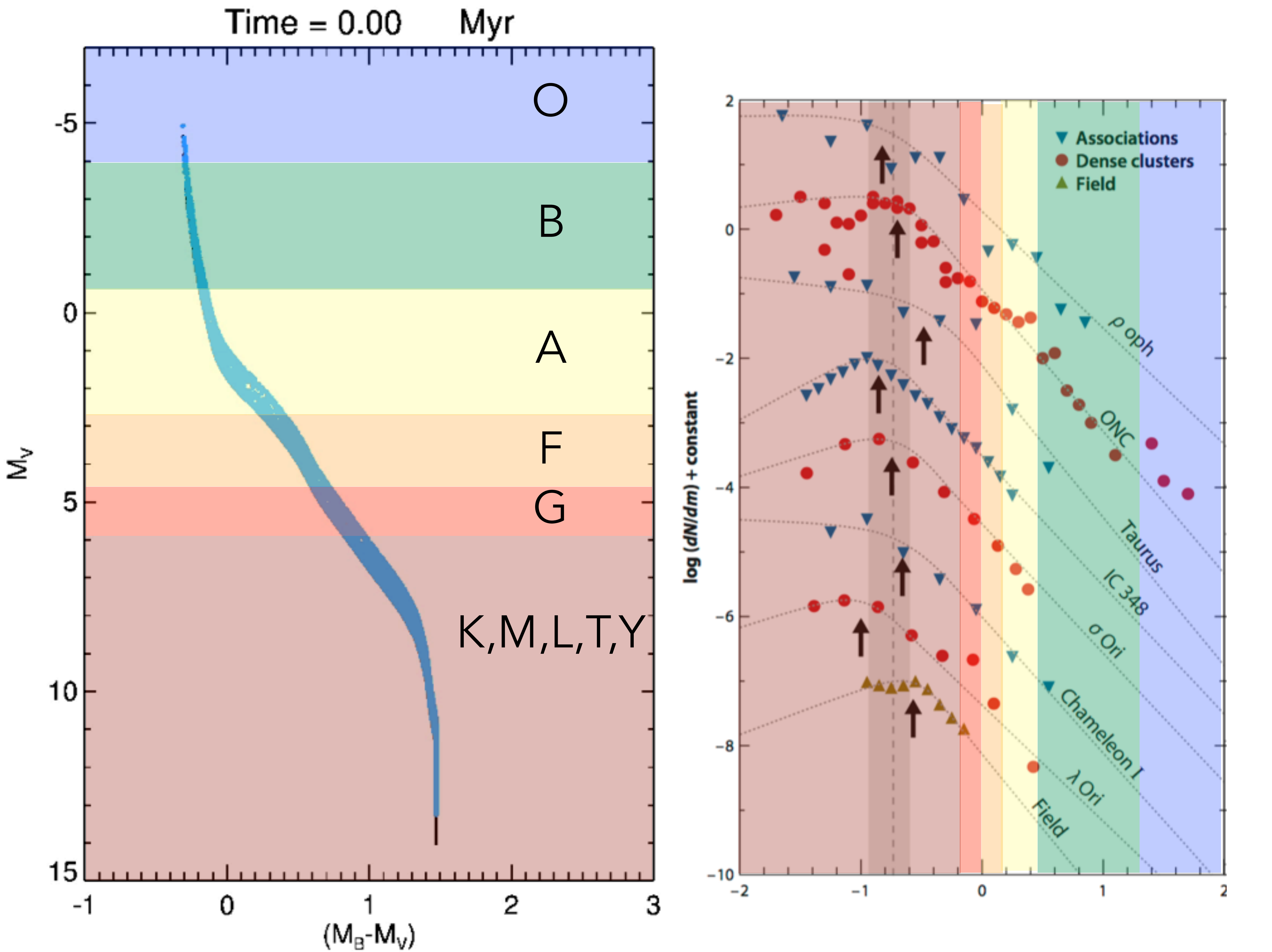
Physics 224
The Interstellar Medium

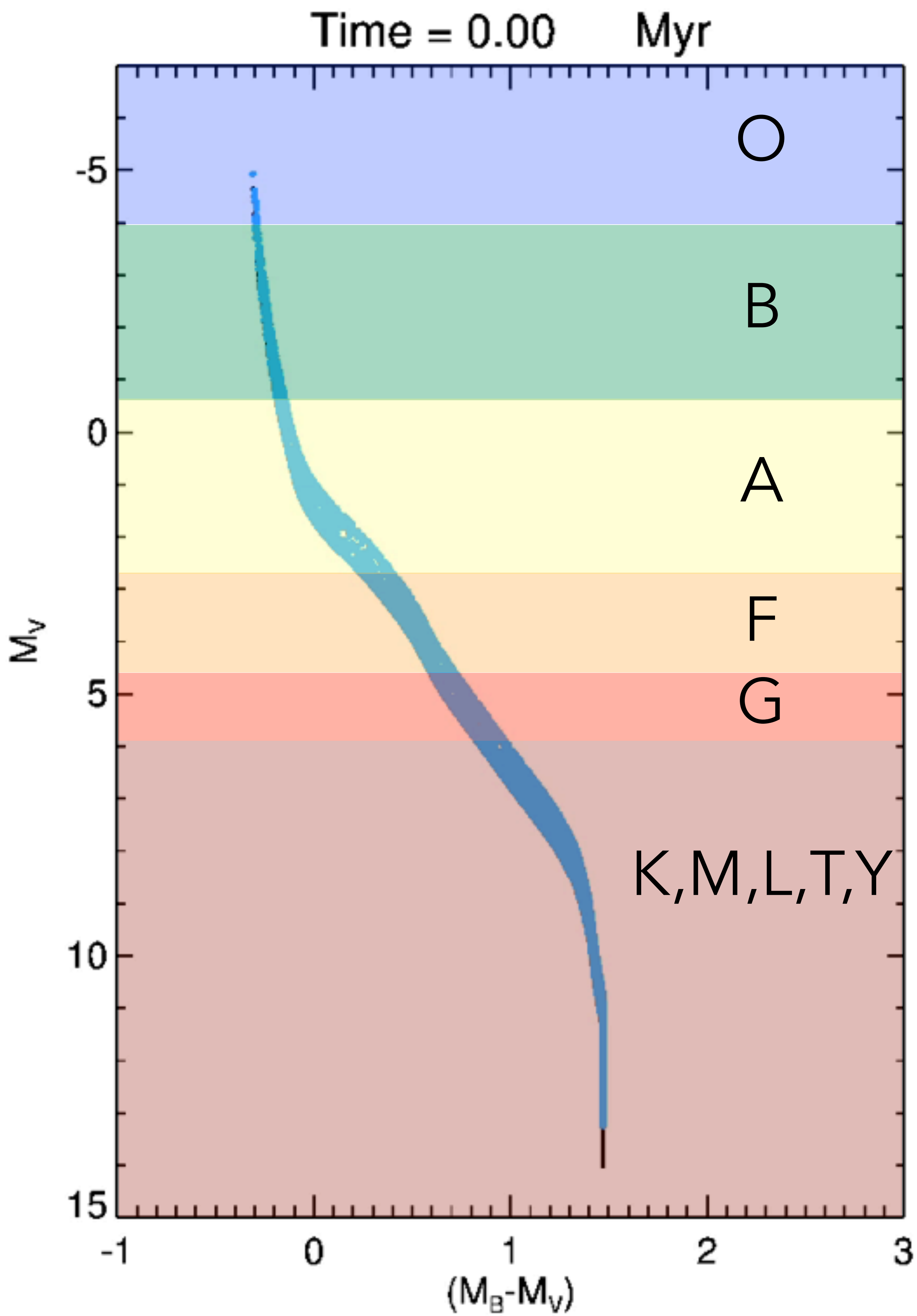
Lecture #21: Feedback, Cosmic Rays & Closing the Loop

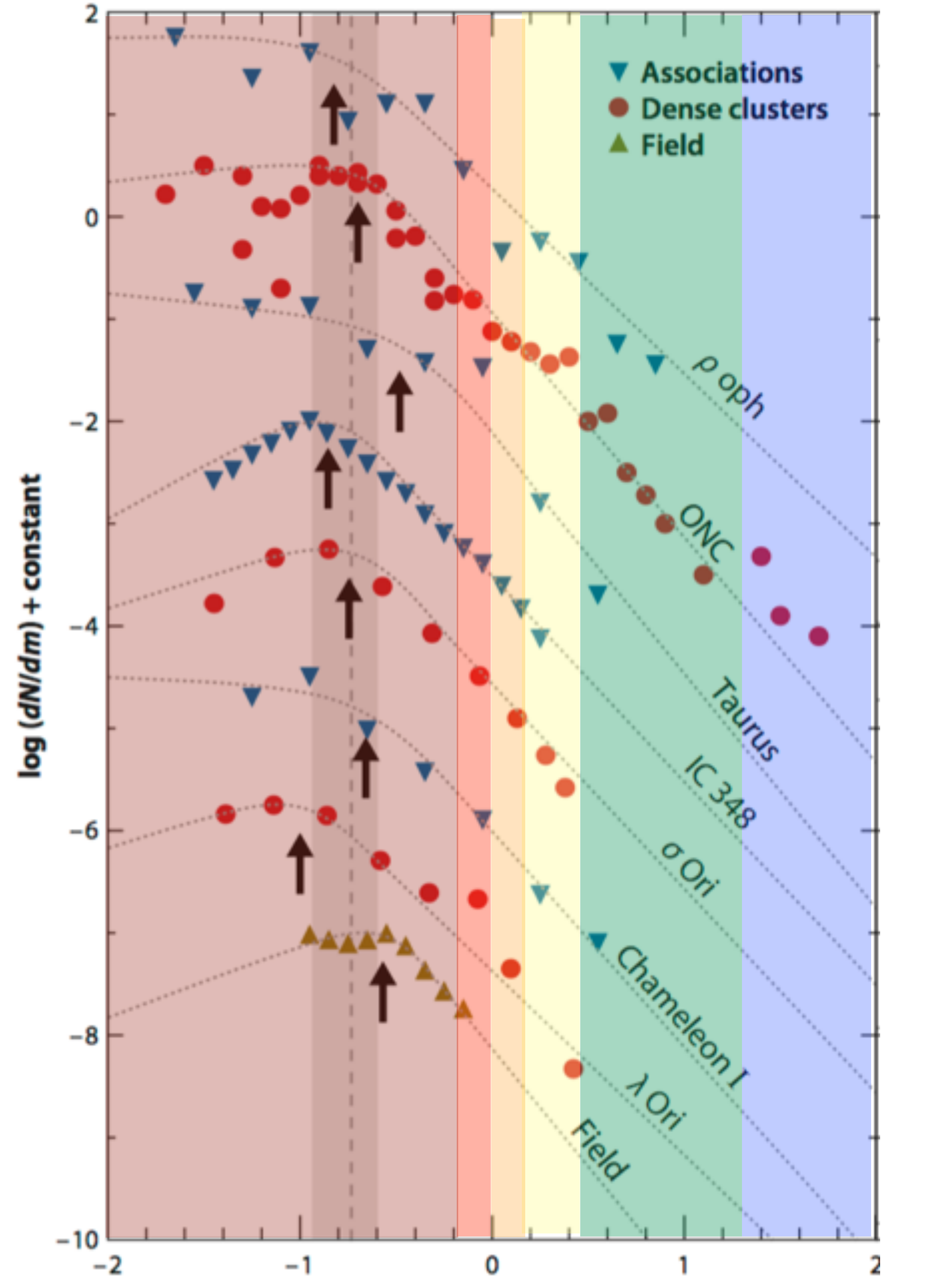
Outline

- Part I: Feedback
- Part II: Cosmic Rays
- Part III: Global ISM models



Time = 0.00 Myr
O
B
A
F
G
K,M,L,T,Y
M_V
(M_B-M_V)
Associations
Dense clusters
Field
log (dN/dm) + constant
ρ oph
ONC
Taurus
IC 348
σ Ori
Chameleon I
λ Ori
Field


Time = 0.00 Myr
O
B
A
F
G
K,M,L,T,Y
M_V
(M_B-M_V)
-5
0
5
10
15
-1
0
1
2
3


Associations
Dense clusters
Field
ρ oph
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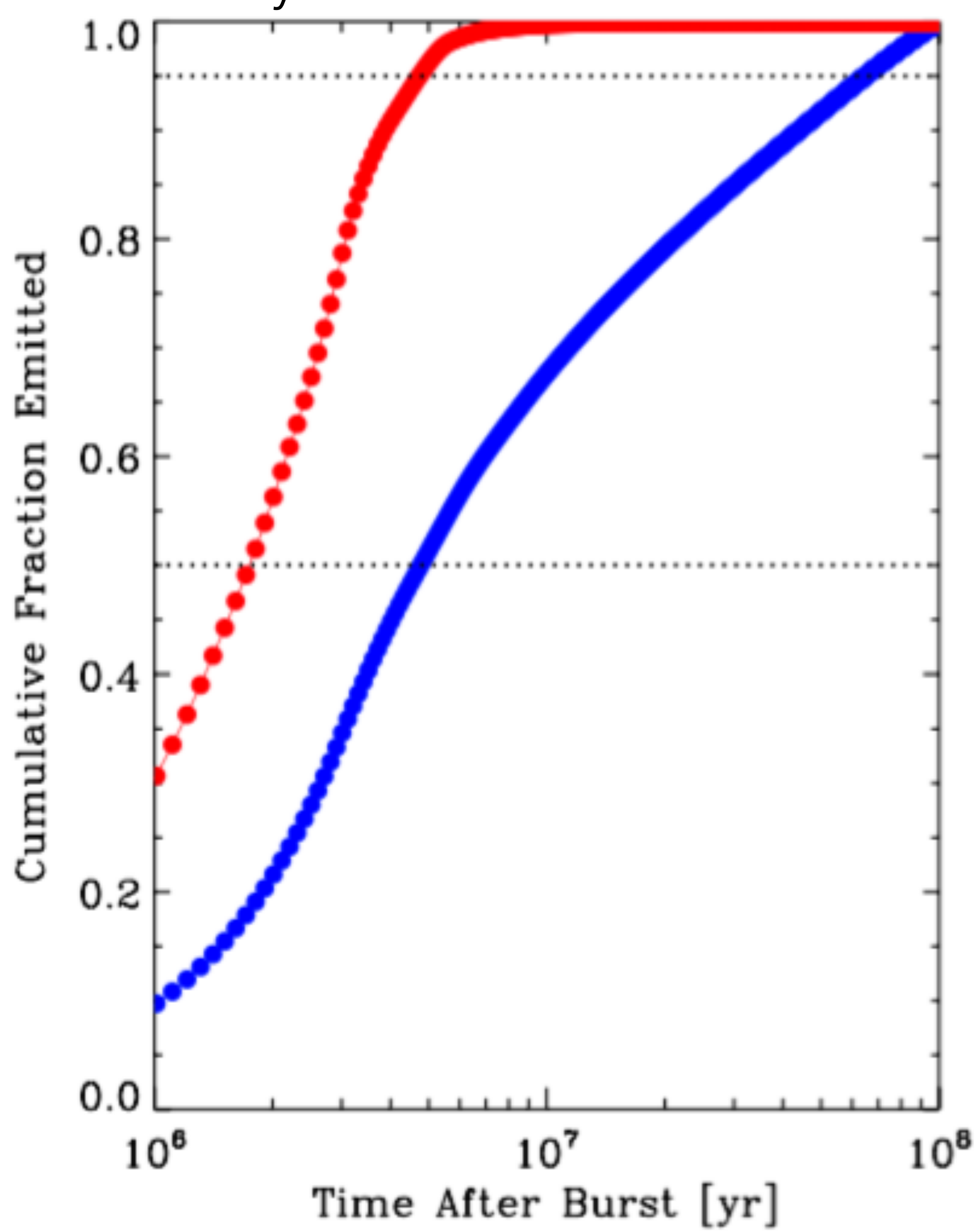
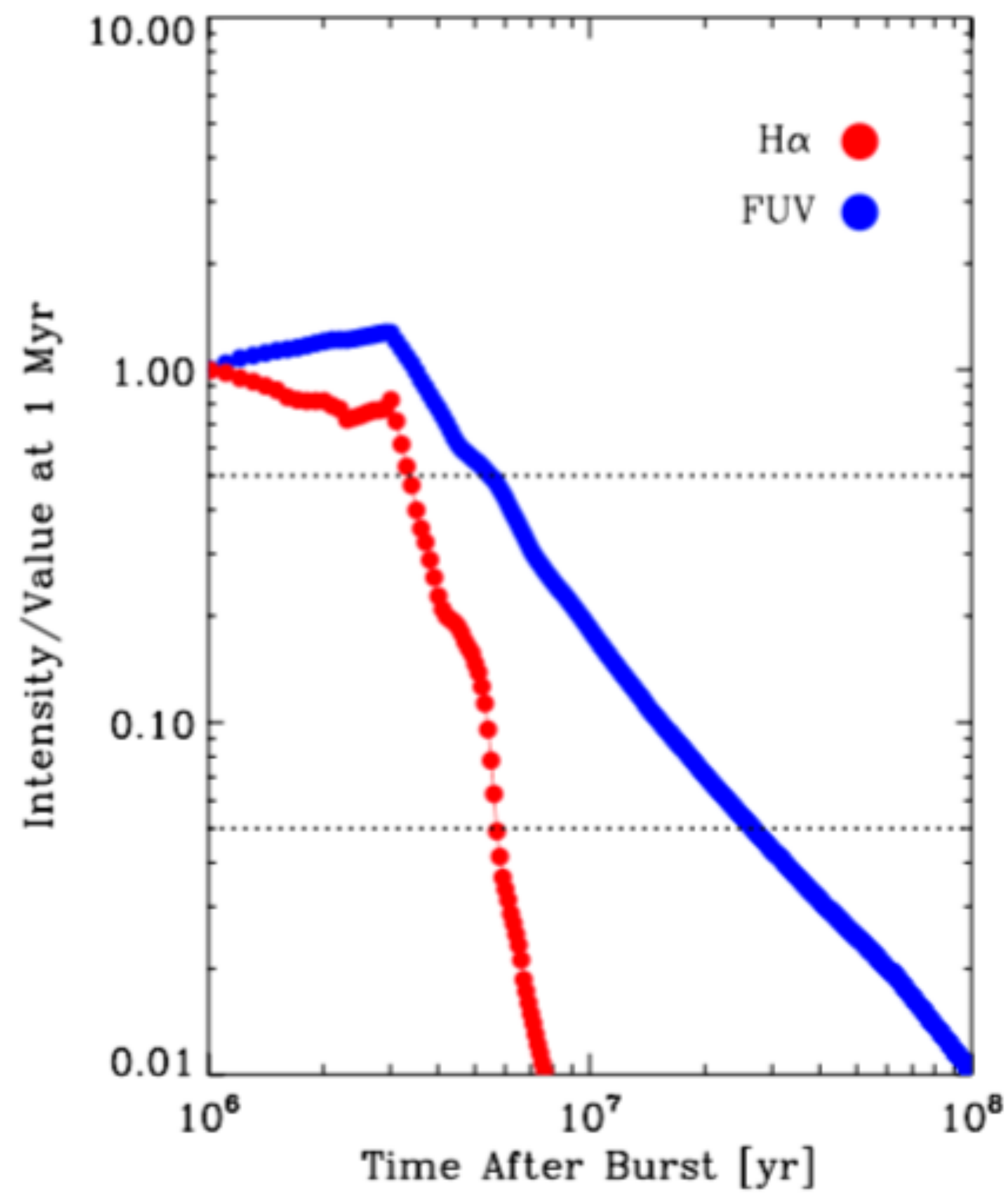
σ Ori
Chameleon I
λ Ori
Field
log (dN/dm) + constant
2
0
-2
-4
-6
-8
-10
-2
-1
0
1
2

