Physics 224
The Interstellar Medium

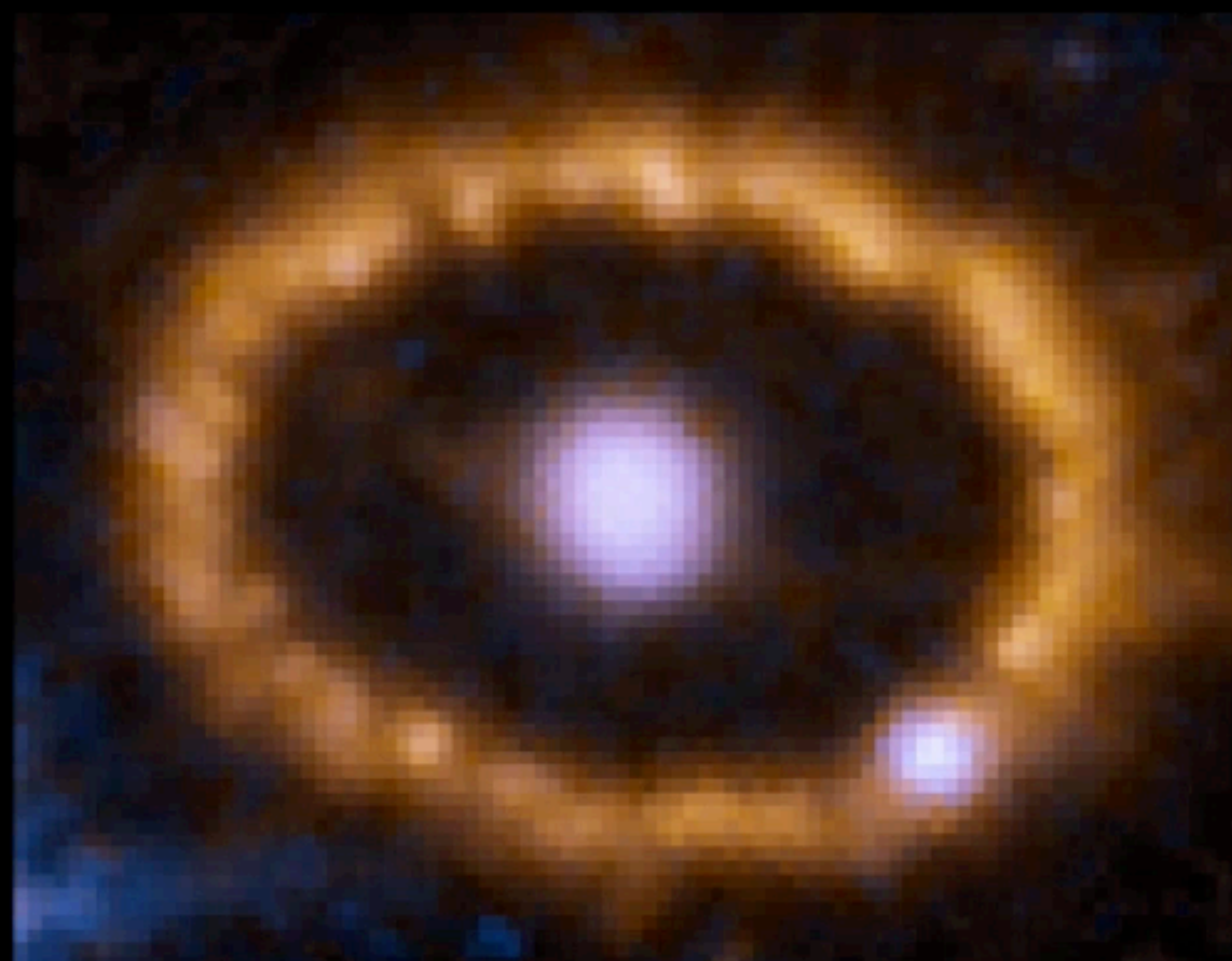
Lecture #19

Supernovae

Initially: M_{ejecta} ~ few $M_{\odot}$, v_{ejecta} ~10^4 km/s

Phase	Characteristics	Ends when…	Radius & time dependence
Free Expansion	ballistic expansion, shock wave into ISM/CSM, ejecta cools due to adiabatic expansion, reverse shock when $P_{shocked\ ISM} > P_{ej}$	$M_{swept} > M_{ej}$	$R \sim t$
Sedov-Taylor	ejecta is very hot, $P_{ej}>P_{ISM}$ expansion driven by hot gas, radiation losses are unimportant	radiative losses become important	$R \sim t^{2/5}$
Snow Plow	pressure driven expansion with radiative loss, then momentum driven	shock becomes subsonic	$R \sim t^{2/7}$ $R \sim t^{1/4}$
Fadeaway	turbulence dissipates remnant structure and merges with ISM	-	-

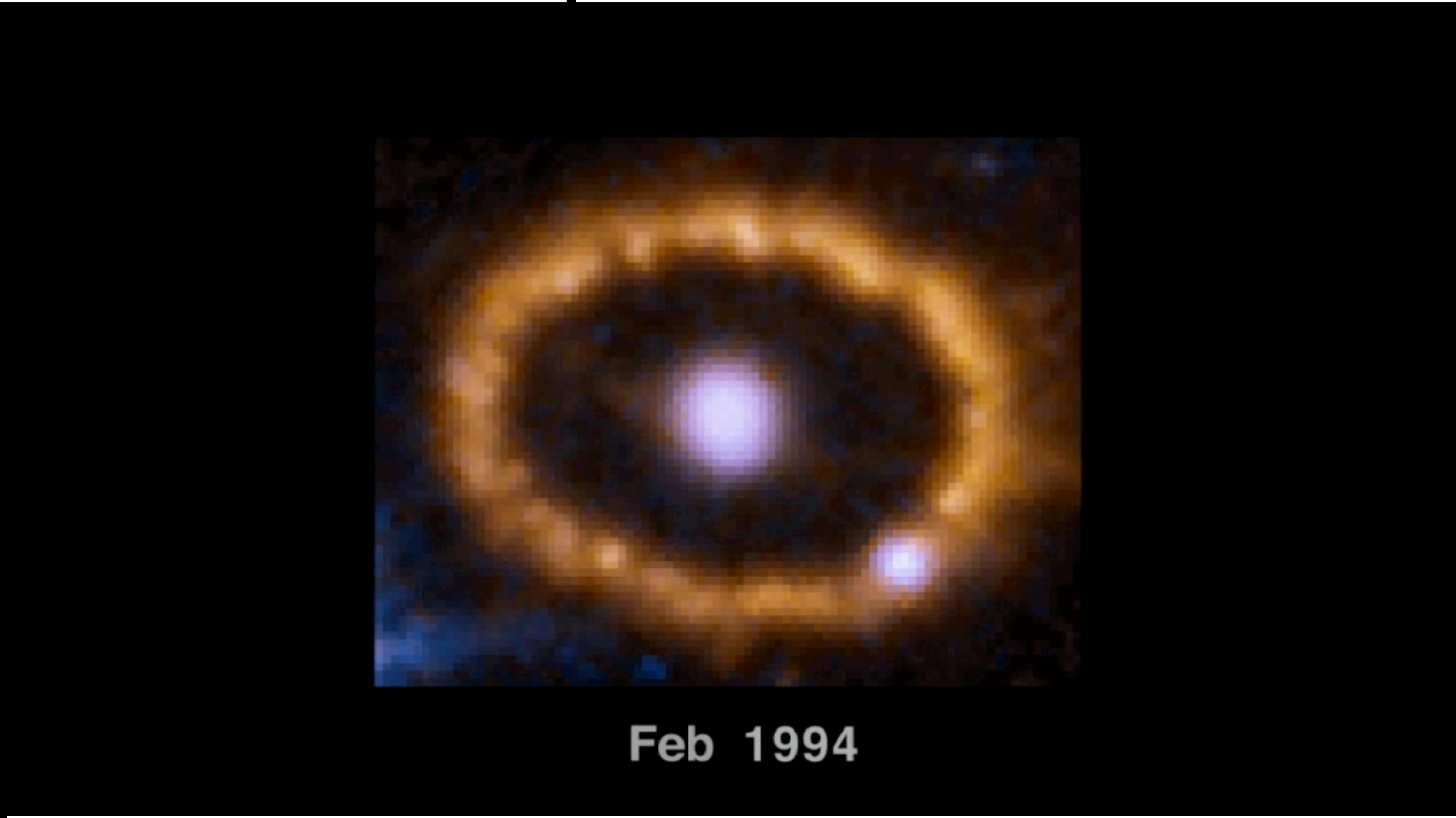
Supernovae



Feb 1994

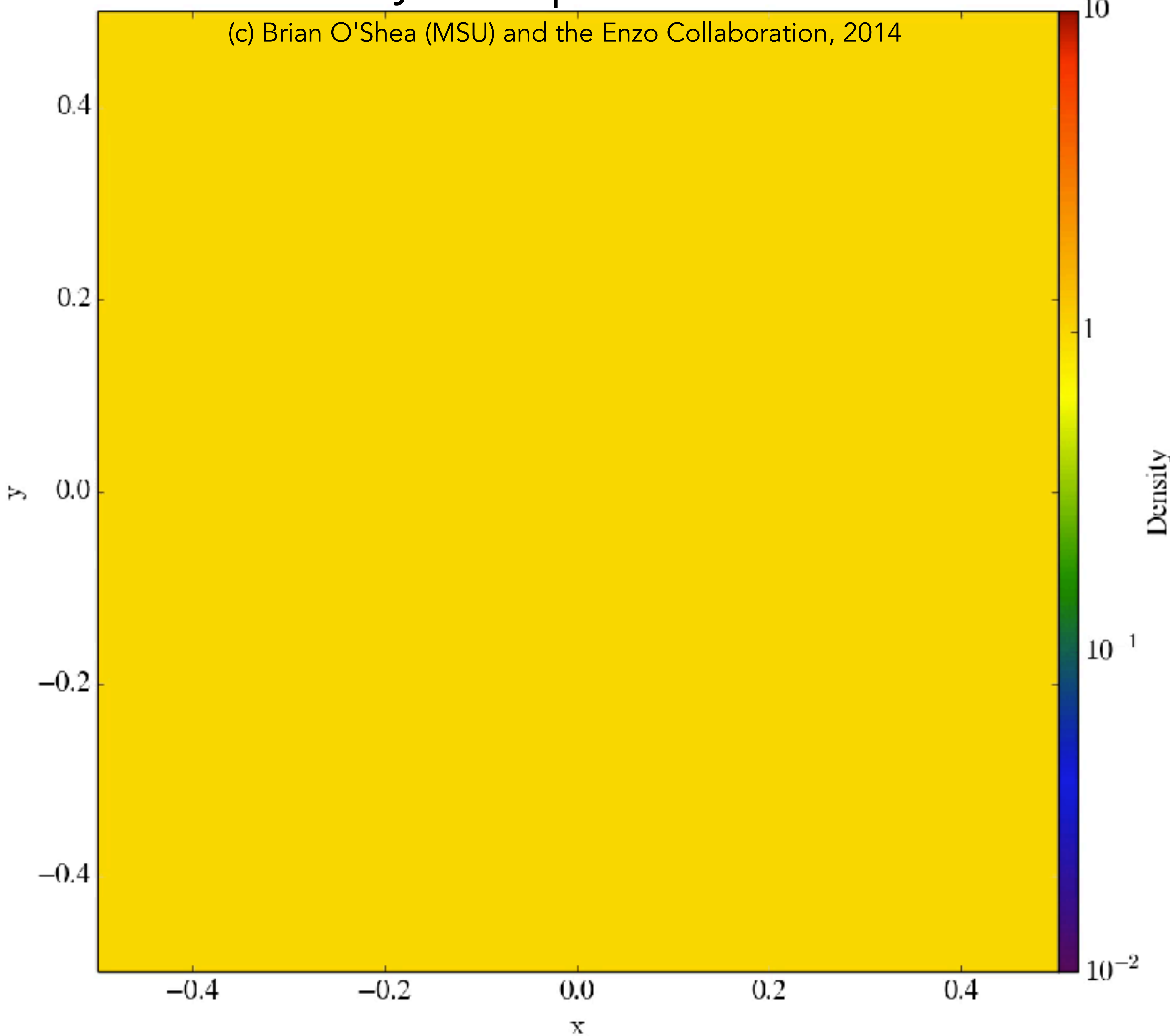
Credit: NASA, ESA, and R. Kirshner (Harvard-Smithsonian Center for Astrophysics and Gordon and Betty Moore Foundation) and P. Challis (Harvard-Smi

