Into the void — detecting *extragalactic* SNe

Sebastian Böser

CCSNe workshop | Orsay | July 4th 2018

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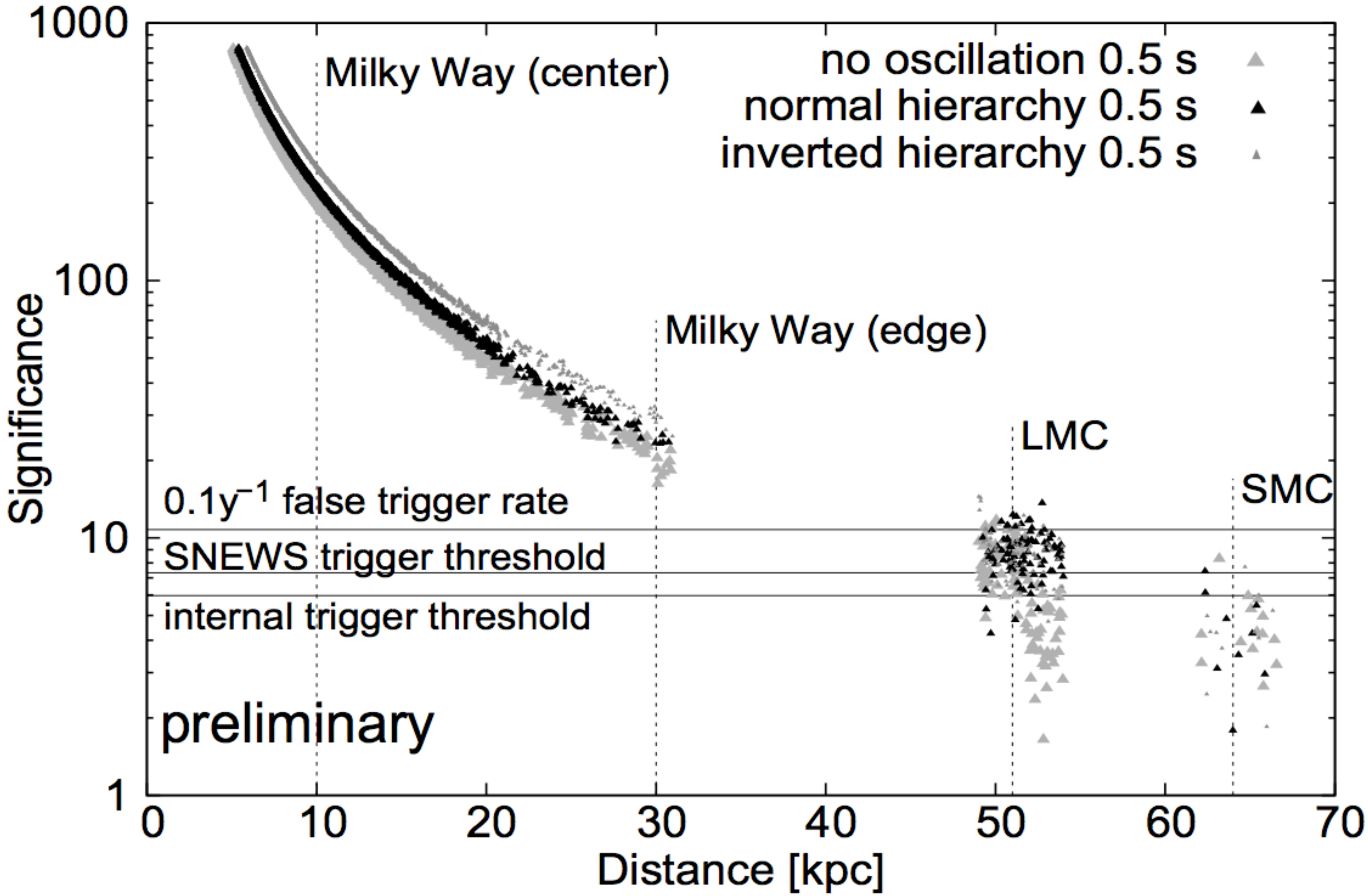
IceCube's reach for SNe



Detecting more supernovae in neutrinos

IceCube

- sensitive to galactic SNe
  - expected rate:
    1-2 SNe **per century!**

Goal

- routine SNe Detection

SN detection in IceCube Gen2

IceCube-Gen2

- new sensor technology
  - mDOM/WOM/dEgg → 3x Aeff
- total photo-effective area
  - ~ 38.400 DeepCore DOMs

Single-hit sensitivity scaling

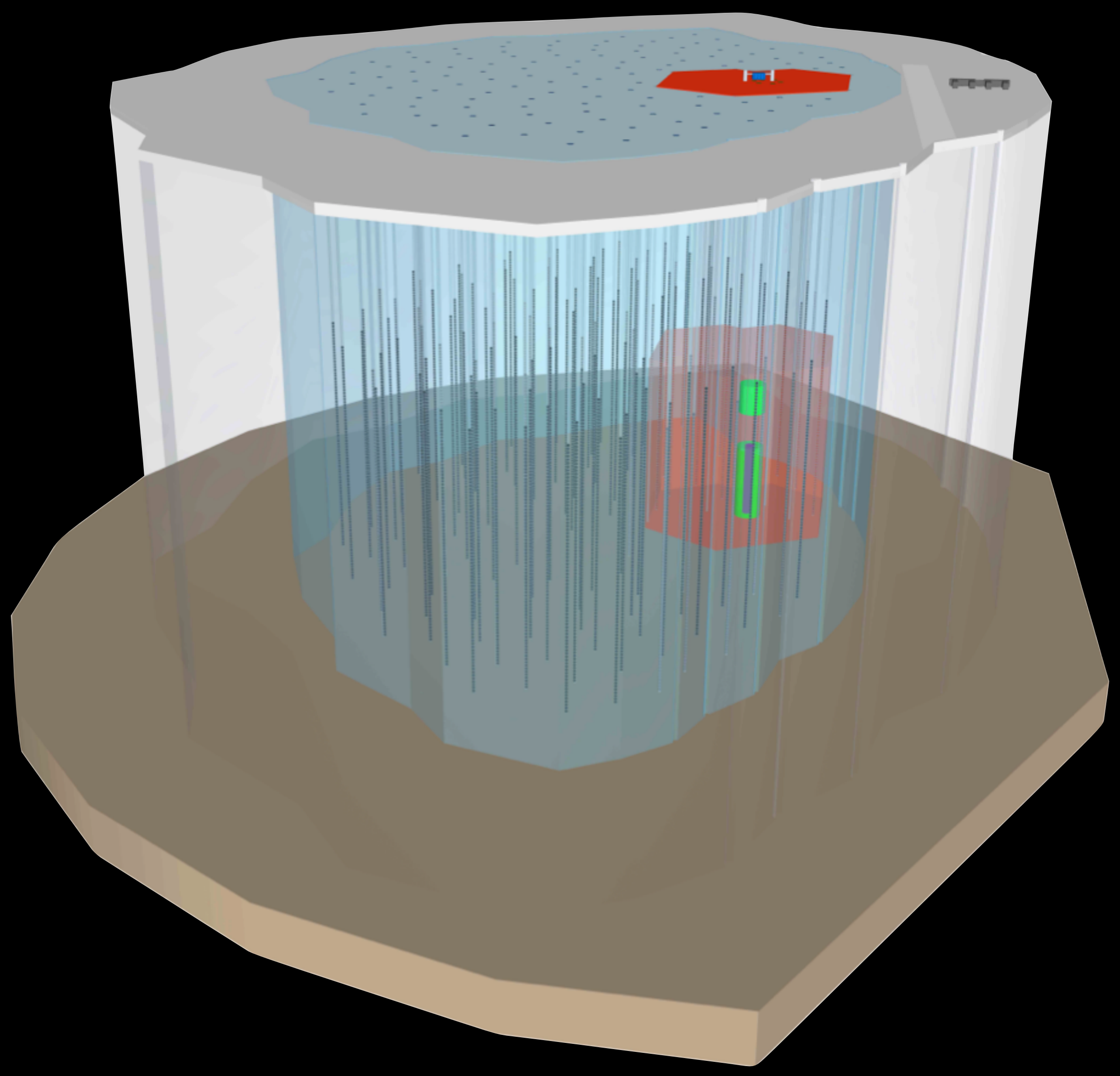
- effective mass 26Mton
  - reach about 150-200kpc

Nearest galaxies

- LMC @ 50kpc

⋮
void
⋮

- Andromeda M31 @780 kpc

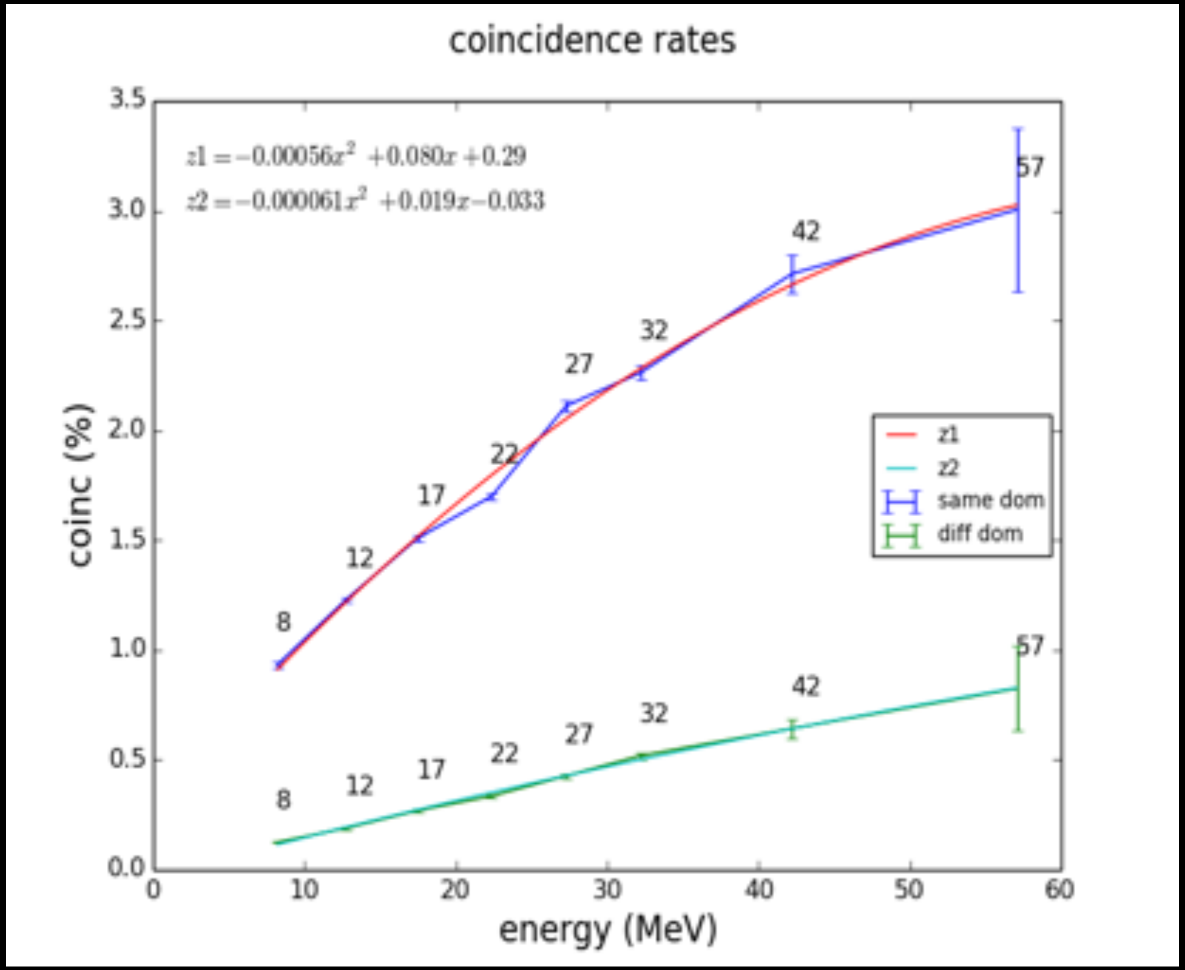


Classic IceCube SN scheme doesn't work!

Beating the noise…

IceCube DOM

- noise rate ~580Hz (pre-deadtime)
- coincidence chance for SN neutrinos: 2%



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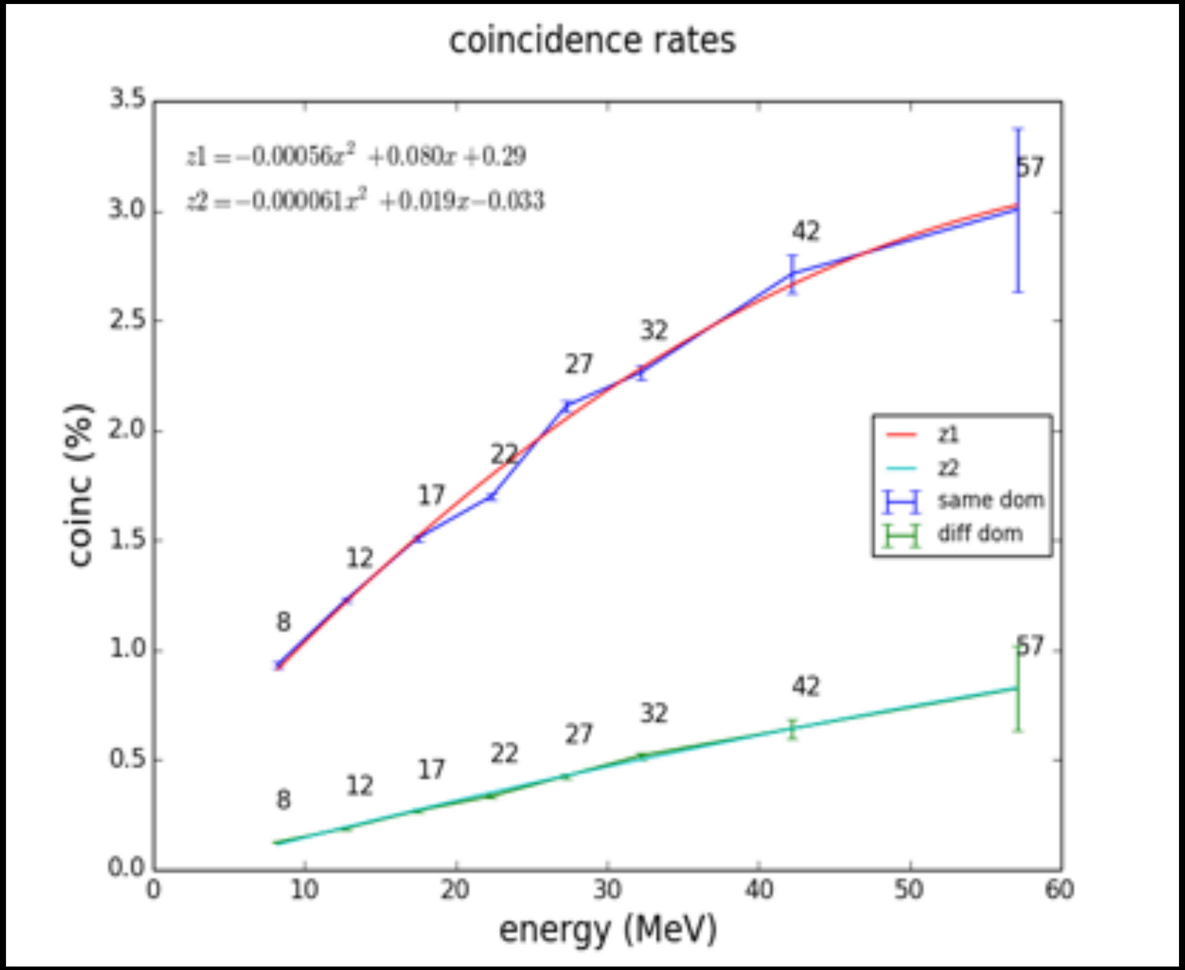
New sensors (A_{eff} x 3)

- coincidence chance for SN neutrinos: 6%
- assume noise rate 1.5kHz
- for 300ns window
  - random noise coincidences: 0.9Hz
  - S/N for 2 hit ~ 115·S/N for 1 hit

[similar study arXiv:1106.1937]



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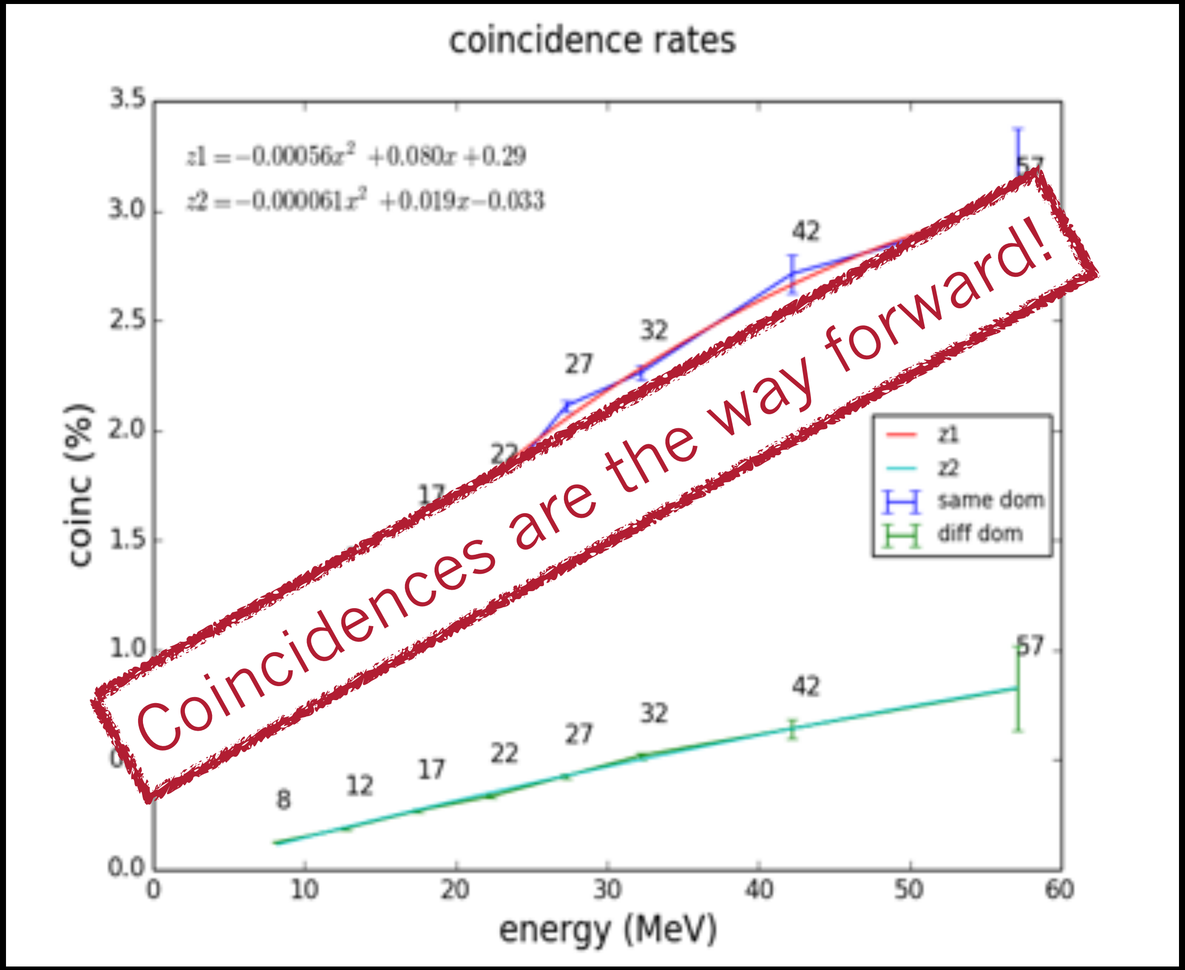

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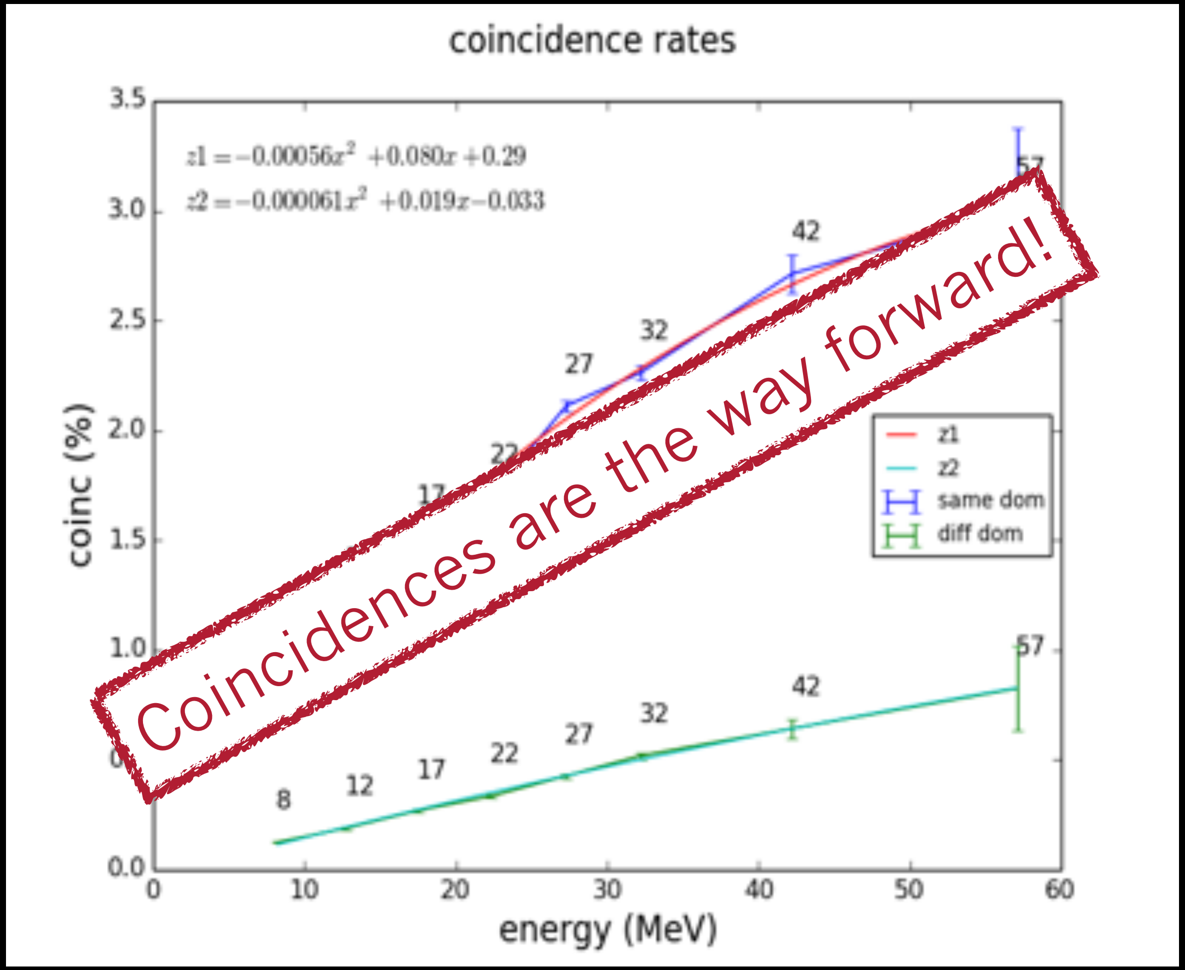

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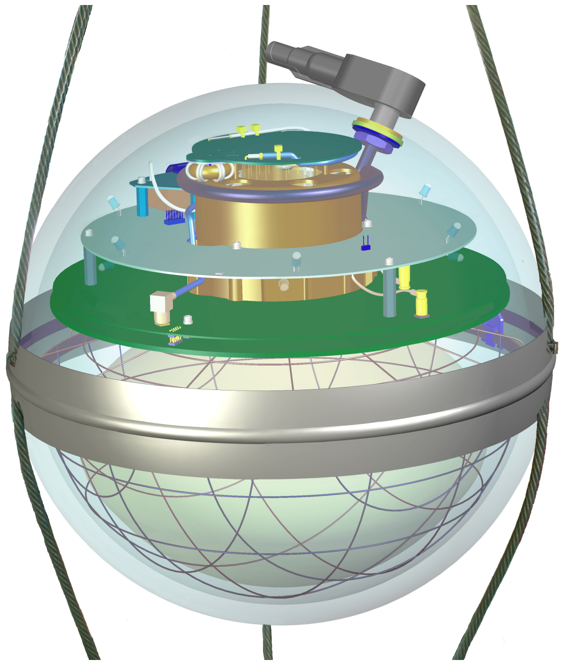
However...

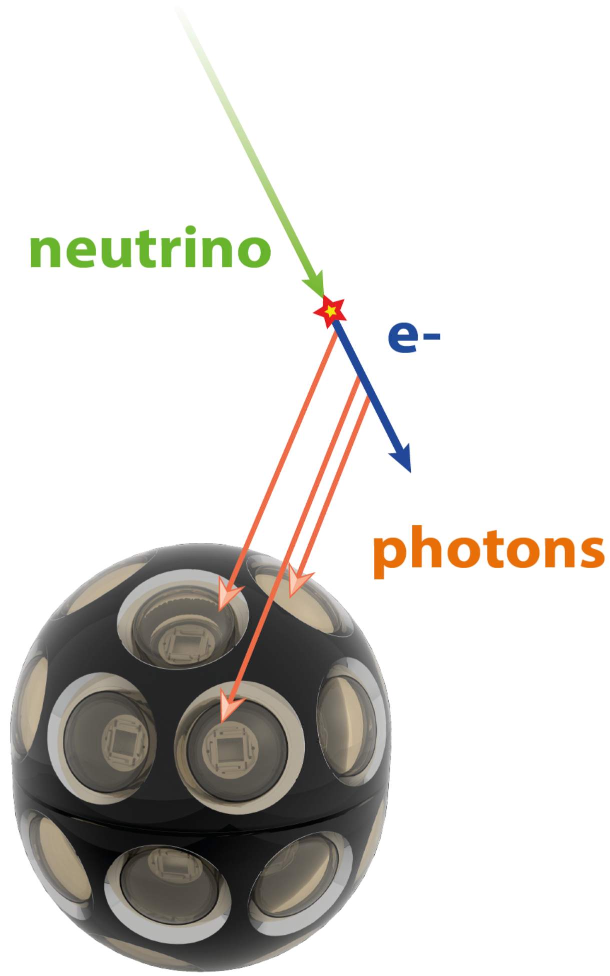
- correlated noise → simple scaling does not hold
- muon and other backgrounds → need to be rejected

The multi-PMT Optical Module (mDOM)



Features

- 4π angular acceptance
- Directional sensitivity
- Larger photocathode
- **Local concidences**



DOM

- 13 inch diameter
- One 10 inch PMT
  facing downward

mDOM

- 14 inch diameter
- 24 PMTs of 3 inch
  facing all directions

Galactic SNe with mDOMs

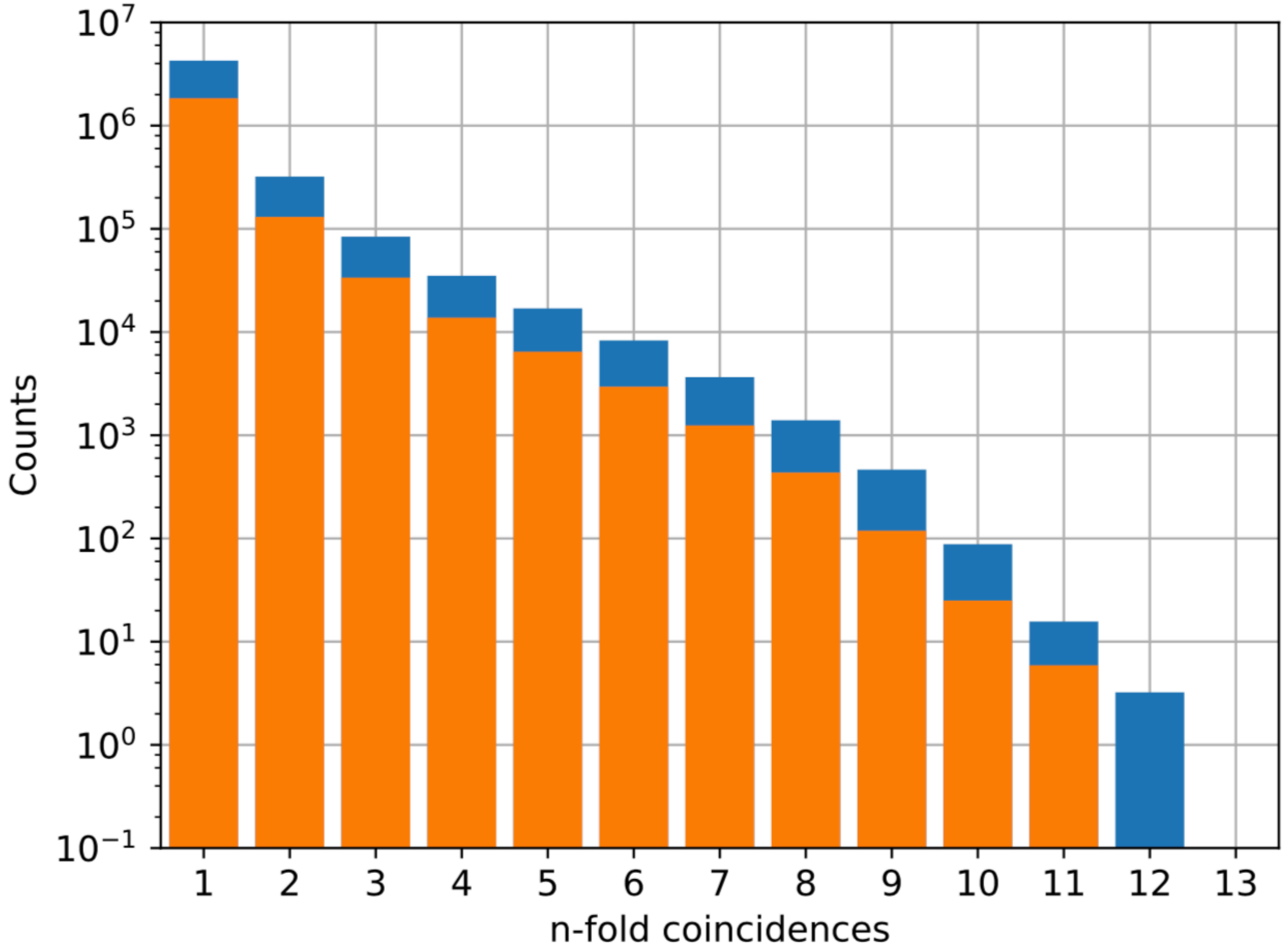
C. J. L. Mariscal, master thesis

IceCube-Gen2

- 10.000 mDOMs
  - each as individual detector

Local coincidences

- > 7% of events are detected in 2 or more PMTs
- 99% of coincidences occurs in less then 10ns
  - Use to define **trigger conditions**



