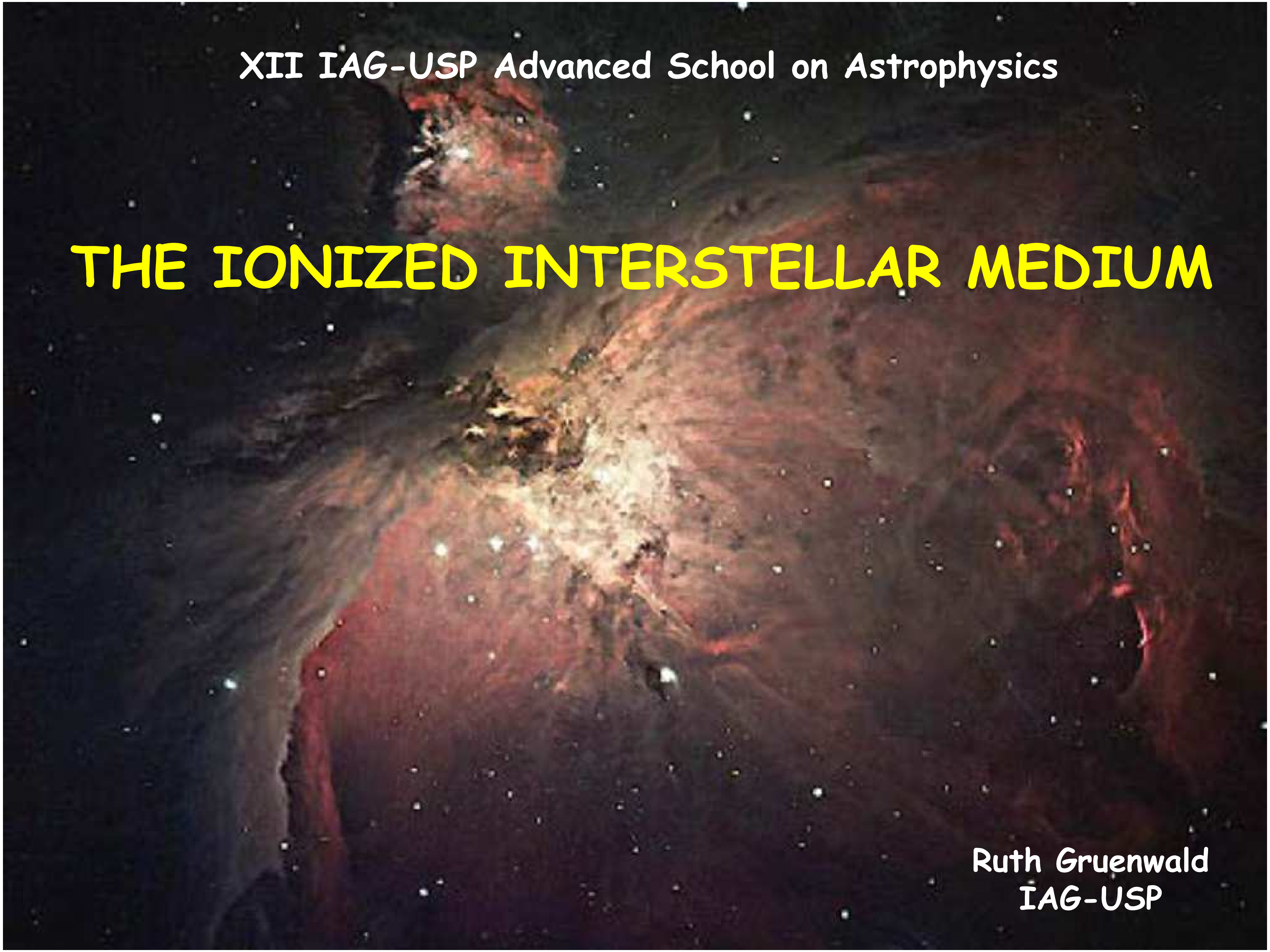
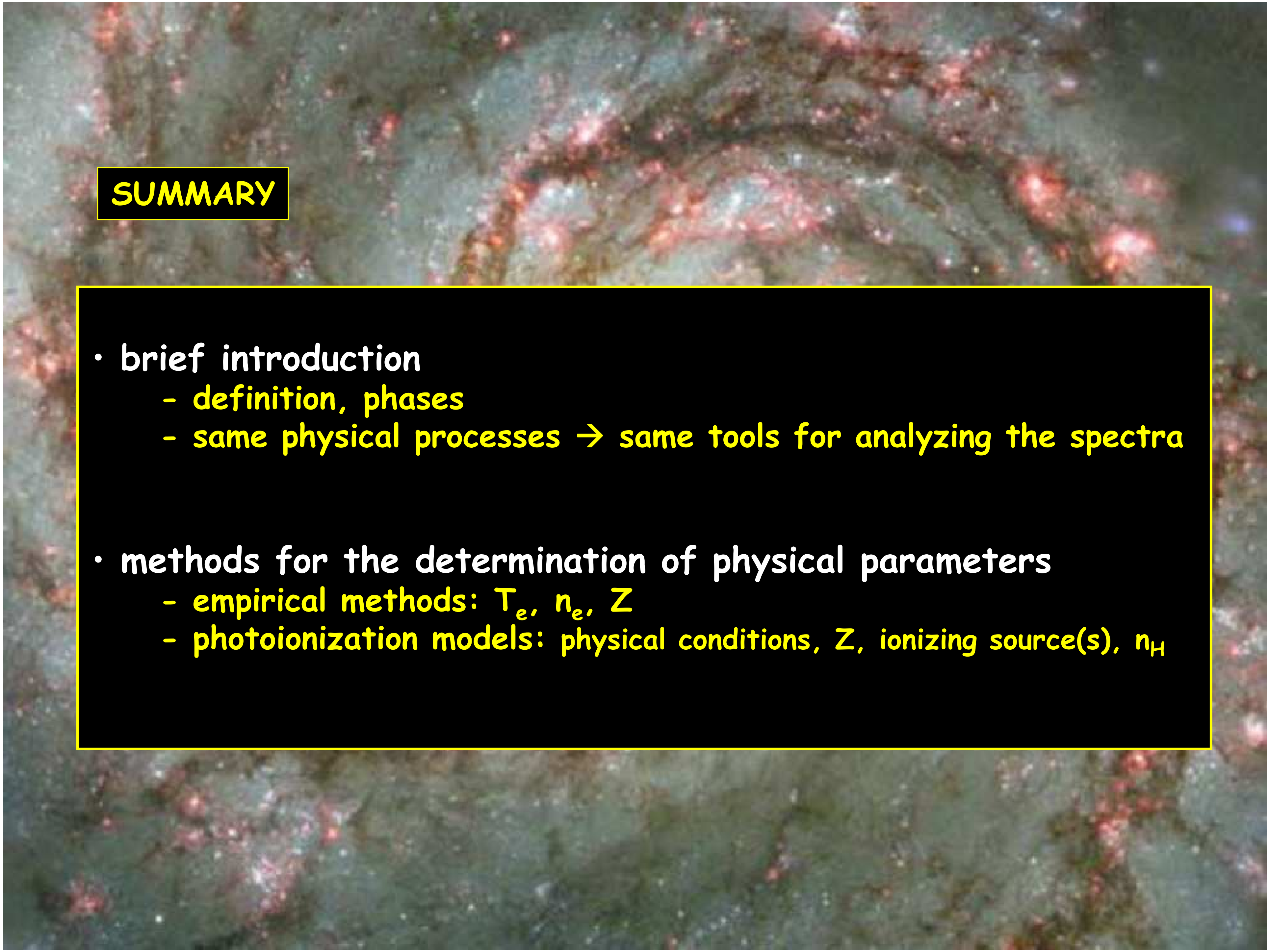
XII IAG-USP Advanced School on Astrophysics

THE IONIZED INTERSTELLAR MEDIUM



Ruth Gruenwald
IAG-USP



SUMMARY

- brief introduction
  - definition, phases
  - same physical processes → same tools for analyzing the spectra
- methods for the determination of physical parameters
  - empirical methods: T_e, n_e, Z
  - photoionization models: physical conditions, Z, ionizing source(s), n_H

definition: "*ionized* medium"

- H is the most abundant element → *ionized* medium ≡ presence of H^+
- H ionization potential = 13.6 eV

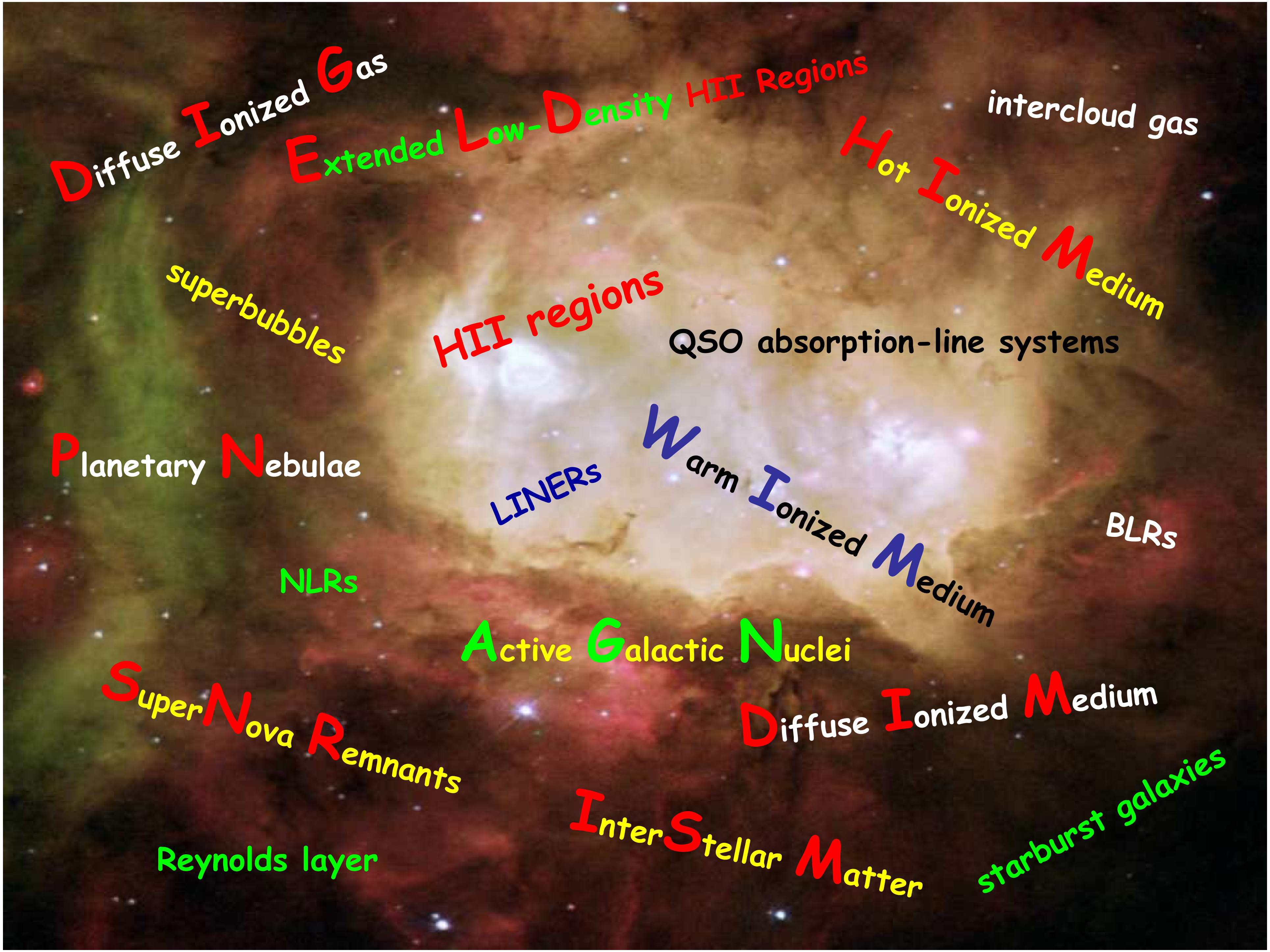
∴ if H^+ ions are present,

- incident radiation with E > 13.6 eV
  and/or
- energetic ionizing particles
  and/or
- winds, shock waves, …

