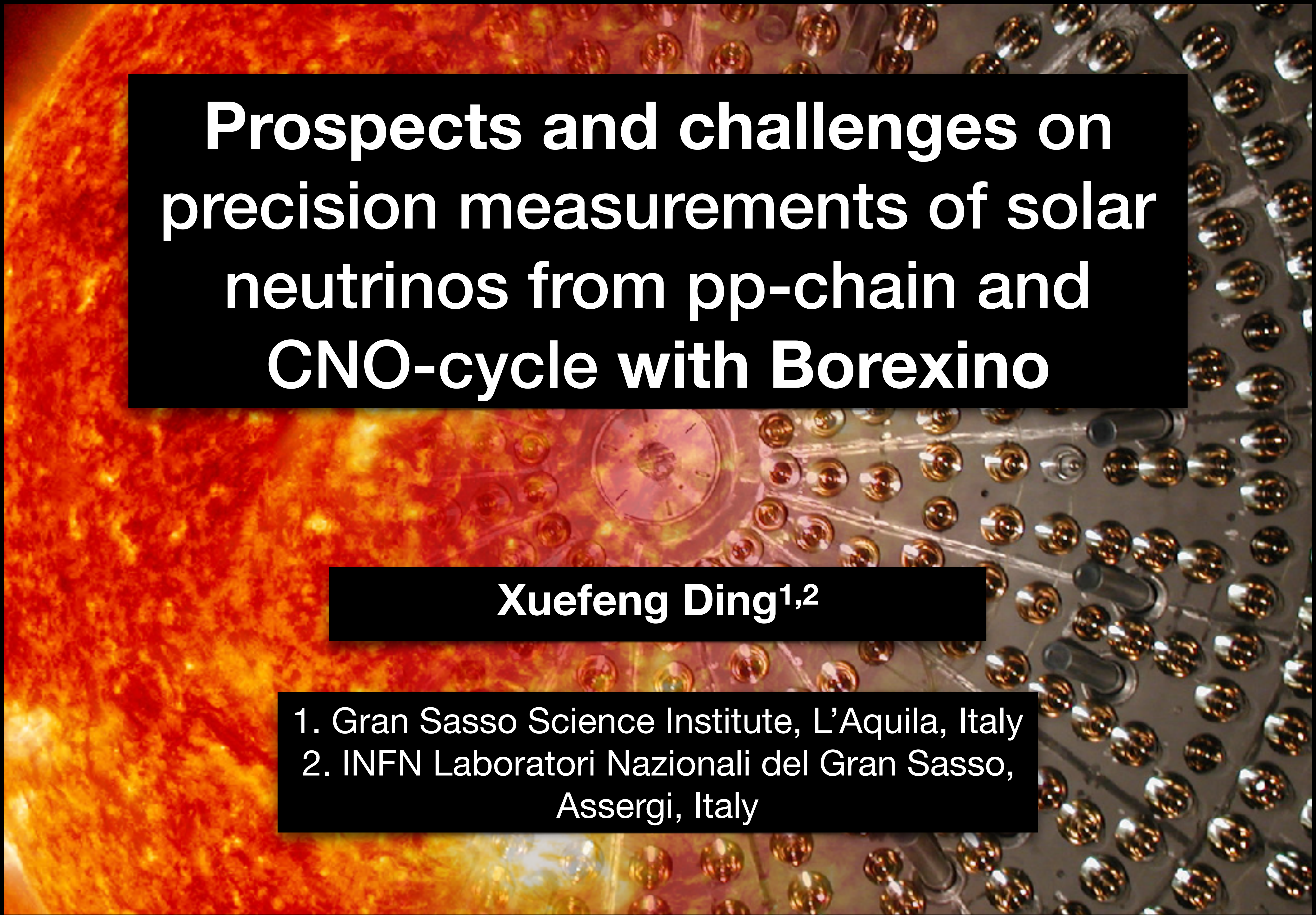


Prospects and challenges on precision measurements of solar neutrinos from pp-chain and CNO-cycle with Borexino

Xuefeng Ding[1,2]

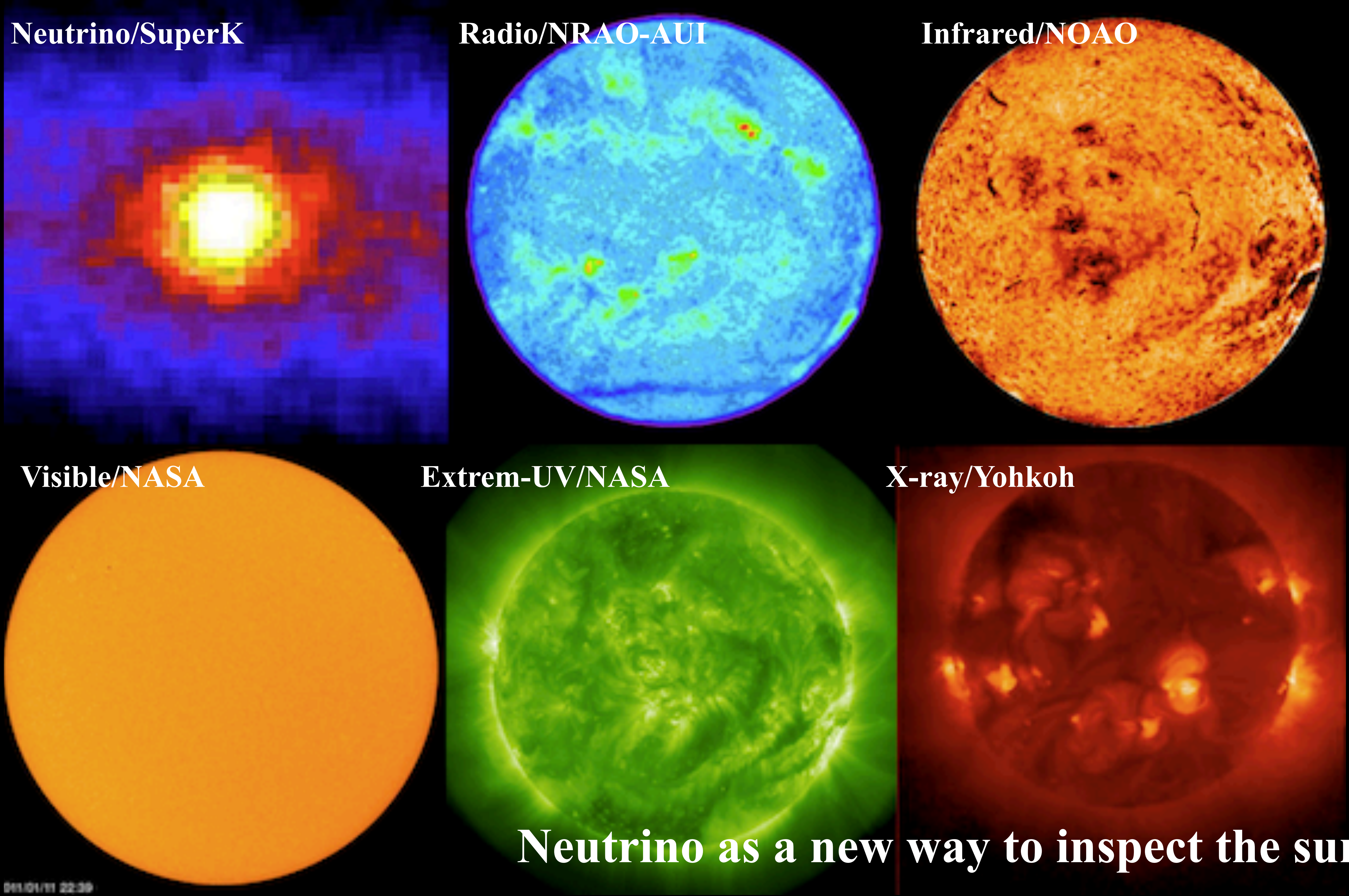
1. Gran Sasso Science Institute, L'Aquila, Italy
2. INFN Laboratori Nazionali del Gran Sasso, Assergi, Italy

Seminar on solar neutrino physics with Borexino
@ IHEP, Beijing, China 20 July 2018

170922A neutrino coincident with the flaring blazar TXS 0506+056

Neutrinos astronomy

In an artist's depiction that is very, very not-to-scale, a blazar is shown shooting a beam of cosmic rays at the Earth. IceCube/NASA



Neutrino/SuperK

Radio/NRAO-AUI

Infrared/NOAO

Visible/NASA

Extrem-UV/NASA

X-ray/Yohkoh

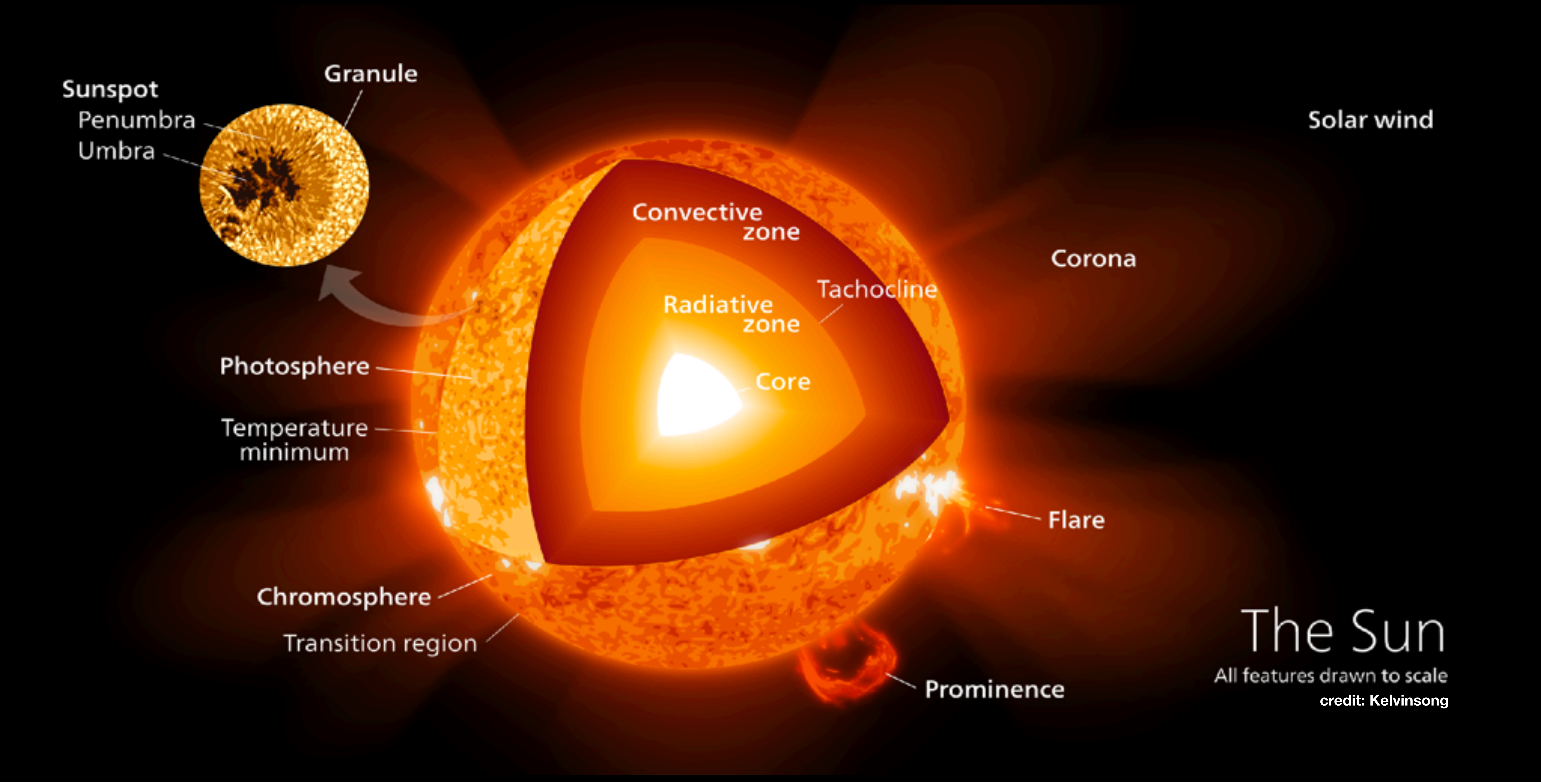
Neutrino as a new way to inspect the sun

Images of the Sun: whereas the neutrino emission originates in the dense core of the Sun, photonic observations originate in the solar surface and atmosphere. From top left: Neutrino ‘image’ of the Solar core (Image credit: R. Svoboda, K. Gordan, LSU), radio emission from the solar atmosphere (Image credit: S. White, University of Maryland, NRAO/AUI), infrared image from the solar chromosphere (Image credit: National Solar Observatory, Kitt Peak/NOAO), visible image of the solar surface (Image credit: SOHO/ESA/NASA), extreme ultraviolet emission from the corona (Image credit: NASA/SDO/AIA), X-ray emission from the solar corona (Image credit: Yohkoh).

Photons vs Neutrinos

O(10^5) years to escape

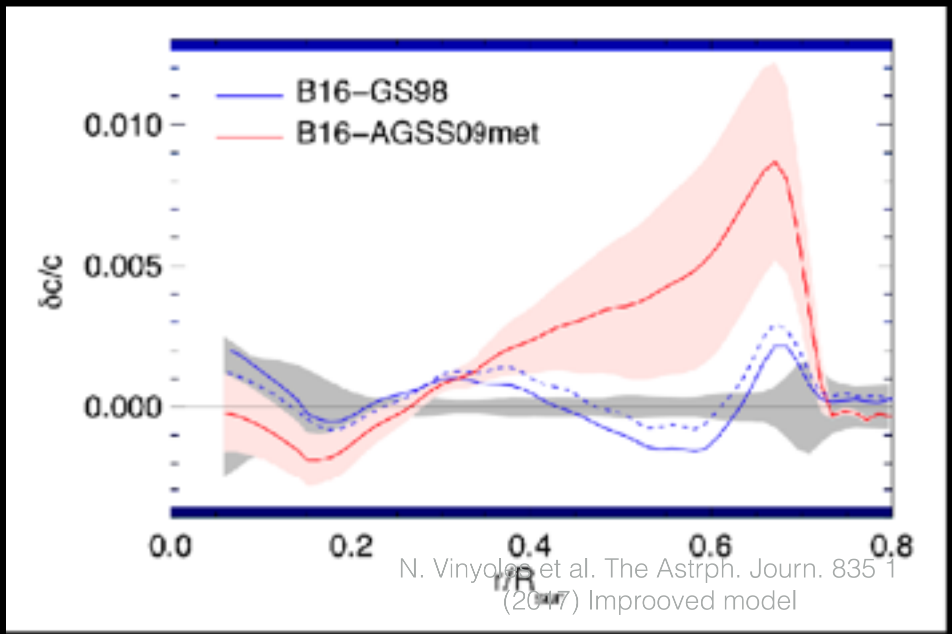
~2 seconds to escape



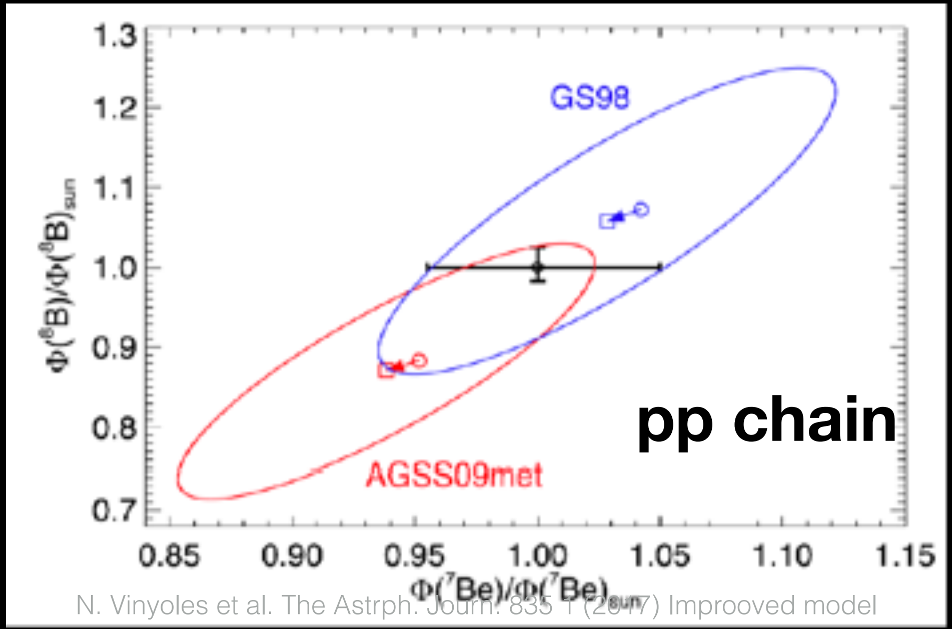
credit: Kelvinsong

Probe of the sun

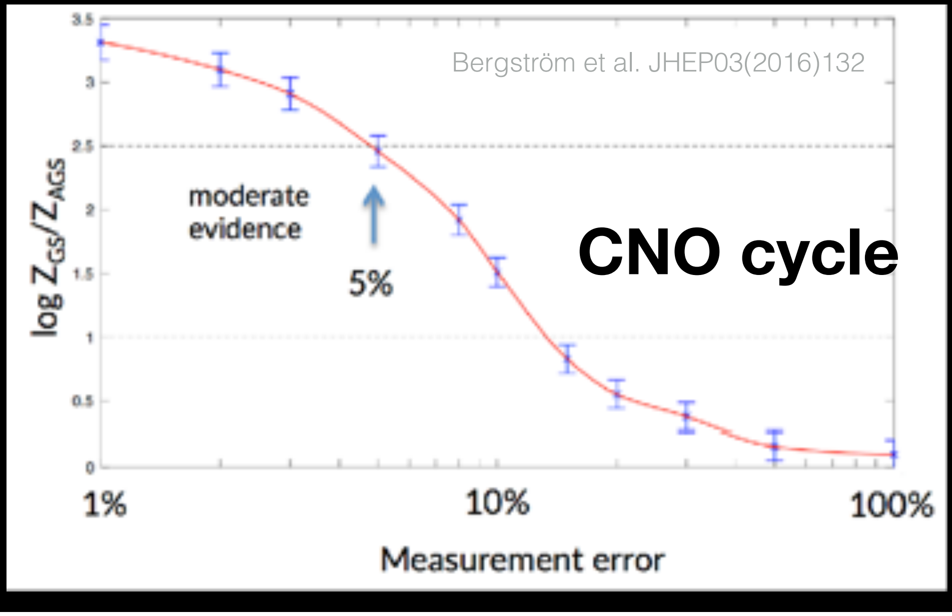
- **Helioseismology** + **solar ν**
  - GS98: old, 1D model
  - AGSS09: new, 3D model
- Solar neutrino to resolve HZ/LZ
  - pp chain: ^{8}B(SuperK) lies in the exact middle of HZ/LZ
    - BX alone have moderate discrimination power, see later
  - CNO chain: 5% to resolve



N. Vinyoles et al. The Astrph. Journ. 835 1 (2017) Improoved model

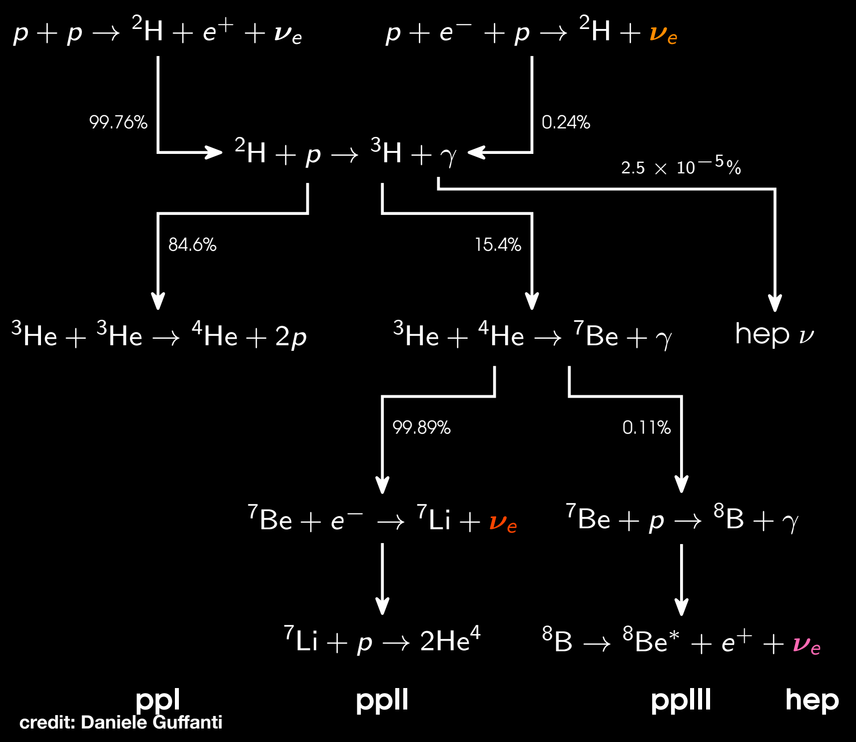


N. Vinyoles et al. The Astrph. Journ. 835 1 (2017) Improoved model



Bergström et al. JHEP03(2016)132

What is pp-chain and CNO-cycle?



$p + p \to {}^2\mathrm{H} + e^+ + \nu_e$

$p + e^- + p \to {}^2\mathrm{H} + \nu_e$

99.76%

0.24%

${}^2\mathrm{H} + p \to {}^3\mathrm{H} + \gamma$

$2.5 \times 10^{-5}\%$

84.6%

15.4%

${}^3\mathrm{He} + {}^3\mathrm{He} \to {}^4\mathrm{He} + 2p$

${}^3\mathrm{He} + {}^4\mathrm{He} \to {}^7\mathrm{Be} + \gamma$

hep ν

99.89%

0.11%

${}^7\mathrm{Be} + e^- \to {}^7\mathrm{Li} + \nu_e$

${}^7\mathrm{Be} + p \to {}^8\mathrm{B} + \gamma$

${}^7\mathrm{Li} + p \to 2\mathrm{He}^4$

${}^8\mathrm{B} \to {}^8\mathrm{Be}^* + e^+ + \nu_e$

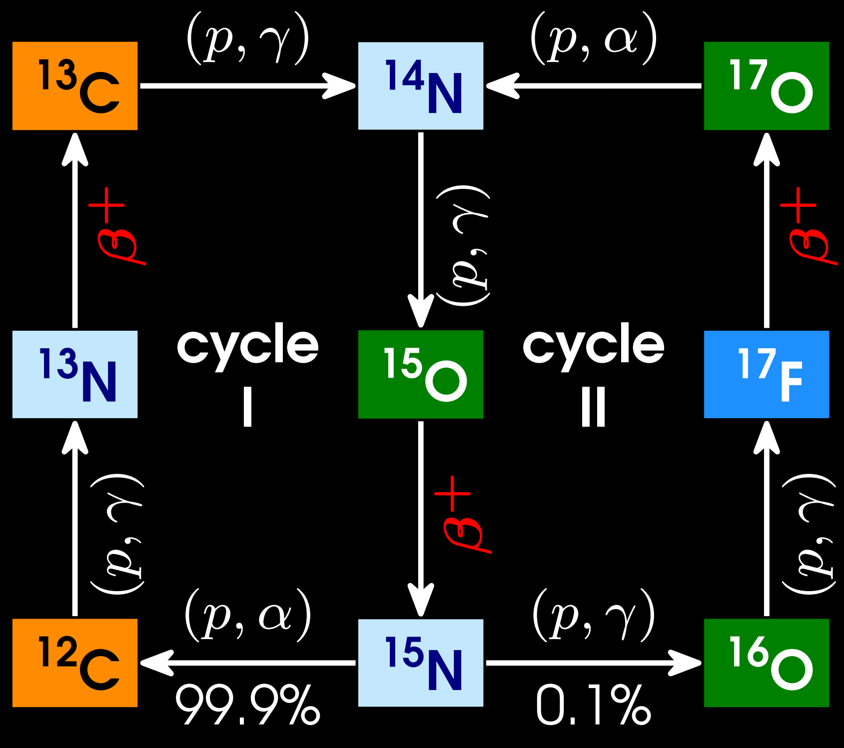
ppI

ppII

ppIII

hep

credit: Daniele Guffanti



credit: Daniele Guffanti

- Two ways of pp-fusion (4p -> ^{4}He + 26.73 MeV)
  - pp-chain: happens sequentially
  - CNO-cycle: C,N,O as catalyst

The Sun to study MSW

thick & ultra-high density

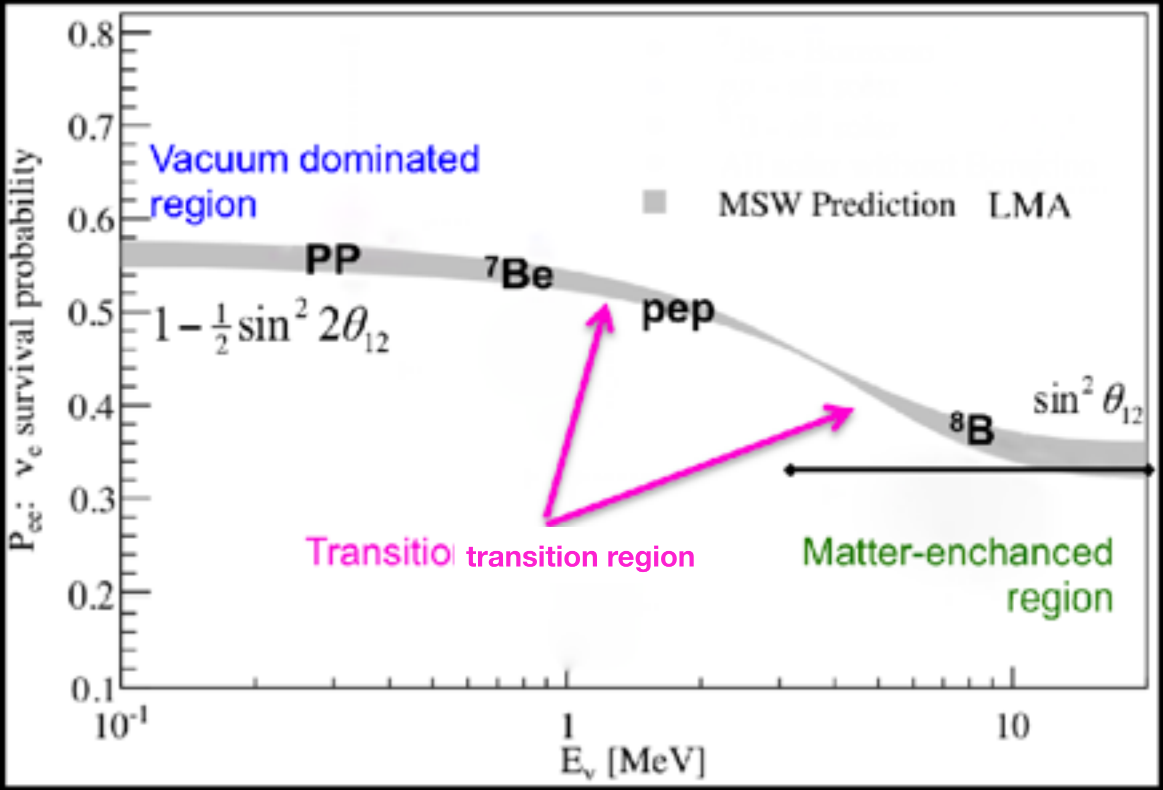
$$A_{\mathrm{CC}} \equiv 2\,E\,V_{\mathrm{CC}} = 2\sqrt{2}\,E\,G_{\mathrm{F}}\,N_e$$

ν_e and electron

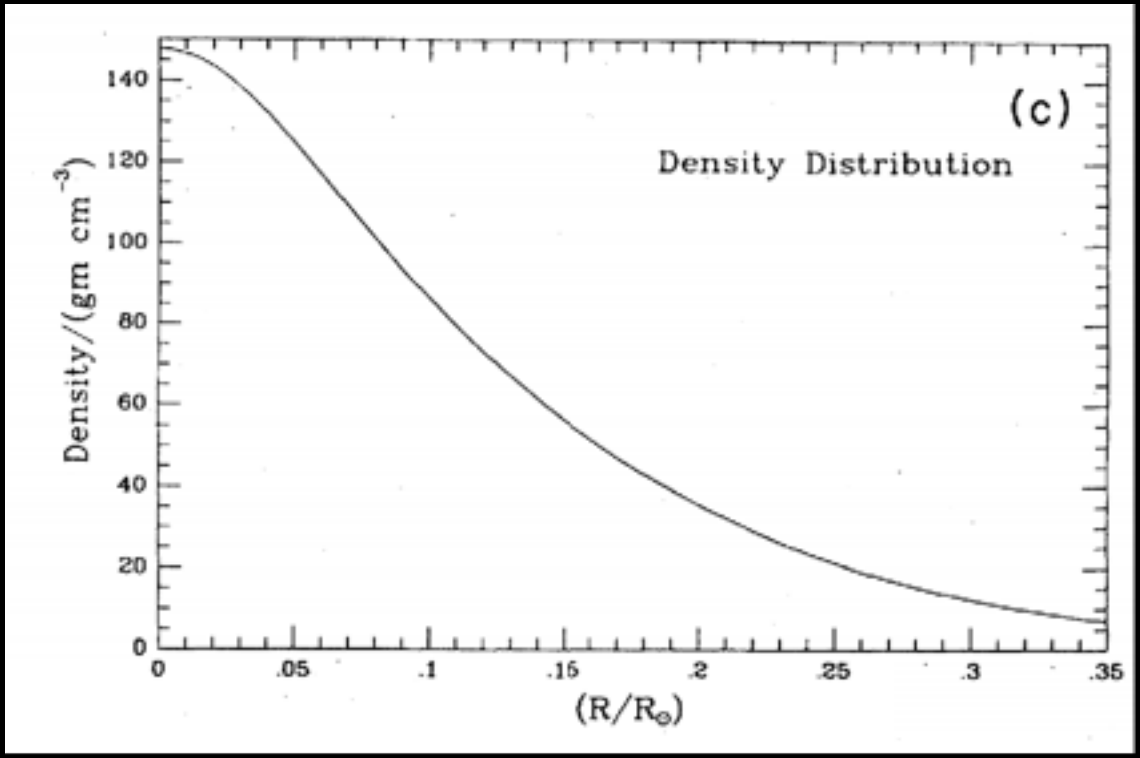
$$\overline{P}^{\text{adiabatic}}_{\nu_e\to\nu_e} = \frac{1}{2} + \frac{1}{2}\cos 2\vartheta^{(\mathrm{i})}_{\mathrm{M}}\cos 2\vartheta$$

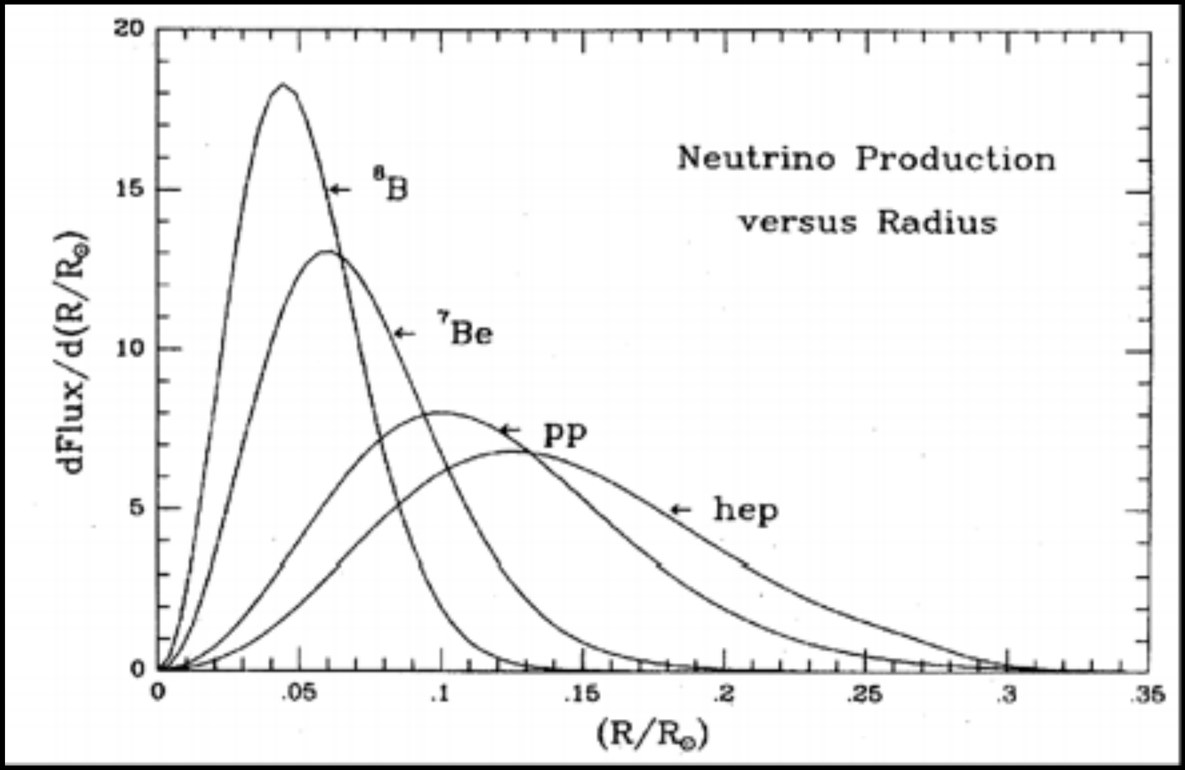
Survival probability

[1] C. Giunti and C. W. Kim, Fundamentals of neutrino physics and astrophysics, vol. 54, no. 2. Oxford University Press, USA, 2007.