Supernovae

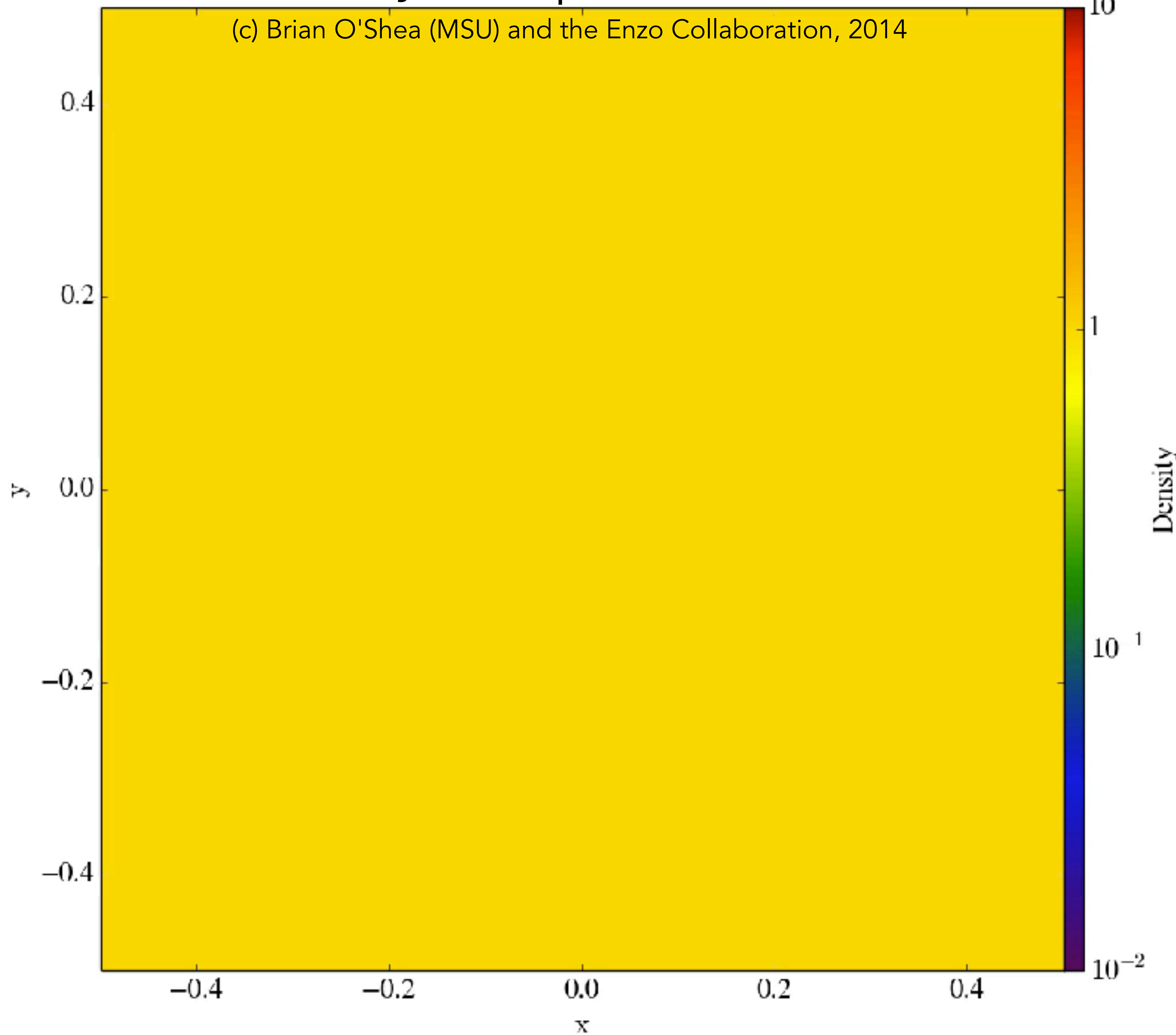


Credit: NASA, ESA, and R. Kirshner (Harvard-Smithsonian Center for Astrophysics and Gordon and Betty Moore Foundation) and P. Challis (Harvard-Smi

Sedov-Taylor expansion with ENZO

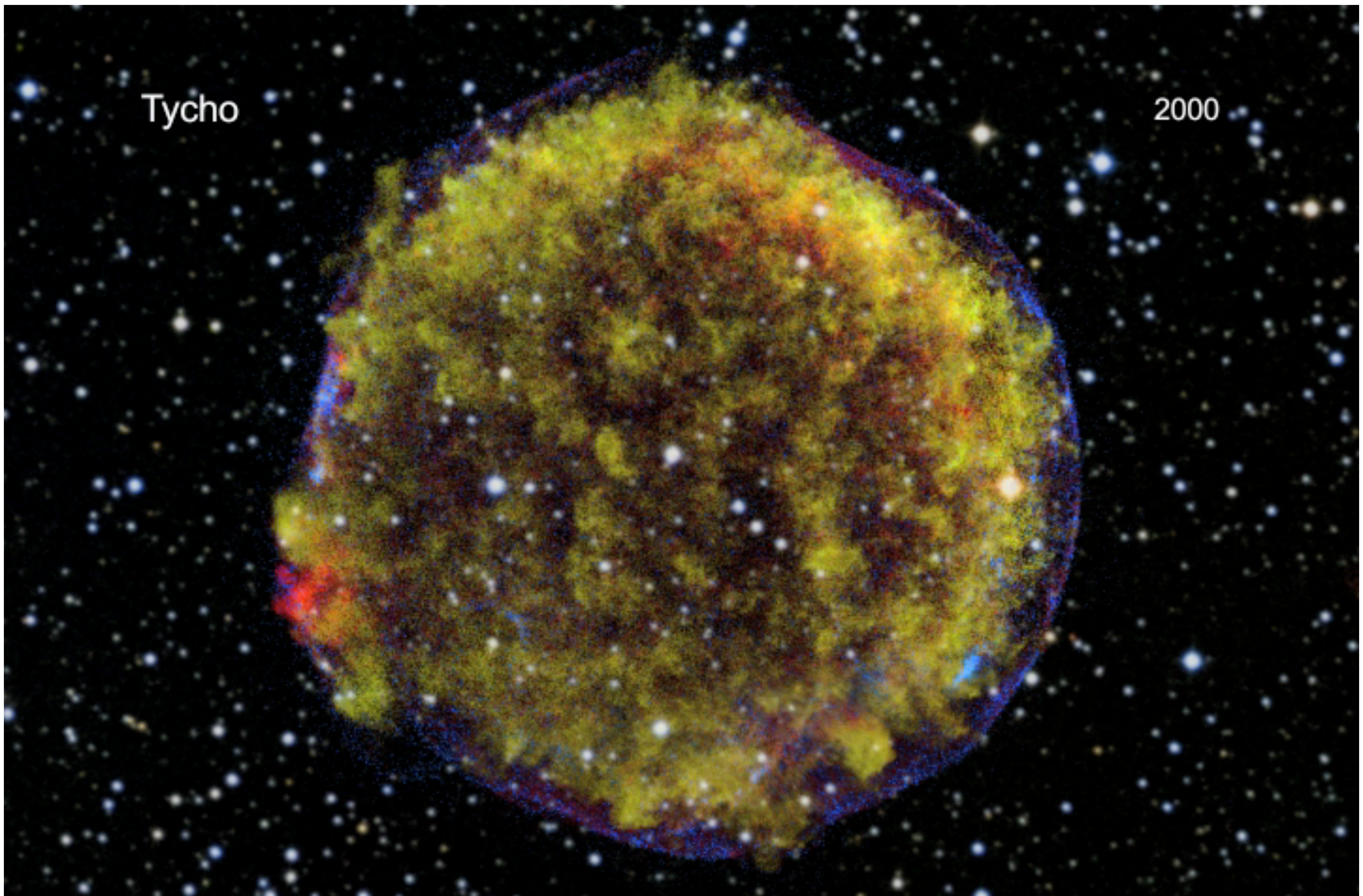


Sedov-Taylor expansion with ENZO



Supernovae

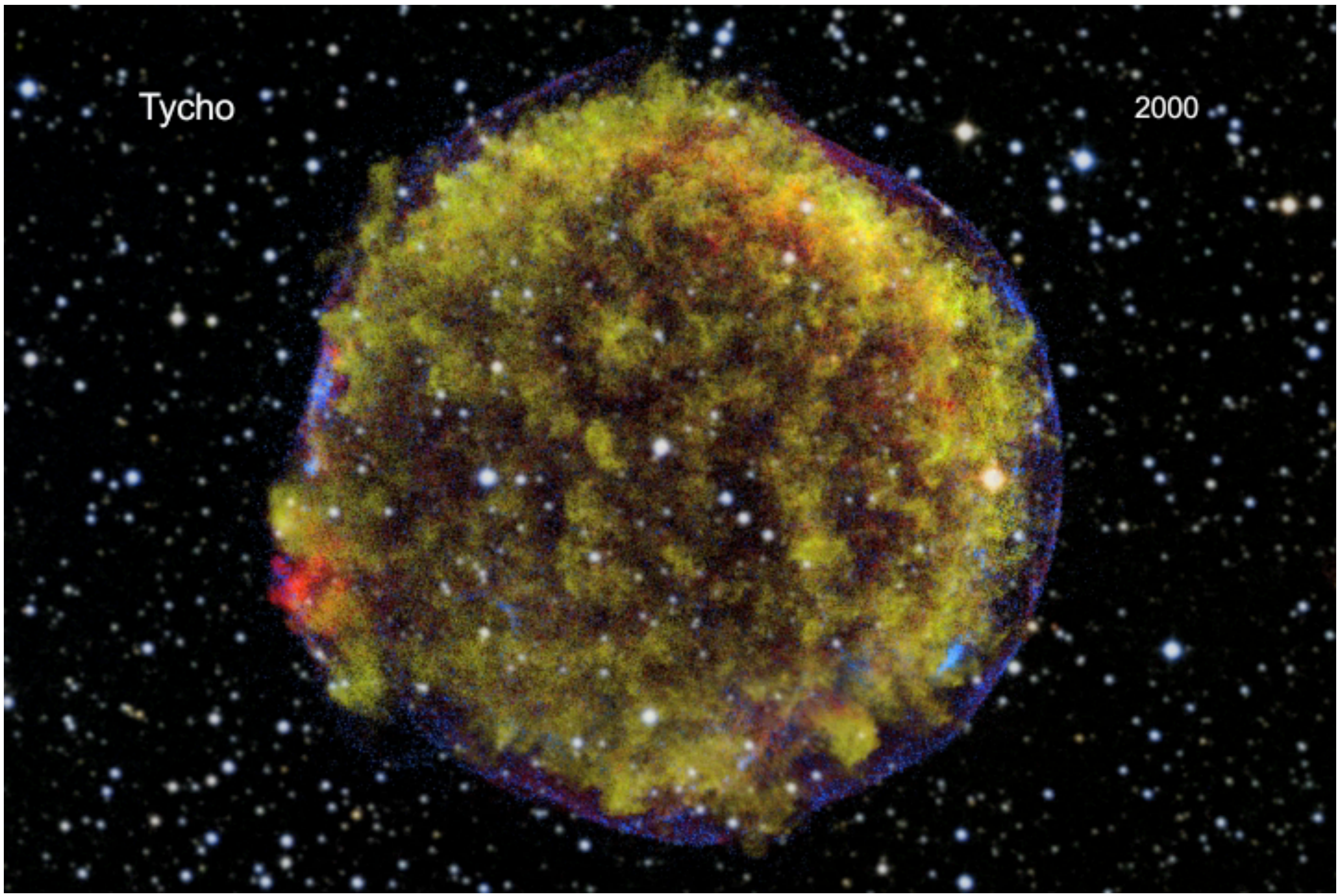
Tycho SN Remnant in Sedov-Taylor phase



(Credit: NASA/CXC/GSFC/B.Williams et al;)

