THE INTERSTELLAR MEDIUM: XI
The Warm Ionized Medium

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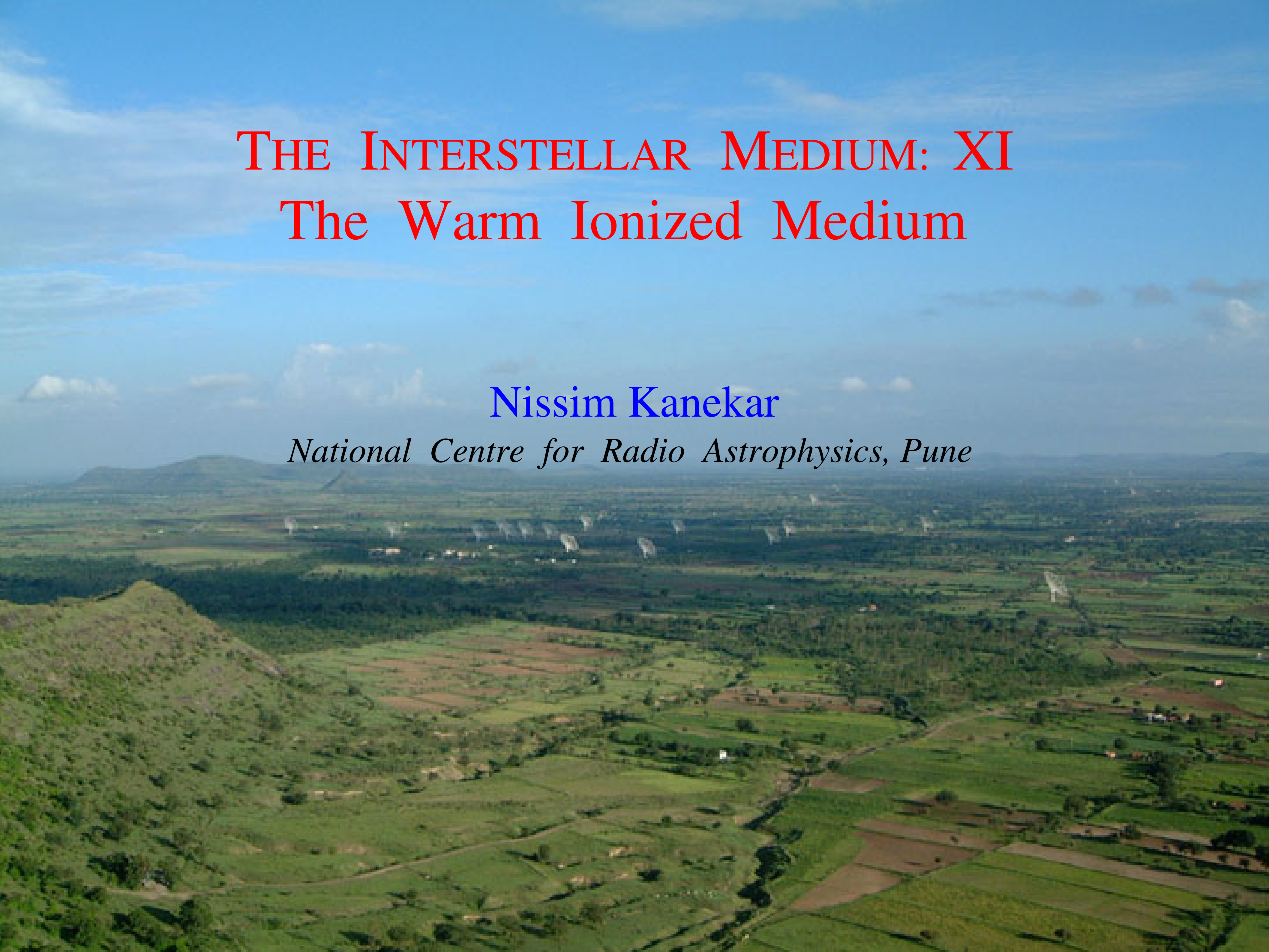


OUTLINE

- Background.
- The warm ionized medium: Probes of conditions.
- Pulsar dispersion measures.
- Hα emission studies: The emission measure.
- The WIM filling factor.
- Temperature, ionization, and energetics.

BACKGROUND

- Dust in the ISRF: (1) Far-IR thermal emission, (2) Mid-IR PAH bands, (3) ~ 20 GHz emission from spinning charged grains.

- Radiative heating rate: $(dE/dt)_{abs} = \langle Q_a \rangle_\star \times \pi a^2 \times c\, u_\star$.

  $\langle Q_a \rangle_\star \equiv \int d\nu\, u_{\nu,\star}.Q_a(\nu) \;/\; \int d\nu\, u_{\nu,\star}$ & $u_\star \equiv$ Starlight energy density.

- Radiative cooling rate: $(dE/dt)_{em} = \langle Q_a \rangle_T \times 4\pi a^2 \times \sigma T^4$.

