CORRELATION BETWEEN NEUTRAL AND TOTAL HYDROGEN COLUMN DENSITIES IN GPS GALAXIES

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OUTLINE

MOTIVATION

BACKGROUND
- Radio emission and HI absorption
- X-ray emission and absorption
- NH vs. NHI

WORK
- Source sample
- Observations with the WSRT
- Data analysis

RESULTS
- NH-NHI correlation

CONCLUSIONS

MOTIVATION

Constraining

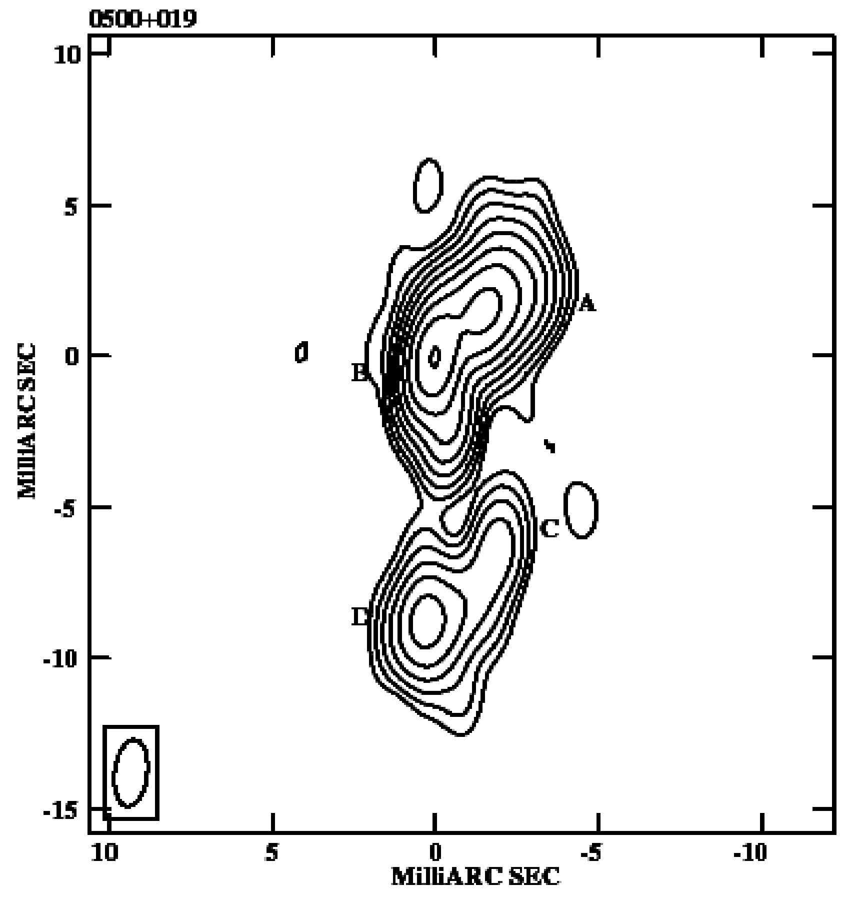
- the dominant source of the X-ray emission
- the location of the radio and X-ray absorbing gas

in GPS galaxies, through absorption studies.

BACKGROUND: Radio emission

GPS galaxies with CSO morphology:

* Spectral turnover at 0.5-10 GHz
* Linear size: < 1 kpc
* Symmetric emission
* Dominance of radio lobes