} in most ionized regions the gas is mainly *photoionized*

(cosmic rays can ionize H at the borders of neutral clouds)

- Ionized Interstellar Medium can be found in different phases
  - ≠ gas densities: ~0.01 → $10^{9...}$ cm^{-3}
  - ≠ ionizing/heating sources: star(s), power-law spectrum, shocks, …
  - ≠ gas temperatures: ~500 → $10^{6-7...}$ K
  - ≠ ionization degrees: H^+/H = >0 → 1
  - ≠ sizes: < 1pc → galactic



Diffuse Ionized Gas

Extended Low-Density HII Regions

intercloud gas

Hot Ionized Medium

superbubbles

HII regions

QSO absorption-line systems

Planetary Nebulae

LINERs

Warm Ionized Medium

BLRs

NLRs

Active Galactic Nuclei

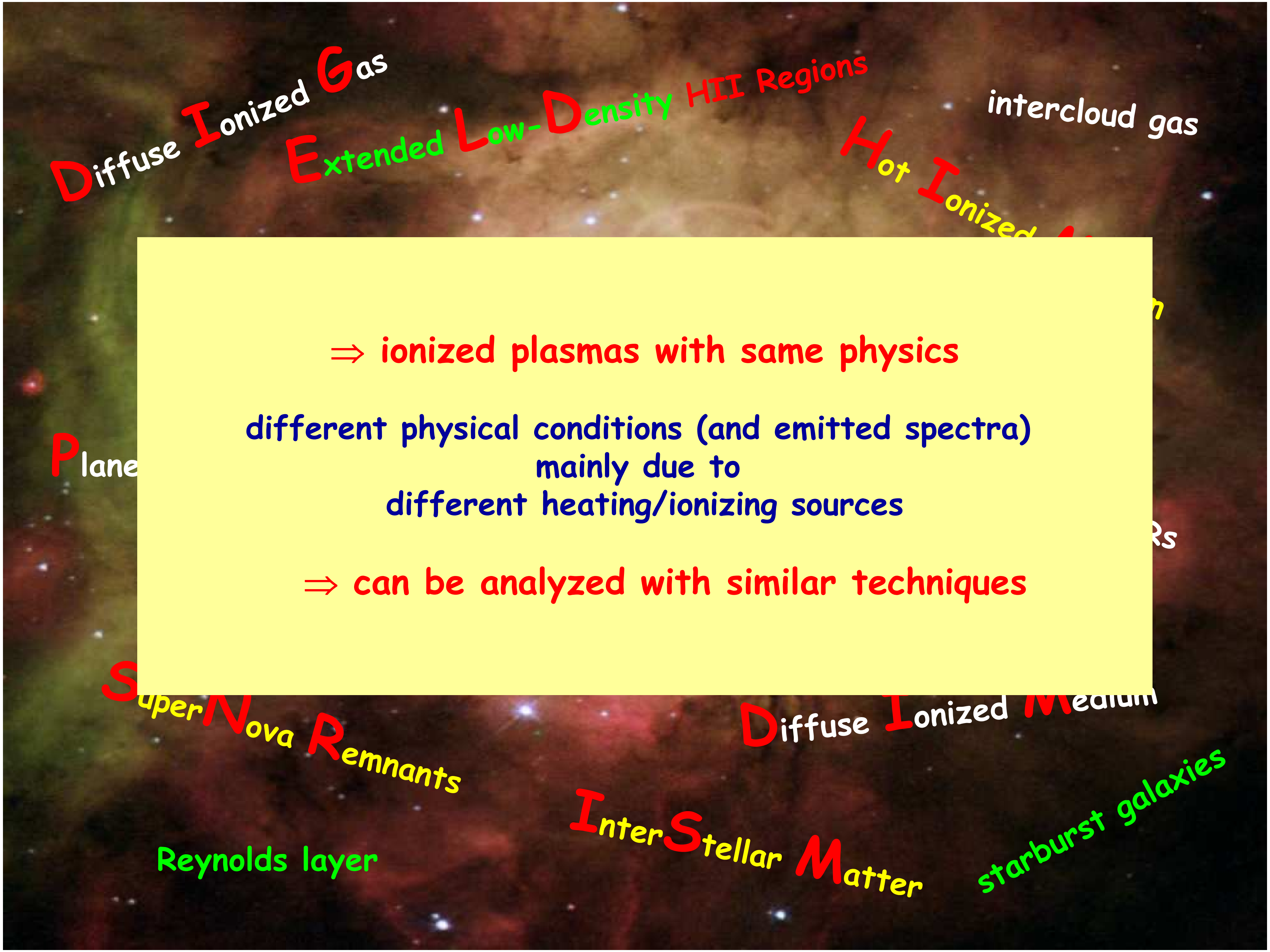
SuperNova Remnants

Diffuse Ionized Medium

InterStellar Matter

starburst galaxies

Reynolds layer



Diffuse Ionized Gas

Extended Low-Density HII Regions

intercloud gas

Hot Ionized M

n

Plane

Rs

$\Rightarrow$ ionized plasmas with same physics

different physical conditions (and emitted spectra)
mainly due to
different heating/ionizing sources

$\Rightarrow$ can be analyzed with similar techniques

SuperNova Remnants

Diffuse Ionized Medium

Reynolds layer

InterStellar Matter

starburst galaxies

→ the ionized interstellar gas produces

- continuum emission
- emission-line spectrum
- can present absorption lines when observed against continuum sources

→ the details of the spectrum are determined by the physical conditions of the emitting gas

⇓

→ observed line (and continuum) intensities can be used as probes of the excitation conditions of the gas, providing robust information on:

- properties of the ionizing/heating source(s)
- gas density (distribution)
- chemical composition
- gas temperature

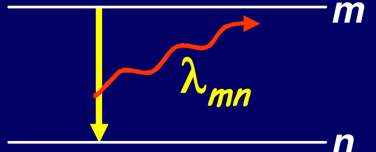
→ many of these regions are also useful laboratories for atomic physics

→ LTE relations (Boltzmann, Saha) do not apply at these densities

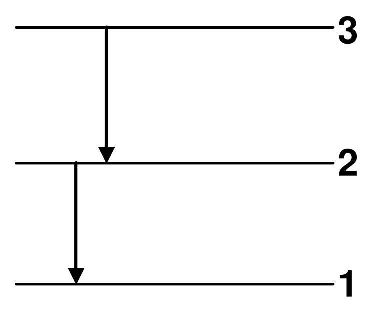
empirical methods – I. The gas temperature

⇒ forbidden line intensities

$$L_{\lambda_{mn}} = n_m(X^i)\,A_{mn}\,E_{mn}\,V = n(X^i)\,n_e\,\varepsilon_{\lambda_{mn}}(T_e,n_e)\,V$$

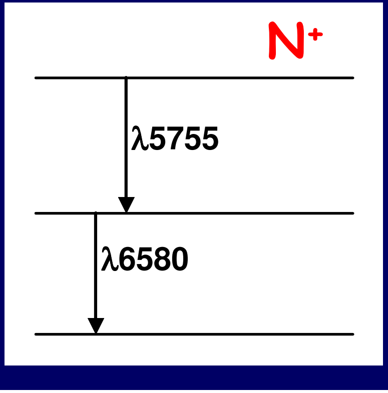


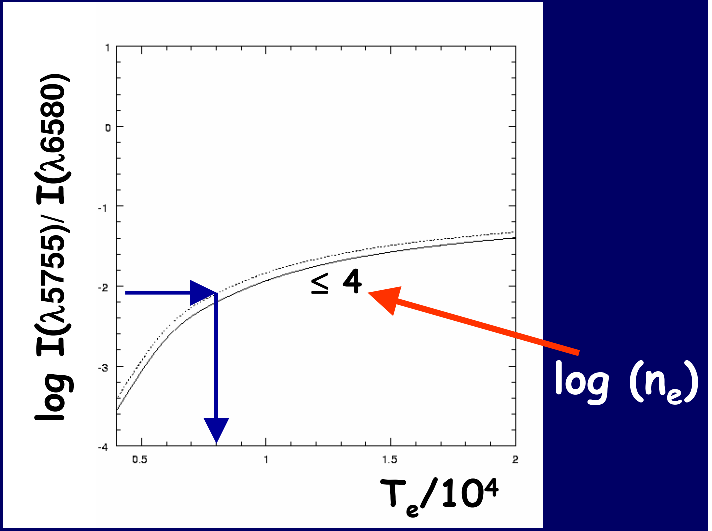
- lines from 2 ≠ upper levels with very ≠ E_{exc} → line intensity ratio = $f(T_e)$



$$\underbrace{\frac{I_{\lambda_{32}}}{I_{\lambda_{21}}}}_{\text{observed}} = \underbrace{\frac{\varepsilon_{\lambda_{32}}(T_e,n_e)}{\varepsilon_{\lambda_{21}}(T_e,n_e)} = f(T_e,n_e)}_{\text{obtained from the statistical equilibrium of the energy levels}} \sim f(T_e) \longrightarrow \boxed{T_e}$$

exs.: [OIII]λ4363/5000
[NII] λ5755/6580
[SIII]λ6312/9532
.
.