Supernovae

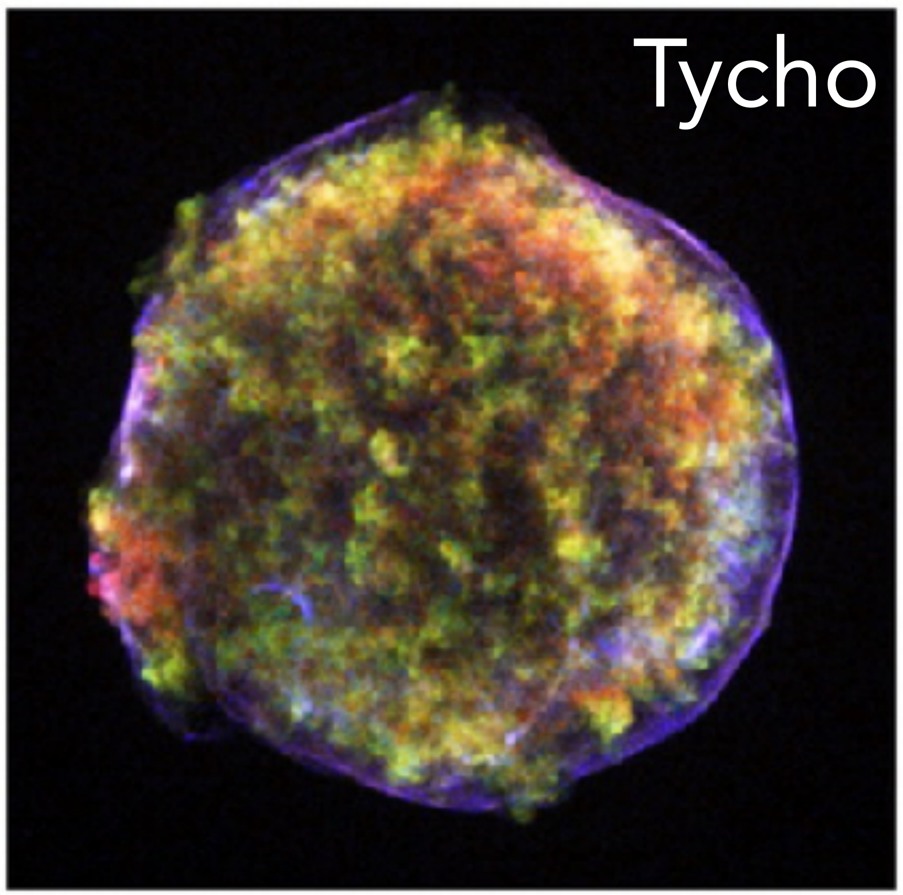
Tycho SN Remnant in Sedov-Taylor phase

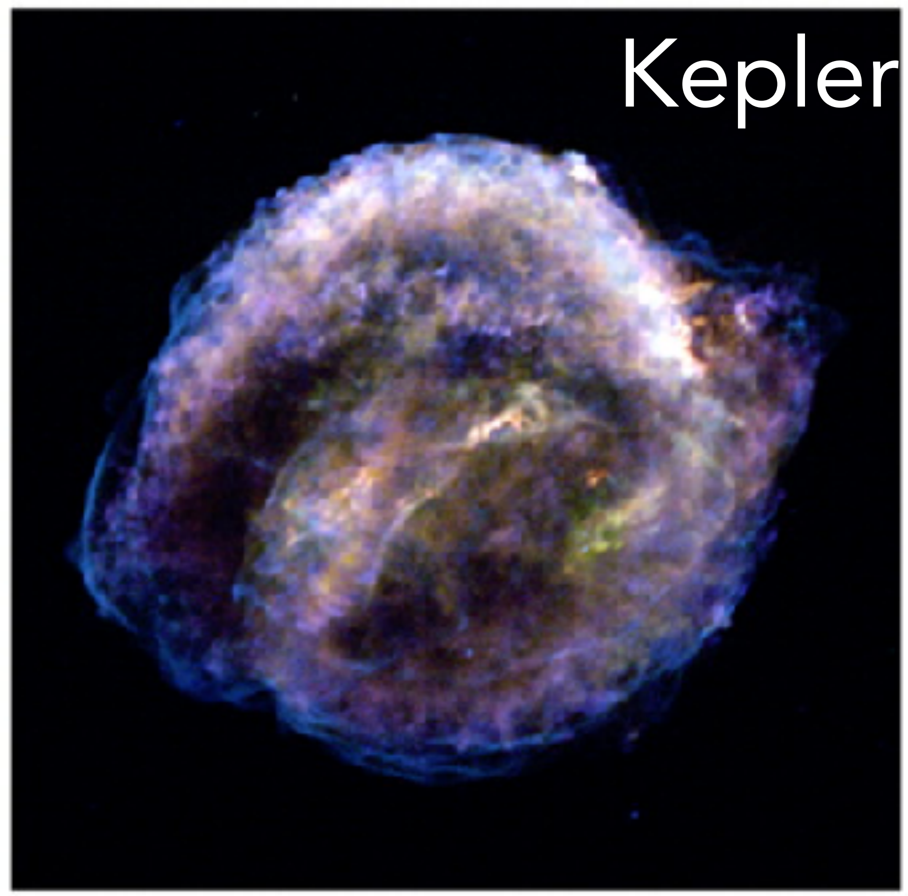


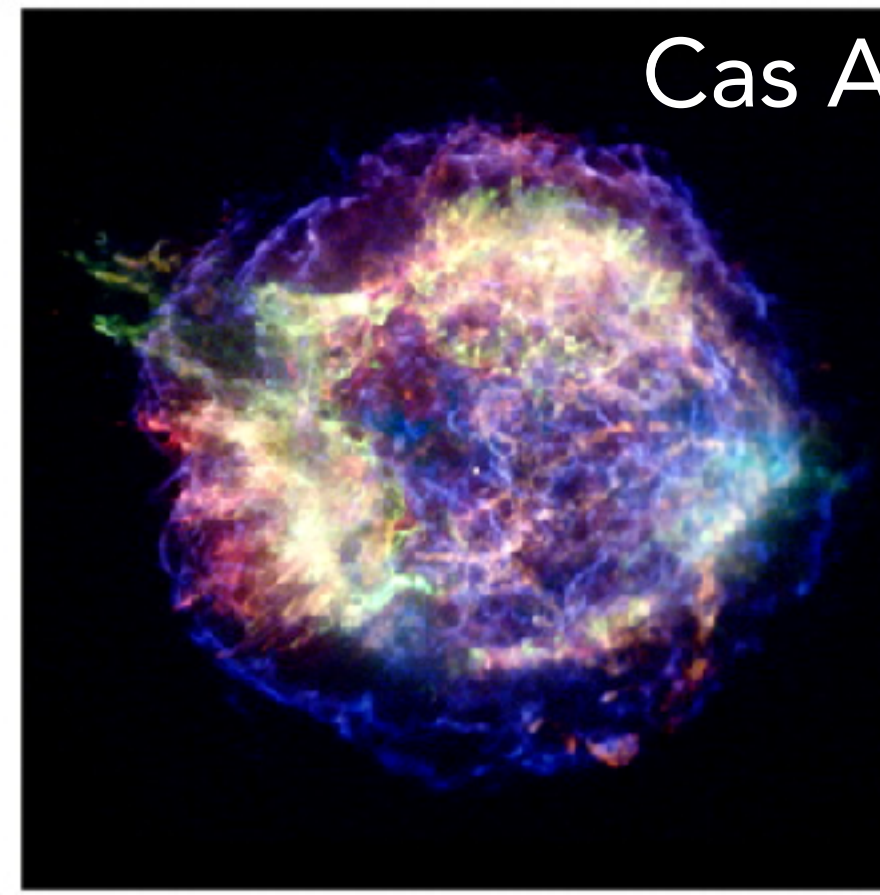
(Credit: NASA/CXC/GSFC/B.Williams et al;)