  $\langle Q_a \rangle_T \equiv \int d\nu\, B_\nu(T)\, Q_a(\nu) \;/\; \int d\nu\, B_\nu(T)$

- In thermal balance: $T_D = [\, \langle Q_a \rangle_\star \times (c/4\pi) \times u_\star / \langle Q_a \rangle_T \,]^{1/4}$

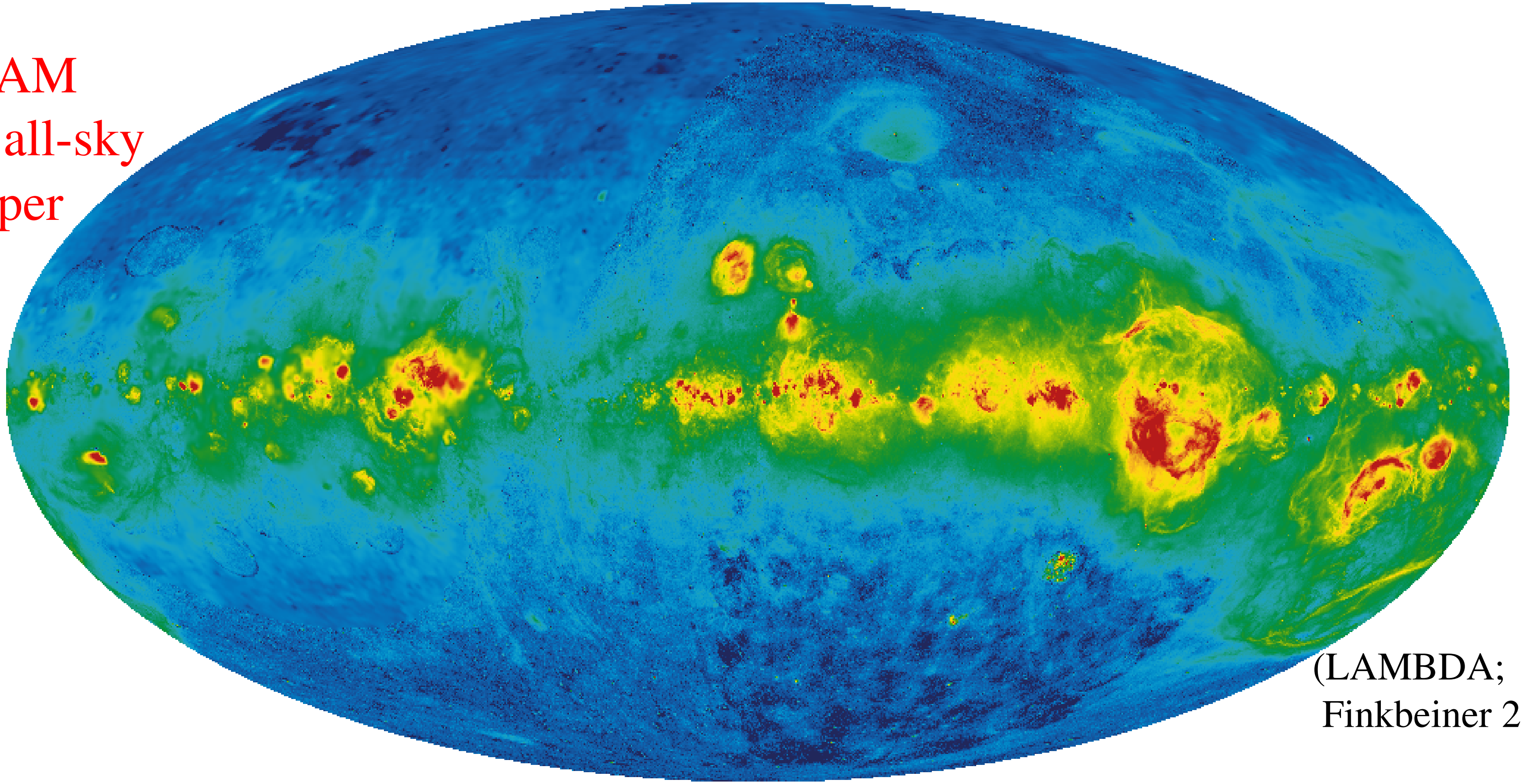
  $T_D = 16.4\, (a/0.1\mu m)^{-1/15}\; U^{1/6}$ K : Silicates, $0.01\ \mu m \leqslant a \leqslant 1\ \mu m$.

  $T_D = 22.3\, (a/0.1\mu m)^{-1/40}\; U^{1/6}$ K : Graphite, $0.005\ \mu m \leqslant a \leqslant 0.15\ \mu m$.

- Multi-parameter fits to the IR SED, including dust composition, PAH fraction, ISRF, size/temperature distribution, ISRF, … ?
  Or dust mass, via "modified black-body fits", to the far-IR SED ?

THE WARM IONIZED MEDIUM

WHAM
Hα all-sky
mapper



(LAMBDA;
Finkbeiner 2003)

- Diffuse ionized gas: T ~ 8000 K; *n* ~ 0.03 cm^{-3}; Mass ~ 10^9 $M_\odot$.

- Probes: Hα emission, pulsar dispersion, forbidden lines, free-free emission/absorption, radio recombination lines, Faraday rotation, interstellar scintillation, scatter broadening...

PULSAR DISPERSION MEASURES

- Wave equation for electromagnetic radiation travelling in a plasma:
  $\nabla^2\mathbf{E} - (1/c^2).\partial^2[\varepsilon\mathbf{E}]/\partial t^2 = 0$, where ε is the permittivity.