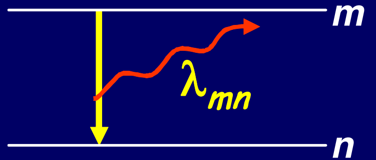




empirical methods - I. The gas temperature

⇒ forbidden line intensities

$$L_{\lambda_{mn}} = n_m(X^i)\, A_{mn}\, E_{mn}\, V = n(X^i)\, n_e\, \varepsilon_{\lambda_{mn}}(T_e, n_e)\, V$$



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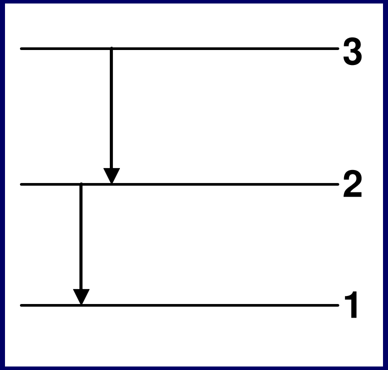

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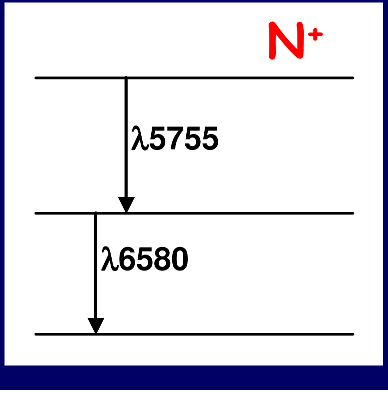
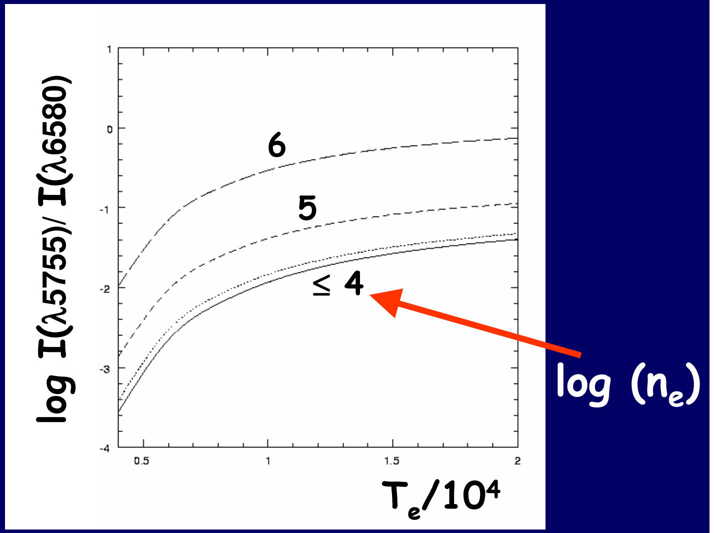




empirical methods – I. The gas temperature

⇒ optical continuum measurements

- recombination continuum/H recombination line = f (T_e)

two choices for the continuum:

$$\frac{I(\lambda 4861)}{I(H\beta)}$$

$$\frac{I_\nu(\lambda 3646^-) - I_\nu(\lambda 3646^+)}{I(H\beta)}$$

Balmer discontinuity

⇒ radio continuum measurements

- at sufficiently low ν, nebulae are optically thick $\Rightarrow I_\nu \sim B_\nu(T_b) \Rightarrow T_b \rightarrow T$

transfer equation
with $\tau_\nu >> 1$

(as shown in L. Rodriguez and M. Elitzur lectures)

⇒ radio recombination lines

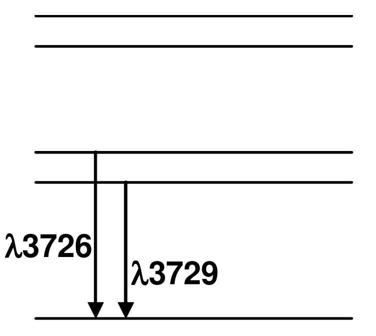
(W. Villas-Boas' lecture)

empirical methods – II. The gas density

⇒ forbidden line intensities

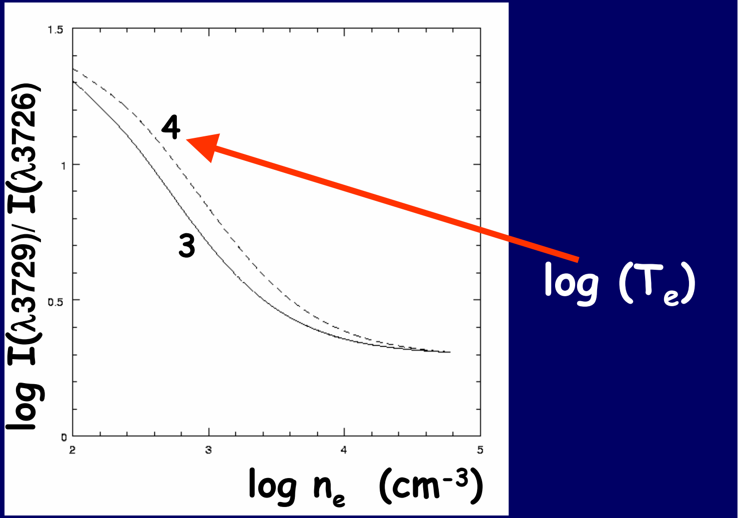
$$L_{\lambda_{mn}} = n(X^i)\, n_e\, \varepsilon_{\lambda_{mn}}(T_e, n_e)\, V$$

- lines from 2 ≠ upper levels with $\underbrace{\sim E_{exc}\ \&\ \neq A_{rad} \text{ or } C_{dexc}}$ → line intensity ratio = f(n_e)



ex.: O^+

$$\underbrace{\frac{I_{\lambda_{31}}}{I_{\lambda_{21}}}}_{\text{observed}} = \frac{\varepsilon_{\lambda_{31}}(T_e,n_e)}{\varepsilon_{\lambda_{21}}(T_e,n_e)} = f(T_e,n_e) \sim f(n_e) \longrightarrow \boxed{n_e}$$



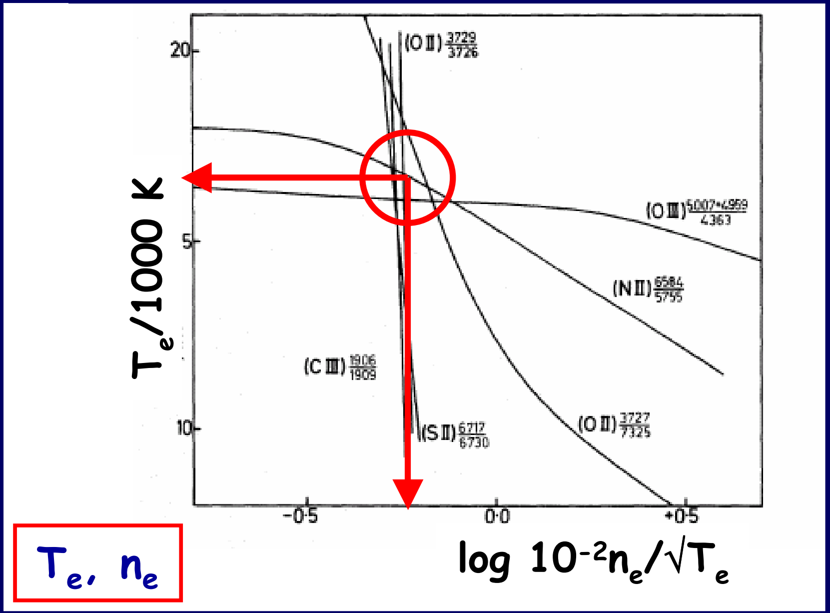
exs.: [OII]λ3729/3926
[SII]λ6716/6731
many IR lines
.
.

⇒ radio recombination lines

(W. Villas-Boas' lecture)

empirical methods - The gas temperature and density

⇒ combining all the information from temperature- and density-sensitive lines ratios for a given nebula



NGC6302 (Aller et al. 81)

lines of a given ion

$$\underbrace{\frac{I_{\lambda_{mn}}}{I_{\lambda_{kl}}}}_{\text{observed}} = \frac{\varepsilon_{\lambda_{mn}}(T_e,n_e)}{\varepsilon_{\lambda_{kl}}(T_e,n_e)} = f(T_e,n_e)$$

empirical methods – III. The gas chemical composition

→ abundance of ions with observed lines

- **collisionally excited line:** $L_{\lambda_{mn}} = n_m(X^i)\, A_{mn}\, E_{mn}\, V = n(X^i)\, n_e \varepsilon_{\lambda_{mn}}(T_e, n_e)\, V$
- **recombination line:** $L_{H\beta} = n(H^+)\, n_e\, \alpha^{eff}_{H\beta}\, V = n(H^+)\, n_e\, \varepsilon_{H\beta}(T_e)\, V$
  (for example, Hβ)

$$\therefore \quad \frac{n(X^i)}{n(H^+)} = \frac{I_{\lambda_{mn}}}{I_{H\beta}} \frac{\varepsilon_{H\beta}(T_e)}{\varepsilon_{\lambda_{mn}}(T_e, n_e)} = \underbrace{\frac{I_{\lambda_{mn}}}{I_{H\beta}}}_{\text{observed}} \times f(T_e, n_e) \quad \rightarrow \quad \boxed{\frac{n(X^i)}{n(H^+)} \quad \left(\equiv \frac{X^i}{H^+} \right)}$$

from the methods
previously discussed

empirical methods - III. The gas chemical composition

$$\frac{X}{H} \sim \frac{X^{o}}{H^{+}} + \frac{X^{+}}{H^{+}} + \frac{X^{++}}{H^{+}} + \ldots$$

- ions with observed lines → $$\frac{X^{i}}{H^{+}} = \frac{I_{\lambda_{mn}}}{I_{H\beta}} \times f(T_e, n_e)$$

- ions with no observed lines → ionization correction factors (icf)

(based on the similarity of the ionization potentials)

⇒ elemental abundances:

$$\frac{He}{H} = \frac{He^{o} + He^{+} + He^{++}}{H^{o} + H^{+}} \sim \frac{He^{+} + He^{++}}{H^{+}}$$

$$\frac{O}{H} \sim \frac{O^{o} + O^{+} + O^{++} + \ldots}{H^{+}} = icf(O) \times \frac{O^{+} + O^{++}}{H^{+}}$$

$$icf(O) \sim \frac{He^{+} + He^{++}}{He^{+}}$$

$$\frac{N}{H} \sim \frac{N^{o} + N^{+} + N^{++} + \ldots}{H^{+}} = icf(N) \times \frac{N^{+}}{H^{+}}$$

$$icf(N) = icf(O)\left(1 + \frac{O^{++}}{O^{+}}\right)$$

etc.

statistical methods for the gas chemical composition (strong line method)

→ to derive metallicities in giant extragalactic HII regions
when the electron temperature cannot be determined
([OIII]λ4363 too weak)

→ based on calibrations from
- HII regions determinations
  and
- theoretical models

for example, $R_{23} = \frac{[OII]\lambda 3727 + [OIII]\lambda 5007}{H\beta} \leftrightarrow \frac{O}{H}$

Pagel et al. (1979) + improvements

(also O_{32}, S_{23}, N_2, …)

However …

- ≠ methods for estimating the gas temperature provide ≠ values for T_e
  → nebulae are not isothermal

