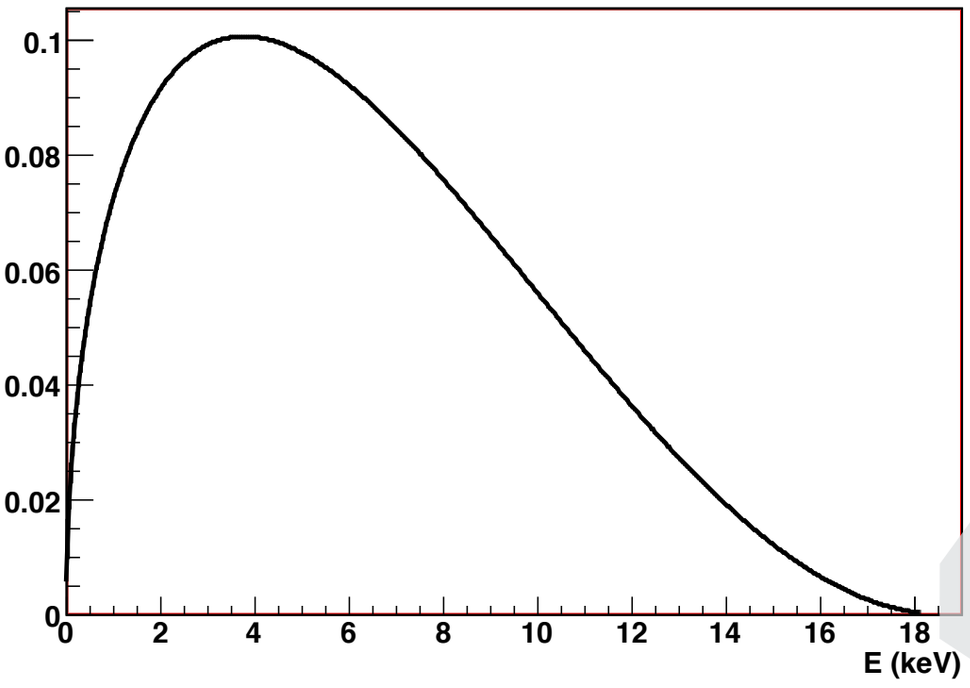
Direct neutrino mass measurement: KATRIN, ^{163}Ho, Project 8

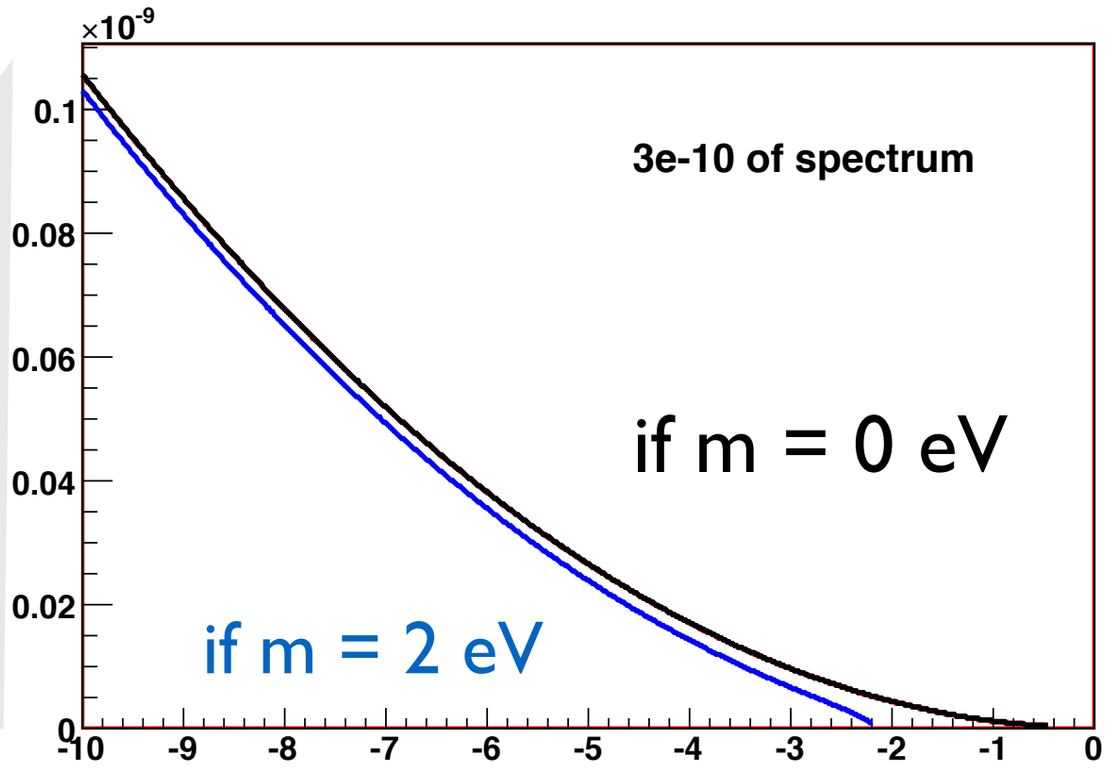
Ben Monreal, UCSB (—> Case Western)

Direct = kinematic neutrino mass measurement

Measure kinematics
of a three-body decay with a
neutrino nearly at rest

- Tiny phase space = rare
- need good energy resolution
- same energy scale as atomic/ molecular effects

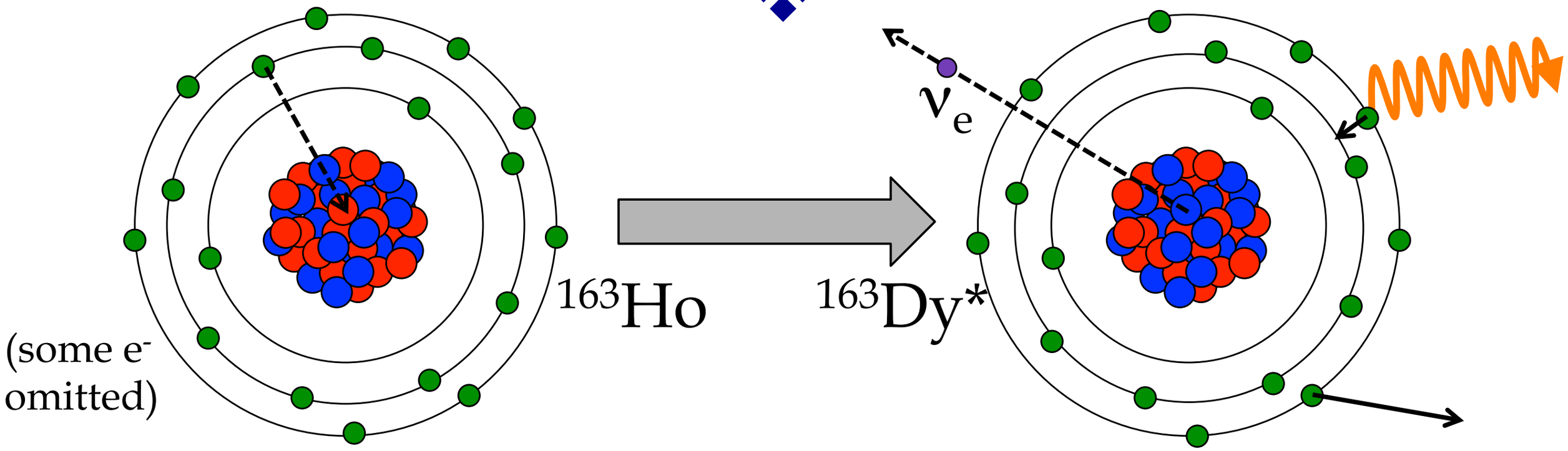




$^{3}H \rightarrow {}^{3}He^{+} + e^{-} + \overline{\nu}_e$

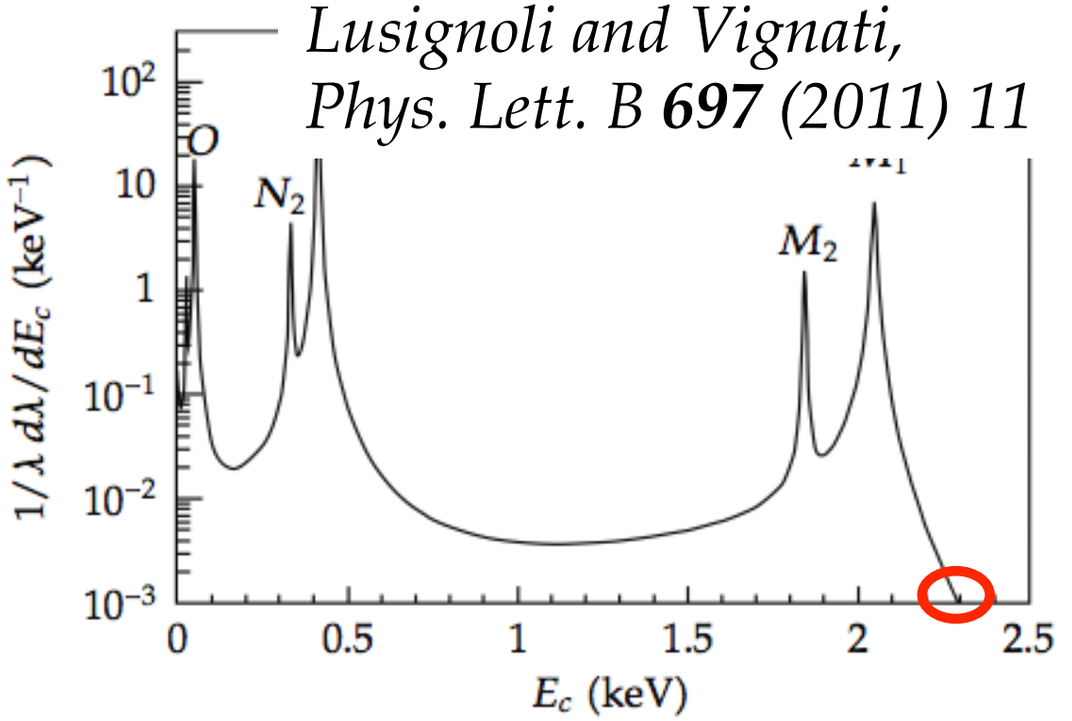
$^{163}Ho \rightarrow 163Dy^{+} + \overline{\nu}_e + \gamma$

Direct m_ν from Electron Capture



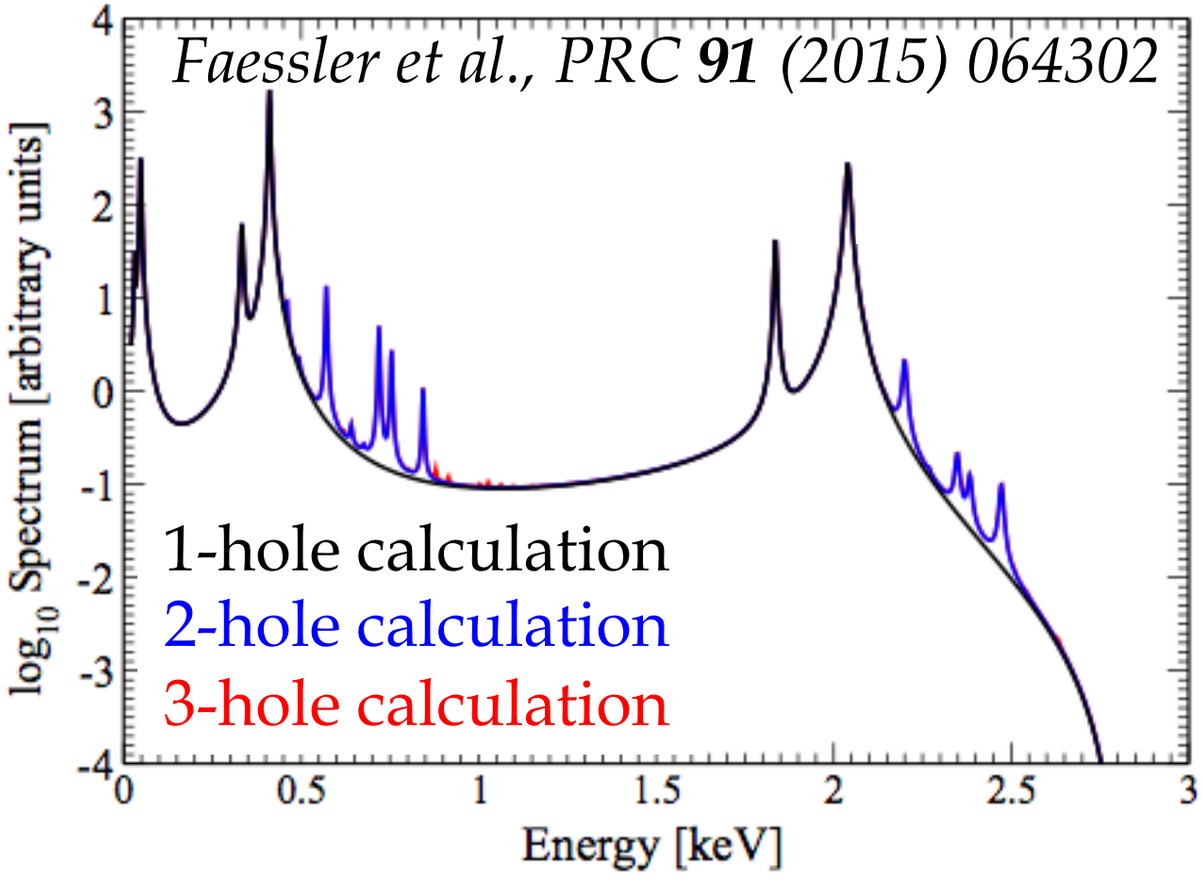
- Capture de-excitation energy in $^{163}Ho \rightarrow {}^{163}Dy^* + \nu_e$

*Lusignoli and Vignati, Phys. Lett. B **697** (2011) 11*



^{163}Ho: Shakeup

- Standard spectral calculation assumes 1 e^- vacancy
- What about ^{163}Dy* states with two or more holes?



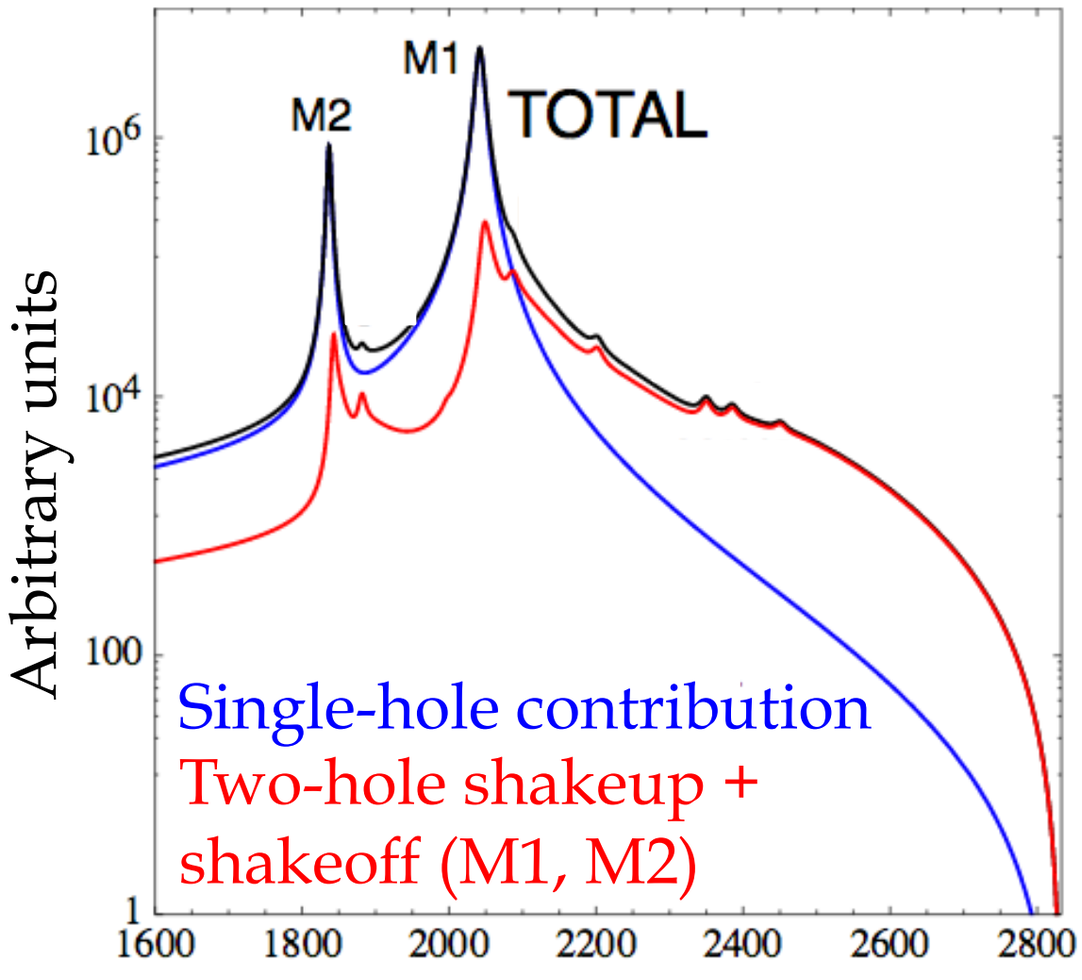
- New resonance(s)
- Structure near endpoint complicates m_ν^2 extraction

*Robertson, PRC **91** (2015) 035504*
*Faessler and Šimkovic, PRC **91** (2015) 045505*
*Faessler et al., PRC **91** (2015) 064302*

- Looks like a few % effect, separated from endpoint

^{163}Ho: Shakeoff

- Electrons can also be excited to the continuum
  - 3-body process, $^{163}\mathrm{Ho} \rightarrow {}^{163}\mathrm{Dy}[H,H'] + e^- + \nu_e$