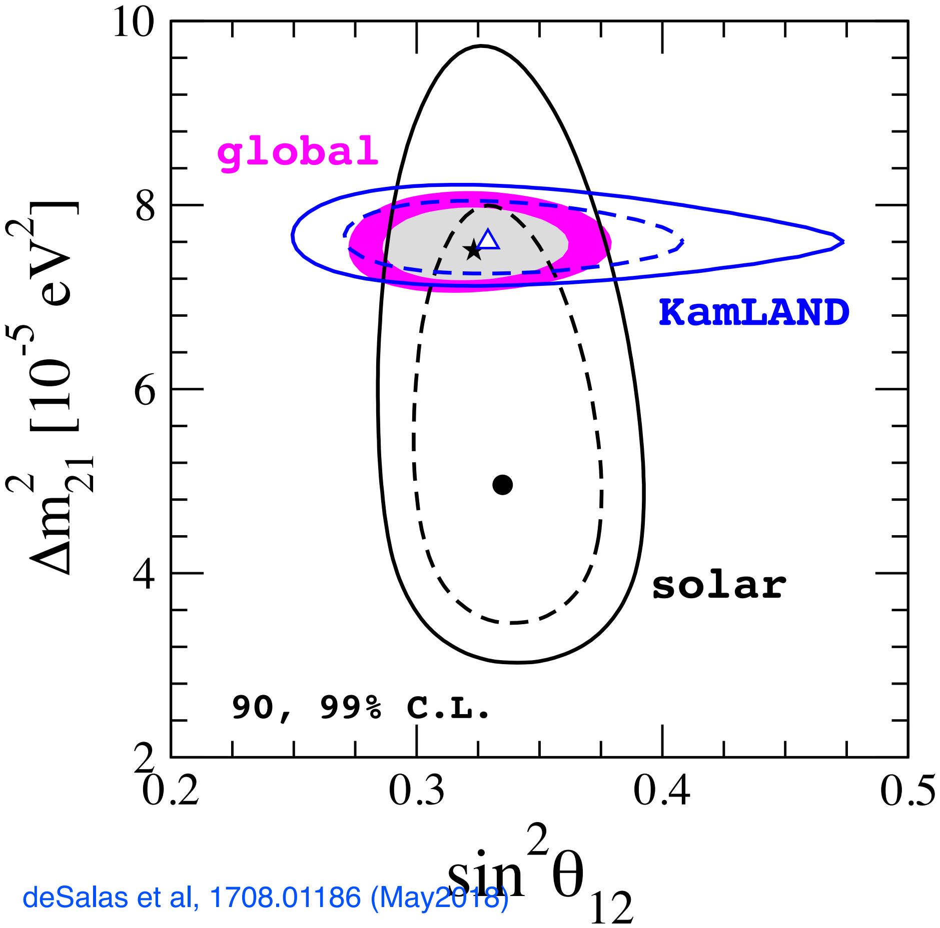
Low Energy Neutrino Measurements Davide D'A 10.1007/s12043-012-0385-3





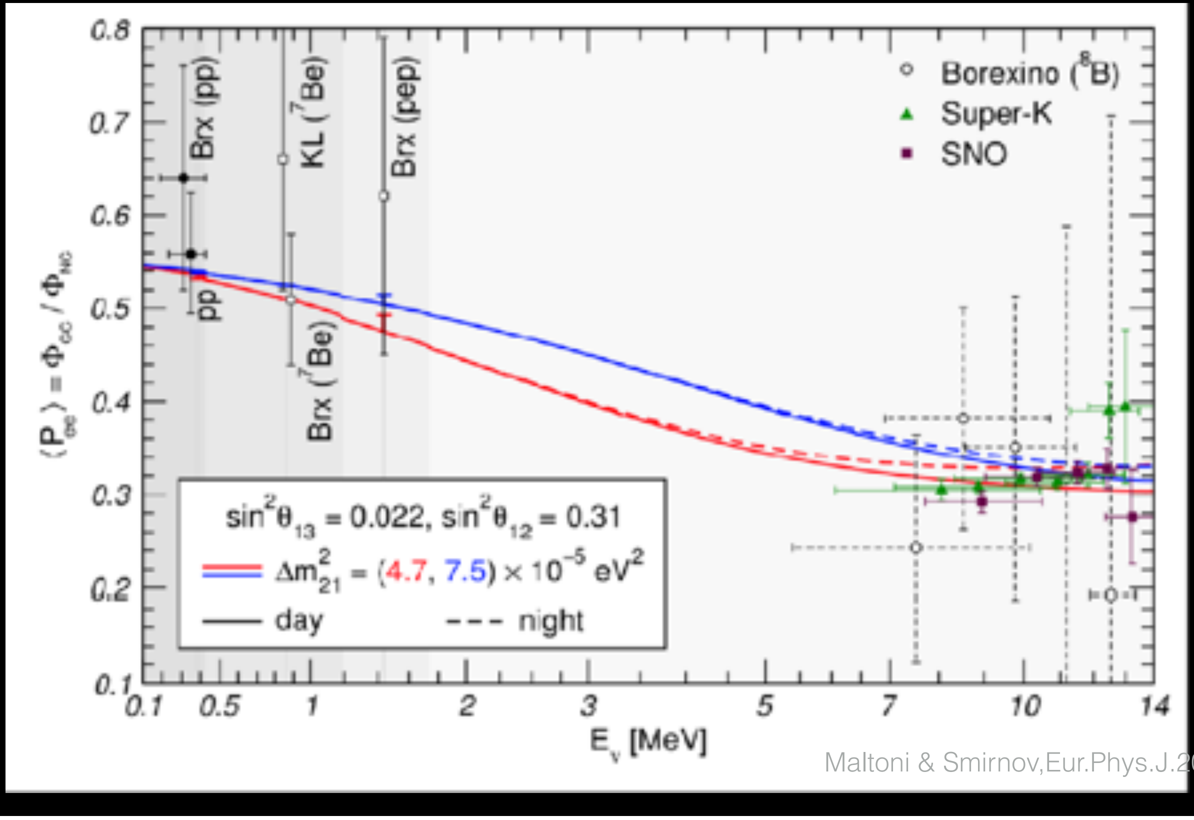
Solar Models, Neutrino Experiments, and Helioseismology Author(s):John N. Bahcall and Roger K. Ulrich Journal: *Reviews of Modern Physics*, 60, No. 2, 297-372 (April 1988).

What’s interesting in **MSW?**

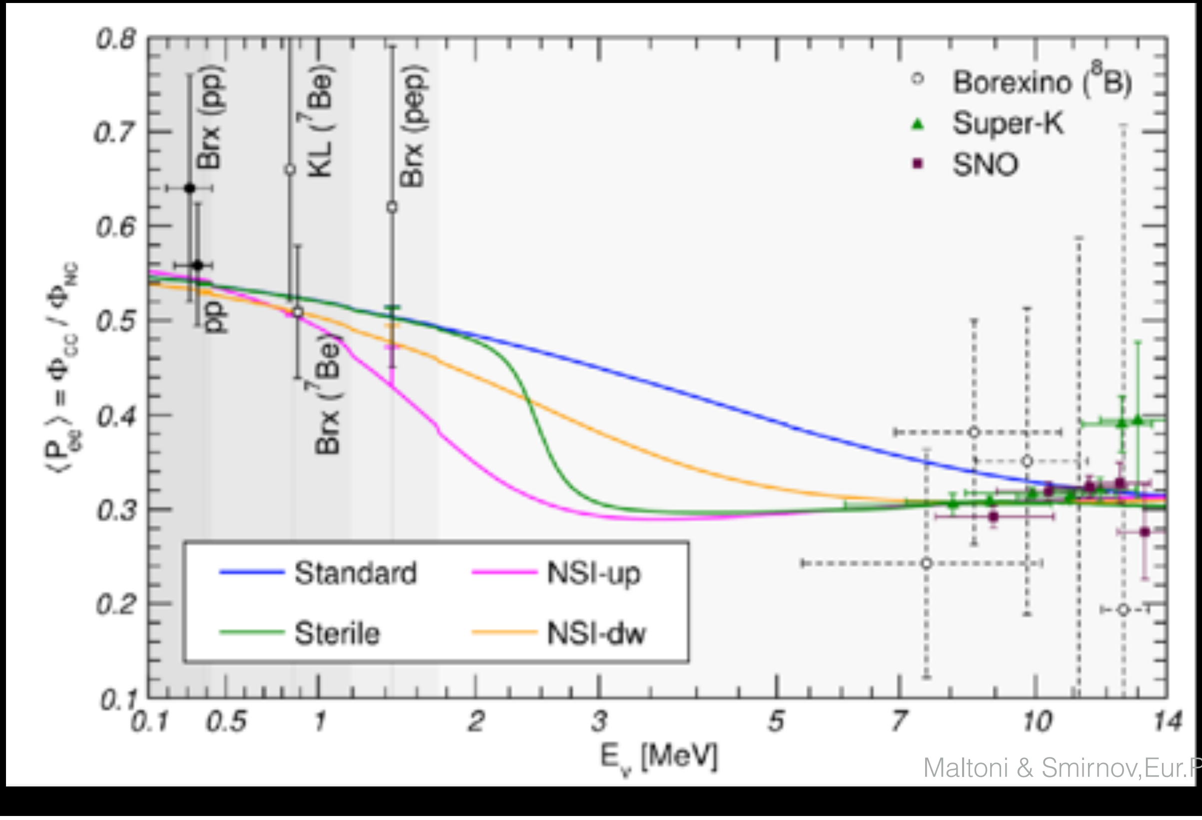


deSalas et al, 1708.01186 (May2018)

- KamLAND prefer steeper upturn and smaller D/N symmetry
- NSI (ε~0.3) reconcile them 10.1103/PhysRevD.80.105009
- Measurement in transition zone needed.

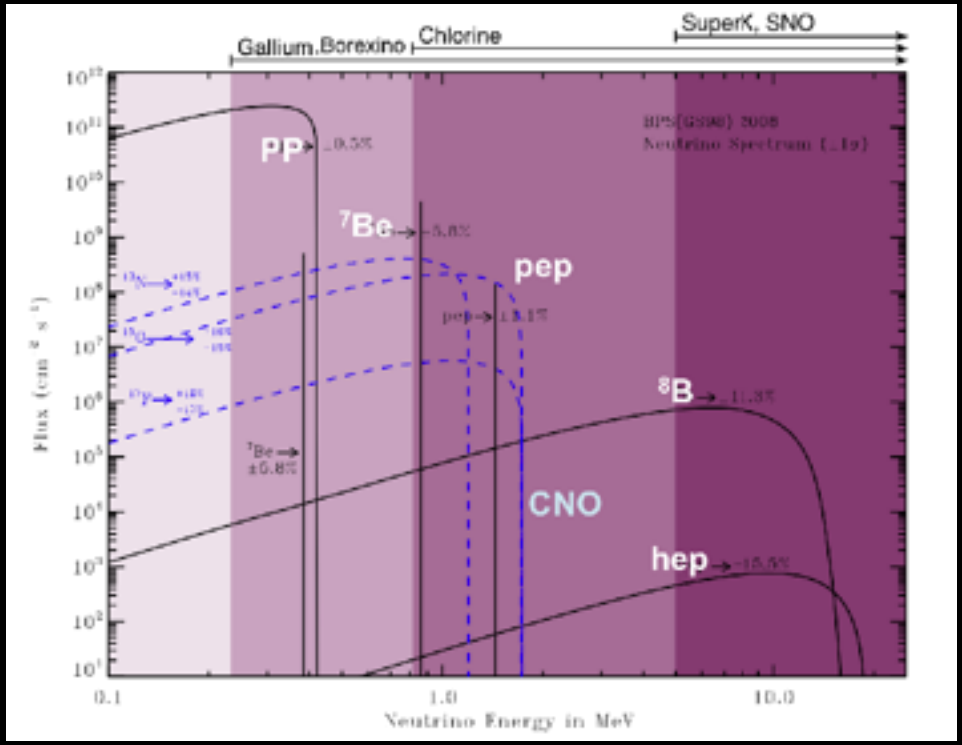


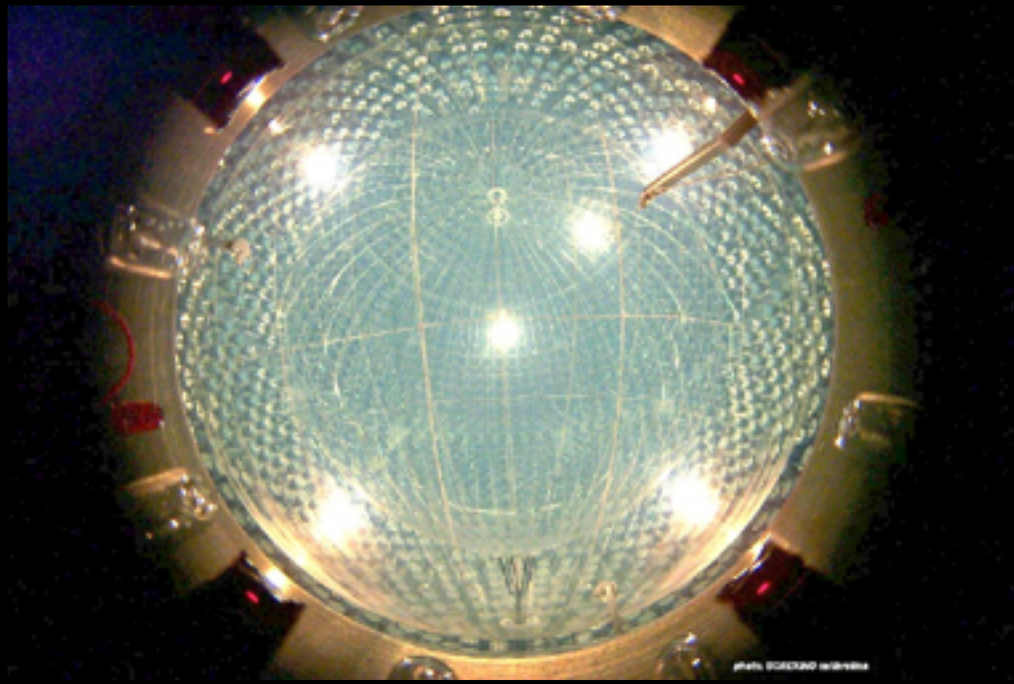
Maltoni & Smirnov,Eur.Phys.J.2016



Maltoni & Smirnov,Eur.Phys.J.2016

Experimental search for solar ν





Borexino inner view

Various detection principles covering different solar neutrinos

- Integrated flux
  - Radio-chemical: Gallium, Chlorine
- Differential spectrum of flux
  - Elastic scattering
    - Liquid scintillator: Borexino
    - Water Cherenkov: SuperK, SNO
    - Noble gas/liquid: Darwin, Darkside
  - Neutral current (ν_x+D -> p+n+ν_x): SNO
  - Charged current (ν_e+D -> 2p + e^-): SNO

Position of Borexino in solar neutrinos

About Science

- Measured all pp-chain solar neutrinos alone, reject LZ at 96.6%.
- Best precision (pp~12%, ^{7}Be~3%, pep~18%,CNO best U.L.) except ^{8}B and hep neutrino.
- Reject MSW-Vacuum at 98.2% alone.
- Cover both vacuum region and matter enchanted region.

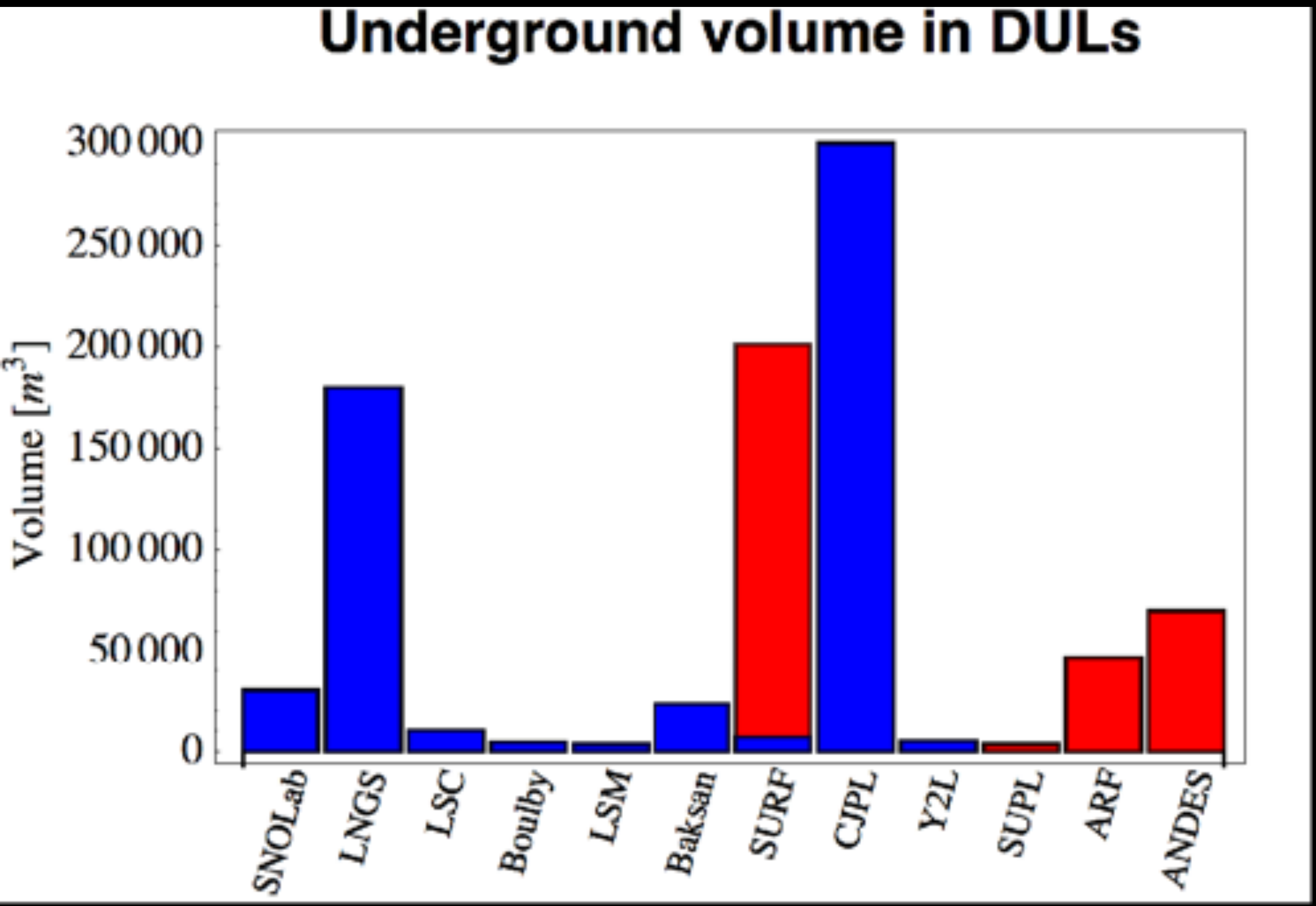
about Technology

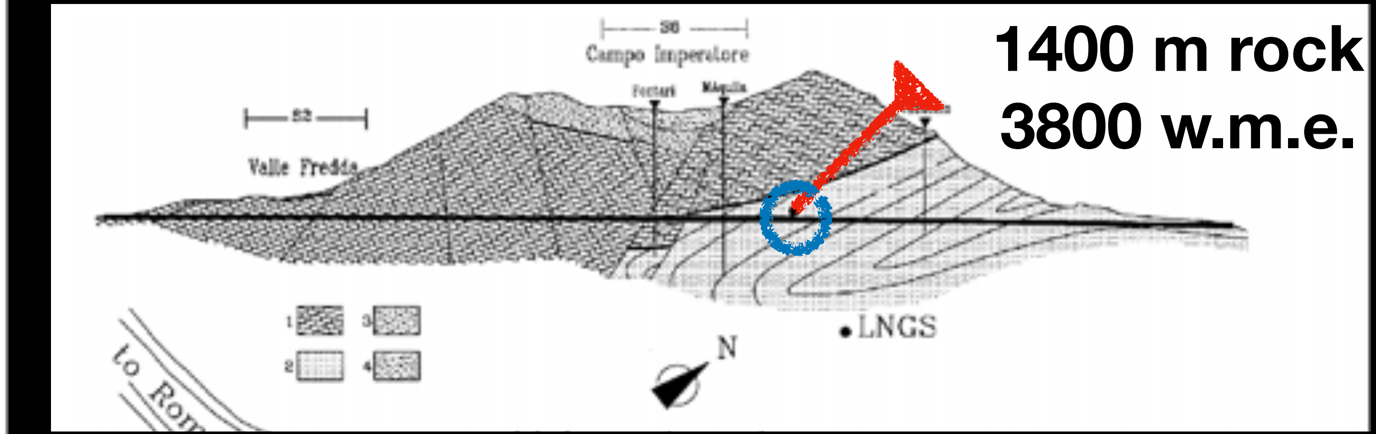
- Best purified LS ($<10^{-19}$ g/g)
- Best hydrodynamical stability.

about Analysis

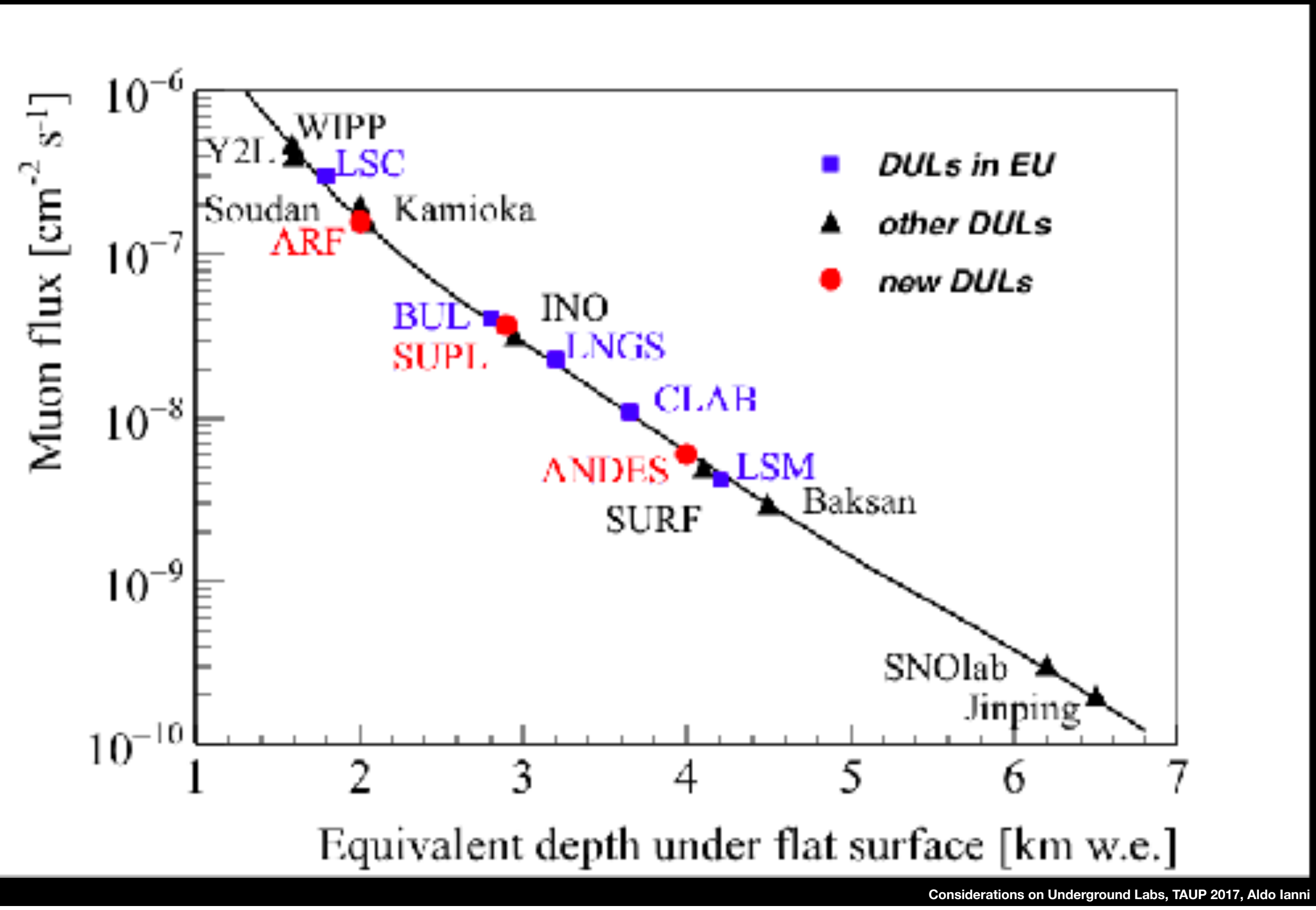
- bkg based real time calibration
- Robust description of pile-up
- Robust detector response modeling and systematics
- MV fit and code parallelization

LNGS lab





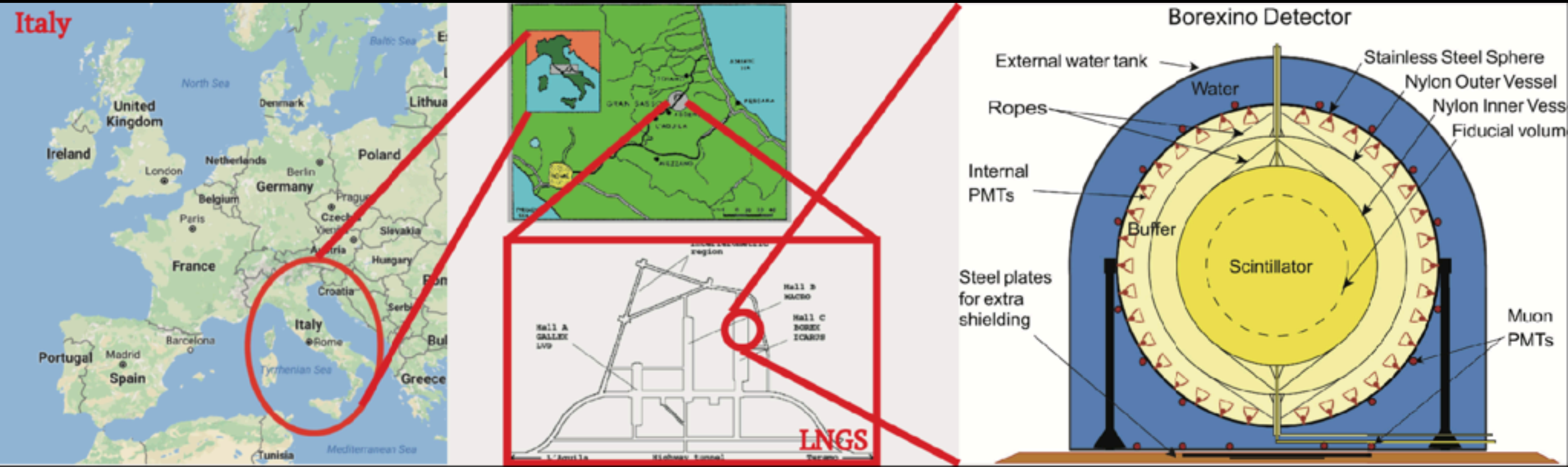
1400 m rock
3800 w.m.e.

