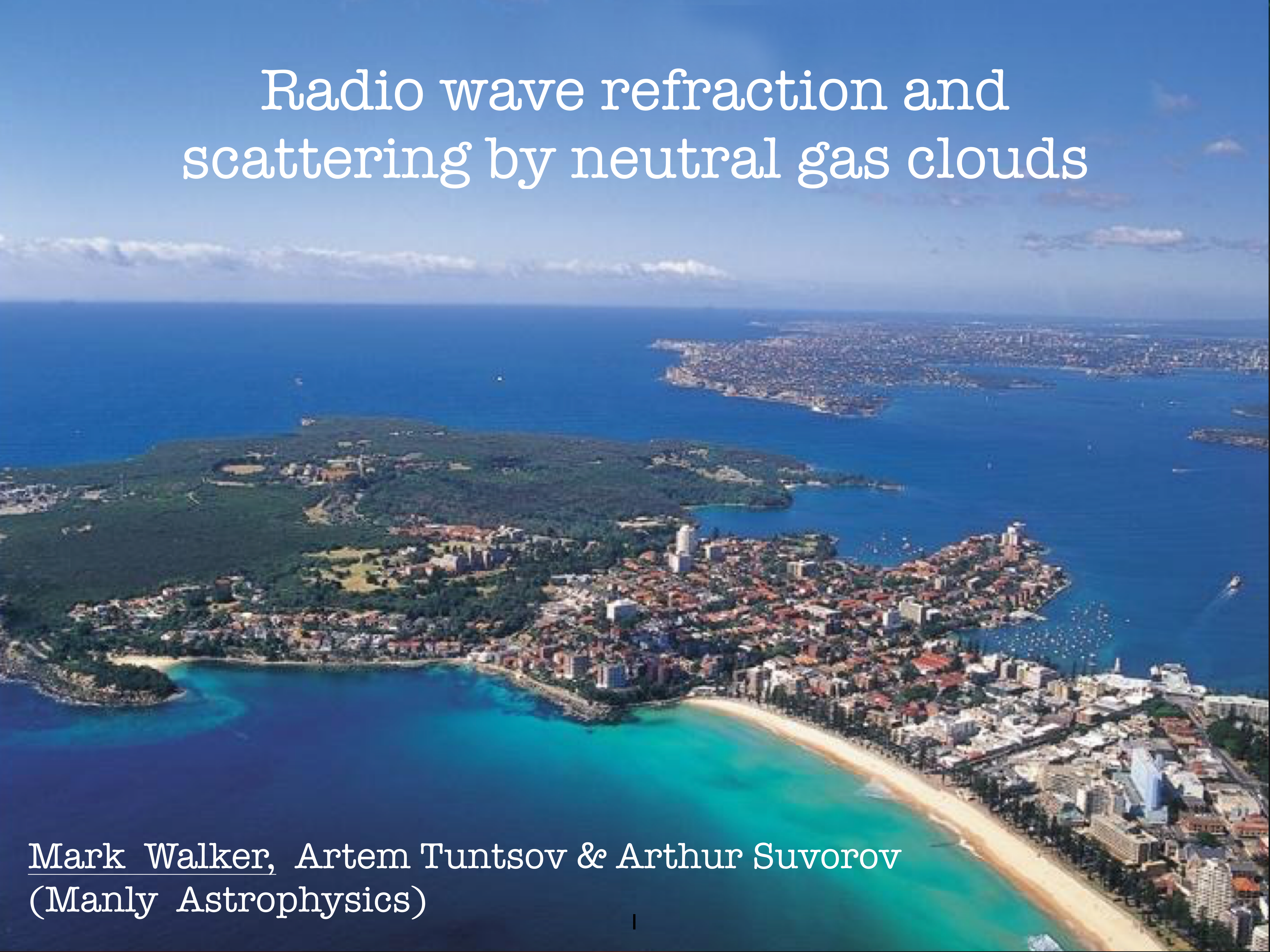


Radio wave refraction and scattering by neutral gas clouds

Mark Walker, Artem Tuntsov & Arthur Suvorov
(Manly Astrophysics)

Caveat

Neutral gas in the ISM will have associated plasma:
UV photons @ surface + interior cosmic-ray ionisation.
But I'm going to say nothing about plasma lensing.

Gas lensing literature

Draine (1998) ApJL, 509, L41
Rafikov & Draine (2000) ApJ, 547, 207
Moniez++ (2013) SPPhys 148, 45
Tuntsov & Walker (2022) MNRAS, 513, 2491

Why spend time on this?

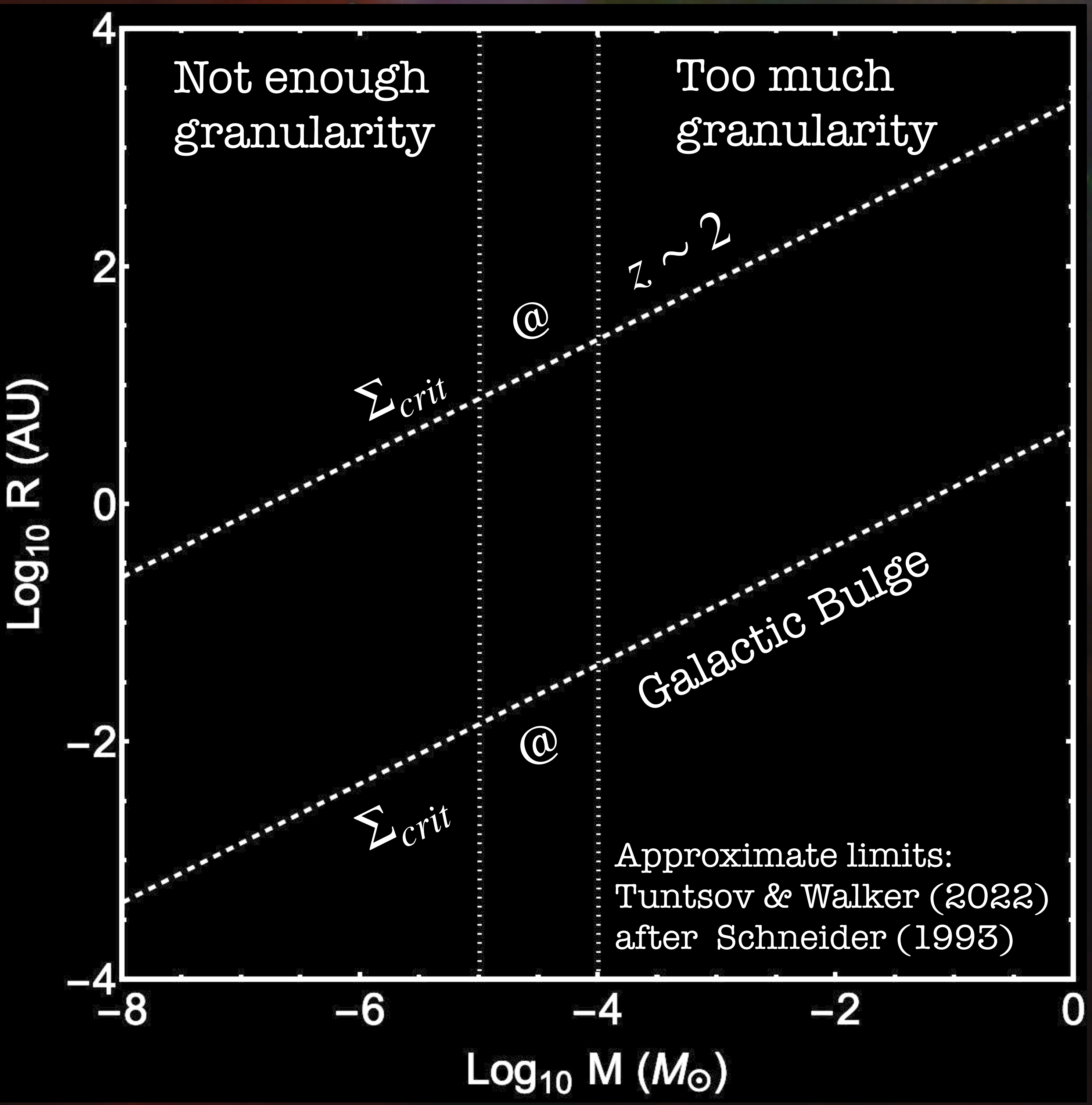
1. Properties of star-forming galaxies are easier to understand if each has a large reservoir of dark molecular gas (Pfenniger, Combes & Martinet 1994; Walker 1999)

2. Low level of CMB fluctuations excludes dark matter in diffuse baryons. But clouds that collapsed before recombination may be OK.

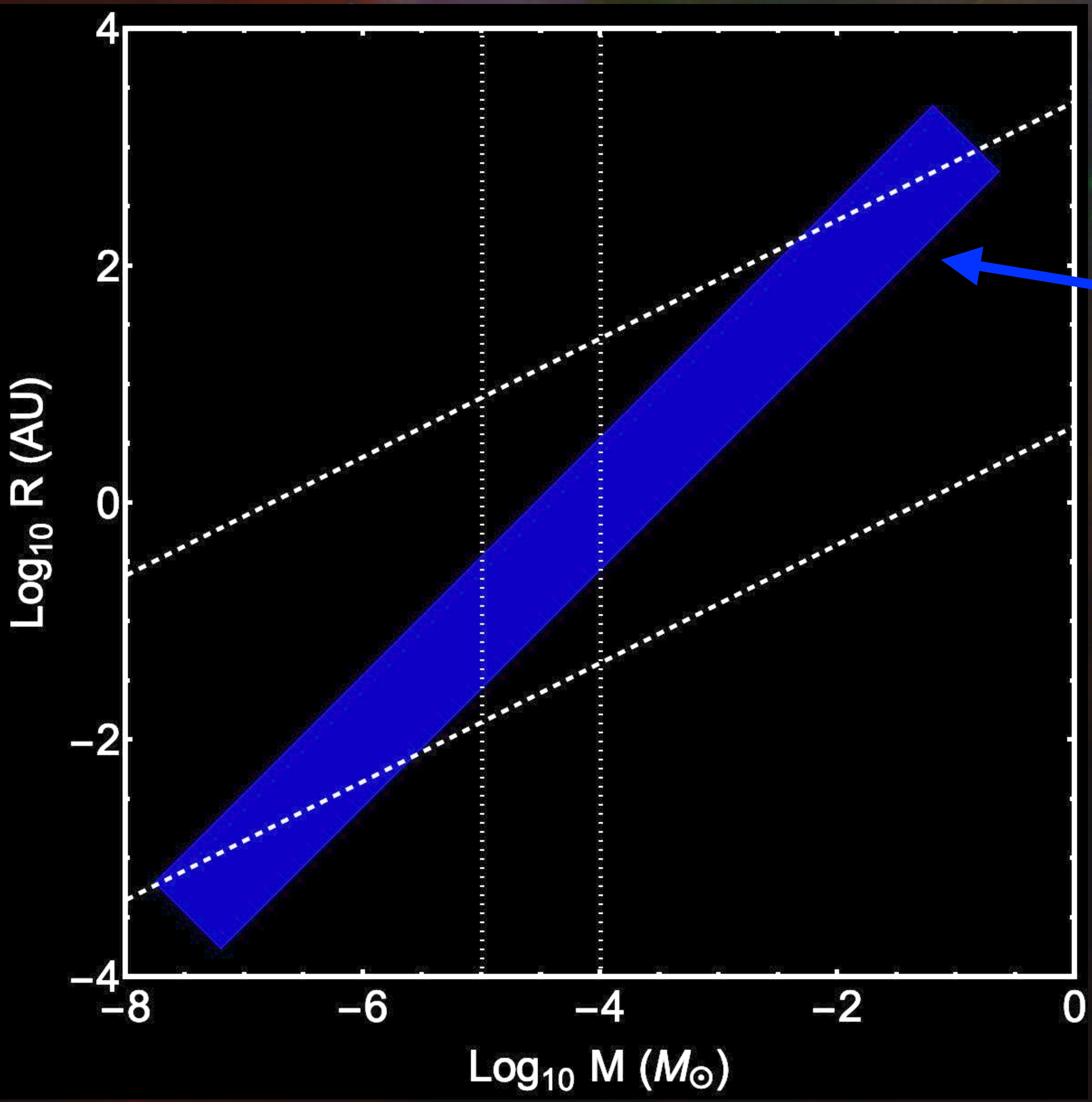
3. Quasar variability is nicely explained as gravitational lensing if $\Omega_{lens} \sim 1$ in planetary mass objects (Hawkins 1993 etc).