Radiative Feedback

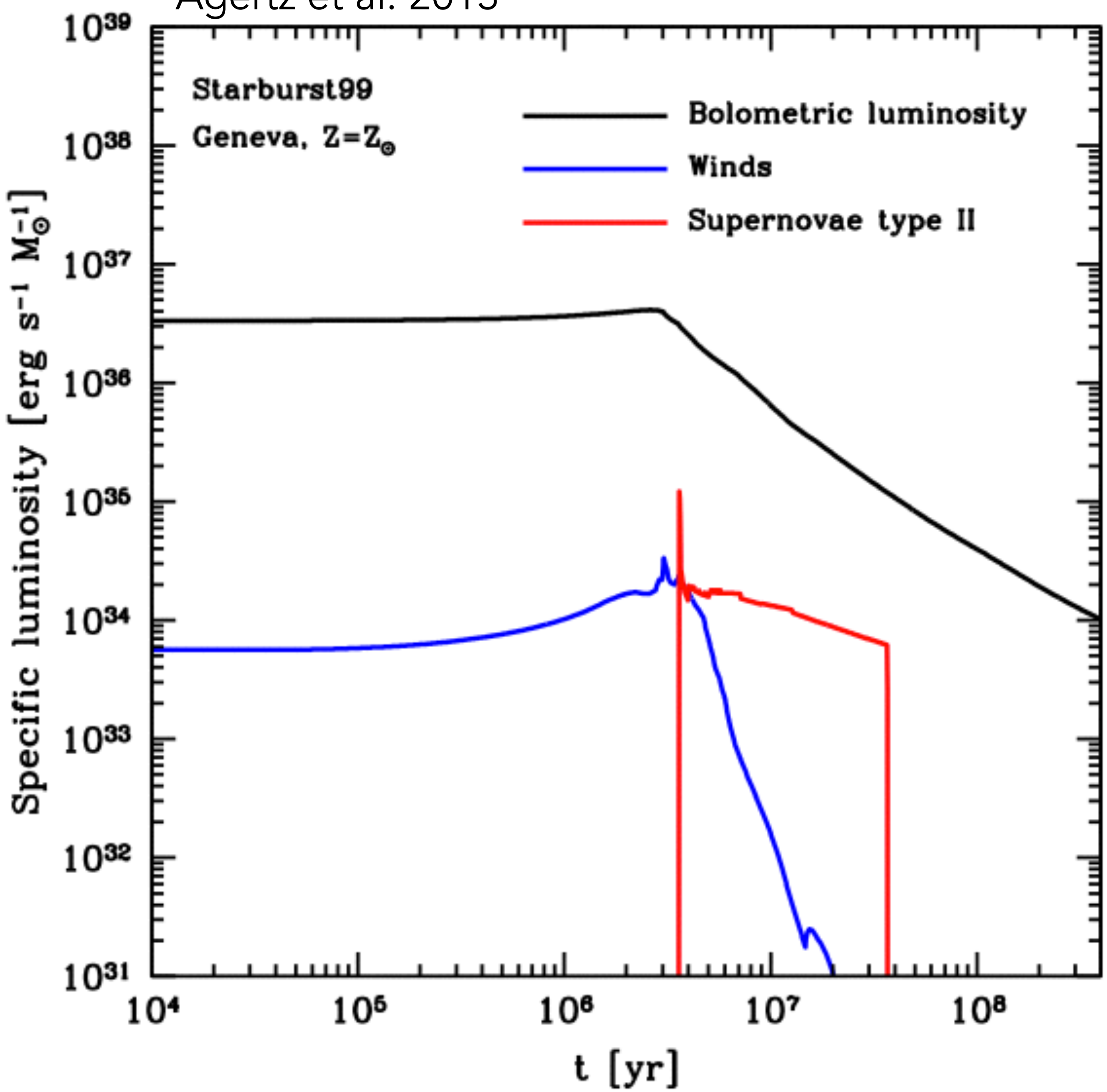
Leroy et al. 2012





Mechanical Feedback

Agertz et al. 2013



Mechanical Feedback

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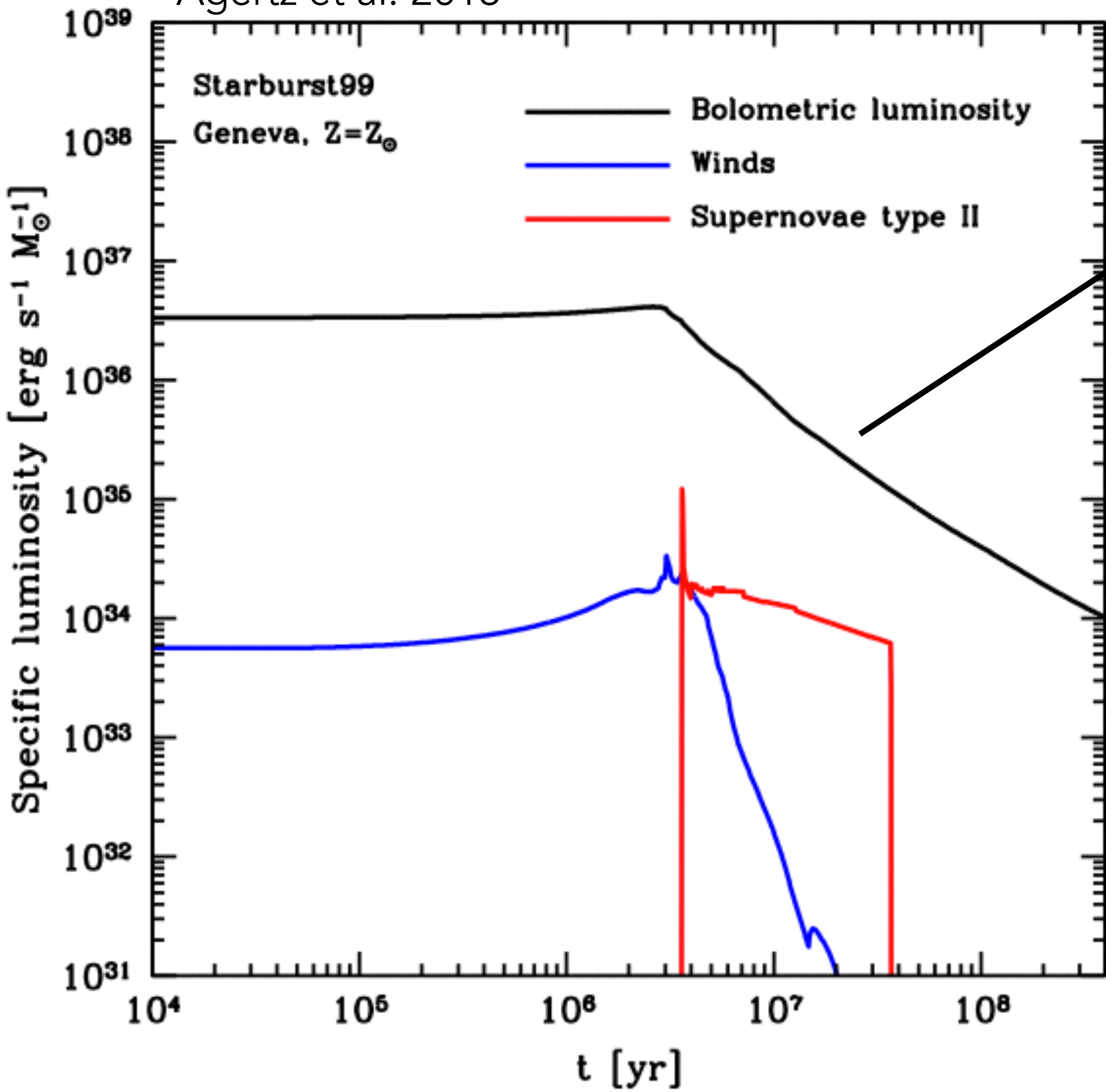
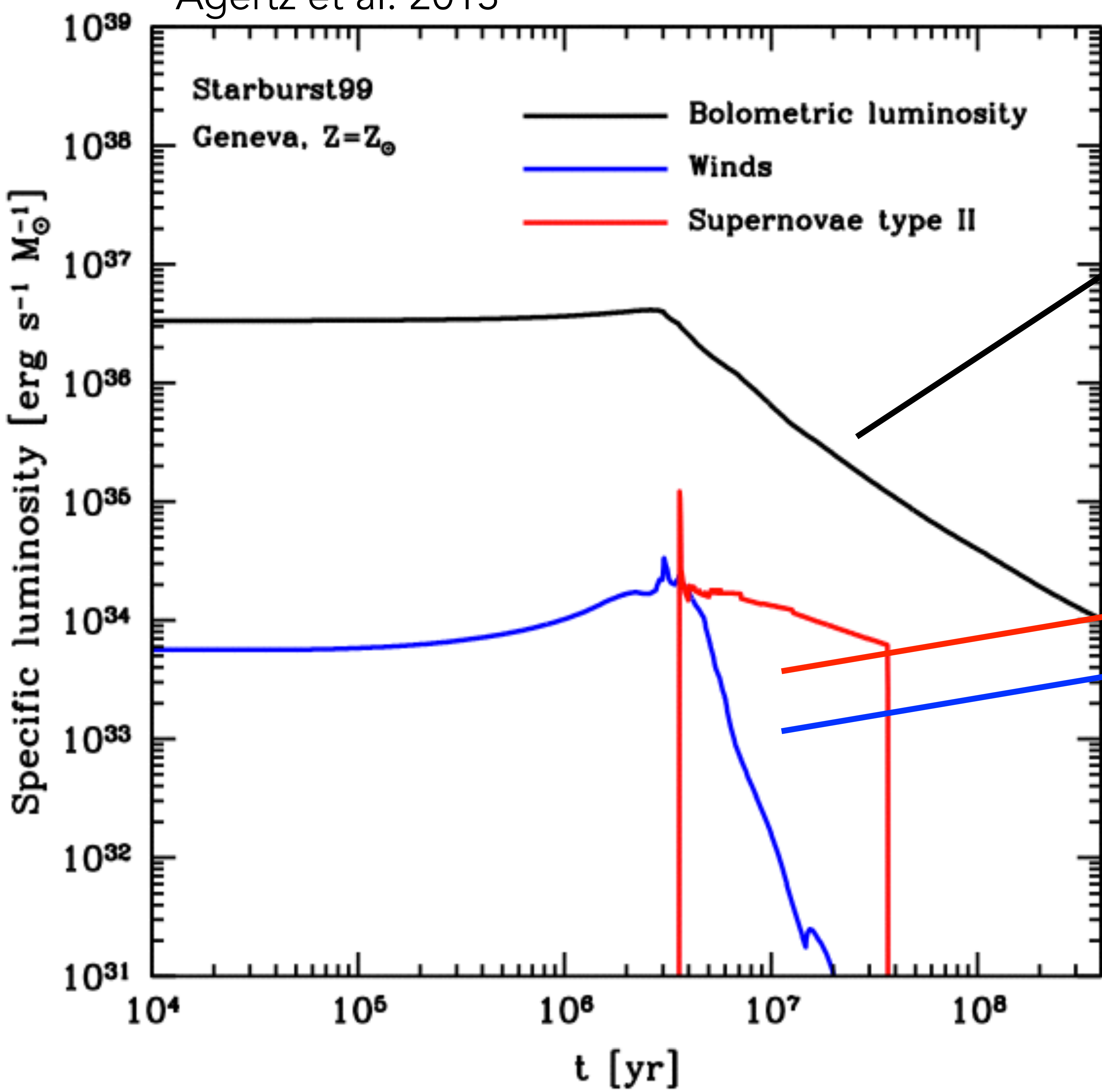


fraction into ionization, photoelectric heating, dust heating?

deposited where?

Mechanical Feedback

Agertz et al. 2013



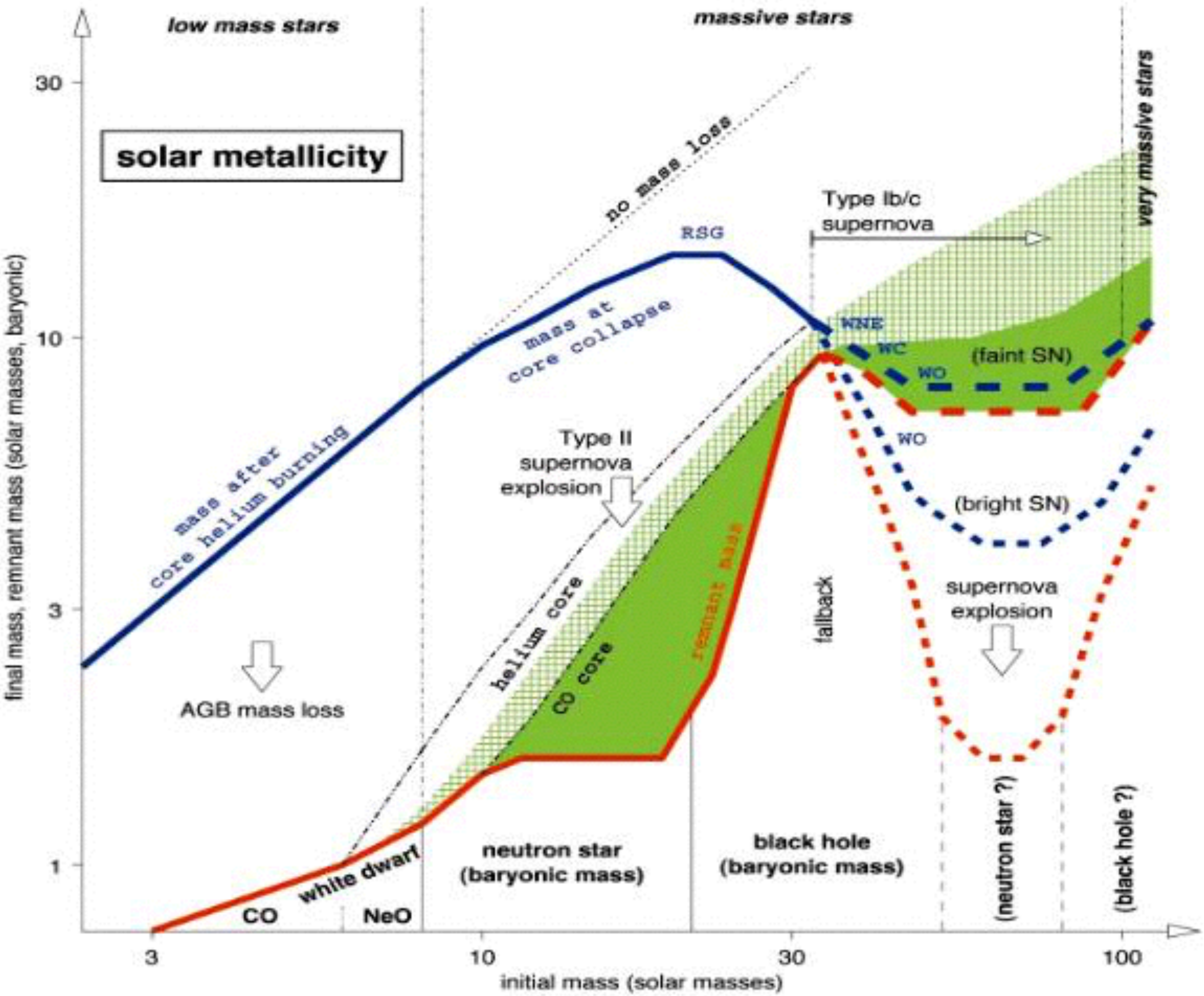
fraction into ionization, photoelectric heating, dust heating?

deposited where?

which phases is this deposited into, at what distances from stars?

Supernovae

Woosley et al. 2002



Stars with masses > 8 $M_{\odot}$ explode.