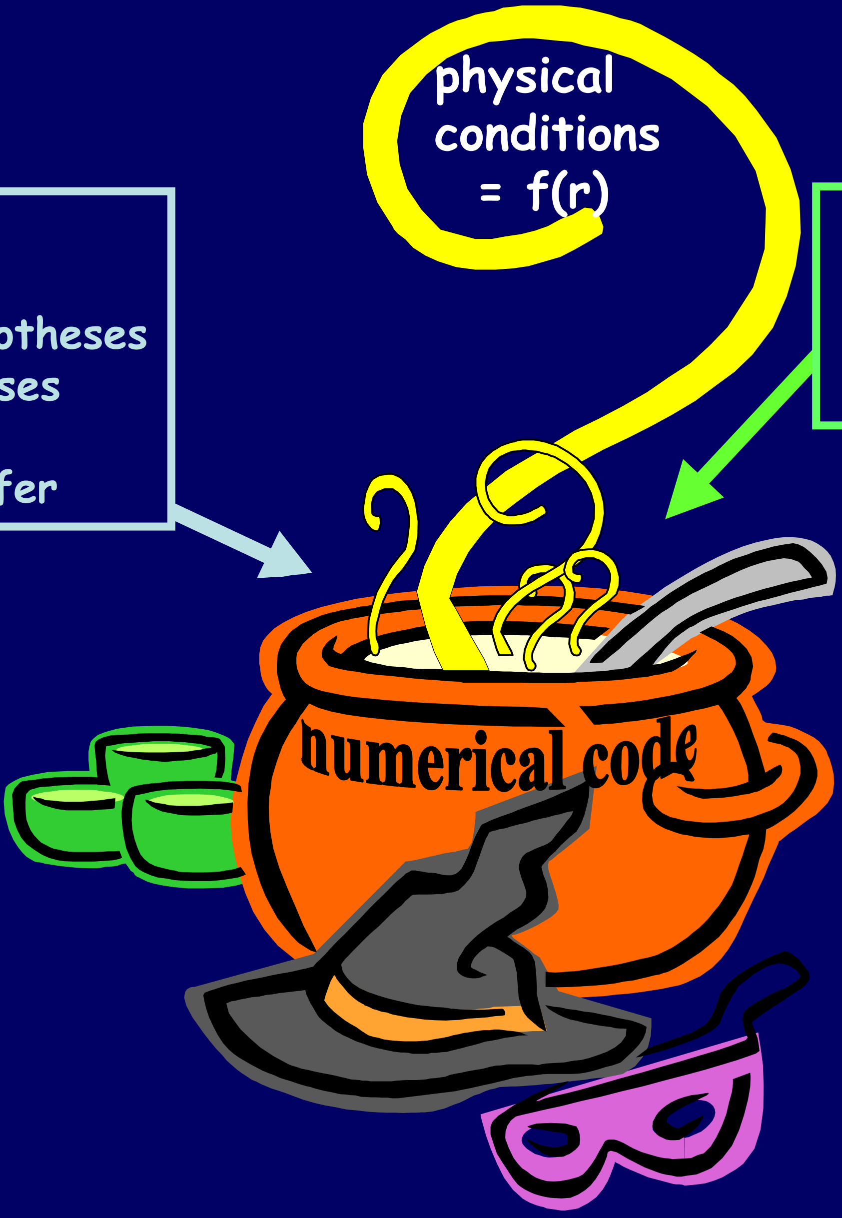
- temperature and ionization distribution depend strongly on
  - the spectral distribution of the incident radiation
  - chemical abundance (cooling)

- detailed calculation shows:
  - simple relations for the icfs do not necessarily hold
  - charge transfer reactions can be very important for some ions
  - ions with different ionization potentials can coexist
  - degeneration of the relation of R_{23} and other indexes with O/H (double value methods)

⇒ more detailed calculations are needed

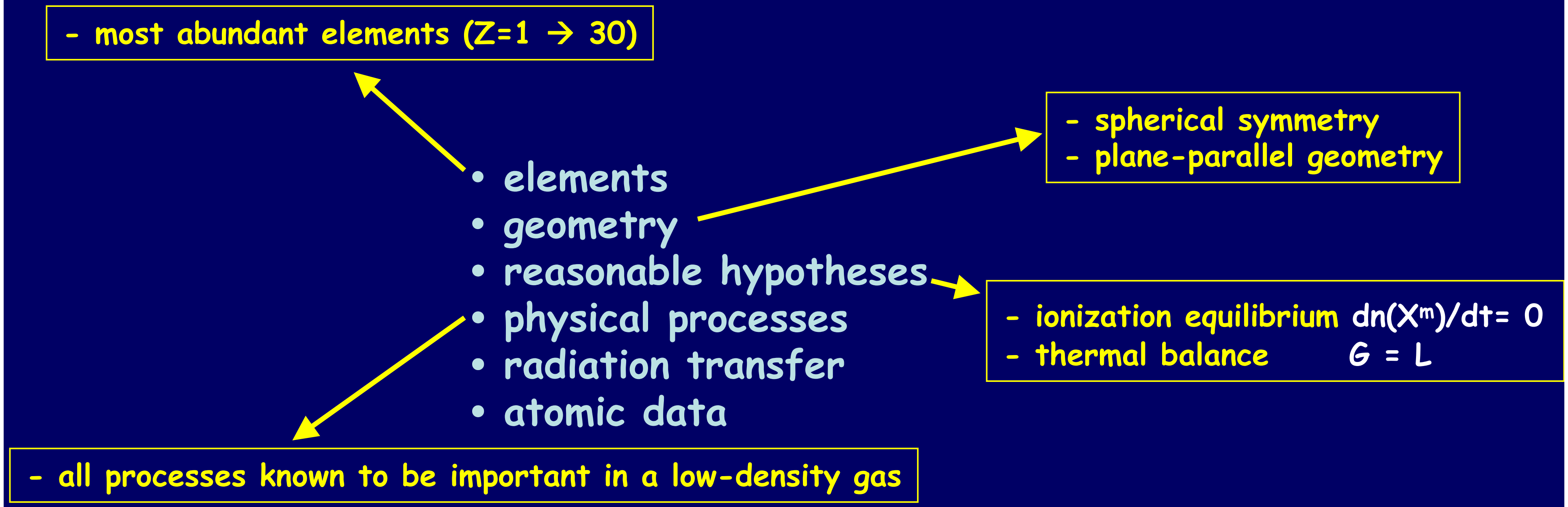
one-dimensional photoionization codes

- elements
- geometry
- reasonable hypotheses
- physical processes
- atomic data
- radiation transfer



physical
conditions
= f(r)

input parameters:
- ionizing radiation spectrum
- gas density
- chemical abundance



- elements
- geometry
- reasonable hypotheses
- physical processes
- radiation transfer
- atomic data

- most abundant elements (Z=1 → 30)

- spherical symmetry
- plane-parallel geometry

- ionization equilibrium $dn(X^m)/dt= 0$
- thermal balance $G = L$

- all processes known to be important in a low-density gas

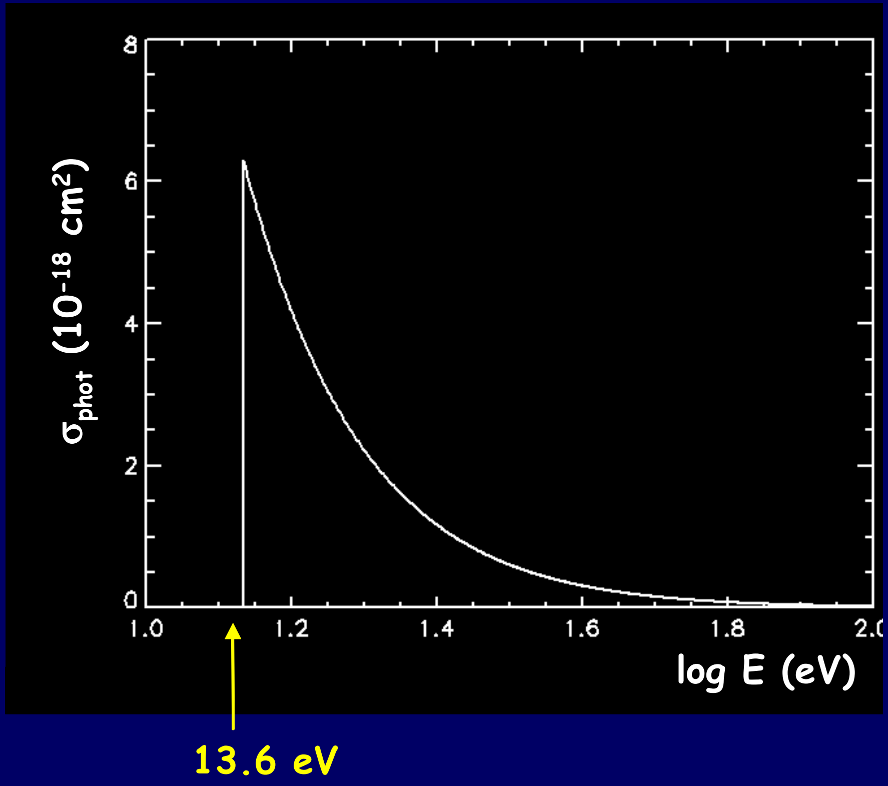
⇒ main assumptions of one-dimensional photoionization codes:

ionization equilibrium:

$$\frac{d\,n(X^m)}{d\,t} = 0$$

ionization rate = recombination rate

- photoionization (+ *Auger effect*) $X^i + h\nu \rightarrow X^{i+1} + e^-$; $X^i + h\nu \rightarrow X^{i+n} + ne^-$
  (primary and diffuse radiation)



⇒ main assumptions of one-dimensional photoionization codes:

ionization equilibrium:

$$\frac{d\,n(X^m)}{d\,t} = 0$$

ionization rate = recombination rate

- photoionization (+ Auger effect) (primary and diffuse radiation) $X^i + h\nu \rightarrow X^{i+1} + e^-$; $X^i + h\nu \rightarrow X^{i+n} + ne^-$
- collisional ionization $X^i + e^- \rightarrow X^{i+1} + e^- + e^-$
- charge transfer reactions (ion.) $X^i + Y^j \rightarrow X^{i+1} + Y^{j-1}$

- dielectronic recombination $X^i + e^- \rightarrow X^{i*} \rightarrow X^{i-1} + h\nu_1 + h\nu_2 + \ldots$
- radiative recombination $X^i + e^- \rightarrow X^{i-1} + h\nu_1 + h\nu_2 + \ldots$
- charge transfer reactions (rec.) $X^i + Y^j \rightarrow X^{i-1} + Y^{j+1}$

(3-body recombination; ionization by cosmic rays; …)

$\Rightarrow$ main assumptions of one-dimensional photoionization codes:

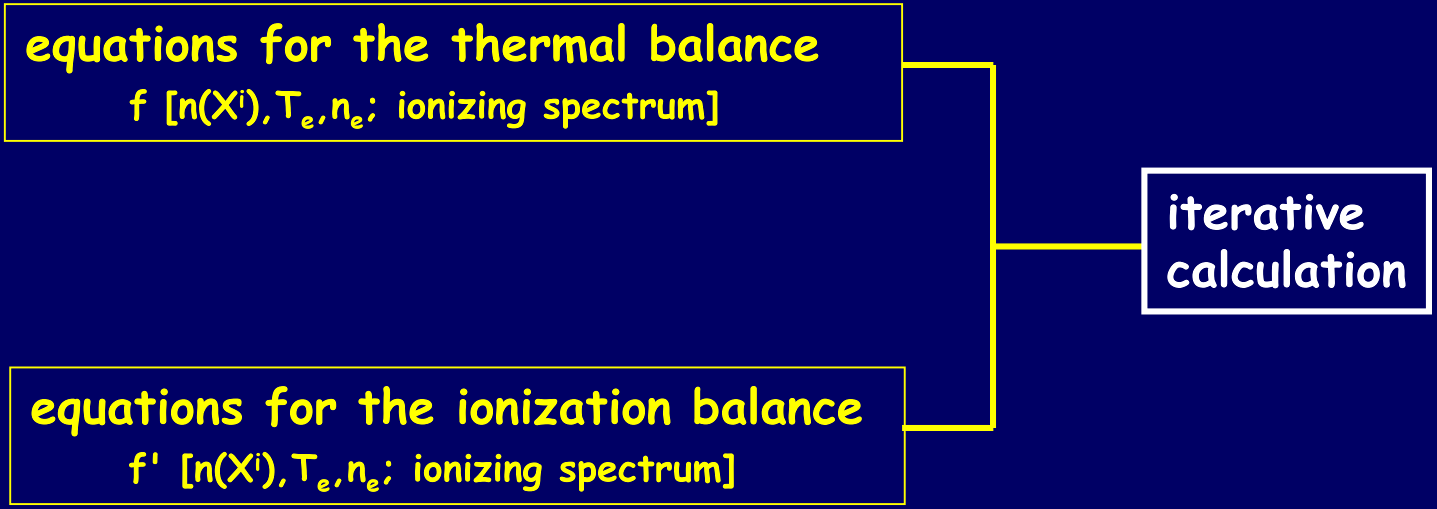
thermal equilibrium: energy gains = energy losses

energy input:

- photoionization $X^i + h\nu \rightarrow X^{i+1} + e^-$ $(E_{e-} = h\nu - I)$

cooling:

- recombination (+ cascade) $X^i + e^- \rightarrow X^{i-1} + h\nu_1 + h\nu_2 + \ldots$ (f-b + line emission)
- thermal bremsstrahlung $e^- + X^i \rightarrow e^- + X^i + h\nu$ (f-f emission)
- coll. exc. + rad. deexcitation $X^i + e^- \rightarrow X^{i*} + e^- \rightarrow X^i + h\nu_{mn} + e^-$ (line emission)
- two-photon decay $H(2^2S) \rightarrow H(1^2S) + h\nu_1 + h\nu_2$ (continuum)



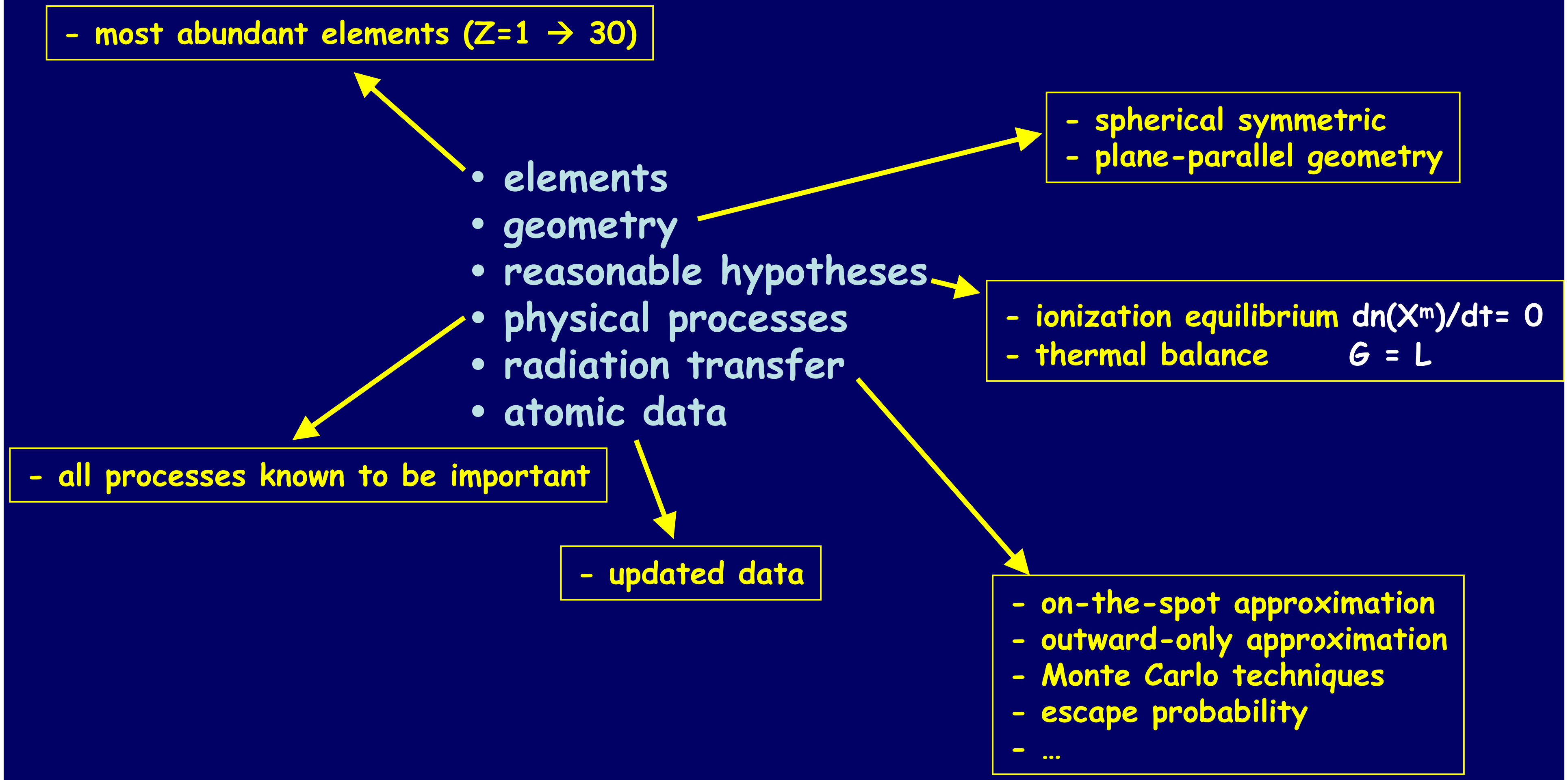
equations for the thermal balance

$f\ [n(X^i), T_e, n_e;\ \text{ionizing spectrum}]$

equations for the ionization balance

$f'\ [n(X^i), T_e, n_e;\ \text{ionizing spectrum}]$

iterative calculation



- most abundant elements (Z=1 → 30)

- elements
- geometry
- reasonable hypotheses
- physical processes
- radiation transfer
- atomic data

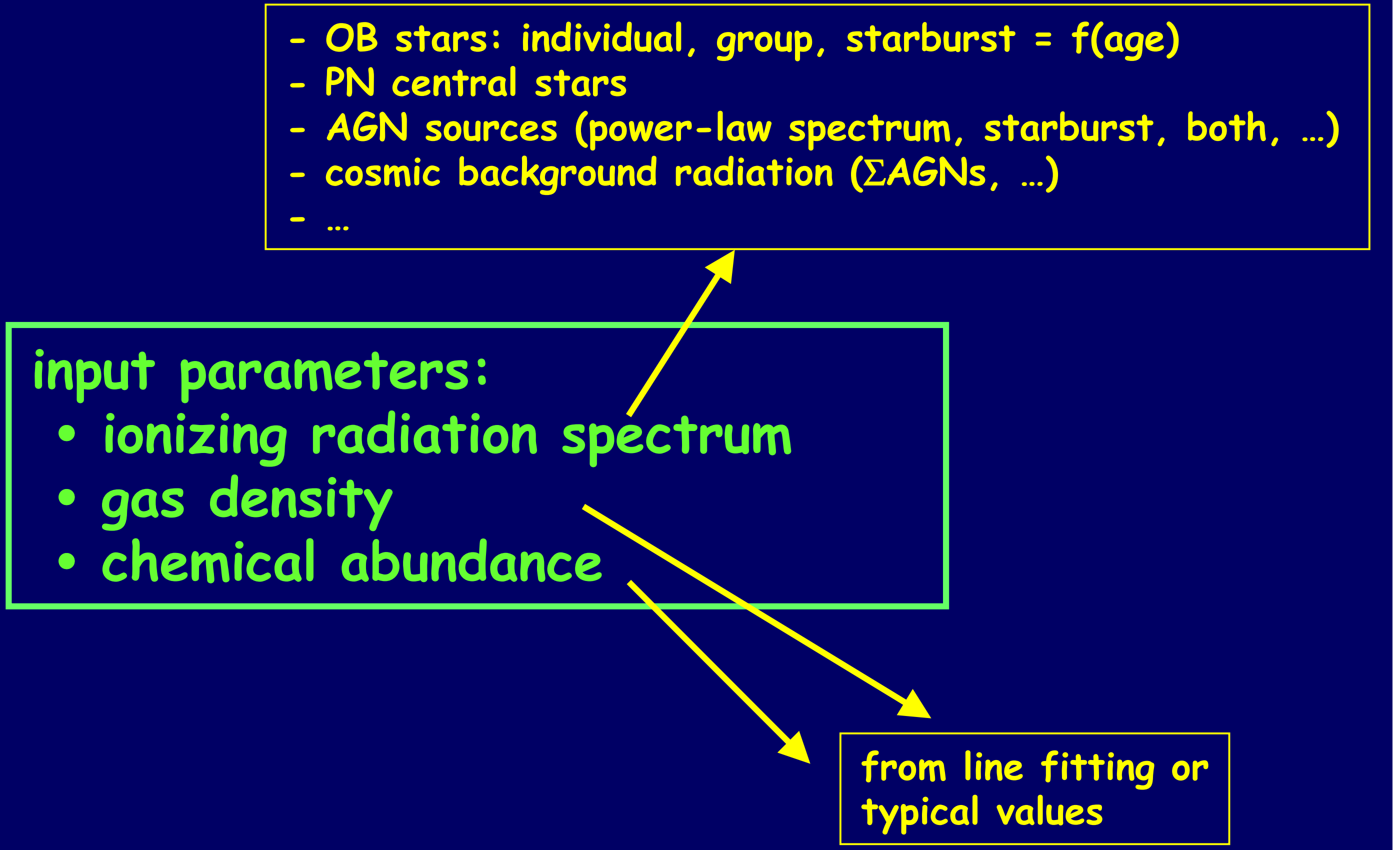
- spherical symmetric
- plane-parallel geometry

- ionization equilibrium $dn(X^m)/dt= 0$
- thermal balance $G = L$

- all processes known to be important

- updated data

- on-the-spot approximation
- outward-only approximation
- Monte Carlo techniques
- escape probability
- …



- OB stars: individual, group, starburst = f(age)
- PN central stars
- AGN sources (power-law spectrum, starburst, both, …)
- cosmic background radiation (ΣAGNs, …)
- …

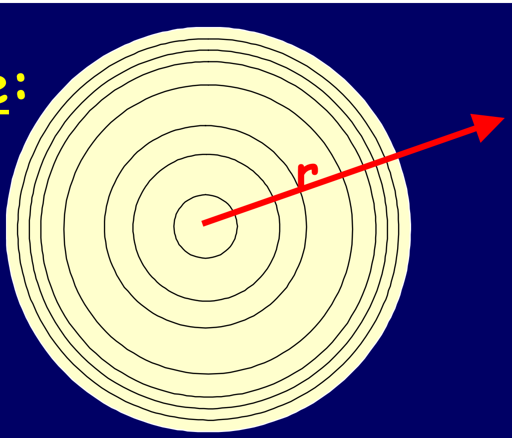
input parameters:

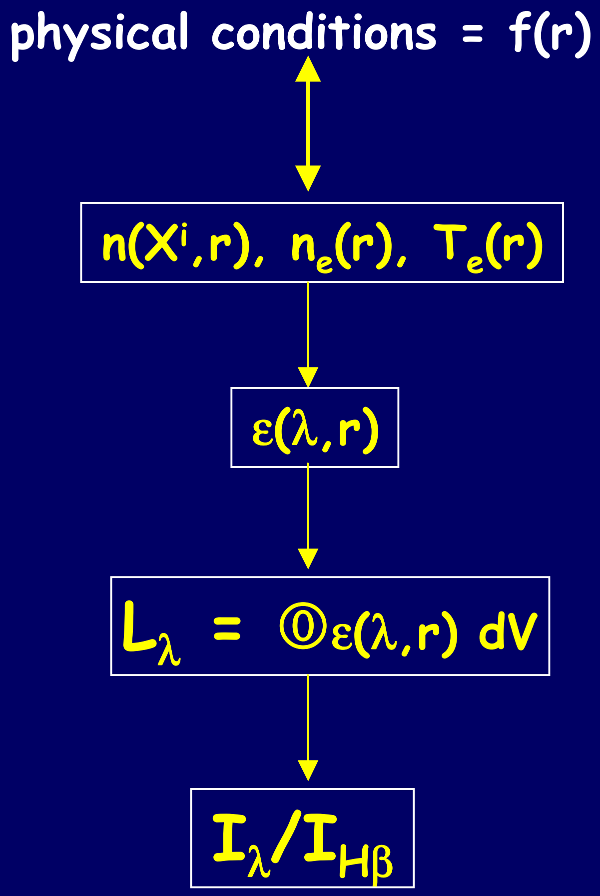
- ionizing radiation spectrum
- gas density
- chemical abundance

from line fitting or typical values

Example of the output of a photoionization code:

- spherical symmetry
- source at the center





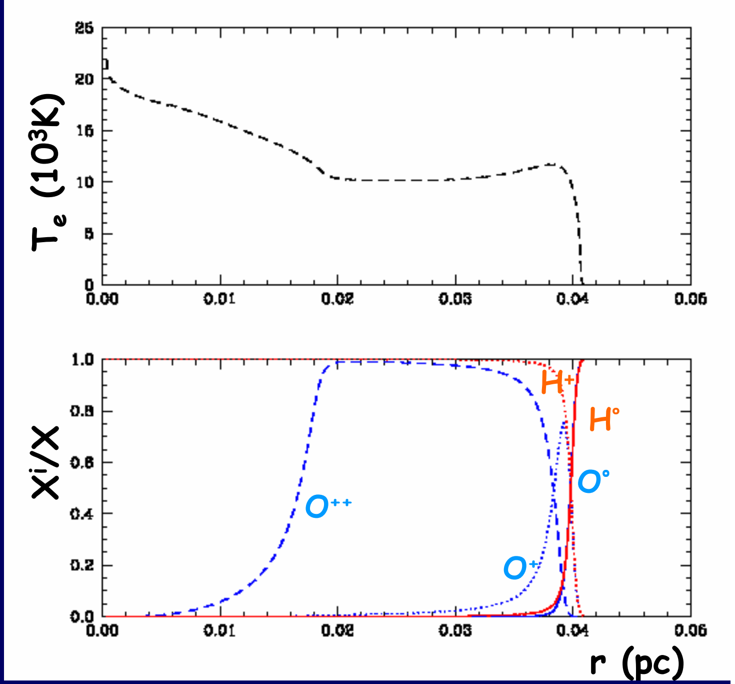
physical conditions = f(r)

$n(X^i,r)$, $n_e(r)$, $T_e(r)$

$\varepsilon(\lambda,r)$

$L_\lambda = \textcircled{0}\varepsilon(\lambda,r)\,dV$

$I_\lambda/I_{H\beta}$



$T_* = 100$kK; $L_* = 3000\ L_\odot$
$n_H = 10^4$ cm^{-3}
$Z = Z_{typical}$

⇒ **photoionization models can be used to:**

a) <u>statistical studies</u>

to derive the general properties of a given class of emission-line objects

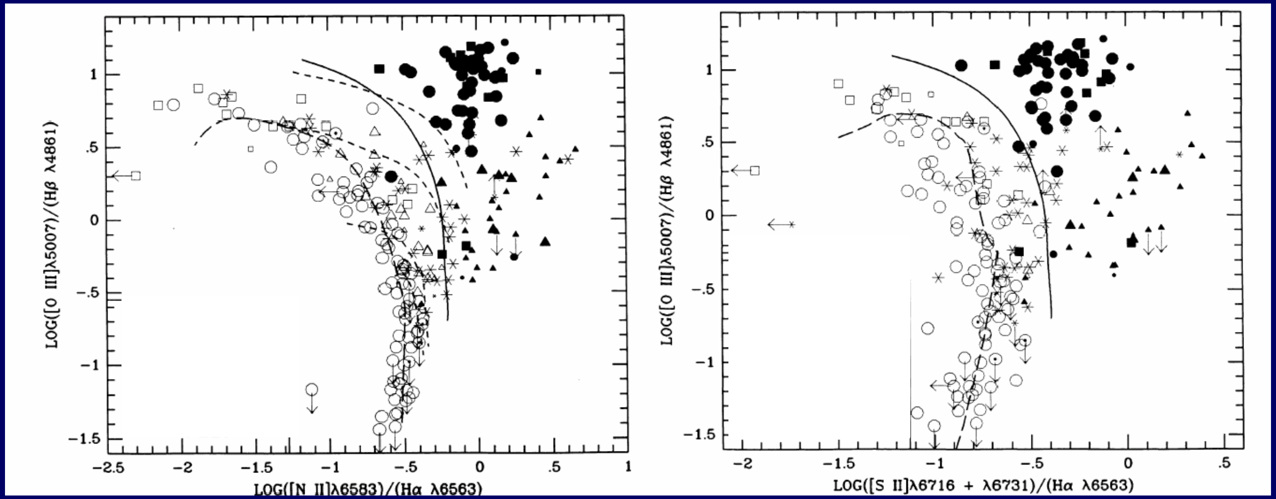
grid of models

+

observations

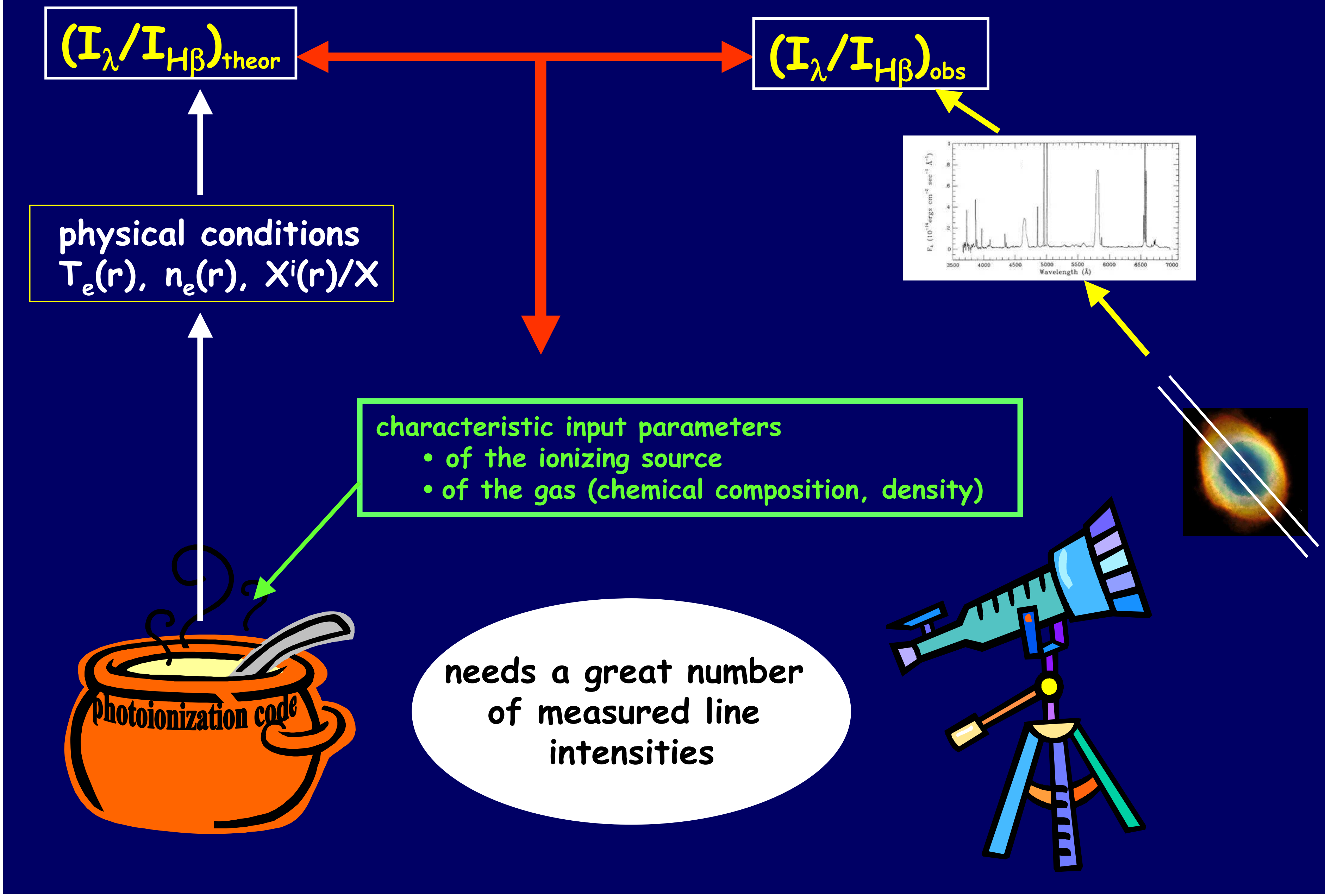
diagnostic diagrams

ex.:



Baldwin et al. (81)

b) detailed analysis of individual objects



$(I_\lambda/I_{H\beta})_{theor}$

$(I_\lambda/I_{H\beta})_{obs}$

physical conditions
$T_e(r)$, $n_e(r)$, $X^i(r)/X$

characteristic input parameters
- of the ionizing source
- of the gas (chemical composition, density)

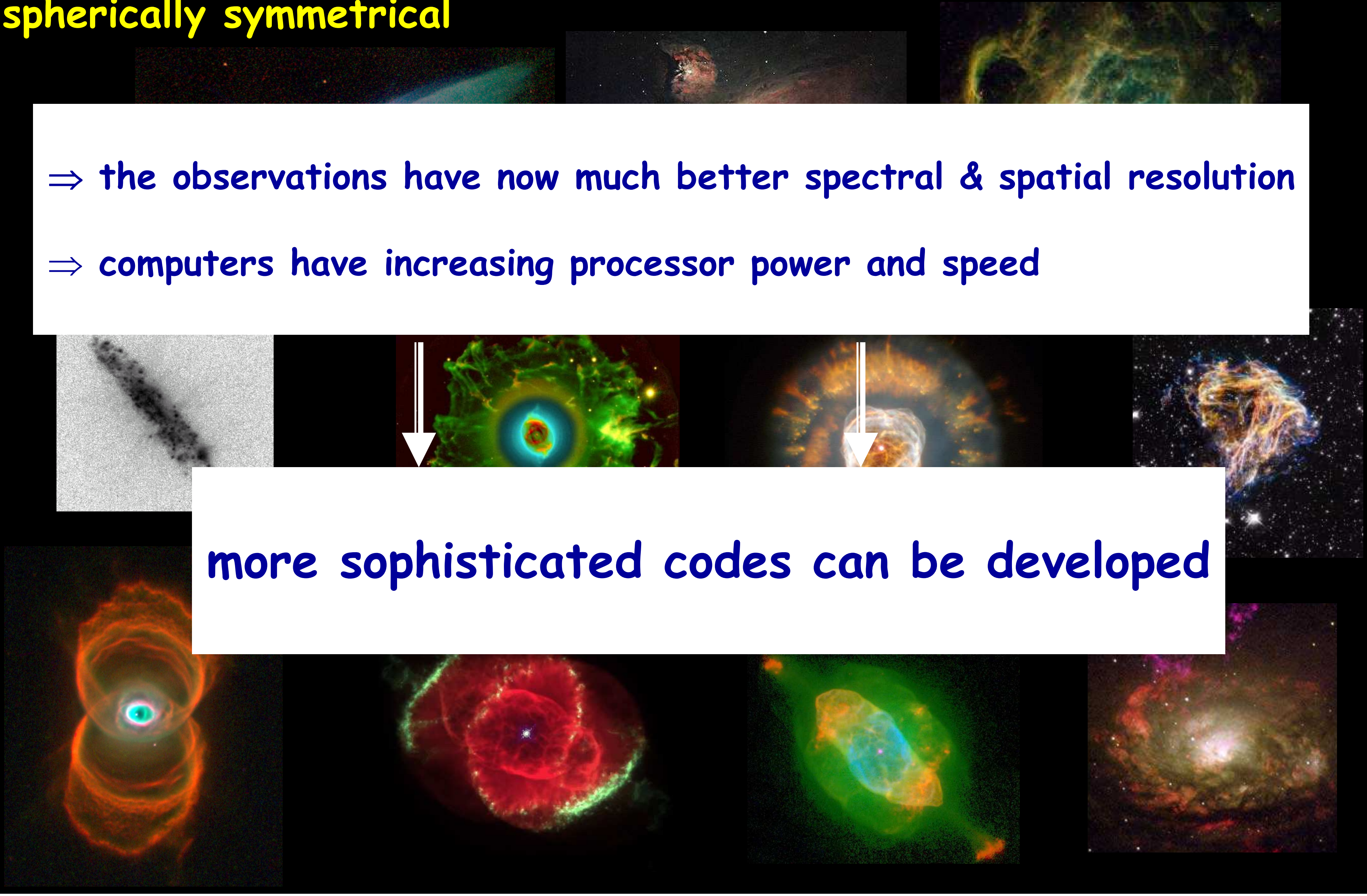
needs a great number of measured line intensities