   But the lenses cannot be point-like in the Galaxy (EROS + MACHO). Much “fluffier” than any planet $\rightarrow$ cold gas clouds

What sort of objects are we talking about?

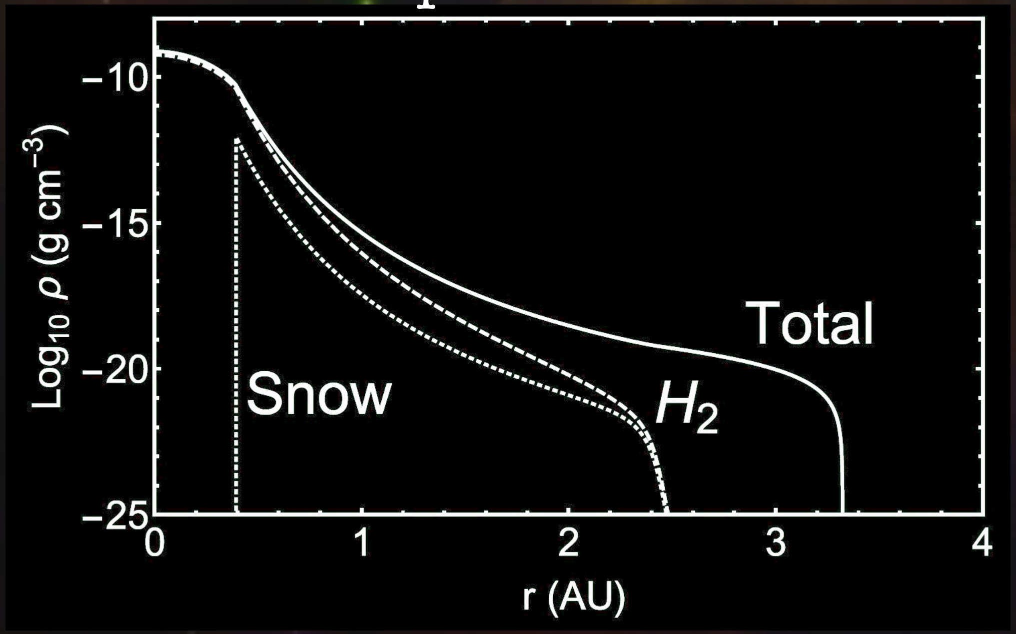


What sort of objects are we talking about?



Structural models from Walker & Wardle (2019)
$T_c \sim 25 - 100$ K

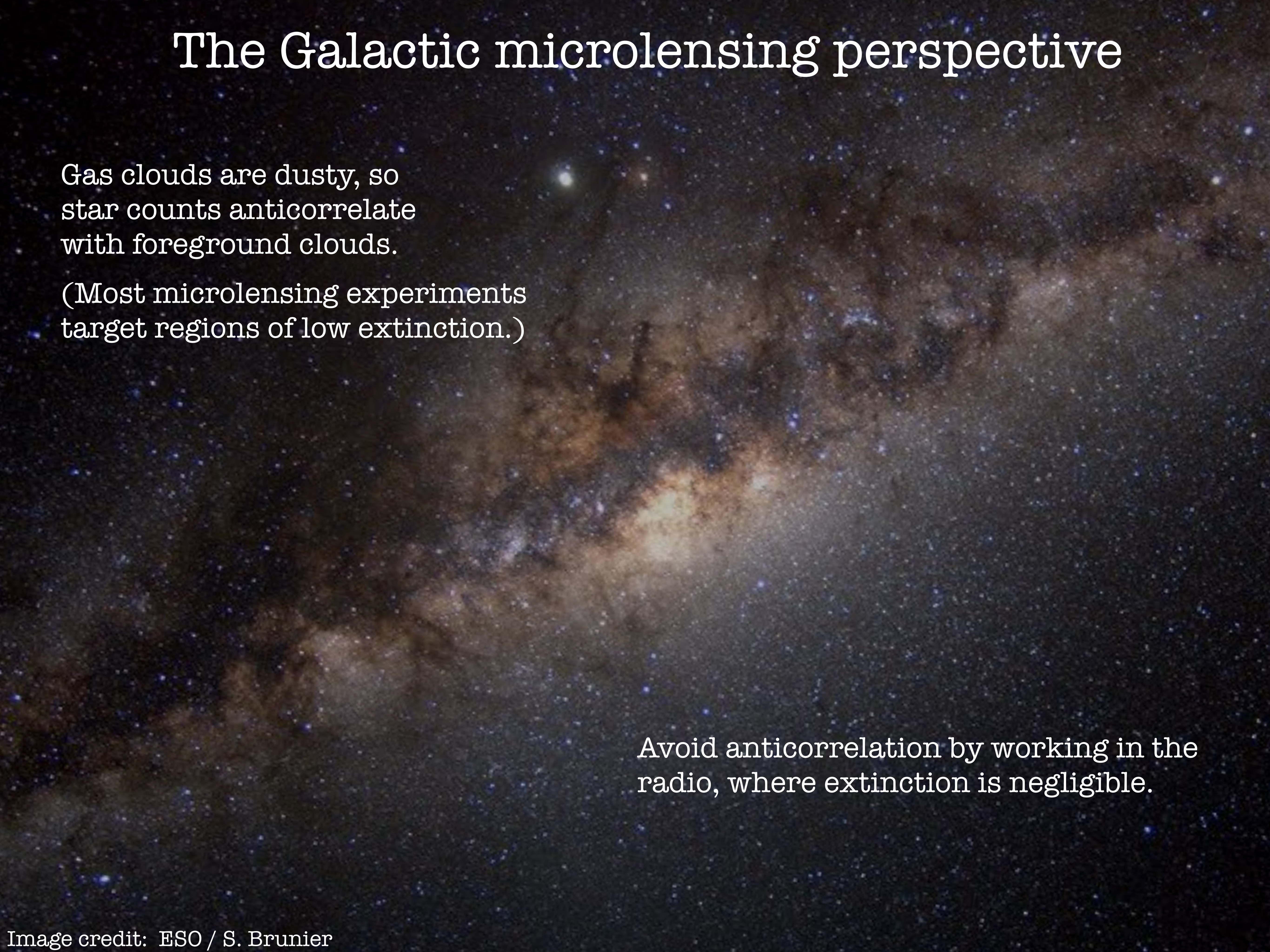
Example cloud model



The Galactic microlensing perspective

Image credit: ESO / S. Brunier

The Galactic microlensing perspective



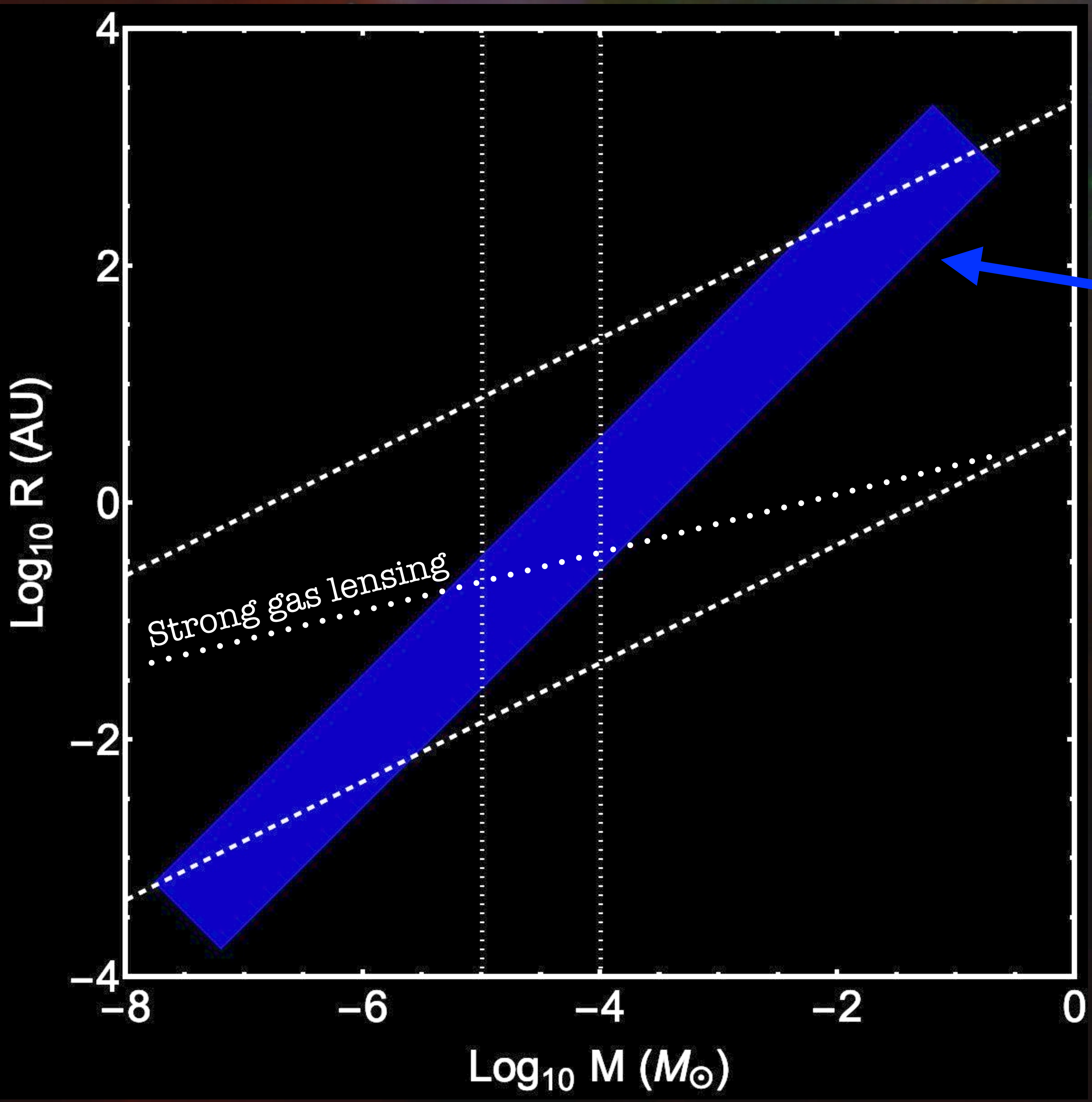
Gas clouds are dusty, so
star counts anticorrelate
with foreground clouds.

(Most microlensing experiments
target regions of low extinction.)

Avoid anticorrelation by working in the
radio, where extinction is negligible.