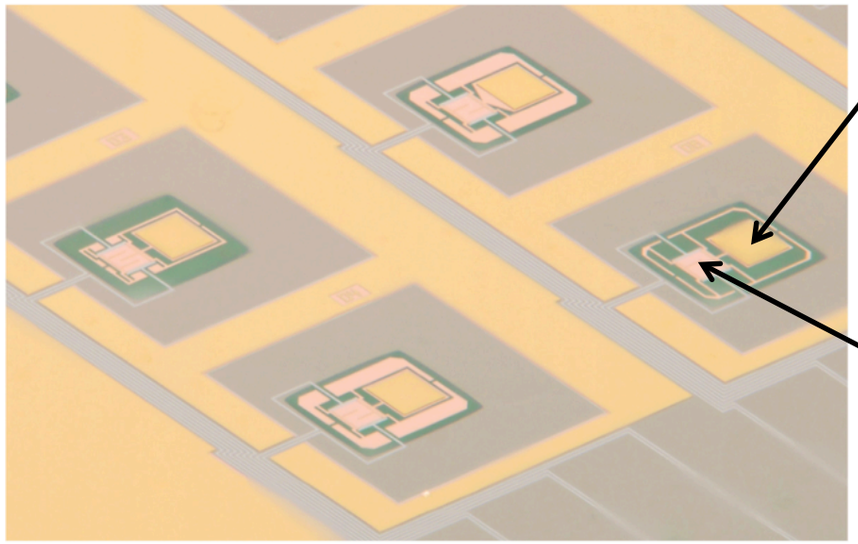


De Rújula and Lusignoli, JHEP ***2016*** *15, 2016*

- Recent preliminary calculations near endpoint
  - Enhanced statistics (40x near endpoint)
  - Relative pileup contribution reduced
  - More complex analysis?
- Ongoing theory work

Direct m_ν from Electron Capture

HOLMES

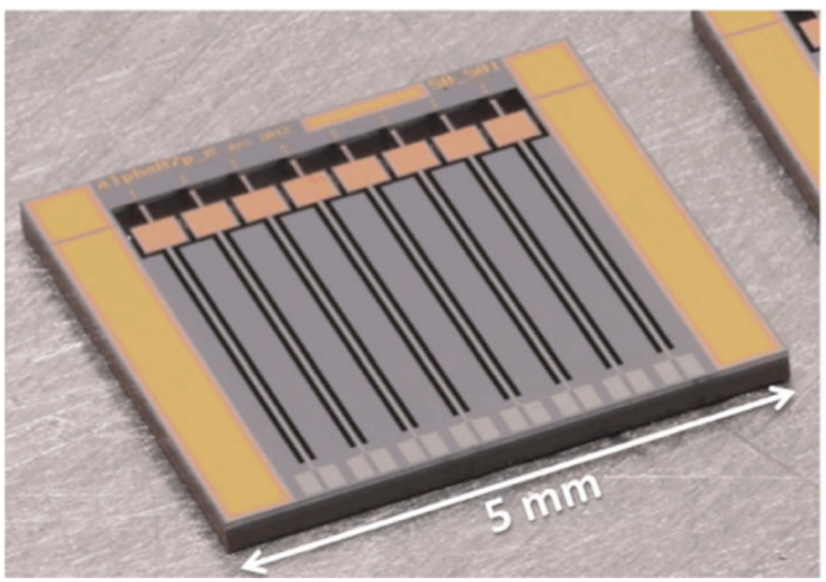


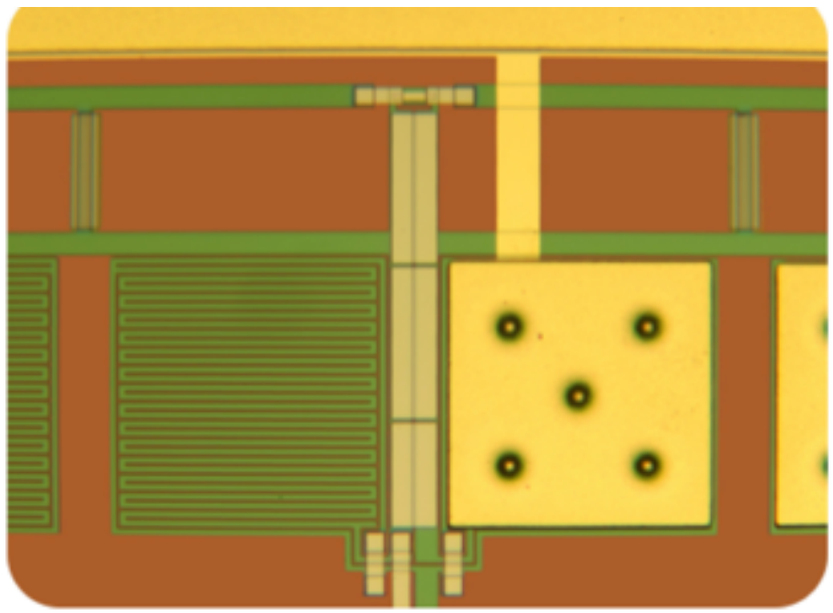
Au absorber with ^{163}Ho filling

Mo-Cu transition edge sensor

ECHo

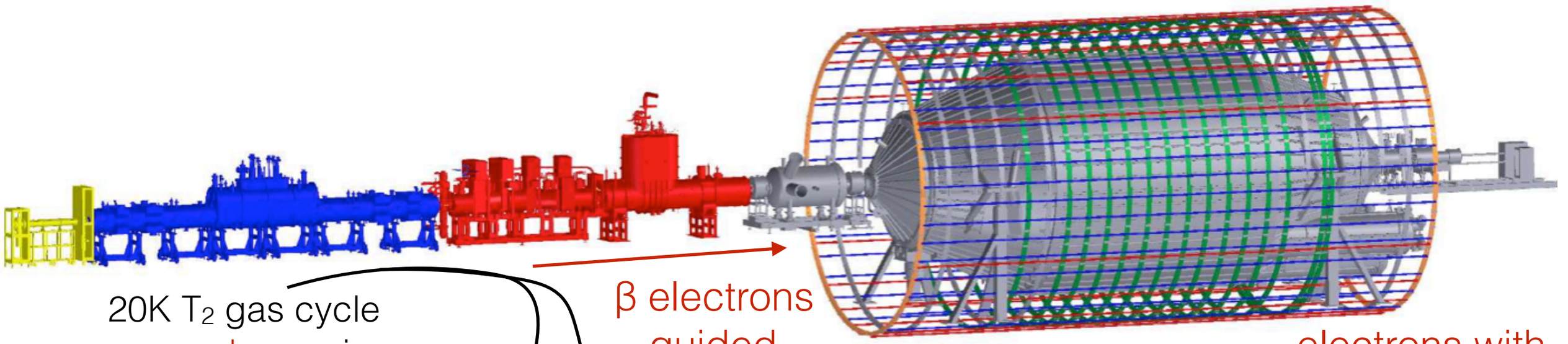
NuMECS





MMC

KATRIN

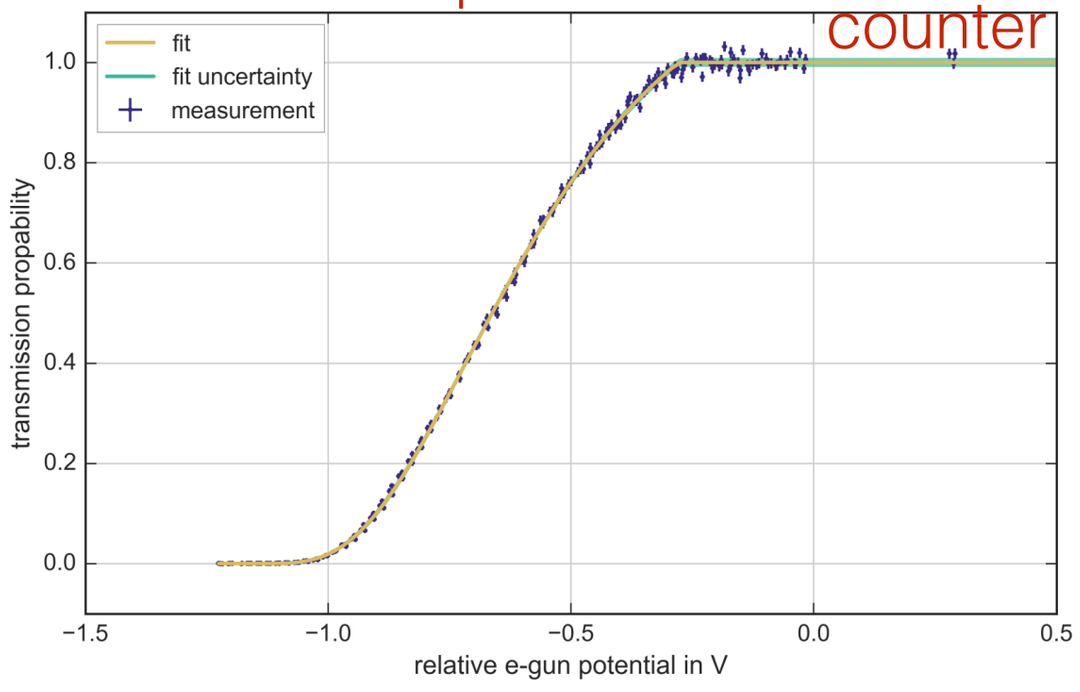


20K T_2 gas cycle some decays in 3.5 T magnet

β electrons guided magnetically

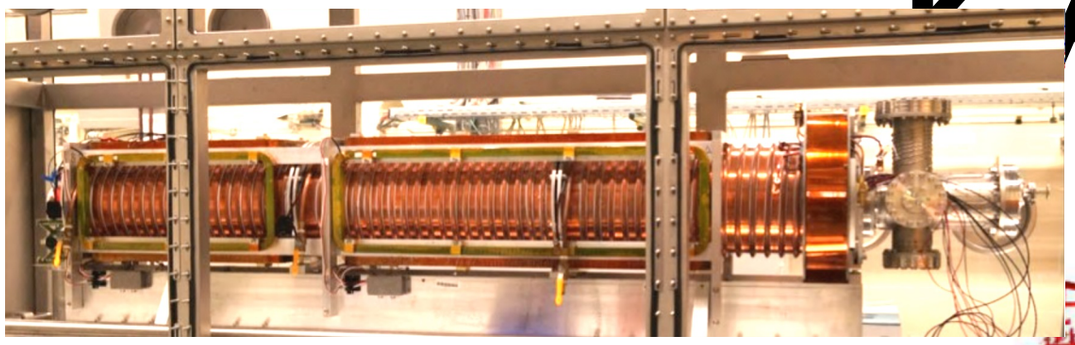
electric potential reflects electrons with E < qV

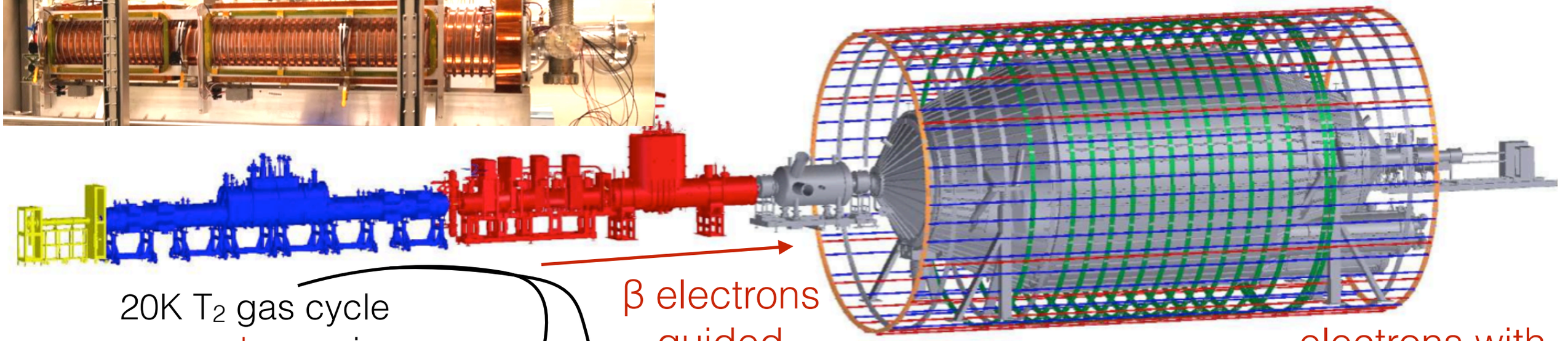
electrons with E > qV pass and arrive at counter



Sharp highpass filter
width = 0.9 eV
very well known shape

KATRIN





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Beamline closed now

e- transmission this month!

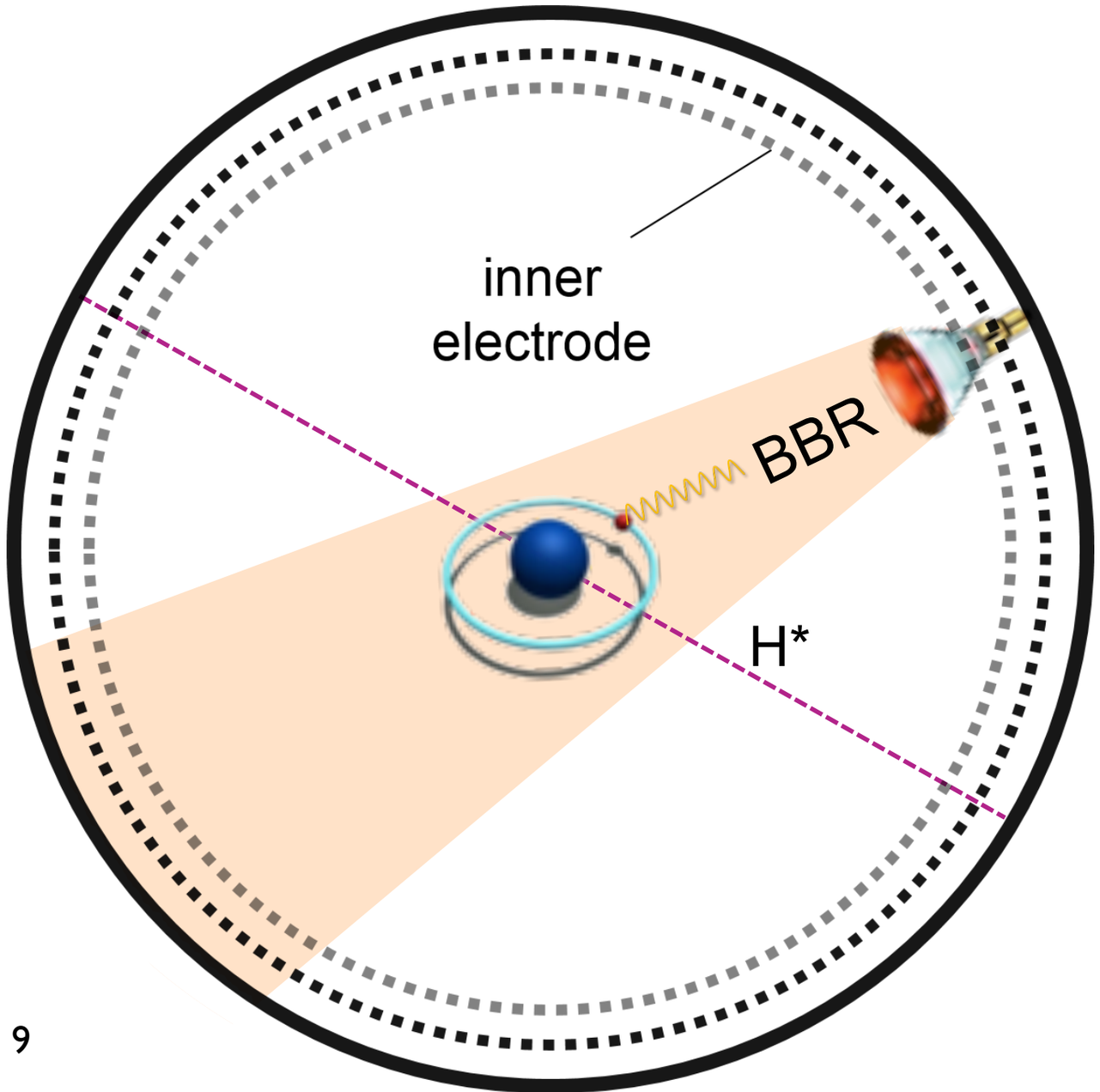
KATRIN status

- Tritium fill/data in 2017
- Current expectations:
  - Background rates *worse* than design report
  - ~~0.20~~ 0.23 eV sensitivity
  - Systematics control *better* than design report

Example of unexpected background:

a) Radioactivity sputters H* from wall

b) H* thermally ionizes in flight



BM & Formaggio, PhysRevD 2009

The Project 8 concept

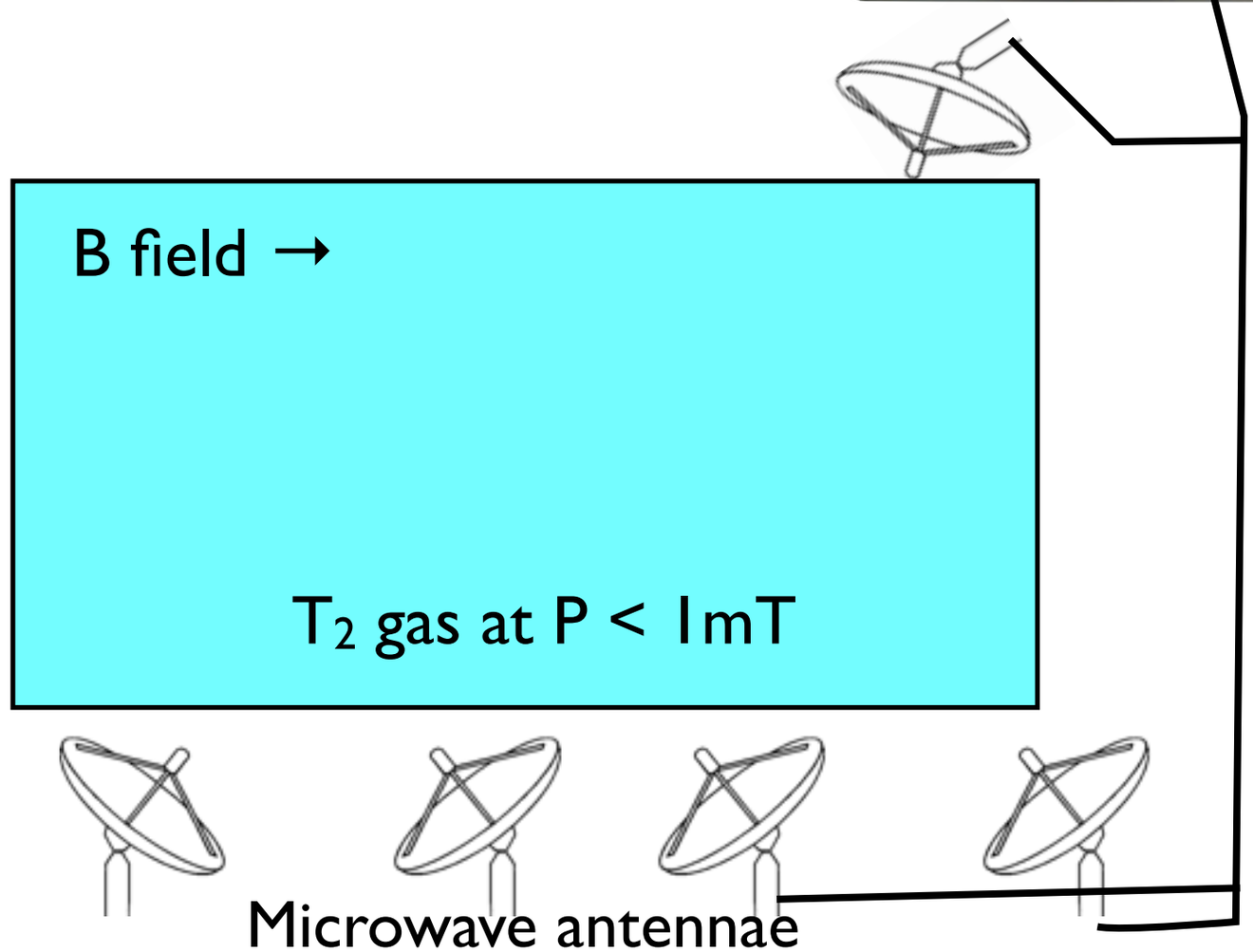
Cyclotron radiation

- emitted by mildly relativistic electrons
- Coherent, narrowband
- 10^{-15} W per electron

$$f_\gamma = \frac{f_c}{\gamma} = \frac{eB}{2\pi(m_e + K/c^2)}$$

$$P_{\text{tot}} = \frac{1}{4\pi\epsilon_0}\,\frac{2q^2\omega_c^2}{3c}\,\frac{\beta_\perp^2}{1-\beta^2}$$

- Electron energy contributes to velocity v, power P, frequency ω
  - *Can we detect this radiation, measure v, P, ω, and determine* E ± 1 eV?



