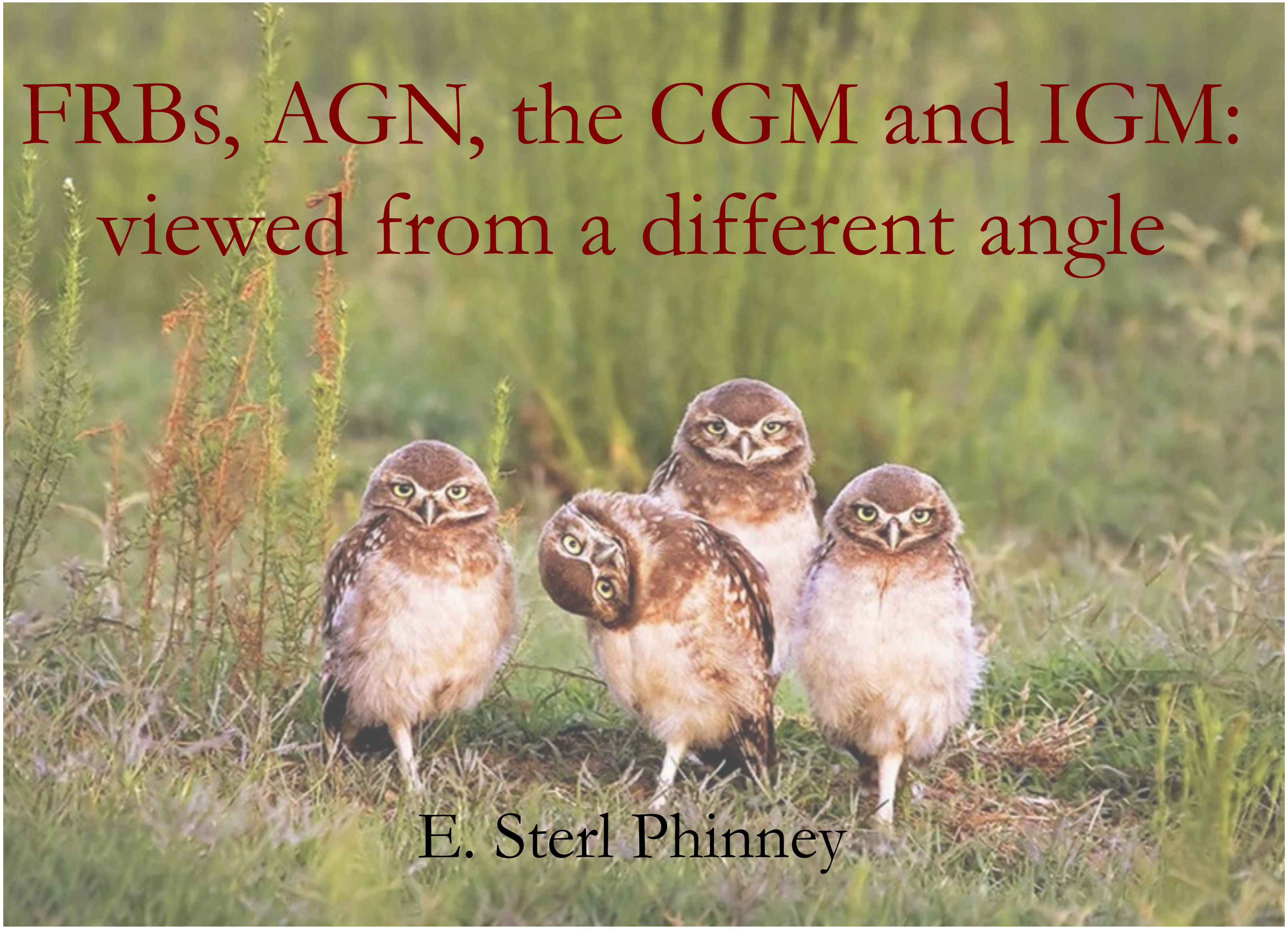
# FRBs, AGN, the CGM and IGM: viewed from a different angle



E. Sterl Phinney

Caltech

# My 1979 Arecibo FRB search…

letters

$0<\mathrm{DM}<640\,\mathrm{cm}^{-3}\mathrm{pc}$

*Nature* **277**, 117 - 118 (11 January 1979); doi:10.1038/277117a0

## A sensitive search for radio pulses from primordial black holes and distant Supernovae

STERL PHINNEY & J. H. TAYLOR

Department of Physics and Astronomy, University of Massachusetts, Amherst, Massachusetts 01003

**THERE are two mechanisms of current theoretical interest which might generate short ( $<1$ ms) radio pulses detectable at interstellar or even cosmological distances. In both cases the pulse is generated by the alteration of a magnetic field by an expanding conducting shell. The phenomenon might occur either as the expanding core of a supernova 'combs' the star's intrinsic dipole field[1,2], or as the shell of charged particles emitted in the explosion of a primordial black hole (PBH) excludes the surrounding magnetic field[3]. In the latter case, the resulting radio pulse would, with suitable particle physics[3,4], be much easier to detect than the $\gamma$-ray pulses that might also accompany the explosion[5]. The best published upper limit on the frequency of such $\gamma$-ray pulses is $4\times10^{-2}$ events $\mathrm{pc}^{-3}\,\mathrm{yr}^{-1}$ (ref. 6). We present here the results of a radio frequency search for isolated pulses, with much higher sensitivity than achieved previously. No definitive pulses have been detected, and the implied limit on PBH explosions is $2\times10^{-9}$ events $\mathrm{pc}^{-3}\,\mathrm{yr}^{-1}$.**

# GRB lessons

- 4 types of GRB
  - Repeating SGR: Magnetars (10kpc)
    - e.g. "Prototypical GRB" 5 March 1979 = now SGR 0525-66 in LMC. Mazets+ 1981 "A comparison of the 5 March 1979 event and other short gamma-ray bursts reveals considerable similarities in their features. This implies their common origin."
  - Short-hard burst: NS merger ($z < 1$)
  - Long bursts: rotating core collapse/SNae ($z<8.2$, 9.4)
  - Jets in Tidal Disruption events (GRB 110328A, aka Swift J164449.3+573451, $z=0.35$)

- Maybe we should beware of forcing a single type of FRB to fit all….

# FRB121102 repeater

- Persistent radio source
  - Spectrum, refractive scintillation variability, VLBI size, X-ray-to-radio and emission lines-to-radio all are typical of a low-ish luminosity AGN (ADAF w/ strong jet).
    - Poor statistics on the fraction of dwarf galaxies with these. $3\times10^{-5}$ $Mpc^{-3}$ @ $10^{22}$ W $Hz^{-1}$ (FRB121102: $10^{22.3}$W $Hz^{-1}$) – Ulvestad & Ho 2001. ~0.002 of $M_B$=-17 dwarfs.
  - vs young Mega-Crab with previously unprecedented ~100% of luminosity in radio (vs $10^{-5}$ for Crab)
- My take: either the AGN is the FRB source, or it is unrelated to the FRB (requires ~0.3% coincidence).

# Hα vs radio: Fanaroff-Riley type I cores

Black filled points:
flat spectrum
radio cores of UGC
galaxies ($m_r$<17) from
Marcha+ 2005
astro-ph/0505170

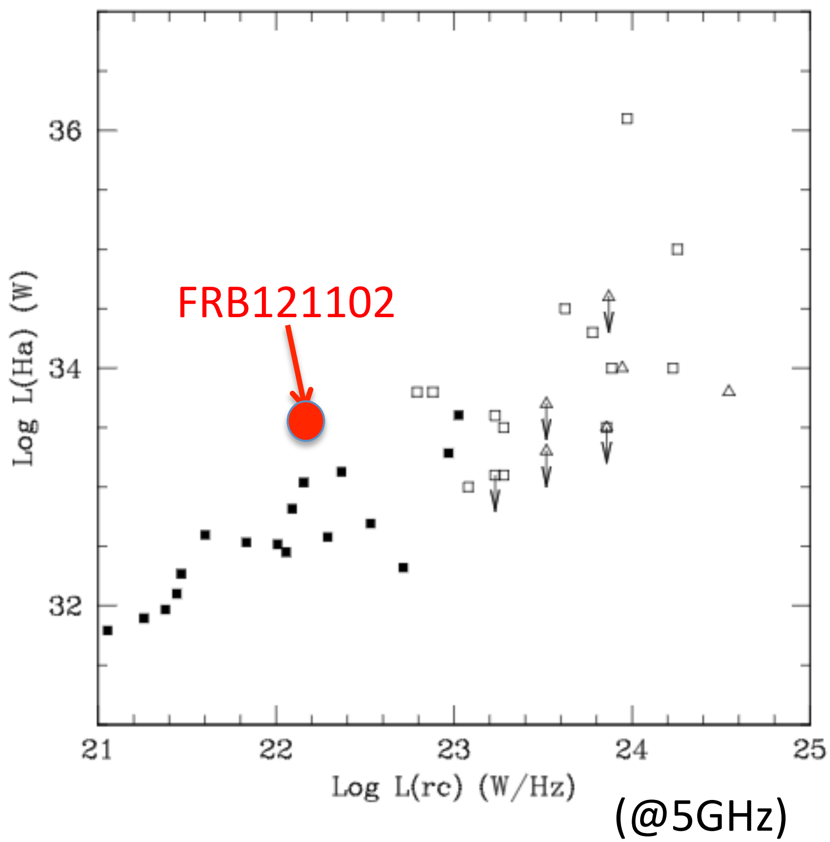



**Figure 2.** Distribution of the line luminosity vs. the radio core luminosity for the UGC FR Is of Verdoes Kleijn et al. (filled squares) the 200 mJy sample (open symbols; triangles are the BL Lacs).

