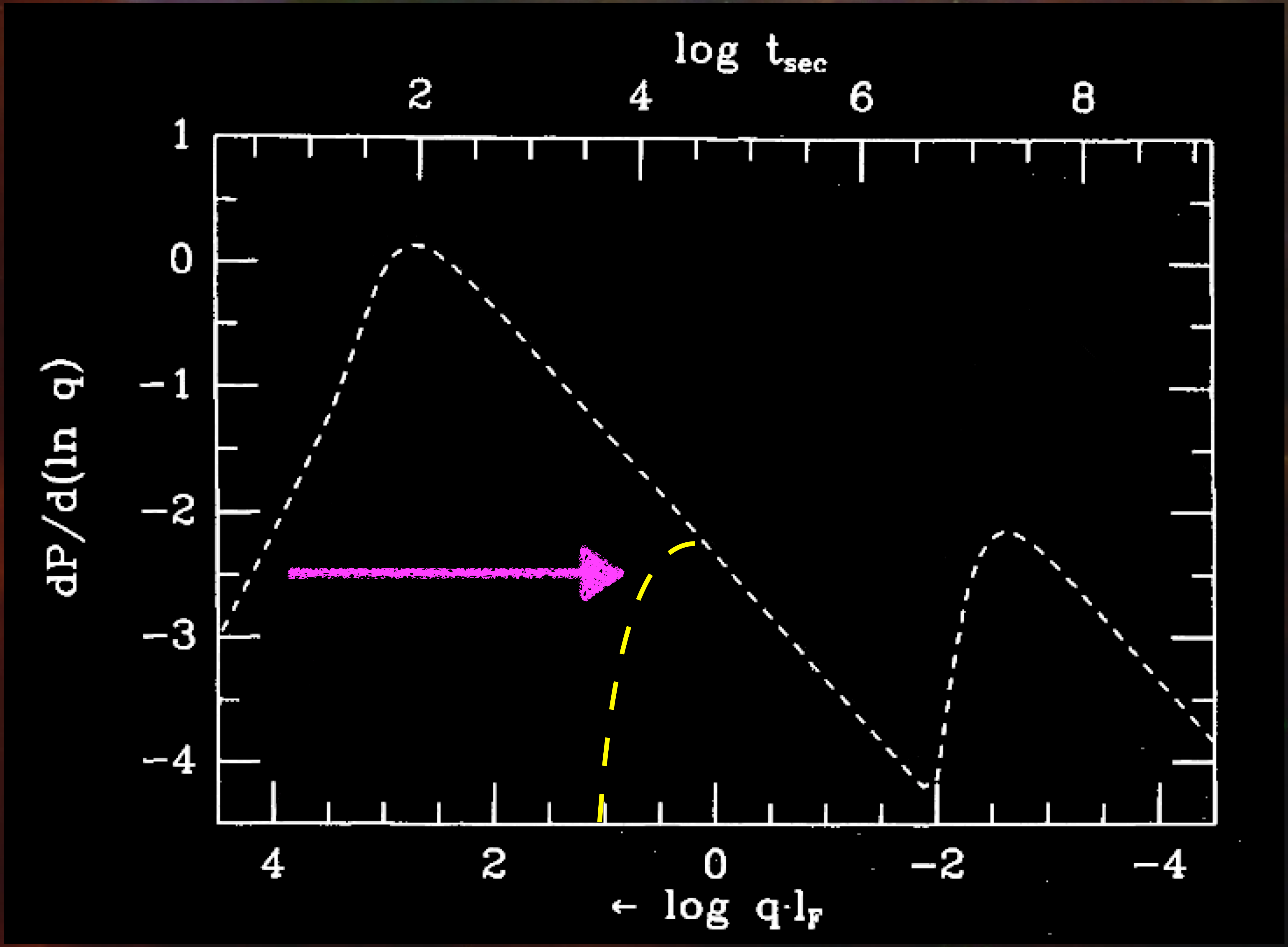


Manly Astrophysics

Influence of source size: Smoothing of small-scale structure



Context

Screen Distance: Log_{10} D(m)