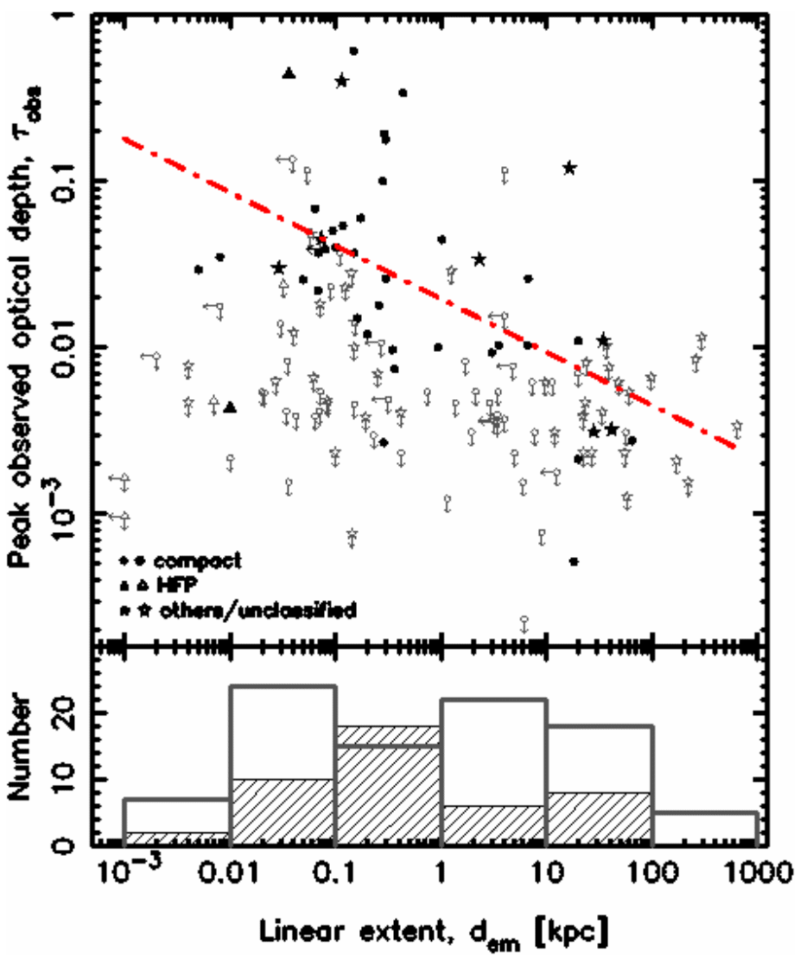
Stanghellini+1997

BACKGROUND: HI absorption

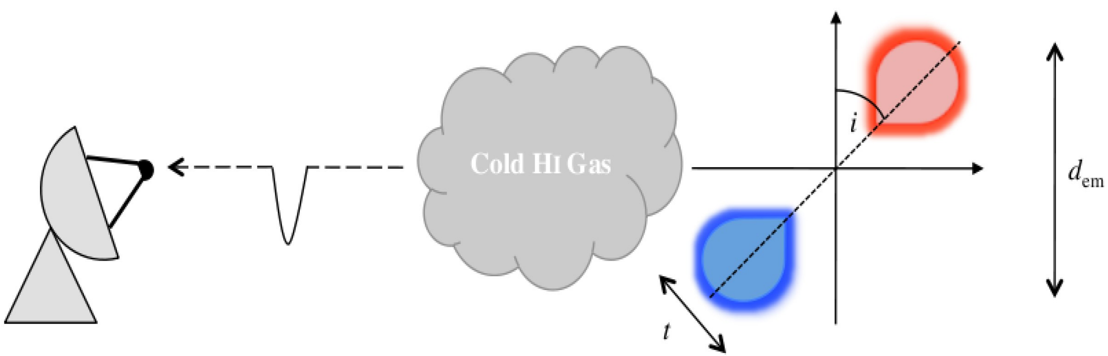
* HI detection rate: - larger in compact than in extended radio sources
[Conway 1997, Pihlström+2003, Vermeulen+2003, Gupta+2006, Curran+2013, Geréb+2014]

- especially large when source size LS=0.1-1 kpc [Curran+2013]

Curran+2013



Cross-section of HI absorbers:
0.1-1 kpc,
"resonance" with the radio source

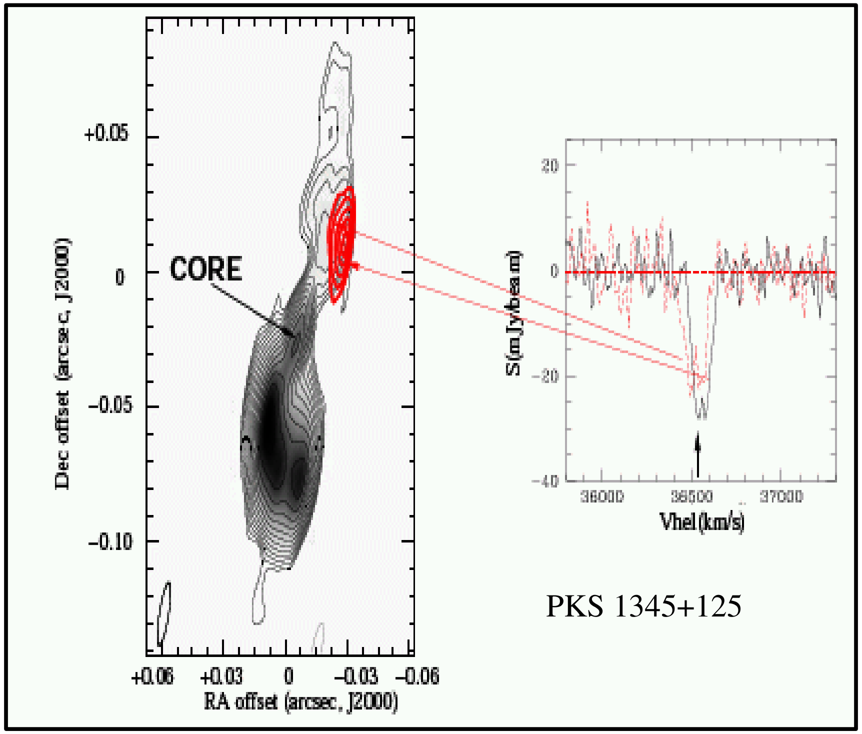


BACKGROUND: HI absorption

* Remarkable variety of $\tau_{obs,peak}$ (0.001-0.6) and FWHM (~10-1000 km/s)
* Spectral velocities red-shifted and blue-shifted (up to ~1000 km/s) w.r.t. host's systemic velocity
* Prominent wings ~1000 km/s

→ <u>COMPLEX GAS DYNAMICS</u>

Morganti++2004



* High angular resolution HI observations:
  - HI generally detected against radio lobe(s) [Araya+2010 and refs. therein]
  - Cf~0.01-1 [e.g., Araya+2010, Morganti+2004,2013]

→ <u>INHOMOGENEOUS OR CLUMPY ABSORBER</u>

BACKGROUND: HI absorbers

ACTUAL DISTRIBUTION OF GAS: UNKNOWN!

- Circumnuclear, clumpy torus (~100 pc)?

- Inclined, thin, clumpy disk? (~100 pc)

- Clouds interacting with the jet/lobe?

- Clouds flowing in and out of the central region of the galaxy?

...

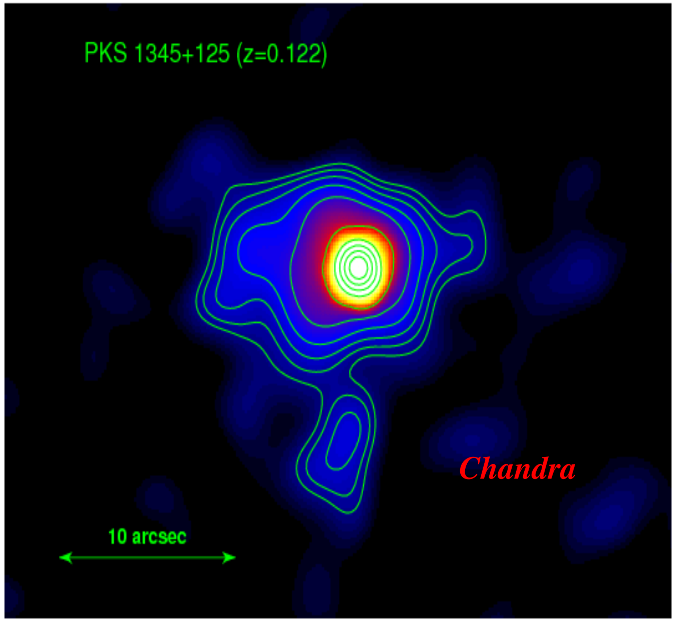
BACKGROUND: X-ray emission

GPS/CSO galaxies:

* High detection rate in X-ray studies

* 18 known sources

* Usually not spatially resolved with Chandra (<1")



Siemiginowska +2008

* Source of X-rays:
  - accretion disc corona: thermal comptonization of disc radiation
    [Guainazzi+2004,2006, Vink+2006, Siemiginowska+2008, Tengstrand+2009]
  - ISM: thermal emission from shocks by the expanding jet
    [Heinz+1998, O'Dea+2000]
  - radio lobes: inverse-Comptonization of local radiation fields
    [Stawarz+2008,Ostorero+2010]

BACKGROUND: X-ray absorption

* Significant degree of absorption [Tengstrand+2009] :

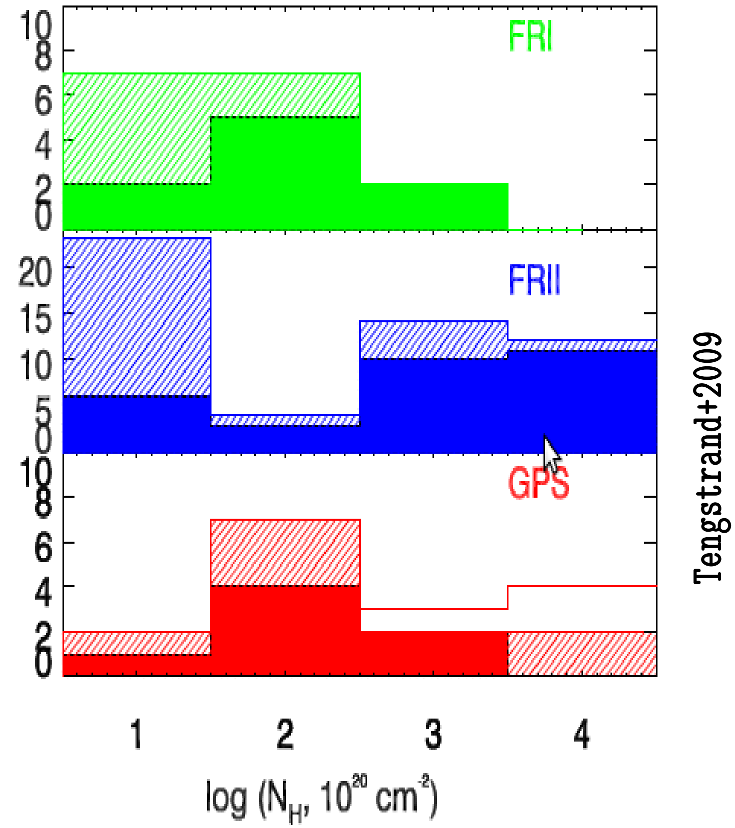
  <NH (GPS)> ~ $3\cdot10^{22}$ cm^{-2}

  To be compared with:

  - NH(FRI)= $3.3\cdot10^{21}$ cm^{-2} (no optically thick torus?)

    [Chiaberge+1999, Donato+2004]

  - NH(FRII)= $<10^{22} \div >10^{23}$ cm^{-2} (optically thick torus)



* Main source of X-ray absorption in GPS galaxies:

  AGN torus? ISM clouds?

  Any relation with radio absorber?

Size (kpc)

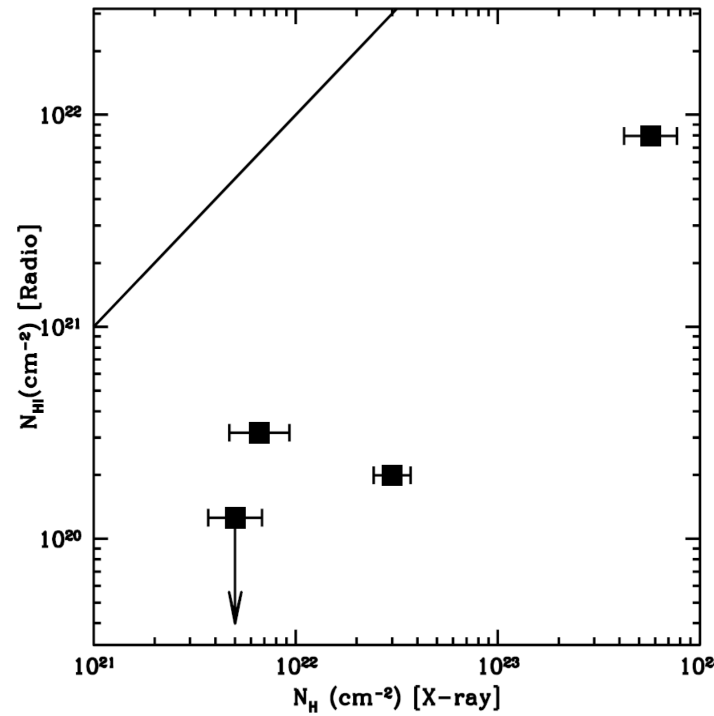
BACKGROUND: NH vs. NHI

* NH = NHI + NHII

* NH is 1-2 orders of magnitude larger than NHI
[Vink+2006, Tengstrand+2009]

→ X-rays and radio waves trace different absorbers
→ X-ray produced in a region more obscured than the radio lobes (e.g., the accretion disc)

unless an unreasonably high fraction of HII (∼ 90%) is assumed.



Vink+2006

* However ...