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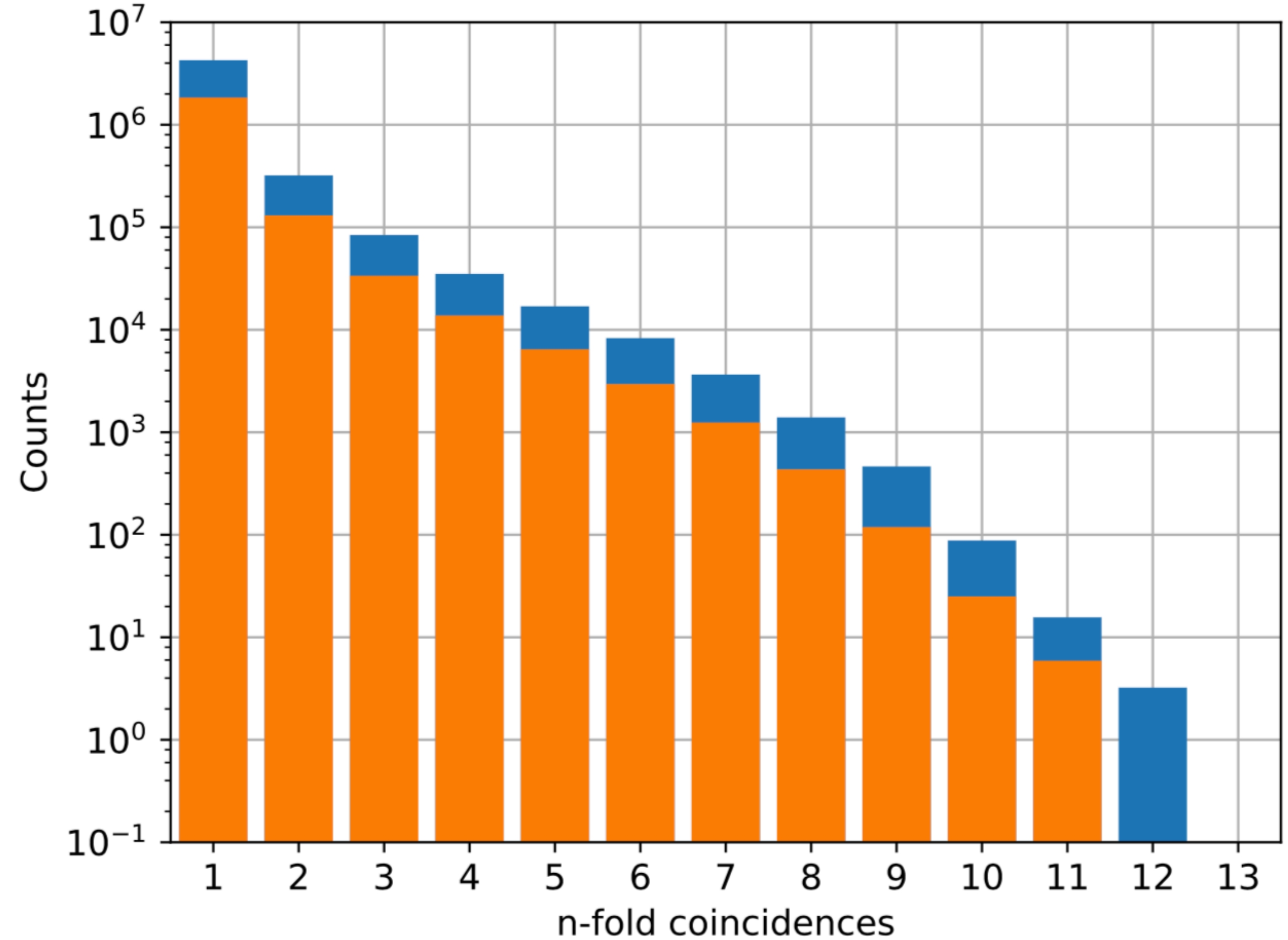


SN models (T. Janka et al)

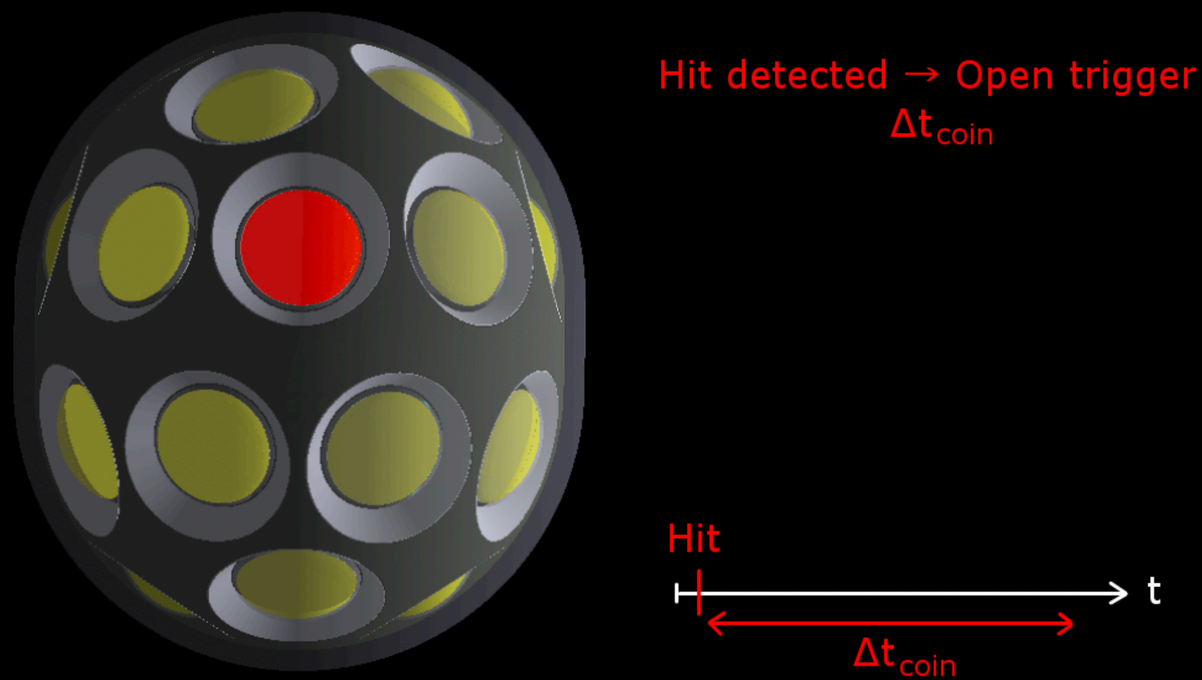
- LS220 EoS
- Heavy (27M$_\odot$) and light (9.2M$_\odot$)

	Heavy SN	Light SN
Detected events*	$(4.263 \pm 0.004)\times10^6$	$(1.842 \pm 0.002)\times10^6$
Coincident events (%)	7.53 ± 0.02	7.08 ± 0.02
R(10 ns) (%)	$\mathbf{99.2 \pm 0.1}$	$\mathbf{99.2 \pm 0.1}$

*Detected events in 1 PMT underestimated due limited size of simulation volume

Event trigger

- identify individual events
  - number of PMTs with hits n_{coinc}
  - in time window Δt_{coinc}



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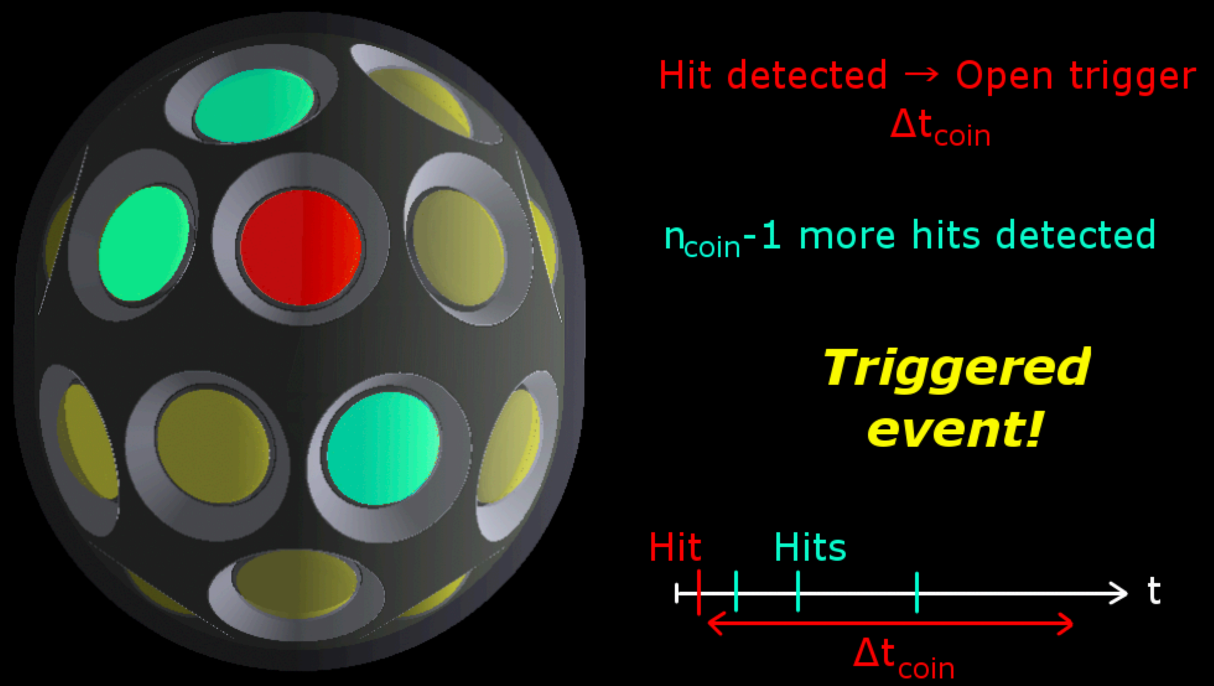

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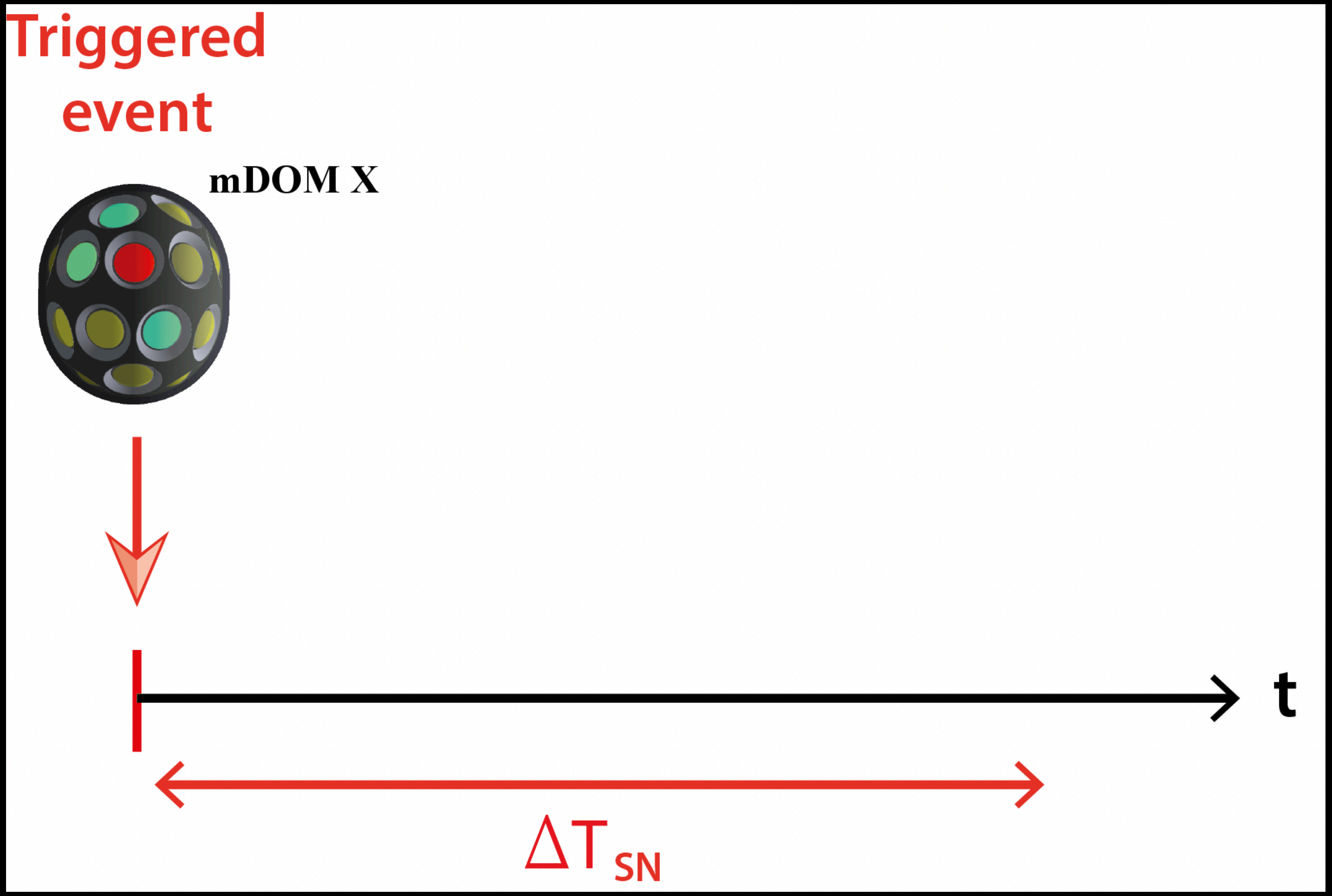
SN Trigger

- identify neutrino bursts
  - number of modules with local coincident N_{ν}
  - in time window Δt_{SN} = 10s



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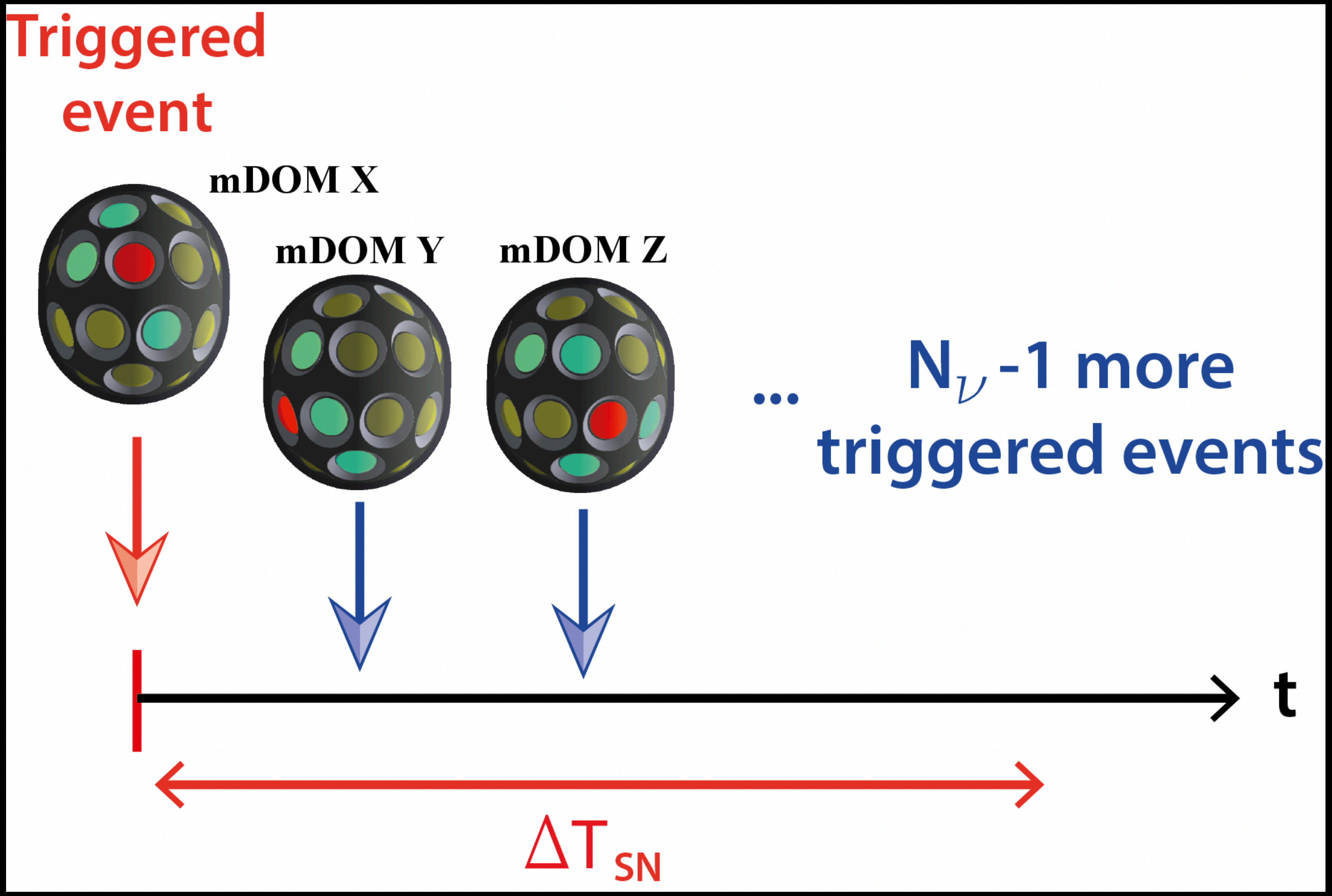
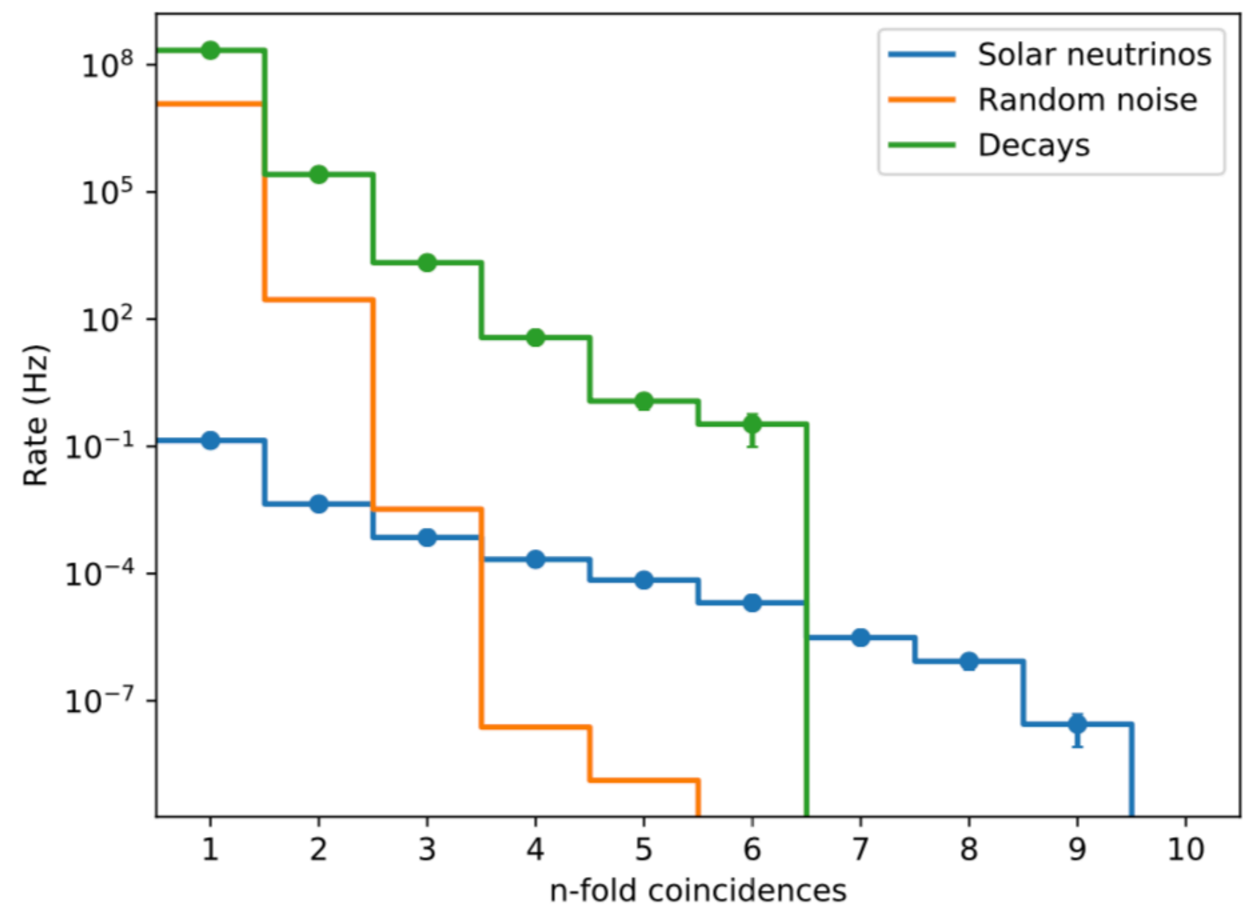


Backgrounds

Fake event sources

- Internal (PMT) dark noise
  - f_N = 50 Hz / PMT (1.2 kHz / mDOM)
- Radioactive decays
  - activity from measurements of glass samples
  - coincidences from detailed GEANT simulation
- Solar neutrinos
  - dominated by 8B flux ($\Phi_{\nu e}$=1.7 $\cdot 10^6$ cm^{-2} s^{-1})

	Activity [Bq/kg]
^{40}K	61.00
^{232}Th	1.28
^{235}U	0.59
^{238}U	4.61



Results with Gen2 / mDOMs

Adjust N_ν and n_{coin} for

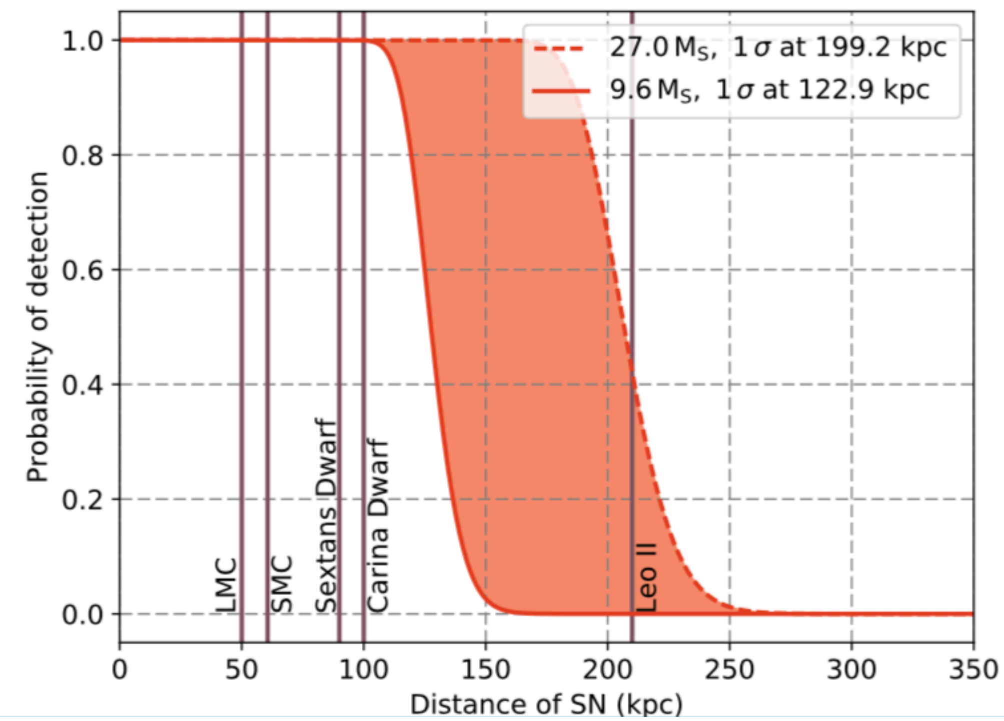
- SN detection range
- Fake SN rate
  - SN trigger from non-SNν (noise/BG) events

n_{coin}	N_ν	False SN rate (year^{-1})	1 σ detection distance (kpc) Heavy SN	Light SN
5	36	1.130	209.6	129.4
	40	0.010	199.2	122.9
	42	<0.001	194.5	120.0
6	18	1.082	205.1	122.5
	20	0.035	195.0	116.4
	22	<0.001	186.2	111.2

- More than 1 fake detection per year
- $\sim$ 1 fake detection in 100 years
- Less than 1 fake detection in 100 years

SN detection range

- $n_{coin} = 40$, $N_\nu = 5$
- **2-3 SNe / 100yrs**
- **1 fake / 100 yrs**



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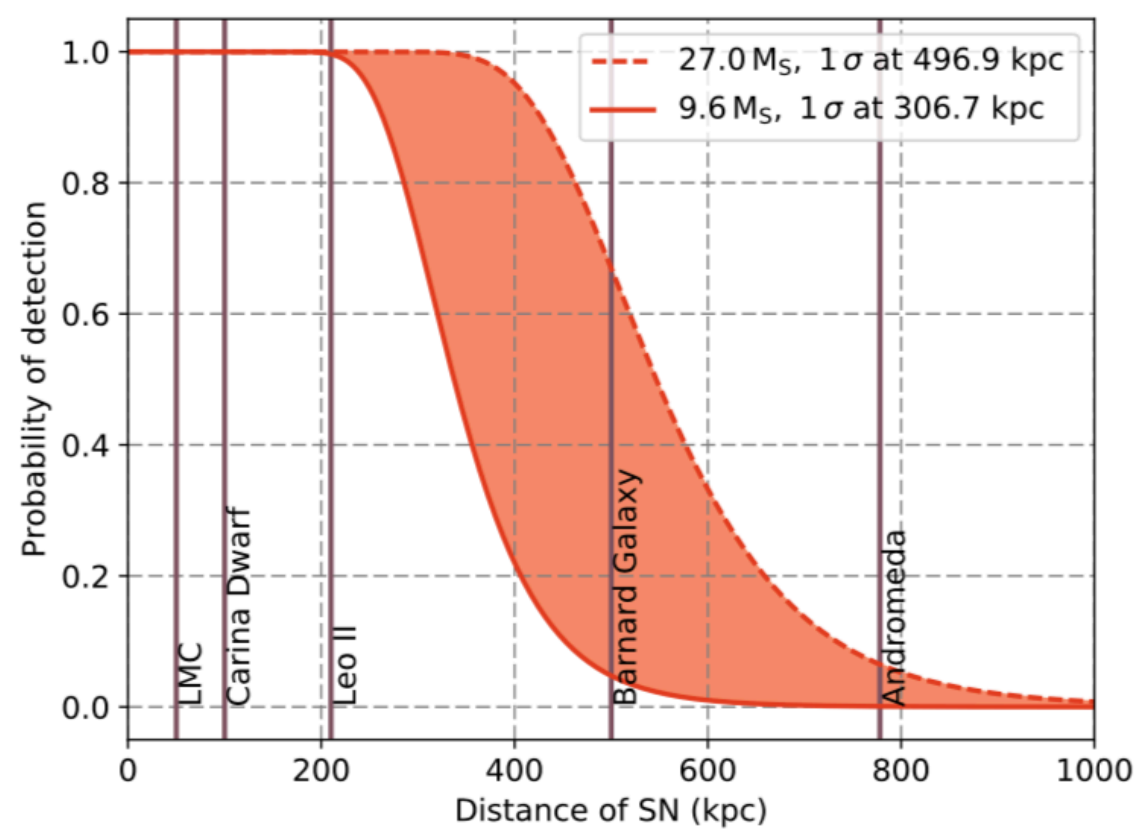
Reduced noise

- low-radioactivity glass (100x less ^{232}Th)

SN detection range

- $n_{coin} = 5$, $N_\nu = 6$
- **4-6 SNe / 100yrs**
- **6 fake / 100 yrs**



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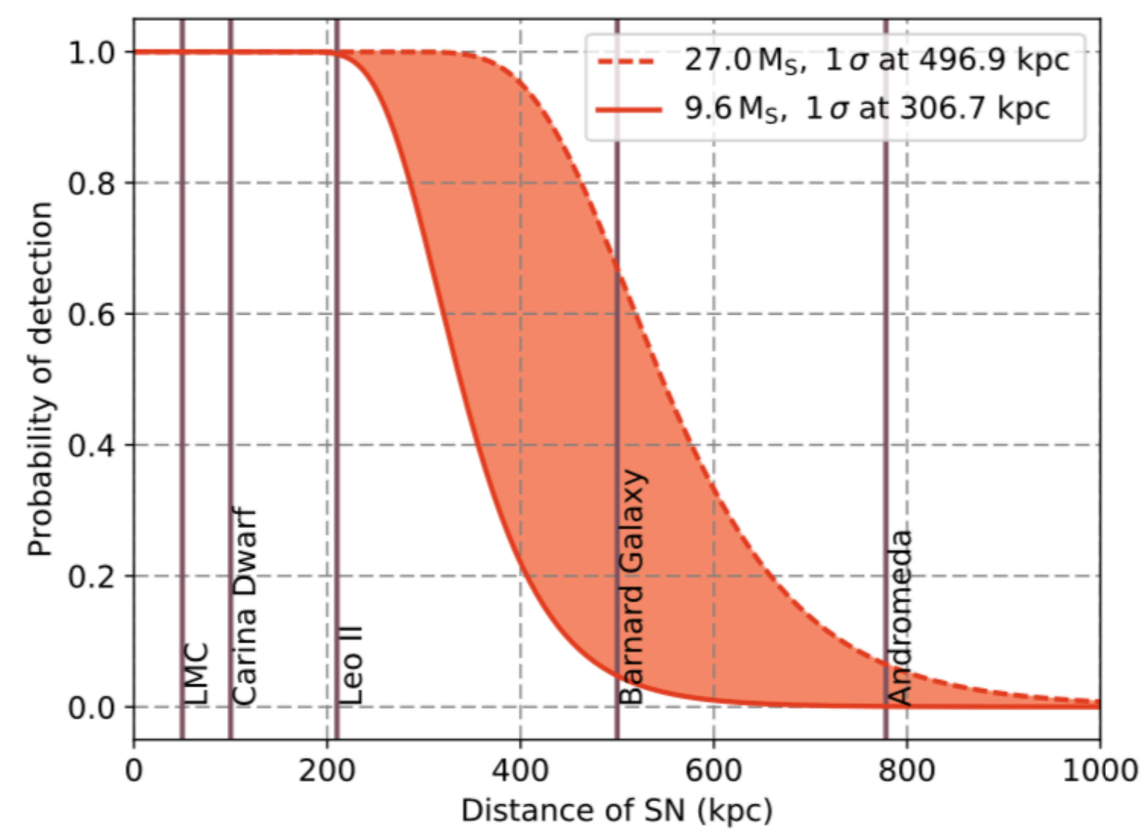
SN detection ran[illegible]

- n_{coin} [illegible]
- [illegible] / 100yrs
- 6 fake / 100 yrs

No routine SN detection with IceCube-Gen2 !