AGN contribution
of FRB121102
would have
L(H$\alpha$) < 0.1-0.3
of star formation
contribution
-not significantly
affect BPT diagram

-low radio power:
ADAF regime –strong
jet, but very low
accretion
radiation efficiency.

# AGN
# Radio vs H $\alpha$
Falke+ 2001

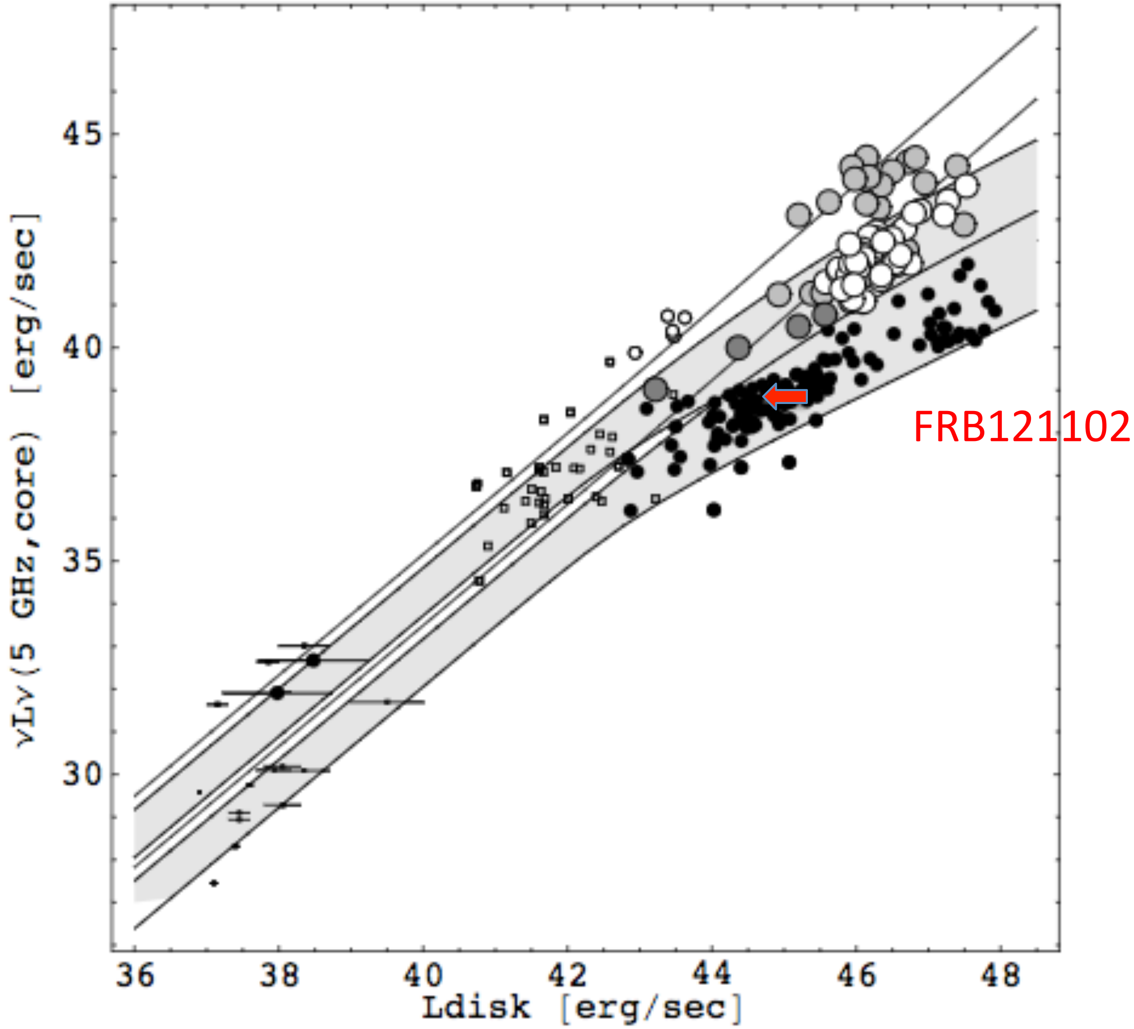
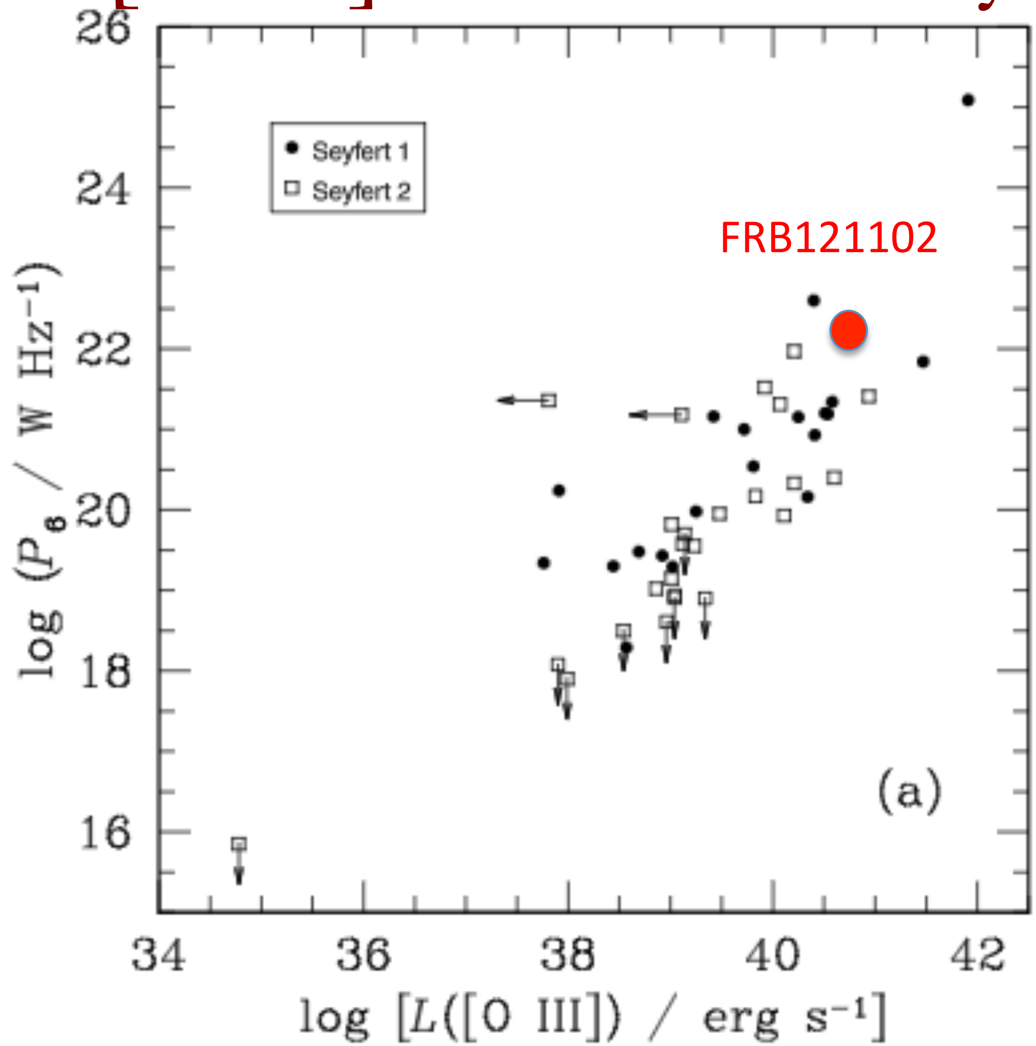