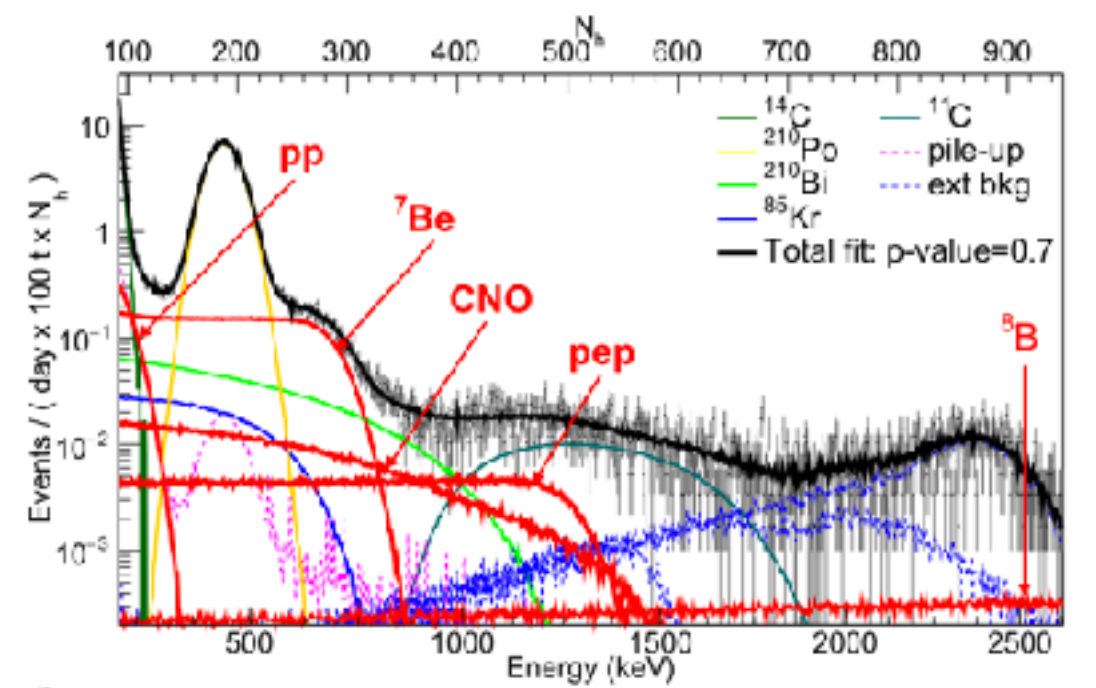


- Creation: 1987
- Volume: 180 k (m^3)
- Depth: 3.8 km w.e.
- Access: Drive in

Considerations on Underground Labs, TAUP 2017, Aldo Ianni

Borexino experiment

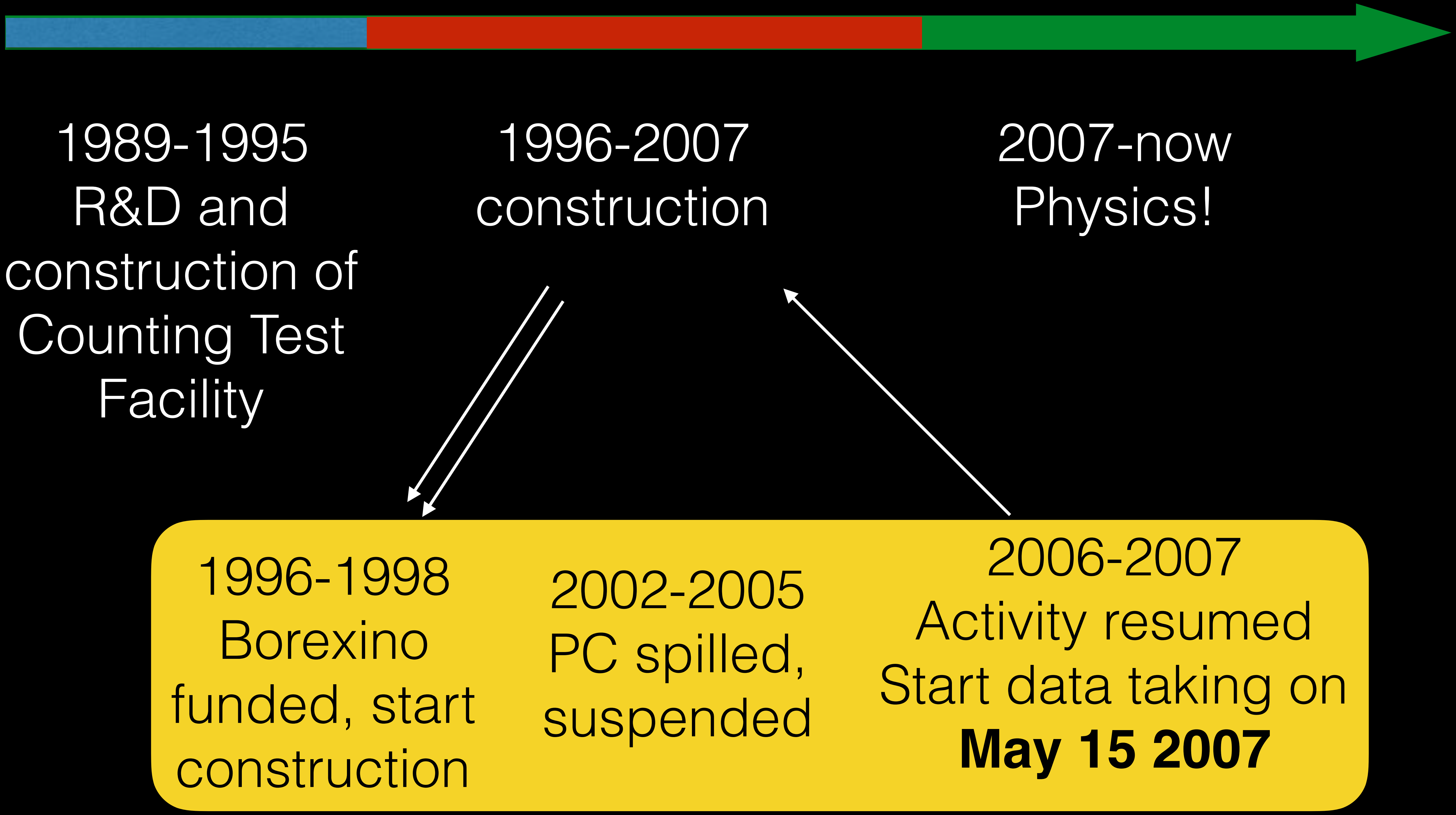




[1] M. Agostini *et al.*, "First Simultaneous Precision Spectroscopy of pp, ^{7}Be, and pep Solar Neutrinos with Borexino Phase-II," pp. 1–8, Jul. 2017.

- In hall C of LNGS in Italy
- CD: Liquid scintillator Detector
- Analysis principle: spectral fitting

History of Borexino experiment



1989-1995
R&D and construction of Counting Test Facility

1996-2007
construction

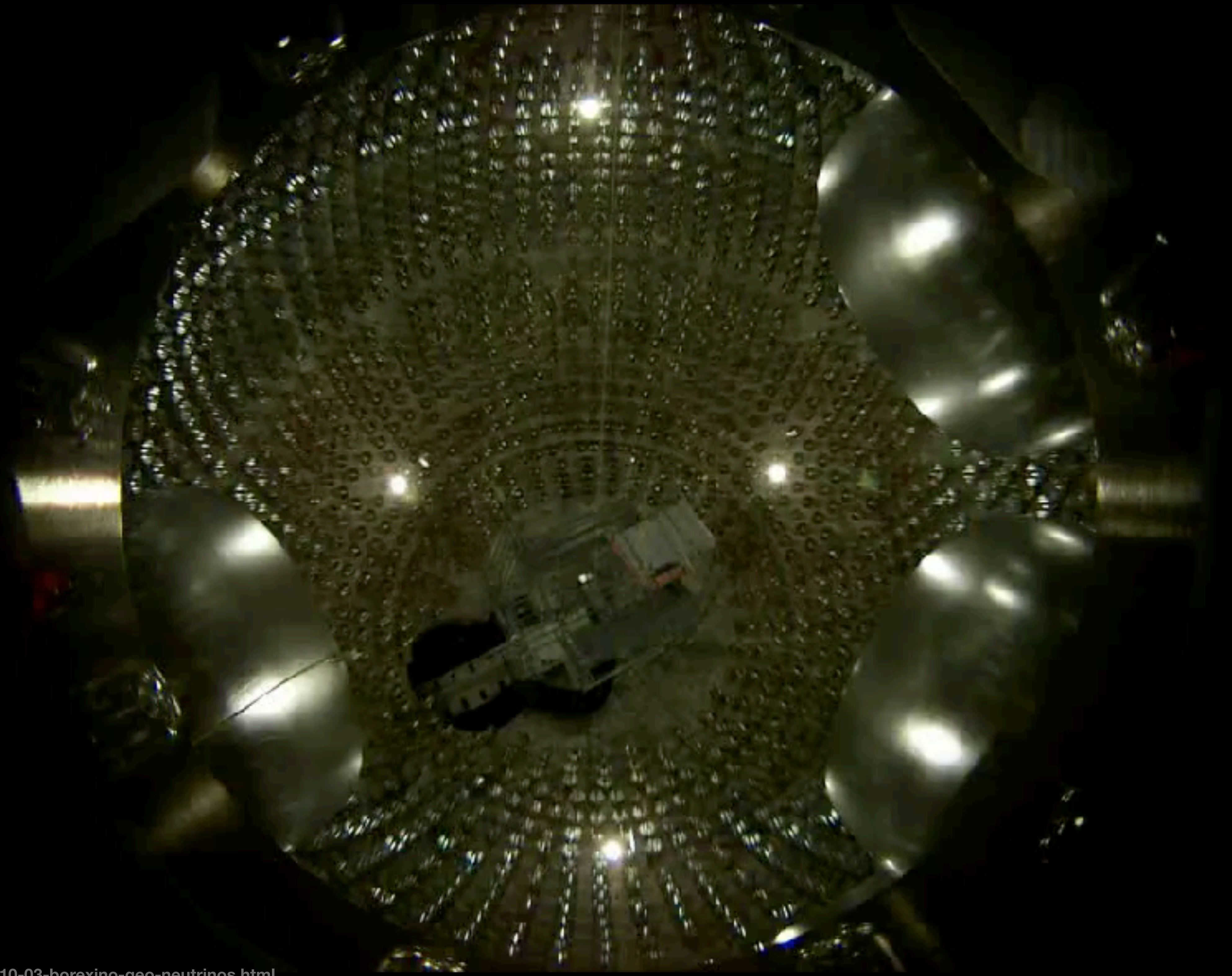
2007-now
Physics!

1996-1998
Borexino funded, start construction

2002-2005
PC spilled, suspended

2006-2007
Activity resumed
Start data taking on **May 15 2007**

Nylon vessel installation



https://phys.org/news/2010-03-borexino-geo-neutrinos.html

Physics program

2007 May-2010 May
Phase-I

2010-2011
Purification + Calibration

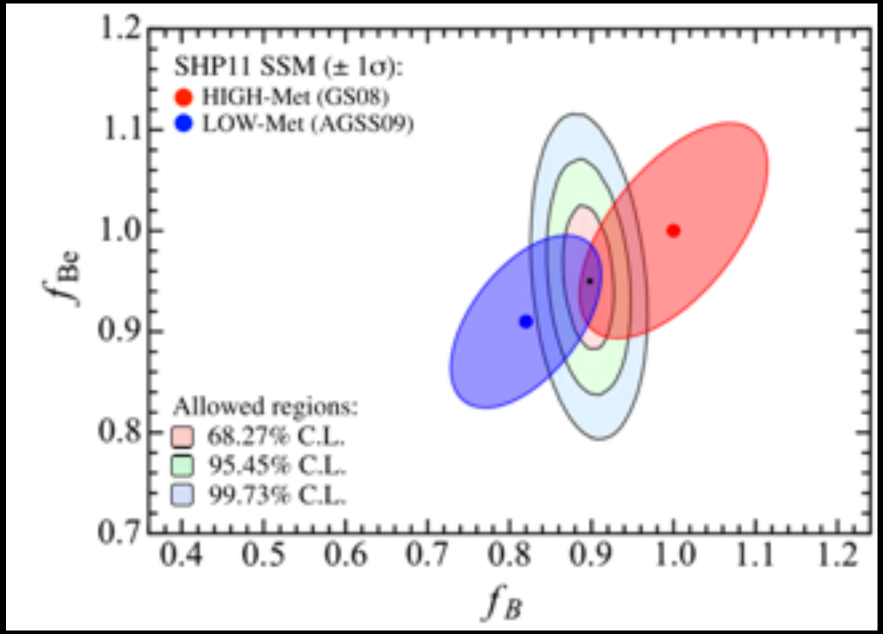
2011 Dec-now
Phase-II

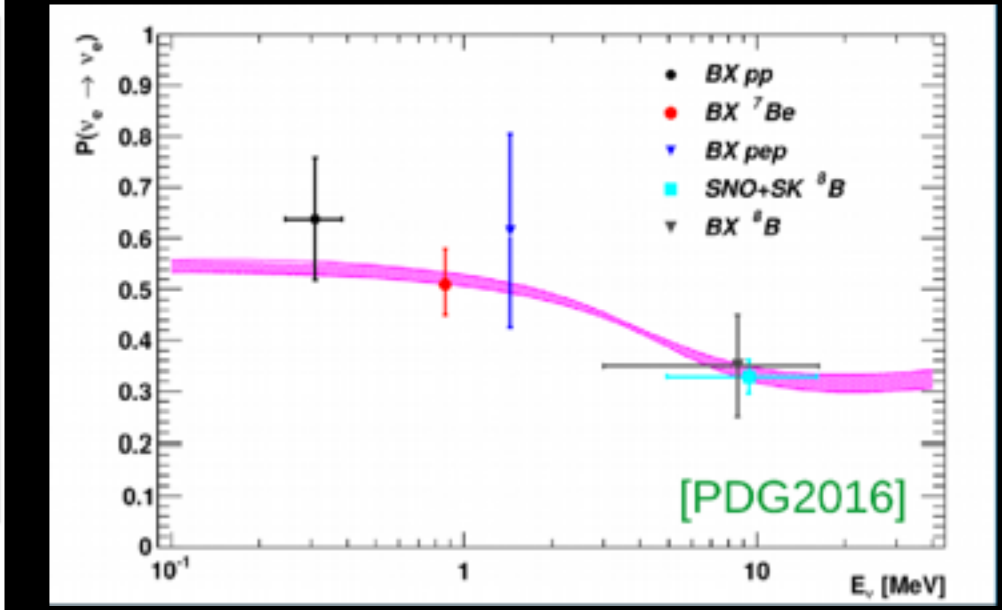
Be7 Phys. Rev. Lett. 107, 141302 (2011)
pep Phys. Rev. Lett. 108, 051302 (2012)
pp Nature 512, 383-386 (28 August 2014)
3 MeV B8 Phys.Rev.D82:033006 (2010)
geo-neutrino PLB 687, 299-340 (2010)
Day-night symmetry PLB 707-1,22-26, (2012)
…

pp+Be7+pep+CNO arxiv 1707.09279
8B arxiv 1709.00756
neutrino magnetic moment PRD 96, 091103 (2017)
gravitational wave ApJ 850-21 (2017)
Be7 seasonal modulation AP, 92, 21-29 (2017)
gamma ray burst AP, 86, 11-17, (2017)
electric charge conservation PRL 115,231802(2017)
geo-neutrino PRD 93, 031101 (2015)
…

A few figures of Borexino..

- Best measurement of solar *pp*, ^{7}*Be*, *pep* flux and limit for *CNO*

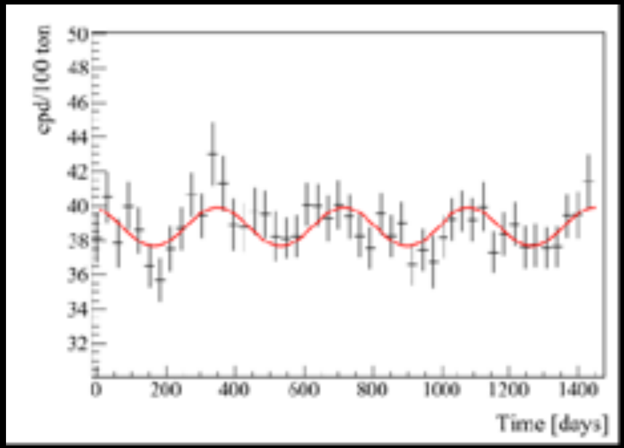


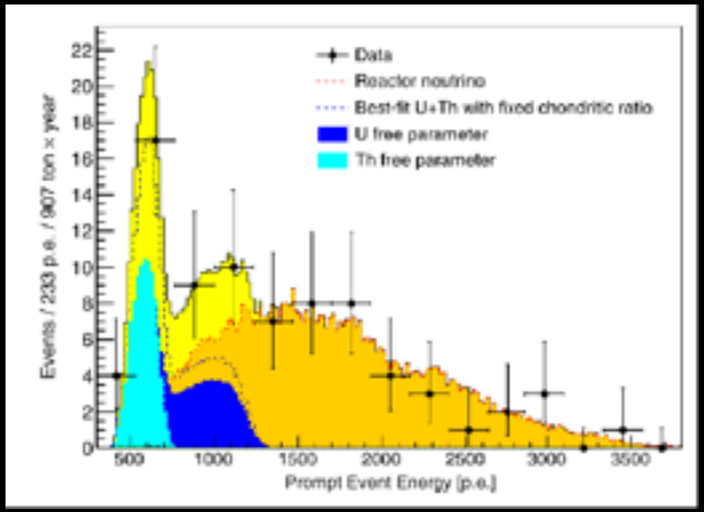


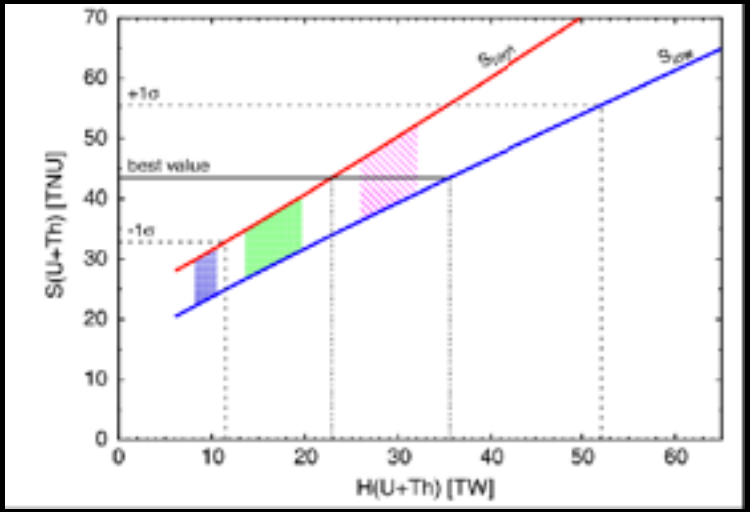
10.1103/PhysRevD.89.112007
Phys.Rev.Lett. 107 (2011) 141302]
[Phys.Rev.Lett. 108 (2012) 051302]
[Phys.Rev. D82 (2010) 033006]
[Nature 512 (2014) no.7515, 383-386

- Seasonal modulation of solar ^{7}*Be* neutrinos

Astropart.Phys. 92 (2017) 21-29





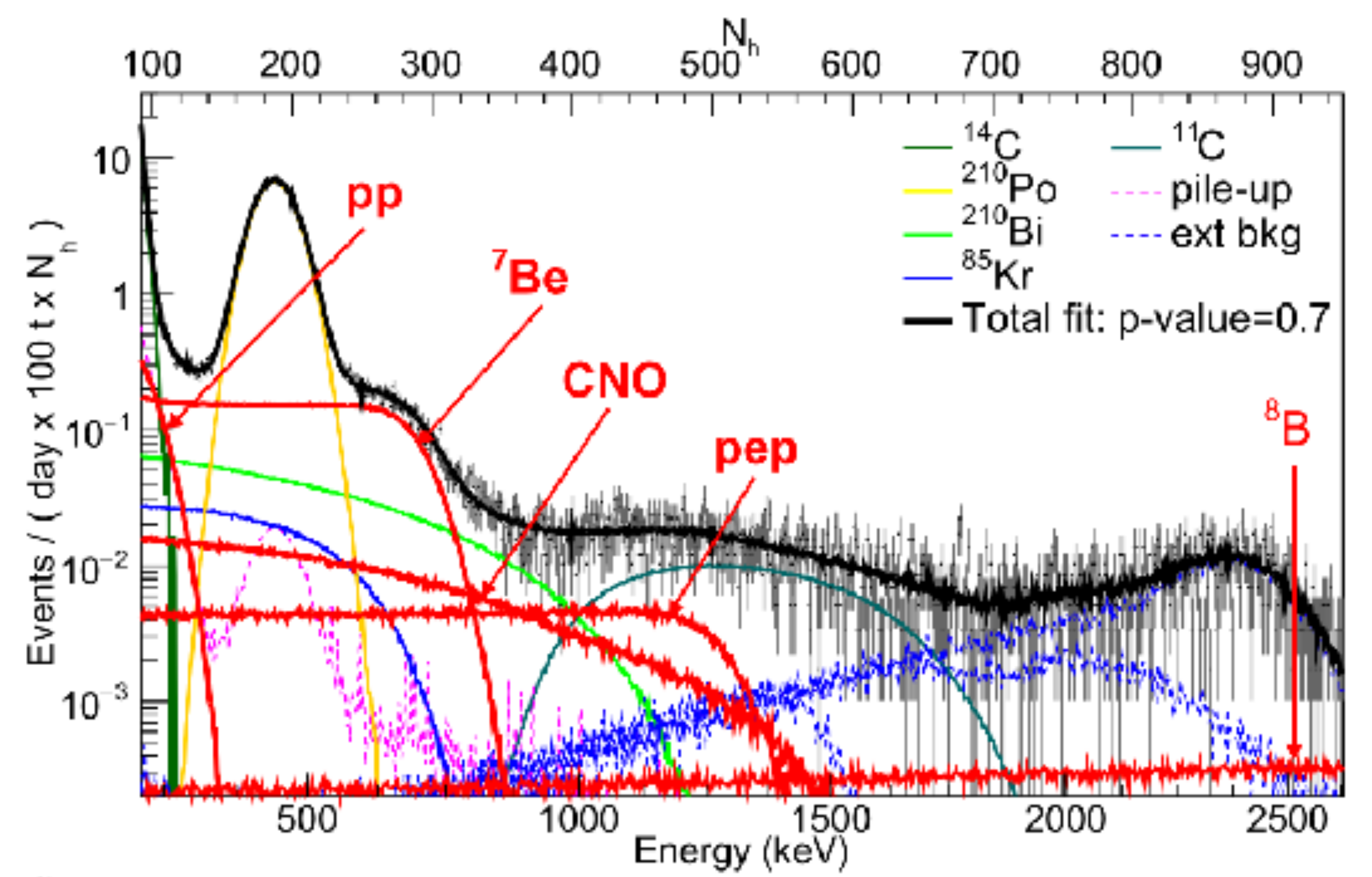


Phys.Rev. D92 (2015) no.3, 031101

- Spectroscopy of geoneutrinos

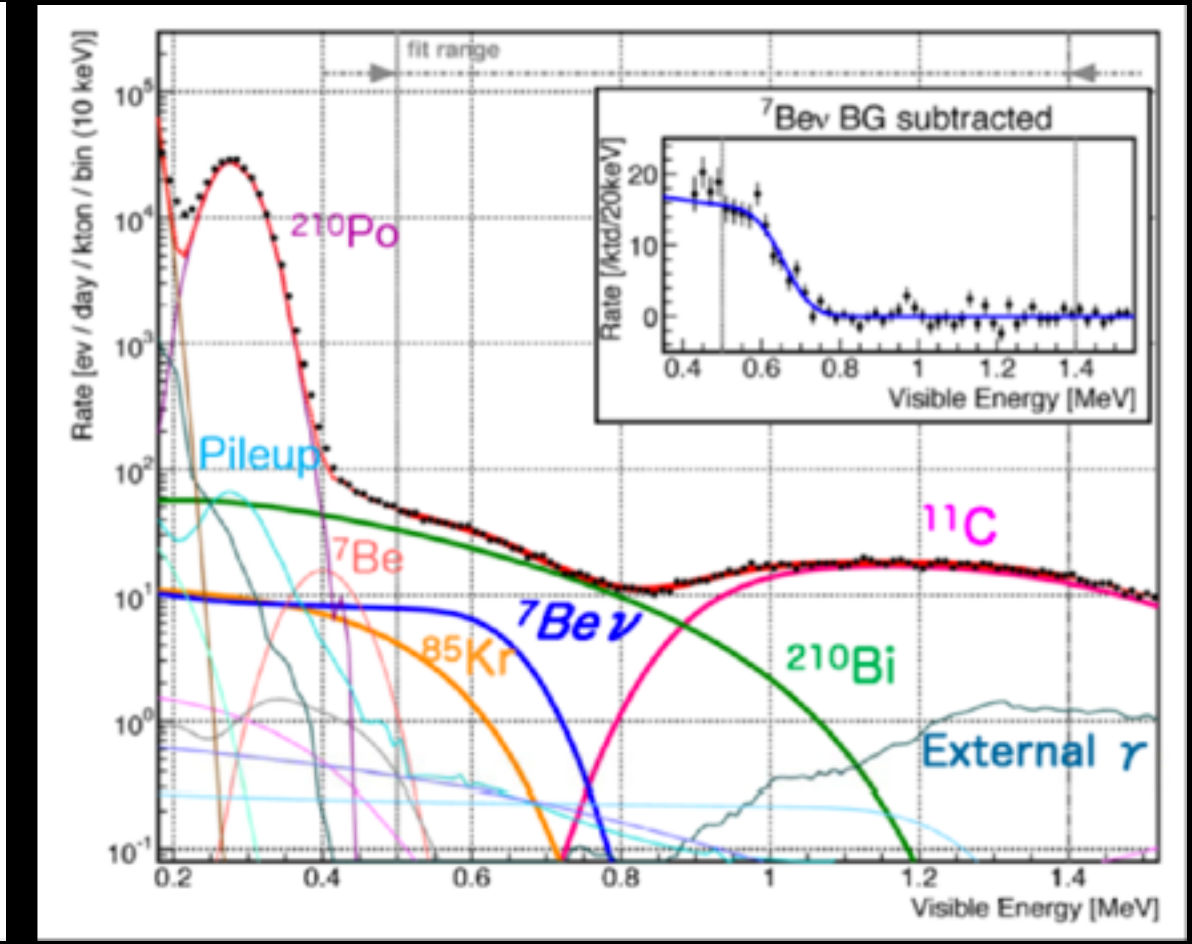
Borexino experiment — challenge

[1] M. Agostini *et al.*, “First Simultaneous Precision Spectroscopy of pp, ^{7}Be, and pep Solar Neutrinos with Borexino Phase-II,” pp. 1–8, Jul. 2017.



Borexino spectra

[2] Y. Takemoto, “7Be solar neutrino observation with KamLAND,” Nucl. Part. Phys. Proc., vol. 265–266, pp. 139–142, Aug. 2015.