- Travelling wave solutions: $E = E_0.e^{i(\mathbf{k.r} - \omega.t)}$, with $k^2 = \varepsilon.(\omega^2/c^2)$

- For a non-relativistic electron, $m_e.d^2\mathbf{r}/dt^2 = -e.\mathbf{E} = -e.\mathbf{E_0}.e^{i(\mathbf{k.r} - \omega.t)}$.
  ⇨ $\mathbf{r} = (e/m_e\omega^2).\mathbf{E}$

- The polarization density, $\mathbf{P} = n_e.(-e).\mathbf{r} = -(n_e e/m_e\omega^2).\mathbf{E}$

- The electric displacement, $\mathbf{D} = \mathbf{E} + 4\pi.\mathbf{P} = \varepsilon\mathbf{E}$
  ⇨ $\varepsilon = (1 - 4\pi.n_e e^2/m_e\omega^2) = 1 - (\omega_p/\omega)^2$,
  where $\omega_p{}^2 = 4\pi.n_e e^2/m_e$ ⇨ $\omega_p = 5.6 \times 10^4 \ (n_e/\mathrm{cm}^{-3})^{1/2}\ \mathrm{s}^{-1}$.

- The group velocity, $V_g = d\omega/dk = c.\varepsilon^{1/2} = c.[1 - (\omega_p/\omega)^2]^{1/2}$.
  ⇨ For $\omega_p < \omega$, low-frequency waves travel slower in a medium!

PULSAR DISPERSION MEASURES

- For the WIM, $n_e \sim 0.03\ \mathrm{cm}^{-3}$

  $\nu_p \approx 1.5$ kHz & $\nu_p \ll \nu$.

  ⇨ $V_g \approx c.[1 - (½).(\nu_p/\nu)^2]$.

- The dispersion delay is then

  $\Delta t(\nu) = \int(1/V_g)ds - (d/c)$.

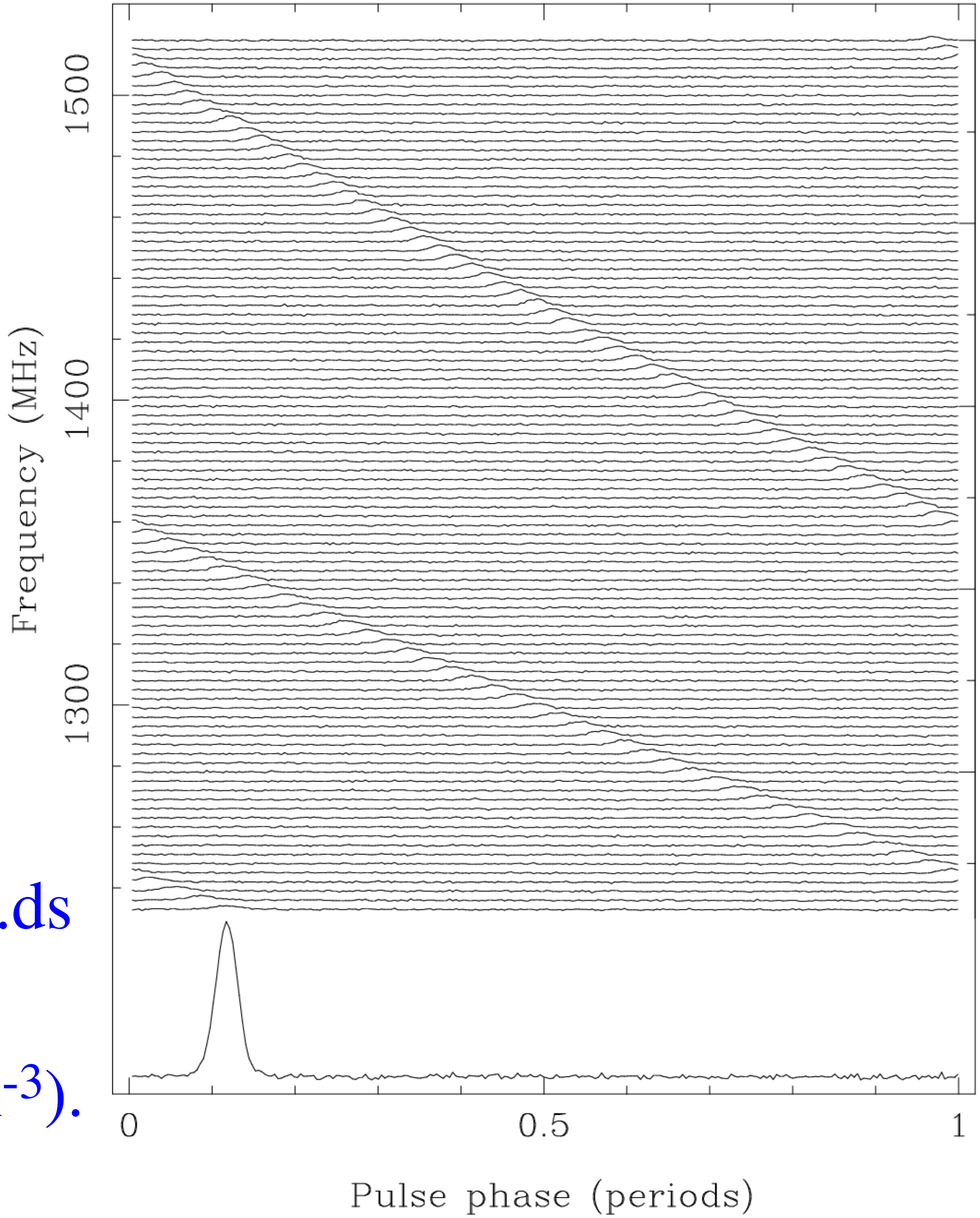
  $\approx (1/c)\int[1 + (½).(\nu_p/\nu)^2].ds - (d/c)$

  $= (e^2/2\pi.m_e c) \times \nu^{-2} \times \int n_e.ds$.