BACKGROUND : NH vs. NHI

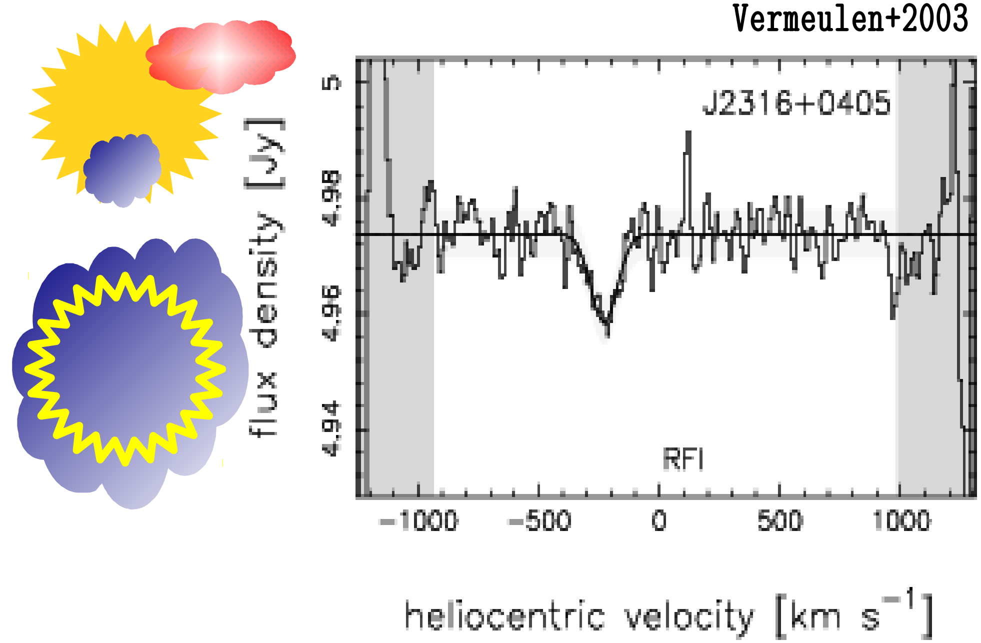
HI absorption:

* Measure τ_{obs} from spectrum
* Compute NHI for a homogeneous source assuming Ts and Cf

$$N_{HI} \propto \frac{T_s}{C_f} \int_{\Delta\nu} \tau_{obs,\nu} d\nu = \frac{T_s}{C_f} \tau_{obs}$$

$$\tau_{obs,\nu} = \Delta S_\nu / S_\nu$$

Vermeulen+2003



Standard assumptions: Ts=100 K, Cf=1 → lower limit to NHI

-Resolved HI observations: Cf<1

-AGN environment: Ts not directly measurable, but as high as ~ several 10^3 K

[Bahcall+1969, Maloney+1996]

→ Ts/Cf likely >100 K

BACKGROUND : NH vs. NHI

X-ray (photolectric) absorption:

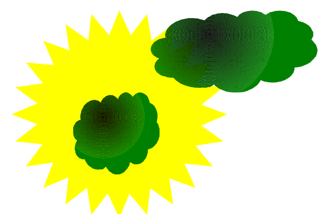
$$S_{\nu} = C_f \, S_{0,\nu_0} \, e^{-\tau_{\nu_0}} + (1 - C_f) \, S_{0,\nu_0}$$

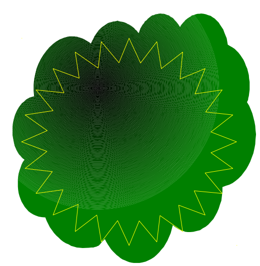
$$\tau_{\nu_0} = N_{H,\nu_0} \sigma_{\nu_0}$$

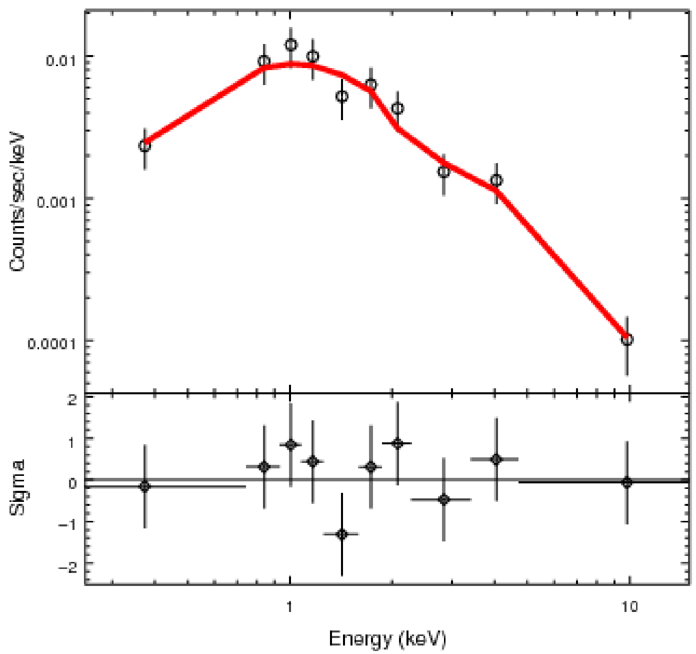
* Measure $S_{ph}(\nu)$
* Model of $S_{ph}(\nu)$ in a given physical scenario (parameters: Γ, Norm., NH, Cf,...)