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Detecting *more* supernovae in neutrinos

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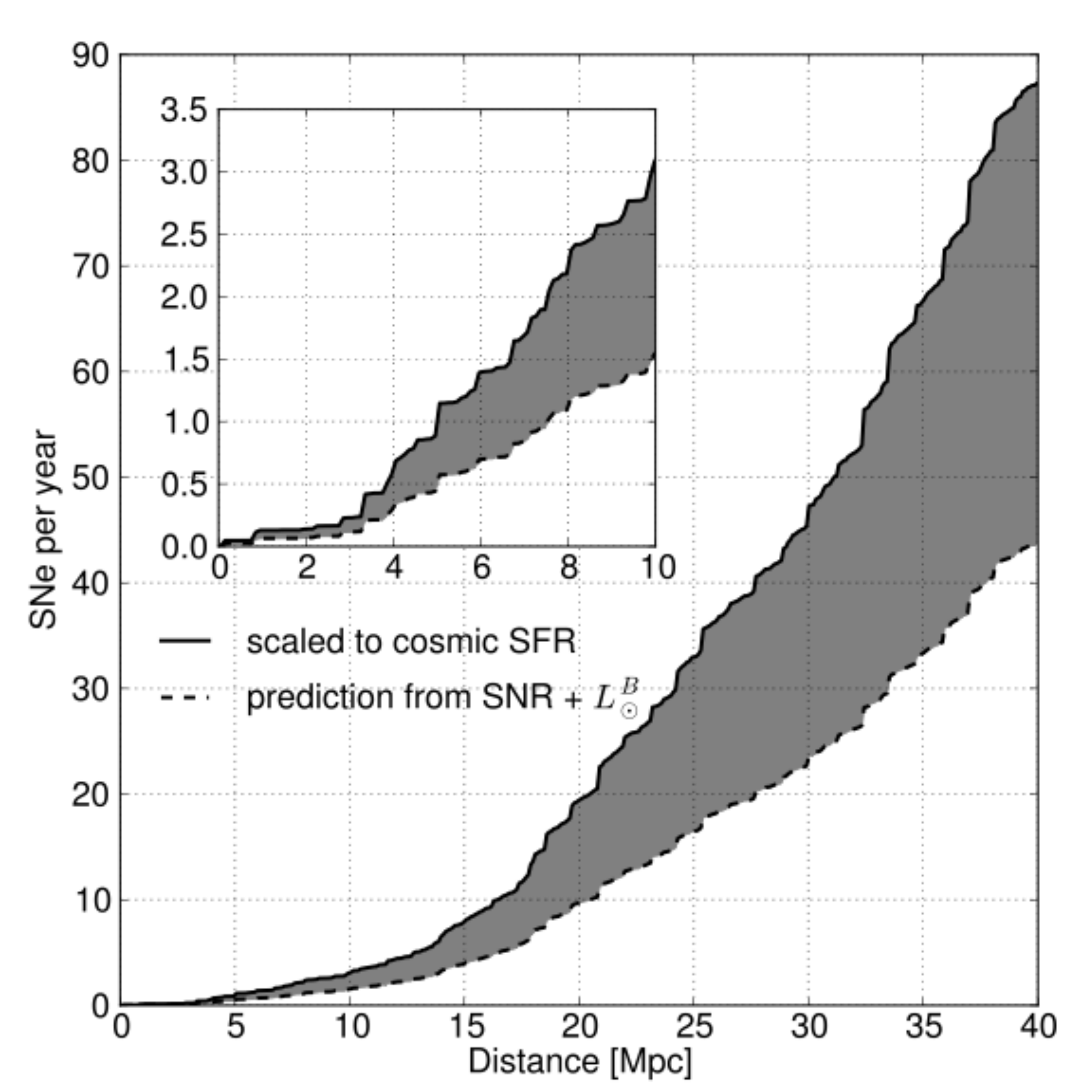
  - expected rate:
    1-2 SNe **per century!**

Goal

- routine SNe Detection
  - use coincident hits



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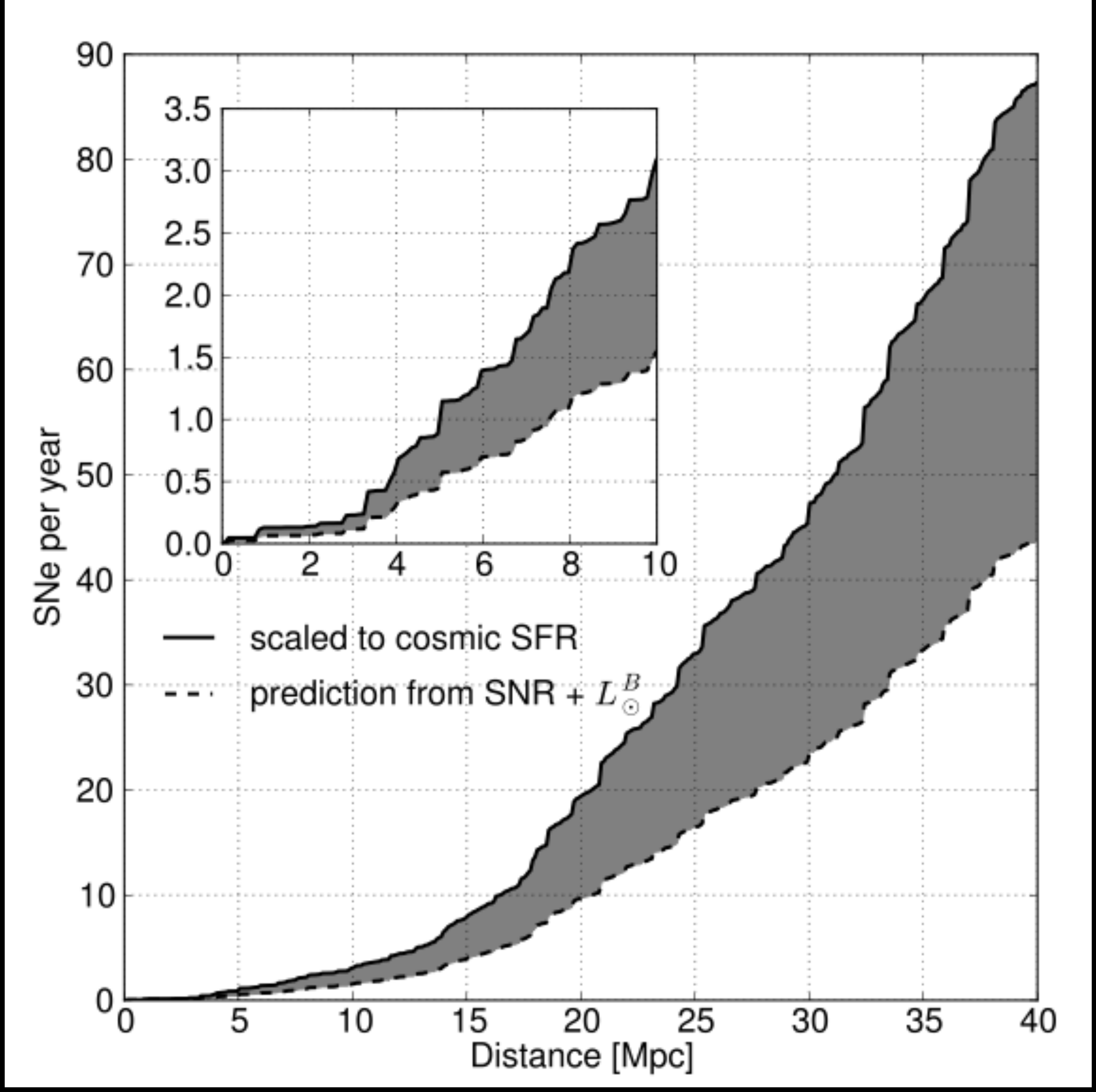
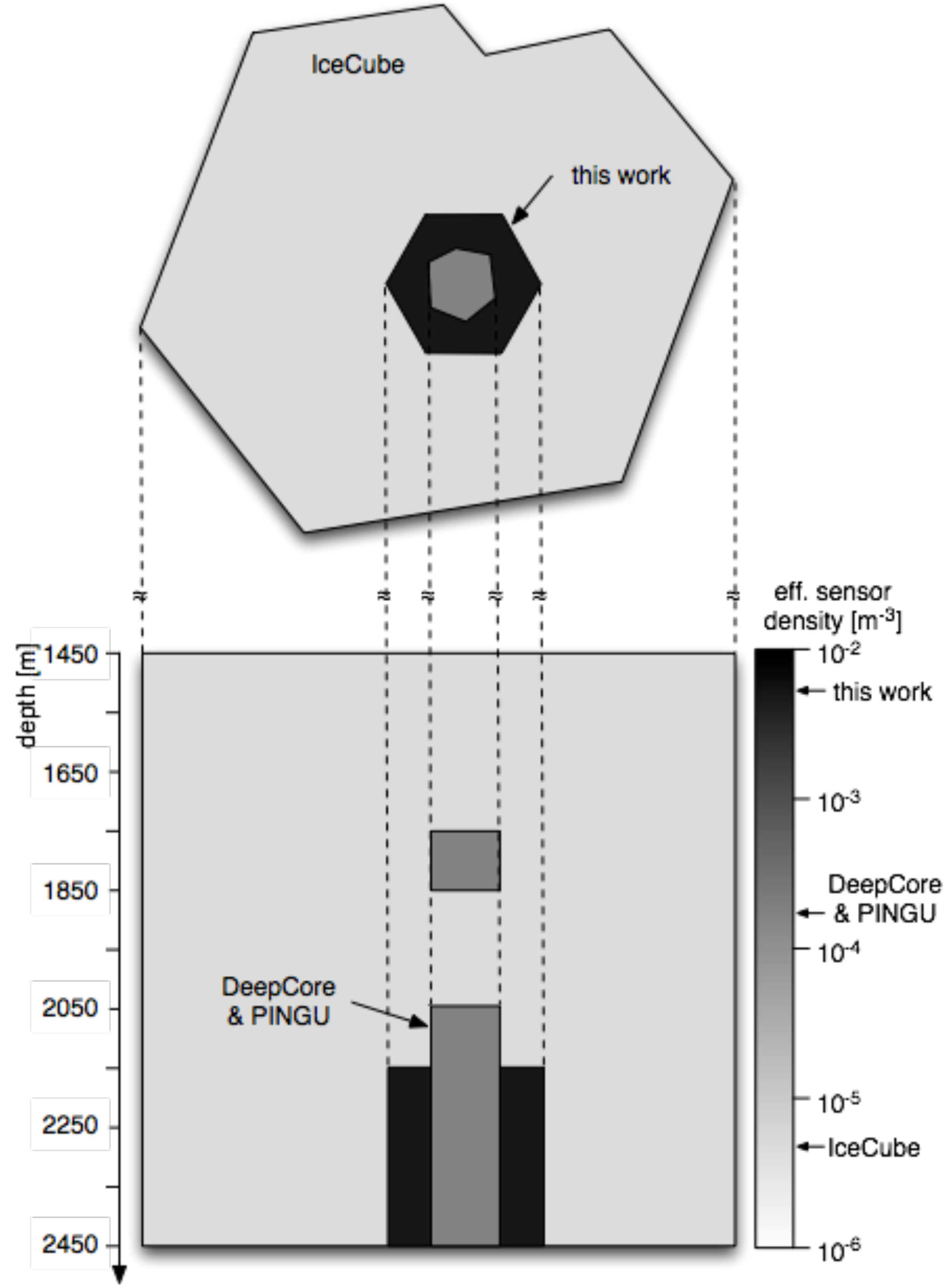


MICA — Megaton Ice Cherenkov Array

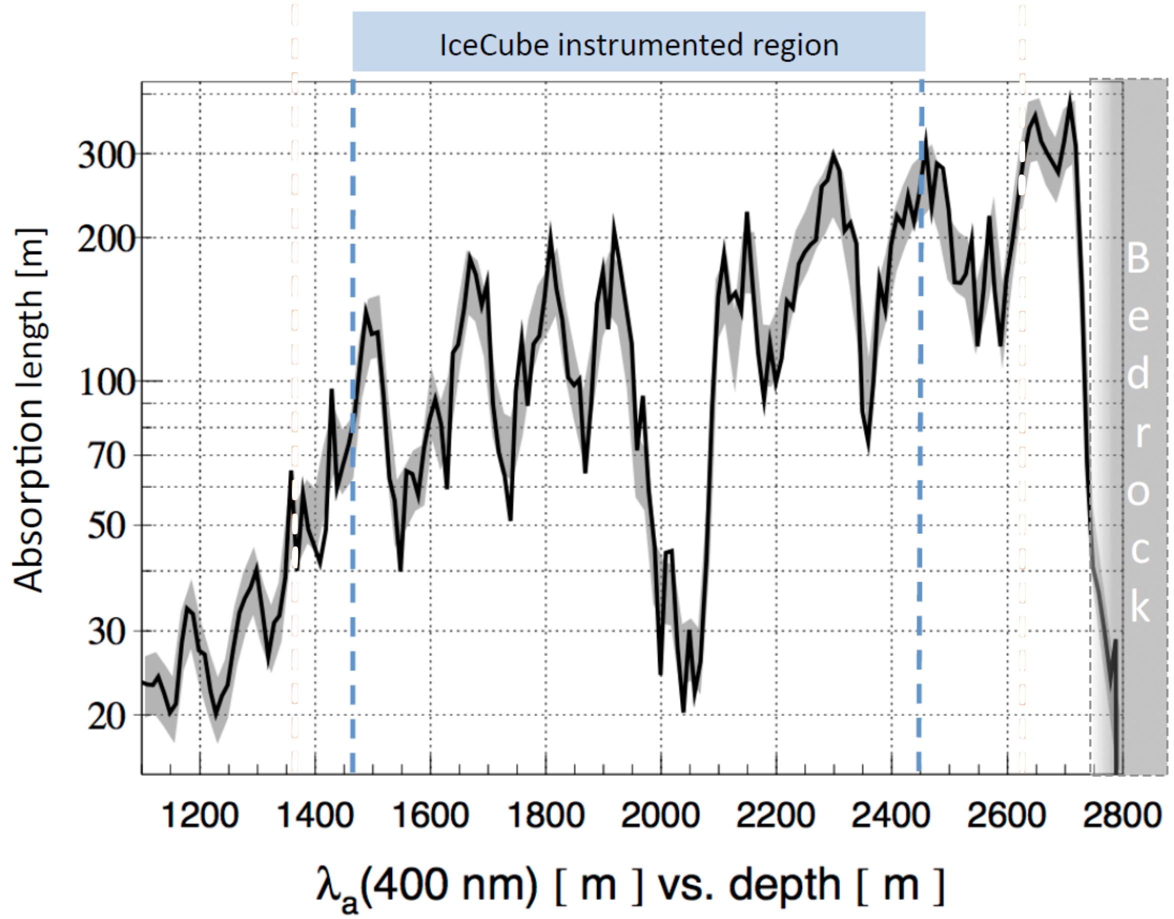
Geometry

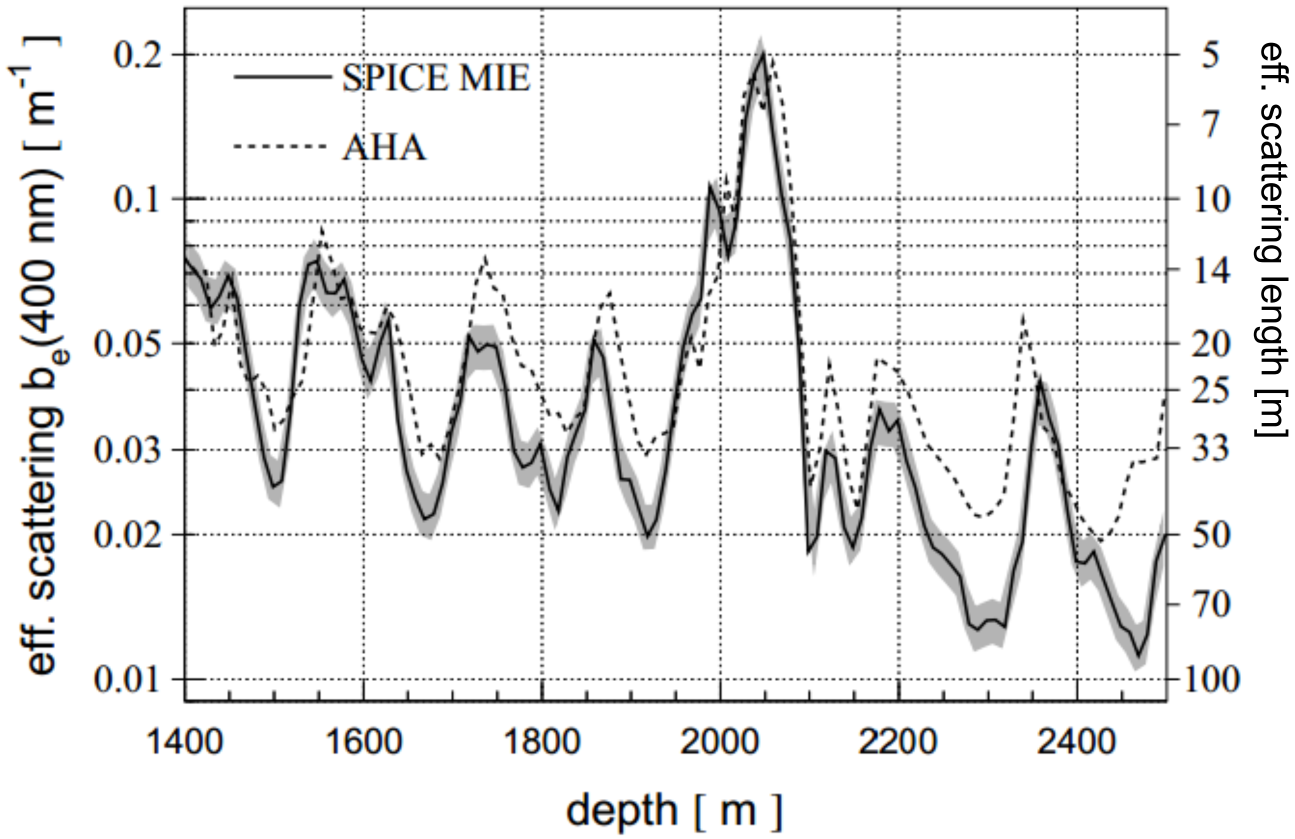
- 127 string
- 2150-2450m depth (clearest ice)
- 300 optical sensors / string
  (one per meter)



[S.B, M. Kowalski, et al.,
J. ApP 62 (2015) / arXiv:1304.2553]

Ice properties

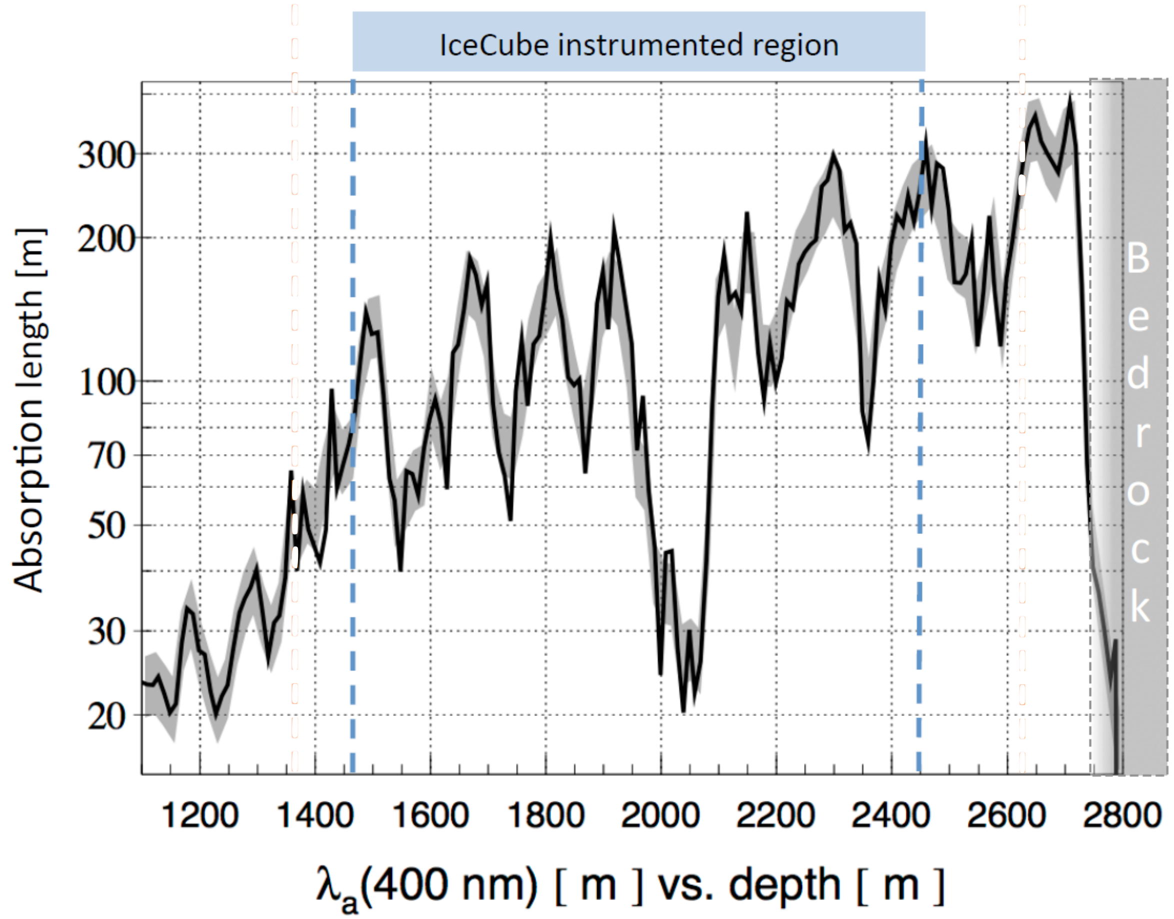


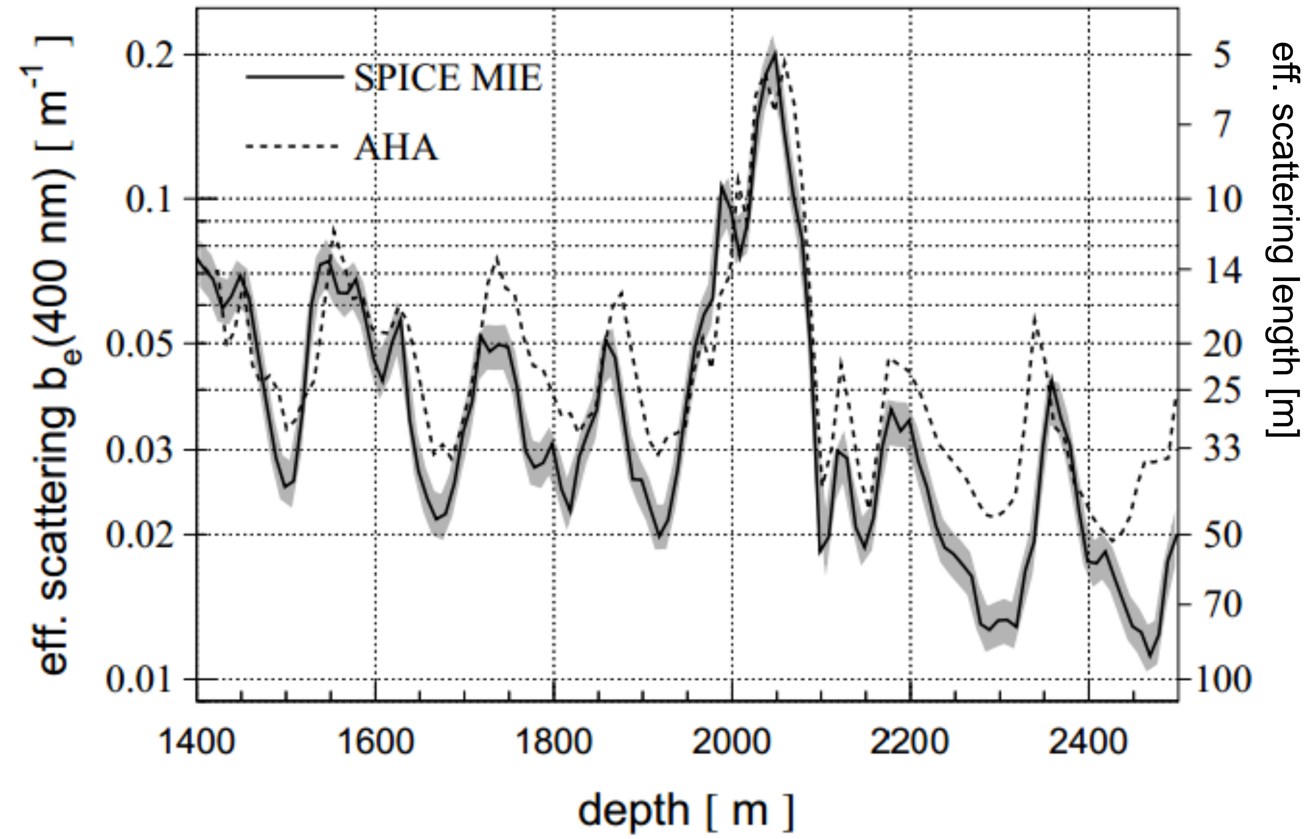


South Pole ice cap

- temperature profile
  -55°C(top) to -10°C (bottom)
- very low radioactivity
  - A ~ Ø(Bq/m³)
- dust layers
  (e.g from volcanic ash)