Image credit: ESO / S. Brunier

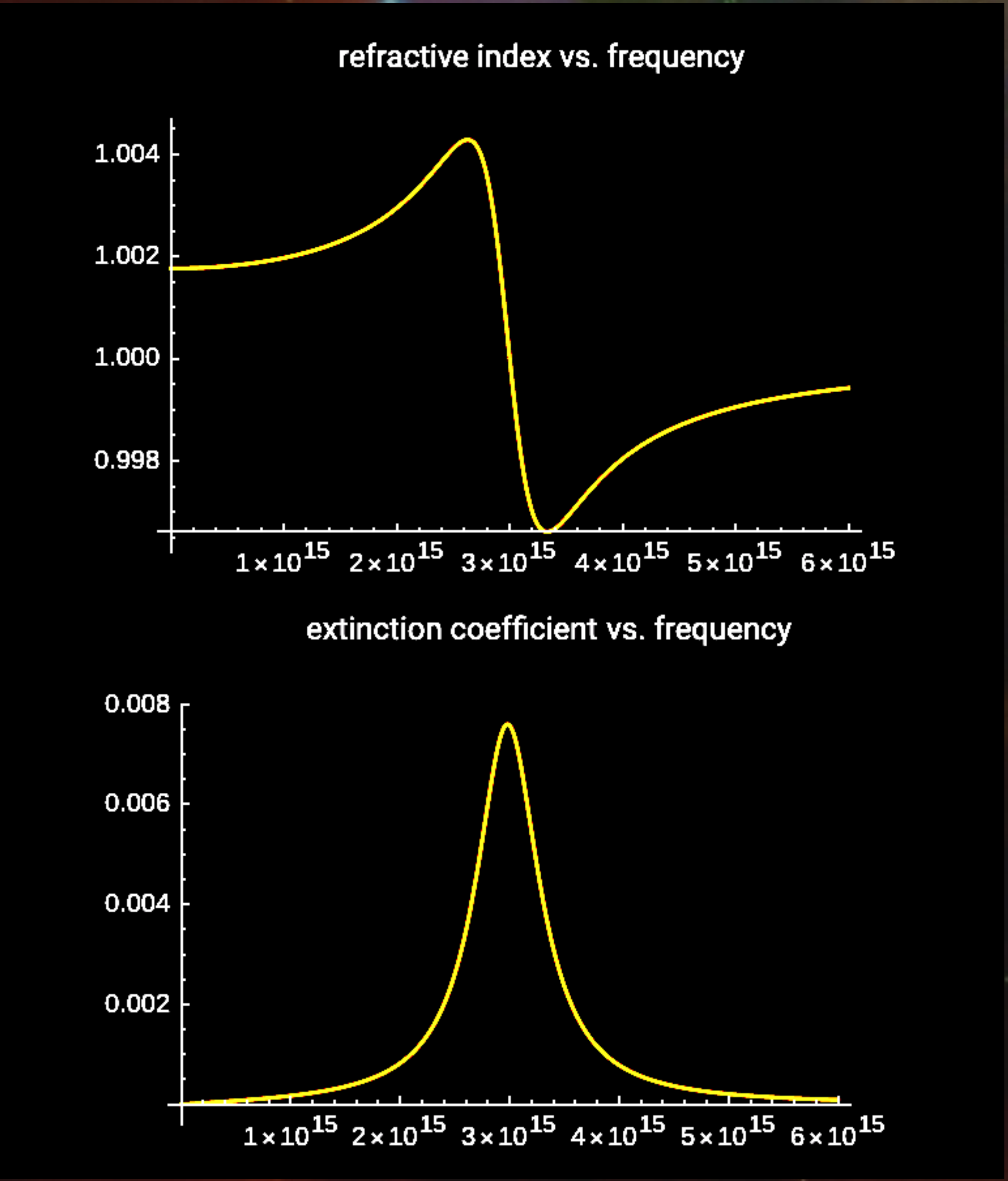
Where is gas lensing important?



Structural models from Walker & Wardle (2019)
$T_c \sim 25 - 100$ K

Gas lensing is stronger than gravitational lensing below a characteristic scale $\simeq 2$ AU

Neutral gas refractive index



Radio lensing is achromatic

<u>Order of magnitude estimates</u>

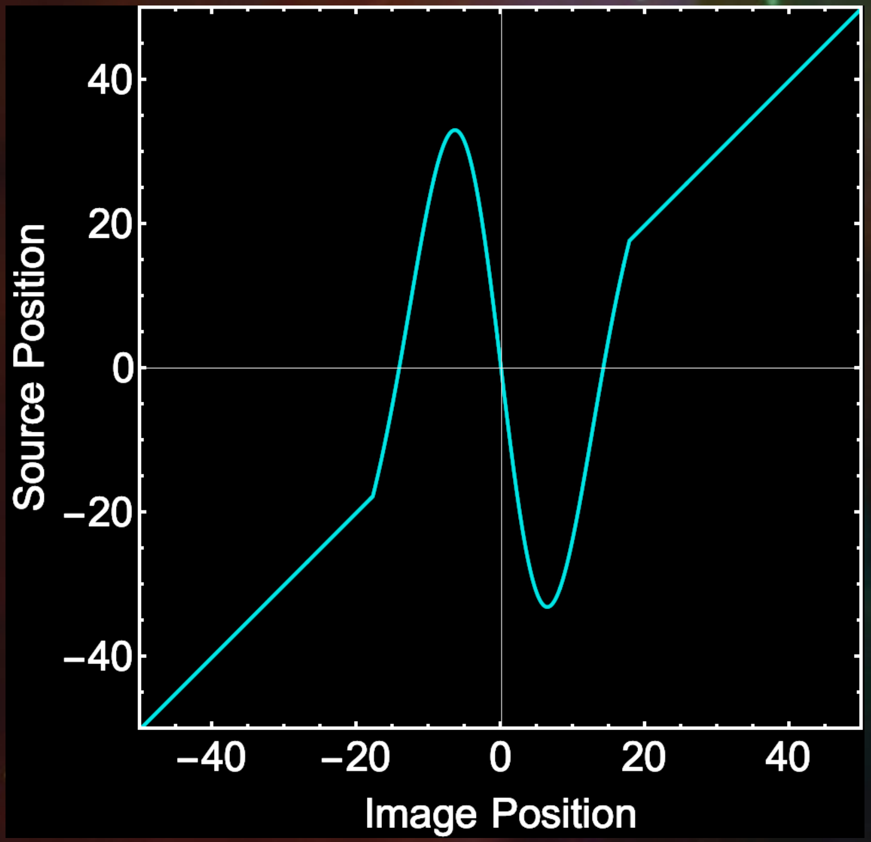
Refractive index for H_2 + He:

$$n - 1 \quad \sim \quad \rho\,(\mathrm{g\,cm^{-3}})$$

Bend angle for spherical cloud:

$$\delta\theta\,(\mathrm{rad}) \quad \sim \quad n - 1$$

Neutral gas lensing: n=3/2 polytrope



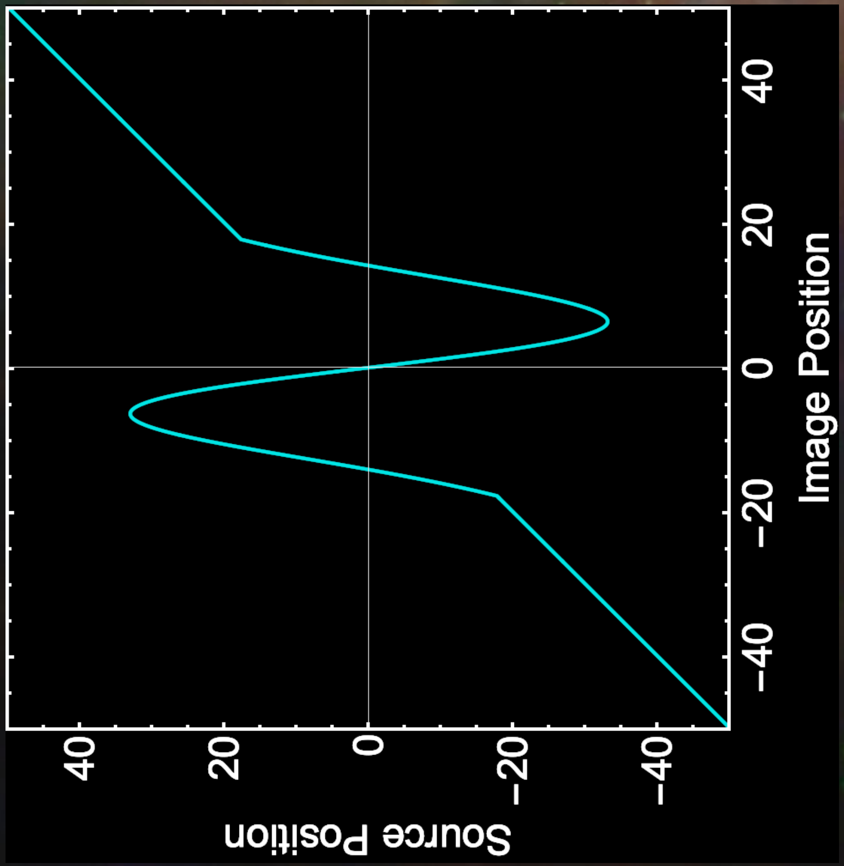
$$M = 3 \times 10^{-5}\ \mathrm{M}_\odot$$

$$R = 0.25\ \mathrm{AU}$$

$$D_{lens} = 1\ \mathrm{kpc}$$

$$D_{psr} = 2\ \mathrm{kpc}$$

Neutral gas lensing: n=3/2 polytrope



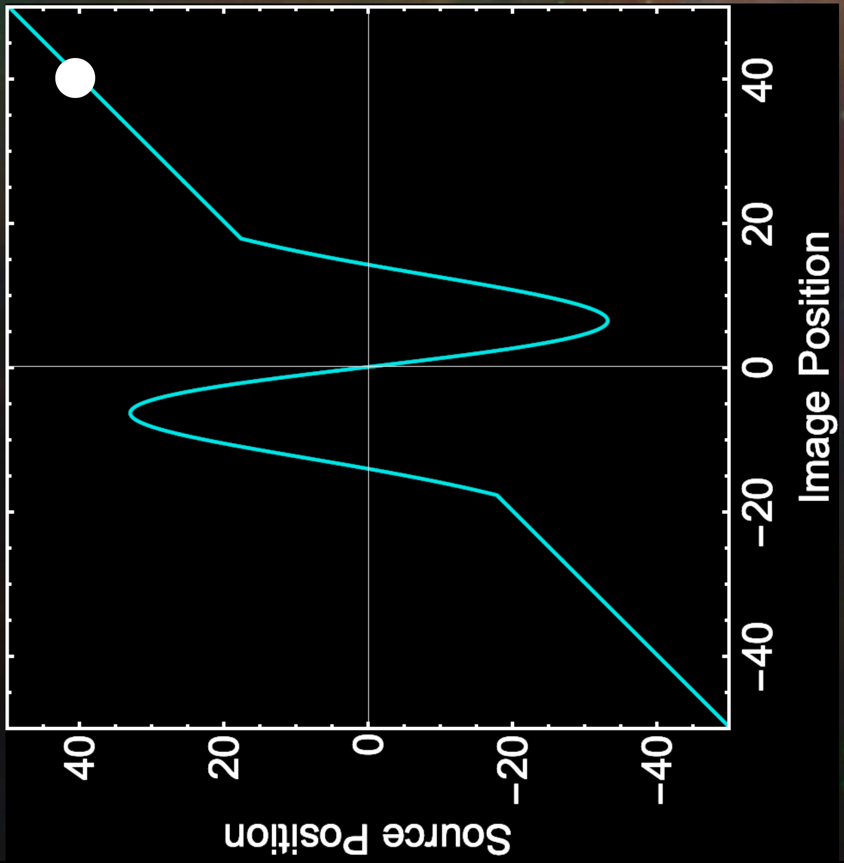
$$M = 3 \times 10^{-5}\ \mathrm{M}_\odot$$

