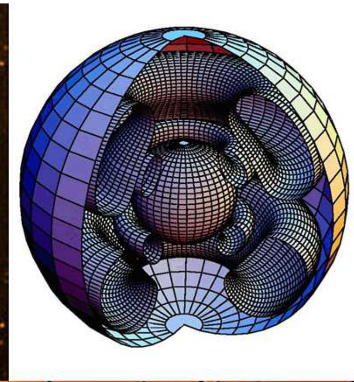
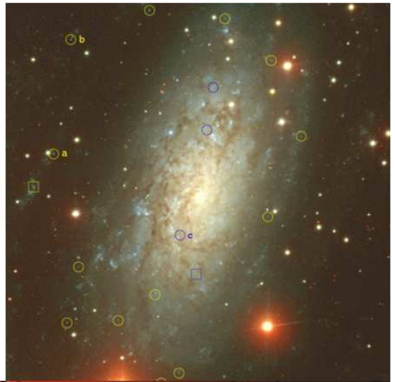
$$n_i \sum_{j\neq i}(R_{ij}+C_{ij}) = \sum_{j\neq i} n_j(R_{ji}+C_{ji})$$

$$\mu\frac{\mathrm{d}I_\nu}{\mathrm{d}\tau_\nu} = I_\nu - S_\nu$$





Blue Supergiants in the E-ELT Era

Extragalactic Stellar Astronomy

Norbert Przybilla

Institute for Astro- and Particle Physics

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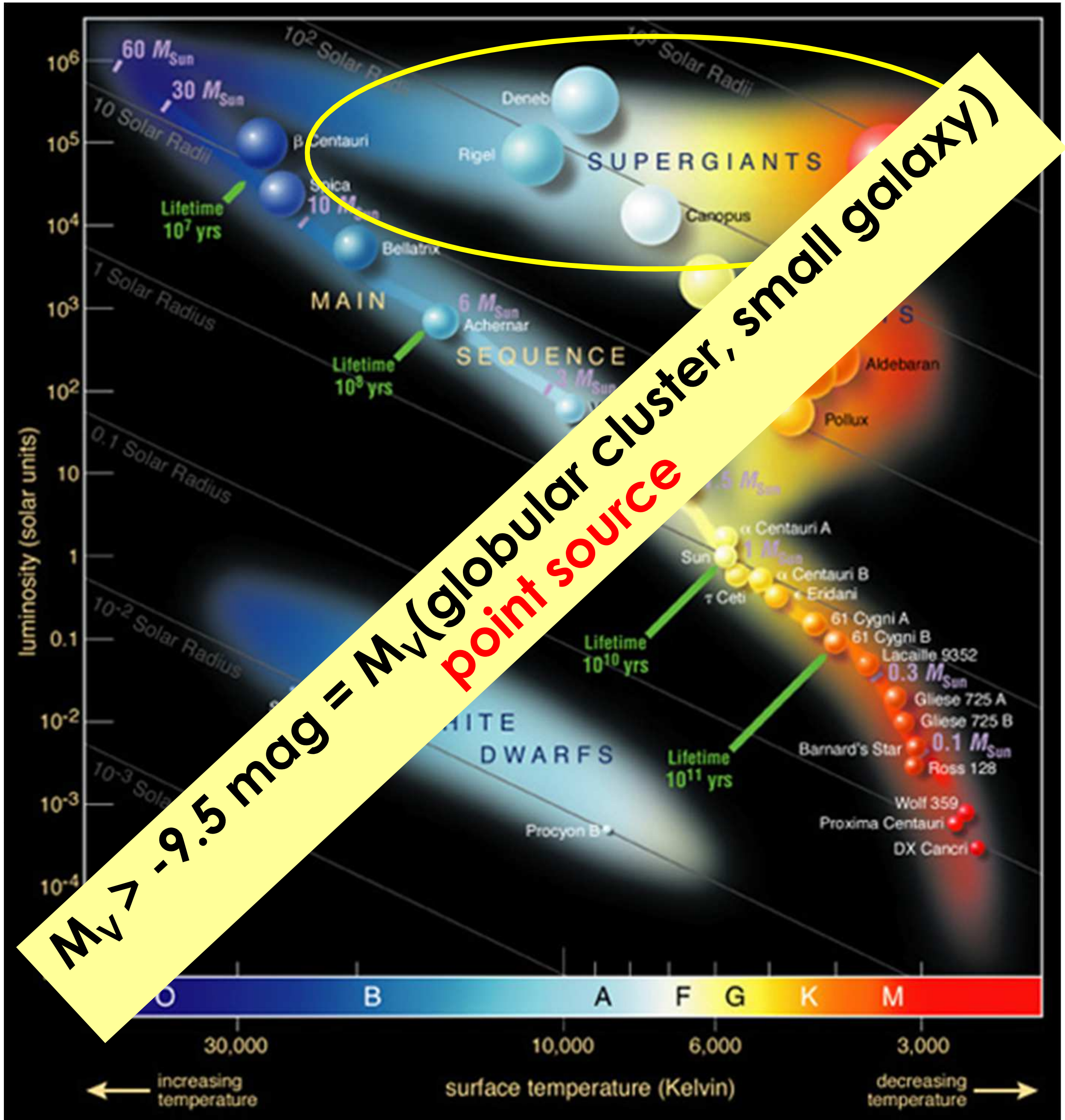

BSGs

Supergiants

- evolved progeny of OB main-sequence stars
- T_{eff}: ~ 3000 ... 25000 K
- M: ~ 8 ... 40 $M_\odot$
- L: ~ 10^4 ...$10^{5.5}$ $L_\odot$
- R: ~ 50 ... 1500 $R_\odot$

BSGs: M_V~M_J > -9.5 mag
RSGs: M_J > -11 mag

with VLT/Keck:

→ spectroscopy@high-res throughout Local Group

→ @med-res: out to 7-8Mpc

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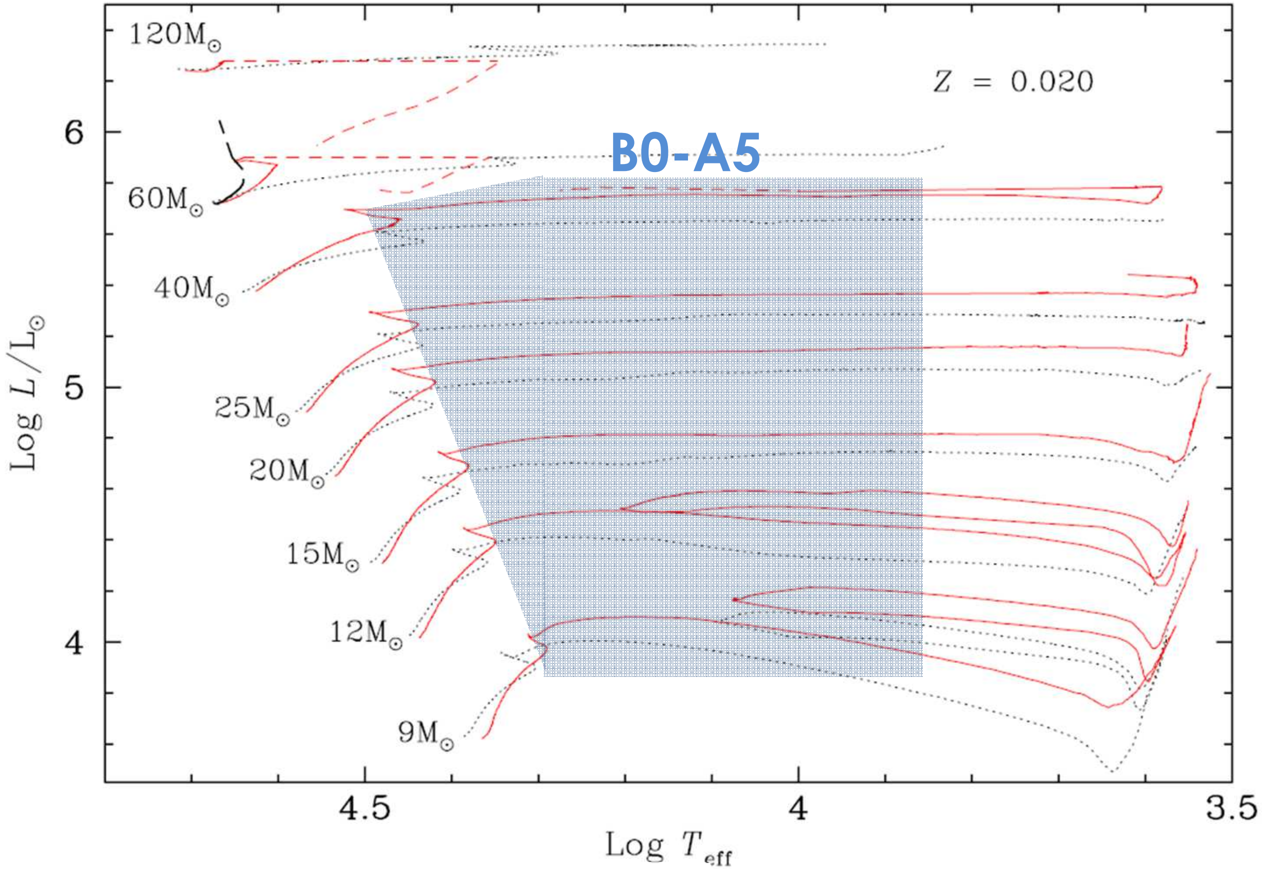
Blue Supergiants (BSGs)

Meynet & Maeder (2000)



- evolved progeny of OB main-sequence stars

T_{eff}: ~ 8000 ... 25000 K

M: ~ 8 ... 40 $M_\odot$

L: ~ 10^4 ...$10^{5.5}$ $L_\odot$

R: ~ 50 ... 400 $R_\odot$

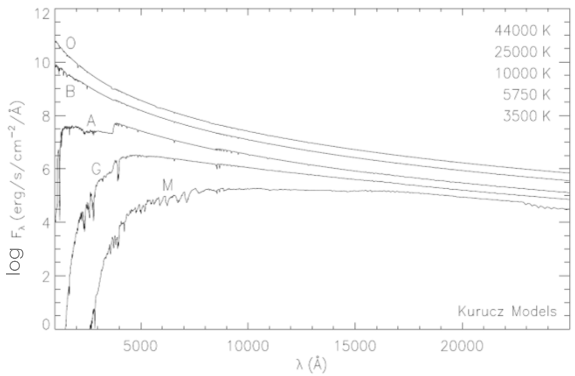
BSGs: $M_V \sim M_J > -9.5$ mag

with VLT/Keck:

➤ spectroscopy@high-res throughout Local Group

➤ @med-res: out to 7-8Mpc

RSGs ➤ **Miguel Urbaneja**



matters:
B.C. & size

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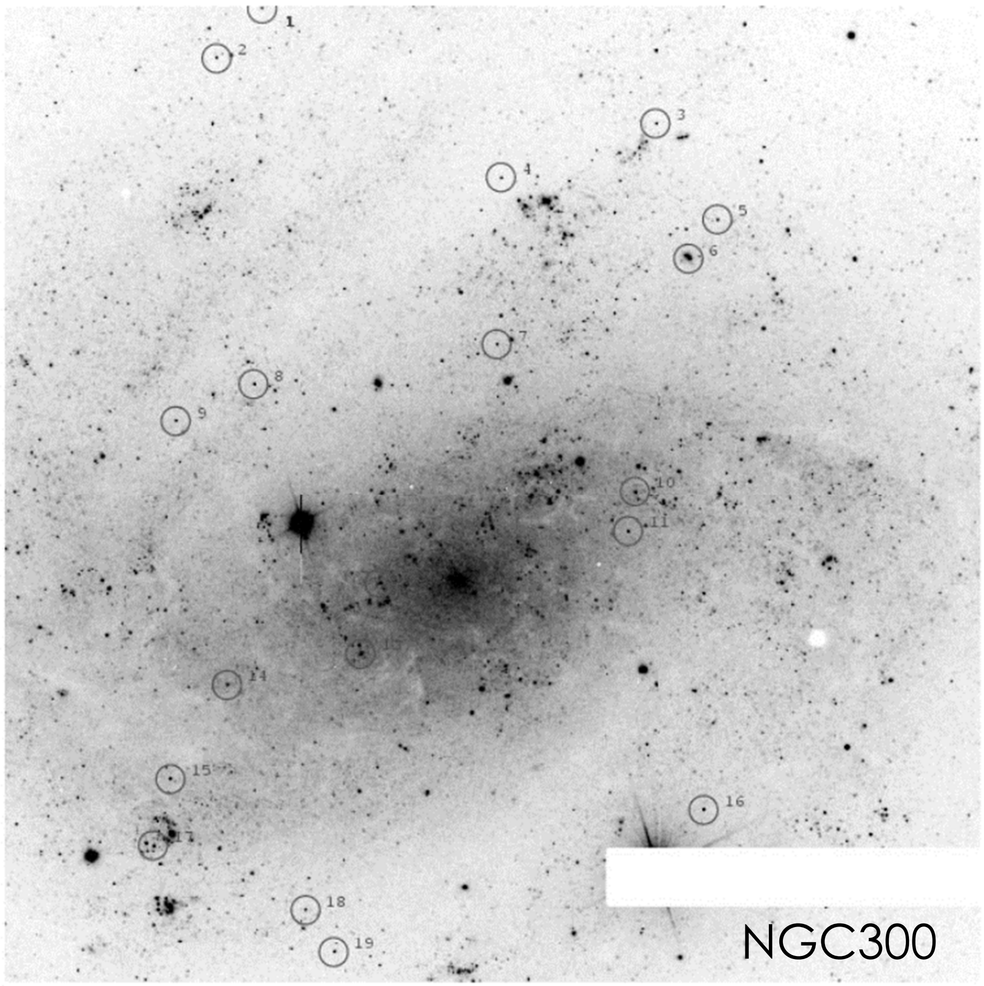
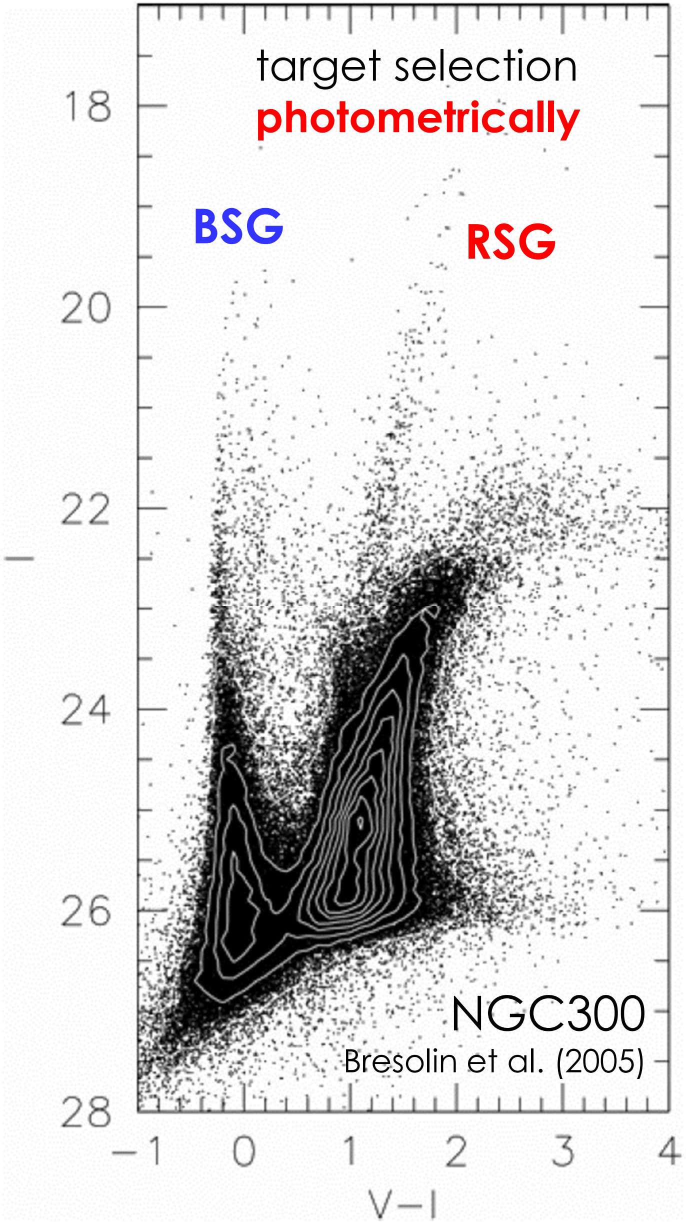
BSGs: how to find them?