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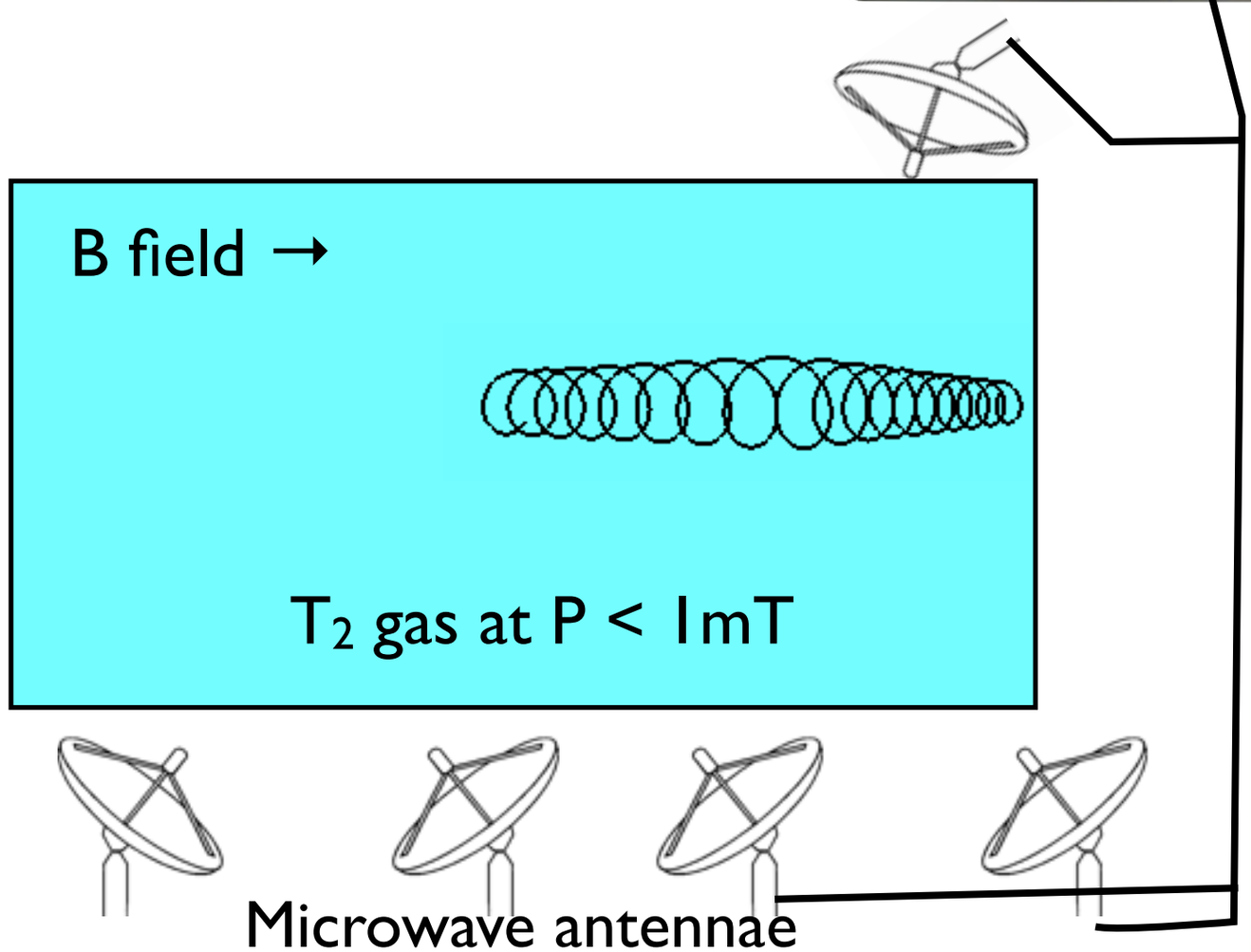

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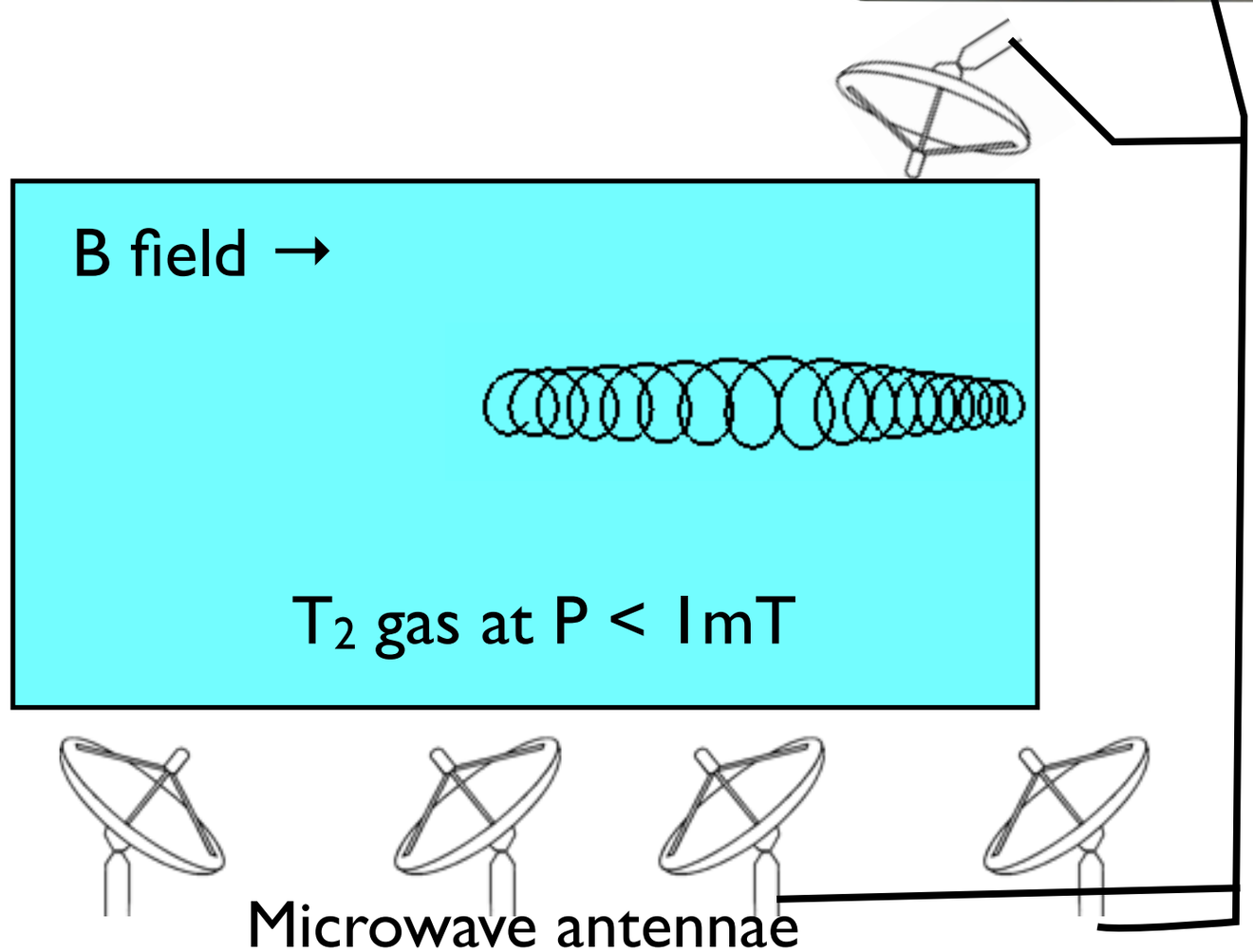
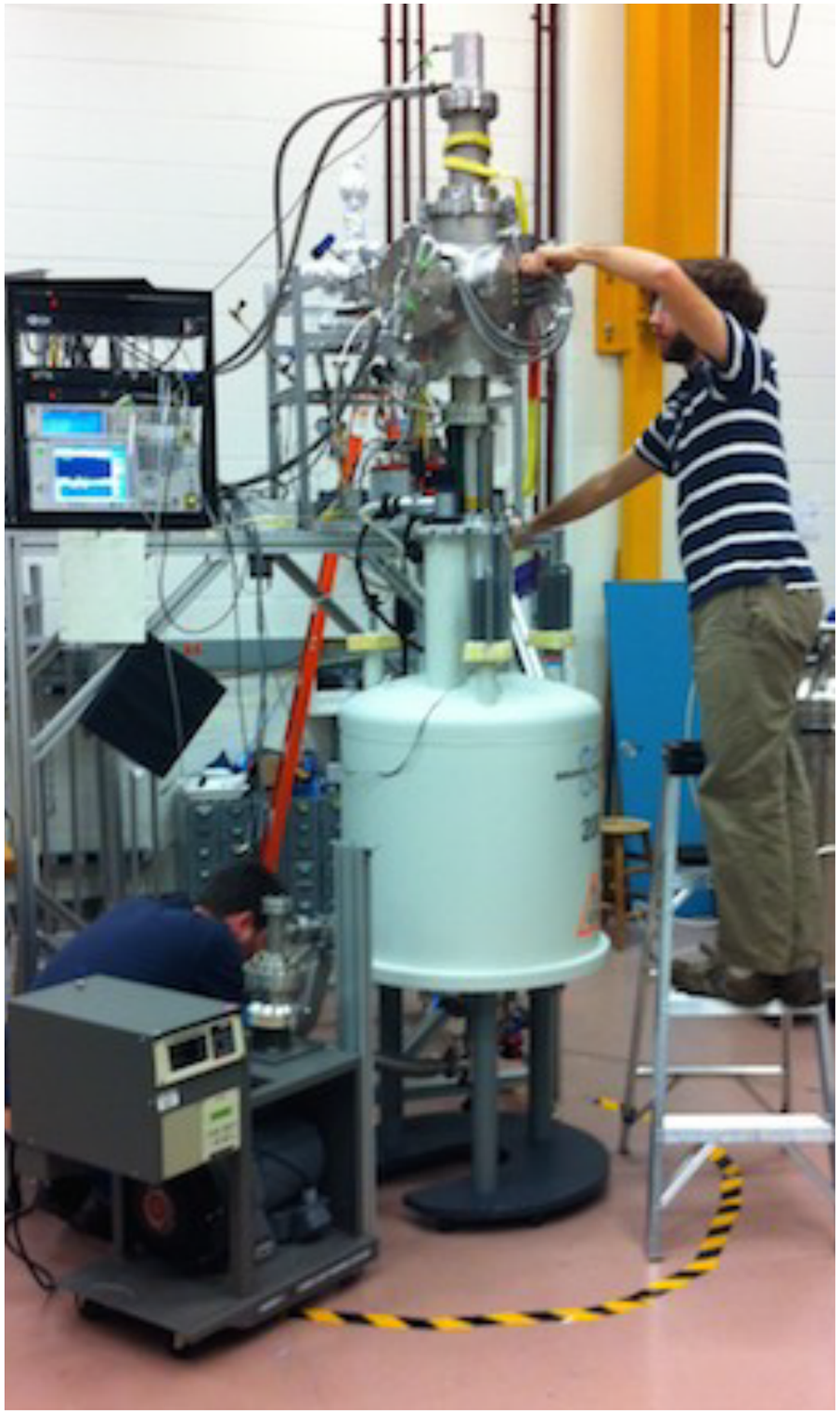
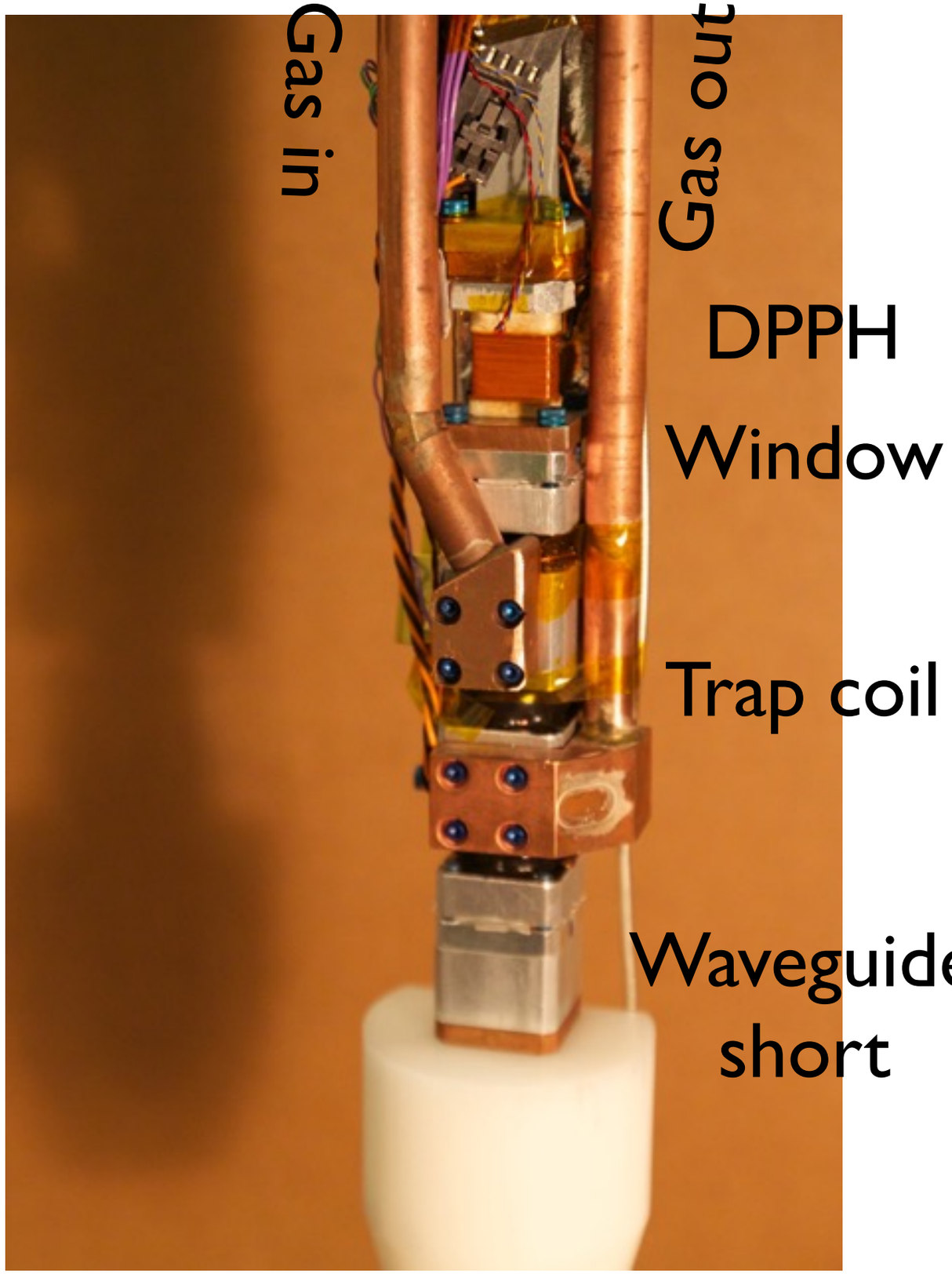