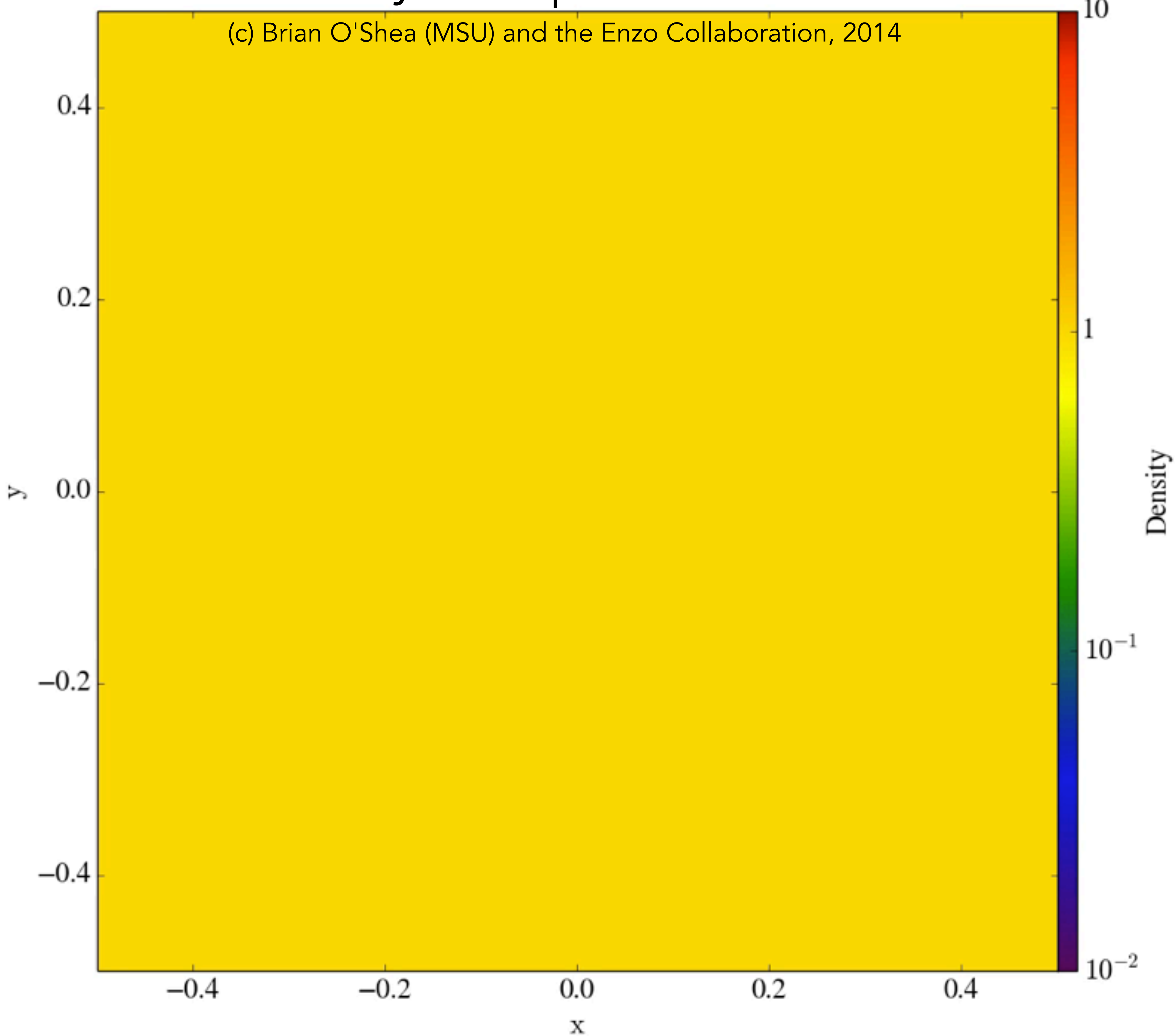
Supernovae produce ~10^{53} ergs in neutrinos ~10^{51} ergs in kinetic energy

Supernovae

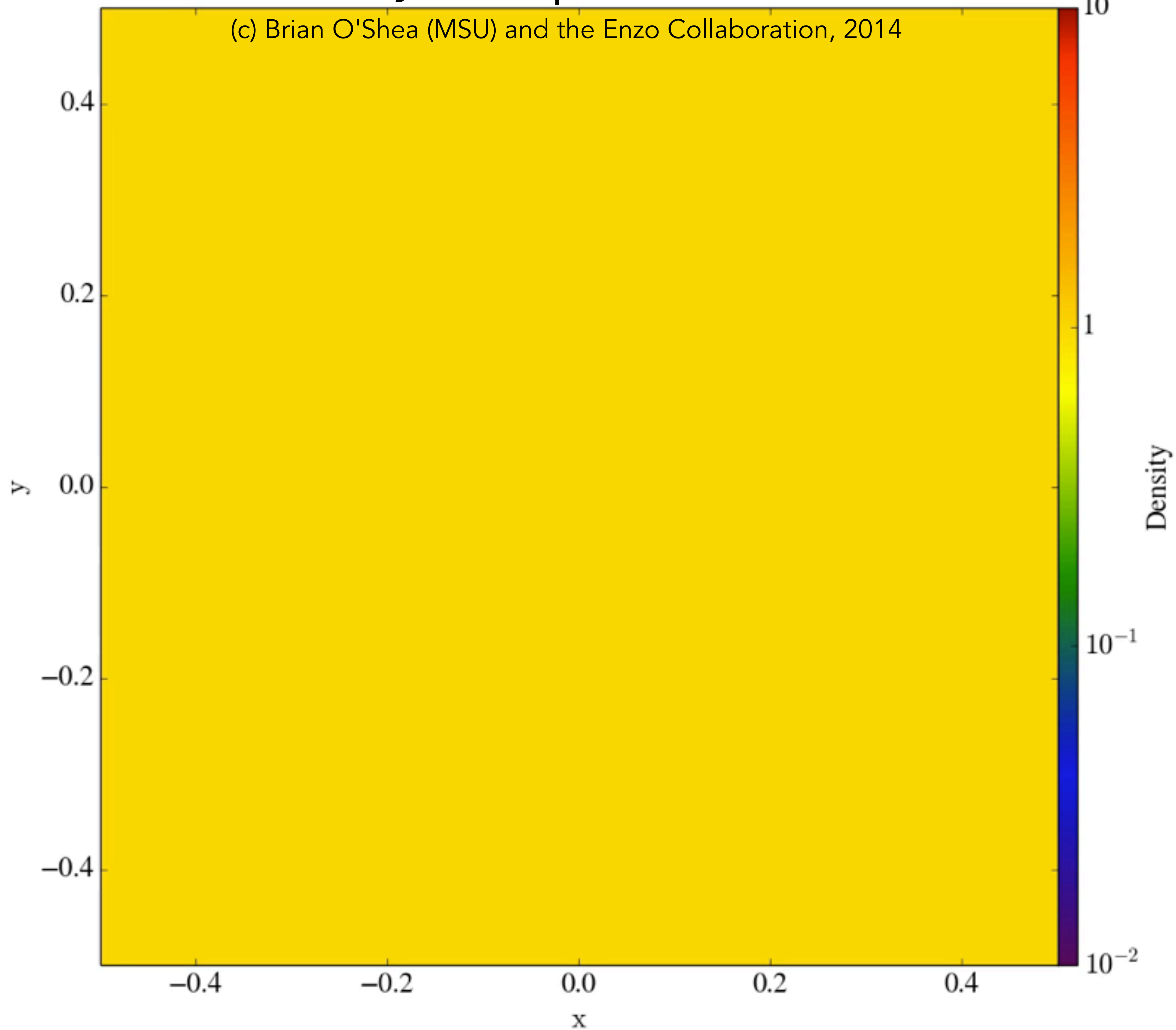
Initially: M_{ejecta} ~ few $M_{\odot}$, v_{ejecta} ~10^4 km/s

Phase	Characteristics	Ends when…	Radius at end
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	-	-

Sedov-Taylor expansion with ENZO



Sedov-Taylor expansion with ENZO



SILCC: **SI**mulating the **L**ife**C**ycle of molecular **C**louds

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Thorsten Naab
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Simon C. O. Glover
Richard Wünsch
Ralf S. Klessen
Paul C. Clark
Thomas Peters
Dominik Derigs
Christian Baczynski

Walch et al., MNRAS 454, 238 (2015)
Girichidis et al., arXiv:1508.06646

KS SN rate, mixed driving

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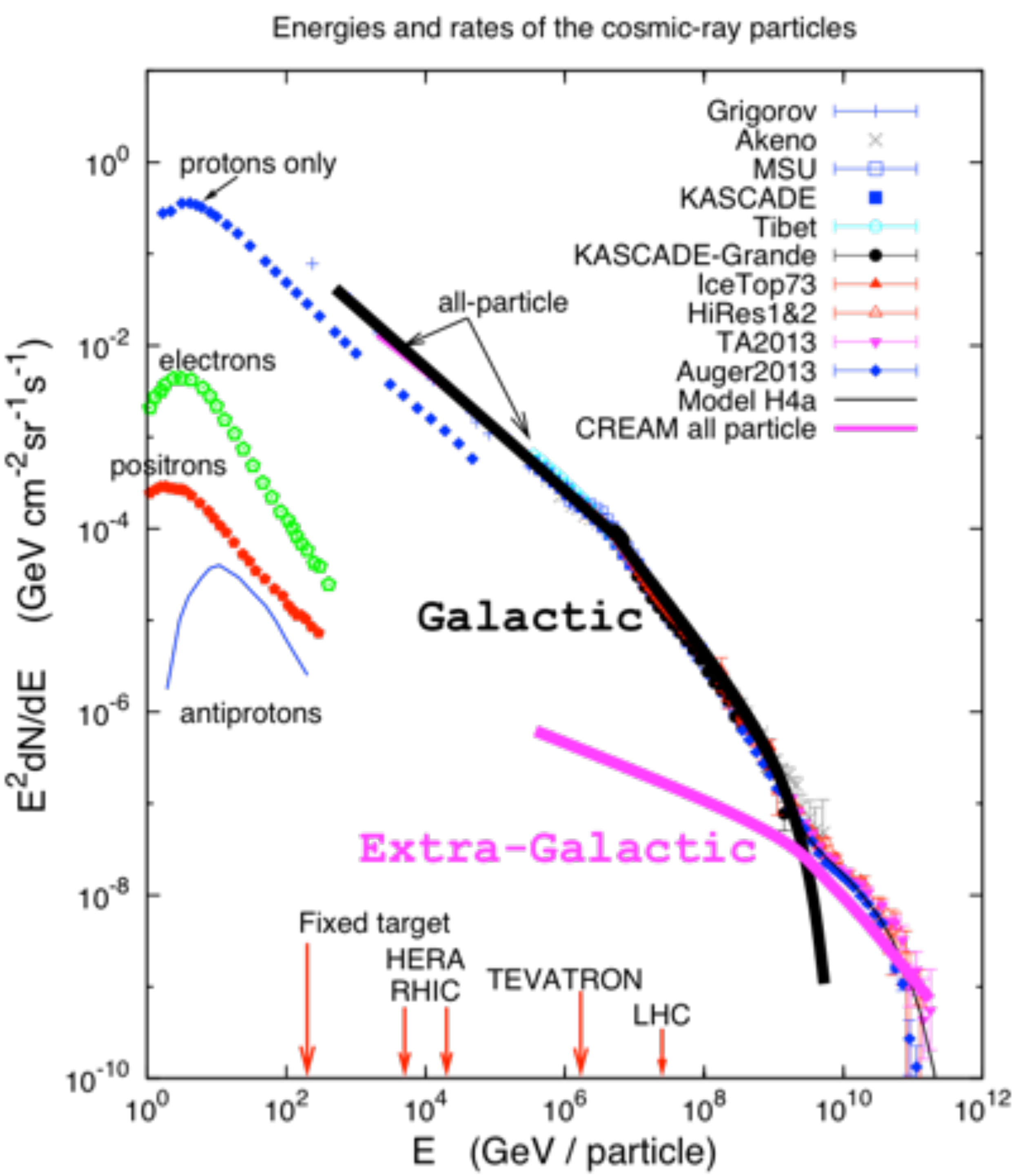
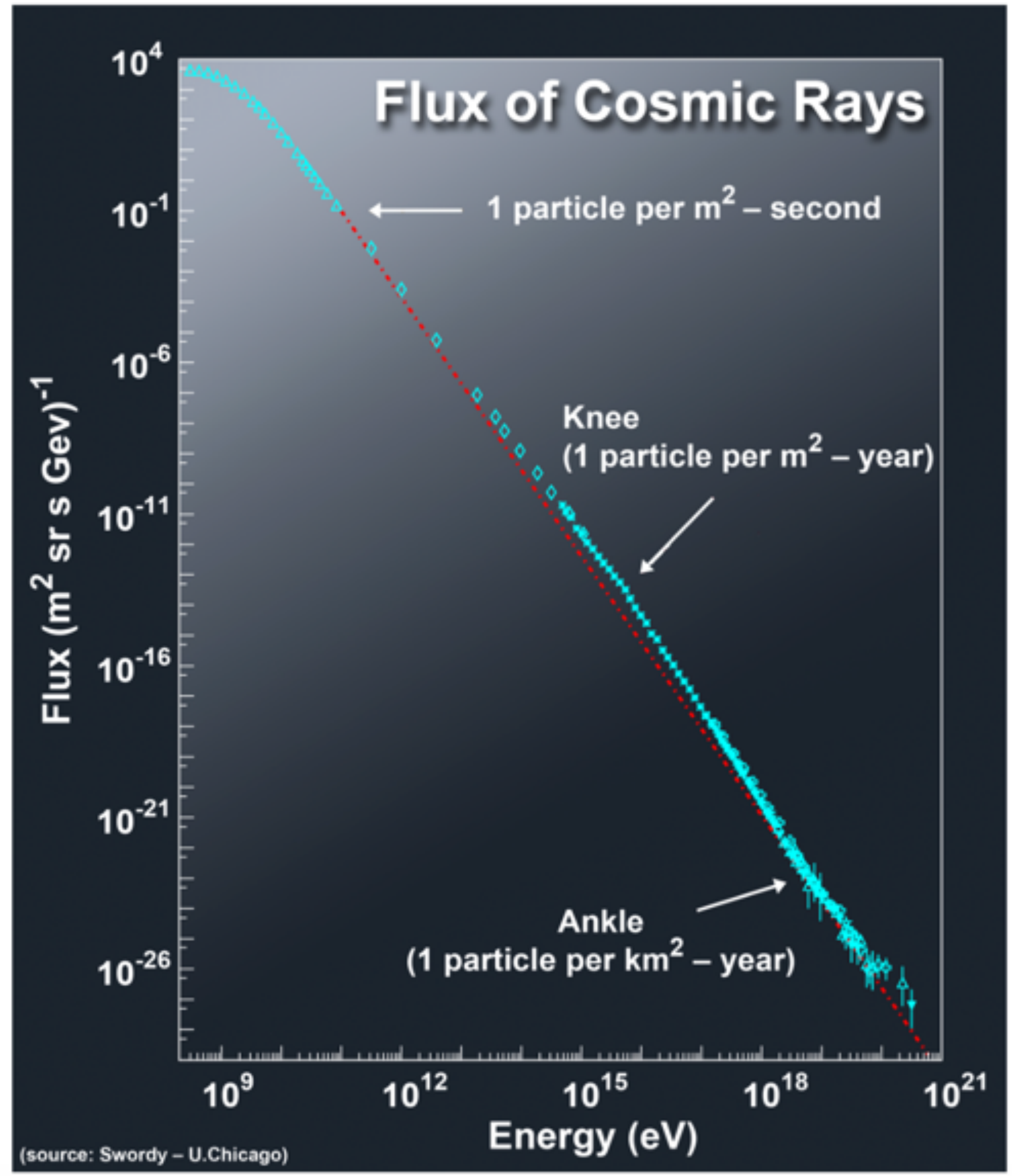
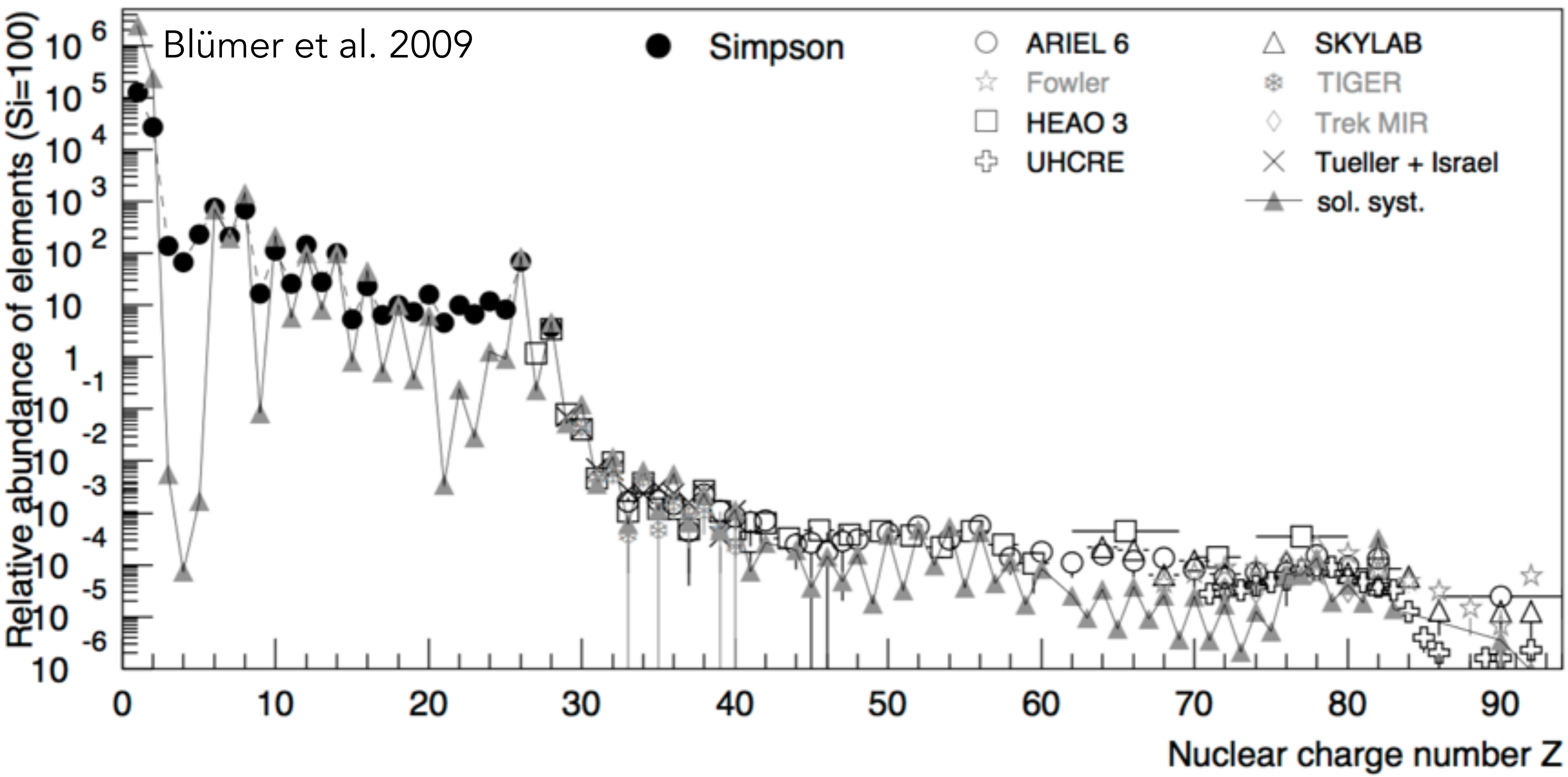
Cosmic Rays