Bresolin et al. (2002)

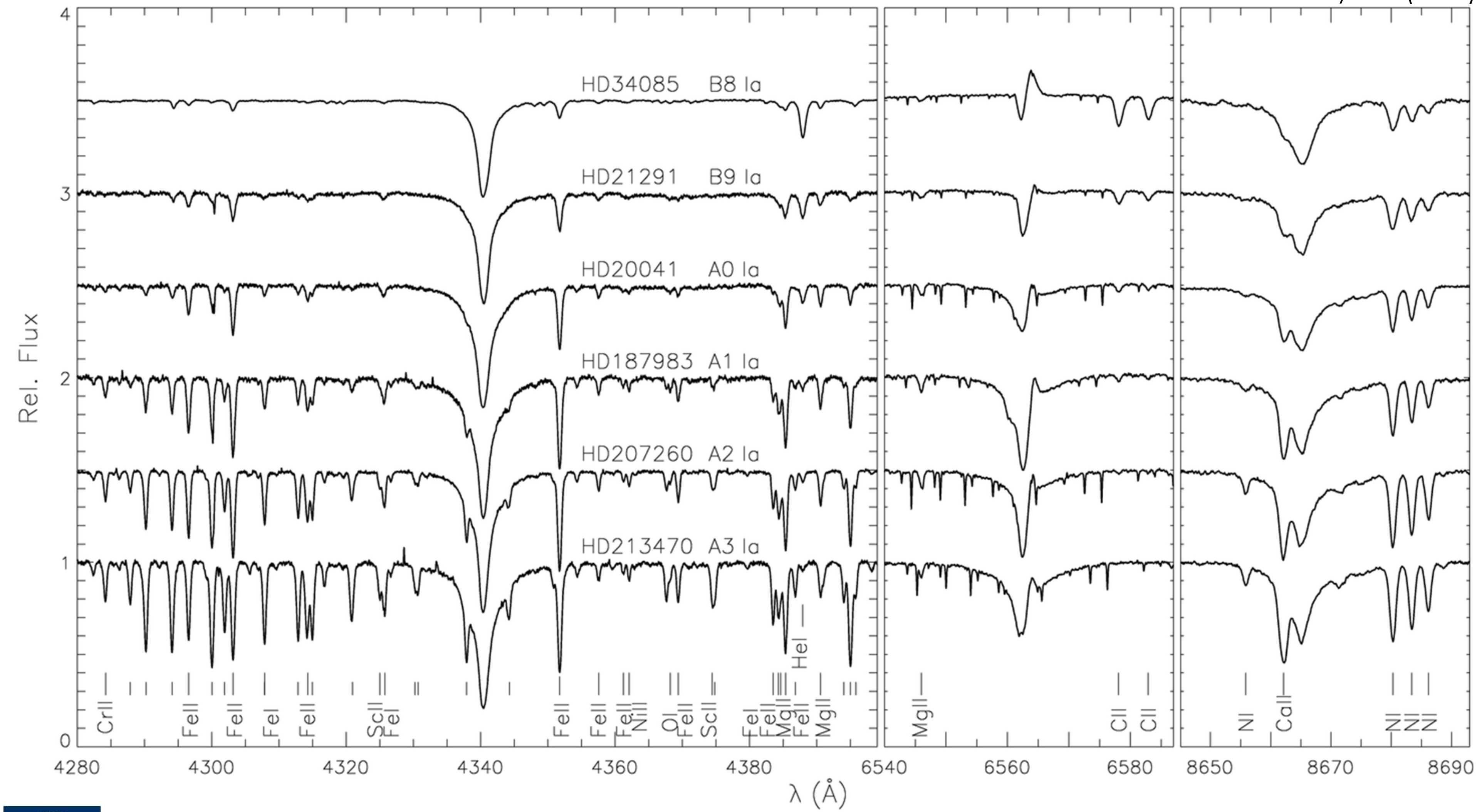




→ easy to identify with ground-based/HST imaging

BSGs: high-quality observations

Firnstein & Przybilla (2012)



high-S/N Echelle spectra: FEROS, FOCES, CAFE, FIES, UVES

$R = \lambda/\Delta\lambda = 40{,}000\text{-}100{,}000$ $3800Å < \lambda < 9000Å$

BSGs: what information can be extracted?

→ **quantitative spectroscopy via model atmospheres**

- atmospheric parameters: T_{eff}, log g, ξ, vsin i, ζ, Y, Z, v_{rad}
- stellar wind parameters: $\dot{M}$, v_{∞}, β
- fundamental stellar parameters: M, R, L, age
- elemental abundances:
  - He, CNO
  - α-process elements
  - iron group elements
  - s-process elemnets
  - (r-process elements)
- reddening, reddening law, ISM lines
- distances

BSGs: what science can be addressed?

- spectral line formation under non-LTE conditions
- stellar wind physics
- stellar evolution
- ISM studies
- galaxy evolution
- cosmic distance scale

Basic equations of classical stellar atmosphere problem

- radiative transfer equation – **energy transport**:

$$\mu \frac{dI_\nu}{d\tau_\nu} = I_\nu - S_\nu \qquad \Rightarrow \qquad J_\nu$$

- radiative equilibrium (+ convective energy transport for cool stars) – **energy conservation**:

$$\int_0^\infty H_\nu \, d\nu = \text{const.} = \frac{\sigma}{4\pi} T_{\text{eff}}^4 \qquad \Rightarrow \qquad T$$

- hydrostatic equilibrium – **momentum conservation**:

$$\frac{dP}{dz} = -\rho \cdot (g - g_{\text{rad}}) \qquad + \text{ideal gas} \qquad \Rightarrow \qquad N$$

- detailed equilibrium (LTE): Saha- & Boltzmann-formula

$$\frac{n_{\text{up}}}{n_{\text{low}}} = \frac{1}{n_e} \cdot 2 \left(\frac{2\pi m_e kT}{h^2} \right)^{3/2} \frac{g_{\text{up}}}{g_{\text{low}}} e^{-\left(\frac{E_{\text{up}} - E_{\text{low}}}{kT}\right)}$$

$$\frac{n_i}{n_j} = \frac{g_i}{g_j} e^{-\left(\frac{E_i - E_j}{kT}\right)}$$

- statistical equilibrium (NLTE): rate equations

$$n_i \sum_{j \neq i} (R_{ij} + C_{ij}) + n_i (R_{ik} + C_{ik}) = \sum_{j \neq i} n_j (R_{ji} + C_{ji}) + n_k (R_{ki} + C_{ki}) \qquad \Rightarrow \qquad n_i$$

- **charge conservation**:

$$\sum_i n_i Z_i - n_e = 0 \qquad \Rightarrow \qquad n_e$$

Codes: hydrostatic: ATLAS/DETAIL/SURFACE
hydrodynamic: FASTWIND & CMFGEN

Level populations: modelling approaches

usually:

LTE: **L**ocal **T**hermodynamic **E**quilibrium

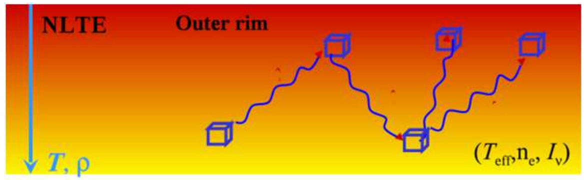
Saha-Boltzmann-Formulae, gf-values, line broadening

→ **L**imited **T**remendous **E**rror

hot, luminous stars: strong radiation field, low densities

non-LTE: **non-L**ocal **T**hermodynamic **E**quilibrium

rate equations, gf-values, line broadening,
detailed level-coupling, millions of atomic cross-sections



→ **non-L**imited **T**remendous **E**rror

(Restricted) **Non-LTE**

Non-Local Thermodynamic Equilibrium

- transfer equation

$$\mu \frac{\mathrm{d}I_\nu}{\mathrm{d}\tau_\nu} = I_\nu - S_\nu$$

- statistical equilibrium:

$$n_i \sum_{j \neq i} (R_{ij} + C_{ij}) = \sum_{j \neq i} n_j (R_{ji} + C_{ji})$$

- radiative rates:

$$R_{ij} = 4\pi \int \sigma_{ij} \frac{J_\nu}{h\nu} \mathrm{d}\nu$$

non-local

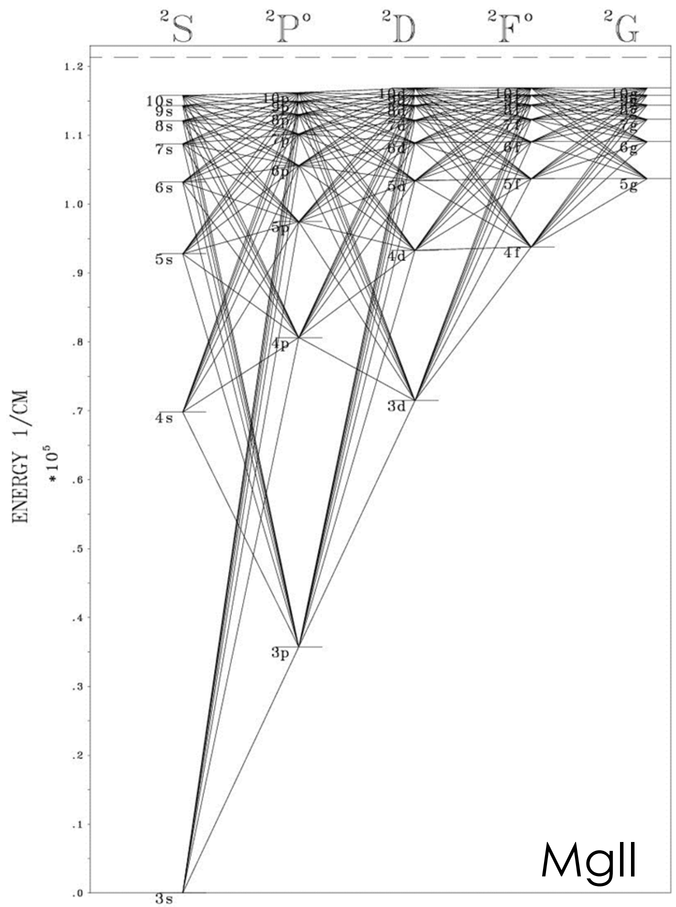
- collisional rates:

$$C_{ij} = n_e \int \sigma_{ij}(v) f(v) v \, \mathrm{d}v$$

local

- excitation, ionization, charge exchange, dielectronic recombination, etc.

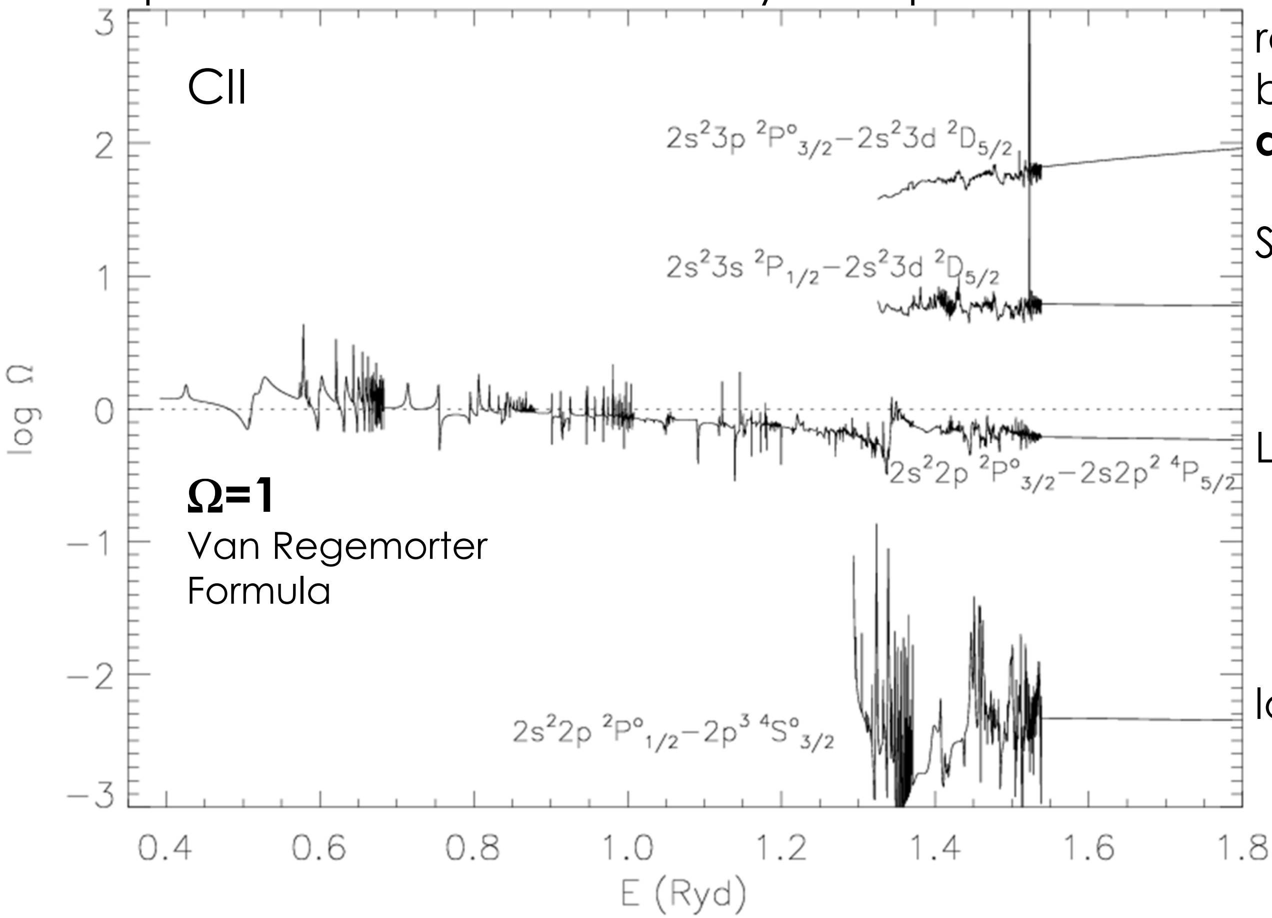
→ model atoms



Przybilla et al. (2001)

Atomic data

Example: collisional excitation by e⁻-impact



replacing approximations by **experimental** or **ab-initio data**

Schrödinger equation

$$H_{N+1}\Psi = E\Psi$$

LS-coupling:

$$H_{N+1} = \sum_{i=1}^{N+1}\left\{-\nabla_i^2 - \frac{2Z}{r_i} + \sum_{j>i}^{N+1}\frac{2}{r_{ij}}\right\}$$

low-Z Breit-Pauli Hamiltonian

$$H_{N+1}^{BP} = H_{N+1} + H_{N+1}^{mass} + H_{N+1}^{Dar} + H_{N+1}^{so}$$

huge amounts of atomic data: OP/IRON Project & own

Methods:

- R-matrix/CC approximation
- MCHF/MCDHF
- CCC

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Basic equations of classical stellar atmosphere problem

- radiative transfer equation – **energy t**

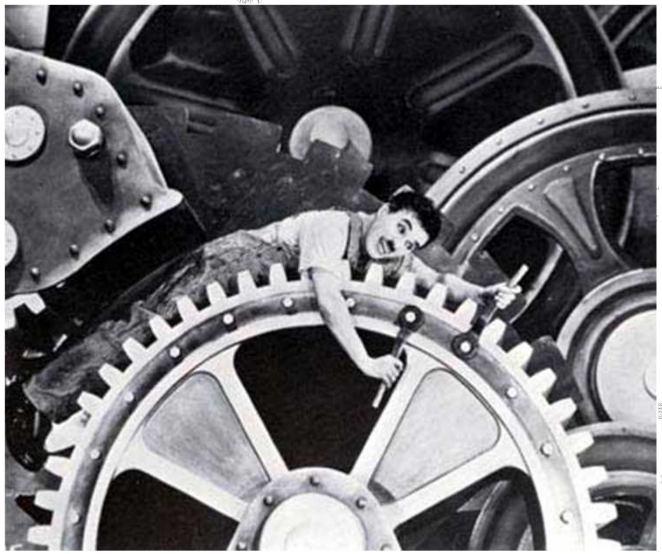
$$\mu \frac{dI_\nu}{d\tau_\nu} = I_\nu - S_\nu \qquad \Rightarrow \qquad J_\nu$$

- radiative equilibrium (+ convective en **conservation**:

$$\int_0^\infty H_\nu \, d\nu = \text{const.} = \frac{\sigma}{4\pi} T \qquad \Rightarrow \qquad T$$

- hydrostatic equilibrium – **momentum conservation**:

dP



+ ideal gas

mann-formula

$e^{-\left(\frac{E_{up}-E_{low}}{kT}\right)}$

ns

$= \sum_{j\neq i} n_j(R_{ji} + C$

- **charge conservation**:

$$\sum_i n_i Z_i - n_e = 0 \qquad \Rightarrow \qquad n_e$$

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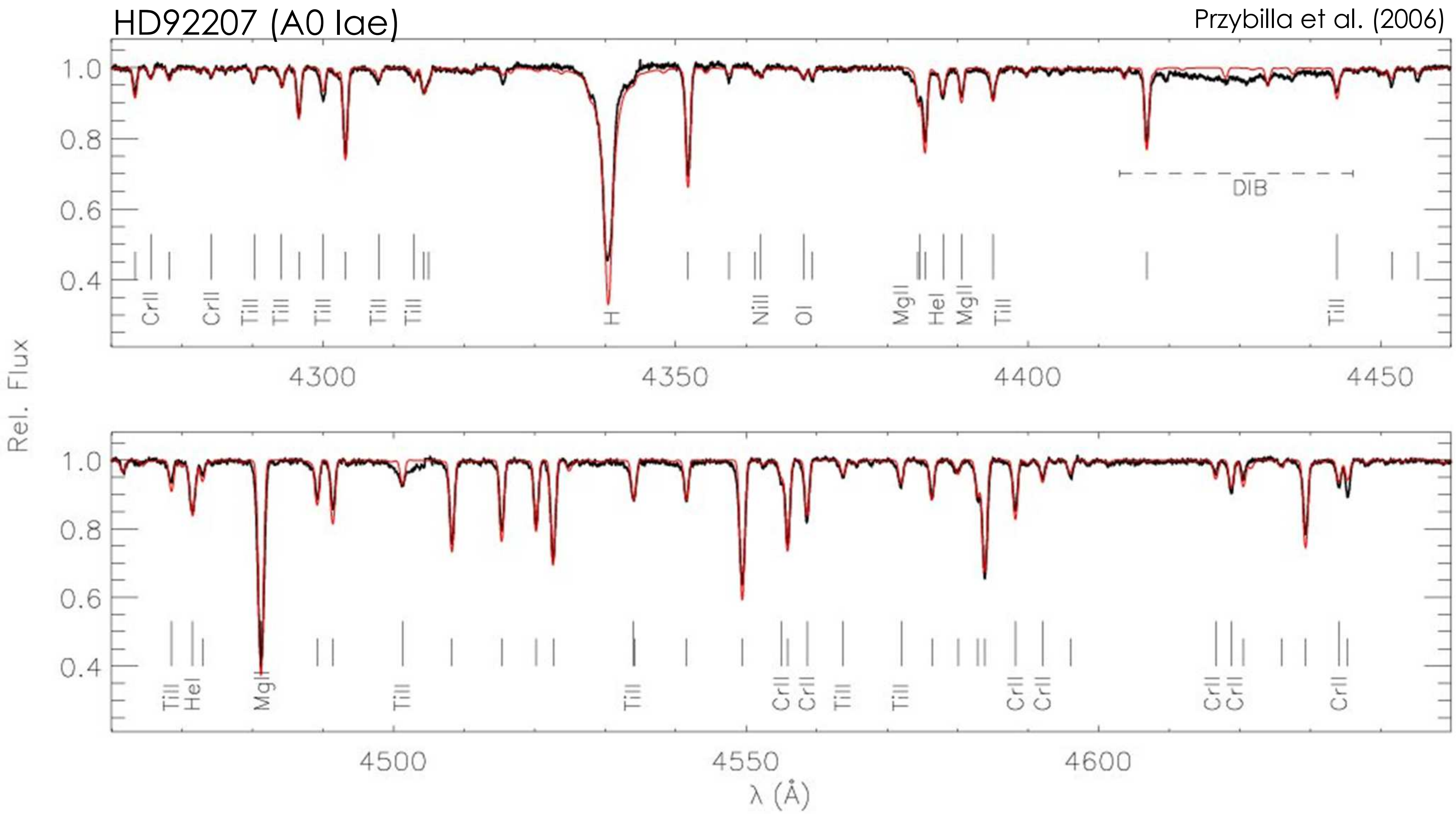
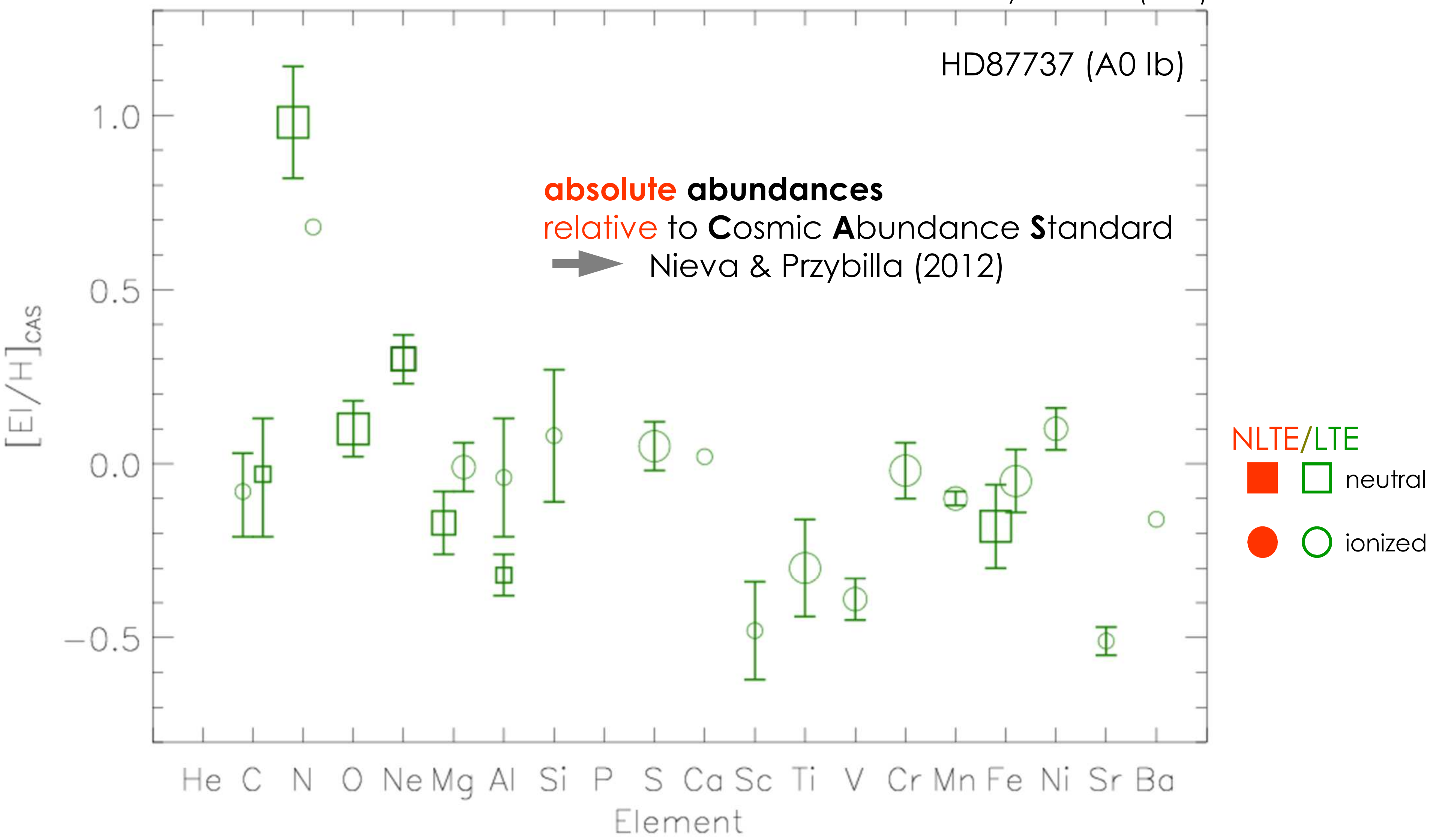
Modelling: testing @ visual wavelengths



- several 10^4 lines: ~30 elements, 60+ ionization stages
- complete spectrum synthesis in visual (& near-IR) ~70-80% in non-LTE
- close match of models and observations

Elemental Abundances

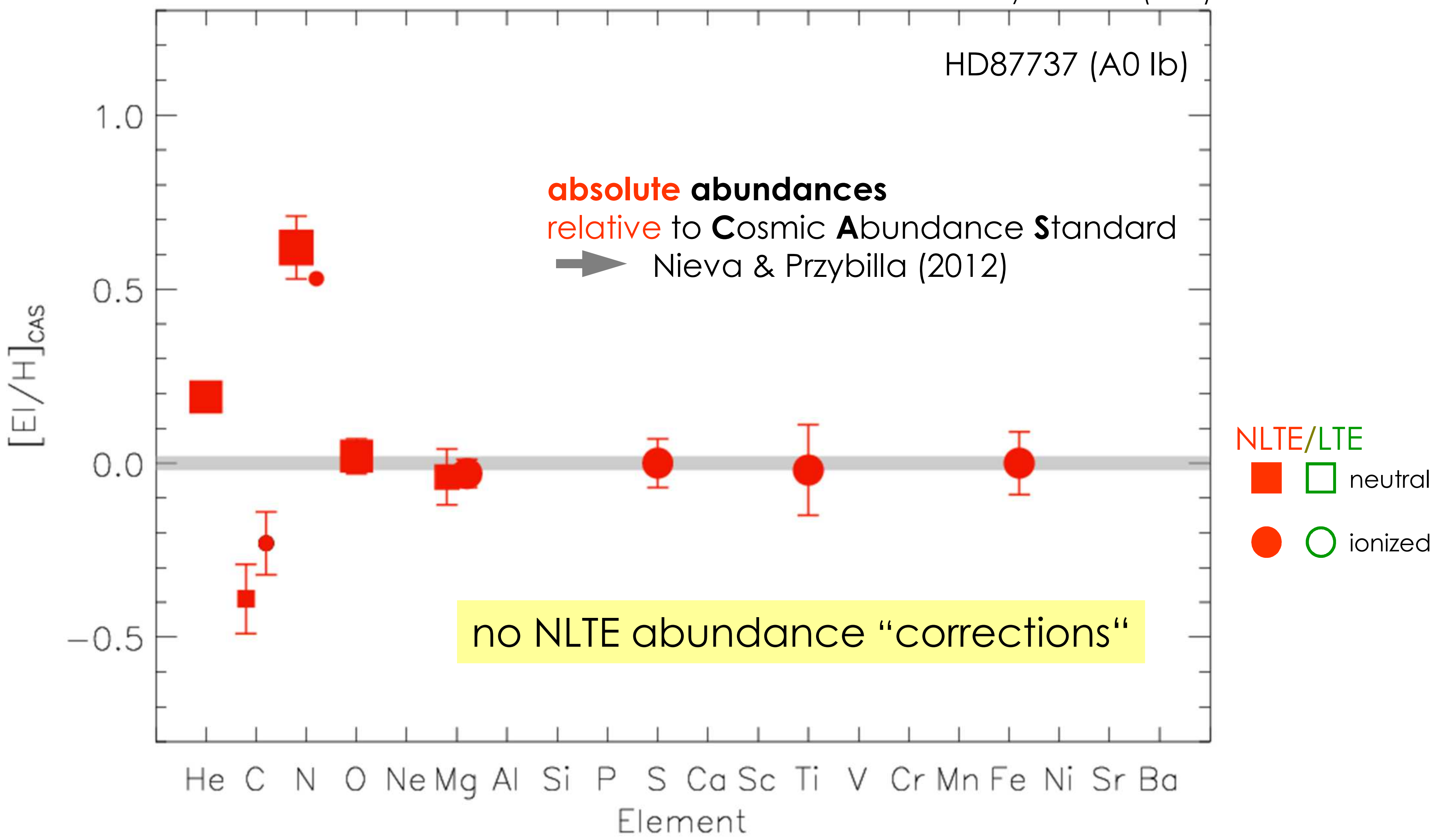
Przybilla et al. (2006)



- LTE: abundance pattern?   - large uncertainties

Elemental Abundances

Przybilla et al. (2006)



- **NLTE: consistency & reduced uncertainties**

Summary: non-LTE Modelling

using **robust analysis methodology** &
comprehensive model atoms

minimising systematics !