Fresnel scales @ 1 GHz

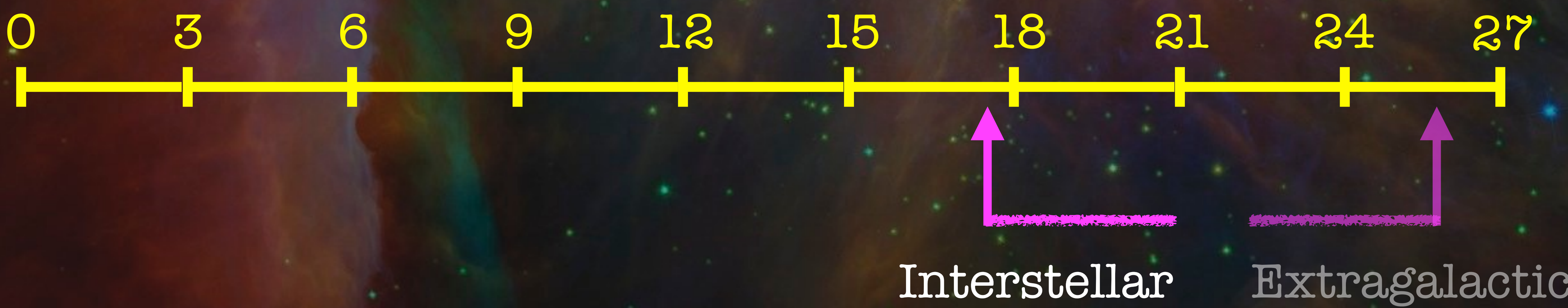
$\theta_F \sim 4$ nano-arcsec

$t_F \sim 1$ month

Sources: ?? Fast Radio Bursts ?? (Terra Incognita)

Context

Screen Distance: Log_{10} D(m)



Fresnel scales @ 1 GHz

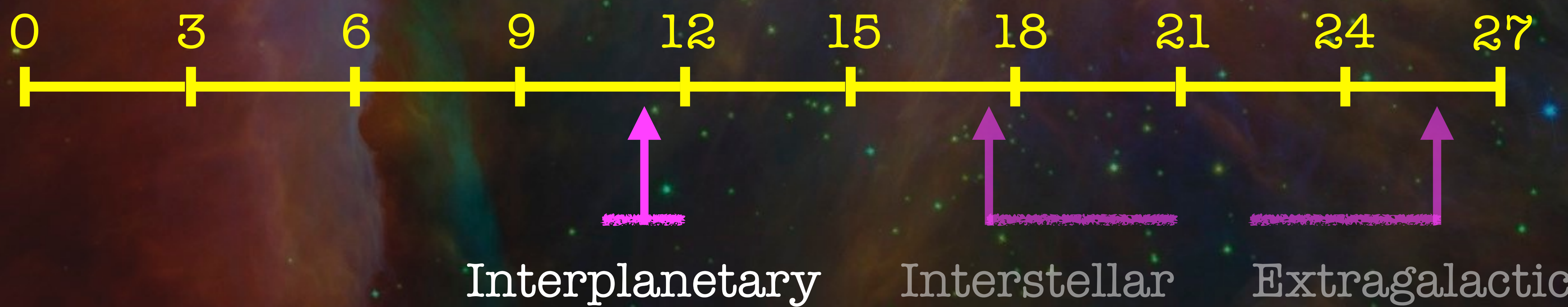
$\theta_F \sim 80\ \mu$arcsec

$t_F \sim 2$ hours

Sources: quasars and pulsars

Context

Screen Distance: Log_{10} D(m)