Ice properties





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Light propagation

- scattering / absorption
  - optimize for photon yield

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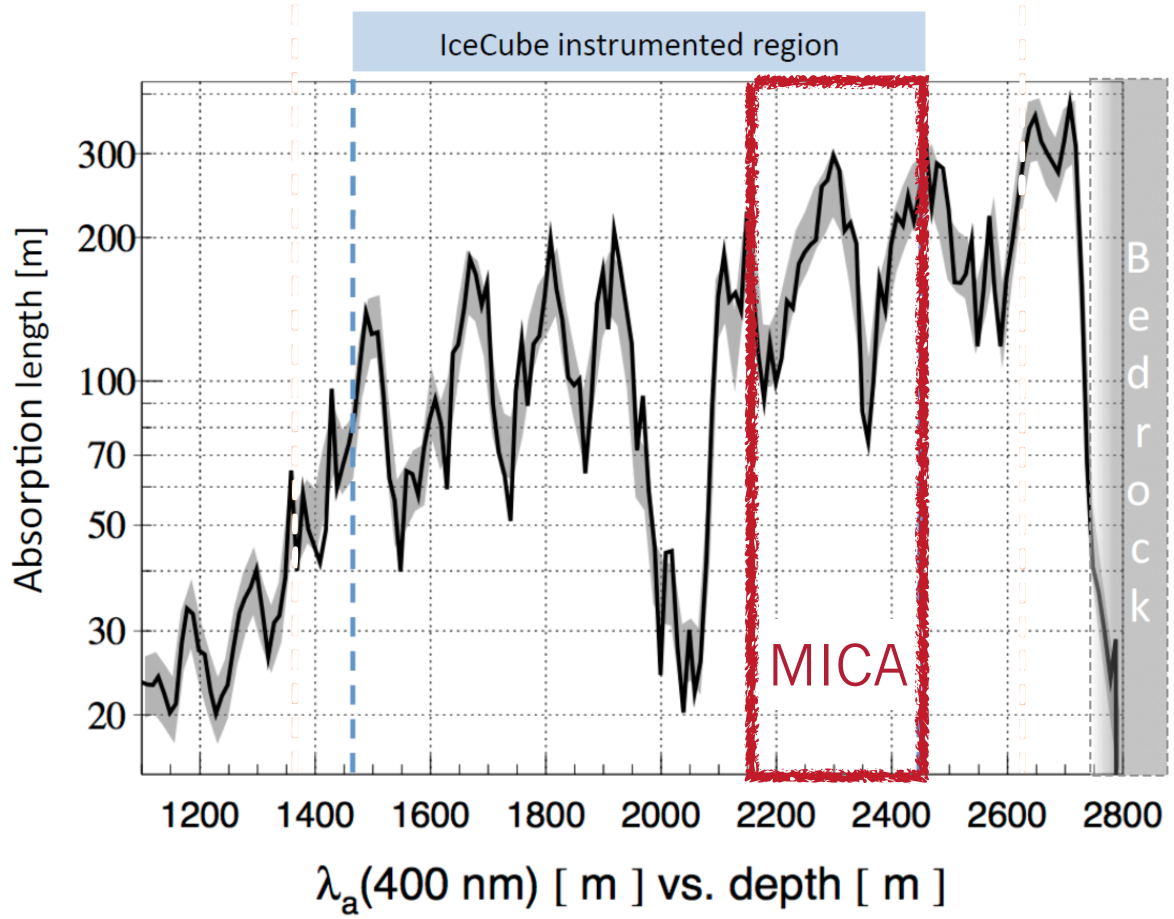

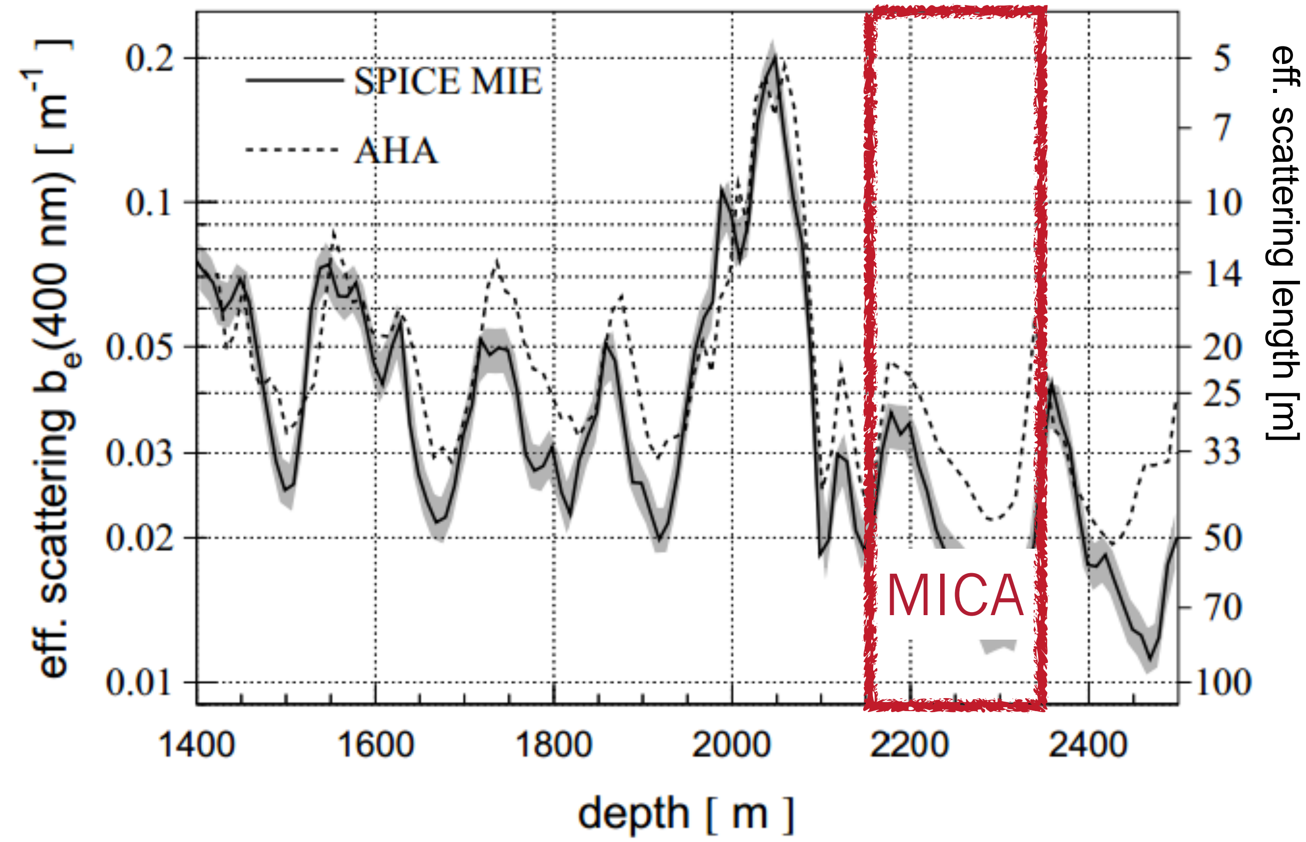

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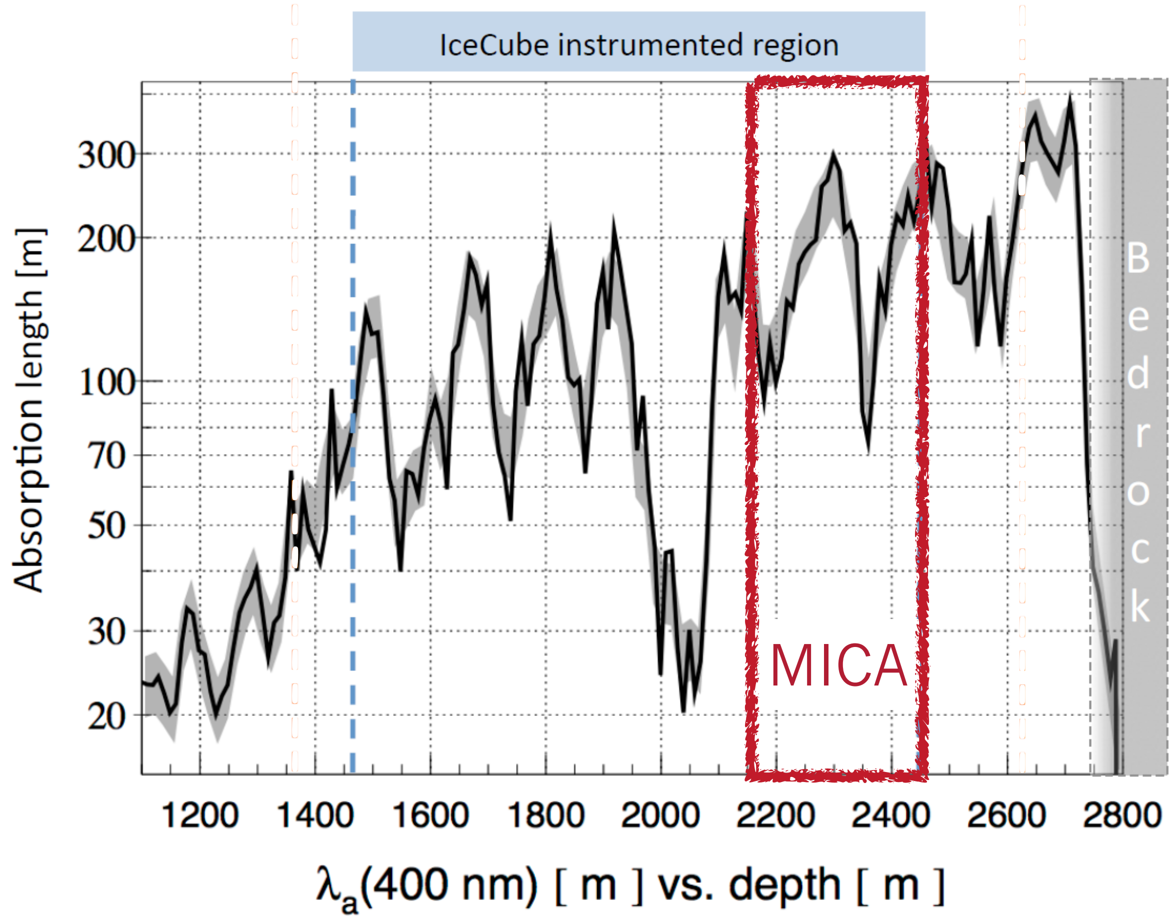

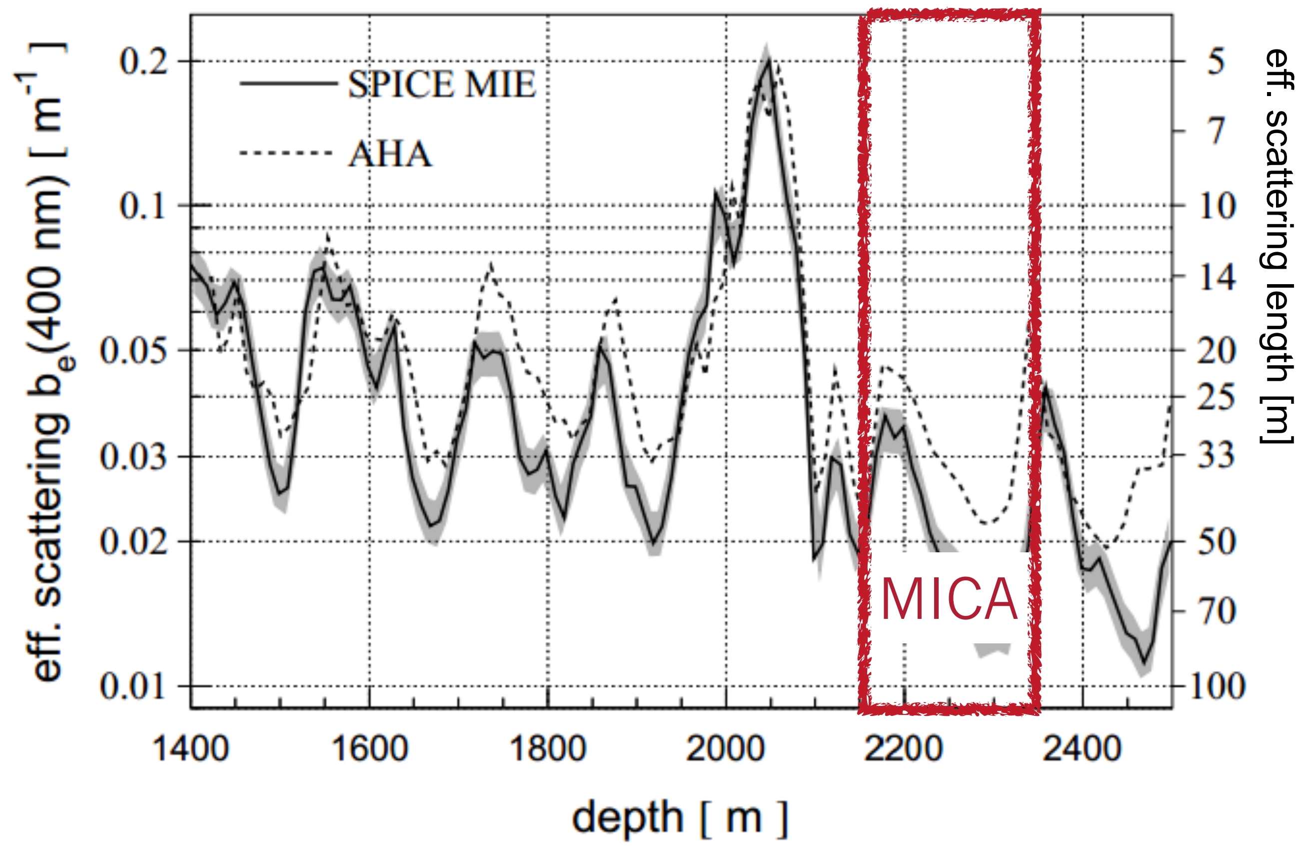

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Alternative location: 750-1050m

- absorption **λ_{abs} = 350m**
- scattering **λ_{scat} = 0.3m**

MICA — Megaton Ice Cherenkov Array

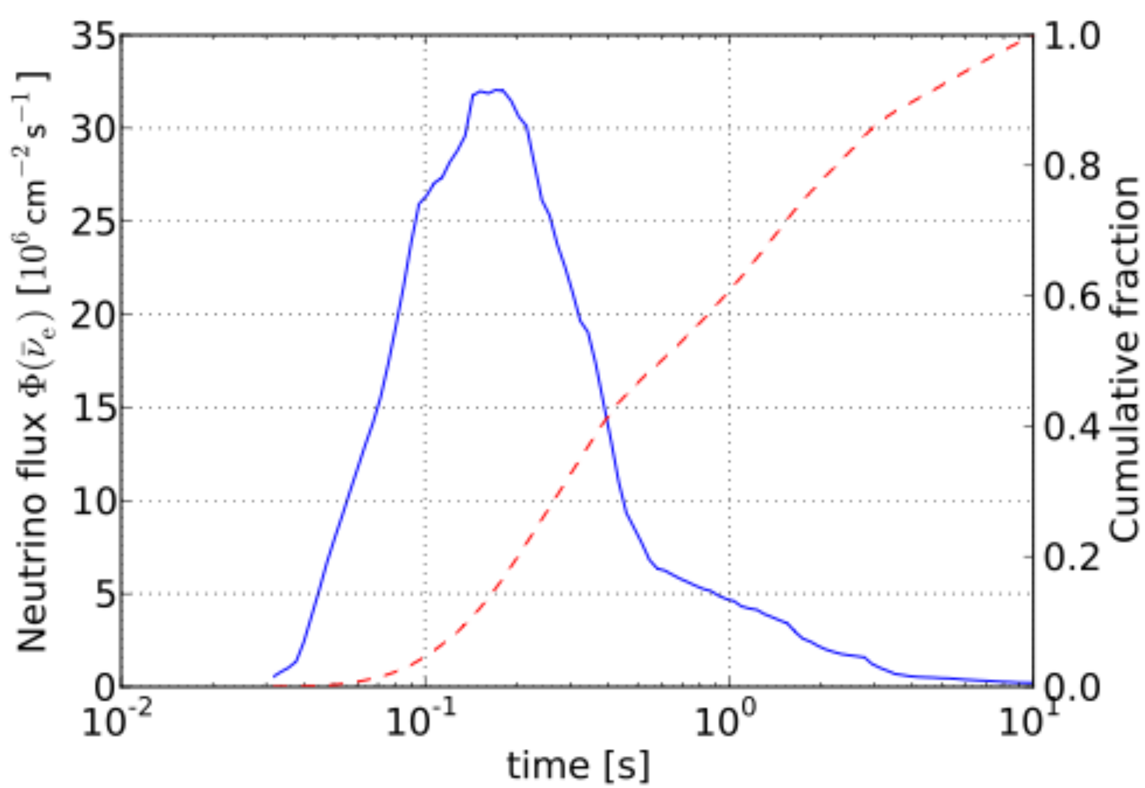
SNe trigger

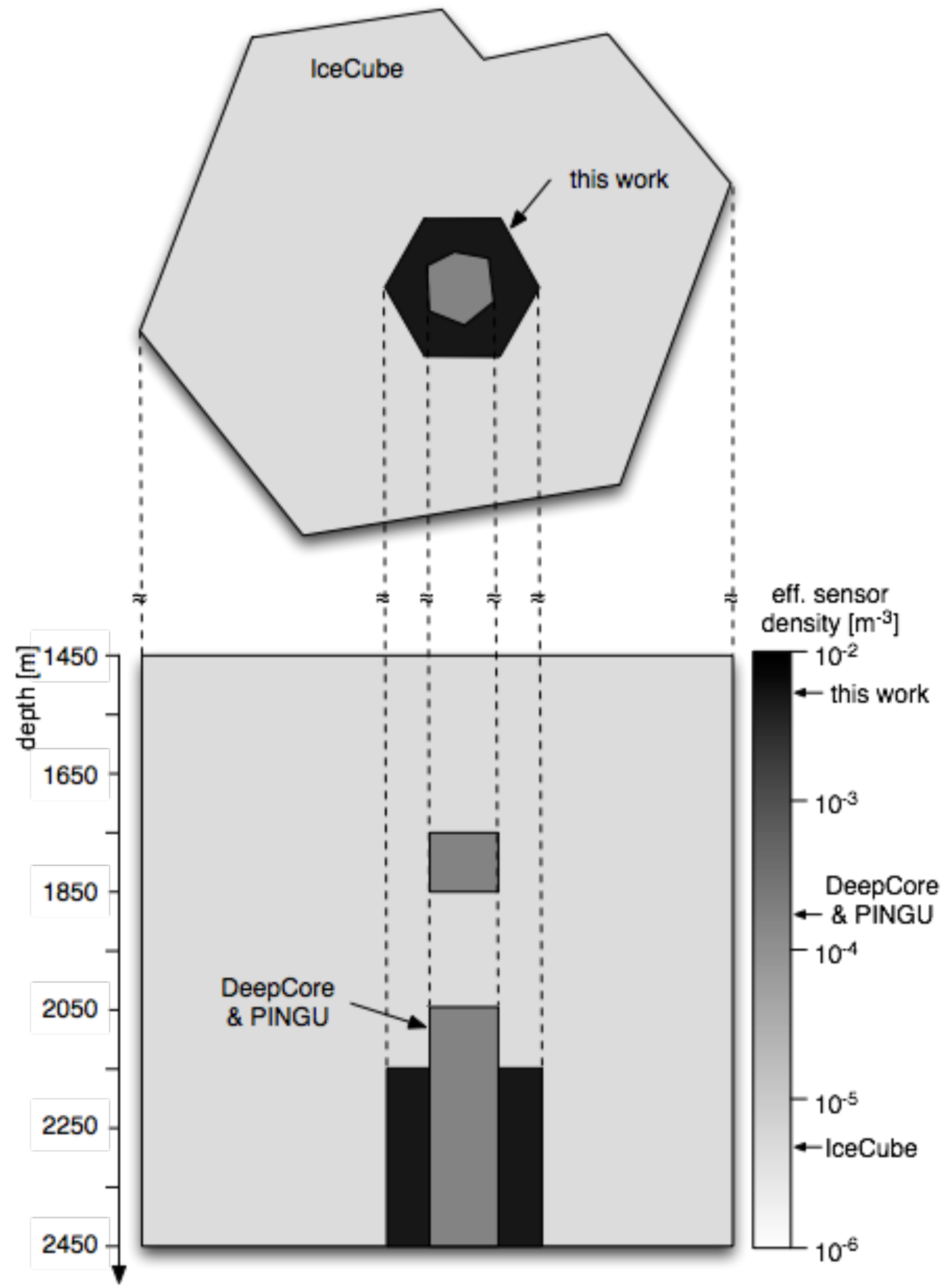
- require $N_\nu = 3$, $\Delta t = 10$s

$$R_{\rm SN}^{\rm fake} = f_{\rm noise}\left(1 - P_{\rm CDF}(N_\nu - 2, \mu = f_{\rm noise}\Delta t_{\rm SN}\right)$$

Backgrounds

- less than 1 fake SN trigger / year
  - **less than 1mHz fake ν-triggers**





Sensor noise

Neutrino event trigger

- require 5 hits in Δt_{coinc}

Sensor self noise f_{module}

- fake trigger rate f_{noise}
  - need to reject noise hits !

f_{module}	f_{noise}	Δt_{coinc}
500 Hz	19 MHz	1000ns
10 Hz	247 Hz	1000ns
target	0.001 Hz	1500ns

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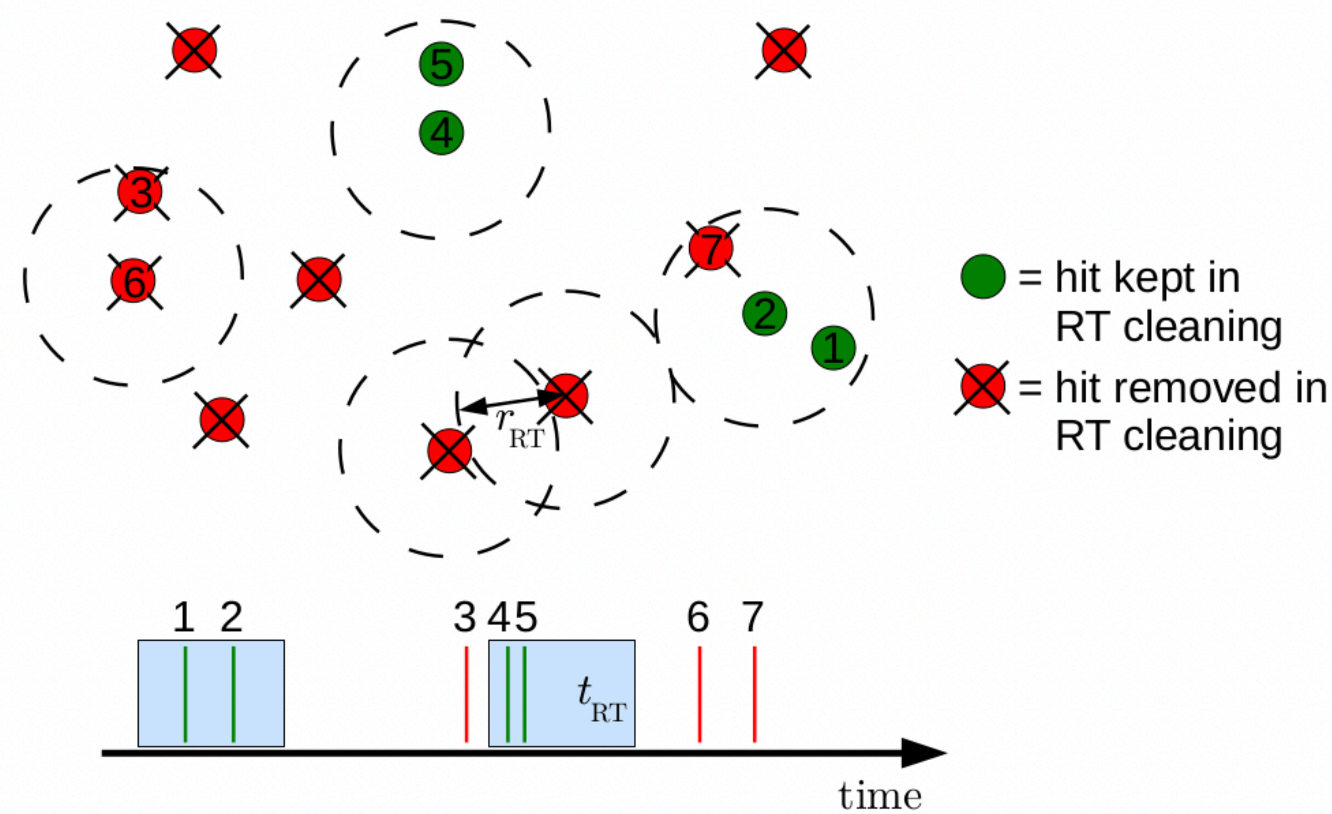
Radius-time cleaning

- exploit local coincidences
  - **between** modules (c.f mDOM)



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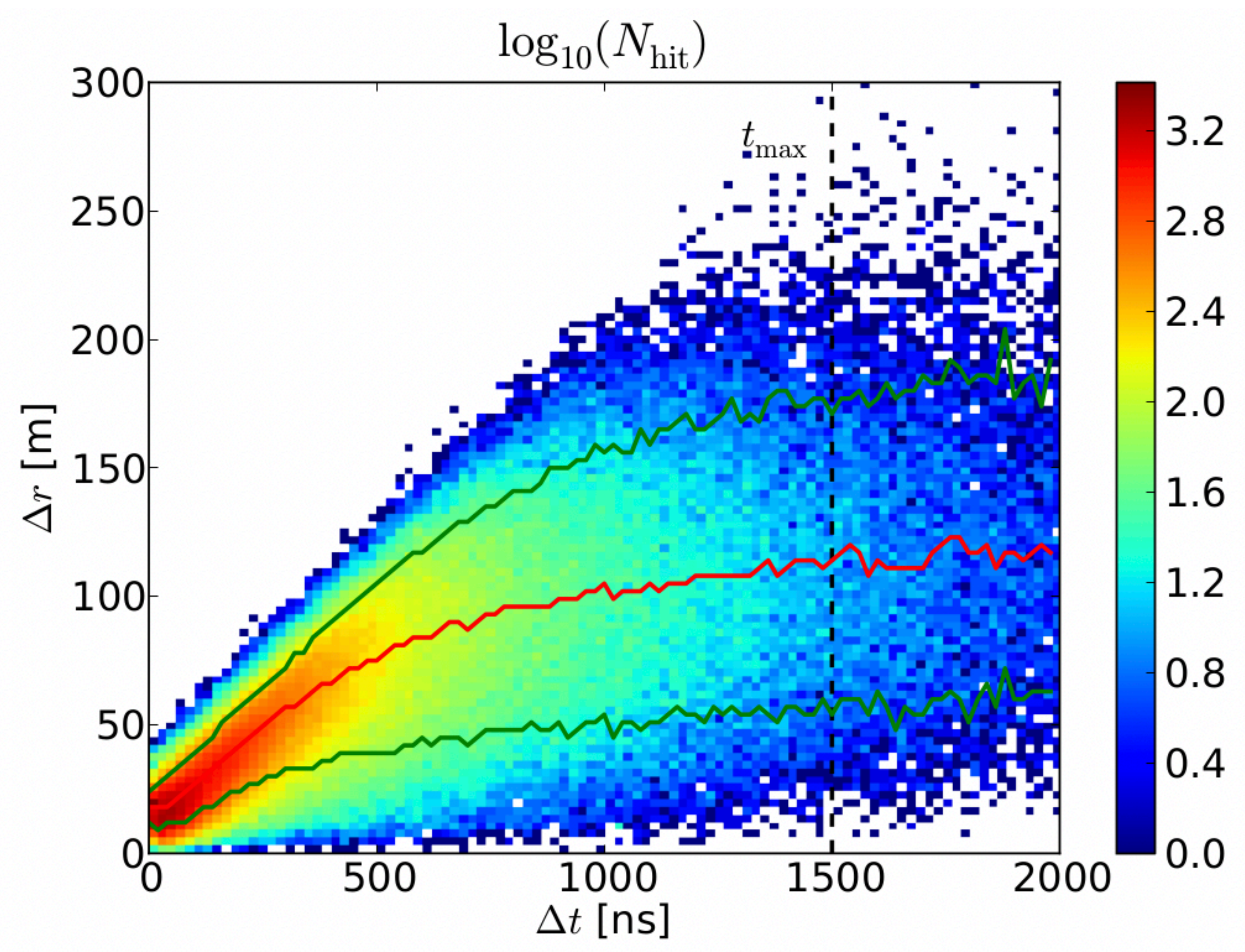
Phase-space cut

- exploit photon propagation
  - reject **too slow** and **too fast** hits w.r.t reconstructed vertex
  - adjust t_{coinc} for f_{noise} = 1mHz