KamLAND spectra

- Challenge: Purification of liquid scintillator
  - Phase-I: ~O(10^{-18} g/g) ^{238}U/^{232}Th ~50 BNU ^{210}Bi ~20 BNU ^{85}Kr
  - Phase-II: <O(10^{-19} g/g 95% C.L.) ^{238}U/^{232}Th ~20 BNU ^{210}Bi ~5 BNU ^{85}Kr

Outline

- Keys of Spectral analysis
  - Detector response modeling and corresponding systematics
  - Advanced analysis: Breaking the Correlation
  - Revolution of fitting tool utilizing parallel processors
- Keys of CNO analysis
  - Analysis principle and statistical sensitivity
  - ^{210}Bi measurement from ^{210}Po

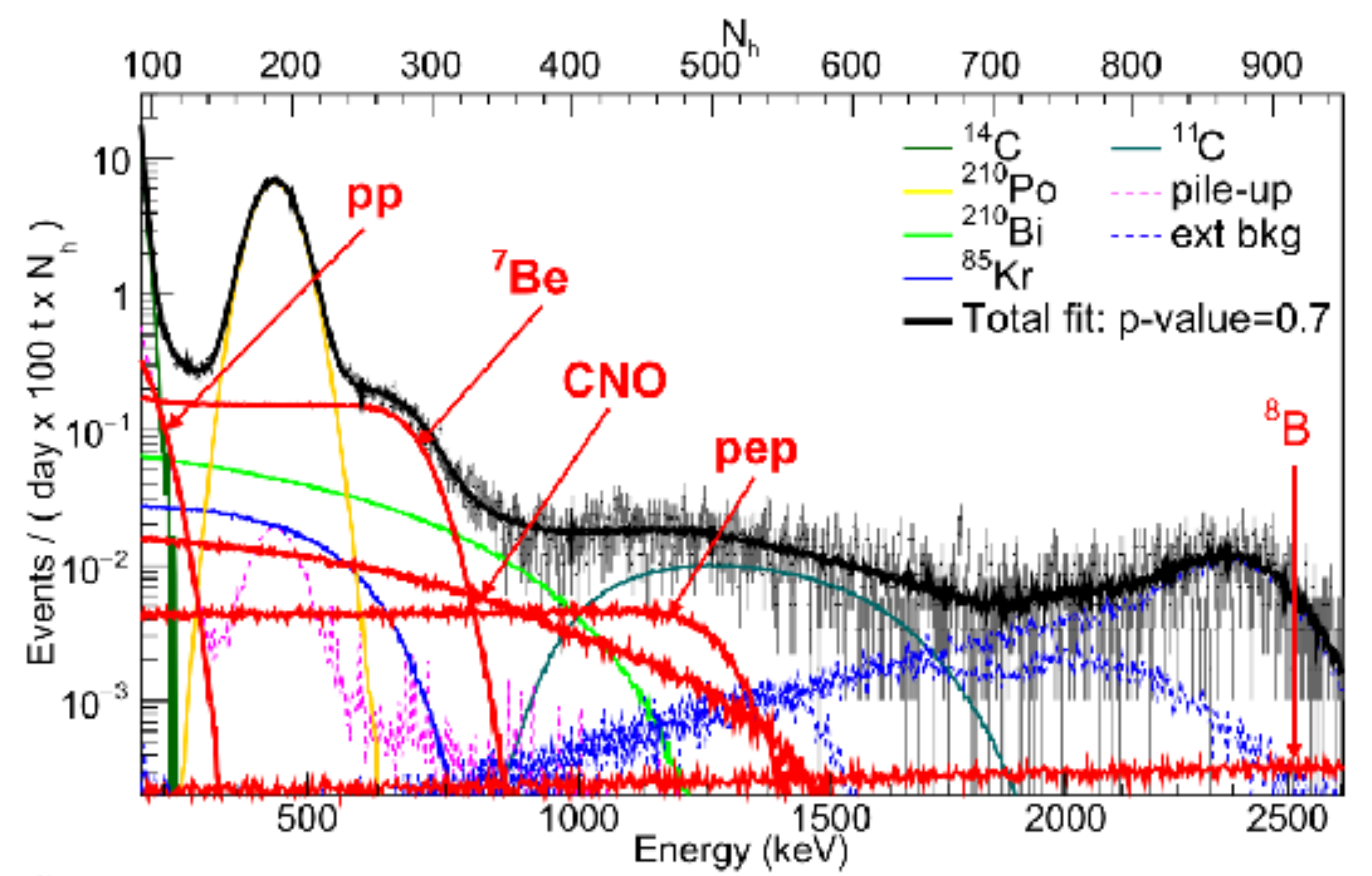
Current stage of the talk

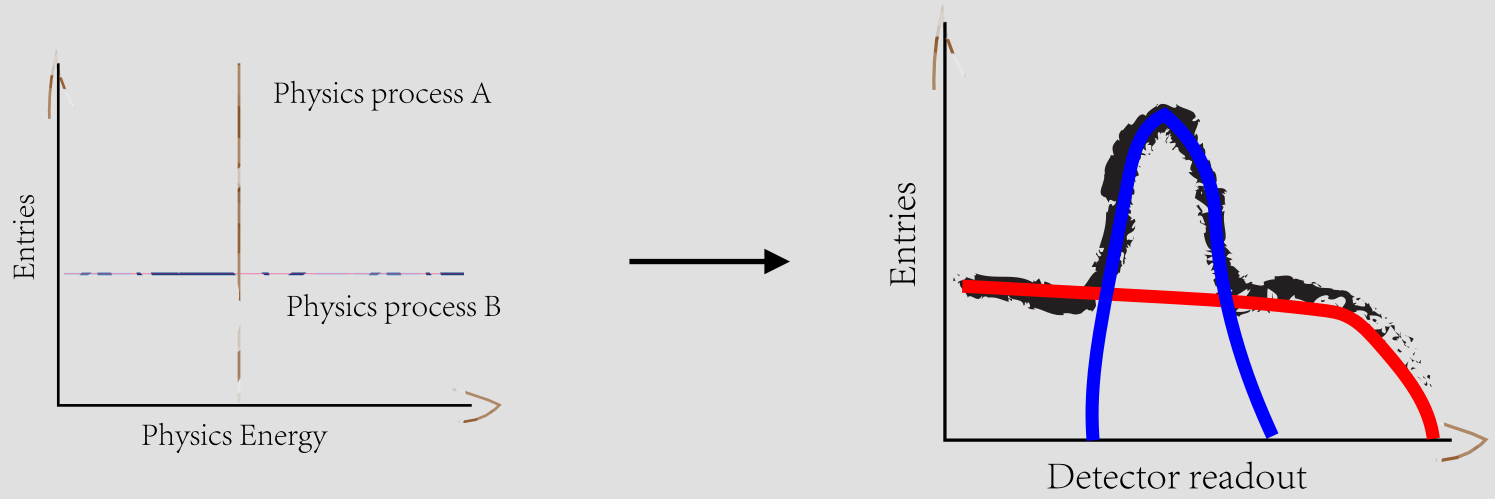
- Keys of Spectral analysis
  - Detector response modeling and corresponding systematics
  - Advanced analysis: Breaking the Correlation
  - Revolution of fitting tool utilizing parallel processors
- Keys of CNO analysis
  - Analysis principle and statistical sensitivity
  - ^{210}Bi measurement from ^{210}Po

Spectral analysis

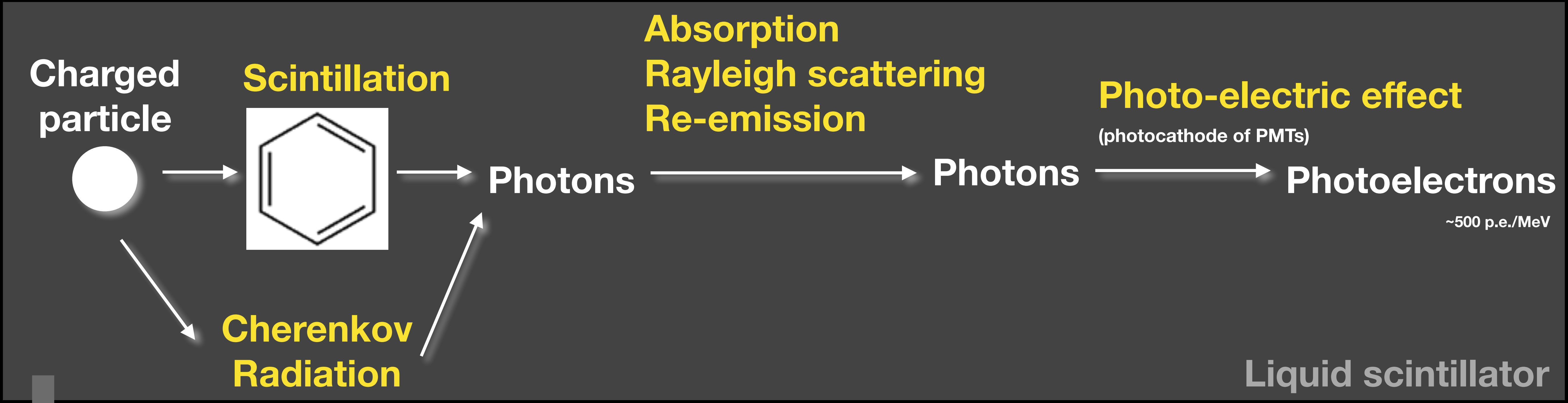
- Use spectral shape to differentiate signal and backgrounds

- Keys of shape analysis
  - Theoretical shape
  - Detector response
  - Break the correlation





Principle of Liquid Scintillator Detector



Charged particle → **Scintillation** → Photons

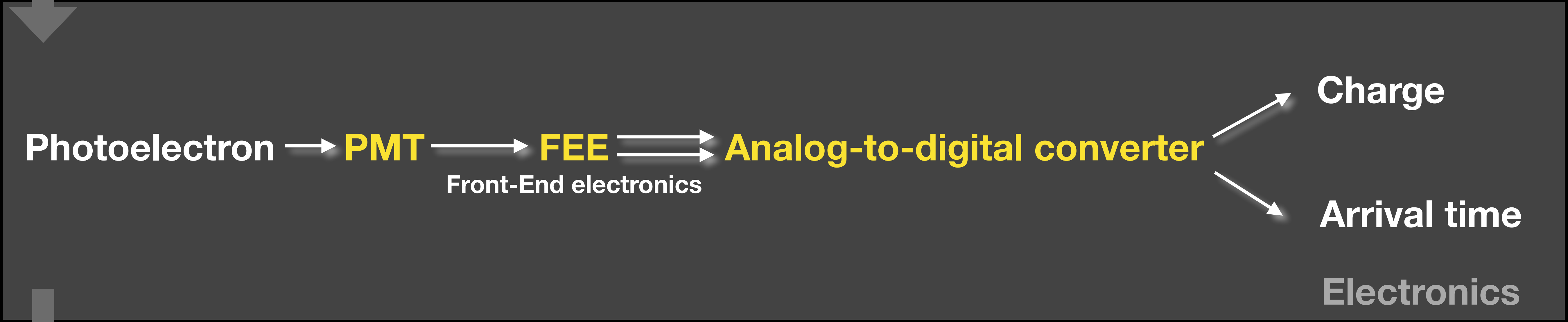
Charged particle → **Cherenkov Radiation** → Photons

Photons → **Absorption** **Rayleigh scattering** **Re-emission** → Photons

Photons → **Photo-electric effect** (photocathode of PMTs) → Photoelectrons

~500 p.e./MeV

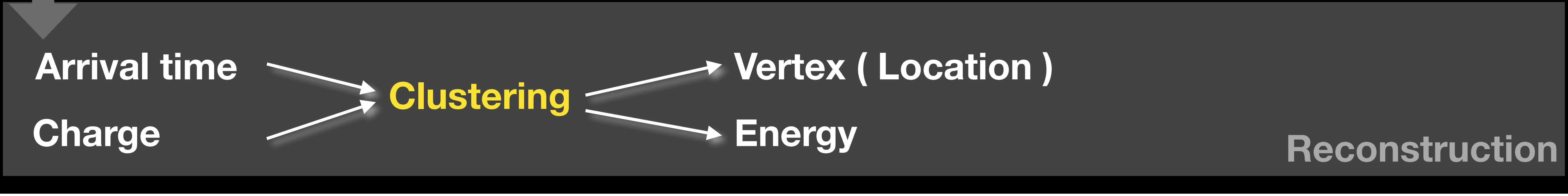
Liquid scintillator



Photoelectron → **PMT** → **FEE** ⇉ **Analog-to-digital converter** → Charge / Arrival time

Front-End electronics

Electronics

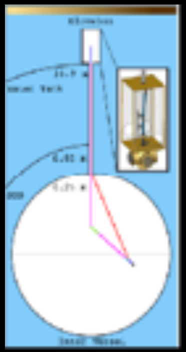


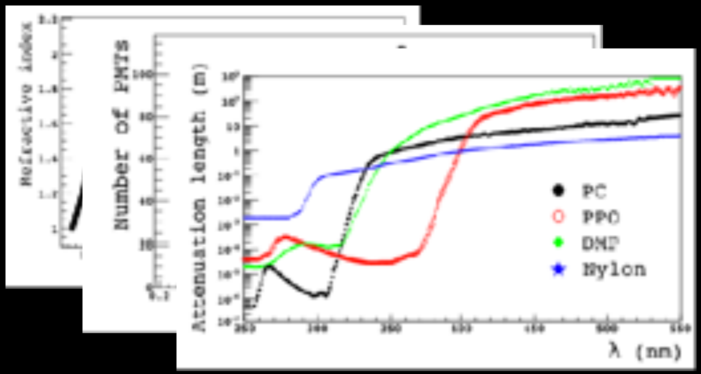
Arrival time, Charge → **Clustering** → Vertex (Location), Energy

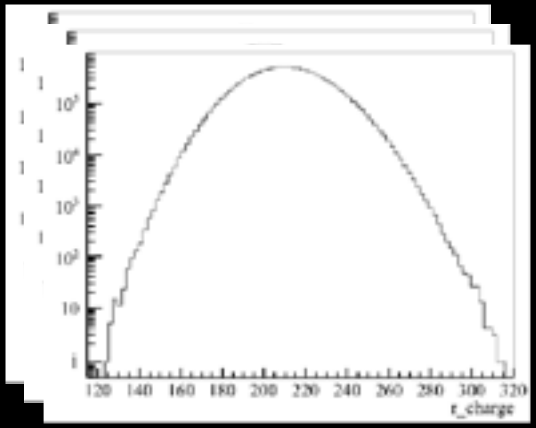
Reconstruction

Model of Liquid Scintillator Detector

- Monte Carlo







Calibration **Monte Carlo input** **Output p.d.f.**

- Analytical response function

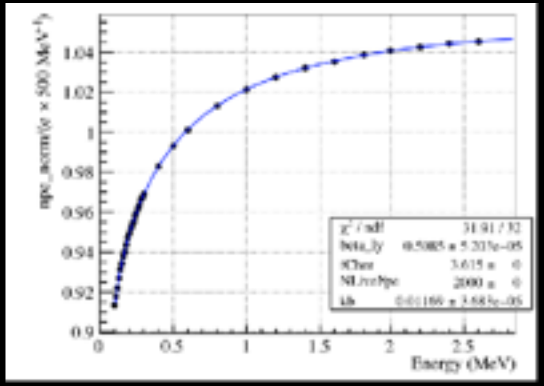
$$M : f(E) \mapsto g(\text{charge}) = \int_0^{E_\text{end}} \mathrm{d}E \cdot f(E) \cdot \text{RPF}\left[\text{charge}; \mu(E), \text{var}(\mu)\right]$$

Analytical Model of Detector Response

- Analytical shape of spectrum of mono-energetic events
    - **Momentum based approximation**
    - Match the average (energy scale + non-linearity model)
    - Match the variance (energy resolution model)
    - Match the skewness
    - … (—> simplified)
    - More: “Mask”, “pile-up” etc.
- We can simplify because
    - small FV in center, low energies => no irregular tail
    - We are not sensitive => small systematics
    - **Fit full MC to get the bias introduced in simplification**

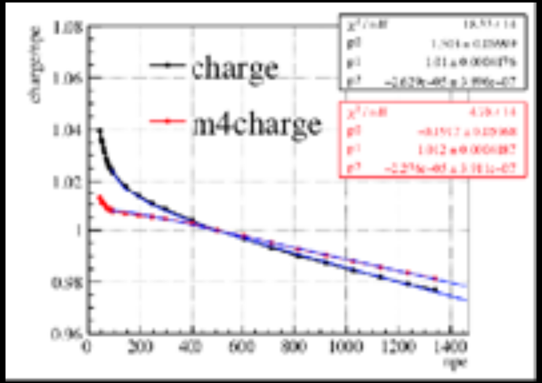
Analytical Model — energy scale and non-linearity

Energy -> photo-electrons

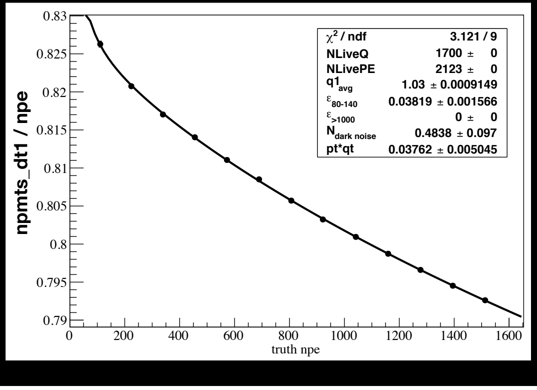


$$\mathrm{EToNpe}(E) = E \cdot \mathrm{Quenching}(k_b, E) \cdot \mathrm{LY}_{\mathrm{ph}} \cdot \varepsilon_{\mathrm{scitillation}}(\mathrm{ph.} \to \mathrm{p.e.}) + \mathrm{N}(\mathrm{Cherenkov\ ph.}) \cdot \varepsilon_{\mathrm{Cherenkov}}(\mathrm{ph.} \to \mathrm{p.e.})$$

photo-electrons -> charge / occupancy



$$\frac{\mathrm{charge}}{\mathrm{npe}} = \frac{p_{\mathrm{dn}} + (1 + p_{\mathrm{miscalib}}) \cdot \mathrm{npe} + p_{\mathrm{quadr}} \cdot \mathrm{npe}^{2}}{\mathrm{npe}}$$

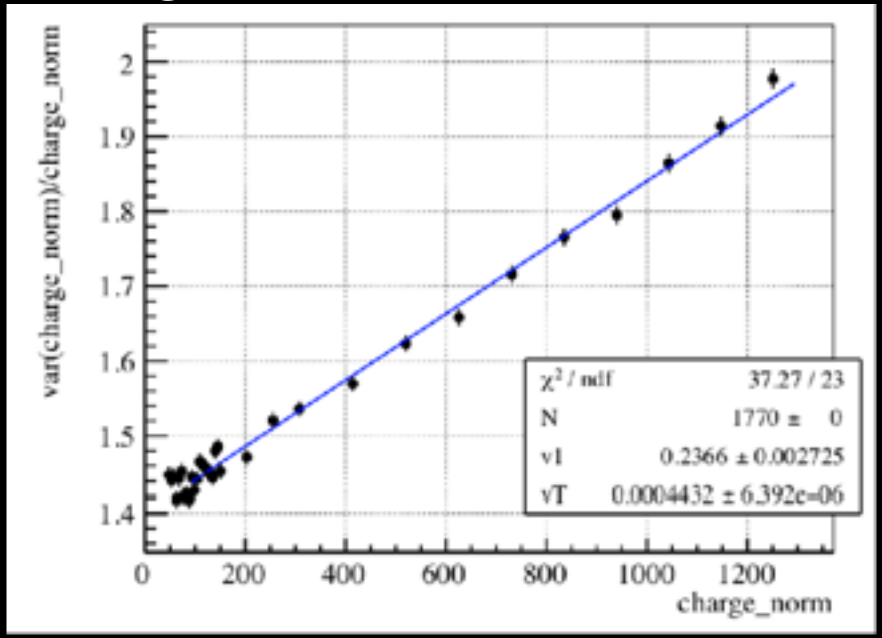


$$\mathrm{NpeToNpmt}(\mathrm{npe}) = \mathrm{NLiveT}' \cdot [1 - \exp(-\mu) \cdot (1 - pt \cdot \mu)]\,(1 - gc \cdot \mu)$$

$$\mu = \frac{\mathrm{npe}}{\mathrm{NLiveNpe}'} + \frac{N_{\mathrm{dark\ noise}}}{\mathrm{NLiveT}'}$$

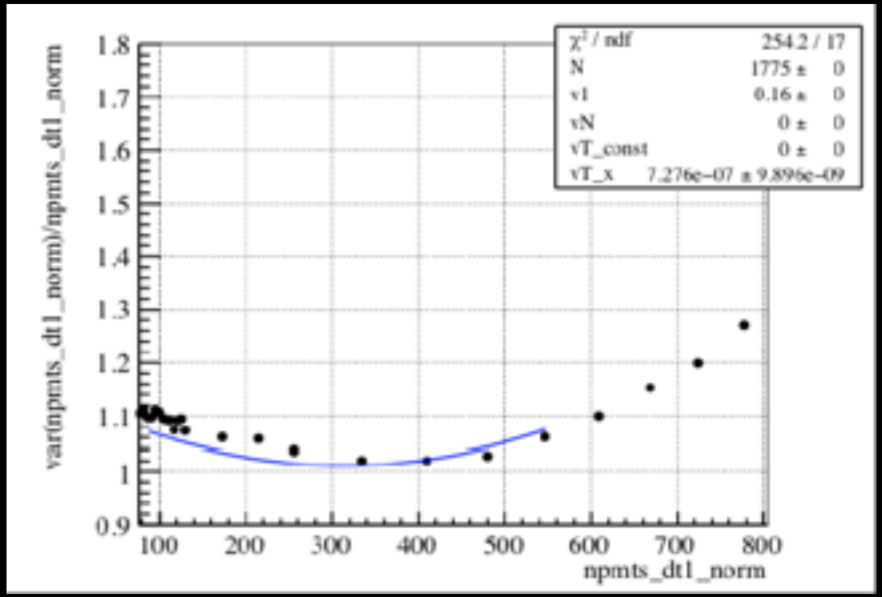
Analytical Model — energy resolution model

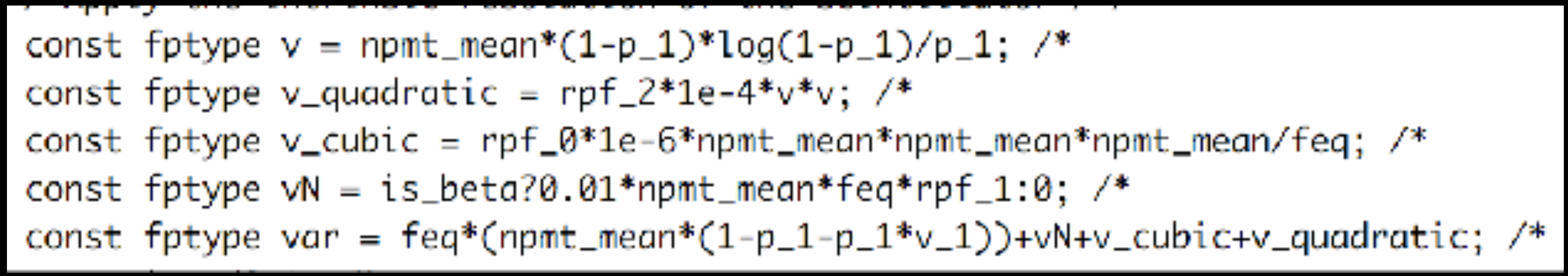
charge



$$\mathrm{var}(\mathrm{charge}\ ) = f_{\mathrm{eq}}(1+v_1)\cdot \mathrm{charge}\ + \frac{v_T}{2000}\cdot \mathrm{charge}\ ^2$$

npmts_dt1





```
const fptype v = npmt_mean*(1-p_1)*log(1-p_1)/p_1; /*
const fptype v_quadratic = rpf_2*1e-4*v*v; /*
const fptype v_cubic = rpf_0*1e-6*npmt_mean*npmt_mean*npmt_mean/feq; /*
const fptype vN = is_beta?0.01*npmt_mean*feq*rpf_1:0; /*
const fptype var = feq*(npmt_mean*(1-p_1-p_1*v_1))+vN+v_cubic+v_quadratic; /*
```

Analytical Model — mono-energetic line shape

- Modified Gaussian

$$f(Q;\mu) = \frac{1}{\sqrt{2\pi}\sqrt{a+b\cdot Q}}\exp\left(-\frac{(Q-\mu+b)^2}{2(a+b\cdot Q)}\right)$$

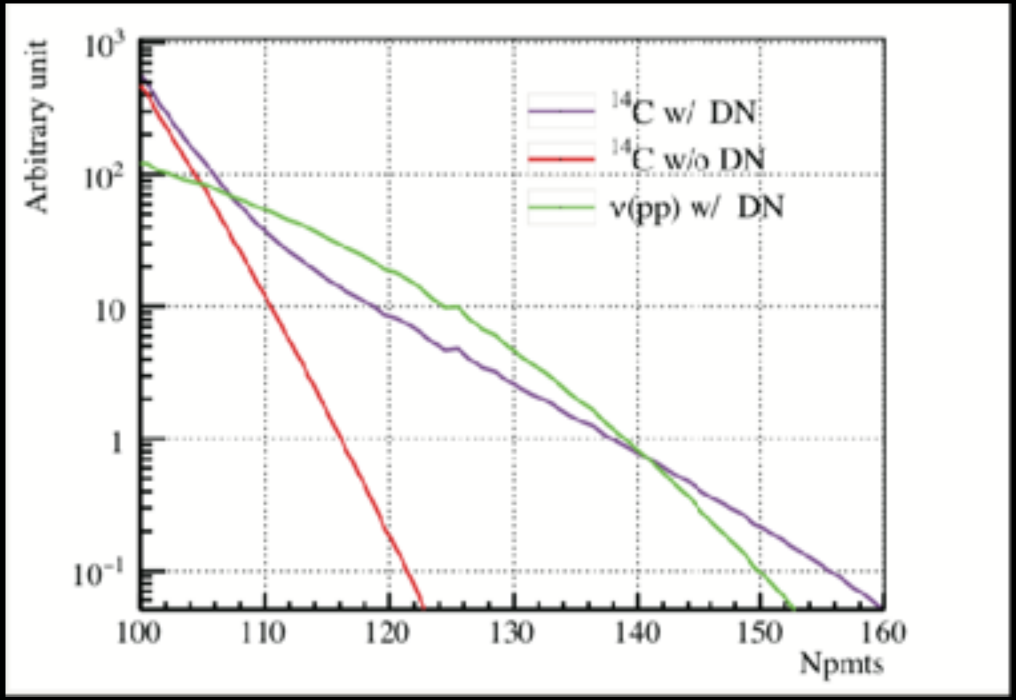
- Generalized gamma

$$f(Q;\mu) = \frac{2\beta^{\alpha}\mu^{2\alpha-1}}{\Gamma(\alpha)}\exp(-\beta\mu^2)$$

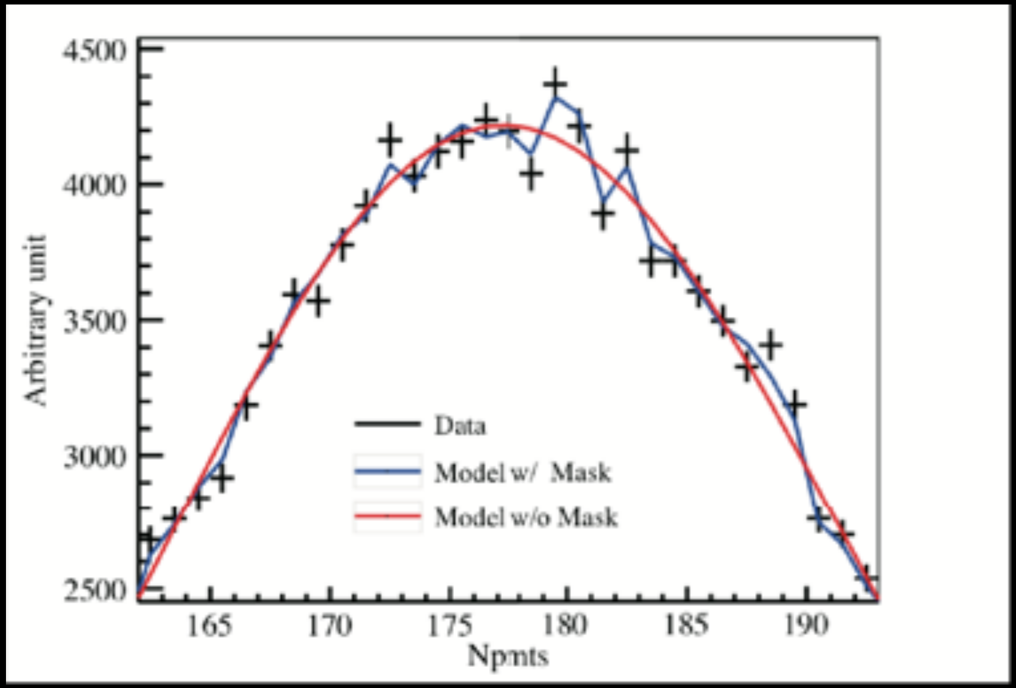
- Scaled Poisson

$$\begin{aligned}
\mathrm{Poisson}(x;\mu) &= \frac{\mu^k}{\Gamma(k+1)}e^{-\mu} \\
\mathrm{RawSP}(x;\mu,\mathrm{var}) &= \frac{\mathrm{Poisson}(\frac{x}{s},\frac{\mu}{s})}{s} \qquad s = \frac{\mathrm{var}}{\mu} \\
\mathrm{SP}(x;\mu,\mathrm{var}) &= \frac{\mathrm{RawSP}(x)+4\cdot\mathrm{RawSP}(x+0.5)+\mathrm{RawSP}(x+1)}{6}
\end{aligned}$$

Analytical Model — More details



- Pile-up effect: Hits from more than one source piled up.
  - Dark noise, ^{14}C
  - Crucial background for *pp* analysis
- **Solution: “Dark noise convolution”**



- Npmt is an integer variable
- Spikes appeared after normalization 2000/NLive
- **Solution: Apply “mask”**

Analytical Model — Validation

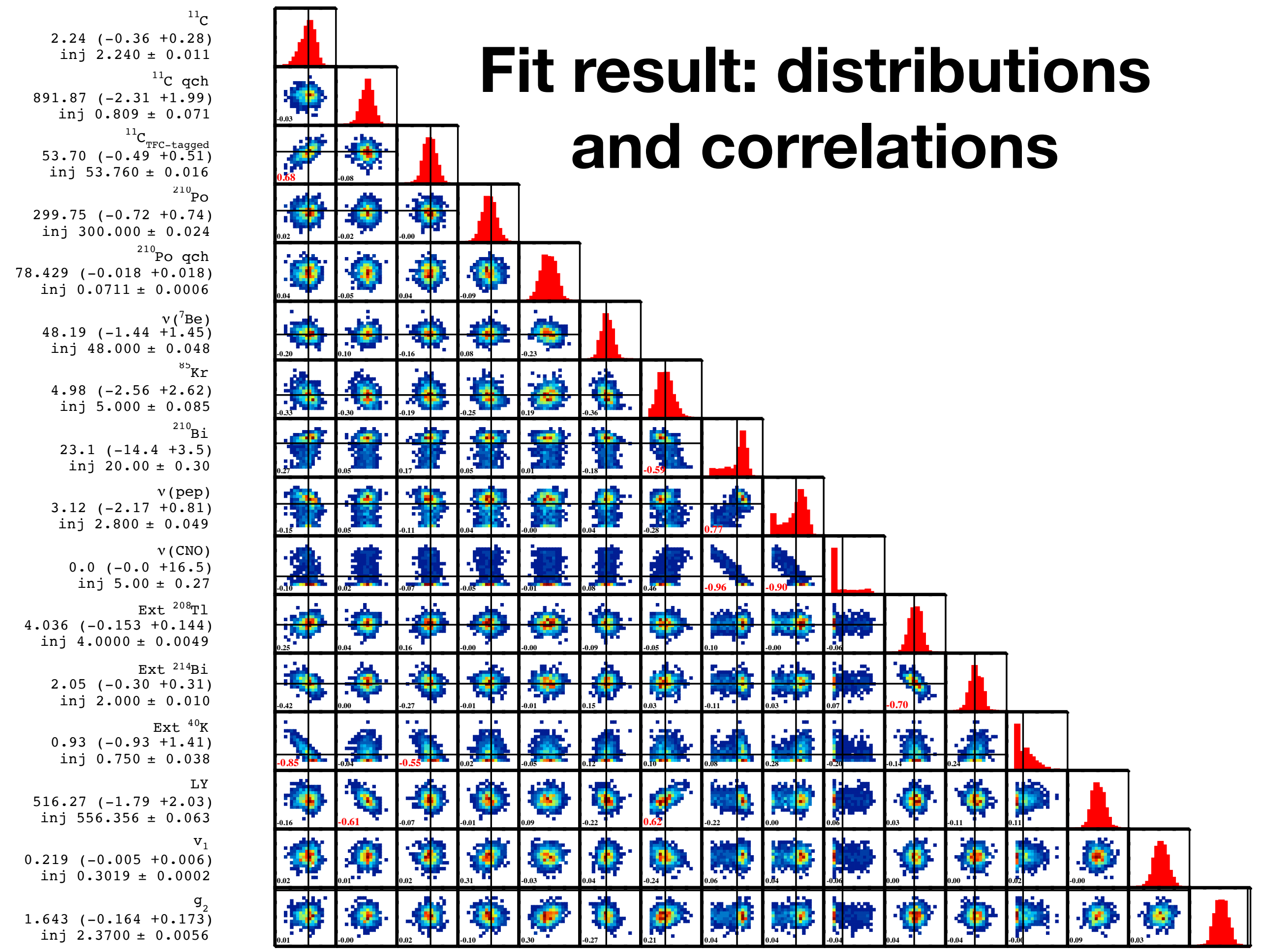
^{11}C
2.24 (−0.36 +0.28)
inj 2.240 ± 0.011

^{11}C$_{\text{TFC-tagged}}$
53.70 (−0.49 +0.51)
inj 53.760 ± 0.016

^{210}Po
299.75 (−0.72 +0.74)
inj 300.000 ± 0.024

^{210}Po qch
78.429 (−0.018 +0.018)
inj 0.0711 ± 0.0006

ν(^{7}Be)
48.19 (−1.44 +1.45)
inj 48.000 ± 0.048



Fit result: distributions and correlations

- FIT MC WITH ANALYTICAL
- **NO BIAS FOUND**

Statistics or systematics?