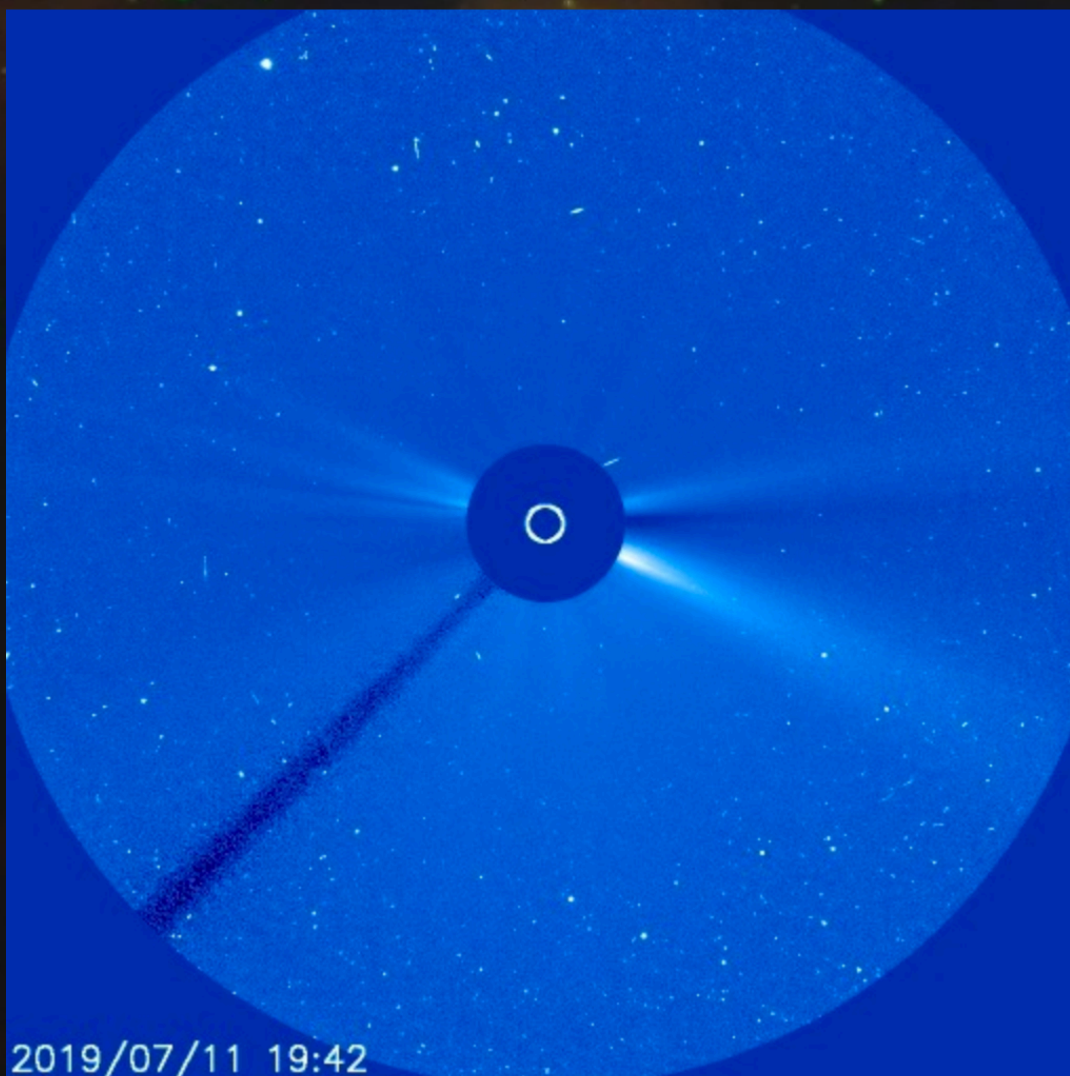


Fresnel scales @ 1 GHz

$\theta_F \sim 0.1$ arcsec

$t_F \sim 0.4$ seconds

Sources: quasars



Context

Screen Distance: Log_{10} D(m)