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



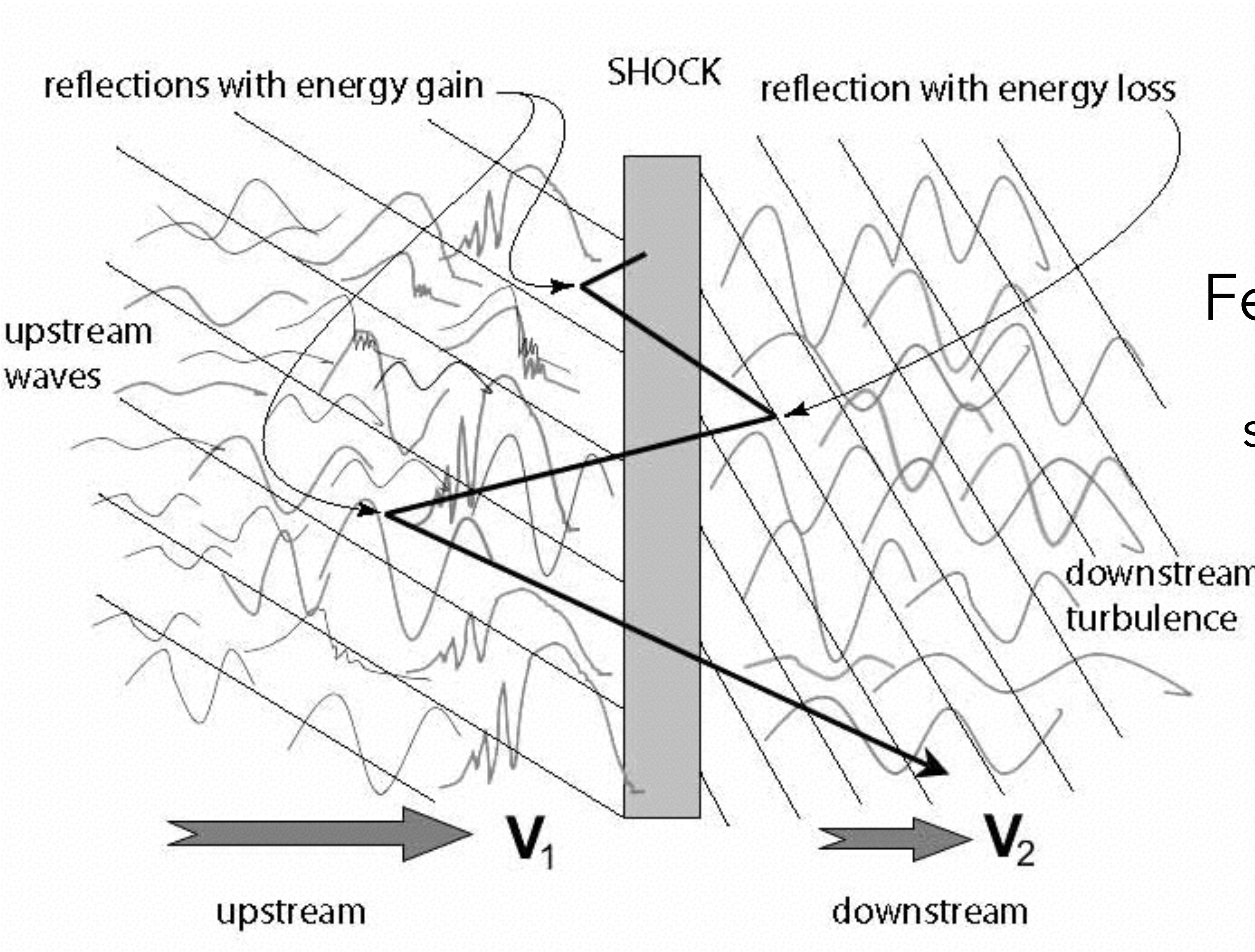
Cosmic Rays



Protons are most abundant, He next.

^{6}Li, ^{9}Be, ^{10}B, ^{11}B from "spallation".

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

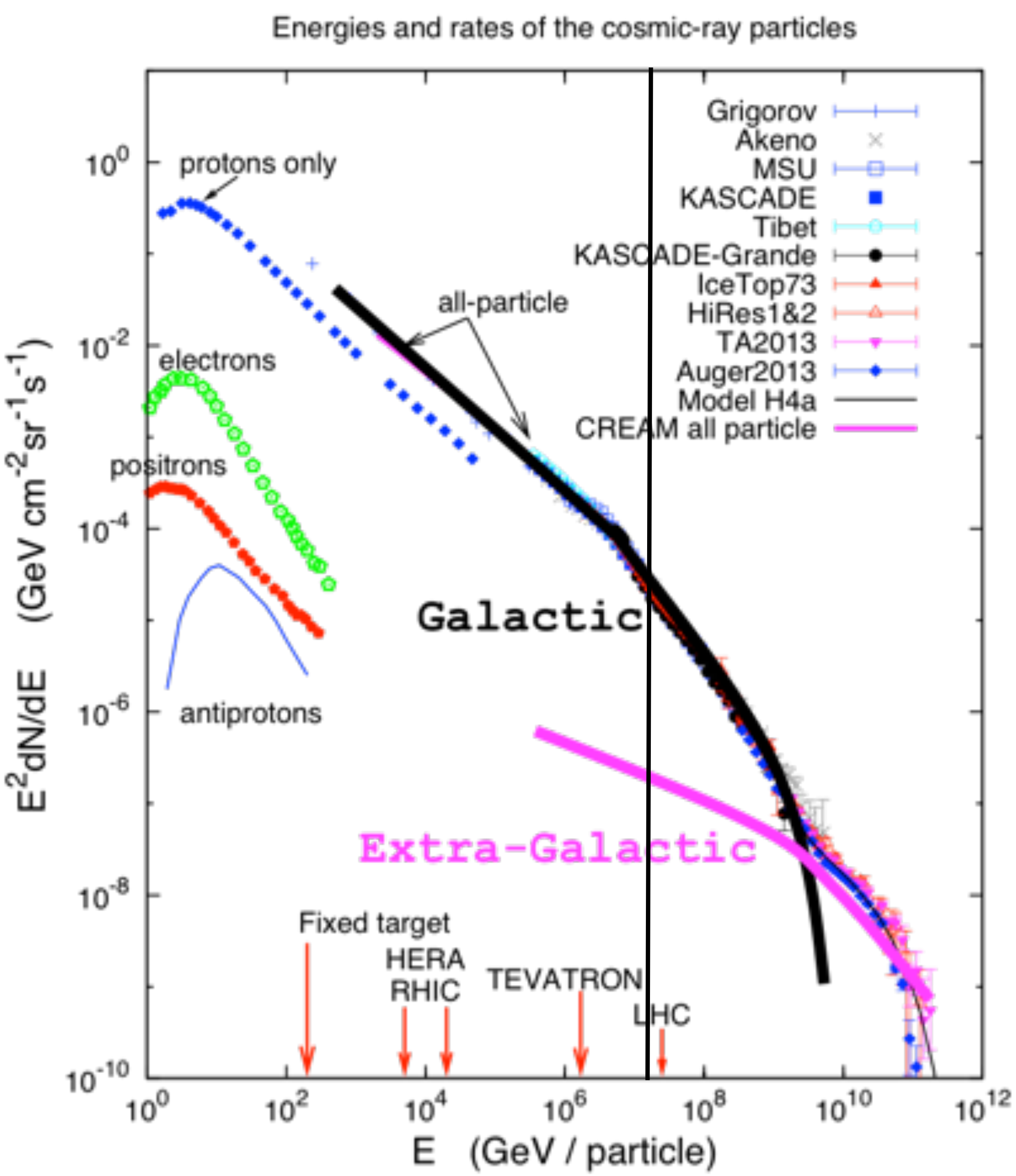
$$R_{\rm gyro} = \frac{pc}{eB_\perp}$$

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

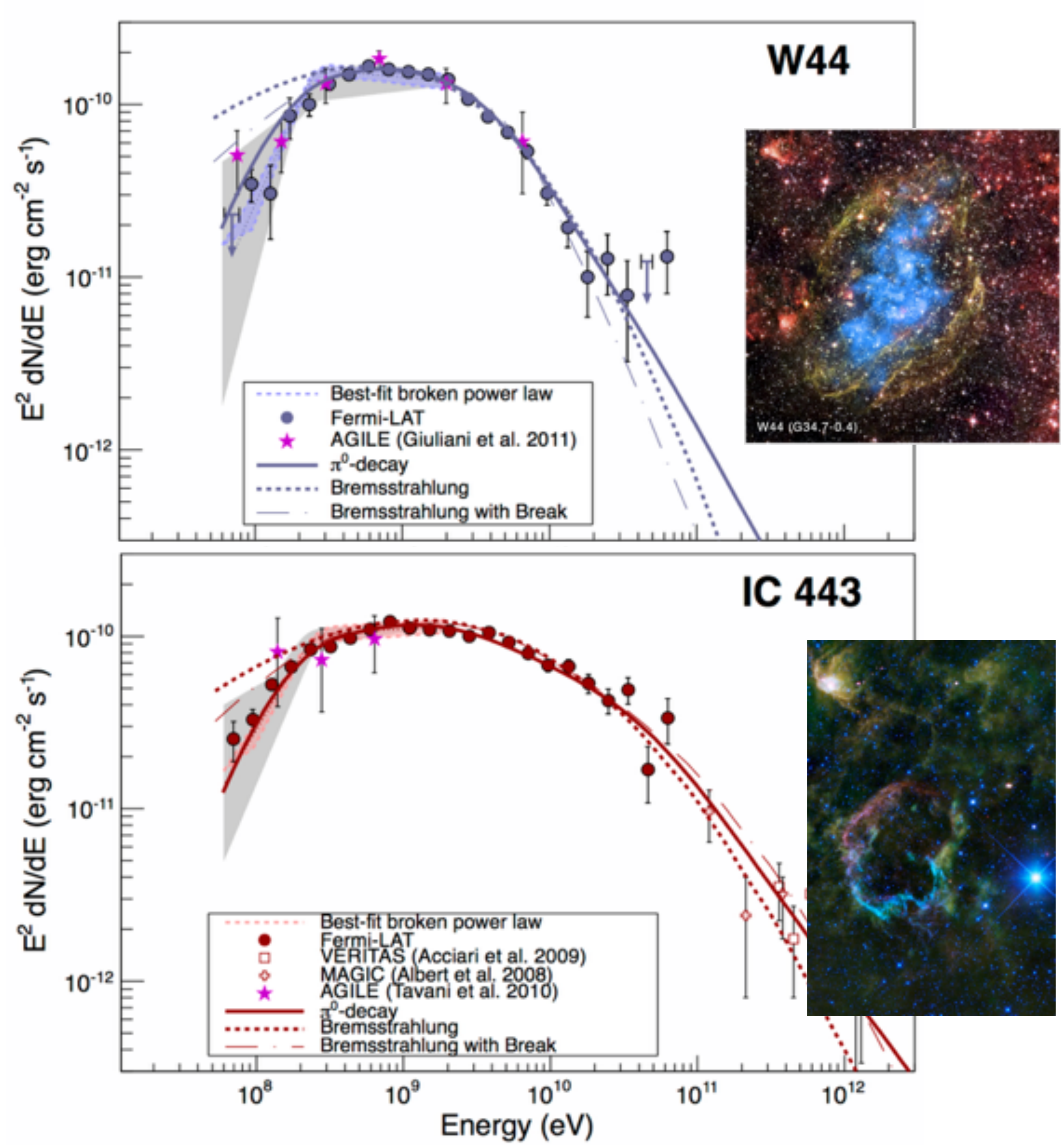


$$E_{\rm max} \approx 10^{7.0}{\rm GeV} \left(\frac{L}{23{\rm pc}}\right)\left(\frac{B_{\rm SNR}}{10\mu{\rm G}}\right)$$

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

Recently, first direct evidence…

Acceleration of Cosmic Rays



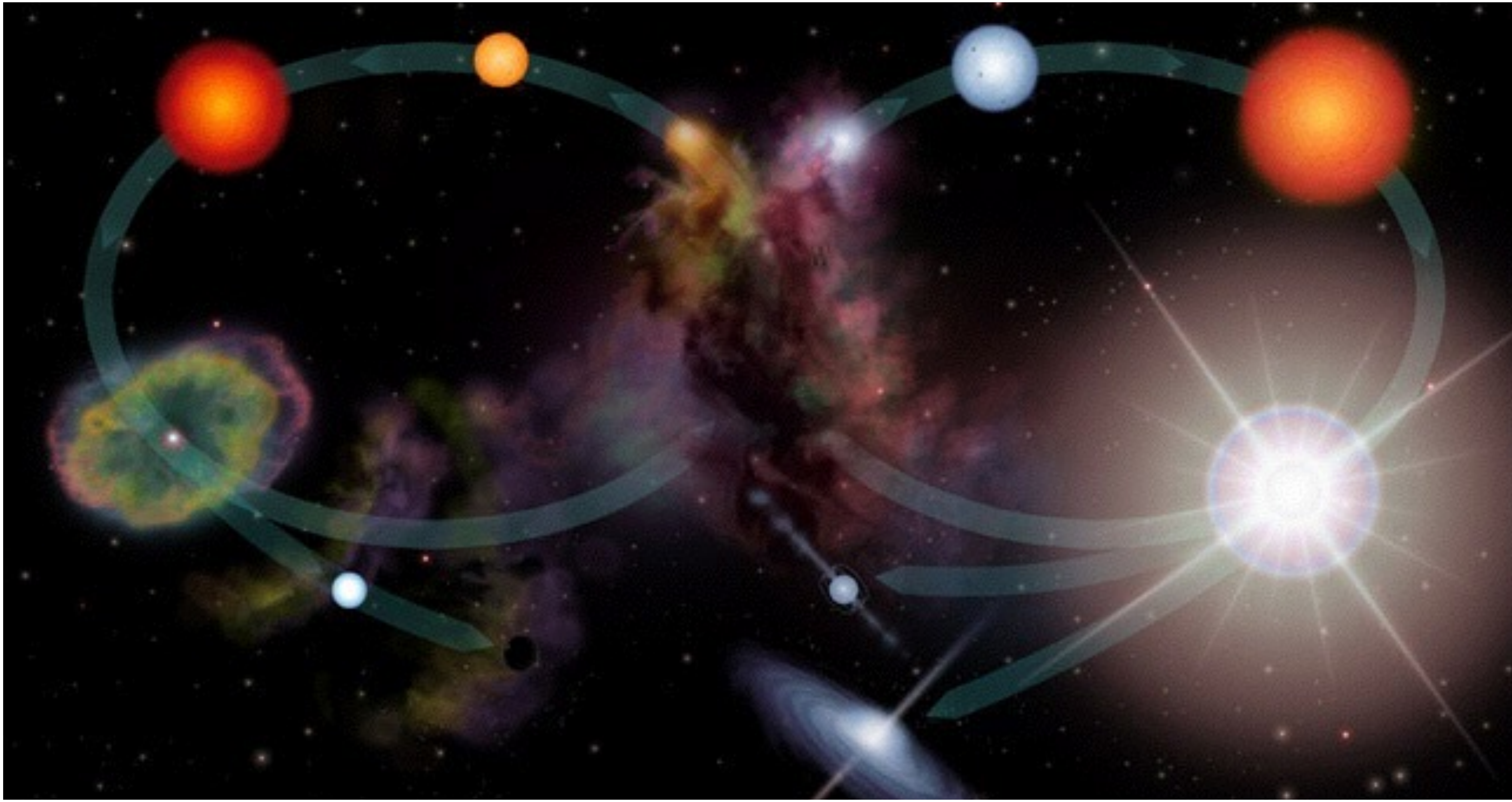
Accelerated protons create pions when they run into the surrounding ISM. Pions decay and produce gamma rays.