- ionization equilibria → T_{eff}/log g
  elements: e.g. C I/II, N I/II, O I/II, Mg I/II, Si II/III, S II/III, Fe I/II
  Δ T_{eff} / T_{eff} ~ 1…2% usually: 5…10%
- Stark broadened hydrogen lines → log g/T_{eff}
  Δ log g ~ 0.05 (cgs) usually: 0.2
- microturbulence, helium abundance, metallicity

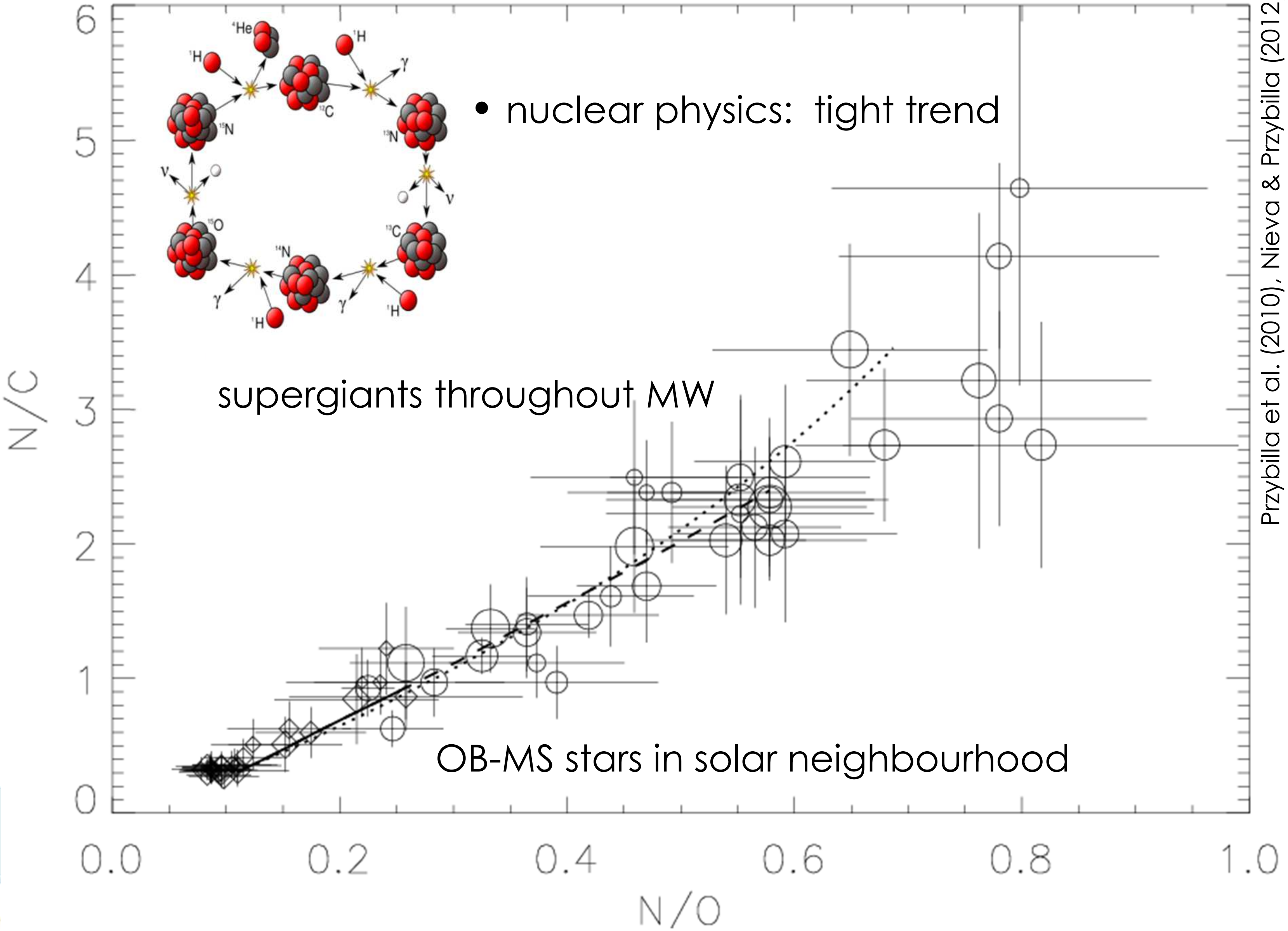
+ other constraints, where available: SED's, near-IR, …

- abundances: **Δlogε ~ 0.05...0.10 dex** (1σ–stat.) usually: factor ~2
  Δlogε ~ 0.07...0.12 dex (1σ–sys.) usually: ???

→

+ automatisation: tens to hundreds of stars analysable

CNO mixing: objective quality test for analyses



Przybilla et al. (2010), Nieva & Przybilla (2012), Firnstein & Przybilla (in prep.)

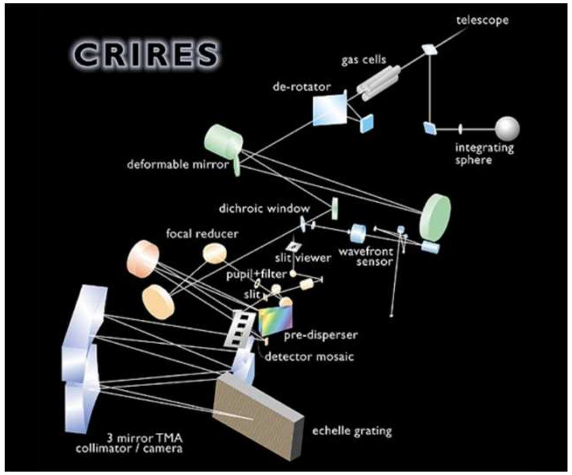
Preparing for E-ELT: Galactic BSGs with CRIRES

CRyogenic high-resolution **I**nfrared
Echelle **S**pectrograph CRIRES@VLT-UT1

- high resolving power R = $\lambda/\Delta\lambda \leq$ 100,000
- wavelength coverage 0.95 to 5.3 µm
- **~ 200 settings for full spectral coverage**
  → CRIRES+
- detector: 4 x 4096 x 512 Aladdin III InSn

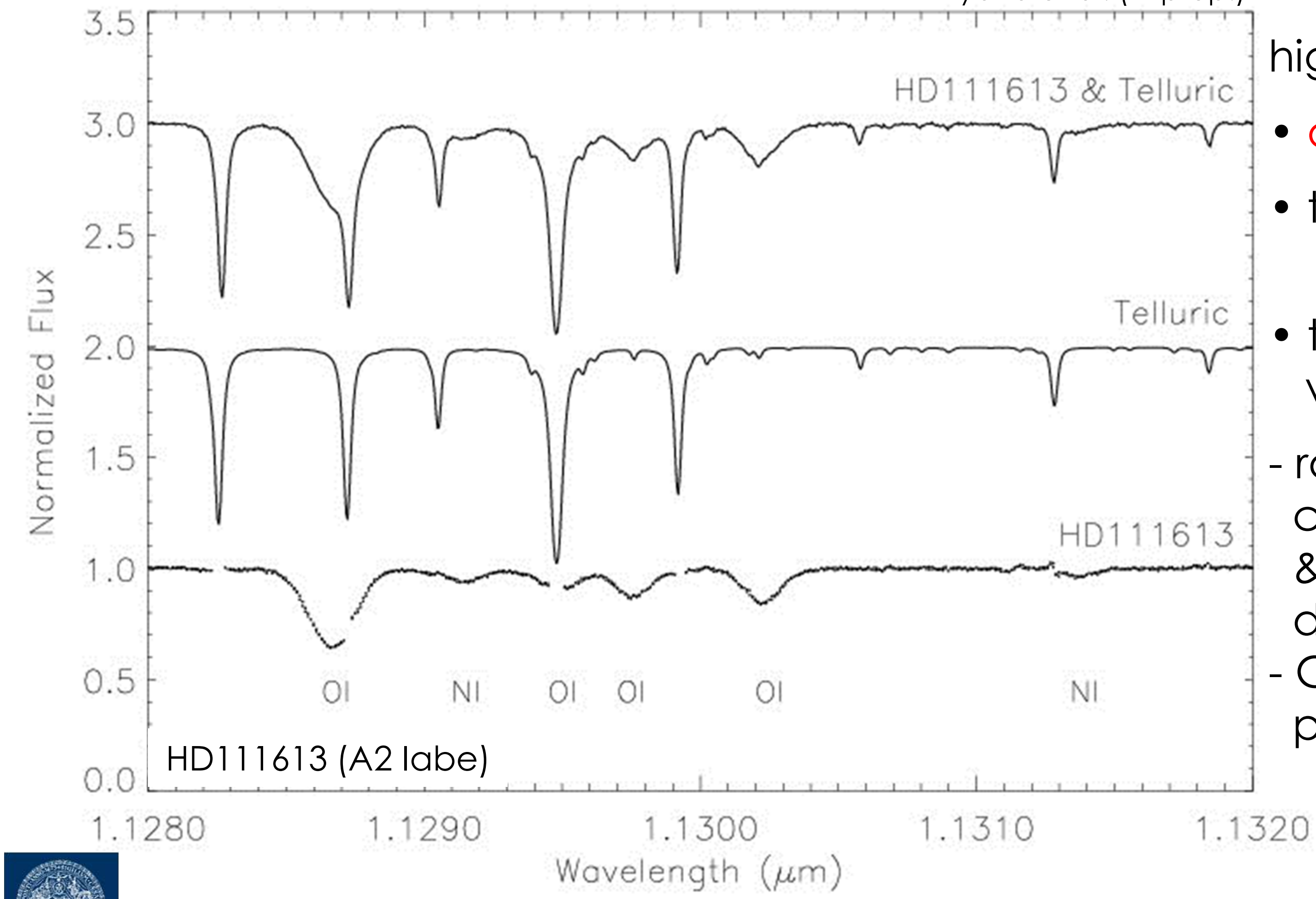
Pilot program: 3 A-SGs HD87737 (A0 Ib)
HD111613 (A2 Iabe)
HD92207 (A0 Iae)

- (partial) coverage of J, H, K, L band



Near-IR: Telluric Line Correction

Przybilla et al. (in prep.)



high-resolution:

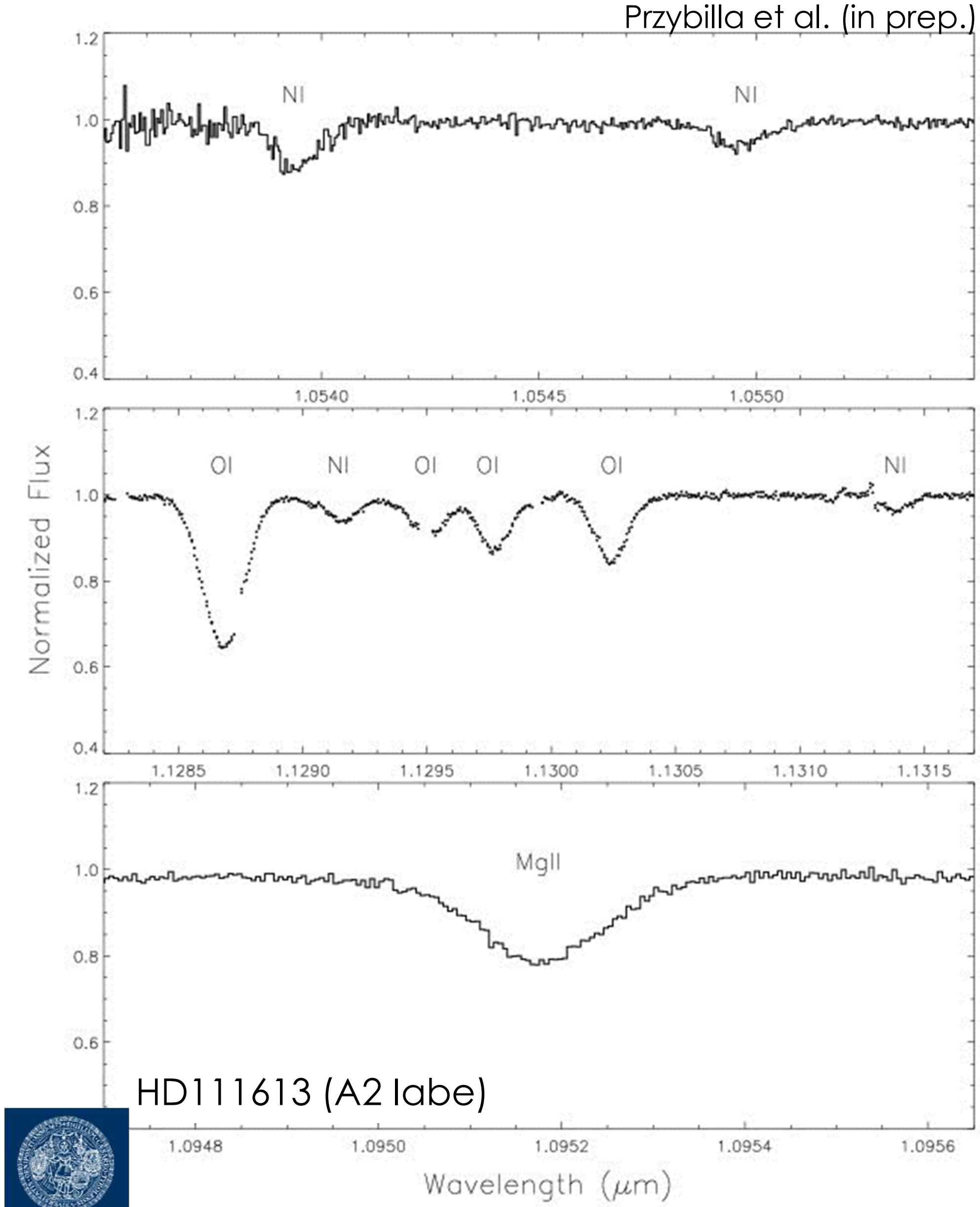
- detailed line profiles
- telluric lines resolved

- telluric line removal via modelling:

- radiative transfer code LBLRTM & HITRAN molecular database
- GDAS atmospheric profiles

adaptation expertise of Innsbruck ESO In-Kind Project

Near-IR spectra



- H + He → atmospheric parameters
- metal lines in near-IR:
  C, N, O, Mg, Si, Fe, Sr + He

→ stellar evolution

→ **galactochemical evolution**

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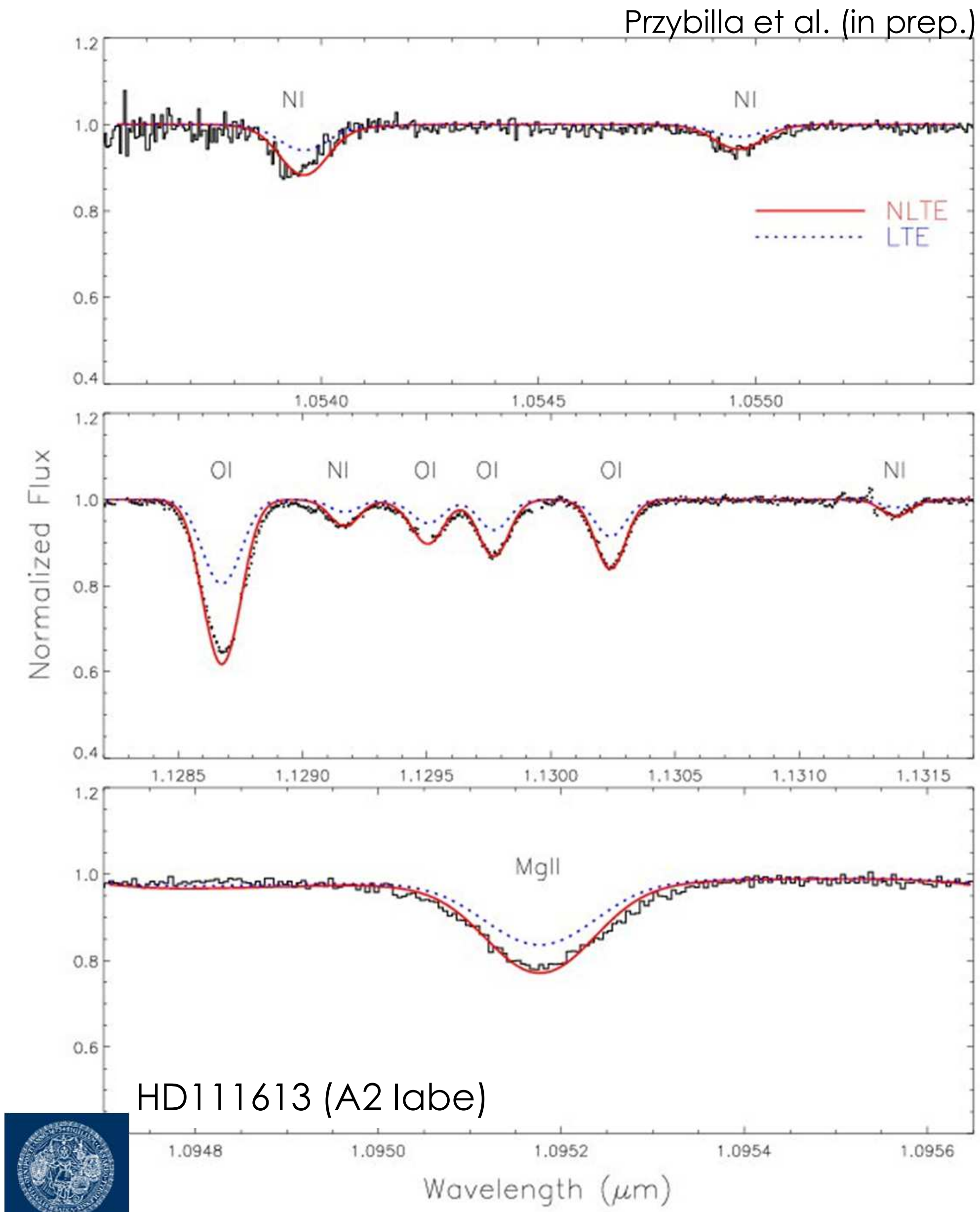
Near-IR spectra