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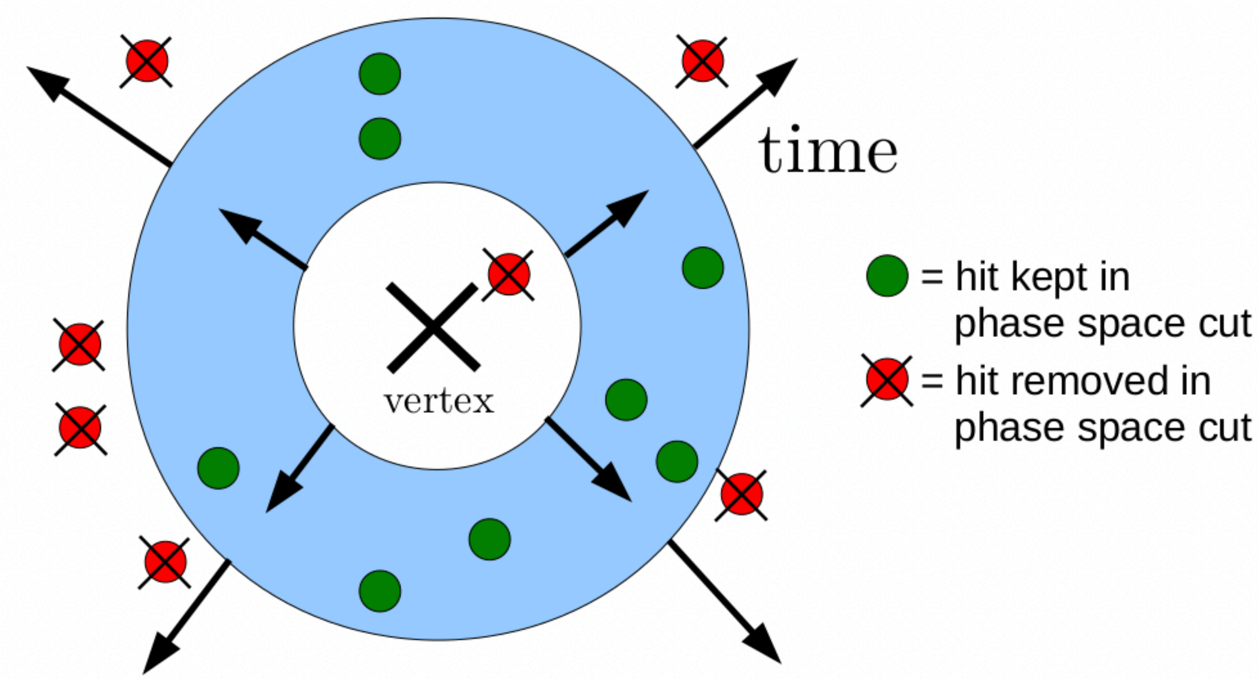
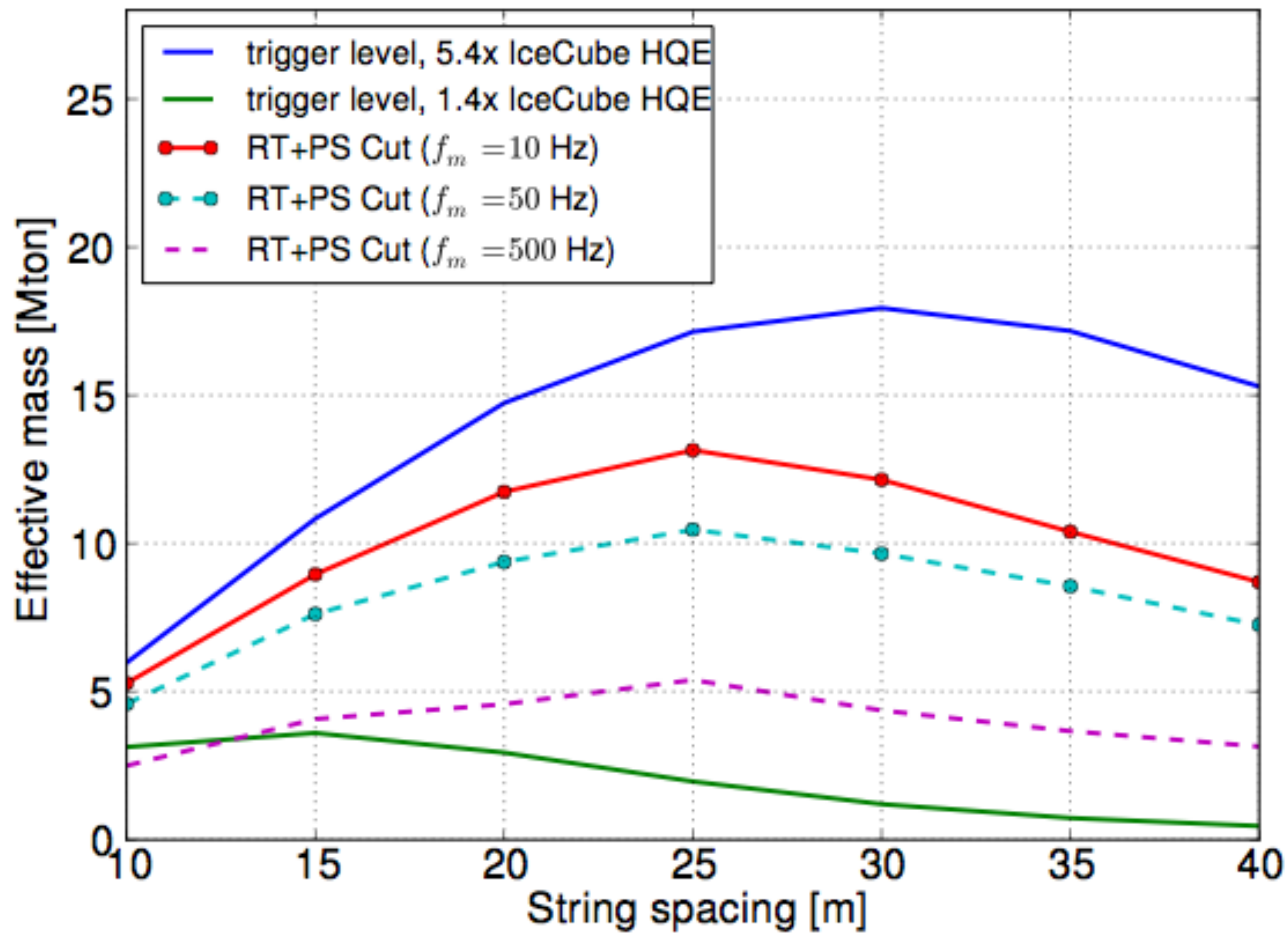


MICA sensors and self noise

Topological cuts

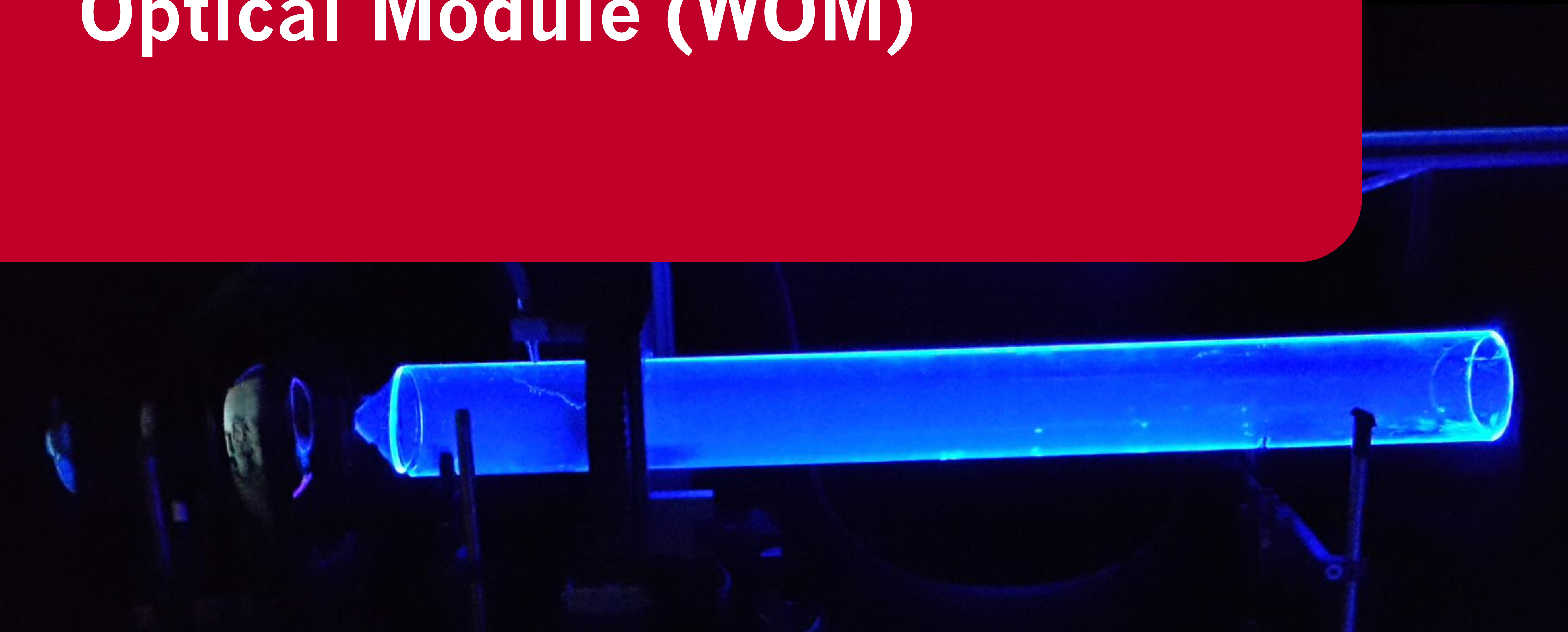
- adjust for 1mHz fake ν-triggers



Sensor requirements

- need **~100cm² eff.** photon sensitive area per meter of instrumented string
- at a self **noise rate of < 50Hz** per meter

Interlude:
The Wavelength-shifting Optical Module (WOM)



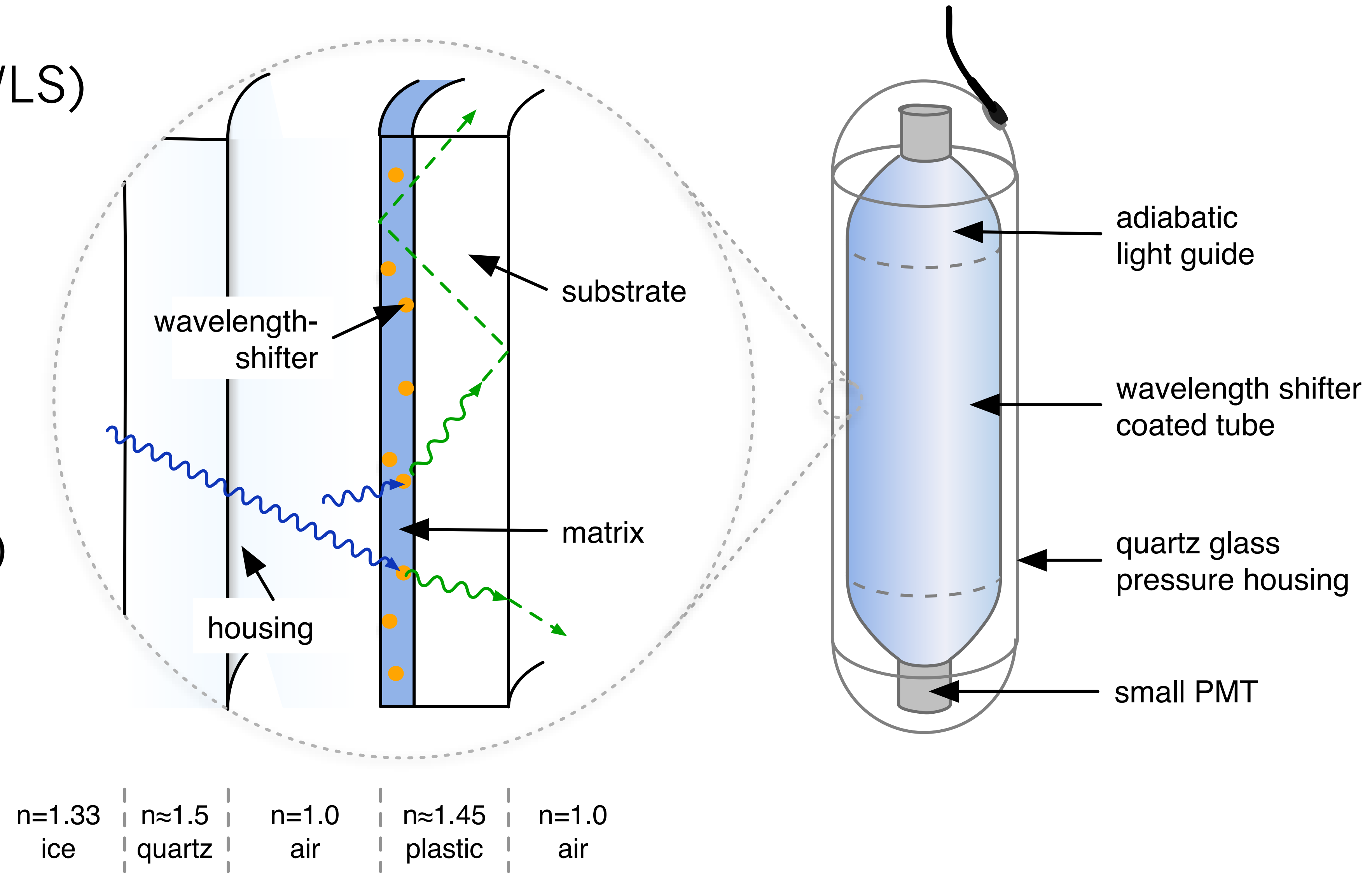
Wavelength-shifting Optical Module (WOM)

Basic concept

- Wavelength shifters (WLS)
  - concentrate light

Features

- large collection area
- better UV sensitivity
- low noise rate (few Hz)
- cost effective



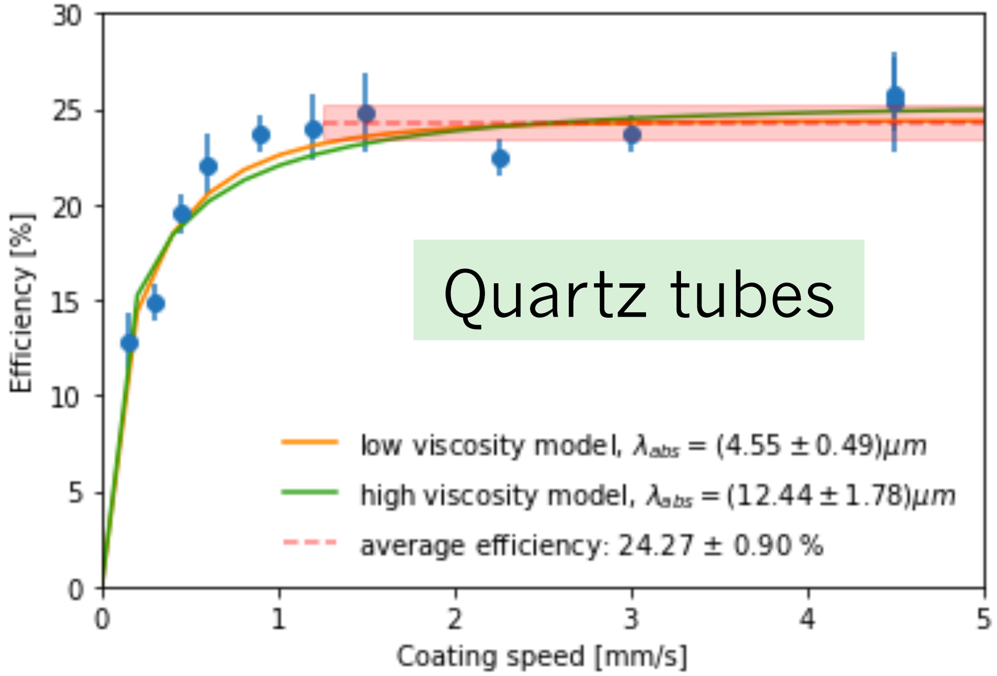
WOM manufacturing

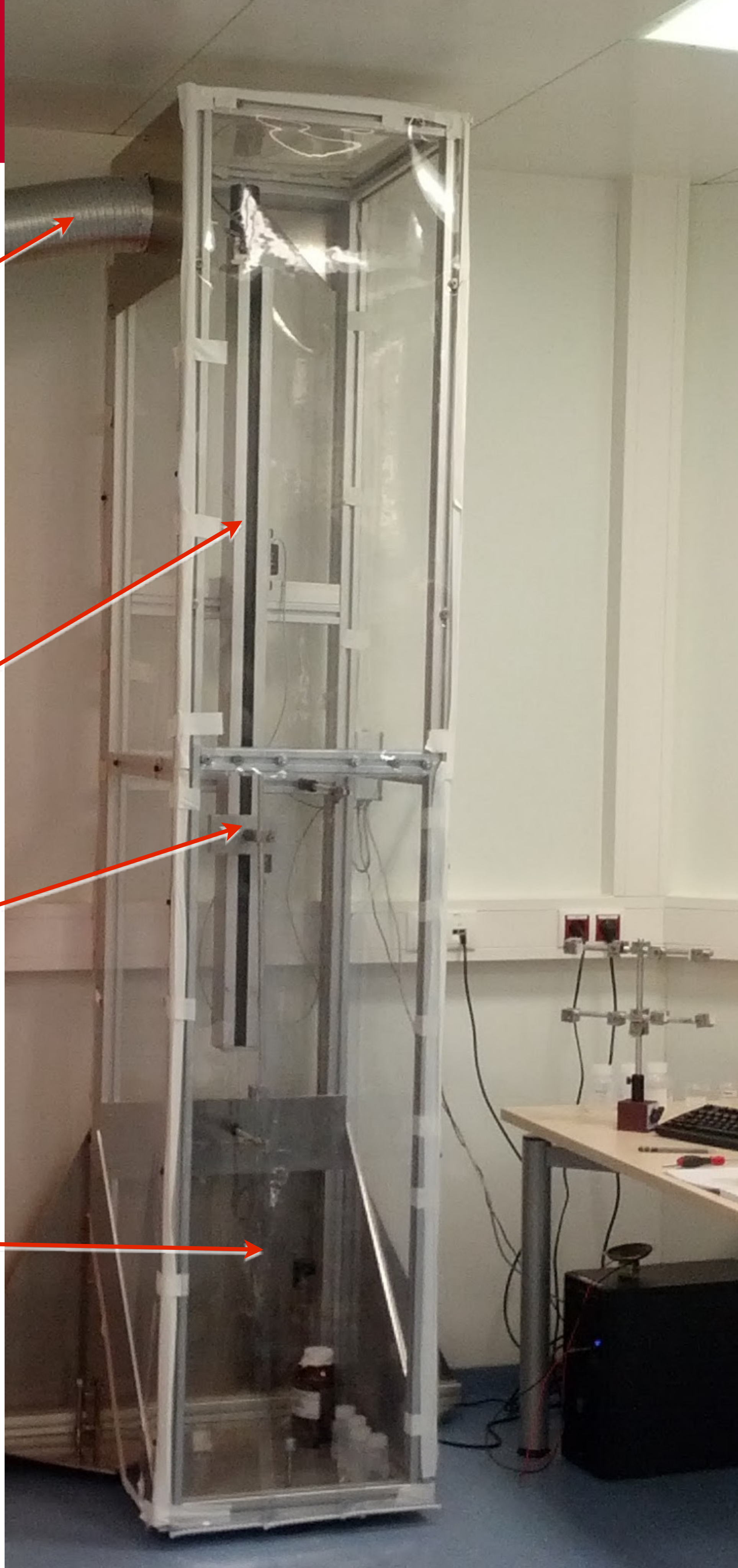
Dip coating

- slowly drag sample out of bath
  - very uniform WLS paint layer
- coating 90cm tubes (PMMA & Quartz)
  - Quartz → well reproducible

Average efficiency @ 150mm

- one-sided: ε = 24.3 ± 1%
- WLS fibers: ε = 3.1%





suction unit

linear motor

sample holder

paint container

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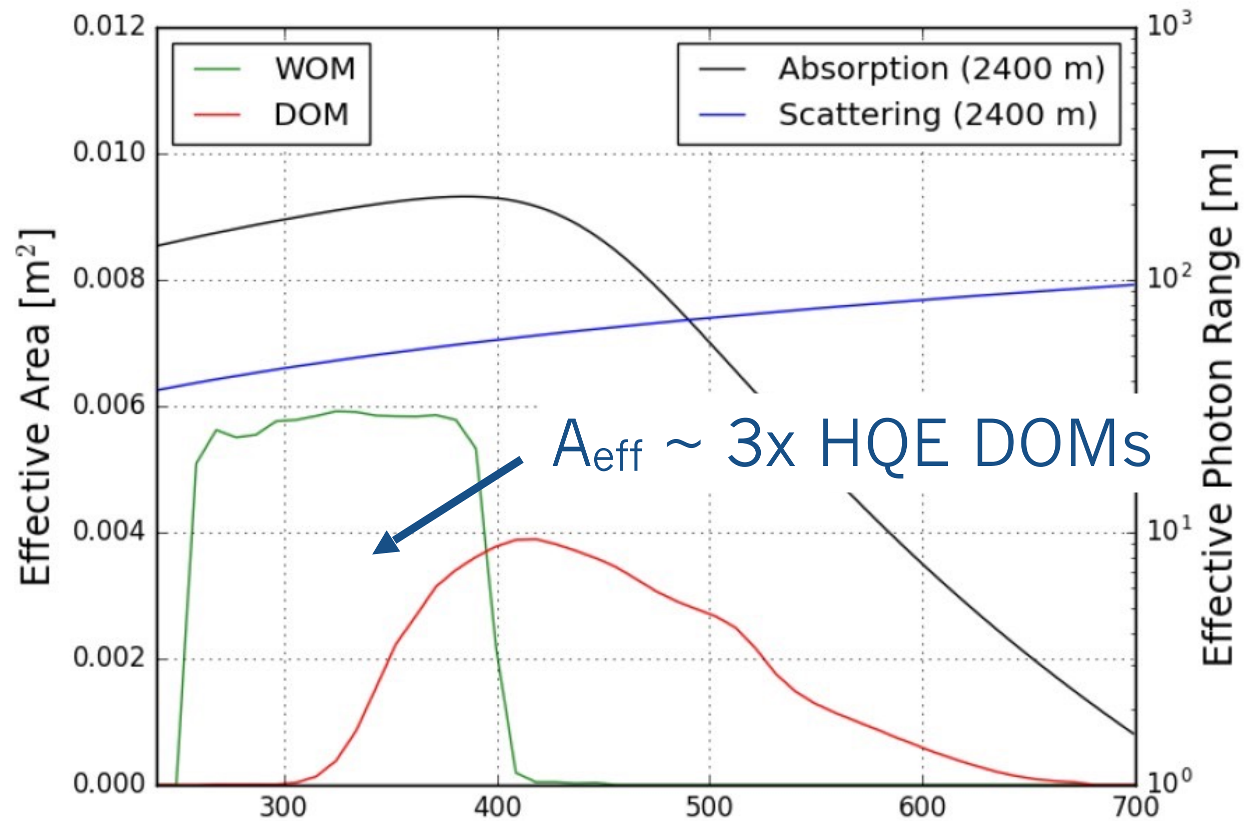
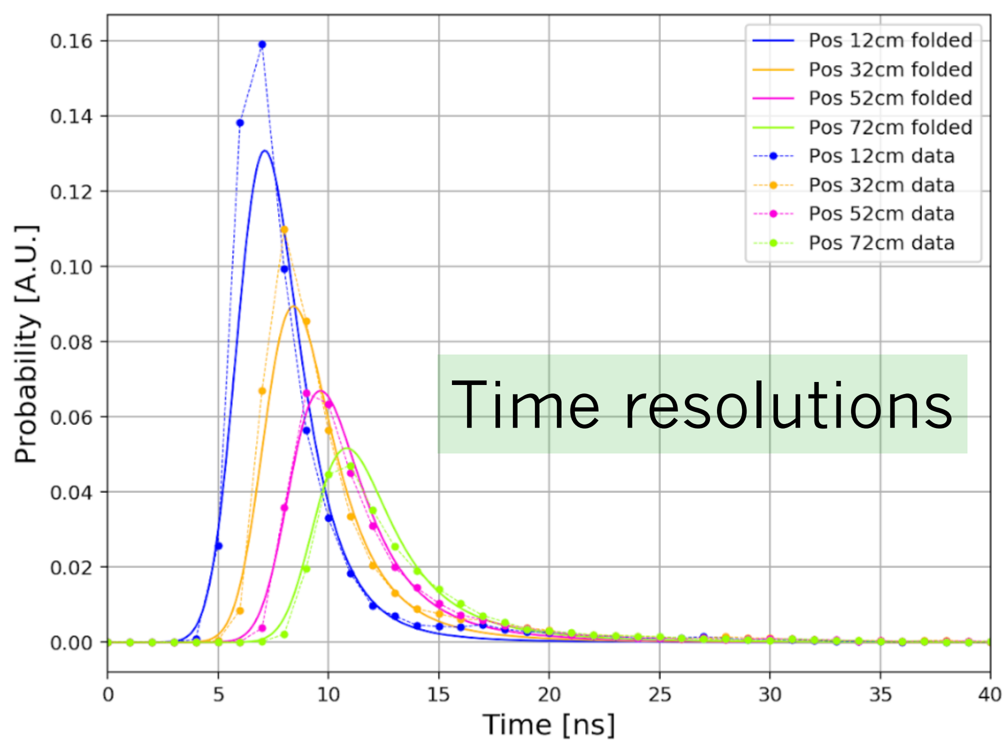
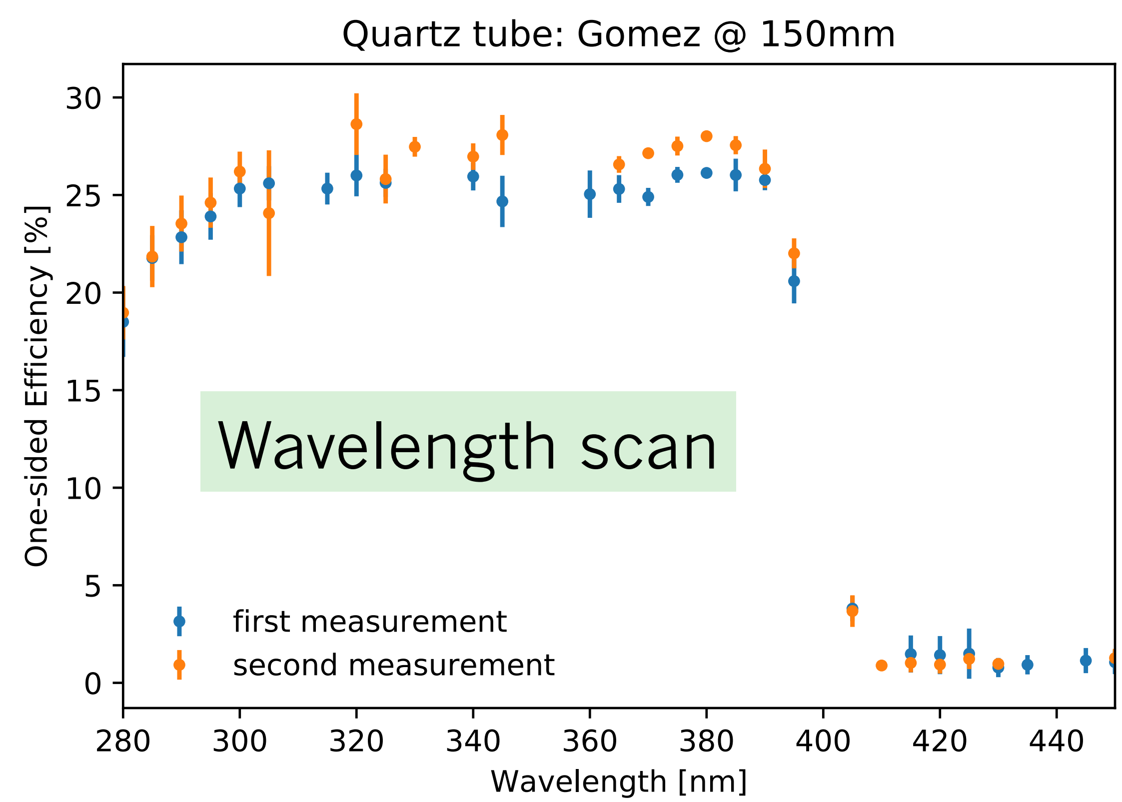
Wavelength-shifting module (WOM)