$$R = 0.25\ \mathrm{AU}$$

$$D_{lens} = 1\ \mathrm{kpc}$$

$$D_{psr} = 2\ \mathrm{kpc}$$

Neutral gas lensing: n=3/2 polytrope

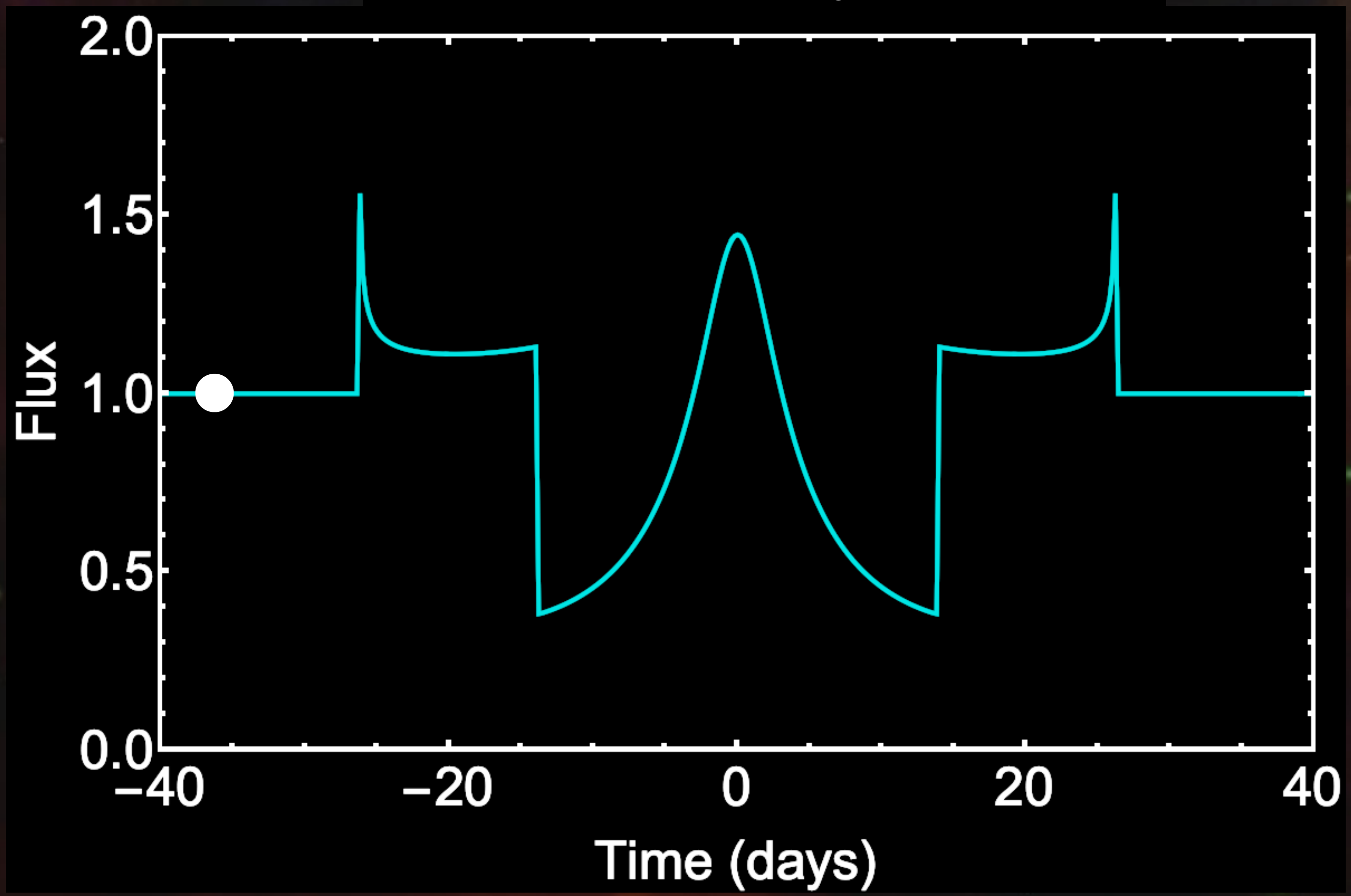


$$M = 3 \times 10^{-5}\ \mathrm{M}_\odot$$

$$R = 0.25\ \mathrm{AU}$$

$$D_{lens} = 1\ \mathrm{kpc}$$

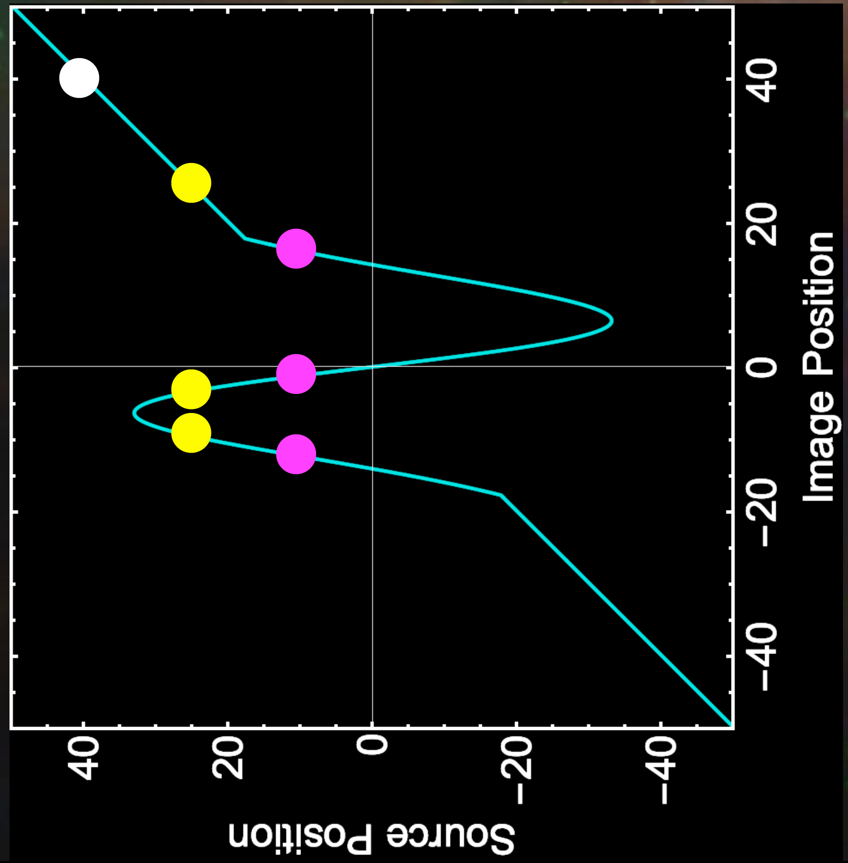
$$D_{psr} = 2\ \mathrm{kpc}$$

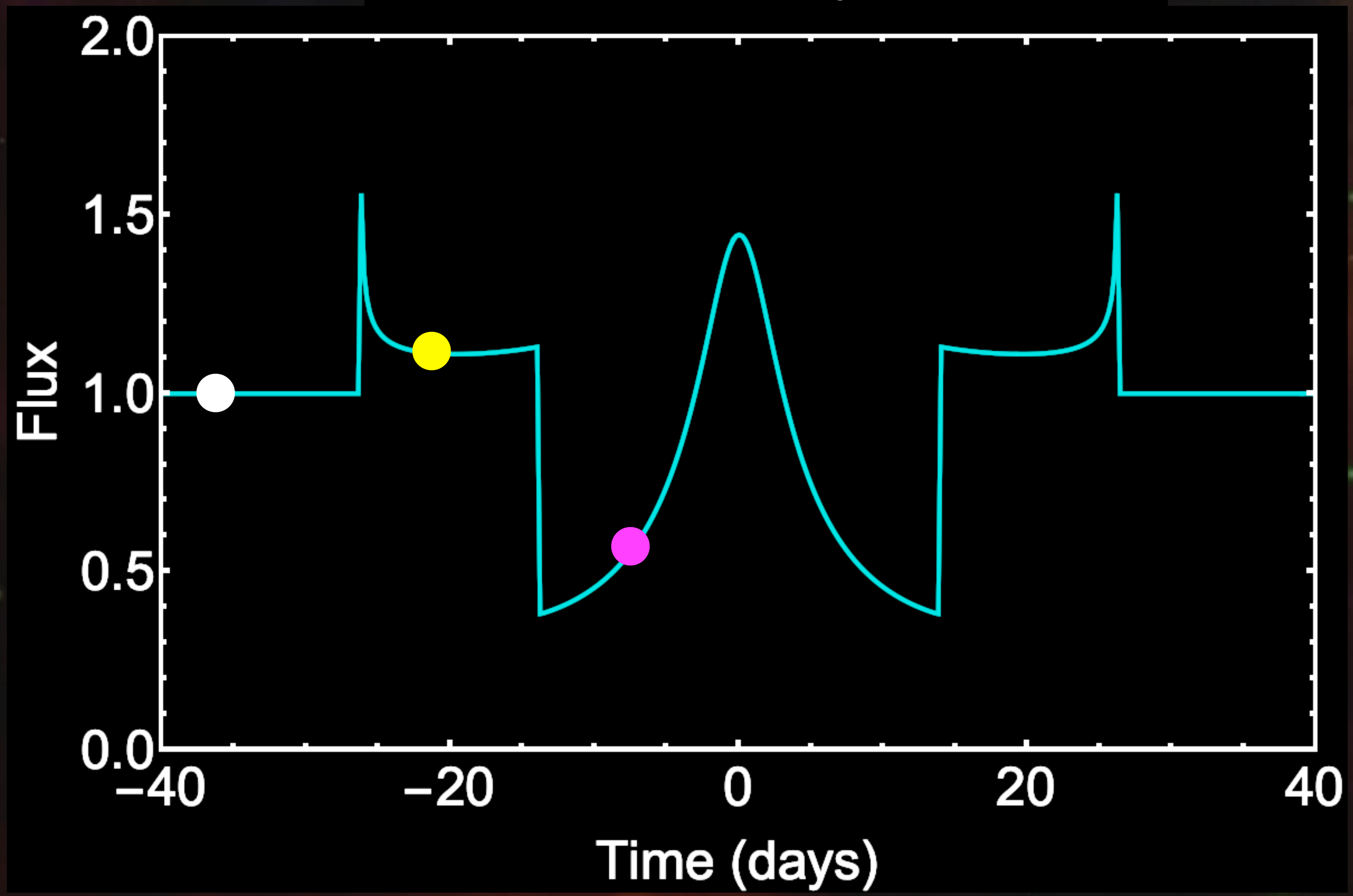


$$b = 0.05\ \mathrm{AU}$$

$$V_\perp = 30\ \mathrm{km\,s^{-1}}$$

Neutral gas lensing: n=3/2 polytrope





$M = 3 \times 10^{-5}\ \mathrm{M}_\odot$

$R = 0.25\ \mathrm{AU}$

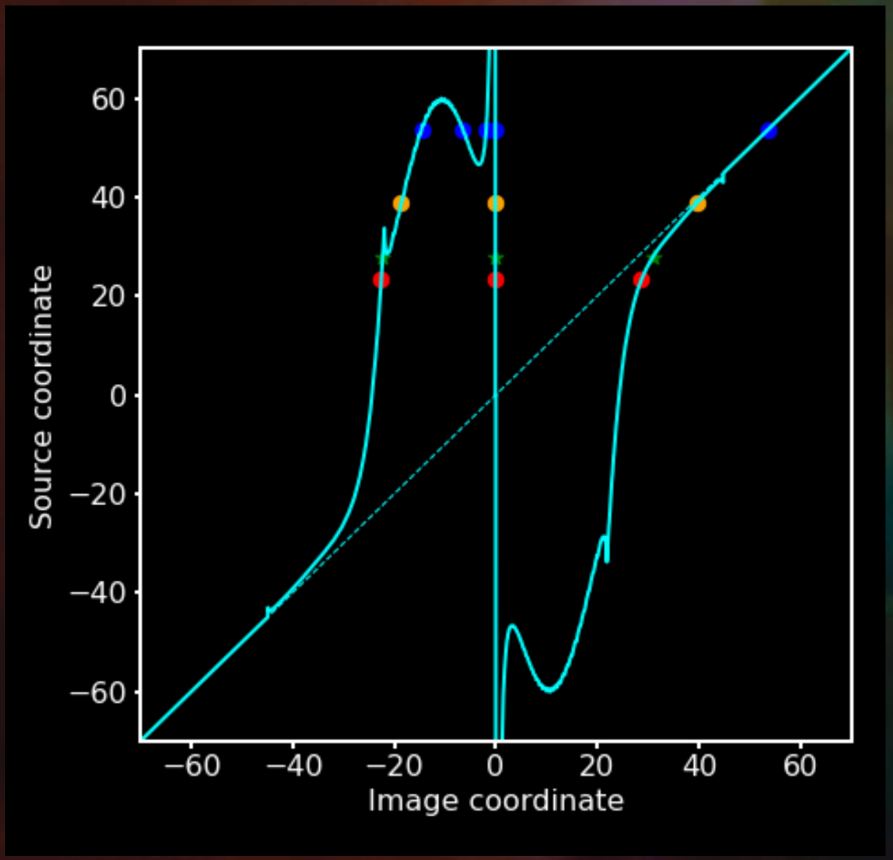
$D_{lens} = 1\ \mathrm{kpc}$

$D_{psr} = 2\ \mathrm{kpc}$

$b = 0.05\ \mathrm{AU}$