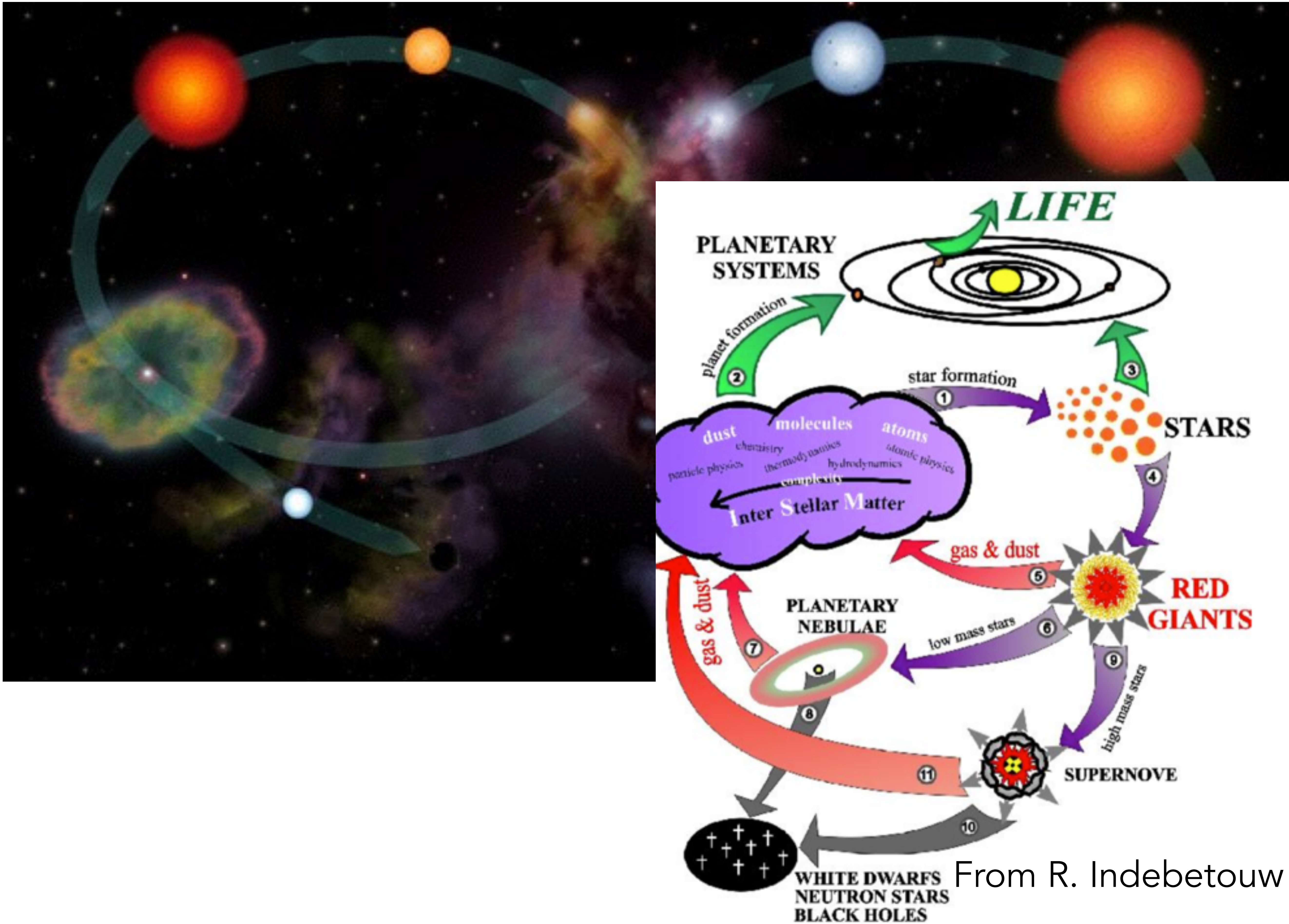
Fermi confirmation of gamma-ray spectrum following pion decay prediction for some SNRs in the MW. (Ackermann et al. 2013)

ISM Energy Density

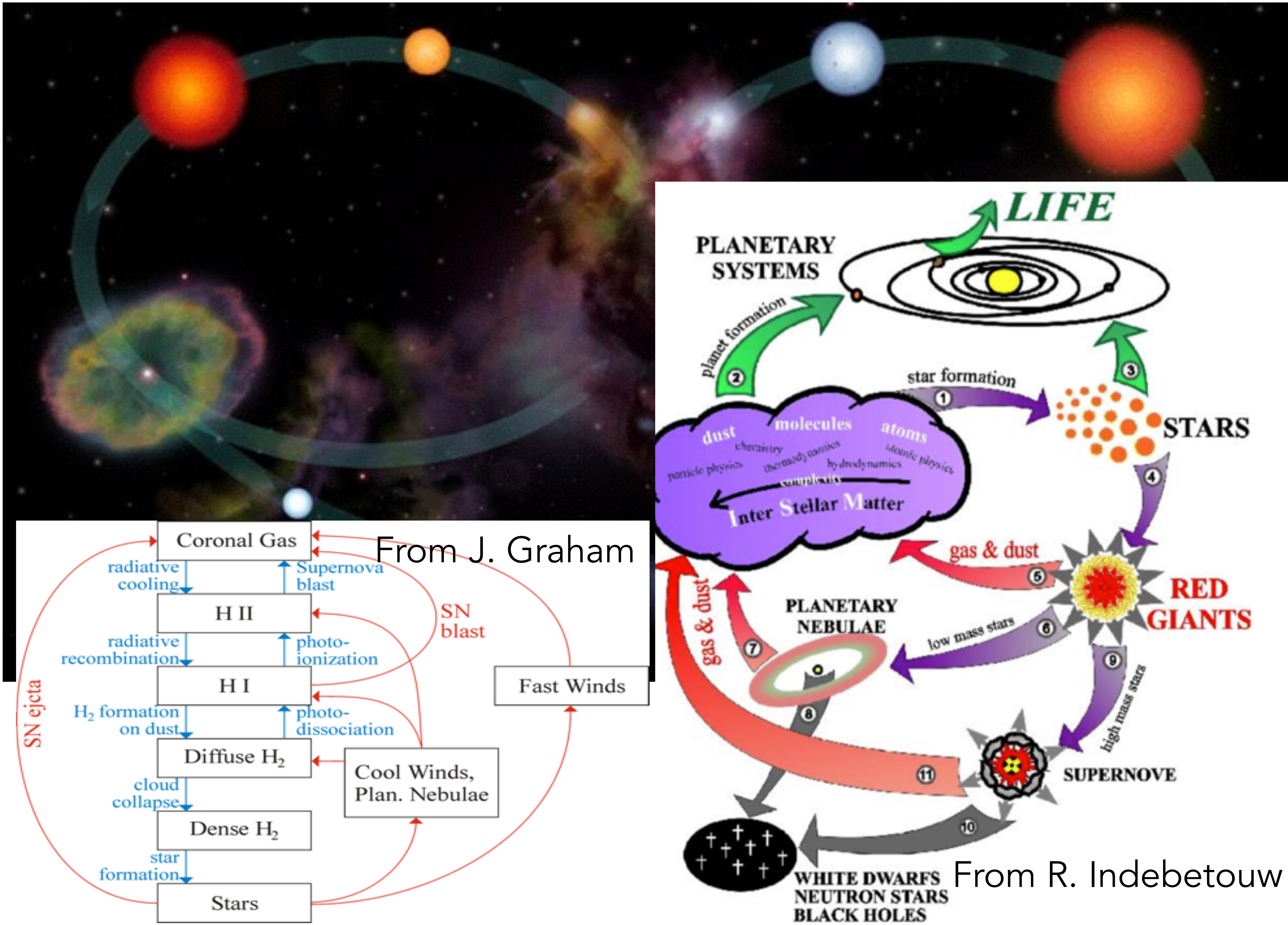
Component	*u* (eV cm^{-3})
Cosmic Microwave Background	0.25 (T_{CMB} = 2.725 K)
Gas Thermal Energy	0.49 (for nT = 3800 cm^{-3} K)
Gas Turbulent Kinetic Energy	0.22 (for n = 1 cm^{-3}, v_{turb} = 1 km/s)
B-Field	0.89 (for 6 μGauss)
Cosmic Rays	1.39 (see Draine ch 13)
Starlight	0.54 (for hν < 13.6 eV)

All the same order of magnitude!

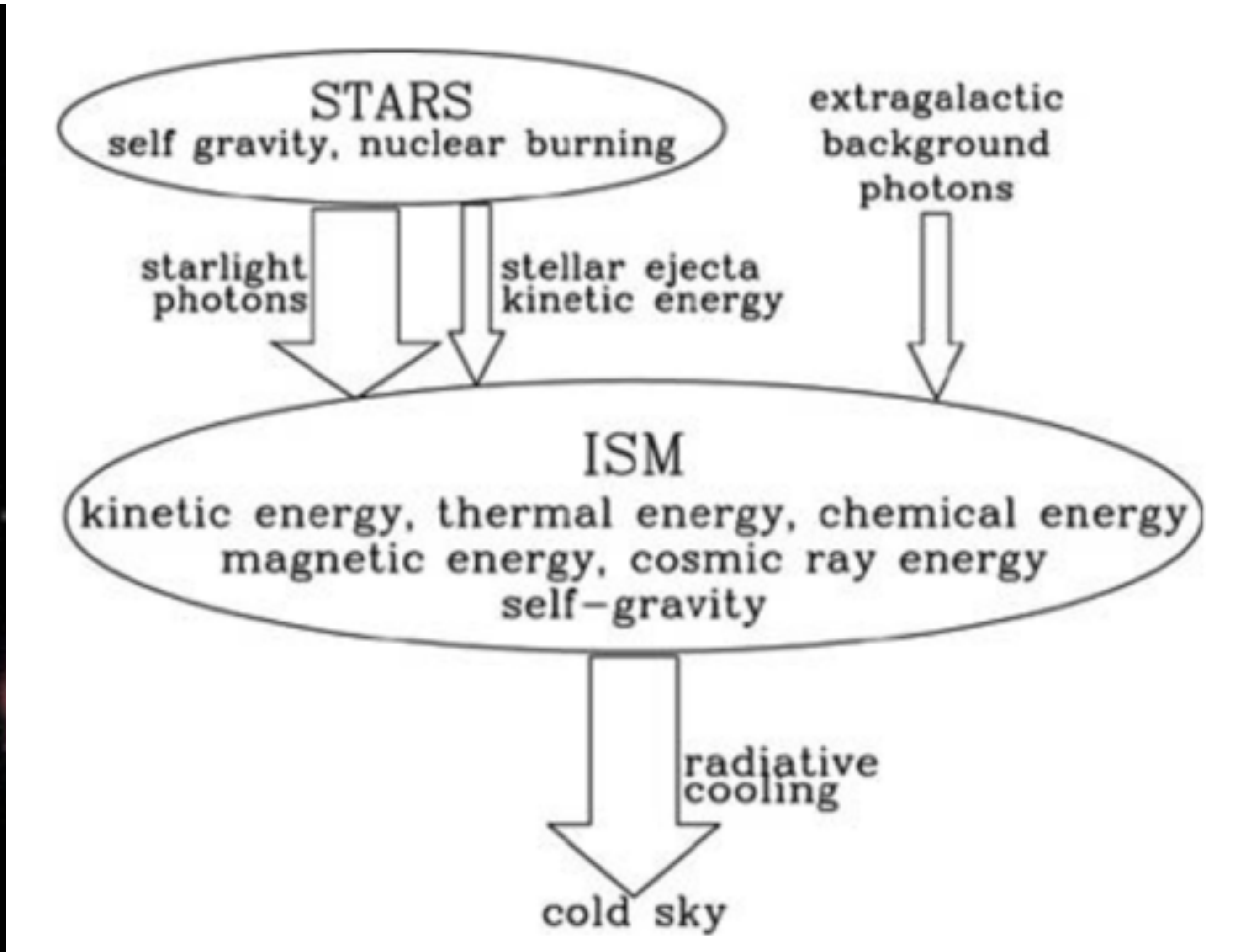


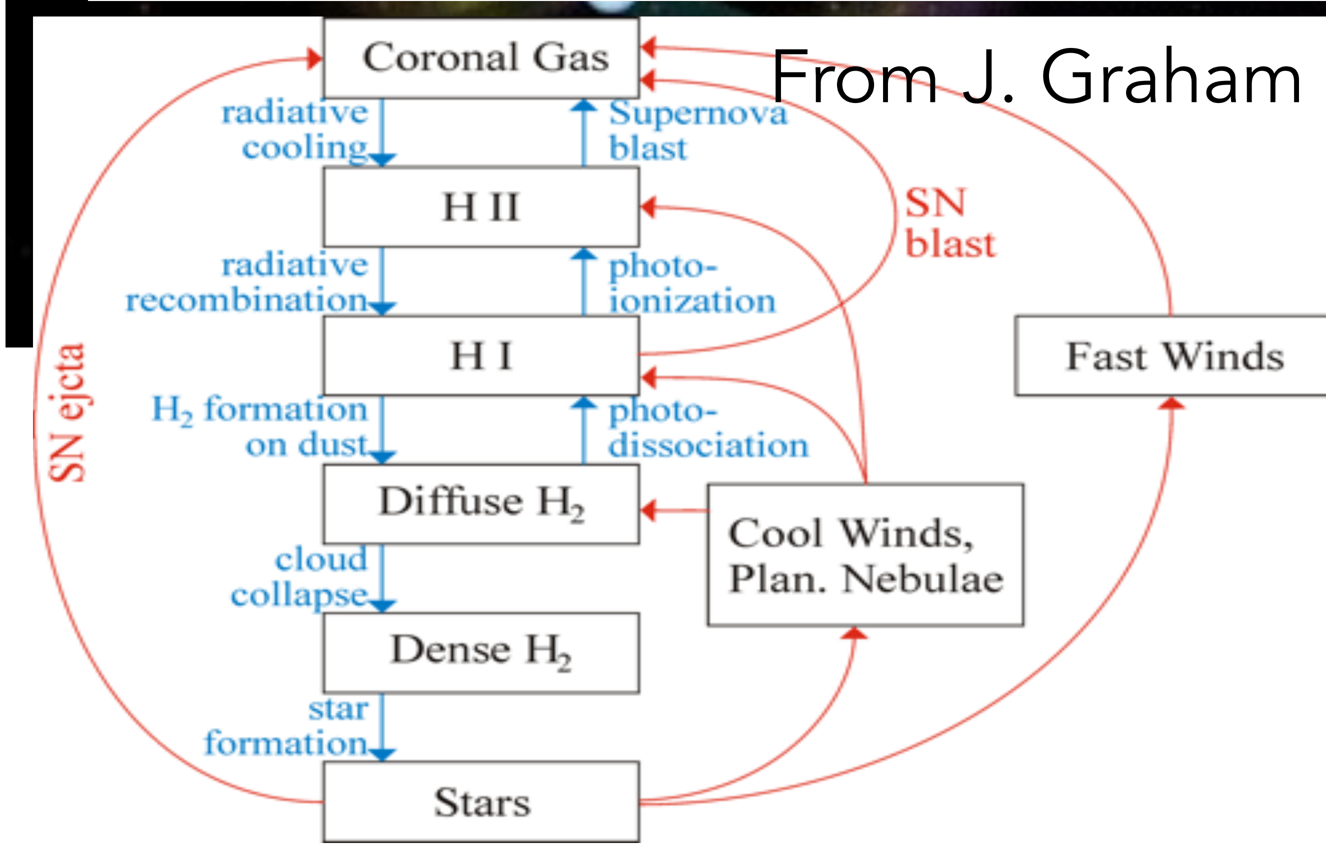


From R. Indebetouw



Coronal Gas
radiative cooling
Supernova blast
H II
radiative recombination
photo-ionization
H I
H_2 formation on dust
photo-dissociation
Diffuse H_2
cloud collapse
Dense H_2
star formation
Stars
SN ejcta
SN blast
Fast Winds
Cool Winds, Plan. Nebulae
From J. Graham
LIFE
PLANETARY SYSTEMS
planet formation
star formation
STARS
dust
molecules
atoms
Inter Stellar Matter
gas & dust
RED GIANTS
PLANETARY NEBULAE
low mass stars
high mass stars
SUPERNOVE
WHITE DWARFS
NEUTRON STARS
BLACK HOLES
From R. Indebetouw





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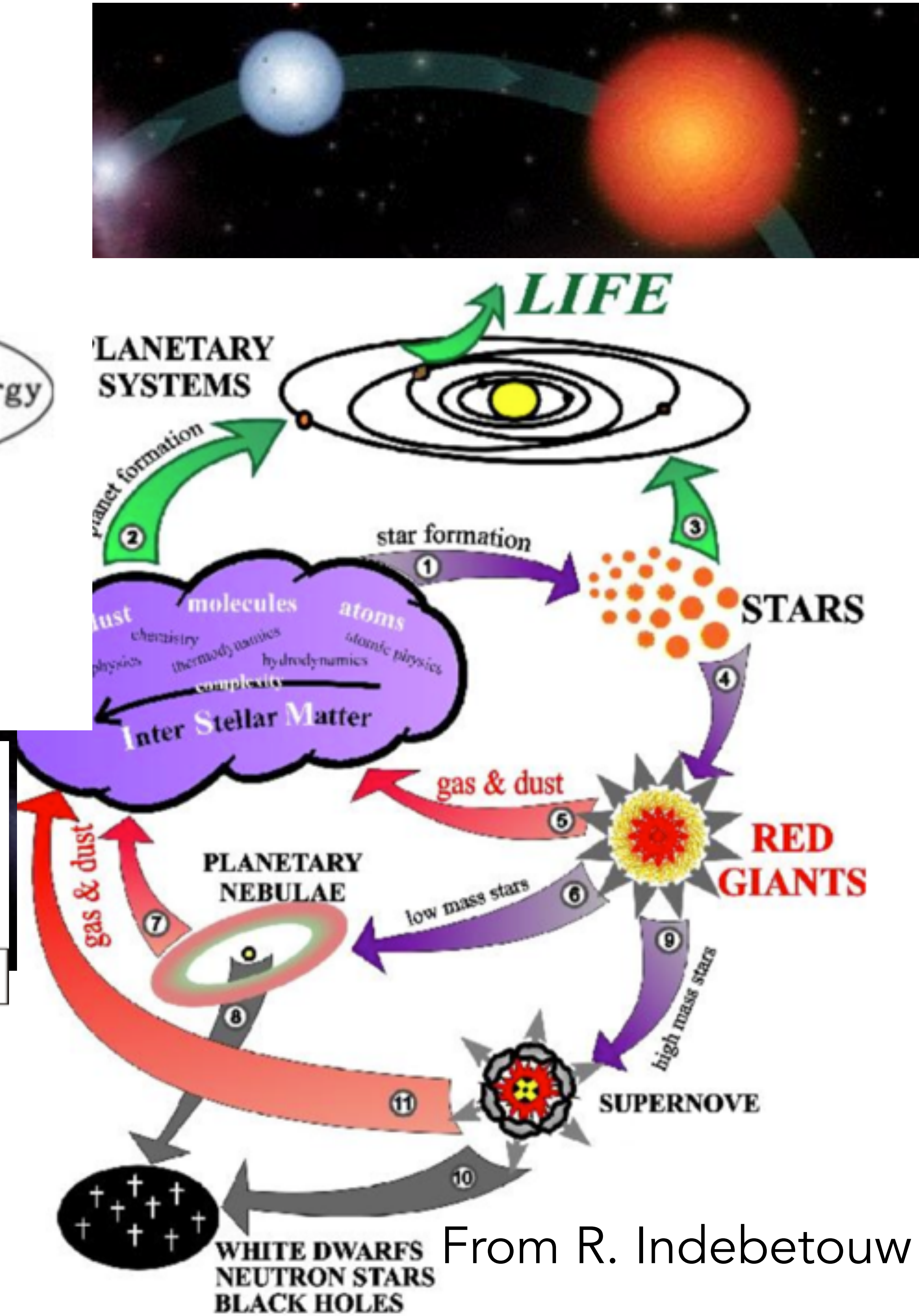