Features

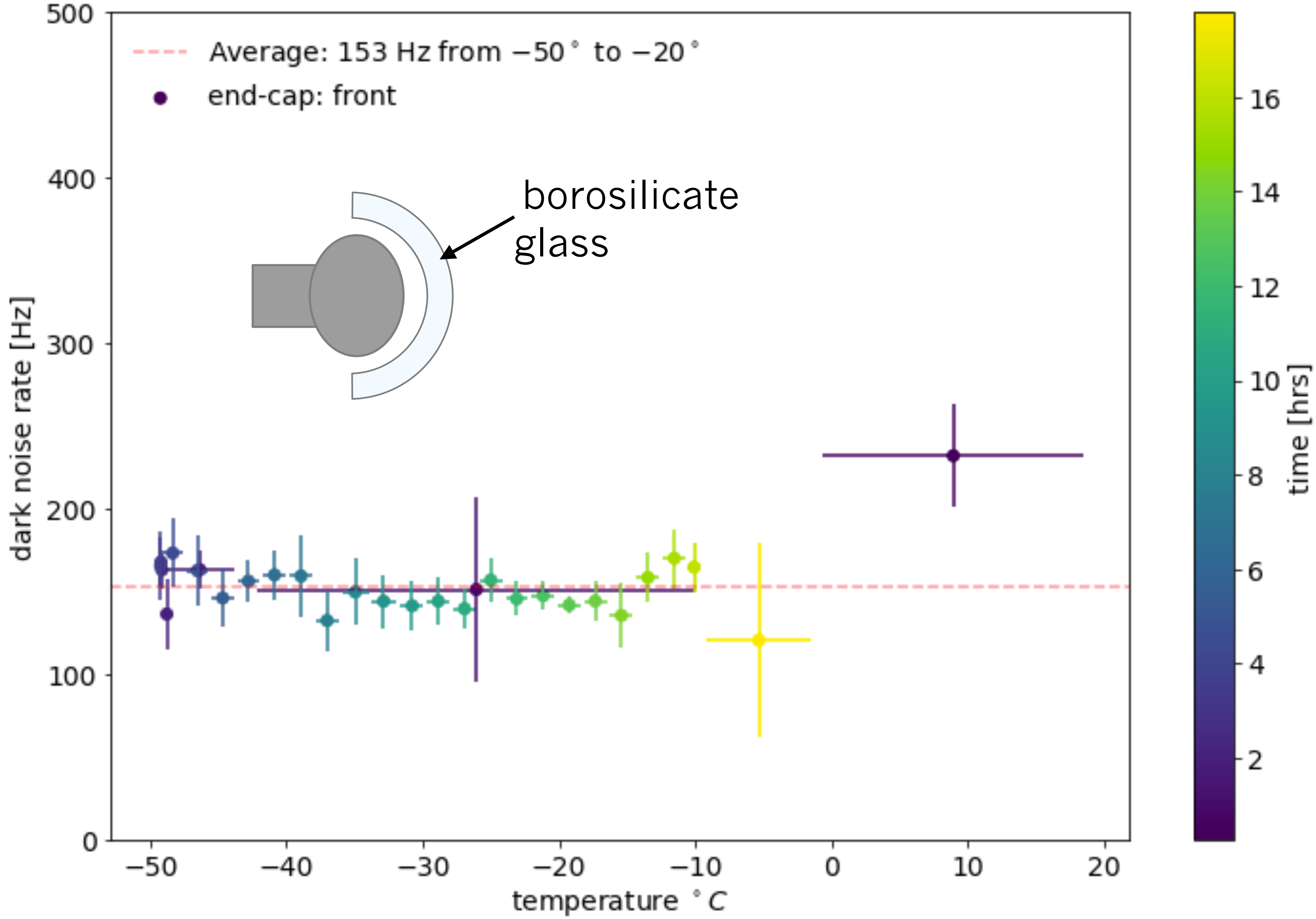
- **large collection area**
  - better UV sensitivity
- time resolution
  - $\sigma(t) \sim 10$ns
- **low noise rate ?**
  - freezer test







Noise measurements



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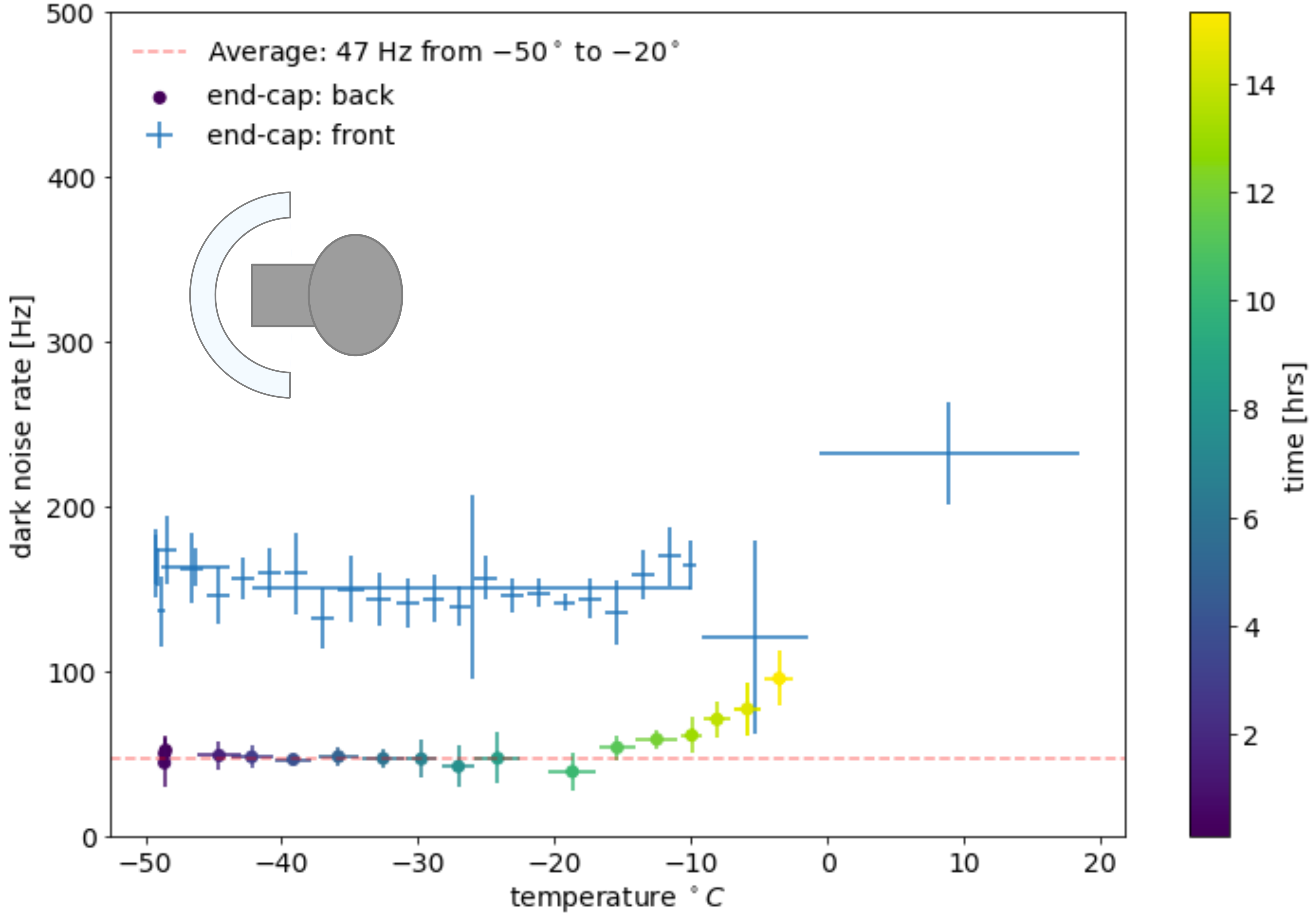

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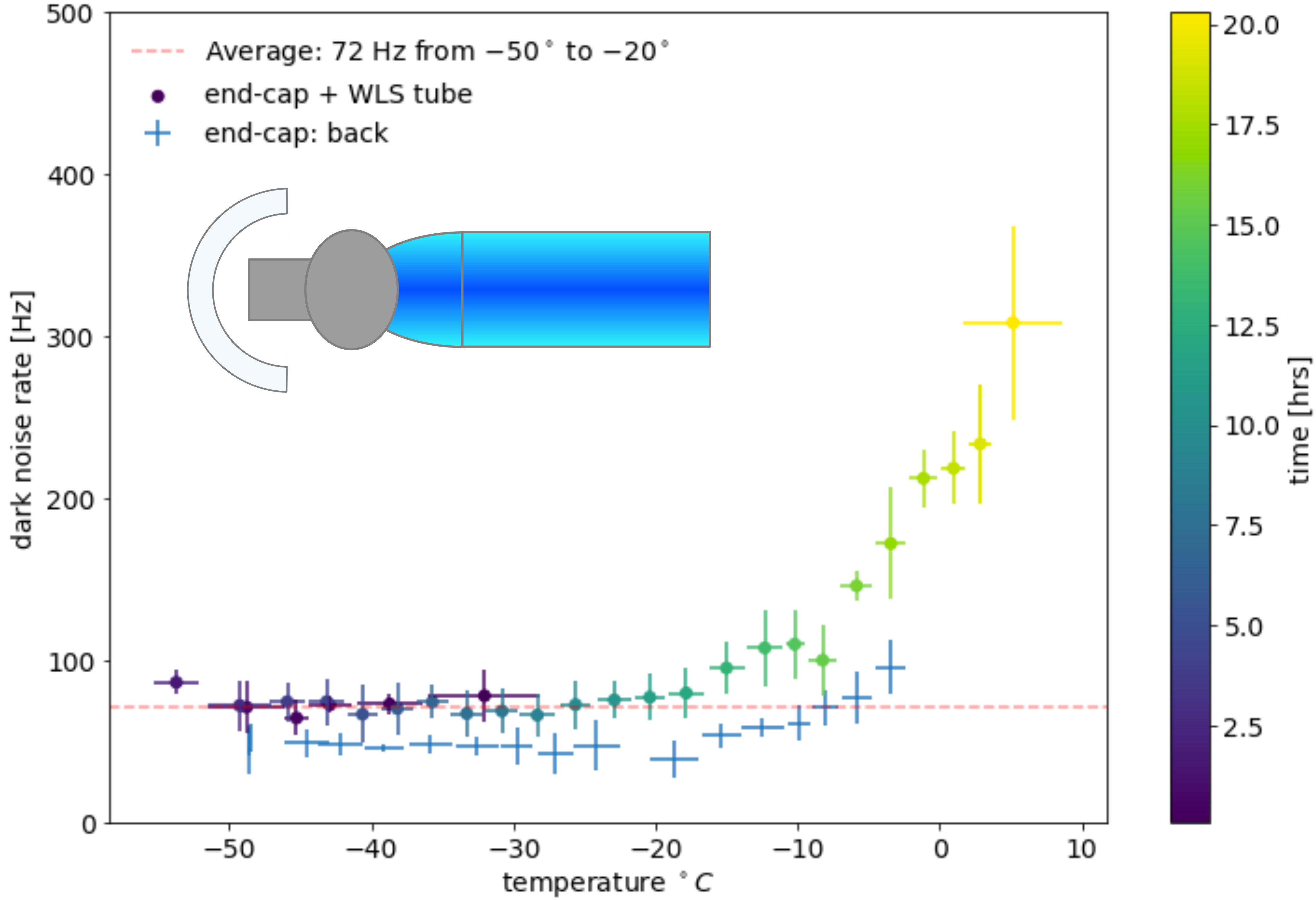

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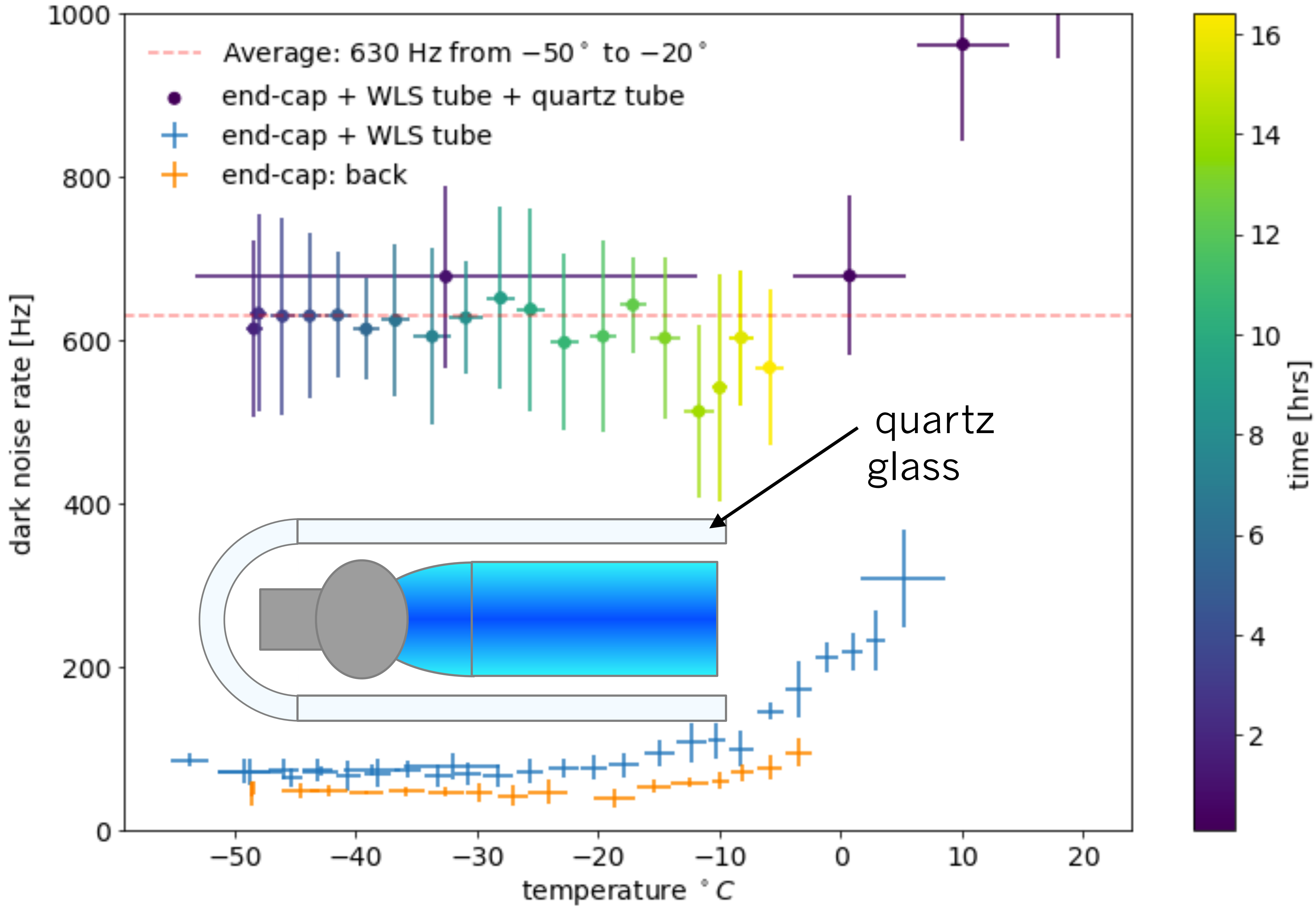

Quartz pressure housings

Measurements

- Long-duration gamma spectroscopy (4 samples)
- Neutron-activation analysis (1 sample)
  - **~150 Bq/g ^{238}U** in Quartz tubes from Nautilus!

Alternatives

- Heraeus quartz
  - typical < 10 Hz/tube
- SUP310
  - flame fused
  - down to < 200nm
- HSQ/HLQ
  - electrically fused
  - down to ~250nm

Heraeus

mBq/kg	226-Ra	228-Th	228-Ra	40-K	Price / tube [€]
HSQ 300	480±30	< 86	< 90	< 200	< 1400
SUP 310	< 29	< 46	< 43	< 100	< 6500
RQ200	350±120	< 270	< 370	< 1920	?
RQ500	520± 80	< 360	< 340	< 1150	?

Compatible with Heraeus data

WOM Summary

Passive light-concentration scheme

- WLS coated quartz tubes
  - **averaged two-sided collection efficiency** over 90-cm tube is **41 ± 1.7%** (reproducible!)

Noise rate is 75Hz/PMT

- **150 Hz** per module
  - A_{eff} ~ 3HQE DOMs (similar to mDOM)

Simple 3''PMT + 7cm∅ tube setup

- improvement in **SNR ~ 10** w.r.t to PMT alone
  - can be improved using adiabatic light guide

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MICA requirements

- 10 Hz per module
- 5x Aeff of HQE DOMs
  - **way to go but maybe not crazy ?**

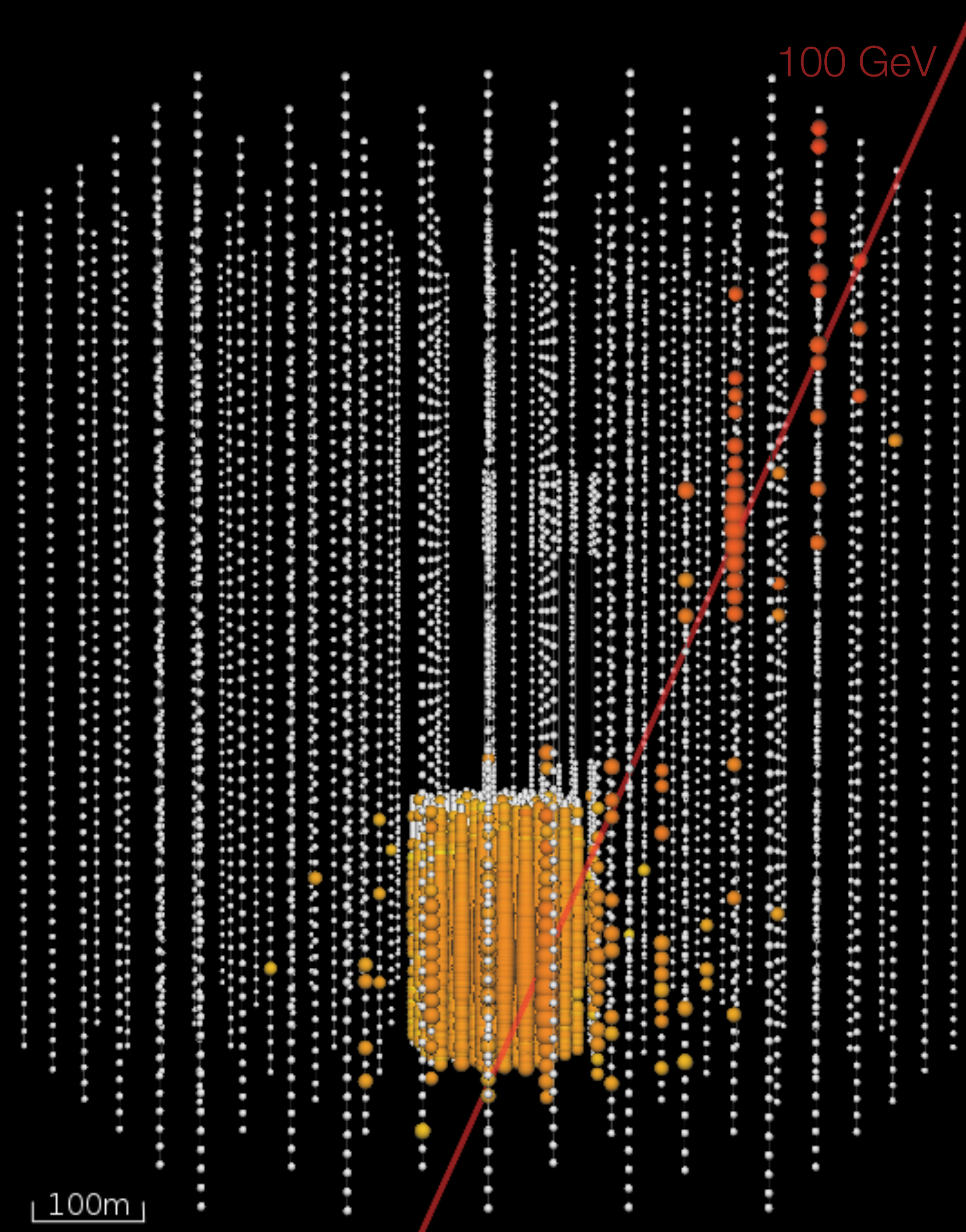
Atmospheric backgrounds

Atmospheric muons

- $R(\mu) \sim 230$Hz
  - easily recognizable
- photon diffusion time ~ 7μs
  - deadtime 0.16%

Atmospheric neutrinos

- $R(\overline{\nu}_e) = 0.4$mHz
  - ν_e suppressed (only ES, no IBD)
- Michel electrons from ν_μ
  - $\nu_\mu + N \rightarrow \mu_{invisible} \rightarrow e + \nu_\mu$
  - R(Michel) ~ 3mHz
  - need to veto showers



The shallow ice

Ice properties at 750-1050m

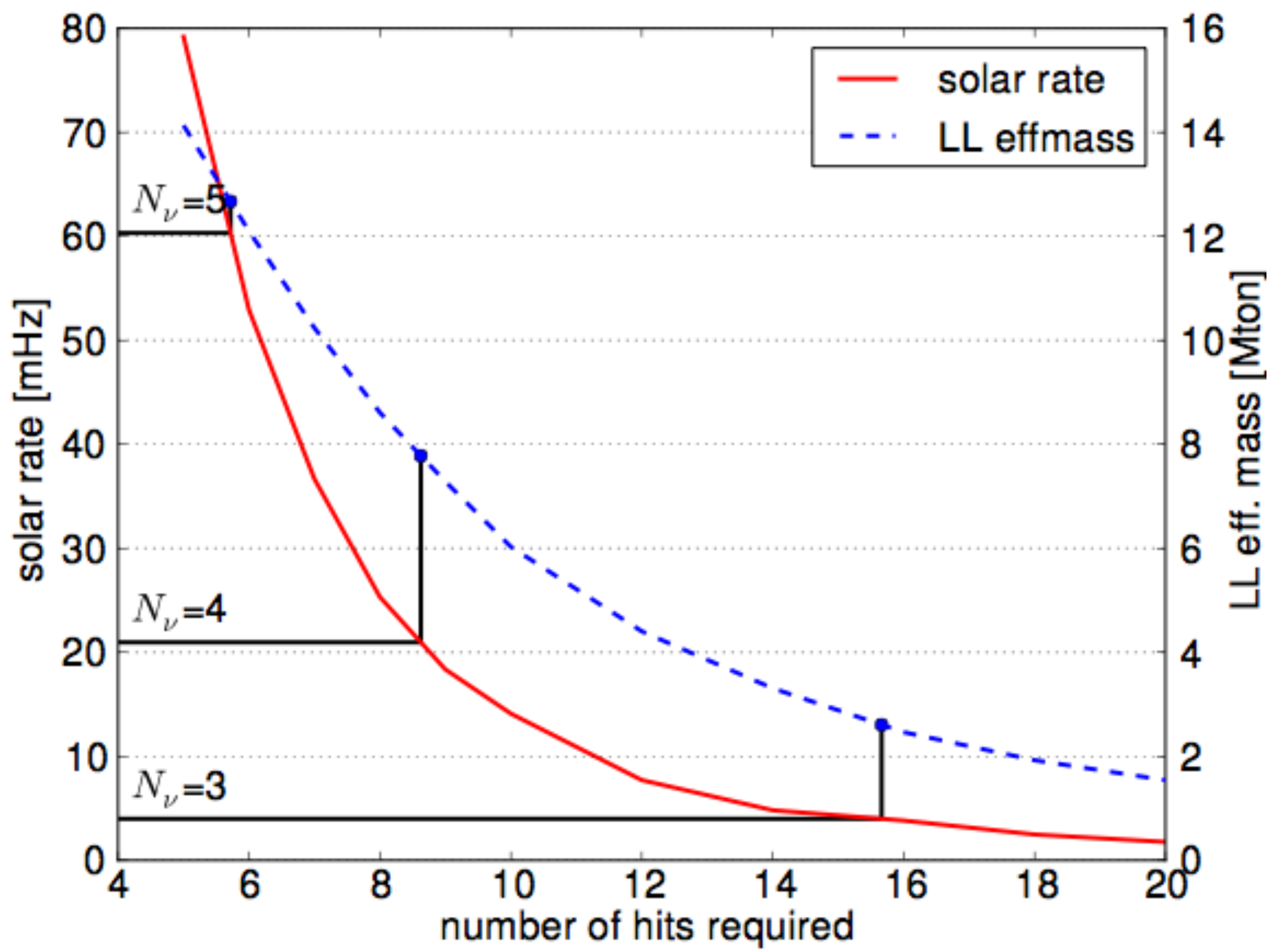
- absorption λ_a = 350m
- scattering λ_s = 0.3m
  - calculate photon yield analytically

Photon diffusion model

- easily get >10Mton...
- ... but **no reconstruction**

Backgrounds

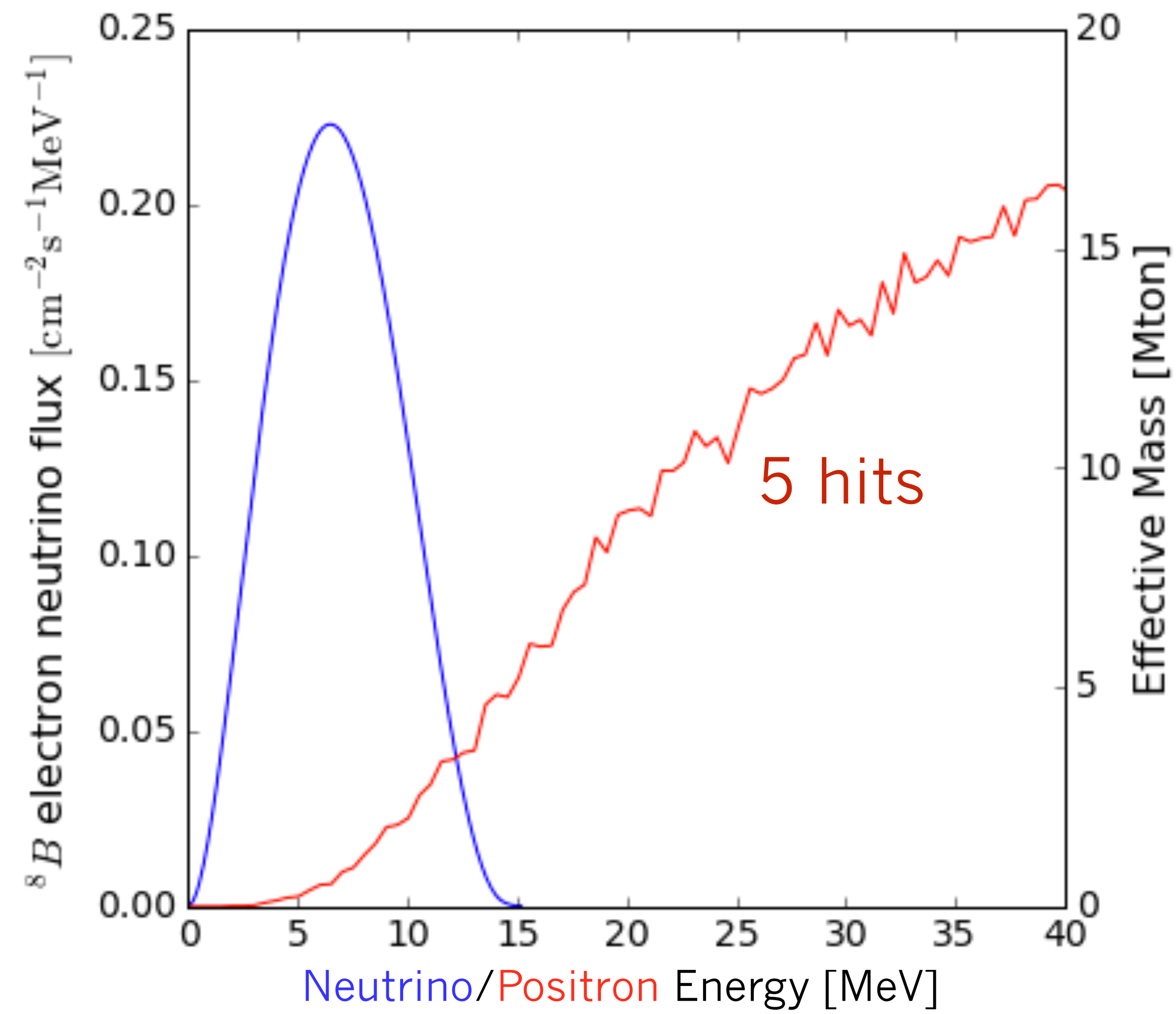
- atmo. μ deadtime = 14%
  - more spallation...
- solar rejection
  - only by energy → tough



Solar background

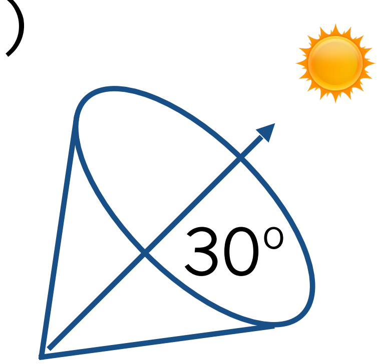
Solar flux

- several generation cycles
- most important
  - ^{8}B flux with $E^{max}(\nu_e)$ = 15 MeV
- only ν_e, no $\overline{\nu}_e$
  - only elastic scattering (ES)
  - R(^{8}B) = 30mHz