**Figure 11:** Correlation between thermal emission from the accretion disk (with the exception of X-ray binaries this is basically normalized to the narrow H$\alpha$ emission) and the monochromatic luminosity of black hole radio cores. Open circles: Radio-loud quasars; small open circles: FR I radio galaxies; open gray circles: Blazars and radio-intermediate quasars (dark grey); black dots: radio-quiet quasars and Seyferts; small dots: X-ray binaries; small boxes: detected sources from the "48

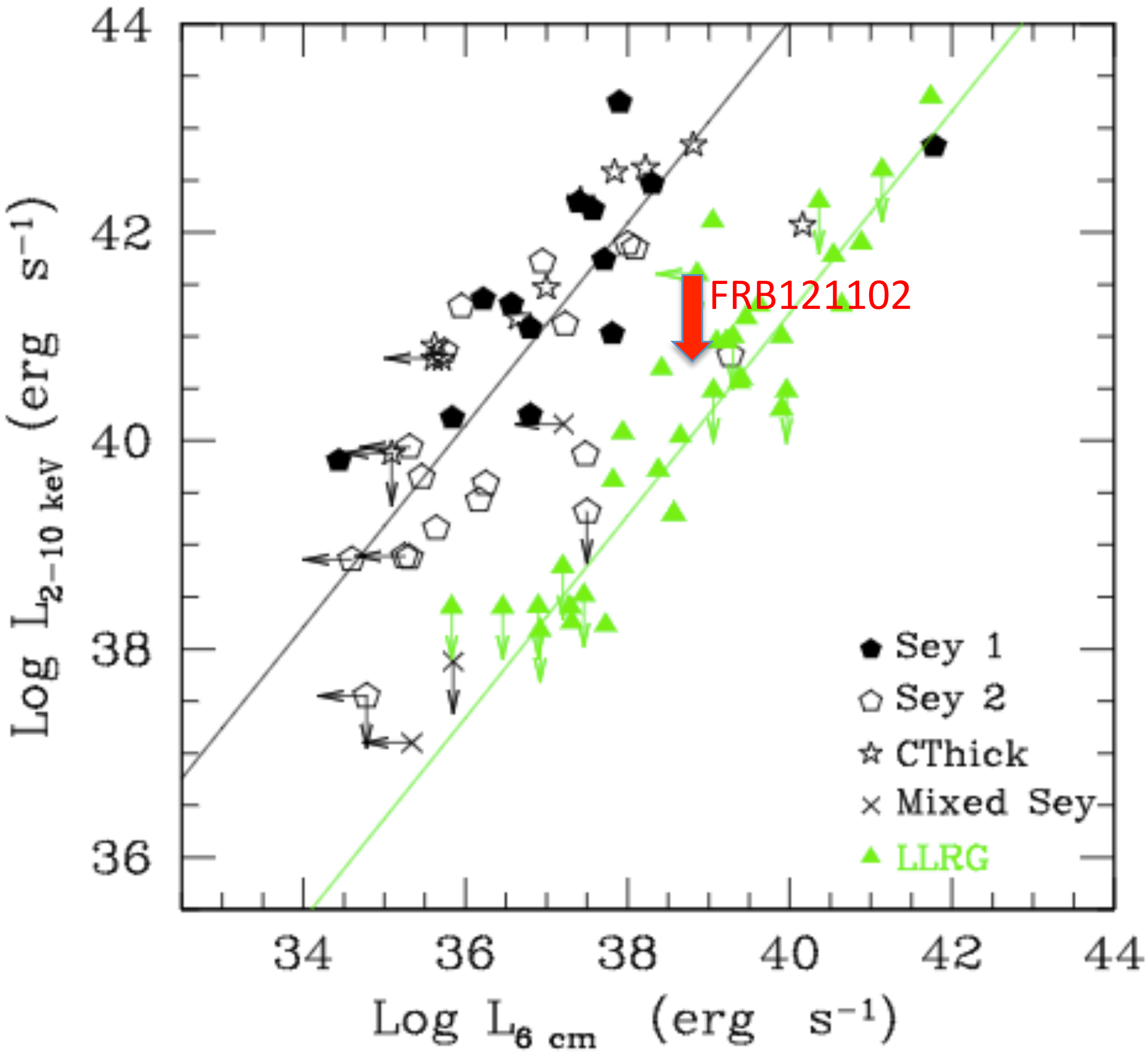
# Radio vs [OIII] –low lum Seyferts

Ulvestad & Ho 2001
Palomar Seyfert Galaxies
(i.e. low lum Seyferts. Half are flat spectrum like FRB121102).



# X-ray vs Radio for low Lum Seyferts

X-ray vs Radio for low luminosity Seyfert galaxies. Panessa+ 2007



# Repetition rate on AGN hypothesis:

$$\phi(LLAGN) \sim 3 \times 10^{-5}\mathrm{Mpc}^{-3}$$

$$\rightarrow N(LLAGN, z < 0.5) \sim 10^6$$

$$R(FRB, > 1\mathrm{Jy}, z < 0.5) \sim 7 \times 10^5 \mathrm{sky}^{-1}\mathrm{y}^{-1}$$

$$\rightarrow \text{required repetition rate} > 1\mathrm{y}^{-1}$$

equality if all AGN participate; higher rates if only a small fraction do.

# Strong Waves

$$eE(c/\omega) = m_e c^2 \to cE^2/4\pi = c\pi \left(\frac{m_e c\nu}{e}\right)^2$$
$$= 1.5 \times 10^{14} \text{erg cm}^{-2}\text{s}^{-1} \nu_{\rm GHz}^2$$

FRB:

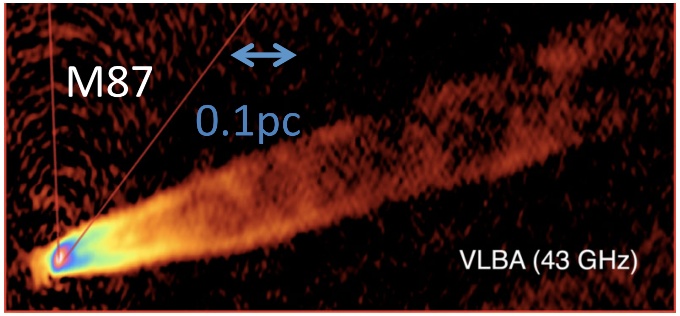
$$1\text{Jy GHz} \left(\frac{1\text{Gpc}}{r}\right)^2 = 1.5 \times 10^{14} \text{erg cm}^{-2}\text{s}^{-1} \left(\frac{2.5 \times 10^{13}\text{cm}}{r}\right)^2$$

Typical FRB: GHz pulse is a strong wave within 1 AU.

$$f \equiv \frac{eE}{m_e c 2\pi\nu}$$

Infinite plane wave: electron at rest accelerated to $\gamma_{max} \approx f^2$ (not $f$, due to phase locking). Single pulse: $\gamma_{max} \approx f$ if $B_{ext}=0$. In large $B_{ext}$ get c $(E\times B/B_{ext}^2)$ drift instead.