From R. Indebetouw

How does THIS affect THIS	Gravitational Potential	Gas	Dust	Radiation Field	Cosmic Rays	Magnetic Fields	Stars
Gravitational Potential	———-	hydrostatic pressure, dynamics, spiral arms, large scale gas stability	2nd order	2nd order	pressure confinement, dynamical influence (e.g. spiral arms)	gas dynamics, pressure arrange B-field	sets stellar mass distribution, 2nd order hydrostatic pressure -> SF
Gas	self-gravity in dense gas clouds	gas dynamics, collisional excitation, self gravity	dust growth in dense gas, collisional heating/cooling, charging, dust destruction in shocks	alters radiation field (H2 shielding, ionizing photons absorbed)	creation (shocks accelerate), collisions (CR + p+ -> γ ray), confinement (B-field)	dynamically, MHD turbulence, dynamos create/ amplify B-field	star formation
Dust	2nd order	heating/cooling gas, shielding, chemistry, metal abundance (grain sputtering)	grain-grain collisions, shielding small grains from UV	extinction (absorption & scattering)	2nd order	ionization of grains and gas, keeps B-field tied to gas	key role in SF
Radiation Field	2nd order	heating of gas, ionization, photoelectric effect	heating dust, charging grains (PE effect), destruction of small grains	———-	2nd order	ionization of gas, keeps B-field tied to gas	key role in SF
Cosmic Rays	2nd order	ionization in dense gas, connection to B-field	2nd order	2nd order	———-	tied closely to B-field, equipartition?	heats dense gas that forms stars
Magnetic Fields	2nd order	dynamically, MHD turbulence	grain alignment, charged grains coupled to B-field	2nd order	tied closely to B-field, equipartition?	? reconnection & dissipation	dynamically important in collapse -> SF
Stars	large part of the overall mass that sets the grav potential	SNe/winds - dynamics, nucleosynthesis (metals), radiation field generation	create & destroy dust, generate radiation field that heats dust	directly produce it	SNe shocks -> CR	2nd order	feedback shuts off SF

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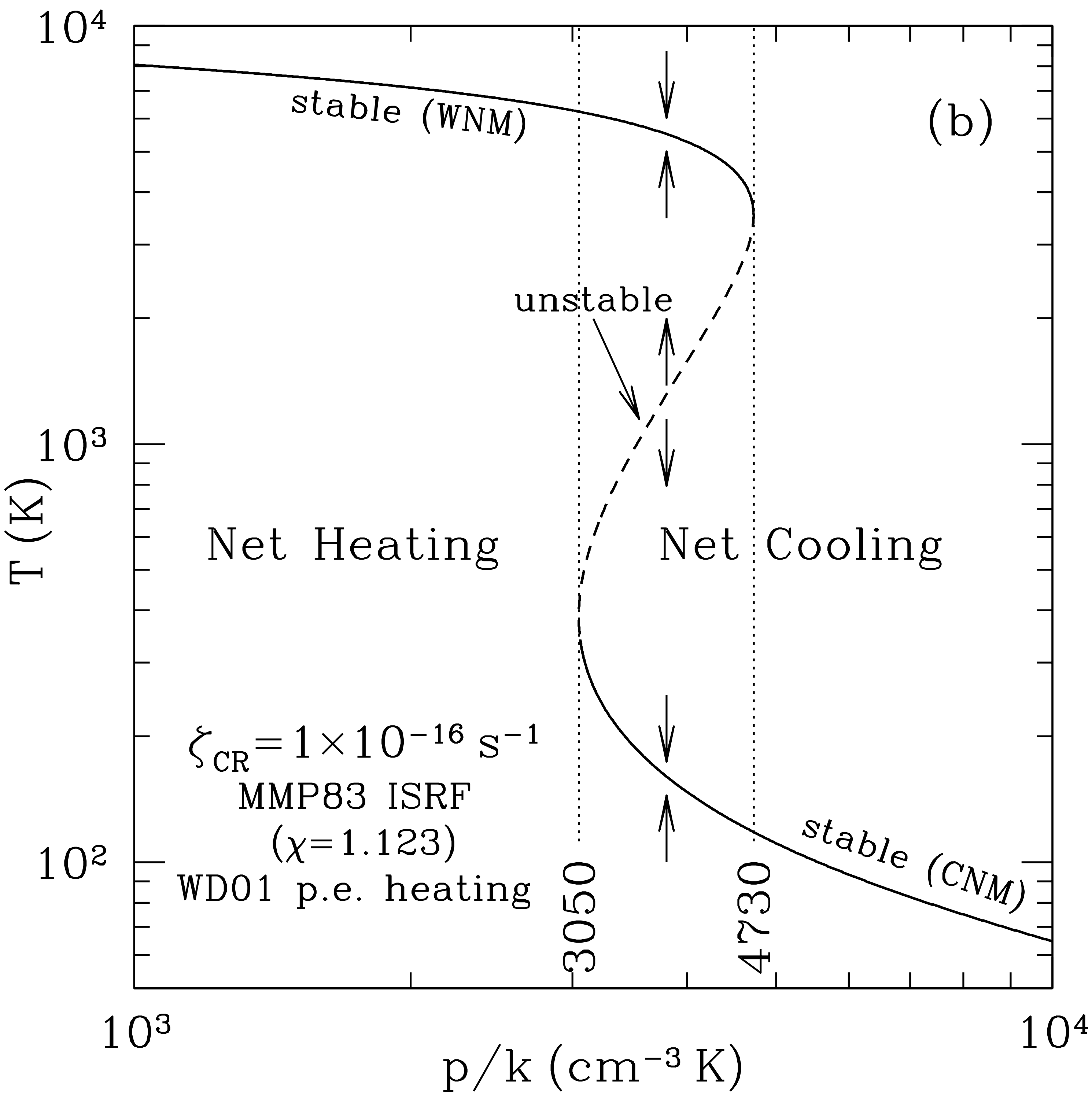
Global ISM Models

- FGH 1969 - Thermal Instability 2 phase model
- McKee & Ostriker 1977 - SNe regulated 3 phase model
- Hydrostatic Balance models - Ostriker, McKee & Leroy 2010
- Simulations of SNe regulated ISM

FGH 1969 Thermal Instability



Not a full ISM model, predicts existence of two phases in thermal equil. given heating and cooling rates and average ISM pressure.

Observational prediction: CNM/WNM n,T, & filling factors

Issues:
why is P what it is?

MO 1977 SNe Driven 3 Phase

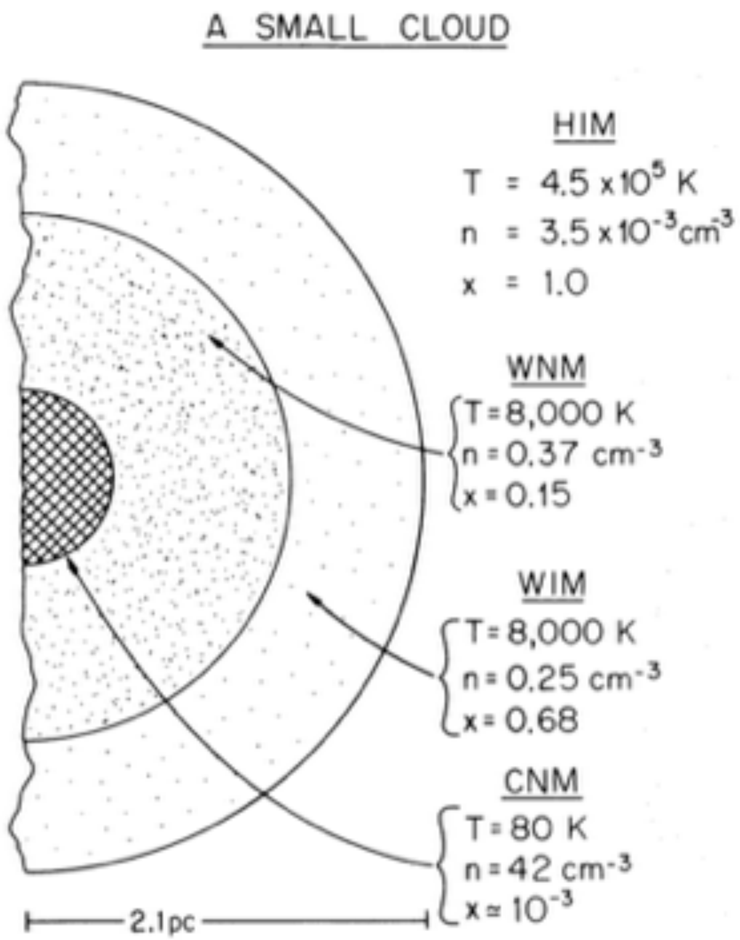


FIG. 1

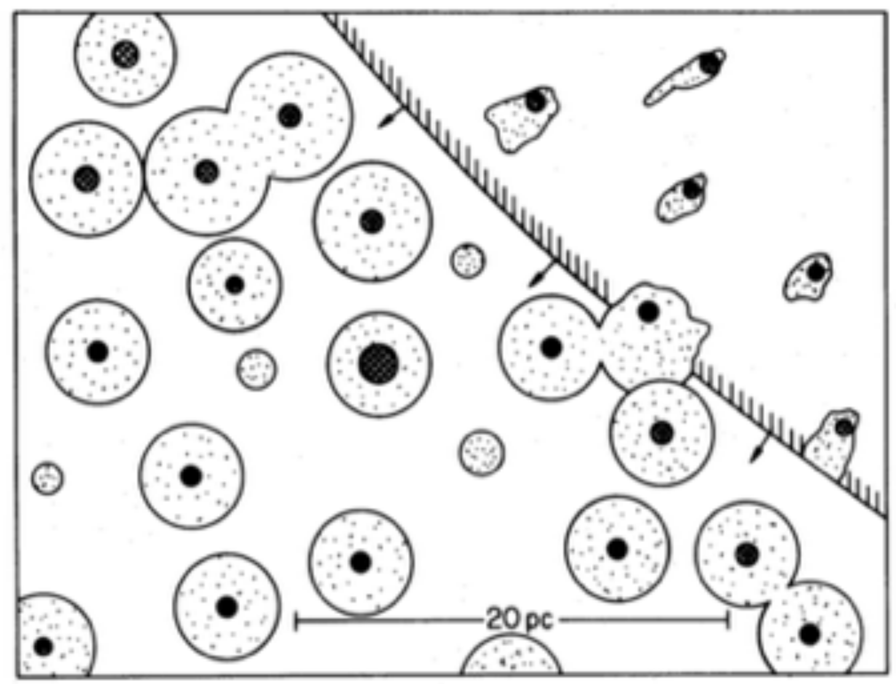


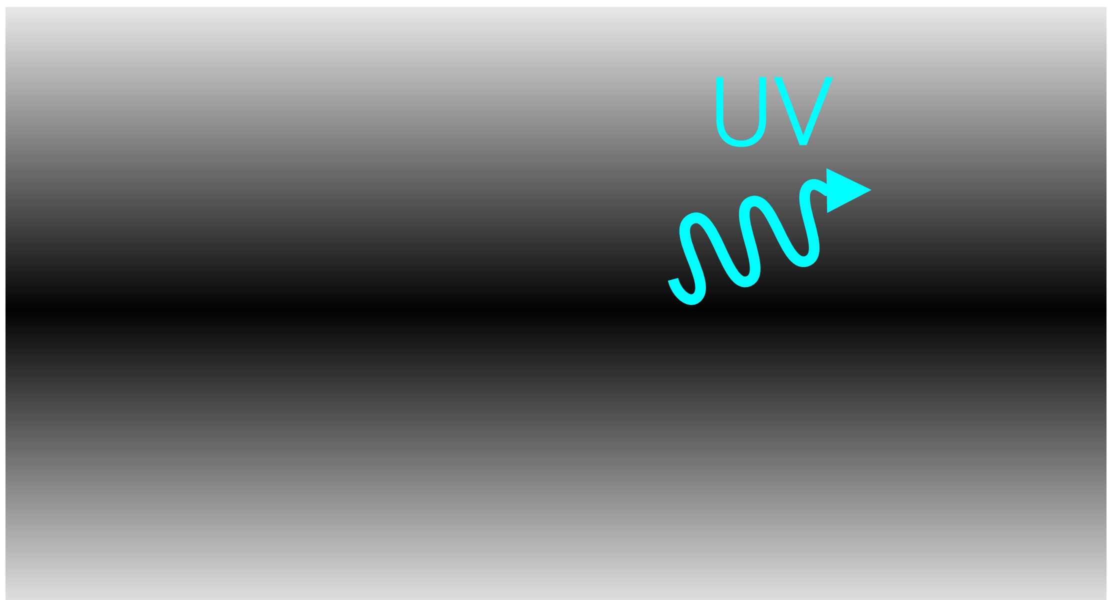
FIG. 2

SNe rate, ISM density structure, cloud evaporation combine to set radius (& therefore pressure) at which SN remnants overlap.

Observational prediction: filling factors of hot ionized gas, CNM/WNM, ISM pressure

Issues:
WNM fraction lower than observed, how does SNR pressure balance relate to hydrostatic pressure? clustered vs random SNe?

Hydrostatic Balance OML 2010



In equlibrium:

heating from UV

$\Gamma_{diffuse} \propto SFR \propto M_{self\text{-}grav}$

balances:

cooling from far-IR lines

$\Lambda_{diffuse} \propto n \propto P_{diffuse} \propto \Sigma$

Observational prediction: relationship between Σ_{tot}, $\Sigma_{self\text{-}grav}$, $\Sigma_{diffuse}$

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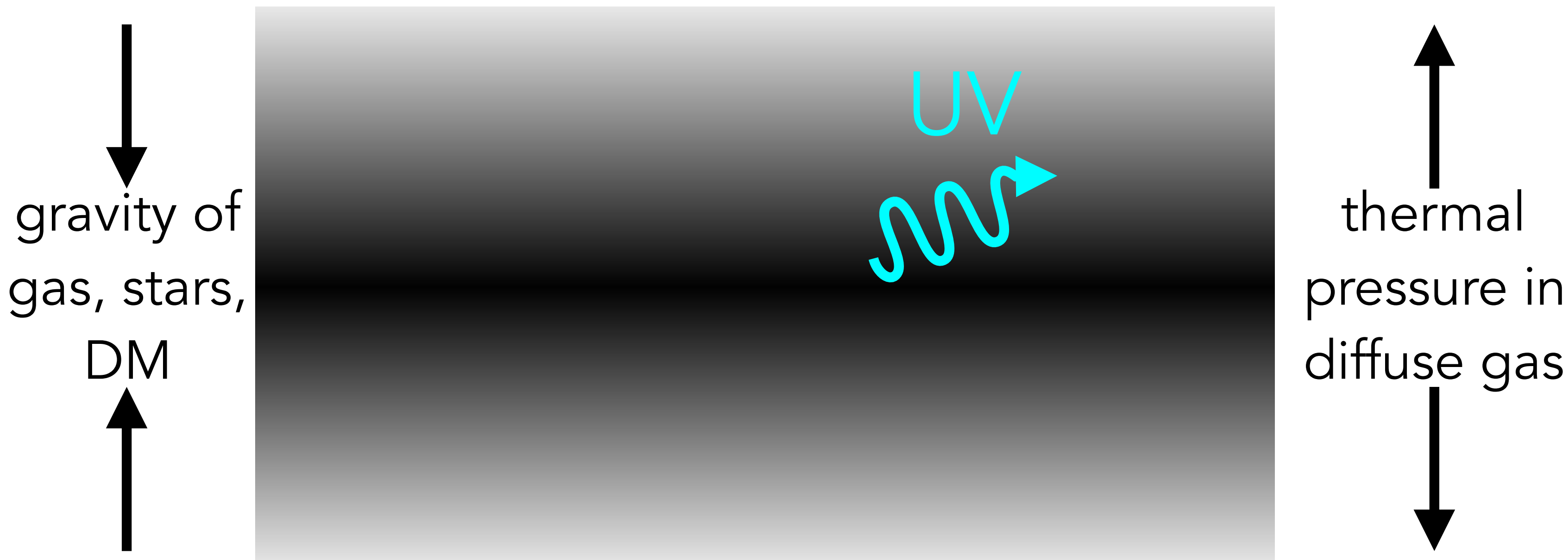

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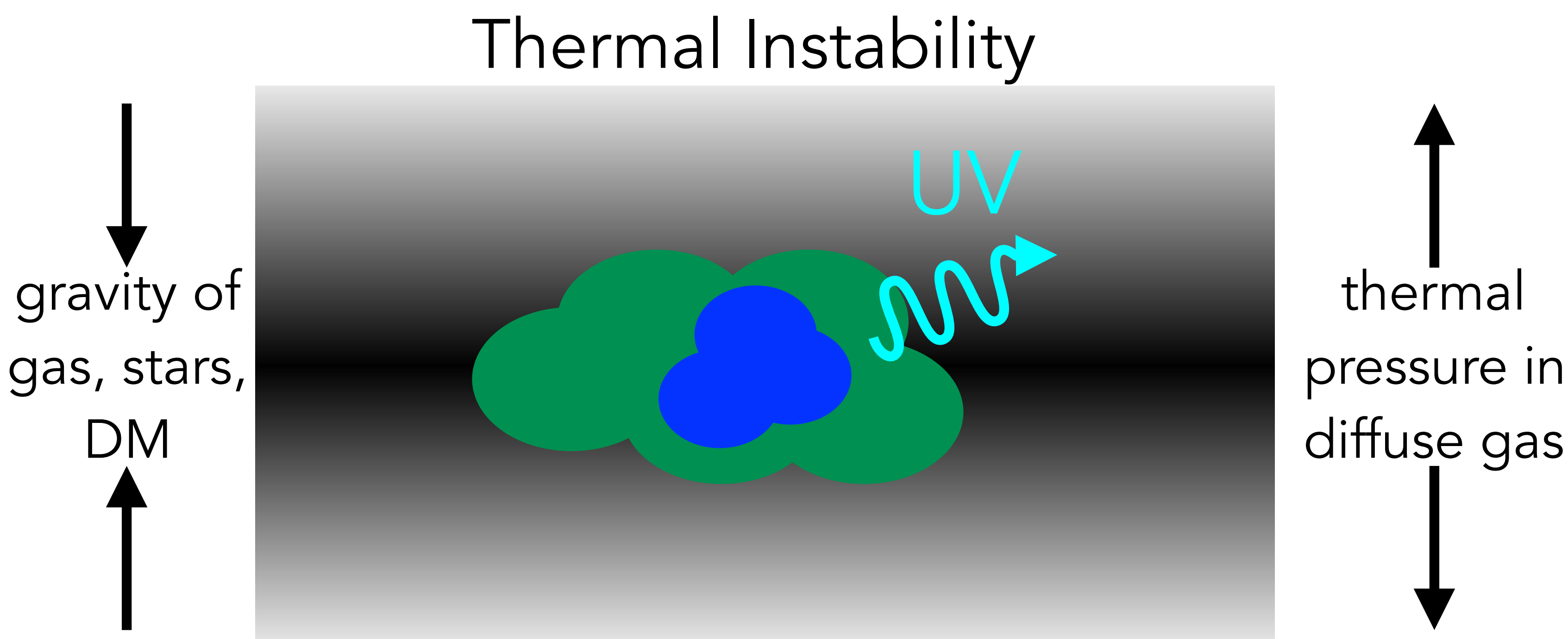