- H + He ➤ atmospheric parameters
- metal lines in near-IR:
  C, N, O, Mg, Si, Fe, Sr + He

  ➤ stellar evolution

  ➤ **galactochemical evolution**

- **modelling**:
  - extension of previous modelling
  - strong NLTE effects
  - good agreement with visual
    but
    adjustment of some model atoms necessary (NLTE amplification)
    ➤ improved atomic data

preparation for E-ELT (✓)

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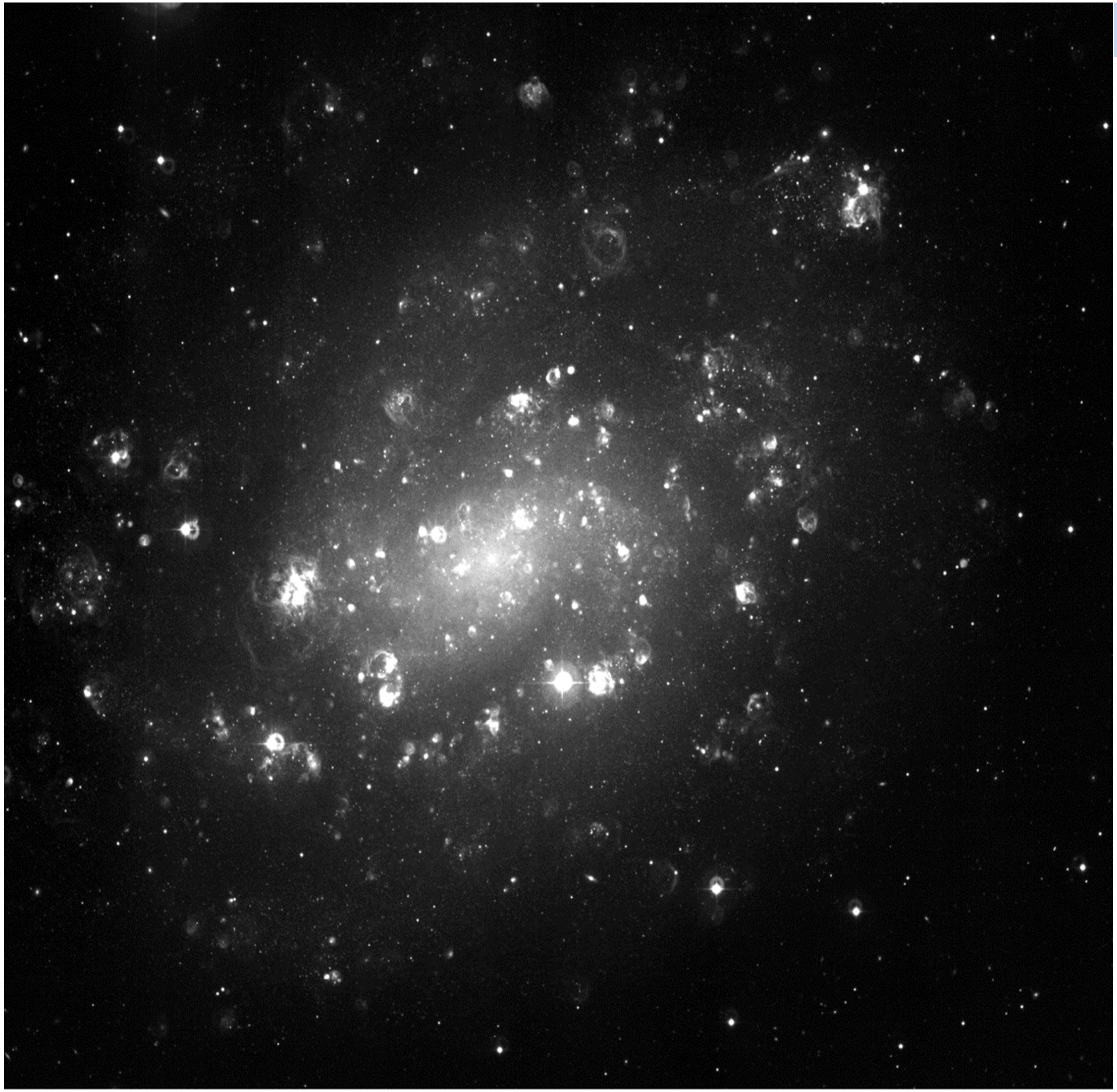


Spiral Galaxy NGC 300 (H-alpha band)
(MPG/ESO 2.2-m + WFI)

ESO PR Photo 18c/02 (7 August 2002)

Extragalactic Abundances

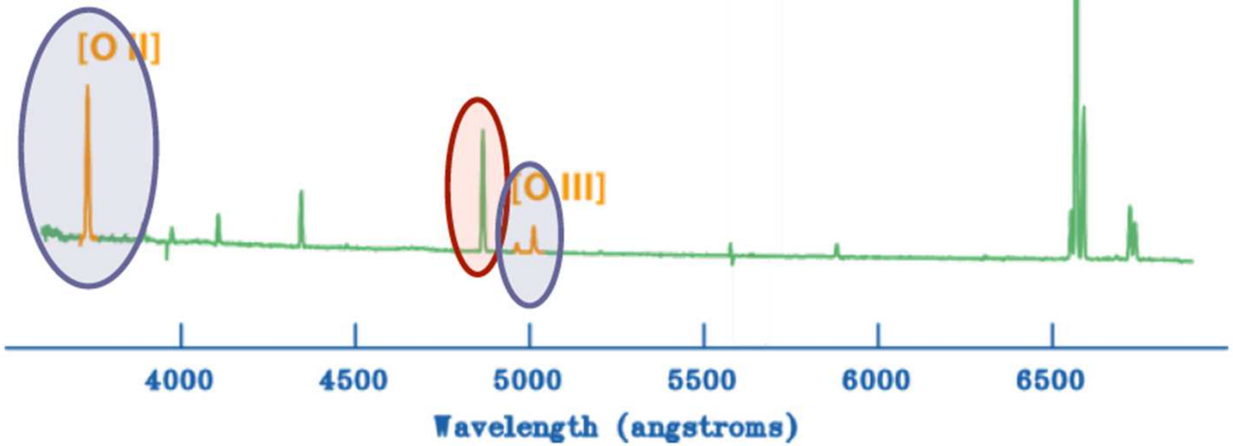
- so far:
  HII regions
  only indicators for abundances
  in nearby galaxies:
  He, N, O, Ne, S
- verification and extension via stars

Nebular abundances

strong line method: $R_{23} = f[N(O)/N(H)]$

$$R_{23} = \frac{[\mathrm{O\,II}]3727 + [\mathrm{OIII}]4959, 5007}{\mathrm{H}\beta}$$

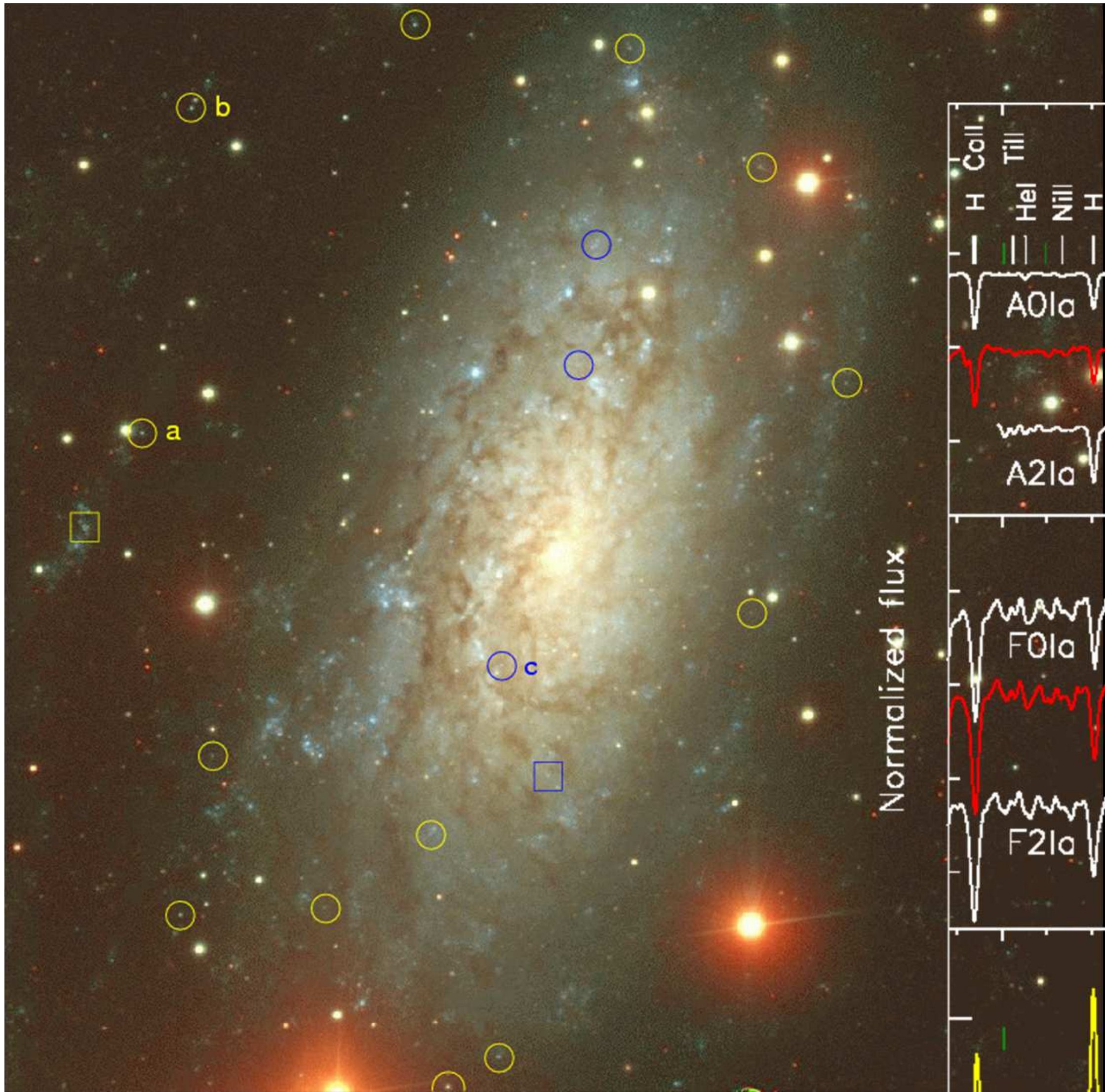
Pagel et al. (1979)

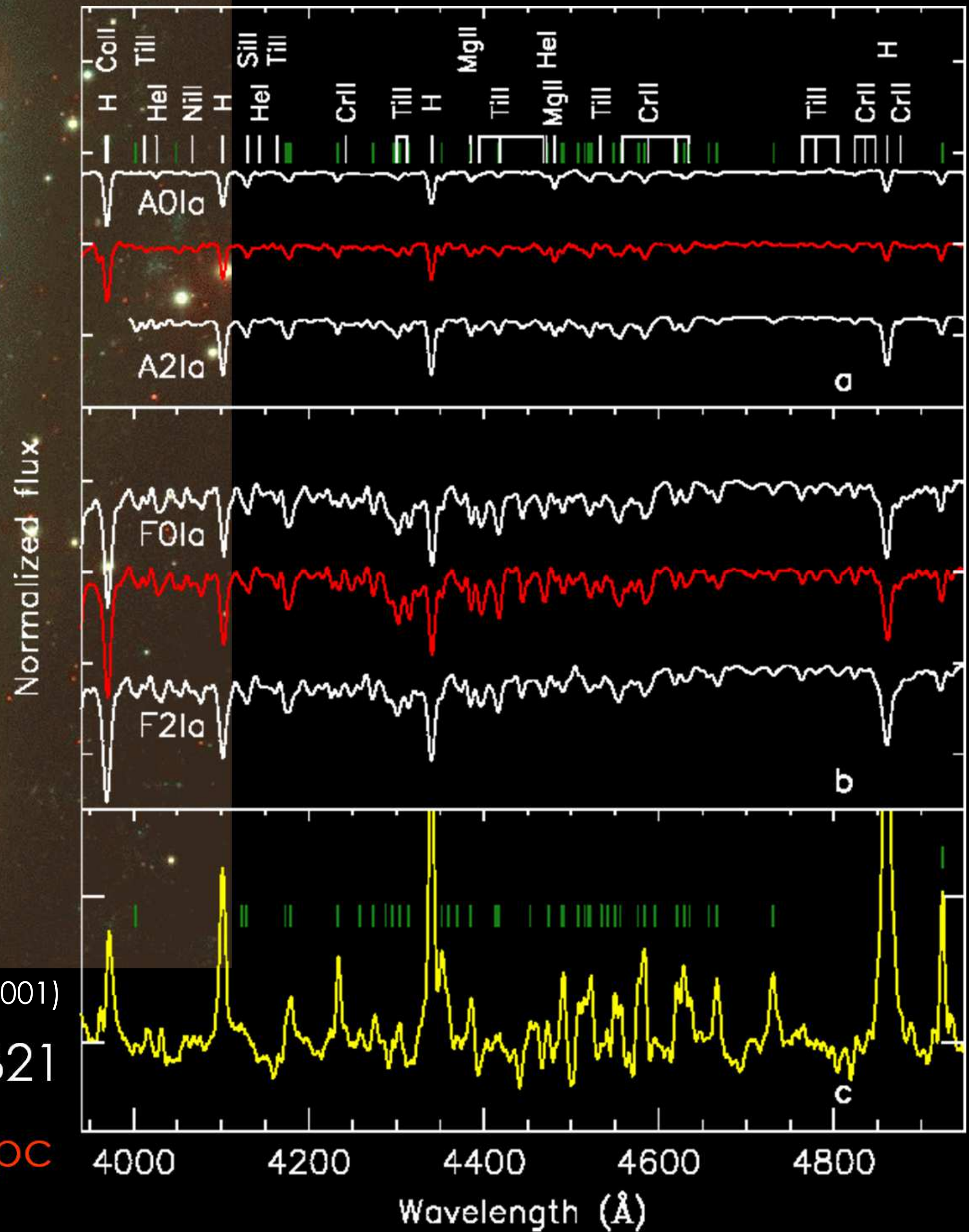


simple empirical calibration, but...