- The dispersion measure, $DM = \int n_e.ds$

  ⇨ $\Delta t(\nu) = 4.149 \times \nu^{-2} \times DM$,

  (Δt in s, ν in MHz, DM in pc cm^{-3}).

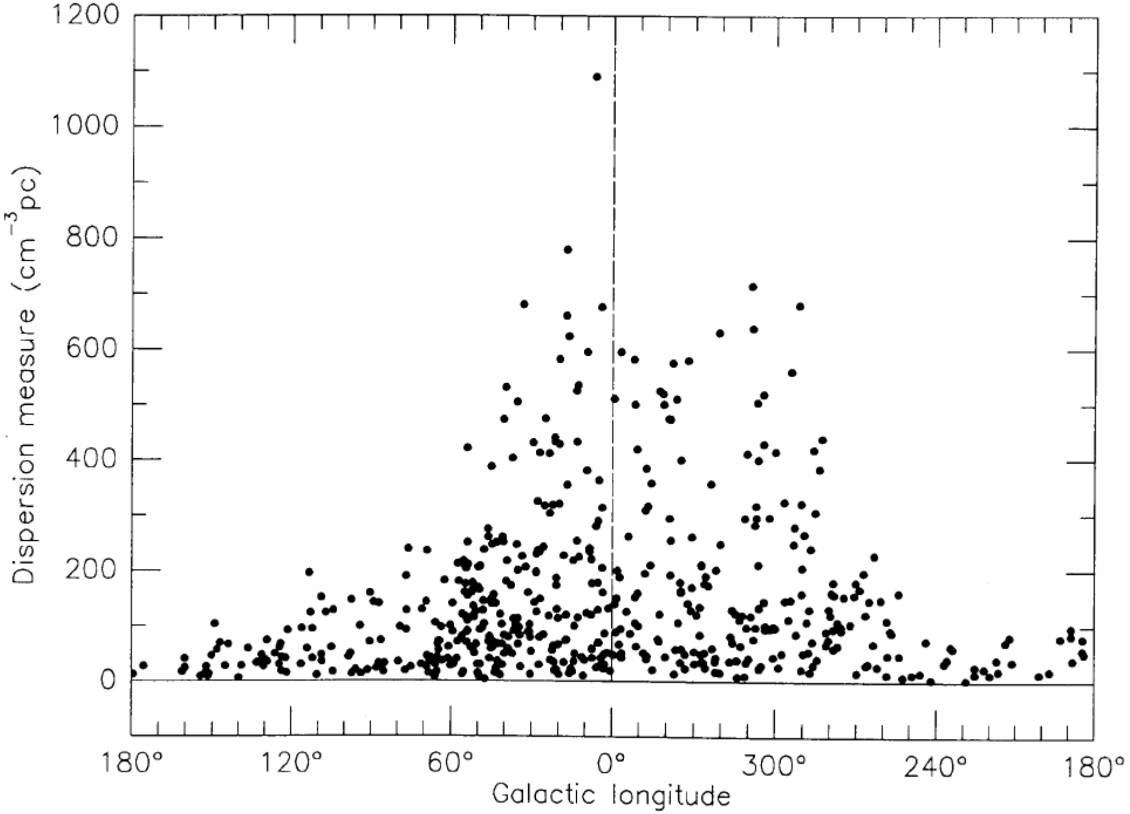


(Lorimer & Kramer 2007)

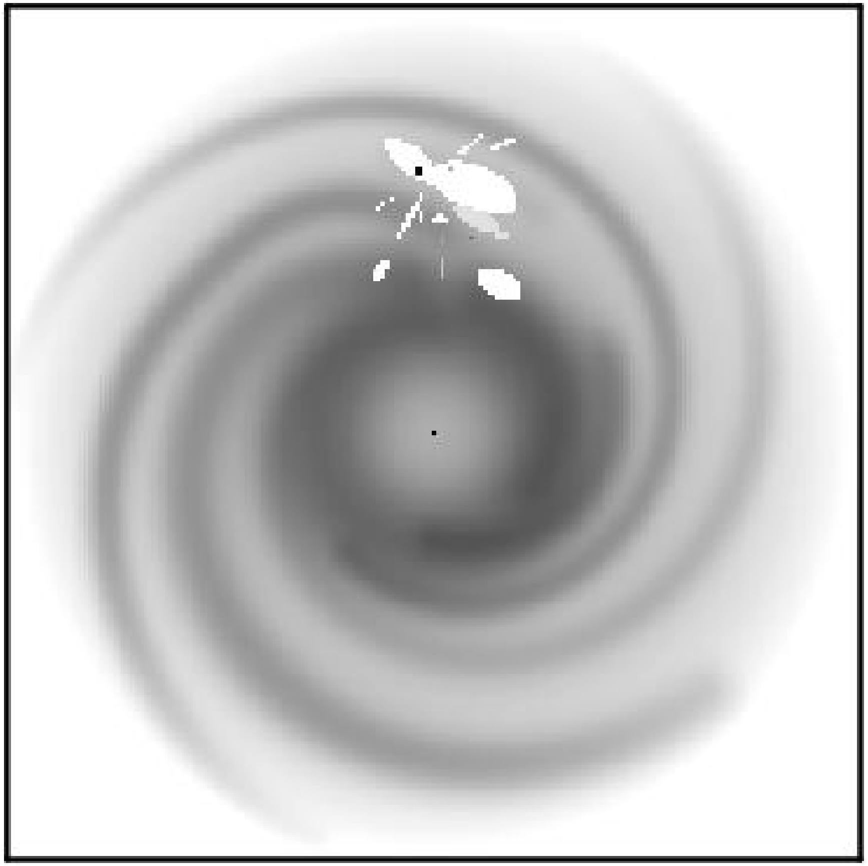
⇨ Measure DM and pulsar distance: Infer average electron density!