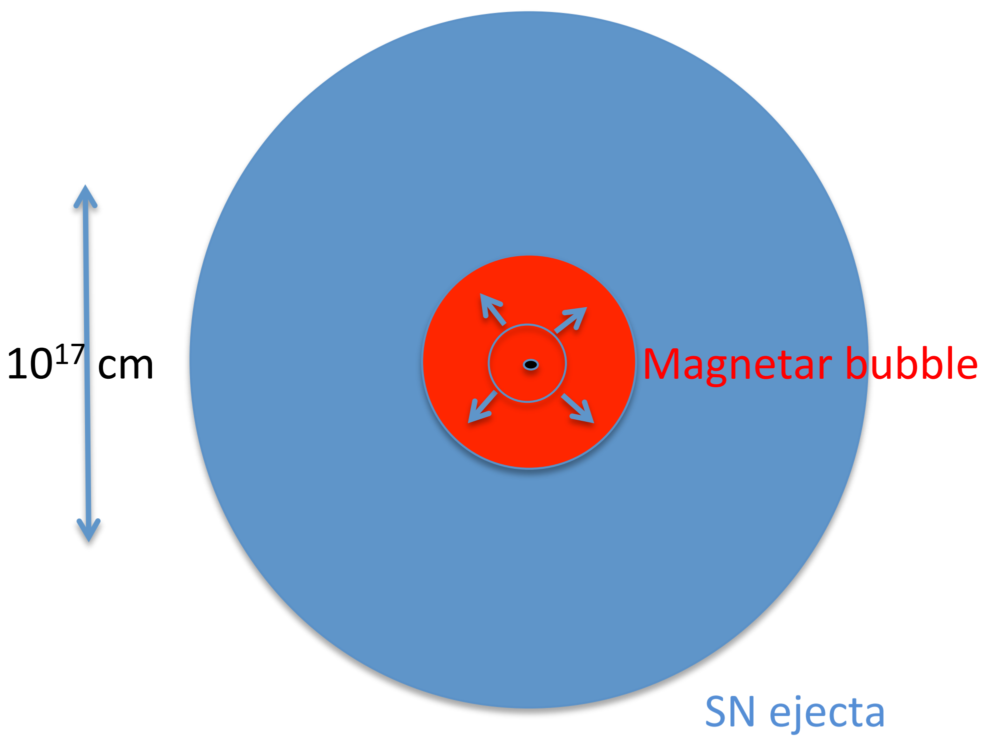
# AGN jet




- Typical flat-spectrum jet with FRB 121102's persistent radio luminosity $L_\nu \sim 2 \times 10^{22}$ W Hz$^{-1}$ has
- $L_{jet} \sim 10^{43}$ erg s$^{-1}$ ($3\times10^{50}$ erg/y)
  - Similar to 10-100y old magnetar bubble ($10^{52}$ erg/100y) [cf Beloborodov 1702.08644]
- Projected synchrotron self-absorption size (3 GHz) ~ 0.1pc ~$3\times10^{17}$cm
  - Also similar to size of 10-100y old magnetar remnant.
  - Deprojected size ~ $\Gamma_j$ larger if jet bulk relativistic Lorentz factor $\Gamma_j$ .