R_{23} depends on

$T_{electron}$, $n_{electron}$, nature of ionizing stars, gas inhom., filling factors, depletion onto dust, velocity distribution, ...



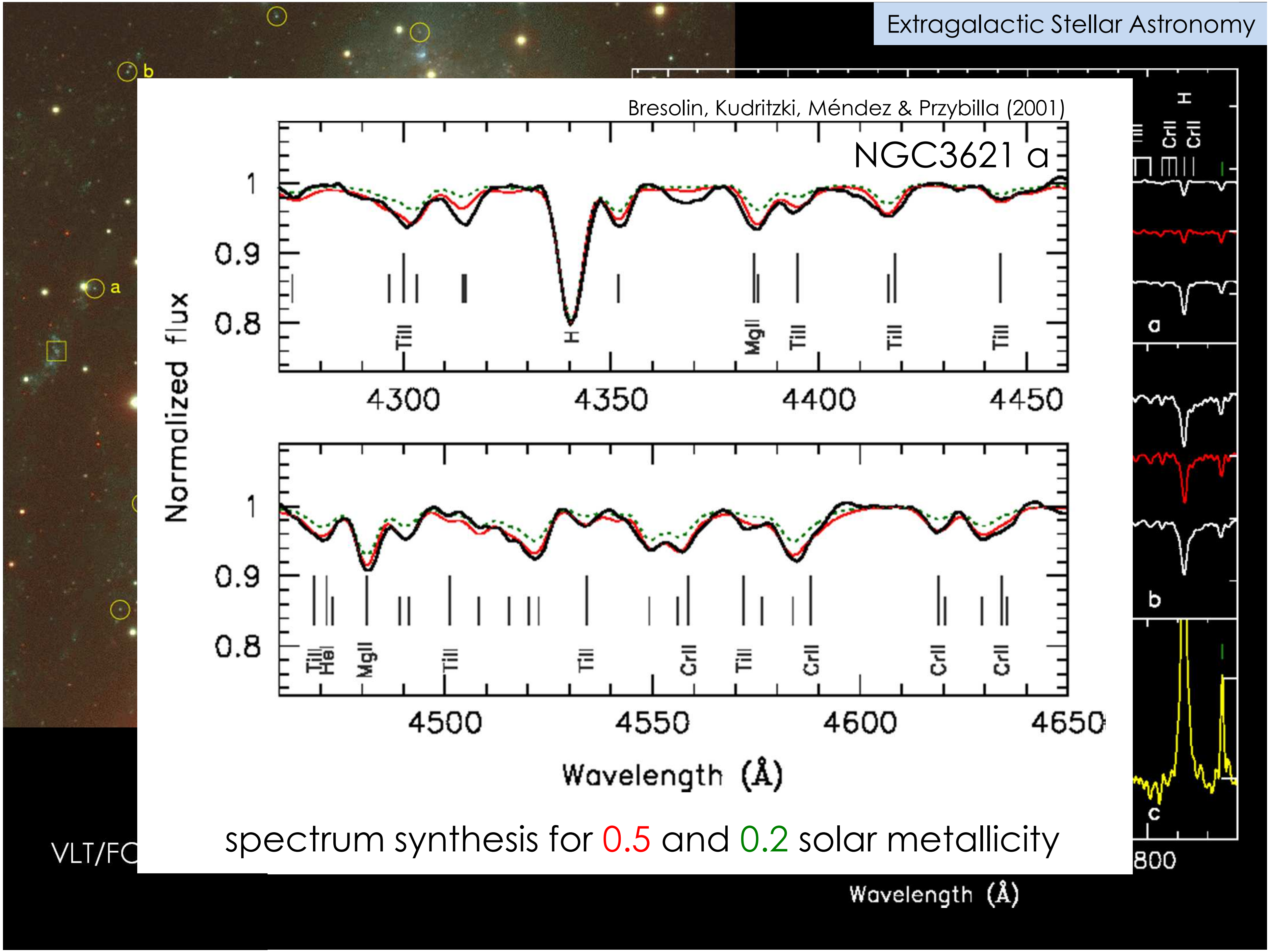


Bresolin, Kudritzki, Méndez & Przybilla (2001)

NGC 3621

VLT/FORS1

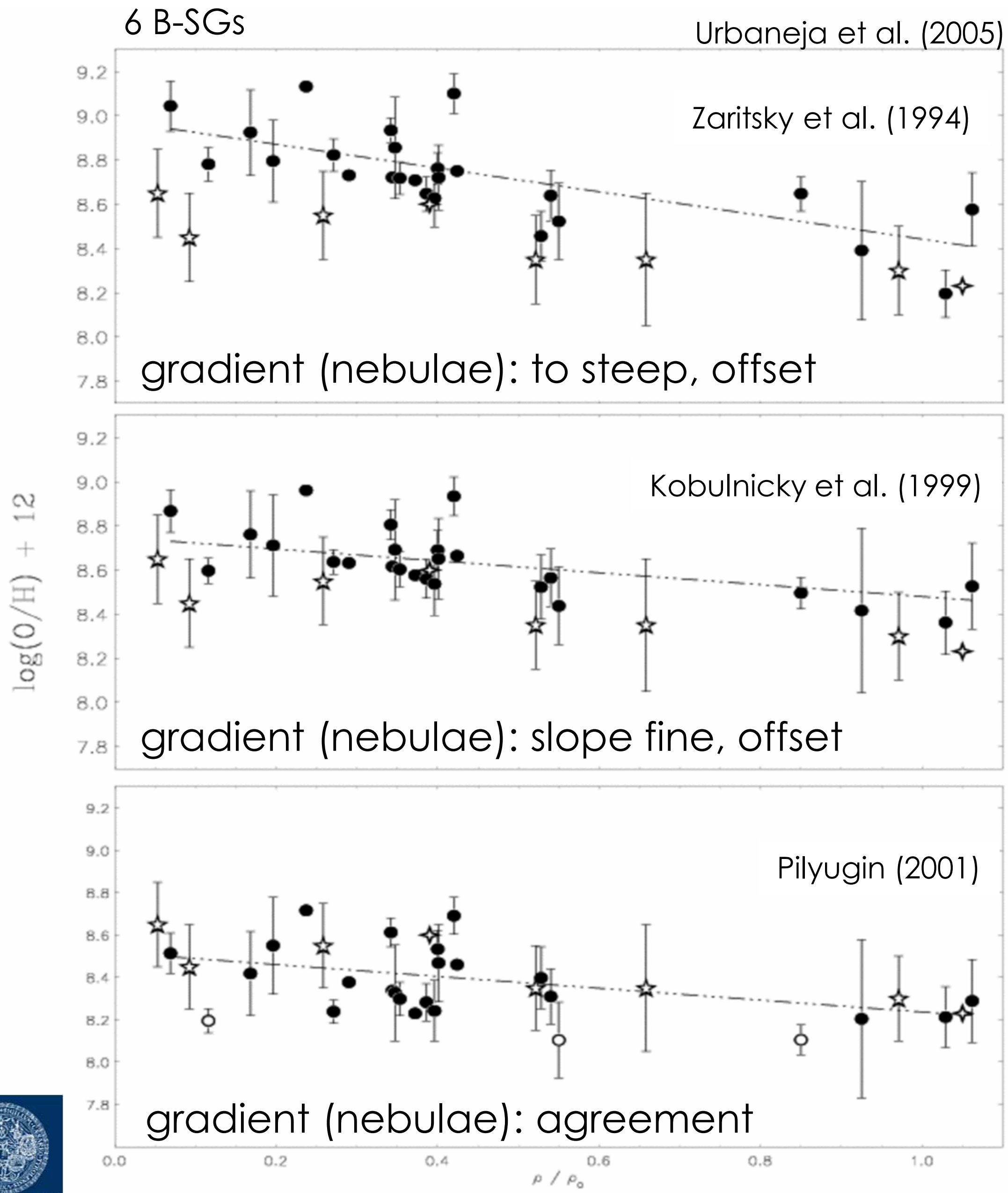
d ~ 6.6 Mpc



spectrum synthesis for 0.5 and 0.2 solar metallicity

Abundance Gradients

NGC300



- radial trend of O abundances
- different trends for HII-regions from 3 different R_{23}-calibrations
- **independent verification and extension via stellar analyses**
- **systematic bias in published gradients?**

→ Talk Miguel Urbaneja

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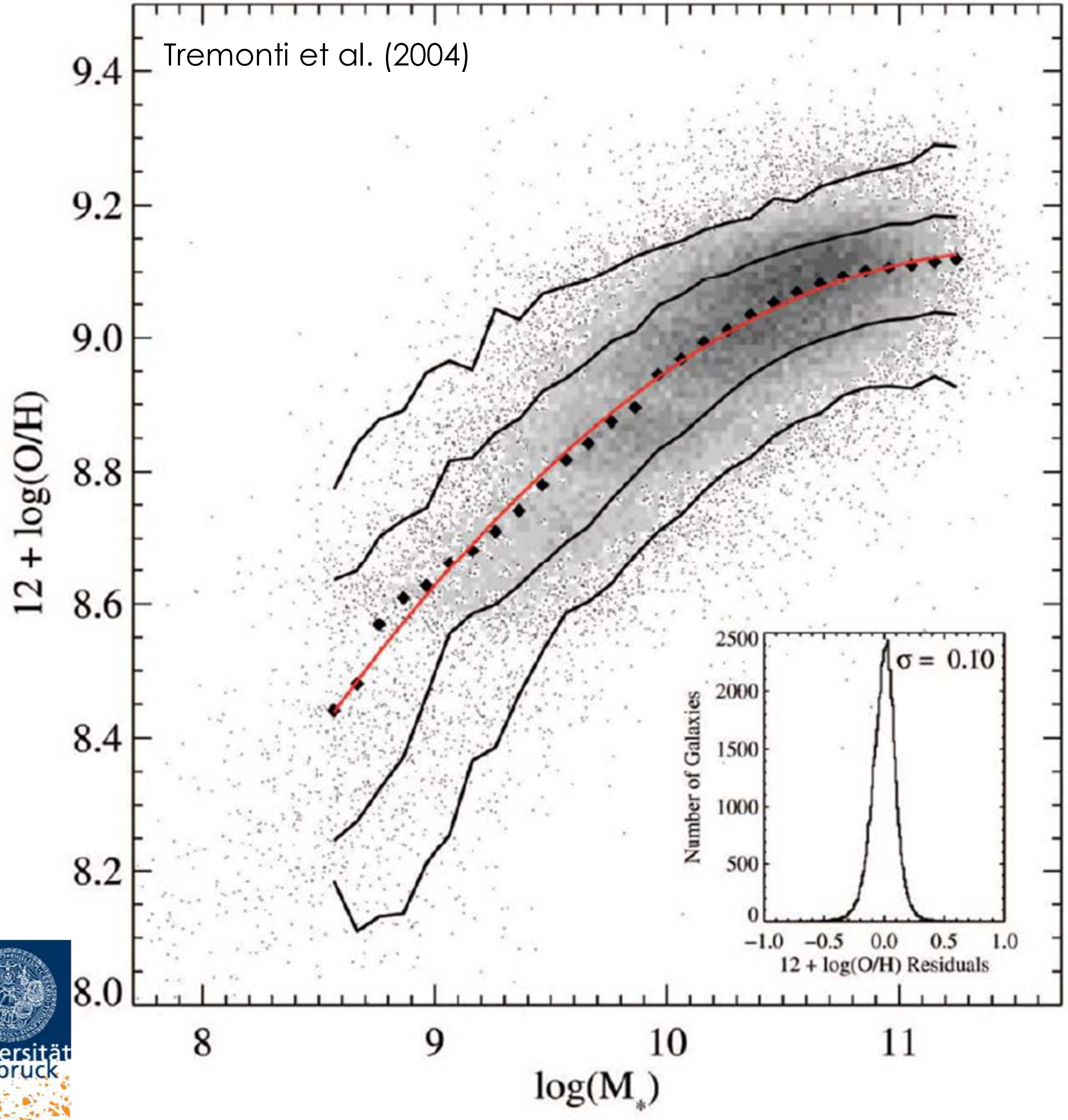
Mass-metallicity relationship