$V_\perp = 30\ \mathrm{km\,s^{-1}}$

Wave optics: isentropic snow cloud



$$M = 3 \times 10^{-5}\ \mathrm{M}_\odot$$

$$R \simeq 0.75\ \mathrm{AU}$$

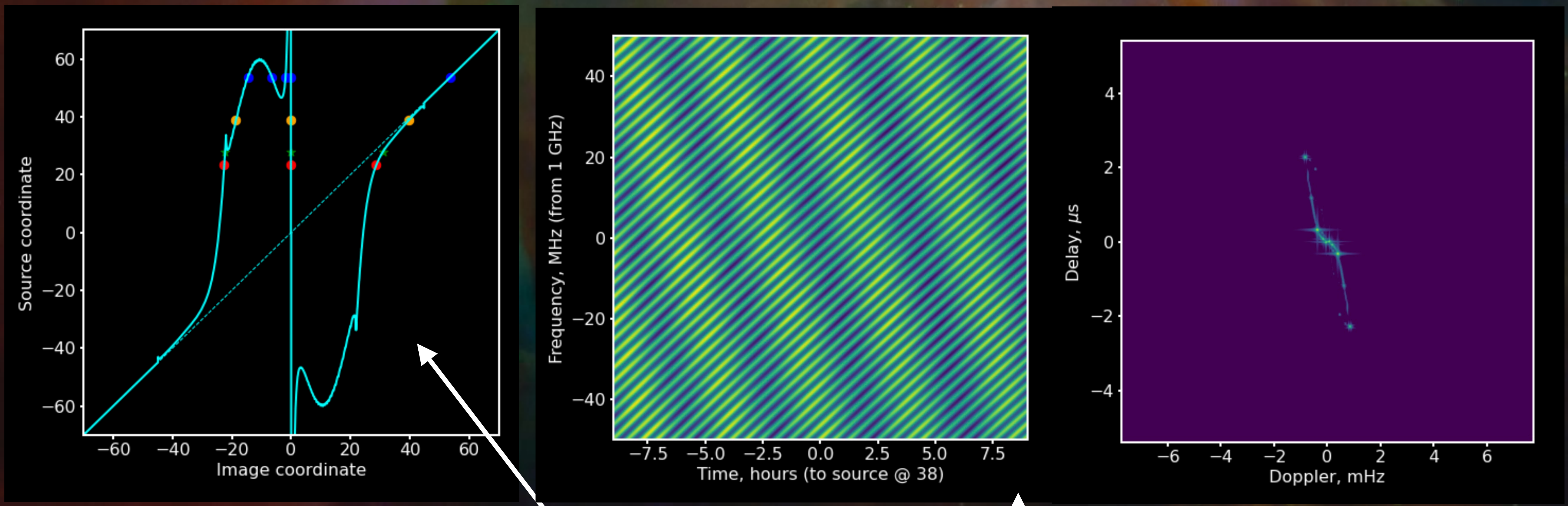
$$D_{lens} = 1\ \mathrm{kpc}$$

$$D_{psr} = 2\ \mathrm{kpc}$$

$$b = 0.00\ \mathrm{AU}$$

$$V_\perp = 30\ \mathrm{km\,s^{-1}}$$

Wave optics: isentropic snow cloud



$$M = 3 \times 10^{-5}\ \mathrm{M}_\odot$$

$$R \simeq 0.75\ \mathrm{AU}$$

$$D_{lens} = 1\ \mathrm{kpc}$$

$$D_{psr} = 2\ \mathrm{kpc}$$

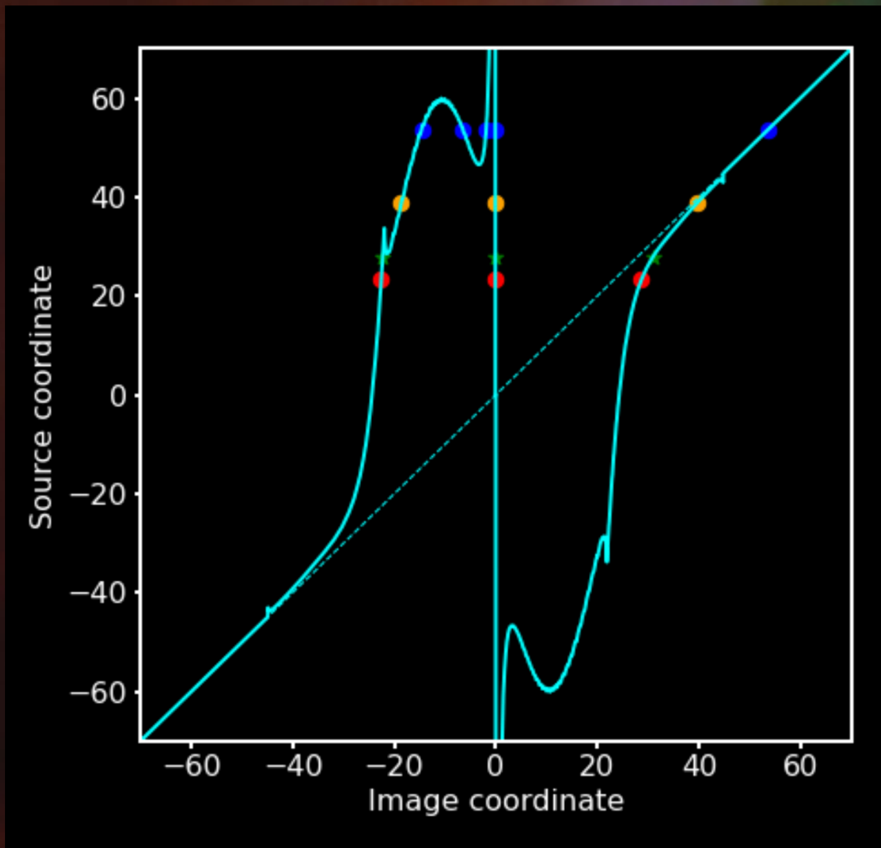
$$b = 0.00\ \mathrm{AU}$$

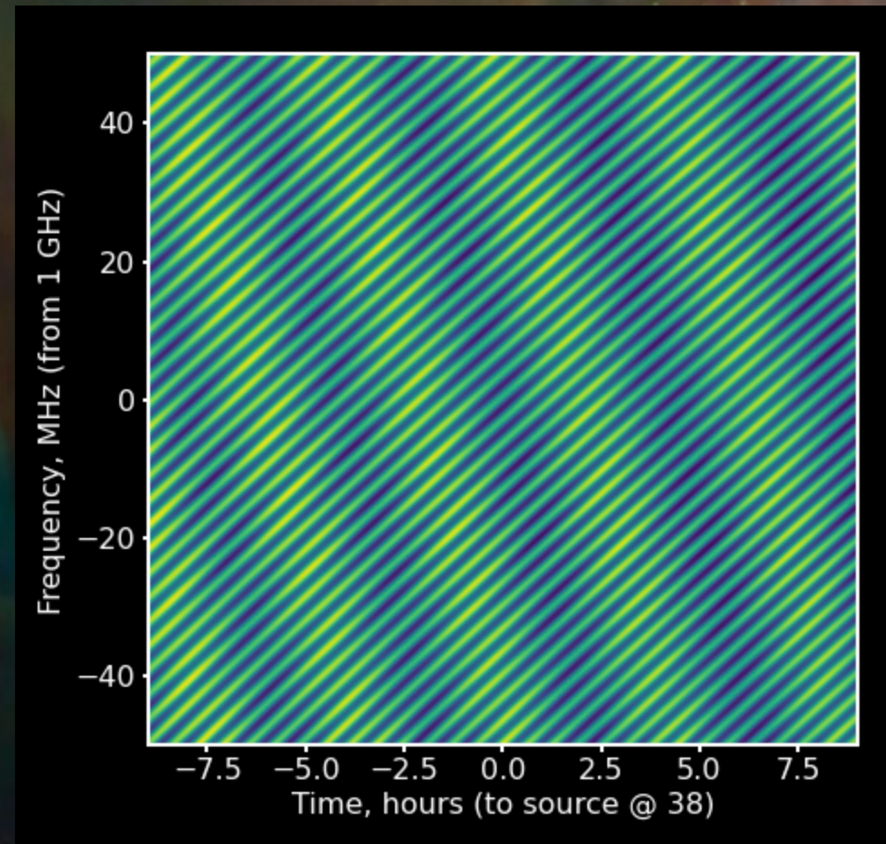
$$V_\perp = 30\ \mathrm{km\,s^{-1}}$$

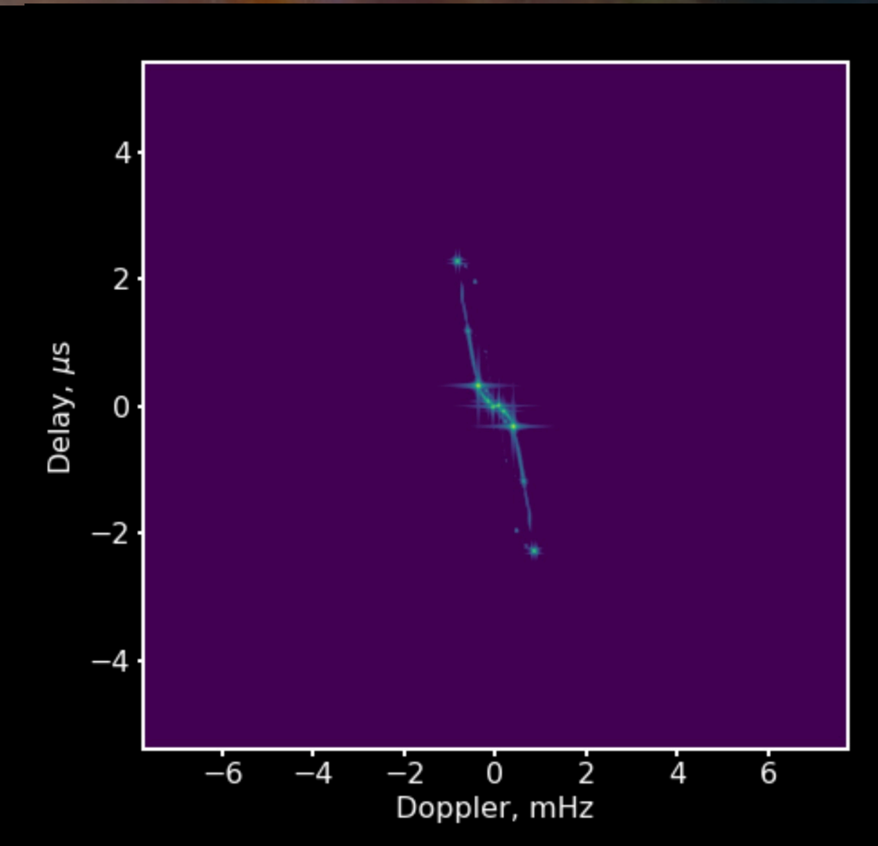
Numerical
phase profile, so ...