- Nuisance parameter method -> move sys. to stat.
  - Analytical det. response -> move det. response sys. to stat.
  - Introduce new sys. during simplificatoin
- Covariance matrix
  - similar to put larger σ, but including correlations
  - not correlation among systematics.. <- challenging
- toy MC method <- used by BX
  - large bin content dynamic range -> can only use Poisson LL
  - correct coverage <- important when imposing R>0

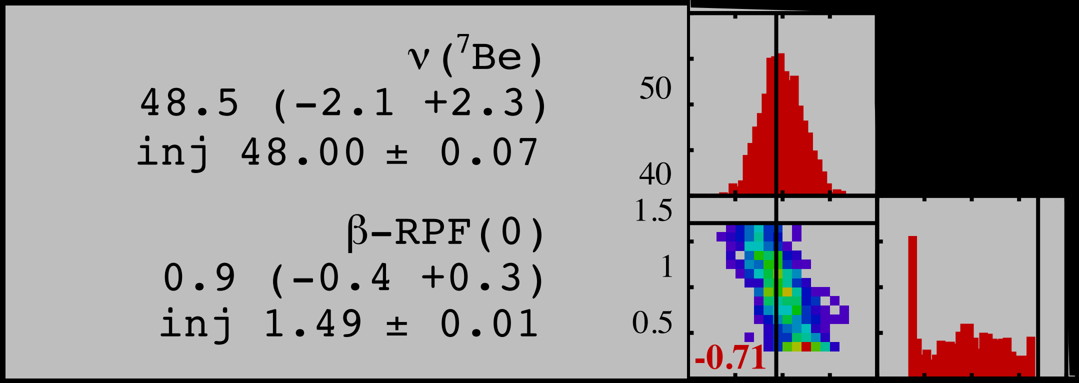
3 levels of “Nuisance” method

- **Full MC**: during each iteration of the fit, vary **kb / absorption length spectrum etc.** **re-simulate and produce new pdf on the fly** —> when one day computer is fast enough
  - ~200, 000 CPU x years per fit
- **Semi-analytical**: analytical non-linearity model + response Matrix
  - ~30 minutes per fit
- **Full analytical**
  - ~2 hours per fit

Systematics uncertainty — semi-analytical

- semi-analytical: response Matrix+ analytical non-linearity model
    - WorkFlow: E => NL => μ_{Evis} => response Matrix => distribution of E_{vis}
    - $\mu_{Evis}=f^{NL}(E) = a_i f^{NL}_i(E)$ $f^{NL}_i(E)$ is the base of f^{NL} space
- Feature: trust MC to deal with complex tail shape from γ energy leak
- Constrain: systematics from resolution model **not included**

        - For example, the ^{7}Be rate is correlated with the resolution model parameters.

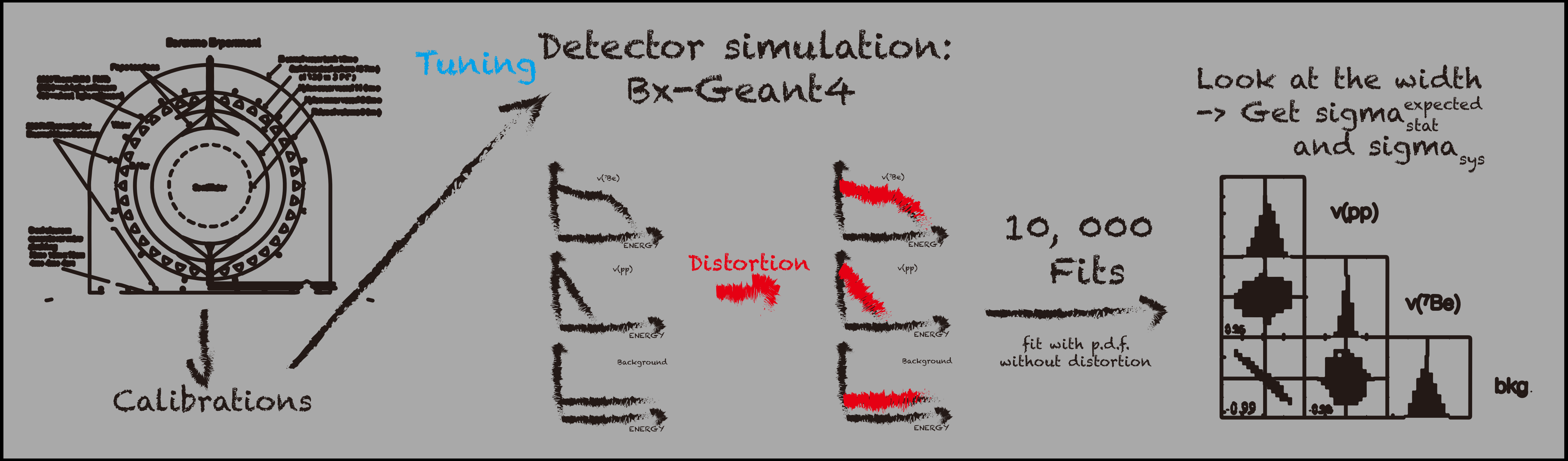


Systematics uncertainty — full-analytical

$$M : f(E) \mapsto g(\text{charge}) = \int_0^{E_{\text{end}}} \mathrm{d}E \cdot f(E) \cdot \text{RPF}\left[\text{charge}; \mu(E), \text{var}(\mu)\right]$$

- Systematics from NL, resolution model absorbed to the statistical uncertainty term.
- Systematics from simplification of higher order terms: Fit the tuned MC model spectra

Systematics — Monte Carlo method



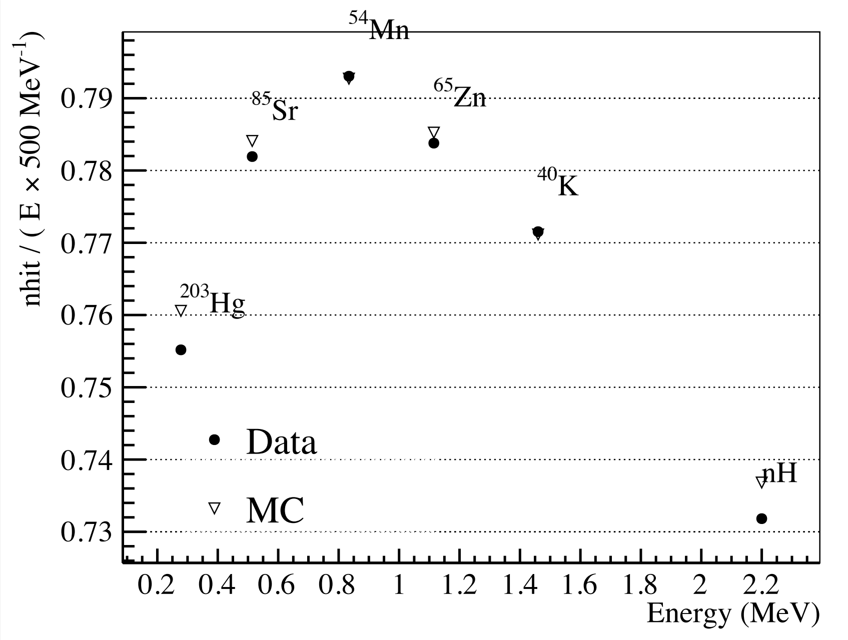
1. pseudo-experiment spectra without distortion —> **statistical sensitivity**

2. pseudo-experiment spectra with distortion —> **statistical** + **systematic uncertainty**

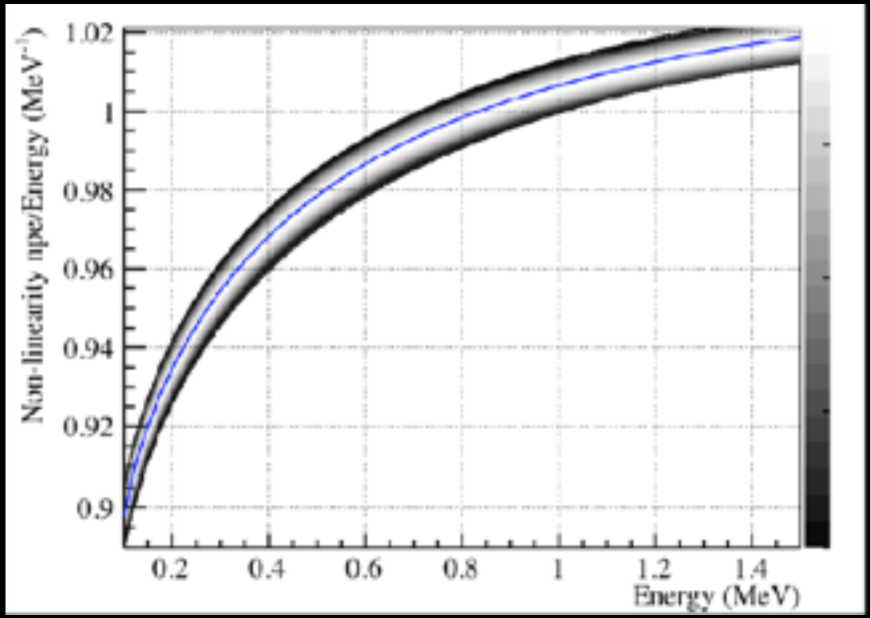
Systematics — Monte Carlo method (NL)

- **Determine 1-σ band of allowed NL**
  - Precision of MC (γ)
  - Assume same Precision of e^-/e^+
- **Generate the ensemble of models**
  - Find a presentation, say, E’ = E (a+bE)
  - Decide the distribution of coordinate
  - Generate pseudo-experiment spectra and verify the density plot of sampled models

Precision of non-linearity from calibrations



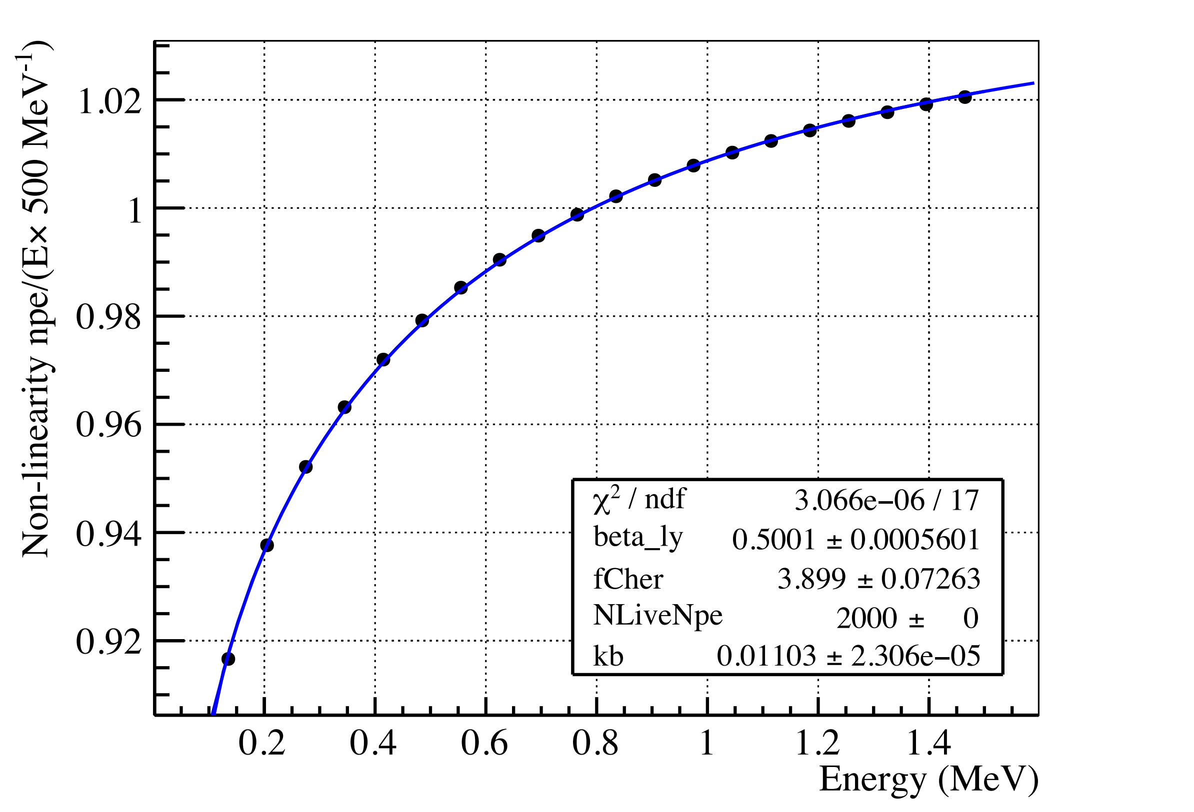
Density plot of generated non-linearity models



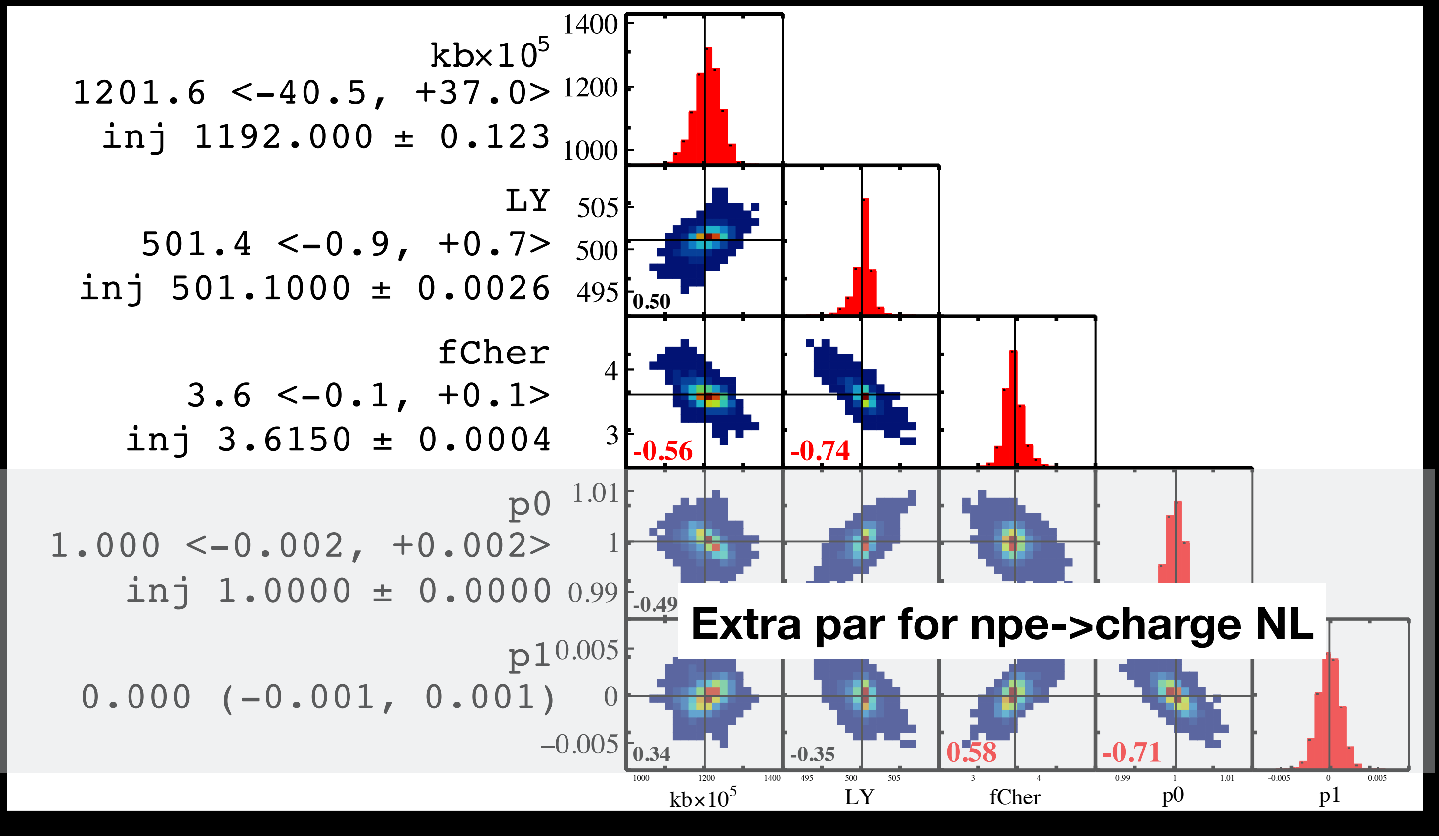
MC method — covered Phase space (NL)

- Generate NL: **(MC NL)x(a+bE)**, vary **(a,b)**
- **Interpretate with** mu = **LY***[Qch(**kb**,E) + **fCher***Cherenkov(E)]

An example generated non-linearity model



Covered phase-space from linear distortion



Extra par for npe->charge NL

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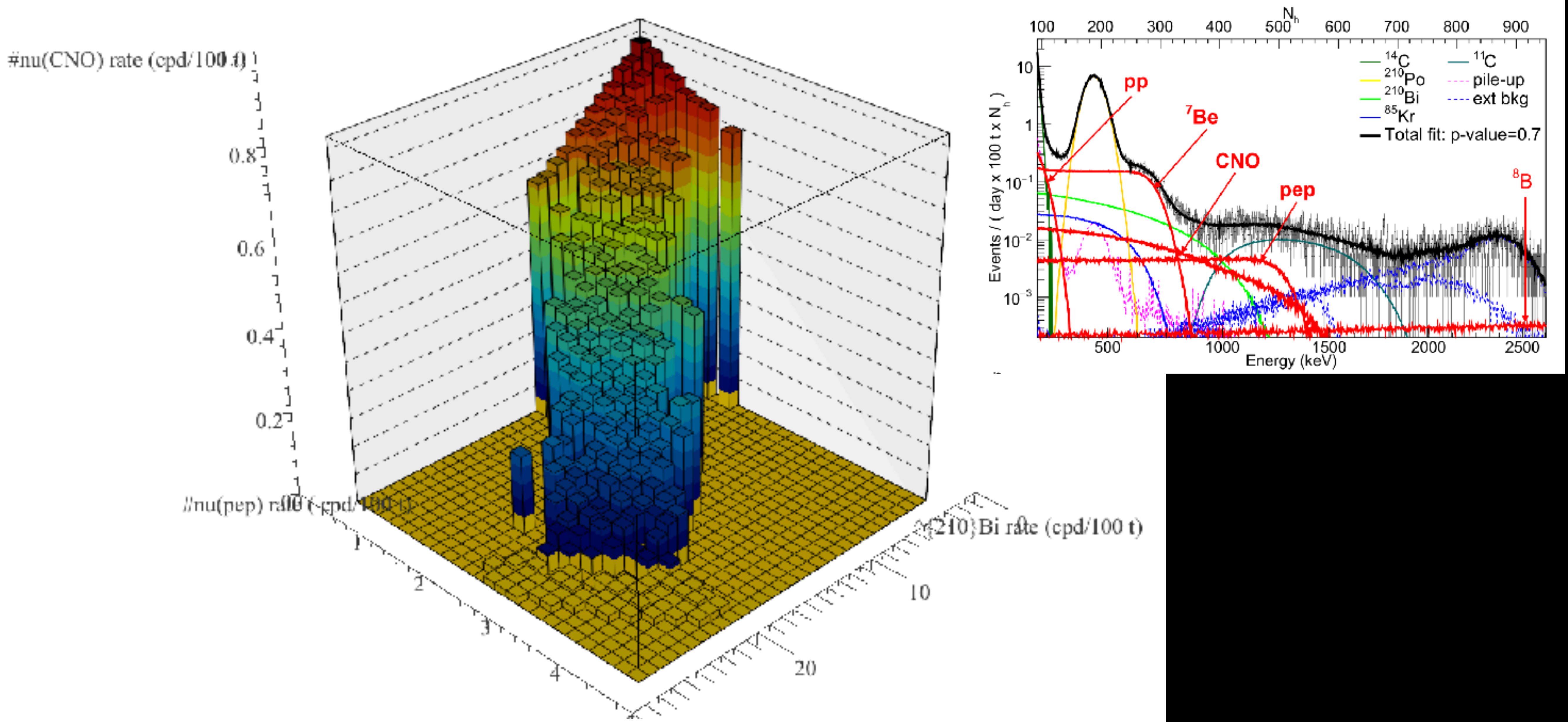
Break the correlation

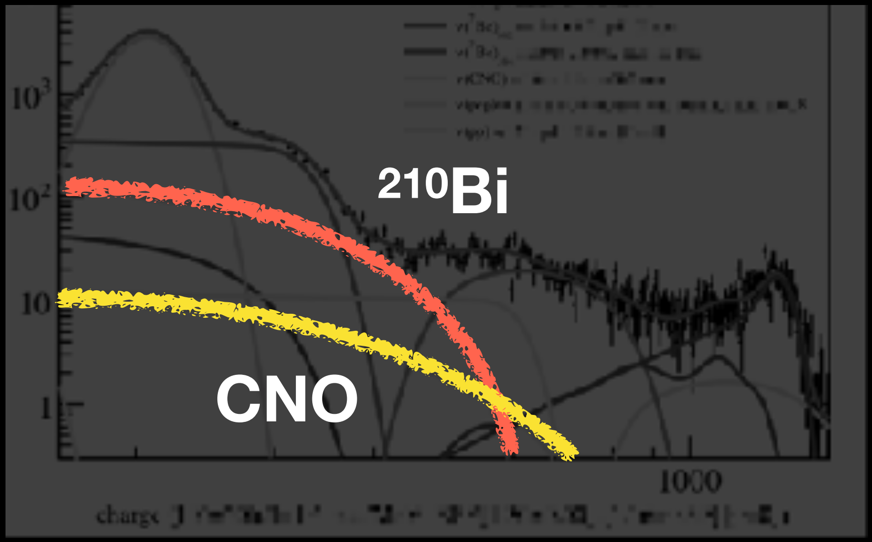
Concept of Correlation in spectral analysis

- The best fit of different species are not independent

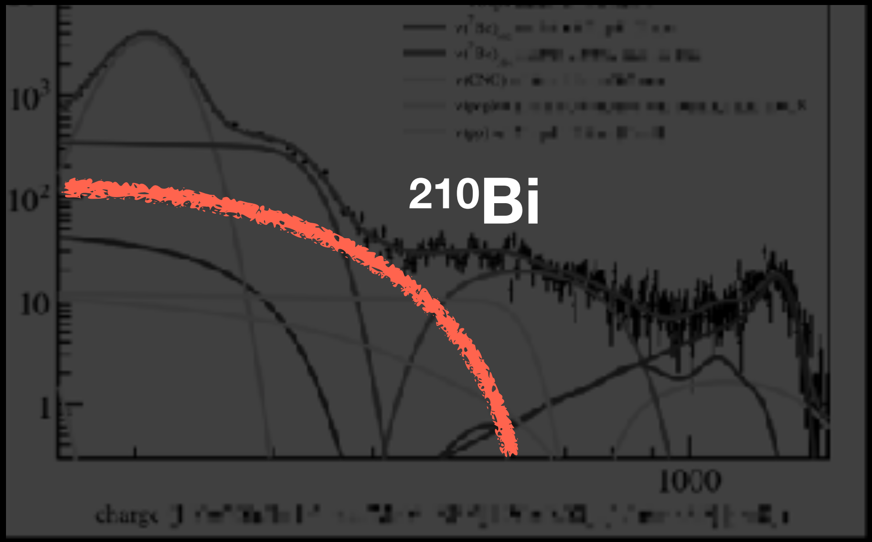


We only know precisely the sum of CNO, ^{210}Bi and pep

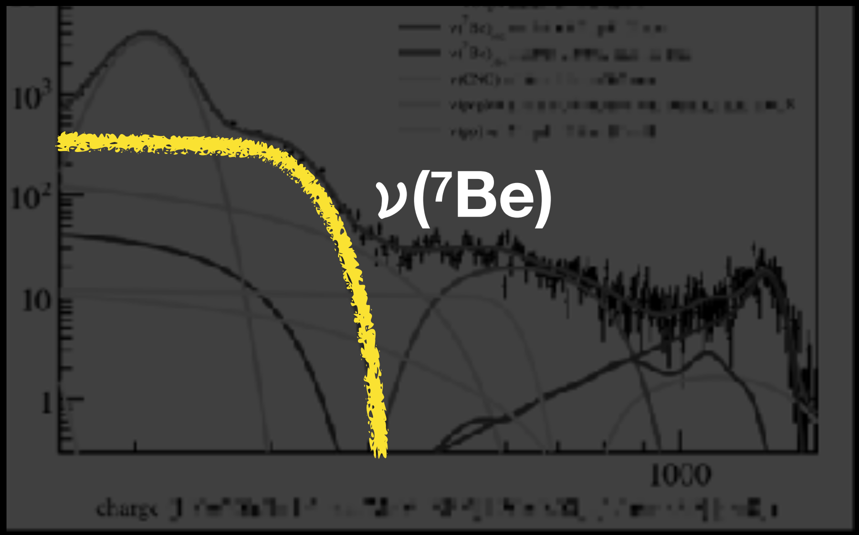
Advanced analysis: Formation of Correlation



^{210}Bi vs CNO: similar shape



^{210}Bi vs LY: wedge shape



ν(^{7}Be) vs resolution: sharp shape

- Correlation is formed when
  - **Extracting informations of degrees of freedom more than available**

Advanced analysis: Correlation in different analysis

- pp: ^{14}C, pile-up, light yield (LY) or kb
- ν(^{7}Be): energy resolution, ^{85}Kr, ^{210}Bi (and thus LY)
- ν(pep): ^{11}C, external ^{40}K
- ν(CNO): ^{210}Bi (and thus ^{85}Kr and LY)

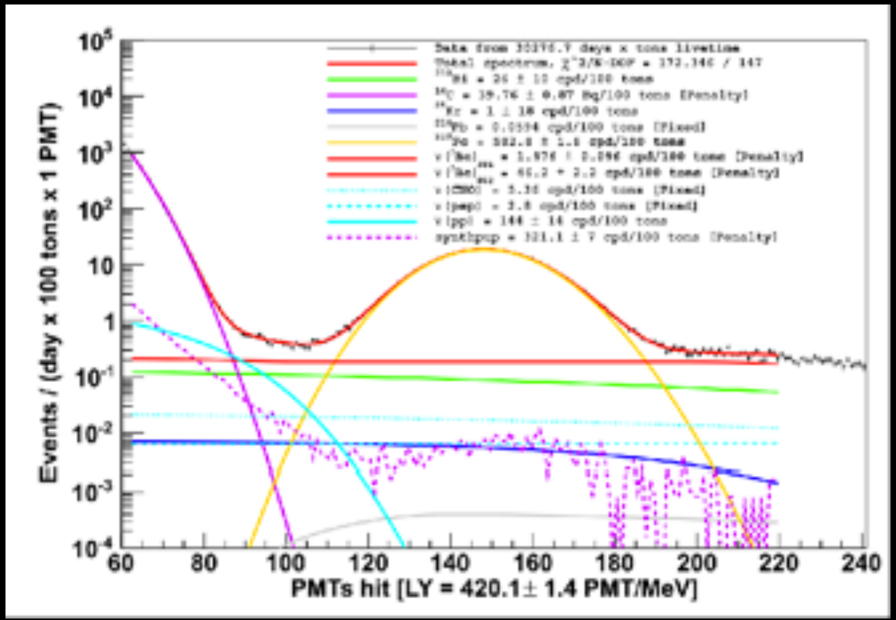
Advanced analysis: Break the correlation

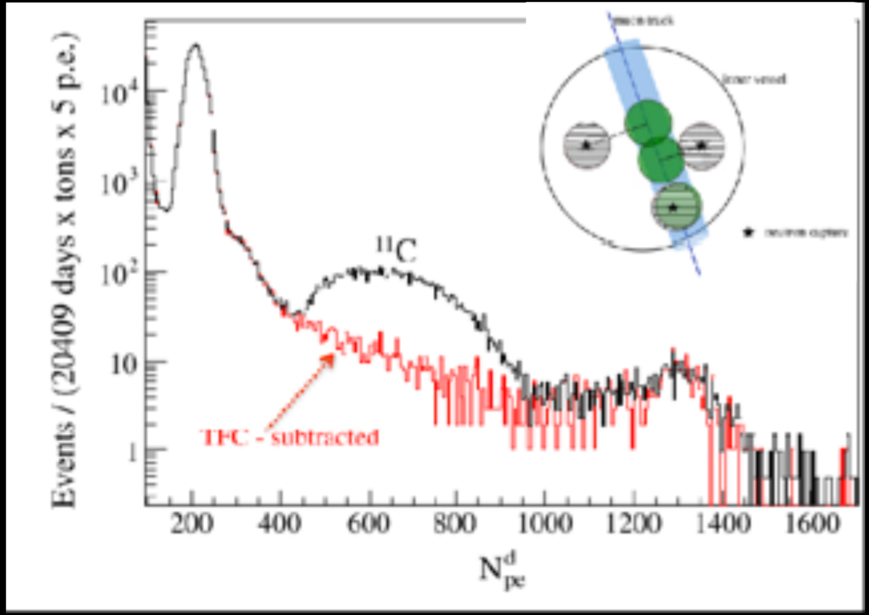
- To break the correlation, you need to put in information
  - fix / constrain
  - cut / remove
  - multivariate analysis: use more than energy

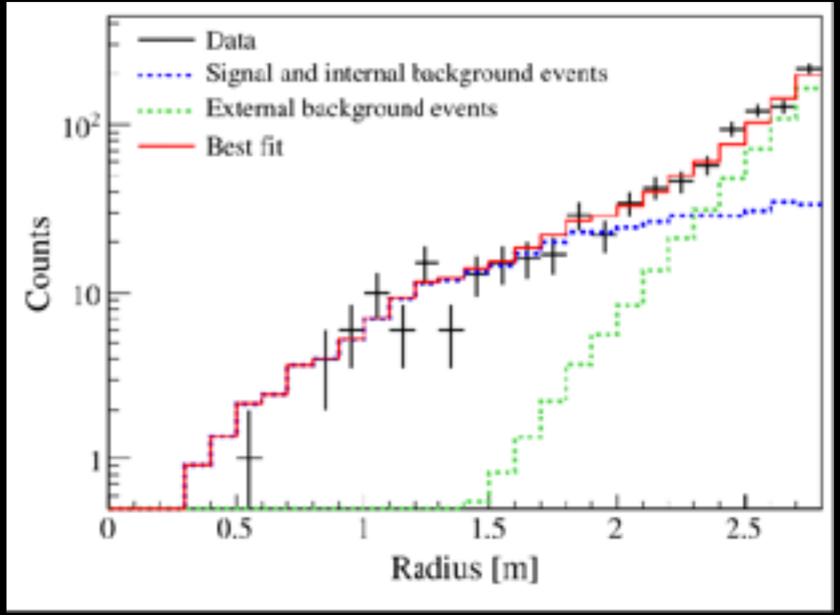
constrain rates from independent measurement ^{14}C, pile-up rate

suppress cosmogenic ^{11}C using muon track and neutron coincidence

suppress external backgrounds using radius: mutlivariate analysis







[1] G. Bellini, et al., "Final results of Borexino Phase-I on low-energy solar neutrino spectroscopy," Phys. Rev. D - Part. Fields, Gravit. Cosmol., vol. 89, no. 11, pp. 1–68, 2014.