Rosetta Stone

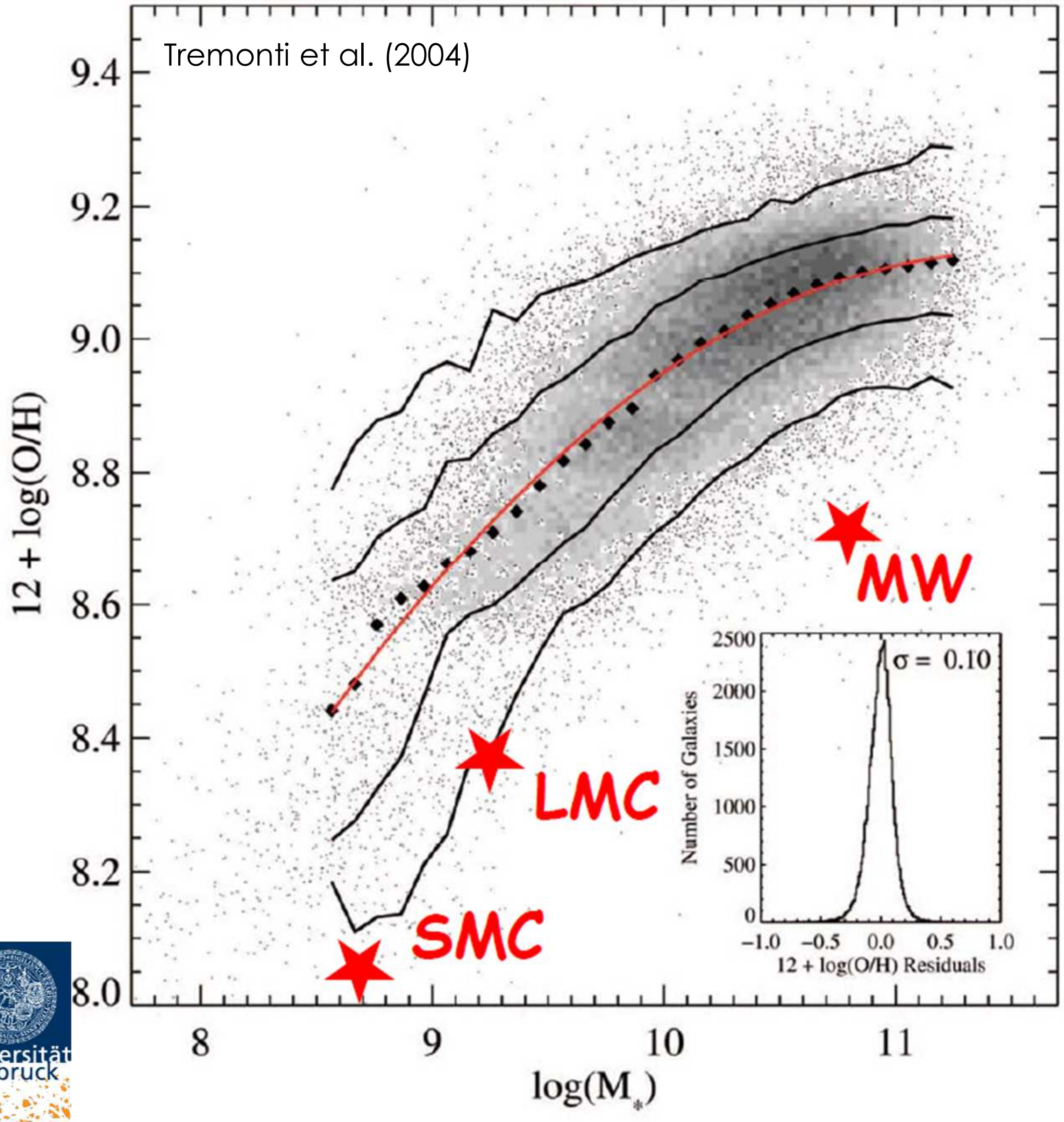
for understanding

galaxy formation

and

chemical evolution

Mass-metallicity relationship

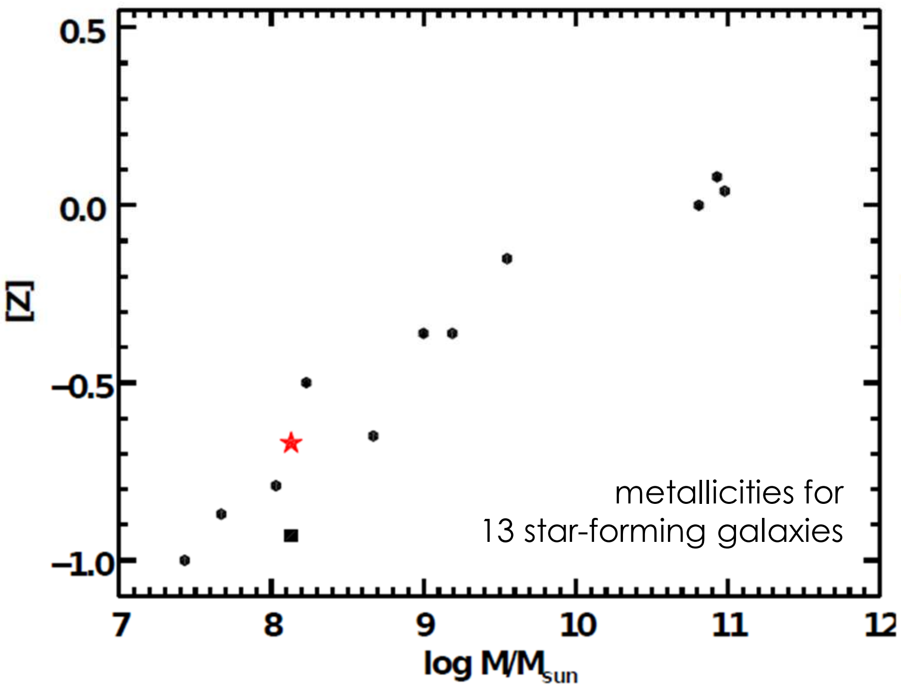


However...

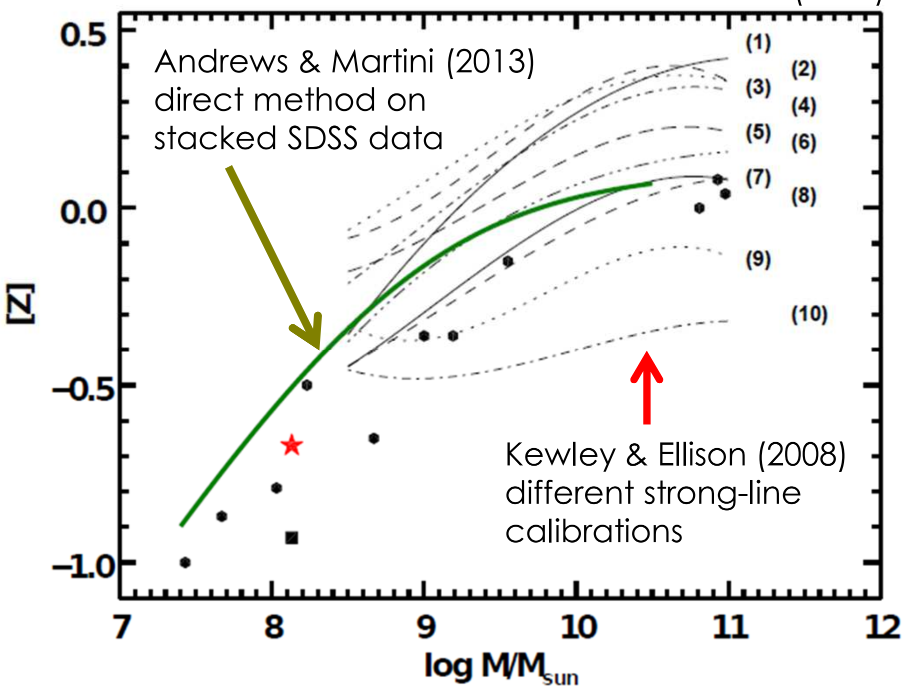
something must be wrong ...

based on simplified emission line analysis

Mass-metallicity relationship - the stellar case



Hosek et al. (2014)



stellar

Local Group and beyond

stellar

vs.

strong line analyses of HII regions

→ investigate and minimise
systematic bias of extragalactic metallicities

H_0 uncertainty and universe equation of state

Hubble constant uncertainty
→ EoS parameter w

$$\frac{\delta w}{w} \approx 2 \frac{\delta H_0}{H_0}$$

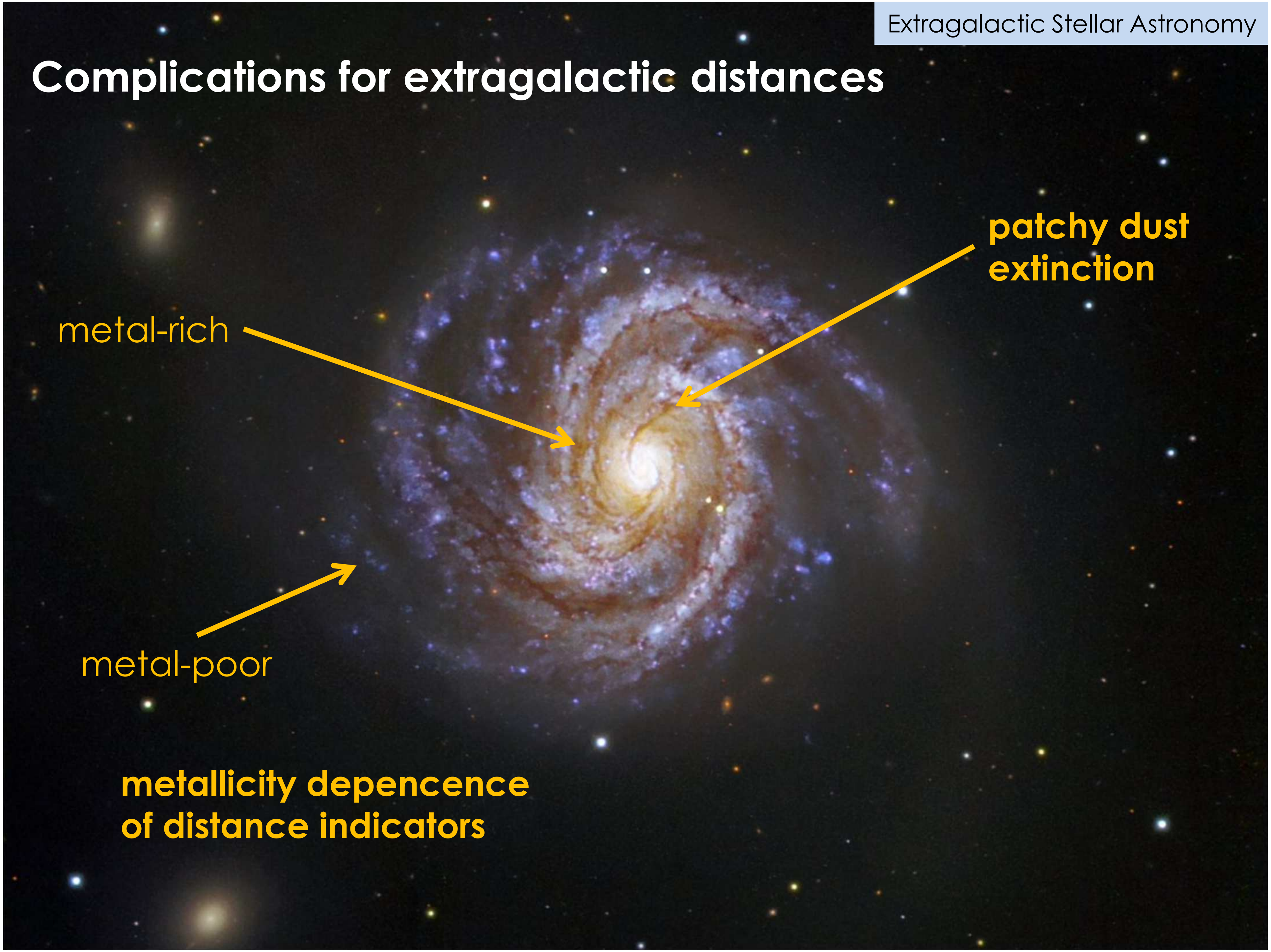
$$w = \frac{p}{c^2 \rho}$$

despite enormous effort still: δH_0 ~ 5-10% w ~ 10-20%

compare
Freedman et al. (2001)
Saha et al. (2001), Sandage et al. (2006)
Mould & Sakai (2008, 2009ab)
Riess et al. (2009, 2011, 2012) → **δH_0 ~ 3%**

→ **δH_0 ~ 1%**

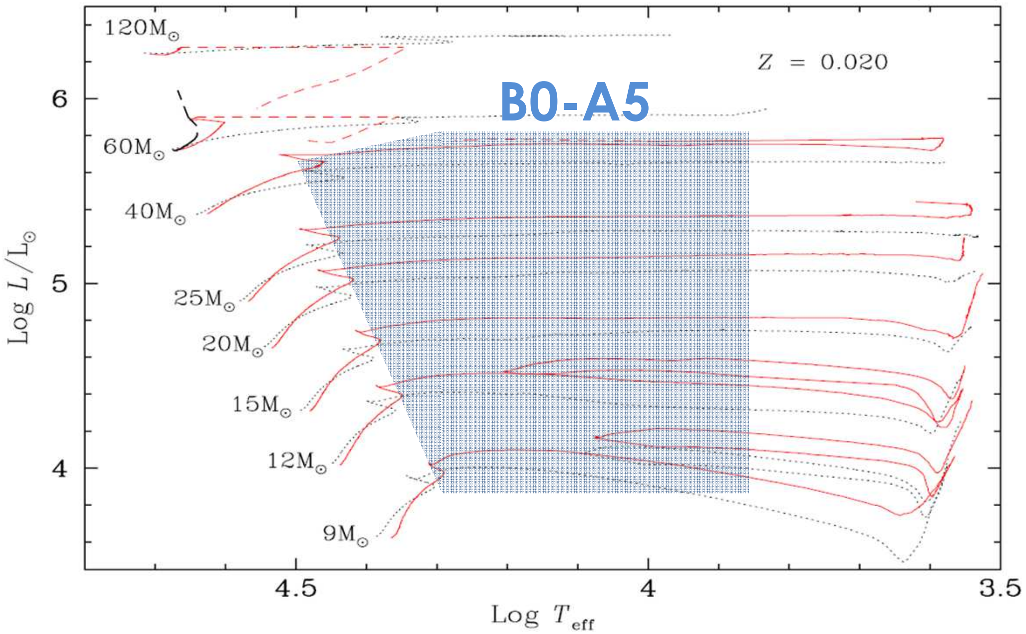
Complications for extragalactic distances



Flux weighted Gravity – Luminosity Relationship (FGLR)

Kudritzki, Bresolin & Przybilla (2003)

Meynet & Maeder (2000)



L, M ~ const.

M ~ g × R² ~ L × (g/T⁴) = const.

const.

with L ~ M^x ~ $L^x(g/T^4)^x$ x ~ 3

$L^{1-x} \sim (g/T^4)^x$

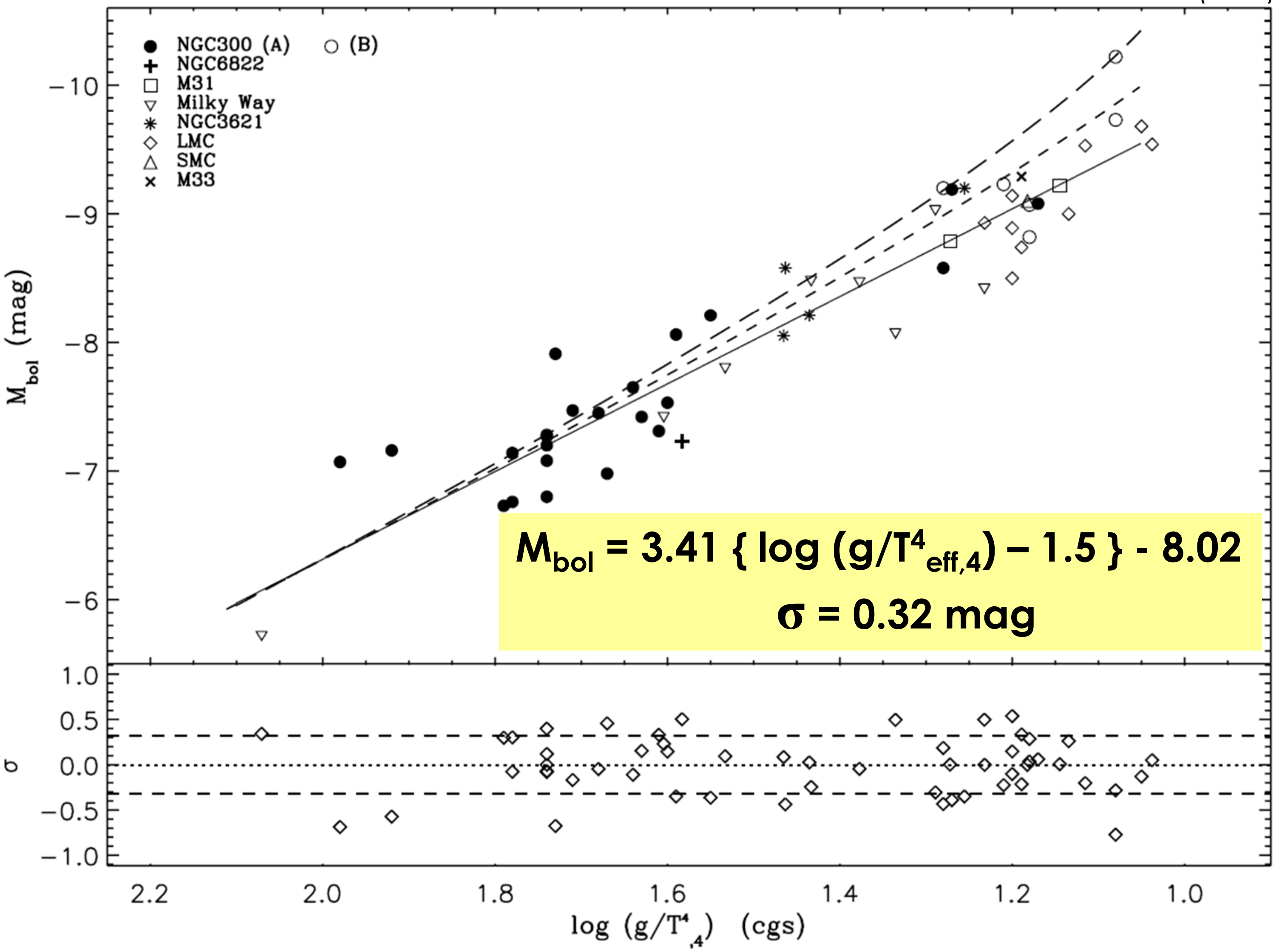
or with M_{bol} ~ -2.5log L

$M_{bol} = a \log (g/T^4) + b$ FGLR

a = 2.5 x/(1-x) ~ 3.75

Calibration of the FGLR

Kudritzki et al. (2008)