GALACTIC FREE ELECTRON DISTRIBUTION

(Taylor & Cordes 1993)



(Cordes & Lazio 2001)



- Use a model for the Galactic spiral structure (e.g. HII regions).

(Georgelin & Georgelin 1976)

- Determine n_e from pulsar DMs & distance estimates (via parallax, HI-21cm absorption, etc), scattering estimates, pulse broadening...

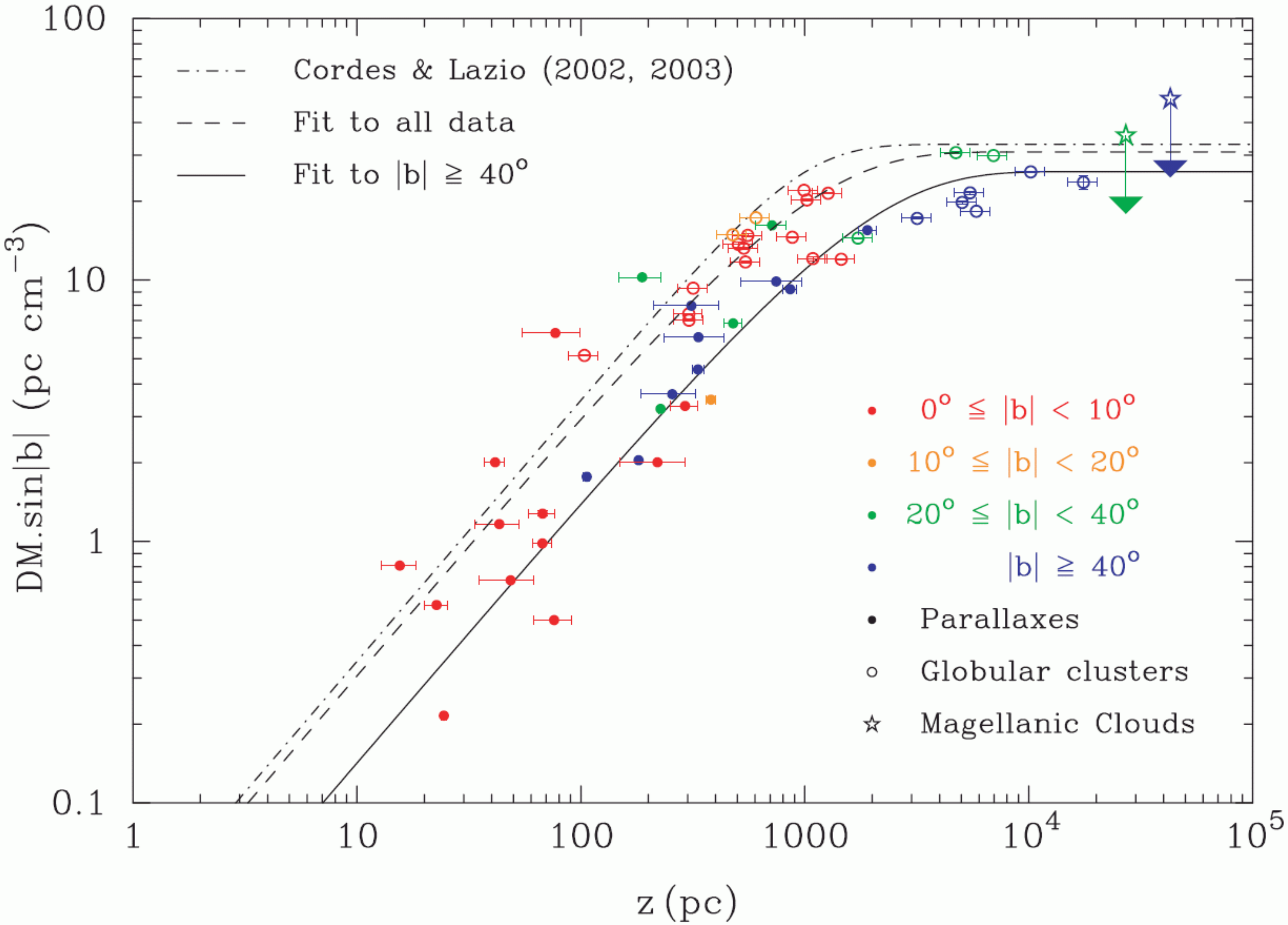
(e.g. Taylor & Cordes 1993; Cordes & Lazio 2001)

- Make many enemies (and a few friends)!