Supernovae

Chandra Observations of SN Remnants



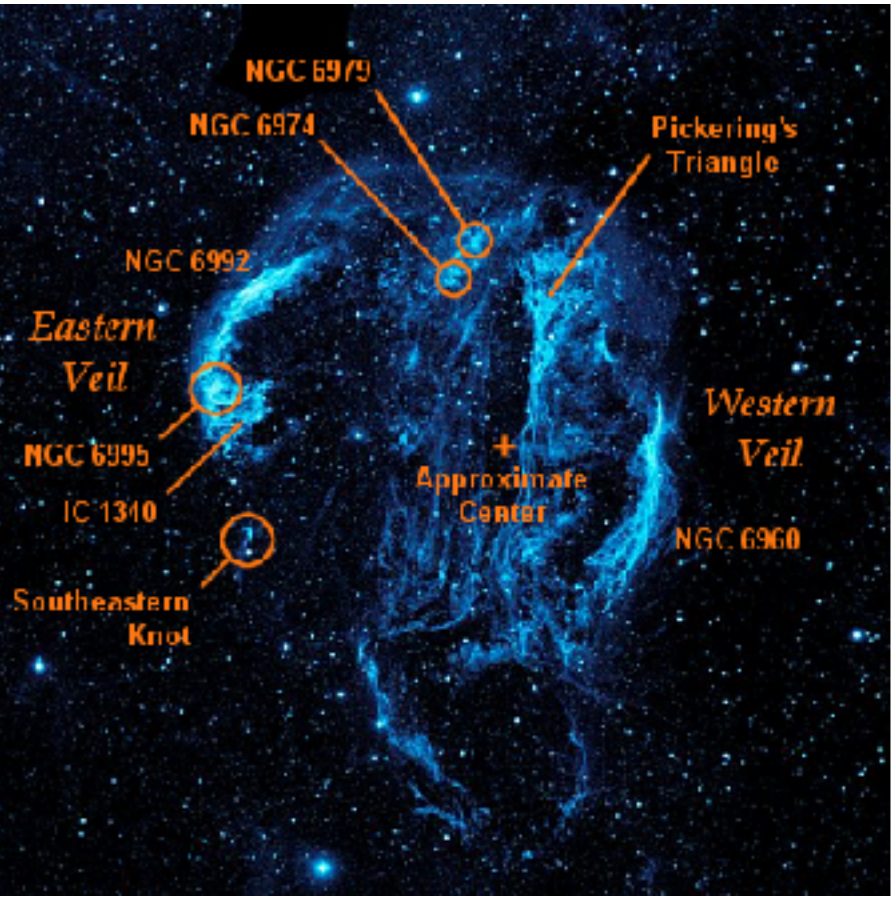




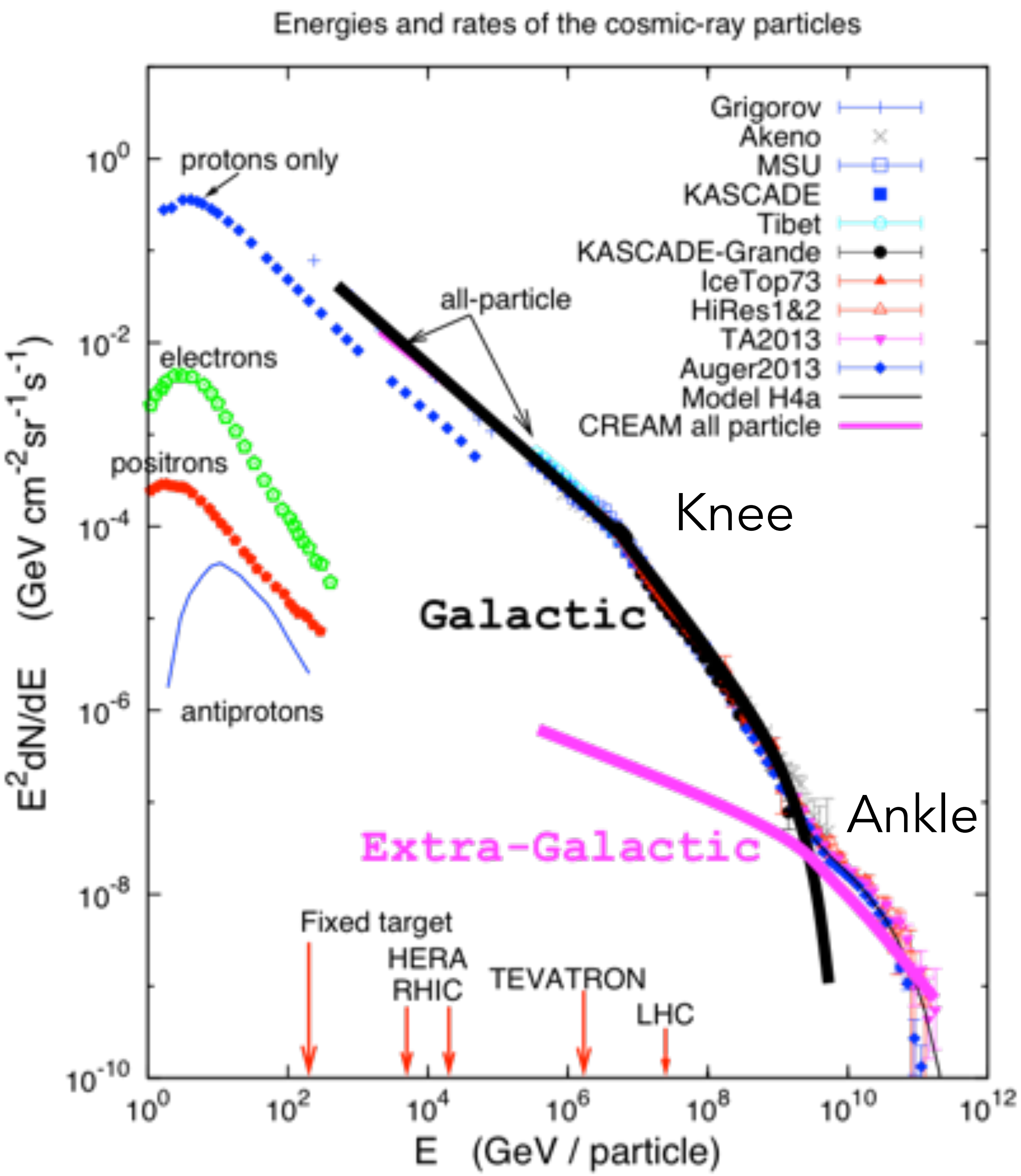
Badenes 2010, PNAS

Supernovae

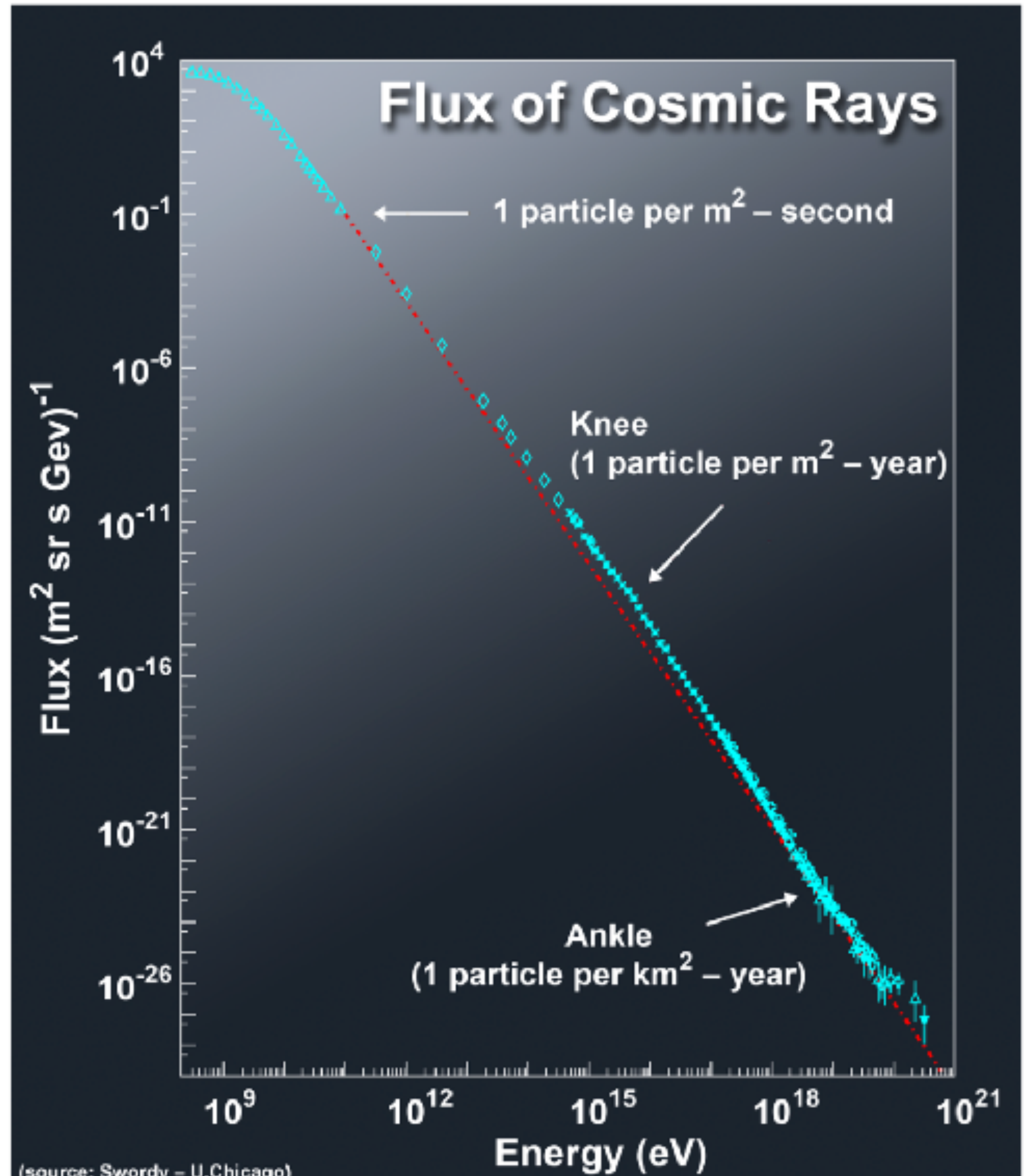
Cygnus Loop - snowplow phase

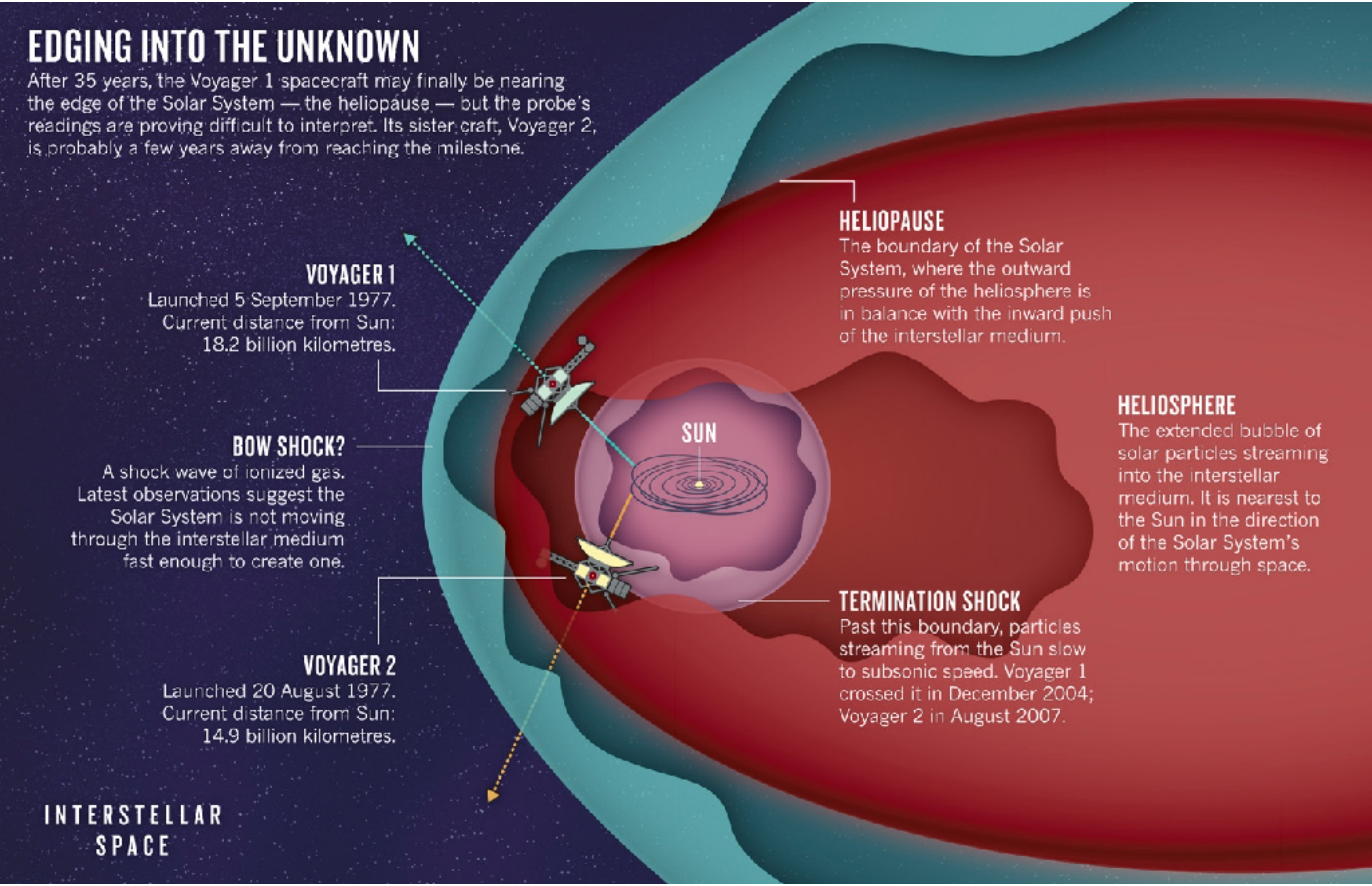


Cosmic Rays

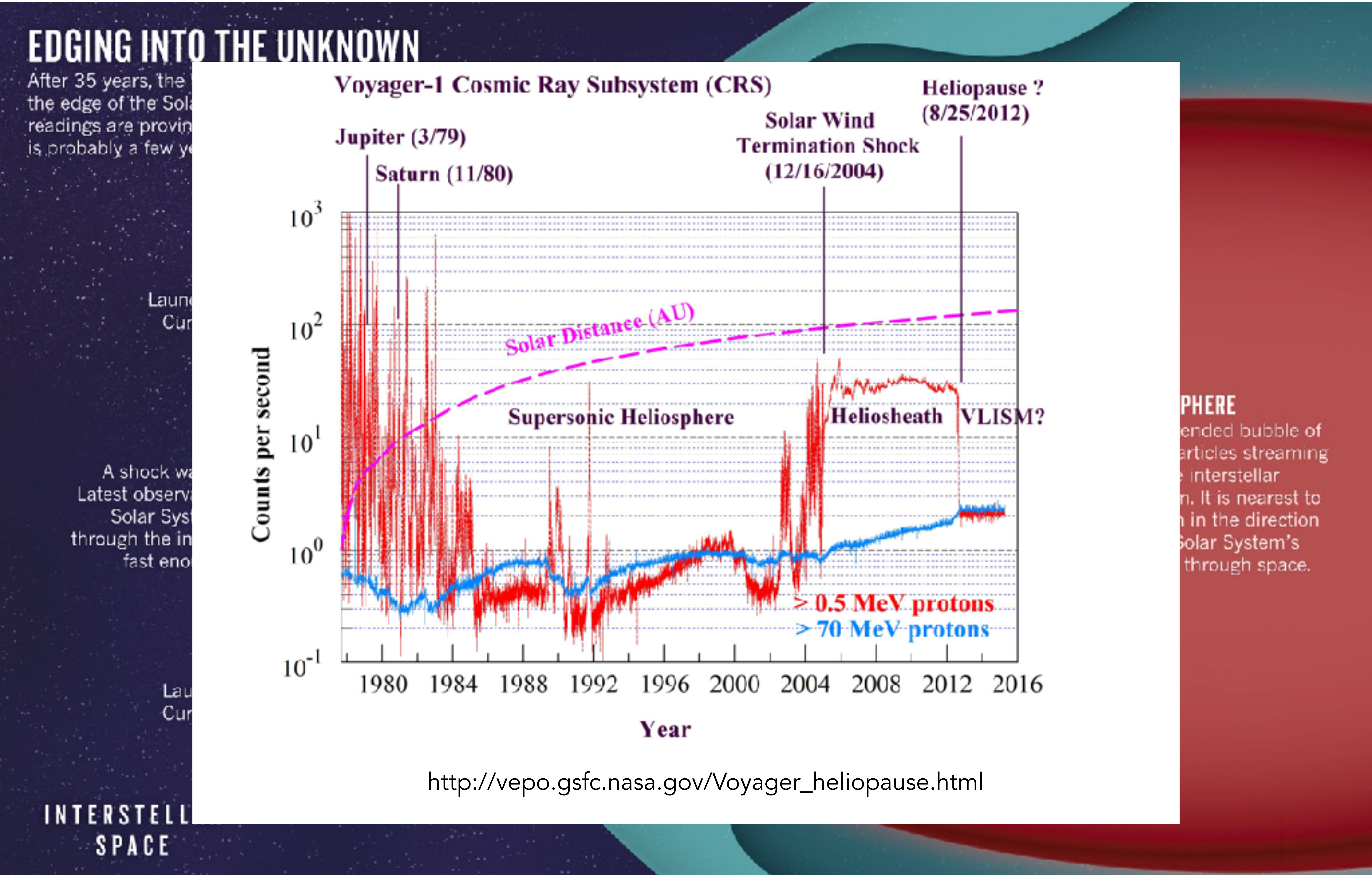


https://masterclass.icecube.wisc.edu/en/analyses/cosmic-ray-energy-spectrum





Cowen, *Nature*, 2012



Cowen, *Nature*, 2012

Cosmic Rays

Cosmic ray interaction with gas can produce γ-rays

Neutral pion production: $CR_p + p \rightarrow p + p + \pi^0$ → Pion decay $\pi^0 \rightarrow 2\gamma$

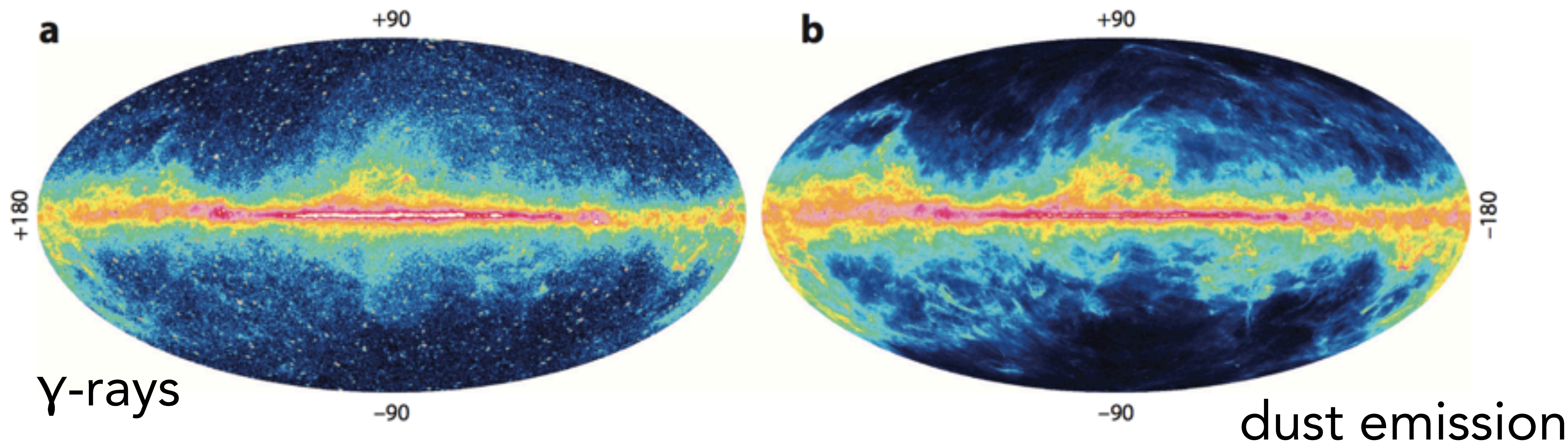
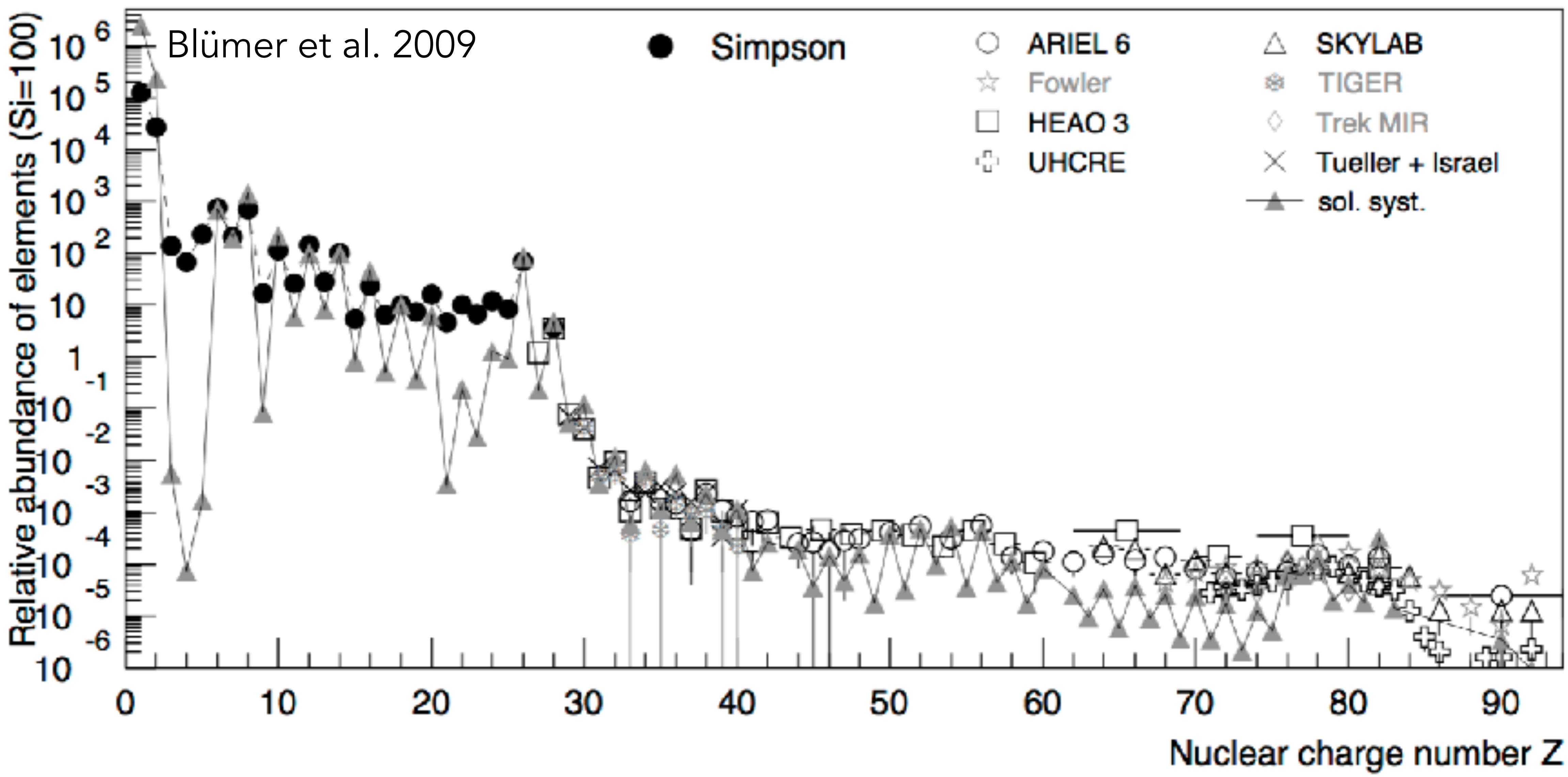


Figure 5

Sky maps of (*a*) the γ-ray intensity recorded by *Fermi*-LAT above 1 GeV in six years of observations (**http://fermi.gsfc.nasa.gov/ssc/**) and of (*b*) the dust optical depth measured at 353 GHz from the *Planck* and IRAS surveys (Planck Collab. et al. 2014b). Both maps broadly trace the same total gas column densities, weighted by the ambient cosmic-ray density in γ rays and by the ambient dust-to-gas mass ratio and starlight heating rate in the dust map. They exhibit striking similarities in details of the gas features. The γ-ray map also contains numerous point sources and faint non-gas-related diffuse components.