RF chain and reciever





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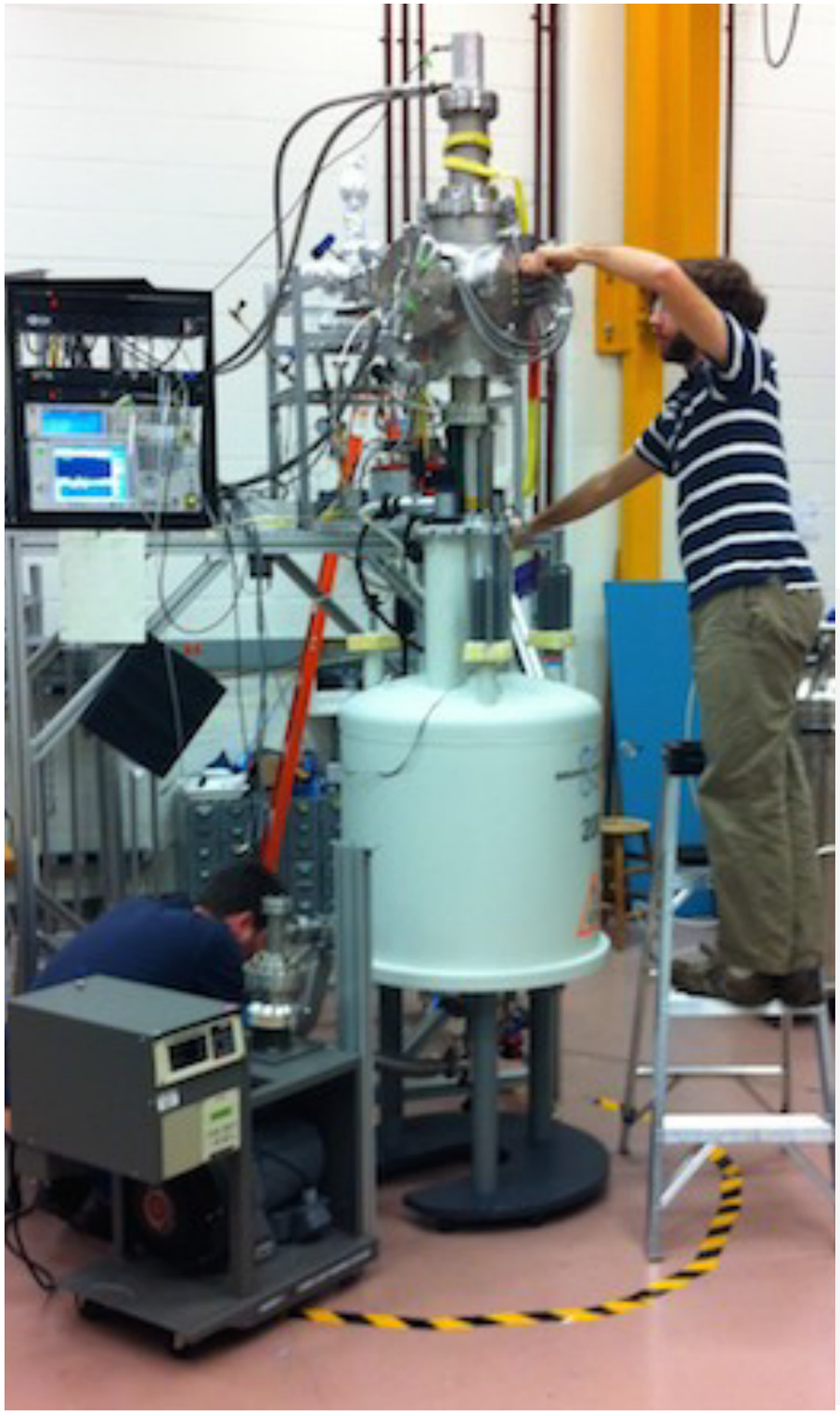
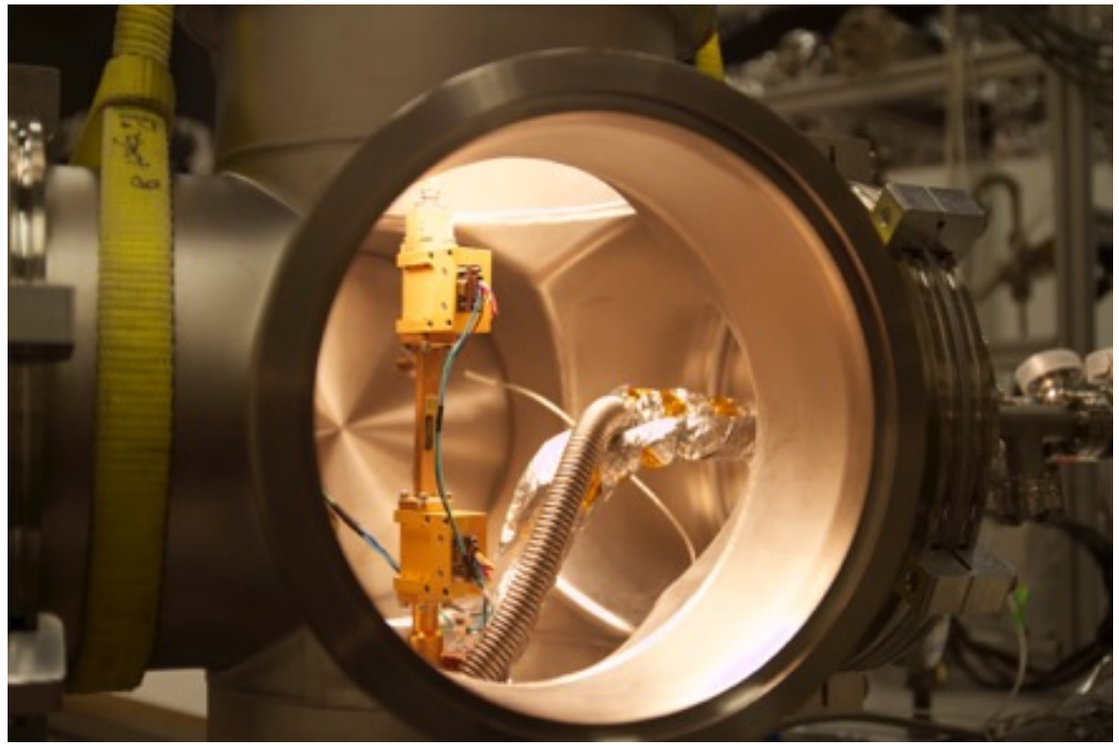
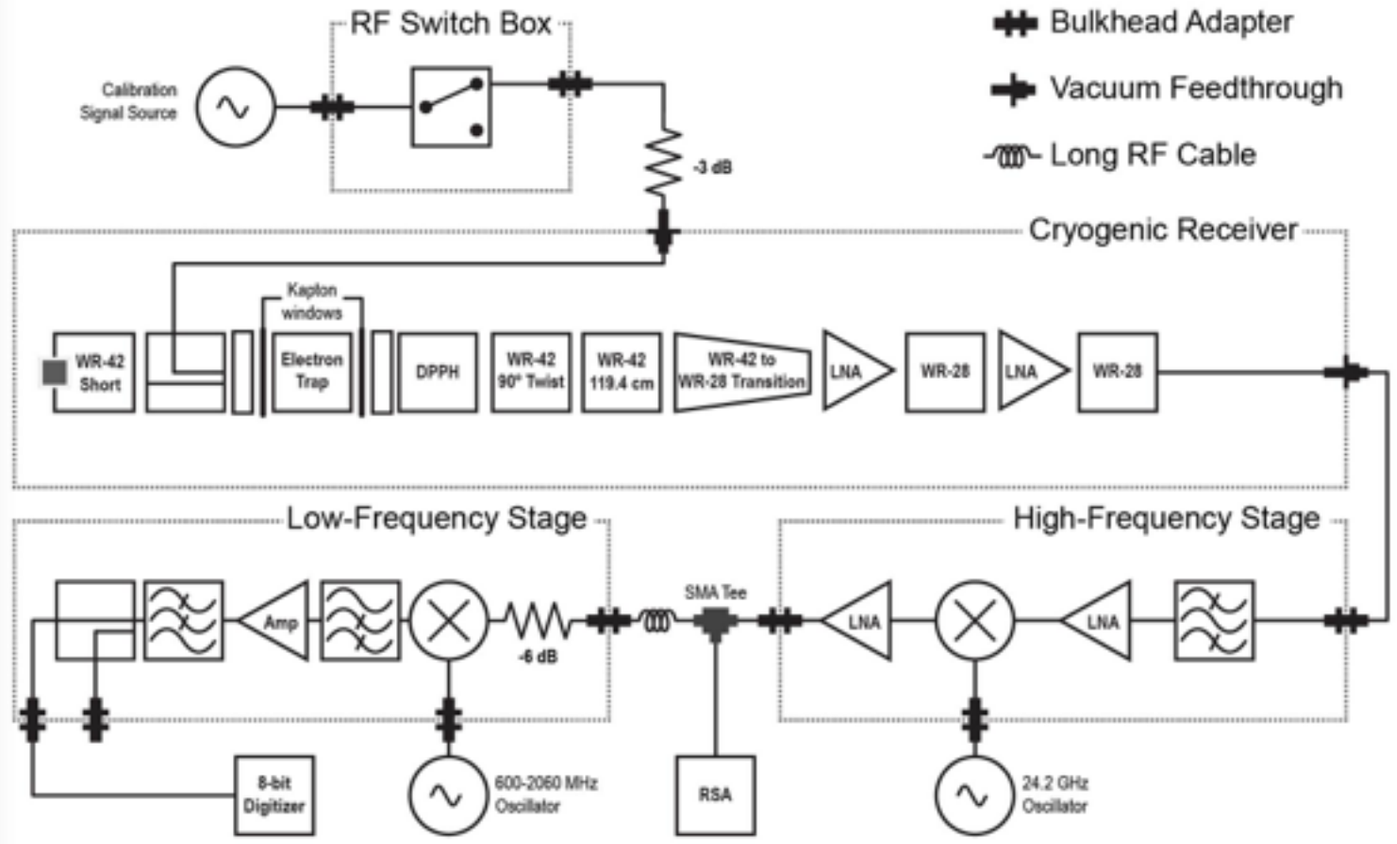
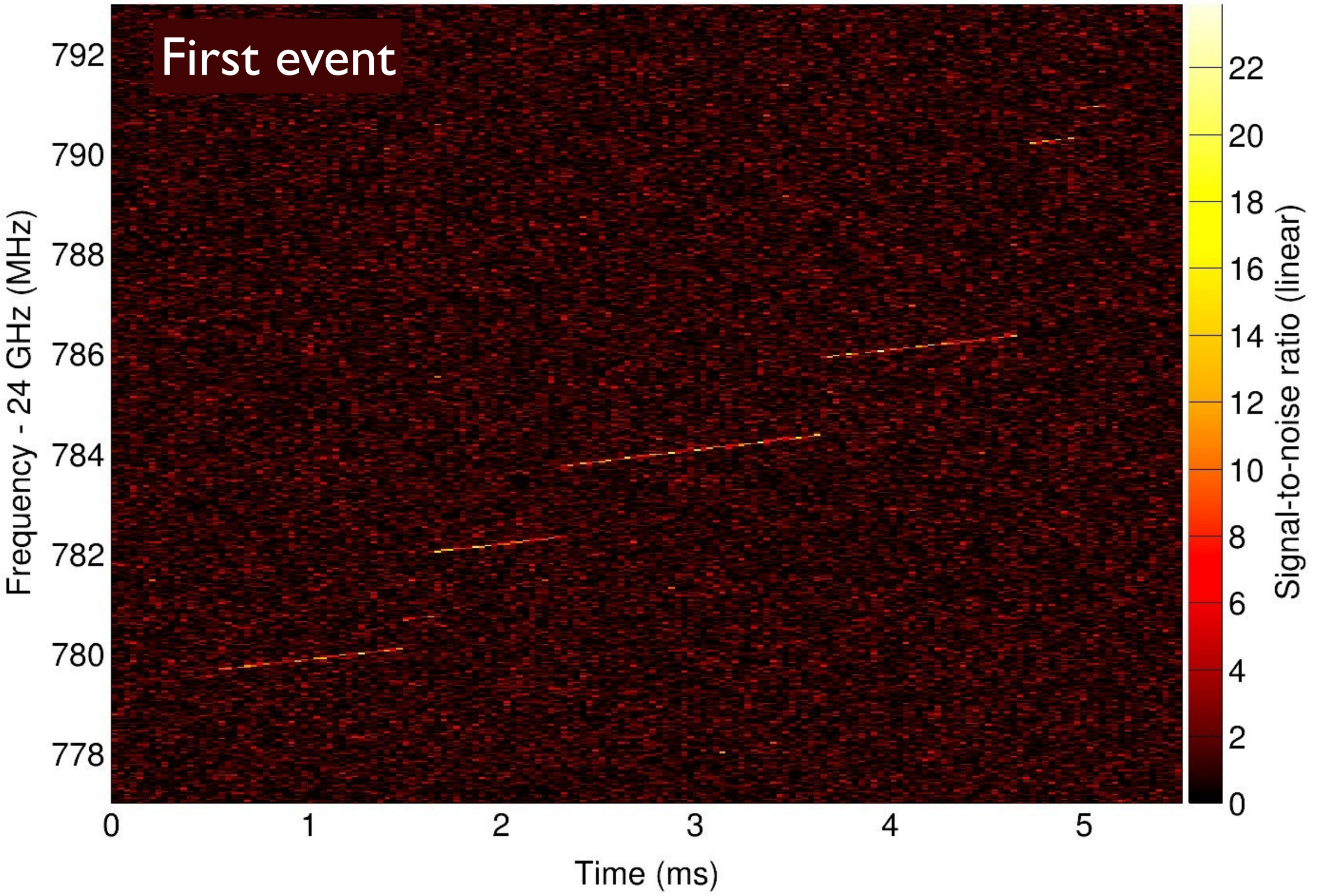