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Accelerating fitting using Graphic Processing Units

What is a GPU?

watch a short video to get a feeling

video length: 1 minutes 33 seconds

What is Graphic Processing Units

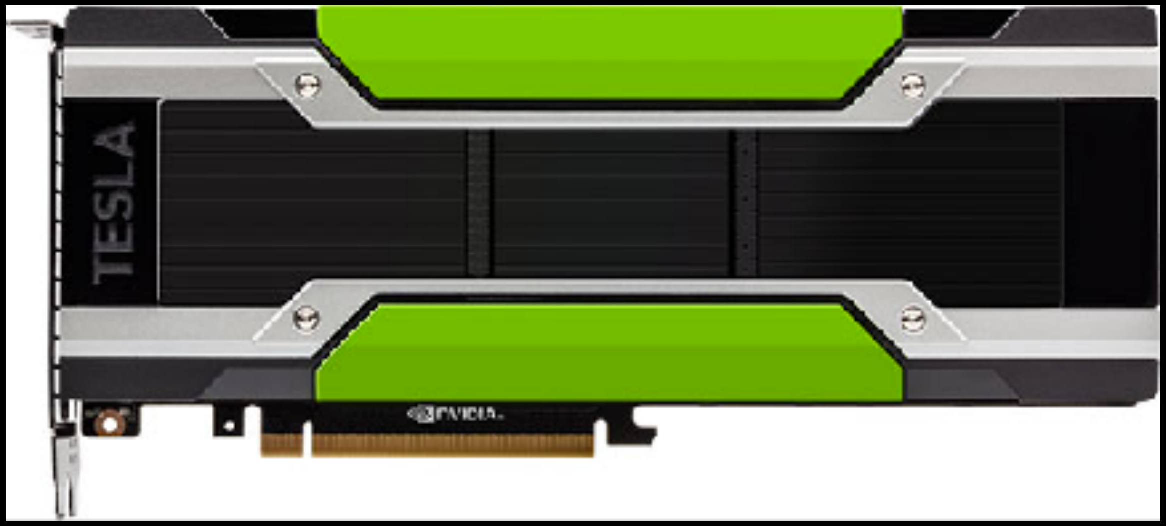
Credit: Nvidia Youtube channel https://www.youtube.com/watch?v=-P28LKWTzrI

How Graphic Processing Units accelerate fitting

- General Purpose **G**raphic **P**rocessing **U**nits
  - Decompose computation into parallel jobs
    - Transformation f(vec x) -> veg y (calculate likelihood on each bin)
    - Reduction Σx_i -> S (sum up log-likelihoods)
  - Compute on thousands of cores in parallel

1 Tesla P100 GPU
= 3584 CUDA cores
~ 6,900€

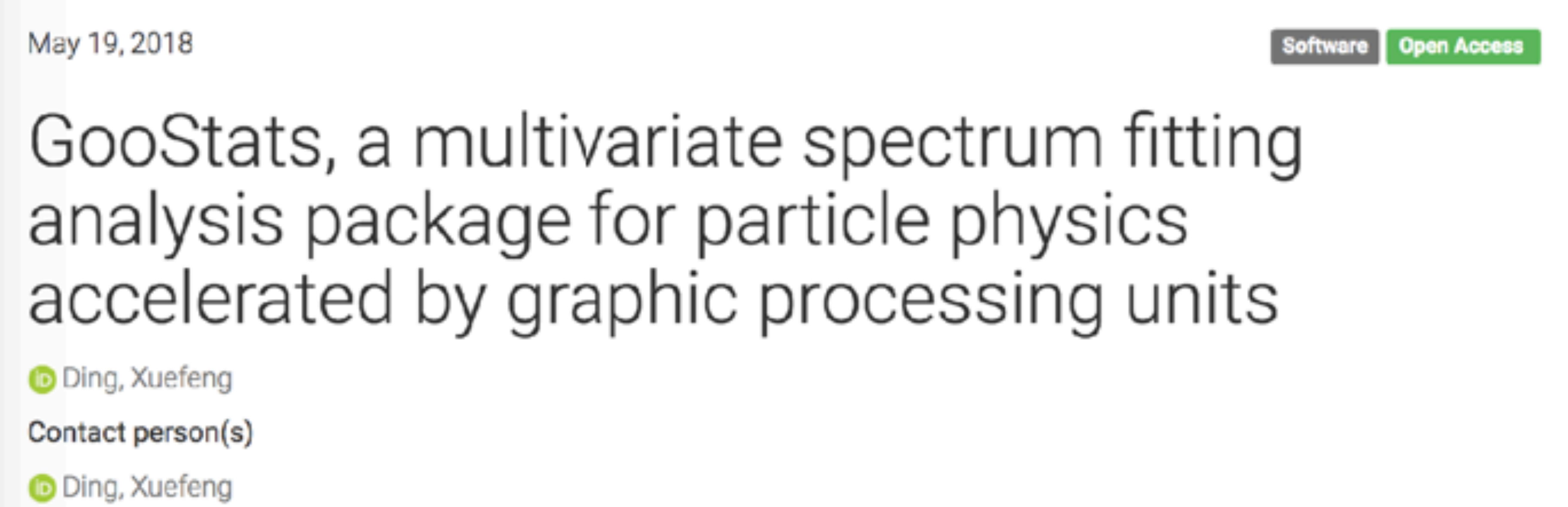
nVidia Tesla P100



http://www.nvidia.cn/object/tesla-p100-cn.html

Revolution of fitting tools

Accelerating fitting — GooStats package



May 19, 2018

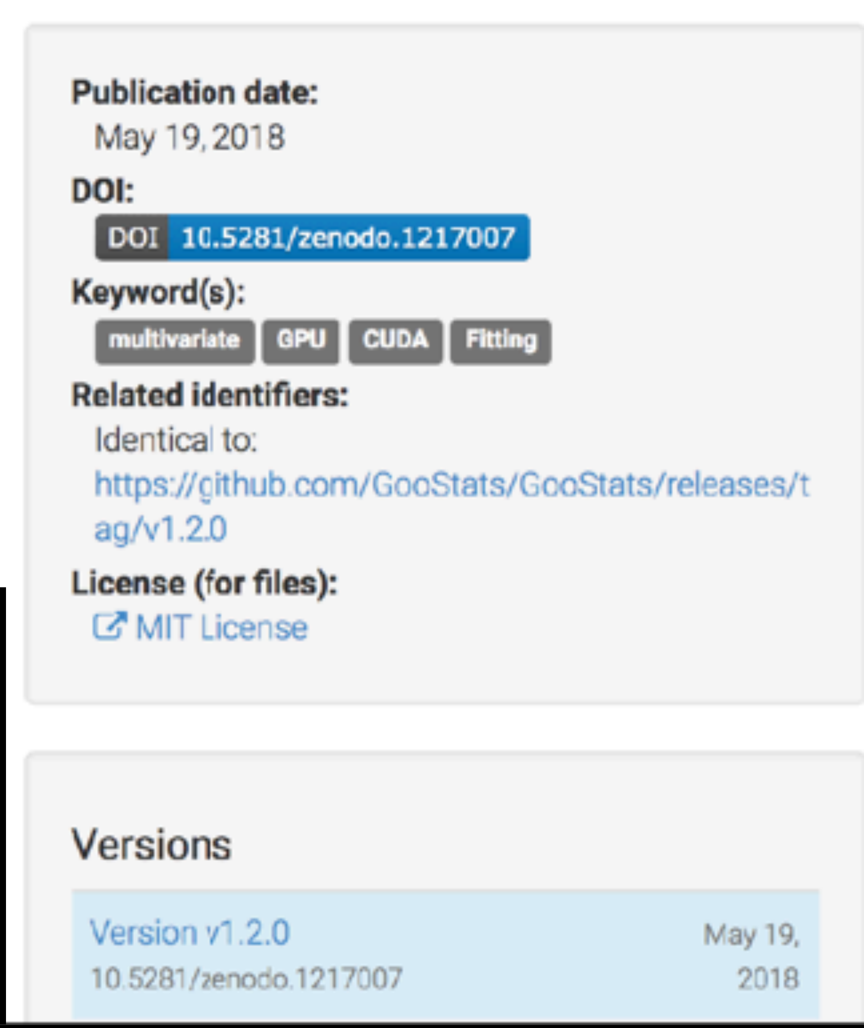
Software Open Access

GooStats, a multivariate spectrum fitting analysis package for particle physics accelerated by graphic processing units

Ding, Xuefeng

Contact person(s)

Ding, Xuefeng



Publication date:
May 19, 2018

DOI:
DOI 10.5281/zenodo.1217007

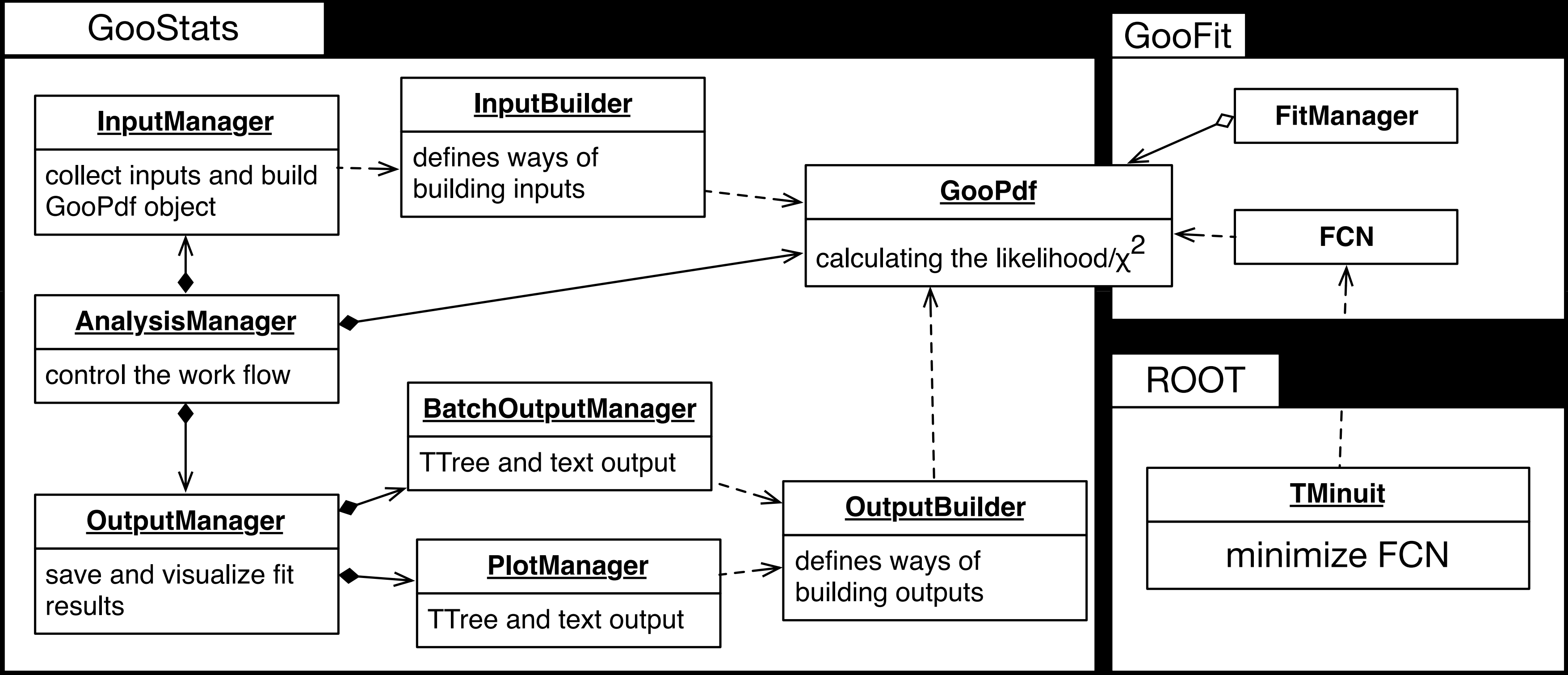
Keyword(s):
multivariate GPU CUDA Fitting

Related identifiers:
Identical to:
https://github.com/GooStats/GooStats/releases/tag/v1.2.0

License (for files):
MIT License

Versions

Version v1.2.0 10.5281/zenodo.1217007	May 19, 2018



GooStats

InputManager
collect inputs and build GooPdf object

InputBuilder
defines ways of building inputs

GooPdf
calculating the likelihood/χ^2

AnalysisManager
control the work flow

BatchOutputManager
TTree and text output

OutputManager
save and visualize fit results

PlotManager
TTree and text output

OutputBuilder
defines ways of building outputs

GooFit

FitManager

FCN

ROOT

TMinuit
minimize FCN

- Middle layer between GooFit and analysis module

[1] Ding, Xuefeng. (2018, May 19). GooStats, a multivariate spectrum fitting analysis package for particle physics accelerated by graphic processing units (Version v1.2.0). Zenodo. http://doi.org/10.5281/zenodo.1217007

Accelerating fitting — Performance

	original fitter	bx-GooStats	speed up
single fit + dn	**~ 1 hour**	**~4 seconds**	x600
complementary + dn	**~ 2 hours**	**~7 seconds**	x1000
dn+comp.+MV	unknown (**> 1 week**)	**~5 minutes**	> x2000

Accelerating fitting — Computing budgets

- Study stage
  - ~150 test x 1000 fit per test
  - CPU fitter: 34 CPU x years
  - GPU fitter: 12 GPU x days
- Finalizing stage
  - 2 job x 10000 multi-variate fit per job
  - CPU fitter: 384 CPU x years
  - GPU fitter: 70 GPU x days

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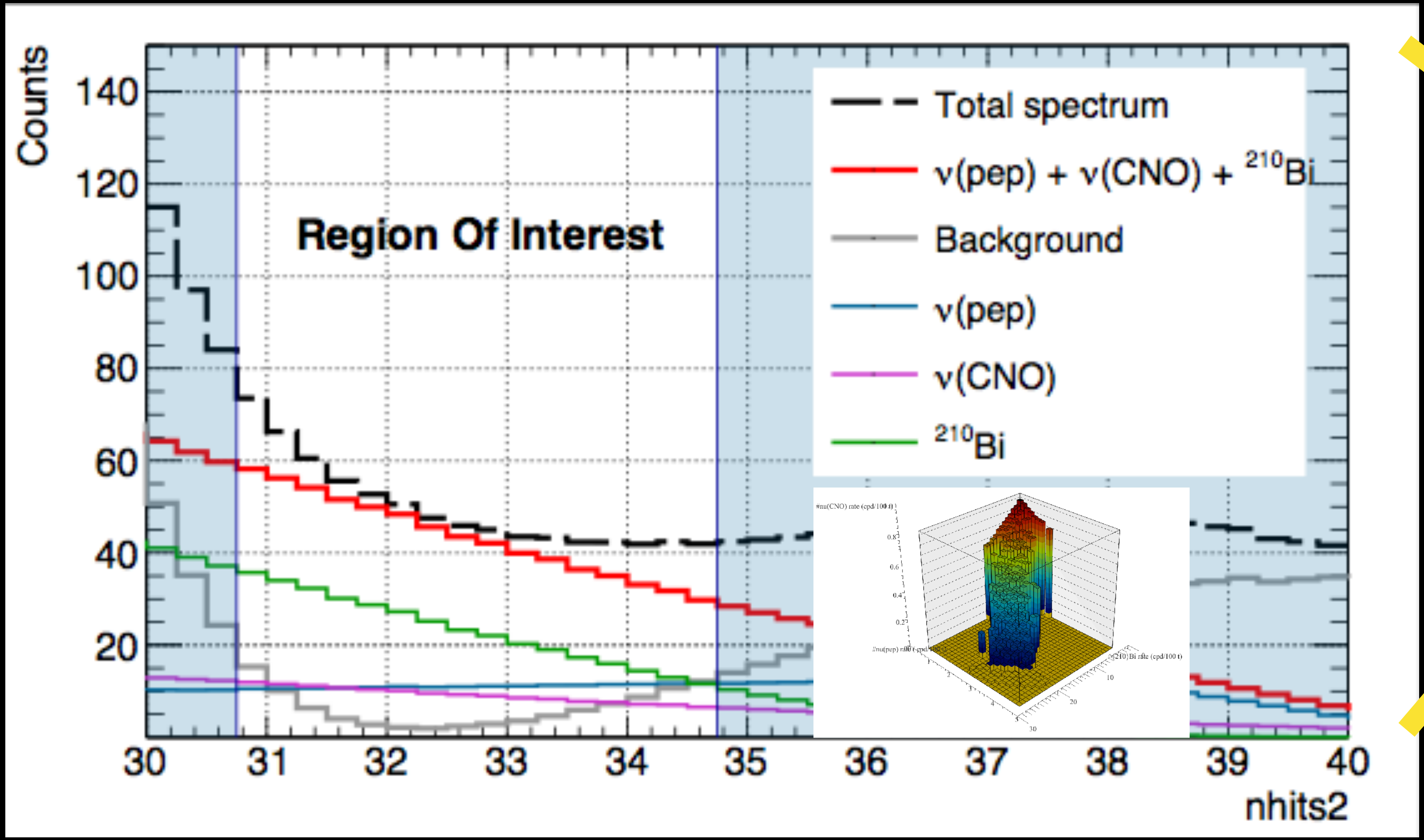
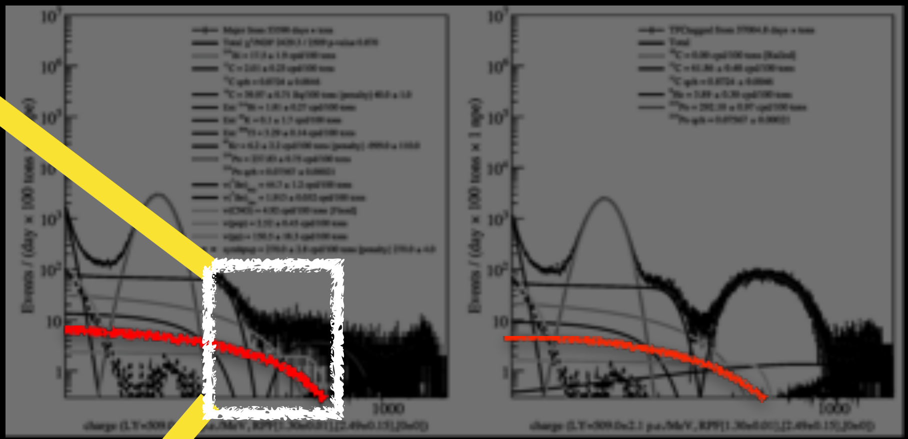
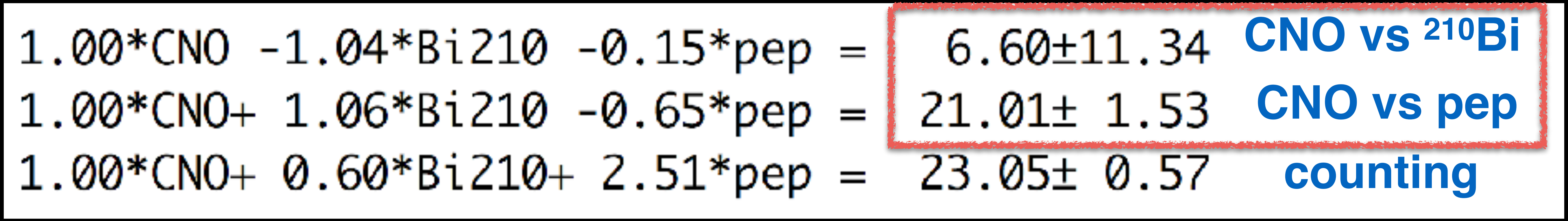
Main challenge of CNO analysis: strong correlations





- We know ν(CNO) + 2.2 ν(pep) + 0.63 ^{210}Bi from the spectrum
- Constrain ν(pep) and ^{210}Bi, we got ν(CNO)

Diagonalize covariance matrix



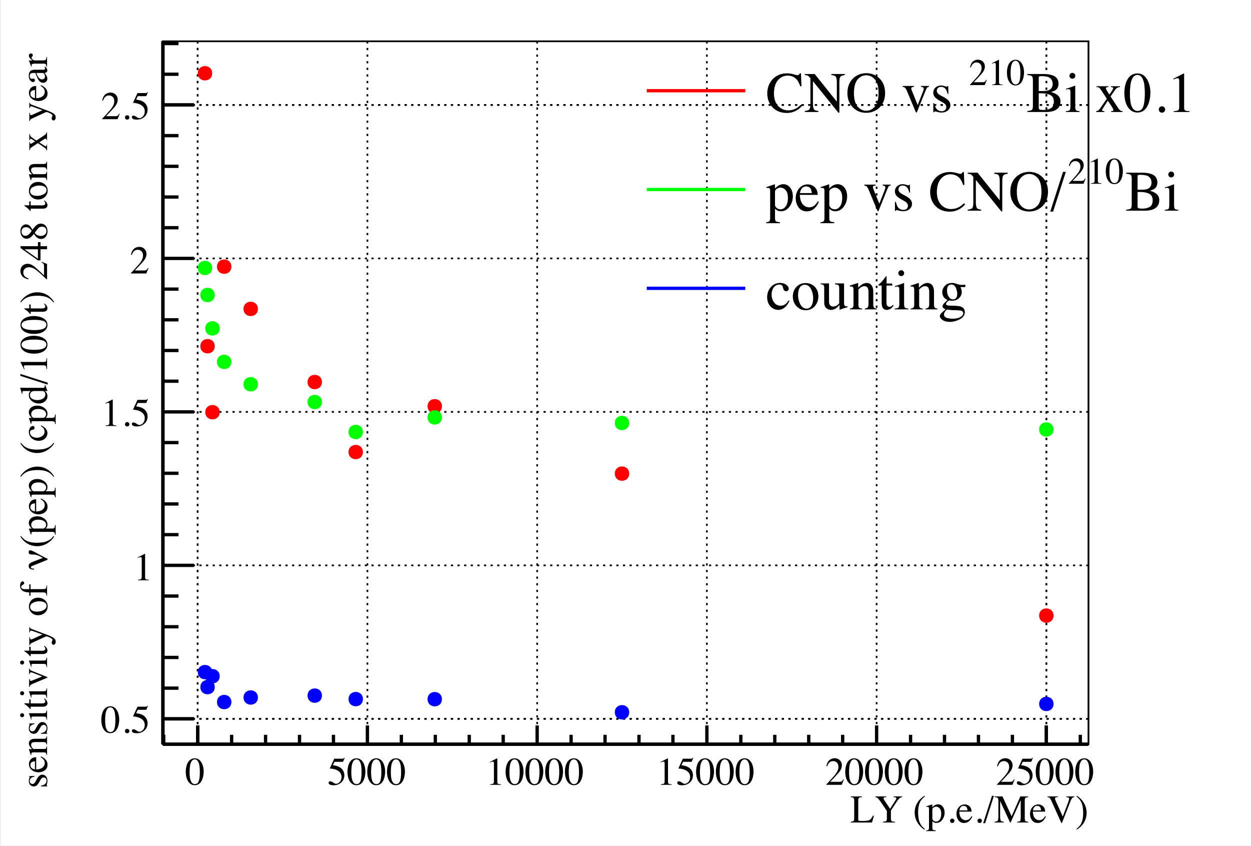
```
1.00*CNO -1.04*Bi210 -0.15*pep =  6.60±11.34
1.00*CNO+ 1.06*Bi210 -0.65*pep = 21.01± 1.53
1.00*CNO+ 0.60*Bi210+ 2.51*pep = 23.05± 0.57
```

- Can get intuitive shape uncertainty
- Counting uncertainty and coefficients are similar
    - Method A: fit plane of CNO-pep-^{210}Bi
    - Method B: counting using efficiency from MC
    - Method C: diagonalizing covariance matrix

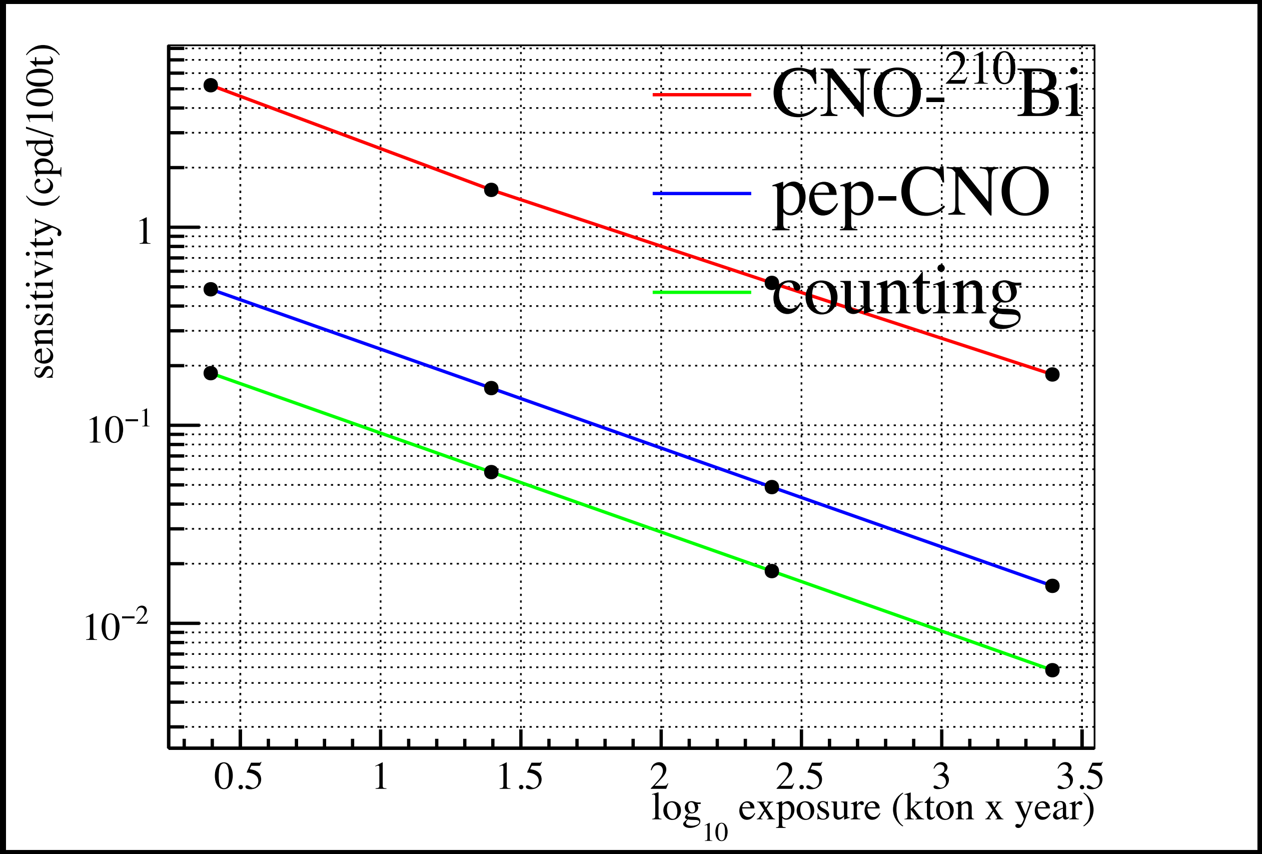
How to improve shape precision?