Cosmic Rays

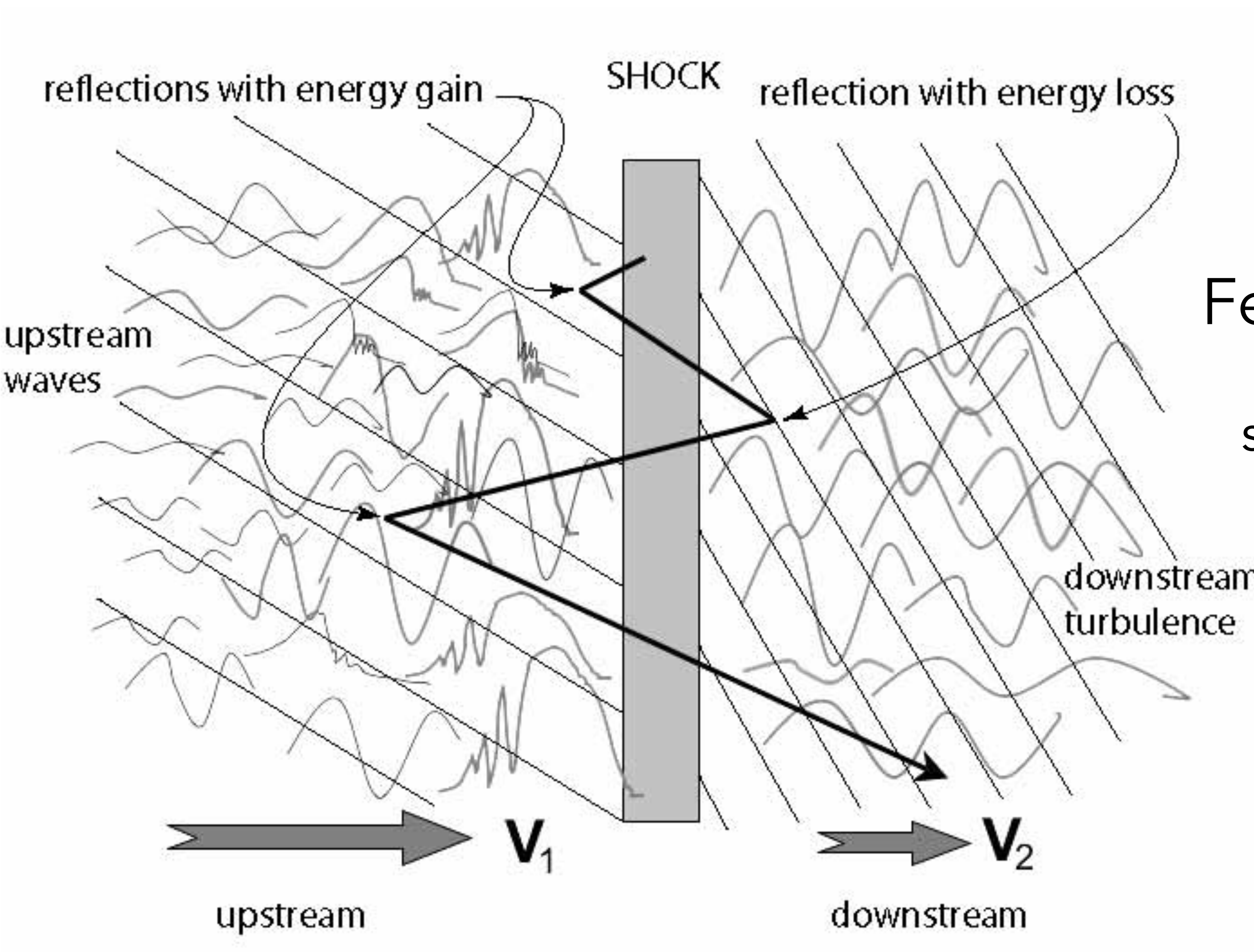


Protons are most abundant, He next.

^{6}Li, ^{9}Be, ^{10}B, ^{11}B from “spallation”

(nuclear reaction from collisions).

Acceleration of Cosmic Rays



Treumann, R.A. et al. arXiv:0806.4046

Diffusive shock acceleration (first order Fermi acceleration)

scattering off B-field fluctuations

analogy to particle bouncing between converging walls

Acceleration of Cosmic Rays

Maximum energy attainable by diffusive shock acceleration is set by when B-fields can no longer confine CR.

gyroradius > scale of system

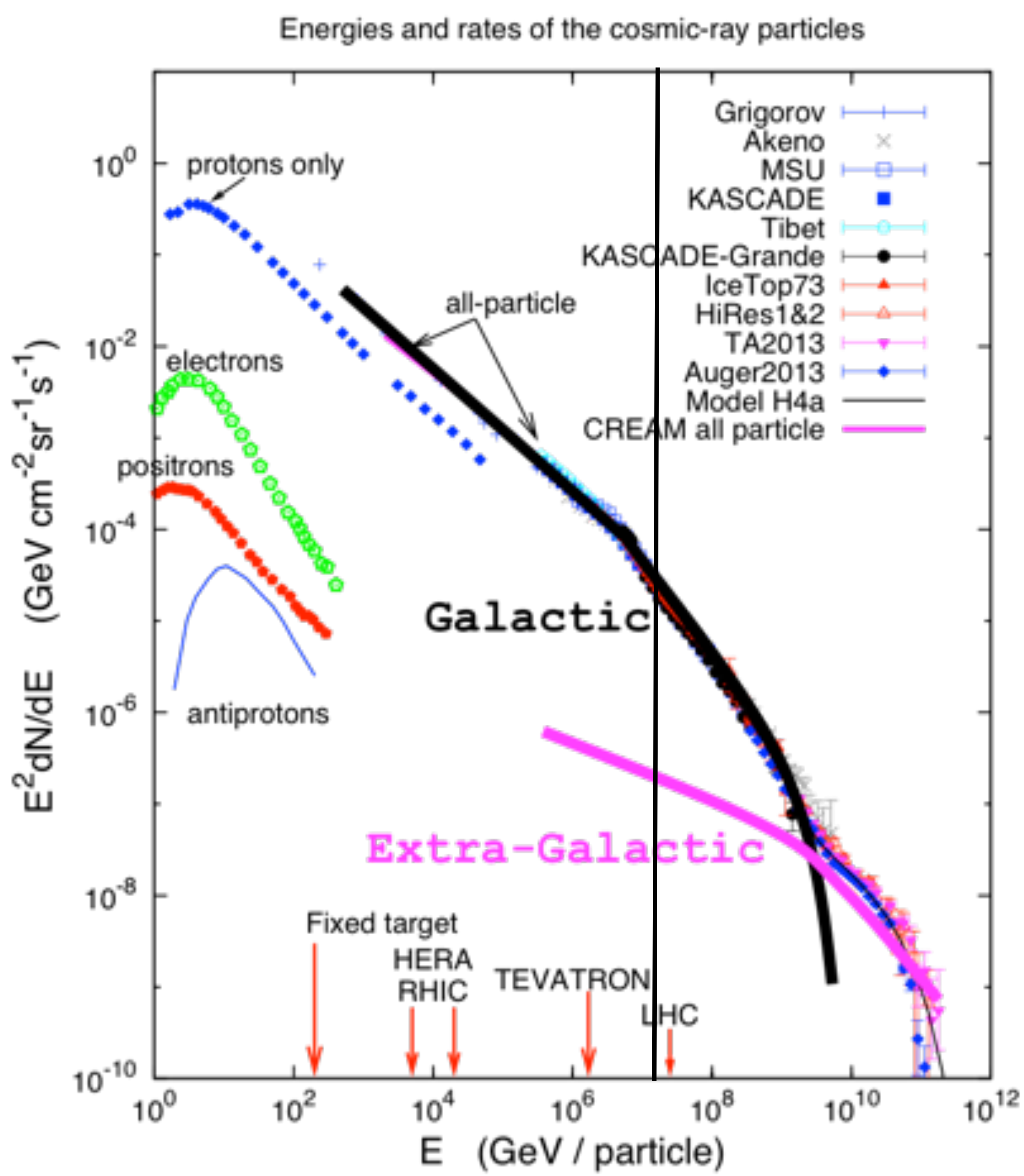
$$R_{\rm gyro} = \frac{pc}{eB_\perp}$$

p = momentum

$$E_{\rm max} = eB_{\rm SNR}L$$

$$E_{\rm max} \approx 10^{7.0}{\rm GeV}\left(\frac{L}{23{\rm pc}}\right)\left(\frac{B_{\rm SNR}}{10\mu{\rm G}}\right)$$

Acceleration of Cosmic Rays

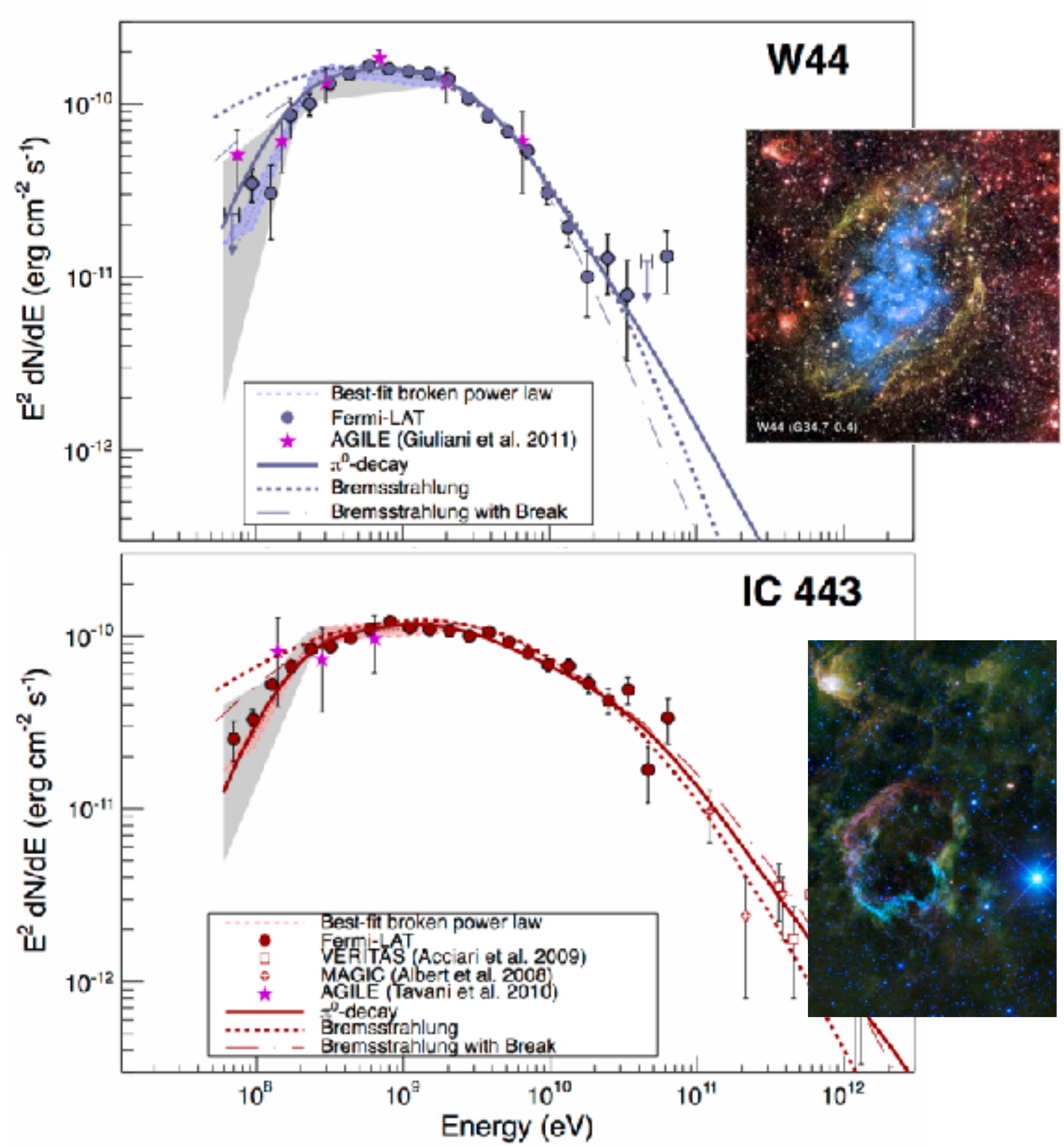


$$E_{\rm max} \approx 10^{7.0}{\rm GeV}\left(\frac{L}{23{\rm pc}}\right)\left(\frac{B_{\rm SNR}}{10\mu{\rm G}}\right)$$

Supernova shocks have long been thought to be the best candidate for CR acceleration.

Recently, first direct evidence…

Acceleration of Cosmic Rays



Accelerated protons create pions when they run into the surrounding ISM. Pions decay and produce gamma rays.