D. M. Asner et al. Phys. Rev. Lett. 114, 162501 (2015)



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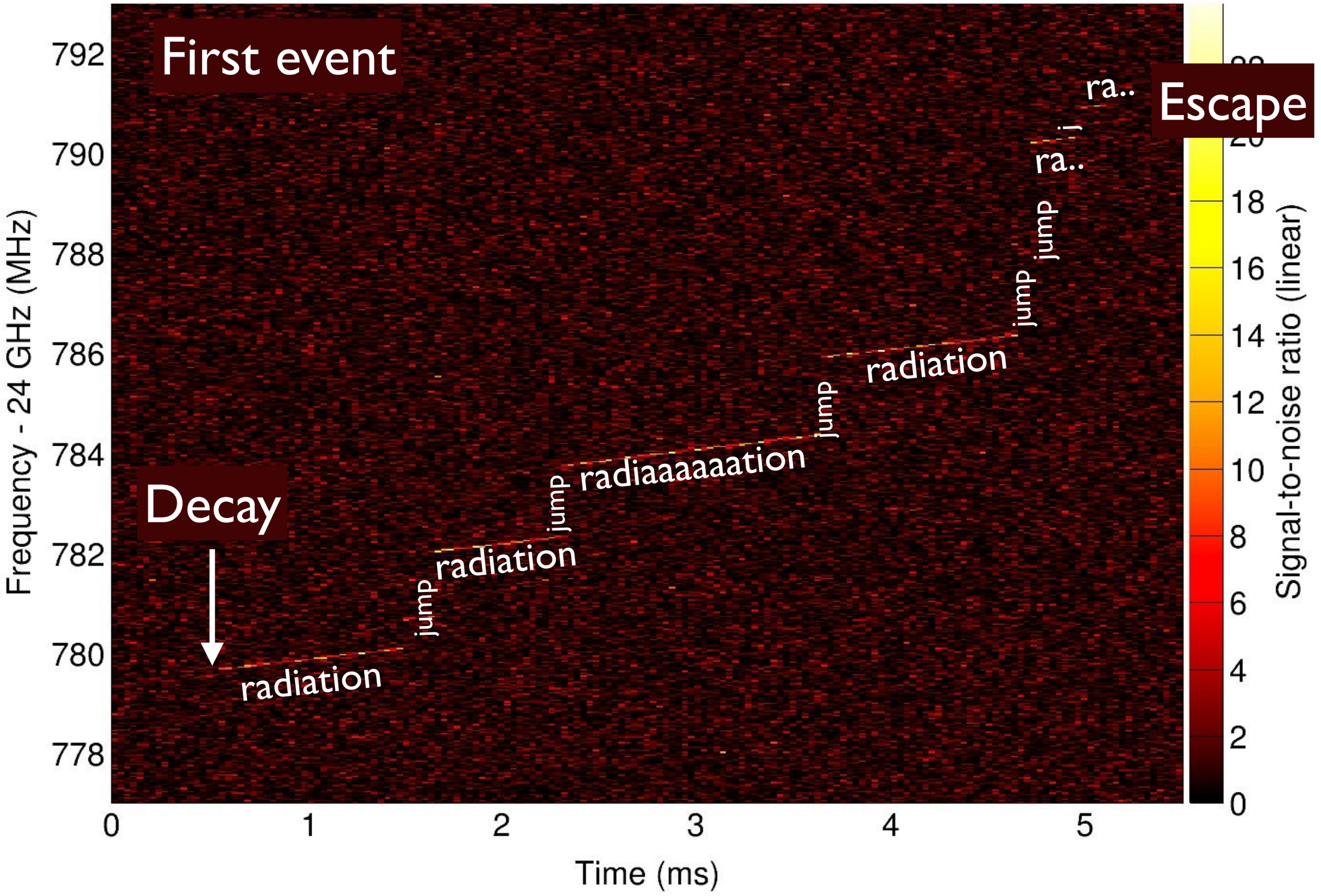
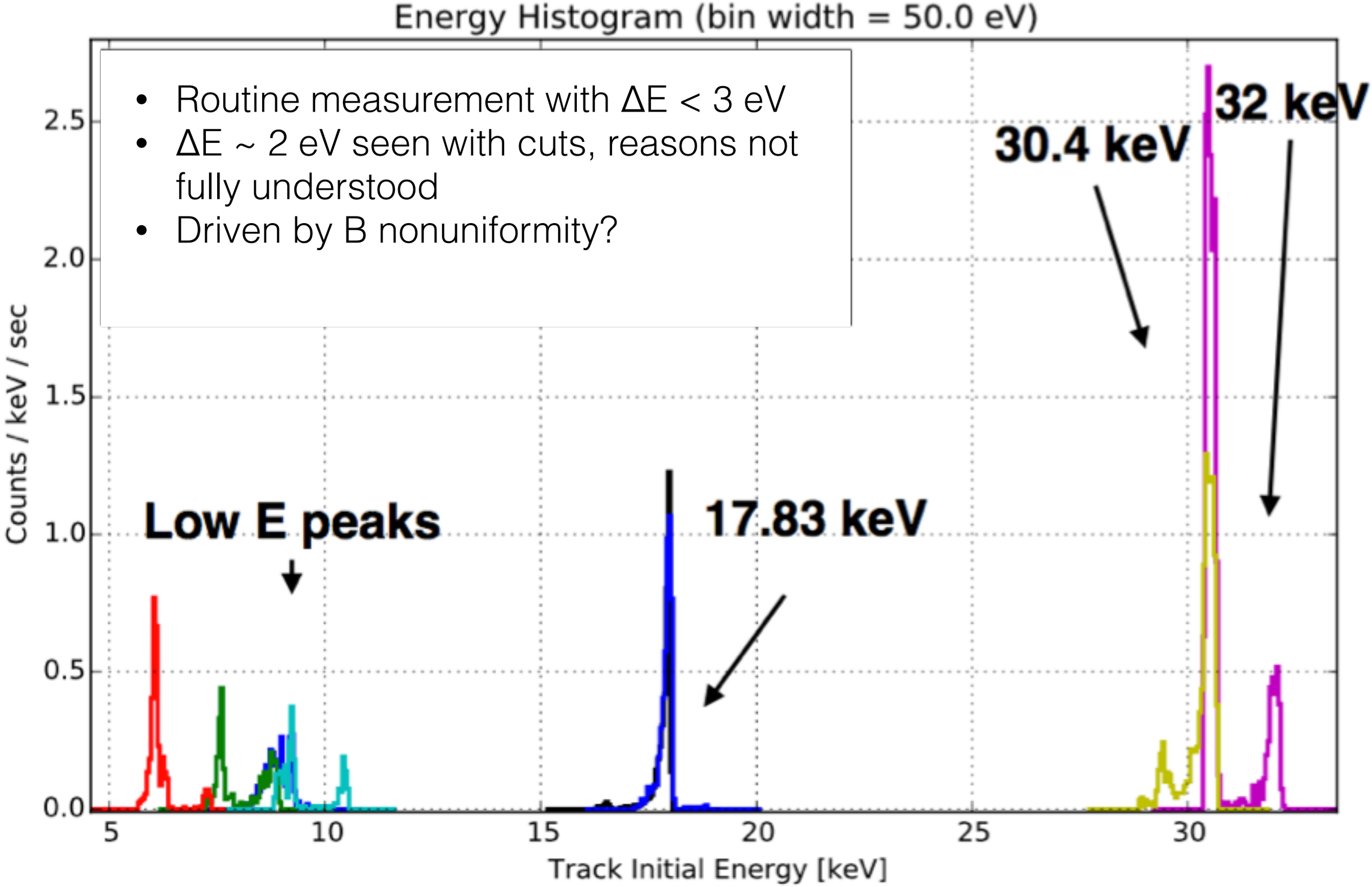
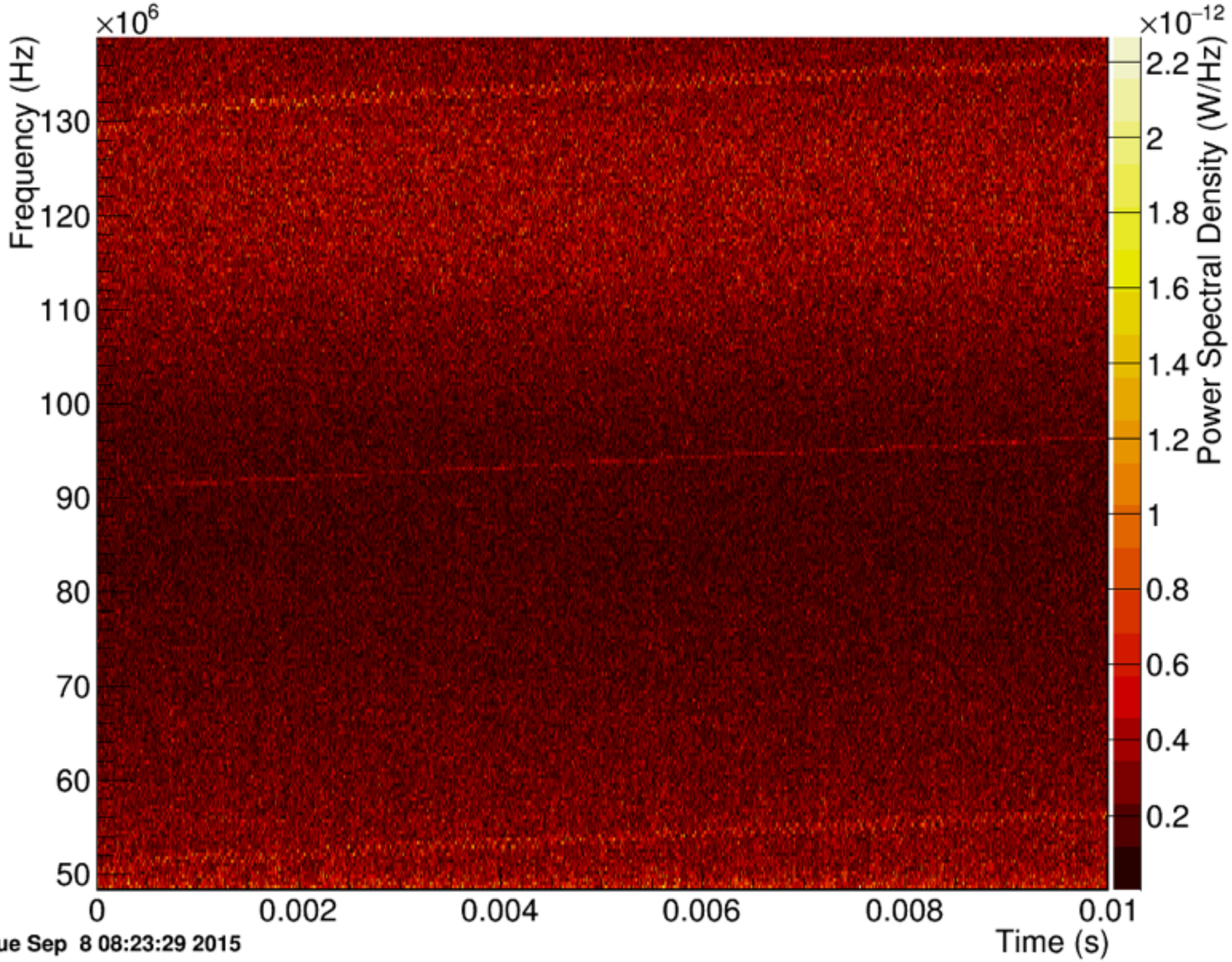


- Routine measurement with ΔE < 3 eV
- ΔE ~ 2 eV seen with cuts, reasons not fully understood
- Driven by B nonuniformity?

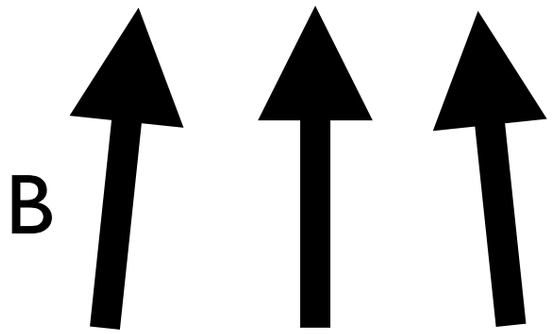


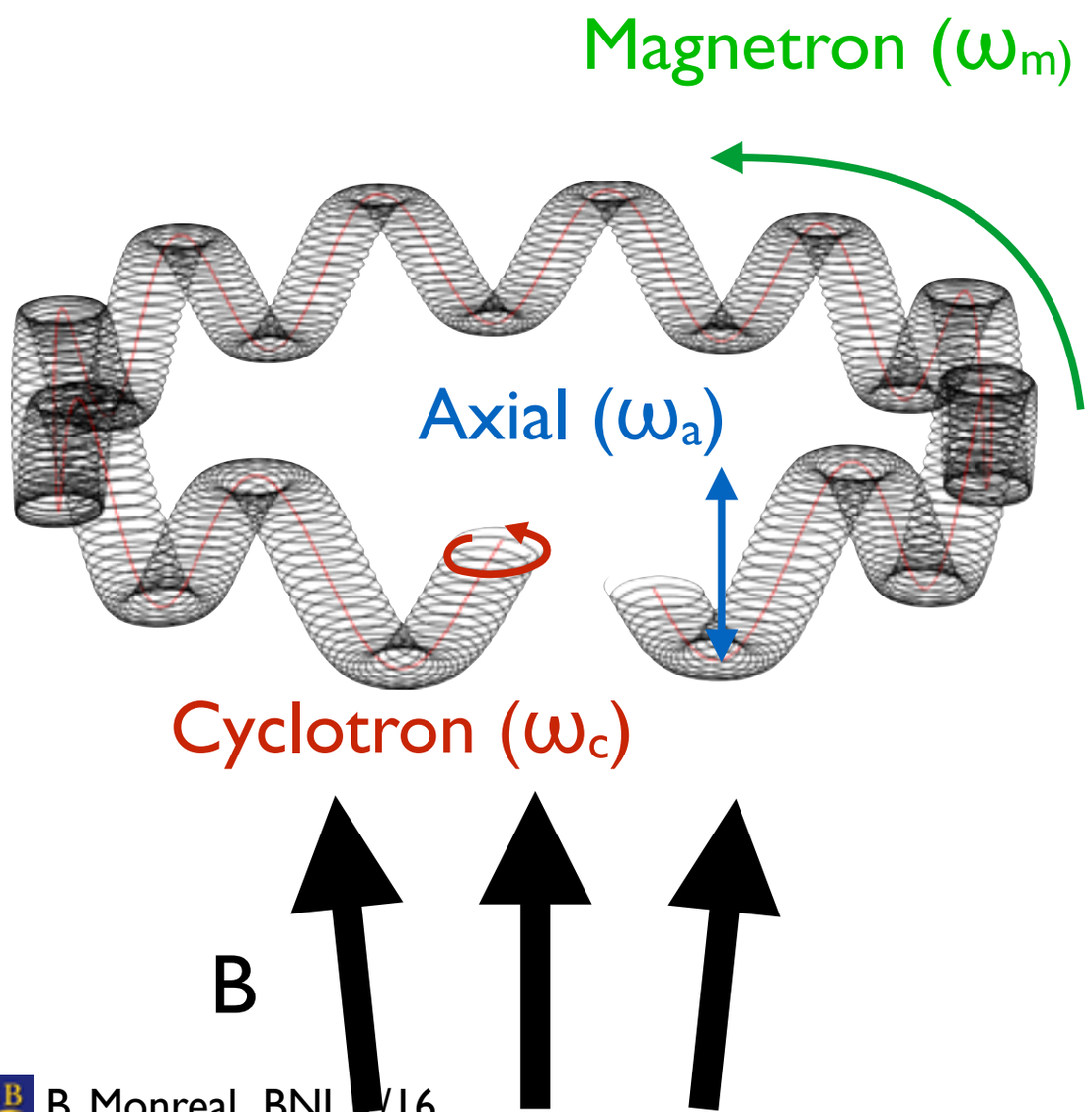
Run 2: knocking down the noise

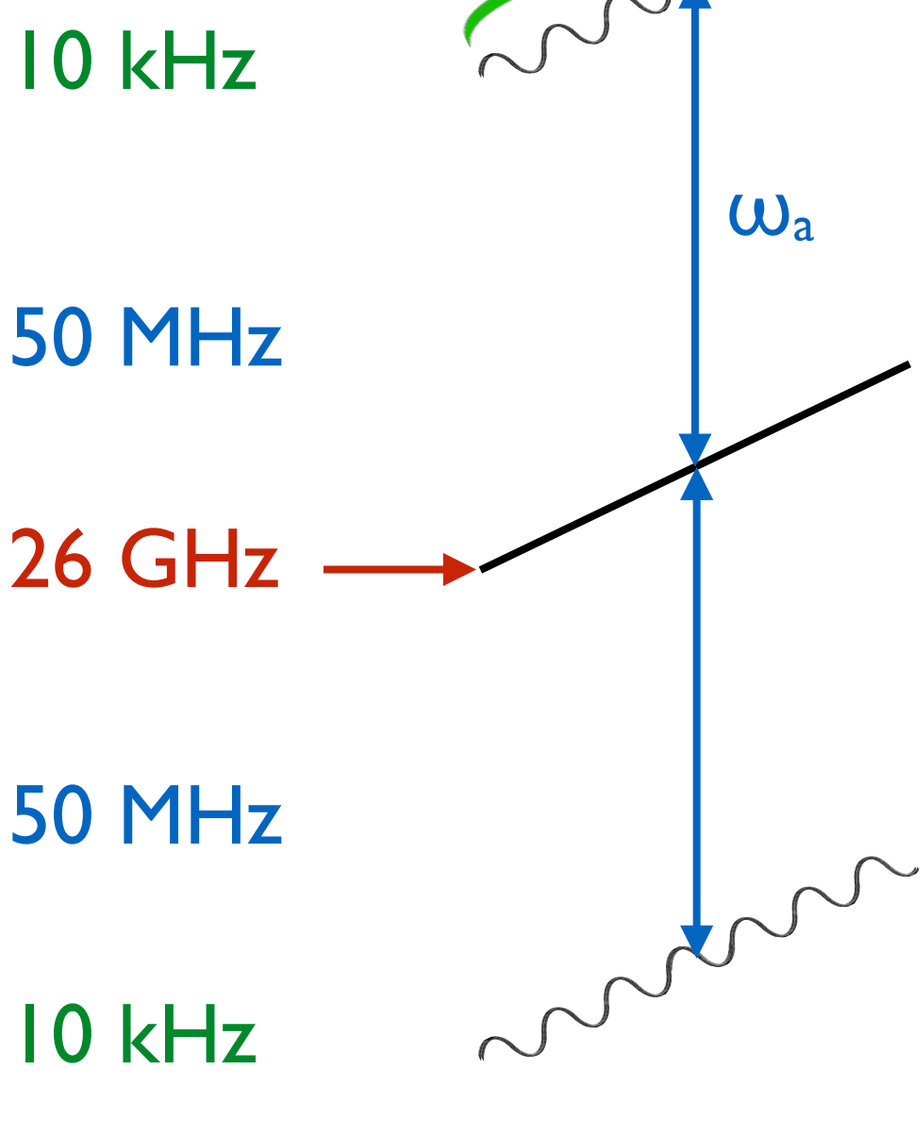
Cold head rebuild
Tighten screws (!)
new DAQ