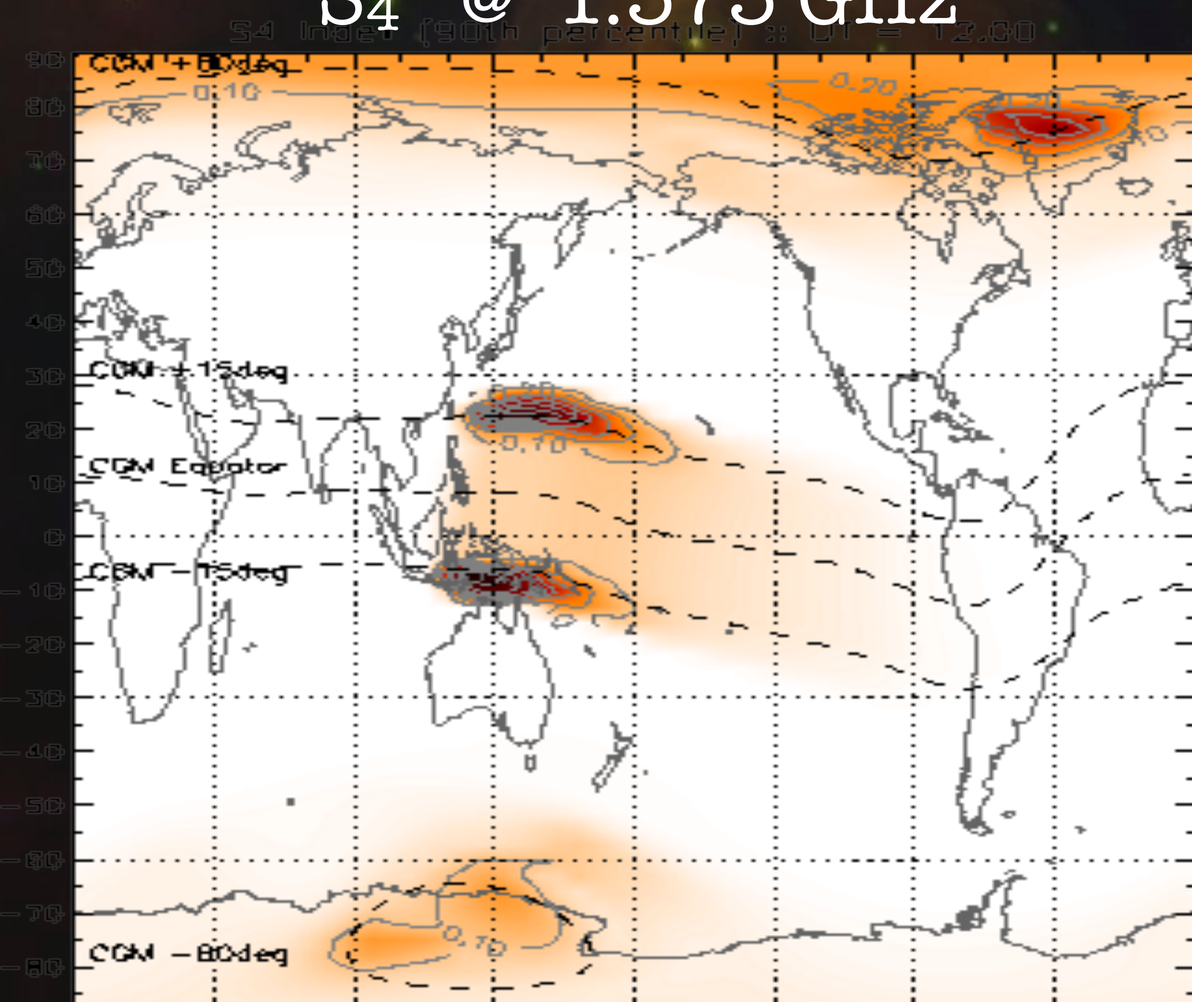
Fresnel scales @ 1 GHz

$\theta_F \sim 1$ arcmin

$t_F \sim 50$ msec

Sources: quasars and satellites

S_4 @ 1.575 GHz



Manly Astrophysics

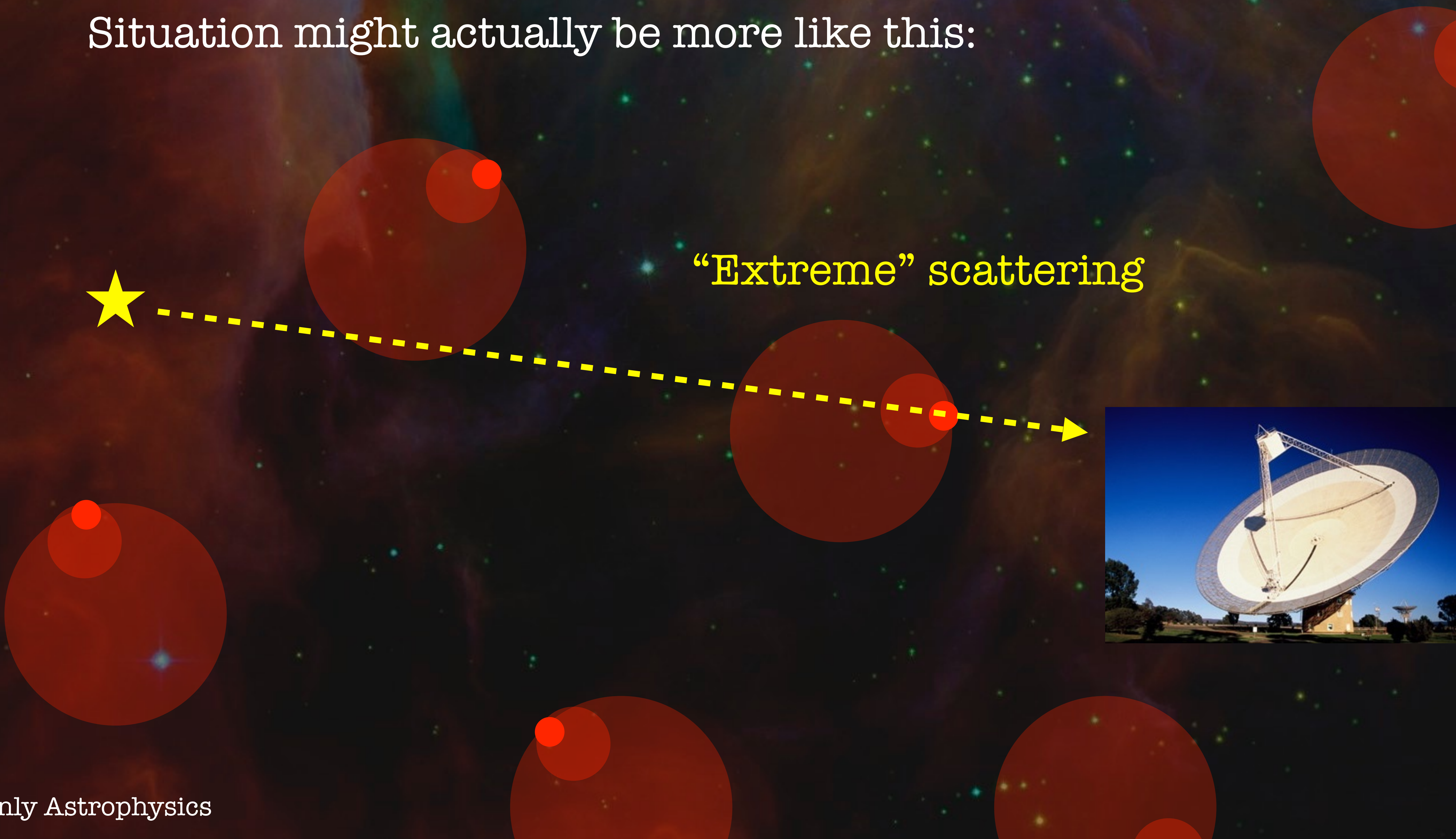
Trends in Interstellar Scintillation

"Reference model": distributed Kolmogorov turbulence

But ...

Several phenomena that don't fit: "Extreme Scattering"

Situation might actually be more like this:



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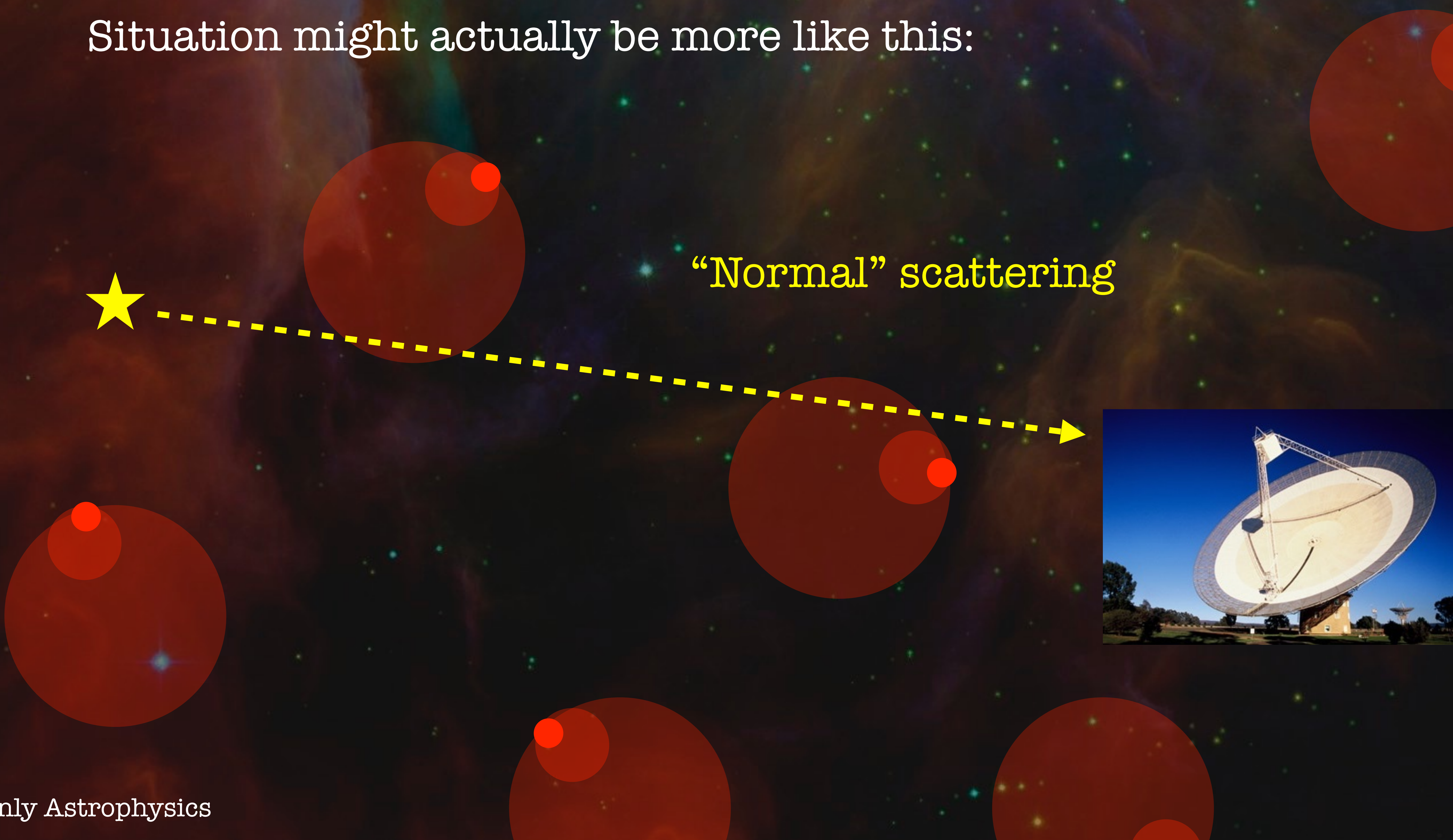

Trends in Interstellar Scintillation

"Reference model": distributed Kolmogorov turbulence

But …

Several phenomena that don't fit: "Extreme Scattering"

Situation might actually be more like this:

Super-strong scattering screens

Size of order $10^{12.5}$ m ?

Highly Anisotropic

Pressure >> Ambient ?

Extreme screens are far more numerous than stars.

What are these extreme screens??

Trends in Interstellar Scintillation

- Modern backends have high information capture rate
  - Great for pulsar spectroscopy
- Detailed analyses of pulsar data
  - "Secondary Spectrum" analysis
  - Holographic approaches
    - Cyclic spectroscopy
- Kinematics and distribution of local screens
  - IntraHour Variable quasars (annual cycles)
- New GHz radio telescopes with high survey speed
  - MEERKAT, APERTIF (Westerbork), ASKAP
  - Expect many new IntraHour Variables