<ins>Standard assumptions</ins>: C_f=1

(point-like sources)







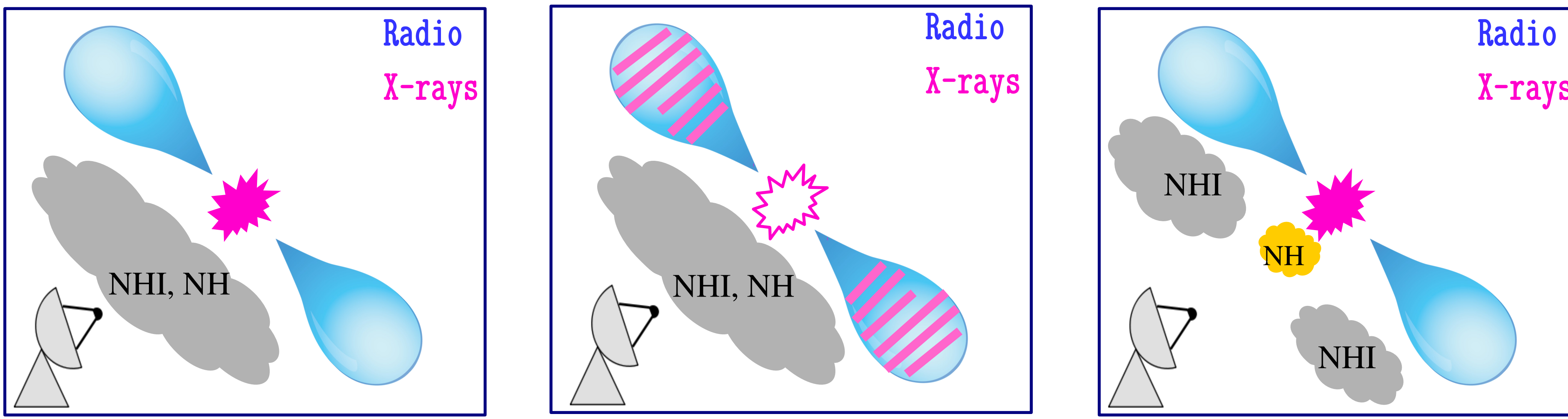
BACKGROUND : NH vs. NHI

* In principle: NH ≥ NHI or NH ≤ NHI

NH~NHI with an ad-hoc increase of Ts/Cf in single sources

If NH~NHI → radio and X-ray absorbers are one and the same

(radio and X-ray sources may still not coincide)



* Comparison between NH and NHI with no further *a priori* assumptions on source and absorber

→ requires *spatially unresolved* NHI measurements

WORK: GOAL

* Assemble the largest possible sample of (NHI, NH) pairs to investigate the connection between NH and NHI, using *spatially unresolved* NHI measurements.

WORK: SOURCE SAMPLE

* Core sample: 21 GPS galaxies, z=0.06 - 0.76
    - from radio samples by Stanghellini+98,Snellen+98,Torniainen+07,Vermeulen+03
    - also classified as CSO
    - either known X-ray emitters or proposed for observations with Chandra by Siemiginowska et al.

* Full sample: 24 sources
    21 GPS/CSO galaxies
    + 3 compact, sub-kpc radio sources (asymmetric GPS, CSO only, candidate CSO)

WORK: OBSERVATIONS

* Westerbork Syntesis Radio Telescope (WSRT)

  - 10/21 sources of the core sample with no HI detections

  - t_{obs} = 4-12 h, 10-20 MHz wide band, 1024 spectral channels

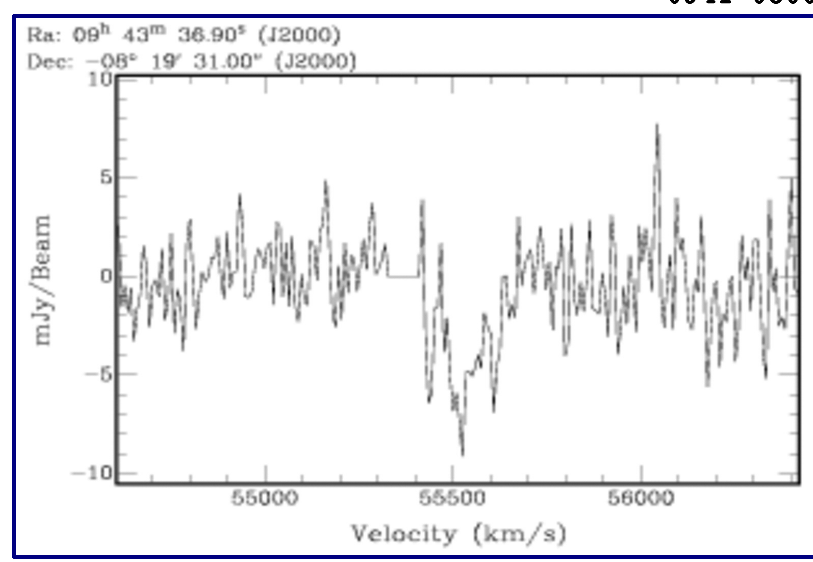
WORK: DATA ANALYSIS

* Core sample:

  - 3 new HI detections
    (0941-080, 0035+22, 1031+567)

  - 4 new 3σ upper limits

0941-0800



RESULTS: NH–NHI CORRELATION

Correlation samples

NHI: detections or upper limits, narrow and/or broad lines

NH: -Compton thin: detections, upper limits, lower limits

-Compton thick: lower limits

DETECTION SAMPLE (detections only) : D

* Pairs of (NHI, NH) detections: available for 9 sources (D sample)
* Each source: N≥1 measurements ⟶ M varieties of D: D_i (i=1...M)

ESTIMATE SAMPLE (detections and limits): E

* Pairs of (NHI, NH) estimates: available for 16 sources (E sample)
* Each source: N≥1 measurements ⟶ K varieties of E: E_i (i=1...K)