Fermi confirmation of gamma-ray spectrum following pion decay prediction for some SNRs in the MW. (Ackermann et al. 2013)

The Warm/Hot Ionized Medium

in MW, approx. 23% ionized, 60% neutral, 17% molecular

Name	T (K)	Ionization	frac of volume	density (cm^{-3})	P ~ nT (cm^{-3} K)
hot ionized medium	10^6	H^+	0.5(?)	0.004	4000
ionized gas (HII & WIM)	10^4	H^+	0.1	0.2-10^4	2000 - 10^8
warm neutral medium	5000	H^0	0.4	0.6	3000
cold neutral medium	100	H^0	0.01	30	3000
diffuse molecular	50	H_2	0.001	100	5000
dense molecular	10-50	H_2	10^{-4}	10^3-10^6	10^5 - 10^7

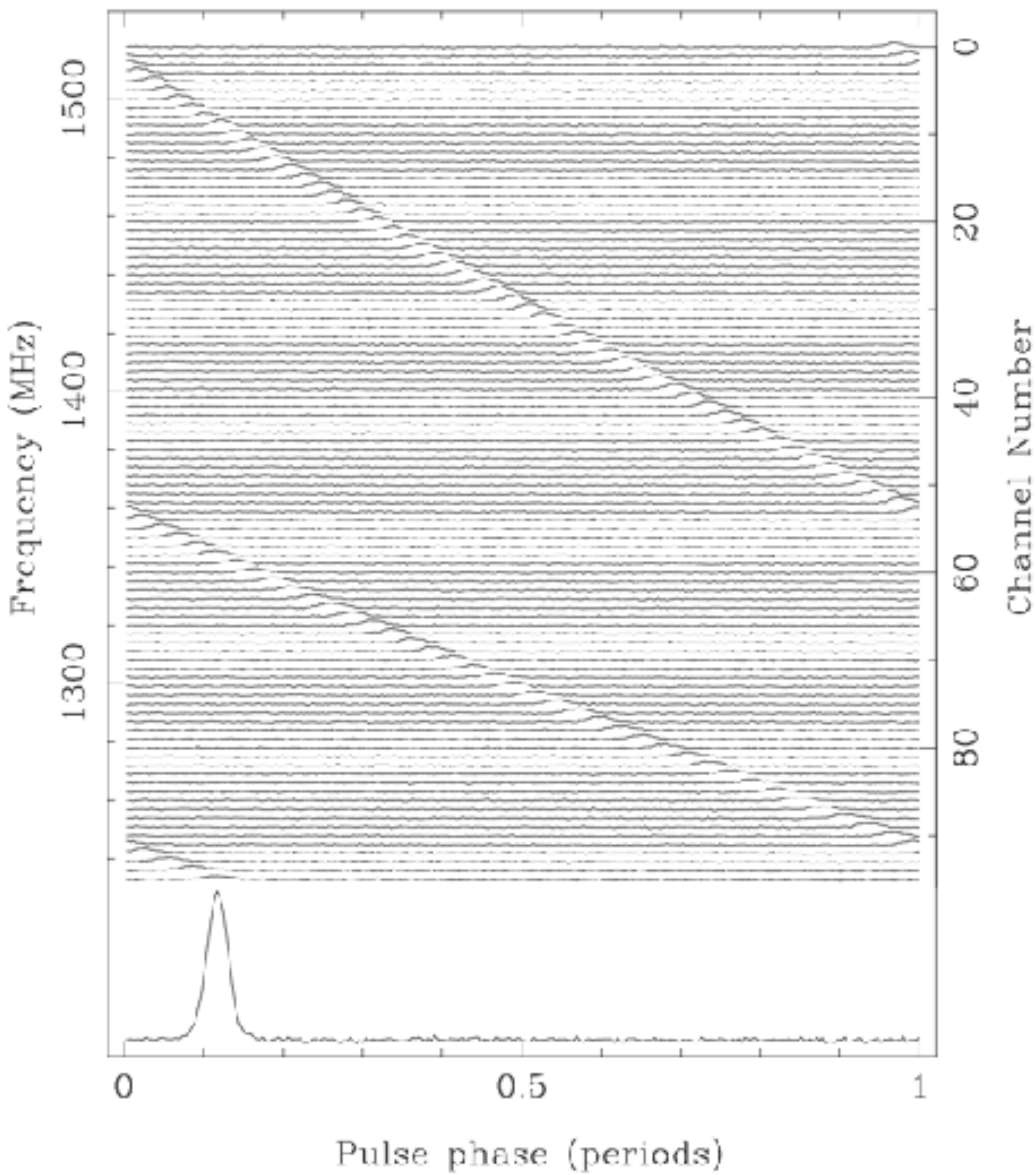
The Diffuse Ionized Medium

Two key tracers of diffuse ionized gas:

1) dispersion of pulses from pulsars propagating through ionized gas

2) faint optical emission lines from the diffuse ISM seen throughout the MW

Diffuse Ionized Gas



From the *Handbook of Pulsar Astronomy*, by Lorimer & Kramer

Dispersion of Pulsar Signals

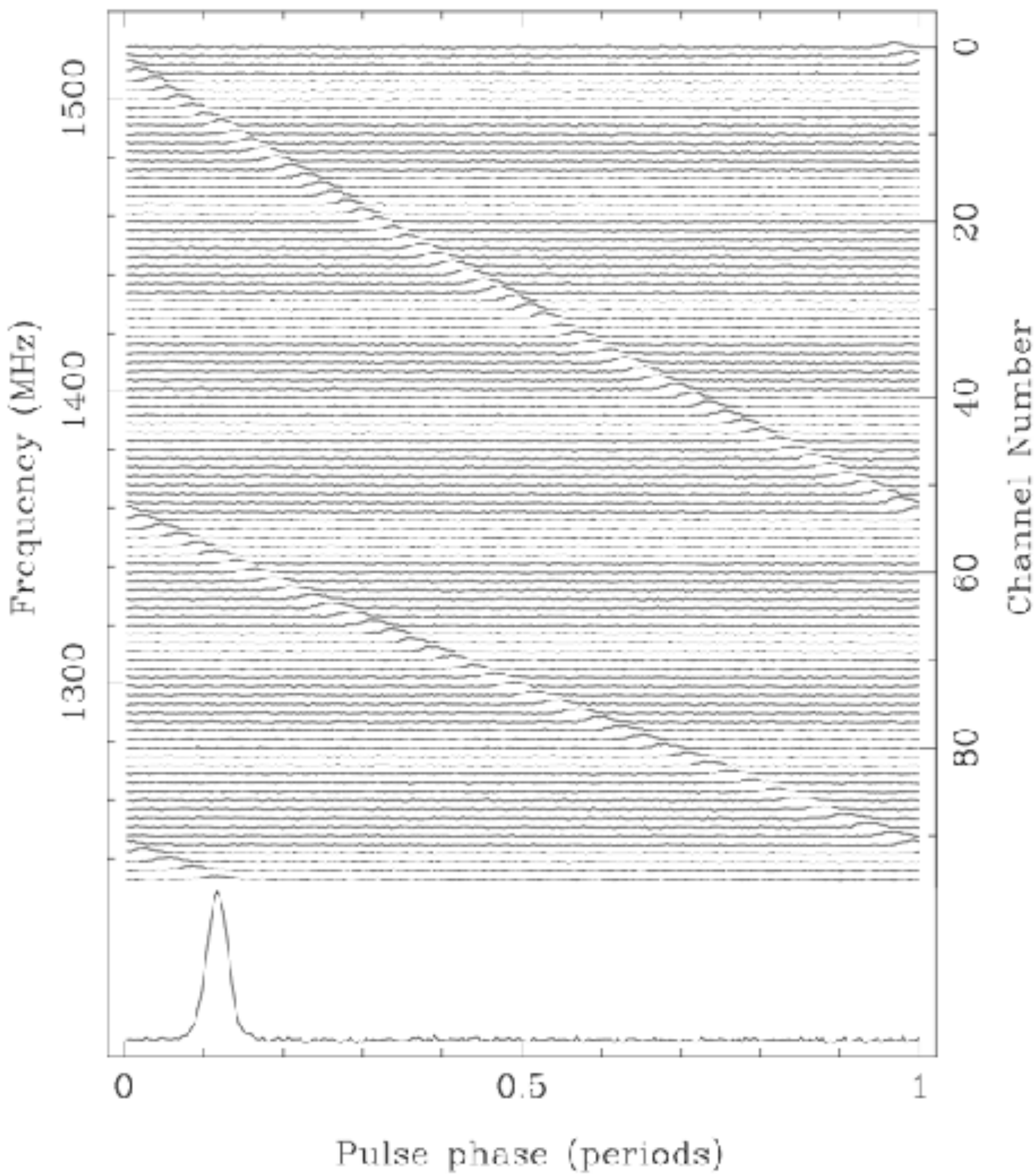
EM waves traveling through a plasma with electron density n_e satisfy the dispersion relation:

$$k^2c^2 = \omega^2 - \omega_p^2$$

with plasma frequency:

$$\omega_p = \left(\frac{4\pi n_e e^2}{m_e}\right)^{1/2}$$

Diffuse Ionized Gas



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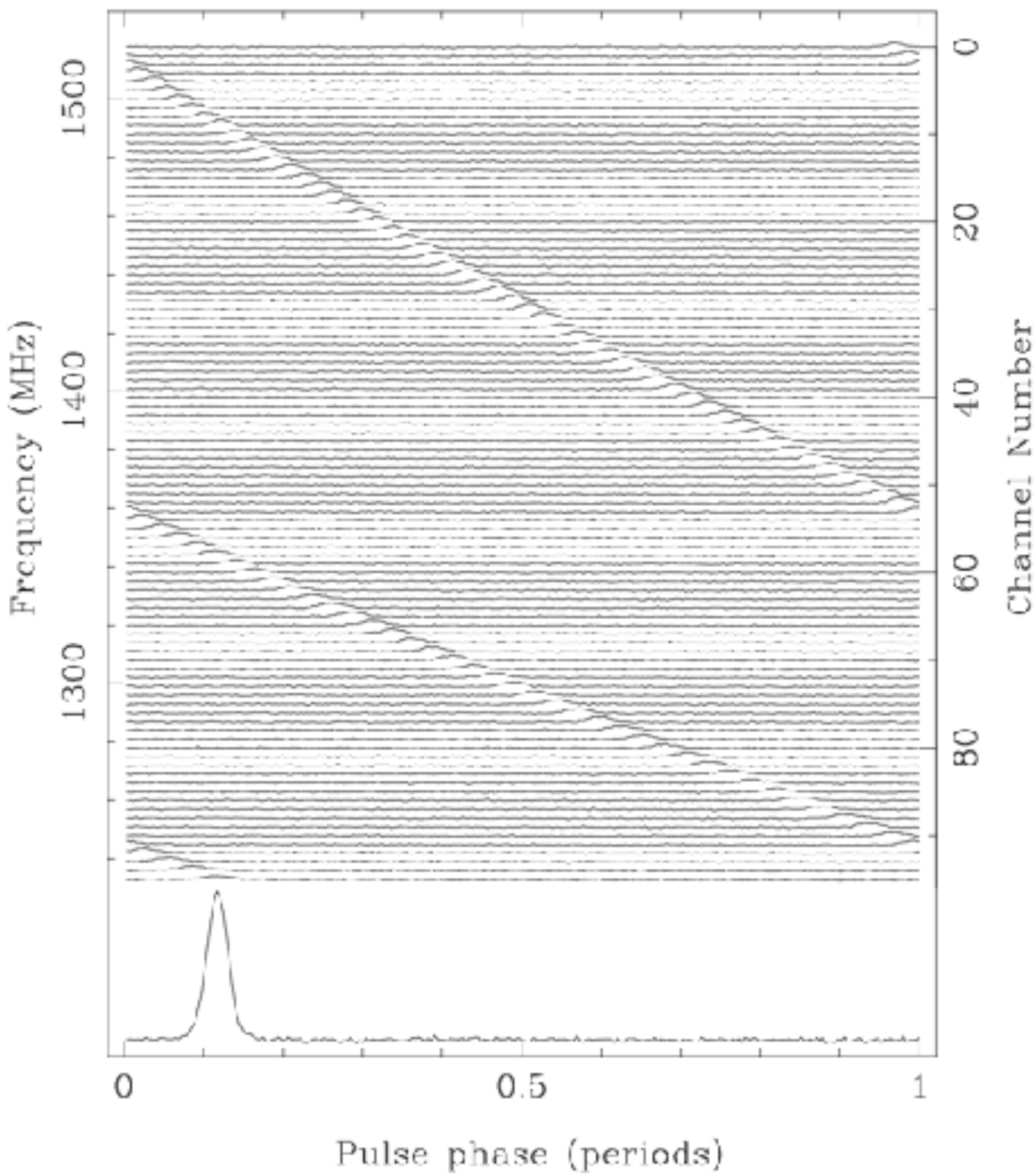
Dispersion of Pulsar Signals

A pulse travels with the "group velocity" (i.e. the velocity of the envelope of the wave packet)

$$v_{\rm group}(\omega) = \frac{d\omega}{dk}$$

$$v_{\rm group}(\omega) = c\left(1 - \frac{\omega_p^2}{\omega^2}\right)^{1/2}$$

Diffuse Ionized Gas



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Dispersion of Pulsar Signals

arrival time of a pulse:

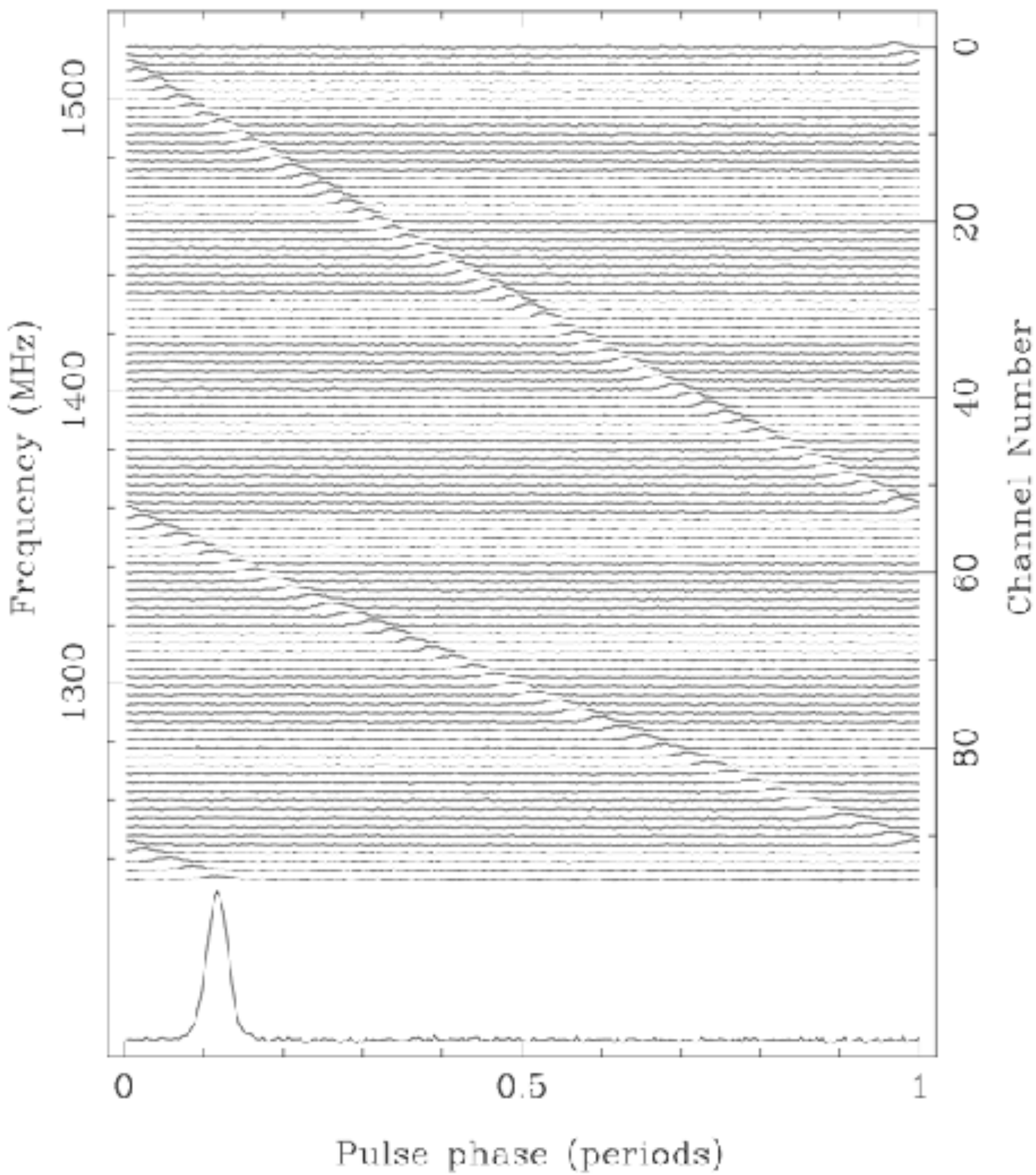
$$t_{\rm arrival} = \int_0^L \frac{dL}{v_{\rm group}(\omega)} \approx \int_0^L \frac{dL}{c}\left(1 + \frac{1}{2}\frac{\omega_p^2}{\omega^2}\right)$$

$$t_{\rm arrival} = \frac{L}{c} + \frac{1}{2c\omega^2}\int_0^L \omega_p^2 dL$$

"dispersion measure"

$$\mathrm{DM} = \int_0^L n_e dL$$

Diffuse Ionized Gas



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Dispersion of Pulsar Signals

arrival time of a pulse:

$$t_{\rm arrival} = \frac{L}{c} + \frac{e^2}{2\pi m_e c}\frac{1}{\nu^2}{\rm DM}$$

"dispersion measure"

$${\rm DM} = \int_0^L n_e dL$$

Diffuse Ionized Gas

$$t_{\rm arrival} = \frac{L}{c} + \frac{e^2}{2\pi m_e c}\frac{1}{\nu^2}{\rm DM}$$

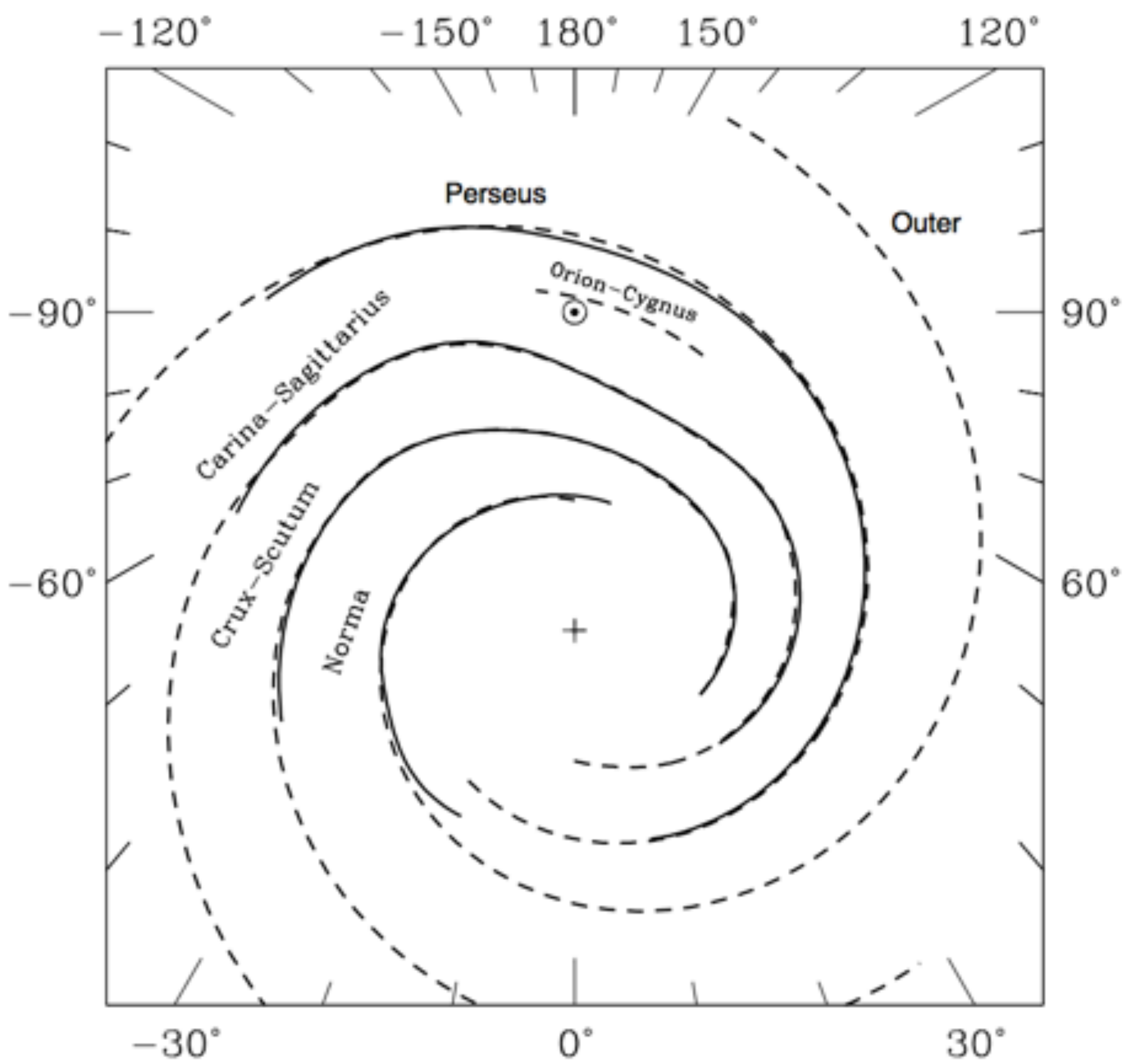
If you know the distance, you can measure DM!

$${\rm DM} = \int_0^L n_e dL$$

From the *Handbook of Pulsar Astronomy*, by Lorimer & Kramer

Diffuse Ionized Gas

The NE2001 model of Cordes & Lazio (2003)



Cordes & Lazio 2003

NE2001 Model Components

$$n_e(\mathbf{x}) = (1 - w_{\rm voids})\{(1 - w_{\rm lism})\,[n_{\rm gal}(\mathbf{x}) + n_{\rm GC}(\mathbf{x})] + w_{\rm lism} n_{\rm lism}(\mathbf{x})\} + w_{\rm voids} n_{\rm voids}(\mathbf{x}) + n_{\rm clumps}$$

Component	Functional Form	Parameters	No. Parameters	C
Smooth Components	$n_{\rm gal}(\mathbf{x}) = [n_1 G_1(r,z) + n_2 G_2(r,z) + n_a G_a(\mathbf{x})]$			
Thick Disk	$n_1 G_1(r,z) = n_1 g_1(r) h(z/H_1)$	n_1, H_1, A_1, F_1	4	
Thin Disk	$n_2 G_2(r,z) = n_2 g_2(r) h(z/H_2)$	n_2, H_2, A_2, F_2	4	
Spiral Arms	$n_a G_a(\mathbf{x})$	$f_j n_a, h_j H_a, w_j w_a, F_j$ $j = 1, \ldots, 5$	20	
Galactic Center ($n_{\rm GC}$)	$n_{\rm GC0} e^{-[\delta r_\perp^2/R_{\rm GC}^2 + (z - z_{\rm GC})^2/H_{\rm GC}^2]}$ $\delta r_\perp^2 = (x - x_{\rm GC})^2 + (y - y_{\rm GC})^2$	$n_{\rm GC0}, R_{\rm GC}, h_{\rm GC}$	3	
Local ISM ($n_{\rm lism}$)	$n_{\rm lism}(\mathbf{x})$, $F_{\rm lism}(\mathbf{x})$, $w_{\rm lism}(\mathbf{x})$ See below & Appendix A	See Table 4	36	Exclud
Clumps ($n_{\rm clumps}$)	$\sum_{j=1}^{N_{\rm clumps}} n_{cj} e^{-\lvert\mathbf{x} - \mathbf{x}_{cj}\rvert^2/r_{cj}^2} t_{cj}(\mathbf{x})$	$N_{\rm clumps}$	$6N_{\rm clumps} + 1$	Includ
		$n_{cj}, \mathbf{x}_{cj}, r_{cj}, F_{cj}$	(6/clump)	
Voids ($n_{\rm voids}$)	$\sum_{j=1}^{N_{\rm voids}} n_{vj} g_v(\mathbf{x}; \boldsymbol{\theta}_{vj}) t_{vj}(\mathbf{x})$	$N_{\rm voids}$	$8N_{\rm voids} + 1$	
		$n_{vj}, \mathbf{x}_{vj}, \boldsymbol{\theta}_{vj}, F_{vj}$	(8/void)	

Functions:

$h(x) = \mathrm{sech}^2(x)$

$U(x) =$ unit step function

$g_1(r) = [\cos(\pi r/2A_1)/\cos(\pi R_\odot/2A_1)]U(r - A_1)$

$g_2(r) = \exp(-(r - A_a)^2/A_a^2)U(r)$

$G_a(\mathbf{x}) = \sum_j f_j g_{a_j}(r, s_j(\mathbf{x})/w_j w_a) h(z/h_j h_a)$ s_j

$g_{a_j}(\mathbf{x}) = e^{-(s_j(\mathbf{x})/w_j w_a)^2} \mathrm{sech}^2(r - A_a)/2U(r - A_a)$

$n_{\rm lism}(\mathbf{x}) = (1 - w_{\rm lhb})\{(1 - w_{\rm loopI})[(1 - w_{\rm lsb}) n_{\rm ldr}(\mathbf{x}) + w_{\rm lsb} n_{\rm lsb}(\mathbf{x})] + w_{\rm loopI} n_{\rm loopI}(\mathbf{x})\} + w_{\rm lhb} n_{\rm lhb}(\mathbf{x})]$

$F_{\rm lism}(\mathbf{x}) = (1 - w_{\rm lhb})\{(1 - w_{\rm loopI})[(1 - w_{\rm lsb}) F_{\rm ldr}(\mathbf{x}) + w_{\rm lsb} F_{\rm lsb}(\mathbf{x})] + w_{\rm loopI} F_{\rm loopI}(\mathbf{x})\} + w_{\rm lhb} F_{\rm lhb}(\mathbf{x})]$

$w_{\rm lism}(\mathbf{x}) = \max[w_{\rm ldr}(\mathbf{x}), w_{\rm lhb}(\mathbf{x}), w_{\rm lsb}(\mathbf{x}), w_{\rm loopI}(\mathbf{x})] = (0, 1)$ LISM w

$t_{cj}(\mathbf{x}) = [1 - e_{cj} U(\lvert\mathbf{x} - \mathbf{x}_{cj}\rvert - r_{cj})]$, $e_{cj} = (0, 1)$ trunc

$g_v(\mathbf{x}, \boldsymbol{\theta}_{vj}) =$ elliptical gaussian $= \exp(-Q(\mathbf{x} - \mathbf{x}_{cj})$, $\boldsymbol{\theta}_{vj} = (a_j, b_j, c_j, \theta_{y_j}, \theta_{z_j})$