(NE2001 model, Cordes & Lazio 2001, arxiv:0207156)

PULSAR DISPERSION MEASURES

(Reynolds 1989)



- Distances: Trigonometric parallax, globular clusters, LMC/SMC.
- Exponential fit: $n(z) = n_0.e^{-z/H}$ ⇨ $H = 1830$ pc , $n_0 = 0.014$ cm^{-3} !

(Gaensler et al. 2008)

- Typical DM ~ 30 pc cm^{-3} at 1 kpc distance ⇨ $n_0 = 0.03$ cm^{-3} !

Hα STUDIES: THE EMISSION MEASURE

(Ron Reynolds!)

- Hα line: Recombination in ionized gas; strong from HII regions.

- Hα intensity on a sightline: $I_{H\alpha} = (h\nu_{H\alpha}/4\pi) \times \int n_e \,.\, n_p \,.\, \alpha_{H\alpha} \,.\, ds$
  where $\alpha_{H\alpha}$ is the rate of Hα production by e-p recombination.

- For a uniform sightline: $I_{H\alpha} = (h\nu_{H\alpha}/4\pi) \times \alpha_{H\alpha} \times \int n_e^2\, ds$
  $= (h\nu_{H\alpha}/4\pi) \times \alpha_{H\alpha} \times \mathrm{EM}$,
  where the Emission Measure, $\mathrm{EM} = \int n_e^2\, ds$.

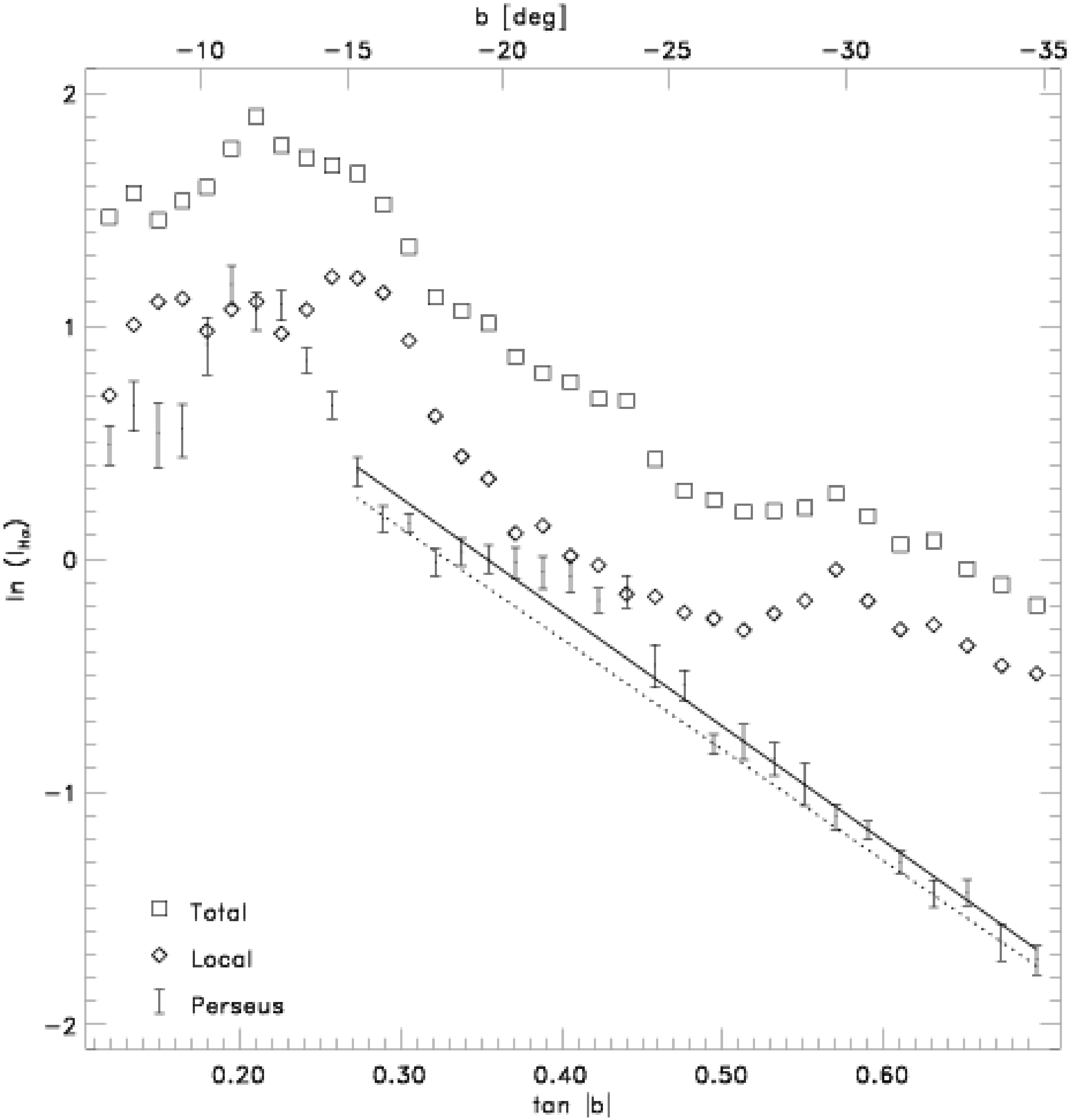
- Emission measures in the Galactic plane ~ (9 – 23) cm^{-6} pc.
  Dust absorption ⇨ Path < 2 kpc ⇨ $n_e^2 \sim (4.5 - 11.5) \times 10^{-3}\ \mathrm{cm}^{-6}$.
  (e.g. Reynolds et al. 2004)