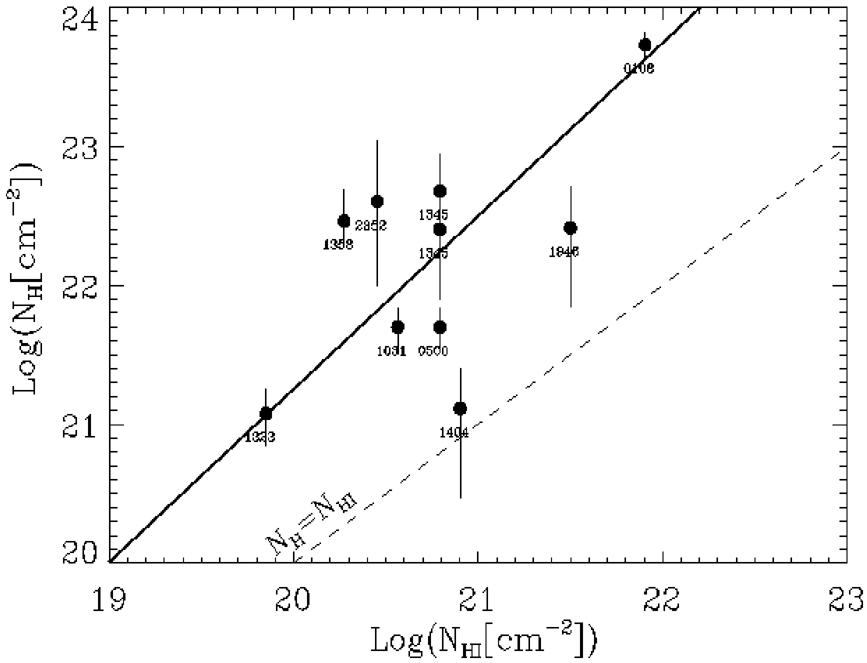
RESULTS: NH–NHI CORRELATION

Detections only (D sample)

CORRELATION TESTS

* Pearson: $r \sim 0.9$, Prob. of no correlation $=(0.8\text{-}3) \cdot 10^{-4}$
* Spearman: $\rho \sim 0.09\text{-}0.3$, Prob.$=(0.4\text{-}0.8)$
* Kendall: $\tau \sim 0.02\text{-}0.3$, Prob.$=(0.3\text{-}0.9)$

→ *Correlation driven by 0108+388!*



LINEAR REGRESSION: Log(NH)= a + b Log(NHI)

b=(0.86 - 1.2) +- 0.1

$\chi^2_{red} \sim 10$! → regression lines are not a good description of the data!

VISUAL INSPECTION: internal dispersion larger than error bars!

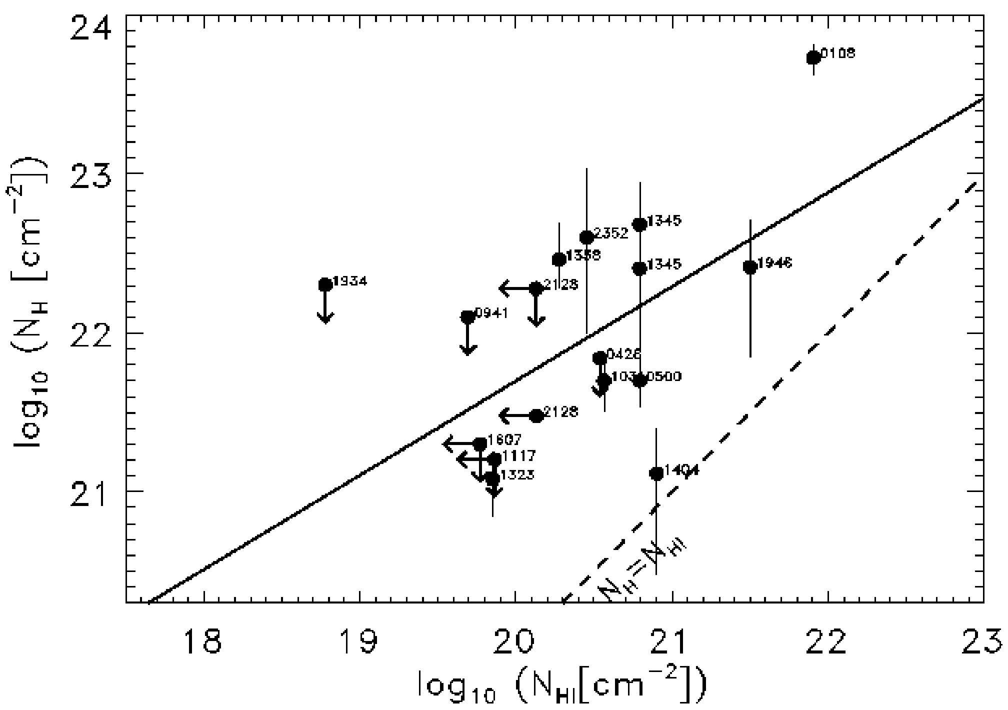
RESULTS: NH–NHI CORRELATION

Estimates (E sample)

SURVIVAL ANALYSIS TECHNIQUES (ASURV PACKAGE [Lavalley+1992])

* Generalized Spearman: Prob.~$(0.9\text{-}9)\cdot 10^{-2}$
  [$(1\text{-}10)\cdot 10^{-2}$ without 0108+388]

* Generalilzed Kendall: Prob.~$(0.6\text{-}9)\cdot 10^{-2}$
  [$(3\text{-}30)\cdot 10^{-2}$ without 0108+388]



LINEAR REGRESSION: Log(NH)= a + b Log(NHI)

$\longrightarrow$ b~0.6

Not possible to evaluate the goodness of the fit!

RESULTS: NH–NHI CORRELATION

Bayesian analysis (detections only)

Correlation analysis reveals: - existence of a correlation
- dispersion larger than the typical error bars

→ additional variables are involved in the correlation!