$t_{vj}(\mathbf{x}) = [1 - e_{vj} U(Q - 1)]$, $e_{vj} = (0, 1)$ trunc

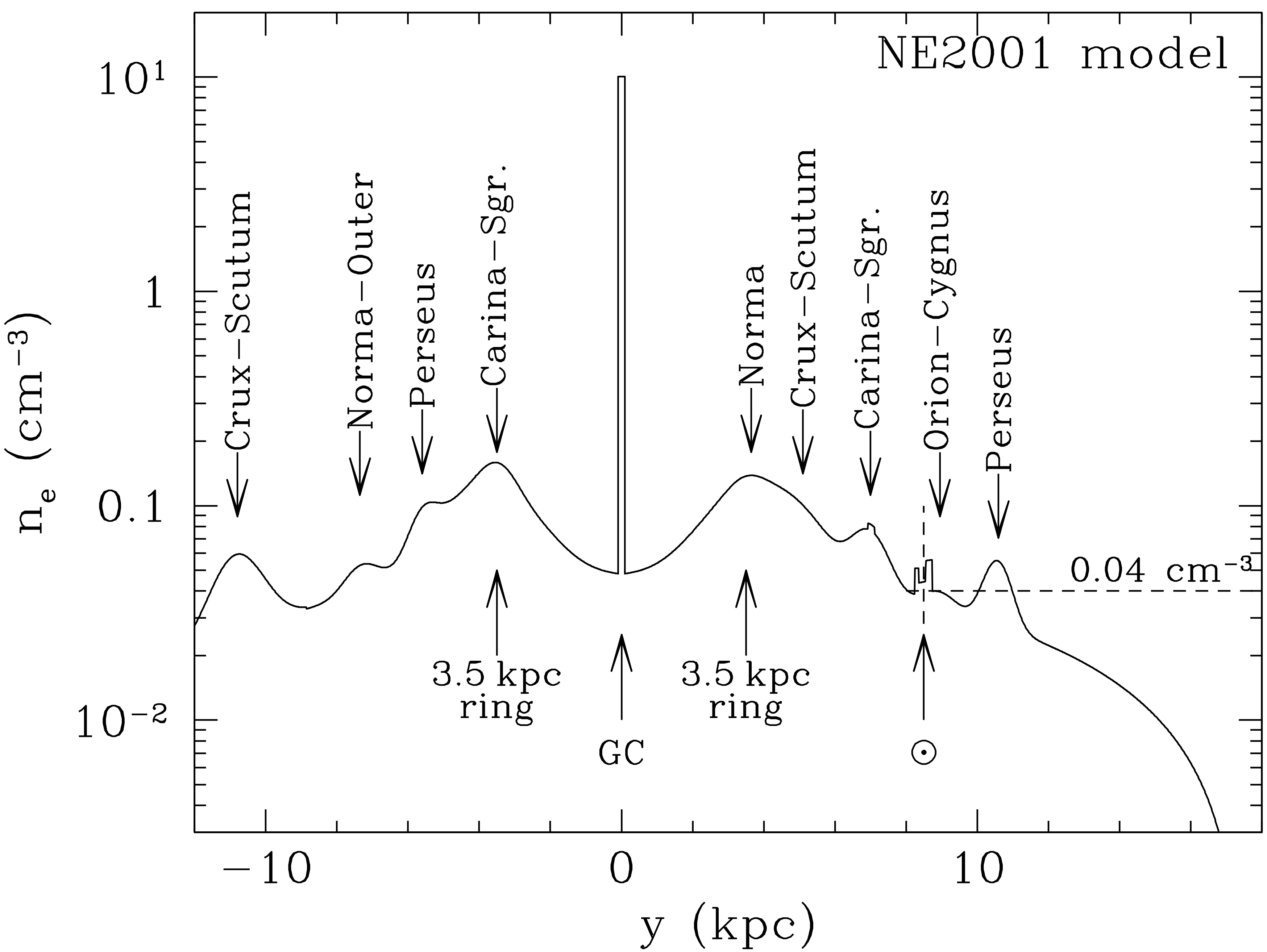
$Q = (\mathbf{x} - \mathbf{x}_{cj})^\dagger \mathbf{V}^{-1} (\mathbf{x} - \mathbf{x}_{cj})$, $V =$ rotation matrix ellipsoidal q

$w_{\rm voids} = (0, 1)$ weight func

Weight functions:

Diffuse Ionized Gas

The NE2001 model of Cordes & Lazio (2003)



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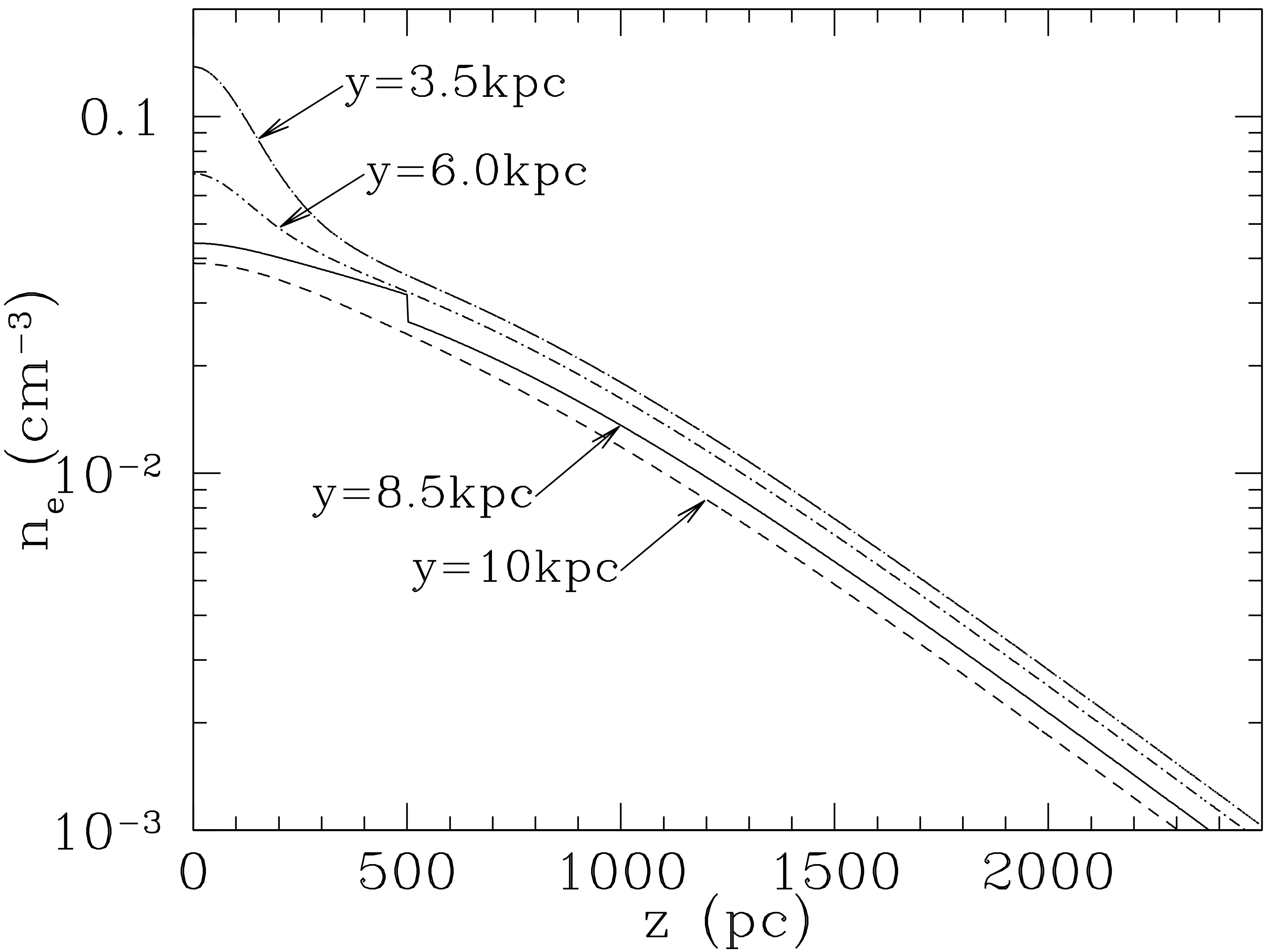

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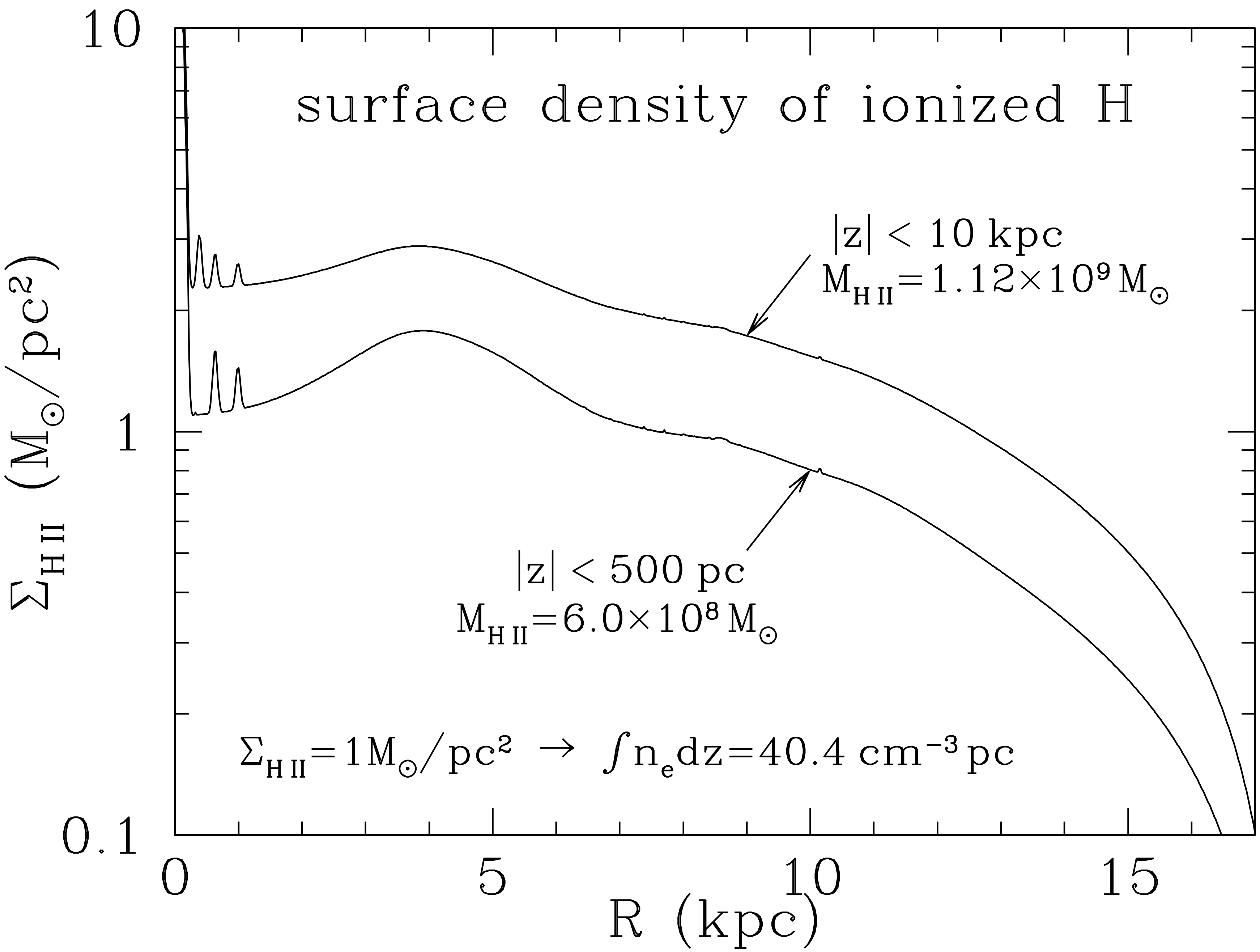

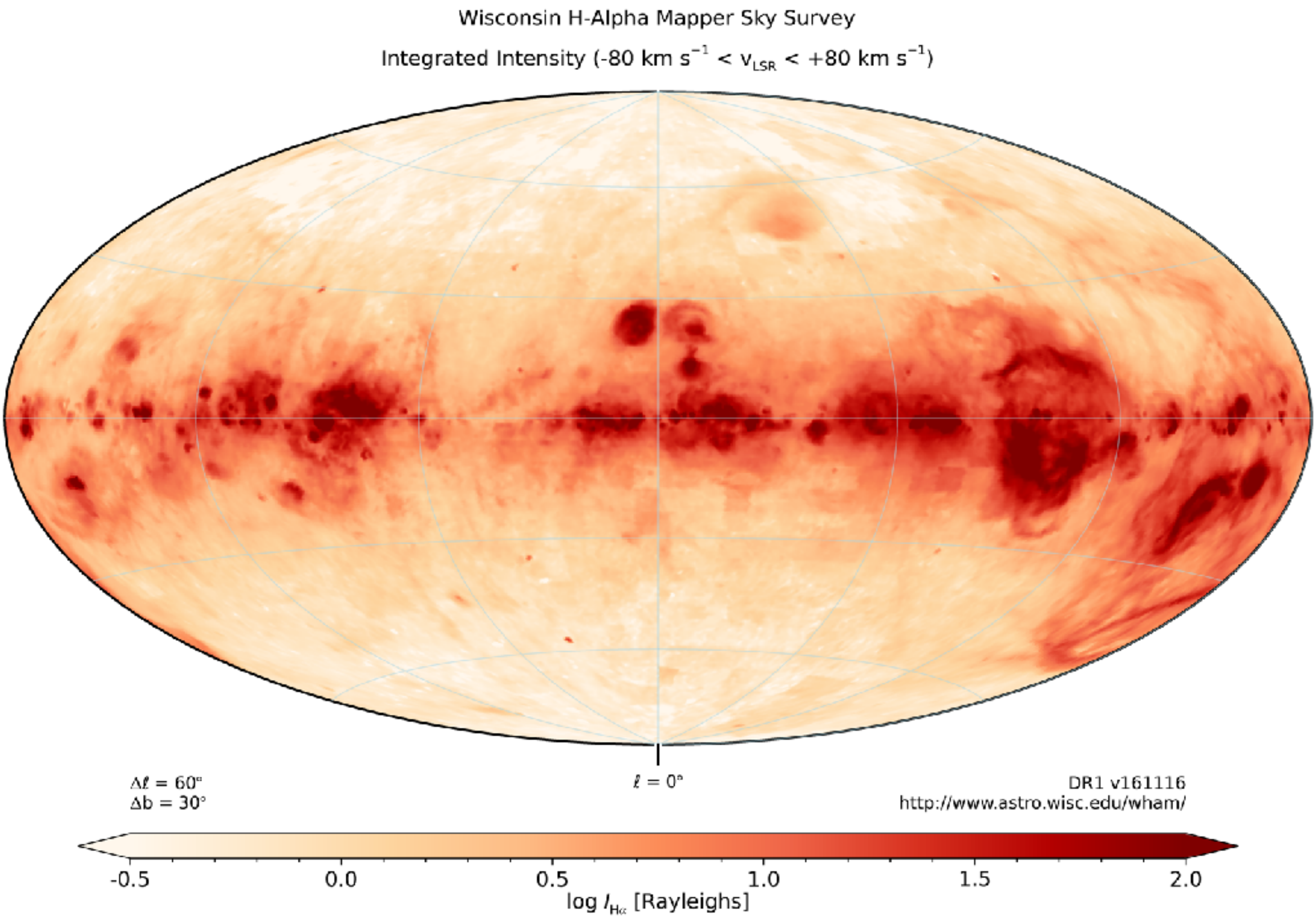
Wisconsin H-Alpha Mapper Sky Survey
Integrated Intensity (-80 km s^{-1} < v_{LSR} < +80 km s^{-1})
$\Delta\ell$ = 60°
Δb = 30°
ℓ = 0°
DR1 v161116
http://www.astro.wisc.edu/wham/
-0.5
0.0
0.5
1.0
1.5
2.0
log $I_{H\alpha}$ [Rayleighs]