... Picard-Lefschetz is not
useful for evaluating
Fresnel-Kirchhoff

Wave optics: isentropic snow cloud







$$M = 3 \times 10^{-5}\ \mathrm{M}_\odot$$

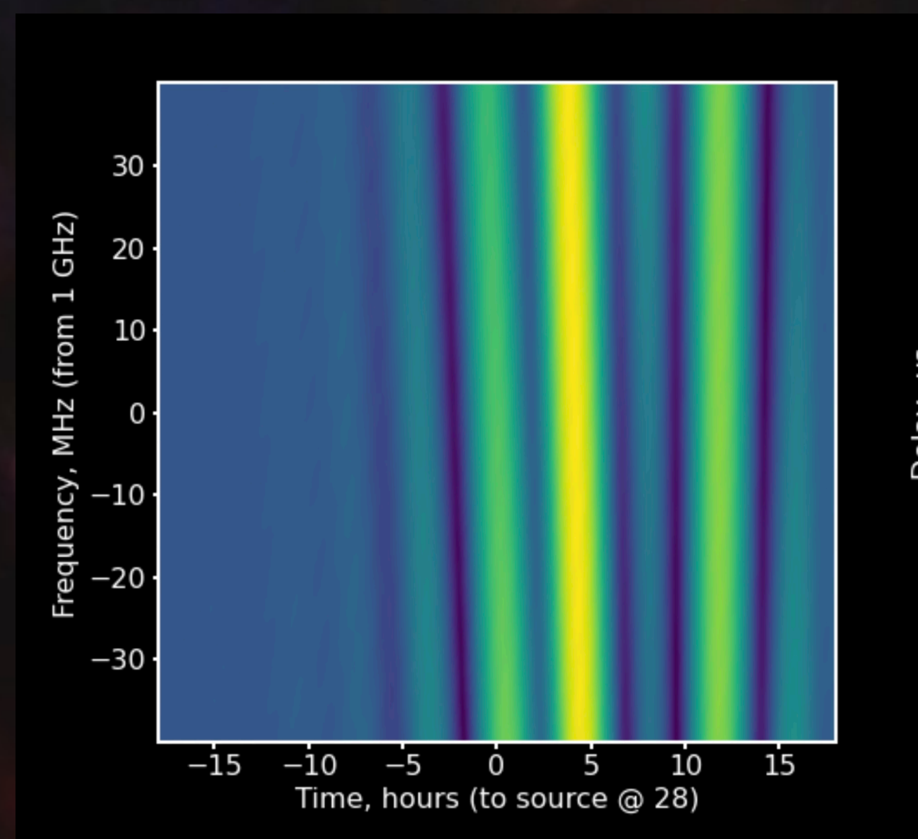
$$R \simeq 0.75\ \mathrm{AU}$$

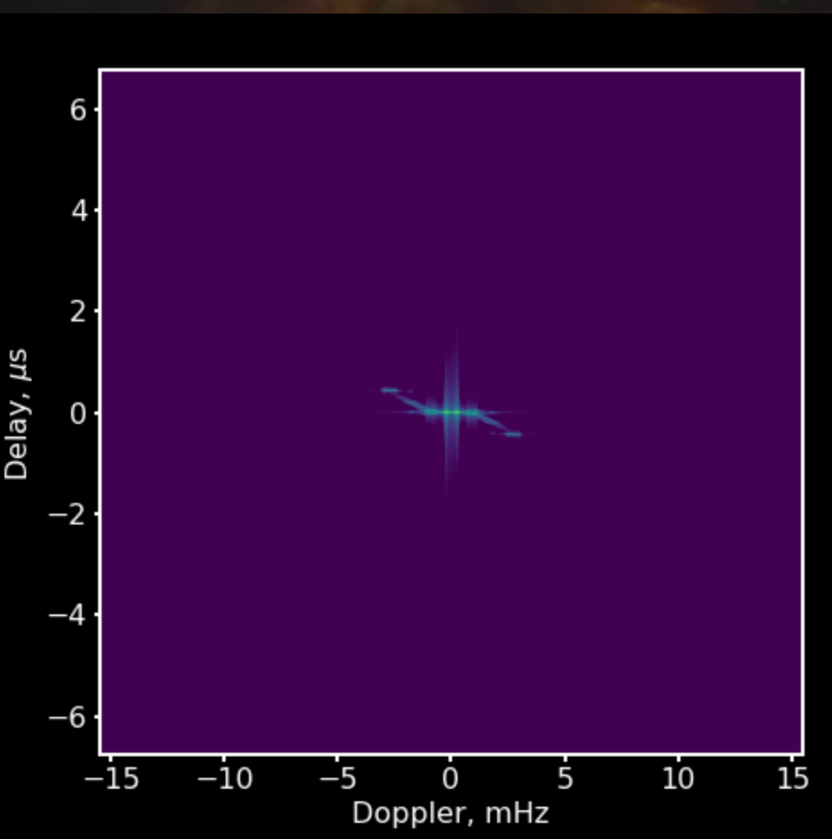
$$D_{lens} = 1\ \mathrm{kpc}$$

$$D_{psr} = 2\ \mathrm{kpc}$$

$$b = 0.00\ \mathrm{AU}$$

$$V_\perp = 30\ \mathrm{km\,s^{-1}}$$

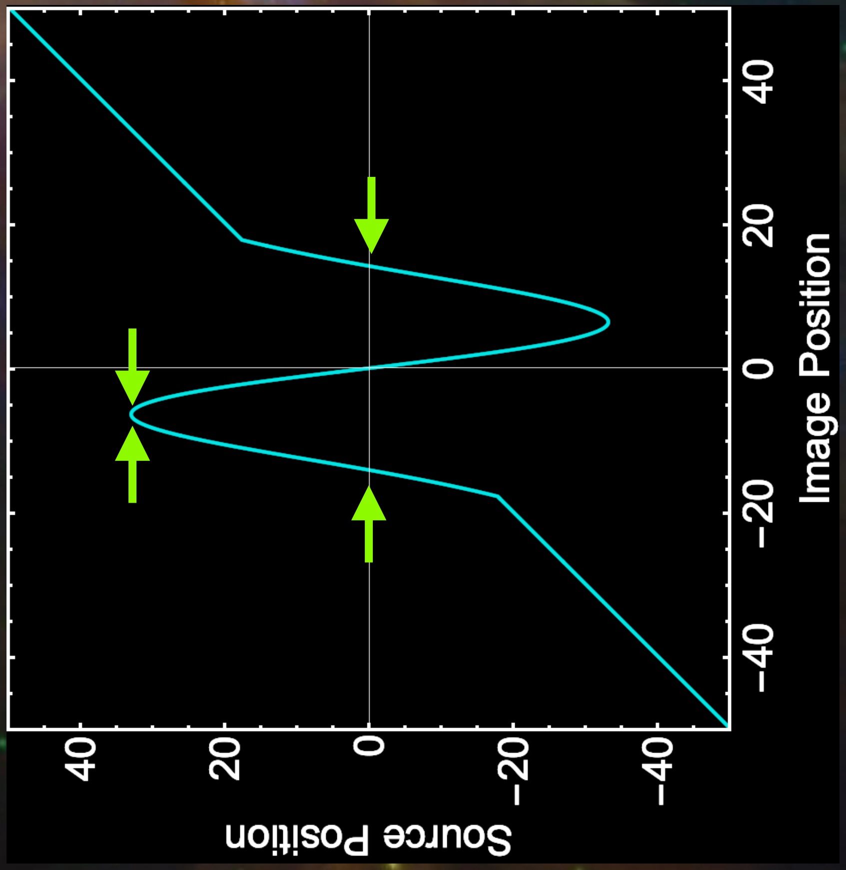




Possible connections to data

1. Rare: high magnification events

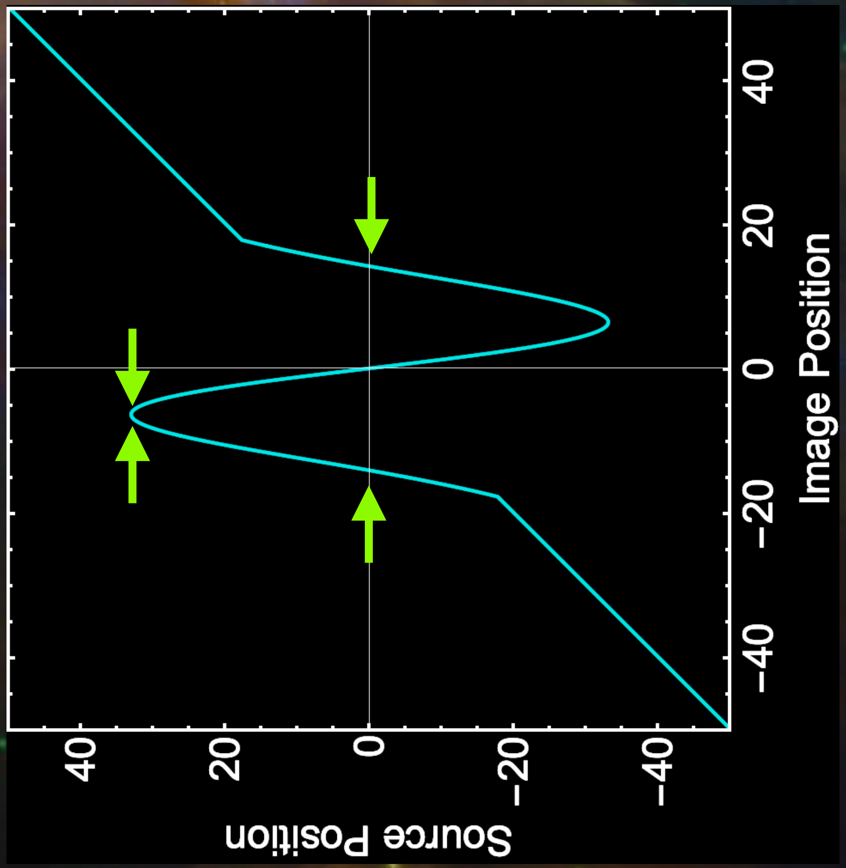
- Gas lensing is achromatic in the radio
  - Caustics are broad-band
  - Caustics present at high radio frequencies



Possible connections to data

1. Rare: high magnification events

- Gas lensing is achromatic in the radio
    - Caustics are broad-band
    - Caustics present at high radio frequencies



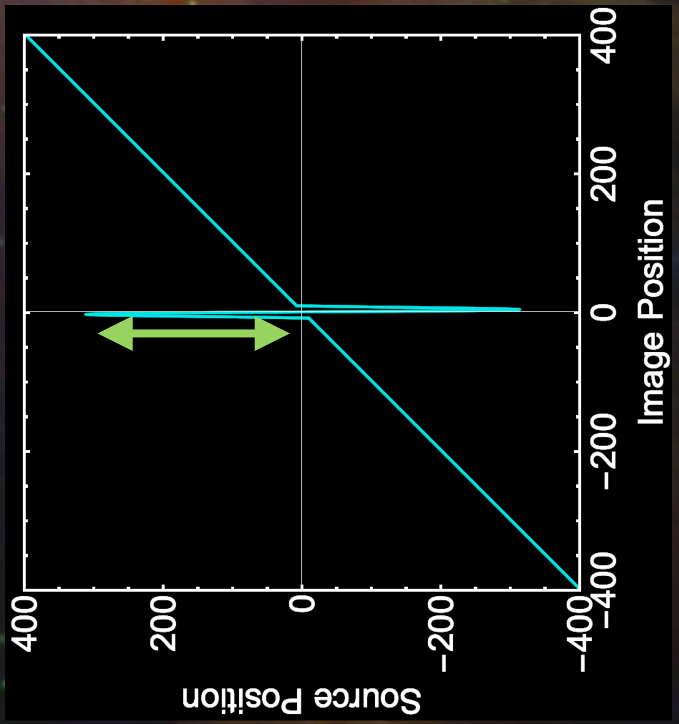
May be relevant to:

- Giant pulses
    - NB Crab giants at 40+ GHz (Hankins++ 2016)
- Rotating Radio Transients (McLaughlin++ 2006)
    - Faint pulsars, highly magnified for a short time?
- Fast Radio Bursts (Lorimer++ 2007)

Possible connections to data

2. Common: low magnification images

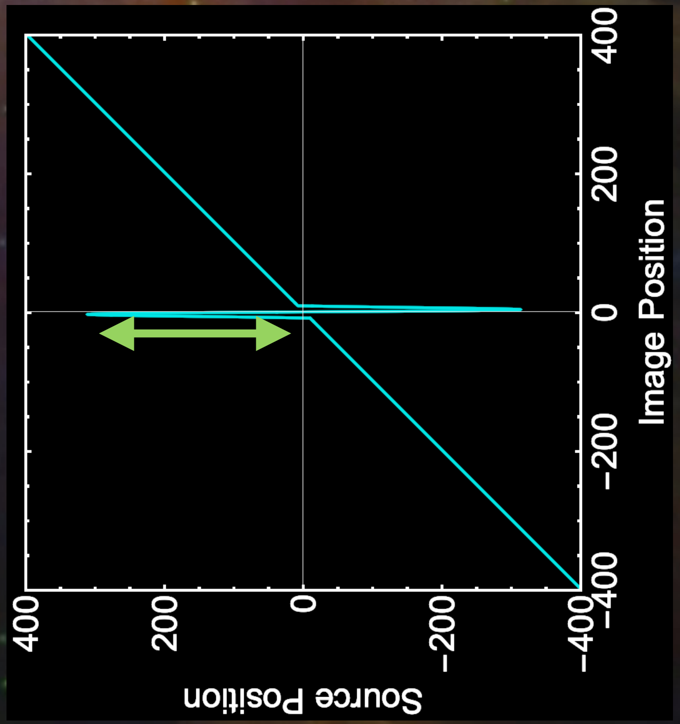
- Refraction through large angles is possible
  - Large cross-section ∴ common
  - Faint images at large delays
    - Present at all frequencies



Possible connections to data

2. Common: low magnification images

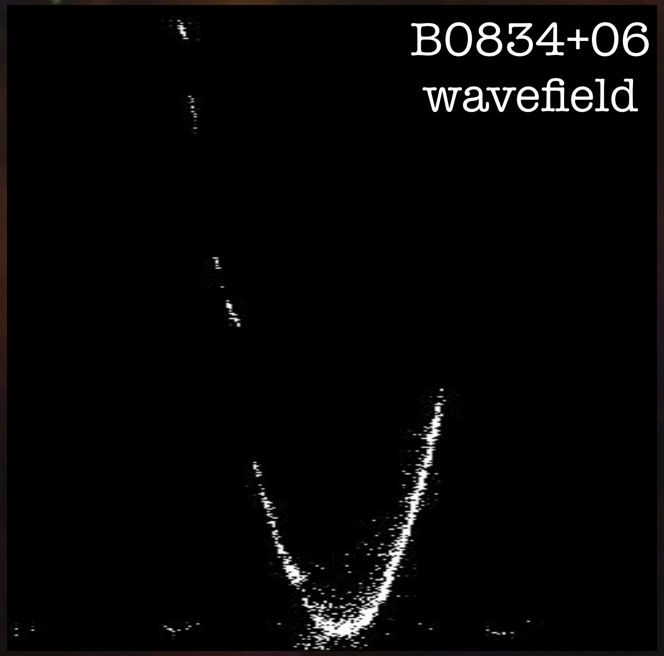
- Refraction through large angles is possible
  - Large cross-section ∴ common
  - Faint images at large delays
    - Present at all frequencies



May be relevant to:

- Isolated signals in the wavefield / sec. spec.
  - B0834+06 Hill++ (2005)
- Pulsar timing perturbations
  - Constraints from existing PTA data?

Data courtesy Dan Stinebring

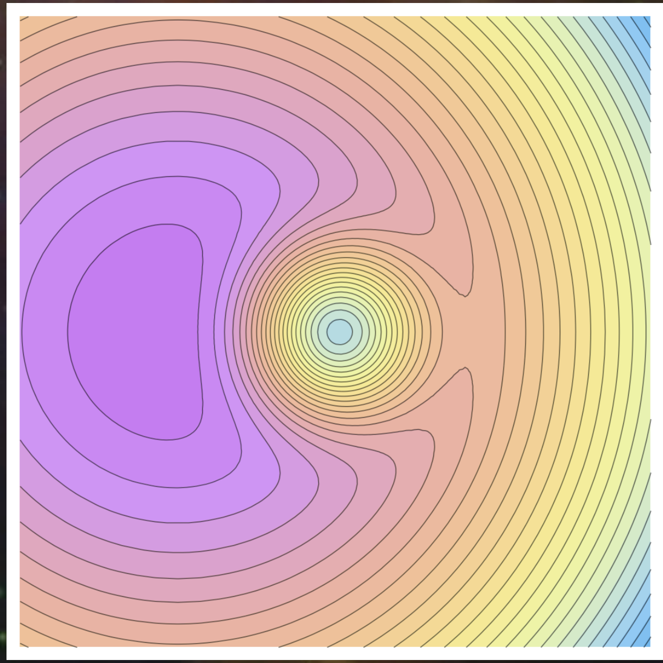


Possible connections to data

3. Achromatic wave speed delays

- Total delay is geometric + wave-speed delay
- Wave-speed delay is $\propto$ neutral gas column
    - Frequency-independent
        - Difficult to distinguish from geometry
- Multiple images → multiple arc curvatures
- High magnification → small arc curvature

Gaussian lens: total delay



Possible connections to data

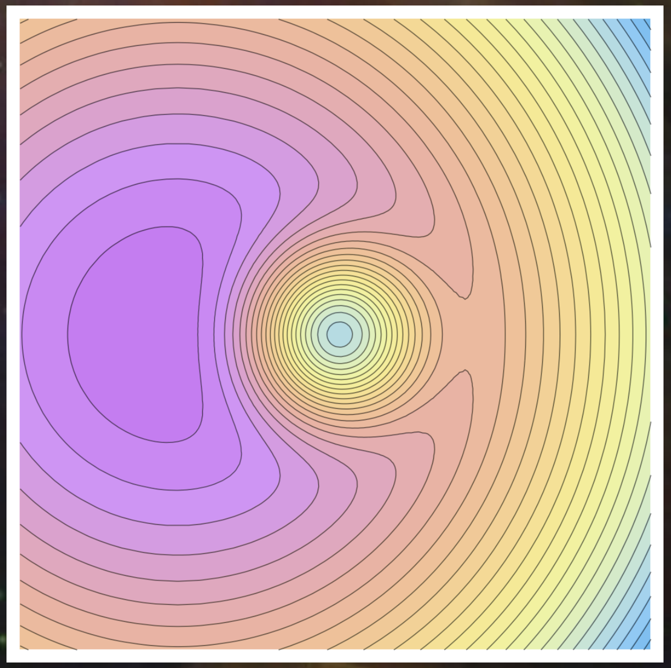
3. Achromatic wave speed delays

- Total delay is geometric + wave-speed delay
- Wave-speed delay is $\propto$ neutral gas column
  - Frequency-independent
    - Difficult to distinguish from geometry
- Multiple images → multiple arc curvatures
- High magnification → small arc curvature

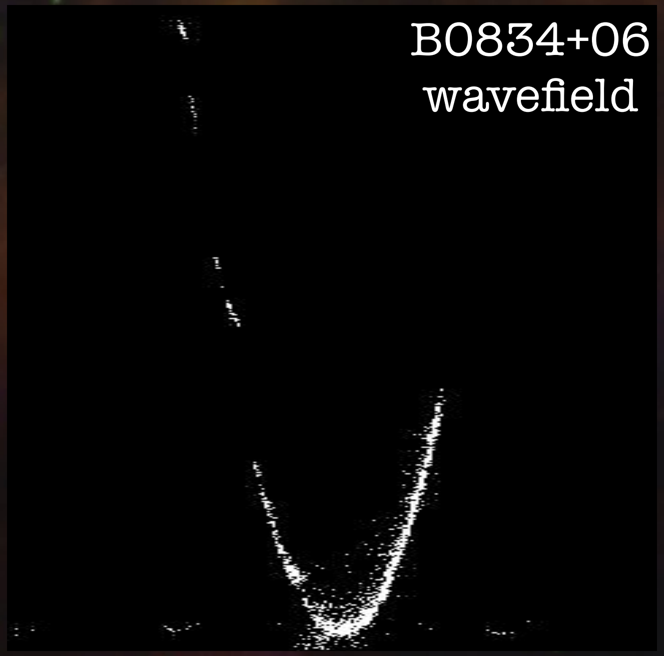
May be relevant to:

- Positive deviations from parabolic loci
  - Examples in B0834+06:
    Hill++ (2005), Brisken++ (2010)
    - Are all observed deviations +ve ??
- B1508+55: flat arcs and multiple curvatures
  Sprenger++ (2022)

Gaussian lens: total delay



Data courtesy Dan Stinebring



Possible connections to data

4. H_2 snow clouds: scattering from convection cells

- Thermohaline convection is expected
  - Convection cells radially elongated
    - Azimuthal scattering
    - Arc curvature evolves during occultations
- Scattering field has limited spatial extent
  - Within convection zone(s), inside cloud

Density field

Possible connections to data

4. H_2 snow clouds: scattering from convection cells

- Thermohaline convection is expected
  - Convection cells radially elongated
    - Azimuthal scattering
    - Arc curvature evolves during occultations
- Scattering field has limited spatial extent
  - Within convection zone(s), inside cloud

Density field

May be relevant to:

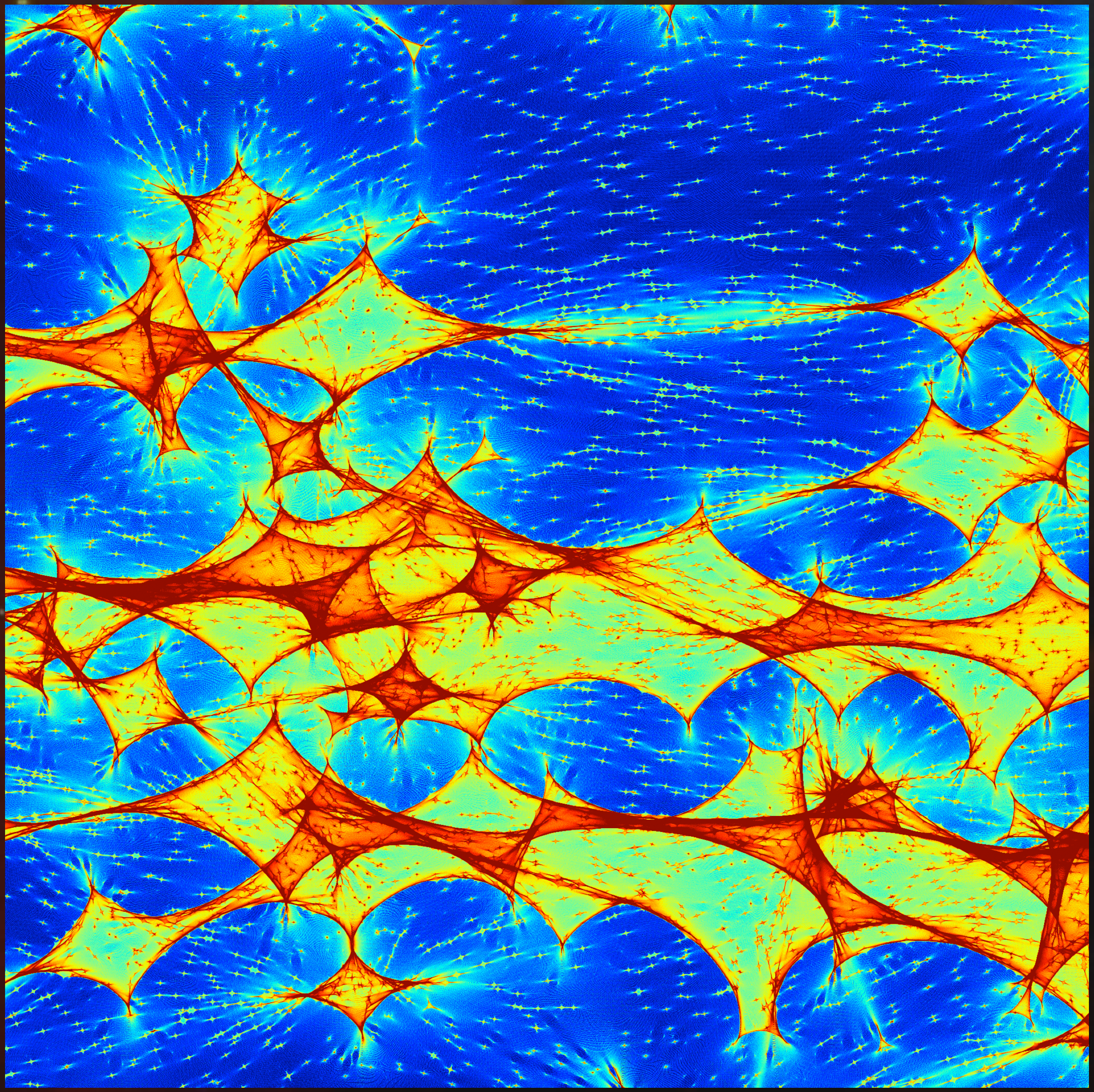
- Anisotropic scattering
- Abrupt transitions in scattering characteristics
  - Episodic Intra-Day Variability of quasars
    - e.g. PKS0405-385 — Kedziora-Chudczer (2006)
  - e.g. B1508+55 — Sprenger++ (2022)

Summary of Ideas

- Cold gas clouds are a "live" dark matter candidate
- Expect weak gravitational- but strong gas-lensing in our Galaxy
    - Plus some plasma-lensing
- Neutral-gas refractive index is achromatic in the radio
    - Can have high magnification with broad bands and high frequencies
    - Achromatic wave-speed delays mimic geometry
        - Lensing can modify arc curvature
            - Multiple imaging → multiple curvatures
        - Deviations from parabolic delay-Doppler
- H_2 snow clouds likely introduce anisotropic scattering
    - Radially elongated convection cells: azimuthal image elongation
        - Arc curvatures evolve during occultation events
    - Scattering zones are limited in spatial extent
- Fresnel-Kirchhoff integral evaluation remains challenging
    - Picard-Lefschetz doesn't help with numerically defined phase profiles

Planets in Huchra's Lens?

Magnification map
courtesy Geraint Lewis



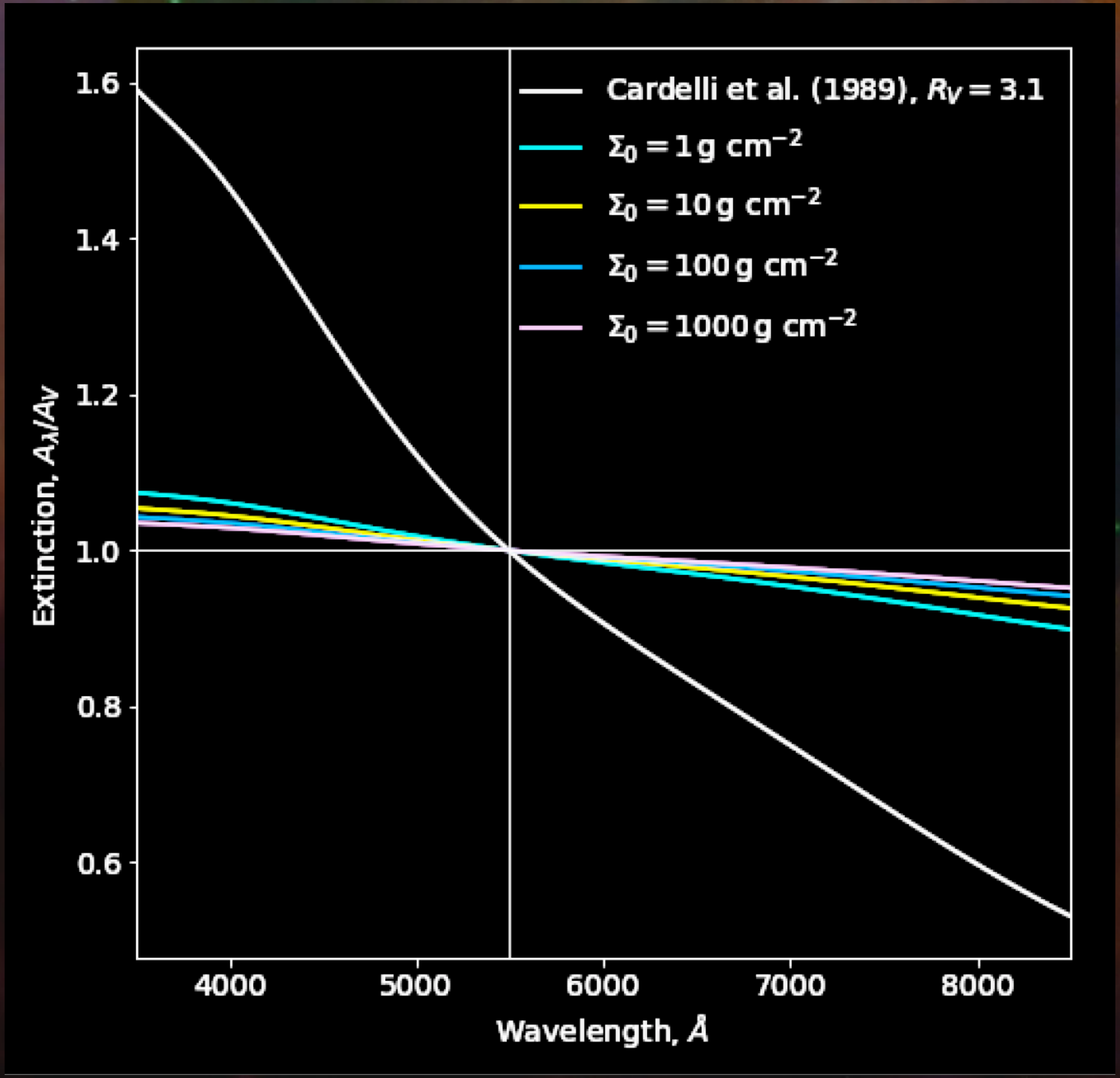
(code courtesy Joachim Wambsganss)

Image A:

Stars	Planets
$M_s = 10^{-1}\ \mathrm{M}_\odot$	$M_p = 10^{-4}\ \mathrm{M}_\odot$
$\kappa_s = 0.348$	$\kappa_p = 0.043$

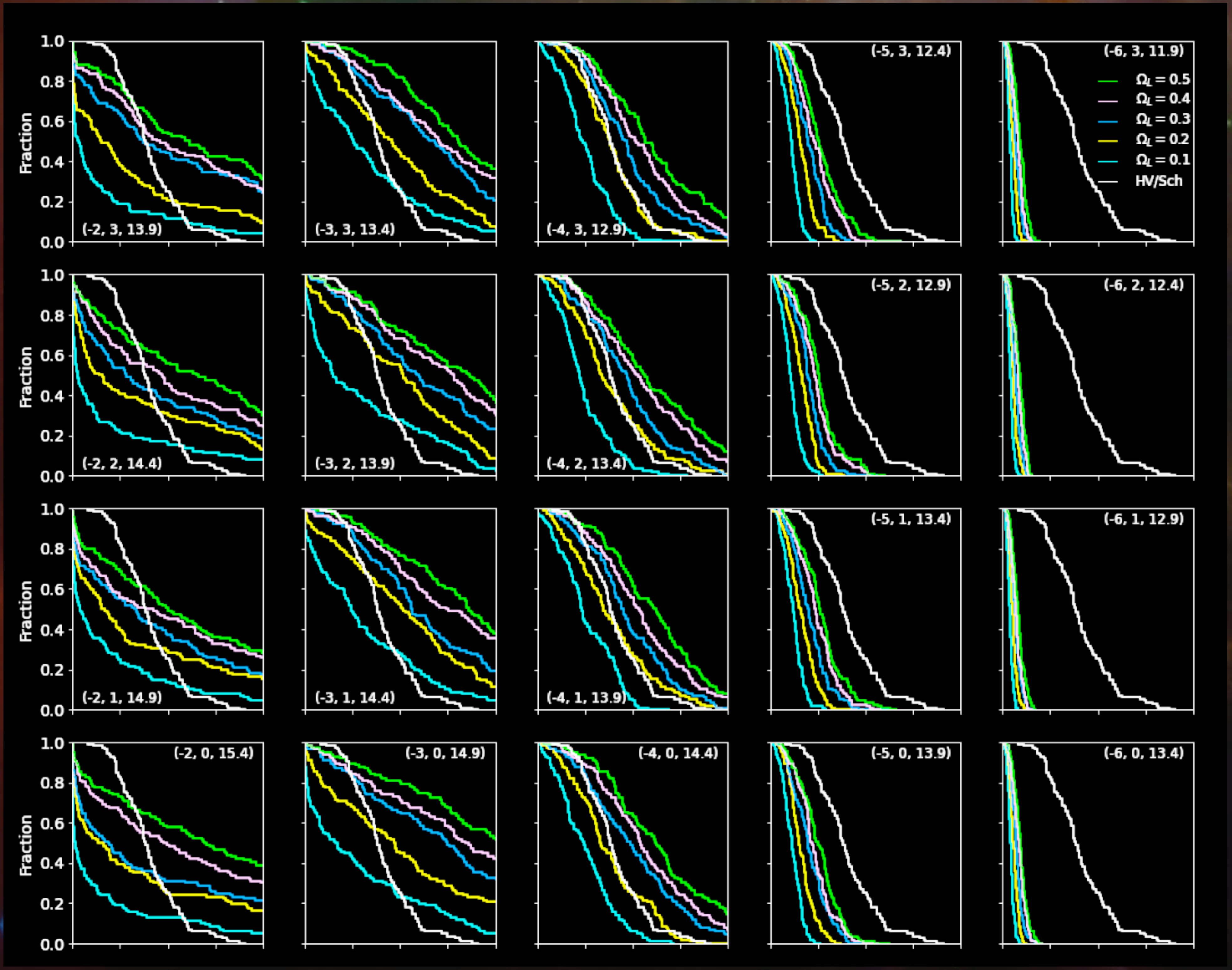
Signature of planets would be difficult to see in the OGLE photometry of Q2237.

SNe Ia dimming: geometry or dust?



Tuntsov & Walker (2022)

Amplitude of quasar variability



Tuntsov & Walker (2022)