some more ingredients …

- dust – most codes
- shocks - Viegas & Contini, Dopita (M.Elitzur lecture)
- line radiative transfer - Elitzur & Ferland, Netzer, Collin-Souffrin, ..
- relativistic electrons - Viegas & Gruenwald
- molecules in the ionized region - Aleman & Gruenwald
- hydrodynamical equations - Frank, Mellena, …
  + microphysical processes (simplified)
- time dependent models - Tylenda, Szczerba
- chemodynamical models - Friaça & Terlevich

➔ the photoionization codes are, in general, one-dimensional

➔ but most photoionized regions are neither homogeneous nor spherically symmetrical

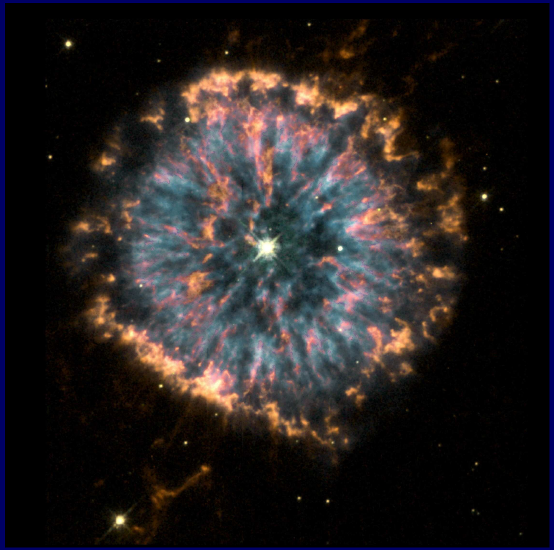


⇒ the observations have now much better spectral & spatial resolution

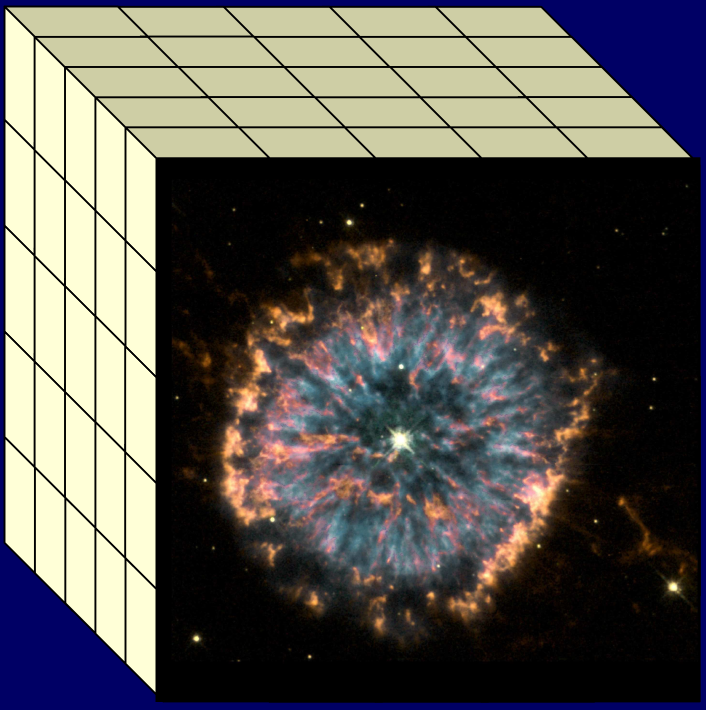
⇒ computers have increasing processor power and speed

more sophisticated codes can be developed

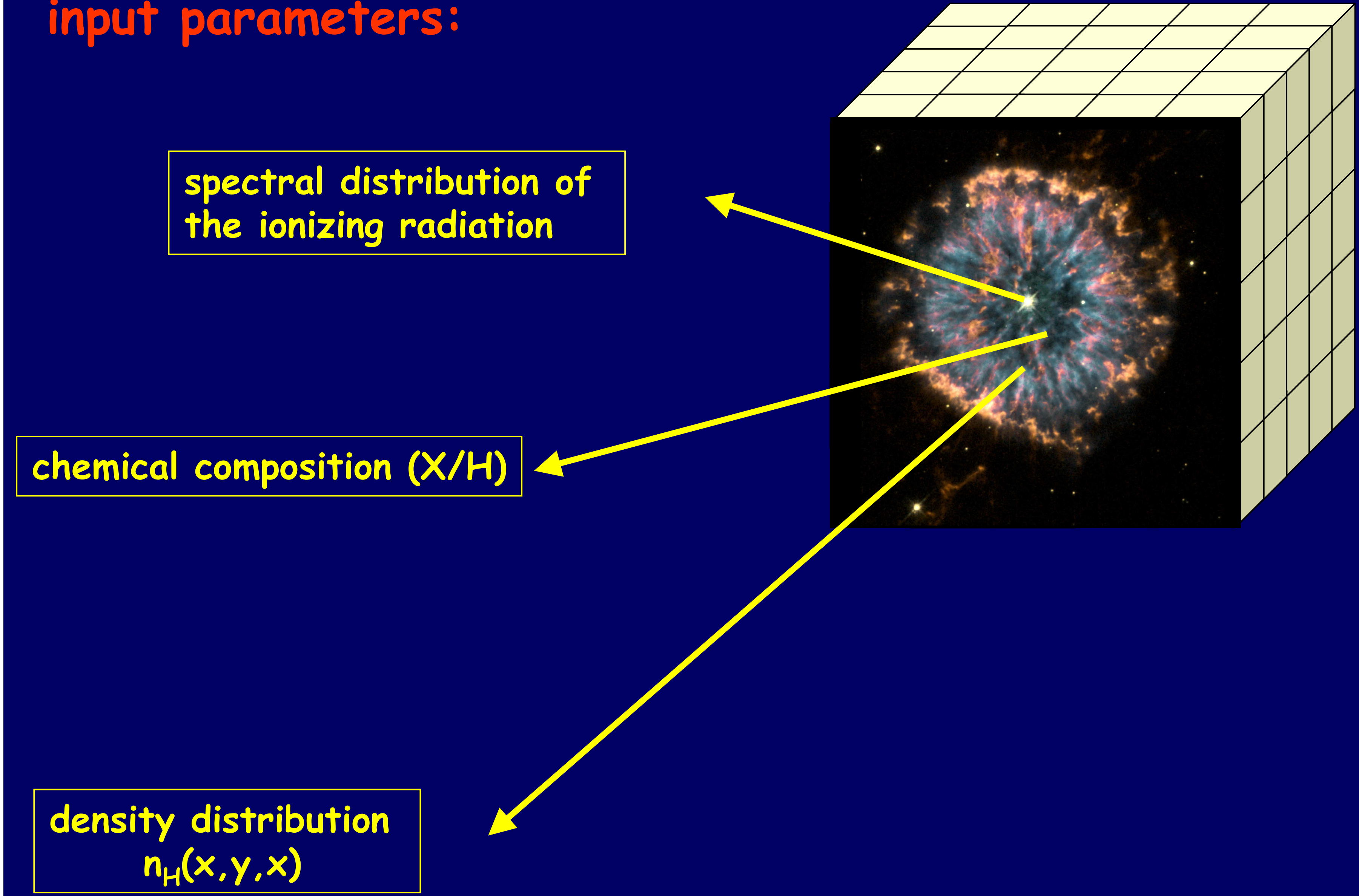
3D photoionization code



Gruenwald et al. (1997)



input parameters:

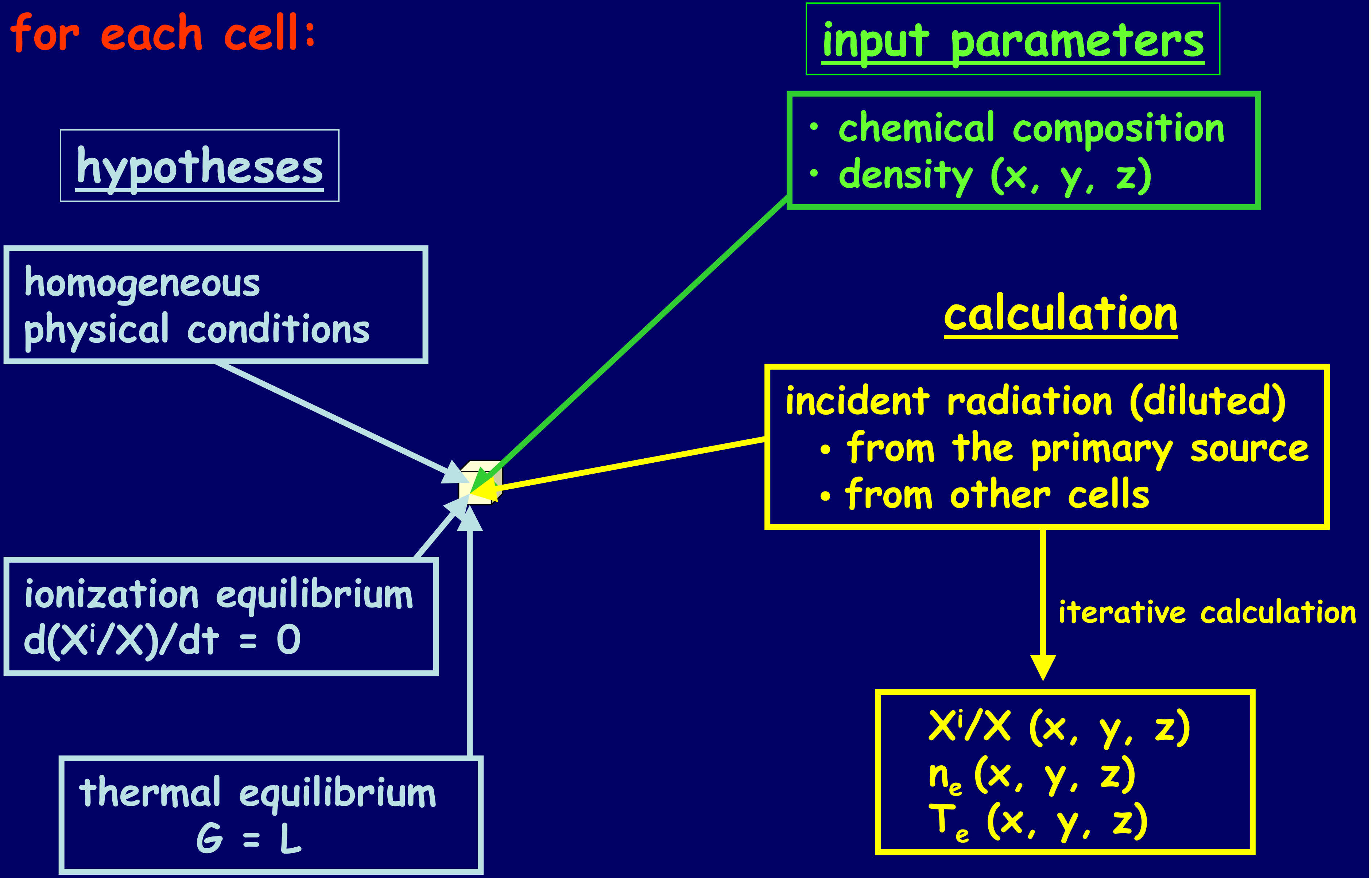


spectral distribution of
the ionizing radiation

chemical composition (X/H)