Rejection options

- energy
  - not sufficient
- direction (ES mostly forward)
  - cut cone with σ(ψ) = 30°
  - R(^{8}B) = 1mHz



	solar ν_e	SNe ν
5 hits	30mHz	100 %
6 hits	18mHz	85 %
7 hits	10mHz	69 %

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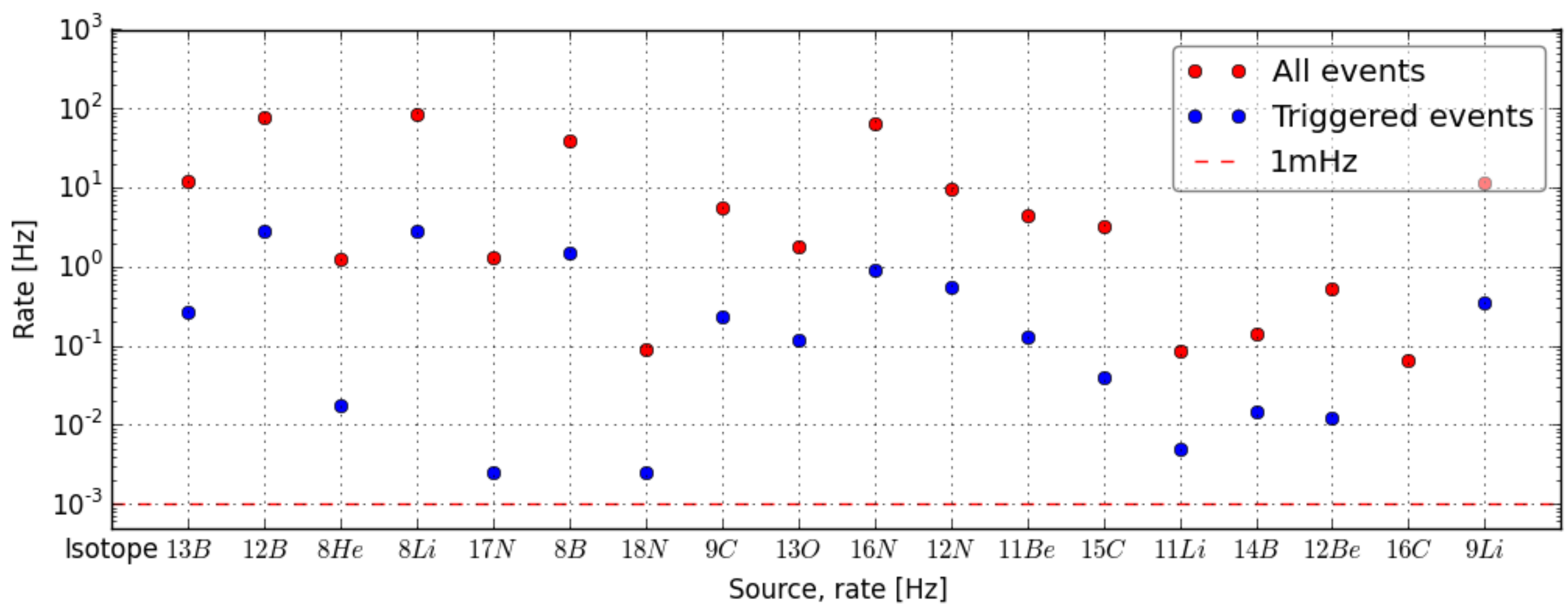
Spallation background

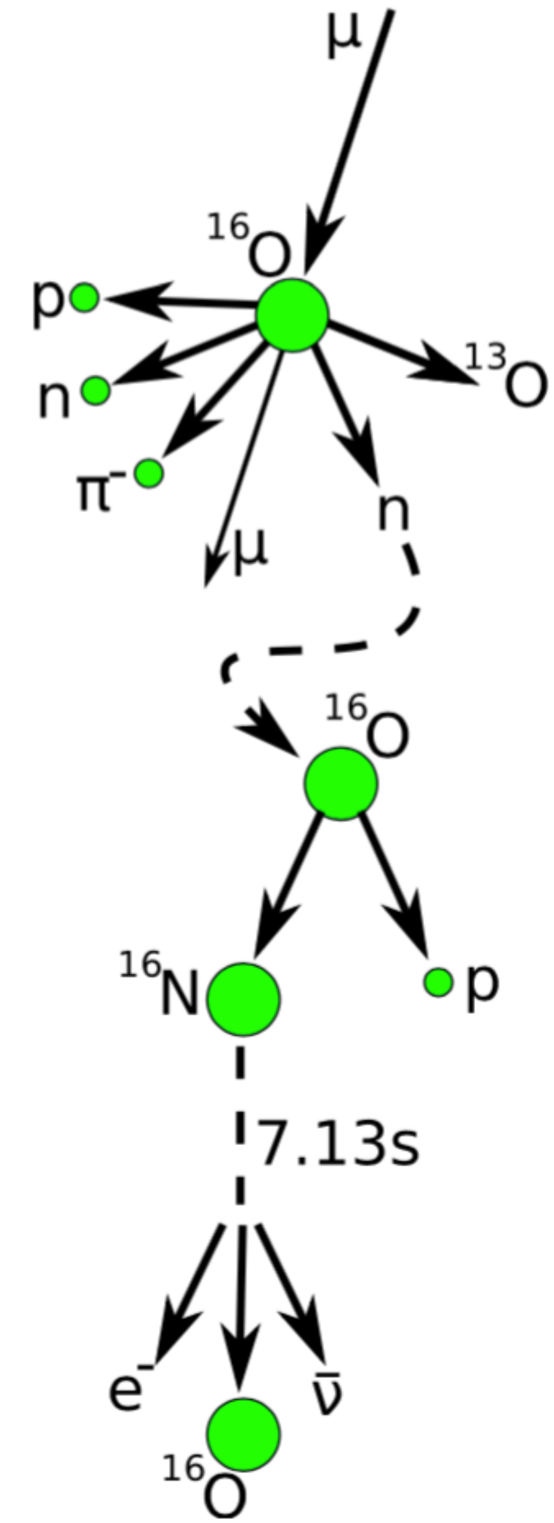
E. Lohfink, master thesis

Muon-induced spallation

- direct production of unstable isotopes
  - mostly short-lived (→ μs)
- neutron/pion captures
  - long-lived isotopes (→ **seconds**)

- R(spallation) = 36,8 Hz*



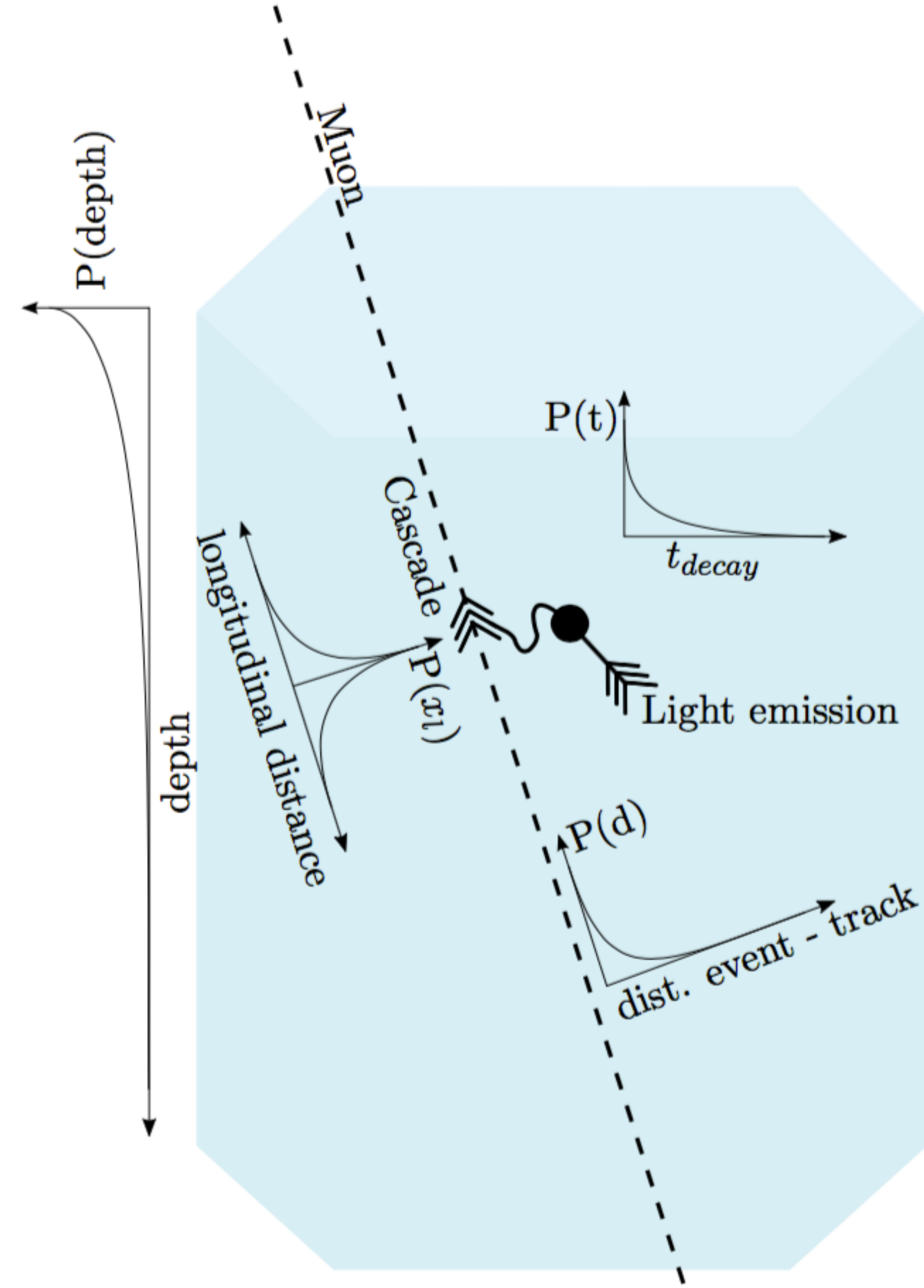


* Caveat: air in ice not included yet

Spallation rejection

Likelihood approach

- time relative to muon
  - many short-lived isotopes
- distance to muon track
  - neutrons propagate ~ meters
- depth in detector
  - flux decreases to bottom



Additional option

- isotopes (n,π,...) are generated in secondary cascades
  - identify showers along track

Spallation rejection

E. Lohfink, master thesis

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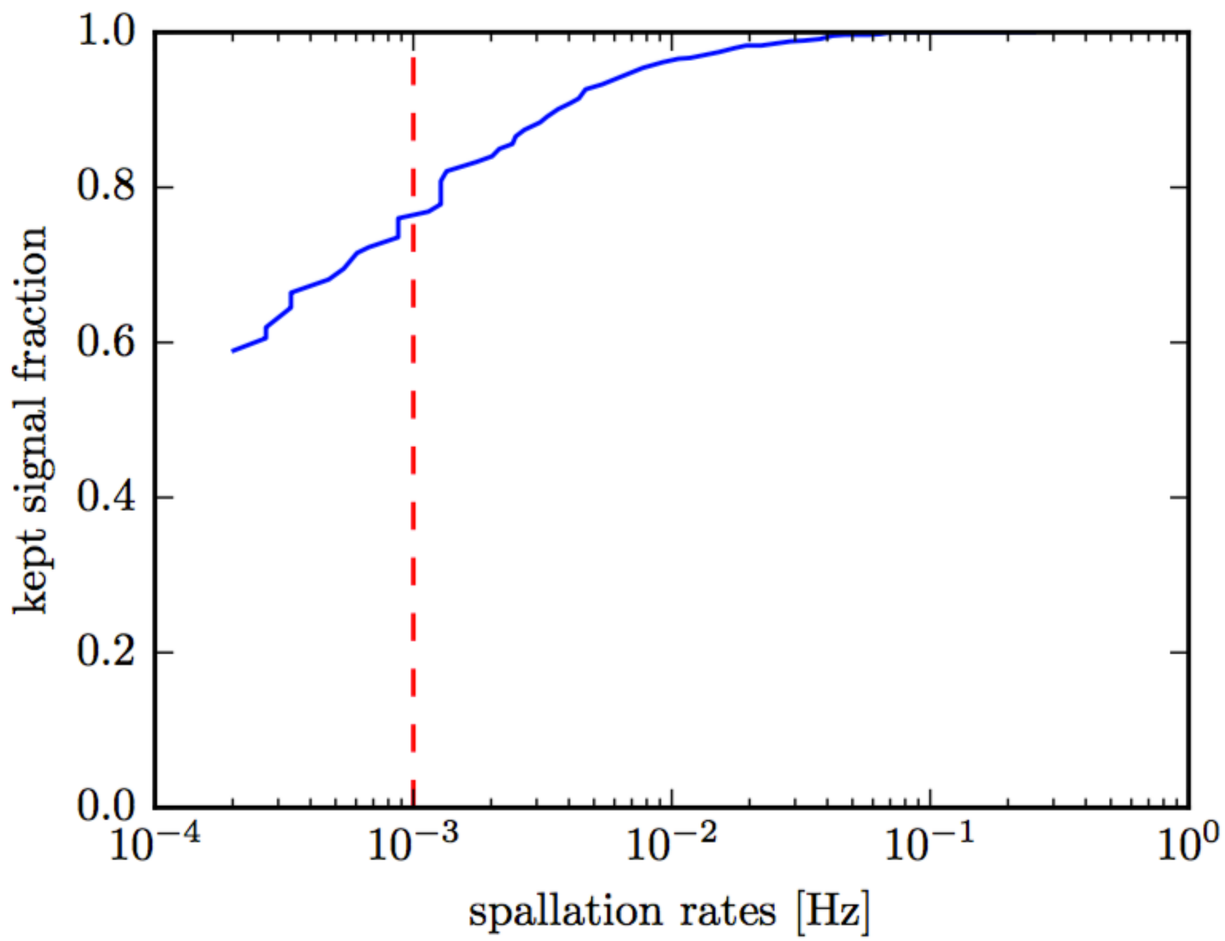
→ 85% signal at 1mHz spallation



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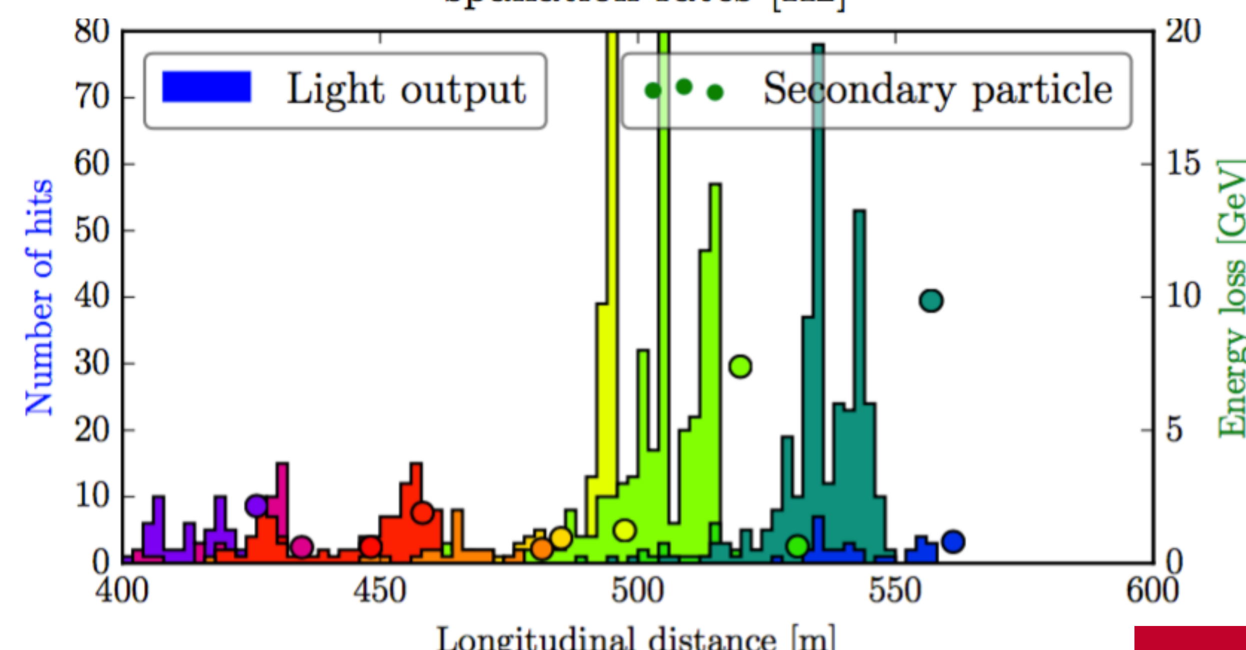


Supernova rate estimates

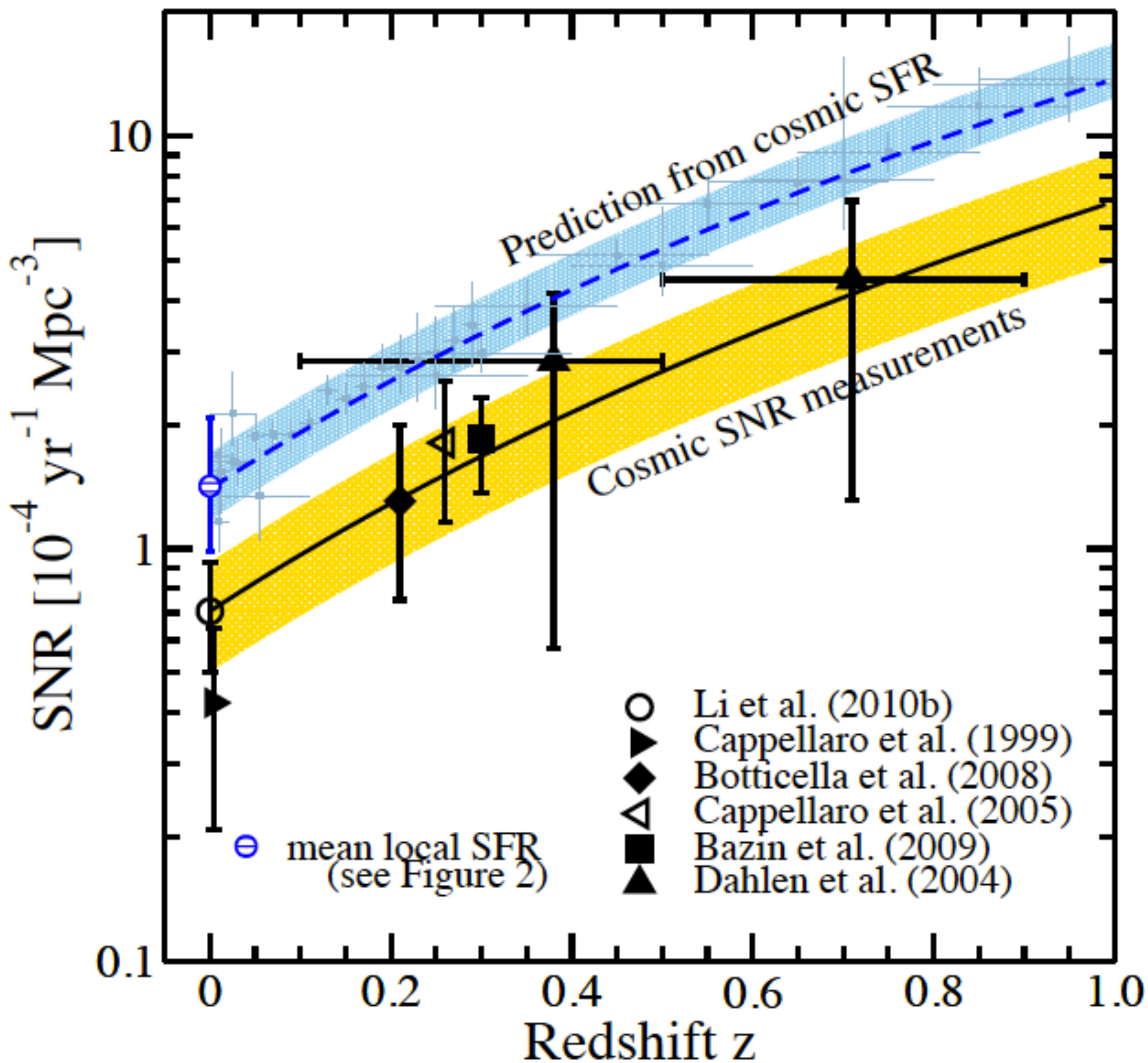
Supernova rate (SNR)

- cosmological SNR
  - proportional to galaxy blue luminosity

Star formation rate (SFR)

- heavy stars short-lived
  - SNR ∝ SFR
- cosmic SFR
  - twice as high as cosmic SNR
- many missed (e.g *dark*) SNe?

[S. Horiuchi, et al, arxiv:1102.1977v2]



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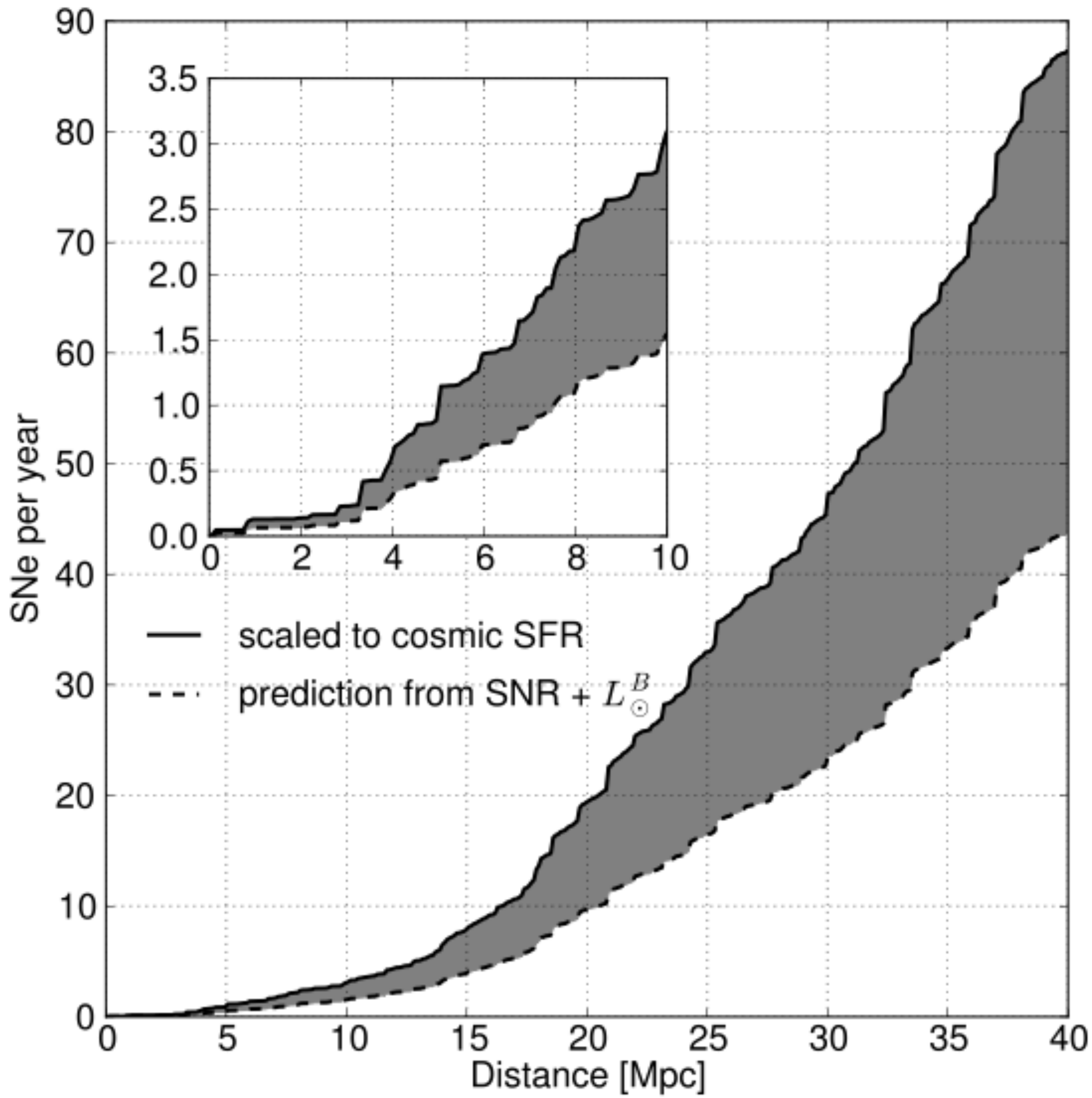


Black hole vs. neutron star

Neutrino signature

- inverse beta decay
  - $\nu + p \rightarrow e^+ + n$
- near-thermal profil

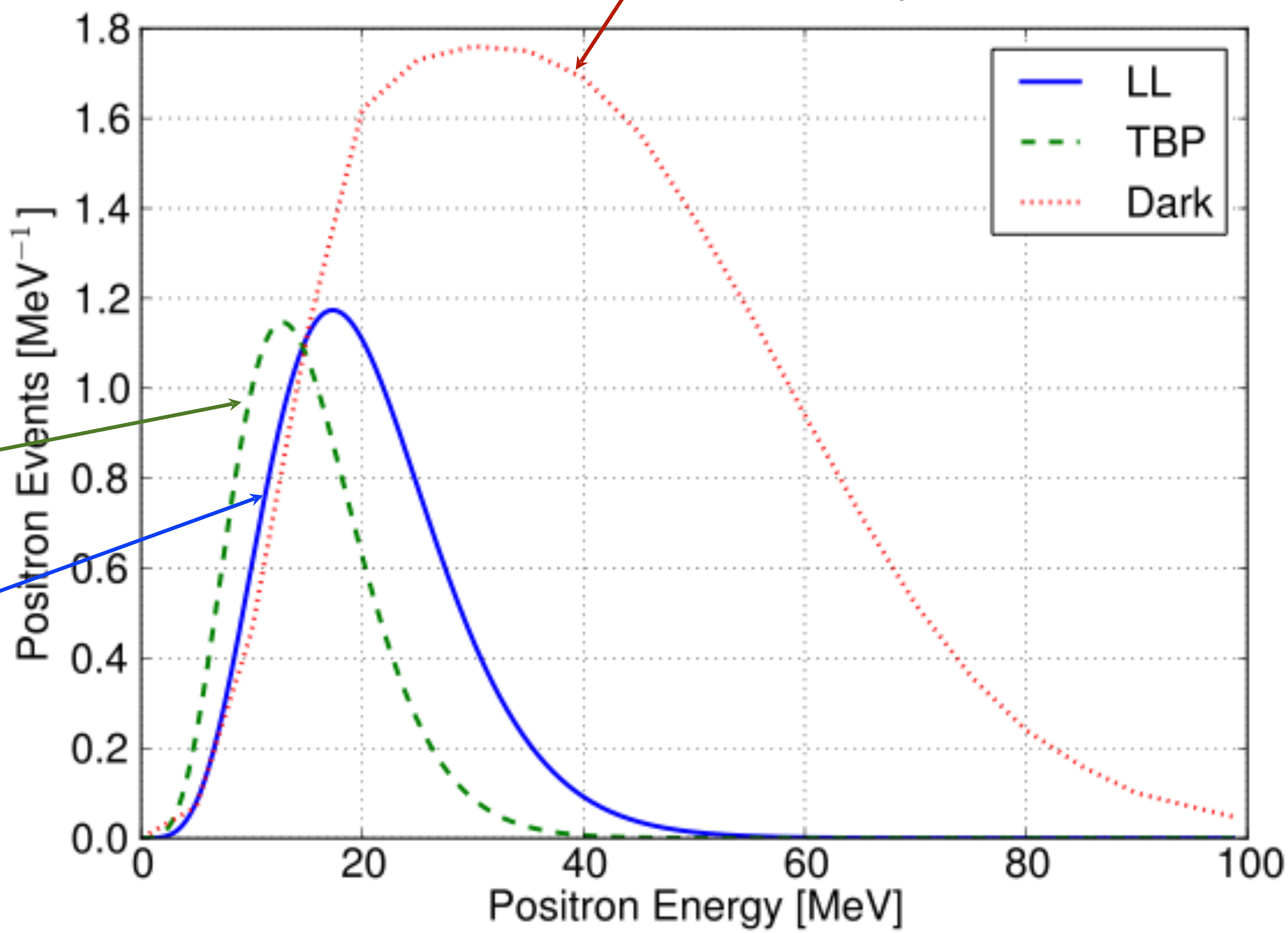
[Nakazato et al., PRD 78 (2008)]

Black hole

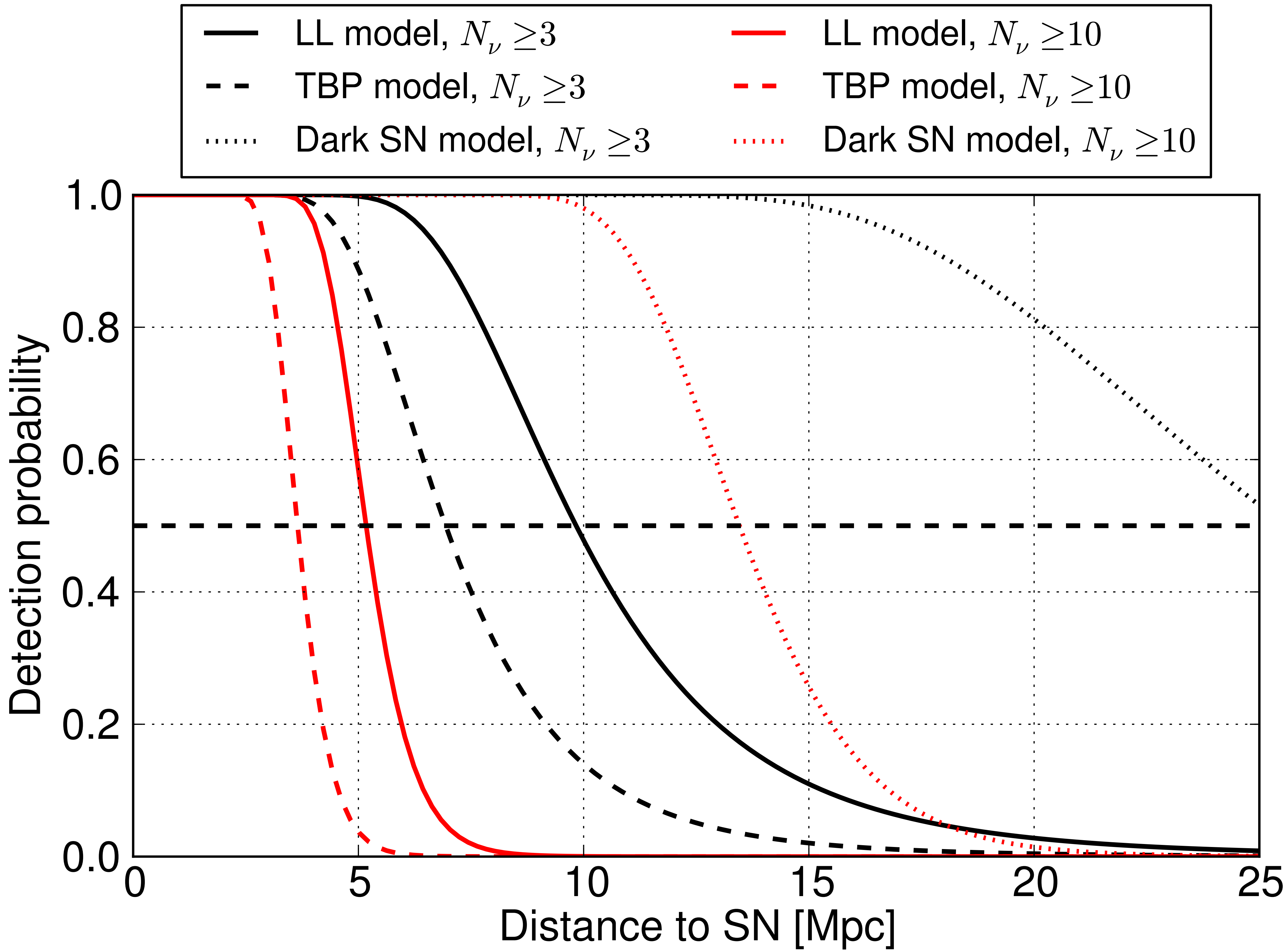
- failed SNe
  ➔ optically dark

Neutron star formation

- TBP model
  [Thompson et al., APJ 592 (2003)]
- LL model
  [Totani et al., APJ 496 (1998) 1]