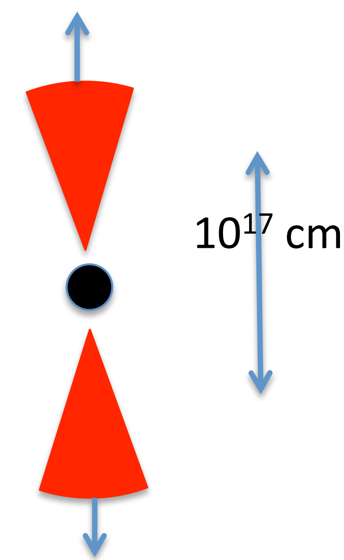
# Magnetar vs AGN jet

Bubble energy ~ $10^{52}$ erg/100y




Inner scale ~NS magnetosphere ~ $10^{7}$ cm

Jet energy ~ $10^{50.5}$ erg/1 y



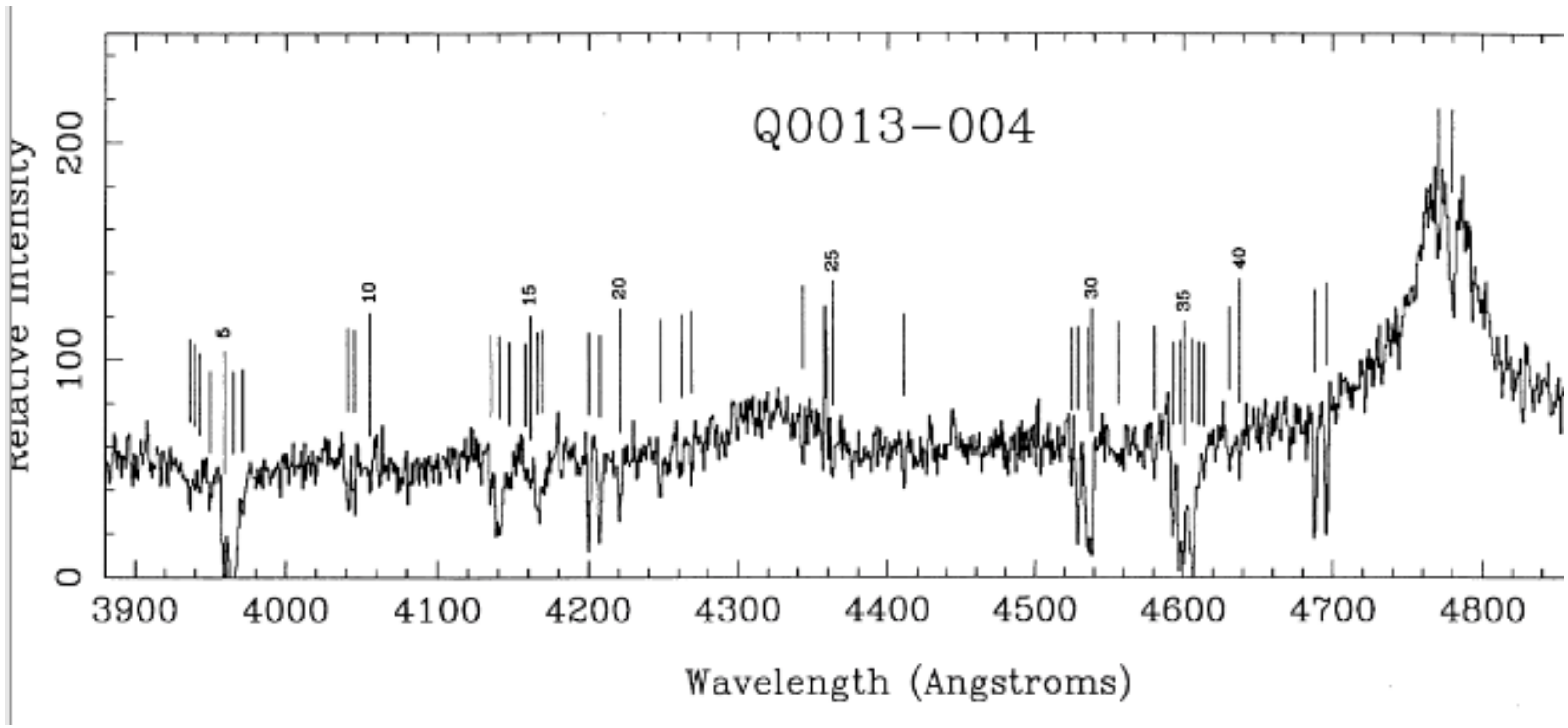

Inner scale $4GM/c^2 \sim 10^{13}$ cm

# FRBs from AGN jets?

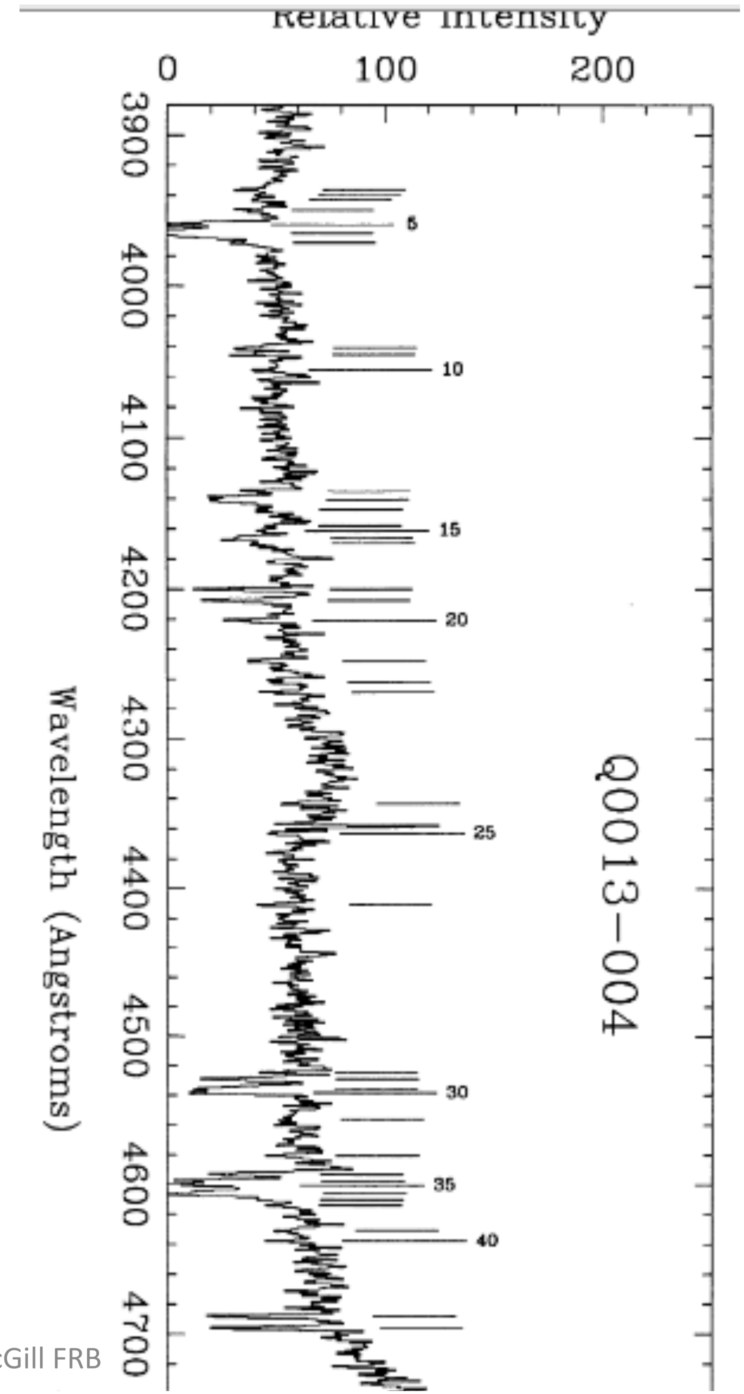
- Need $ct \sim c(\mathrm{ms}) \sim 10^{7.5}$ cm = $R/(4\Gamma_b^2)$
  - $R \sim 3\times10^{17}$cm ➔ $\Gamma_b \sim 10^4$
- Synchrotron maser at transverse internal shock in jet?
  - (cf similar $R$, $\Gamma_b$ in magnetar nebula termination shock model of Lyubarsky 2014).
  - Bad problem for repeater: recycle time ~R/c ~ months.
- reconnection-powered mini-jets within a Poynting-flux dominated e +e- jet (cf models proposed for gamma-ray flares from Crab and Blazars: Giannios+ 2009, Yuan+ 2016, Lyutikov+2016), with coherent emission from the accelerated particles (current-driven instabilities -> maser). Flopping reconnection sheets also possible.
  - possible problem: models were tuned to produce GeV-TeV gamma-rays via synchrotron. Perhaps don't want these for FRBs…
  - Recycle time $\sim R/(c\Gamma_b^2)$ ~ ms –no problem. Solid angle $\sim 1/\Gamma_b^2$
  - Mean repetition time of randomly beamed events > R/c ~ months - correct rate! [actual events will be correlated in time by large-scale reconnection structures]

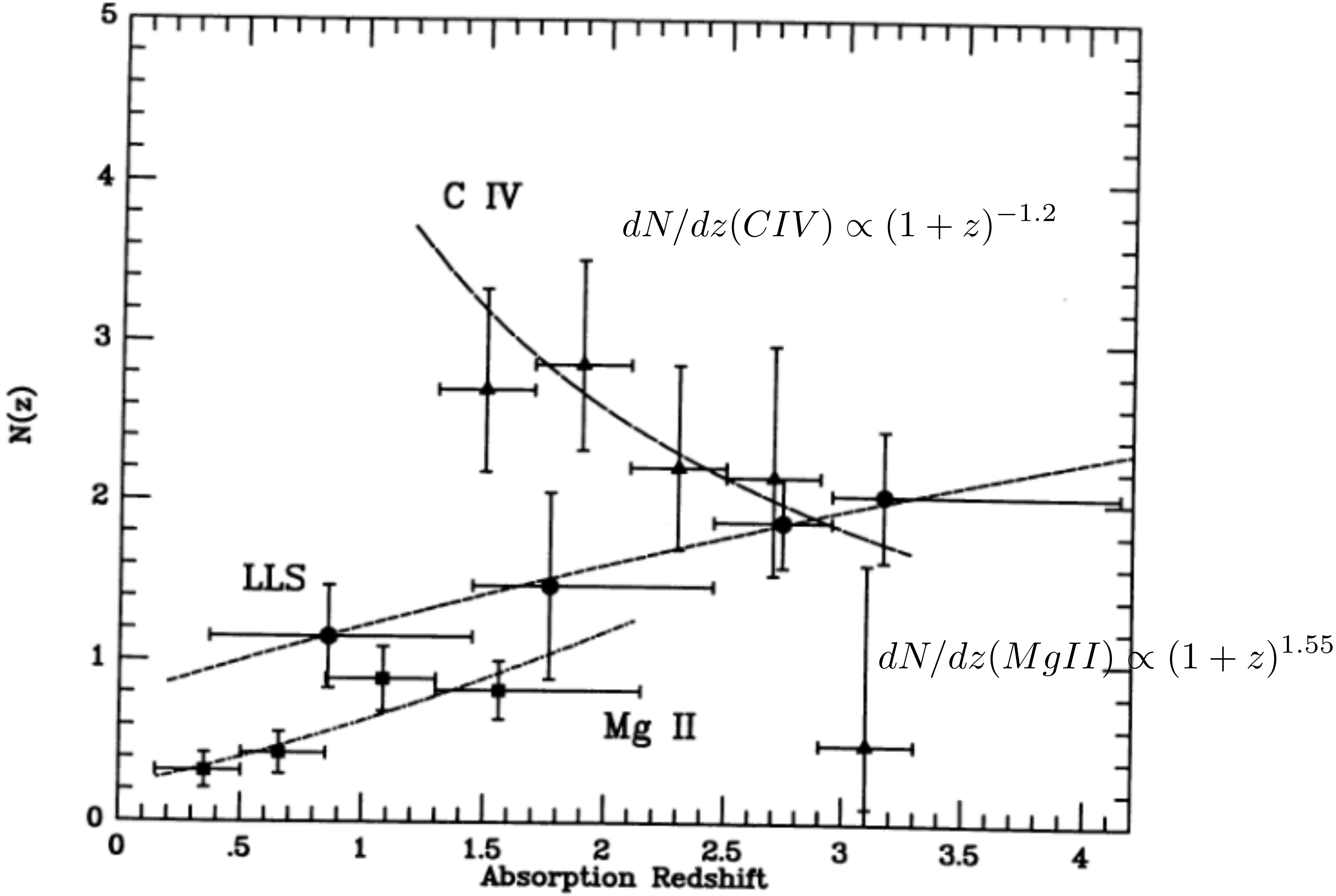
# New Topic: lensing by cold clumps in intervening systems

- Line of sight to objects with $z>0.5$ typically pass through the halos ($R<100$kpc) of one ($z\sim0.5$) to many ($z>2$) intervening galaxies.
  - $10^{-2}$ Mpc$^{-3}$ $\times$ $\pi$ $(0.1\text{Mpc})^2 = 1/(3\text{Gpc})$
  - mean free path between galactic halos ~ 3Gpc.
- Galactic halos have covering factor O(1) in $T\sim10^4$ K photoionized gas, with $N_e\sim10^{20}$ cm$^{-2}$ (DM ~ 30 pc cm$^{-3}$ ), $n_e\sim 2$ cm$^{-3}$ .
  - $N_e / n_e \sim 15$ pc. Unnatural for a 100kpc thin shell or galactic wind!
    - Long-standing mystery…


Q0013−004
Relative Intensity
0
100
200
3900
4000
4100
4200
4300
4400
4500
4600
4700
4800
Wavelength (Angstroms)
5
10
15
20
25
30
35
40