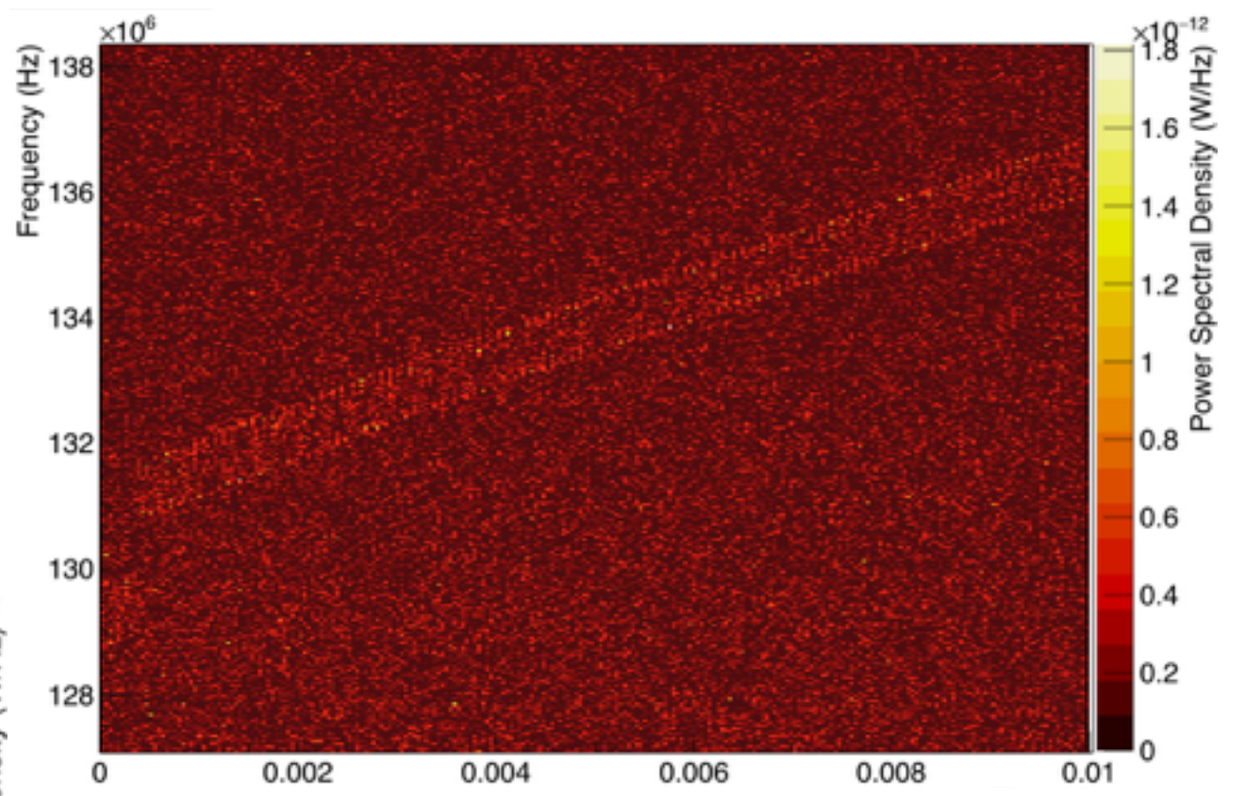
Doppler shifts and nonuniformities



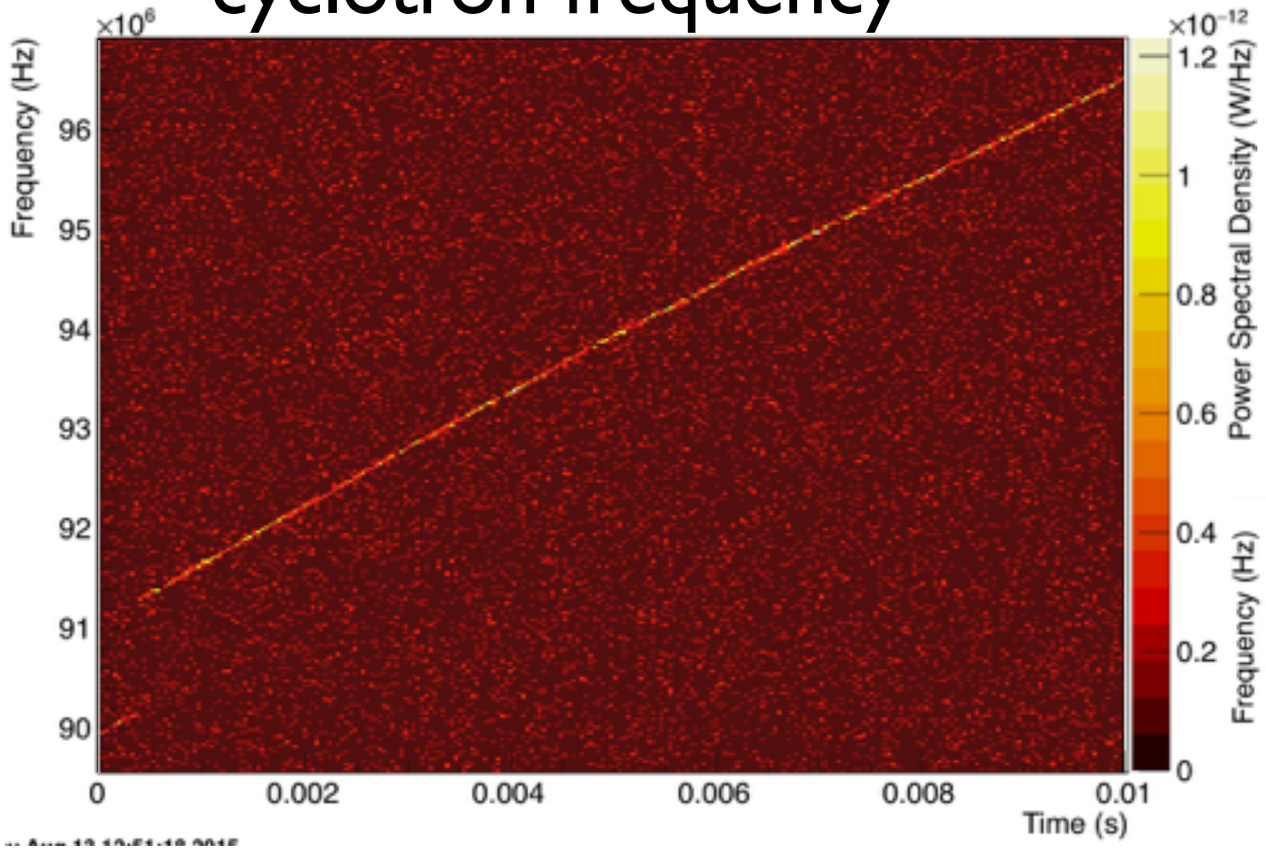




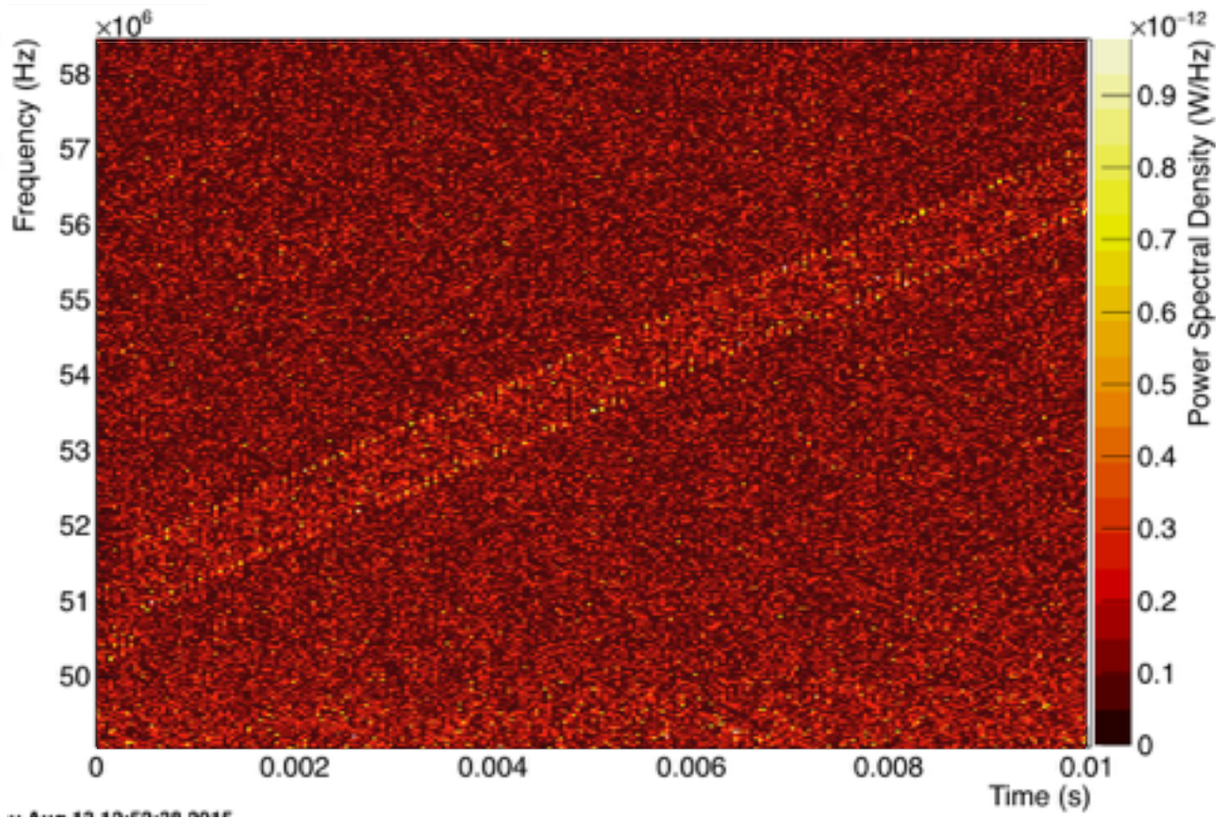
upper sideband



cyclotron frequency

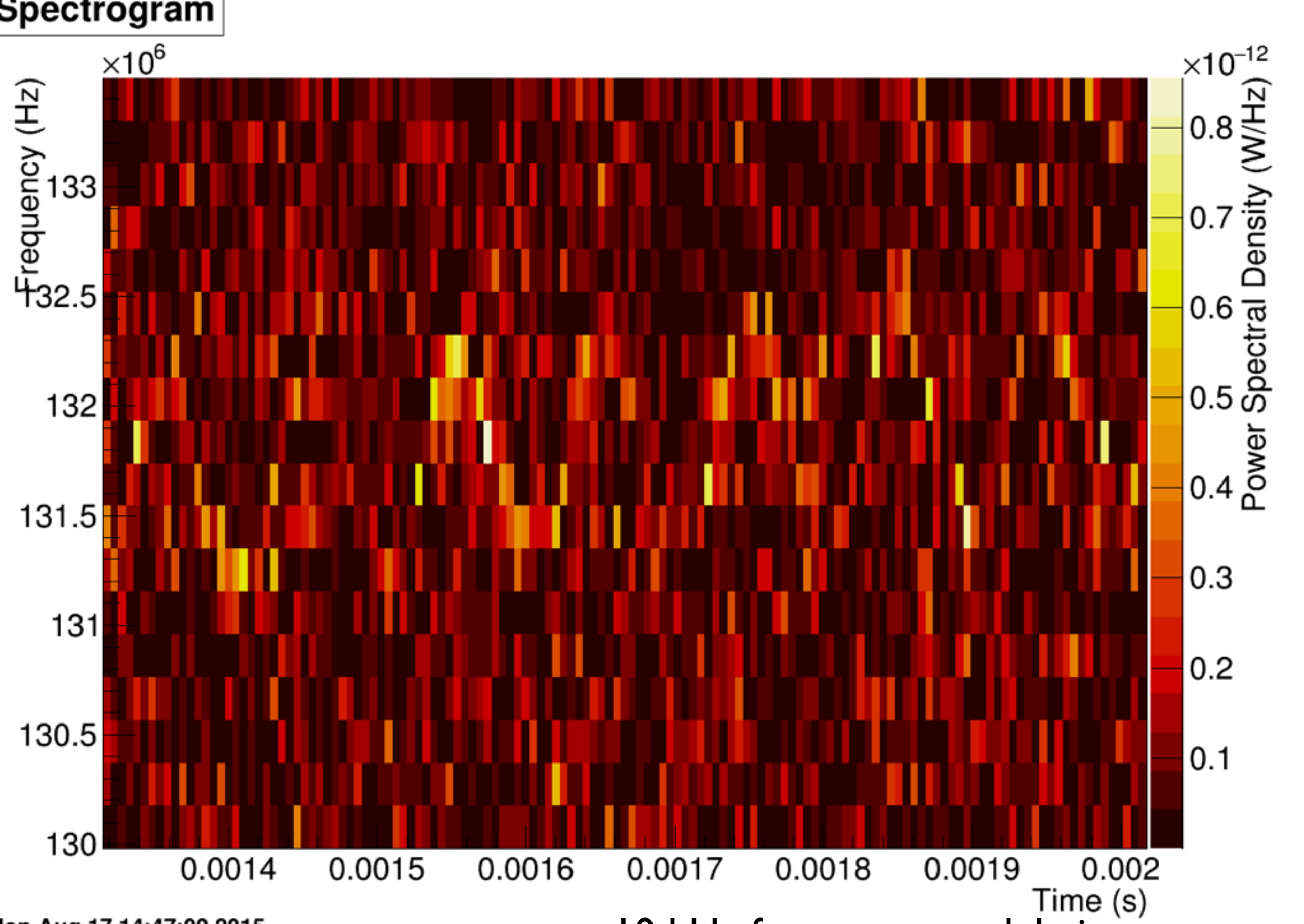


± 40 MHz



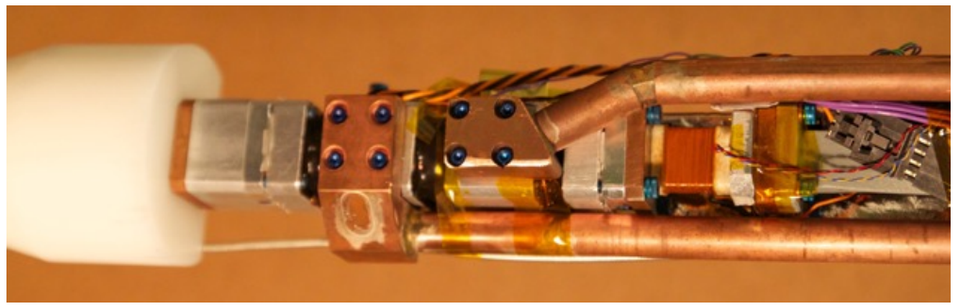
lower sideband

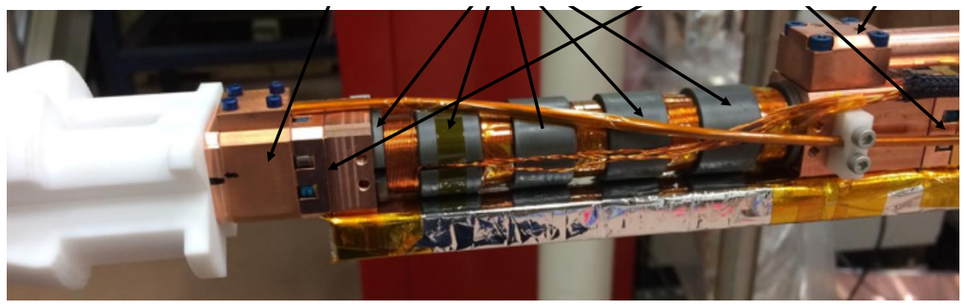
Spectrogram



lon Aug 17 14:47:00 2015

10 kHz frequency modulation





Phase I

- Demonstrate single-electron detection
- CRES spectrum of 83mKr
- 2010 – 2016
- ^{83m}Kr source
- Waveguide

done!

Phase II

- Kurie plot and systematics studies
- m_ν < 10-100 eV
- 2015 – 2017
- T_2 source
- Waveguide

imminent

Phase III

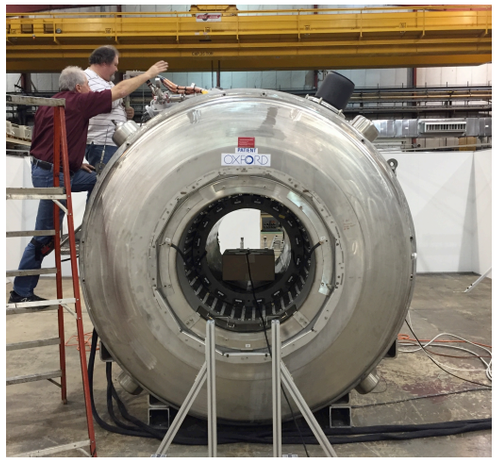
- High-rate sensitivity
- m_ν < 2 eV
- 2016 – 2020
- T_2 source
- Phased antenna array

design

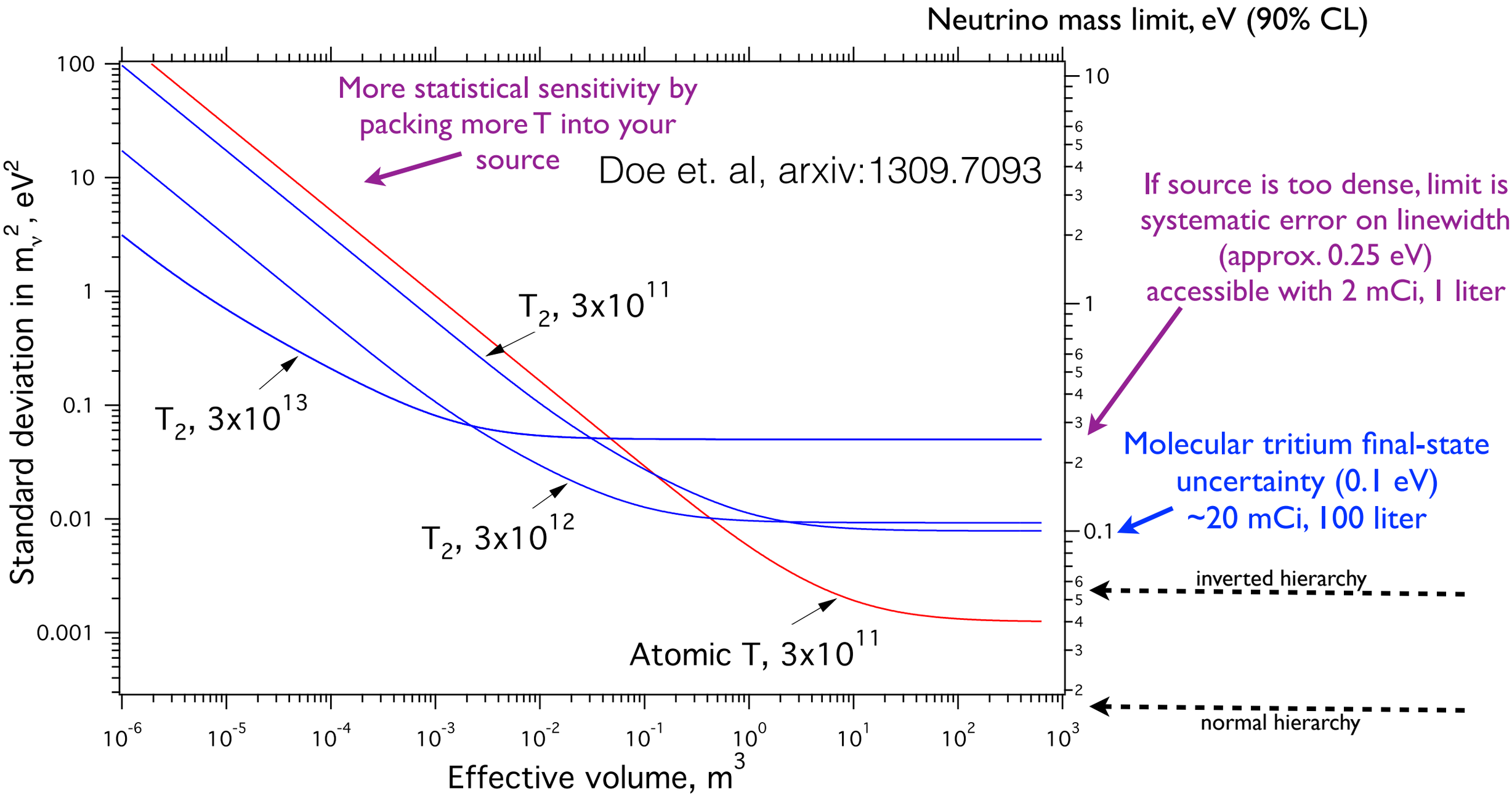
Phase IV

- Atomic tritium source
- m_ν < 40 meV
- 2017 –
- T source
- ?

concept studies



Project 8 sensitivity estimates:
Small and high-density or large and low-density?