- Better precision: little improvement
- Larger detector: only limited by systematics

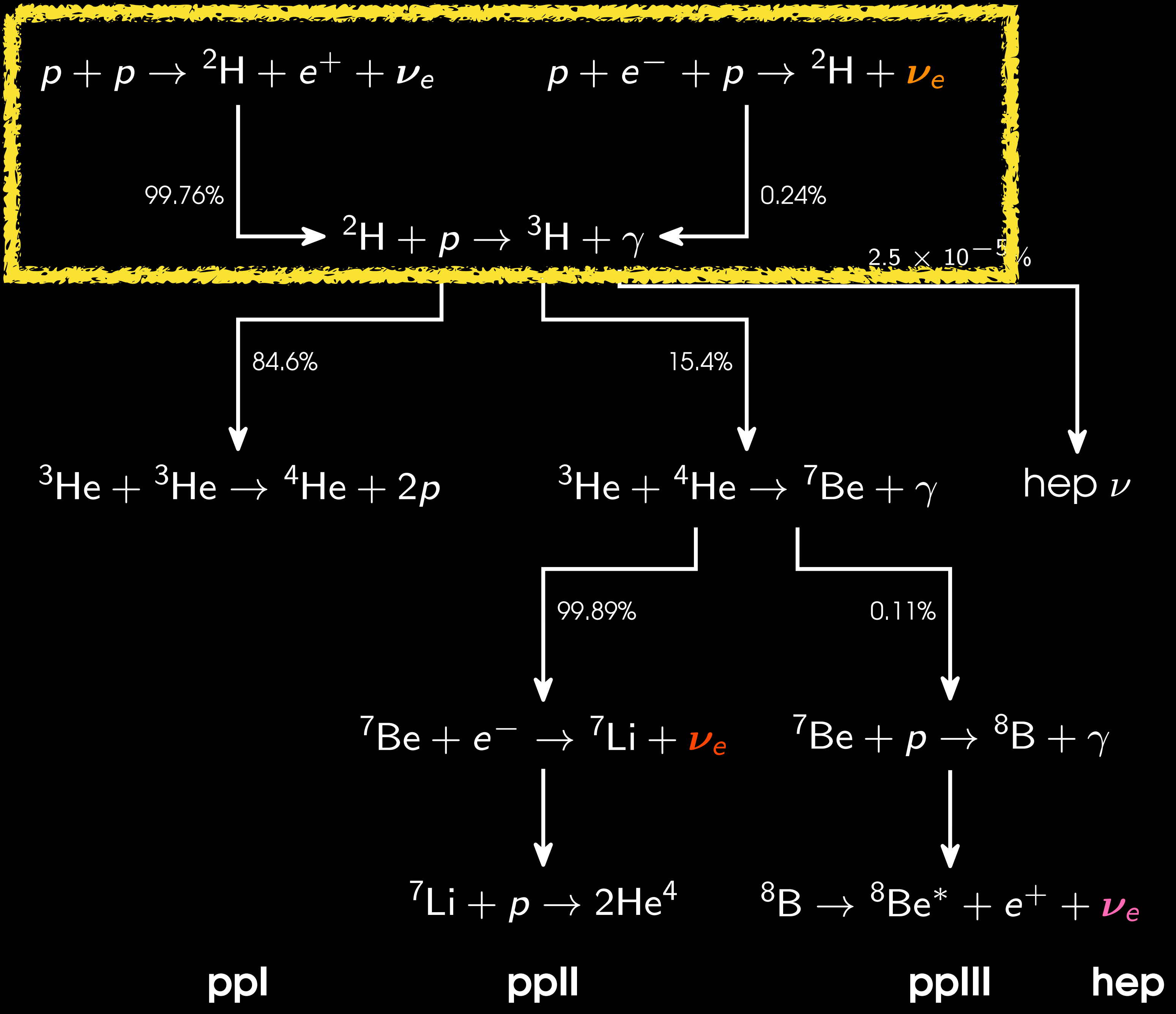
Better precision



Larger detector



CNO analysis — constraining v(pep)



$p + p \rightarrow {}^{2}\text{H} + e^{+} + \nu_e$

$p + e^{-} + p \rightarrow {}^{2}\text{H} + \nu_e$

99.76%

0.24%

${}^{2}\text{H} + p \rightarrow {}^{3}\text{H} + \gamma$

2.5×10^{-5} %

84.6%

15.4%

${}^{3}\text{He} + {}^{3}\text{He} \rightarrow {}^{4}\text{He} + 2p$

${}^{3}\text{He} + {}^{4}\text{He} \rightarrow {}^{7}\text{Be} + \gamma$

hep ν

99.89%

0.11%

${}^{7}\text{Be} + e^{-} \rightarrow {}^{7}\text{Li} + \nu_e$

${}^{7}\text{Be} + p \rightarrow {}^{8}\text{B} + \gamma$

${}^{7}\text{Li} + p \rightarrow 2\text{He}^{4}$

${}^{8}\text{B} \rightarrow {}^{8}\text{Be}^{*} + e^{+} + \nu_e$

ppI **ppII** **ppIII** **hep**

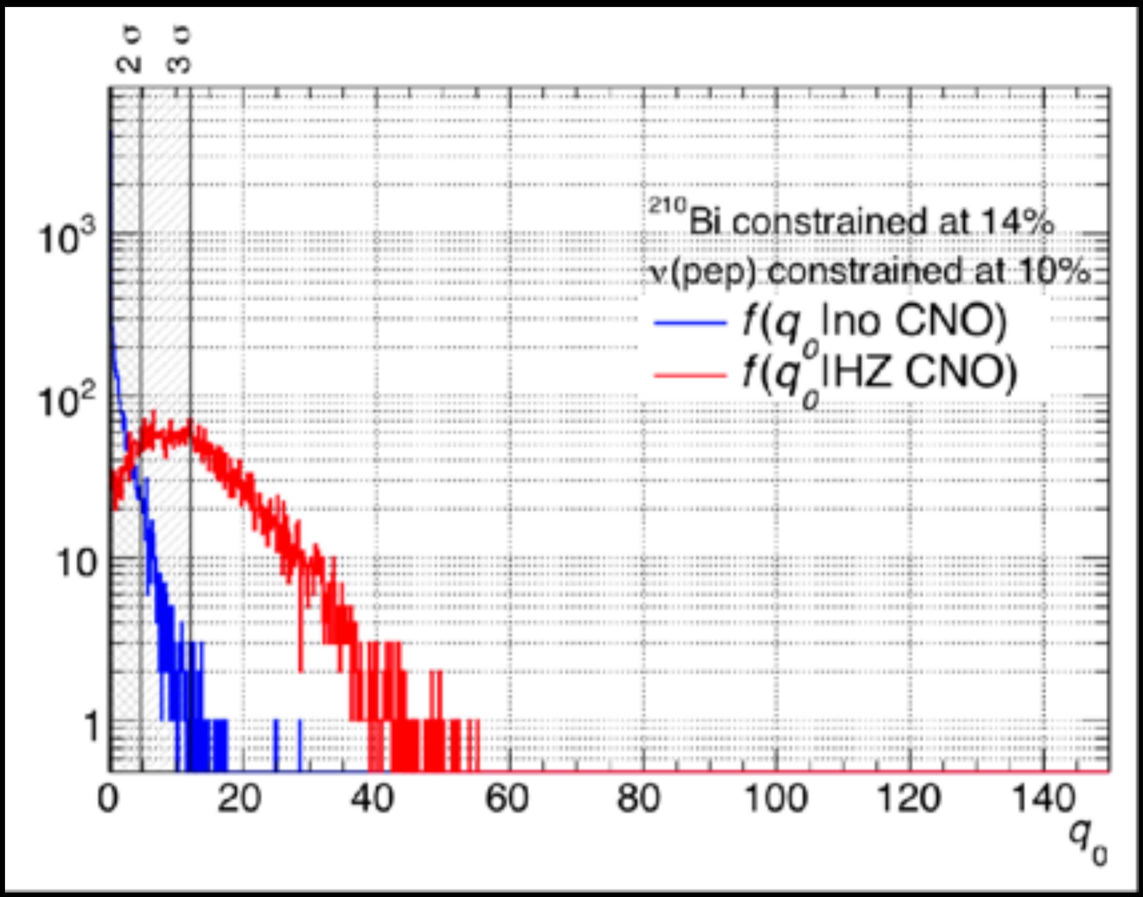
- Φ(pp) / Φ(pep): from cross-section and independent of solar models
- R(pp) / R(pep): extra uncertainty from $\sin^2\theta_{12}$
- R(pp): constrained through fit

CNO analysis: Statistical sensitivity

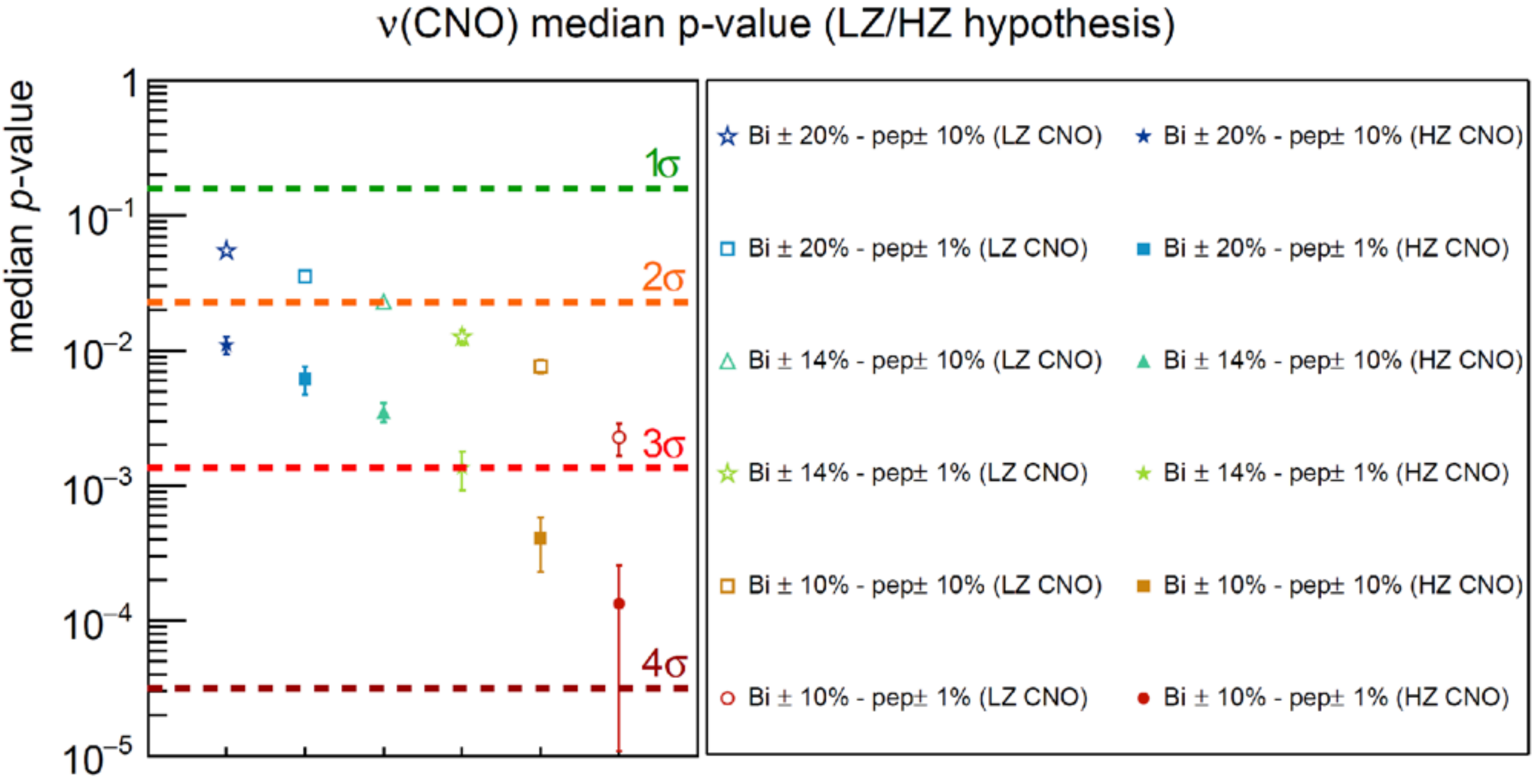
$$q(\mathrm{HZ}) = \log \mathcal{L}_{\text{no CNO}} - \log \mathcal{L}_{\text{CNO HZ}}$$

- Hypothesis test method
- Get q for null and for HZ
- Report the median sensitivty

Distribution of test statistics q_0



CNO analysis: Statistical sensitivity



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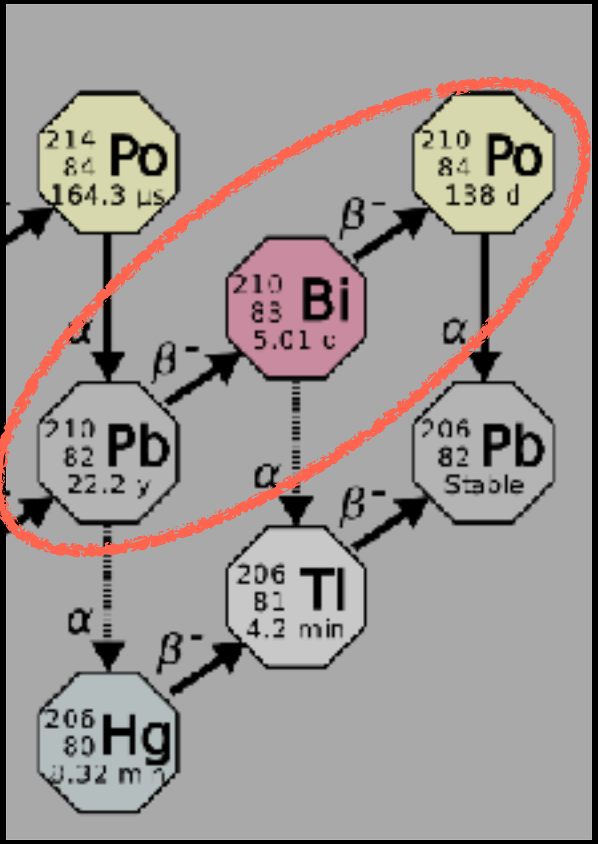
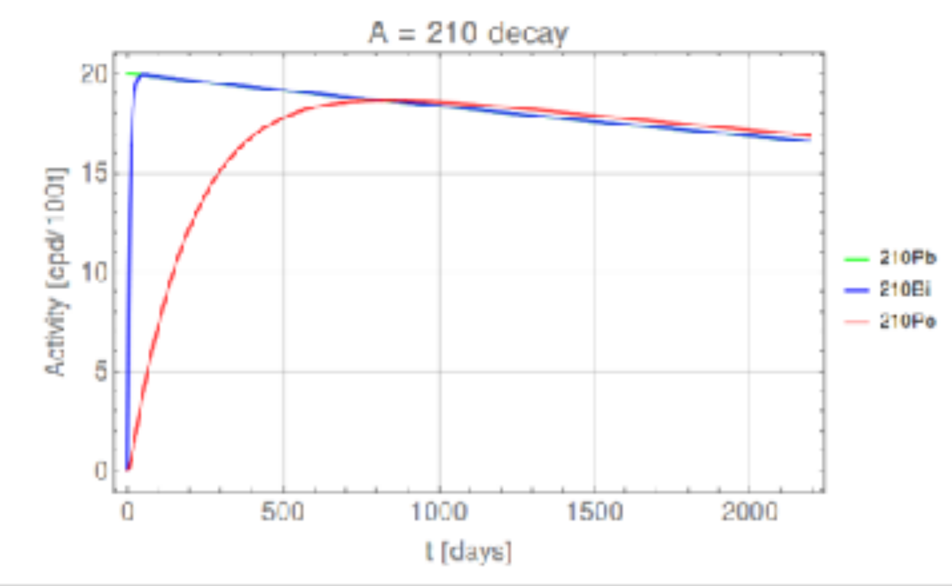
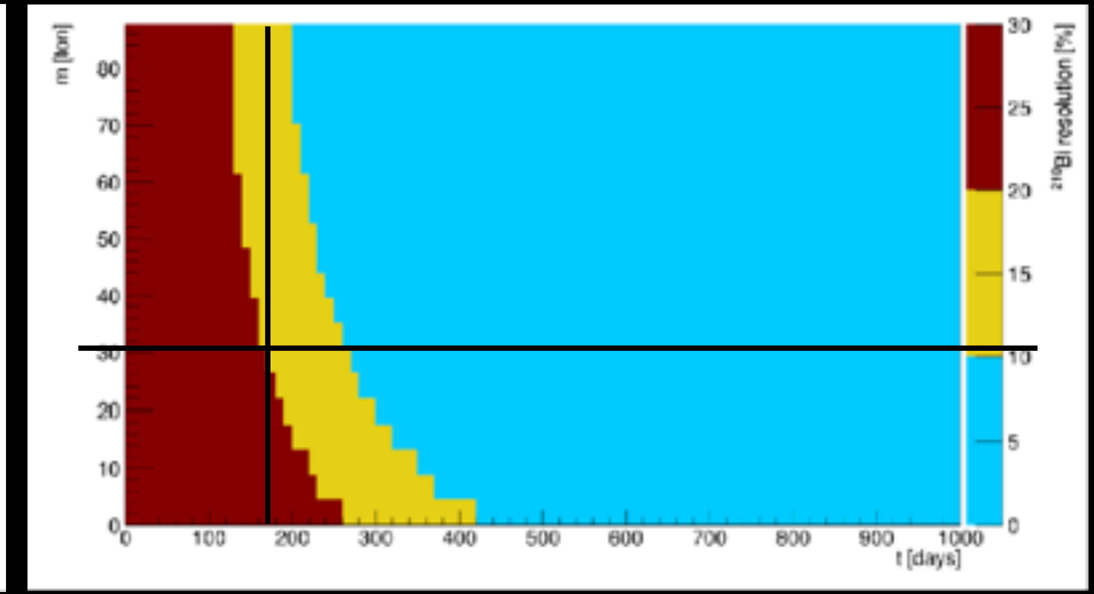
^{210}Bi from ^{210}Po: principles







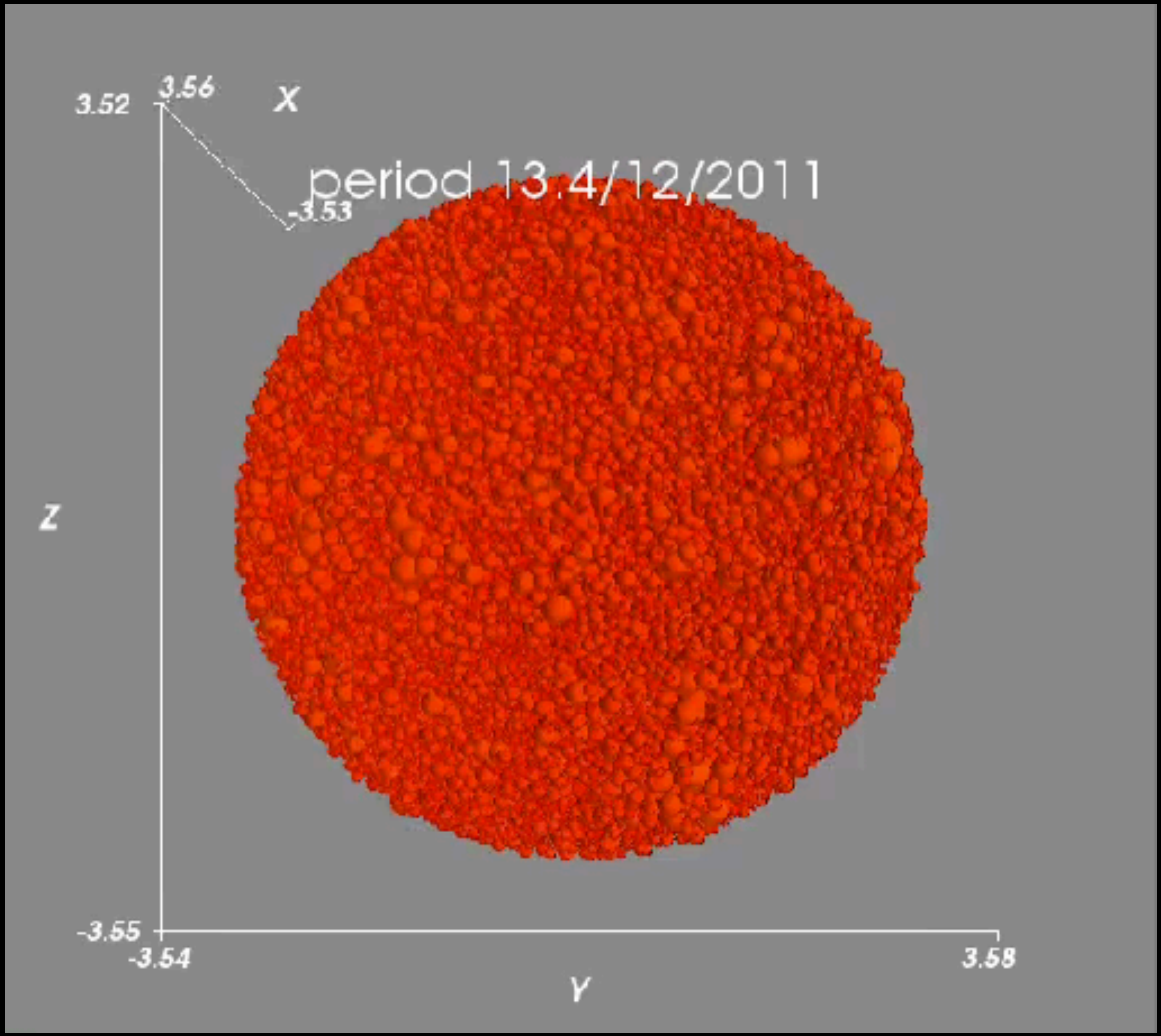
- When ^{210}Pb, ^{210}Bi and ^{210}Po reached secular equilibrium, ^{210}Bi can be measured by ^{210}Po
- With 30 ton FV ~ 6 months ^{210}Bi can reach 10% precision (statistical).

^{210}Bi from ^{210}Po: convection and disturbed ^{210}Po

Diffusion

Convection

$$\frac{\partial X_{\mathrm{Po}}}{\partial t} = X_{\mathrm{Bi}} \cdot \lambda_{\mathrm{Bi}} - X_{\mathrm{Po}} \cdot \lambda_{\mathrm{Po}} + \Delta \cdot (D_{\mathrm{Po}} \cdot \Delta X_{\mathrm{Po}} \boxed{- \vec{v} X_{\mathrm{Po}})}$$



- Temperature instability induces convective current
- Convection makes local ^{210}Po concentration contaminated by extra component

Stop convections: thermal insulation

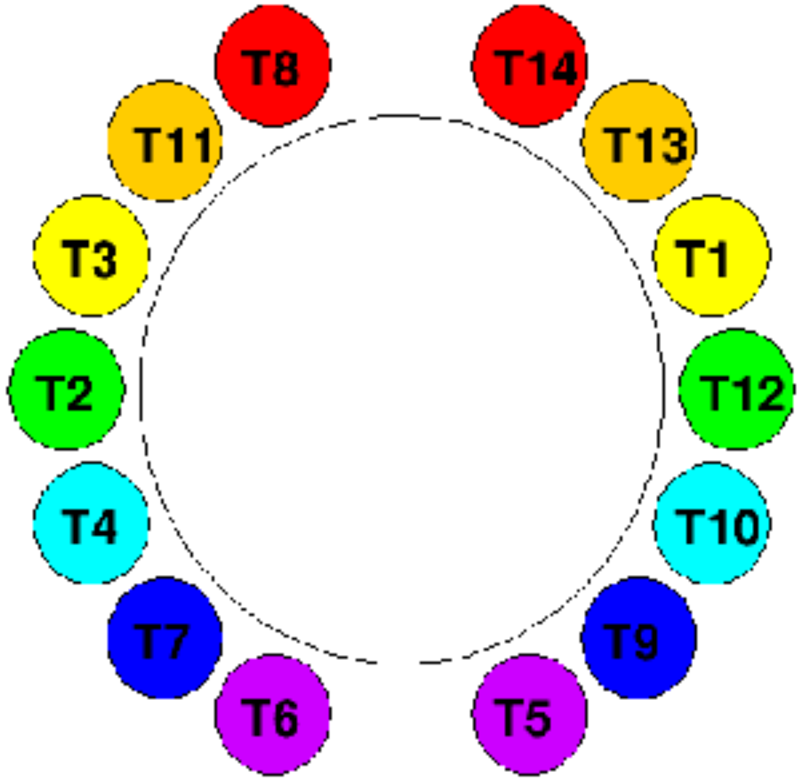
Before insulation

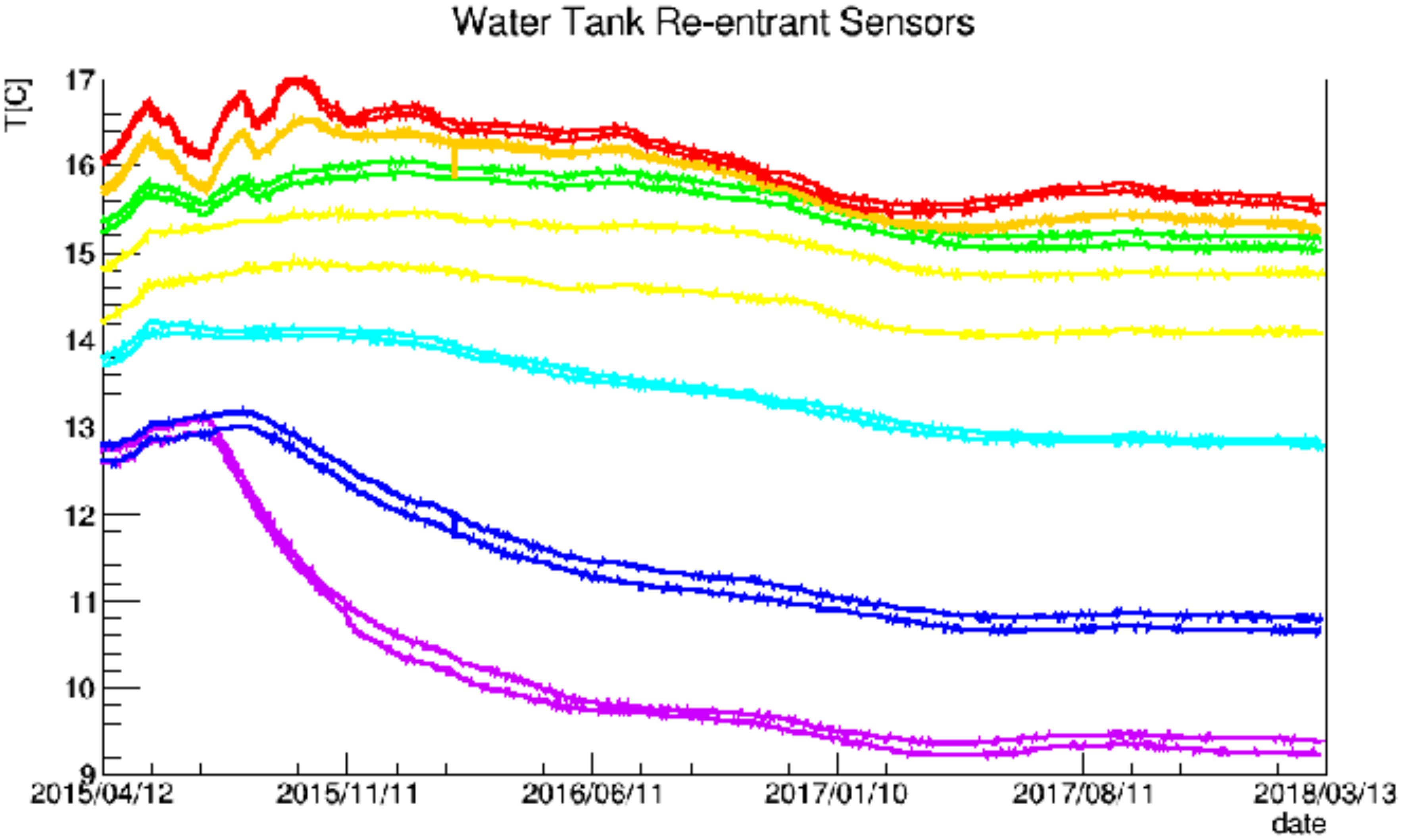
During insulation

- 20 cm Rockwool dressed to maximize the temperature gradient and stabilize the detector's stratification in order to **reduce** convective transport of ^{210}Po from the **periphery** to the **FV**