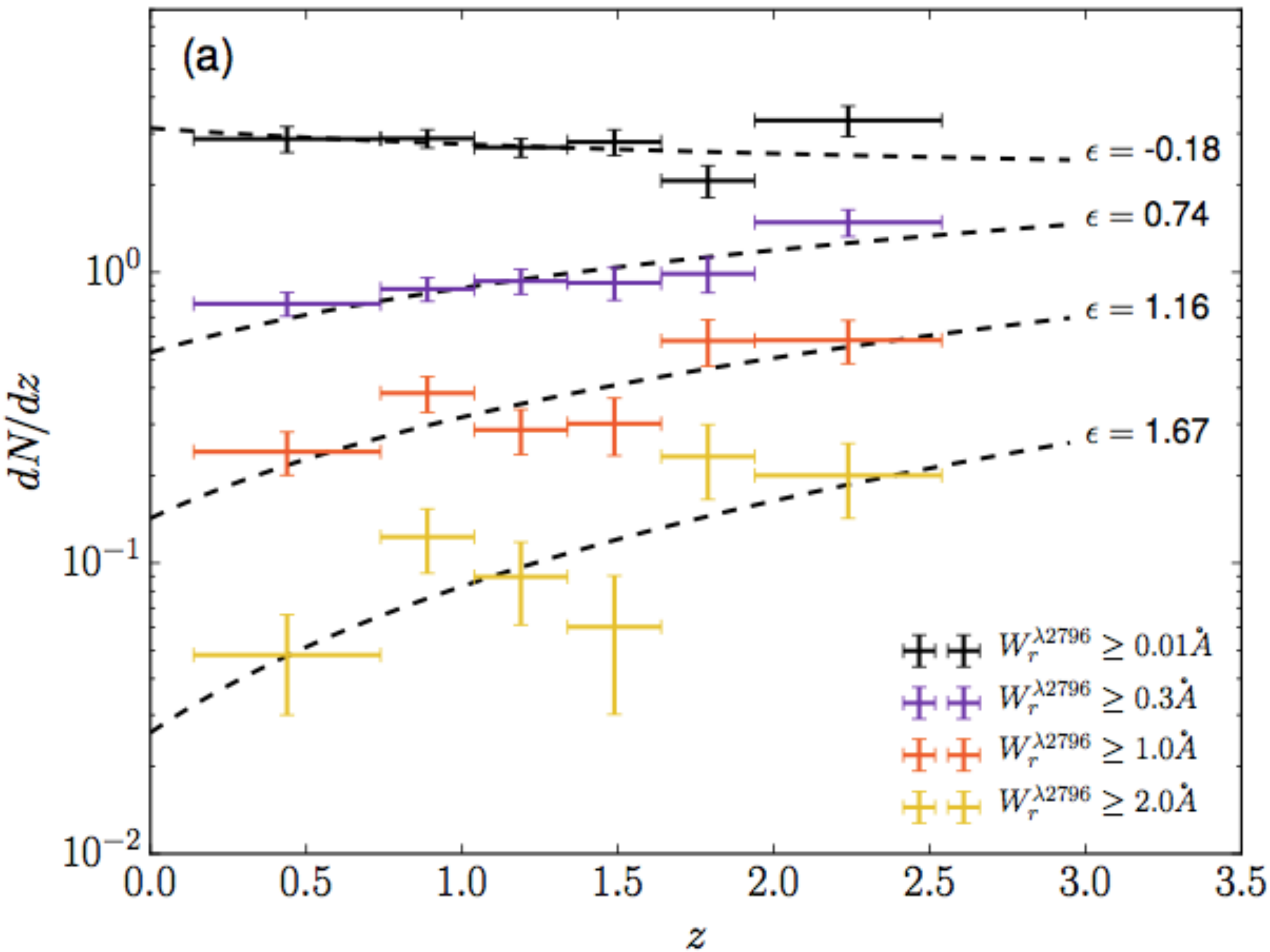
| No. | $\lambda_{obs}$ | $\sigma(\lambda)$ | $W_{obs}$ | $\sigma(W)$ | S/N | ID | $z_{abs}$ |
|---|---|---|---|---|---|---|---|
| | | | | Q0013−004 | | | |
| 1 | 3937.06 | 0.18 | 0.92 | 0.10 | 17.3 | | |
| 2 | 3940.53 | 0.17 | 0.44 | 0.07 | 17.0 | | |
| 3 | 3944.05 | 0.19 | 0.54 | 0.08 | 16.9 | OI(1302) | 2.0288 |
| 4 | 3950.95 | 0.18 | 1.12 | 0.11 | 16.9 | SiII(1304) | 2.0290 |
| 5 | 3960.36 | 0.13 | 3.35 | 0.10 | 16.9 | CII(1334) | 1.9676 |
| 6 | 3966.10 | 0.13 | 7.11 | 0.13 | 16.9 | CIV(1548) | 1.5617 |
| | | | | | | +CII(1334) | 1.9719 |
| 7 | 3972.58 | 0.18 | 1.64 | 0.12 | 17.2 | CIV(1550) | 1.5617 |
| | | | | | | +CII(1334) | 1.9768 |
| 8 | 4041.96 | 0.18 | 1.36 | 0.12 | 14.6 | CII(1334) | 2.0287 |
| 9 | 4046.46 | 0.15 | 0.99 | 0.10 | 14.7 | MgII(2796) | 0.4470 |
| 10 | 4056.83 | 0.19 | 0.62 | 0.10 | 14.4 | MgII(2803) | 0.4470 |
| 11 | 4136.39 | 0.15 | 1.01 | 0.10 | 14.3 | SiIV(1393) | 1.9678 |
| 12 | 4141.67 | 0.15 | 3.60 | 0.15 | 14.4 | SiII(1526) | 1.7128 |
| | | | | | | +SiIV(1393) | 1.9716 |
| 13 | 4148.35 | 0.19 | 1.10 | 0.12 | 14.7 | SiIV(1393) | 1.9764 |
| 14 | 4159.24 | 0.20 | 0.44 | 0.09 | 14.7 | | |
| 15 | 4162.32 | 0.17 | 0.80 | 0.10 | 15.1 | SiIV(1402) | 1.9672 |
| 16 | 4167.45 | 0.14 | 1.78 | 0.11 | 14.7 | SiIV(1402) | 1.9709 |
| 17 | 4170.93 | 0.16 | 0.95 | 0.10 | 14.9 | | |
| 18 | 4201.18 | 0.14 | 1.56 | 0.11 | 15.3 | CIV(1548) | 1.7136 |
| 19 | 4208.71 | 0.16 | 1.96 | 0.12 | 15.3 | CIV(1550) | 1.7139 |
| 20 | 4222.24 | 0.15 | 1.32 | 0.11 | 15.7 | SiIV(1393) | 2.0294 |
| 21 | 4249.39 | 0.20 | 1.01 | 0.11 | 15.8 | SiIV(1402) | 2.0293 |
| 22 | 4263.17 | 0.16 | 0.42 | 0.07 | 16.3 | CIV(1548) | 1.7536 |
| 23 | 4270.17 | 0.15 | 0.64 | 0.08 | 17.1 | CIV(1550) | 1.7536 |
| 24 | 4344.38 | 0.16 | 0.66 | 0.09 | 15.1 | | |
| 25 | 4364.26 | 0.18 | 0.57 | 0.10 | 14.6 | FeII(1608) | 1.7133 |
| 26 | 4411.76 | 0.18 | 0.59 | 0.10 | 14.2 | | |
| 27 | 4525.47 | 0.20 | 0.57 | 0.11 | 13.3 | | |
| 28 | 4530.31 | 0.15 | 2.18 | 0.14 | 13.2 | SiII(1526) | 1.9674 |
| 29 | 4536.86 | 0.14 | 3.38 | 0.16 | 12.9 | SiII(1526) | 1.9716 |
| 30 | 4539.80 | 0.13 | 2.03 | 0.11 | 13.2 | | |
| 31 | 4557.38 | 0.45 | 1.60 | 0.22 | 12.8 | | |
| 32 | 4582.03 | 0.32 | 0.68 | 0.14 | 14.2 | | |
| 33 | 4594.41 | 0.15 | 2.07 | 0.13 | 14.9 | CIV(1548) | 1.9676 |
| 34 | 4598.85 | 0.13 | 2.46 | 0.11 | 15.4 | CIV(1548) | 1.9704 |
| 35 | 4601.80 | 0.13 | 2.28 | 0.10 | 15.4 | CIV(1550) | 1.9674 |
| 36 | 4607.04 | 0.14 | 5.14 | 0.15 | 15.0 | CIV(1550) | 1.9708 |
| | | | | | | +CIV(1548) | 1.9757 |
| 37 | 4611.38 | 0.14 | 1.05 | 0.10 | 14.8 | | |
| 38 | 4615.11 | 0.20 | 0.98 | 0.12 | 14.7 | CIV(1550) | 1.9760 |
| 39 | 4631.94 | 0.21 | 0.71 | 0.12 | 14.3 | SiII(1808) | 1.5619 |
| | | | | | | +CIV(1548) | 1.9918 |
| 40 | 4639.15 | 0.16 | 0.54 | 0.09 | 14.4 | CIV(1550) | 1.9915 |
| 41 | 4689.58 | 0.15 | 1.92 | 0.12 | 16.3 | CIV(1548) | 2.0290 |
| 42 | 4697.20 | 0.15 | 1.71 | 0.11 | 16.2 | CIV(1550) | 2.0289 |
| 43 | 4772.00 | 0.21 | 0.60 | 0.09 | 18.4 | FeII(1608) | 1.9668 |
| 44 | 4781.19 | 0.21 | 1.84 | 0.14 | 18.7 | | |