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balances:

cooling from far-IR lines

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Observational prediction: relationship between $\Sigma_{\rm tot}$, $\Sigma_{\rm self\text{-}grav}$, $\Sigma_{\rm diffuse}$

Issues:

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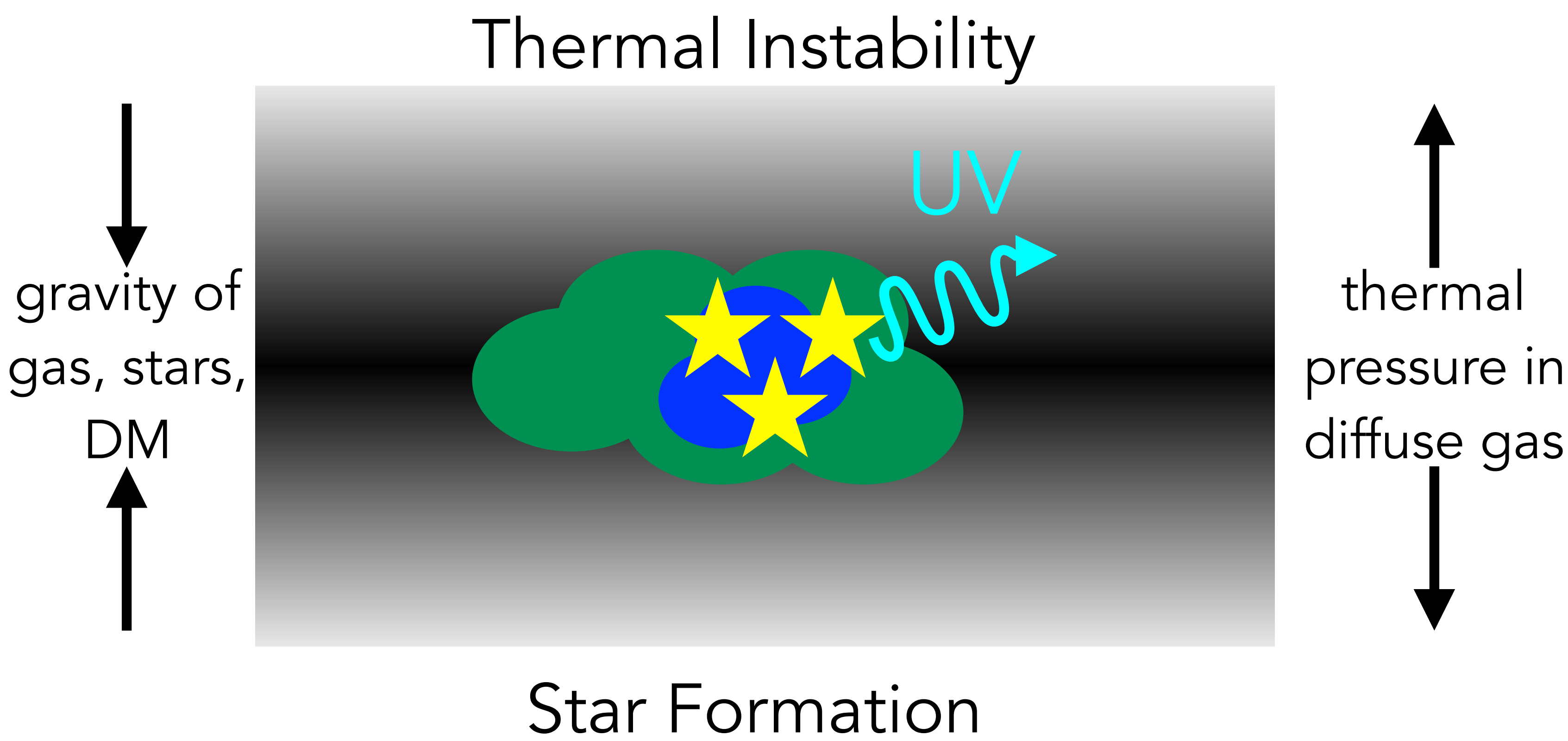
Hydrostatic Balance OML 2010



In equlibrium:

heating from UV

$\Gamma_{\text{diffuse}} \propto \text{SFR} \propto M_{\text{self-grav}}$

balances:

cooling from far-IR lines

$\Lambda_{\text{diffuse}} \propto n \propto P_{\text{diffuse}} \propto \Sigma$

Observational prediction: relationship between Σ_{tot}, $\Sigma_{\text{self-grav}}$, Σ_{diffuse}

Issues:

WNM fraction lower than observed, how does SNR pressure balance relate to hydrostatic pressure? clustered vs random SNe?

Global ISM Models

Test models with observables:

Easier:

Stellar mass surface density

Gas mass surface density

Star formation rate

Dust mass surface density (& dust-to-gas ratio)

Mass spectrum of molecular clouds

Metallicity

Gas "phase" (CNM/WNM, H_2 fraction)

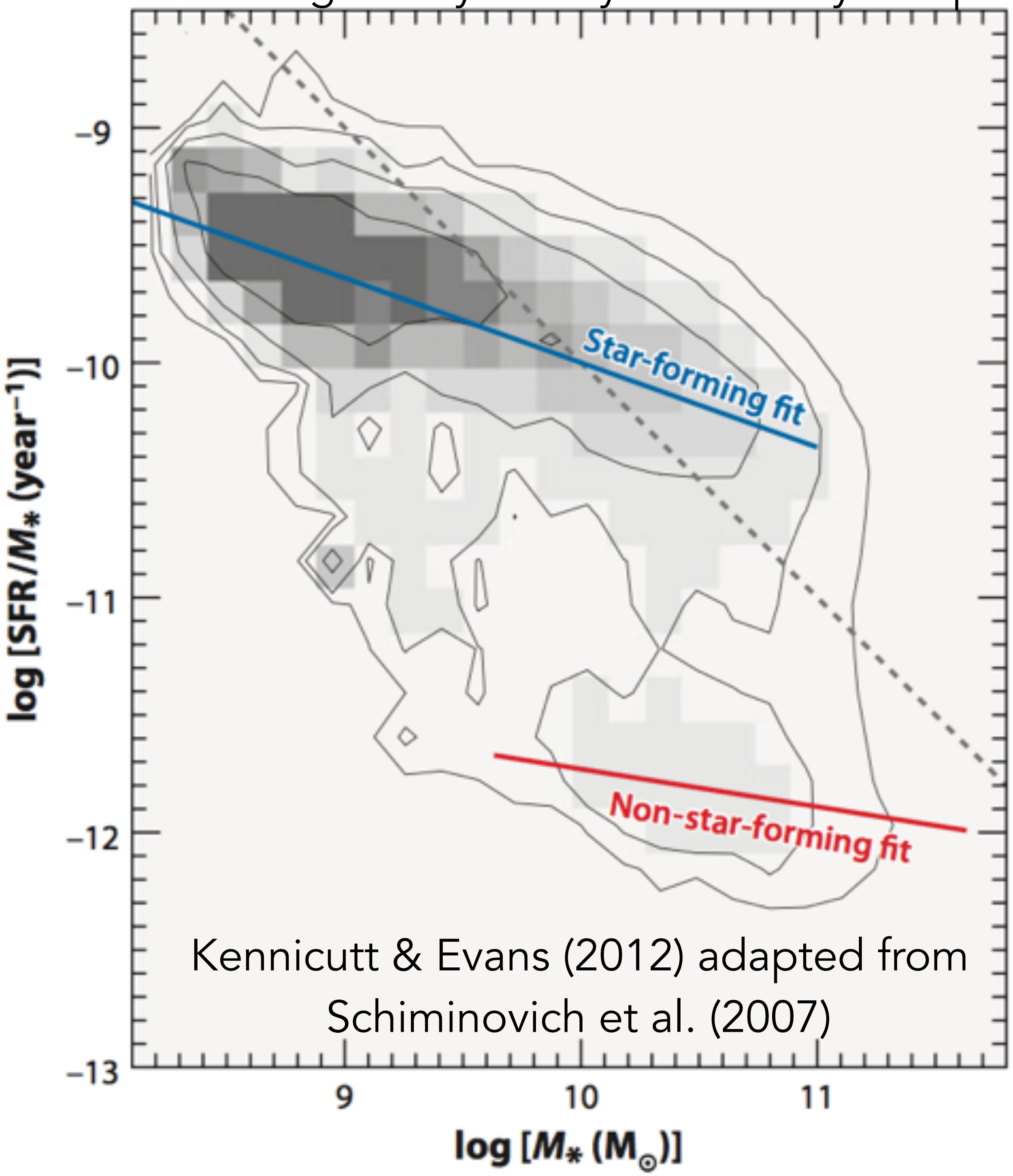
Harder:

B-field strength

Cosmic ray flux

Moving beyond the Milky Way

Sloan Digital Sky Survey z~0 Galaxy Sample



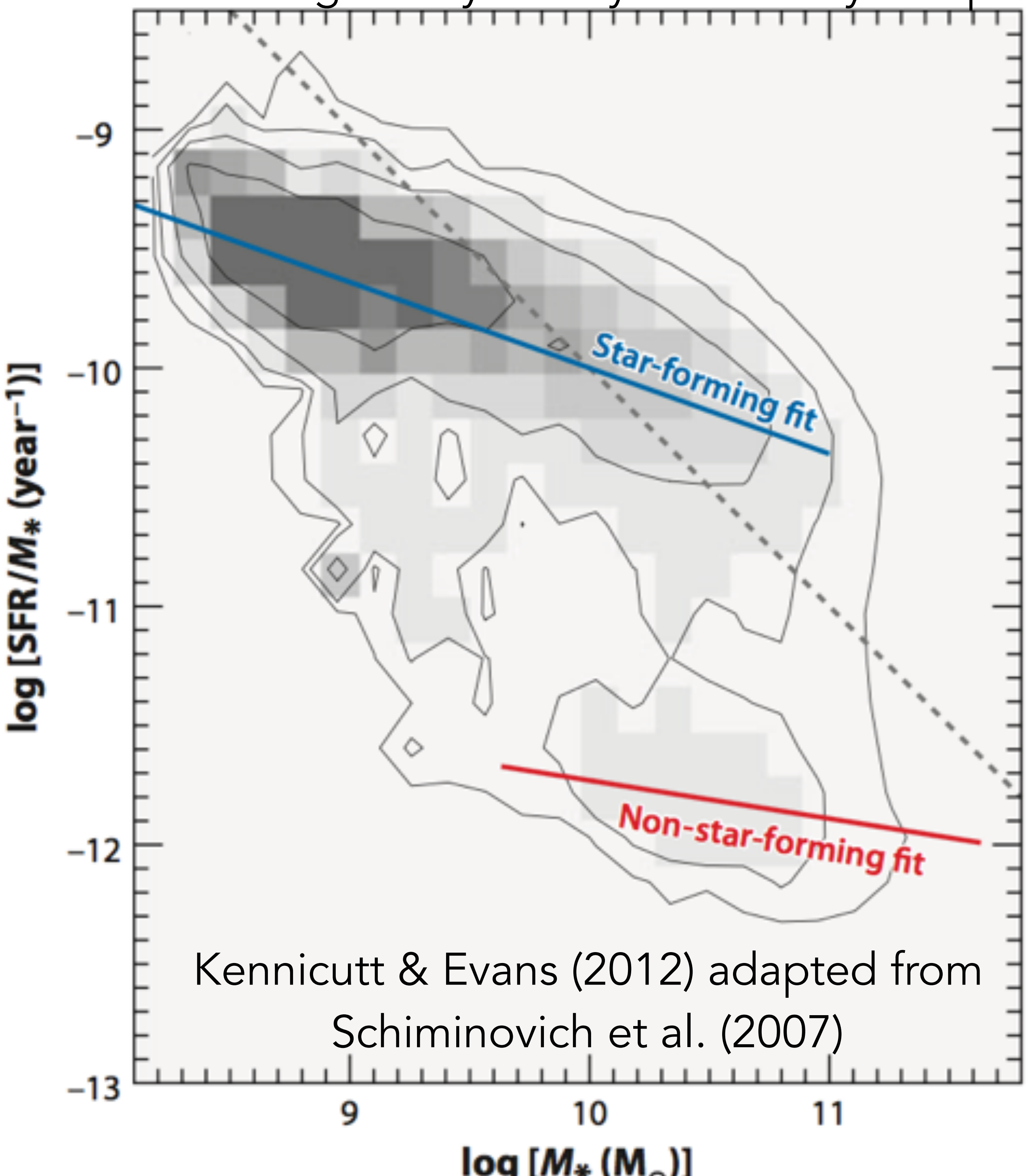
Kennicutt & Evans (2012) adapted from Schiminovich et al. (2007)

A variety of models reproduce the basic properties of the MW's ISM.

To test models need to see if they also work in conditions different from the MW, i.e. local galaxies.

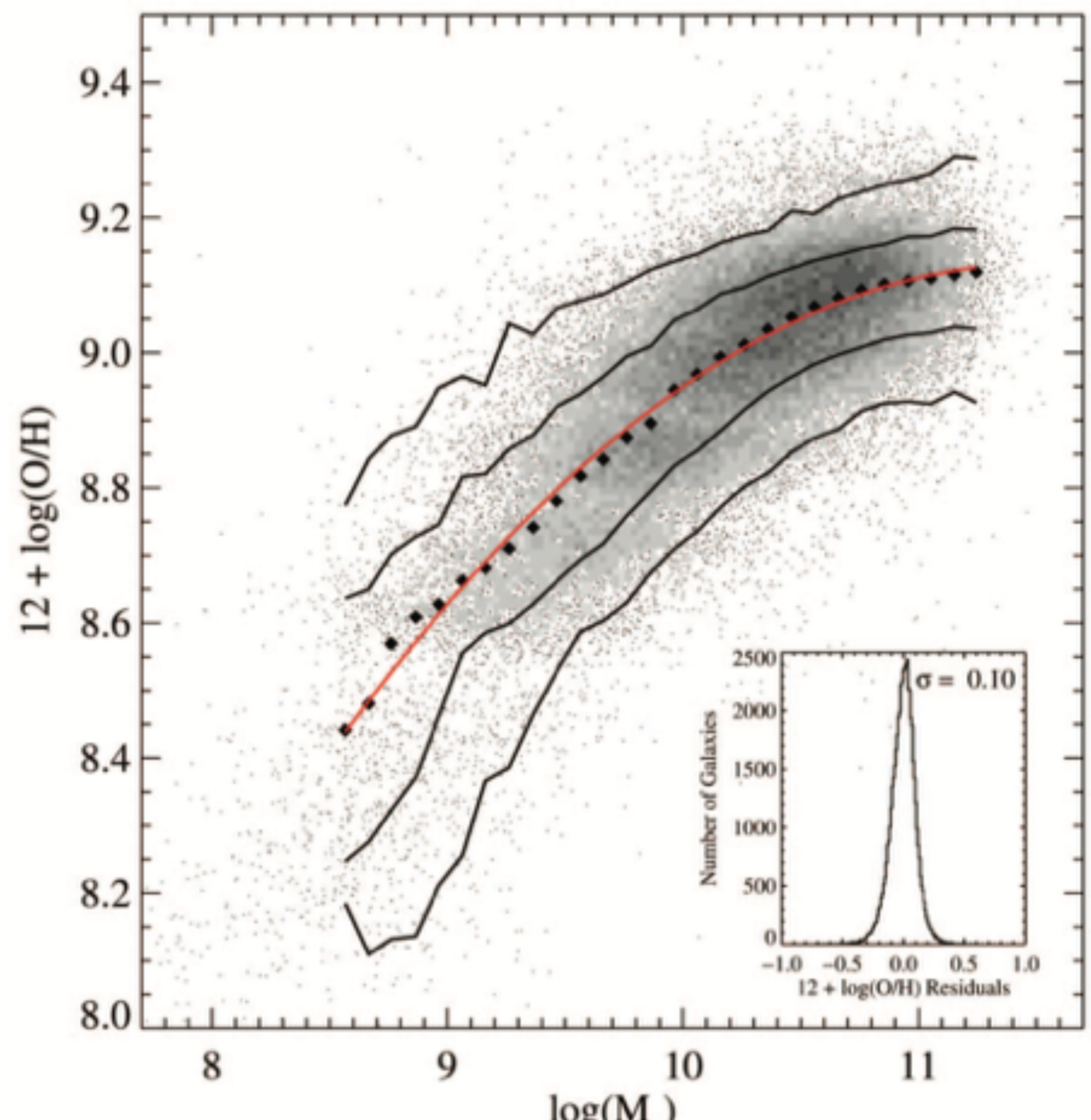
Moving beyond the Milky Way

Sloan Digital Sky Survey z~0 Galaxy Sample

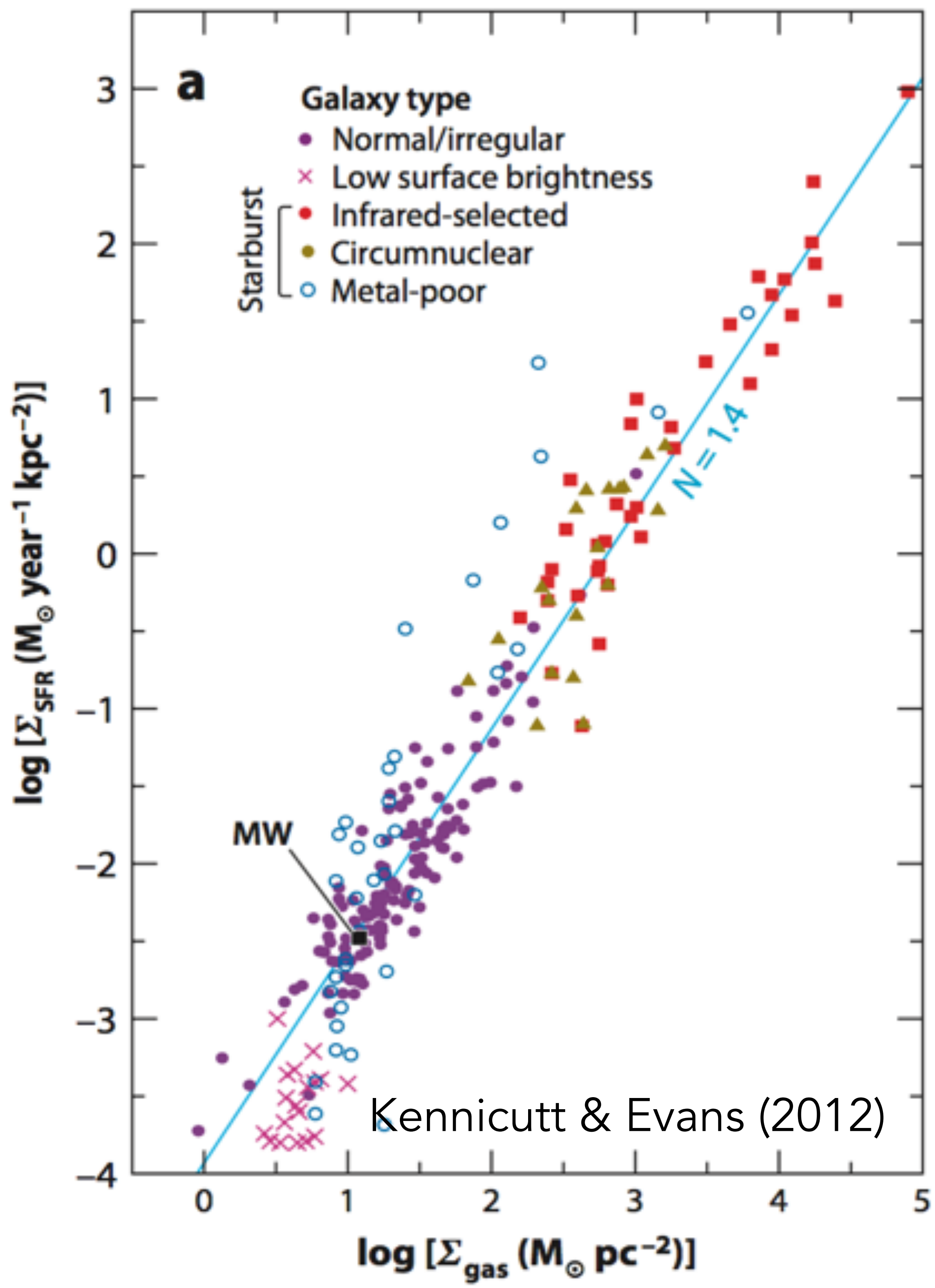


Kennicutt & Evans (2012) adapted from Schiminovich et al. (2007)