Details: B=1 Tesla, background = 1 μHz/eV, livetime 1y, angular acceptance 1 ster, pressure broadening known to 1%, field broadening < 10^{-7}

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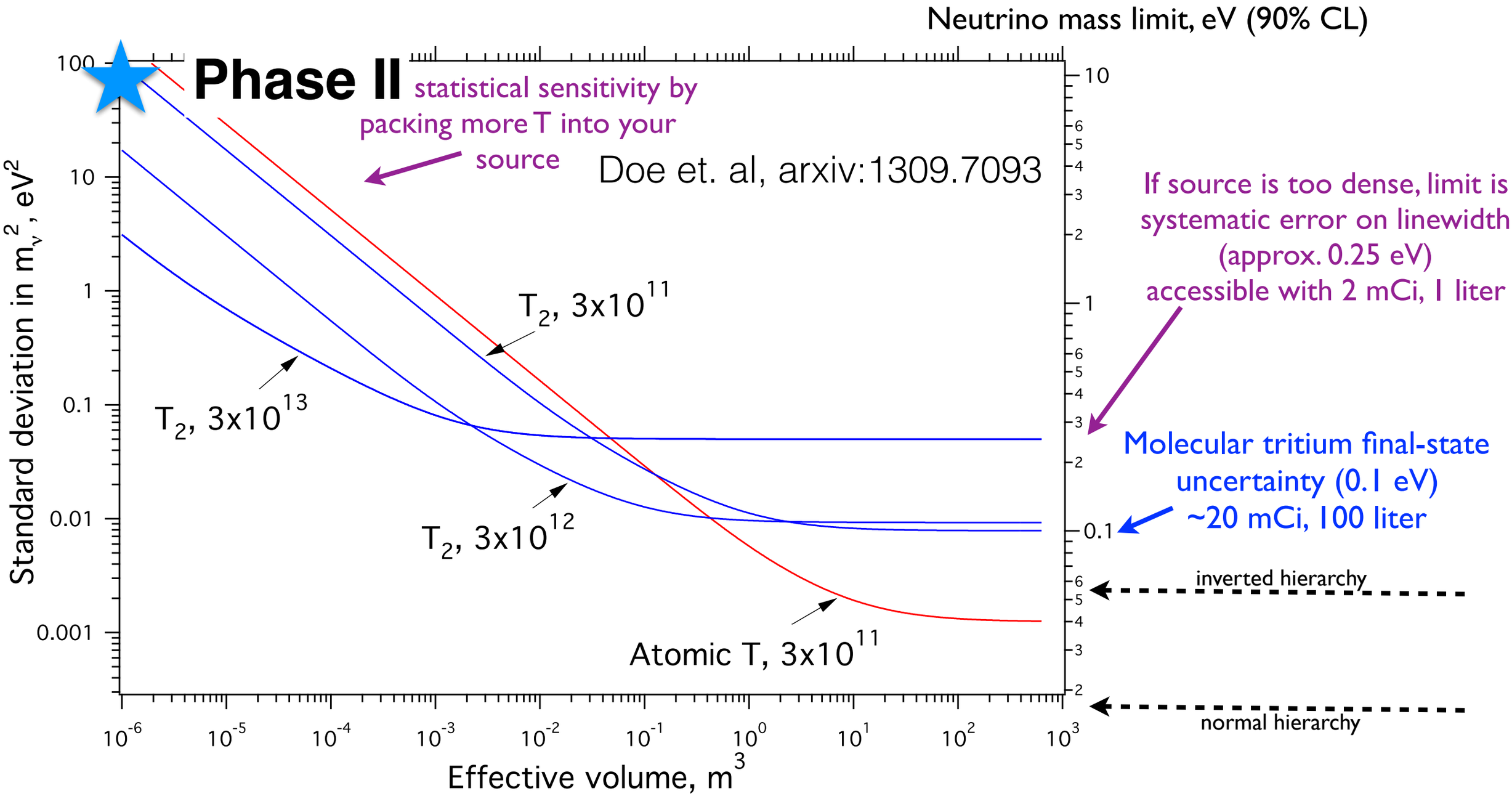

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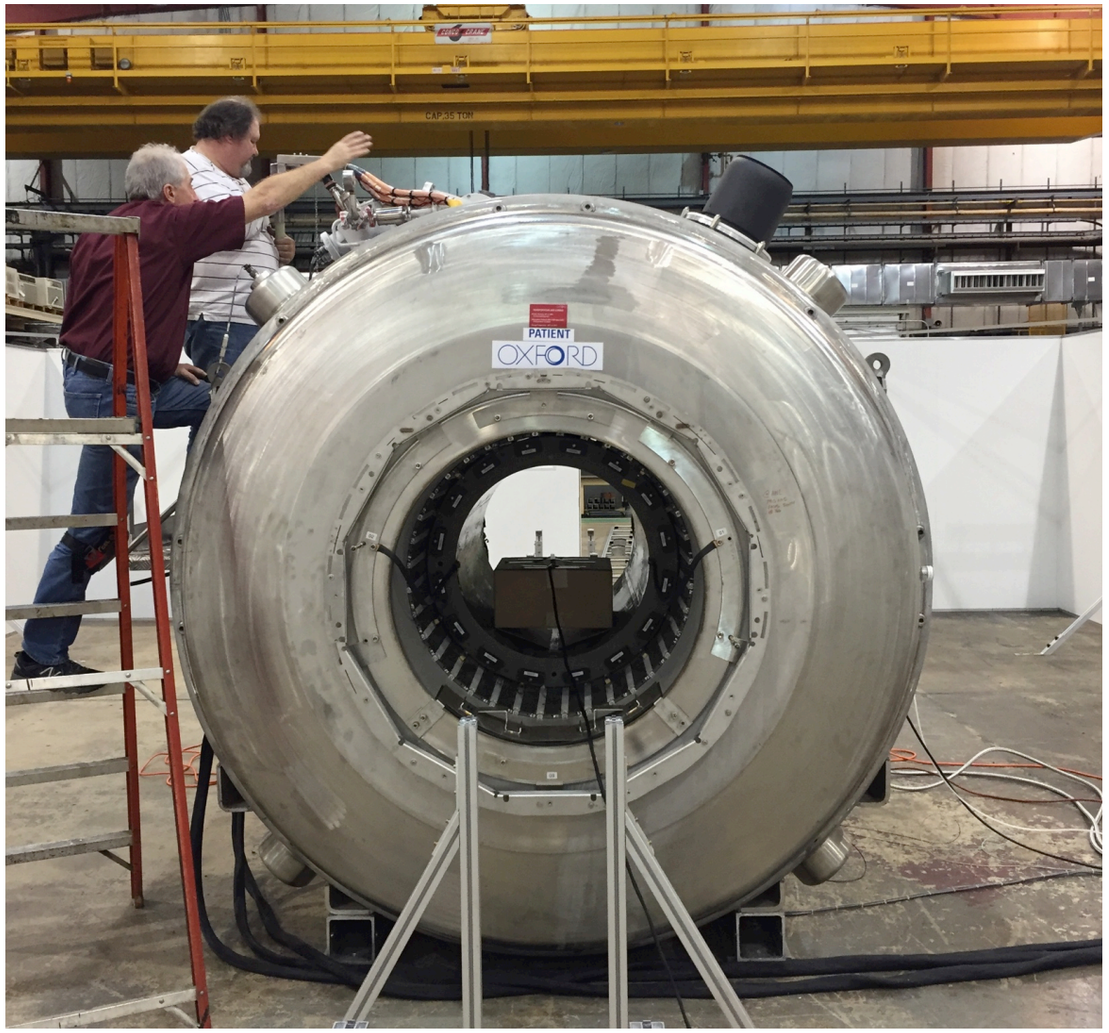
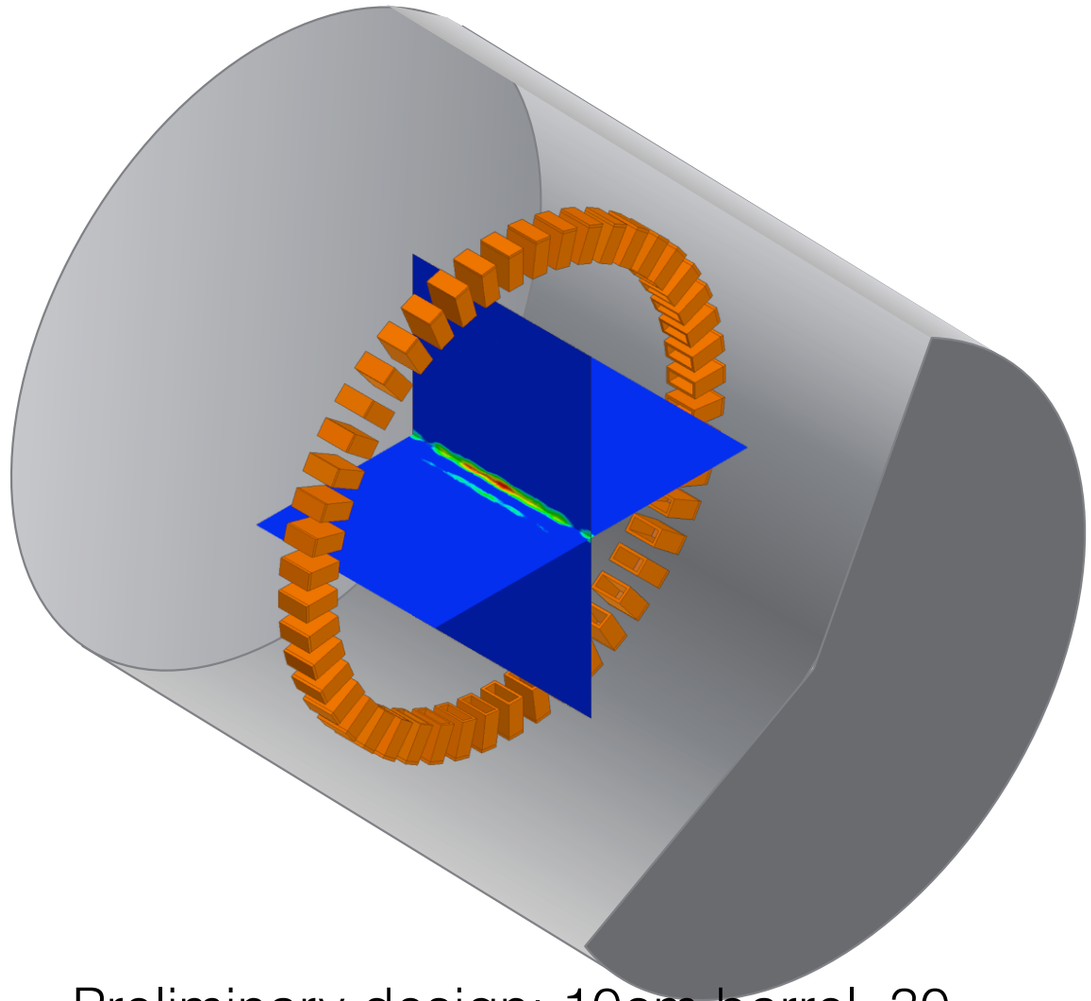
Phase III: multi-antenna



- Surplus MRI magnet
- 10^{-6} uniformity in central 50cm

"Antenna barrel": must choose a focus if you want to coherently add signals



Preliminary design: 10cm barrel, 30 antennas, >10 dB SNR.

ROACH2 + GPU farm for synthetic focus = radio astronomy tech

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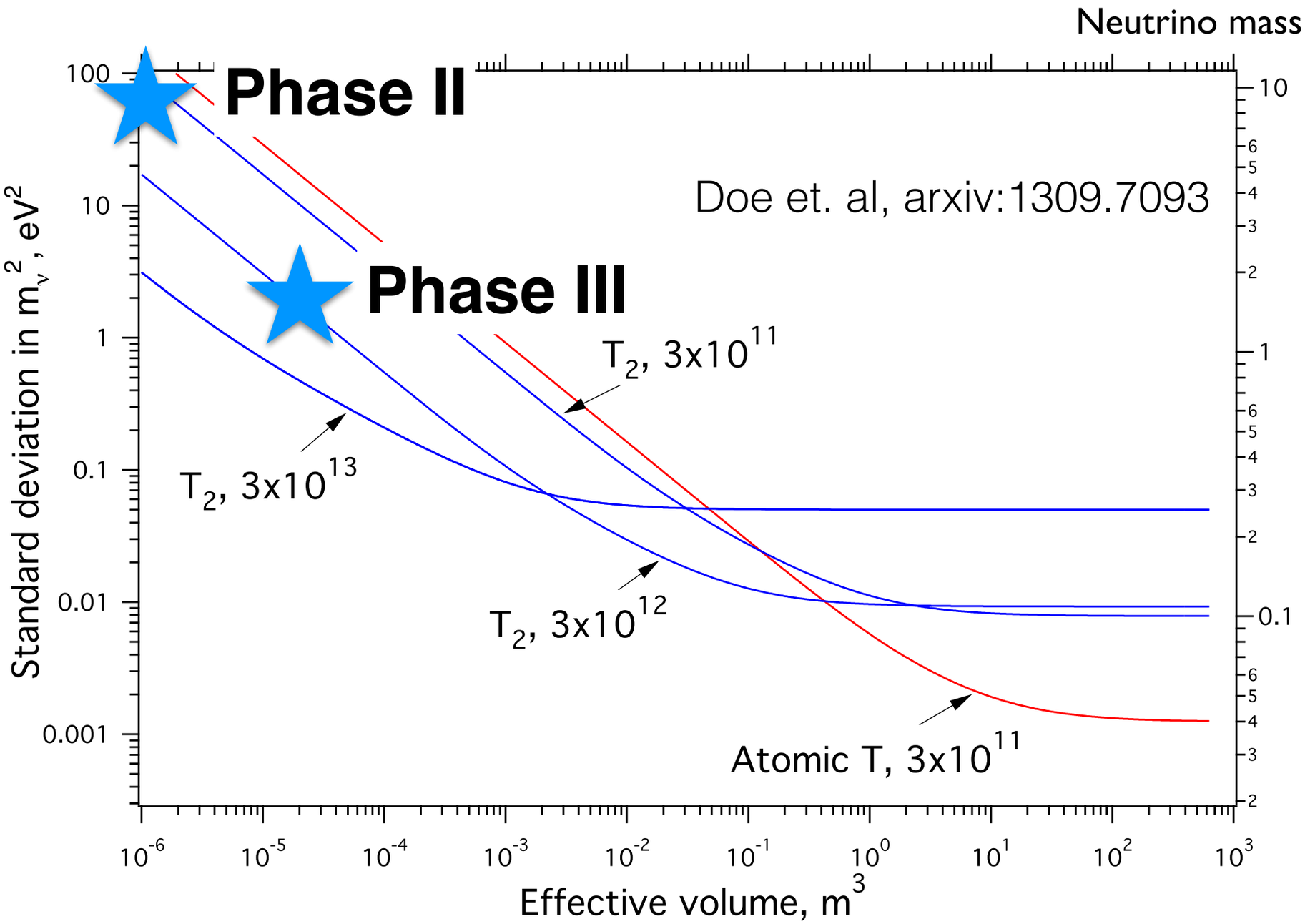
Small and high-density or large and low-density?



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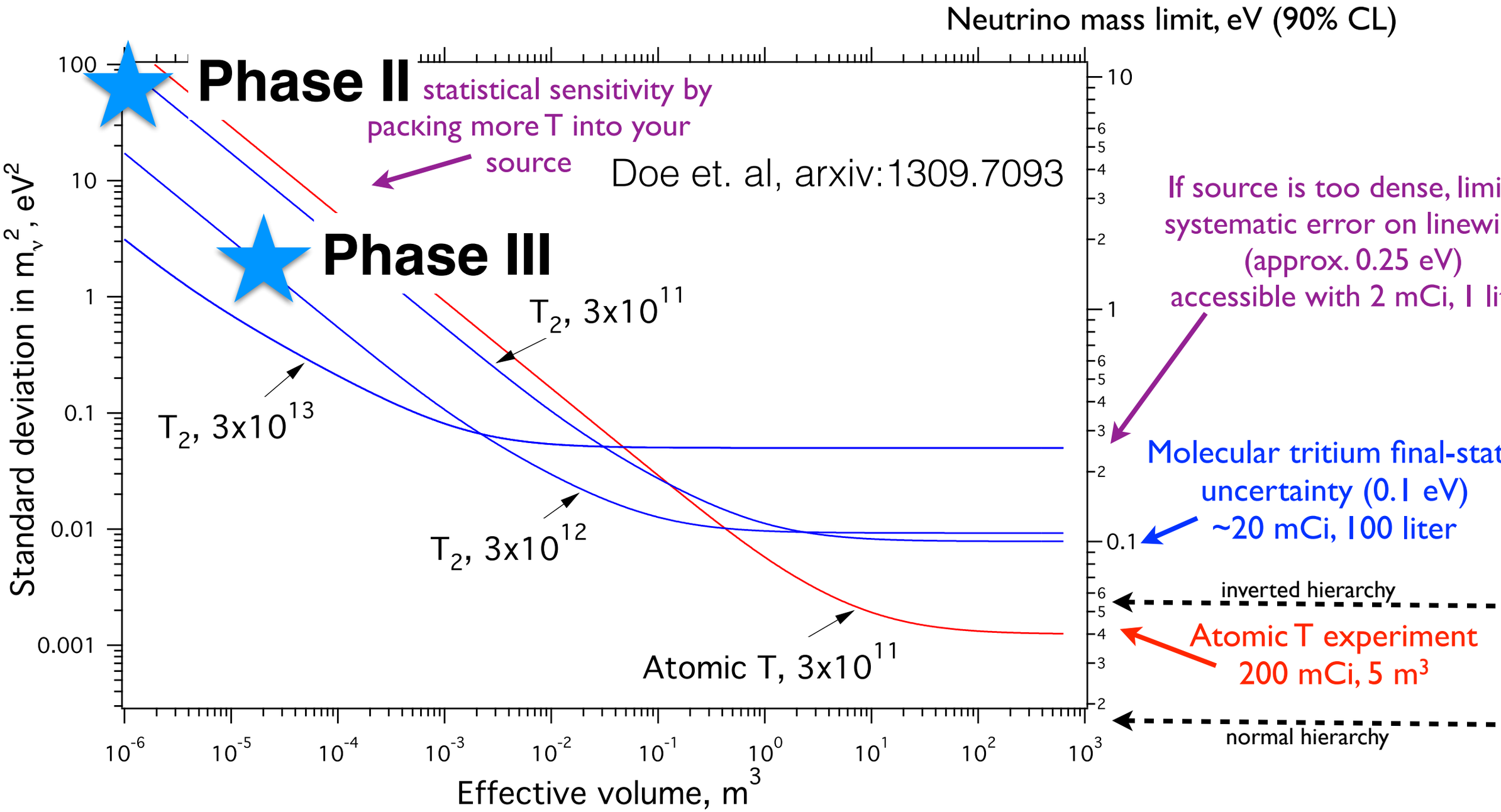