Steidel, Sargent & Boksenberg 1988 ApJ 333, L5

Mg II intervening absorption lines in quasar spectra (Mathes+ 2017)




weak MgII lines don't evolve

Strong Mg II lines much more common at z~2 than z~0.

$$dN/dz(MgII) \propto (1+z)^{\epsilon}$$

# Mystery solved?

## A Characteristic Scale for Cold Gas

Michael McCourt,[†‡] S. Peng Oh,[†] Ryan M. O'Leary,[§] & Ann-Marie Madigan[§]

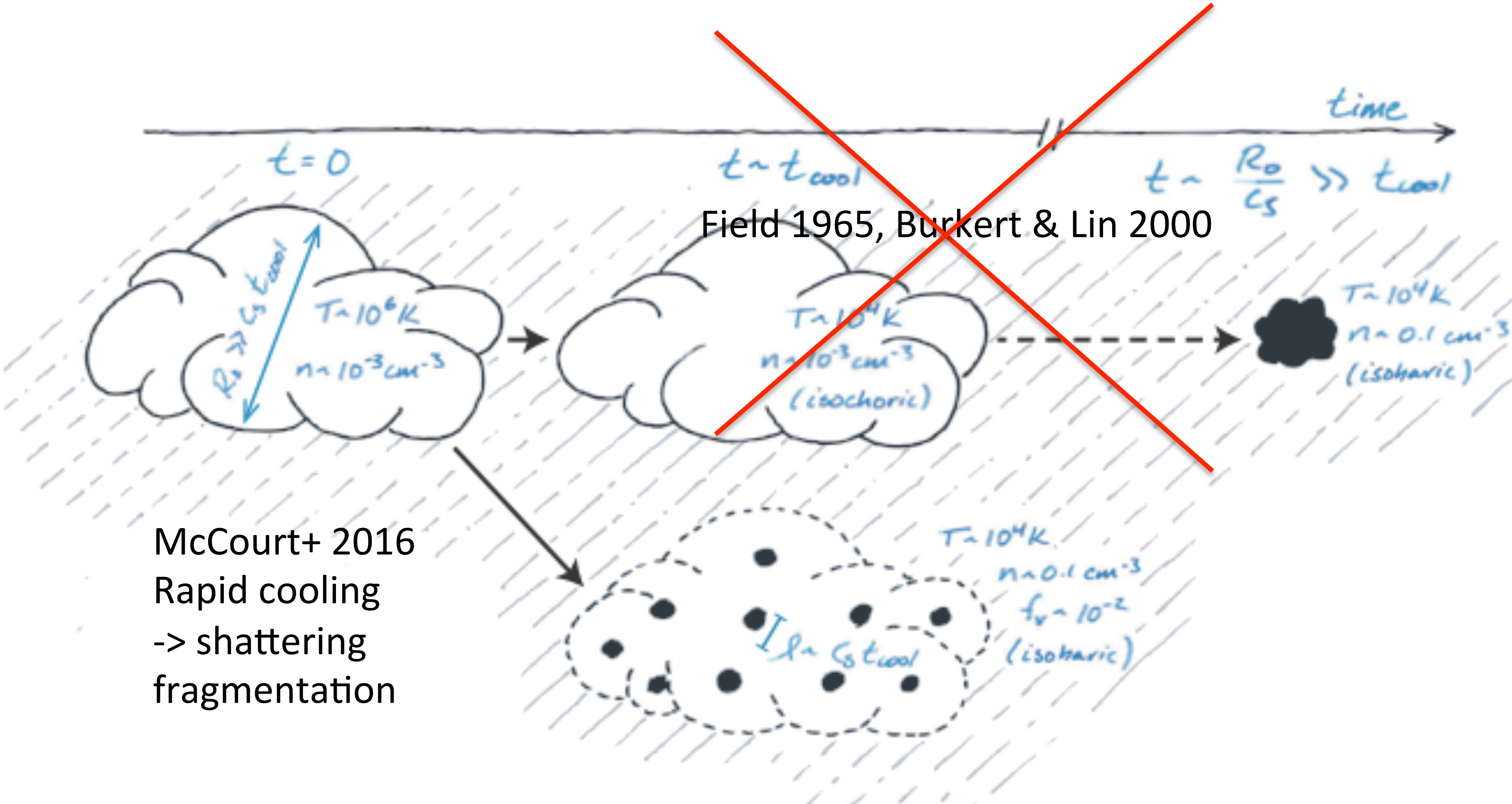
October 6, 2016

**Abstract**

We find that clouds of optically-thin, pressure-confined gas are prone to fragmentation as they cool below $\sim 10^6$ K. This fragmentation follows the lengthscale $\sim c_s t_{\rm cool}$, ultimately reaching very small scales ($\sim 0.1\,{\rm pc}/n$) as they reach the temperature $\sim 10^4$ K at which hydrogen recombines. While this lengthscale depends on the ambient pressure confining the clouds, we find that the column density through an individual fragment $N_{\rm cloudlet} \sim 10^{17}\,{\rm cm}^{-3}$ is essentially independent of environment; this column density represents a characteristic scale for atomic gas at $10^4$ K. We therefore suggest that "clouds" of cold, atomic gas may in fact have the structure of a mist or a fog, composed of tiny fragments dispersed throughout the

arXiv:1610.01164

$$\ell_{\rm cloudlet} \sim \min\left(c_s t_{\rm cool}\right) \sim (0.1\,{\rm pc})\left(\frac{n}{{\rm cm}^{-3}}\right)^{-1}$$




Field 1965, Burkert & Lin 2000

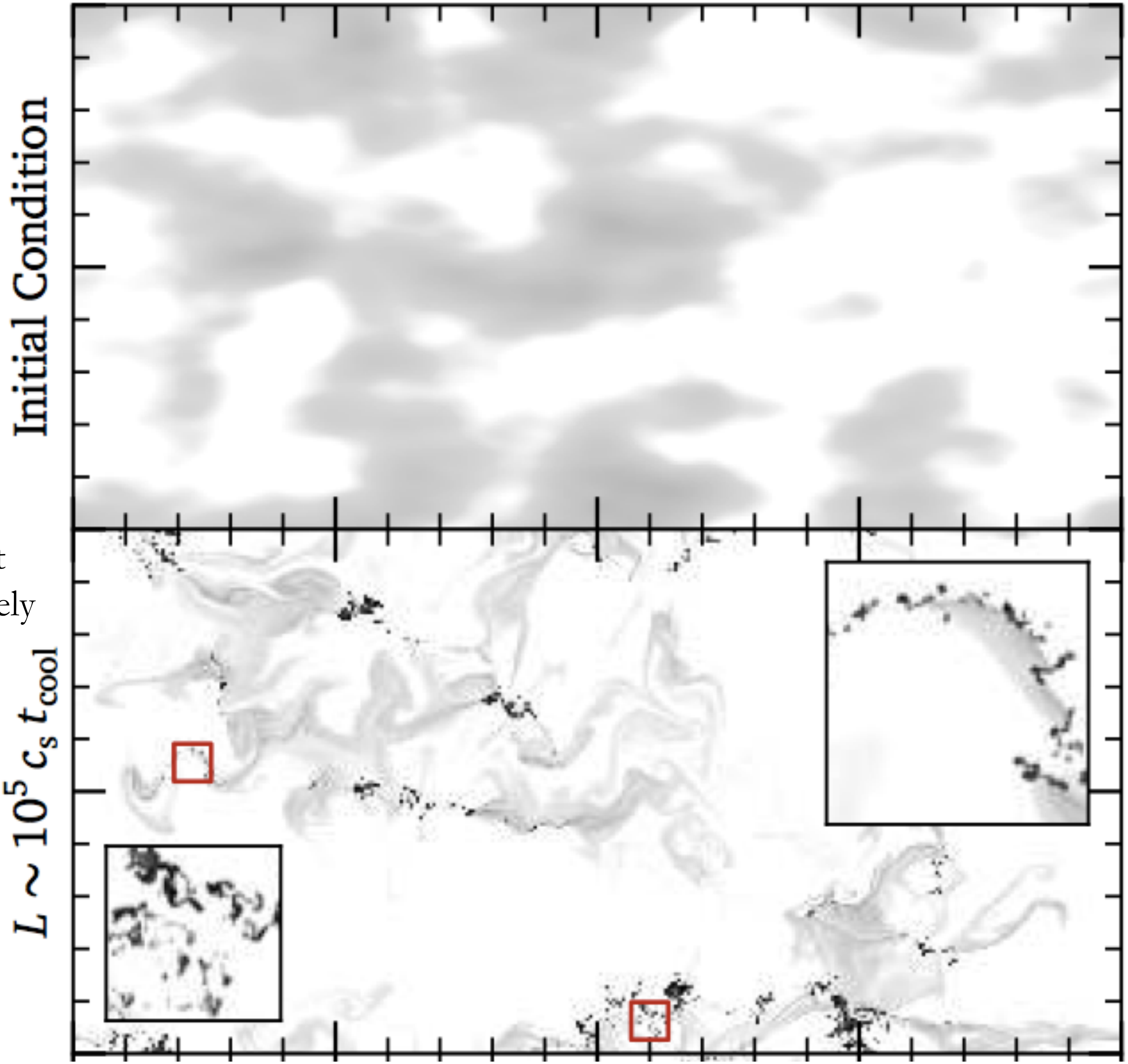
McCourt+ 2016
Rapid cooling
-> shattering
fragmentation

Individual fragments N~$10^{17}$ cm$^{-3}$ , size~0.03pc
Photoionized. Are in pressure equlibrium with hot virial gas.
Any line of sight passes through ~1000 to 3000 fragments.