density distribution
$n_H(x,y,x)$

for each cell:



hypotheses

homogeneous physical conditions

ionization equilibrium
$d(X^i/X)/dt = 0$

thermal equilibrium
$G = L$

input parameters

- chemical composition
- density (x, y, z)

calculation

incident radiation (diluted)
- from the primary source
- from other cells

iterative calculation

X^i/X (x, y, z)
n_e (x, y, z)
T_e (x, y, z)

ex.: results for a nebula with a dense waist of matter:

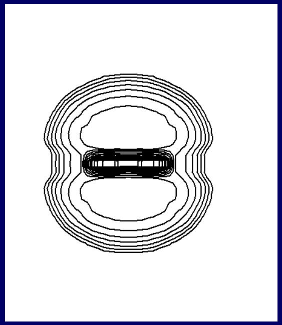
$X^i/X\ (x,y,z)$
$T_e(x,y,z)$
$n_e(x,y,x)$

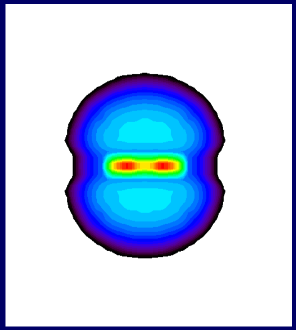
$\varepsilon_\lambda(x,y,z)$

$L_\lambda=\int\varepsilon_\lambda(x,y,z)dV$

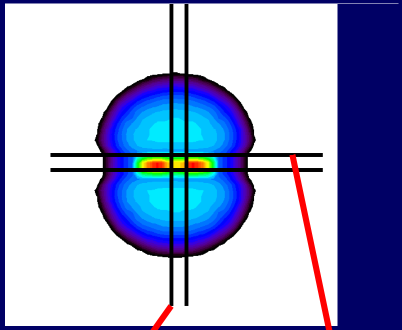
$I_\lambda/I_{H\beta}$

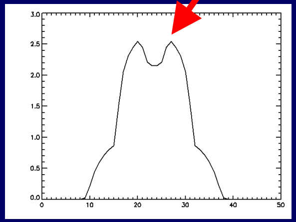
monochromatic images

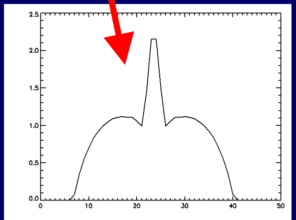




F_λ distribution in a given aperture



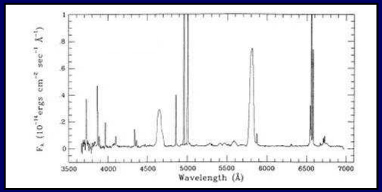




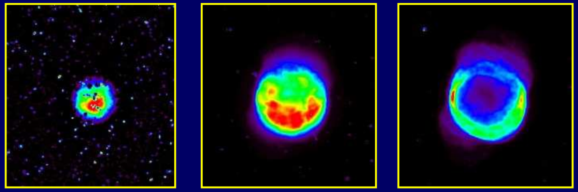
typical input parameters:
- **for the ionizing radiation** (T_*, L_*)
- **for the gas** (chemical composition, spatial structure)

observations

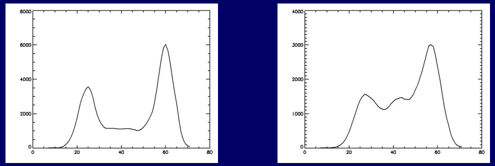
numerical code



$I_\lambda / I_{H\beta}$



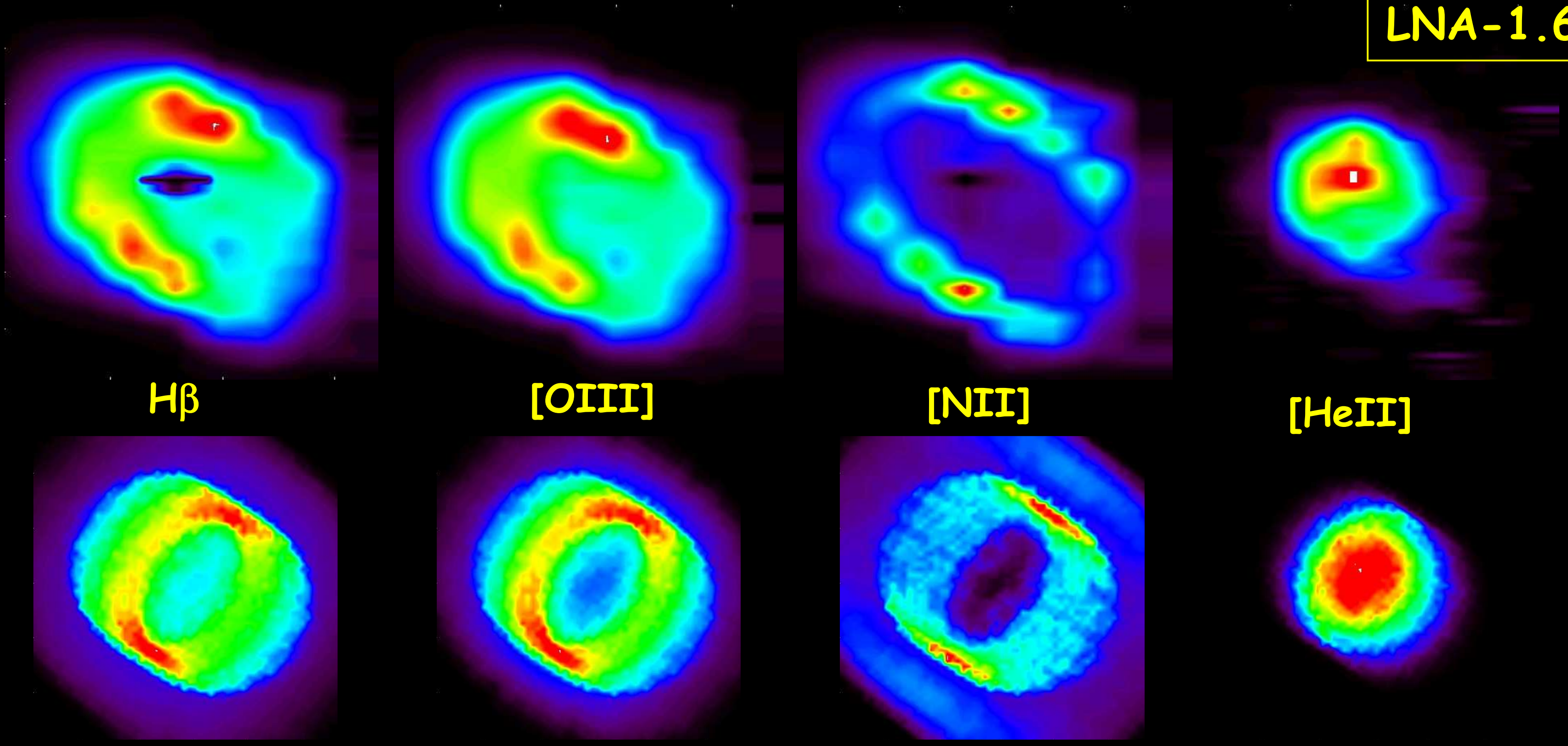
monochromatic images

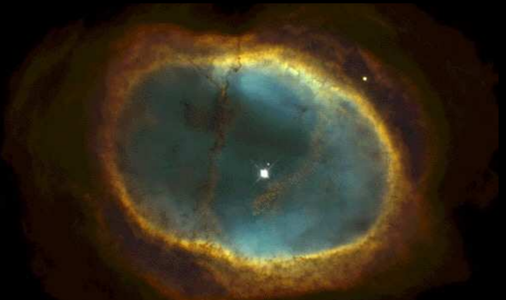


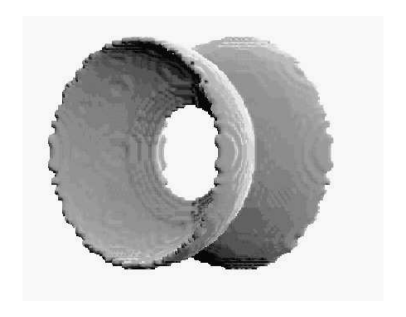
F_λ distribution in a given aperture

NGC 3132

LNA-1.6m







conclusion: the geometry is not ellipsoidal, as suggested by the observed images

what can be improved?

- ➔ more accurate atomic data → Opacity Project
  Iron Project
- ➔ better resolution of the observations (spectral and spatial)
- ➔ better resolution of the models (higher processor power and speed)
- ➔ information about grain composition and structure
- ➔ more reliable model atmosphere (enormous progress in last years)
- ➔ increasing sensibility of the observations
- ➔ coupling of photoionization codes with hydrodynamical calculations
- ➔ detailed analysis of additional heating – winds, shocks, …
- ➔ for giant H II regions – correction of stellar absorption
- ➔ ...

Some references for the study of (photo-)ionized regions:

- basic physics of photoionized nebulae
    - Osterbrock (1989) – "Astrophysics of Gaseous nebulae and AGN"
    - Aller (1984) – "Physics of Thermal Gaseous Nebulae"

- empirical methods for abundance determination; icfs
    - many authors, mainly Peimbert & collaborators

- models for very dense photoionized regions, including with line transfer
    - Elitzur & Ferland, Collin-Souffrin, Netzer, Kwan & Krolik

- models including shocks (SNR, AGN)
    - Viegas & Contini, Dopita

- DIM, WIM, DIG, ...
    - Dettmar, Reynolds, Rand, Walterbos, Fergunson, ...

- dust in ionized regions
    - Stasinska & Szczerba, van Hoof, ...

- free photoionization code "Cloudy" - Ferland & co-workers

  http://www.nublado.org