Supernova detection probability



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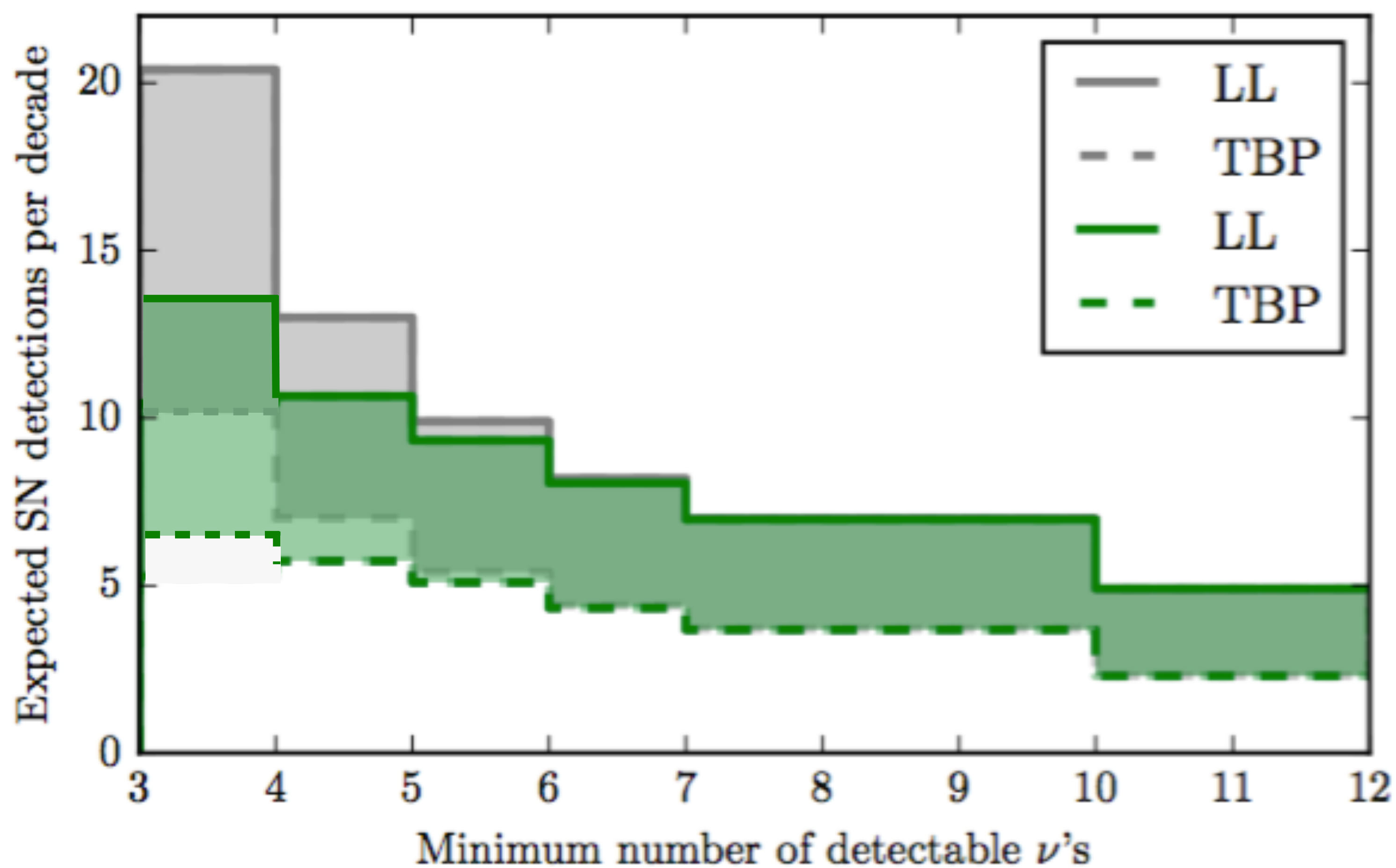
Are we there?

SNe detection range

- collapse to neutron star
  - reach 6-9 Mpc
- collapse to black hole
  - reach 25 Mpc

SNe detection rate

- from blue luminosity
  - **min. 1 SNe every 2 years**
- from star formation rate
  - **2-4 SNe per year**
- direct BH formation
  - *additional* **3-4 SNe per year**



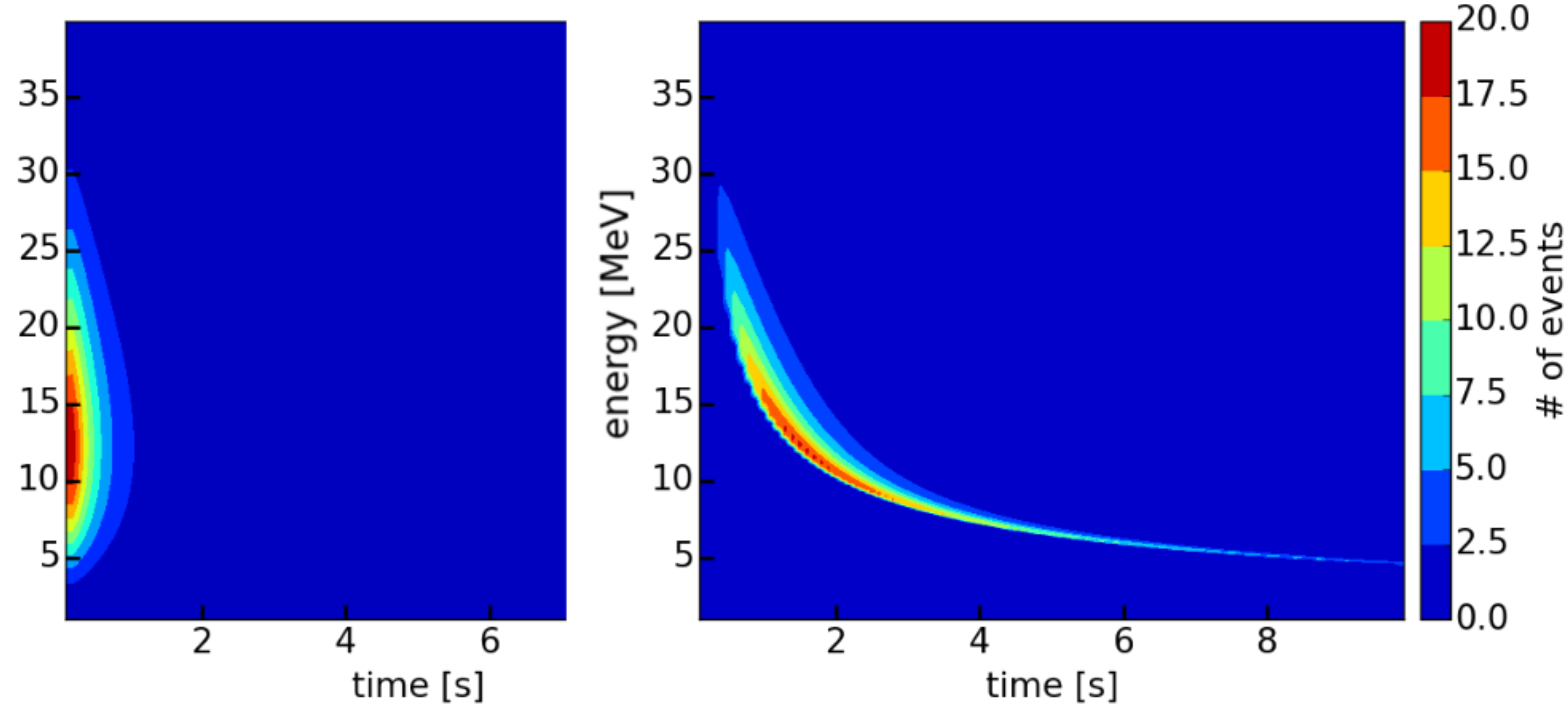
Astrophysics

- solve SNe rate puzzle
- are there dark SNe?
- ...

Particle Physics

- neutrino oscillations
- neutrino mass ordering
- **neutrino mass?**
- ...

$$\Delta T = D/2\,(m_\nu/E_\nu)^2$$



$m_{\overline{\nu}_e} = 0\,\mathrm{eV}$ $m_{\overline{\nu}_e} = 2\,\mathrm{eV}$

Physics with SN neutrinos

$\Delta T = D/2\,(m_\nu/E_\nu)^2$

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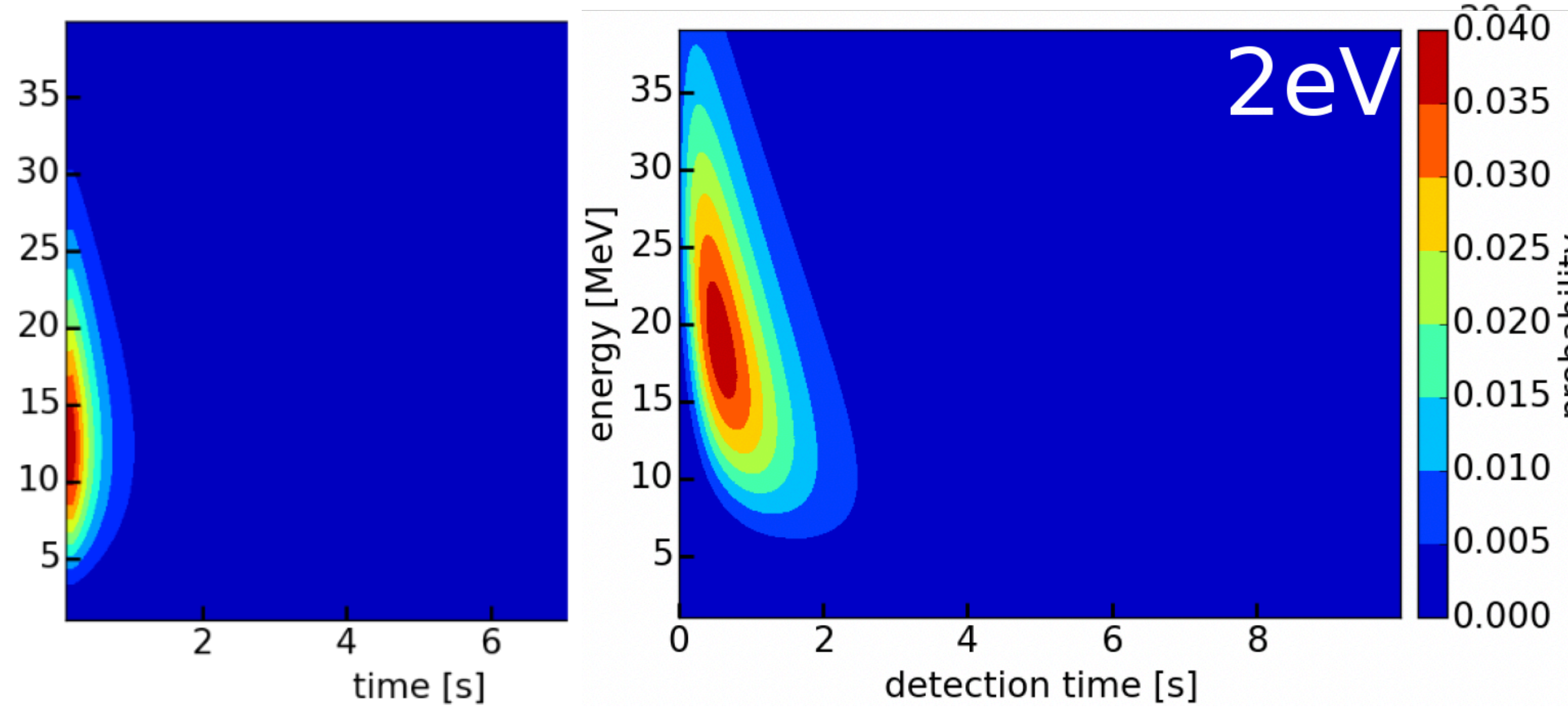


$m_{\overline{\nu}_e} = 0\,\mathrm{eV}$ $m_{\overline{\nu}_e} = 2\,\mathrm{eV}$

Need to account for

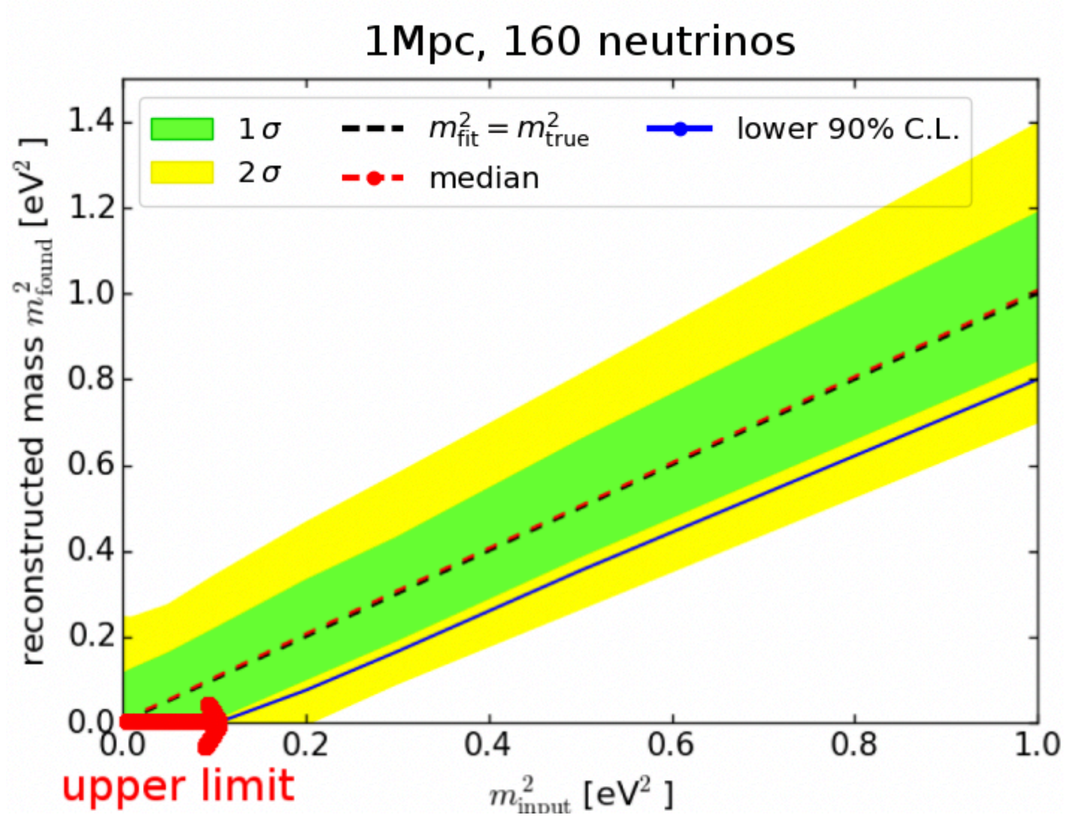
- start time resolution (1st hit)
- trigger efficiency (simulation)
- energy resolution (number of hits)
- backgrounds (uniform, 1mHz)
- systematics uncertainty in
  - light curve
  - spectrum

→ not yet included

Neutrino mass sensitivty

Single SN analysis

- likelihood approach (E_ν,t_ν)
- sensitivity is highest mass which gives 90% CL to reconstruct non-zero mass



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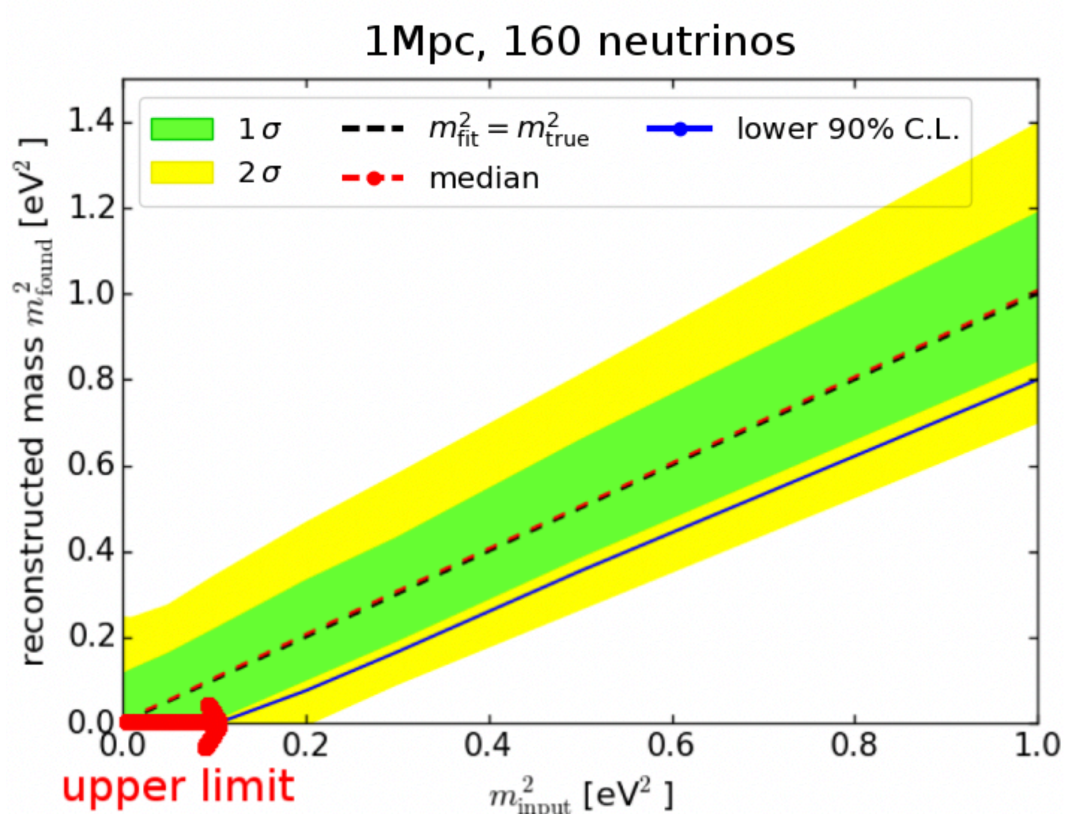
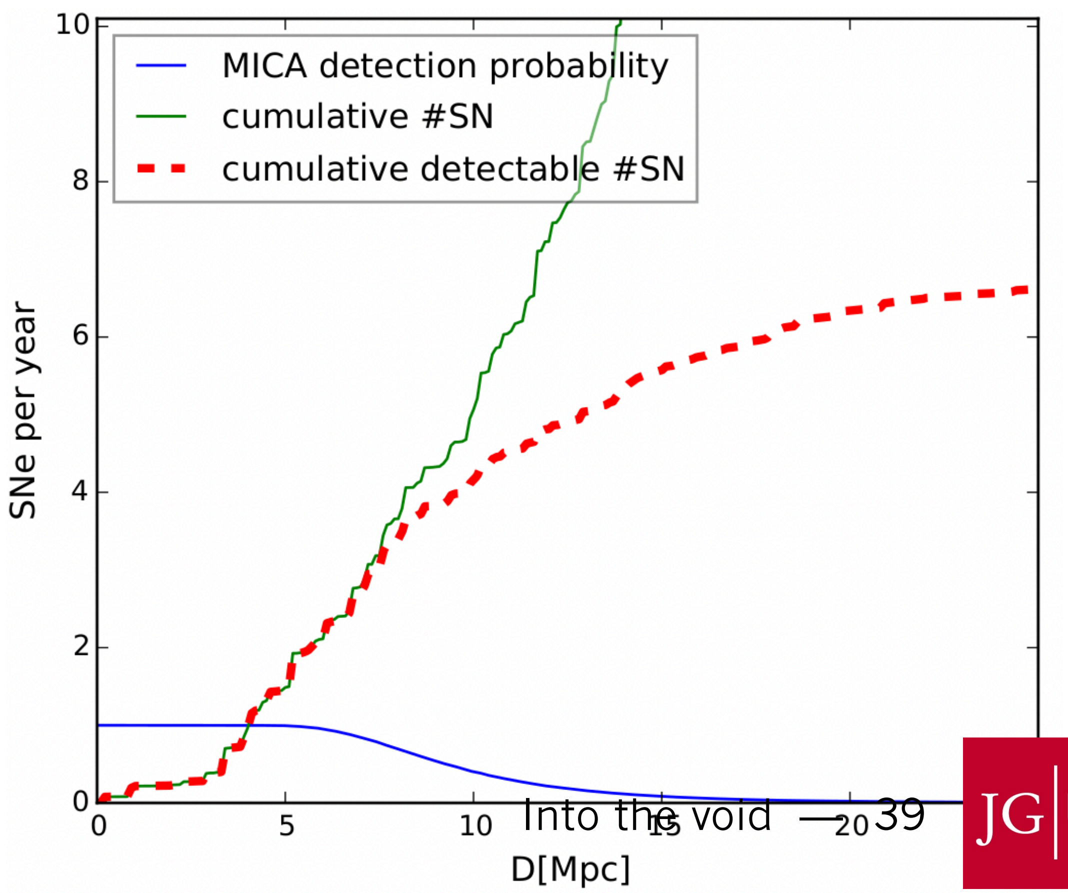
- draw realistic SN distances
- combine SNe information by minimizing LLH sum

$$\sum_{\mathrm{SNe}} \mathscr{L}\left(E_i, t_i \,|\, m_\nu\right)$$





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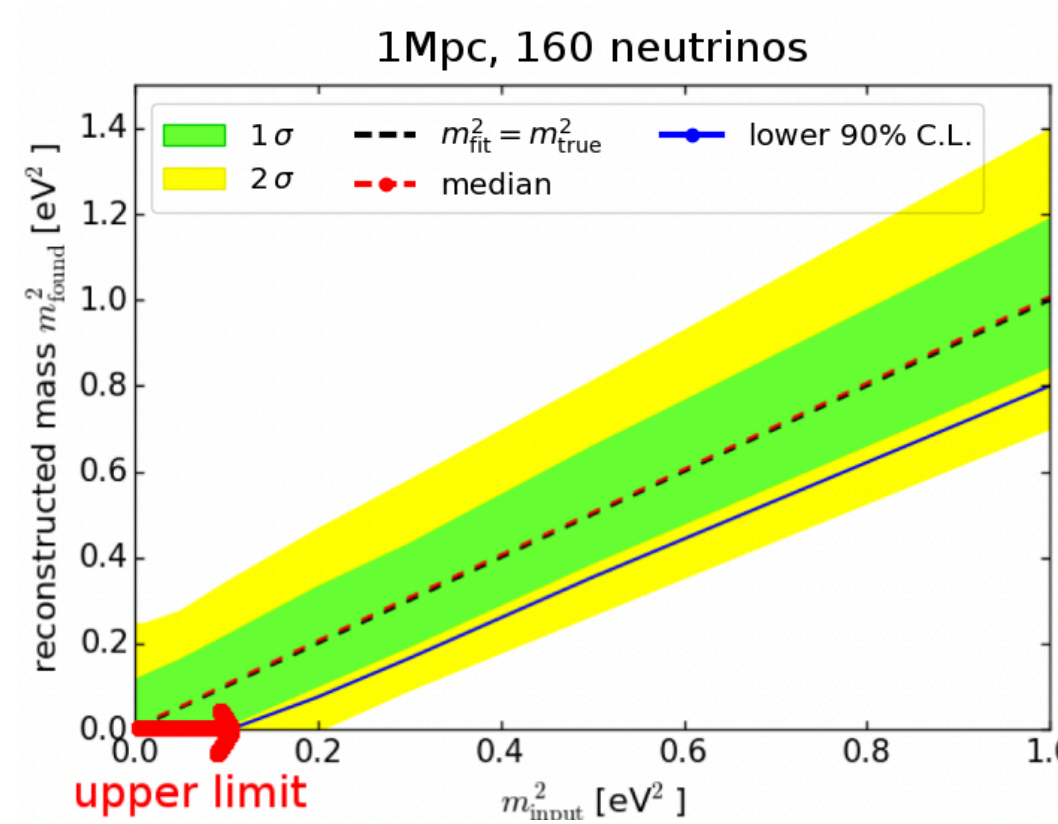
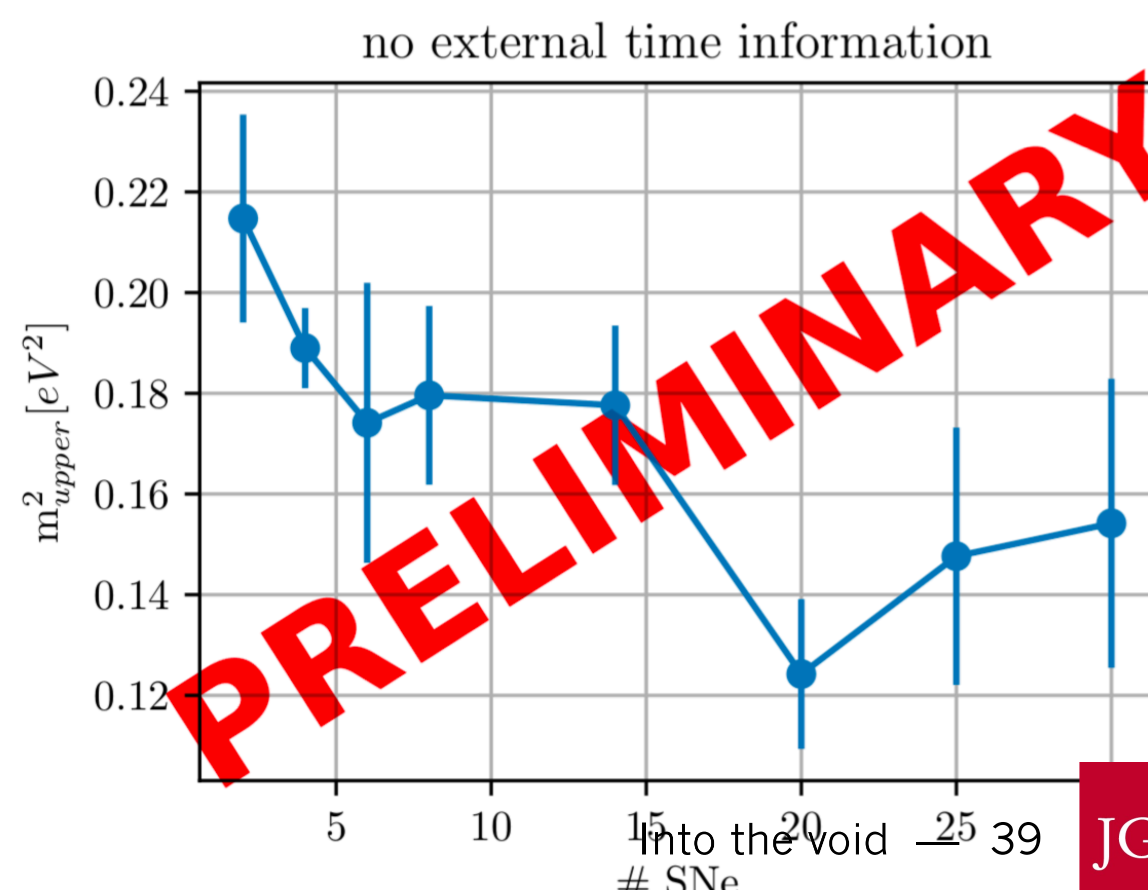
Results from ensemble fit

- $m_\nu \leq 0.35$eV
  - in up to 7.5 years runtime (30SNe)
- mostly limited by start time resolution





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Summary

- IceCube's chances of detecting SNe in MeV neutrinos mostly limited by
  - "*small*" effective mass of detector
  - low number of SNe in local environment

  → need **O(10Mton)** detector = **MICA**

- **Background** rejection is critical
  - very low-noise sensors required
  - spallation background can be rejected
  - solar neutrino still require some effort

  → have not used sub-threshold events yet

- However, we may not be so far from...

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Thank you!