McCourt+ consider shattering, entrainment in high Mach # winds, hot/cold temp ratios. Very little effect.

Issues mentioned, but not quantitatively addressed:

Effect of Magnetic pressure and (related) thermal conduction.




McCourt+ arXiv:1610.01164

# Plasma lensing by cooling fragments in intervening systems: for FRB, GRB, AGN

Vedantham & ESP 2017

Total phase change though a single fragment $\sim 8\times10^5\ (\lambda\ /30\mathrm{cm})$. Refraction angle given by $\theta_{\rm sc} = \frac{\lambda}{2\pi}\frac{\partial\phi}{\partial r}$

$$\theta_{\rm sc} \sim 3\,\mu{\rm as}\left(\frac{\lambda}{30\,{\rm cm}}\right)^2\left(\frac{N_e}{10^{17}\,{\rm cm}^{-2}}\right)\left(\frac{r_c}{0.1\,{\rm pc}}\right)^{-1} \times N_{cl}^{1/2} \sim 100\ \mu{\rm as}$$

$N_{cl} \sim 1000$

Individual clump
Size ~$10^3$ x Fresnel scale

Pass through single galactic halo.
No turbulence in clouds.

# Circumgalactic gas clumps

- Lensing by McCourt+photoionized cooling fragments:
- Implications
  - Sources (FRB, GRB radio afterglows, Blazars) at z>1 will pass through one or more (or many if z>2) galactic halos covered by thousands of fragments
  - If gas in the fragments is quiescent, refractive scattering disk ~0.1mas at 1GHz, comparable to MW scintillation size limits.
    - Radio observations may provide powerful test of McCourt+ model.
  - Can probably rule out hypothesis that fragments have turbulence with M~1 at outer scale=fragment scale, since that would produce 10mas scattering disks and 10s scattering times. Probably ok, since fragments moving relative to hot phase are quickly slowed: no large shear around them to excite turbulence. Sound crossing time $\sim 10^4$ y.
    - But maybe surprisingly small turbulence limit?
  - TBD: effects of magnetic fields on turbulence, conductive lifetimes, RM structure…
- In any event, intervening systems clearly exist and have smooth velocity profiles that are hard to explain without lots of fragments. But >1pc fragments rather than McCourt+'s 0.1pc fragments would be less constrained by radio.

Limits to caustic magnification due to wave optics.

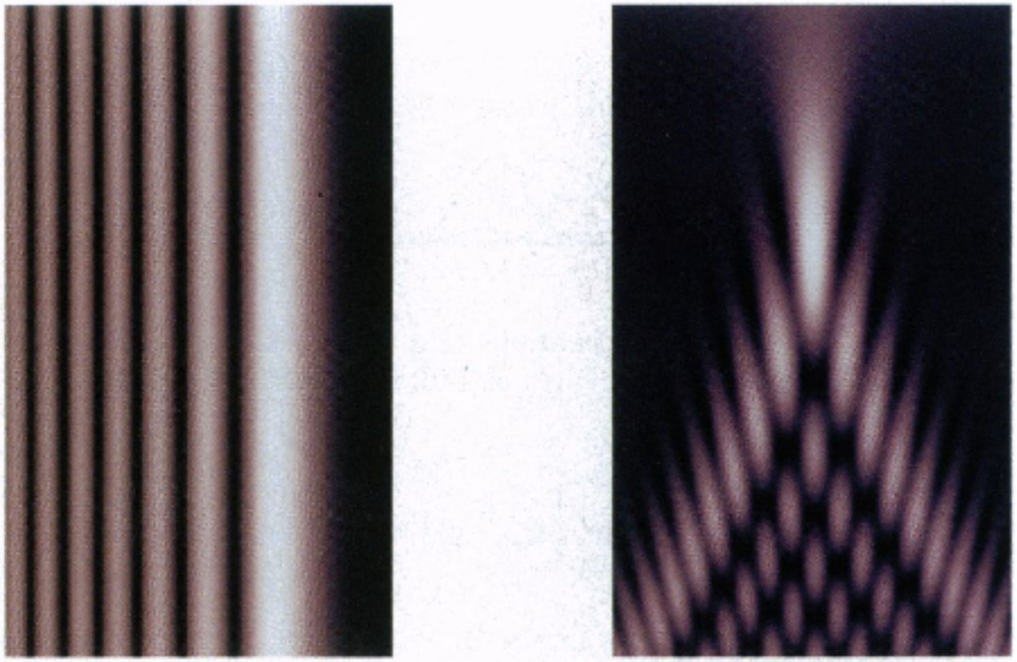
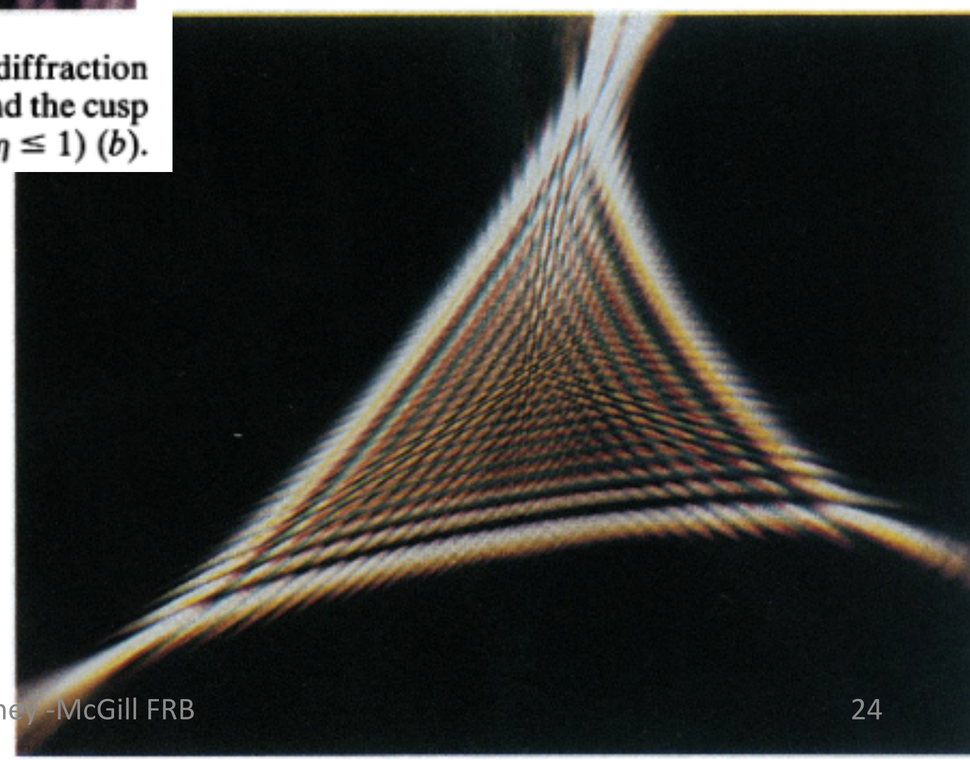


FIG. 1. Density plots of intensity of the monochromatic diffraction catastrophes for the fold (Airy function: $-10 \leq \xi \leq 3$) (*a*) and the cusp (Pearcey function: ordinate, $-9 \leq \xi \leq 2$; abscissa, $-10 \leq \eta \leq 1$) (*b*).

white light photo pf cusp/folds caustics
through
rippled bathroom window glass



Berry & Klein 1996, PNAS 93, 2614