Bayesian analysis (APEMoST [Buchner & Gruberbauer 2011])

Given the existence of an x-y correlation, it enables to derive:

- the parameters of the x-y relation
- the intrinsic scatter of the dependent variable, $\sigma_{int}(y)$

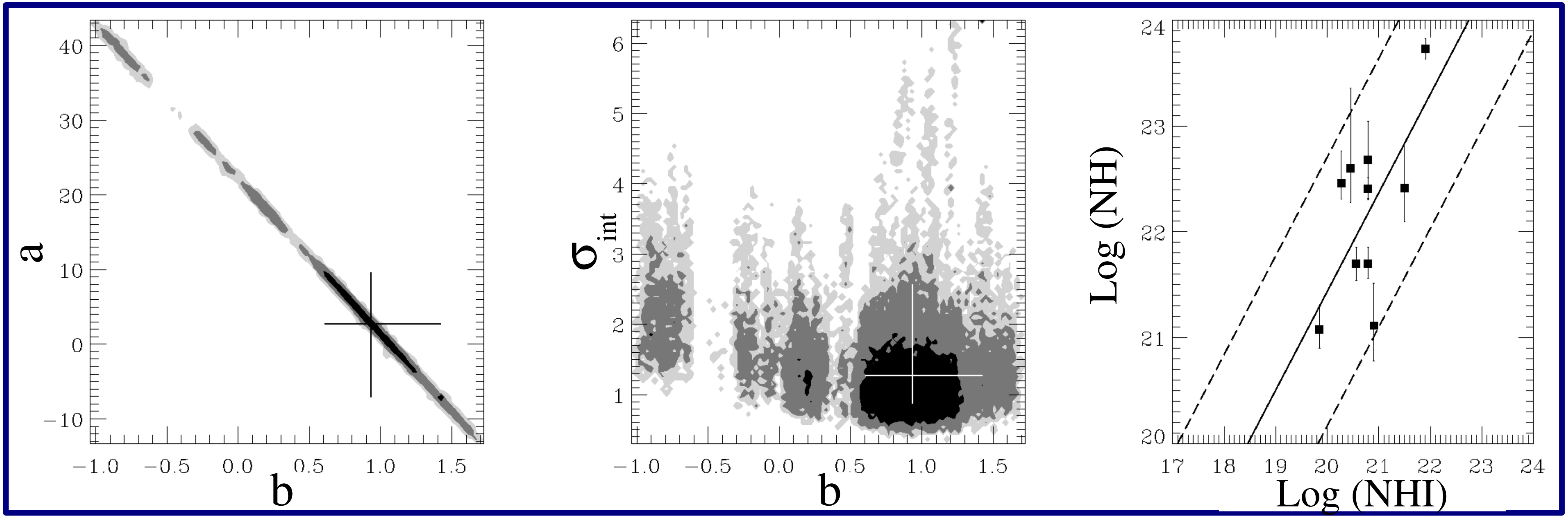
Additional hidden parameters are mimiked by assuming y as a random variate with

Mean: $\langle y \rangle = a + b\,x$

Variance: $\sigma_{int}(y)$

RESULTS: NH–NHI CORRELATION

Bayesian analysis (detections only)



x = Log NHI, y = Log NH → y = a + b·x

Parameters: a=2.78 (+6.82, -9.83)

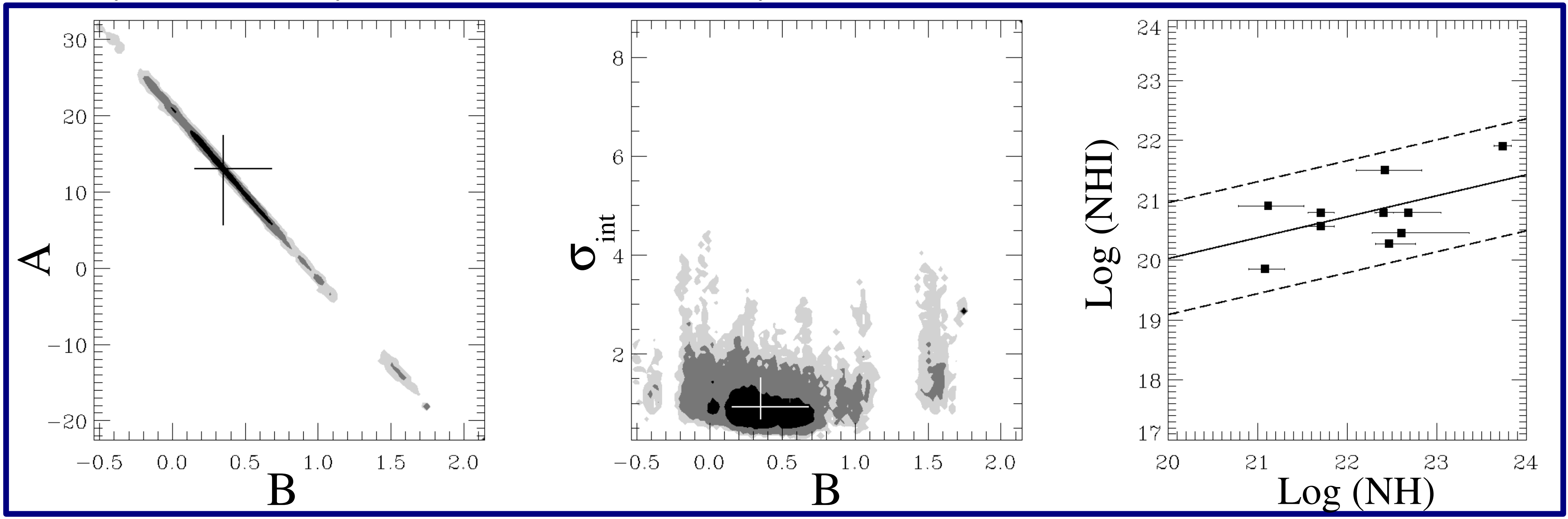
b=0.93 (+ 0.49, -0.33)

σ_{int} (y) = 1.27 (+1.30, - 0.40)

Slope of NH vs. NHI

RESULTS: NH–NHI CORRELATION

Bayesian analysis (detections only)



X = Log NH , Y = Log NHI → Y = A + B·X

Parameters: A=13.0 (+4.4, -7.3)