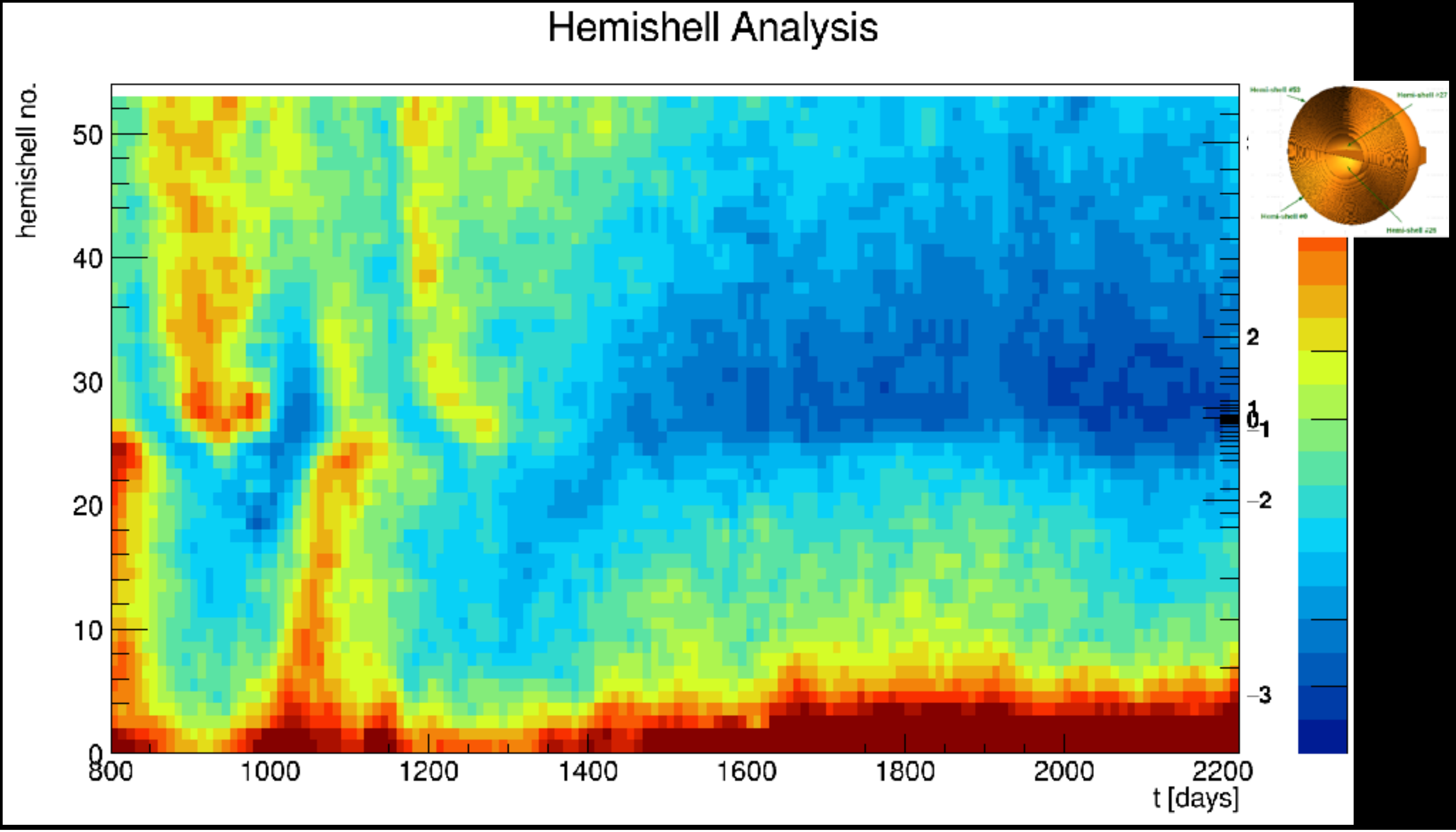
- **Detector** wide and **experiment hall** wide Heating system

Temperature profile



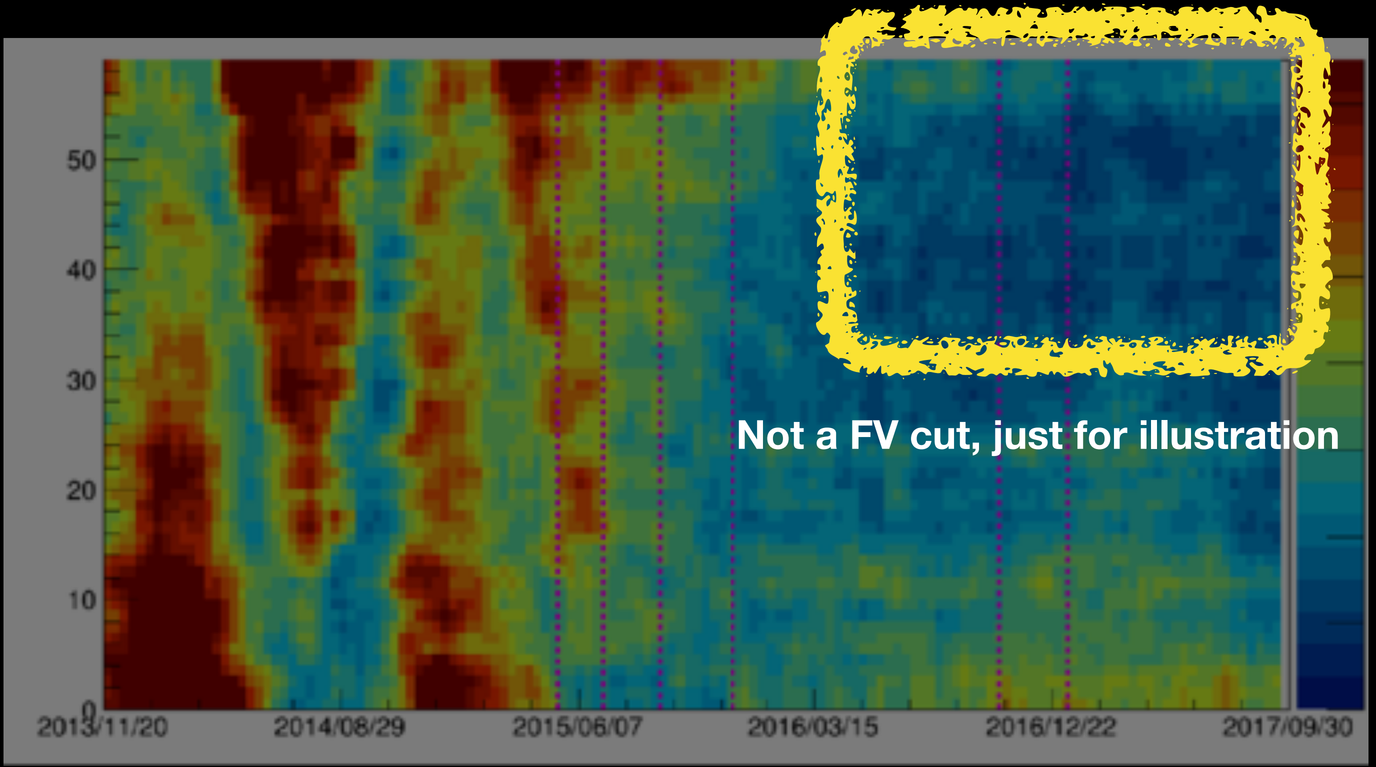


^{210}Po local concentration



Measure ^{210}Bi from ^{210}Po

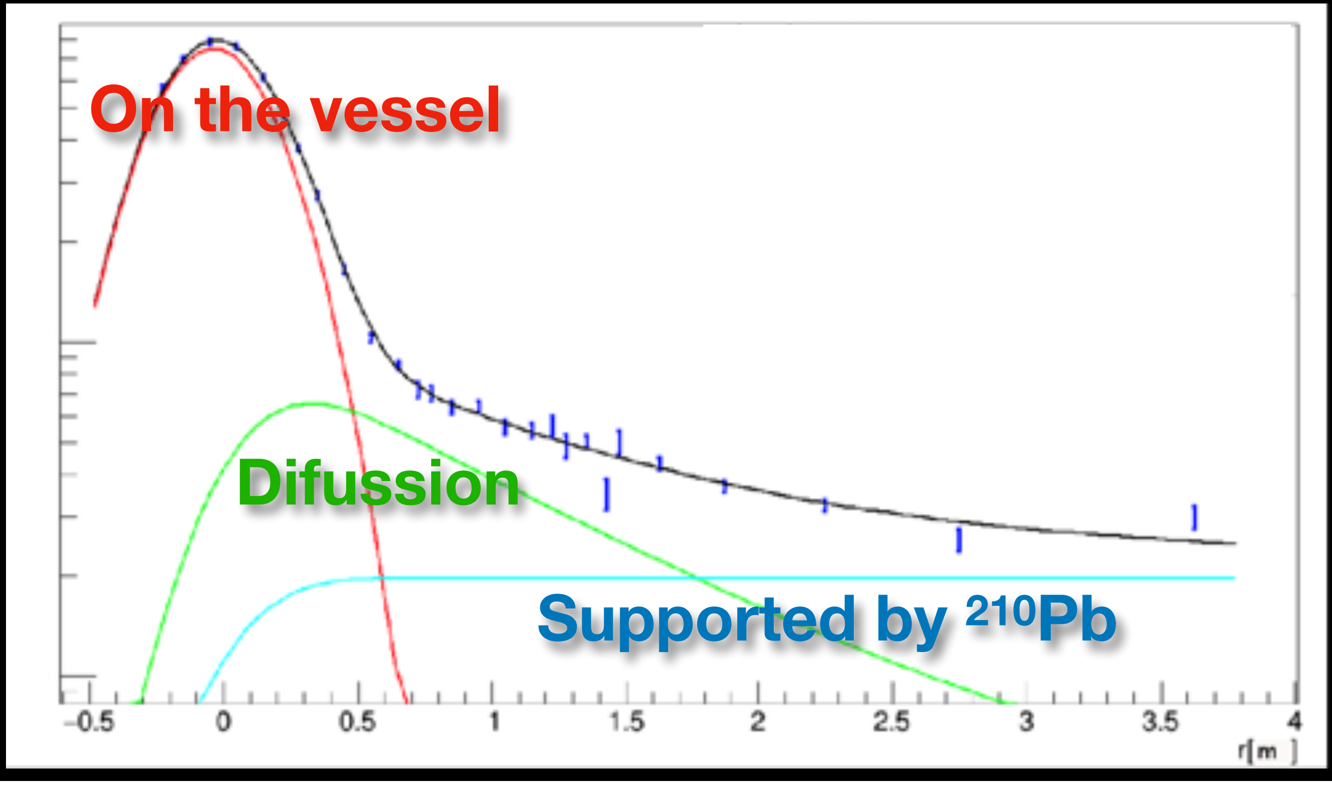
Step 1: find the clean region



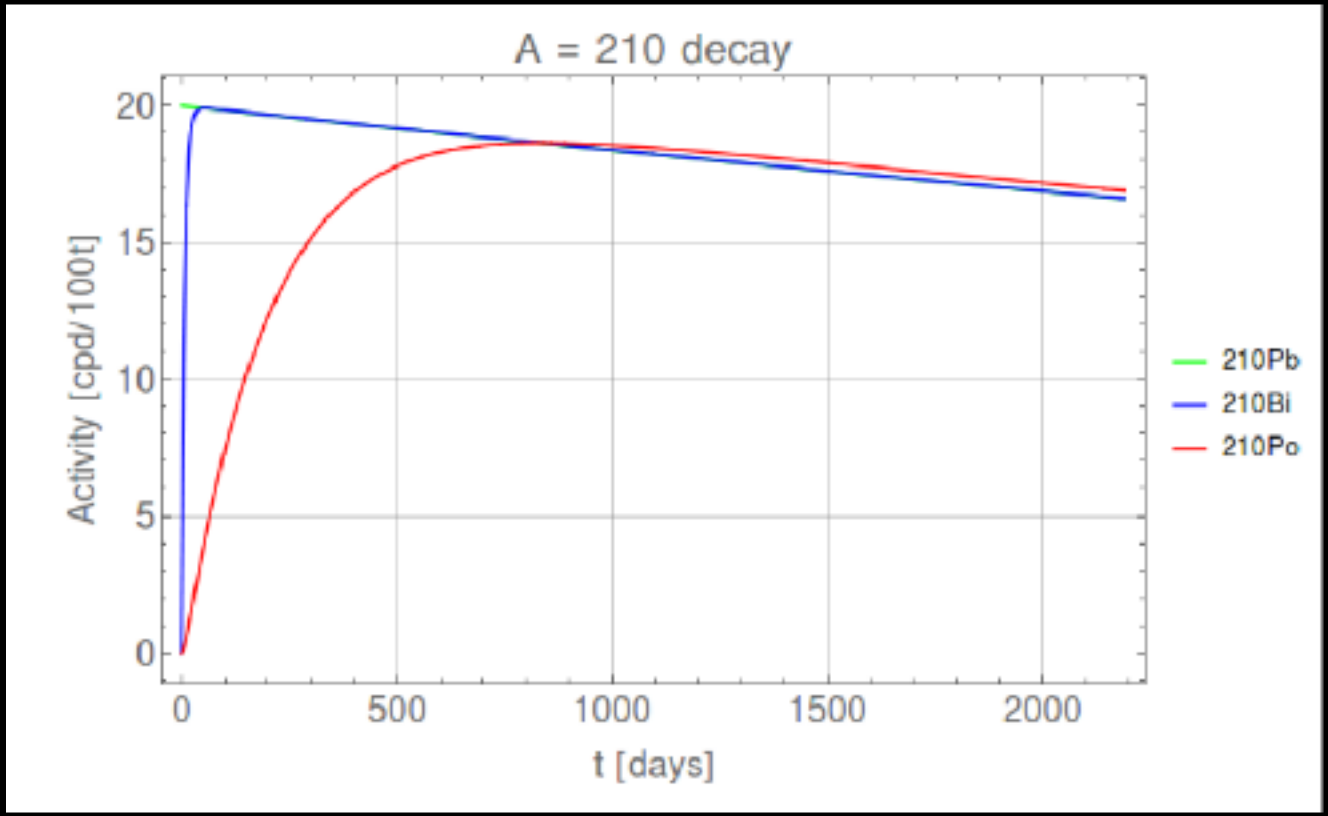
Not a FV cut, just for illustration

Clean region: region free from convection

- In clean region, ^{210}Po spatial distribution simply follows diffusion + uniform supported term



Step 2: temporal fit + systematics



- **After found the clean region, do a temporal fit to extract ^{210}Bi**

- **Residual convection component:** systematics. Study is still ongoing to evaluate its magnitude.

Remarks

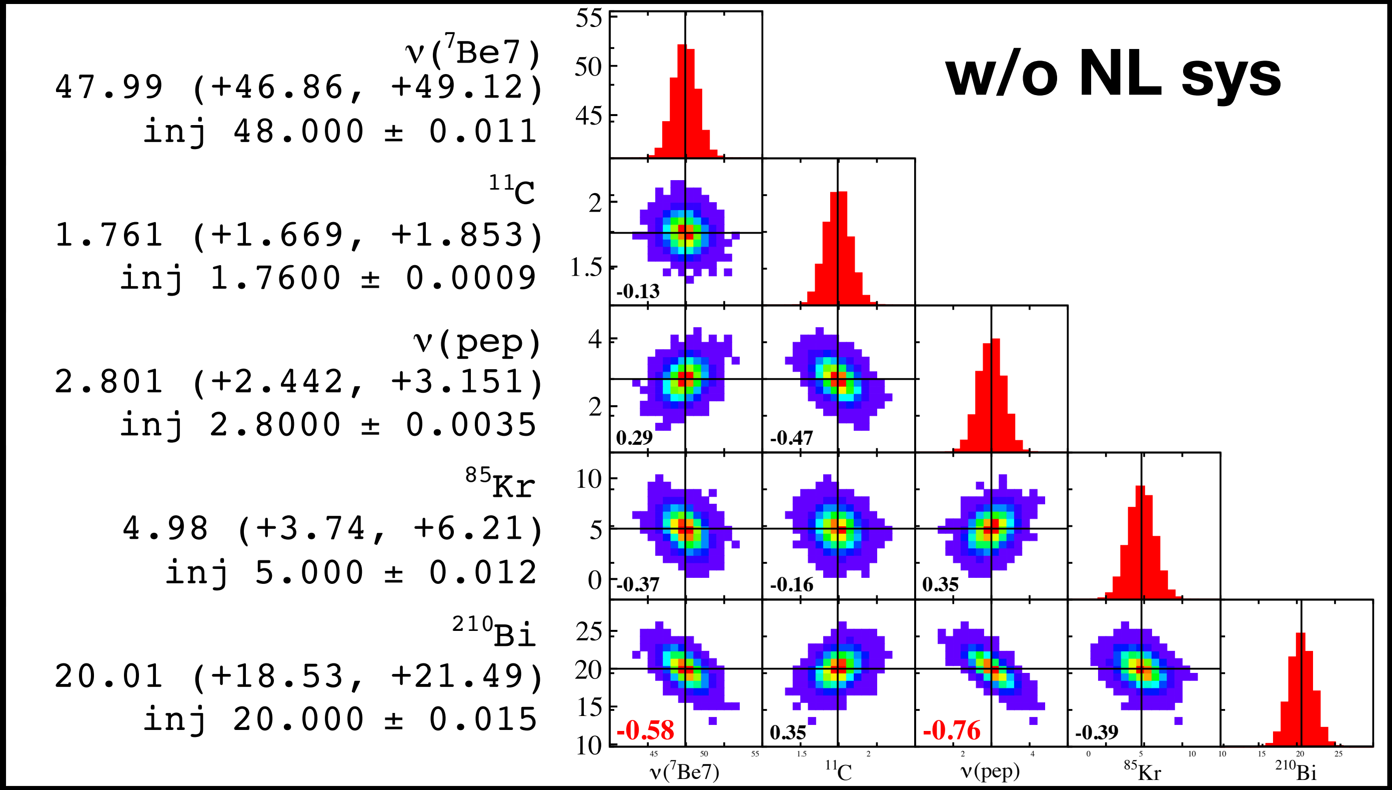
- GPUs are used in Borexino analysis and makes impossible things possible.
- For CNO analysis, we are in the best time. Convection motion of ^{210}Po has stopped in the top and ^{210}Bi measurement is about to come. In the HZ case, our CNO discovery sensitivity would reach 3σ if the ^{210}Bi is measured to be better than 10%.

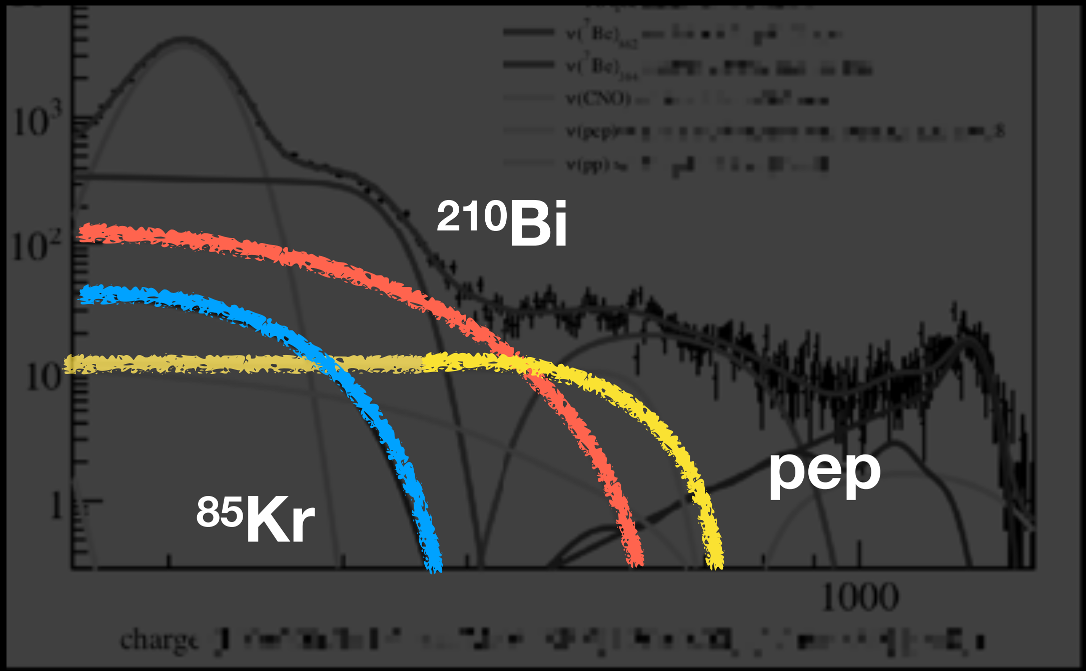
Conclusions

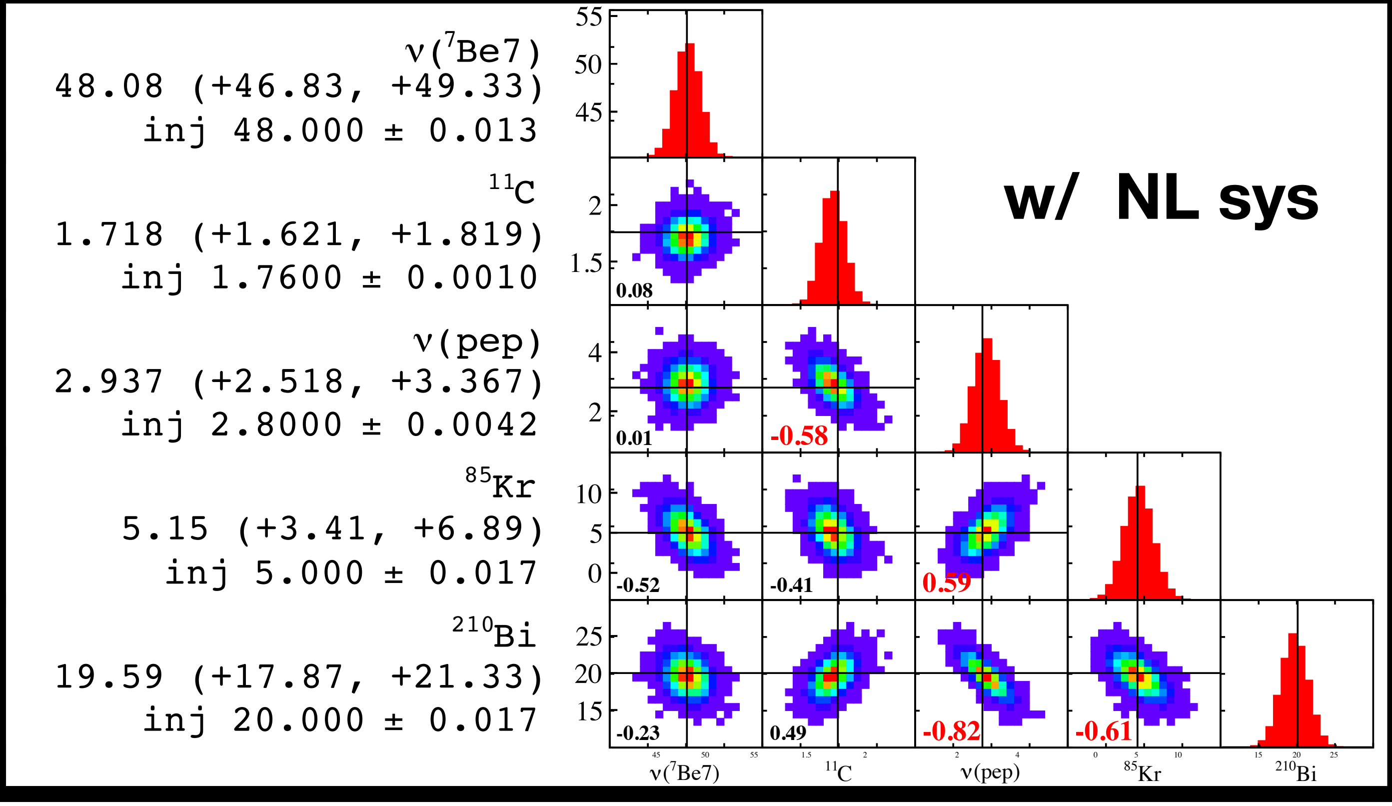
- Analytical response function is improved in Phase-II analysis
- New toy-MC method for systematics evaluation
- GPU based parallelization of likelihood computation -> fast fit
- Promising CNO sensitivity

Backup

Monte Carlo method — extra correlation





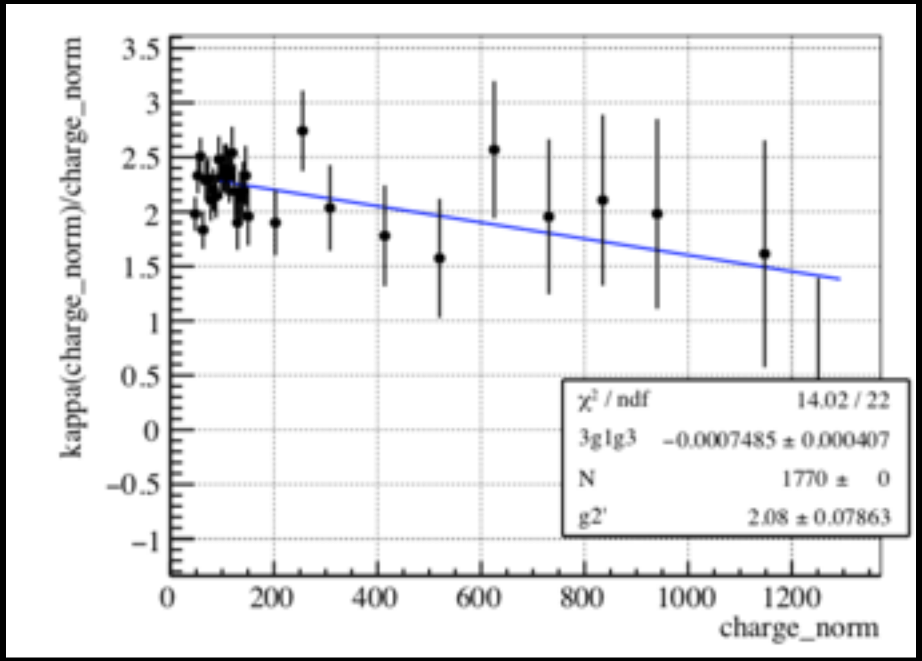


- After injecting NL systematics, new correlation is introduced

- Equivalent to fit varying models

Analytical Model — energy skewness model

charge



$$\kappa_{\mathrm{eq}} = g_2' \cdot \mathrm{feq}^2 \cdot \mu_{\mathrm{eq}} + 3(1+v_1) f_{\mathrm{eq}} \frac{v_T}{2000} \cdot \mu_{\mathrm{eq}}^2$$

Principle of Liquid Scintillator Detector

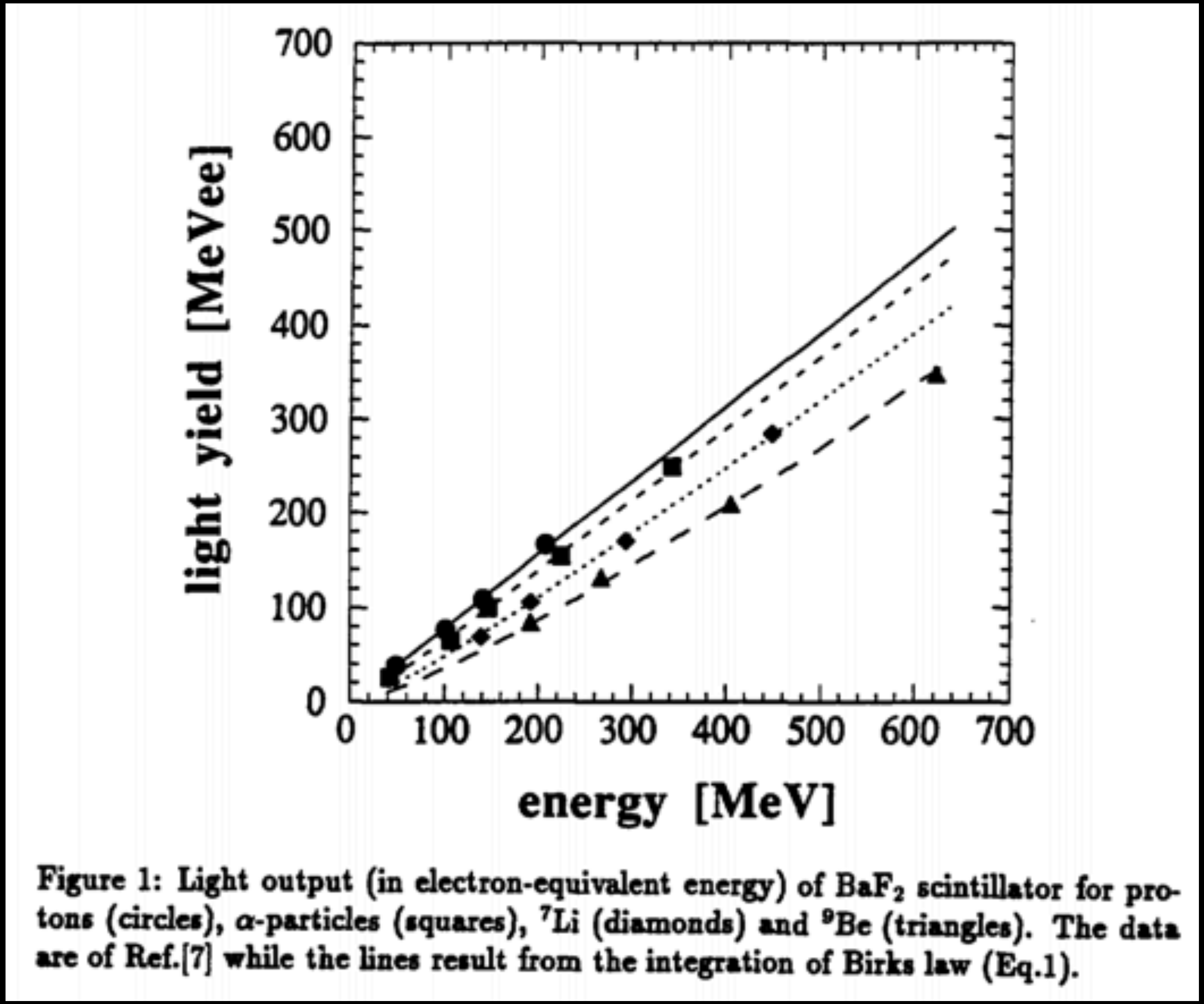


Figure 1: Light output (in electron-equivalent energy) of BaF_2 scintillator for protons (circles), α-particles (squares), ^7Li (diamonds) and ^9Be (triangles). The data are of Ref.[7] while the lines result from the integration of Birks law (Eq.1).

- Birk's law: Photon produced is quenched and inverted proportianal to the ($1+k_b\,dE/dx$)
- k_b: Birk's constant

Advanced analysis: Multivariate analysis

- Straightforward strategy: use muti-dimentional p.d.f. and fit multi-dimentional dataset.

- Stefano’s strategy: sum-up log-likelihood of all observables
  - Stefano’s trick: Same dataset are used for each observable and thus introduced correlations. They are removed using self-calibrated coefficients and results become un-biased and precise.

$$L_T(\vec{\theta}) = \prod_{i=1}^{m_E} L(\vec{\theta}) \times \prod_{j=1}^{m_p} L_p(\vec{\theta})$$

[1] S. Davini, “Measurement of the pep and CNO solar neutrino interaction rates in Borexino-I,” Springer International Publishing, Cham, 2013.