- At high Galactic latitudes, low EMs, ~ (1 – 2) cm^{-6} pc .

- Wisconsin Hα Mapper Survey: All-sky survey (0.1 cm^{-6} pc) with velocity resolution of ~ 12 km/s! Also covers other nebular lines.
  (e.g. Haffner et al. 1999)

Hα Studies: The Emission Measure

$\ln(I_{H\alpha})$



Total

Local

Perseus

- Hα studies towards the Perseus arm: EM scale height ~ 800 pc.

(e.g. Haffner et al. 1999)

DM AND EM: THE WIM FILLING FACTOR

- Typical DM ~ 30 pc cm^{-3} at 1 kpc distance ⇨ $n_0 = 0.03$ cm^{-3} !

  ⇨ Expected EM at 1 kpc distance ~ 1000 × 0.03^2 ~ 0.9 cm^{-6} pc.
  But typical EM values in the plane ~ (9 – 23) cm^{-6} pc.

  ⇨ Indicates a filling factor $f < 1$ for the WIM!

- Emission measure ⇨ $f.n_e^2 \approx (4.5 - 11.5) \times 10^{-3}$ cm^{-6}.
  Dispersion measure ⇨ $f.n_e \approx 0.03$ cm^{-3}.

  ⇨ Filling factor, $f \approx 0.05 - 0.2$! True density, N ~ 0.15 – 0.4 cm^{-3}.

  ⇨ The WIM is quite lumpy! Significant regions with little WIM.

(e.g. Ferriere 2001)

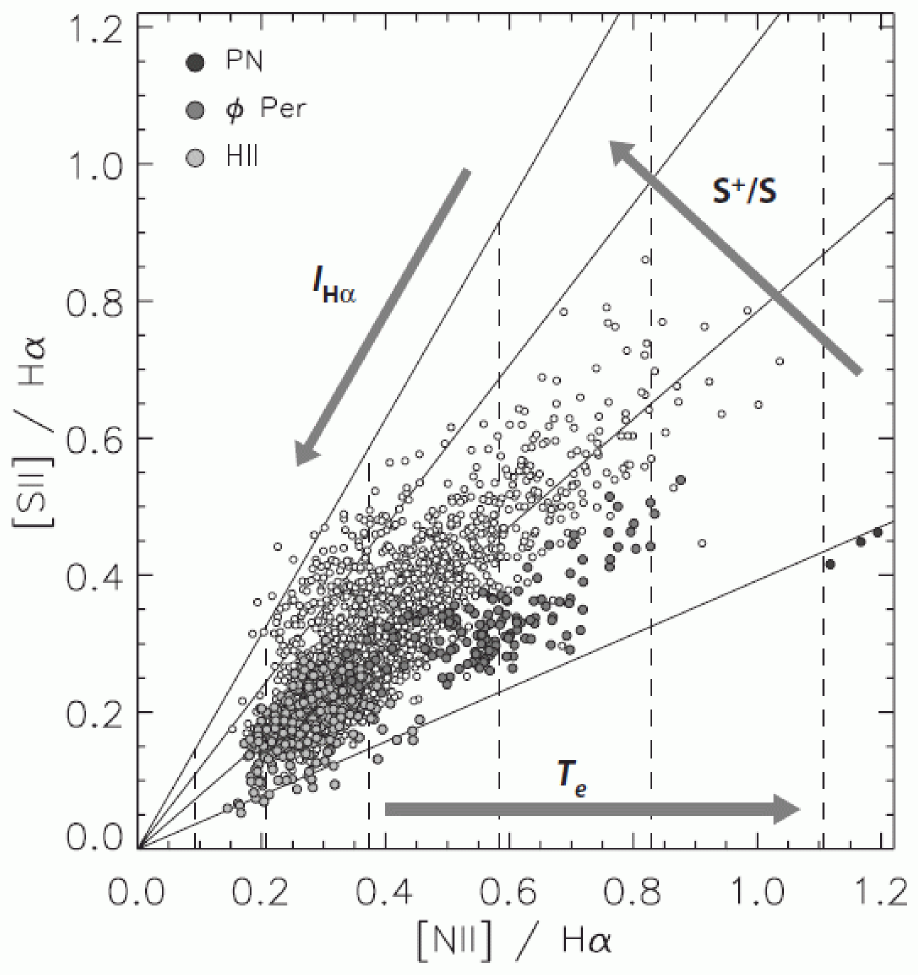
- Assuming $N(z) = N_0.e^{-z/H_N}$ and $f(z) = f_0.e^{+z/H_f}$, i.e. an increasing filling factor with distance from the Galactic plane:
  ⇨ $H_N = 500$ pc, $H_f = 710$ pc, $N_0 = 0.34$ cm^{-3} and $f_0 = 0.04$.