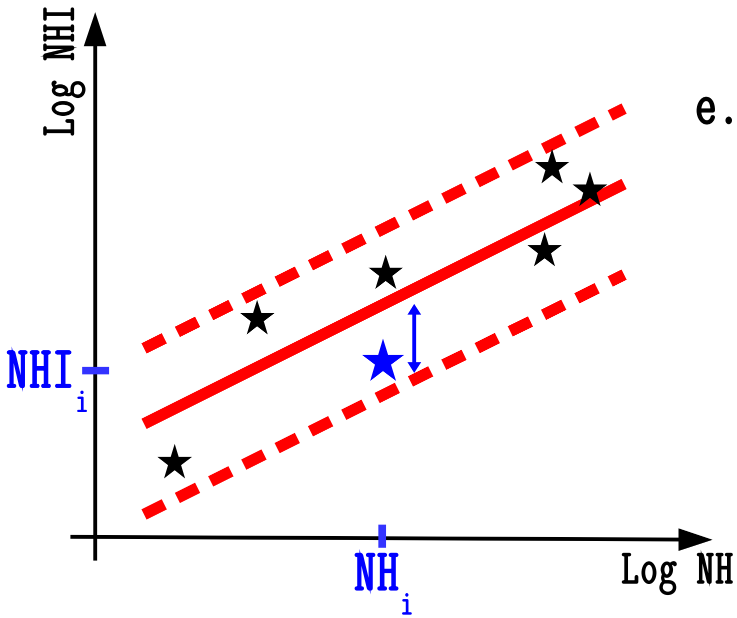
B=0.35 (+ 0.33, -0.20)

σ_{int} (Y) = 0.93 (+0.58, -0.26) ➡ intrinsic spread on NHI

RESULTS: NH–NHI CORRELATION

Bayesian analysis on NHI vs. NH sample:

Quantifies the intrinsic spread on NHI, for any given NH



e.g. For a given NH → Log NHI = < Log NHI > $\pm\ \sigma_{int}$(NHI)

with σ_{int} (NHI) = $\pm$0.93 dex

→ NHI can vary by a factor ~70 about the mean relation

Because $N_{HI} \propto \frac{T_s}{C_f} \tau_{obs}$, if τ_{obs} and NH were tightly correlated

→ Ts/Cf can vary of a factor ~70 about Ts/Cf=100 K,

i.e. Ts/Cf ~ 12-851 K

→ "true" Ts/Cf of a source: deviation from the mean relation

RESULTS: NH–NHI CORRELATION

* Warning:

  - Sources are inhomogeneous

  - Relation $N_{HI} \propto \frac{T_s}{C_f} \tau_{obs}$: more appropriate for spatially resolved observations

* With NHI data from spatially resolved measurements:

  - if the correlation is confirmed: σ_{int}(NHI) $\longrightarrow$ Ts/Cf range

  - if Cf~1: σ_{int}(NHI) $\longrightarrow$ Ts range

    $\longrightarrow$ "true" Ts of a source: deviation from the mean relation

CONCLUSIONS

* We performed new *spatially unresolved* HI absorption measurements of GPS galaxies with the WSRT to increase the NH-NHI sample

* We find a significant correlation between NH and NHI

* Linear regression yields: $NH \sim NHI^{b}$, with $b \sim 1$, however the fit is not acceptable

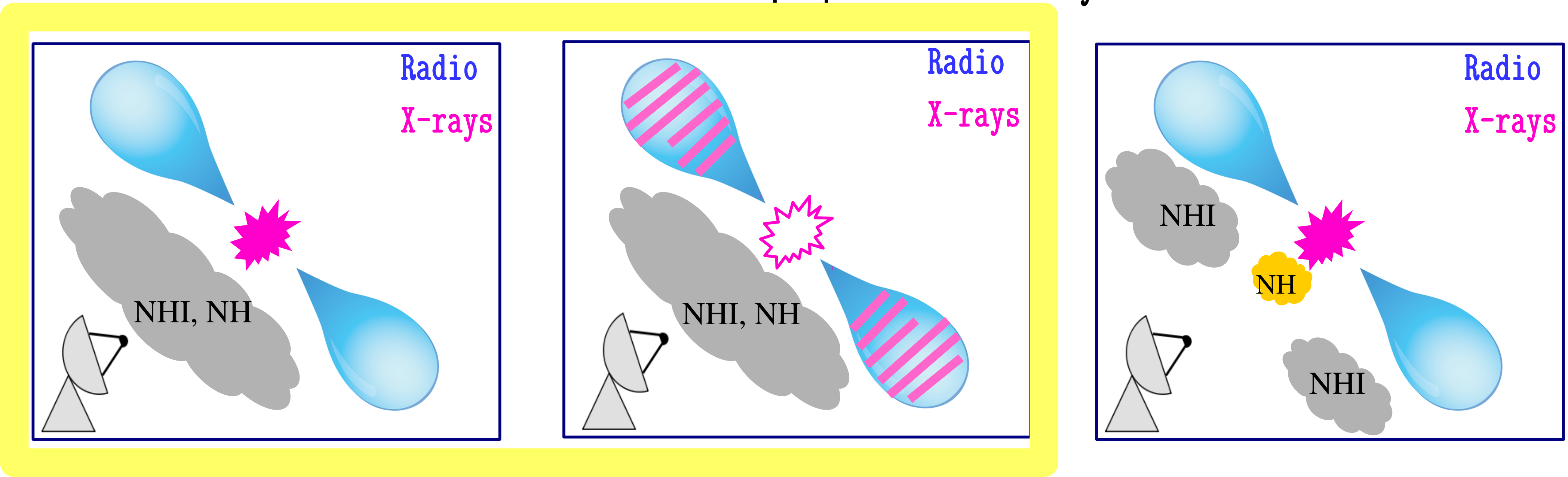
  → The NH-NHI relationship (with Ts/Cf=100 K) is not a 1-to-1 relation: intrinsic spread due to Ts/Cf

CONCLUSIONS

* Bayesian analysis simultaneously quantifies:

- the parameters of the NH-NHI relation

  $NH \sim NHI^{b}$, with $b \sim 0.9$ → suggestive of strong correlation between intrinsic properties of X-ray and HI absorbers



- the intrinsic spread of the data set

  $\sigma_{int}(NHI) = 0.93$ dex → factor ~70 in NHI for any NH

  → Ts/Cf estimate

  → Ts estimate if Cf~1 (resolved HI observations)

Thank you!