$$M_{bol} = 3.41 \{ \log (g/T^4_{eff,4}) - 1.5 \} - 8.02$$

$$\sigma = 0.32 \text{ mag}$$

10 objects per galaxy → $\Delta(m - M) \sim 0.1$ mag

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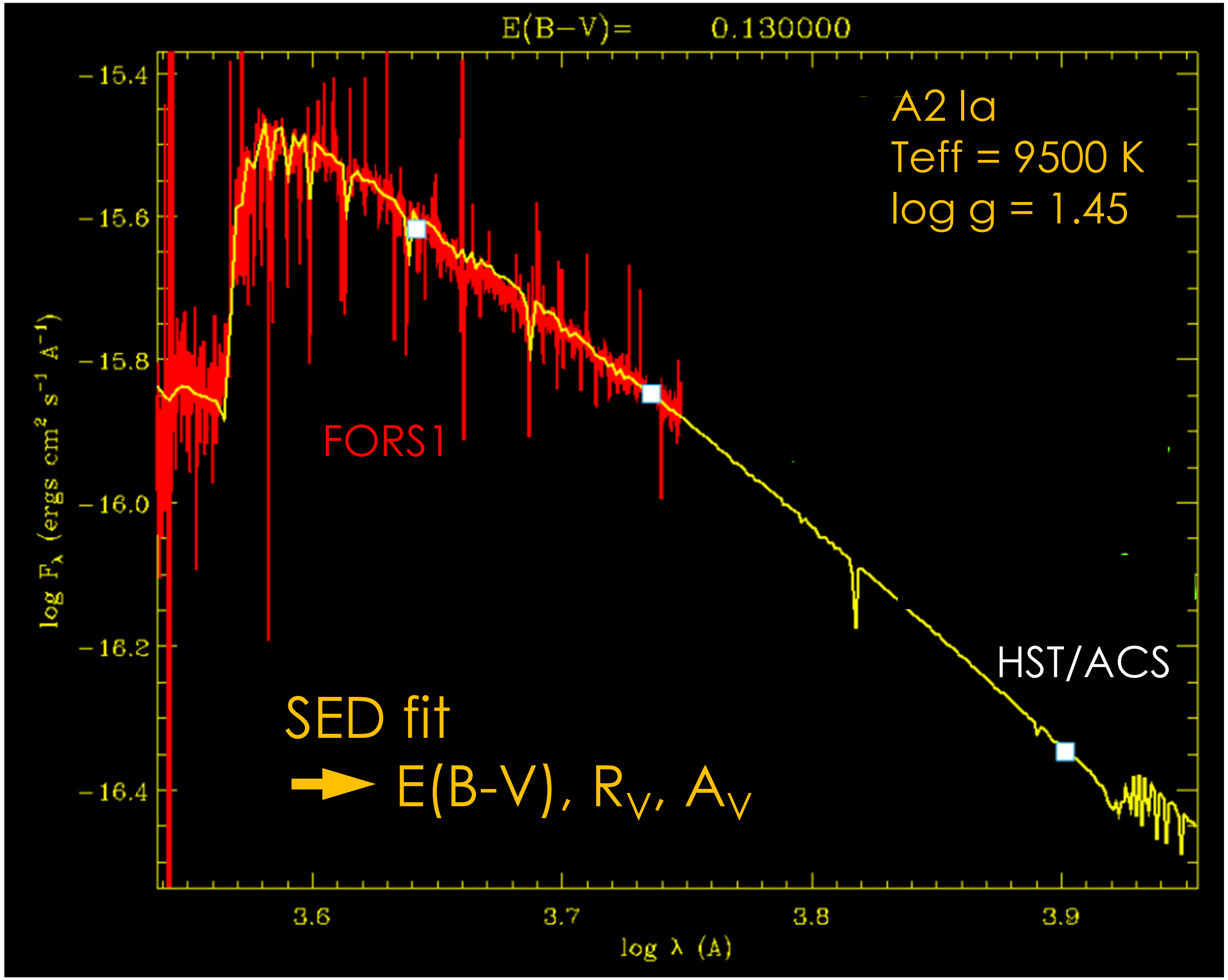
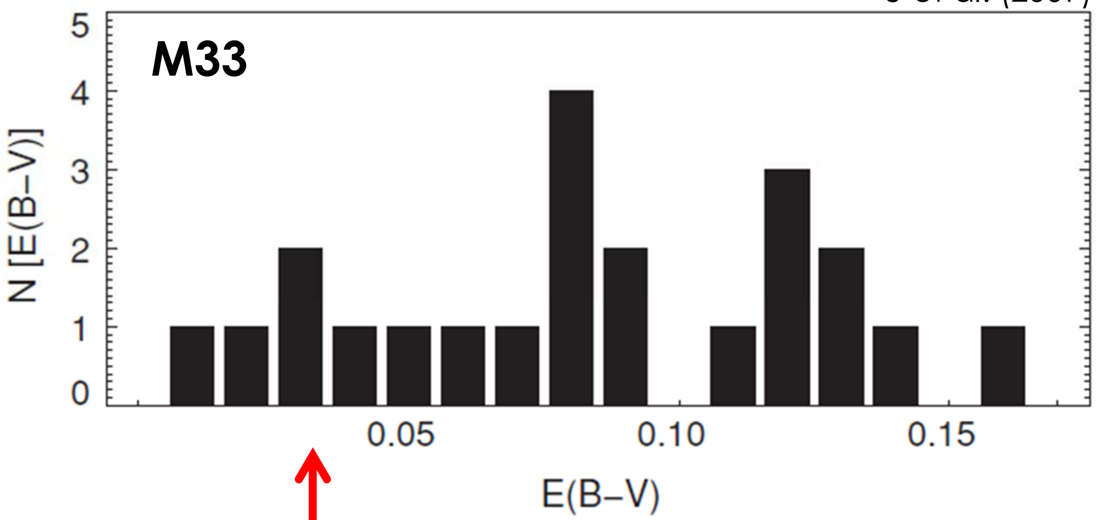
Reddening, reddening law, extinction

Kudritzki et al. (2008)



Reddening & impact on distances

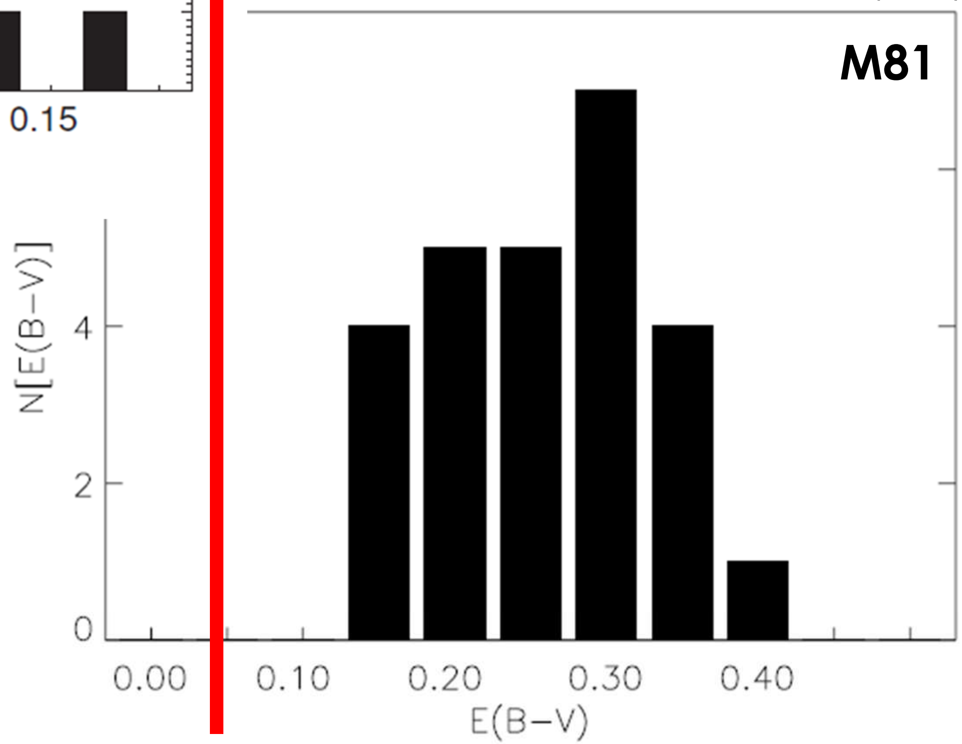
U et al. (2009)



distance too short

distance too large

Kudritzki et al. (2012)

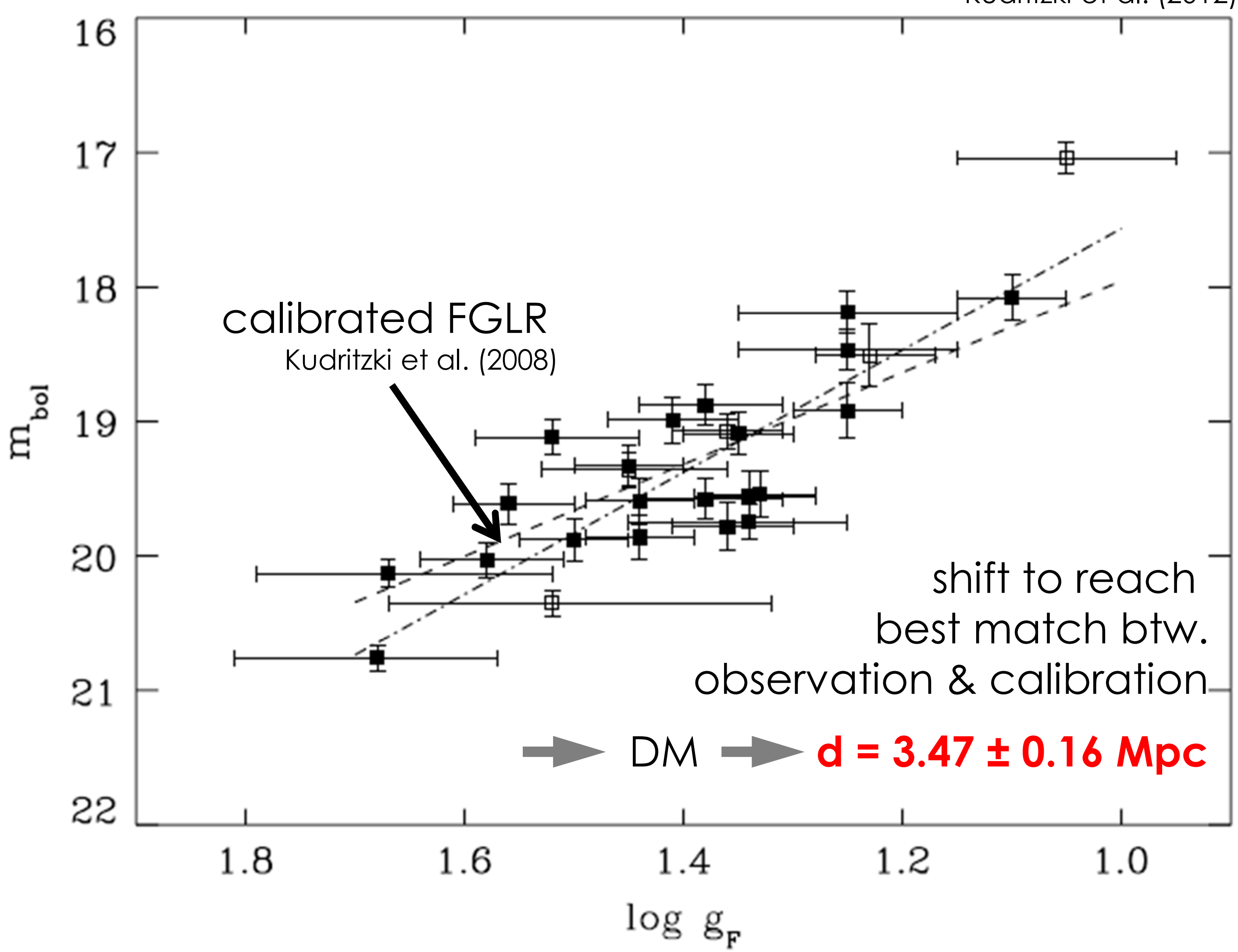


adopted by HST Key Project

Freedman et al. (1994, 2001)

Distance determination with FGLR

Kudritzki et al. (2012)



The E-ELT perspective

from the Local Group to Virgo & Fornax

NGC6822 14'

NGC300 27'

NGC253 26'

Field of View: several arcmin ideal

CenA 16'

M100 (Virgo) 22'

Target density O(100) in FoV
depends on galaxy

NGC1365 (Fornax) 12'

R ~ 5000 sufficient for quantitative work on BSGs

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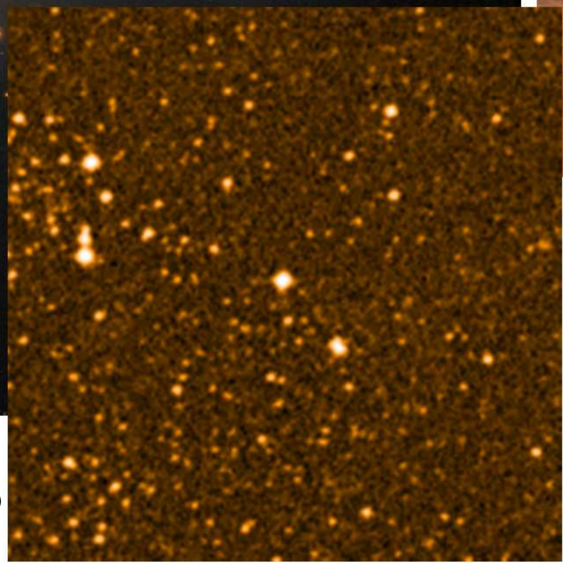
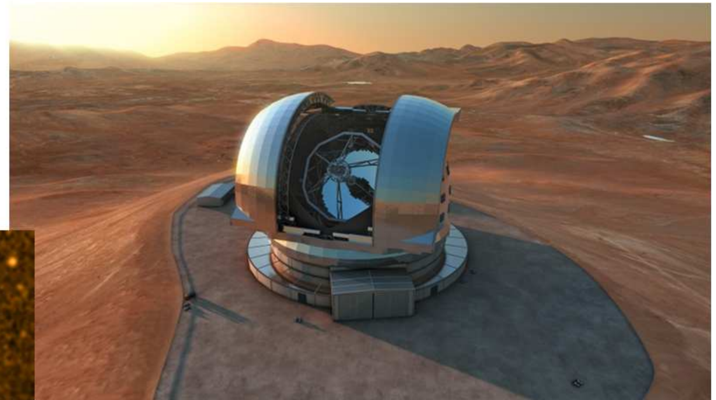
Stellar Spectroscopy in Virgo & Fornax



5.5‘ x 5.5‘ in LMC
→ 1“ x 1“ @ Virgo

problem: spatial resolution
1“@16.5Mpc: ~80pc

→ **diffraction-limited observation with ELT using AO (near-IR)**



deployable IFUs

S/N constraints:
S/N > 50 100 ☺

Summary: BSGs are unique tools

- stellar atmosphere physics: non-LTE, winds, ...
- stellar evolution: metallicity effects → He, CNO
- ISM studies in other galaxies
- **galactic evolution:**
  abundance patterns/gradients
  → galaxies in Hubble sequence
  in field, groups & clusters
- cosmic distance scale: FGLR $L \sim \log g/T_{eff}^4$

Flux-weighted Gravity-Luminosity Relationship