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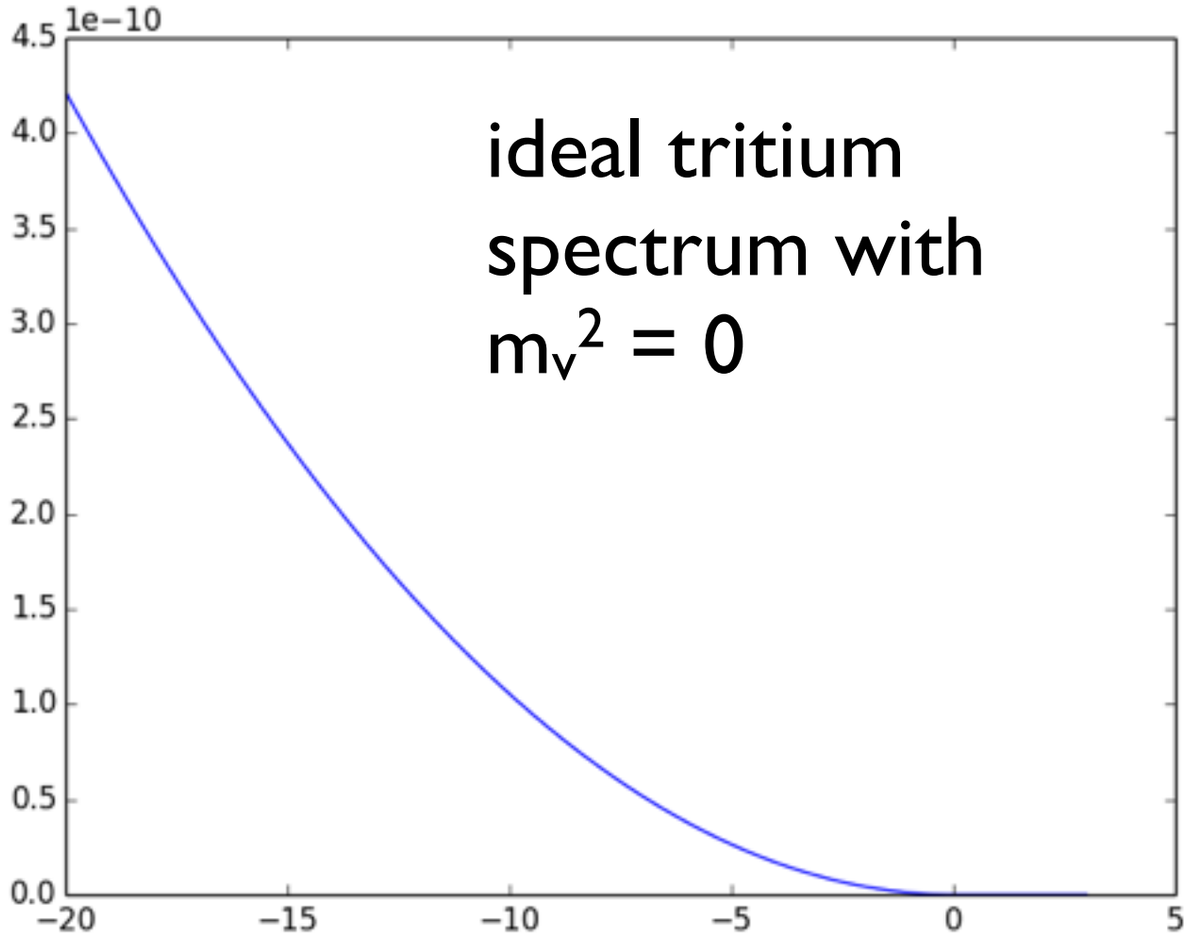
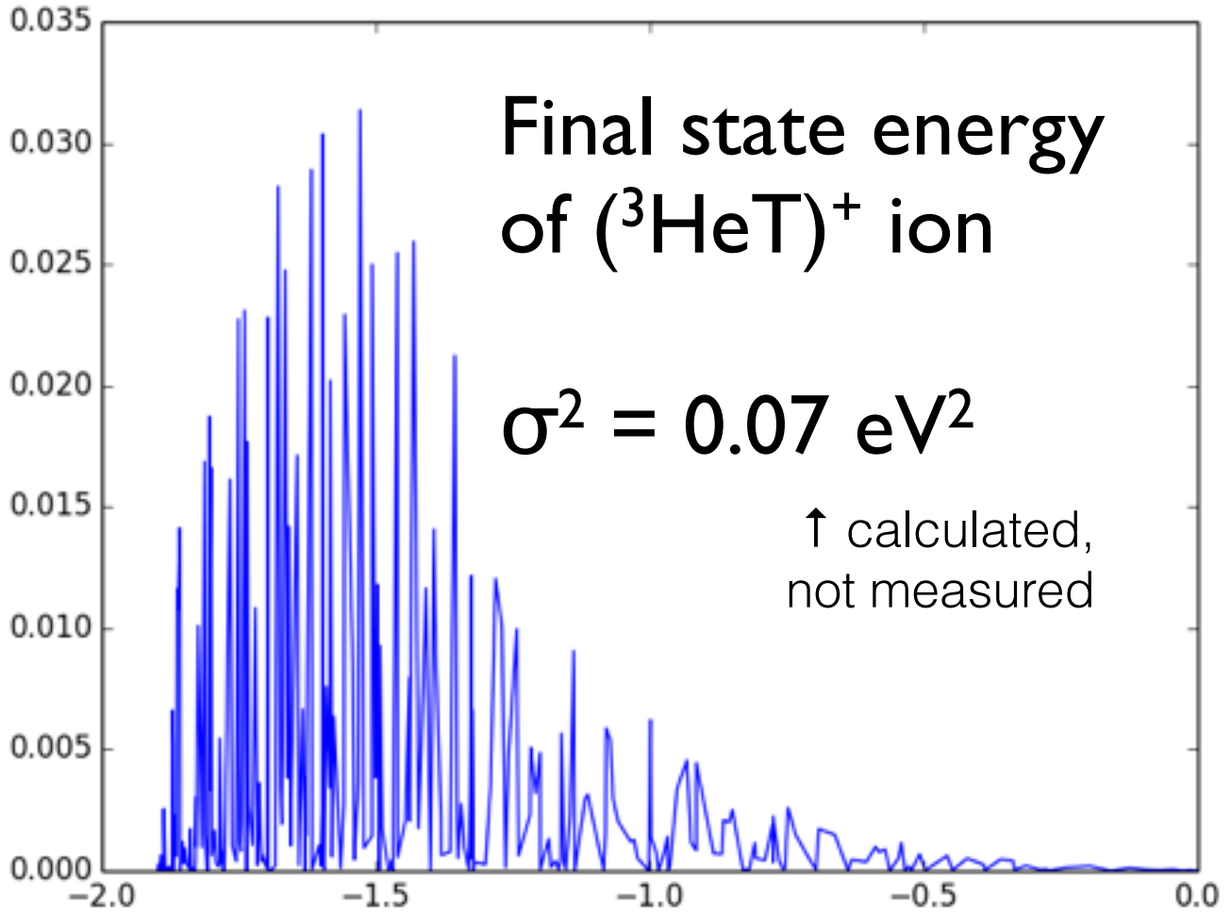


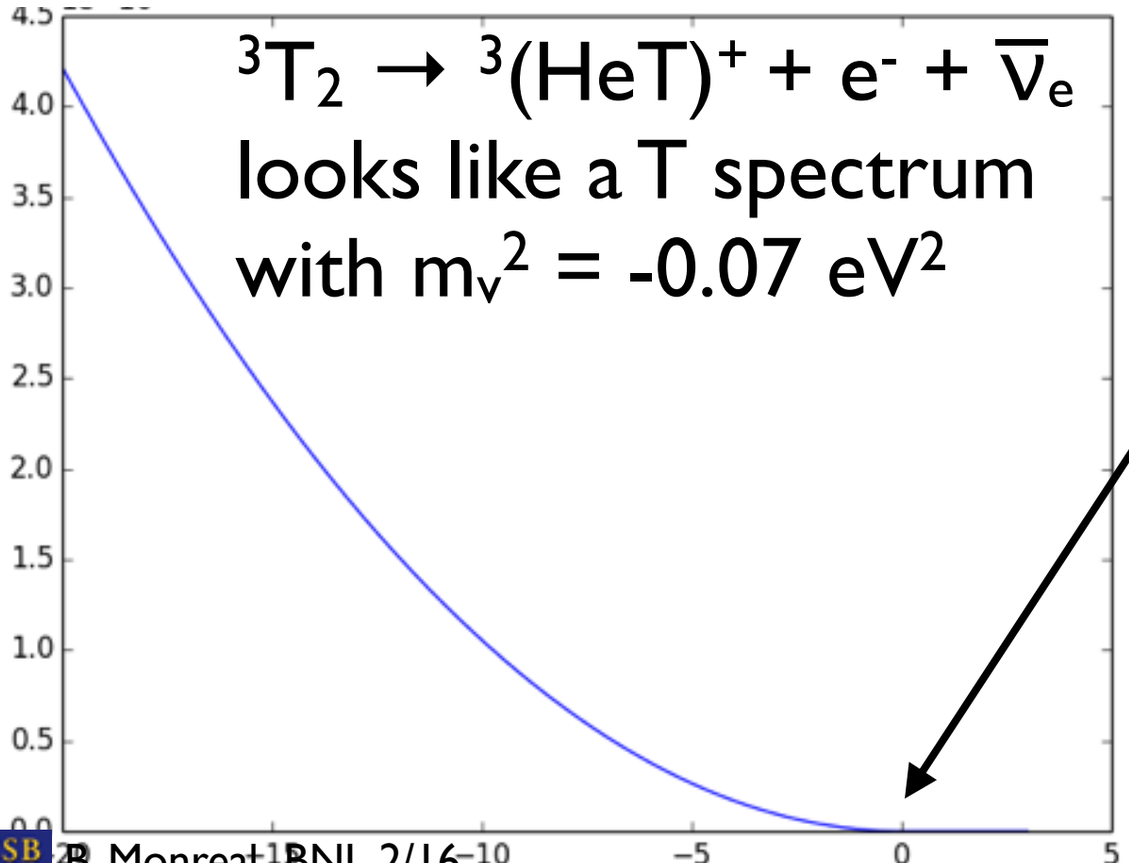
ideal tritium spectrum with $m_\nu^2 = 0$



Final state energy of $(^3HeT)^+$ ion

$\sigma^2 = 0.07\ eV^2$

↑ calculated, not measured



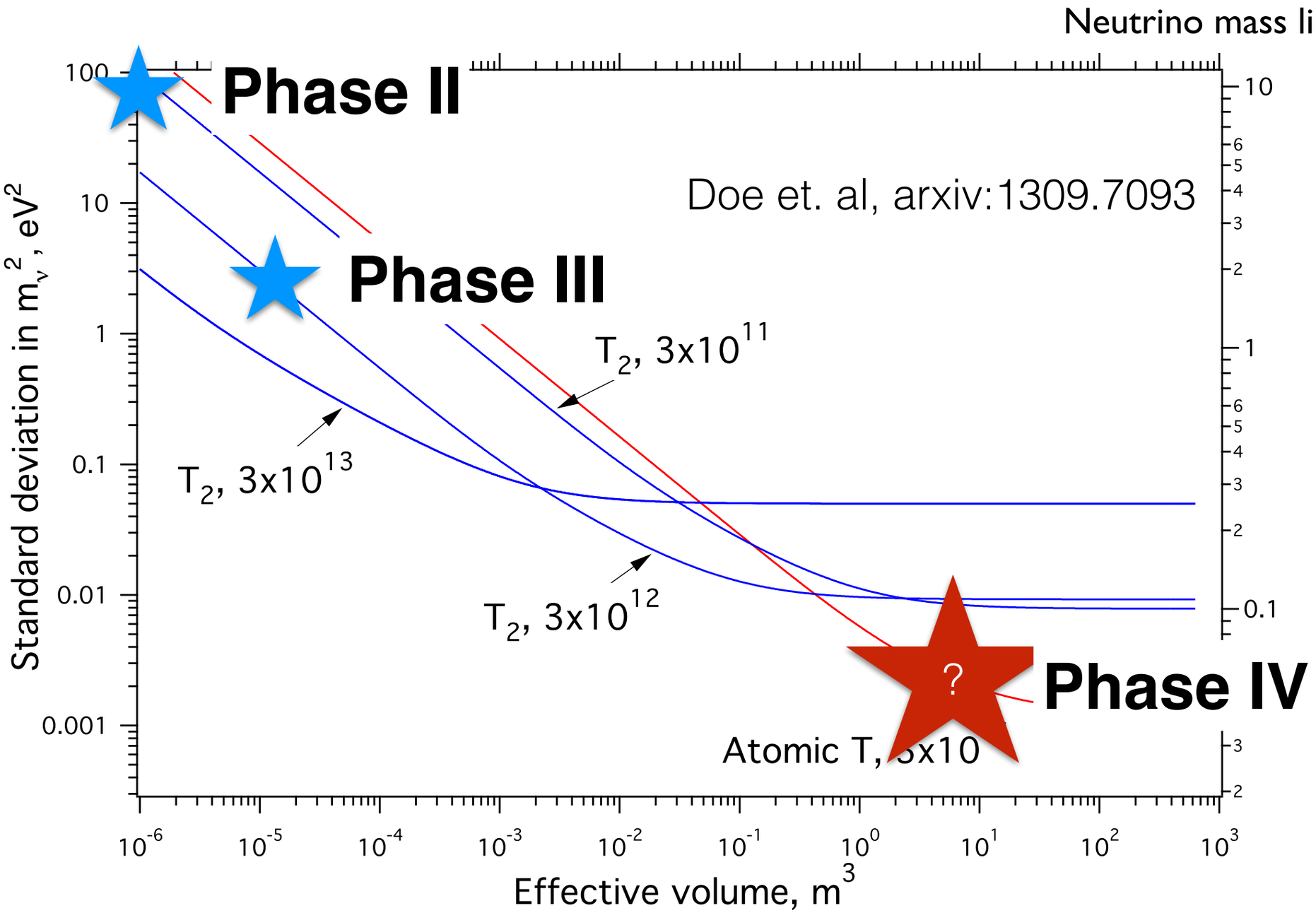
$^3T_2 \rightarrow {}^3(HeT)^+ + e^- + \bar{\nu}_e$ looks like a T spectrum with $m_\nu^2 = -0.07\ eV^2$

different here, but usually not resolvable

- T_2 molecular physics is both blurring and adding systematics
- Worth moving to T_1 source if at all possible

Project 8 sensitivity estimates:

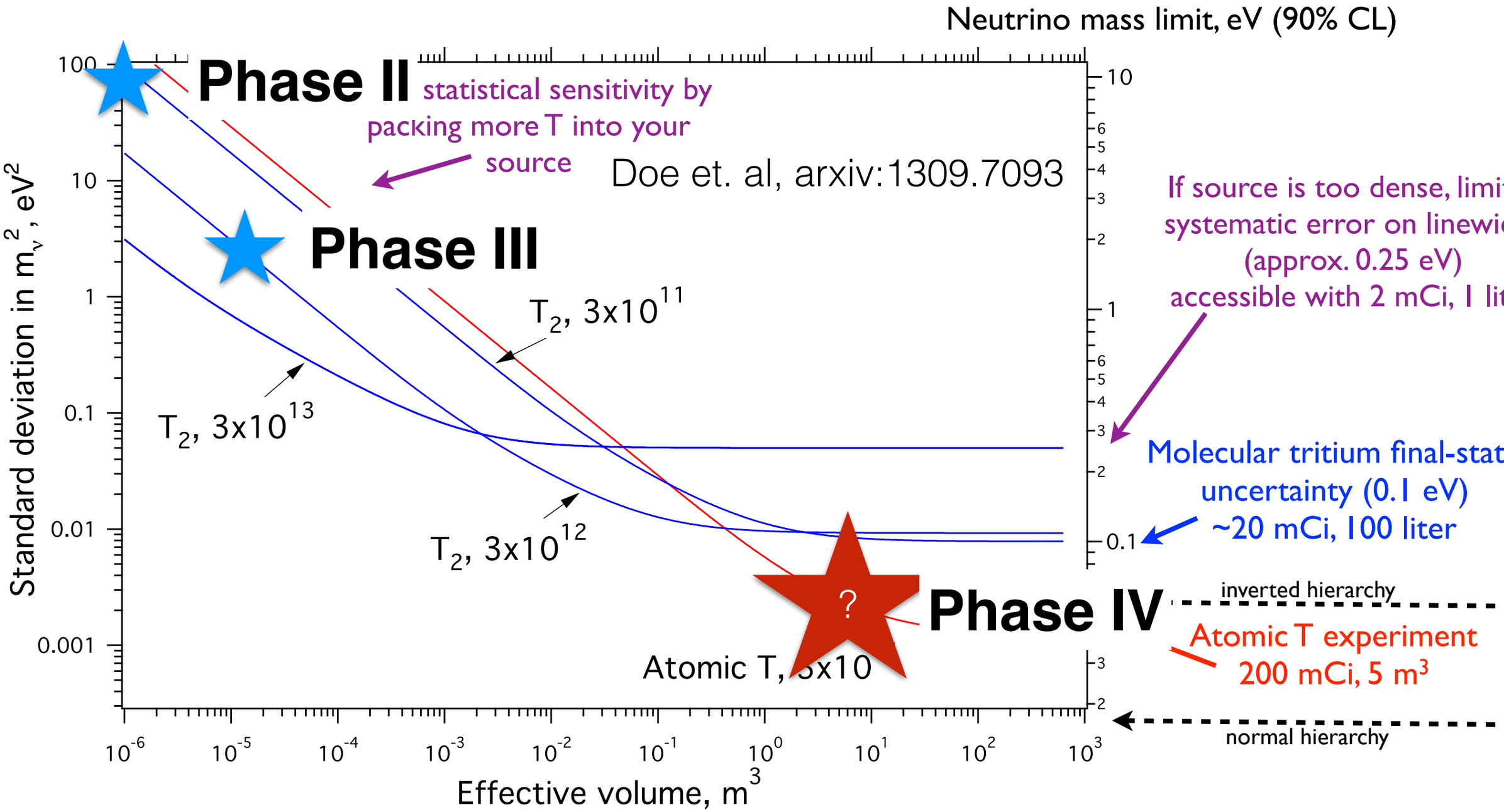
Small and high-density or large and low-density?



Details: B=1 Tesla, background = 1 μHz/eV, livetime 1y, angular acceptance 1 ster, pressure broadening known to 1%, field broadening < 10^{-7}

Project 8 sensitivity estimates:

Small and high-density or large and low-density?



Details: B=1 Tesla, background = 1 μHz/eV, livetime 1y, angular acceptance 1 ster, pressure broadening known to 1%, field broadening < 10^{-7}