Tremonti et al. (2004)



Moving beyond the Milky Way

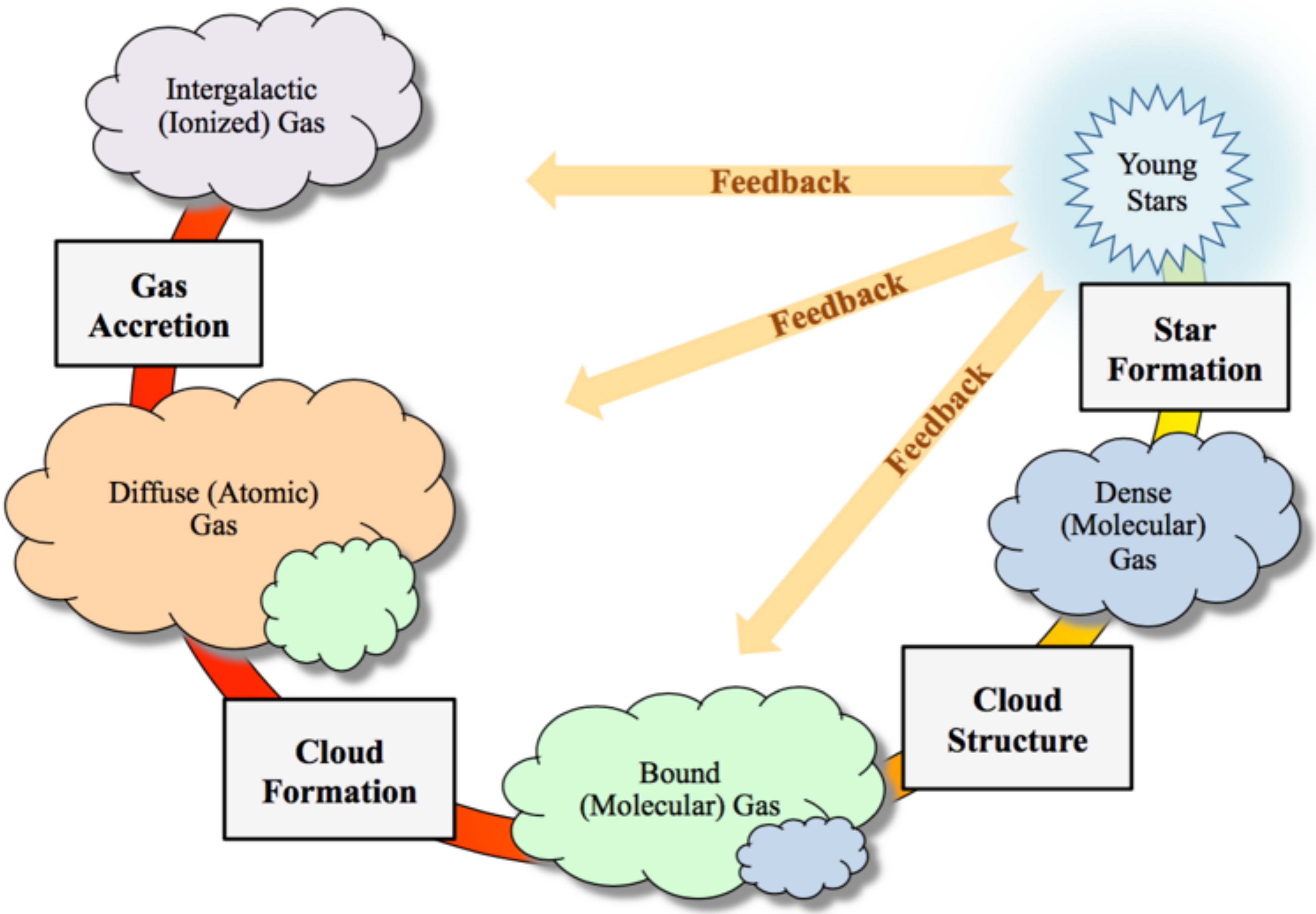


Beyond the MW, don't have access to the same detailed measurements. Key observations include "scaling relations" that show how gas, SFR, stars, dust are related.

The Schmidt-Kennicutt relation is a key scaling connecting galaxy averaged SF surface density and total gas surface density.

Schmidt (1959), Kennicutt (1989, 1998)

Moving beyond the Milky Way



slide from Adam Leroy

Moving beyond the Milky Way

On kiloparsec scales, KS relation shows SF associated with H_2 and a variety of HI-to-H_2 ratios

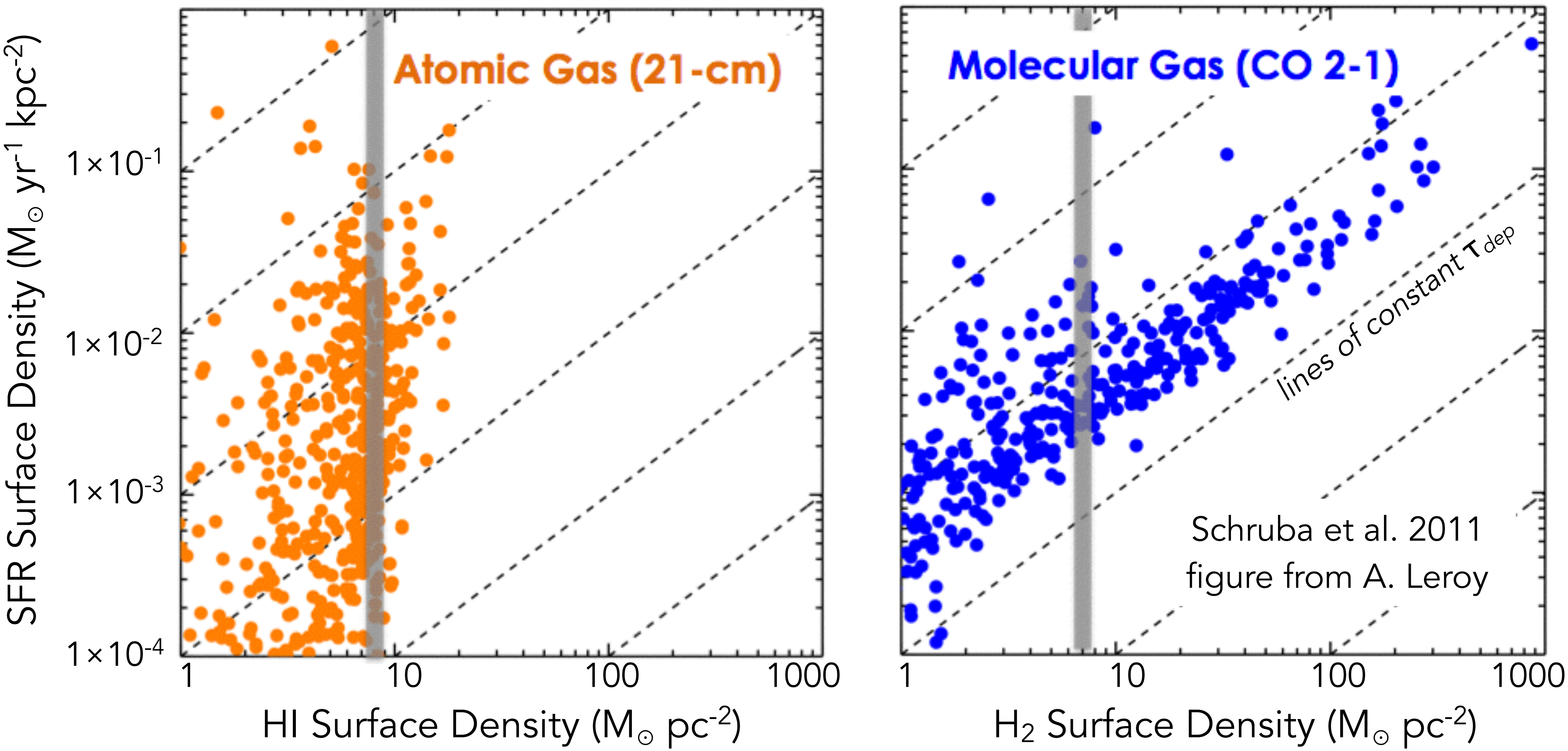
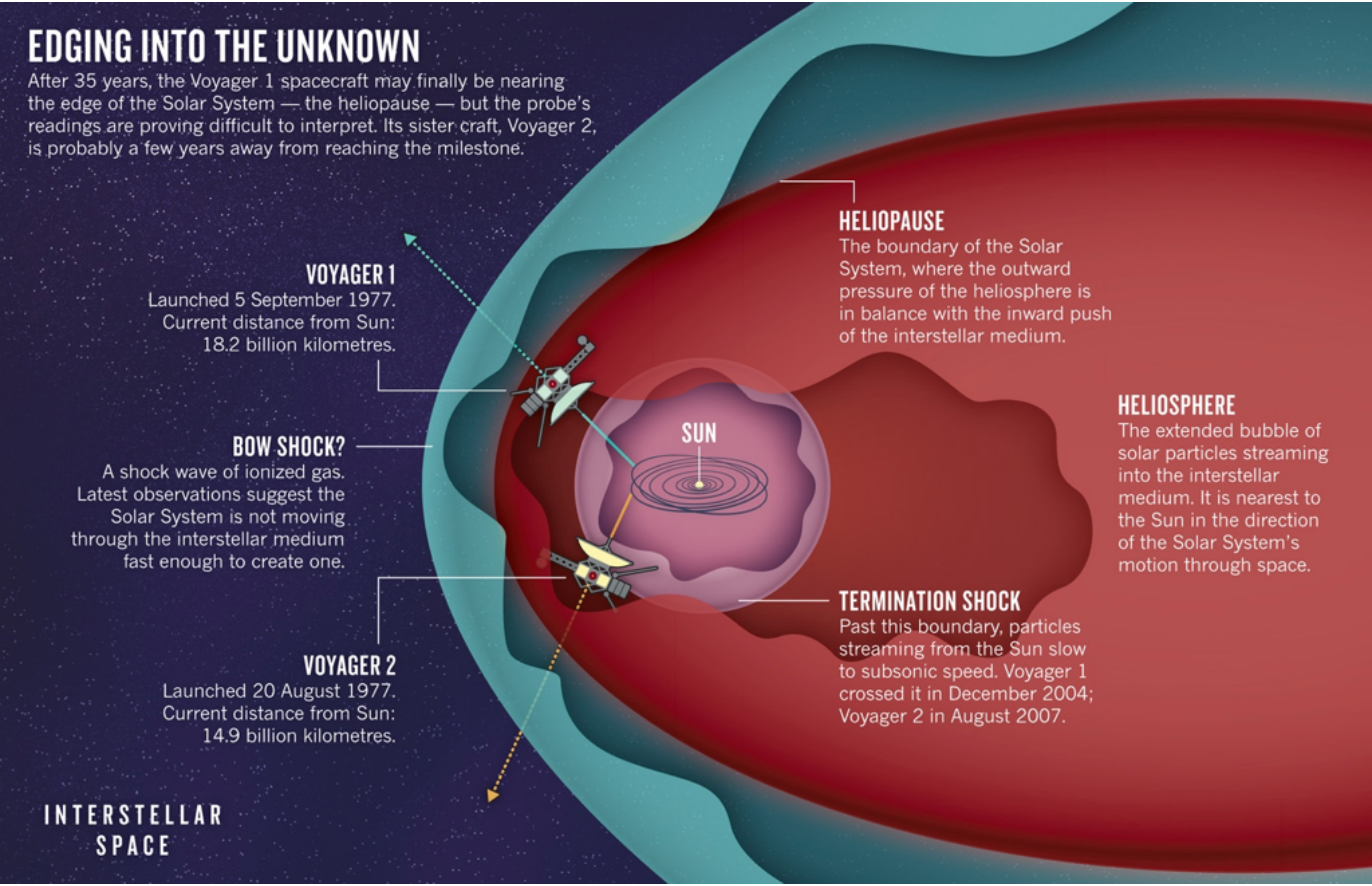
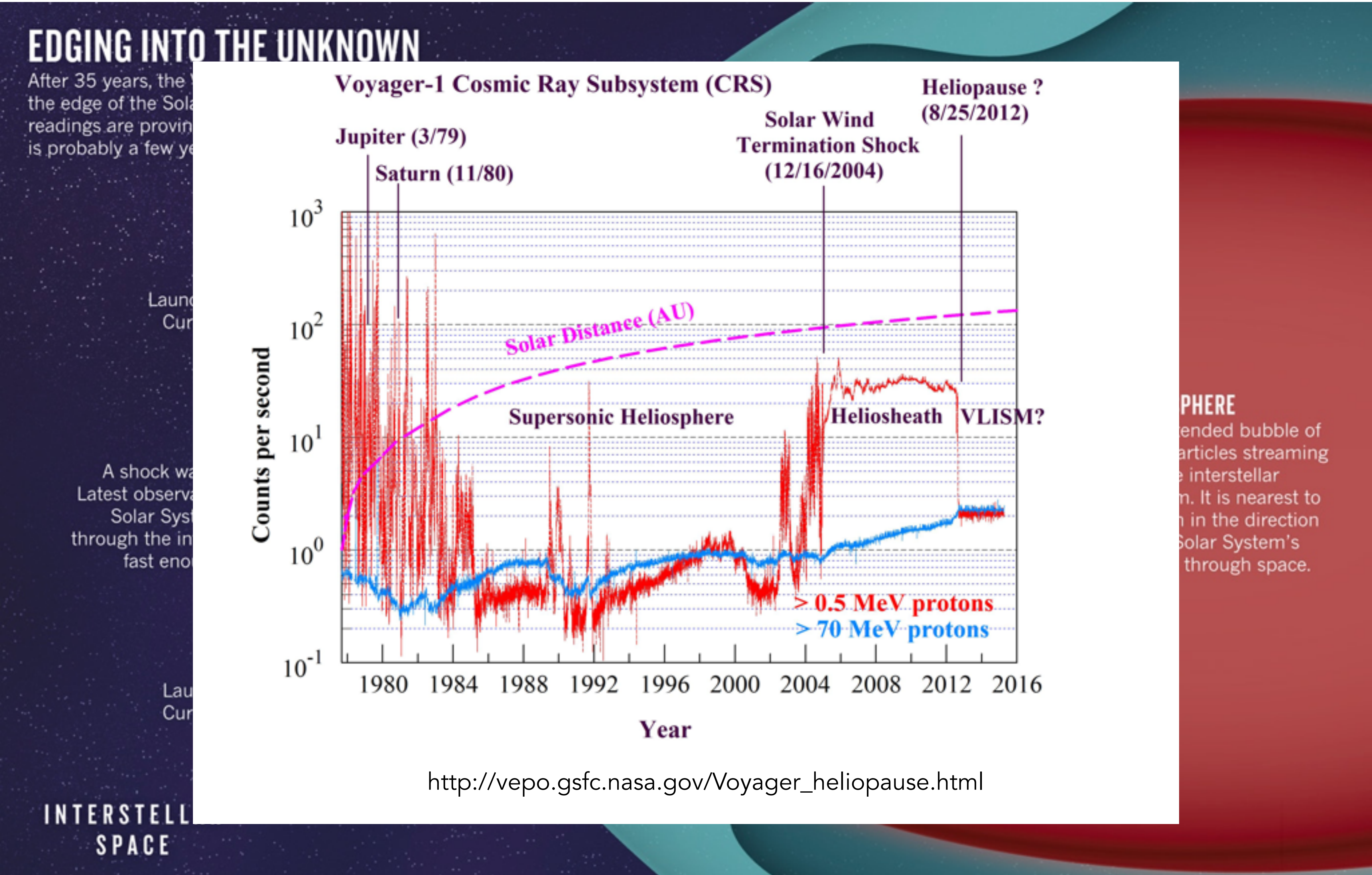


Image from:
https://public.nrao.edu/AlmaExtras/



Cowen, *Nature*, 2012



http://vepo.gsfc.nasa.gov/Voyager_heliopause.html

Cowen, *Nature*, 2012