(Berkhuijsen et al. 2006; Gaensler et al. 2008)

OTHER DIAGNOSTICS

- [SII]/Hα and [NII]/Hα ratios
  ⇨ $T_e \sim (6000 - 10000)$ K.
  Higher temperature (by ~ 2000 K) in WIM than in HII regions!

(Haffner et al. 2009)



- Hα and [NII], [SII] line widths
  Thermal v/s non-thermal broadening.
  ⇨ $T_e <$ 10000 K.

- [NII] λ5755/λ6784 lines: Different excitation energies ⇨ Direct estimate of gas temperature, higher by ~ 2000 K.

(Reynolds et al. 2001)

- HI/HII and OI/OII fractions coupled by large charge exchange cross-section: Can use OI/OII fraction to infer HI/HII fraction!
  OI λ6300/Hα ~ 0.0015 – 0.005 ⇨ WIM is mostly ionized!

(e.g. Hausen et al. 2002)

ENERGETICS: THE SOURCE OF IONIZATION

- Number of ionizing photons inferred from the recombination rate:

  $= \int n_e^2 \alpha \, ds = \alpha.\mathrm{EM}$

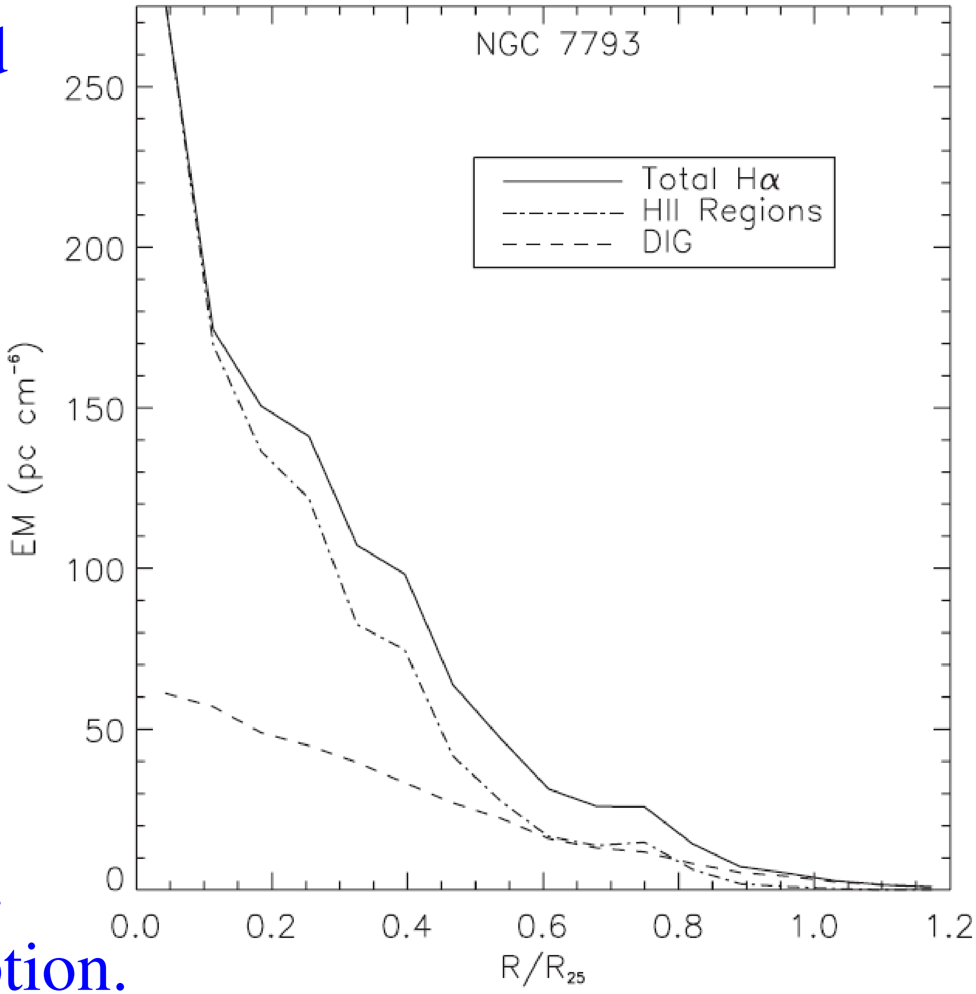
  $\approx (10 \text{ cm}^{-6} \text{ pc}) \times (3 \times 10^{-13} \text{ cm}^3 \text{ s}^{-1})$

  $\approx 10^7 \text{ cm}^{-2} \text{ s}^{-1} \sim 10^{50} \text{ phot. s}^{-1} \text{ kpc}^{-2}$

- High rate: > 1 O5 star per kpc^2! > 10% of hot star luminosity.

- Too little power from other sources. Photo-ionization by O stars only option.

(Ferguson et al. 1996)



- Can Lyman continuum photons travel long distances in the ISM ? Requires HI in the Milky Way to have holes to allow propagation of ionizing radiation. Must also reach high (~ 1 kpc) altitudes.